# Superconducting Technology for Future Colliders and Detectors

**Akira Yamamoto**
(KEK and CERN)

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September 8, 2023

# *Acknowledgements*

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***for their kind cooperation and information*** *provided for preparing this talk.*

# References:

**Overview:**

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- N. Mounet (Editor), "European Strategy for Particle Physics, Accelerator R&D Roadmap", CERN Yellow Report, CERN 2022-001. (2022),

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- U. Bassler, "A portfolio of HEP Colliders",
- G. Bisoffi and P. Mcintosh, et al., "RF achievements and plans",
- A, Siemko, "High field magnet R&D programme status of HFM within the accelerators roadmap".
- J.G. M.Jimenez, "Magnet developments for future physics programmes",

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- A. Ballarino, "HTS developments".

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- T. Roser et al., "On the feasibility of future colliders", Snowmass'21 Implementation Task Force, 2023 JINST **18**, P05018 (2023).
- S. Belomestnykh amd S. Posen, I., "Key directions for research and development of superconducting radio frequency cavities", arXiv:2204.01178.
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- S. Gourlay, T. Raubenheimer, and V. Shiltsev , "Snowmass'21 Accelerator Frontier"
- S. Belomestnynkh, "ILC and SRF " (not uploaded).
- S, Prestemon, "Magnets for energy frontier colliders", US-P5 Townhall meeting, May 2023.

**AFAD-2023:**

- K. Umemori, "Development of SRF technology at KEK-iCASA" Asian Forum for Accs & Detectors 2023.

# Outline

- **Introduction :**
  - Future Colliders baaed on **S**uper**c**onducting (Sc) Technology

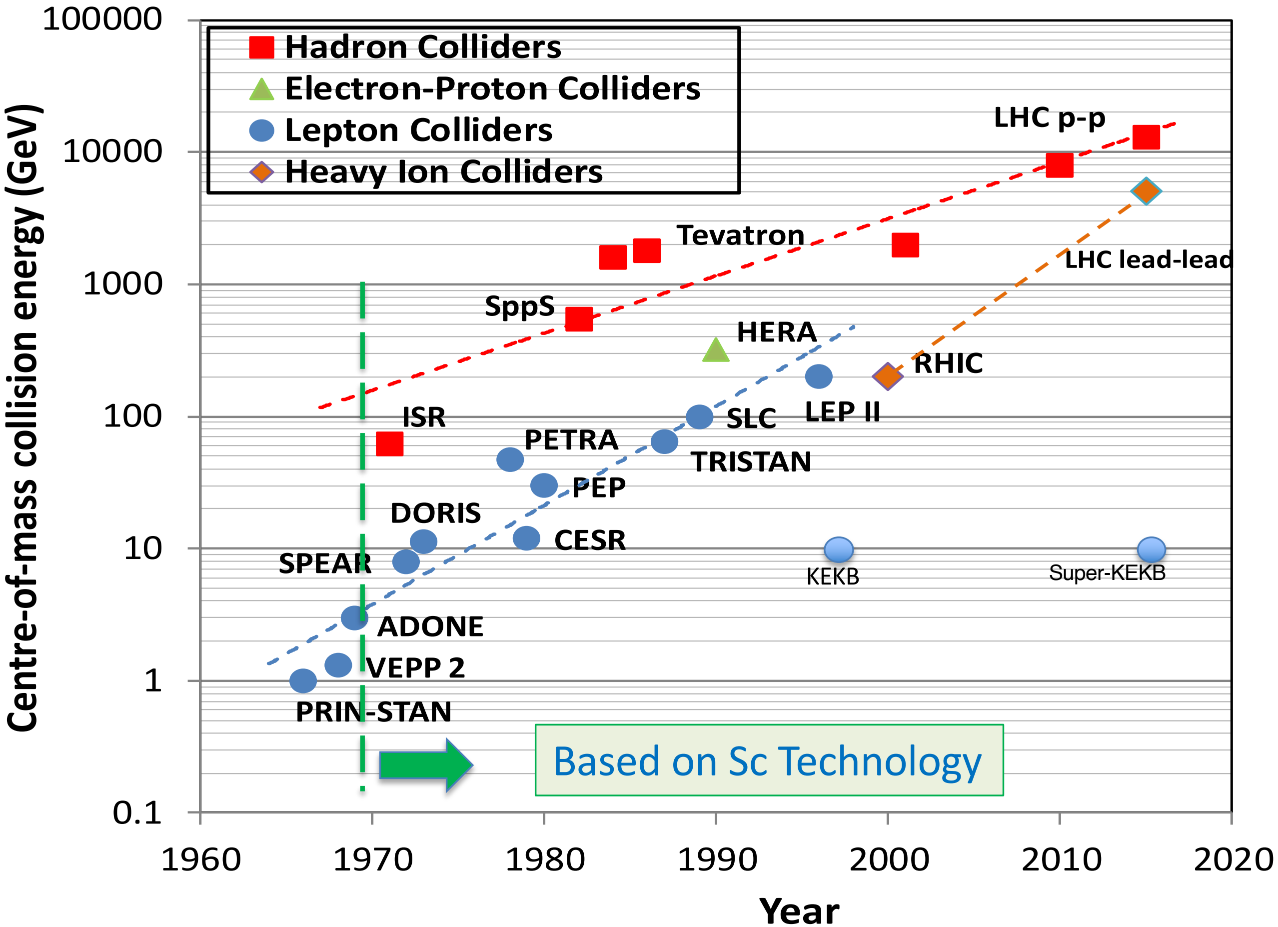
- **Sc Technology for Colliders:**
  - Sc RF Cavities
  - Sc Magnets

- **Sc Technology for Detector Magnets**

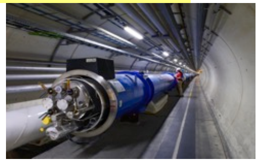
- **Summary**

# Frontier Accelerators based on SC Technology

Courtesy, A. Ballarino



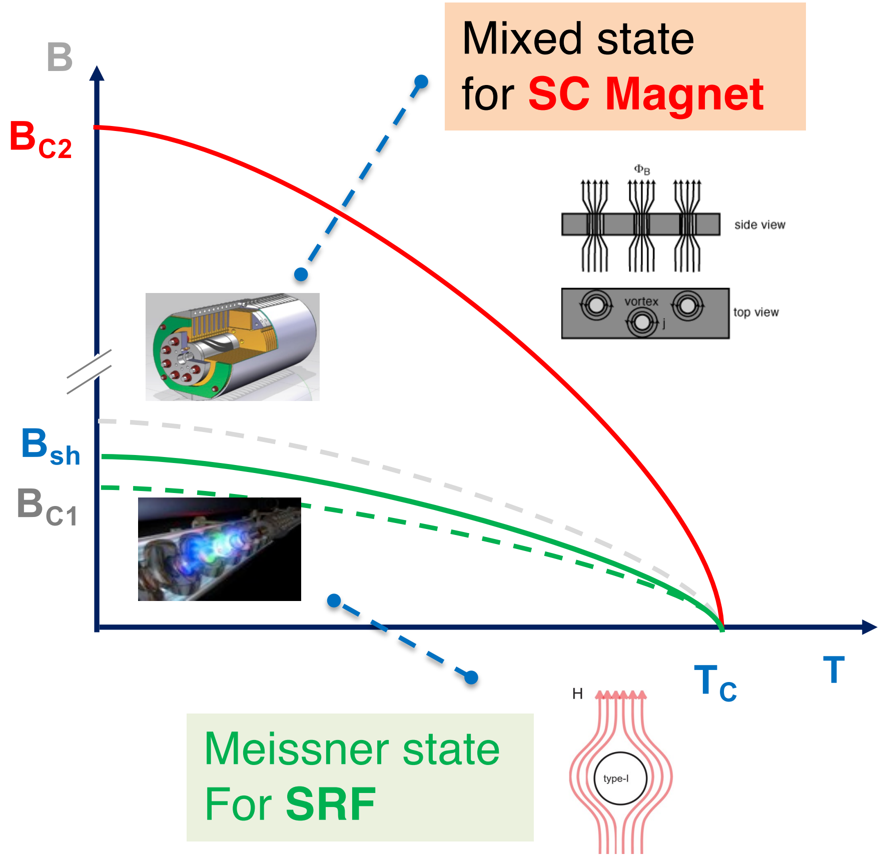

Colliders w/ Sc magnets



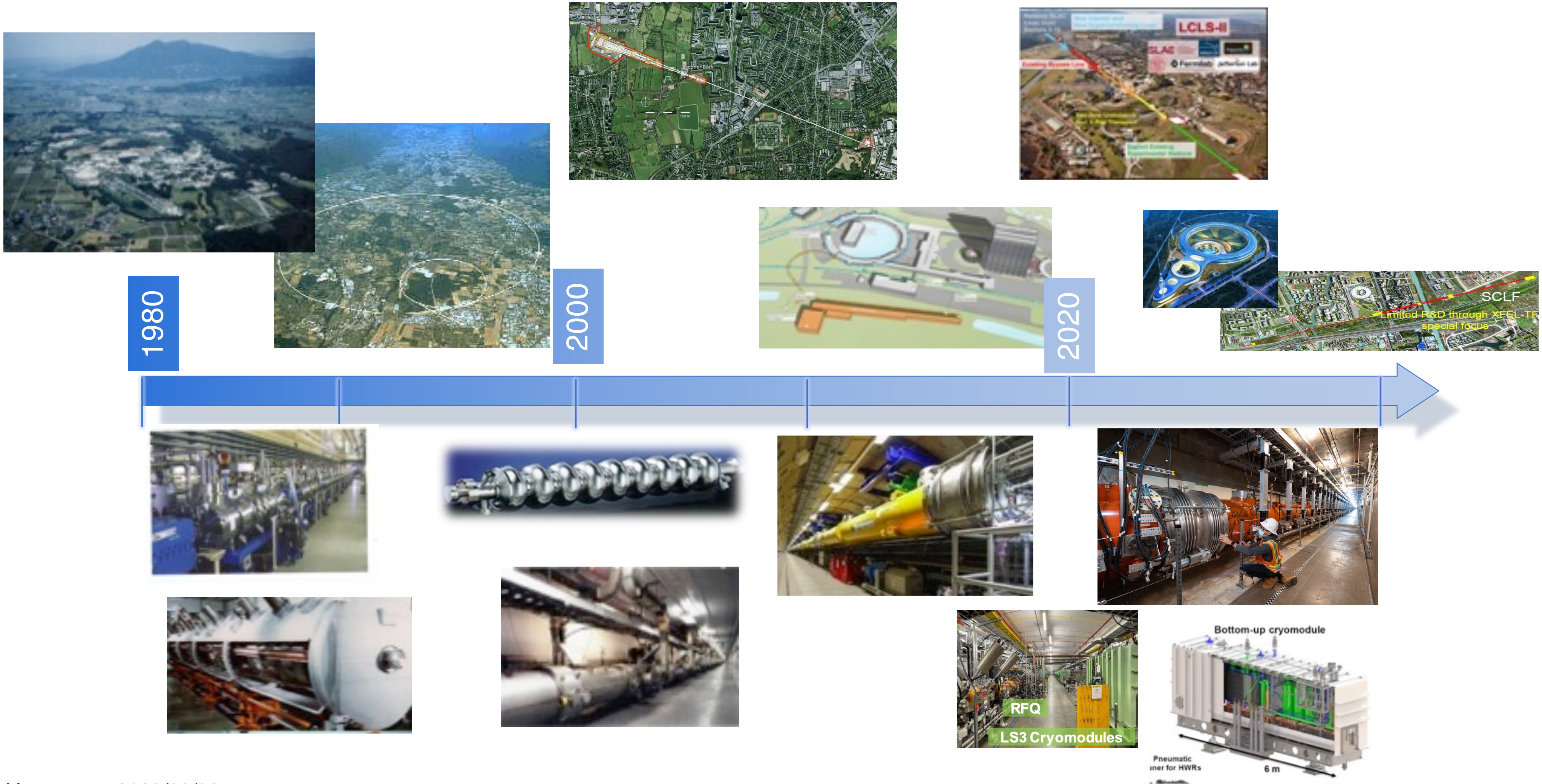
Colliders w/ Sc RF system

# Superconductor Applications for
# Accelerator Magnet and RF

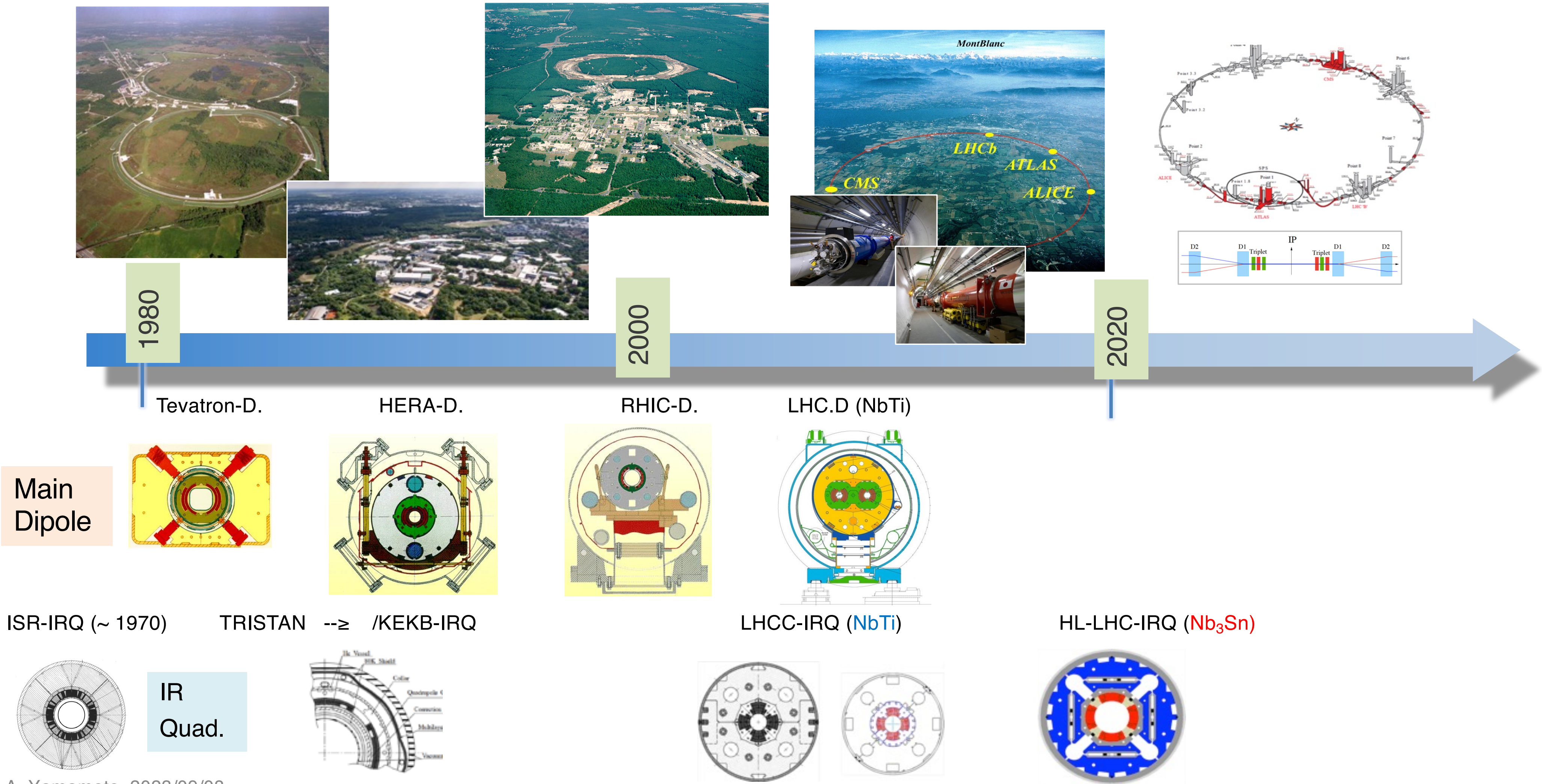
| Material | $T_c$ [K] | $B_c(0)$ [T] | $B_{c1}(0)$ [T] | $B_{sh}(0)$ [T] | $B_{c2}(0)$ [T] |
|---|---|---|---|---|---|
| **Nb** | **9.2** | (0.25) | 0.18 | **0.21** | **0.28** |
| **NbTi** | **~ 9.3** | -- | 0.067 | **--** | **11.5 ~ 14** |
| **$Nb_3Sn$** | **~ 18.3** | (0.54) | (0.05) | **0.43** | **28 ~30** |
| **Application** | | | | **RF** | **Magnet** |



# Advances in SRF Technology for Accelerators



# Advances in SC Magnets for Colliders



# Future Colliders based on Sc Acc. Technology

**Courtesy:**
ILC
FCC-ee, -hh
CEPC/SPPC
MC
EIC

**<u>Linear Colliders</u>:**

**ILC e+e- ( 250 GeV → 1 TeV) :**
- **SRF:** for High-Q ($10^{10}$) and high-G (**31.5 → 45 MV/m**)
- Highest efficiency and AC-power balance

**CLIC e+e- ( 380 GeV → 3 TeV) :**
- **NRF:** Very high G (100 MV/m)

**<u>Circular Colliders :</u>**

**FCC-e+e- ( 90 → 350 GeV):**
- **SRF: (400 – 800 MHz, 20 ~ 30 MV/m)**

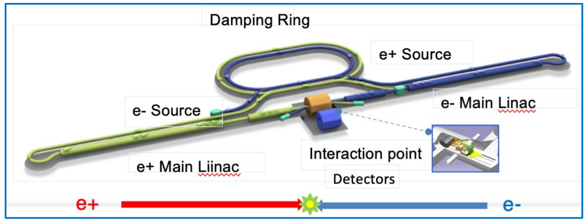
**FCC-hh ( 80 -120 TeV):**
- HF SC magnets (SCM: **14 – 20 T**)
- **SRF: (400, 800 MHz)**

**CEPC e+e- ( 90 - 240 GeV):**
- **SRF:** (0.65, 1.3 Ghz, 5 – 30 MV/m)

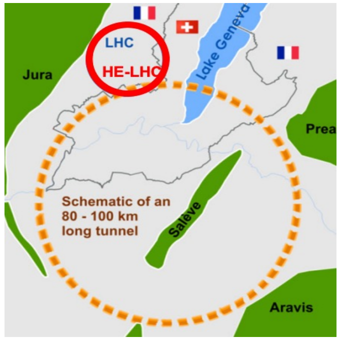
**SPPC- pp ( 75 - 125 TeV):**
- HF SCM (**12 -20** T)

**EIC Ion•e-(275/100 GeV/n v.s. 18 GeV, approved)**
- **SCM and SRF**

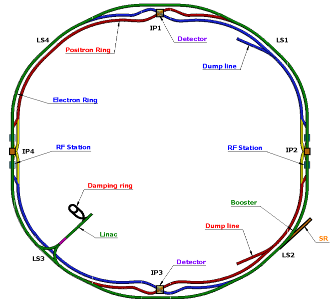
**MC μ+μ− (3 – 14 TeV)**
- SRF (1, 3 GHz, 30 MV/m, HF solenoid (≥ 40 T, Dipole, 16 T).




ILC

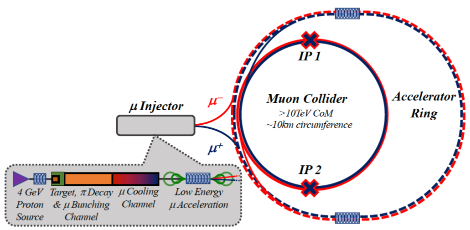



FCC-ee / -hh

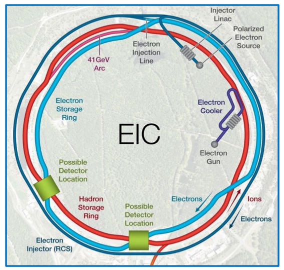



CEPC / SPPC

Ref.: T. Resiak, TIPP23, Thu., F5




MC

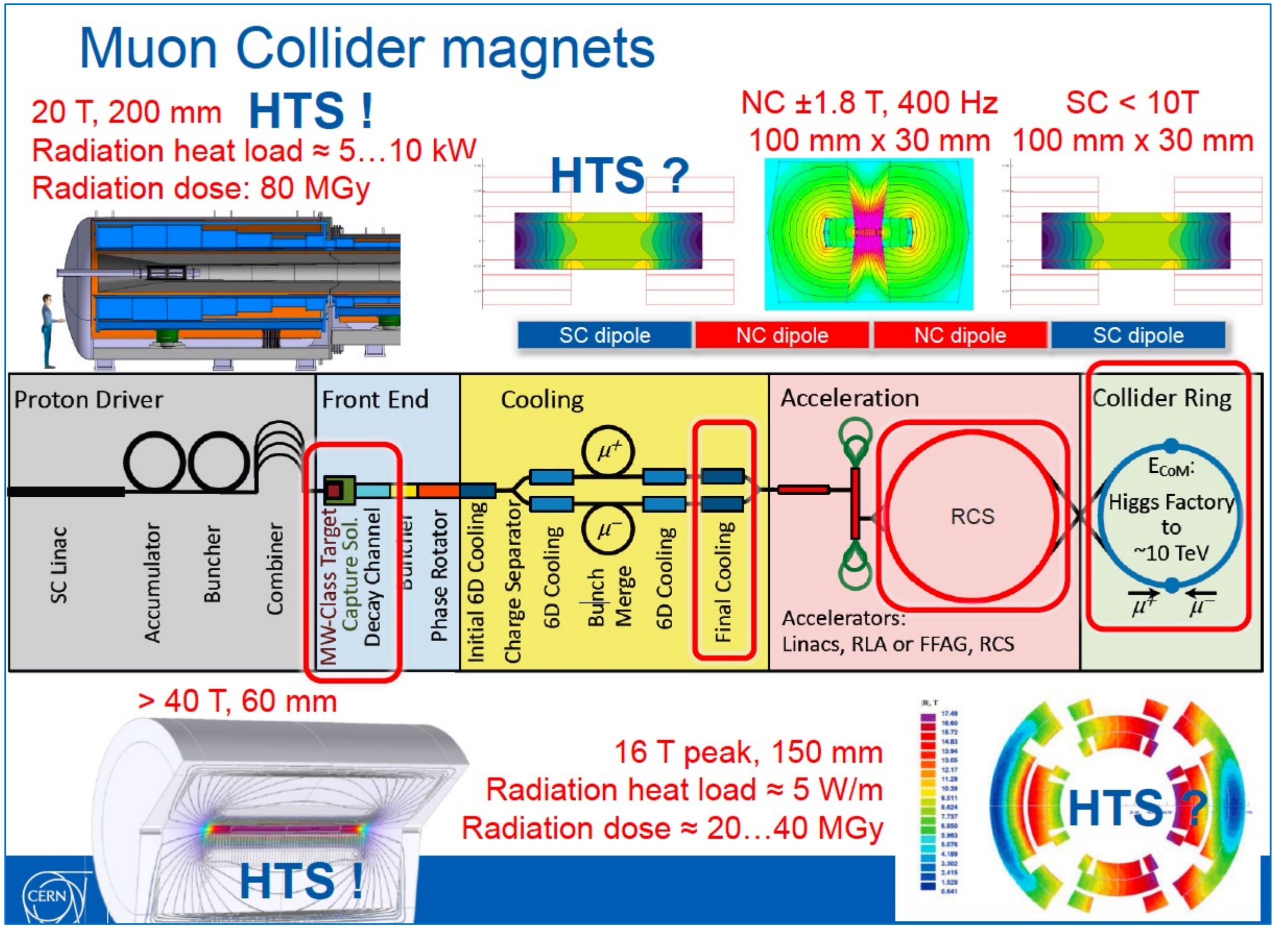



EIC

A. Yamamoto, 2023/09/08

# A new/revived Direction for Muon Collider:

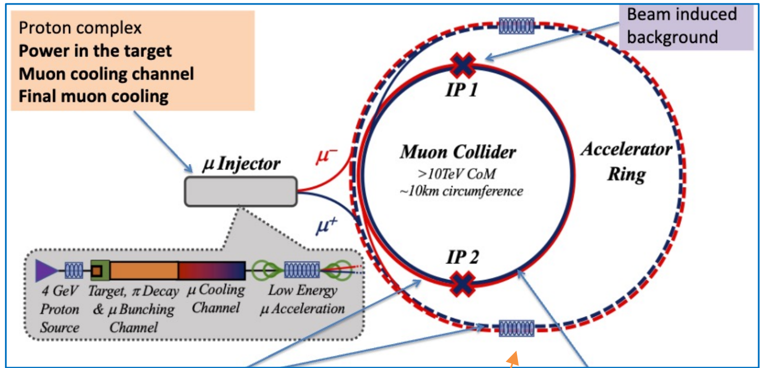
Courtesy: D. Schultz,
Luca Bottura, A. Grudiev




## SRF Cavities

Acceleration:

- 1.3 GHz, - 31.5 MV/m




# Outline

- **Introduction :**
  - Future Colliders, relying on Superconducting (SC) Technology
- **SC Technology for Colliders/Accelerators:**
  - **Superconducting RF Cavities**
  - Superconducting Magnets
- **Superconducting Detector Magnets (SC-DM)**
- **Summary**

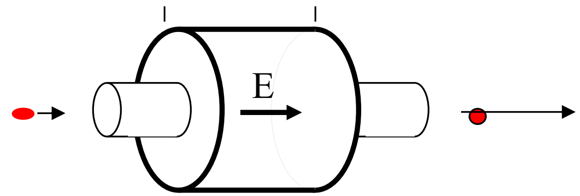
# Features of Superconducting RF (SRF)

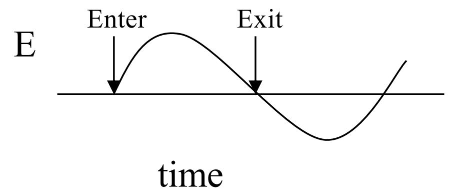
## Features:

- **High $Q_0$ ( > $10^{10}$):**
  - Small surface resistance → nearly zero
  - Efficient acceleration
- **Low Freq. (~ 1GHz) → Long beam pulses :**
  - intra-pulse feedback (in **1 ms** pulse)
- **Larger aperture( ~ 70 mm ϕ) :**
  - better beam quality
  - lower wake-fields

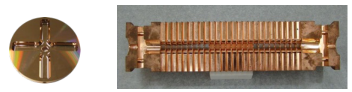
## Drawback:

- **Cryogenics required**




**SRF:** 1.3 GHz
~ 70 mm ϕ



**NRF:** 12 GHz
~ 10 mm ϕ

Courtesy: R. Geng,

# Advances in L-band (~ 1GHz) SRF Cavity Gradient

Achievable gradient

Cavity surface chemistry

Nb: > 2000 Oe (exp.)
2400 Oe (the.)
$Nb_3Sn$: > 4000 Oe (the.)

$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$

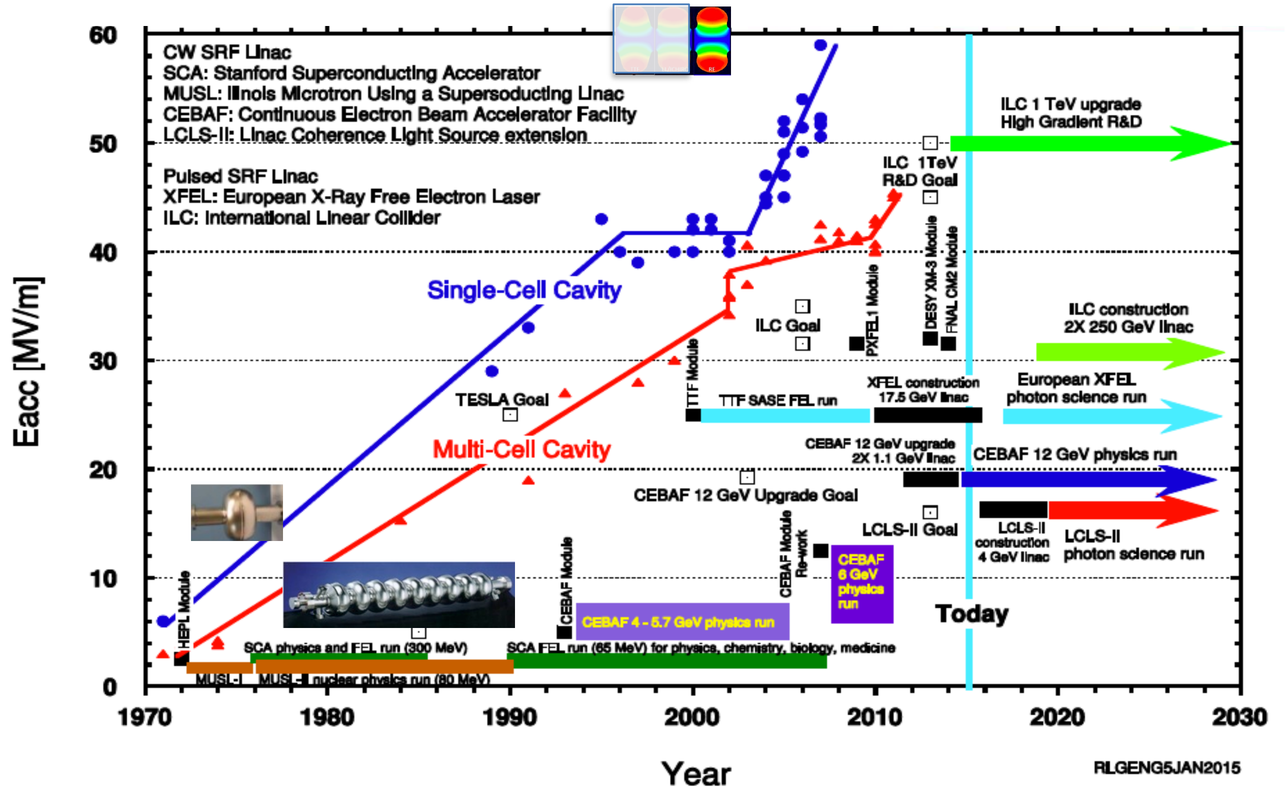
Cavity wall thermal conductance

Cavity surface smoothness

Cavity shape

**d:** The phenomenological factor signifies the penalty effect due to finite thermal conductivity of the cavity wall at cryogenic temp.

R.L. Geng, Physica C: Superconductivity, V441, Issues 1–2 (2006), P.145-150, ISSN 0921-4534,




R. L. Geng, Y. Fuwa, H. Hayano, H. Ito, Y. Iwashita, and Z. Li, Proc. SRF'19, MOP064, Dresden (2019) pp. 222-226.

Courtesy: S. Michizono

# ~ 1.3 GHz SRF Accelerators, worldwide

European XFEL
(in operation, 2017~)

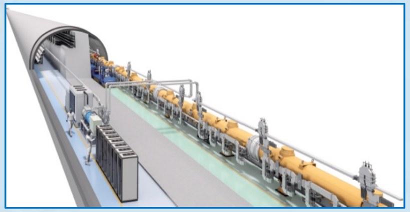
800 cavities
100 CMs
17.5 GeV (Pulsed)

ESS (0.8 GHz)
(under construction)

SHINE
(under construction)

~600 cavities
75 CMs
8 GeV (CW)

S1 Global:
DESY, Fermilab, KEK
8-cavity string Test,
2010



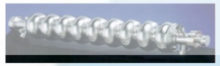
ILC (planned)

8,000 9-cell cavities
900 CMs
2 x 125 GeV (Pulsed)

LCLS-II -HE
(under construction)

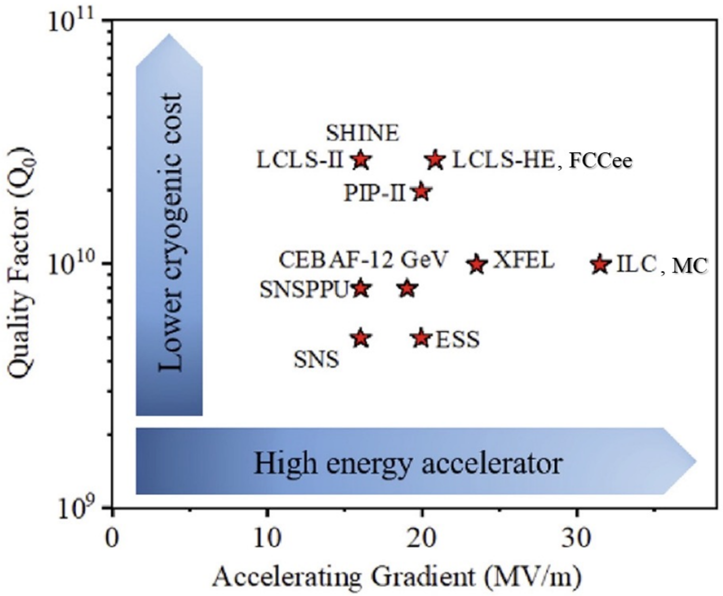
-280+200 cavities
-35+25 CMs
- 4 +4 GeV (CW)

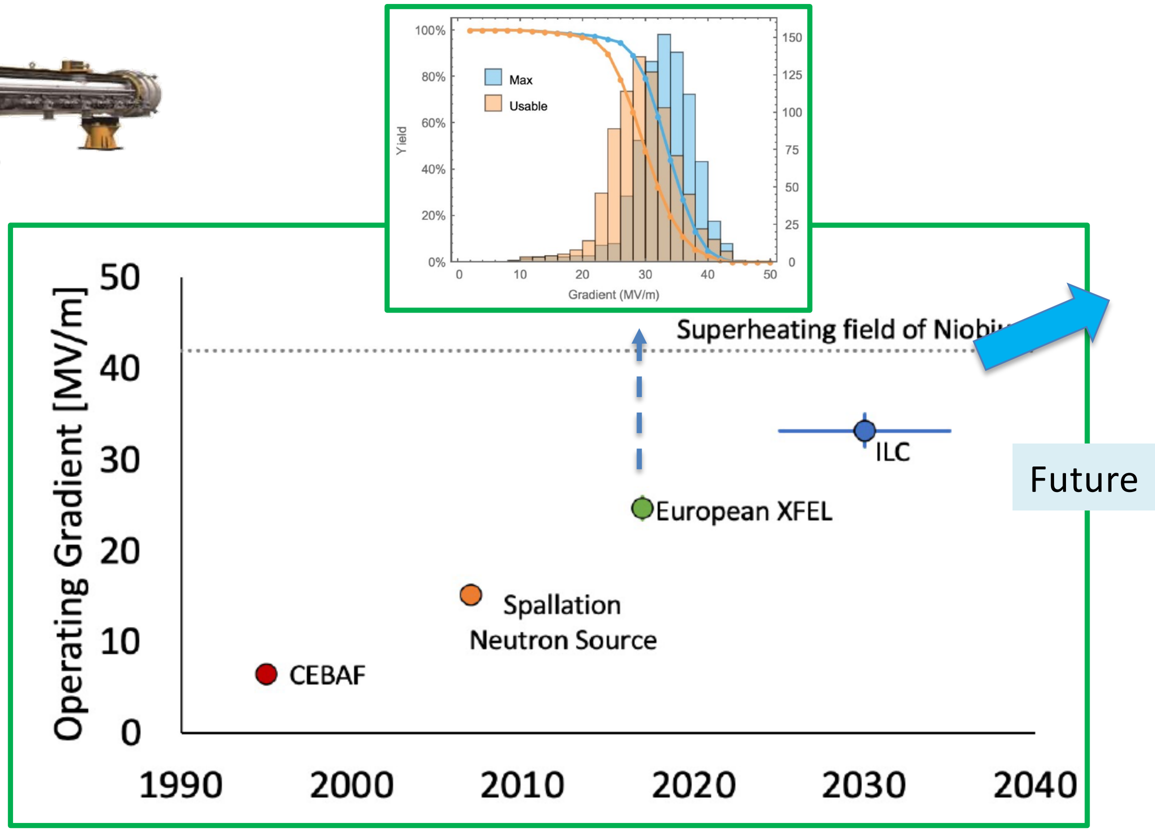
JLab-CEBAF(1.5 GHz)
(in operation)
40 CMs
6~12 GeV(CW)



Courtesy: R. Geng

# Advances in ~ 1 GHz, SRF Accelerators




S. Belomestynkh and S. Posen, arXiv:2204.01178v2

Courtesy: K. Umemori, S. Belomestnykh, S. Psen, M. Yamanaka, M. Garlasche, G. Rosaz

# Prospects for High-Performance & Cost Reduction

## High Performance: High -Gradient (-G) and –Q:

**Nb-Cavity:**

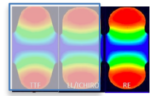
- **Shape** cavities will be limited by **~ 60 MV/m, as** $B_{sh}$ ~ 200 mT
- **Tesla Type, Surface Process to reach G ~50 MV/m, Q = ~ 3E10 :**
  - Surface treatment, Heat treatment, **Thin film** coating etc…
- **Traveling Wave** (TW), Acc. structures
  - Expecting Effective Gradient to be **~ 70 MV/m** or higher

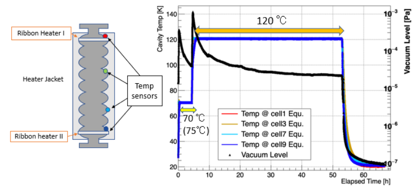
**Nb3Sn-Cavity:**

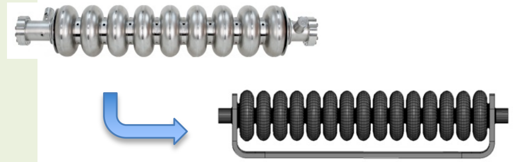
- **Gradient limit** expected to be **~ 80 MV/m**, at $B_{sh}$ ~ 430 mT

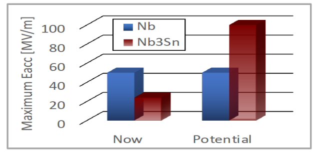
## Cost Effective Production (for Nb Cavity):

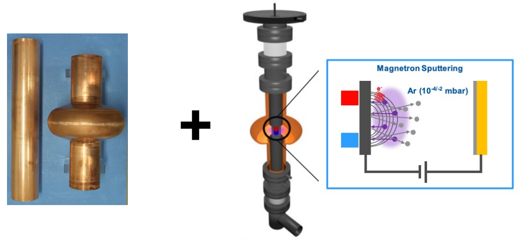
- Larger/Medium Grain Nb material: clean and cost-reducted
- **Cu-hydroforming** followed by **thin-layer SC coating**





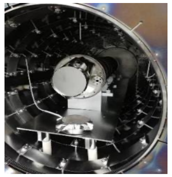








"**ILC:** The International Linear Collider -- Report to Snowmass 2021", Aryshev *et al.*, arXiv:2203.07622 (15 March, 2022)

Courtesy: K. Umemori, A. Grassellino

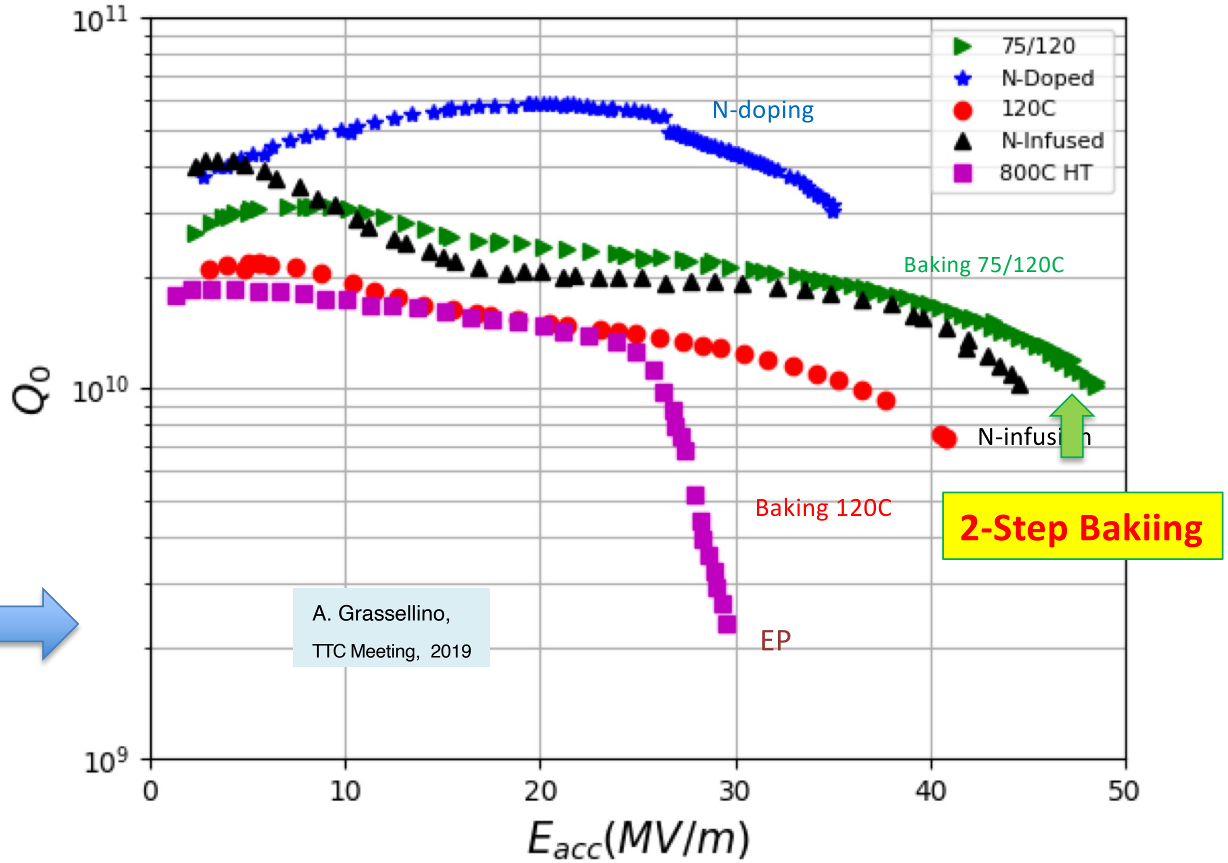
# For High Performance: Surface Treatment

**Baseline (EP+baking)**

- EP-1 ( > 100 μm)
- Heat treatment ( > 800°C, 3h)
- EP-2 (10~20 μm)
- HPR Assembly
- Baking ( 120°C, 48h)

**2-step Baking**

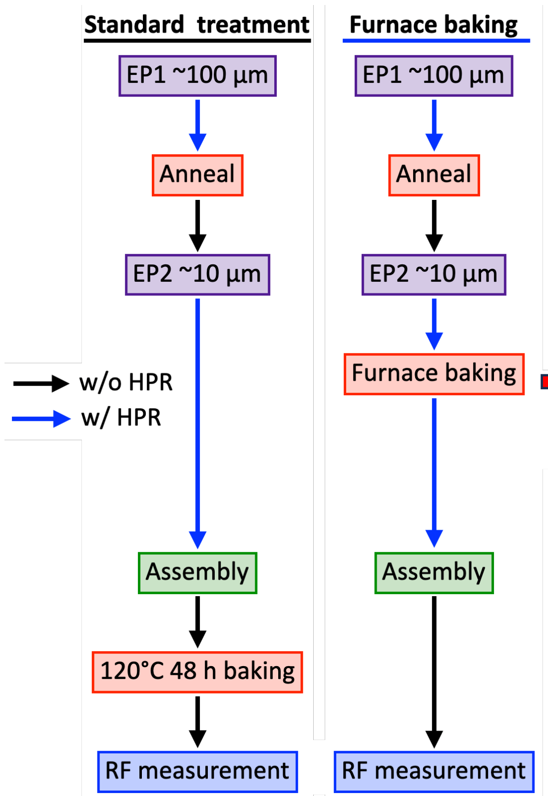
- EP-1 ( > 100 μm)
- Heat treatment ( > 800°C, 3h)
- EP-2 (cold EP, 10~20 μm)
- HPR Assembly
- 2-step Baking ( 75°C, 4h + 120°C, 48h)

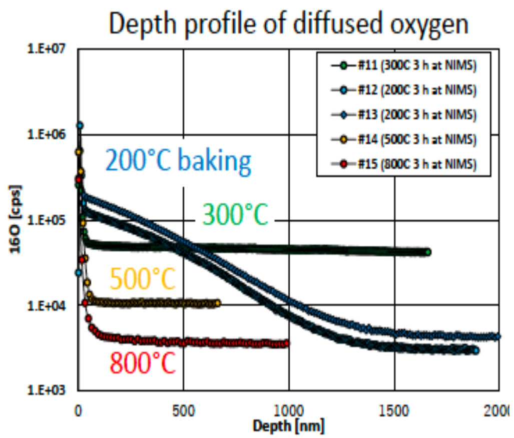


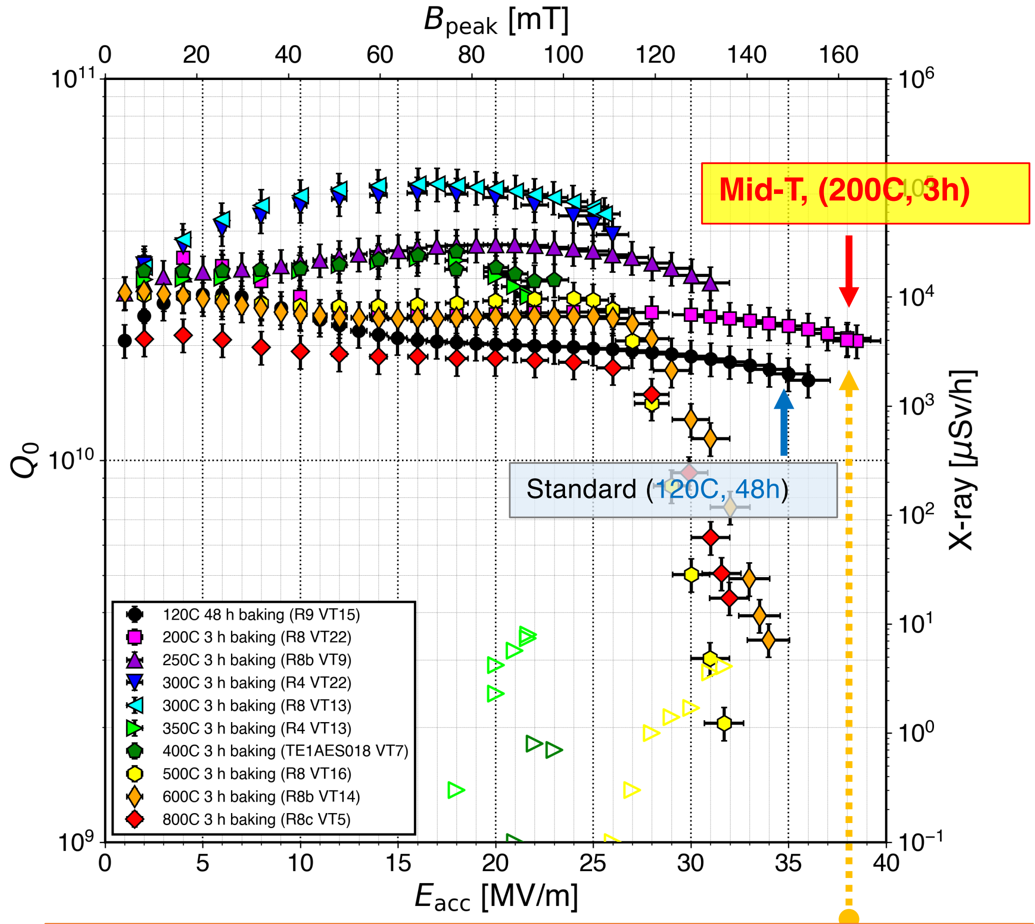

75/120 bake: A. Grassellino et al., arXiv: 1806/09824

# For High Performance: Mid-T. Furnace Baking

Courtesy; H. Ito, K. Umemori (SRF2023)




- **Mid-T Baking:** Easy to achieve high-Q
- Oxygen diffusion is important process to control the performance of Nb cavity.
- Suppression of HFQS is important to reach high gradient.



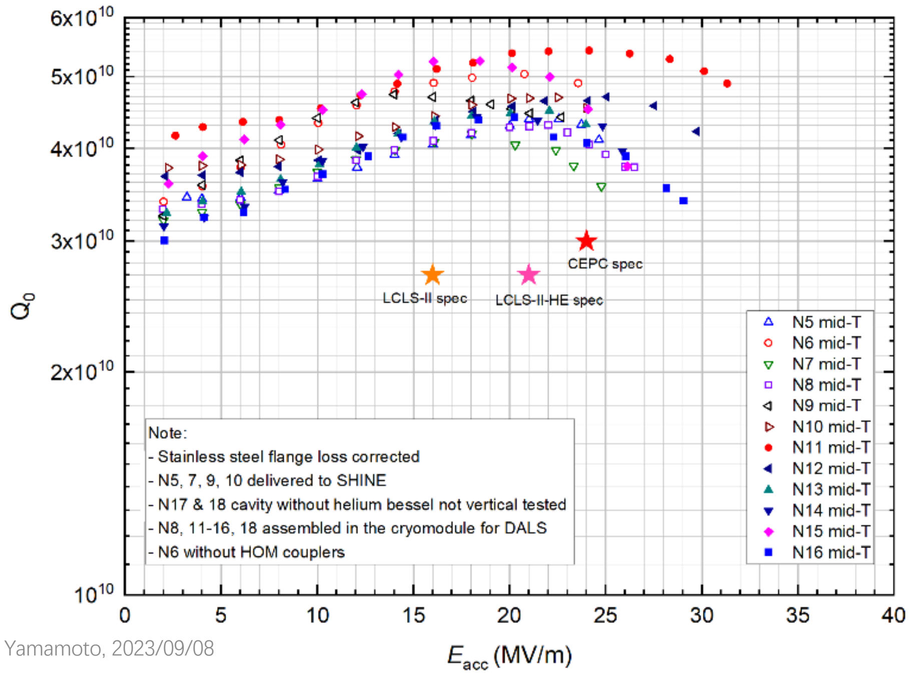
- **Q value 1.4 times higher** than that of standard treatment, and
- **Eacc performance** comparable to standard treatment.

Courtesy: J. Zhai

# A Highlight: World's First Mid-T High Q, 1.3 GHz Cryomodule

- IHEP made a 1.3 GHz cryomodule, with 8 mid-T baking, 9-cell cavities
  - w/ individual vertical tests showing high average **<$Q_0$> 4.5E10 at 16 ~ 21 MV/m**.
- Module horizontal test shows usable gradient and $Q_0$ exceeds CEPC and CW FEL projects specs, and first time demonstrates excellent performance and distinct advantage of mid-T baking, in a module.

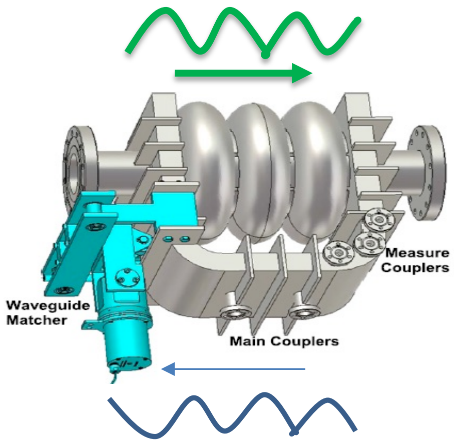
IHEP Mid-T 1.3 GHz 9-cell Cavities without Helium Vessel
Vertical Test Results




| Parameters | IHEP Mid-T CM | LCLS-II (SHINE, S³FEL) Spec | LCLS-II-HE Spec | CEPC Booster Higgs mode Spec |
|---|---|---|---|---|
| Avg. usable CW $E_{acc}$ | > 23 MV/m | $2.7\times10^{10}$ @ 16 MV/m | 2.7E10 @ 20.8 MV/m | $3.0\times10^{10}$ @ 21.8 MV/m |
| Avg. $Q_0$ @ 21 MV/m | $3.6\times10^{10}$ | | | |

Courtesy: H. Padamsee, S. Belomestnykh

# For High Performance:
## A new concept for SRF Acc. : Standing → Travelling Wave




- **Red:** standing wave ➔ High Peak Fields
- **Green** (acceleration) and **Blue** (return): travelling Waves → Lower peak fields

- Note: Guide blue wave in a return wave-guide to avoid SW peak fields – attached to both ends

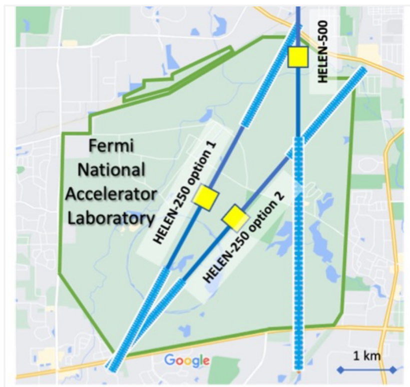
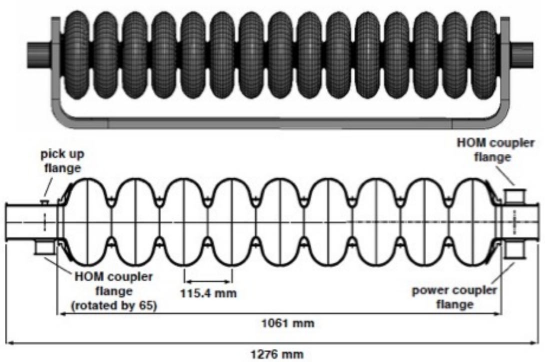
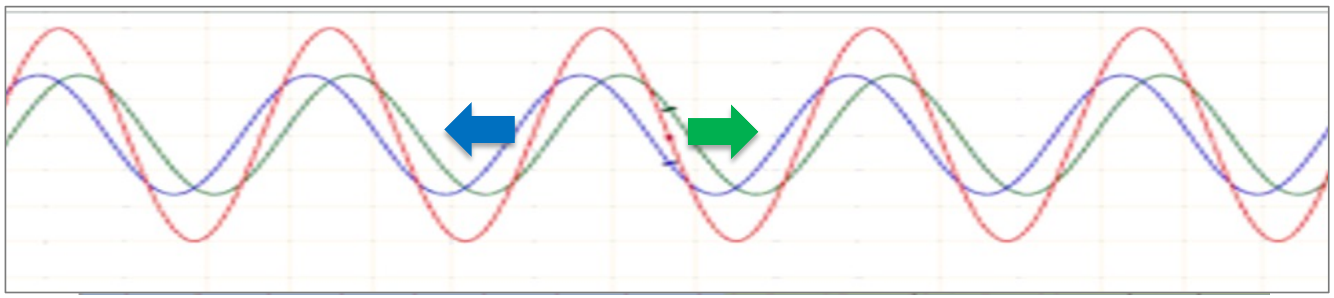



Figure 3: Options for HELEN collider at Fermilab.



Courtesy, S. Posen

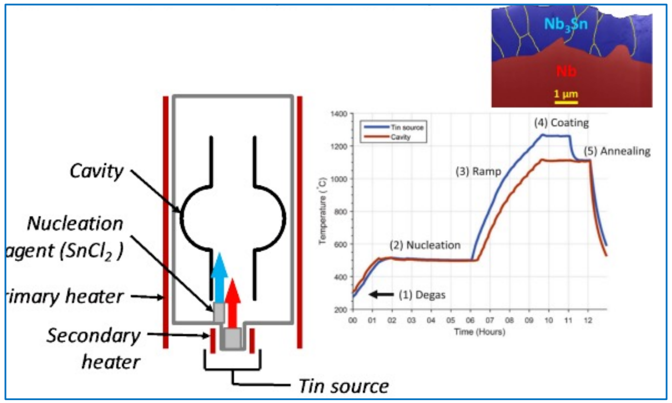
# For High Performance: $Nb_3Sn$ coating on Nb

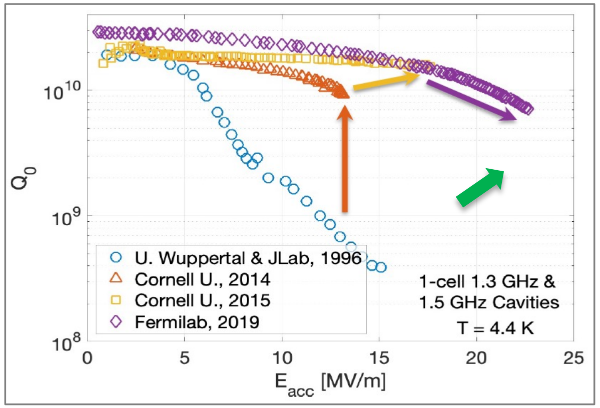
**SRF cavity**

- $B_{sh}$ = strict limit for SRF
  - $Bs_{sh\text{-}Nb}$ : 210 mT
  - $Bs_{sh\text{-}Nb3Sn}$ : 430mT

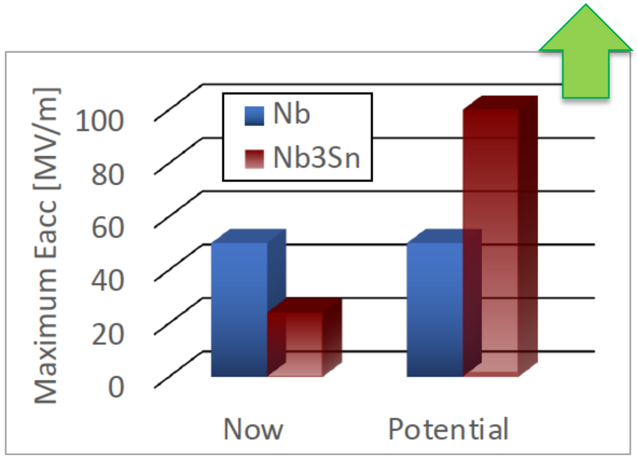
x2

| Material | $T_c$ [K] | $B_{c1}(0)$ [T] | $B_{sh}(0)$ [T] |
|---|---|---|---|
| Nb | 9.2 | 0.18 | 0.21 |
| $Nb_3Sn$ | 18.3 | (0.05) | 0.43 |
| $MgB_2$ | 39 | (0.03) | 0.31 |




$Nb_3Sn$ progress at Fermilab.
S. Posen et al., SUST, 34, 02507 (2021)




$Nb_3Sn$ Potential in high-G future

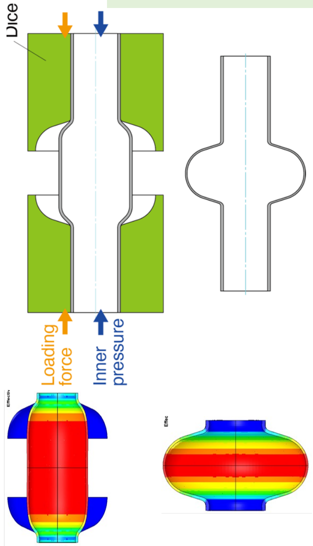
Courtesy: M. Yamanaka,
M. Carlasche, G.J. Rosaz, et al.

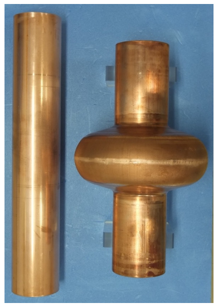
## For Cost Effective Production:

# Cu full-seamless cavity + Thin-film coating

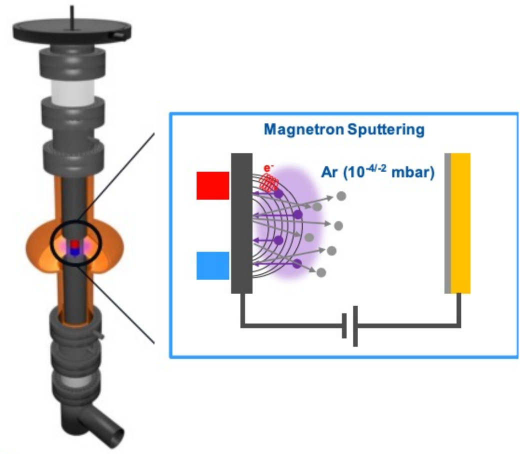
**New Cu Hydroforming (succeeded)** → **Thin-film Coating (in progress)**

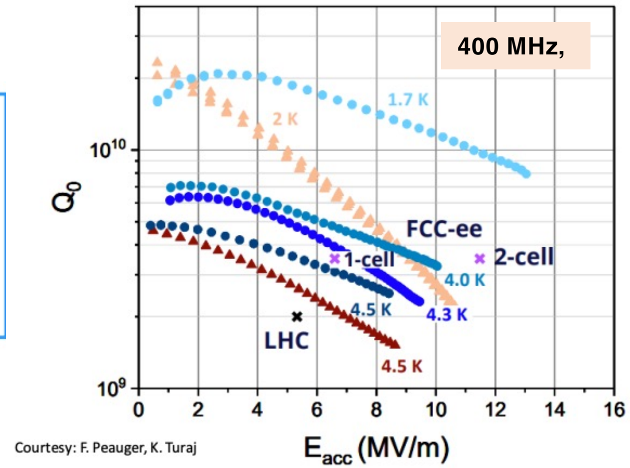
**High Power Impulse Magnetron Sputtering (HiPIMS)**



1.3 GHz




**KEK – CERN cooperation:**
**M. Yamanaka** et al.,
**J. Swieszek, A. Gallifa, M. Garlasche** et al.
- reported, SRF 2023 & published in JACOW

**R&D Goal:**
Cu-hydroforming + Thin-film w/ Nb (→ Nb3Sn)
- Higher-Q and -G,
- Exploring production cost reduction for large series,
- Saving Cryogenics → operational cost reduction

**European cooperation:**
**F. Peauger, K. Turaj, et al ,**
- reported, FCC-2023

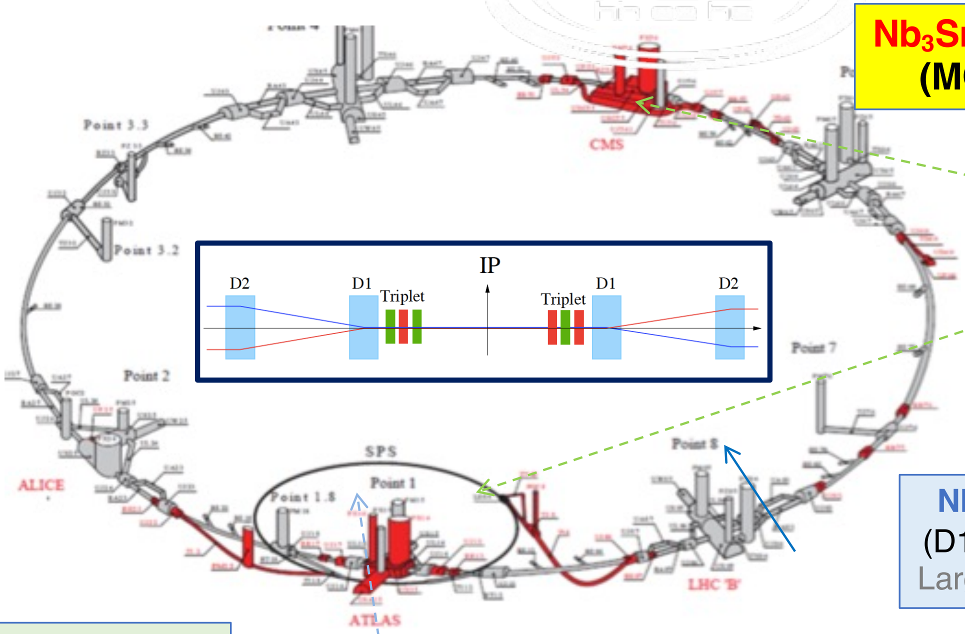
# Outline

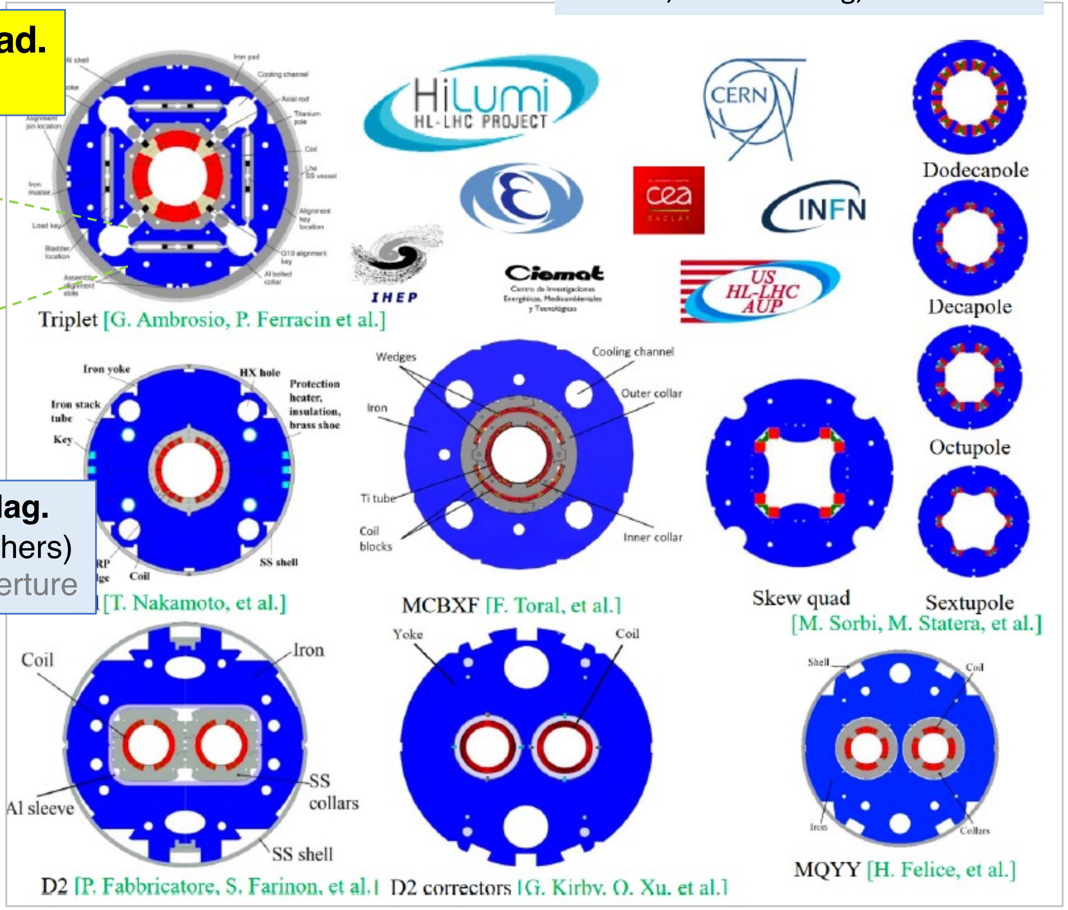
- **Introduction :**
  - Future Colliders, relying on Superconducting (SC) Technology
- **SC Technology for Colliders:**
  - Superconducting RF Cavities (Acc. Structure)
  - **Superconducting Magnets**
- **Superconducting Detector Magnets (SC-DM)**
- **Summary**

# $Nb_3Sn$, NbTi Superconducting Magnets and $MgB_2$ SC Link for HL-LHC

Courtesy, **E. Todesco,** A. Ballarino, L. Rossi, & O. Bruning,

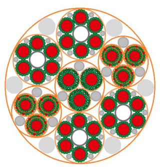
**$Nb_3Sn$ Quad. (MQXF)**

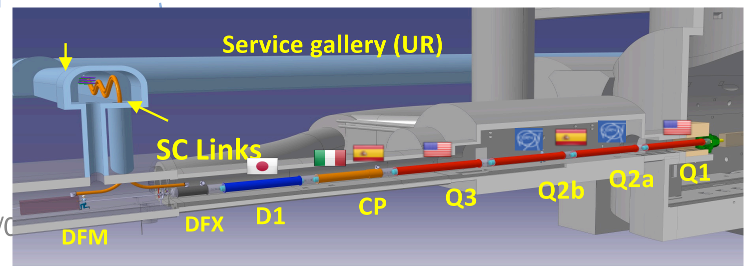



**NbTi Mag.**
(D1, & others)
Large aperture

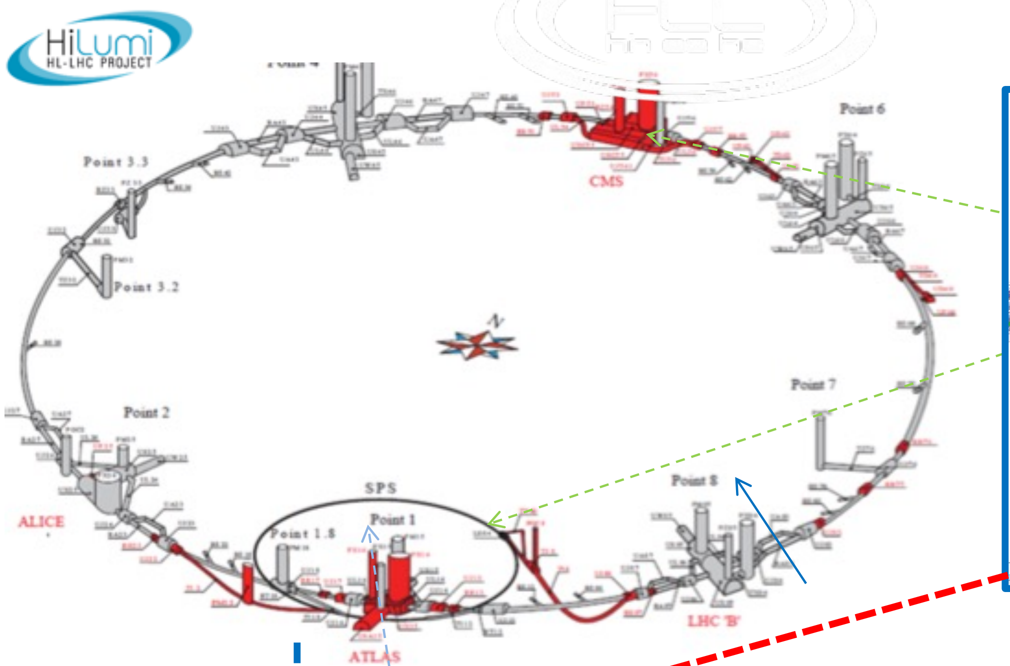
**MgB2 Superc. Link**

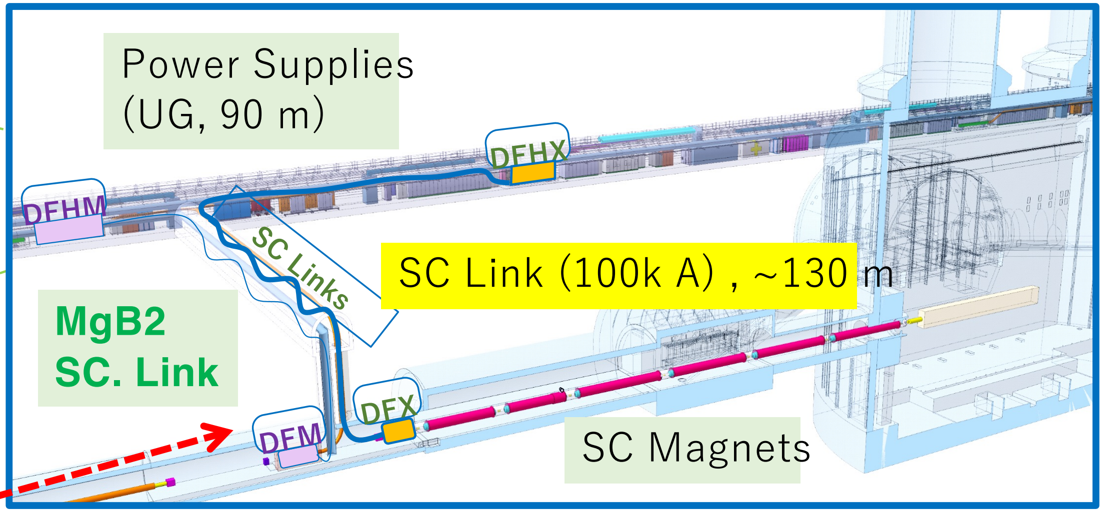


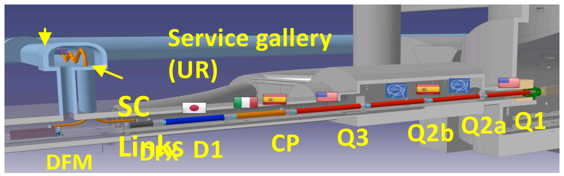


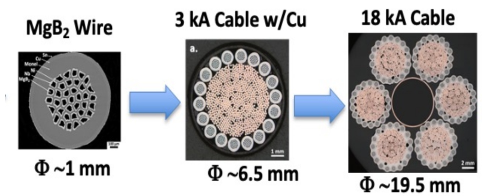
# $MgB_2$ SC Link for HL-LHC IR Region Magnets

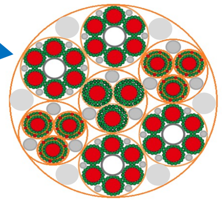
Courtesy, **A. Ballarino,**



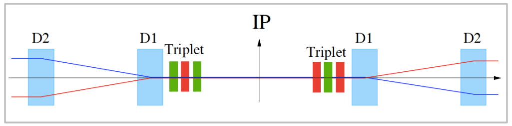



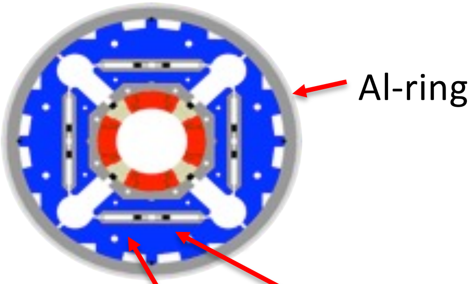



Courtesy: E. Todesco, G. Apolinari, & G. Ambrosio

# CERN and US-LARP/AUP Cooperation for $Nb_3Sn$ IR Quadrupoles




- **US-LARP/AUP Collaboration** taking a critical leading role for:
  - **establishing Nb3Sn** magnet-technology up to **B > 11 T** and **L = 4 m**, with:
    - overcoming the very brittle feature (like ceramic),
    - developing **Al-ring** and **Bladder & Key (B&K) technology**
      - for rigid support of ***magnetic pressure*** proportional to ***j·B*** ,
- **CERN** leading HL-LHC global collaboration and maturing the $Nb_3Sn$ acc. magnet technology with:
  - **establishing the Nb3Sn technology** up to **B > 11 T** and **L = 7 m**
    - overcoming the difficulty and sensitivity critical with longer magnets,
  - **integrating acc. operation**, to prepare for future energy frontier colliders

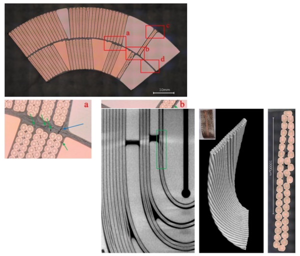


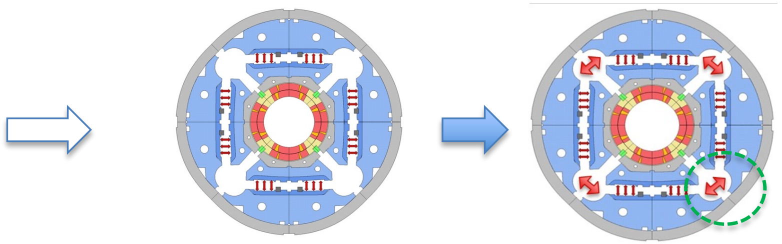

Structure based on
**Al-ring and B&K loading**

Courtesy: E. Todesco, A. Devred

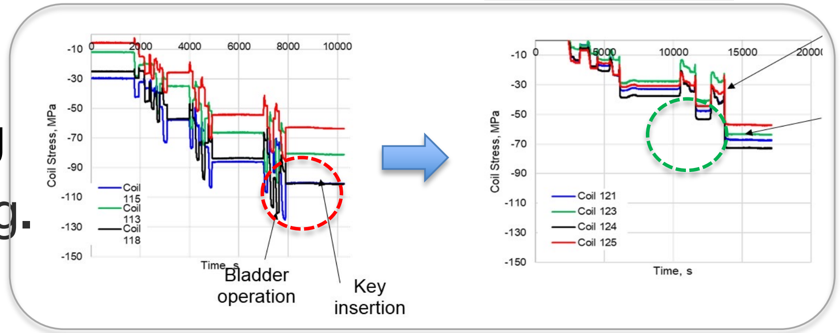
# Extreme Efforts for establishing the Technology to reach 7 m long $Nb_3Sn$ Magnets

- **Route-cause analysis on:**
  - Performance limitation and instability

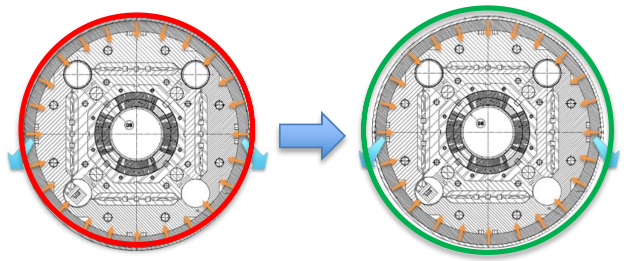




- **Magnet/Coil loading:**
  - **Bladder & Key process upgraded** for pre-stressing
  - **Stress-overshoot minimized** during magnet loading.



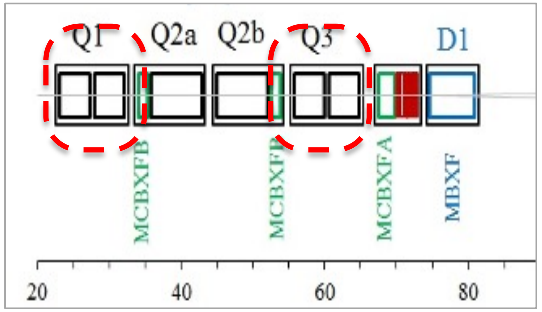

- **Cold mass assembly:**
  - **Shell welding condition optimized,**
  - **Longitudinal friction eliminated** between magnet (coil, Yoke, **Al-ring**) and outer-shell (**St. St.)**



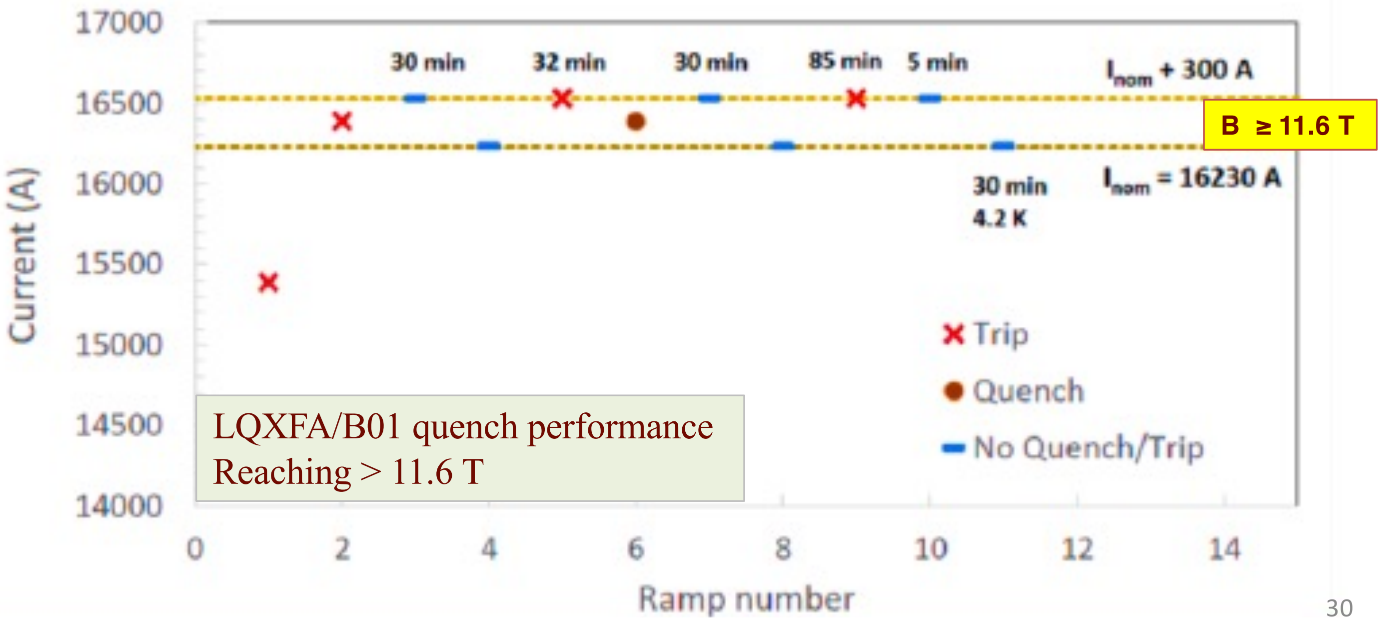
- **Ultimate care of handling and monitoring:**

Courtesy; G. Ambrosio, S. Feher, & E. Todesco

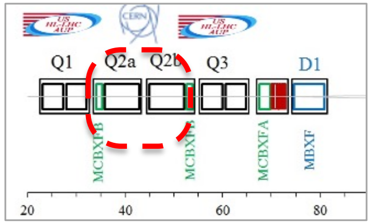
# $Nb_3Sn$ HL-LHC IR Quadrupoles

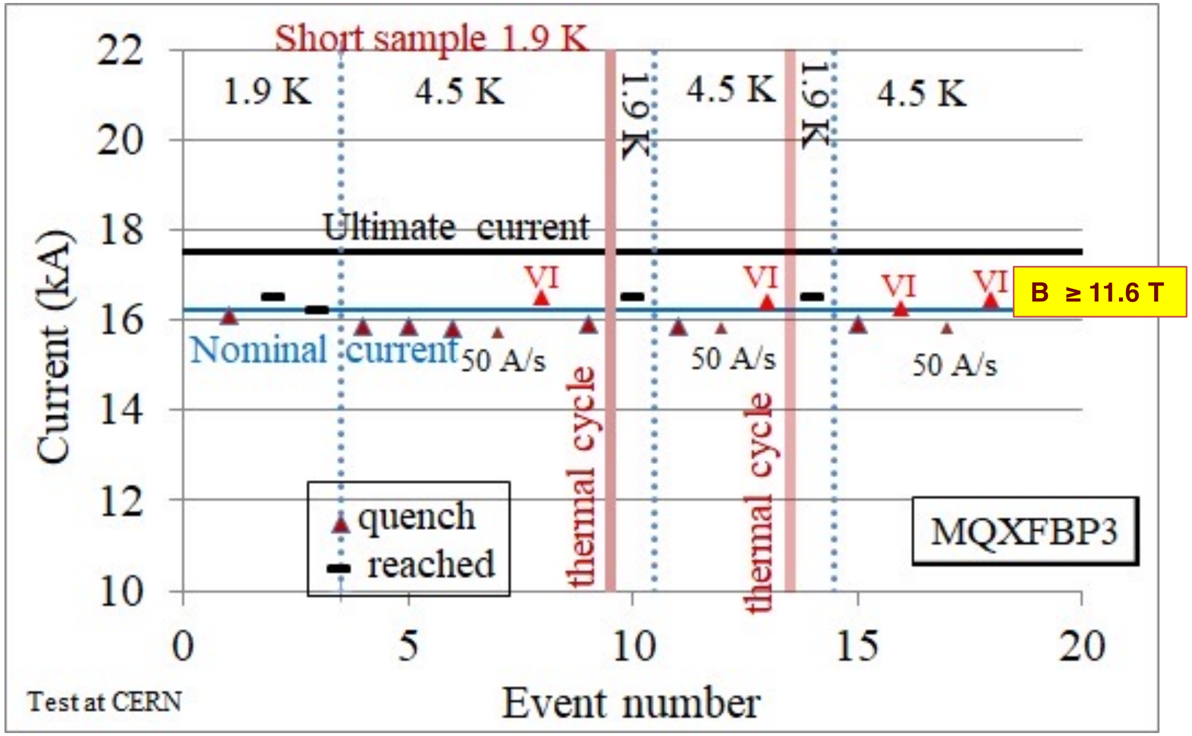



- First 2-magnet cold-mass LQXF01 assembled &
- tested successfully in May 2023, and
- reached the nominal current + 300A at 1.9 and 4.2 K



# $Nb_3Sn$ HL-LHC IR Quadrupoles



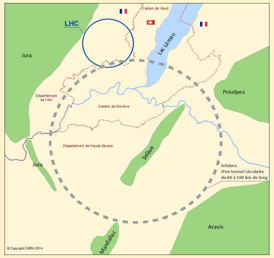

MQXF-BP3 and –B02 tested at CERN:

- Reachding I-nom.+ 300 A at 1/9 K and $T_c$.
- Experiencing 3 thermal cycles w/o degradation

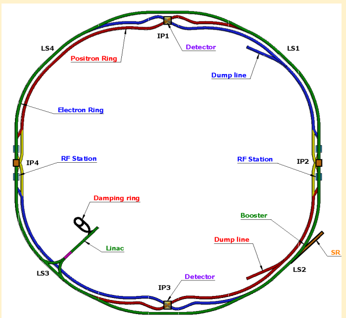
HL-LHC $Nb_3Sn$ Program **demonstrated** **≥ 11 T** **acc. magnet** **up to 7 m**, as an important step for the future !!

# Future Hadron Colliders based on SC Magnet Technology

**FCC-hh ( 80 – 120 TeV):**
- HF magnet: **14 - 20 T**




**SPPC- pp ( 75 - 125 TeV):**
- HF magnet: **12 -20** T



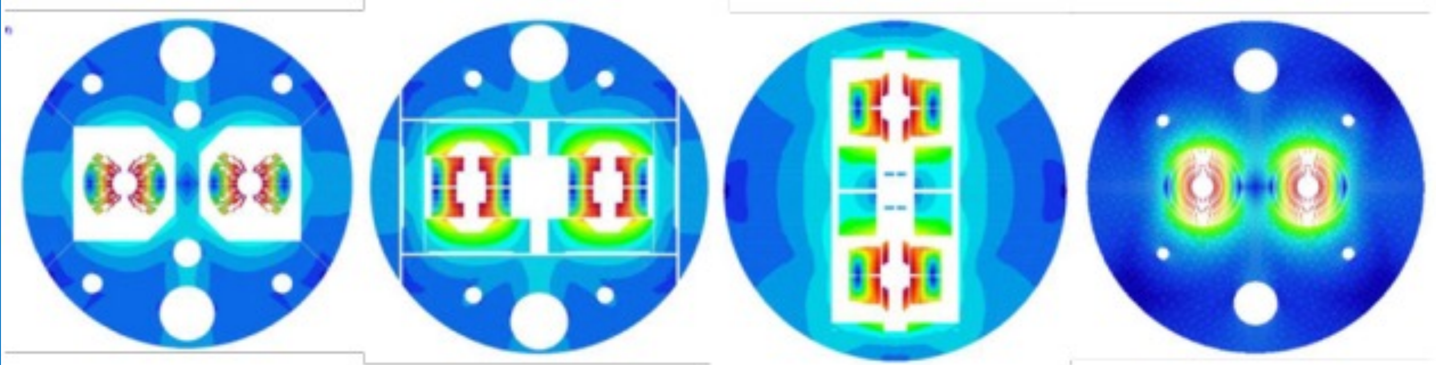



**Figure 7-4.** *Cross section of the four main dipole design options explored within the EuroCirCol program. From left to right, cos-theta (INFN), bock (CEA), common coil (CIEMAT), and CCT (PSI) designs.*

**Table 7-1.** *Parameters of design options for the 16 T arc dipole.*

| Parameter | Cos-theta | Block-coil | CCT | Common-coil |
|---|---|---|---|---|
| Peak field on conductor (T) | 16.40 | 16.73 | 16.35 | 16.57 |
| Operating current (A) | 11441 | 10176 | 18135 | 15880 |
| Inductance @ 16 T (mH/m) | 38 | 48 | 18 | 26 |
| Outer yoke diameter (mm) | 660 | 616 | 750 | 650 |
| Mass of conductor (kg/m) | 115 | 120 | 148 | 145 |

S. Izqioerdp Ber,idez. G. Sabbi, A.V. Zlobin, arXiv: 2208.13349, v2 (2022)

Courtesy: L. Bottura, G. De Rijk, A. Devred, A. Zlobin

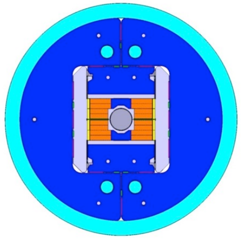
# Advances in $Nb_3Sn$ HF Magnet Development

2003: LBNL HD1
(16 T @4.2 K)

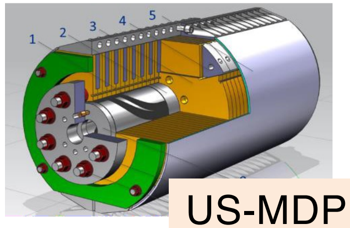
**without No bore**

2015:CERN RMC
(16.2 T @1.9 K)

**With no bore**

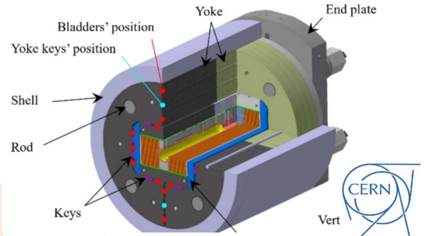


**2018: CERN**. **FRESCA2** (100ϕ ap)
(14.6/14.95 T bore/peak @1.9 K))

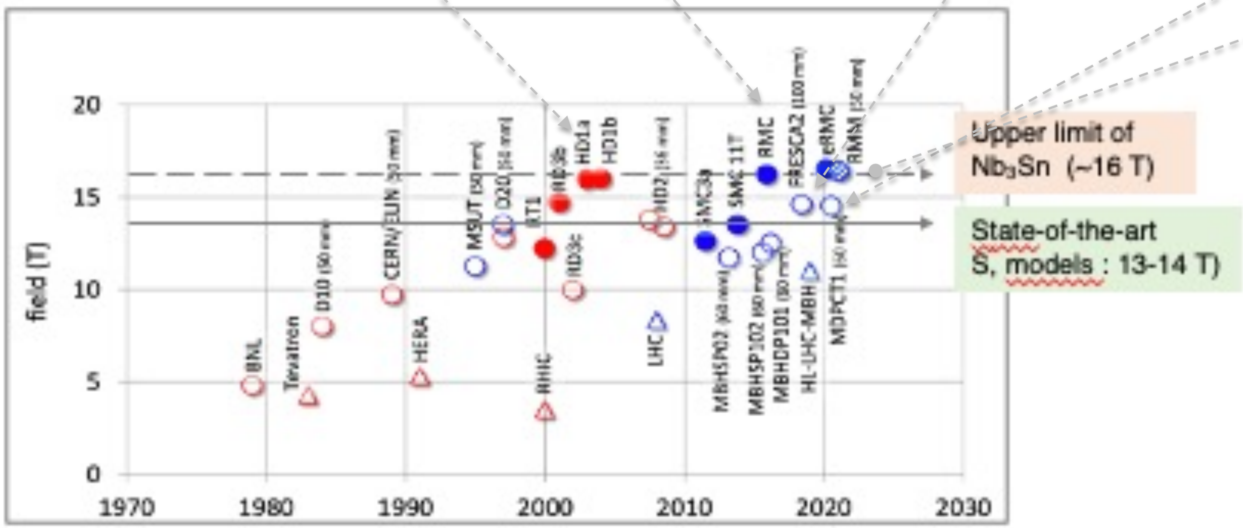


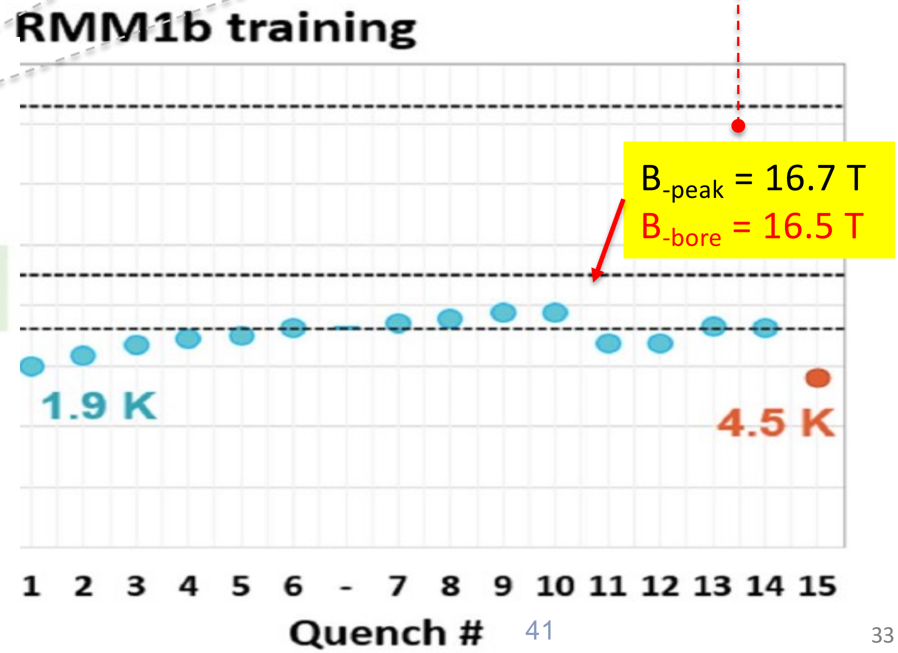
US-MDP

**MDPCT1b** **Fnal, MDPCT1b** (50ϕ ap)
(~14.5 T bore @1.9 K))



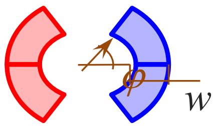

2022?:CERN RMM
(16.5/16.7 T @1.9 K)
with **Cavity**-Gap: 50 mm



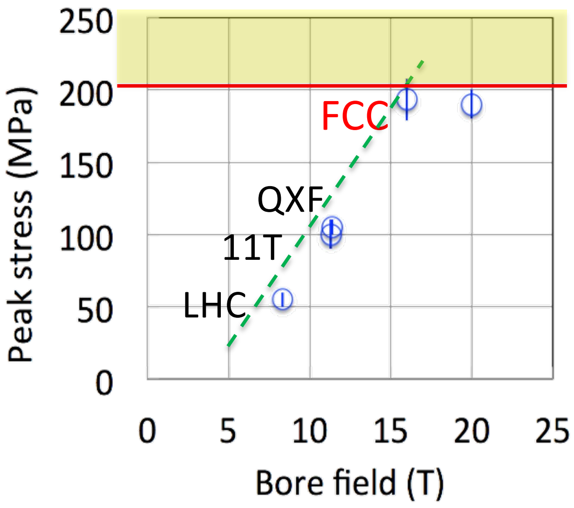



Courtesy: E. Todesco, A. Godeke, A. Siemko

# Mechanical Constraint to consider Operating Margin



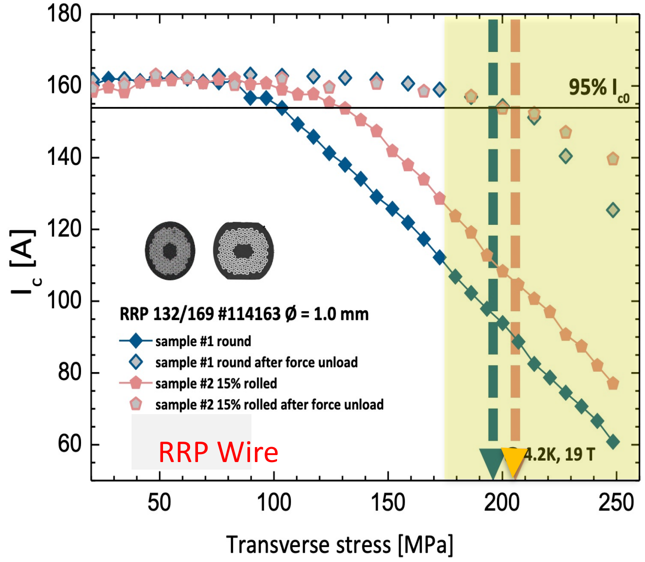

$$\left.\begin{array}{l} F \propto B^2 \\ w \propto \dfrac{B}{J} \end{array}\right\} \rightarrow \boxed{\sigma \approx \dfrac{F}{w} \propto JB}$$



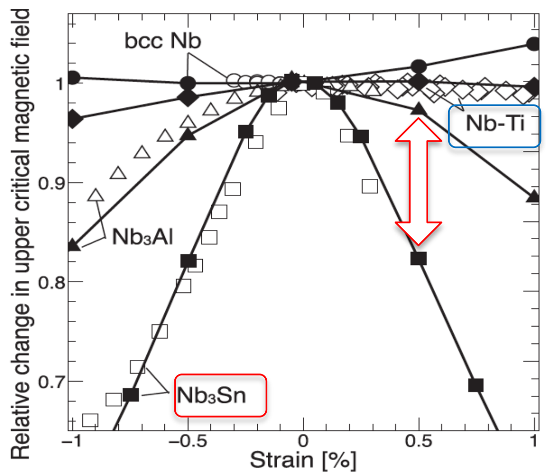

**Attention: $I_c$ ($J_c$) reduction:**

- Significant Ic (Jc) reduction by 25 to 35% at ~ 170 MPa, followed by irreversible degradation.

Measurement at Univ. Geneve



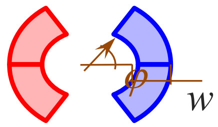

- **Large Impact** of Strain on Jc, reduction,
- Nb3Sn superconductor much different from **NbTi**



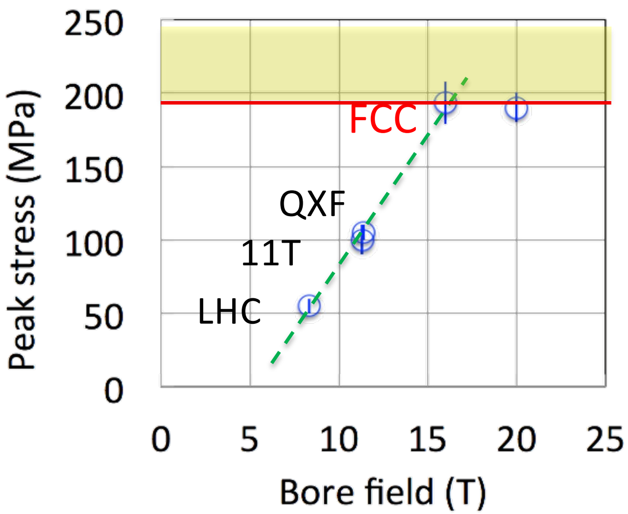

A.Godeke, F. Hellman, H.H.J ten Kate, and M.G.T. Mentink et al.
Supercond. Sci. Technol. **31** (2018) 105011.

Courtesy: E. Todesco, A. Godeke,, A. Zlobin

# Mechanical Constrain to consider Operating Margin




$$F \propto B^2, \quad w \propto \frac{B}{J} \quad \rightarrow \quad \boxed{\sigma \approx \frac{F}{w} \propto JB}$$

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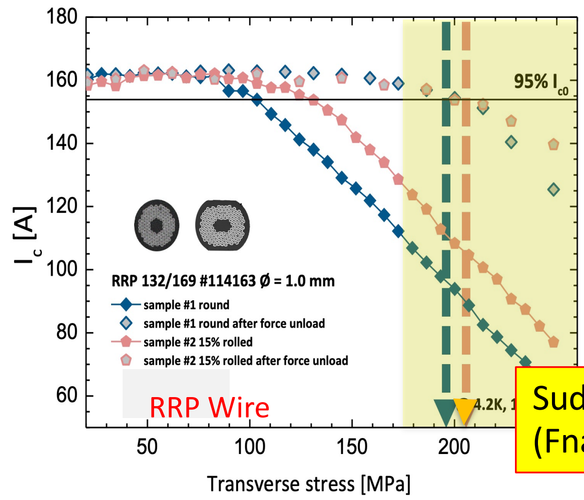
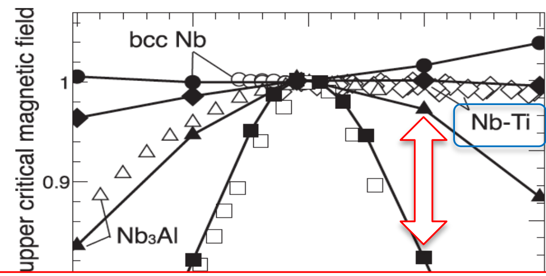
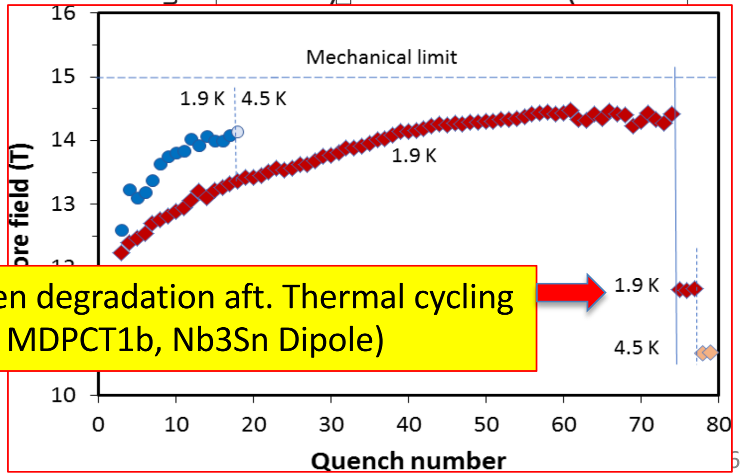
Measurement at Univ. Geneve




- **Large Impact** of Strain on Jc, reduction,
- Nb3Sn superconductor much different from **NbTi**



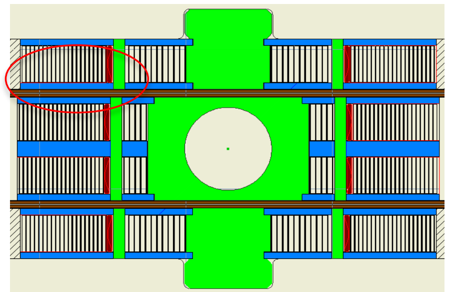




Sudden degradation aft. Thermal cycling (Fnal, MDPCT1b, Nb3Sn Dipole)

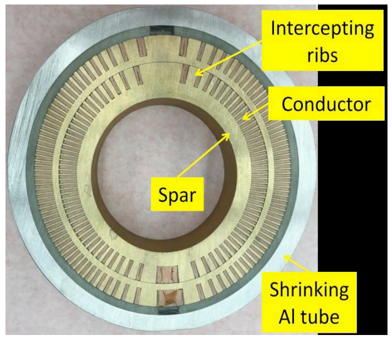
Courtesy: A. Zlobin

# Stress management in HF (14+ T) acc. magnets

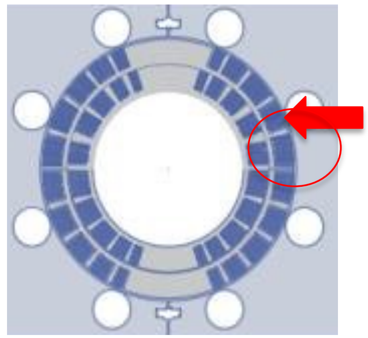
- **Stress Management (SM) concept:**
  - Coil blocks or individual turns are **placed in their own compartments** inside a strong coil structure
  - **A significant portion of the Lorentz forces in coil blocks is transmitted to the magnet's external mechanical structure, reducing stress build-up.**
- **Effect:** Stress management helps minimizing coil geometry deformations (field quality) and superconductor $I_c$ degradation (magnet margins)
- **Examples → :**



Block-type coil (TAMU)




Canted cos-θ coil (LBNL)



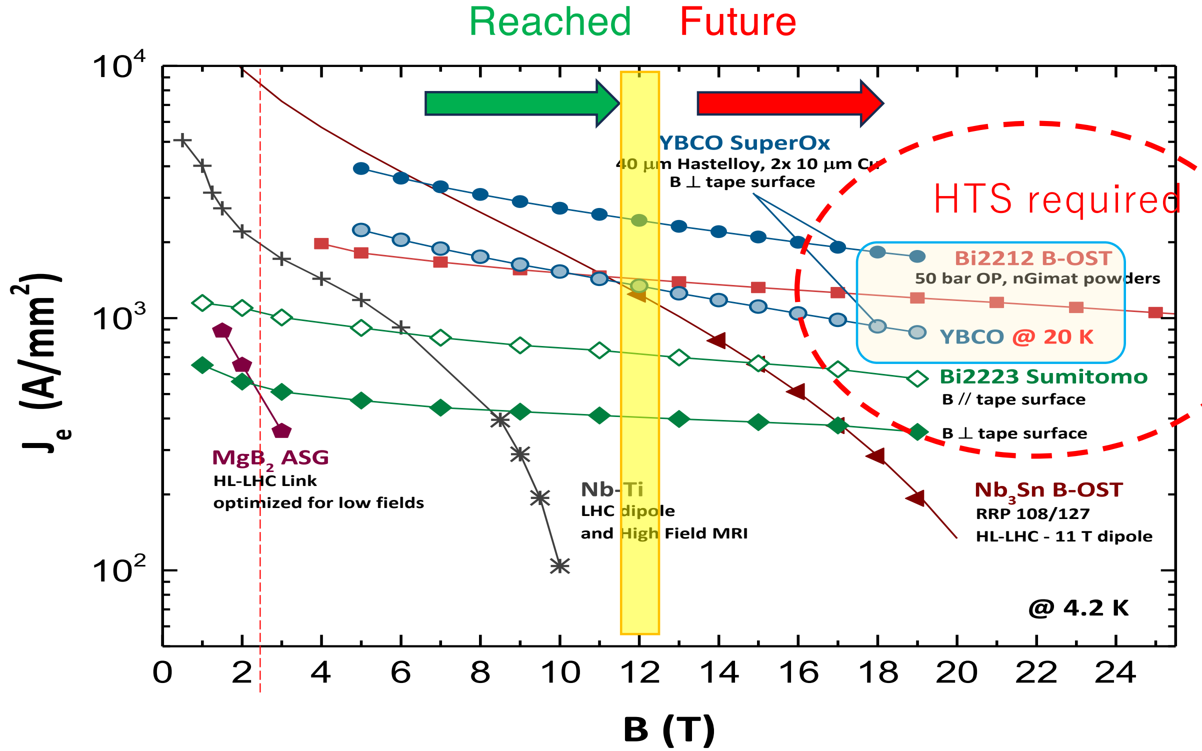
SM w/ structure

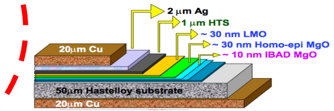
Shell-type coil (FNAL)

- **SM concept applications:**
  - **Large-aperture** dipole and quadrupoles (e.g. 2nd EIC IR, Muon Collider SR and IR)
  - **Very high-field magnets** with brittle **HTS/LTS** coils (see HFM programs in US and EU)

Courtesy, A. Ballarino, A. Siemko

# Future Prospect: HTS anticipated at B ≥ ~ 16 T




**Advantages:** **H**igher Jc at Hifh Field, **L**arger T-margin, Cryogenic Efficiency, ,,,

**Challenges:** Mechanical sensitivity, Magnetisation, AC-loss, Quench protection, ,,,

See more: **Appendix**

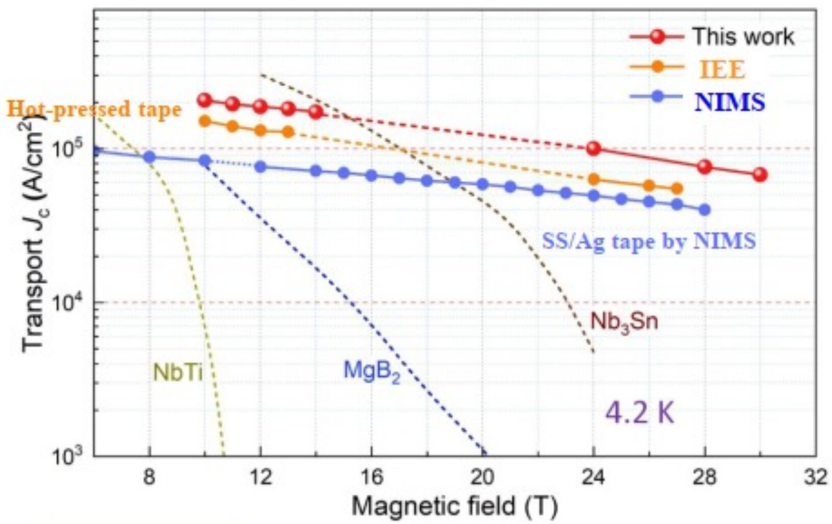
# A Highlight: HTS (IBS) and Magnet in China

Courtesy, A. Ballarino, Q. Xu, Y. Ma

Iron Based Superconductor (IBS) development in China., toward 12 --> 24 T

## New record high $J_c$ in PIT SS/Ag Ba122 tapes

**Special technique to remove FeAs wetting phase, details will be published soon.**




New record!

- **High $J_c$ @ 4.2 K :**
  - $J_c$~2.2×10$^5$ A/cm$^2$ @ 10 T
  - $J_c$>10$^5$ A/cm$^2$ even @ 24 T
- High mechanical strength
- Low material cost
- Easy fabrication process scalable to long length tapes

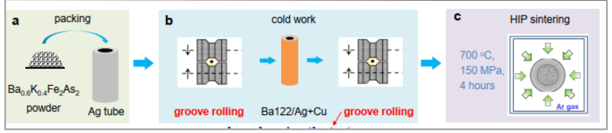
*Very promising to be used in high field magnets!*

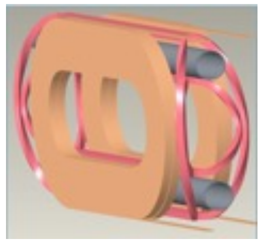
No published data

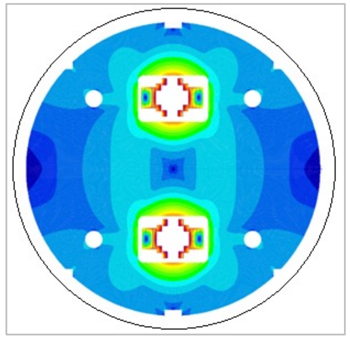
18

*Y. Mao et al., Supercond. Sci. Technol. 31 (2018) 015017*

**High-$J_c$ Ba-122 HIP wires improved by GR+HIP**





Presented by D. Wang and Y. Ma, at HiTAT Workshop, March 2023, CERN

Courtesy: A. Siemko

# Directions for HFM in LDG Program

- **Development** of **new HFM grade $Nb_3Sn$ conductor** with
  - target Jc of 1500 A/mm2 @ 16 T and enhanced mechanical properties

- **Demonstration of the 12 T $Nb_3Sn$ technology matured**
  - for collider-scale production through 12 T dipole magnet design, to establish industrial production readiness with cost reduction:

- **Demonstrators of the $Nb_3Sn$ technology potential above 14 (+) T:**
  - **Single aperture graded conductor block coil demonstrator** (CEA)
  - **Block coil** demonstrator with coil stress management, targeting 16 T (CERN)
  - **Common coil** demonstrator (CIEMAT)
  - **Common coil** demonstrator with coil stress management, targeting 16 T (PSI)

- **R&Ds for Hybrid (Nb3Sn+HTS) magnets** targeting **16 T** and **beyond.**

# Personal Scope for HFM Development Timeline

## for reaching Accelerator Construction and Operation

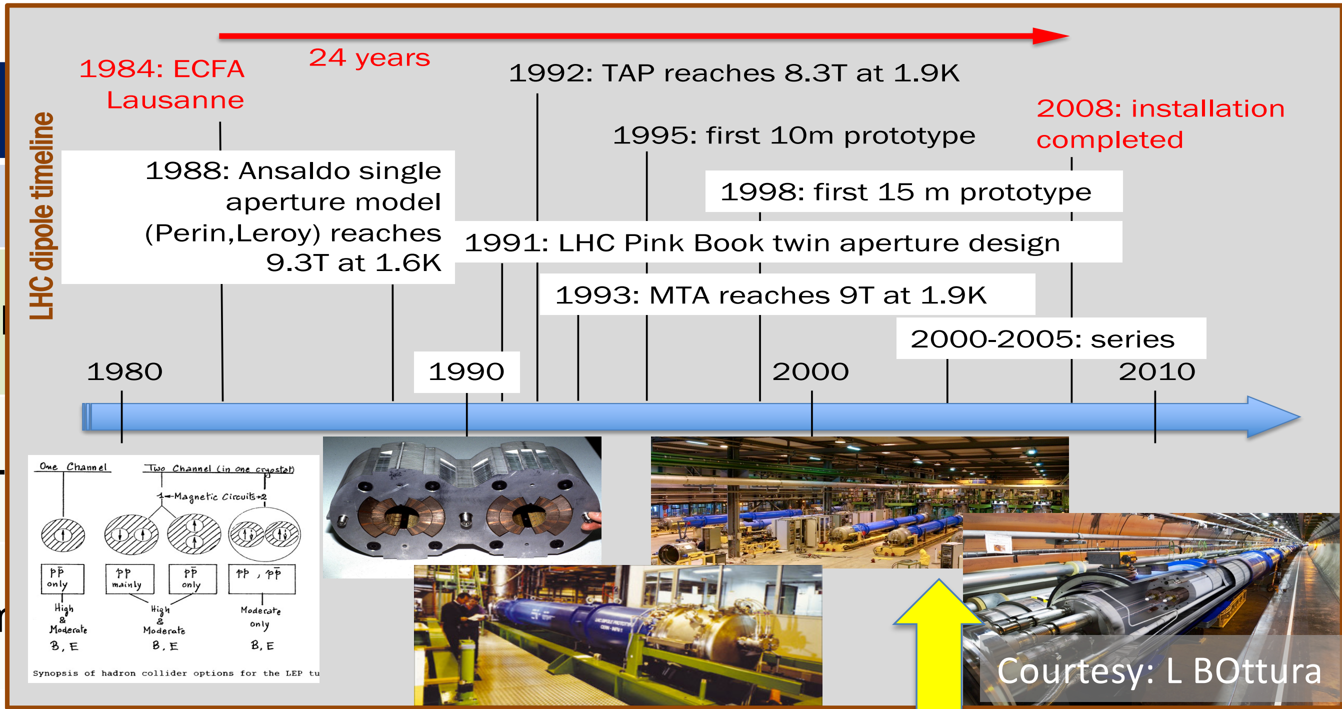
| Timeline | ~ 10 | ~ 20 | ~ 30 | |
|---|---|---|---|---|
| | | | | |
| 12~14T $Nb_3Sn$ | Short-model R&D | Proto/Pre-series | Construction | Operation |
| 14+ (~16)T $Nb_3Sn$ (+HTS) | Short-model R&D | Prototype/Pre-series | Construction | |
| > 15 ~ 16 T $Nb_3Sn$ + **HTS** | Fundamental and Short Model R&D | Prototype/Pre-series | | |

**Note: LHC experience**: **NbTi (10 T)** R&D started in 1980's
--> **(8.3 T) Production** started in late 1990's, in **~ 15 years**
→ **LHC Operation** started in later 2000's, in ~ 25 years

# Personal Scope for HFM Development Timeline

## for reaching Accelerator Construction and Operation

| Timeline | | |
|---|---|---|
| | | |
| 12~14T $Nb_3Sn$ | Short-model | on |
| 14+ (~16)T $Nb_3Sn$ (+HTS) | Short- | |
| > 15 ~16 T $Nb_3Sn$ + **HTS** | Fundam | |




**Note:** **LHC experience: NbTi (10 T)** R&D started in 1980's

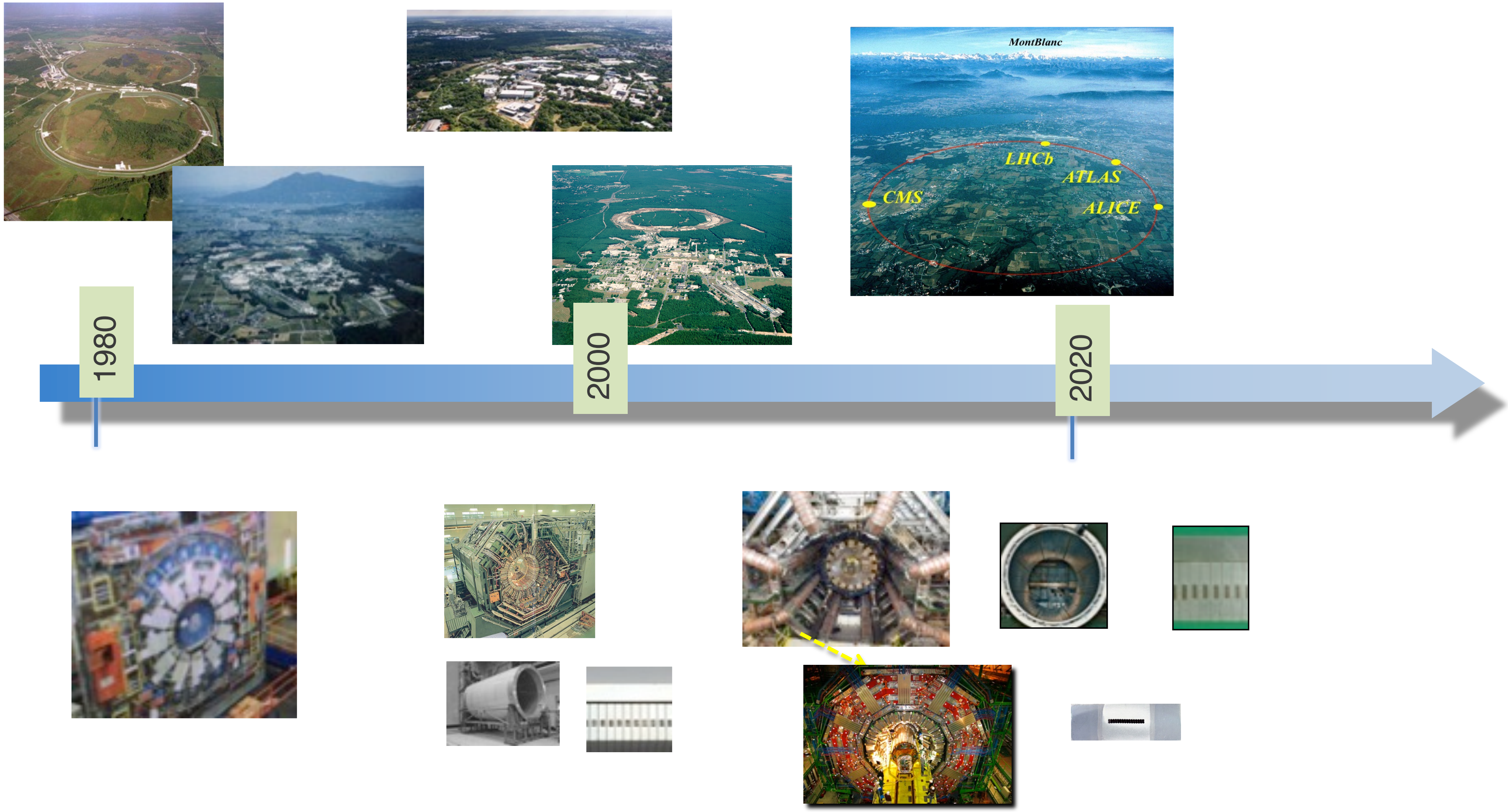
--> **(8.3 T) Production** started in late 1990's, in **~ 15 years**

→ **LHC Operation** started in later 2000's, in **~ 25 years**

# Outline

- **Introduction :**
  - Future Colliders, relying on Superconducting (SC) Technology
- **SC Technology for Colliders:**
  - Superconducting RF Cavities (Acc. Structure)
  - Superconducting Magnets
- **Superconducting Detector Magnets (SC-DM)**
- **Summary**

# Advances in SC Detector Magnets for Colliders



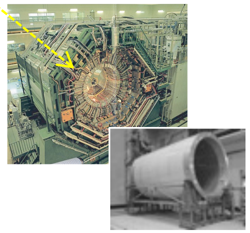

Tevatron: CDF

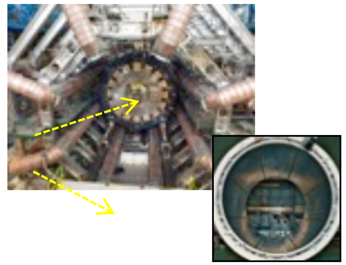
Tristan; Topaz, Venus, Amy

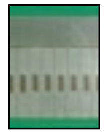
LHC: ATLAS, CMS

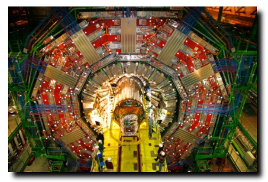
# Advances in Detector Solenoids

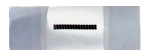
| Experiment | Laboratory | $R$ (m) | $B$ (T) | $I$ (kA) | $X$ ($X_0$) | $E/M$ (kJ/kg) | $E$ (MJ) | Year | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| PLUTO | DESY | 0.75 | 2.2 | 1.3 | 4.0 | 2.3 | 4.1 | 1972 | 18 |
| ISR point 1 | CERN | 0.85 | 1.5 | 2 | 1.1 | 1.8 | 3.0 | 1977 | 19 |
| CELLO | Saclay/DESY | 0.85 | 1.5 | 3 | 0.6 | 5.0 | 7.0 | 1978 | 20 |
| PEP4/TPC | LBL/SLAC | 1.1 | 1.5 | 2.27 | 0.83 | 7.6 | 11 | 1983 | 21 |
| CDF | KEK/FNAL | 1.5 | 1.6 | 5 | 0.84 | 5.4 | 30 | 1984 | 22 |
| TOPAZ | KEK | 1.45 | 1.2 | 3.65 | 0.70 | 4.3 | 19 | 1984 | 23 |
| VENUS | KEK | 1.75 | 0.75 | 4 | 0.52 | 2.8 | 11.7 | 1985 | 24 |
| AMY | KEK | 1.2 | 3 | 5 | N/A | N/A | 40 | 1985 | 25 |
| CLEO-II | Cornell | 1.55 | 1.5 | 3.3 | 2.5 | 3.7 | 25 | 1988 | 26 |
| ALEPH | Saclay/CERN | 2.75 | 1.5 | 5 | 2.0 | 5.5 | 136 | 1987 | 27 |
| DELPHI | RAL/CERN | 2.8 | 1.2 | 5 | 1.7 | 4.2 | 110 | 1988 | 28 |
| ZEUS | INFN/DESY | 1.5 | 1.8 | 5 | 0.9 | 5.2 | 10.5 | 1988 | 29 |
| H1 | RAL/DESY | 2.8 | 1.2 | 5 | 1.8 | 4.8 | 120 | 1990 | 28 |
| BESS | KEK | 0.5 | 1.2 | 0.38 | 0.2 | 6.6 | 0.25 | 1990 | 30 |
| WASA | KEK/Uppsala | 0.25 | 1.3 | 0.9 | 0.18 | 6 | 0.12 | 1996 | 31 |
| BABAR | INFN/SLAC | 1.5 | 1.5 | 6.83 | 0.5 | N/A | 27 | 1997 | 32 |
| D0 | FNAL | 0.6 | 2.0 | 4.85 | 0.9 | 3.7 | 5.6 | 1998 | 33 |
| BELLE | KEK | 1.8 | 1.5 | 4.16 | N/A | 5.3 | 37 | 1998 | 34 |
| ATLAS-CS | KEK/CERN | 1.25 | 2.0 | 7.8 | 0.66 | 7.1 | 38 | 2001 | 35 |
| BESS-polar | KEK | 0.45 | 1.0 | 0.48 | 0.156 | 9.2 | 0.34 | 2005 | 36 |
| CMS | CMS/CERN | 3.0 | 4.0 | 19.5 | N/A | 12 | 2600 | 2007 | 37 |
| BESIII | IHEP (China) | 1.45 | 1.0 | 5 | N/A | 2.6 | 9.5 | 2008 | 38 |
| CMD-3 | BINP | 0.35 | 1.5 | 1 | 0.085 | 8.2 | 0.31 | 2009 | 39 |



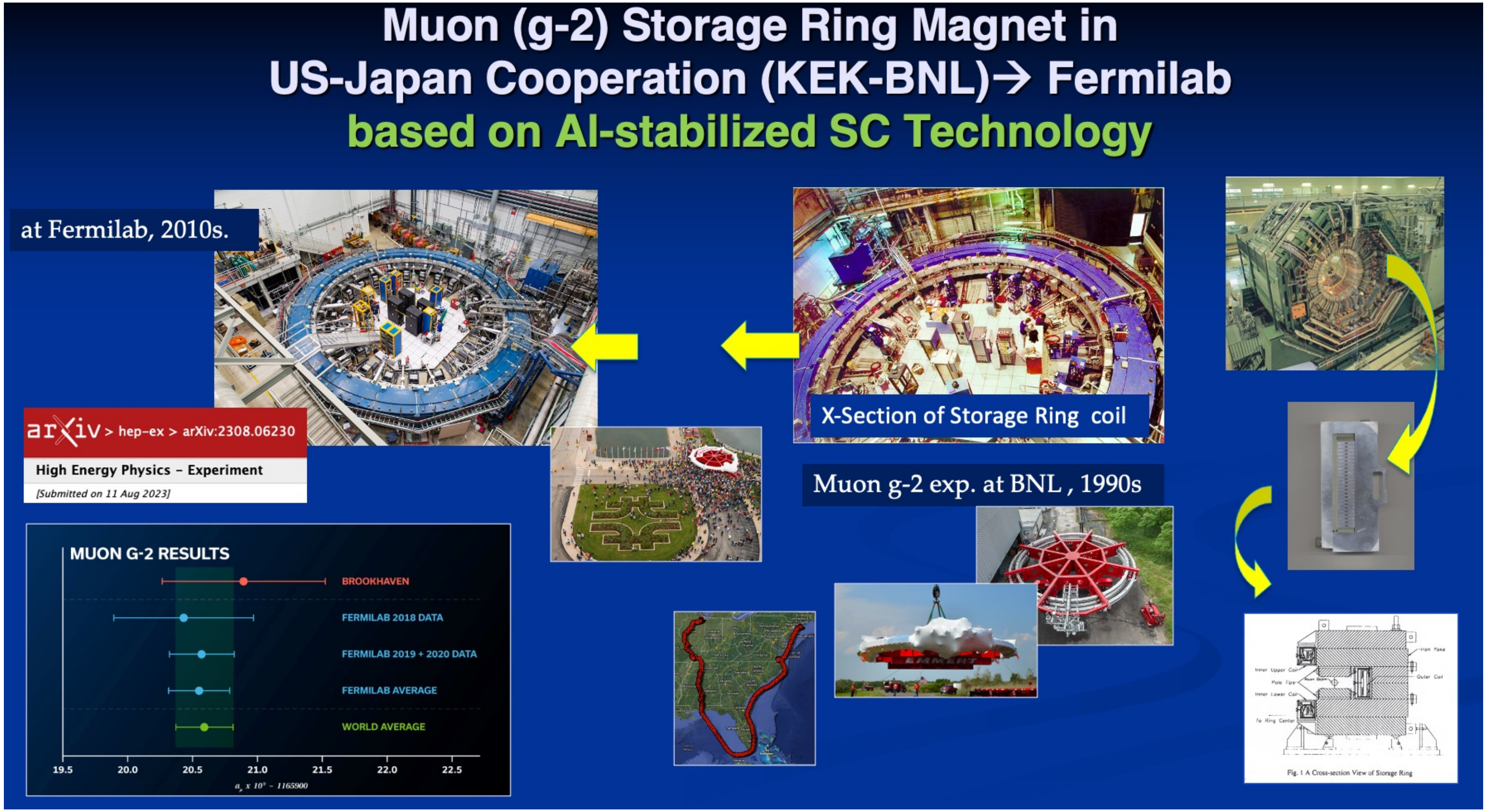




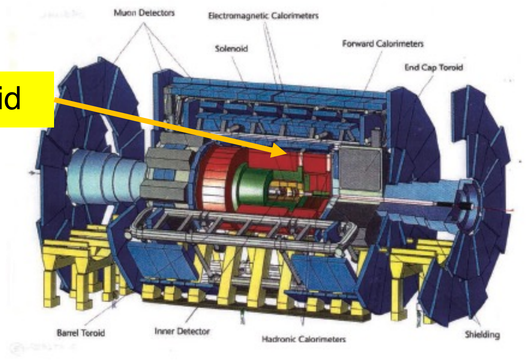




# A Spin-out of the Al-SC Technology

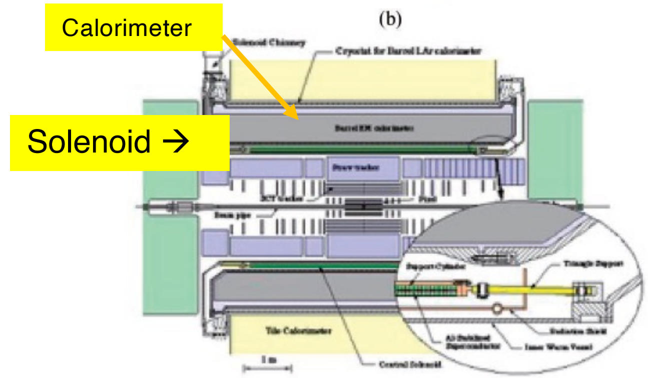


# Status: LHC, ATLAS and CMS Detector Magnets

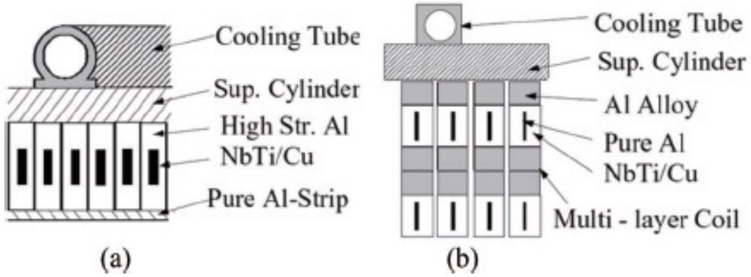



(a)

(b)




ATLAS-CS, placed inside Calorimeter



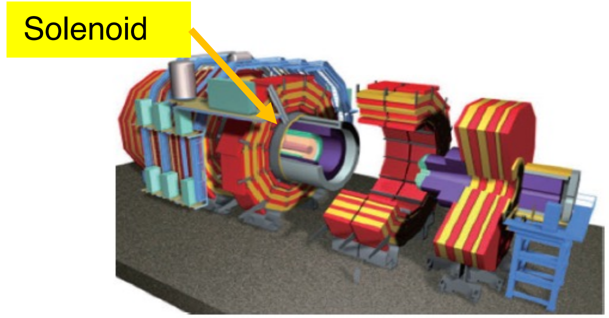

**Al-stabilized SC:**

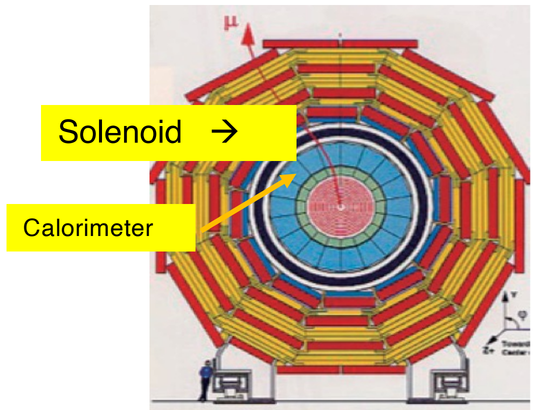
Serving an essential role for:

- **B field w/ Large volume**
- **Reliable operation**
- **Particle passing through**

⇩

**We need to prepare for Future Programs**




CMS Solenoid placed outside alorimeter


## Motivation:

- Preparing **SC Detector Magnets technology,, for future Colliders**
- **Re-establishing: Al-stabilized SC technology, as a critical issue**

# Future Colliders and Physics Experiments Expected

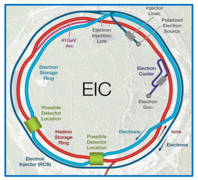

**Future proposed particle physics experiments being studied: from LDG Accelerator R&D Report, CERN 2022-001**

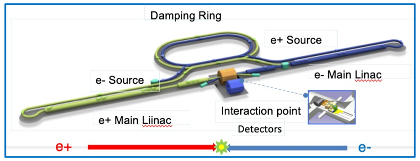
| < 2030 | 2030-2035 | 2035-2040 | 2040-2045 | > 2045 |
|---|---|---|---|---|
| SPS fixed target<br>Other fixed target; FAIR (hep)<br>Belle II<br>ALICE LS3<br>PIP-II/DUNE/Hyper-K | ALICE 3<br>LHCb (≥ LS4)<br>EIC<br>LHeC | ILC | FCC-ee<br>CLIC | FCC-hh<br>FCC-eh<br>Muon Collider<br>Plasma Collider |

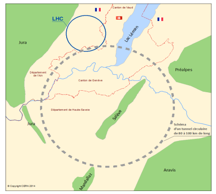
2007 ~ 2022

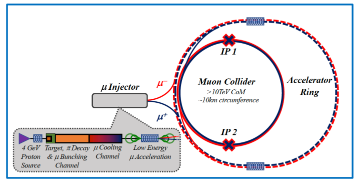
COMET, Mu2e

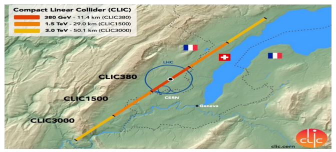
Other phys. Experiments: Mu2e, G-2 (fnal), Comet, G-2)J-Parc), BabyAXIO, AXIO (desy)

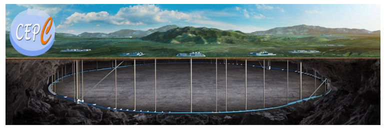


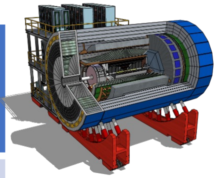



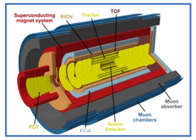



# Future Particle Detector Plans proposed

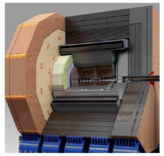
| Subject / Project | Institutes in charge |
|---|---|
| The Electron-Ion Collider (EIC) | BNL / JLab |
| International Linear Collider –ILD (ILC-ILD) | ILC-IDR |
| International Linear Collider - SiD (ILC-SiD) | SLAC |
| Compact Linear Collider (CLiC) | CERN |
| Leptron Future Circular Collider (FCC-ee) | CERN |
| Hadron Future Circular Collider (FCC-hh) | CERN |
| Circular Electron Positron Collider (CEPC) | IHEP |
| A Large Ion Collider Experiment 3 (ALICE-3) | CERN |
| Muon to Electron (Mu2e) | ermilab |
| Muon Experiments in Japan | KEK |
| antiProton ANihilation at Darmstadt (PANDA) | GSI |
| Baby International Axion Observatory (BabyIAXO) | DESY |
| MAgnetized Disc & Mirror Axion eXp. (MADMAX) | CEA for DESY |
| Alpha Magnetic Spectrometer 100 (AMS-100) | Rheinish West. |

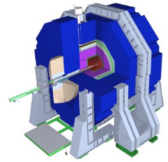


EIC

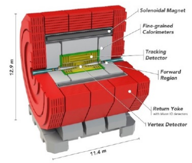


ALICE-3

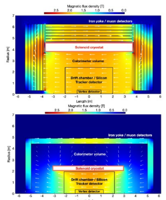




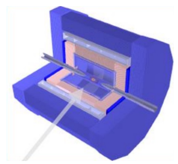
ILC-ILD /SiD



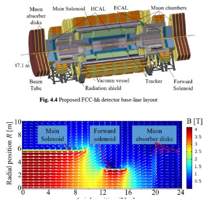
CLIC



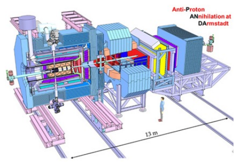
FCC-ee



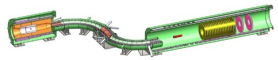
CEPC



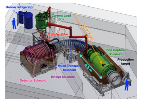
FCC-hh



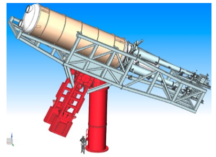
PANDA



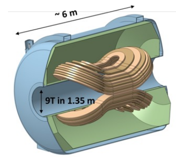
Mu2e



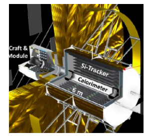
Comet



BabyIAX0

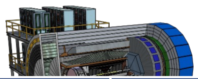


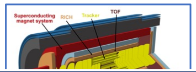
MadMax



AMS100

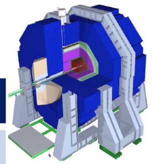
# Future Particle Detector Plans proposed



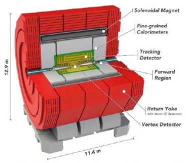


| Subject / Project | Institutes in |
| --- | --- |
| The Electron-Ion Collide | |
| International Linear Colli | |
| International Linear Colli | |
| Compact Linear Collider | |
| Leptron Future Circular ( | |
| Hadron Future Circular ( | |
| Circular Electron Positro | |
| A Large Ion Collider Exp | |
| Muon to Electron (Mu2e | |
| Muon Experiments in Ja | |
| antiProton ANihilation at | |
| Baby International Axion | |
| MAgnetized Disc & Mirro | |
| Alpha Magnetic Spectro | |

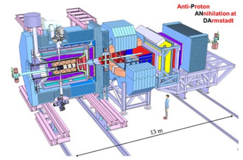
| Experiments | Site | B [T} | Size, ID x L [m] | Note |
| --- | --- | --- | --- | --- |
| EIC-Detector | BNL | 1.5~3 | 2.5~3.2 x 8.5 | Solenoid |
| ILC-ILD | Japan | 4 | 6.88 X 7.35 | Solenoid |
| ILC-SiD | Japan | 5 | 5 X 5 | Solenoid |
| CLIC-ILD | CERN | 4 | 6.8 X 8.3 | Solenoid |
| CLIC-SiD | CERN | 5 | 5.4 X 6.5 | Solenoid |
| CLIC | CERN | 4 | 7 X 8.3 | Solenoid |
| FCC-ee IDEA | CERN | 2 | 4.2 X 6.0 | Solenoid |
| FCC-ee CLD | CERN | 2 | 7.4 X 7.4 | Solenoid |
| FCC-hh | CERN | 4 | 10 X 20 | Solenoid |
| ALICE-3 | CERN | 2 | 3 x 7.5 | Solenoid |
| M2e | Fermilab | 5 ~ 2.5 | 1.5 X 4 | Production |
| Muon-g-2 | Fermilab | 1.473 | 0.09 X 14.22 ▪ $2\pi$ | Storage solenoid |
| COMET | J-PARC | 5 ~ 3 | 1.3 X 1.6 | Capture Sol. |
| Muon-g-2 | J-PARC | 3 | 0.66 X 0.33 | Solenoid |
| BabyAXIO | DESY | 2 | 0.7 X 10 | D. Racetrack |
| IAXO | DESY | 5 - 6 | 5 X 25 | Toroid |
| Panda | GSI | 2 | 1.8 x 3.1 | Solenoid |
| Madmax | DESY | 9 | 1.35 x 1.2 | Dipole |



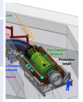
LD /SiD



CLIC



PANDA



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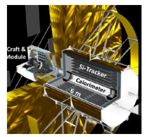


AMS100

Courtesy: B. Cure, Y. Makida

# Al-stabilized Superconductor, reinforced, required

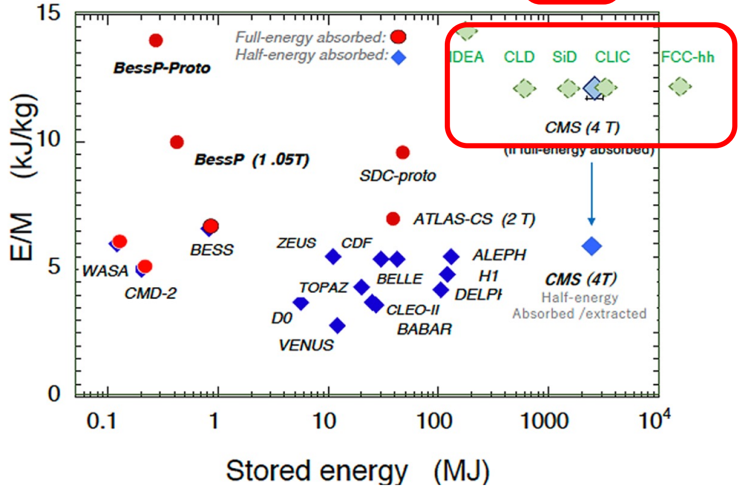
All future solenoids need **Al-stabilized** and reinforced superconductor:

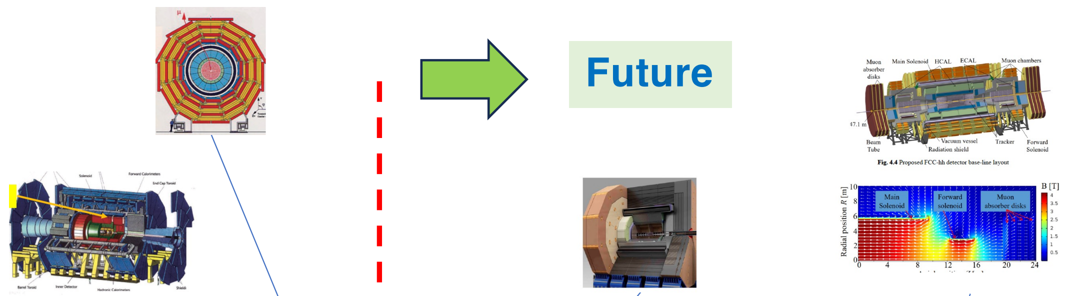
- **Large solenoids → high B** resulting large stored **Energy, and with small Mass**

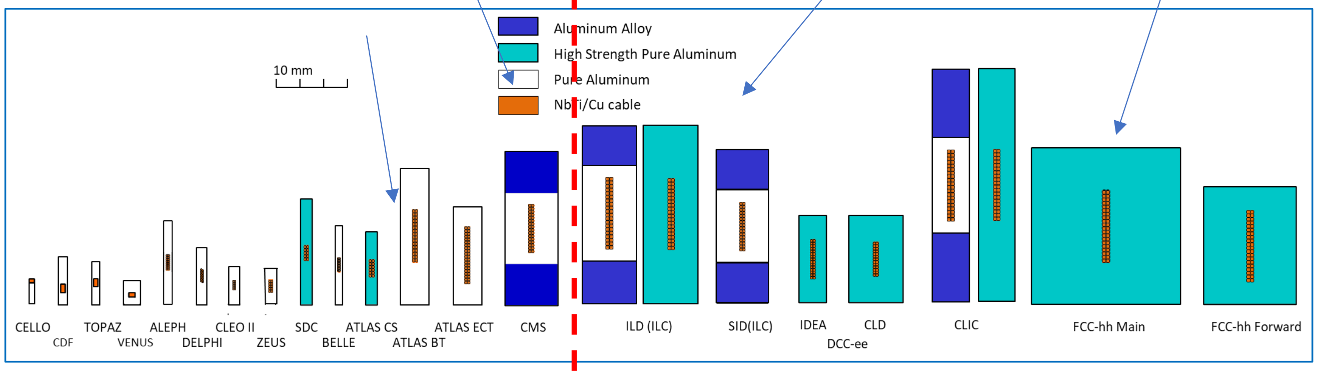
  **→ high E/M → reinforcement crucially important**

**Table 4**. The proposed design parameters for the detector solenoids for future projects.

| Projects | Magnet | $B_c$ (T) | InnerR (m) | Length (m) | E/M (kJ/kg) | Stored energy (GJ) |
|---|---|---|---|---|---|---|
| FCC-ee | IDEA | 2 | 2.24 | 5.8 | 14 | 0.17 |
| | CLD | 2 | 4.02 | 7.2 | 12 | 0.6 |
| FCC-hh | | 4 | 5 | 20 | 11.9 | 13.8 |
| CLIC | | 4 | 3.65 | 7.8 | 13 | 2.3 |
| ILC | ILD | 4 | 3.6 | 7.35 | 13 | 23 |
| | SID | 5 | 2.5 | 5 | 12 | 1.4 |



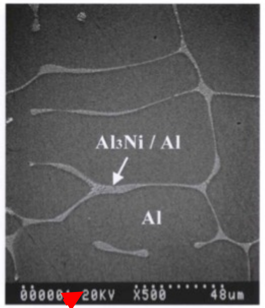




M. Mentink, K. Sasaki et al., JINST113P 0323 (2023)

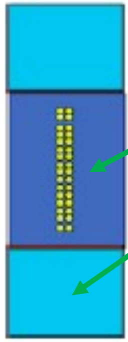
# Ultimate effort for maximizing the peroformance

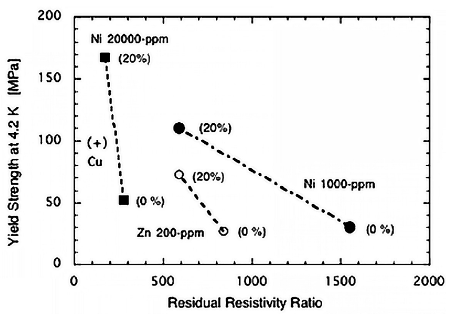
- **Reinforcement of Al**
  - **with keeping low resistivity**
- **Uniform reinforcement**
  - **Micro-alloying and cold work**
  - **ATLAS-CS**

- **Hybrid reinforcement**
  - **Welding Al-Alloy with pure-Al**
  - **CMS**

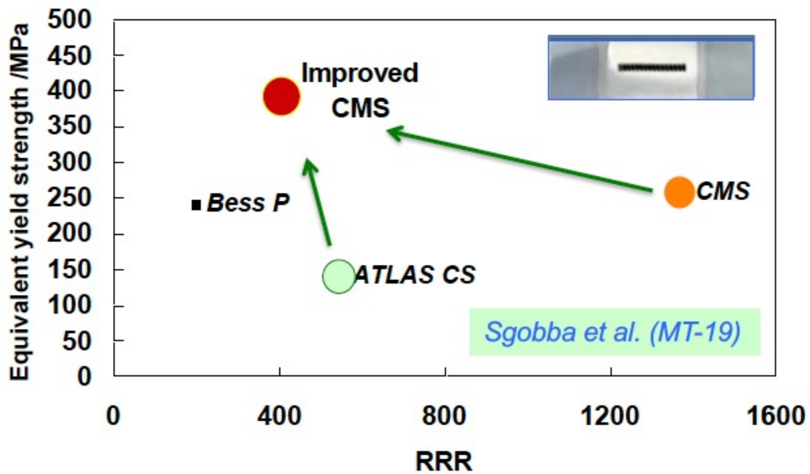



b) Al-0.5wt%Ni Alloy






| | Rein-force | Feature | Al Y. S. (MPa) | Full cond. Y.S. | Full cond. RRR |
|---|---|---|---|---|---|
| ATLAS-CS | Uniform | Ni-0.1% Al | 110 MPa | 146 MPa | 590 |
| CMS | Hybrid | Pure-Al & A6082-T6 | 26 / 428 | 258 | (1400) |
| **Future** | **Hybrid** | **Ni-Al & A6082-T6** | **110 / 428** | **300** | **400** |
| **Future** | **Hybrid** | **Ni-Al & A7020-T6** | **110 / 677** | **400** | **400** |



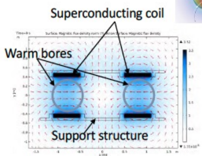
# Urgent Near Future Programs :

## BabyIAXO

| | Detector dipole |
|---|---|
| Warm bore diameter [m] | 2x 0.7 |
| Cold mass length [m] | 11 |
| Magnetic field in the centre [T] | 2.0 |
| Stored magnetic energy [MJ] | 40 |

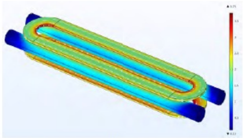
*Magnet parameters*

*BabyIAXO detector*

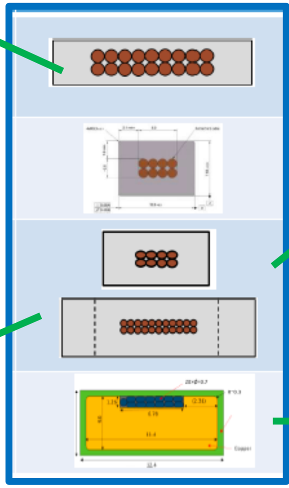



*Magnetic field in cross-section*

- Presentation by U. Schneekloth (DESY)
- BabyIAXO detector, for studying axions emanating from the sun
- Featuring a superconducting common-coil dipole with a 2 T transverse magnetic field in two 0.7 meter warm bores of 11 meters length
- Conductor: Featuring an aluminum-stabilized Nb-Ti/Cu conductor



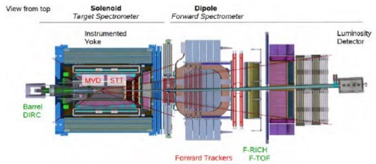
*Common-coil dipole, with counter-flowing current in two superconducting race-track coils*



## The PANDA detector

| | Target spectrometer solenoid |
|---|---|
| Warm bore diameter [m] | 1.8 |
| Cold mass length [m] | ~3.1 |
| Magnetic field in the centre [T] | 2 |
| Stored magnetic energy [MJ] | 22 |

*Magnet parameters*



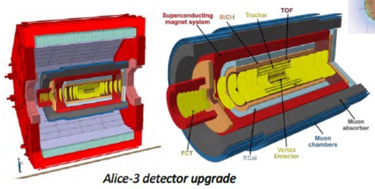

*The PANDA detector layout*

- Presentation by L. Schmitt (GSI)
- For fixed-target anti-matter physics at FAIR, foreseen to start operation by 2029
- With strong involvement of various Russian institutes, including the Budker Institute of Nuclear Physics
- Featuring a 2 T superconducting solenoid, with a stored magnetic energy of 22 MJ
- Conductor: Aluminum-stabilized Nb-Ti/Cu conductor technology, under development through a R&D effort by Russian institutes and industry (BINP, VNIINM Bochvar, VNIIKP, SARKO)

## Alice-3

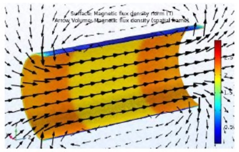
| | Detector solenoid |
|---|---|
| Warm bore diameter [m] | 3 |
| Cold mass length [m] | 7.5 |
| Magnetic field in the centre [T] | 2 |
| Stored magnetic energy [MJ] | 130 |

*Magnet parameters*




*Alice-3 detector upgrade*

- Presentation by W. Riegler (CERN)
- Planned to be installed by LS4 (which is currently foreseen to start in 2033)
- Featuring a superconducting solenoid, with 2 T in the center and additional windings at the end to augment bending power for high-pseudo-rapidity particles
- Also featuring a forward (superconducting) dipole
- Conductor: Proposal to use a reinforced aluminum-stabilized conductor



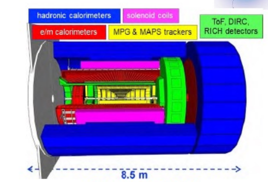
*Magnetic field configuration*

## The Electron-Ion Collider

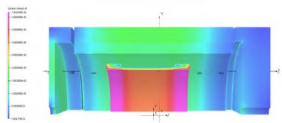
| | Detector solenoid #1 | Detector solenoid #2 |
|---|---|---|
| Warm bore diameter [m] | 2.8 | 3.2 |
| Cold mass length [m] | 3.5 | 3.6 |
| Magnetic field in the centre [T] | 2.0 | 3.0 |
| Stored magnetic energy [MJ] | 46 | ~150 |

*Magnet parameters*

- Presentation by R. Rajput-Ghoshal (Jefferson Lab)
- For the Electron-Ion Collider project to be hosted at BNL, with full project finalization foreseen by 2034
- Two superconducting detector solenoids, for two interaction points:
  - #1: 2 T in solenoid with a 2.8 meter warm bore diameter and a 3.5 meter cold mass length
  - #2: 3 T in solenoid with a 3.2 meter warm bore and a 3.6 meter cold mass length
- Conductor:
  - Solenoid #1, initial preference for reinforced aluminum-stabilized Nb-Ti/Cu, but copper-stabilized conductor can work as well
  - Solenoid #2, a reinforced aluminum-stabilized Nb-Ti/Cu conductor is foreseen



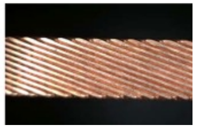

*Detector solenoid #1*



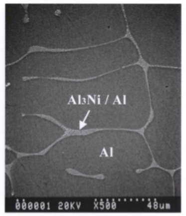
*Detector solenoid #2*

# Al-Stabilized SC Technology  to be re-established

- **NbTi/Cu SC and Cable production: remaining:**
  - SC strand: industry
  - Cable: CERN, FNAL, LBNL, and industry*.

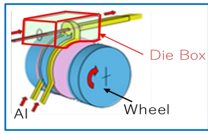


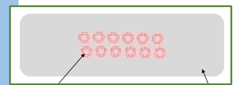
- **Al-stabilizer reinforcement remaining:**
  - with micro-alloying and cold work remain feasible
  - Industrially available in Japan.



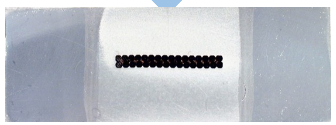

b) Al-0.5wt%Ni Alloy

- **Al-NbTi/Cu co-extrusion technology  :disappearing:**
  - All the experienced industrial facilities have been shut-downed and dismantled,
  - Toly E. (in China) started the development with aiming for the CEPC detector solenoid. The progress sounds promising and needs to watch further progress.
  - The technology shall be widely transferred to the industry to maintain production capability



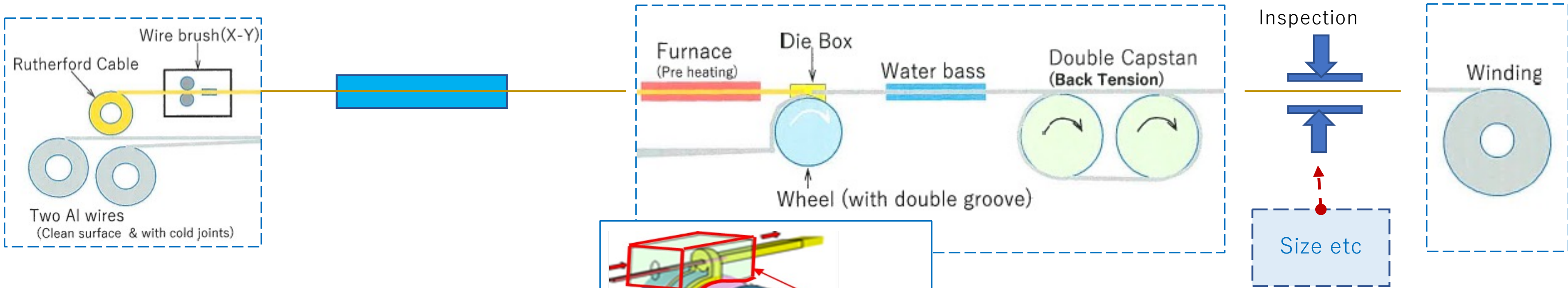
- **EBW for conductor reinforcement: remaining:**
  - Technology kept at TECHMETA in France

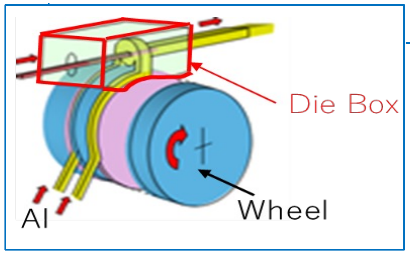


Courtesy; Toly and Hitachi

# A Critical Issue: Co-extrusion for Al-stab.SC

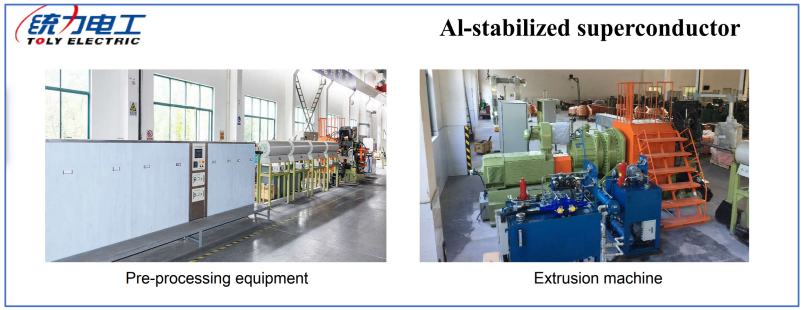
| NbTi/Cu cable Al-wire | Brushing (x, Y) | U-Sonic Cleaning | Pre-heating | Co-extrusion | Water-cooling | D-capstan or Caterpillar | Winding / Spooling | Inspection QA |
|---|---|---|---|---|---|---|---|---|




- All experienced supplier's facilities **shut-down in past 10 years**

- Except for A company, **Toly Electric,** in China, is starting new R&Ds (for CEPC?)
- We need to prepare for other capabilities



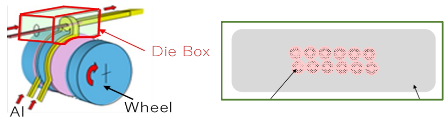
# We need to action it, NOW ?

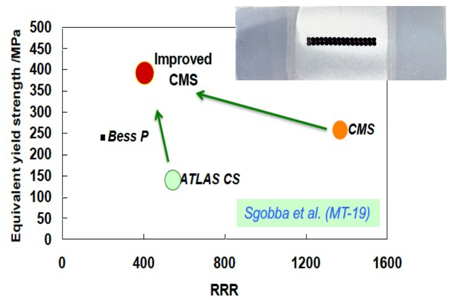
## Urgent Action Required:

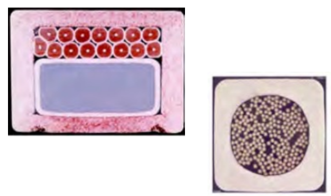
- **Al-stabilized superconductor technology** needs to be resumed,
  - **"Co-extrusion technology"** of Al-stabilizer to be resumed, and
  - "Hybrid-structure technology" by using electron beam welding (EBW)
  - **Laboratory's leading effort very important** to advance the technology
- CERN is now working for establishing a program on coextrusion process for Al-stab SC with institutional and industrial partners.

## Remarks:

- It will be **needed** to investigate **backup solutions** such as:
  - soldering technology of NbTi/Cu conductor with Cu-coated Al-stabilizer, and/or CICC. ,,,
- It will be encouraged to investigate Al-stabilized HTS for specofoc applications



# Outline

- **Introduction :**
  - Future Colliders, relying on Superconducting (SC) Technology

- **SC Technology for Colliders:**
  - Superconducting RF Cavities (Acc. Structure)
  - Superconducting Magnets

- **Superconducting Detector Magnets (SC-DM)**

- **Summary**

# Summary

- **Acc. SRF Technology :**
  - **Nb-bulk** (for > 1 GHz) :High-G (> 45 MV/m) and High-Q (> 3E10) w/ optimizing the surface process, High-G (> 50 MV/m w/ travelling wave SRF
  - **Thin-Film** (to be combined with Nb → Cu substrate) : New material such as $NB_3Sn$ to improve performance to reach > 50 MV/m .
- **Acc. Magnet Technology:**
  - **$Nb_3Sn$** toward **14 + (toward 16) T,** w/ higher Jc, **mechanical property**, field quality, training quenches,,
  - **$Nb_3Sn$ + HTS-insert**" be inevitably required, for **16 T and beyond**, and cost effective HTS will be essentially required for practical accelerator applications.
- **Detector Magnet Technology :**
  - **Al-stabilized superconductor technology** needs to be revived, and urgently required !
  - **CERN** is acting to **re-establish the technology** in close cooperation with industry.

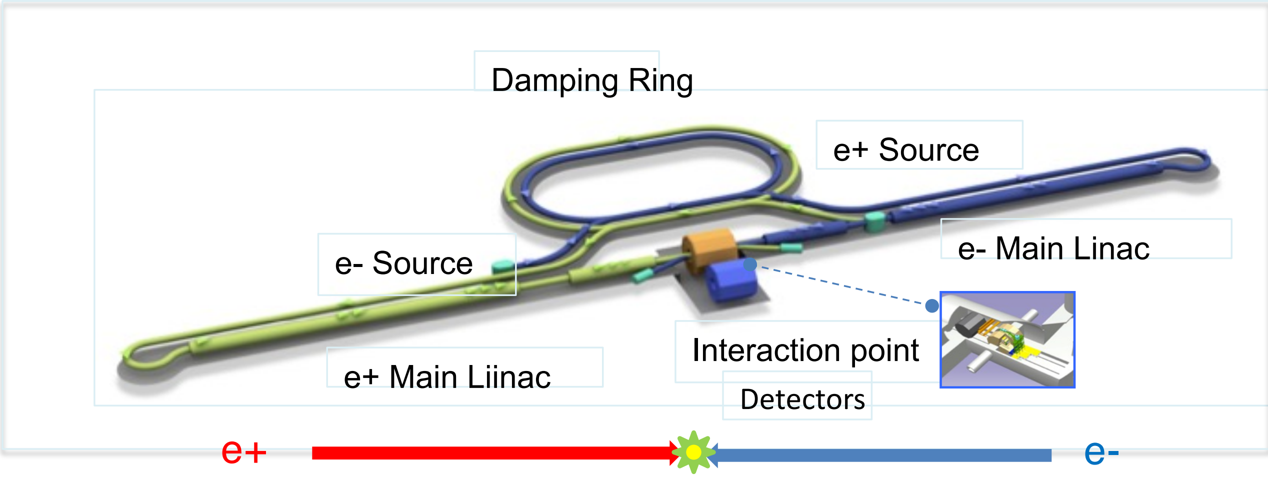
***Superconducting technology is essential for Future Colliders & Detectors !!***

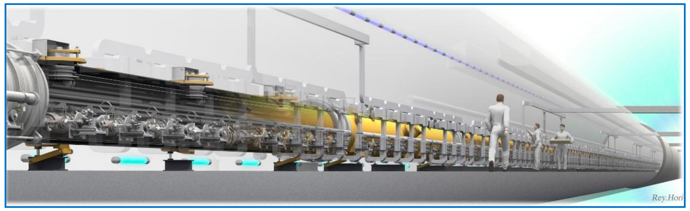
# Reserved

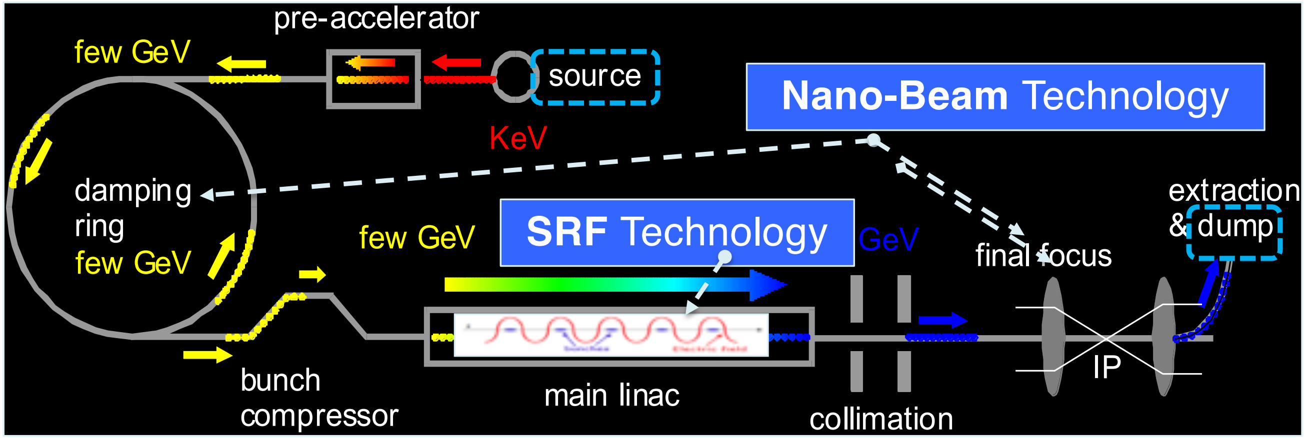
# Challenges in Future Energy-Frontier Colliders

| | | Ref. | E (CM) [TeV] | Luminosity [1E34] | AC-Power [MW] | SRF E [MV/m] [GHz] | SCM B [T] | Major Challenges in Technology |
|---|---|---|---|---|---|---|---|---|
| LC ee | ILC | TDR update | 0.25 -1 | 1.35, 2.7 (~ 4.9) | 110, 138 (~ 300) | 31.5 – 45 [1.3] | | SRF cavity: High-G and high-Q<br>Higher-G for future upgrade including new material,<br>Nano-beam stability |
| | CLIC | CDR | 0.38 - 3 | 1.5 (~ 6) | 100 (~ 580) | 72 – 100 [12] | | Acc. Structure: High-precision, Large-scale production,<br>Two-beam acceleration in a prototype scale,<br>Precise alignment and stabilization. |
| CC ee | FCC-ee | CDR | 0.09 ~ 0.38 | 460 ~ 31 | 260 ~ 350 | 10 – 20 [0.4 - 0.8] | | **SRF cavity: High-Q** at < GHz, Nb thin-film Coating,<br>Synchrotron Radiation absorption,<br>Energy efficiency (RF efficiency). |
| | CEPC | CDR | 0.046 - 0.24 | 32 ~ 5 | 150 ~ 270 | 20 – 40 [0.65] | | SRF cavity: High-Q at < GHz, LG Nb-bulk/thin-film,<br>Synchrotron Radiation constraint,<br>Low-field magnet with high-precision. |
| CC hh | FCC-hh | CDR | 80 - 120 | 5 ~ 30 | 580 | tbd [0.4, 0.8] | 14-20 | SC magnet : High-field<br>- Nb3Sn (+HTS): high Jc, mechanical stress sustainability<br>Energy management |
| | SPPC | CDR | 75 - 125 | 10 | --- | tbd | 12 - 24 | SC magnet : High-field<br>- IBS: High Jc, stress sustainability, energy management |
| Cc e-h | EIC | | | | | | | To be filled |
| CC mm | MC | | 0.12 ~ 14 | 0.008~33 | 200 ~290 | 30 0.8 ~1.3 | 10 -16 (> 40) | Short lifetime, cooling,<br>SC magnet: High-field, RF in strong magnetic field, …. |

# ILC and the Accelerator Technology



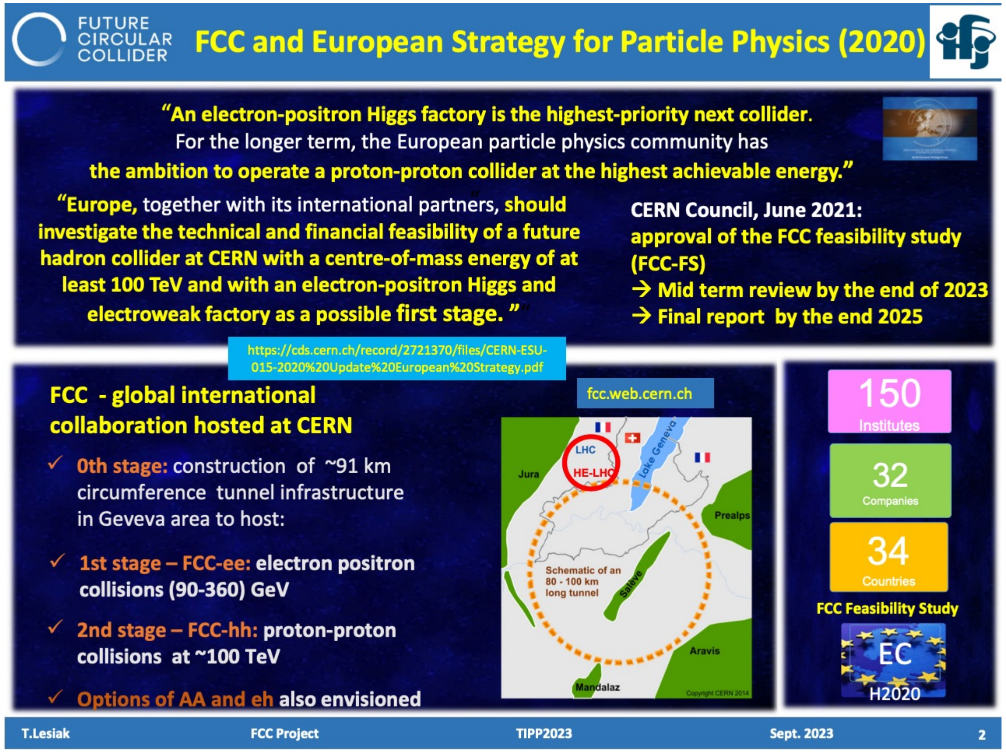



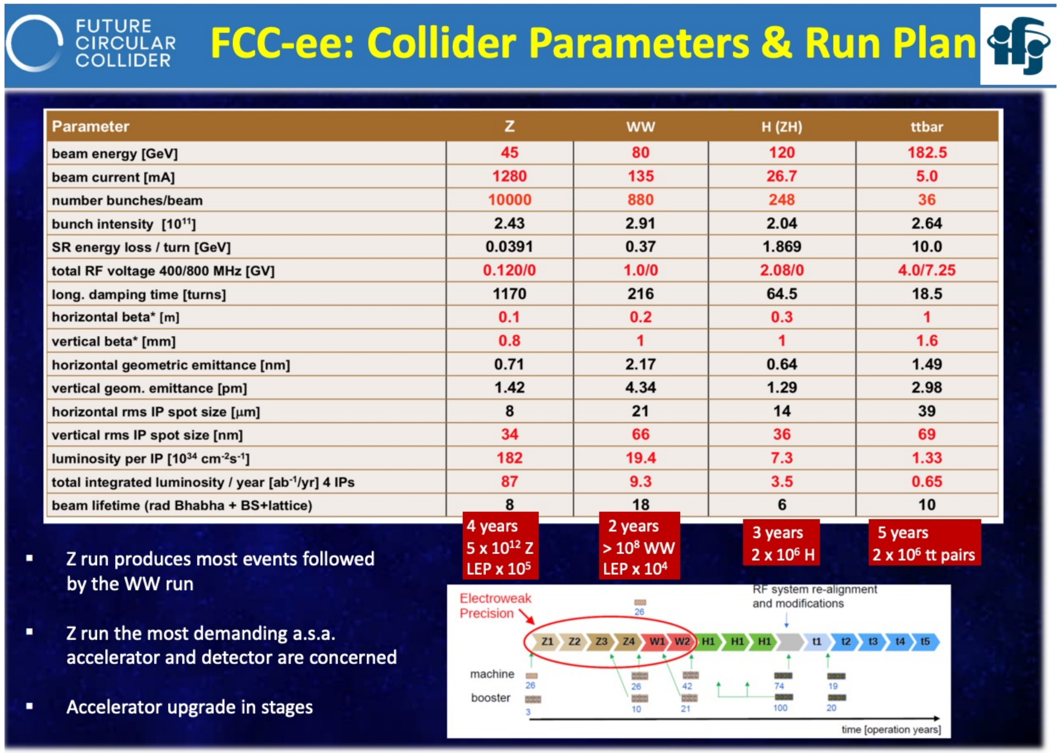



| Parameters | Value |
|---|---|
| Beam Energy | 125 + 125 GeV |
| Luminosity | 1.35 / 2.7 x $10^{10}$ $cm^2$/s |
| Beam rep. rate | 5 Hz |
| Pulse duration | 0.73 / 0.961 ms |
| # bunch / pulse | 1312 / 2625 |
| Beam Current | 5.8 / 8.8 mA |
| Beam size (y) at FF | **7.7** nm |
| SRF Field gradient | < 31.5 > MV/m (+/-20%)<br>$Q_0$ = 1x$10^{10}$ |
| #SRF 9-cell cavities (CM) | ~ 8,000 (~ 900) |
| AC-plug Power | 111 / 138 MW |

Courtesy: T. Lesiak, TIPP2023

# FCC Overview

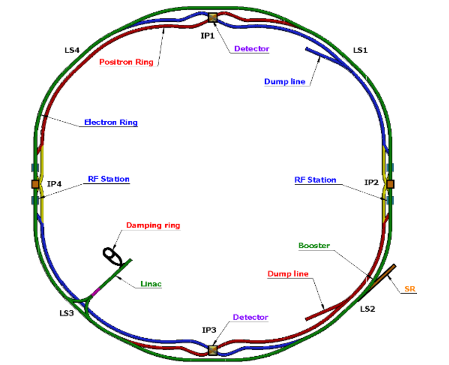


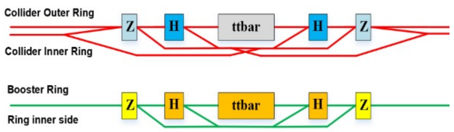

| Parameter | Z | WW | H (ZH) | ttbar |
|---|---|---|---|---|
| beam energy [GeV] | 45 | 80 | 120 | 182.5 |
| beam current [mA] | 1280 | 135 | 26.7 | 5.0 |
| number bunches/beam | 10000 | 880 | 248 | 36 |
| bunch intensity [$10^{11}$] | 2.43 | 2.91 | 2.04 | 2.64 |
| SR energy loss / turn [GeV] | 0.0391 | 0.37 | 1.869 | 10.0 |
| total RF voltage 400/800 MHz [GV] | 0.120/0 | 1.0/0 | 2.08/0 | 4.0/7.25 |
| long. damping time [turns] | 1170 | 216 | 64.5 | 18.5 |
| horizontal beta* [m] | 0.1 | 0.2 | 0.3 | 1 |
| vertical beta* [mm] | 0.8 | 1 | 1 | 1.6 |
| horizontal geometric emittance [nm] | 0.71 | 2.17 | 0.64 | 1.49 |
| vertical geom. emittance [pm] | 1.42 | 4.34 | 1.29 | 2.98 |
| horizontal rms IP spot size [μm] | 8 | 21 | 14 | 39 |
| vertical rms IP spot size [nm] | 34 | 66 | 36 | 69 |
| luminosity per IP [$10^{34}$ $cm^{-2}s^{-1}$] | 182 | 19.4 | 7.3 | 1.33 |
| total integrated luminosity / year [$ab^{-1}/yr$] 4 IPs | 87 | 9.3 | 3.5 | 0.65 |
| beam lifetime (rad Bhabha + BS+lattice) | 8 | 18 | 6 | 10 |

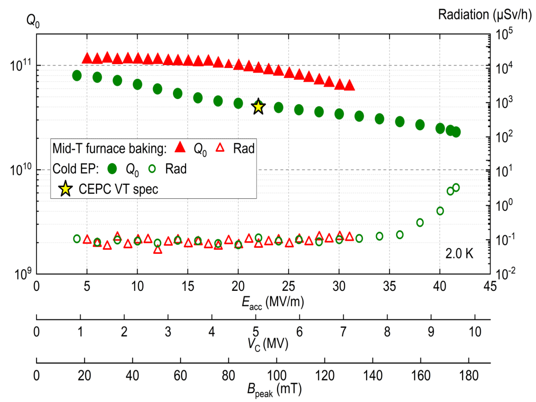
# CEPC Superconducting RF System Design and R&D


- CEPC SRF system has unprecedented challenges in high RF voltage (gradient and Q), high current (power) and mode switching. Progress in 650 MHz and 1.3 GHz SRF R&D.
- TDR review in June. Will publish and release TDR in late 2023.




Bypass scheme of an RF section




**High G High Q 650 MHz 1-cell Cavity**

EP treated: 2.3E10@41.6 MV/m@2 K

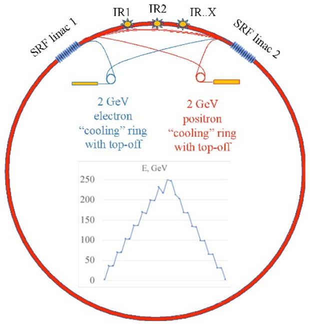
Mid-T treated: 6.3E10@31 MV/m@2 K

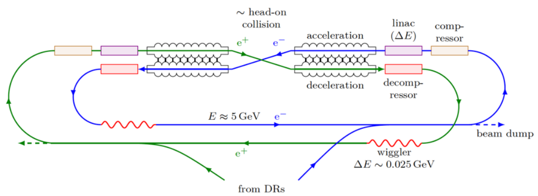
**CEPC 650 MHz test cryomodule**

2x2-cell cavities, high power input couplers, HOM couplers and absorbers, tuners etc. Beam test soon.

# Higgs Factory Summary (from Snowmass)

| Proposal Name | CM energy nom. (range) [TeV] | Lum./IP @ nom. CME $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$ | Years of pre-project R&D | Years to first physics | Construction cost range [2021 B$] | Est. operating electric power [MW] |
|---|---|---|---|---|---|---|
| FCC-ee[1,2] | 0.24 (0.09-0.37) | 7.7 (28.9) | 0-2 | 13-18 | 12-18 | 290 |
| CEPC[1,2] | 0.24 (0.09-0.37) | 8.3 (16.6) | 0-2 | 13-18 | 12-18 | 340 |
| ILC[3] - Higgs factory | 0.25 (0.09-1) | 2.7 | 0-2 | <12 | 7-12 | 140 |
| CLIC[3] - Higgs factory | 0.38 (0.09-1) | 2.3 | 0-2 | 13-18 | 7-12 | 110 |
| CCC[3] (Cool Copper Collider) | 0.25 (0.25-0.55) | 1.3 | 3-5 | 13-18 | 7-12 | 150 |
| CERC[3] (Circular ERL Collider) | 0.24 (0.09-0.6) | 78 | 5-10 | 19-24 | 12-30 | 90 |
| ReLiC[1,3] (Recycling Linear Collider) | 0.24 (0.25-1) | 165 (330) | 5-10 | >25 | 7-18 | 315 |
| ERLC[3] (ERL linear collider) | 0.24 (0.25-0.5) | 90 | 5-10 | >25 | 12-18 | 250 |
| XCC (FEL-based $\gamma\gamma$ collider) | 0.125 (0.125-0.14) | 0.1 | 5-10 | 19-24 | 4-7 | 90 |
| Muon Collider Higgs Factory[3] | 0.13 | 0.01 | >10 | 19-24 | 4-7 | 200 |




T. Roser et al, https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018

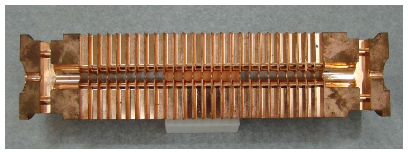
Courtesy: W. Wuensch

## SRF

| Superconducting (ILC) |
|---|
| **Gradient: 31.5 to 35 (to 45) MV/m,** |
| RF Frequency: 1.3 GHz<br>- Large aperture gives low wakefields |
| **$Q_0$: order $10^{10}$,**<br>- low losses at cryogenic temperatures |
| **Pulse structure: 700 μs / 5 Hz** |
| Fabrication<br>- Forming |
| - High-efficiency RF also from long-pulse, low-frequency klystrons |

## NRF

| Normal conducting (CLIC) |
|---|
| **Gradient: 72 ~ 100 MV/m** |
| RF Frequency: 12 GHz<br>- High efficiency RF peak power |
| **$Q_0$: order $< 10^5$,**<br>- Resistive copper wall losses compensated by strong |
| **Pulse structure: 180 ns / 50 Hz** |
| Fabrication:<br>- Machining |
| - High-efficiency RF peak power production through long-pulse, low freq. klystrons and two-beam scheme |

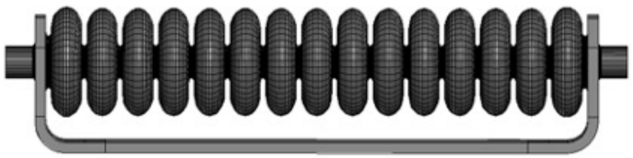


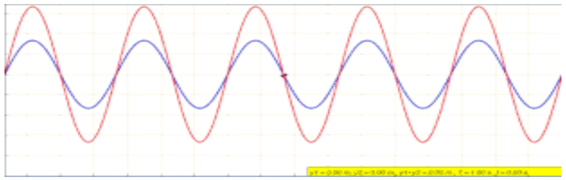
Courtesy: S. Belomestnykh

# Traveling Wave Cavity Technology proposed for HELEN SRF Accelerator

**HELEN: A LINEAR COLLIDER BASED ON ADVANCED SRF TECHNOLOGY***

S. Belomestnykh†,[1], P. C. Bhat, M. Checchin‡, A. Grassellino, M. Martinello‡, S. Nagaitsev[2],
H. Padamsee[3], S. Posen, A. Romanenko, V. Shiltsev, A. Valishev, V. Yakovlev
Fermi National Accelerator Laboratory, Batavia, IL, USA
[1]also at Stony Brook University, Stony Brook, NY, USA
[2]also at University of Chicago, Chicago, IL, USA
[3]also at Cornell University, Ithaca, NY, USA





- **Red** standing wave – High Peak Fields
- **Green** (acceleration) and **Blue** (Return) Waves are Travelling Waves - Lower peak fields
- Guide blue wave in a return wave-guide to avoid SW peak fields – attached to both ends

Table 1: Tentative Baseline Parameters of HELEN

| Parameter | Value |
|---|---|
| Center of mass energy | 250 GeV |
| Collider length | 7.5 km |
| Peak luminosity | $1.35\times10^{34}$ cm$^{-2}$s$^{-1}$ |
| Repetition rate | 5 Hz |
| Bunch spacing | 554 ns |
| Particles per bunch | $2\times10^{10}$ |
| Bunches per pulse | 1312 |
| Pulse duration | 727 µs |
| Pulse beam current | 5.8 mA |
| Bunch length, rms | 0.3 mm |
| Crossing angle | 14 mrad |
| Crossing scheme | crab crossing |
| RF frequency | 1300 MHz |
| Accelerating gradient | 70 MV/m |
| Real estate gradient | 55.6 MV/m |
| Total site power | 110 MW |

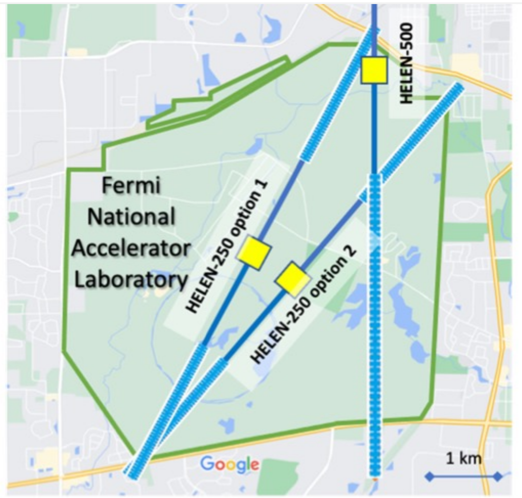
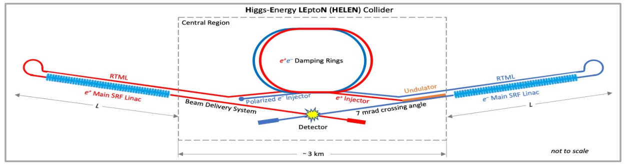


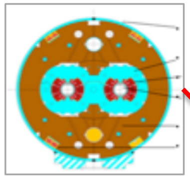

Figure 3: Options for HELEN collider at Fermilab.

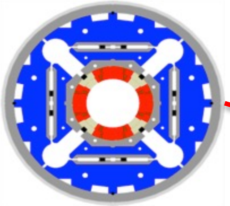


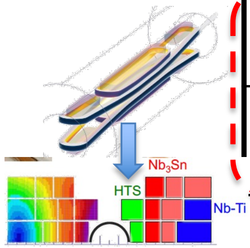

https://doi.org/10.48550/arXiv.2209.01074

Courtesy, H. Padamsee, R. Flukiger, A. Ballarino

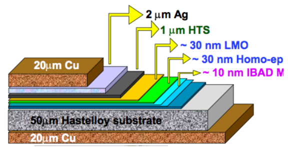
# Possible Choices among SC Materials for Magnets








| Material | $T_c$ [K] | $\rho_n$ [μΩ.cm] | $B_{c1}(0)$ [T] | $B_c(0)$ [T] | $B_{c2}(0)$ [T] | Type, Feature | Year |
|---|---|---|---|---|---|---|---|
| Pb | 7.2 | -- | -- | 0.08 | -- | I | 1913 |
| Nb | 9.2 | 2 | 0.18~0.185 | 0.2~0.25 | 0.28-0.42 | II | 1930 |
| NbTi | 9.2 ~9.5 | -- | 0.067 | -- | 11.5 ~ 14 | II, Wire | 1962 |
| NbN | 17.3 | 35 | (0.02) | -- | | II, Film | 1940 |
| $Nb_3Sn$ | 18.3 | 20 | (0.02-0.05) | 0.54 | 28 ~30 | II | 1954 |
| $MgB_2$ | 39 | 0.1-10 | (0.03) | 0.43 | 39 | II | 2001 |
| $YBa_2Cu_3O_7$ (REBCO family) | 92 | -- | 0.01 | 1.4 | 100 | II, Tape | 1987 |
| $Bi_2Sr_2Ca_1Cu_2O_8$ (BSCCO-2212) | 94 | -- | 0.025 | -- | >100/30 | II, Wire | 1988 |
| $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO-2223) | 110 | -- | 0.0135 | -- | >100/30 | II, Tape | 1988 |
| Note Important for: | | | | SRF | Magnet | | |




Courtesy, A. Ballarino

# HTS Advantages

## Very high in-field current density at low temperature:

- **Enabling technology** for magnets with fields **> 16 T**
- No magneto-thermal instability,
- Higher temperature margin

## Operation at higher temperature:

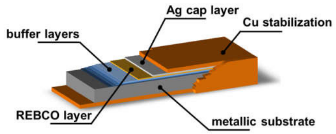
- **Low(er) field magnets** operated at temperatures higher than liquid helium (dry-cooling, He gas cooling, $LH_2$, $LN_2$): operational **power saving**
- High specific heat, and. high thermal stability (MQE)
- Higher temperature margin to the benefit of an easier cryogenic control

# Main challenges facing the development of future HTS high-field magnets

Courtesy: A. Siemko
LDG meeting, 2023

**Current main limitations of HTS** conductors specific to accelerator magnets:

- ReBCO conductor shear stress sensitivity and degradation caused by delamination
- Large magnetisation of ReBCO conductors (due to the tape shape), resulting field errors
- AC losses (magnetic hysteresis, coupling and eddy currents) are major drawbacks of ReBCO. With significant “filamentation” the ReBCO losses compare to $Nb_3Sn$ (at > 10 T)
- Limited ability to bend at small radii of ReBCO tapes is forcing specific designs of coil ends
- Quench protection of accelerator size magnets due to low quench propagation velocity and high stored energy density in coils made of ReBCO as well as Bi-2212
- Anisotropy of ReBCO tapes properties, including mechanical properties. Uniformity of tapes and cables along the length and lot to lot, impacting on magnet protection
- Bi-2212 conductor stress/strain sensitivity and degradation
- Very complex Reaction Heat Treatment for Bi-2212



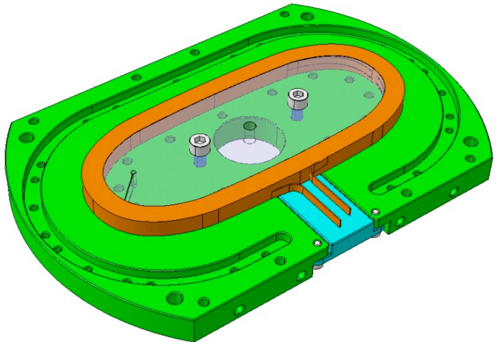

CORC® round cables


Roebel flat cables

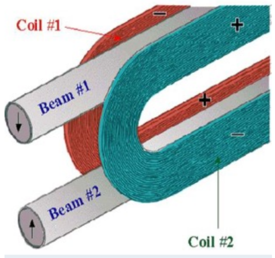
# HFM HTS CERN program

Courtesy, A. Ballarino

- **Objective**: demonstrator of **5 T in** a background field **of 15 T**
- Development of electrically insulated cables. **Target**: 10 kA @ 20 T, 5 kV
- Model racetrack coils
- Common coil design

**Common-coil design, R. Gupta**



# Future Colliders based on SC Technology

**Linear Colliders:**

**ILC e+e- ( 250 GeV → 1 TeV) :**

- **SRF:** for High-Q ($10^{10}$) and high-G (**31.5 → 45 MV/m**)
- Highest efficiency and AC-power balance

**CLIC e+e- ( 380 GeV → 3 TeV) :**

- **NRF:** Very high G (100 MV/m) for energy frontier with compactness

**Circular Colliders :**

**FCC-e+e- ( 90 → 350 GeV):**

- **SRF:** with staging for efficient energy extension
  - Synchrotron radiation (SR) to determine the energy
- Highest luminosity at Z and H,

**FCC-hh ( 80 – 120 TeV):**

- High-field SC magnets (SCM: **14 - 20 T**) for energy frontier
- **SRF:** for acceleration for good energy balance w/ SR

**CEPC e+e- ( 240 GeV):**

- **SRF:** for acceleration,
  - Synchrotron radiation to determine the energy

**SPPC- pp ( 75 - 125 TeV):**

- High-field SCM (**12 -20** T) for energy frontier
- **SRF:** beam acceleration

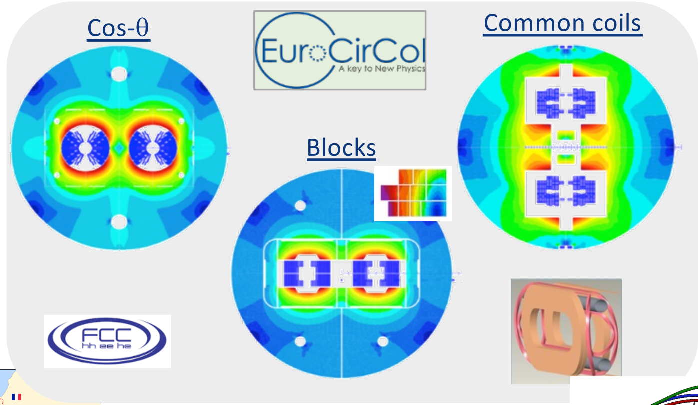
**EIC Ion•e-(275/100 GeV/n v.s. 18 GeV, under constr.)**

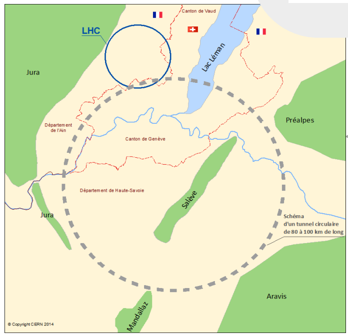
- **SCM and SRF**

**MC μ+μ– (3 – 14 TeV)**

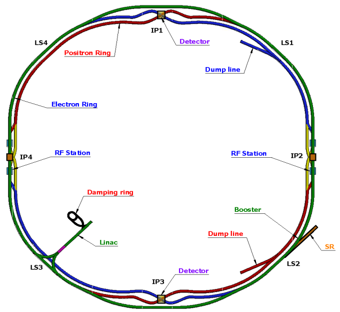
- SRF and NRF with very high-field SCM
- Higher efficiency at > 3 TeV, although short life-time.

A. Yamamoto, 2023/09/08

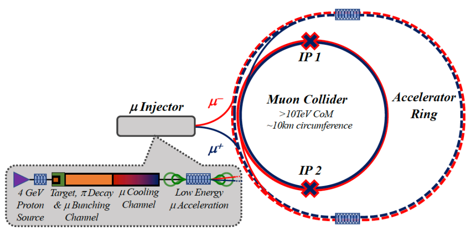


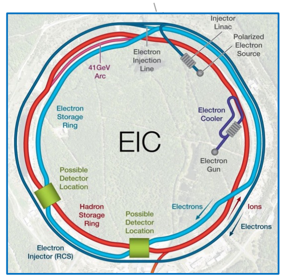

FCC




SPPC




MC




EIC

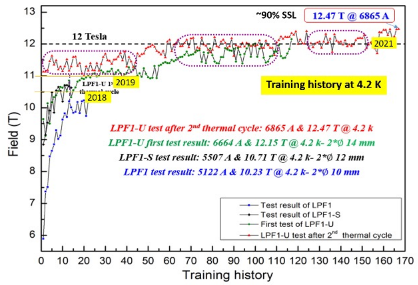
# HF Magnet R&D Roadmap at IHEP-CAS

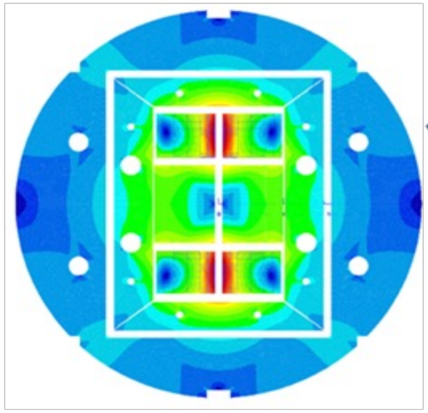
Field (T)

20

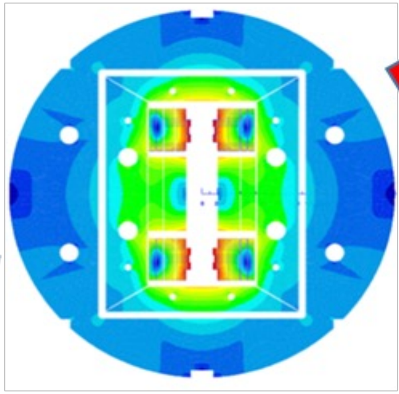
10

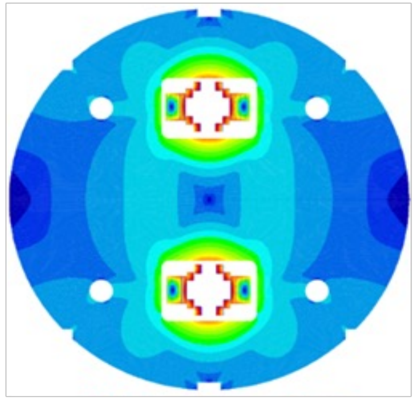
2018-2021, 12.47T @4.2 K



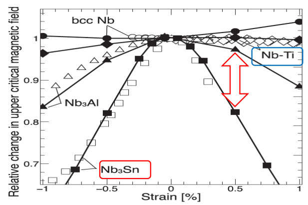
2023





**$Nb_3Sn$+HTS or HTS**
**2*ϕ45 aperture**
**20T @ 4.2K**
**With $10^{-4}$ field quality**

**Challenges**: Stress control, quench protection, field quality control,······




2018

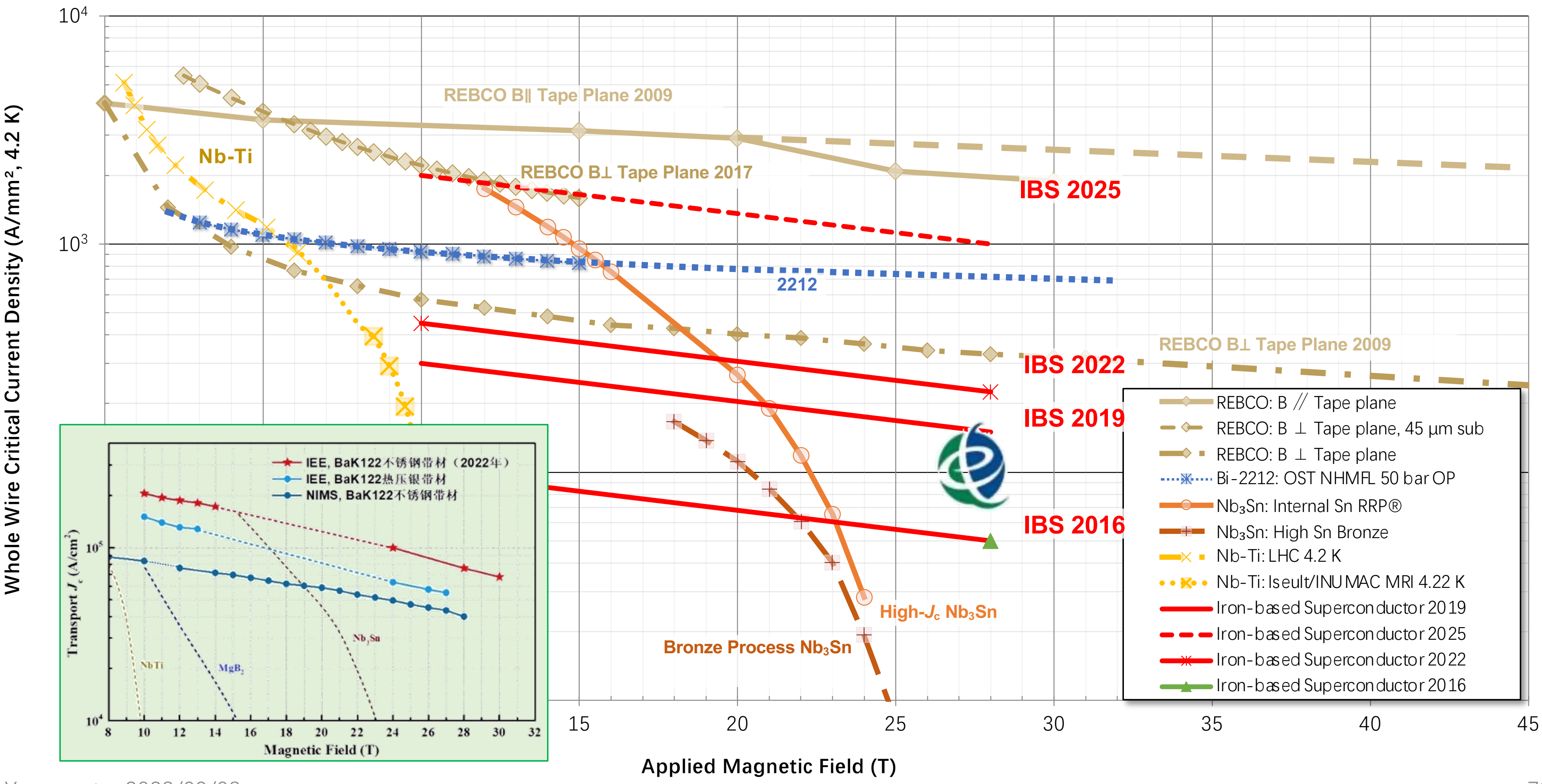
2028

year

# $J_e$ of IBS conductor: Status and Outlook

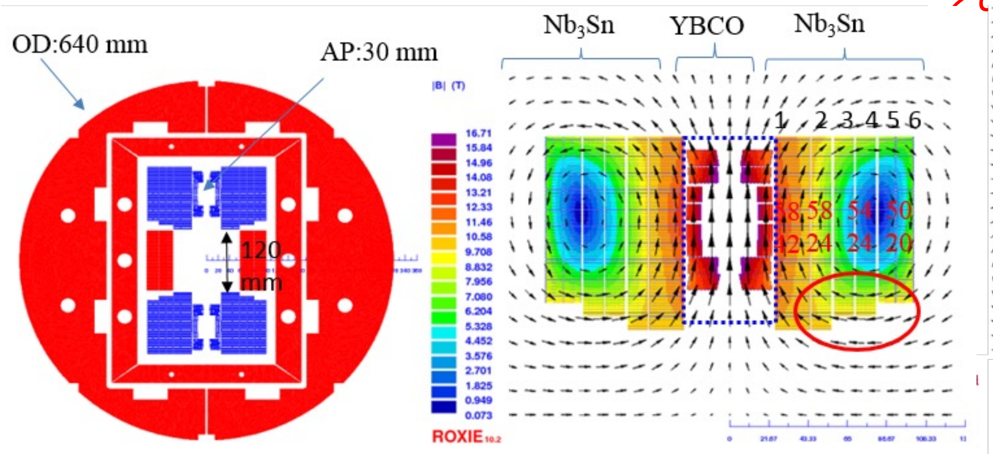
Courtesy: Q. Xu.

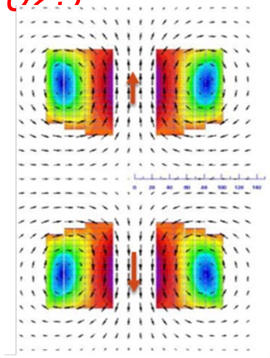
- 90% Stainless-steel & 10% Sliver stabilized IBS tape achieved the highest $J_e$ in 2022!
- Significantly reduced the cost and raised the mechanical properties.

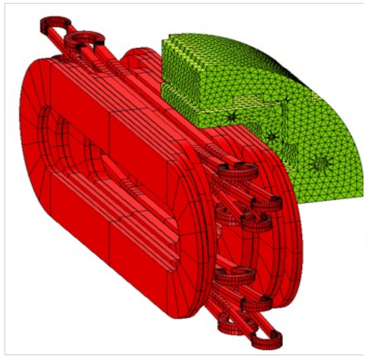


# R&D of the High Field Model Dipoles

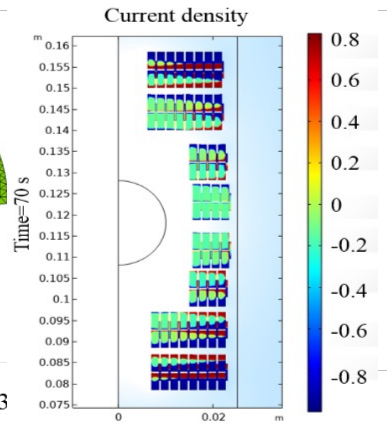
16 T Model Dipole: $Nb_3Sn$ 12~13 T + HTS 3~4 T; *To be tested in Sep-Dec 2023*

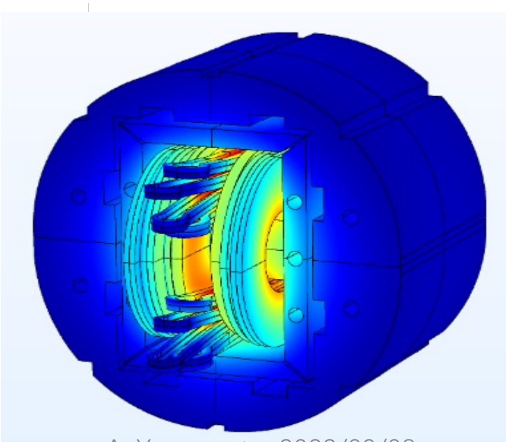


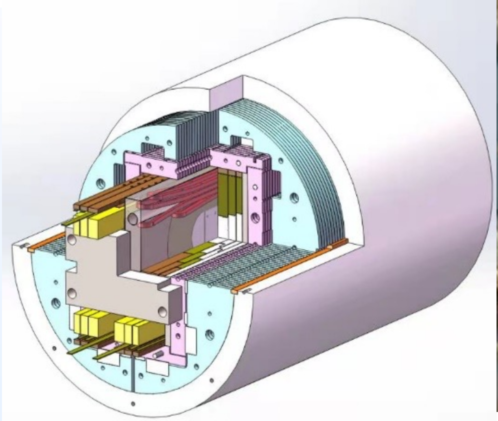





16-T 大孔径高场超导二极磁体 LPF3 ($Nb_3Sn$-13





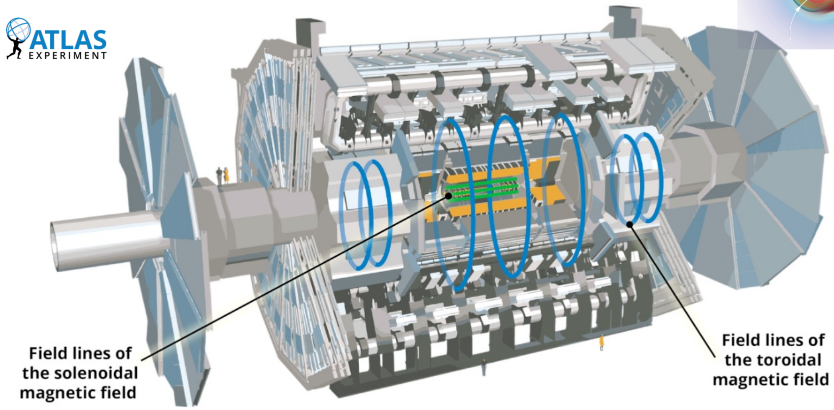
# **Background:** Historical experiences of the ATLAS and CMS magnet projects

**Very large superconducting detector magnet projects!**

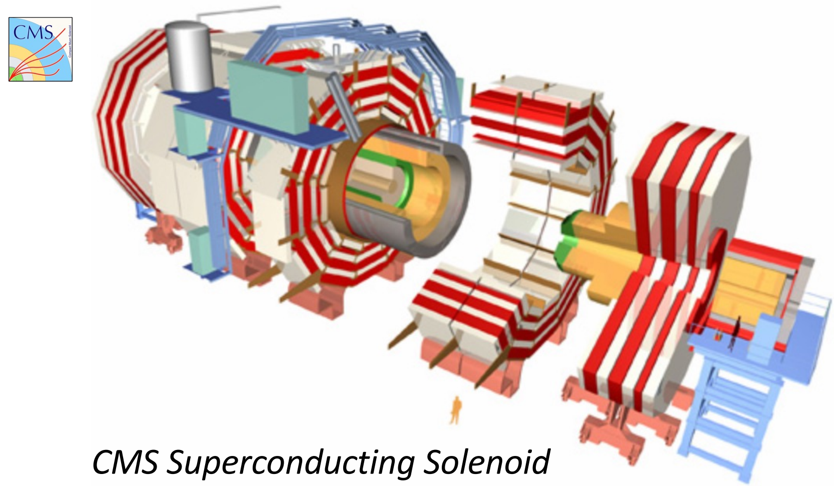
- Time-scale for engineering design and validation effort, the construction, and the commissioning: More than 15 years each
- Production of components (conductor, coils, support structure, etc) in industry, and subsequent assembly at CERN
- Designed, constructed, commissioned, and maintained with strong support from multiple institutes:
  - ATLAS: CEA-Irfu, KEK, INFN-LASA, RAL, NIKHEF, JINR-Dubna, IHEP-Protvino, ITAM Novosibirsk, CERN
  - CMS: CEA-Irfu, ETH Zurich, INFN Genoa, University of Wisconsin, Fermilab, ITEP Moscow, CERN

Important lessons:

- For large superconducting detector magnets a long-term strategy is needed
- **The historical importance of collaboration is evident**

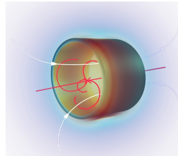



*ATLAS Superconducting magnets*



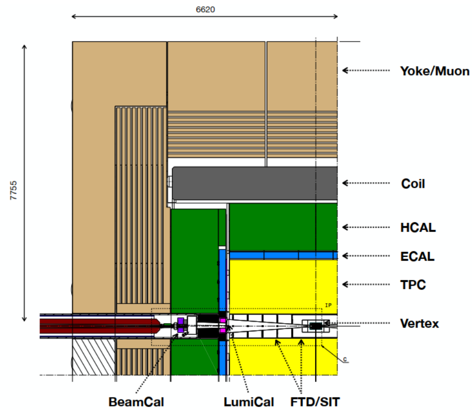

*CMS Superconducting Solenoid*

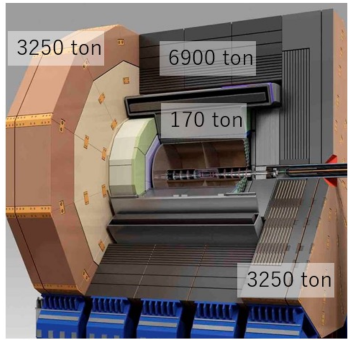
# International Linear Collider: ILC-ILD



| | Detector solenoid |
|---|---|
| Warm bore diameter [m] | 6.9 |
| Cold mass length [m] | 7.35 |
| Magnetic field in the centre [T] | 4.0 |
| Stored magnetic energy [MJ] | 2300 |

*Magnet parameters*

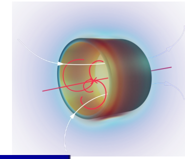



*ILC-ILD detector featuring a 4 T superconducting solenoid*

- Presentations by K. Buesser (DESY) and Y. Makida (KEK)
- For the International Linear Collider project, proposed to be hosted in Japan
- Featuring a superconducting solenoid, with 4 T over a 6.9 m warm bore diameter, and a 7.35 m cold mass length, stored magnetic energy of 2300 MJ
- With optional "Detector-Integrated-Dipole" coil wound on top of the solenoid
- Conductor: Foresees to use a reinforced aluminum-stabilized Nb-Ti/Cu conductor

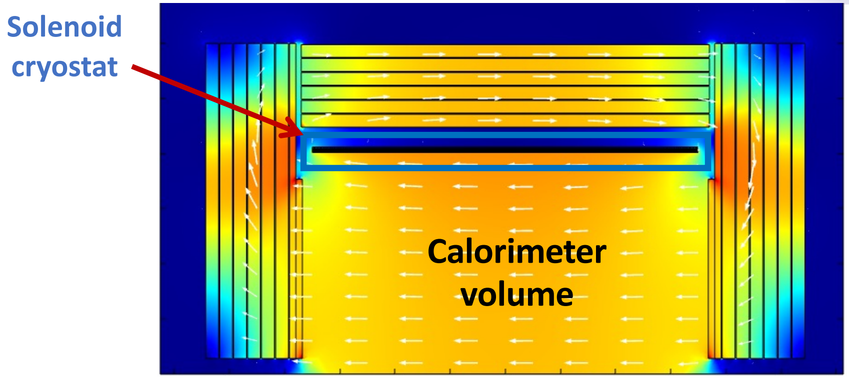
# Future Circular Collider FCC-ee: IDEA and CLD



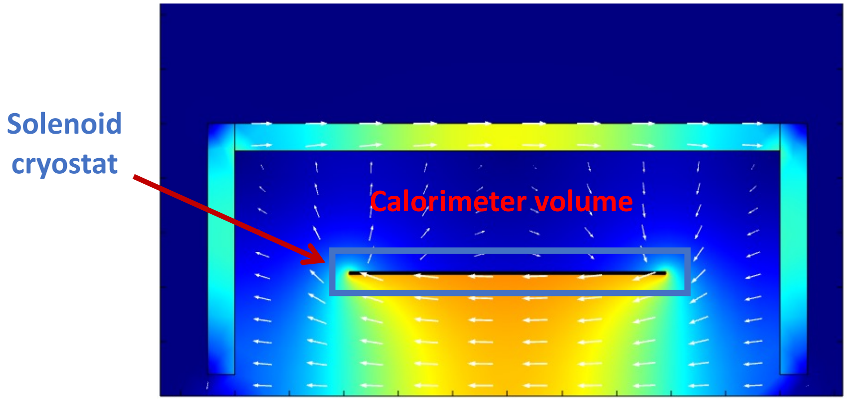
| | Detector solenoid #1 | Detector solenoid #2 |
|---|---|---|
| Warm bore diameter [m] | 8.0 | 4.0 |
| Cold mass length [m] | 7.0 | 5.8 |
| Magnetic field in the centre [T] | 2.0 | 2.0 |
| Stored magnetic energy [MJ] | 600 | 170 |

*Magnet parameters*

- Presentation by N. Deelen (CERN)
- For the FCC-ee project, proposed to be hosted at CERN, with operation foreseen to start in 2045, featuring electron-position collisions
- Two solenoid types (For “IDEA” and “CLD”) detectors
  - One solenoid, featuring 2 T over a free bore of 8.0 meters, and a cold mass length of 7.0 meters, no transparency requirement
  - One solenoid, featuring 2 T over a free bore of 4.0 meters, and a cold mass length of 5.8 meters, with transparency requirement
- Conductor: Reinforced aluminum-stabilized Nb-Ti/Cu conductor




*CLD detector, featuring a 2 T solenoid*




*IDEA detector, featuring a transparent 2 T solenoid*

Courtesy: B. Cure

## Longer Time-scale: Aluminum-stabilized conductor technology

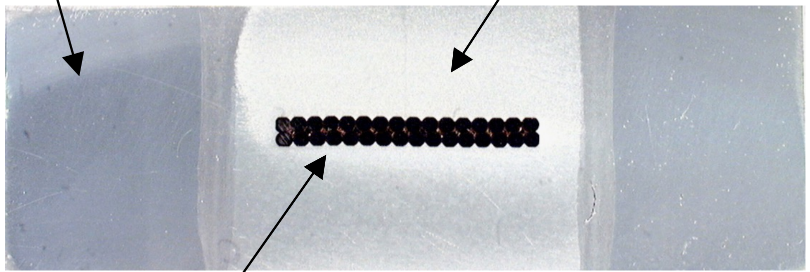
- **The aluminum-stabilized Nb-Ti/Cu (SC) conductor is the traditional workhorse**
  - that is used in nearly all superconducting detector magnets.
- Al-based SC conductors give strong performance needed for SC detector magnets:
  - Significant heat capacity for a given amount of weight
  - Excellent electrical and thermal conductivity at 4 K (pure or nickel-doped aluminum)
  - Very good mechanical properties (nickel-doped aluminum or aluminum-alloy)
  - Affordable, in combination with superconducting Nb-Ti/Cu Rutherford cables

→ **However, in recent years, commercial availability has been an issue**

→ **Can we obtain it? Do viable alternatives exist?**

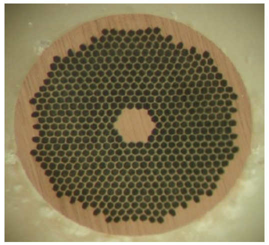
*Aluminum-alloy for mechanical reinforcement*

*Pure aluminum for excellent electrical and thermal properties*



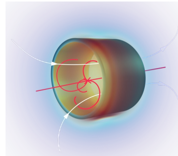
*Nb-Ti/Cu Rutherford cable*

*Courtesy: The CMS collaboration*



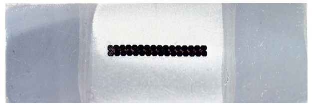
*Cross-section of a Nb-Ti/Cu strand used in the CMS conductor (Blau et al, "The CMS conductor", IEEE Trans 2002)*

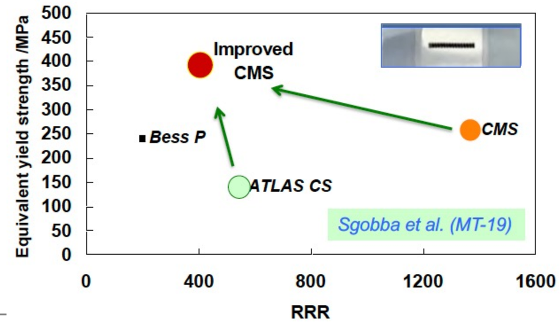
# Future Direction and Back-up/Alternate SC Solutions



**Issue: Al-stabilized Superconductor:**

- No industrial production available, as current status,
- Development to be resumed
  Urgent requests from EIC, BabyIAXO, …
- Laboratory-Industry cooperation inevitable. For
  - **Co-extrusion** technology and/or
  - Soldering technology as backup






**Back-up Solution: Alternate Superconductor :**

**Conductor-In-Conduit-Conductor (CICC)**

- It may be applicable in most detector solenoid design, if no request of "transparency".
- A proposal to apply CICC to ILC-SiD, with no request for "transparency".
- It is Important to study the feasibility, and to learn experiences integrated in the ITER project.

**WIC: (Wire-in Channel)**

**High Temperature Superconductor (HTS)**

- HTS application proposed by AMS-100,
- The feasibility to be investigated.