Institute of High Energy Physics
Chinese Academy of Sciences

Future Colliders

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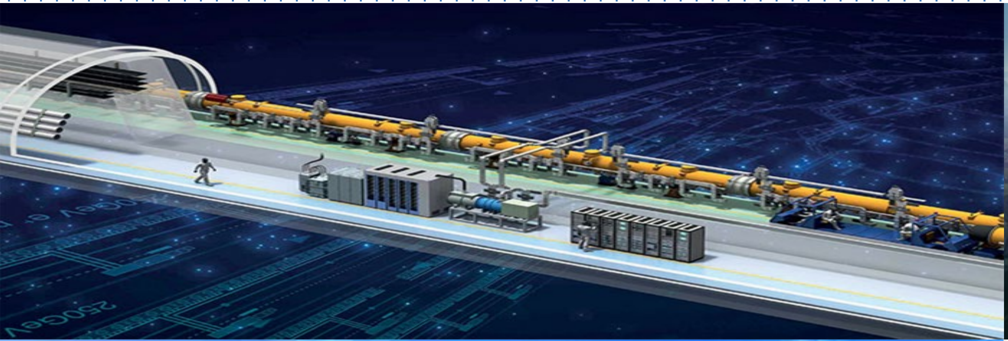
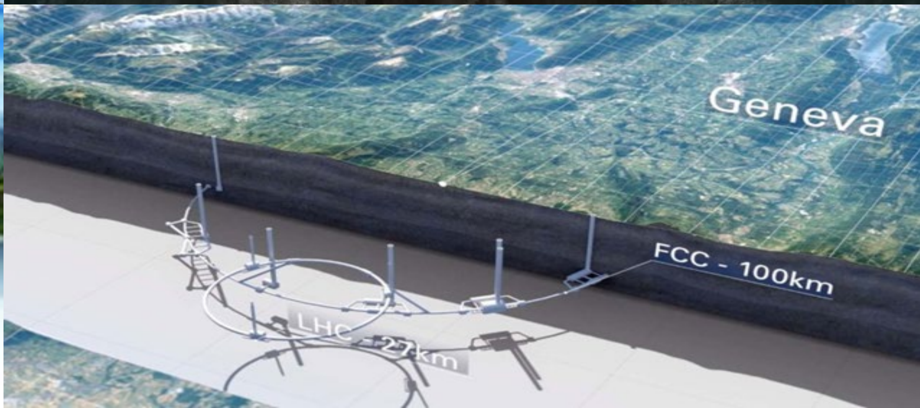
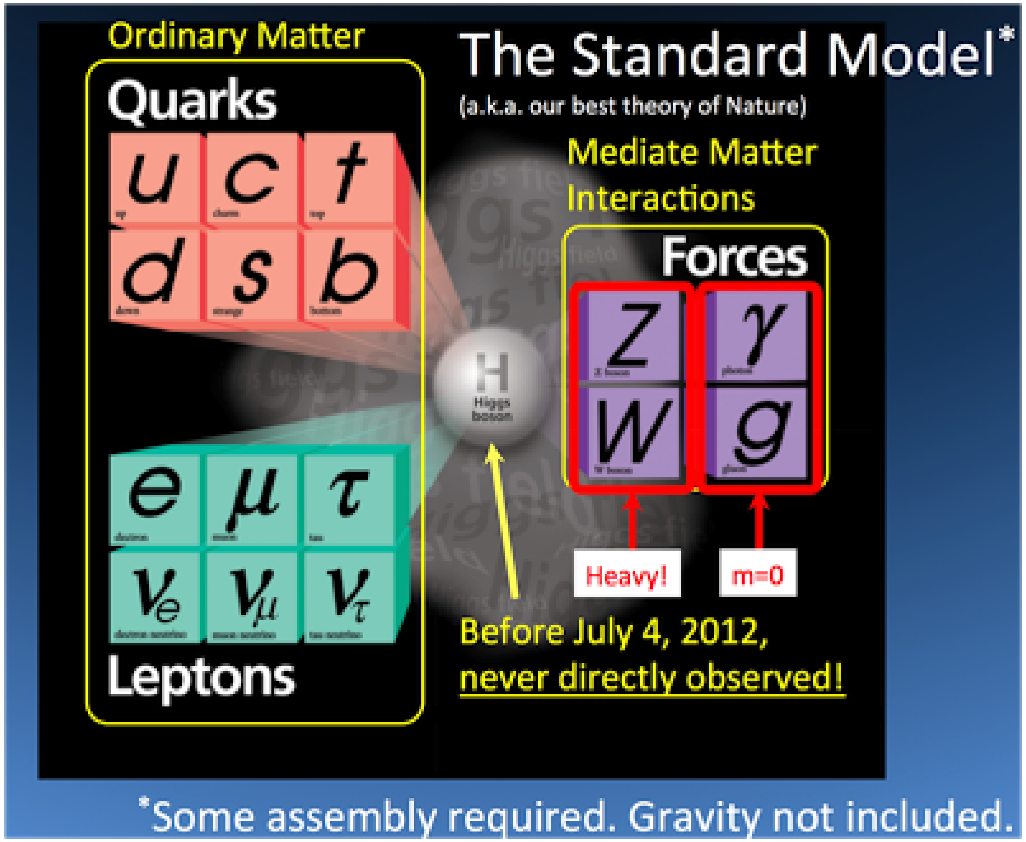




Outline

- Introduction
- Status and development of future colliders
  - Circular Electron Positron Collider (CEPC)
  - International Linear Collider (ILC)
  - Future Circular Collider (FCC)
- Summary

Introduction



SM cannot explain

- neutrino mass
- dark matter
- dark energy
- baryon asymmetry

Etc…..

Higgs is at the center of the Standard Model, unique and special

- **the only particle that talks to everybody**
- **the only particle that doesn't spin**
- **the only particle that is condensed in the universe**
- **the source of all masses of elementary particles**
- **the lowest order coupling to new physics**

Higgs portal to BSM

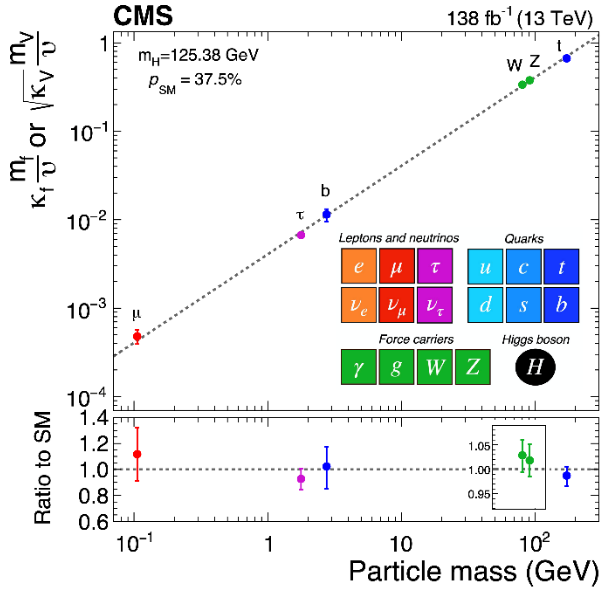
- Supersymmetry
  - Higgs just one of many scalar bosons
  - Superpartners
- Composite
  - spins cancel among constituents
  - condensate by a strong attractive force
  - top partner, vector-like quarks etc.
- Extra dimension
  - Higgs spinning in extra dimensions
  - new forces from particles running in extra dimension
  - KK particles
- Etc…

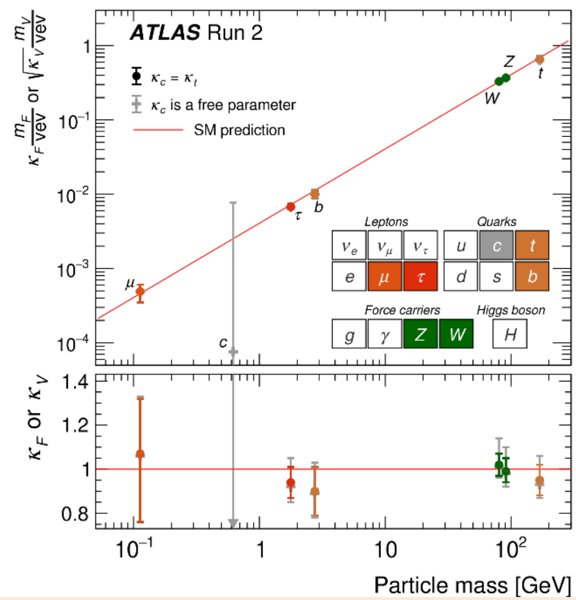
Precise understanding of Higgs boson properties gives hints of BSM

Higgs measurements at the LHC

The Large Hadron Collider(LHC) discovered the Higgs and made possible of many measurements

Coupling of to the Higgs : mass of final state particles





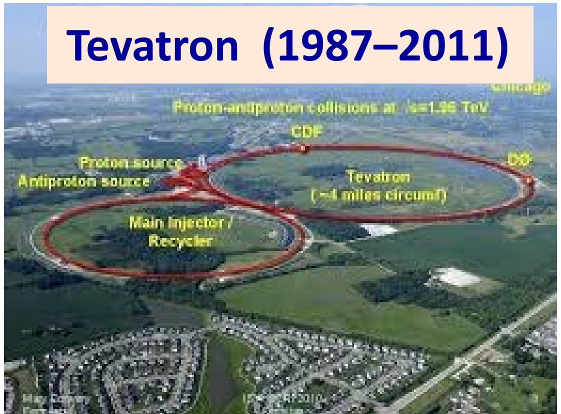
Highly consistent with the Standard Model of Particle Physics

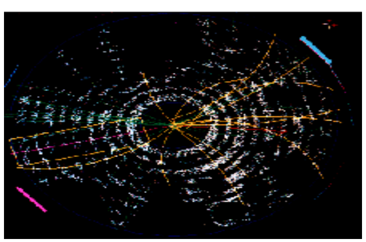
→ origin of fermion mass indeed from the Higgs

No clear evidence of BSM so far

Paths to new physics

Tevatron (1987–2011)





Proton-proton collision ~1 TeV, discovery of the top quark

LEP, LHC (Europe)

Proton-proton collision ~13 TeV, discovery of the Higgs boson

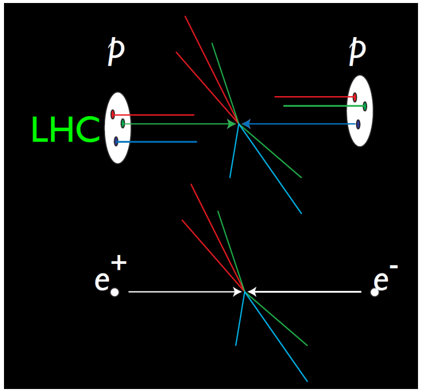
1.Precision measurements of neutral current predicted *mW*, *mZ*
2. UA1/UA2 discovered *W/Z* particles

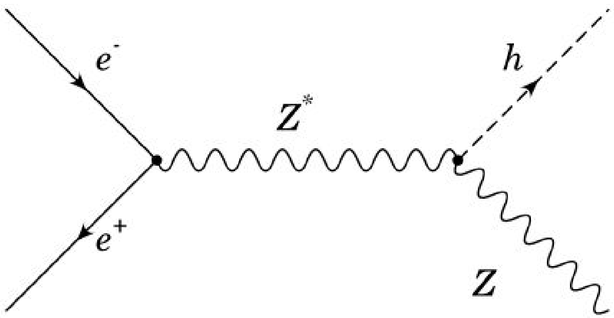
3. Precision measurements of *W* and *Z at* LEP + Tevatron predicted *mt* and *mH*
4. Tevatron discovered top, LHC discovered *a Higgs particle*

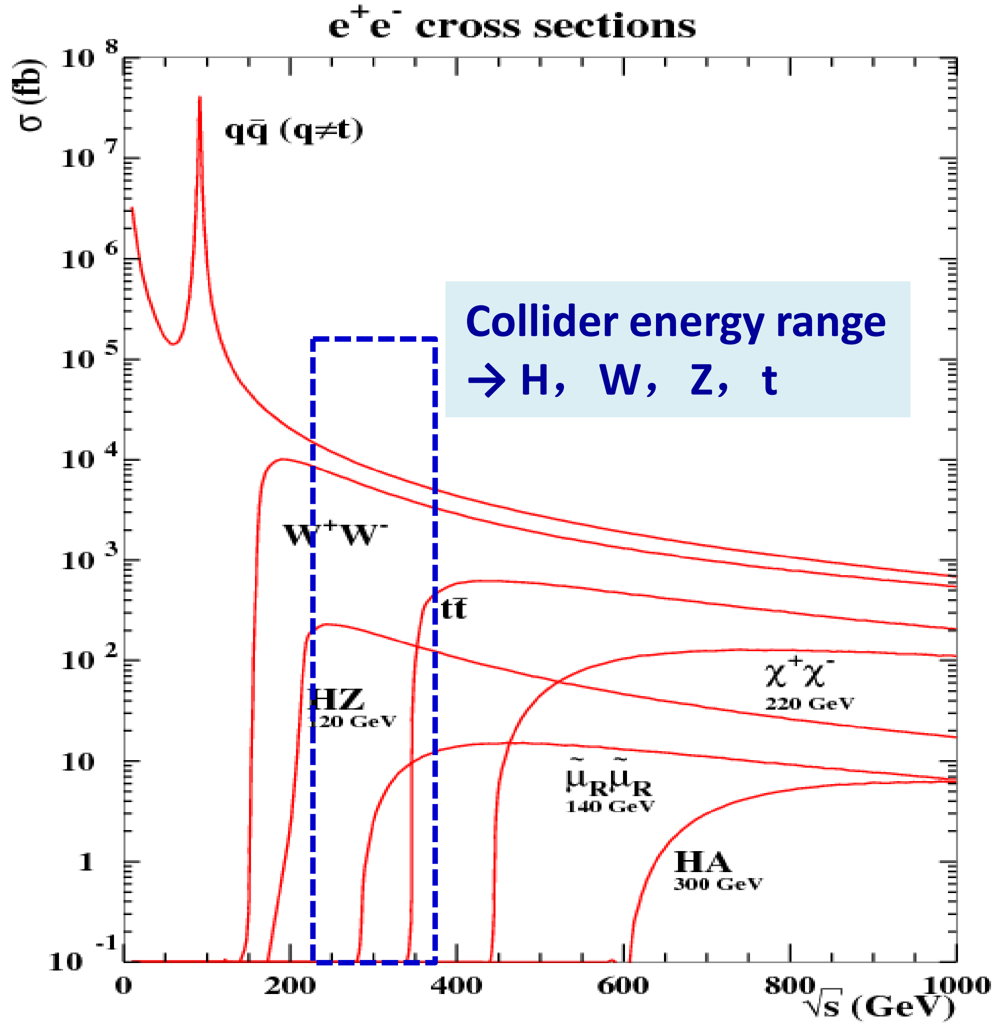
We need precision measurement of Higgs boson to pave ways to BSM

Huge breakthrough with Higgs: the center of the Standard Model, most unique and special particle

Lepton collider vs. hadron collider







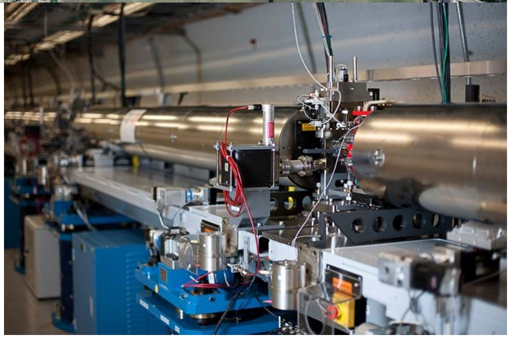
Advantage of lepton collider

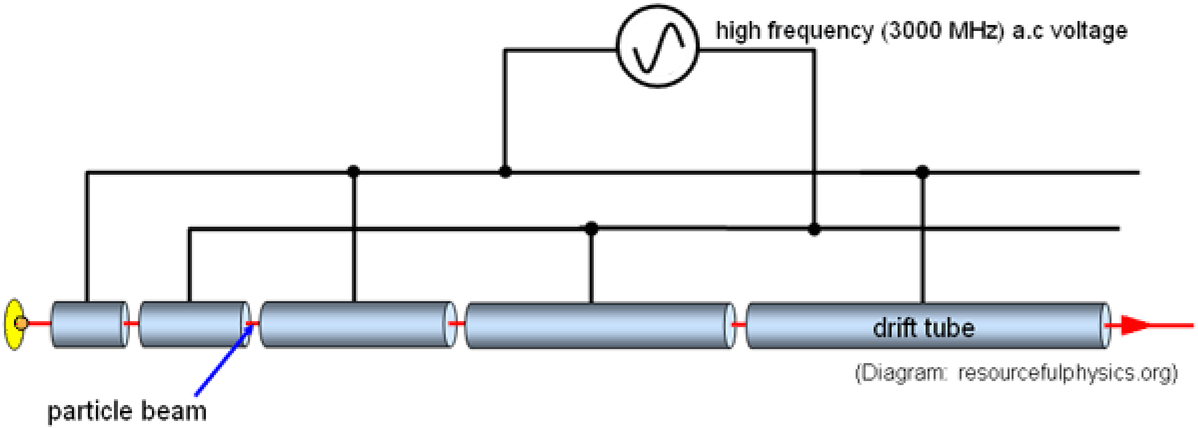
- Much less noise and backgrounds
- Simpler kinematics
- No loss of the longitudinal momentum
- Can make use of all final states and capture all information for a given event

- Increase precision on H by X10
- Increase precision on W,Z by X10-100
- Search for new physics ~10 TeV

Combined measurements of Higgs, top, W/Z allow us to understand various operations that could be added to SM in EFT

Linear Accelerator

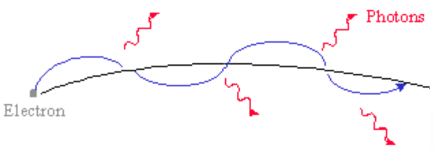


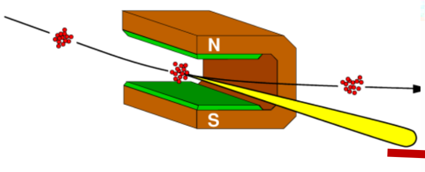


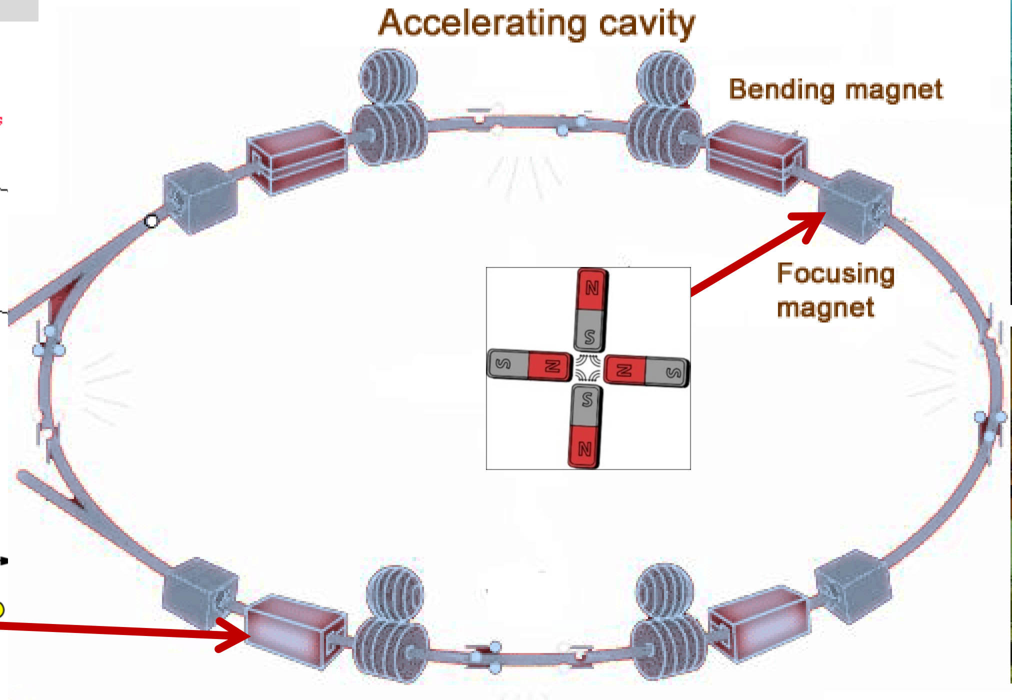
Reach High Energy
Can't Store Beam
Low Intensity

Circular Accelerator

synchrotron light







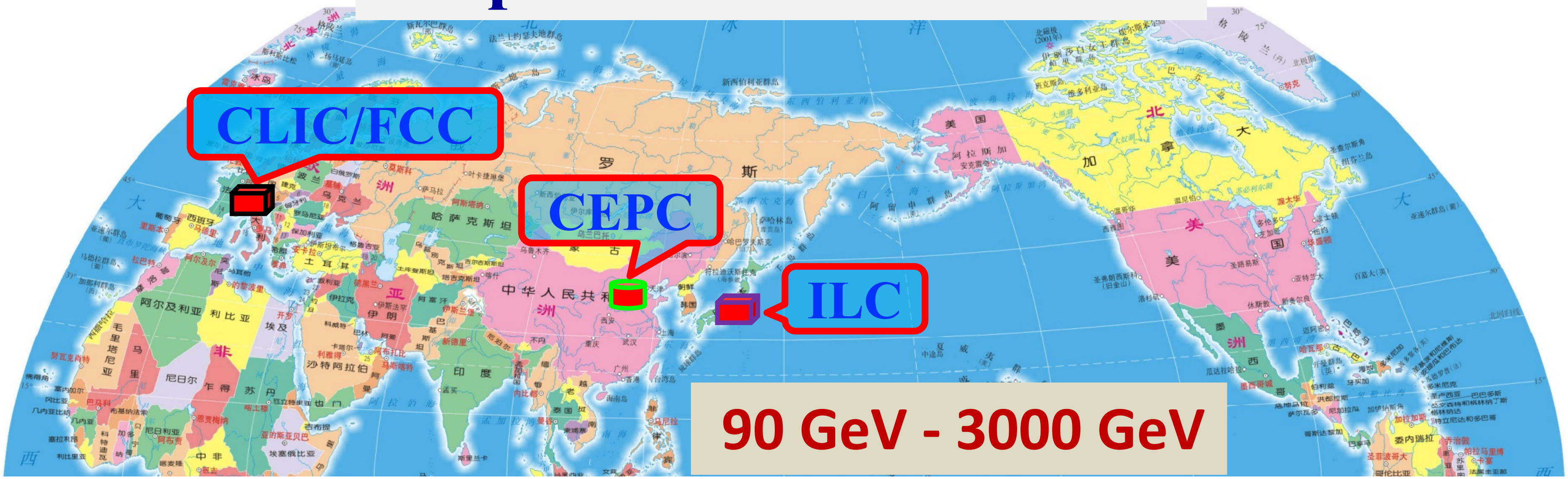
CERN LHC tunnel

Can Store Beams
High Intensity
Limit on Energy

circumference=27km (LHC tunnel)
E=500GeV, I=10mA
$\Rightarrow$ P(power)=13 GW (e^+e^- collider)

Need much bigger tunnel

Proposed Future Colliders



3000 GeV *(CLIC)*

(+ BSM new physics, …)

250-500GeV **1TeV** *(ILC)*

(Higgs, $t\bar{t}$, …)

90-250GeV *(CEPC,FCC-ee)*

(H, W, Z, t,…)

Upgradable to proton-proton collider → 100 TeV!

Future colliders with top priority

The scientific importance and strategical value of an electron positron Higgs factory is clearly identified.

XIANGSHAN SCIENCE CONFERENCES

2013, 2016: the CEPC is the best approach and a major historical opportunity for the national development of accelerator-based high-energy physics program.

2020 European Strategy Update

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

Conclusion from Executive Summary

Given the **strong motivation** and existence of proven technology to build an e^+e^- **Higgs Factory in the next decade**, the **US should participate** in the construction of **any facility that has firm commitment** to go forward.

Sridhara Dasu (Wisconsin)

ICFA

*In April 2022, the International Committee for Future Accelerators (ICFA) "reconfirmed the international consensus on the importance of **a Higgs factory as the highest priority for realizing the scientific goals of particle physics**", and expressed support for the above-mentioned Higgs factory proposals. Recently, the United States also proposed a new linear collider concept based on the cool copper collider (C3) technology [31].*

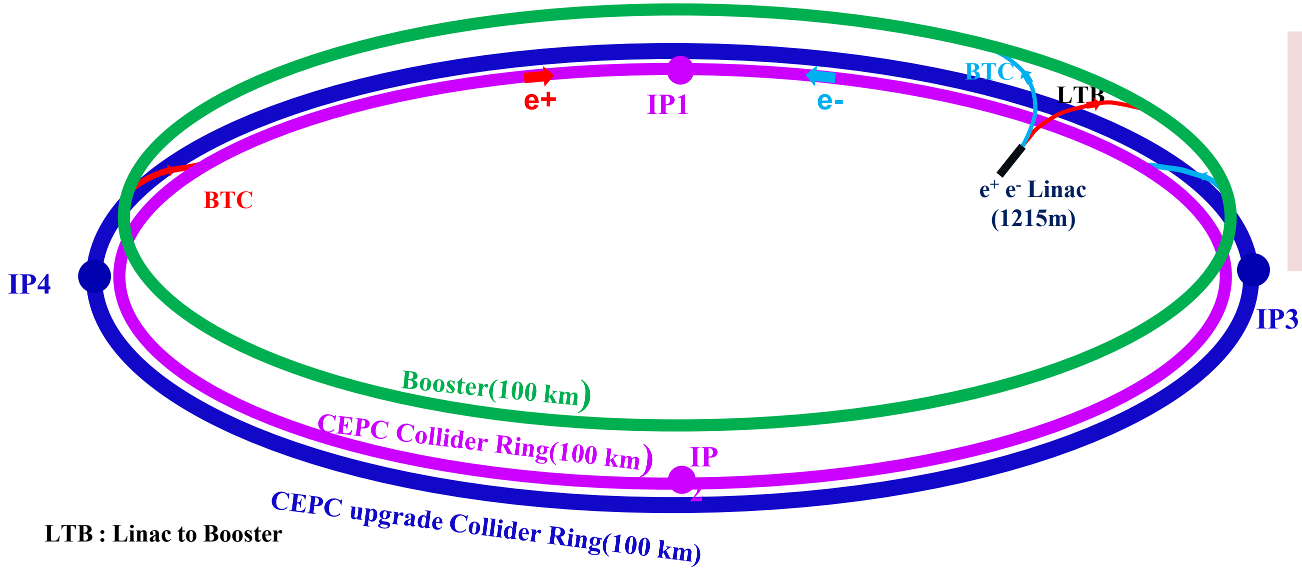
Future High Energy Colliders
Status and Development

Circular Electron Positron Collider
CEPC

Acknowledgement
Additional inputs from João Guimarães da Costa et. all

Circular Electron-Positron Collider (CEPC)

- CEPC is an e+e- Higgs factory producing Higgs, W and Z bosons aims at discovering new physics beyond the Standard Model
  - Proposed in Sept. 2012
  - Circumference ~100 km
  - Centre-of-mass energy 90-240 GeV
  - upgradable to 360 GeV (t quark)
- Continuation of expertise in electron accelerator (BEPC under operation)
- New application: world's first γ synchrotron light source, (high energy ~ 300 MeV) , ……



- Frontier scientific facility
- Long lifetime
  CEPC + upgrade > 50 years
- International collaboration

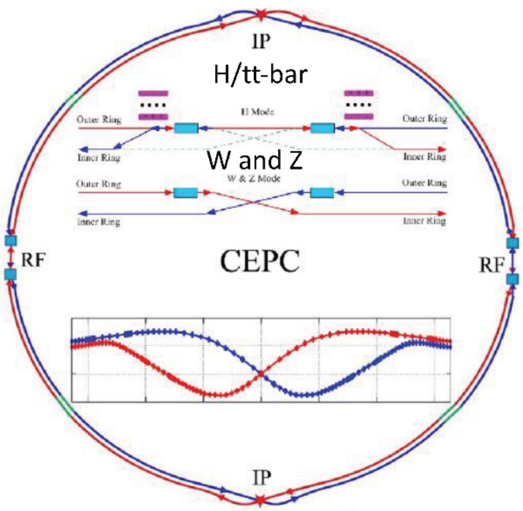
LTB : Linac to Booster

BTC : Booster to Collider Ring

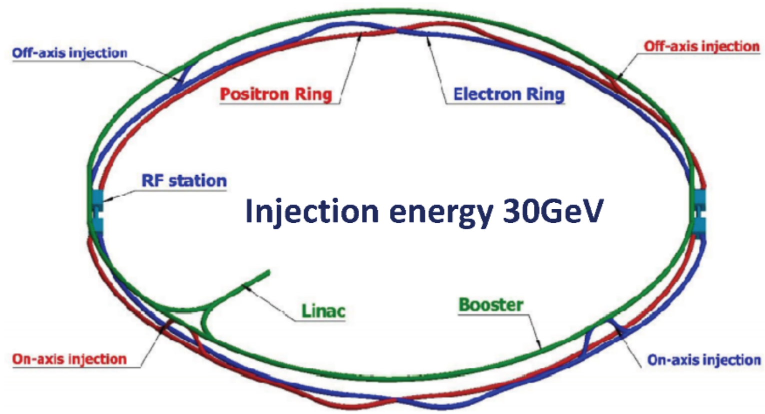
Circular Electron Position Collider (CEPC) - TDR Layout

CEPC as a Higgs Factory： H, W, Z, upgradable to tt-bar, followed by a SppC ~125TeV

30MW SR power per beam (upgradable to 50MW)



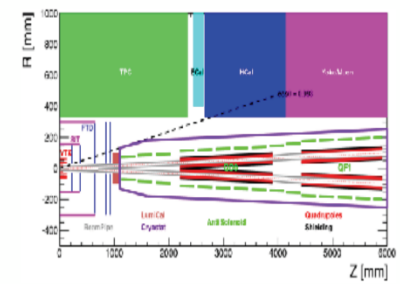
CEPC collider ring (100km)



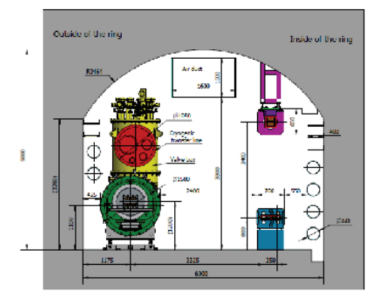
CEPC booster ring (100km)

Common tunnel for booster/collider & SppC

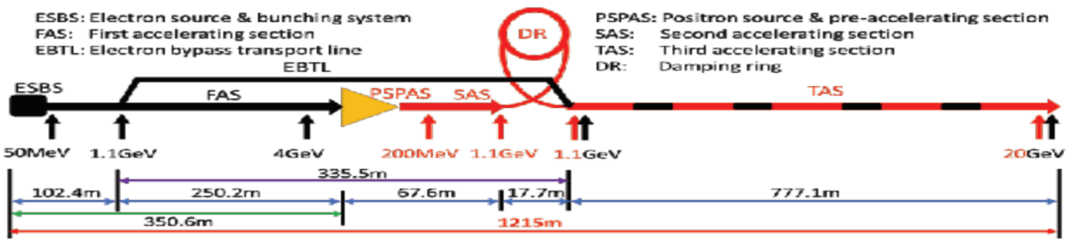
CEPC MDI



CEPC Civil Engineering



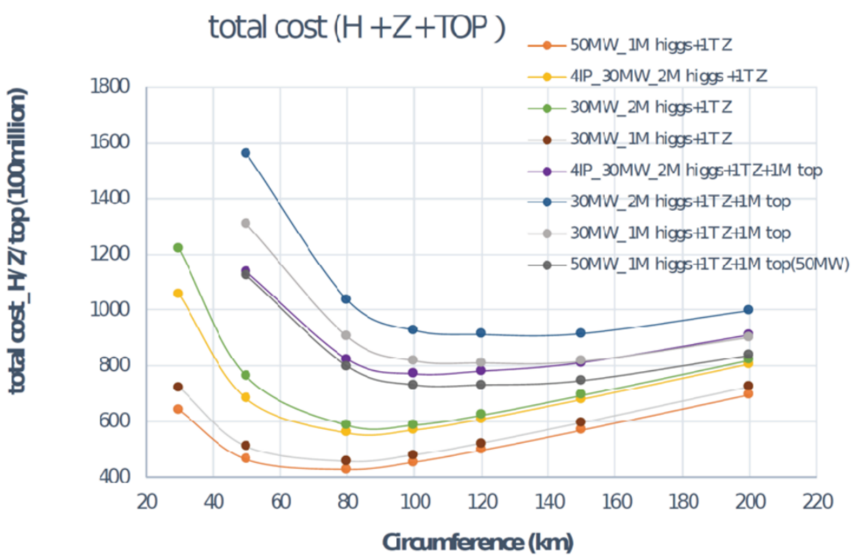
CEPC TDR S+C-band 30 GeV linac injector



Operation mode		ZH	Z	W+W-	tt
		~240	~91.2	158-172	~360
L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	CDR (2018)	3	32	10	
	TDR (30MW)	5.0	115	16	0.5

CEPC TDR Parameters (upgrade version)

Cost optimization vs. circumference



D. Wang *et al* 2022 *JINST* **17** P10018

Main Parameters: High luminosity as a Higgs Factory

	Higgs	W	Z	ttbar
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	**50**			
Energy [GeV]	**120**	**80**	**45.5**	**180**
Bunch number	415	2161	19918	59
Emittance ($\varepsilon x/\varepsilon y$) [nm/pm]	0.64/1.3	0.87/1.7	0.27/1.4	1.4/4.7
Beam size at IP ($\sigma x/\sigma y$) [um/nm]	15/36	13/42	6/35	39/113
Bunch length (SR/total) [mm]	2.3/3.9	2.5/4.9	2.5/8.7	2.2/2.9
Beam-beam parameters ($\xi x/\xi y$)	0.015/0.11	0.012/0.113	0.004/0.127	0.071/0.1
RF frequency [MHz]	650			
Luminosity per IP[10^{34}/cm^2/s]	**8.3**	**27**	**192**	**0.83**

50 MW and 100 km ring a cost effective solution for a higgs, W, Z and top machine

100km accelerator design for all operation modes – completed

GOAL

e+e- circular collider as a high lumi. Higgs factory

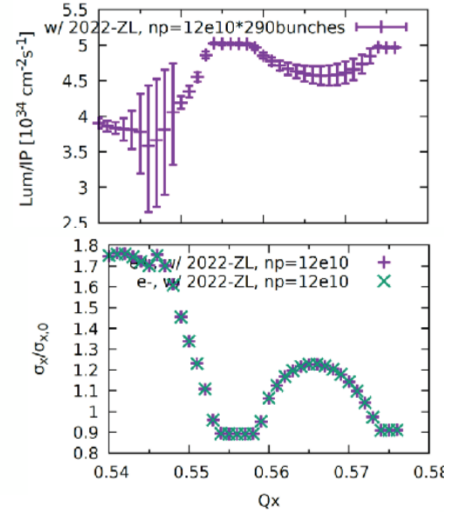
Switchable operation for Higgs, W, Z and Top runs

A green machine with a maximum Luminosity

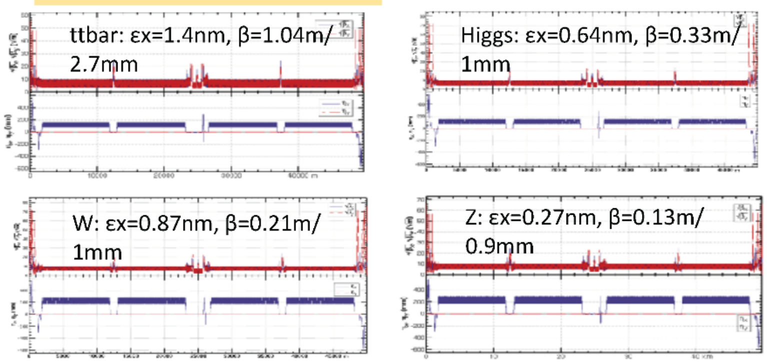
Design

- Complete acc. design w. latest ideas
- Lattice optimization for all energies
- Sufficient DA for all energies
- Beam-beam & collective instability

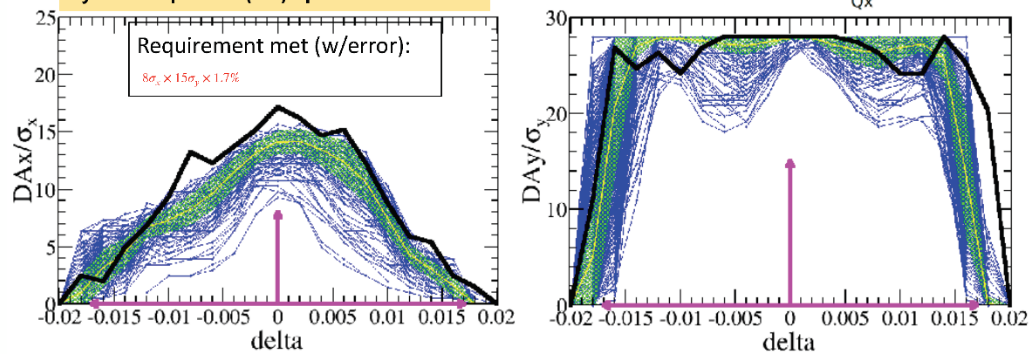
Beam-beam effect study



Lattice for all energies



Dynamic Aperture (DA) optimization



CEPC accelerator technical performance

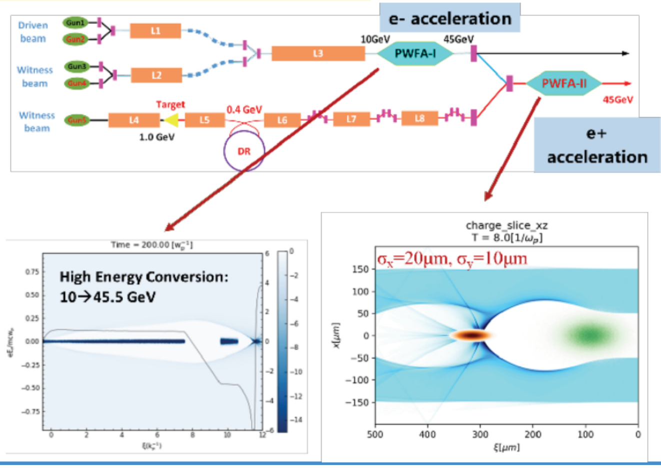
Key Technology	Status
High efficiency klystron	Current eff.>70%, aim at 80%
High Q SRF cavity	Exceeds CEPC requirement
Novel magnet	CEPC requirement met
PWFA injector	Design positron acceleration scheme, >10GeV beam
HTS high field magnet	HTS with IBS

Selected Leading Technologies

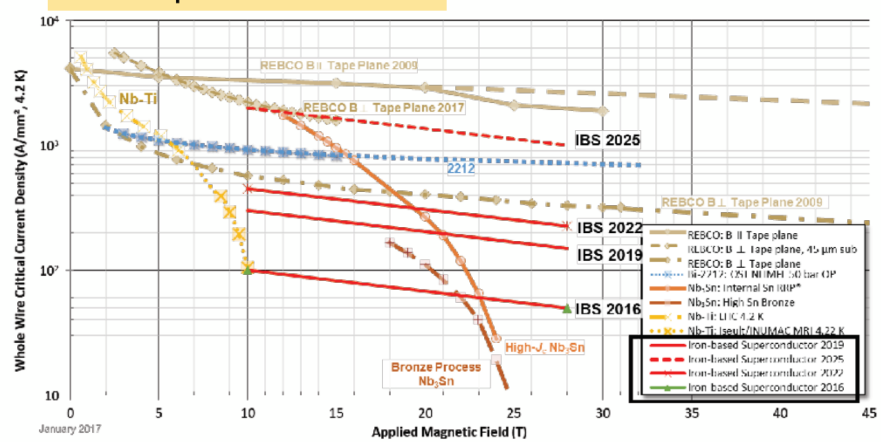
Table 5.3: Status of key technology R&D for CEPC, in comparison with the status quo of world leading accelerator laboratories

Device	Requirement	IHEP status	CERN status	FNAL status	KEK status	LBNL status
1.3 GHz SRF cavity	Q=3 × 10^{10} @24 MV/m	Q=4.3 × 10^{10} @31 MV/m	Preliminary progress	Comparable to IHEP	Comparable to IHEP	N/A
650 MHz 2-cell SRF cavity	Q=4 × 10^{10} @22 MV/m	Q=6 × 10^{10} @22 MV/m	N/A	Comparable to IHEP	N/A	N/A
High-efficiency klystron	Efficiency ≥ 80%	Efficiency ≈ 70%	R&D on Efficiency ≈ 80%	N/A	Efficiency ≈ 60%	N/A
High-field superconducting magnet	20-24 T	12.5 T achieved next goal is 16 T	14-16 T	14.5 T	10 T	14-16 T

PWFA as an alternative Linac injection



Fast development of IBS material



Ultrahigh accelerating gradient and quality factor of CEPC 650 MHz superconducting radio-frequency cavity

CEPC accelerator key technologies under R&D

✓ **Specification Met**

☑ **Prototype Manufactured**

	Accelerator	Cost (billion CNY)	Ratio
✓	Magnets	4.47	27.3%
✓	Vacuum	3.00	18.3%
☑	RF power source	1.50	9.1%
✓	Mechanics	1.24	7.6%
✓	Magnet power supplies	1.14	7.0%
✓	SCRF	1.16	7.1%
✓	Cryogenics	1.06	6.5%
✓	Linac and sources	0.91	5.5%
✓	Instrumentation	0.87	5.3%
☑	Control	0.39	2.4%
☑	Survey and alignment	0.40	2.4%
✓	Radiation protection	0.17	1.0%
☑	SC magnets	0.07	0.4%
✓	Damping ring	0.04	0.2%

Table 5.1: Summary of key technologies under R&D essential for CEPC

Device	Accelerator	Quantity	CEPC specification	R&D status
1.3 GHz SRF cavity (9-cell)	Booster	96	$Q=3\times10^{10}$ @ 24 MV/m	Specification met
650 MHz SRF cavity (2-cell)	Collider	240	$Q=4\times10^{10}$@22 MV/m	Specification met
650 MHz klystron	Collider	120	Efficiency: 80% Power: 800 kW	Prototype manufactured
C-band NC accelerating tube	Linac	292	Gradient: 45 MV/m	Prototype manufactured
S-band bunch compressor	Linac	35	Peak power gain: 7 dB	Prototype manufactured
Positron source flux concentrator	Linac	1	Central peak magnetic field >6 T	Specification met
Dual-aperture dipole magnet	Collider	2384	Field: 140 Gs-560 Gs aperture: 70 mm length: 28.7 m; harmonic$< 5\times10^{-4}$ relative field difference<0.5%	Specification met
Dual-aperture quadrupole magnet	Collider	2392	Gradient: 3.2-12.8 T/m length: 2 m; harmonic$< 5\times10^{-4}$ aperture: 76 mm relative field difference<0.5%	Specification met
Weak field dipole	Booster	16320	Field error $\leq 10^{-3}$@60 Gs	Specification met
Electrostatic separator	Collider	32	Electric field: 2.0 MV/m field uniformity: 5×10^{-4} good field region: 46 mm*11 mm	Specification met by prototype
Cryogenic refrigerator	Collider/ Booster	4	18 kW @ 4.5 K	Collaboration with IPC CAS, a refrigerator system of 2.5 kW @ 4.5 K has been developed
Ceramic vacuum chamber and coating	Transport lines	$\sim$20	$75\times56\times5\times1200$mm	Prototype in production
MDI SCQ	Collider	8	Gradient: 136T/m; length: 2m Aperture: 40mm; included angle: 33mrad	Prototype in manufacture
Visual instrument	All	11	Image accuracy: 5 μm+(5 μm/m) horizontal angle: 1.8 arc-second vertical angle: 2.2 arc-second	Prototype completed

Table 5.2: Summary of key technologies in engineering applications essential for CEPC

Device type	Accelerator	Quantity	CEPC specifications
S-band copper accelerating tube	Linac	111	~30 MV/m
vacuum chamber and coating	Collider/ Booster	Total length 200 km	Length: 6 m aperture: 56 mm vacuum: 3×10^{-10} Torr NEG coating pump speed for H_2: 0.5 L/s· cm^2
BPM and electronics	All	~5000	Closed orbit resolution: 0.6 μm
kicker & fast pulser	Transport line	~25	Pulse width <10 ns (strip-line) trapezoidal pulse width <250 ns (slotted-pipe)
Lambertson septum	Transport line	~20	Septum thickness $\leq$3.5 mm (in-air) thickness $\leq$2 mm (in-vacuum)
Power supply	All	9294	Stability 100-1000 ppm
RF-shielded bellows	Collider Booster	24000 /12000	Contact force 125±25 g/finger

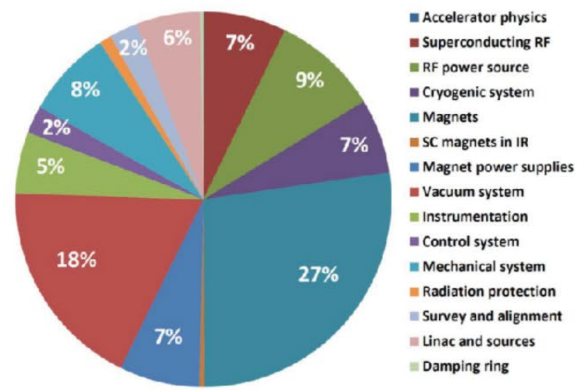
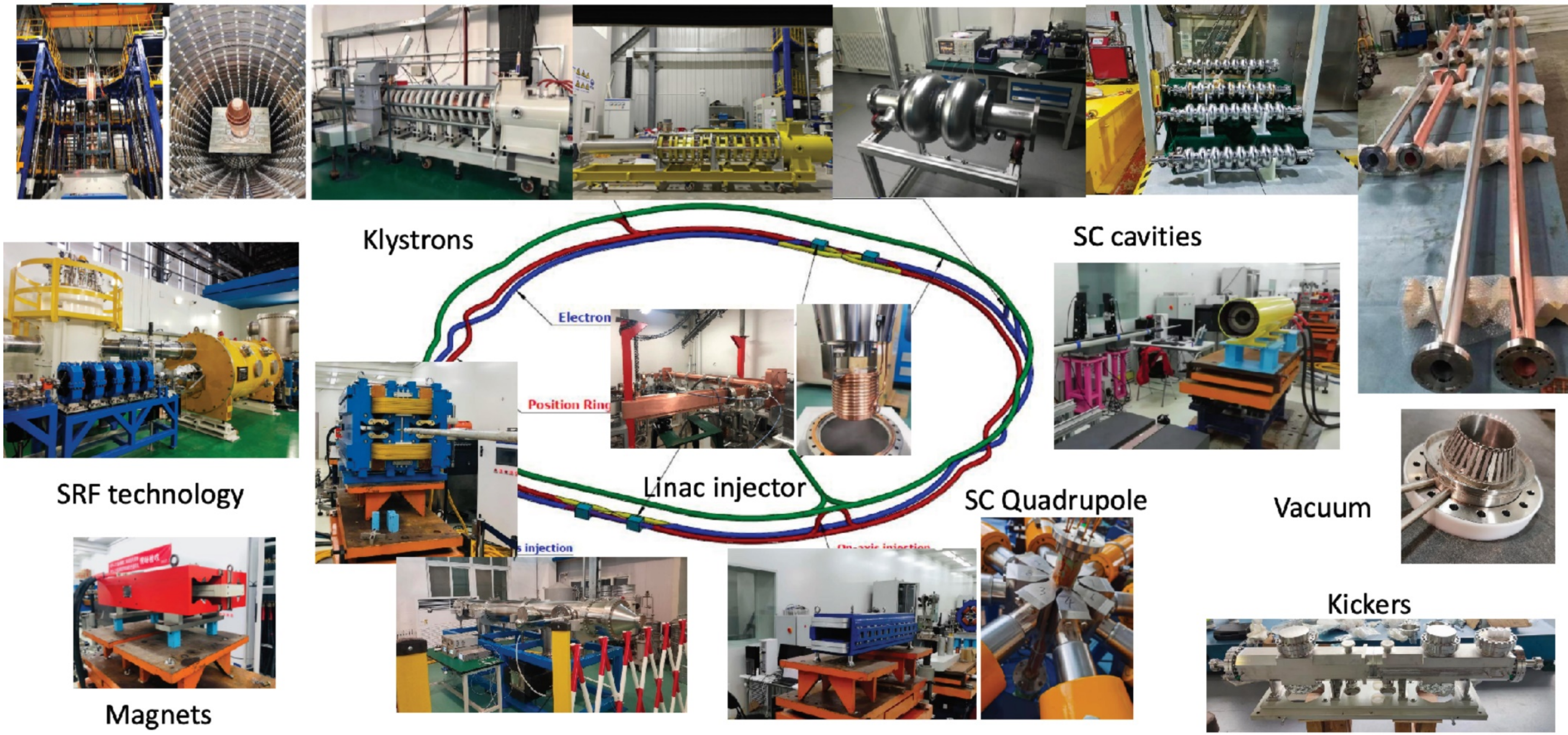


Figure 12.3: Cost breakdown of the CEPC accelerator technical systems.

CEPC TDR: R&D Status of Key Technologies



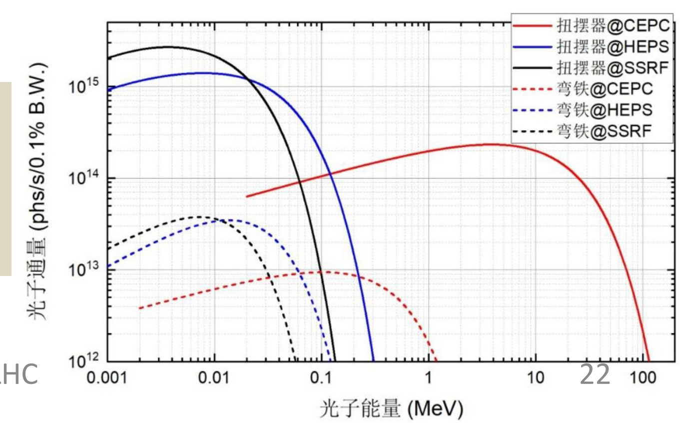
High maturity of key accelerator technologies

Innovations and technology breakthroughs

Innovative Design	➢ 100km Full/Partial Double Rings ➢ Switchable operation for Higgs, W and Z ➢ Flexible injection modes to satisfy different energies ➢ World's 1st design of a high energy/flux gamma-ray synchrotron light (300 MeV)
Technical Performance	➢ High efficiency Klystron (aim at highest transfer efficiency) ➢ High performance SRF cavities (state-of-the-art Q and gradient) ➢ Novel magnets: Weak field dipole, dual aperture magnets (First Qualified Prototype)
Major Technology Breakthrough	➢ Plasma wakefield acceleration for Injector (New Acceleration Principle) ➢ High field superconducting magnet (Iron based HTS proposal)

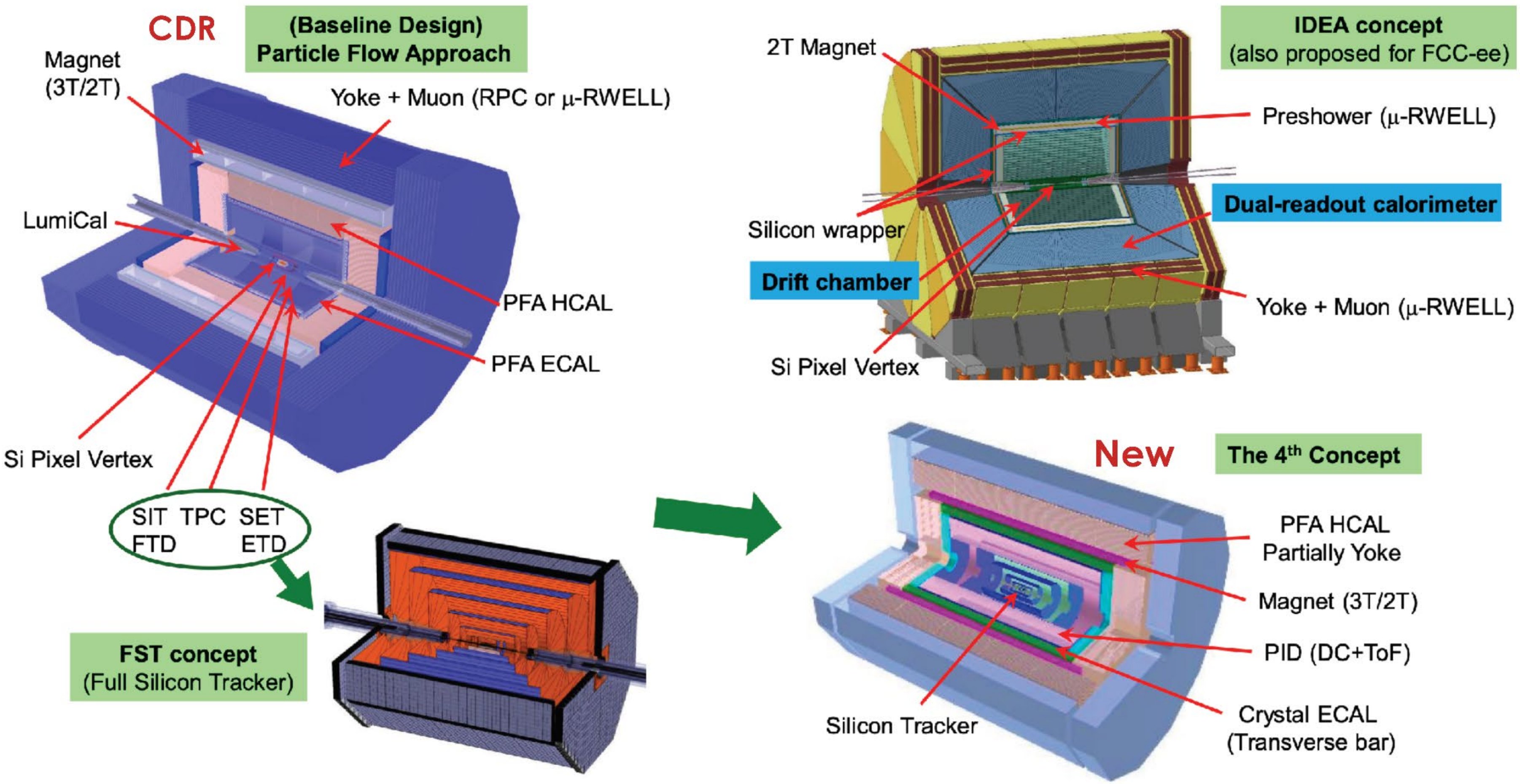
CEPC: World first high energy-high intensity γ synchrotron light source → new applications.

Potentially a broad range of important applications



Kruger 2022: Discovery Physics at the LHC

CEPC Detector Concept Designs



The 4th Conceptual Detector Design

Scint Glass PFA HCAL

Advantage: Cost efficient, high density

Challenges: Light yield, transparency, massive production.

Solenoid Magnet (3T / 2T) Between HCAL & ECAL

Advantage: the HCAL absorbers act as part of the magnet return yoke.

Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Transverse Crystal bar ECAL

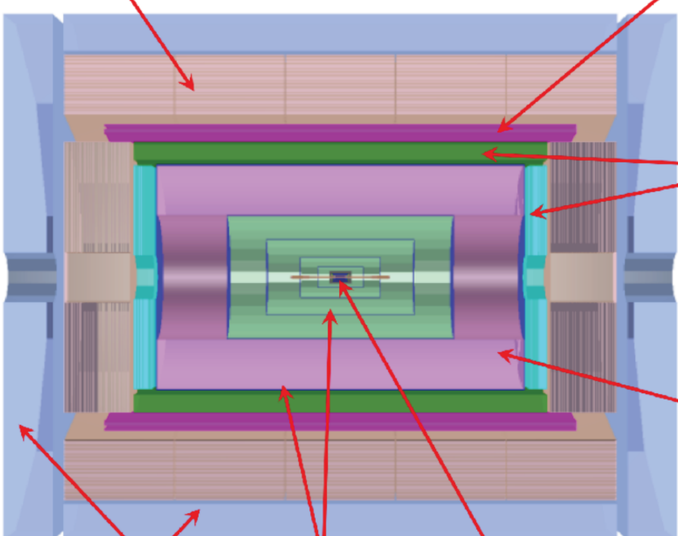
Advantage: better π^0/γ reconstruction.

Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

A Drift chamber that is optimized for PID

Advantage: Work at high luminosity Z runs

Challenges: sufficient PID power; thin enough not to affect the moment resolution.

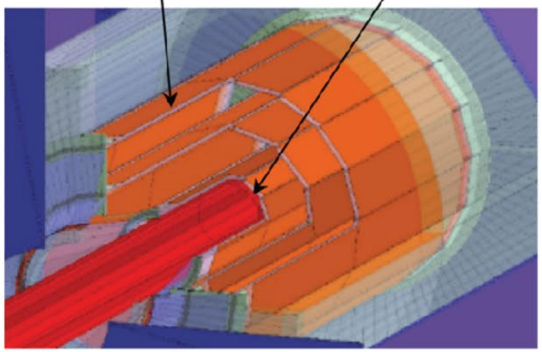


Technologies

Det	Technology
Pixel Vertex	JadePix
	TaichuPix
	Arcadia
	CPV(SOI)
	Stiching
Tracker & PID	TPC
	CEPCPix
	Drift chamber
	PID DC
	LGAD
	Silicon Strip

Det	Technology
Calorimeter	Crystal ECAL
	Si+W ECAL
	Scint+W ECAL
	Scint AHCAL
	ScintGlass AHCAL
	RPC SDHCAL
	MPGD SDHCAL
	DR Calorimeter
Muon	Scintillation Bar
	RPC
	μ-Rwell
Lumi	SiTrk+Crystal ECAL
	SiTrk+SiW ECAL

CEPC R&D: Silicon Pixel Sensors



Goal: σ(IP) ~ 5 μm for high P track

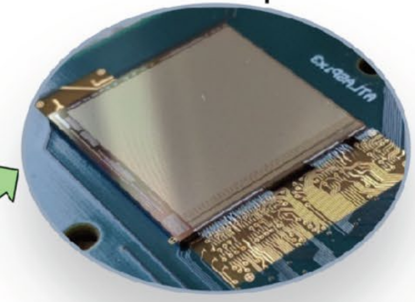
CDR design specifications

- Single point resolution ~ 3μm
- Low material (0.15% X_0 / layer)
- Low power (< 50 mW/cm²)
- Radiation hard (1 Mrad/year)

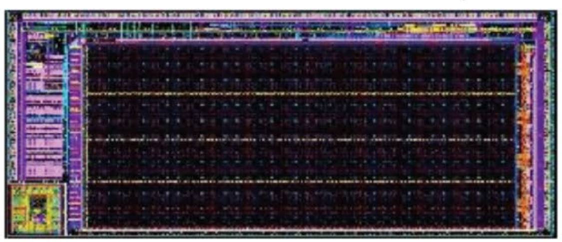
Silicon pixel sensor develops in 5 series:
JadePix, TaichuPix, CPV, Arcadia, CEPCPix

Develop **CEPCPix** for a CEPC tracker based on **ATLASPix3** **CN/IT/UK/DE**

TSI 180 nm HV-CMOS process



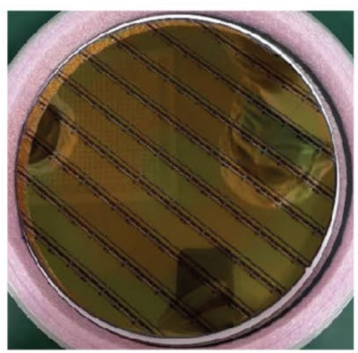
JadePix-3 Pixel size ~16×23 μm²



Tower-Jazz 180nm CiS process
Resolution 5 microns, 53mW/cm²

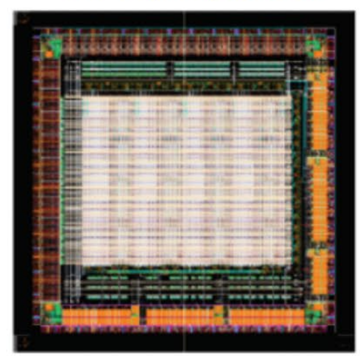
MOST 1

TaichuPix-3, FS 2.5x1.5 cm²
25×25 μm² pixel size



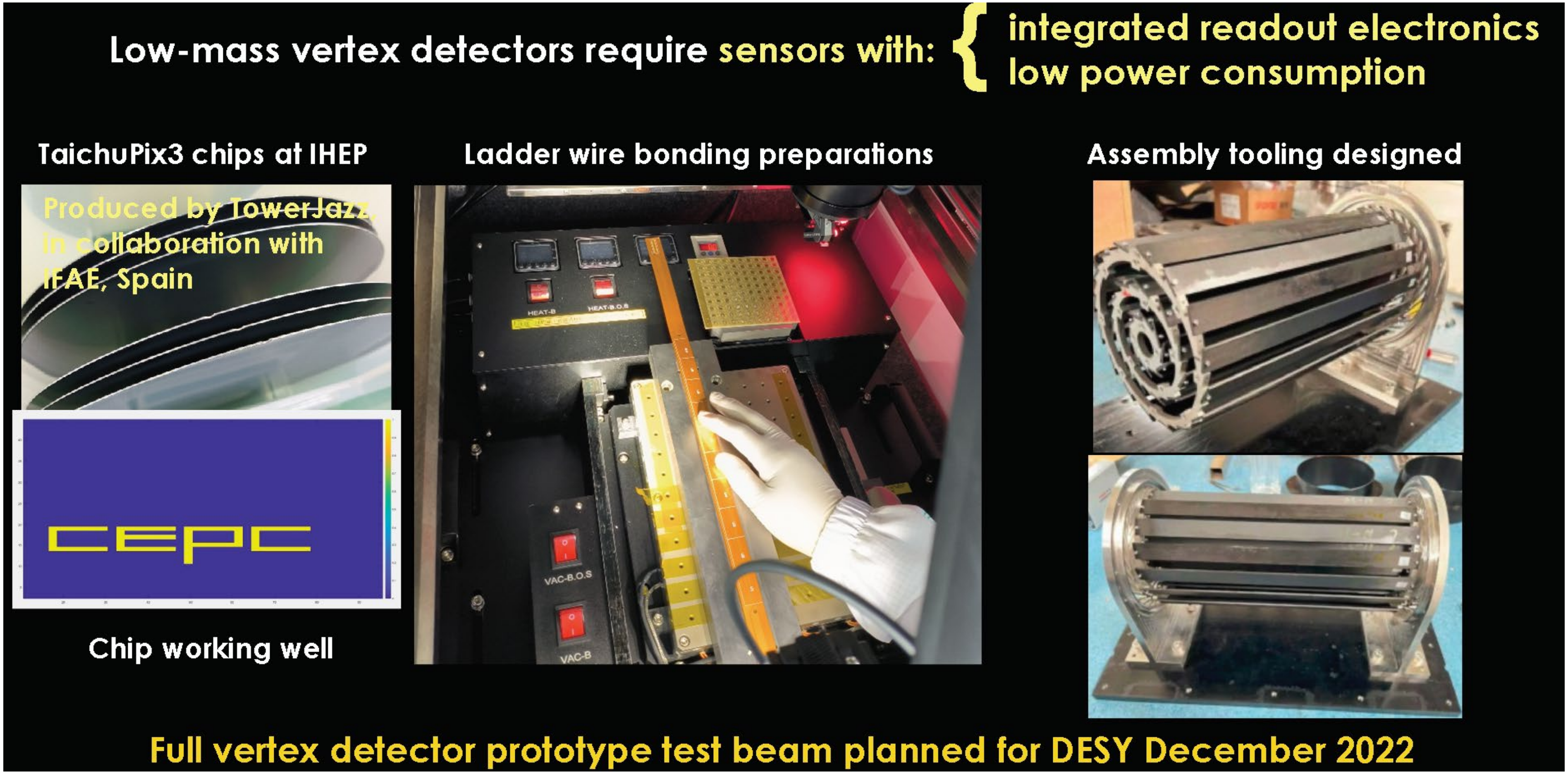
MOST 2

CPV4 (SOI-3D), 64×64 array
~21×17 μm² pixel size



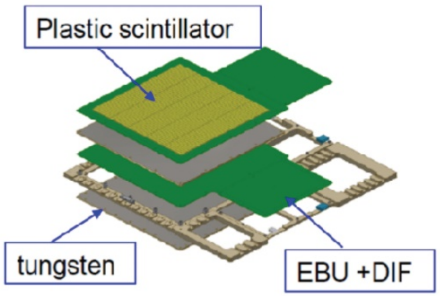
Arcadia by Italian groups for IDEA vertex detector
LFoundry 110 nm CMOS

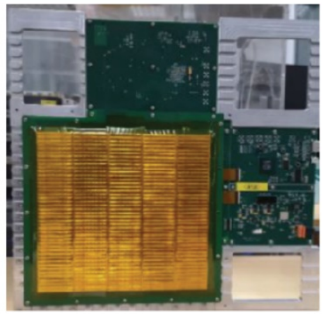
CEPC R&D: Vertex Detector Prototype

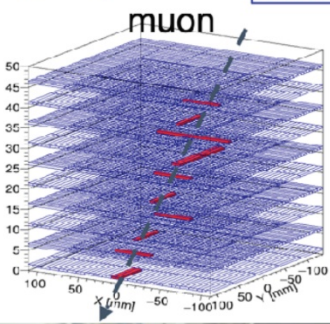


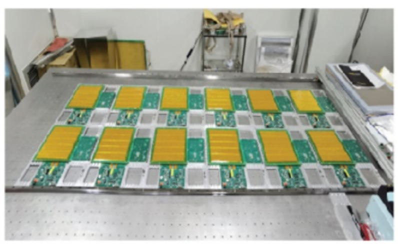
CEPC R&D: Scintillating Calorimeters

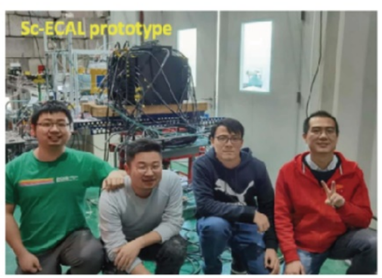
Scintillator-W ECAL Prototype



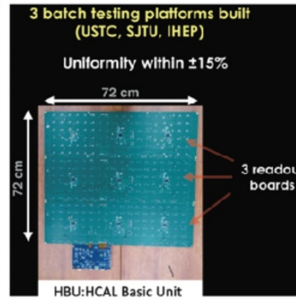


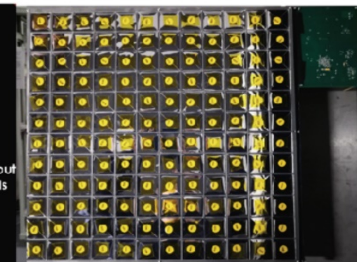




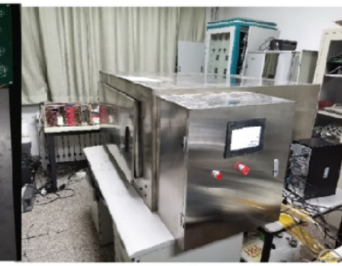


Scintillator + SiPM AHCAL Prototype

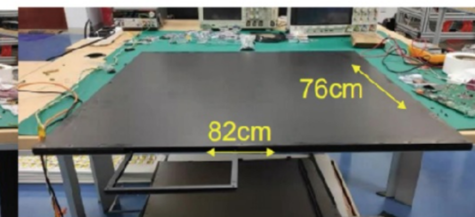


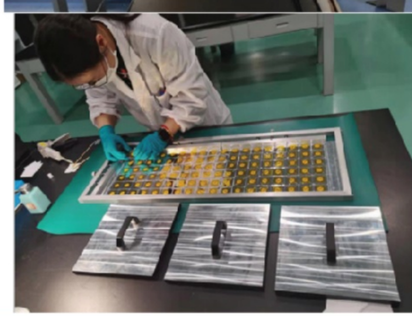


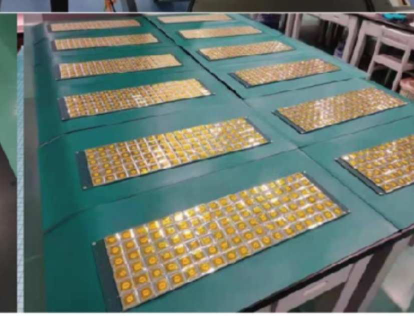
SJTU



IHEP





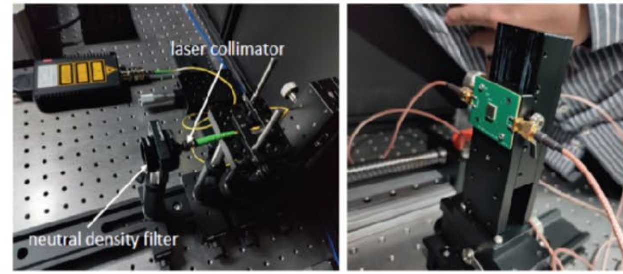


Test beam at CERN SPS on-going, together with CALICE

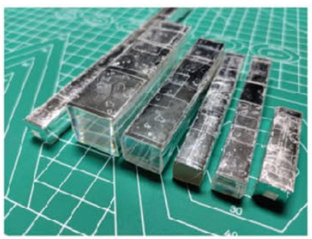
CEPC R&D: High Granularity Crystal ECAL

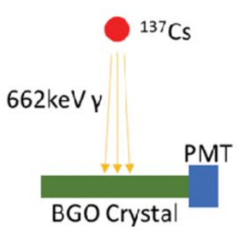
Goal
- Boson Mass Resolution < 4%
- Better BMR than ScW-ECAL
- Much better sensitivity to γ/e, especially at low energy.

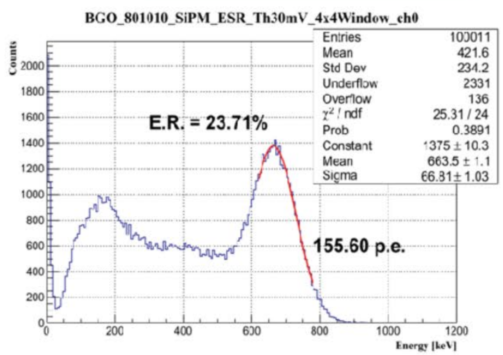
Bench Test



Performance Test

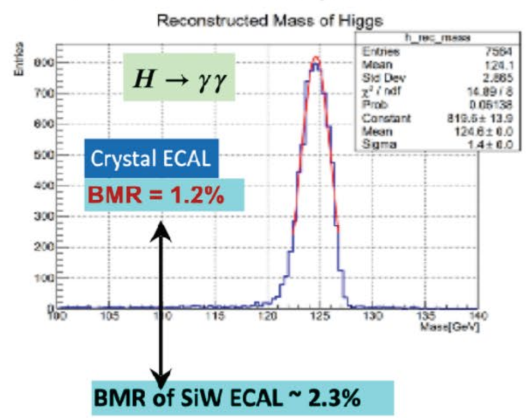


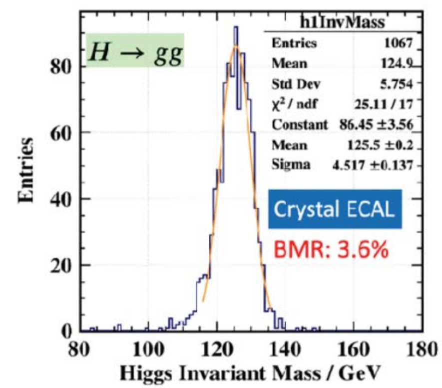




- Different crystals investigated
  - BGO, PbWO

Full Simulation Studies + Optimizing PFA for crystals





CEPC Physics Program

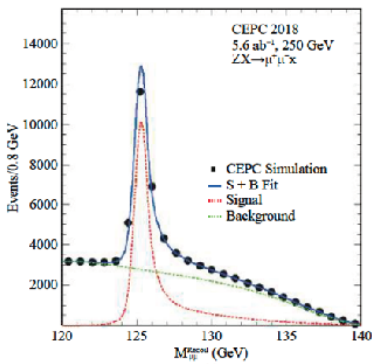
CEPC Operation mode		ZH	Z	W^+W^-	ttbar
		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	-
CDR (30MW)	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	3	32	10	-
	[ab^{-1}, 2 IPs]	5.6	16	2.6	-
	Event yields [2 IPs]	**1×10^6**	**7×10^{11}**	**2×10^7**	-
Run time [years]		10	2	1	5
Latest (50MW)	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	8.3	192	27	0.83
	[ab^{-1}, 2 IPs]	20	96	7	1
	Event yields [2 IPs]	**4×10^6**	**4×10^{12}**	**5×10^7**	**5×10^5**

Large physics samples: ~10^6 Higgs, ~10^{12} Z, ~10^8 W bosons, ~10^6 top quarks

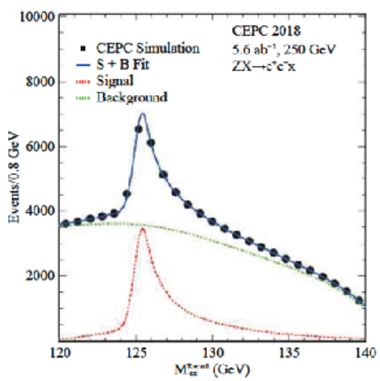
– **Physics potential similar to FCC-ee, ILC, CLIC**

CEPC Physics Program

- **Precision Higgs, EW, flavor physics & QCD measurements**
- **BSM physics (eg. dark matter, EW phase transition, SUSY, LLP, ….) up to ~10 TeV scale**



(a)



(b)

Chinese Physics C Vol. 43, No. 4 (2019) 043002

Precision Higgs physics at the CEPC*

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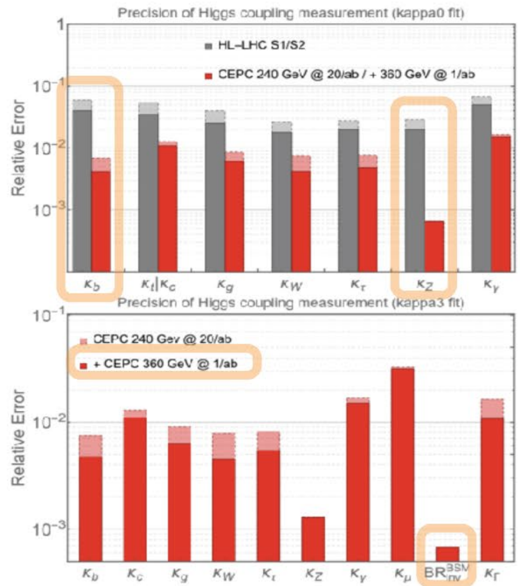
+ O(100) journal/arXiv papers

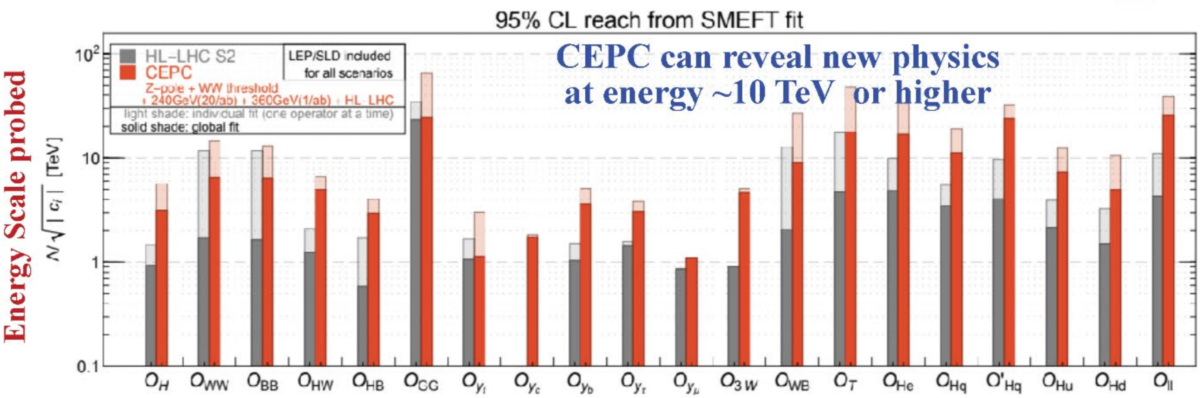
CEPC Physics Program

	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	vvH	ZH	vvH	eeH
inclusive	0.26%		1.40%	\	\
H→bb	0.14%	1.59%	0.90%	1.10%	4.30%
H→cc	2.02%		8.80%	16%	20%
H→gg	0.81%		3.40%	4.50%	12%
H→WW	0.53%		2.80%	4.40%	6.50%
H→ZZ	4.17%		20%	21%	
$H \to \tau\tau$	0.42%		2.10%	4.20%	7.50%
$H \to \gamma\gamma$	3.02%		11%	16%	
$H \to \mu\mu$	6.36%		41%	57%	
$H \to Z\gamma$	8.50%		35%		
$\mathrm{Br}_{upper}(H \to inv.)$	0.07%				
Γ_H	1.65%		1.10%		

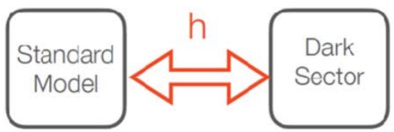


Observable	current precision	CEPC precision (Stat. Unc.)	CEPC runs	main systematic
Δm_Z	2.1 MeV [37–41]	0.1 MeV (0.005 MeV)	Z threshold	E_{beam}
$\Delta\Gamma_Z$	2.3 MeV [37–41]	0.025 MeV (0.005 MeV)	Z threshold	E_{beam}
Δm_W	9 MeV [42–46]	0.5 MeV (0.35 MeV)	WW threshold	E_{beam}
$\Delta\Gamma_W$	49 MeV [46–49]	2.0 MeV (1.8 MeV)	WW threshold	E_{beam}
Δm_t	0.76 GeV [50]	$\mathcal{O}(10)$ MeV[a]	$t\bar{t}$ threshold	
ΔA_e	4.9×10^{-3} [37, 51–55]	1.5×10^{-5} (1.5×10^{-5})	Z pole ($Z\to\tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]	3.5×10^{-5} (3.0×10^{-5})	Z pole ($Z\to\mu\mu$)	point-to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]	7.0×10^{-5}(1.2×10^{-5})	Z pole ($Z\to\tau\tau$)	tau decay model
ΔA_b	0.02 [37, 56]	20×10^{-5} (3×10^{-5})	Z pole	QCD effects
ΔA_c	0.027 [37, 56]	30×10^{-5} (6×10^{-5})	Z pole	QCD effects
$\Delta\sigma_{had}$	37 pb [37–41]	2 pb (0.05 pb)	Z pole	lumiosity
δR_b^0	0.003 [37, 57–61]	0.0002 (5×10^{-6})	Z pole	gluon splitting
δR_c^0	0.017 [37, 57, 62–65]	0.001 (2×10^{-5})	Z pole	gluon splitting
δR_e^0	0.0012 [37–41]	2×10^{-4} (3×10^{-6})	Z pole	E_{beam} and t channel
δR_μ^0	0.002 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δR_τ^0	0.017 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δN_ν	0.0025 [37, 66]	2×10^{-4} (3×10^{-5})	ZH run ($\nu\nu\gamma$)	Calo energy scale

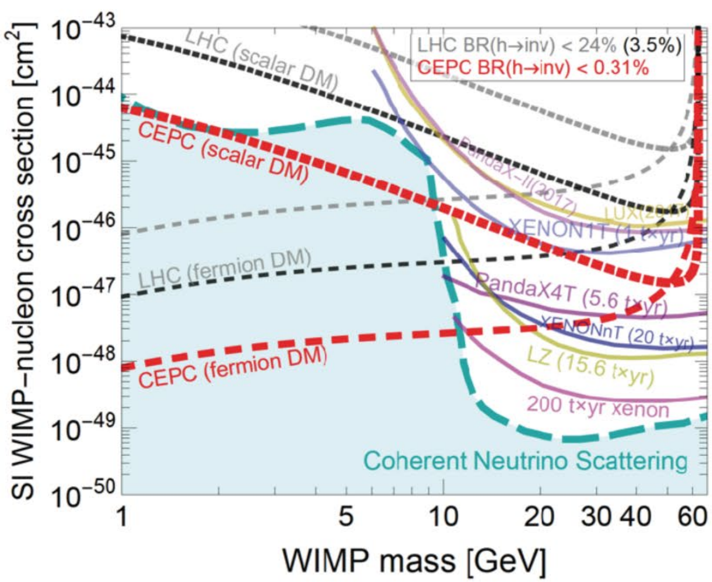
Measurement	Current [126]	FCC [115]	Tera-Z Prelim. [127]	Comments
Lifetime [sec]	$\pm5\times10^{-16}$	$\pm1\times10^{-18}$		from 3-prong decays, stat. limited
$\mathrm{BR}(\tau\to\ell\nu\bar{\nu})$	$\pm4\times10^{-4}$	$\pm3\times10^{-5}$		$0.1\times$ the ALEPH systematics
m(τ) [MeV]	±0.12	$\pm0.004\pm0.1$		$\sigma(p_{\rm track})$ limited
$\mathrm{BR}(\tau\to3\mu)$	$<2.1\times10^{-8}$	$\mathcal{O}(10^{-10})$	same	bkg free
$\mathrm{BR}(\tau\to3e)$	$<2.7\times10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau^\pm\to e\mu\mu)$	$<2.7\times10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau^\pm\to\mu ee)$	$<1.8\times10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau\to\mu\gamma)$	$<4.4\times10^{-8}$	$\sim2\times10^{-9}$	$\mathcal{O}(10^{-10})$	$Z\to\tau\tau\gamma$ bkg , $\sigma(p_\gamma)$ limited
$\mathrm{BR}(\tau\to e\gamma)$	$<3.3\times10^{-8}$	$\sim2\times10^{-9}$		$Z\to\tau\tau\gamma$ bkg, $\sigma(p_\gamma)$ limited
$\mathrm{BR}(Z\to\tau\mu)$	$<1.2\times10^{-5}$	$\mathcal{O}(10^{-9})$	same	$\tau\tau$ bkg, $\sigma(p_{\rm track})$ & $\sigma(E_{\rm beam})$ limited
$\mathrm{BR}(Z\to\tau e)$	$<9.8\times10^{-6}$	$\mathcal{O}(10^{-9})$		$\tau\tau$ bkg, $\sigma(p_{\rm track})$ & $\sigma(E_{\rm beam})$ limited
$\mathrm{BR}(Z\to\mu e)$	$<7.5\times10^{-7}$	$10^{-8}-10^{-10}$	$\mathcal{O}(10^{-9})$	PID limited
$\mathrm{BR}(Z\to\pi^+\pi^-)$			$\mathcal{O}(10^{-10})$	$\sigma(\vec{p}_{\rm track})$ limited, good PID
$\mathrm{BR}(Z\to\pi^+\pi^-\pi^0)$			$\mathcal{O}(10^{-9})$	$\tau\tau$ bkg
$\mathrm{BR}(Z\to J/\psi\gamma)$	$<1.4\times10^{-6}$		$10^{-9}-10^{-10}$	$\ell\ell\gamma$+$\tau\tau\gamma$ bkg
$\mathrm{BR}(Z\to\rho\gamma)$	$<2.5\times10^{-5}$		$\mathcal{O}(10^{-9})$	$\tau\tau\gamma$ bkg, $\sigma(p_{\rm track})$ limited

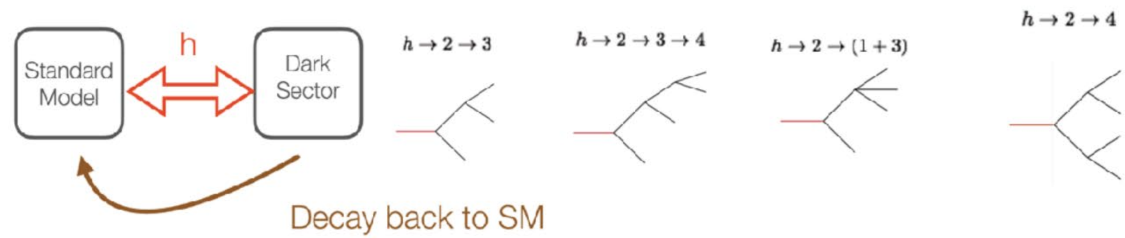


CEPC Physics Program

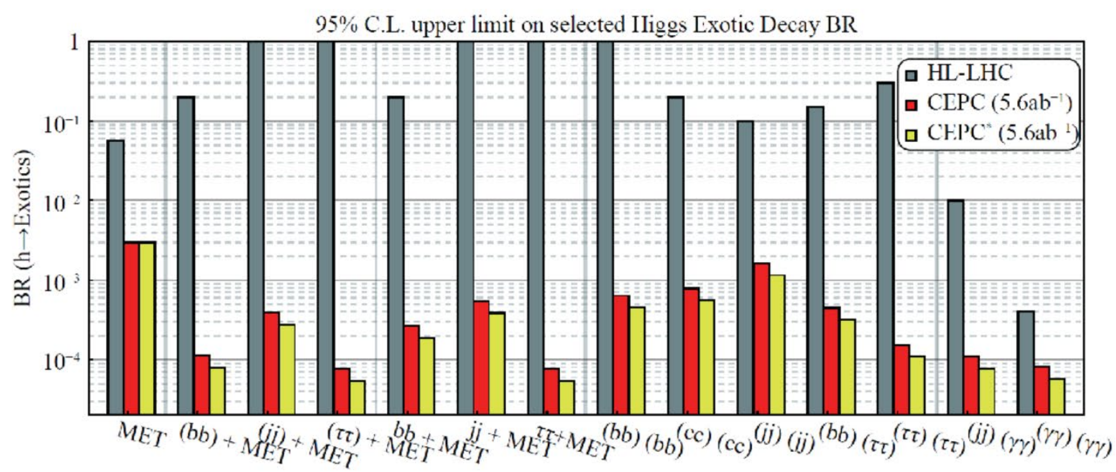


$$h \rightarrow X_{\rm dm} X_{\rm dm}$$





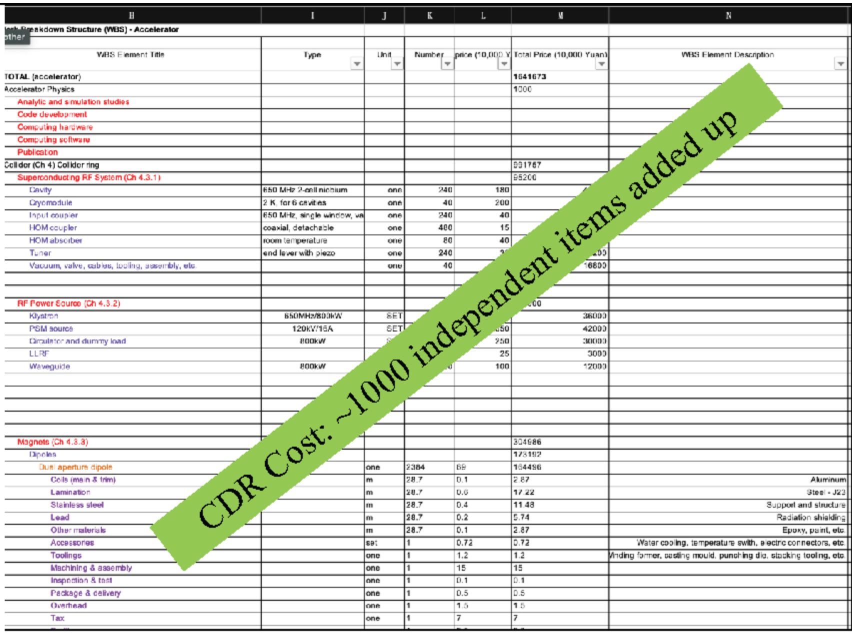
Higgs decays into BSM particles, $H \rightarrow X_1X_2$



CEPC has significantly better detection sensitivity for dark matter and selected Higgs exotic decays than HL-LHC

Budget for CEPC construction

Tier I	Tier II	Amount (100 M CNY)
Accelerator	Collider	99.2
	Booster	39.2
	Linac and sources	9.1
	Damping ring	0.44
	Common: Cryogenics	10.6
	Survey & alignment	4
	Radiation protection	1.7
Conventional facilities	-	102
Detectors	-	40
γ-ray beam lines	-	3
Project management (1%)	-	3
Contingency (15%)	-	46
Total	-	358



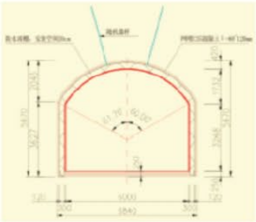
- Cost estimated with two independent methods
  - agrees at 10% level
  - CEPC design relies on well studied, or mature technology
    - reducing uncertainties on cost estimation
  - cost estimation for TDR phase is in progress

CEPC Financial Model

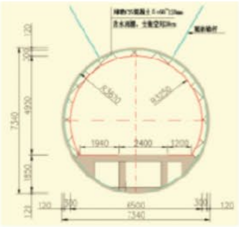
- Total required funding: 36 Billion RMB (5 Billion CHF at today's exchange rate)
- Funding model: Iteration and interaction with relevant entities, especially Local governments (leading contributors)

Funding Sources	Funding Model #1 (B RMB)	Funding Model #2 (B RMB)
Central Government	25	10
Local Government	5	20
International contributions	6	6
Donations	0-3.5	0-3.5

CEPC Sites

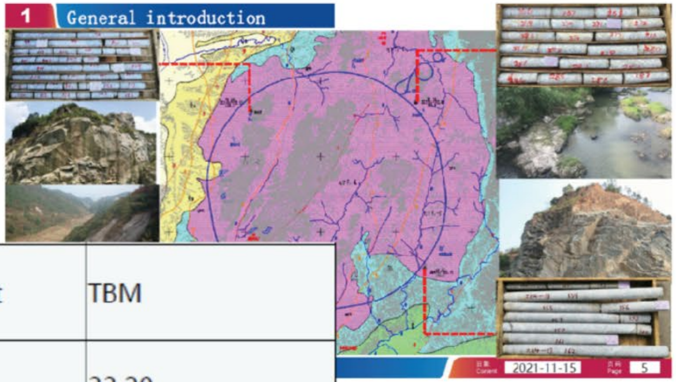


Drill-blast tunnel (6.0m×5.0m)

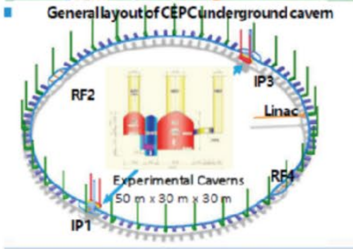


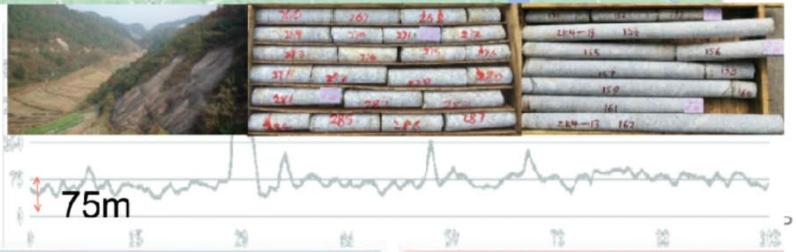
TBM tunnel (D6.5m)

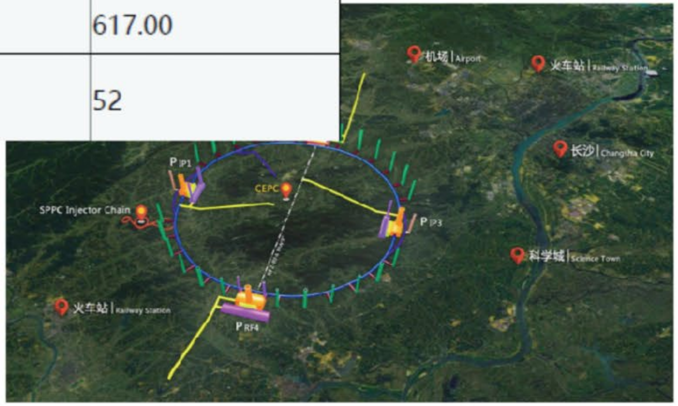
Very good geological condition



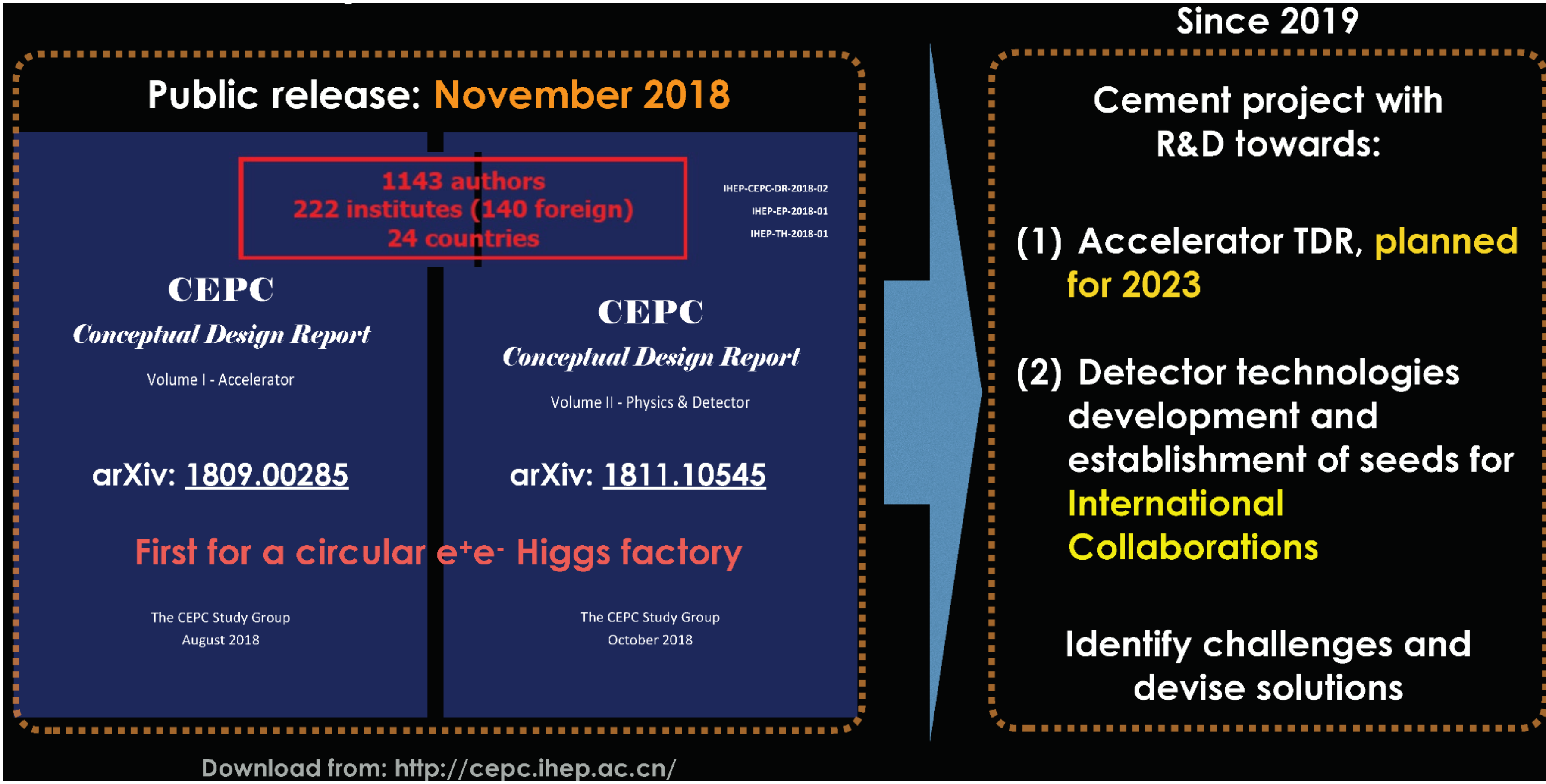
Item	Unit	Drill-blast	TBM
The clearance cross section	m²	27.00	33.20
Excavation unit price	Yuan/m³	278.28	617.00
Construction duration	Month	50	52





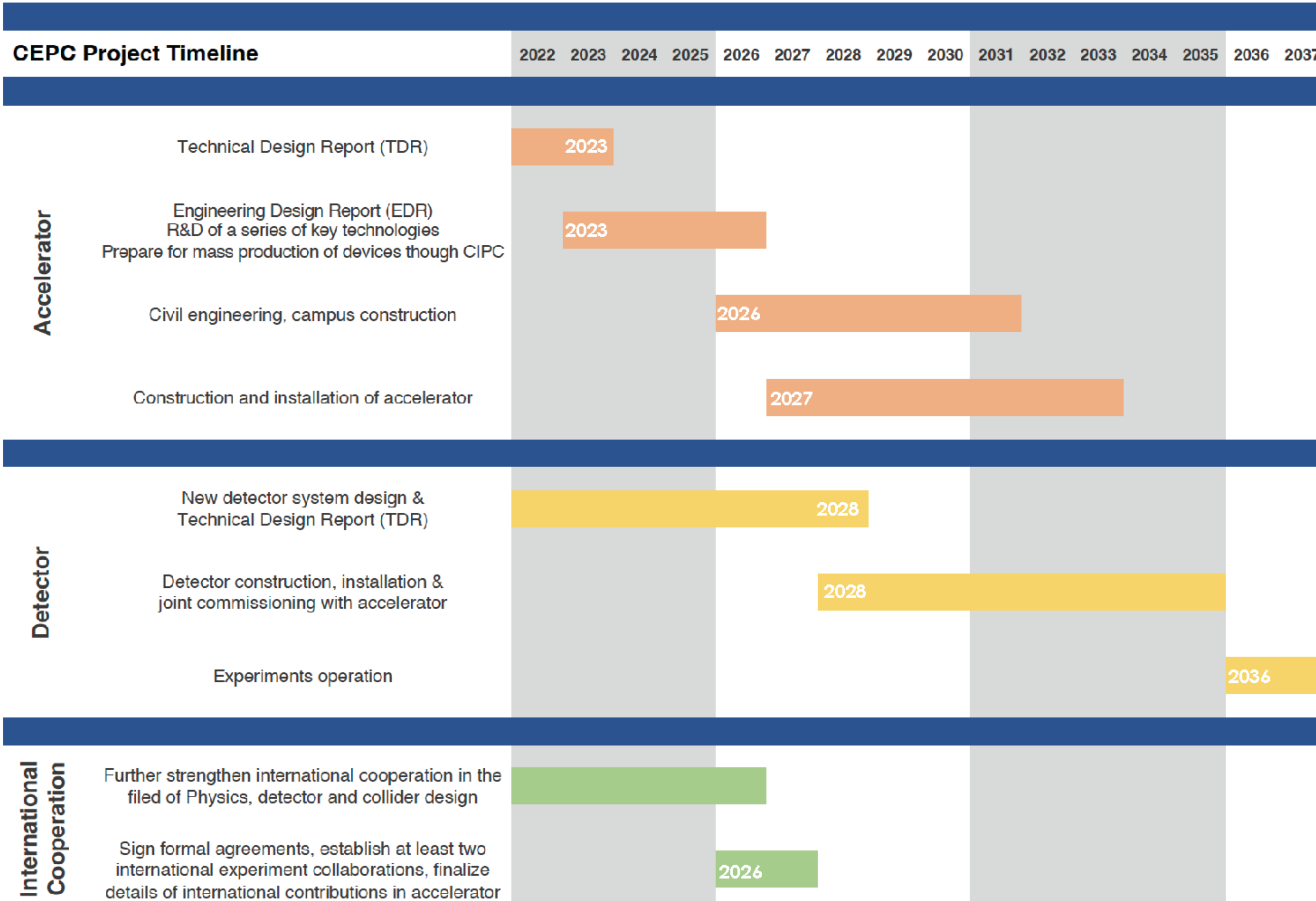


CEPC roadmap



- **Engineering Design Report (EDR) Phase: Jan. 2023-Dec. 2025**
- **EDR document completed for government's approval of starting construction around 2026 (the starting of the "15th five year plan" of China)**

CEPC longer roadmap

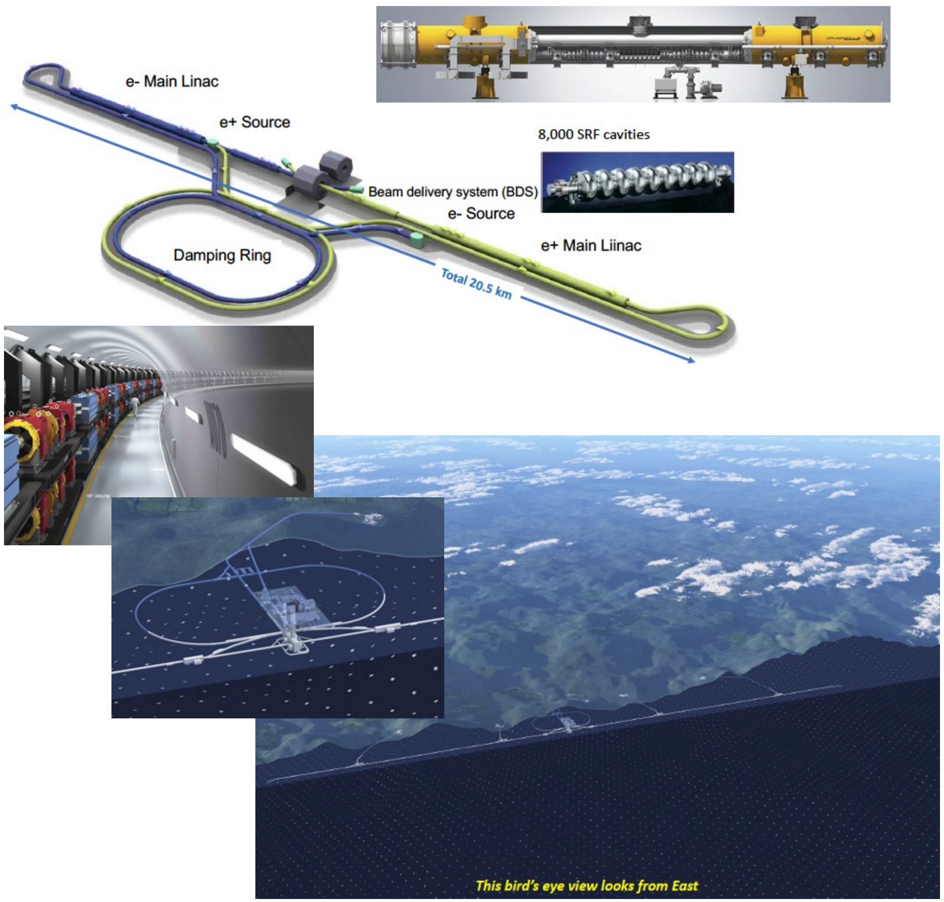


International Linear Collider
ILC

Acknowledgement
Inputs from Benno
List et. all

ILC in a nutshell

- **International Linear Collider ILC**
  - To be built in Japan

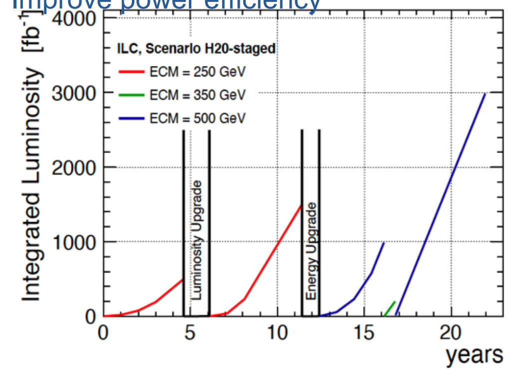


- Superconducting Cavities, Nb 1.3GHz, 31.5 (35) MV/m
- Klystrons
- 250GeV CME, upgradeable to 500, 1000 GeV
- L = 1.35 x 10^{34} $cm^{-2}s^{-1}$ (at initial 250GeV)
- 20km length, in Tohoku / Japan
- Polarisation 80%(e-), 30%(e+)

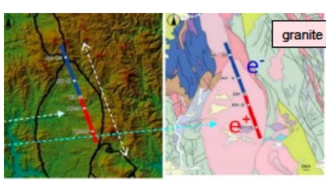
ILC Baseline, extension and upgrades

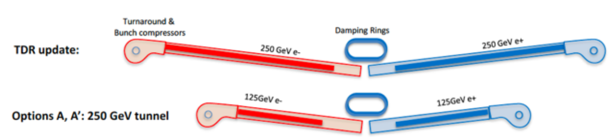
Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	E / $\mathcal{L}$ Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_e	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_b	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Accelerating gradient	G	MV/m	31.5	31.5	31.5	31.5	31.5	45
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ^*_z	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ^*_x	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ^*_y	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

Luminosity upgrades:
- 2 x bunches, 2 x RF (1.35 -> 2.7x10^{34})
- Run 500GeV machine at 250GeV, 10Hz:
  factor 2 (2.7x10^{34} -> 5.4x10^{34})
- Improve power efficiency



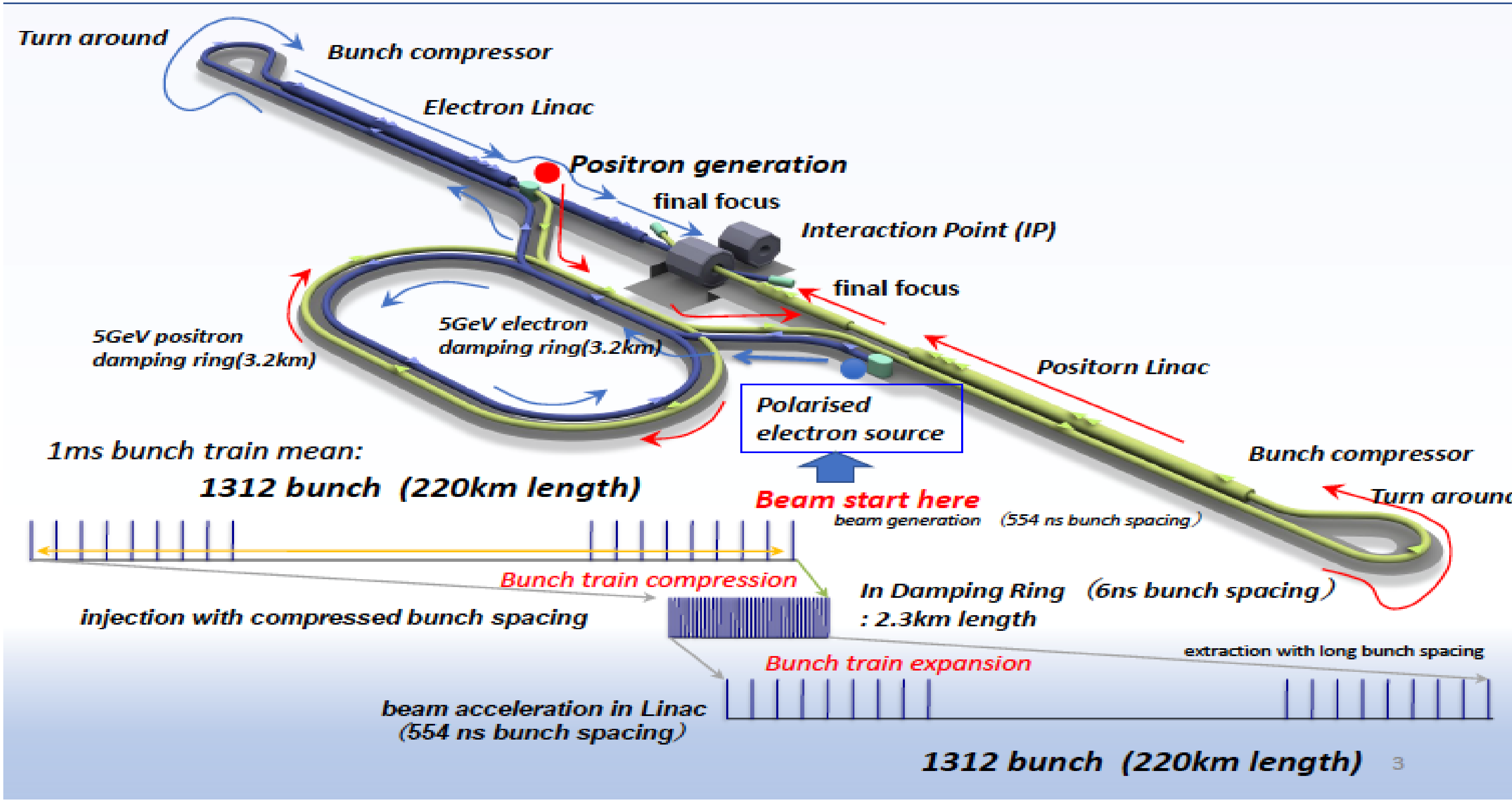
Energy upgrades:
- 500GeV (31.5 MV/m Q_0=1 x 10^{10})
- 1TeV (45 MV/m Q_0=2 x 10^{10}, 300 MW) more SCRF, tunnel extension
- Kitakami site: 50km long, sufficient for 1TeV





Kitakami mountains

ILC Accelerator Design and Challenges



ILC Technology Readiness Level

ILC is a mature design.
R&D is going on to mitigate the identified risks

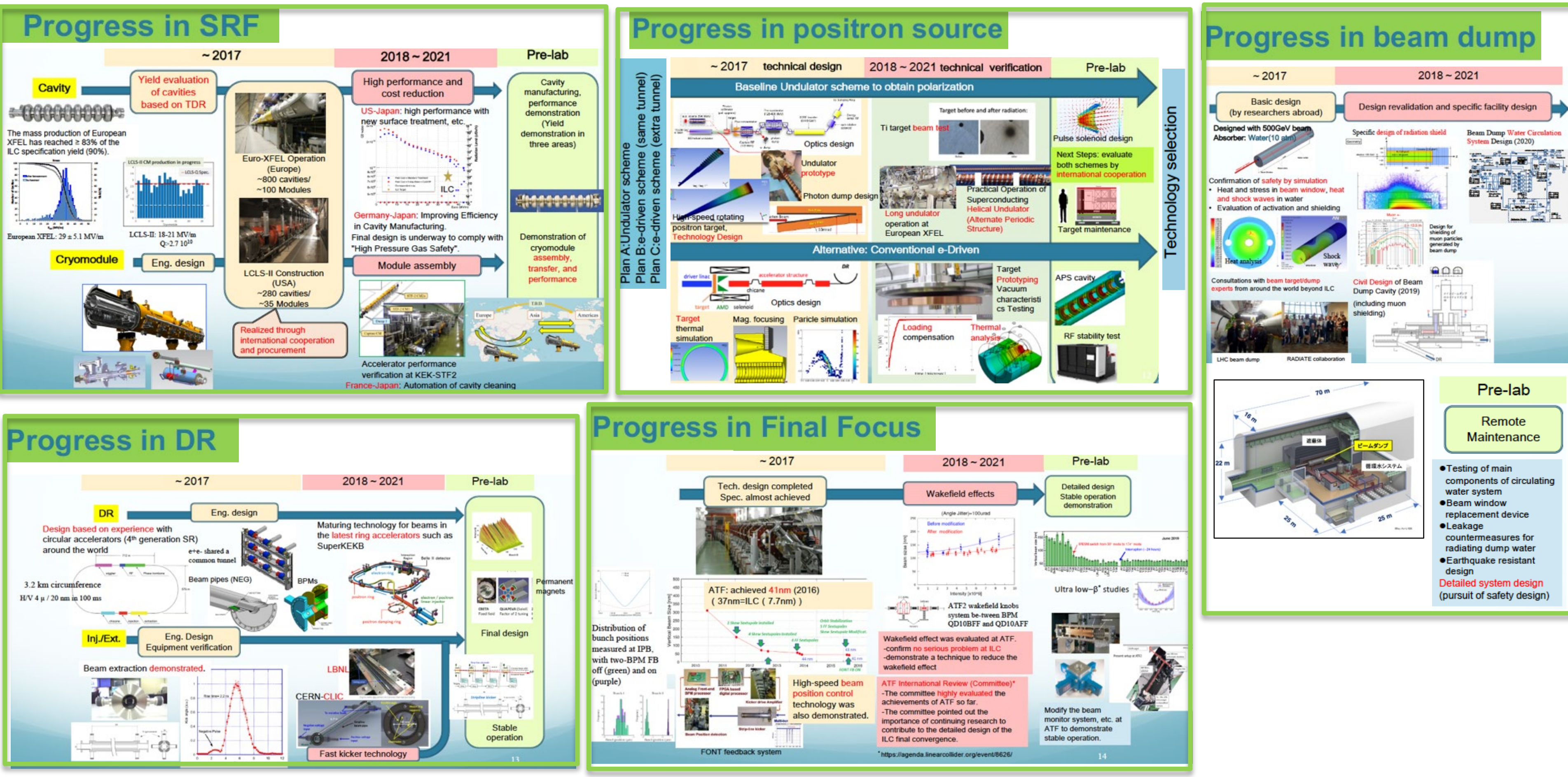
Since the publication of the conceptual design report (RDR) in 2007 and the Technical Design Report (TDR) in 2013, the technical development has been progressing steadily toward the start of construction.

Status	(RDR) (TDR) ~2017	2018~2021	2021 (EDR)*	
SRF cavity, CM	~2017 Technology development ->Model work-> Prototype	2018~2021 High performance and cost reduction of cavities	International mass production, and transfer demonstration	ILC construction
SRF Linac	Model work: small-scale models, partial/component models.	European XFEL user operation		
e- source	~2017 Tech. Design->Tech. Development->Tech. Demonstration		Tech. confirmation	
e+ source Undulator scheme	~2017 Tech. Design->Tech. Development	2018~2021 Tech. Demonstration	Target and magnetic focusing	
e+ source e-driven scheme	~2017 Tech. Design->Tech. Developmen	2018~2021 Tech. Demonstration	Target and capture cavity	
DR	~2017 Design->Tech. Development-> Tech. demonstration achieved at KEK ATF		Kicker	
Final focus	~2017 Design->Tech. Development->Tech. demonstration achieved at KEK ATF		Stable op.	
Dump	~2017 Tech. Design->Tech. Development	2018~2021 Facility design	Remote handling	

: ~2017
: 2018~2021
: Pre-lab

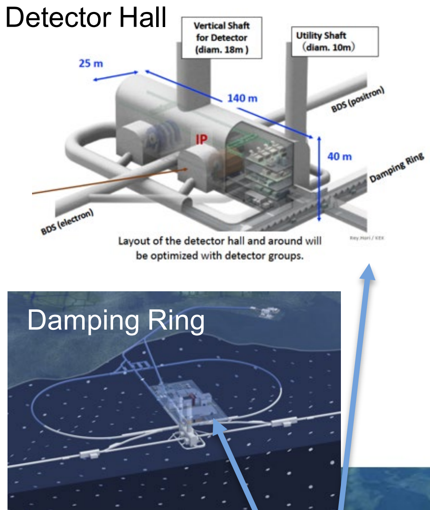
*EDR:Detailed Engineering Design Report required to start construction.

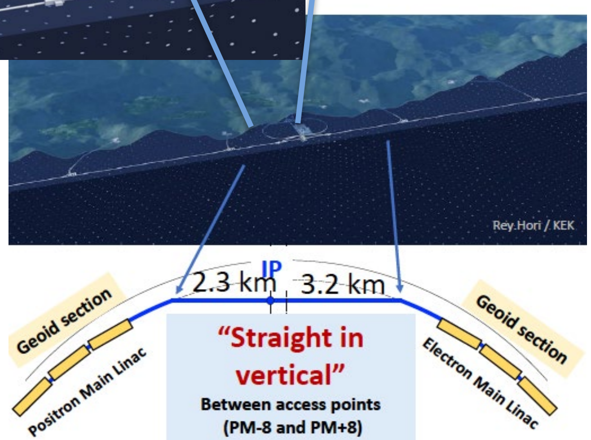
ILC Key technology update



- **Broad progress over the last 5 years**
  - Maturity of key technologies is high
- **Positron source** remains biggest challenge
- Priority work packages have been identified for the next 4 years

ILC Site Selection and Civil Engineering

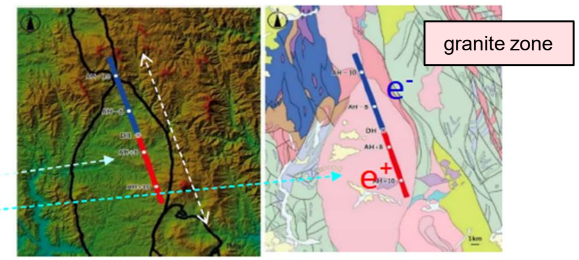




Kitakami mountains

① **ILC Location**

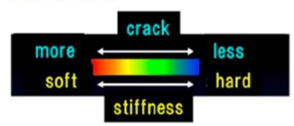
ILC accelerator area : inside the granite rock bodies
→ inside black curves (left)
→ in the pink color (right)
→ possible up to 50 km

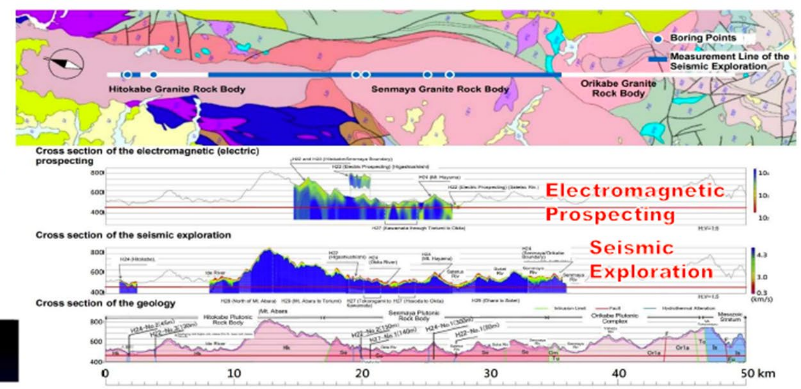


→ On-going jobs : Optimal accelerator placement, considering surface environment, land-use and land-acquisition

② **Geological Surveys**

- Electric Prospecting (crack)
- Seismic Exploration (stiffness)
- Boring Survey
- Borehole Camera
- Measurement of Initial Stress of the Ground





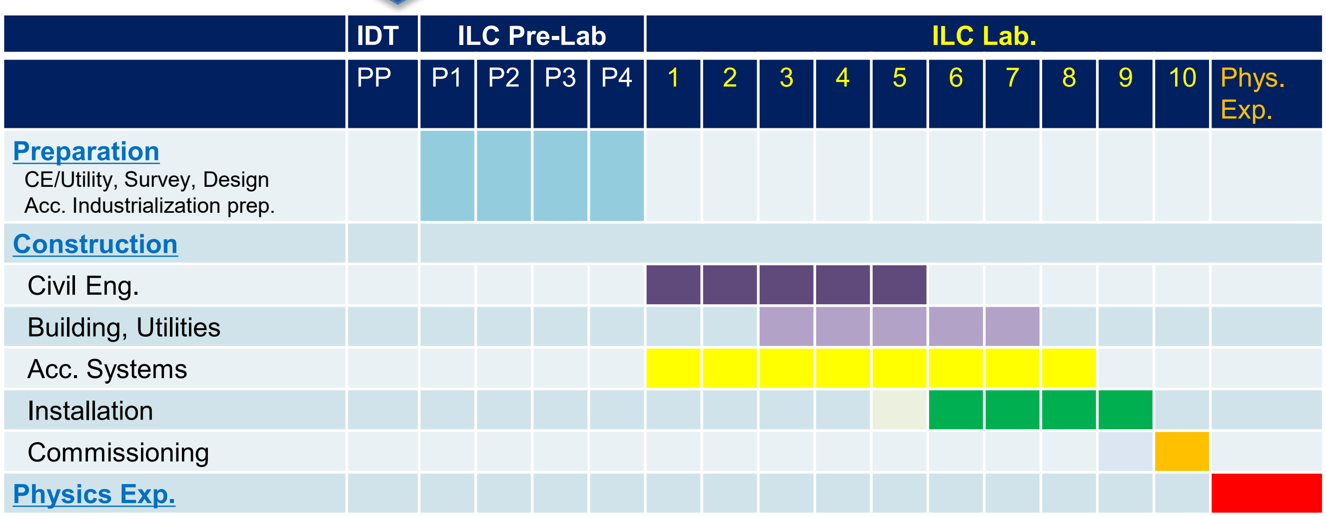
→ no issues from previous surveys

→ requiring : additional surveys around access tunnel head and access tunnel inside for detailed designing

ILC Timeline

2020: ICFA set up International Development Team (IDT) ‘towards … timely realisation of ILC’

- International Development Team (IDT) prepares Pre-Lab
- 4 year Pre-Lab (hosted by KEK, Japan) phase for R&D, Engineering Design Report, Construction preparation, on the premise that Japanese Govt. will express an interest to host ILC
  - Interested countries should continue to work on technical issues
  - Decouple technical progress from ‘hosting issue’
- ILC Laboratory (international): 10 year construction phase



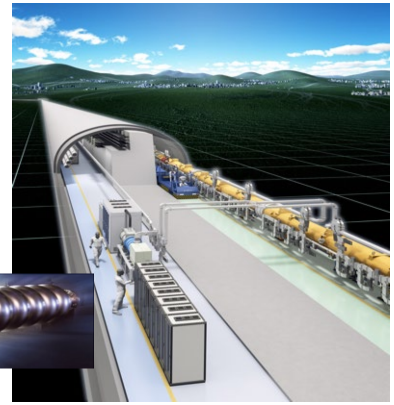
ILC project status

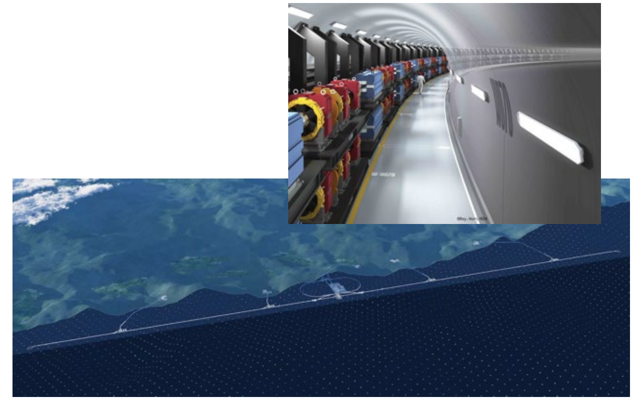
April 2022: ICFA re-stated support for ILC + extended IDT mandate:

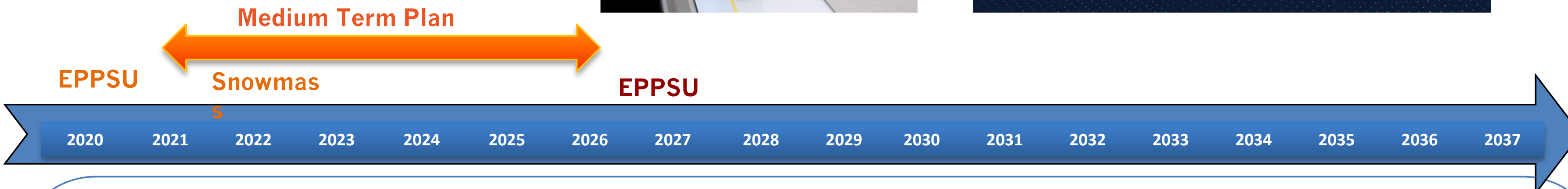
- ‘IDT will … further strengthen collaboration among institutes and labs … and expand the broad support from various stakeholders’.
- ‘ICFA continues to encourage inter-governmental discussions between Japan and potential partner nations … toward realisation of an ILC’.
- IDT has identified ‘time-critical’ work packages (~ years 1-2 of Pre-lab) and is exploring collaboration among KEK and international partners should significant additional funds appear at KEK in JFY2023.
- IDT initiating ‘International Expert Panel’ to develop a model for realising a large global project, such as ILC. Panel members will liaise with respective funding agencies.

https://icfa.hep.net/wp-content/uploads/ICFA_Statement_April2022_Final.pdf

ILC Summary







- **ILC** hosted in Japan is a **mature design** and is set up as international project
  - The main accelerator **technologies** have been **demonstrated** (mass production still a challenge)
  - The cost and implementation time are **similar** to **LHC** (~7B$)* as well as the power (110 MW)
  - The physics case is broad and profound, and being further developed
  - The detector concept and detector technologies R&D are well advanced
  - **ready** for start up ~2038

* Baseline, 2021 value, including 10000FTE-yr from ITF Snowmass report

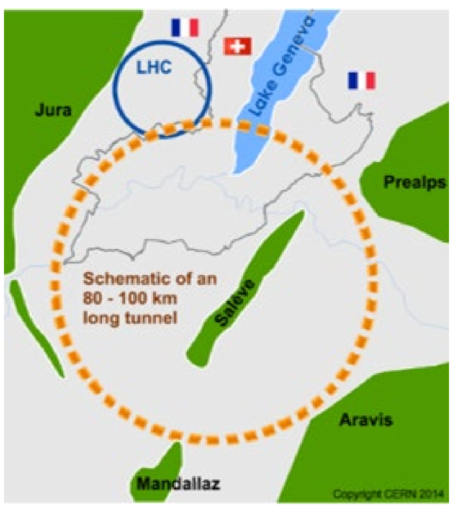
Future Circular Collider
FCC

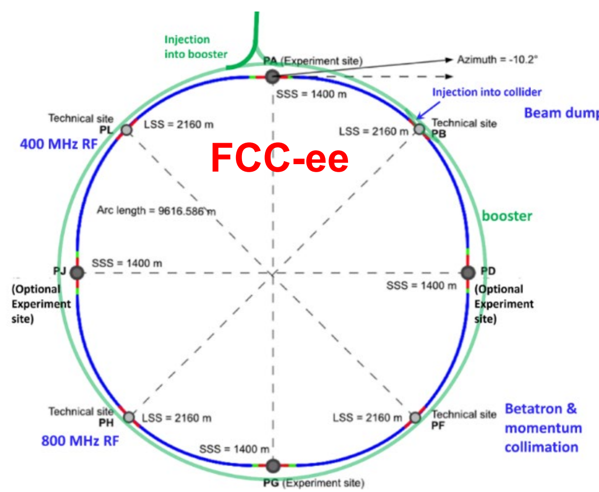
Acknowledgement
Inputs from Michael Benedikt, David d'Enterria et. all

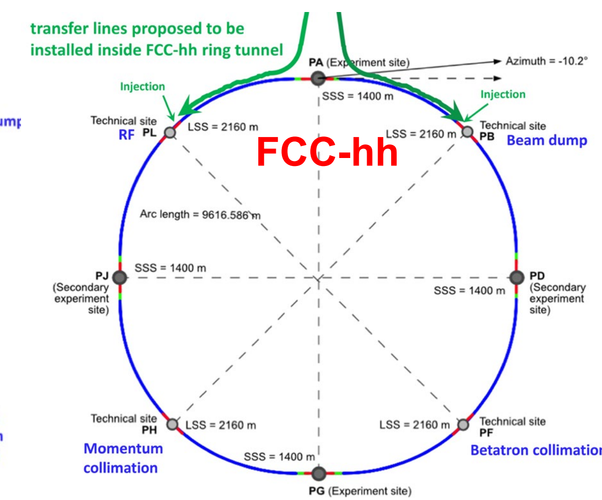
Future Circular Collider in Europe (FCC)

Comprehensive long-term program maximizing physics opportunities

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program







2020 - 2040 | 2045 - 2060 | 2065 - 2090

FCC-ee in a nutshell

- **High luminosity precision study of Z, W, H, and $t\bar{t}$**
  - 2×10^{36} cm^{-2}s^{-1}/IP at Z (or total $\sim10^{37}$ cm^{-2}s^{-1} with 4 IPs)
  - 7×10^{34} cm^{-2}s^{-1} at ZH, 1.3×10^{34} cm^{-2}s^{-1} at $t\bar{t}$,
  - unprecedented energy resolution at Z (<100 keV) and W (<300 keV)
- **Low-risk technical solution**
  - based on 60 years of e^+e^- circular colliders and particle detectors
  - R&D on components for improved performance, but no need for "demonstration" facilities
  - LEP2, VEPP-4M, PEP-II, KEKB, DAΦNE, or SuperKEKB already used many of the key ingredients in routine operation
- Infrastructure will support a **century of physics**
  - FCC-ee → FCC-hh → FCC-eh and/or several other options (FCC-μμ, Gamma Factory ..)
- **Utility requirements** similar to CERN existing use
- **Strong support** from CERN, partners, and 2020 ESPPU
- **Detailed multi-domain feasibility study underway** for 2026 ESPPU

Stage 1: updated parameters

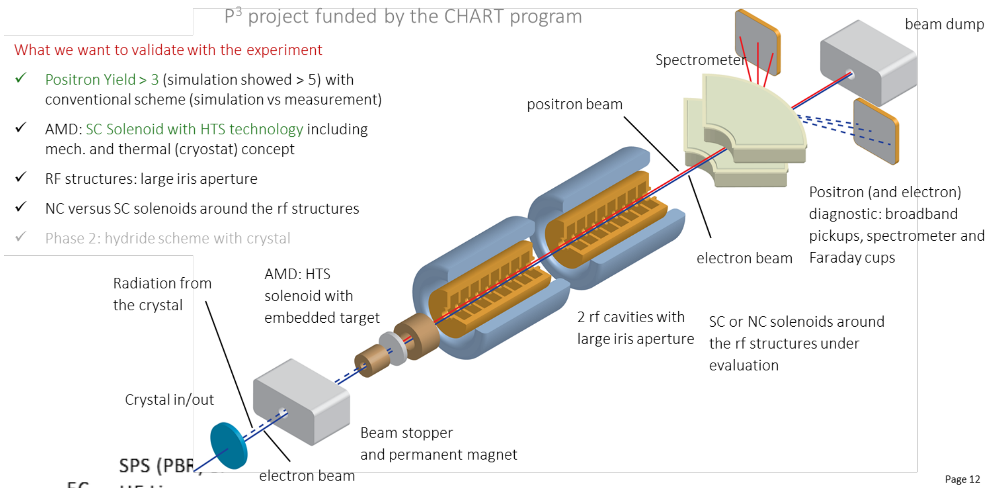
Parameter [4 IPs, 91.2 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	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
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

K. Oide, D. Shatilov,

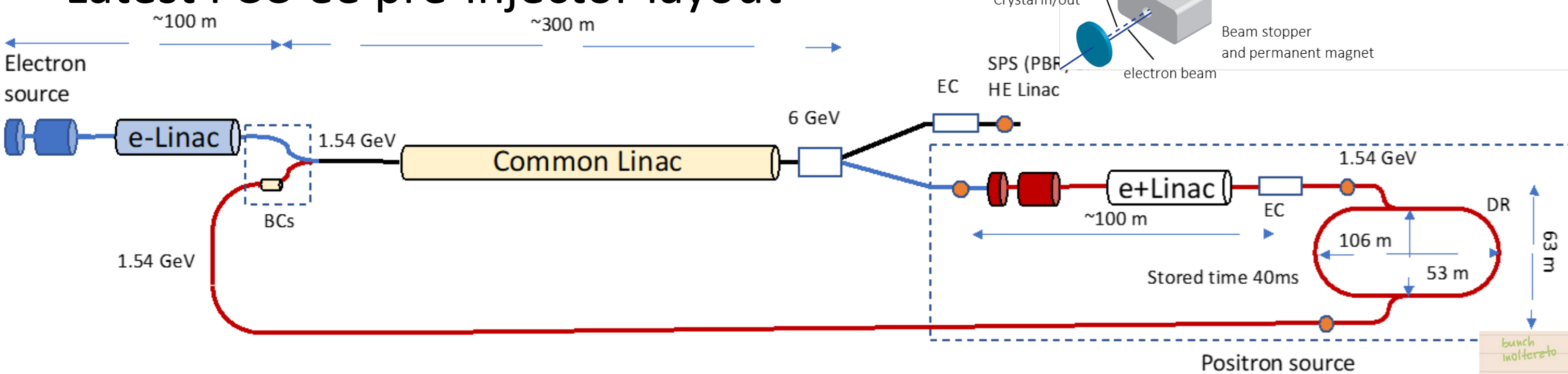
FCC-ee Pre-Injector - Swiss CHART 2 program

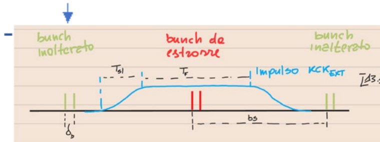
Collaboration between PSI and CERN with external partners: CNRS-IJCLab (Orsay), INFN-LNF (Frascati), KEK/SuperKEKB as observer, INFN-Ferrara – radiation from crystal

P^3: PSI e$^+$ production experiment with HTS solenoid at SwissFEL planned for 2024/25



Latest FCC-ee pre-injector layout

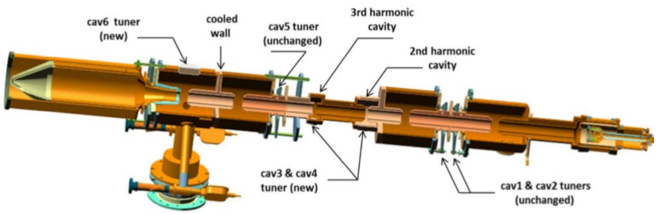




P. Craievich, A. Grudiev, C. Milardi, A. De Santis, et al.

Accelerator R&D examples

efficient RF power sources
(400 & 800 MHz) I. Syratchev

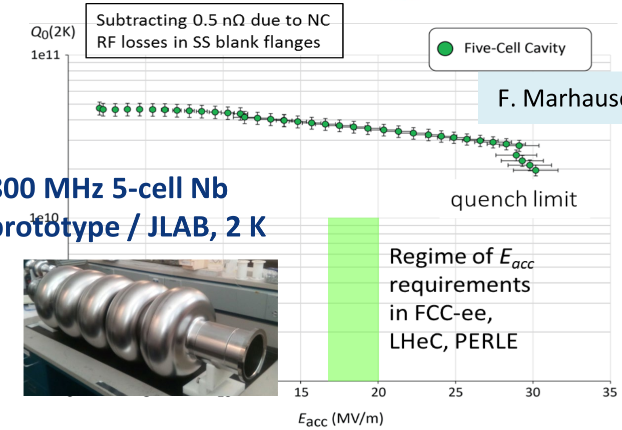


FPC & HOM coupler, cryomodule, thin-film coatings…

efficient SC cavities

400 MHz 1-,2- & 4-cell Nb/Cu , 4.5 K

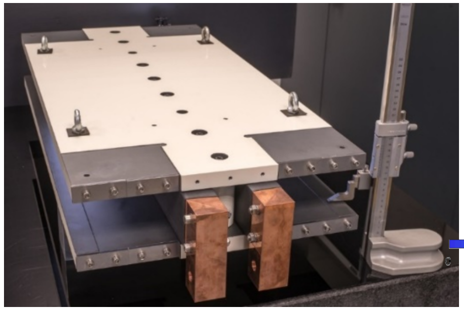
Jefferson Lab

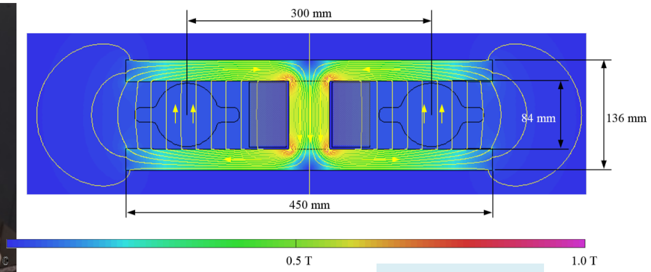


F. Marhauser

800 MHz 5-cell Nb prototype / JLAB, 2 K

energy **efficient** twin aperture **arc dipoles**

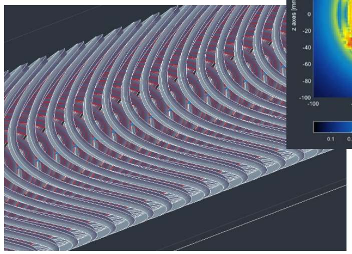


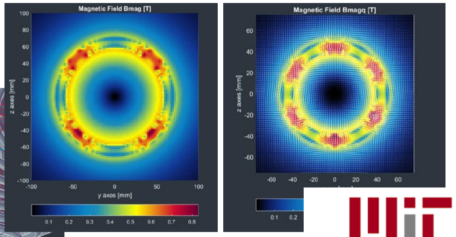


A. Milanese

under study: **CCT HTS quad's & sext's for arcs**

PAUL SCHERRER INSTITUT PSI





Massachusetts Institute of Technology

M. Koratzinos

Stage 2: FCC-hh (pp) collider parameters

FUTURE CIRCULAR COLLIDER

<table>
<tr><th>parameter</th><th colspan="2">FCC-hh</th><th>HL-LHC</th><th>LHC</th></tr>
<tr><td>collision energy cms [TeV]</td><td colspan="2">100</td><td>14</td><td>14</td></tr>
<tr><td>dipole field [T]</td><td colspan="2">~17 (~16 comb.function)</td><td>8.33</td><td>8.33</td></tr>
<tr><td>circumference [km]</td><td colspan="2">91.2</td><td>26.7</td><td>26.7</td></tr>
<tr><td>beam current [A]</td><td colspan="2">0.5</td><td>1.1</td><td>0.58</td></tr>
<tr><td>bunch intensity [10^{11}]</td><td>1</td><td>1</td><td>2.2</td><td>1.15</td></tr>
<tr><td>bunch spacing [ns]</td><td>25</td><td>25</td><td>25</td><td>25</td></tr>
<tr><td>synchr. rad. power / ring [kW]</td><td colspan="2">2700</td><td>7.3</td><td>3.6</td></tr>
<tr><td>SR power / length [W/m/ap.]</td><td colspan="2">32.1</td><td>0.33</td><td>0.17</td></tr>
<tr><td>long. emit. damping time [h]</td><td colspan="2">0.45</td><td>12.9</td><td>12.9</td></tr>
<tr><td>beta* [m]</td><td>1.1</td><td>0.3</td><td>0.15 (min.)</td><td>0.55</td></tr>
<tr><td>normalized emittance [μm]</td><td colspan="2">2.2</td><td>2.5</td><td>3.75</td></tr>
<tr><td>peak luminosity [10^{34} cm^{-2}s^{-1}]</td><td>5</td><td>30</td><td>5 (lev.)</td><td>1</td></tr>
<tr><td>events/bunch crossing</td><td>170</td><td>1000</td><td>132</td><td>27</td></tr>
<tr><td>stored energy/beam [GJ]</td><td colspan="2">7.8</td><td>0.7</td><td>0.36</td></tr>
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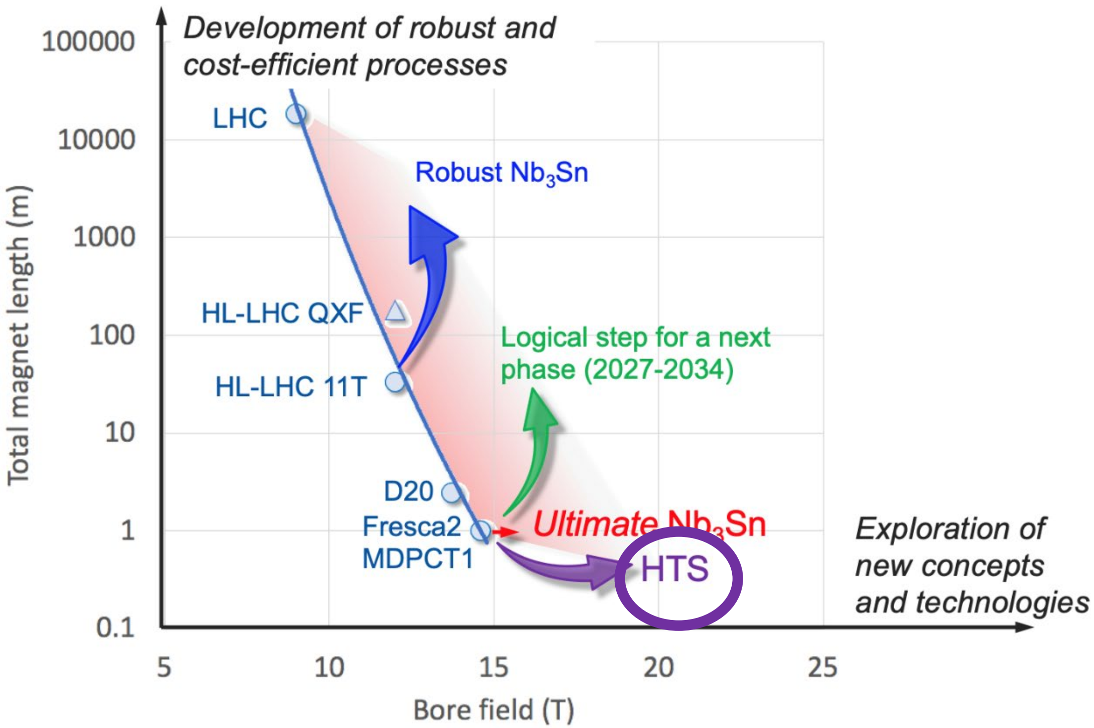
Preparing for FCC stage 2 (FCC-hh)

FUTURE CIRCULAR COLLIDER

In parallel to FCC studies,
High Field Magnet development program as long-term separate R&D project



CERN budget for high-field magnets doubled in 2020 Medium-Term Plan (~ 200 MCHF over ten years)

Main R&D activities:
- materials: goal is ~16 T for Nb_3Sn, at least ~20 T for HTS inserts
- magnet technology: engineering, mechanical robustness, insulating materials, field quality
- production of models and prototypes: to demonstrate material, design and engineering choices,
  industrialisation and costs
- infrastructure and test stations: for tests up to ~ 20 T and 20-50 kA

Detailed deliverables and timescale being defined through Accelerator R&D roadmap under development

L. Bottura, F. Gianotti, A. Siemko

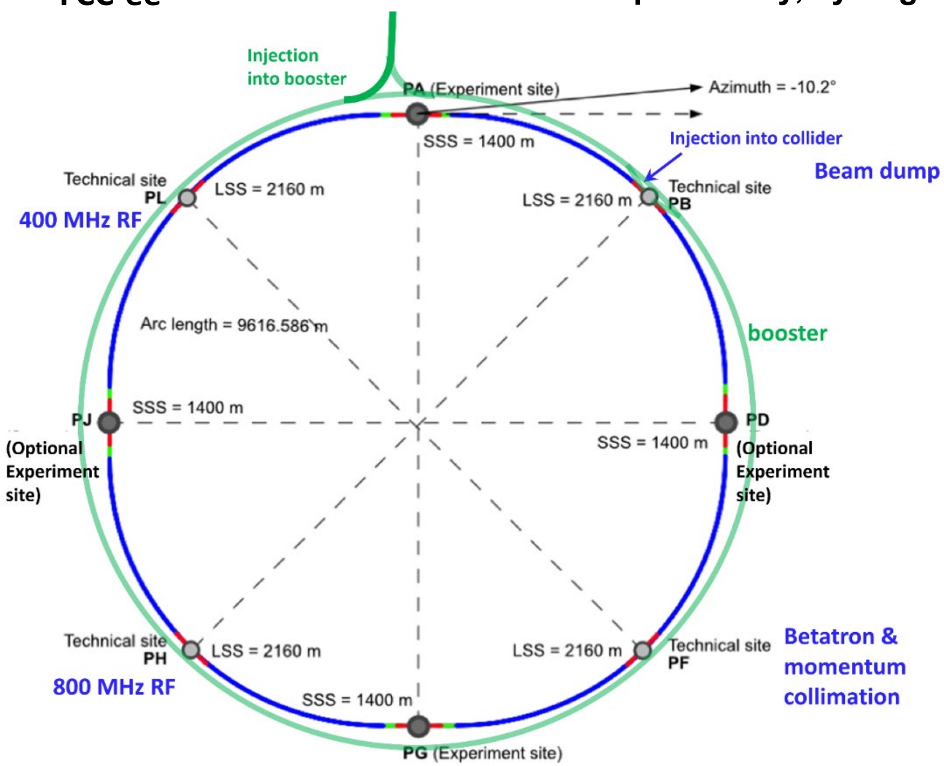
New layouts & preliminary assignments of straight sections

FUTURE CIRCULAR COLLIDER

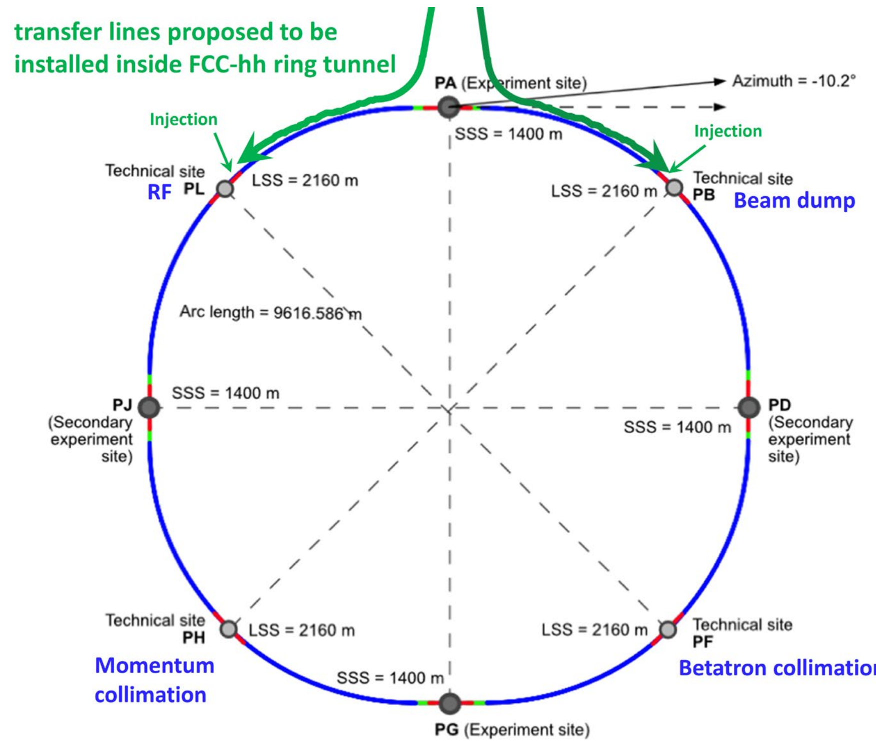
injection-tunnel near PA; 400 MHz RF in PL; 4 exp. caverns for both

4-fold periodicity, synergies ee & hh

FCC-ee



FCC-hh

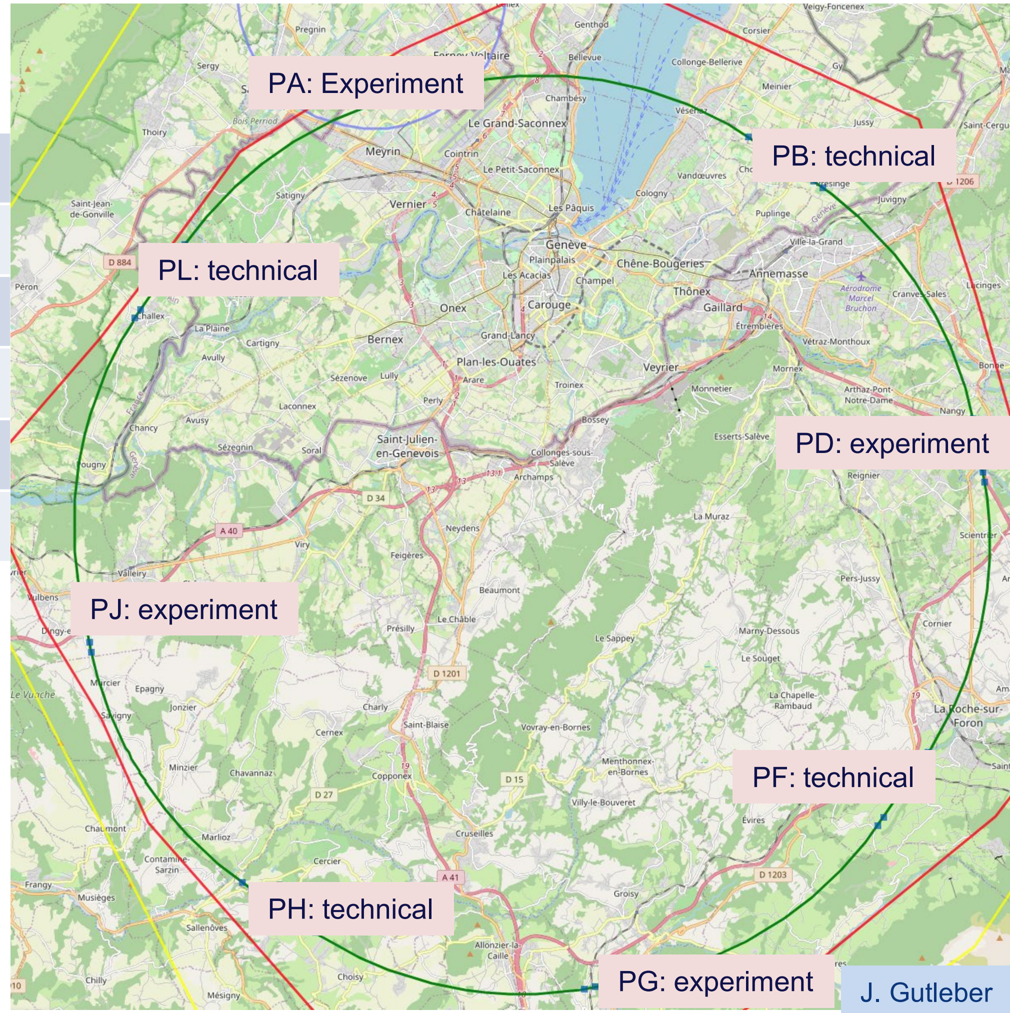


Optimized placement and layout

8-site baseline “PA31”

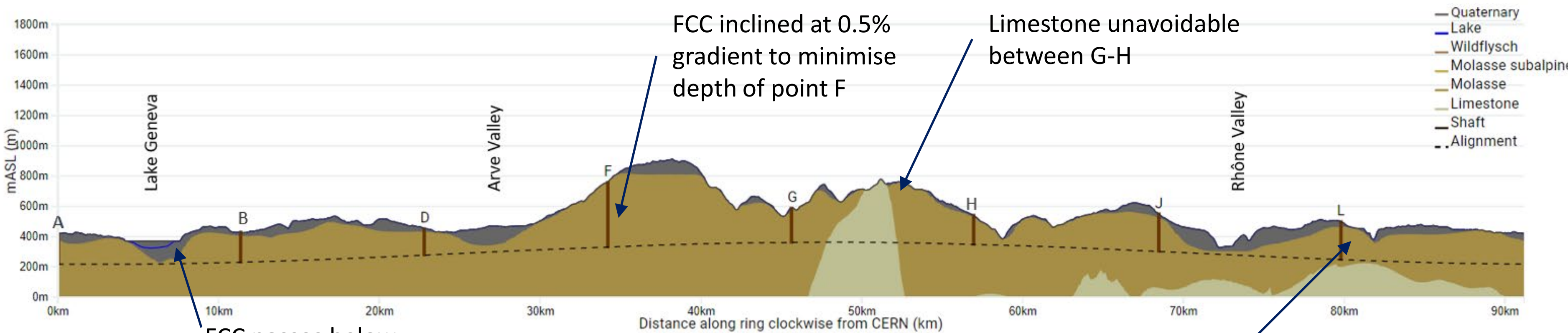
Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2143 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**91.1 km**

- 8 sites – less use of land, <40 ha instead 62 ha
- Possibility for 4 experiment sites in FCC-ee
- All sites close to road infrastructures (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP
- **Exchanges with ~40 local communes in preparation**



J. Gutleber

FCC tunnel - geological conditions



Shaft depth:

A: 202 m   B: 200 m   D: 177 m   F: 399 m   G: 228 m   H: 139 m   J: 251 m   L: 253 m

Tunneling mainly in moraine layer (soft rock), well suited for fast, low-risk TBM construction.

Site investigations campaign planned for 2024 – 2025: ~40-50 drillings, 100 km of seismic lines

John Osborne

Status of Global FCC Collaboration

FUTURE
CIRCULAR
COLLIDER

Increasing international collaboration as a prerequisite for success:

links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

147 Institutes

30 Companies

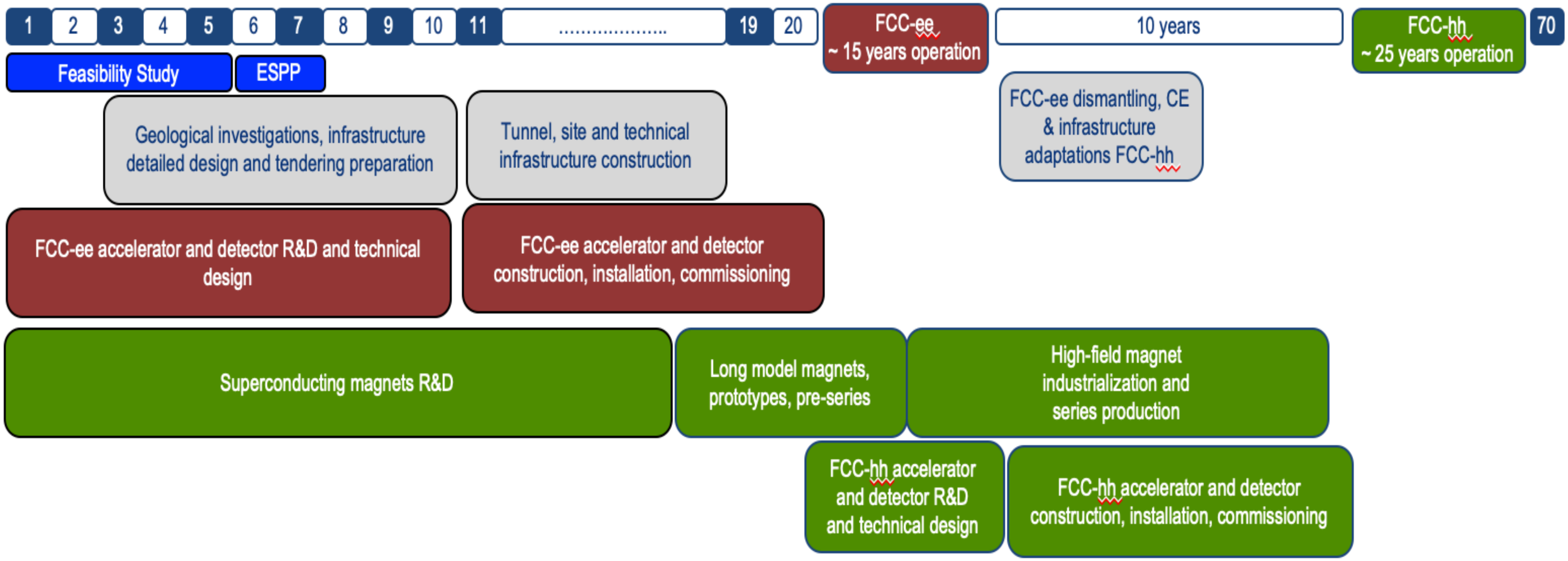
34 Countries

EC H2020

FCC Feasibility Study: 58 fully-signed previous members, 17 new members, MoU renewal of remaining CDR participants in progress

Timeline of FCC programme

- 2013 ESPPU requested FCC Conceptual Design four-volume report → 4 volumes delivered in 2018/19
  - describing the physics cases, the design of the lepton and hadron colliders, and the underpinning technologies and infrastructures
- 2021 Launch of FCC Feasibility Study (FCC FS) by CERN Council: 2021-2025
  - including tunnel construction, financing, and environment etc. key aspects
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++



FCC outlook

Comprehensive R&D program and implementation preparation
EU co-financed FCC Innovation Study, the Swiss CHART program, and the CERN High-Field Magnet Programme.
Goal: demonstrate FCC feasibility by 2025/26

The first stage of FCC could be approved within a few years after the 2027 European Strategy Update
Tunnel construction could then start in the early 2030s
FCC-ee physics program begin in the second half of the 2040s.

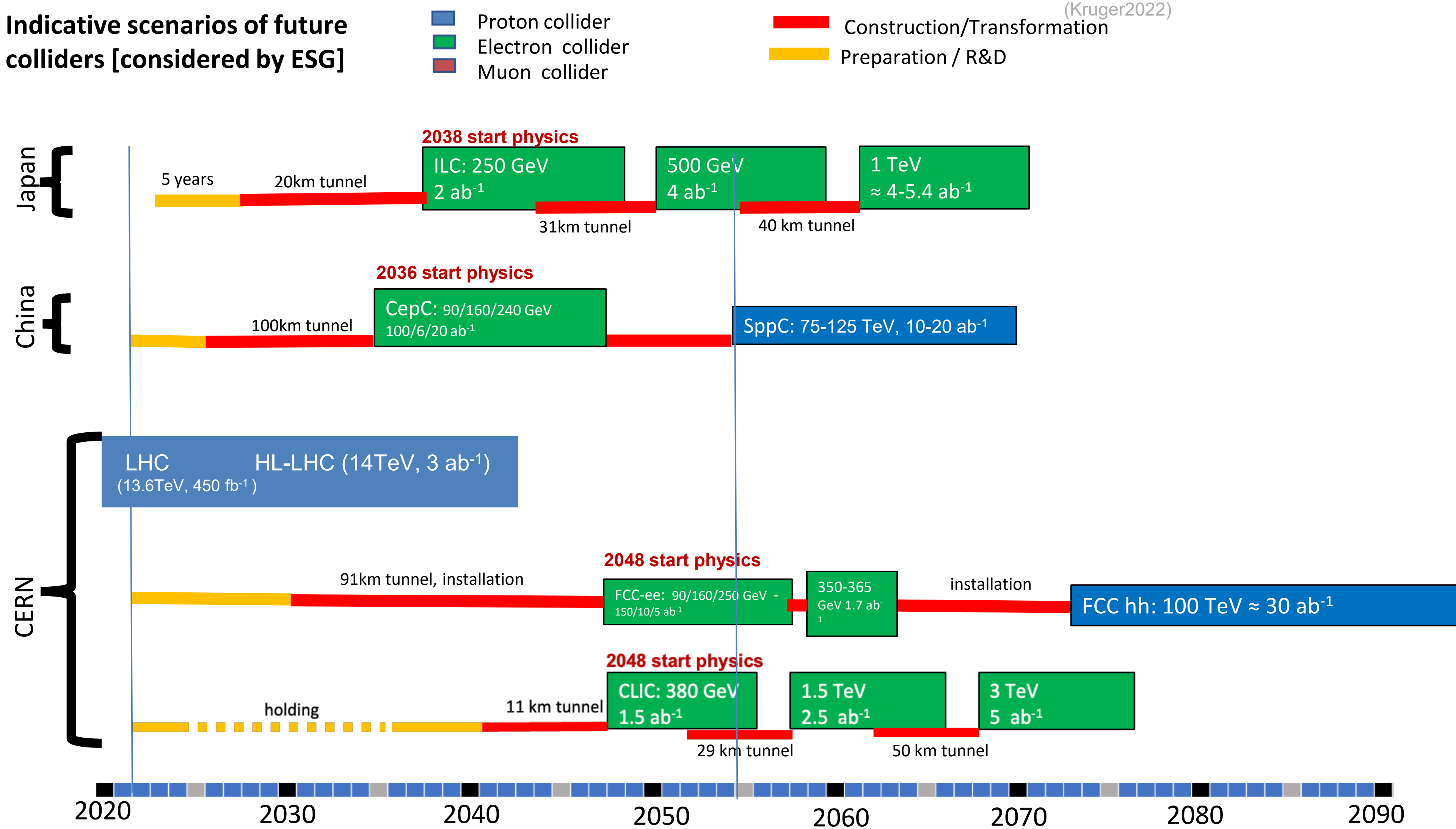
Long term goal: **world-leading HEP infrastructure for 21st century** to push particle-physics **precision and energy frontiers** far beyond present limits

Plenty of opportunities for collaborations (incl. DAFNE, EIC, SuperKEKB/Belle II,…) and for **joint innovative developments** with int'l partners !

Summary

Original from ESG by UB
Updated July 25, 2022 by M.Narain (Snowmass summary),
Modified CEPC Dec. 7th by J. Wang (Kruger2022)

Indicative scenarios of future colliders [considered by ESG]

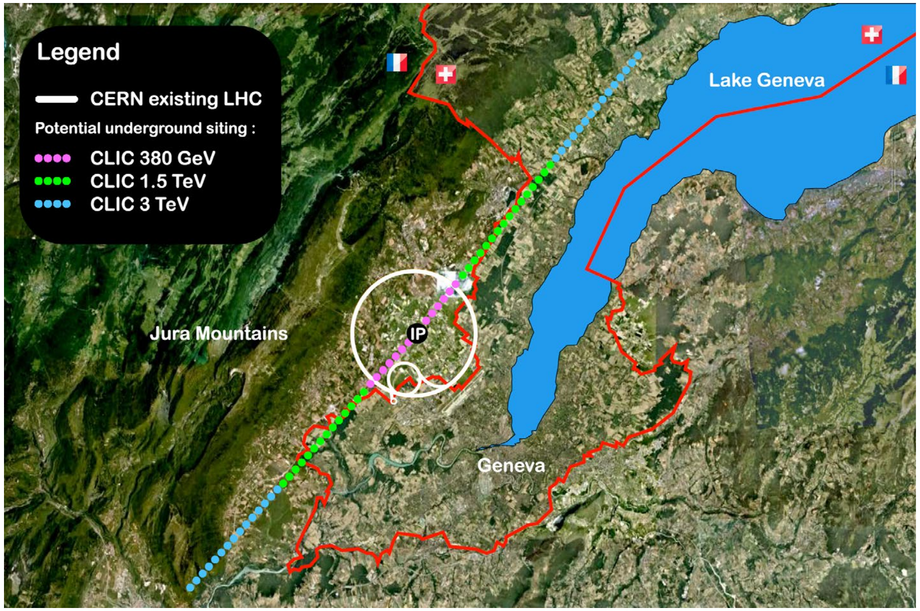


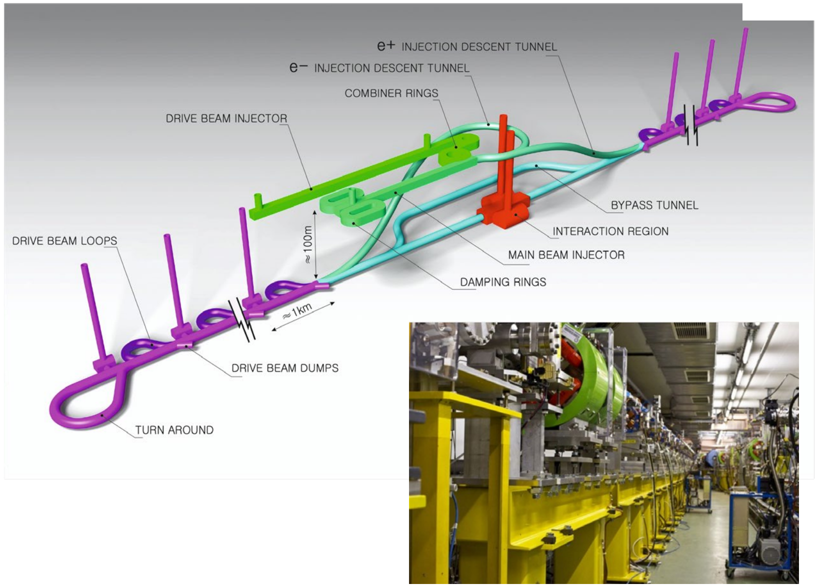
Summary

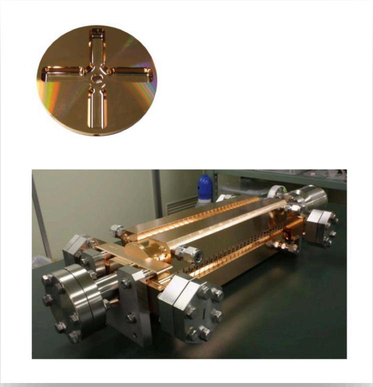
- Future colliders are discovery machines
  - Precision measurements of Higgs, W/Z and top pave paths to BSM
- Development of future collider projects well underway
  - Key accelerator technologies R&D continues and many are put to prototyping
  - Several R&D detector projects reaching a successful conclusion
  - Detailed studies on the site selection, construction and costs
- Roadmaps indicate first operation of future collider as early as 2036.

Back up

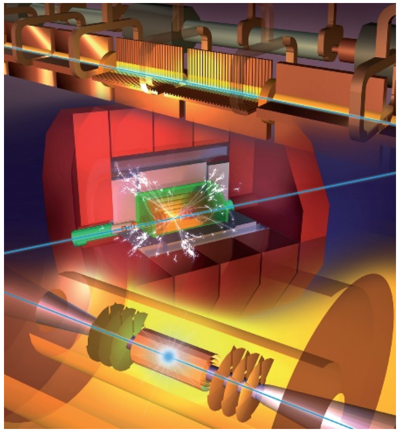
Compact Linear Collider in Europe (CLIC)







Accelerator Structure
12 GHz (L~25 cm)



detector

Compact Linear Collider in Europe (CLIC)

The Compact Linear Collider (CLIC)

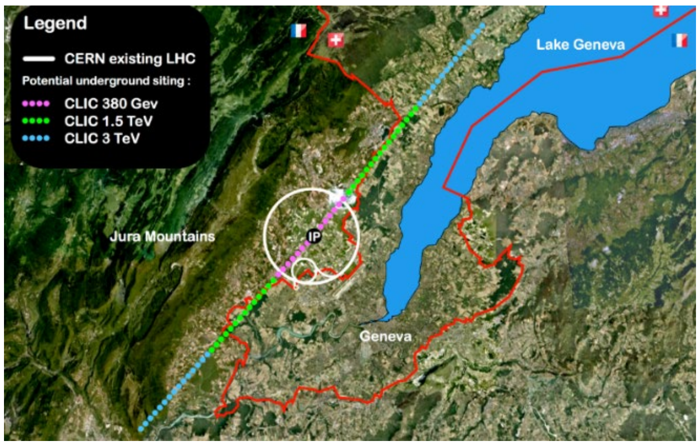
- **Timeline:** at CERN (~2035 Technical Schedule)
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 cavities at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged program with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

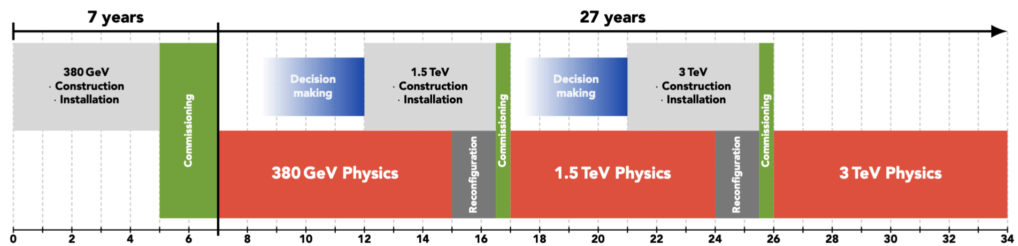
- CDR in 2012. Updated project overview documents in 2018 (Project Implementation Plan).

- **Cost:** 5.9 BCHF for 380 GeV (stable wrt 2012)
- **Power:** 168 MW at 380 GeV (reduced wrt 2012), some further reductions possible

- Comprehensive **Detector and Physics** studies

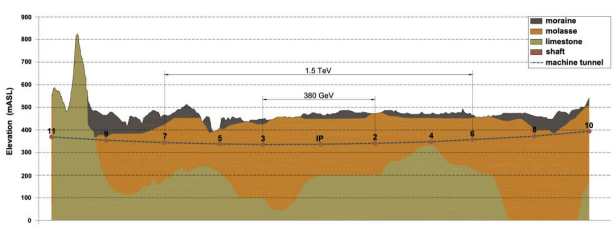
CLIC CE, stages and schedules





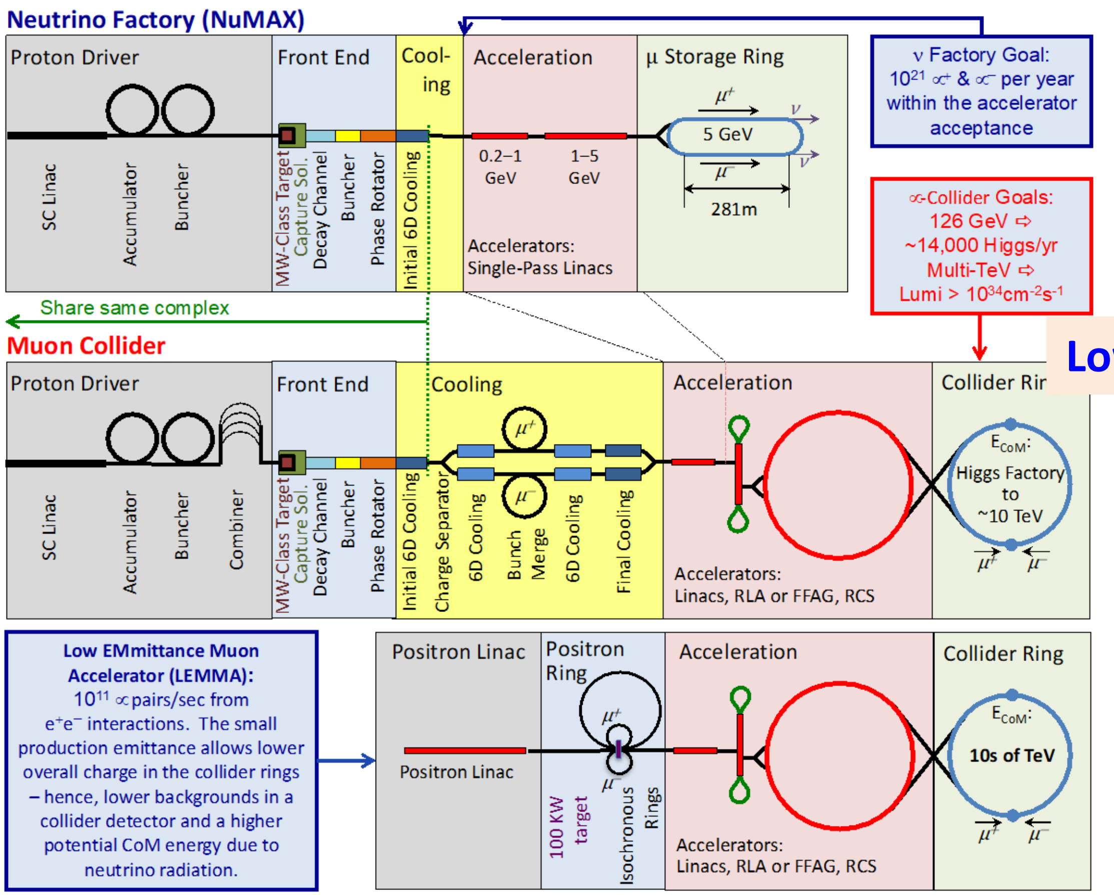
Technology Driven Schedule from start of construction shown above.

A preparation phase of ~5 years is needed before (estimated resource need for this phase is ~4% of overall project costs)



Muon Collider (CERN)

New technology, to be fully developed



Muon collider based on proton driver

Broad Applications:

- Neutrino Factories
- Colliders from ~100 GeV to 10s of TeV scale
- Secondary Beams

Low radiation loss, high energy 10s TeV

- Proton-driver with ionization cooling
- Positron-driver with low emittance

Muon Accelerator Design Status

- Full conceptual designs for NFs
- Key feasibility tests from MAP/MICE completed successfully!
- Now ready for a more detailed collider conceptual design study

High level of complexity
Need CDR and technology development
Long way to go

CLIC Physics Program

- **3 steps**: 380 GeV (updated from 350 GeV for ttbar coupling measurement), 1.5 TeV, 3.0 TeV.
- **Physics**
  - **380 GeV run** : Higgs measurement, top mass scan, top coupling measurement.
    The precisions of Higgs parameters are 1-5% and can reach 1% or better combining 1.5/3 TeV runs
    Top mass measurement can reach tens of MeV
  - **1.5,3 TeV runs** : Higgs self coupling, top-Yukawa coupling, search for BSM new physics.
    Di-Higgs (Heavy Higgs), ttH
    SUSY, Z', etc.

Muon Collider Physics Program

- Larger mass of the muon allows a smaller foot print and higher energies compared to e^+e^- counterparts, although suffering from major challenges of finite lifetime and cooling.
- Physics:
  - **Higgs factory at ~125 GeV** : line-shape scan of the Higgs boson, simultaneous measurement of the Higgs boson mass, width and muon Yakawa at unprecedented precision.
  - **High Energy runs up to 100 TeV to probe** :
    Top Yukawa coupling, Multi-Higgs, possible new physics contributed to Muon g-2
    Muon has a structure
    Vector boson machine
    WIMP dark matter