Study of giant resonances in storage ring experiments with EXL

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Thorsten Kröll for the EXL-E105 collaboration

- **EXL ... in a nutshell**
  Nuclear reactions in storage rings
- **Excitation of ISGMR in ^{58}Ni**
  ... proof of principle experiment
- **Outlook to opportunities at FAIR**

COMEX6

6th International Conference on Collective Motion in Nuclei under Extreme Conditions

October 29 - November 2, 2018, Cape Town, South Africa

EXL - nuclear reactions in storage rings

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EXotic nuclei studied in Light-ion induced reactions at storage rings

... within NUSTAR@FAIR

- **direct reactions of exotic beams in inverse kinematics**
- **internal target in storage ring ... set-up has to meet UHV conditions**
- **kinematically complete measurements**
- **large dynamic range and angular coverage**
- **(mainly) reactions at low momentum transfer**
  ... complementary to R^3B

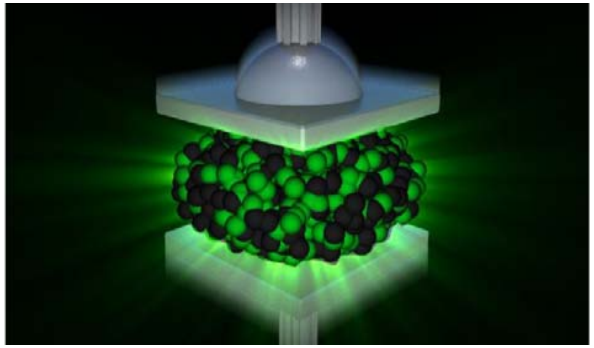
Physics menu

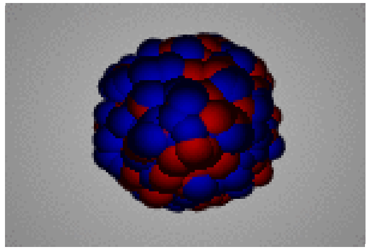
- **elastic and inelastic scattering**
  e.g. to study giant resonances
- **transfer, e.g (p,d), capture, e.g. (p,γ), and charge exchange reactions, e.g. (p,n), (^{3}He,t)**
- **knockout and quasi-free scattering**

IS giant monopole resonance

Incompressibility K of nuclear matter (EoS)

- K_∞ for infinite nuclear matter (bulk modulus K is more than 10^{22} times the value of steel!!!)
- $K_\infty \leftrightarrow K_A$ for finite nuclei of mass A (and Z) at density ρ around ρ_0
- K is no observable
  ... relation to energy of ISMGR $E^2_{ISGMR} \propto K_A/\langle r^2\rangle$
  ISGMR ("breathing mode")
- isoscalar modes excited by inelastic scattering on isoscalar probes
- $\Delta L=0$ peaks at 0° in the CMS


Courtesy of THOMAS FLECHEL

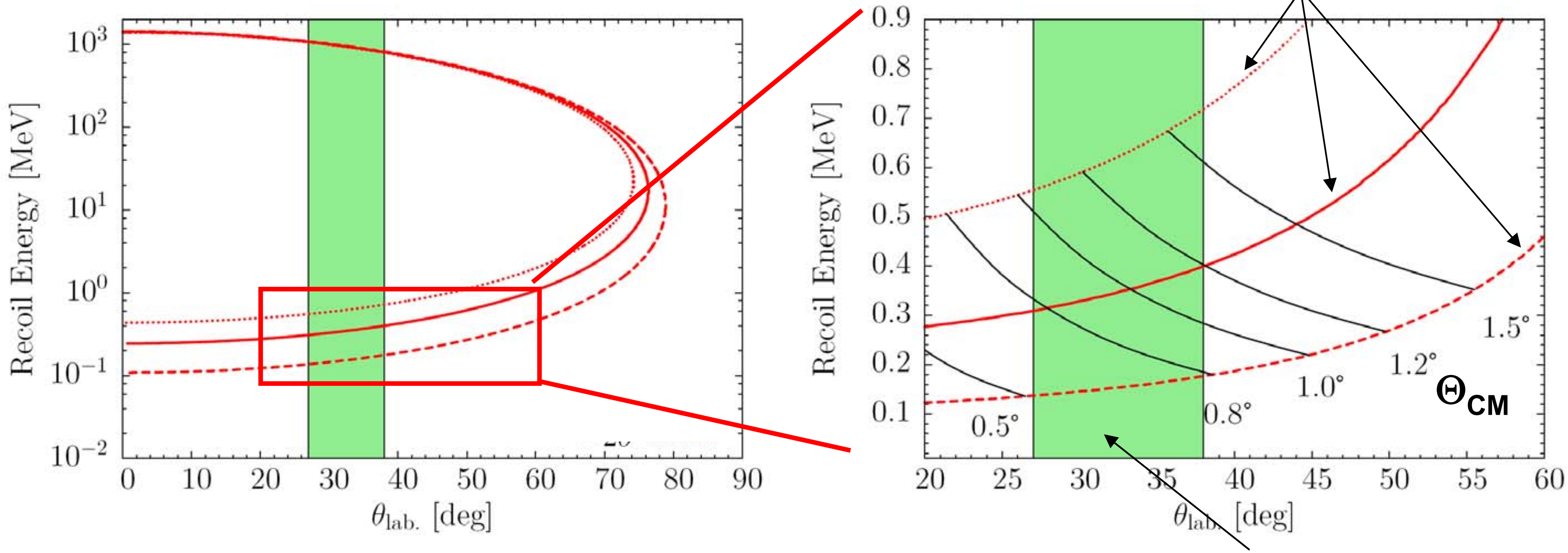

Animation by P. Adrich

M. N. Harakeh, A. van der Woude, Giant Resonances Fundamental High-Frequency Modes of Nuclear Excitation, Oxford University Press, New York, 2001.
U. Garg, G. Colò, arXiv:1801.03672v2

Lecture in inverse kinematics

$^{58}Ni(\alpha,\alpha')$ @ 100 MeV/u

E_x= 19 MeV ± 7 MeV



Energies of recoiling alphas are only several 100 keV

NO thick targets
NO gas targets with windows
NO detectors with windows

Region covered by DSSD2 of EXL demonstrator

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Storage ring ESR at GSI

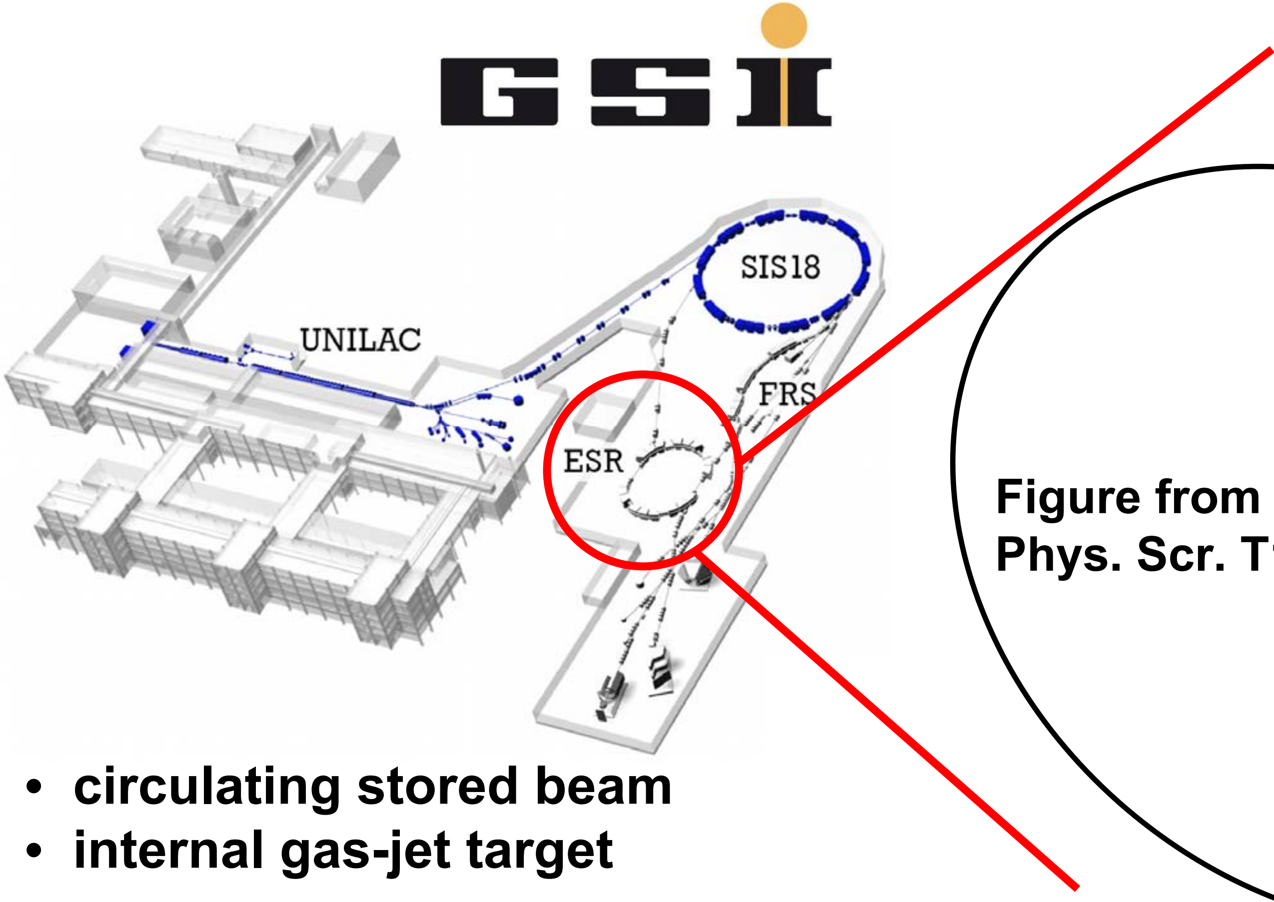

Figure from
Phys. Scr. T156 (2013) 014016

- circulating stored beam
- internal gas-jet target

Rate = cross section x luminosity
"Luminosity" = #beam particles x #target particles x revolution frequency

Storage ring ESR at GSI

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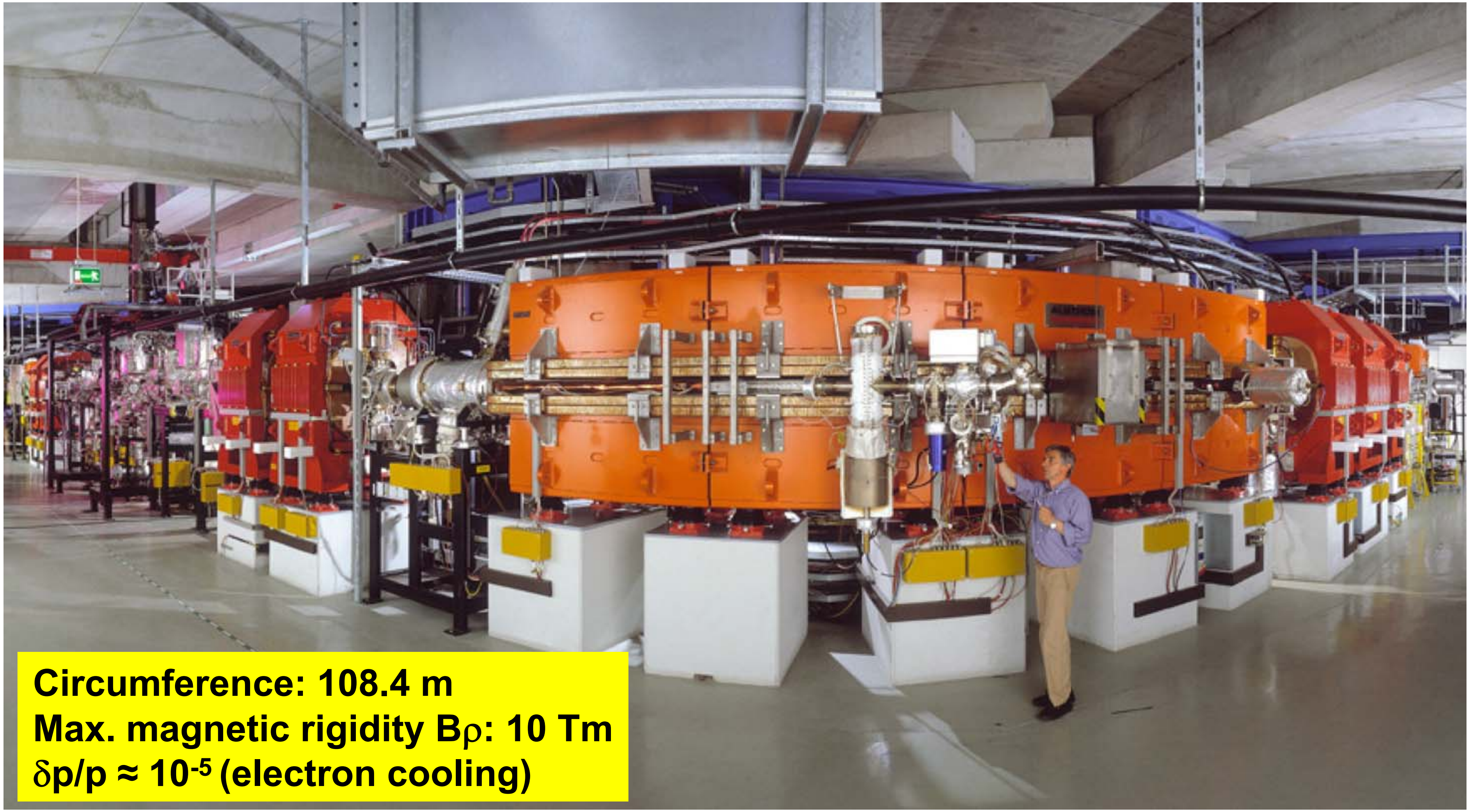

Circumference: 108.4 m
Max. magnetic rigidity Bρ: 10 Tm
$\delta p/p \approx 10^{-5}$ (electron cooling)

First EXL experimental campaign at ESR

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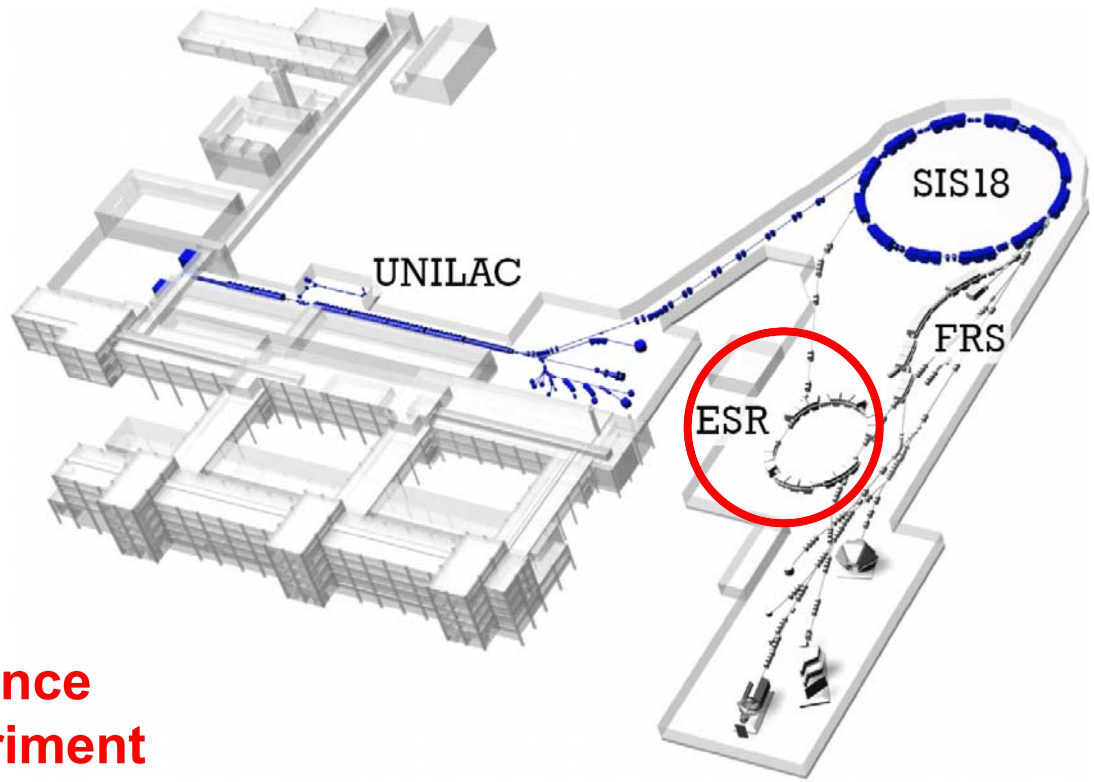
<u>**Commissioning and first physics programme**</u>

^{20}Ne (50 MeV/u)
➔ elastic scattering, (p,d) transfer reaction

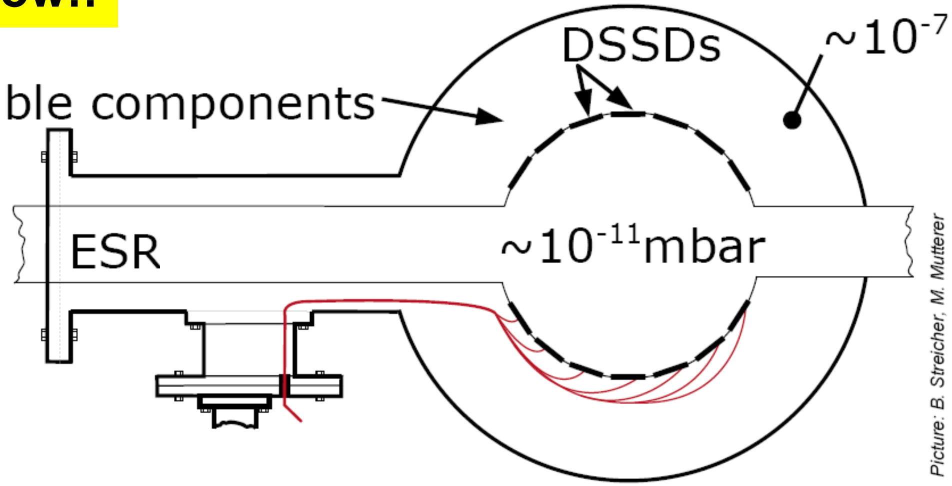
^{58}Ni (100 and 150 MeV/u)
➔ (in)elastic α-scattering
➔ IS giant monopole resonance ... proof of principle experiment

^{56}Ni and ^{58}Ni (390 MeV/u)
➔ elastic proton scattering
➔ matter radius

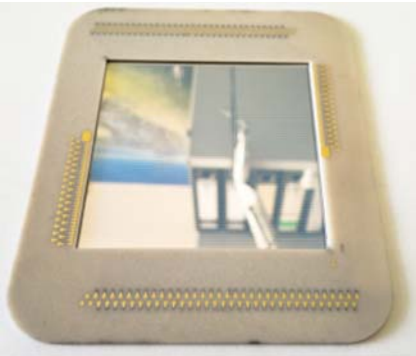


DSSSD as active window

Our solution:
DSSSD as active vacuum window!!



Standard PCB material is not bakeable ...



Our solution:
- **AlN ceramic board**
- **Removable spring pin connectors on backside (PEEK)**

B. Streicher et al., NIM A 654, 604 (2011)

DSSSD as active window

Figure 4

Does the DSSSD keep the UHV?

YES ☺

Figure 6

B. Streicher et al., NIM A 654, 604 (2011)

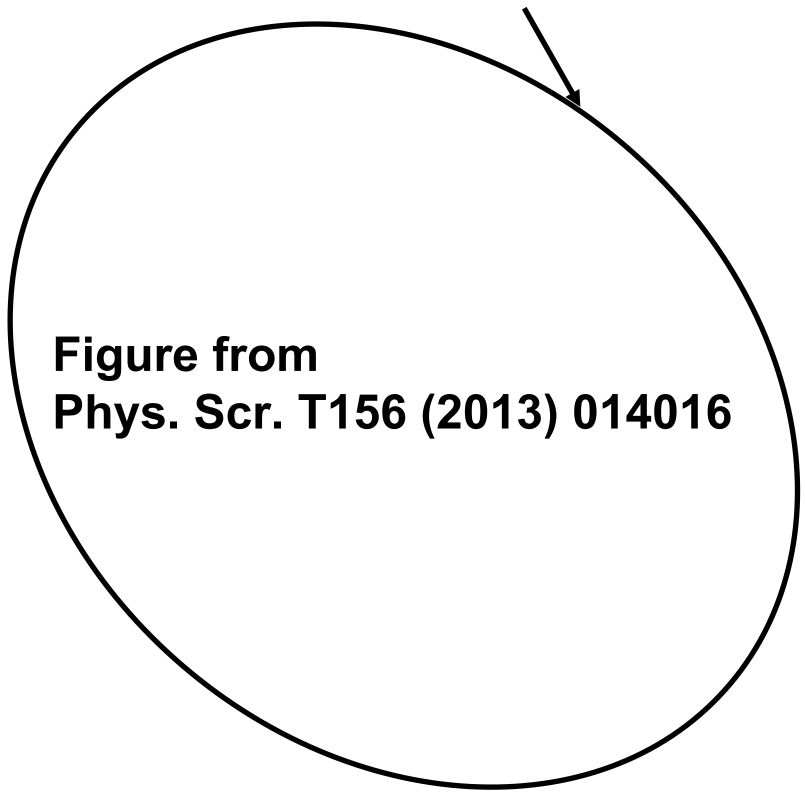
^{58}Ni experiment

Beam energy: 100 MeV/u
Beam intensity: ≈10^8 ions
Beam lifetime: ≈1.5 h
Target density: $7\cdot10^{12}$ part/cm^2
Revolution frequency: 1.2 MHz

Luminosity: 10^{25}-10^{26} cm^{-2} s^{-1}

Figure 1

J.C. Zamora et al., Phys. Lett. B 763, 16 (2016)

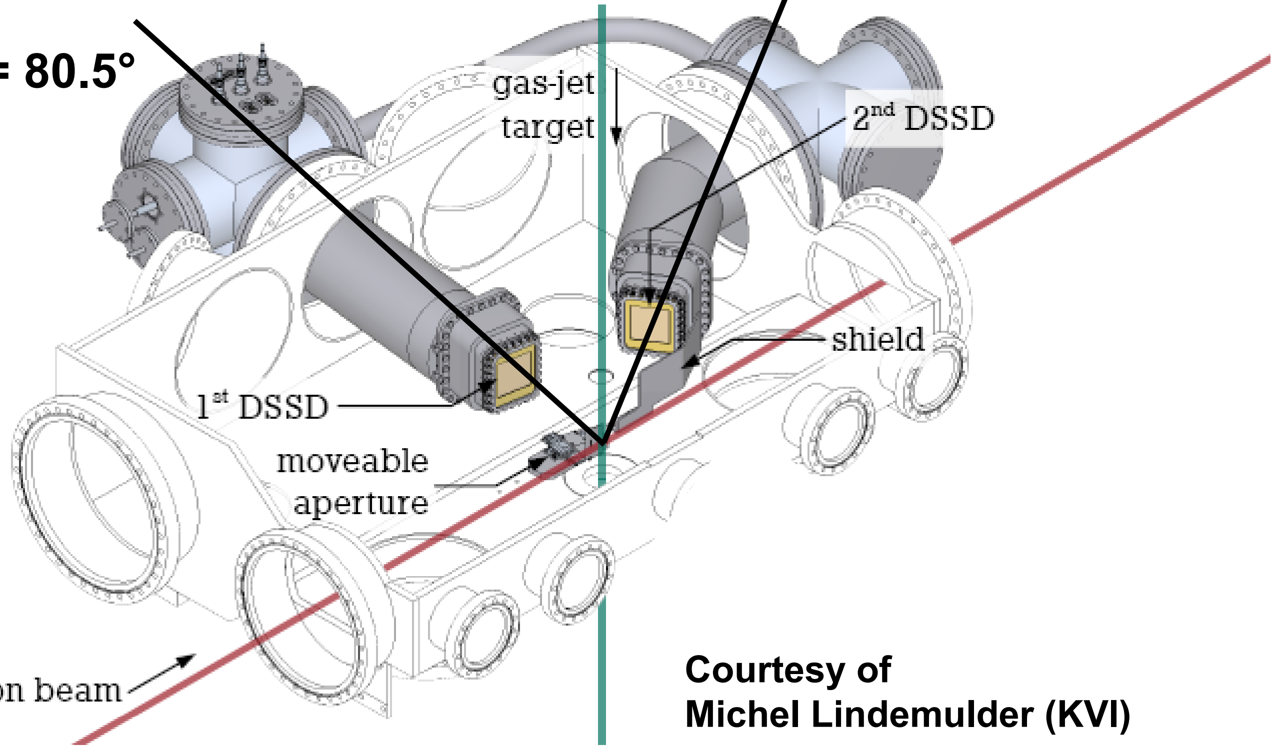


EXL demonstrator

2 detector modules

DSSD 2
mean θ_{Lab} = 32.5°

DSSD 1
mean θ_{Lab} = 80.5°



Courtesy of
Michel Lindemulder (KVI)

Experimental / simulated spectrum

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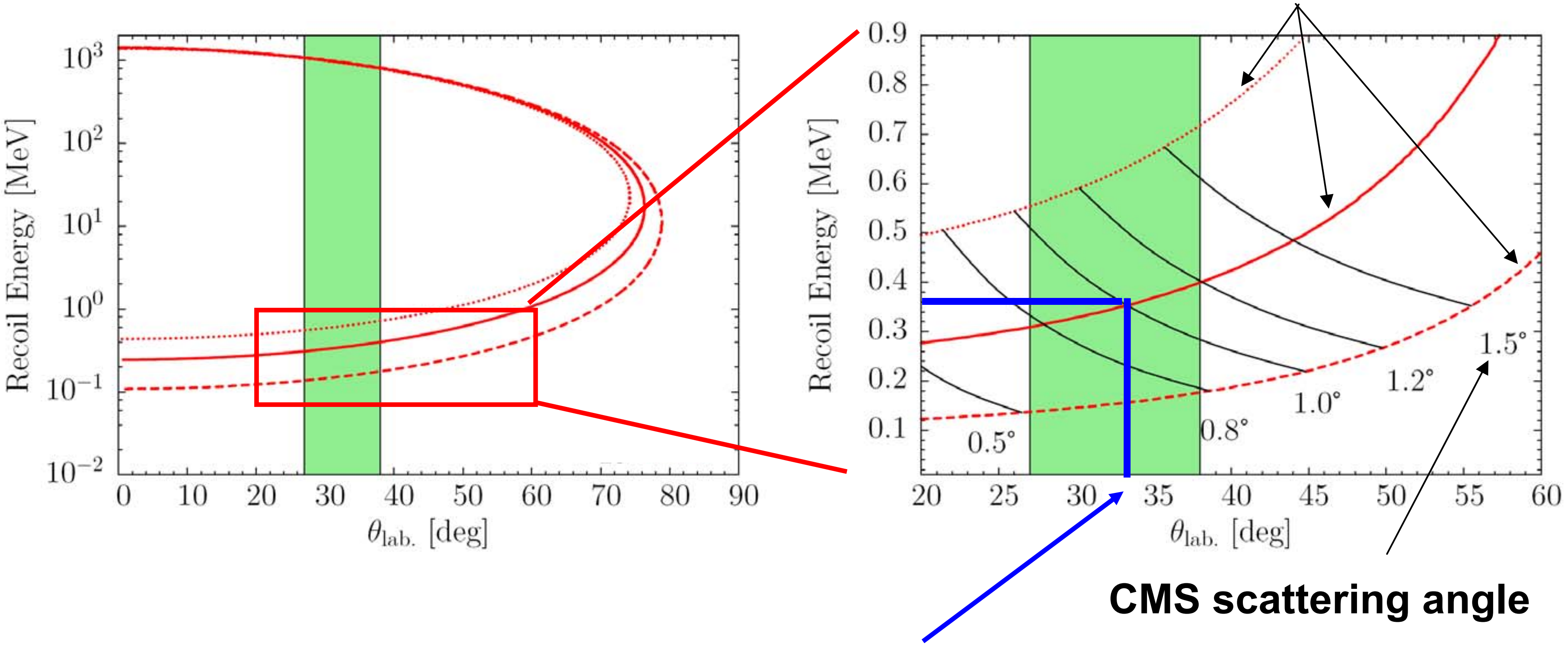
Figure 2

J.C. Zamora et al., Phys. Lett. B 763, 16 (2016)

Inverse kinematics

^{58}Ni(α,α') @ 100 MeV/u

E_x= 19 MeV ± 7 MeV



CMS scattering angle

- Reconstruction of CMS angle and excitation energy from lab angle and recoil energy for each event
- Acceptance corrections from simulations

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Differential cross section

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Figure 3

J.C. Zamora et al., Phys. Lett. B 763, 16 (2016)

Multipole decomposition

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Figure 4

Figure 6.12

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J.C. Zamora et al., Phys. Lett. B 763, 16 (2016)

ISGMR in ^{58}Ni

Figure 4

Reference	Centroid [MeV]	Width$_{RMS}$ [MeV]	EWSR [%]
this work	20.5(6)	4.6(6)	79^{+12}_{-11}
[9]	$19.20^{+0.44}_{-0.19}$	$4.89^{+1.05}_{-0.31}$	85^{+13}_{-10}
[32]	$20.30^{+1.69}_{-0.14}$	$4.25^{+0.69}_{-0.23}$	74^{+22}_{-12}
[26]	$19.9^{+0.7}_{-0.8}$	–	92^{+4}_{-3}

J.C. Zamora et al., Phys. Lett. B 763, 16 (2016)

Elastic α-scattering on ^{58}Ni

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Figure 2

Figure 3

Neutron skin thickness

$$\Delta r_{np} = 0.02(20)\ \mathrm{fm}\ (100\ \mathrm{MeV/u})$$

$$\Delta r_{np} = -0.07(17)\ \mathrm{fm}\ (150\ \mathrm{MeV/u})$$

Lit: -0.05 - 0.01 fm

J. C. Zamora et al., Phys. Rev. C 96, 034617 (2017)

Next step … ISGMR/ISQMR in ^{56}Ni

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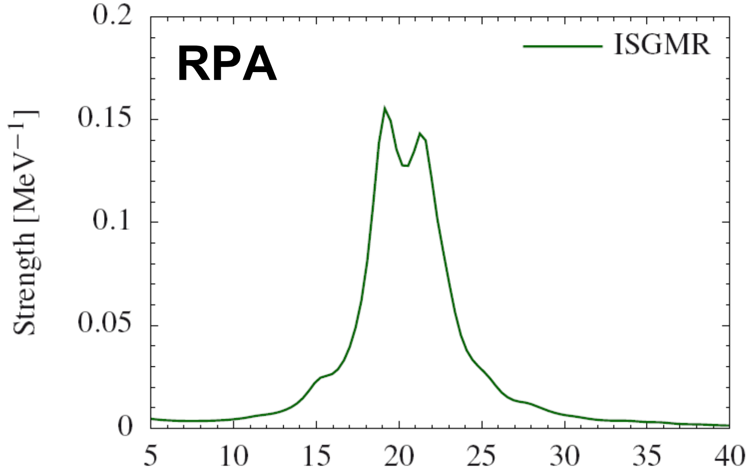

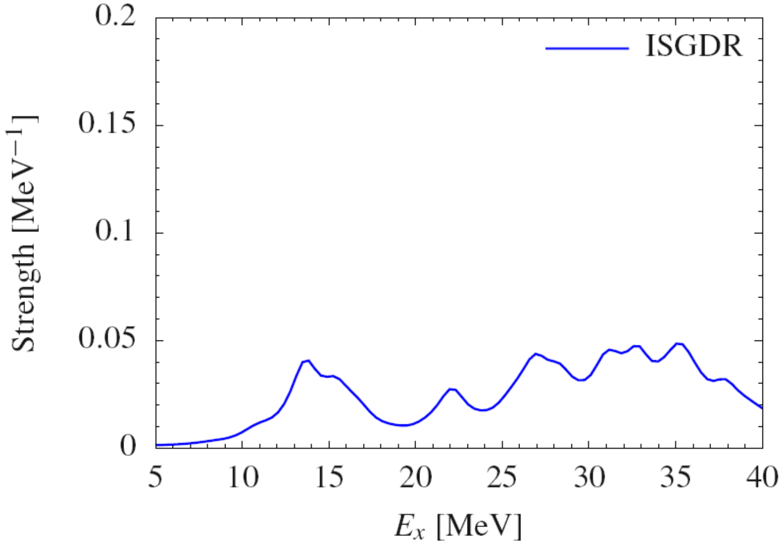

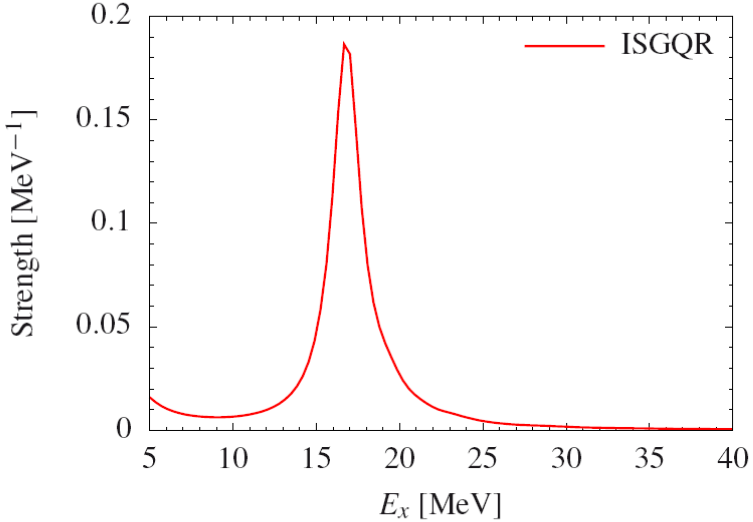

Courtesy of J.C. Zamora

$3 \cdot 10^6$ stored ^{56}Ni ions achieved
... factor 30 less compared to ^{58}Ni
... improvements on the target side are on the way
... larger solid angle covered by detectors

SKYRME_RPA code, SkO' interaction
G. Colò, et al., Comput. Phys. Commun. 184 (2013) 142.
P.-G. Reinhard, et al., Phys. Rev. C 60 (1999) 014316.

Designs for larger array

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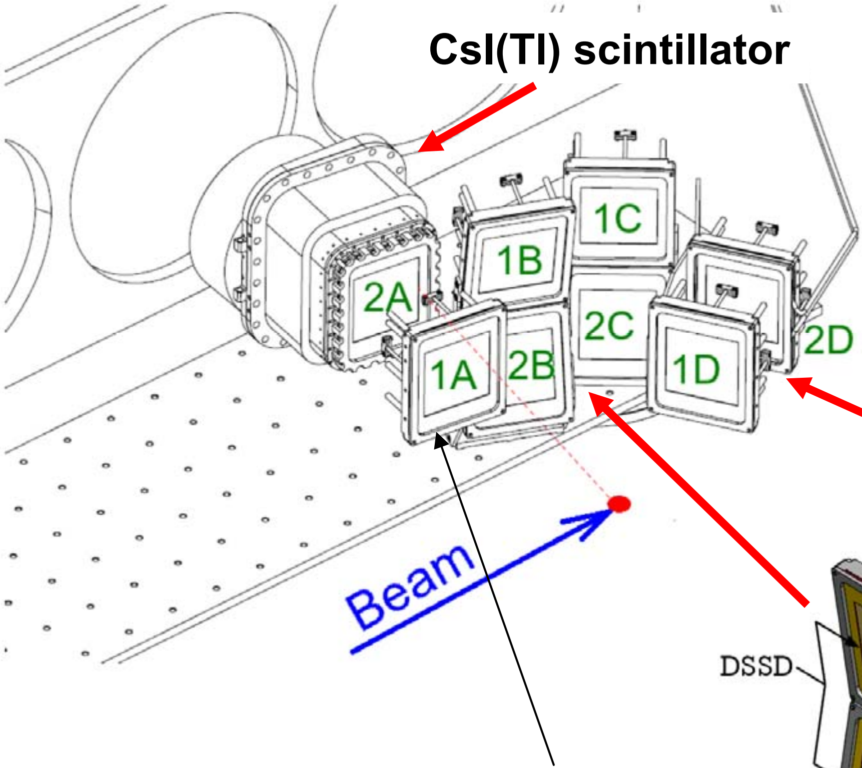
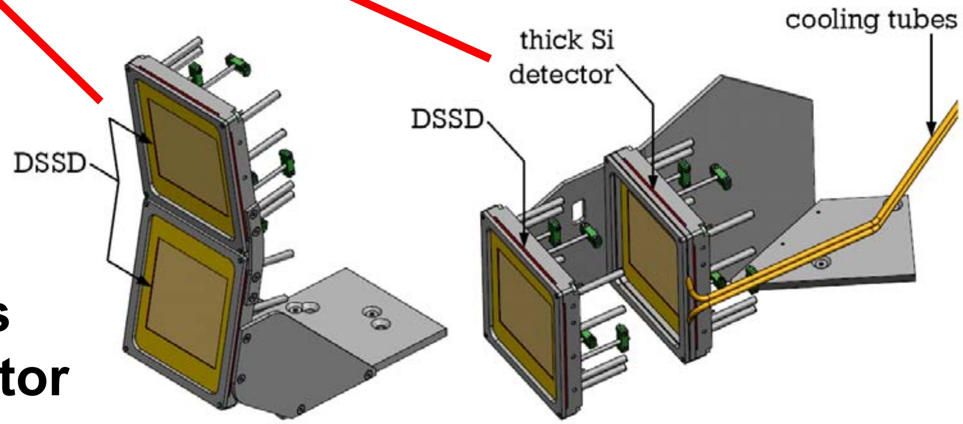
EXL will grow slowly ....

- **Compact ASIC readout for DSSSDs**



- **Detectors entirely in UHV(?)**



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- **Thin DSSSD as tracking detector**

… EXL at FAIR

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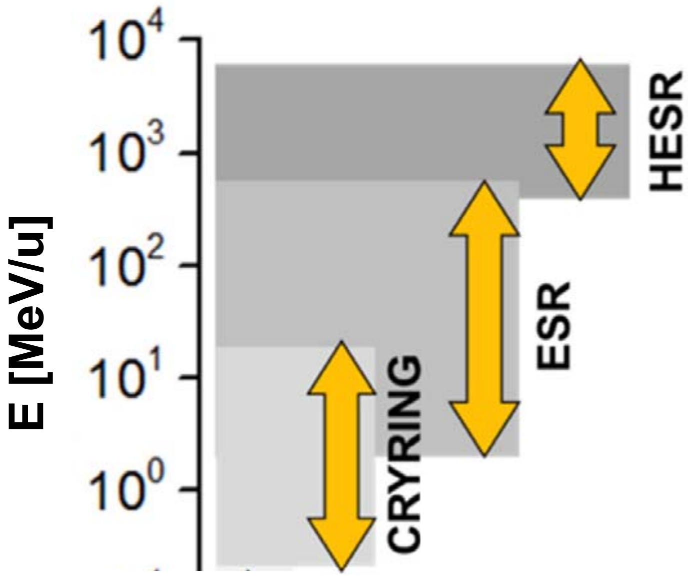
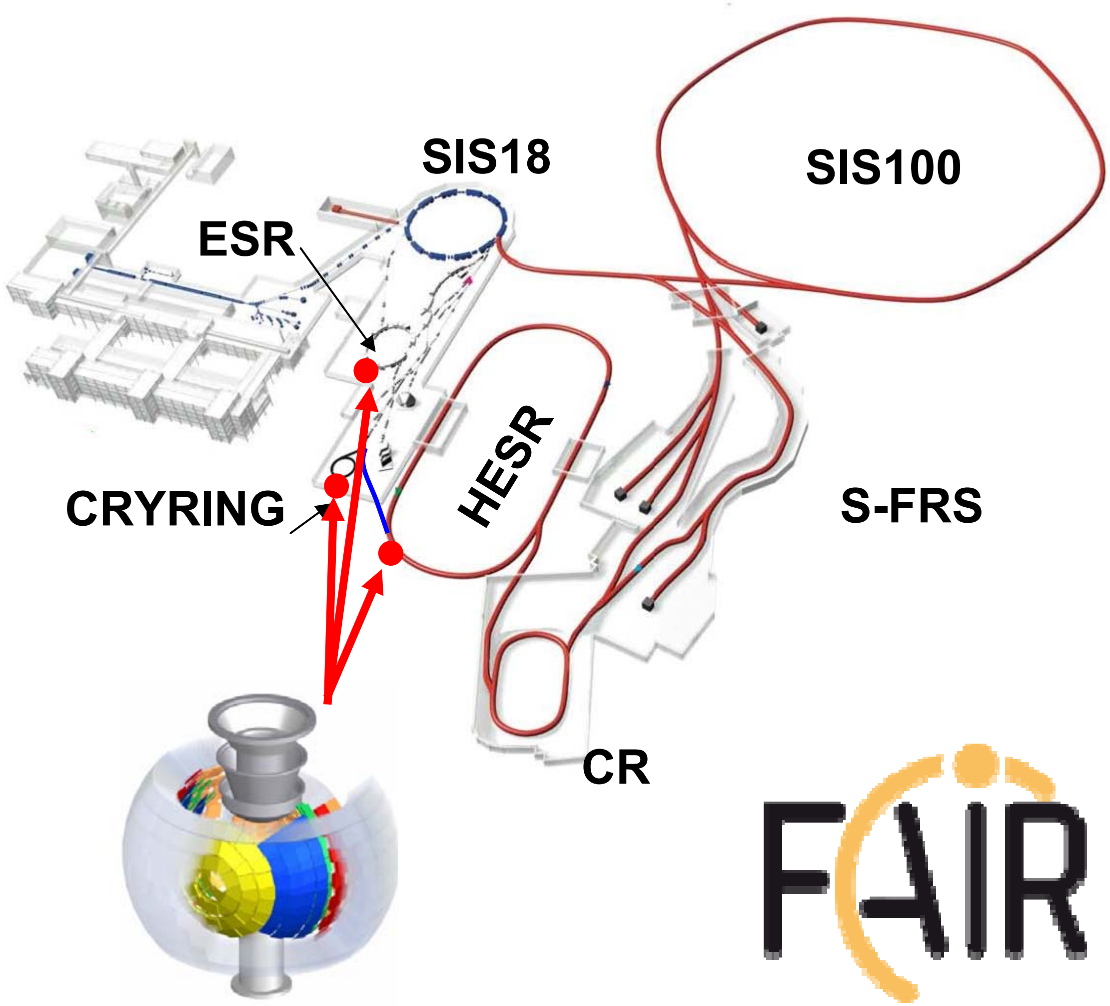
EXL is a versatile experimental set-up … can profit from different storage rings at FAIR



Courtesy of Yu. Litvinov



Summary

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EXL - EXotic nuclei studied in Light-ion induced reactions at storage rings

- First experimental campaign ... with **two detectors only**!
- Several key reaction mechanisms for the EXL physics programme have been successfully performed:

- ^{58}Ni(α,α') - isoscalar giant monopole resonance in ^{58}Ni
- ^{56}Ni(p,p) - first nuclear reaction experiment with a stored radioactive beam ever
  ➔ matter radius of ^{56}Ni measured for the first time
- ^{20}Ne(p,d) - nucleon transfer reaction

Looking forward to further experiments at GSI/FAIR
... ISGMR/ISGQR in ^{56}Ni at ESR
... much more to come at storage rings CRYRING, ESR and HESR at energies ranging from some MeV/u to 5 GeV/u

… acknowledgements

S. Bagchi[1], S. Bönig[2], M. Csatlós[3], I. Dillmann[4], C. Dimopoulou[4], P. Egelhof[4], V. Eremin[5], T. Furuno[6], H. Geissel[4], R. Gernhäuser[7], M. N. Harakeh[1], A.-L. Hartig[2], S. Ilieva[2], N. Kalantar-Nayestanaki[1], O. Kiselev[4], H. Kollmus[4], C. Kozhuharov[4], A. Krasznahorkay[3], T. Kröll[2], M. Kuilman[1], S. Litvinov[4], Yu. A. Litvinov[4], M. Mahjour-Shafiei[1,8], M. Mutterer[4], D. Nagae[9], M.A. Najafi[1], C. Nociforo[4], F. Nolden[4], U. Popp[4], C. Rigollet[1], S. Roy[1], C. Scheidenberger[4], M. von Schmid[2], M. Steck[4], B. Streicher[2,4], L. Stuhl[3], M. Takechi[4], M. Thürauf[2], T. Uesaka[10], H. Weick[4], J. S. Winfield[4], D. Winters[4], P. J. Woods[11], T. Yamaguchi[12], K. Yue[2,4,13], J.C. Zamora[2], J. Zenihiro[10], **T. Aumann[2,4]**

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Thank you for your attention!!!!