Nuclear reactions in storage rings

Thorsten Kröll

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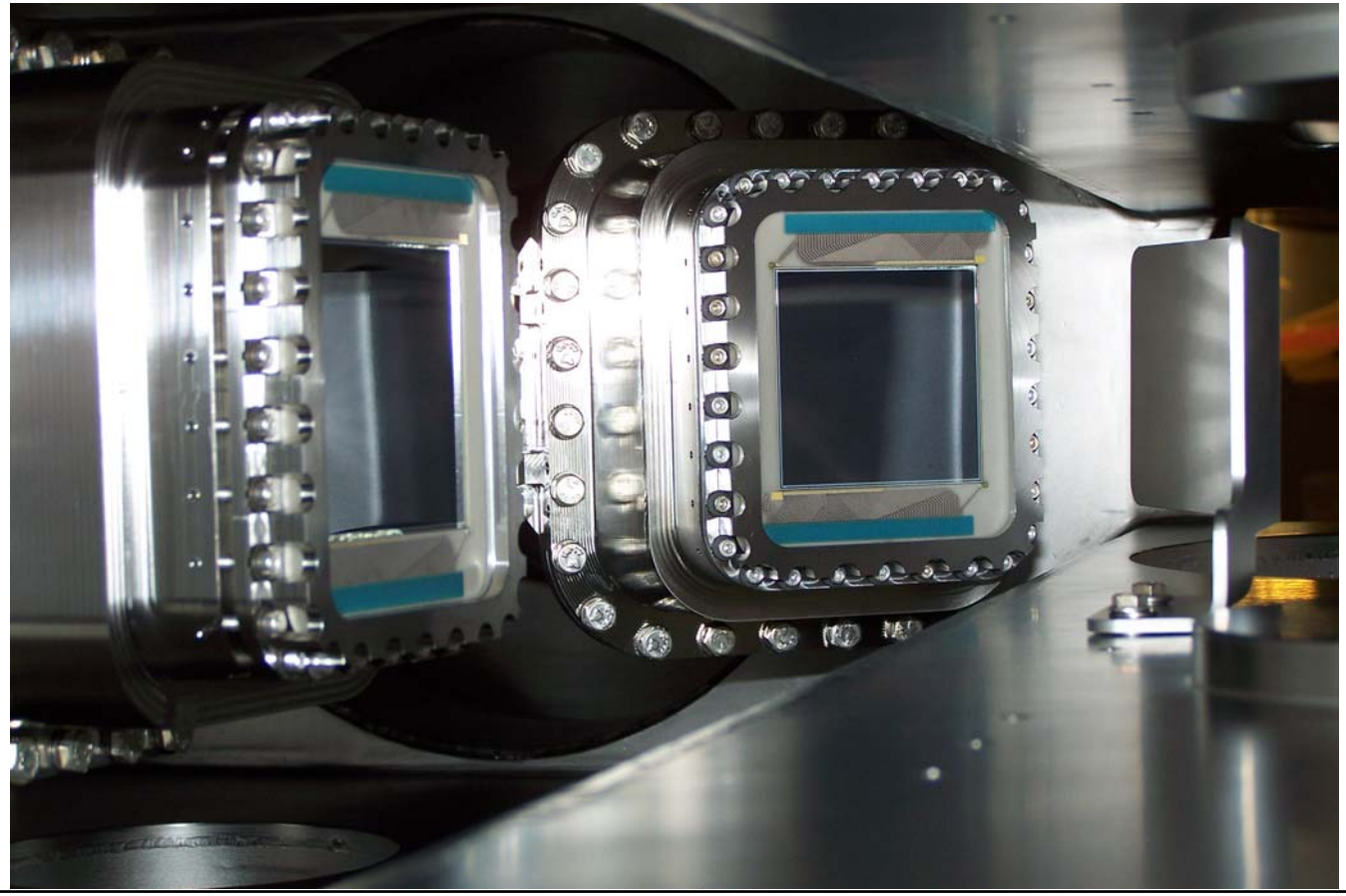

ISOLDE Seminar
12 October 2016
CERN

Menu

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- What's the size of the nucleus?
- Nuclear reactions in a storage ring

  EXL at GSI ... and FAIR (?)
  - the experimental concept
- Elastic proton scattering on ^{56}Ni in inverse kinematics

  ... first nuclear reaction of a stored radioactive ion beam with an internal target
- Isoscalar Giant Monopole Resonance in ^{58}Ni
- (p,d) transfer reaction
- TSR at HIE-ISOLDE (... ???)

What's the size of a nucleus?

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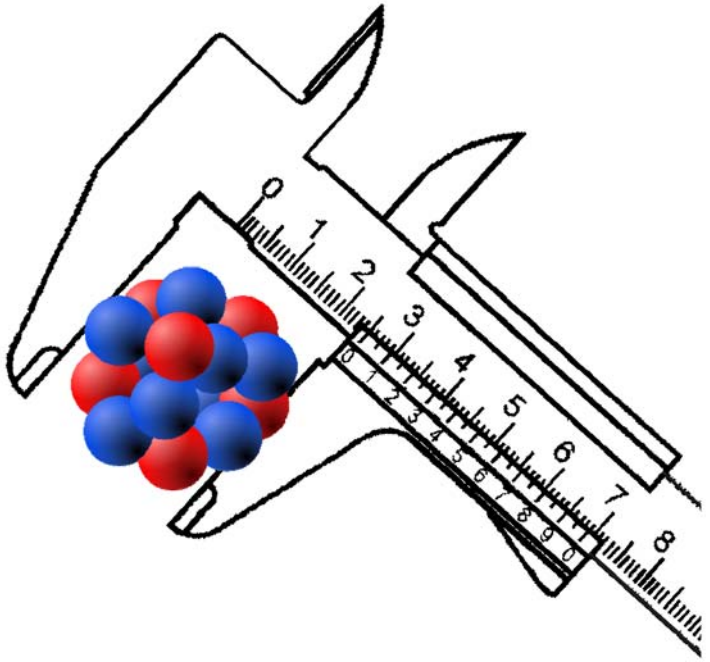
Charge radius

... electromagnetic probes ... well established, very precise, accurate(?)
- elastic electron scattering
- spectroscopy of electronic and muonic atoms

Matter radius (can be very different!!!)

... hadronic probes (strong interaction)
- elastic proton (or α) scattering
- reaction cross sections
- pionic, kaonic and anti-protonic atoms



Neutron radius

... electro(-weak) and hadronic probes
- π^0 photo production
- parity-violating electron scattering
- AIC (anti-proton ion collider) ... proposal for FAIR

What‘s the size of a nucleus?

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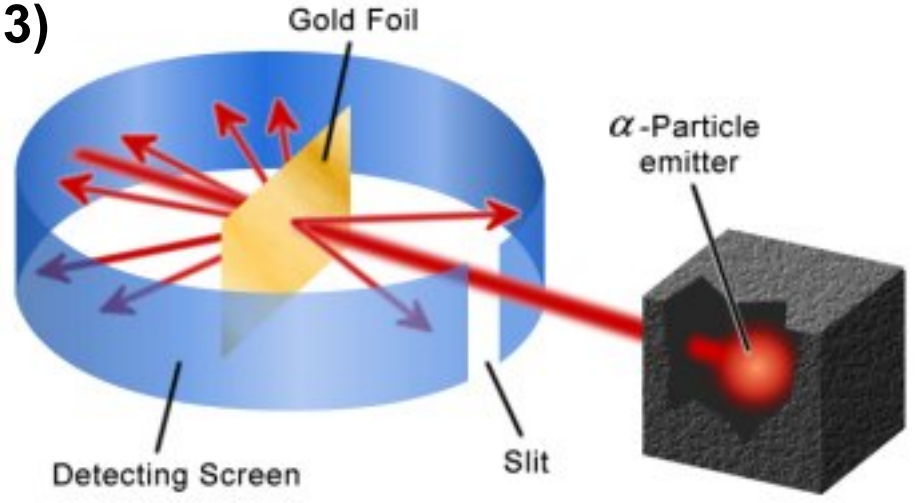
Rutherford’s experiment (1909-13)
... elastic α scattering on Au

The discovery of the nucleus
... but its actual size remained an open question!!!



Upper limit: $R_{Au} < 30$ fm

An α-particle in a direct collision with a gold atom of nuclear charge 79 will be turned back in its path at a distance of 3×10^{-12} cm, indicating that the nucleus may be regarded as a point charge even for such a short distance.

E. Rutherford, Bakerian Lecture (1920)

What‘s the size of a nucleus?

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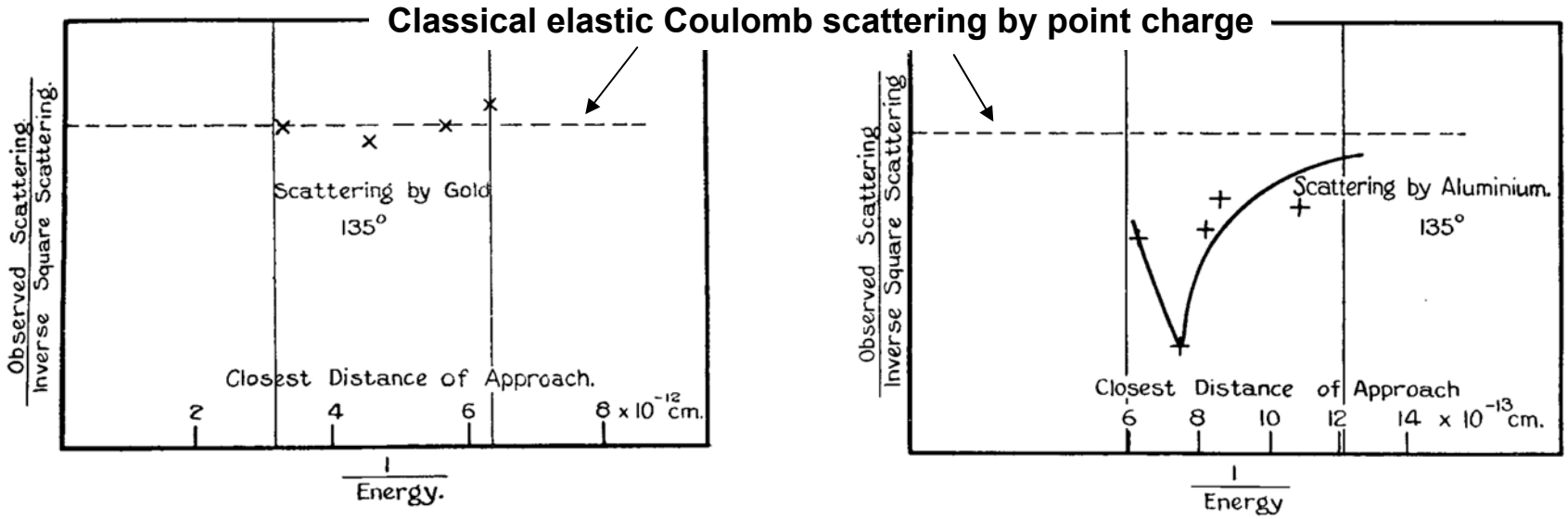
... from 1919 onwards:



E. Rutherford, J. Chadwick, Phil. Mag. 6, Vol. 50, 299 (1925)

- new “strong interaction” sets in for α scattering on Al at small distances
  ... may be responsible for the binding of nuclei too (Chadwick 1921)
- radius of Al (and other light elements) in the order of a few fm
- onset of nuclear reactions at short distances
  ... allows for study of the internal structure of nuclei

Why are such studies still interesting?

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The size is a fundamental property of the nucleus

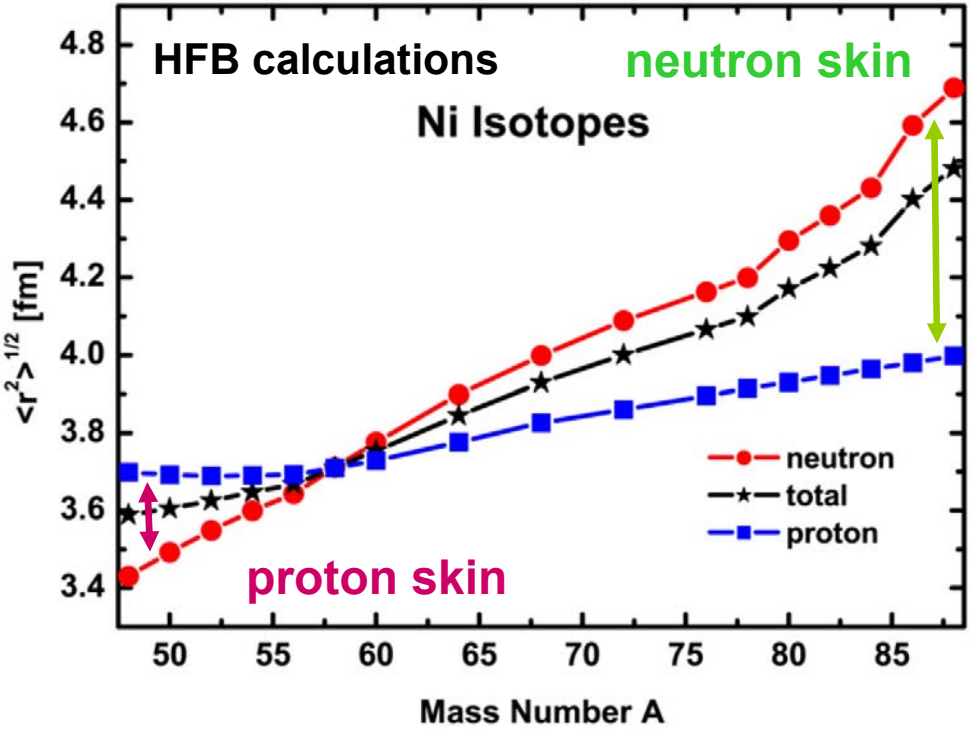
Close relation to nuclear structure

Neutron skin

(difference between the neutron and proton radii)

Related to dipole polarizability of a nucleus and the symmetry energy in the equation of state for nuclear matter

P.-G. Reinhard and W. Nazarewicz, PRC 81, 051303(R) (2010)



H. Lenske, P. Kienle, PLB B 647, 42 (2007)

EXL - nuclear reactions in storage rings

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

- 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
- transfer, capture, e.g. (p,γ), and
  charge exchange reactions, e.g. (p,n), (^{3}He,t)
- knockout and quasi-free scattering

Experimental campaign 2012 at ESR

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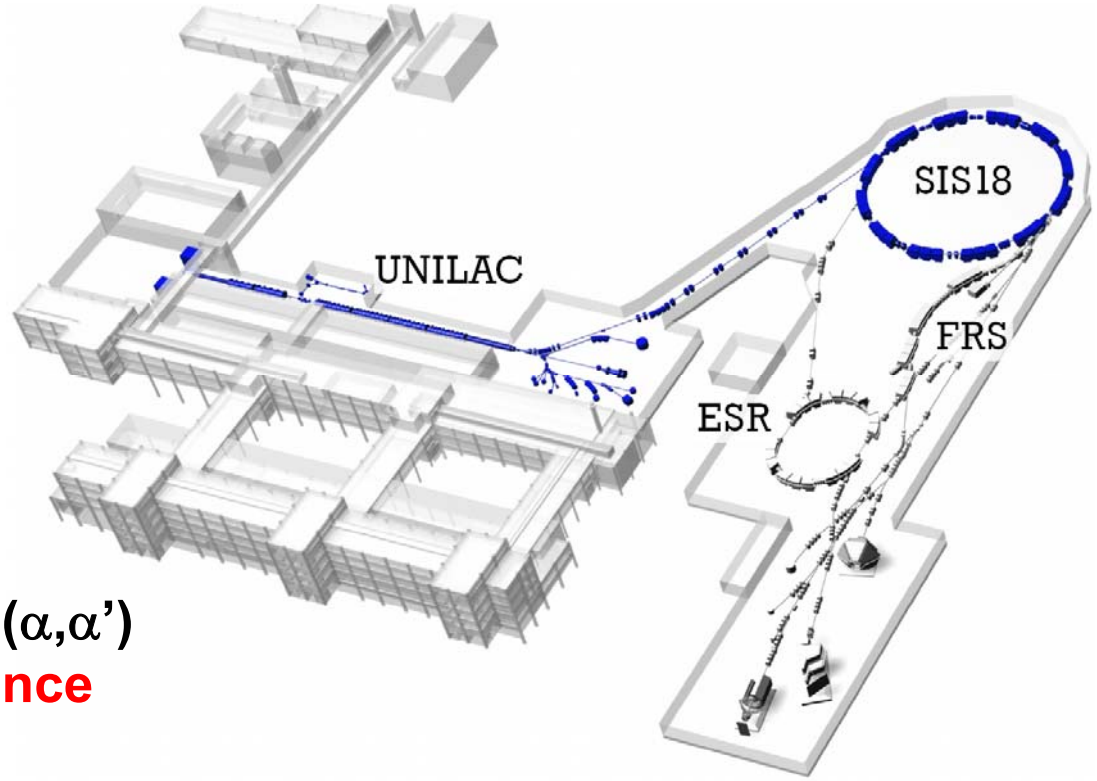
Commissioning and first physics programme



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

^{58}Ni (100 and 150 MeV/u)
➔ **inelastic α-scattering, i.e. (α,α')**
➔ **IS giant monopole resonance**

^{56}Ni and ^{58}Ni (390 MeV/u)
➔ **elastic proton scattering, i.e. (p,p)**
➔ **matter distribution / matter radius**

Storage ring ESR at GSI

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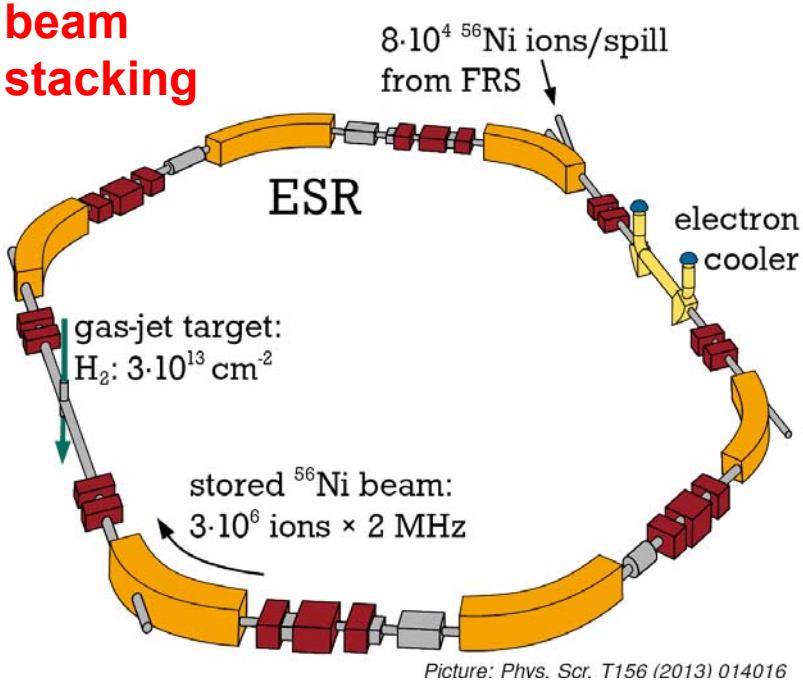
Nolden F et al. 2013 *Proceedings of IPAC2013* 91

beam stacking



Picture: Phys. Scr. T156 (2013) 014016

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

- **beam energy 400 MeV/u**
- beam life-time $\approx$ 1.5 h
- particles stored $\approx 3 \cdot 10^6$
- target density $\approx 3 \cdot 10^{13}$ cm^{-2}
- revolution frequency $\approx$ 2 MHz
- **luminosity of** $\approx 2 \cdot 10^{26}$ **$\frac{\text{particles}}{\text{s cm}^2}$**

Experimental requirements

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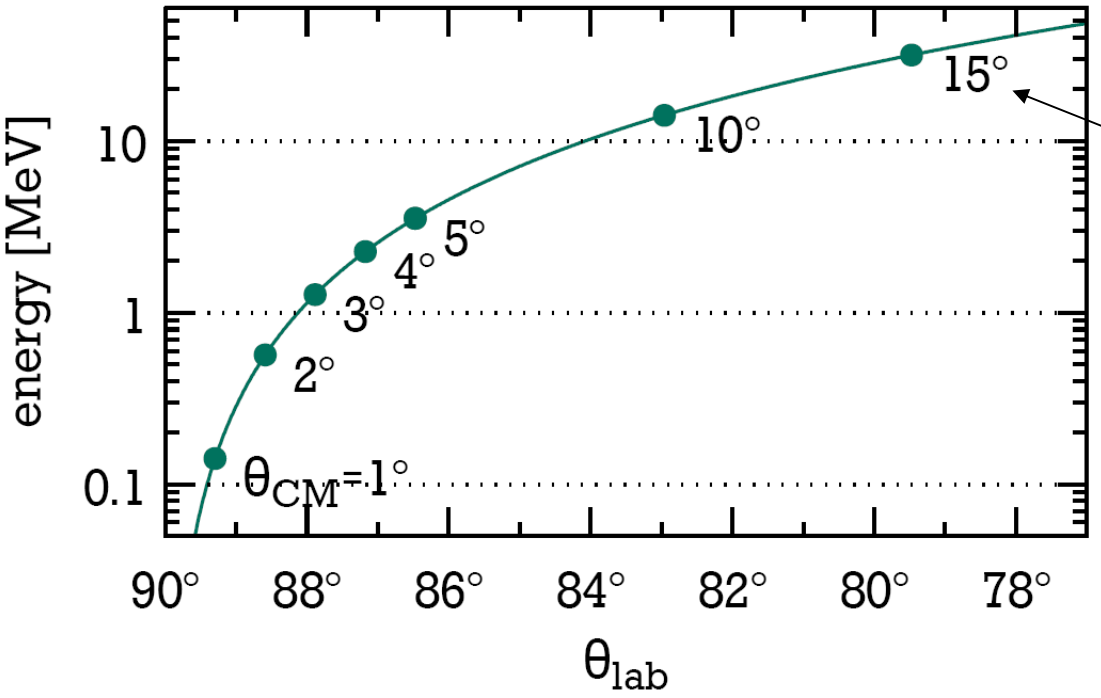
Proton scattering in inverse kinematics: ^{56}Ni(p,p) @ 390 MeV/u



CMS scattering angle

Very low recoil energies of protons around 90° in the lab system
- thin gas target
- windowless detectors (inside of the UHV of the ring)

UHV compatible DSSSD

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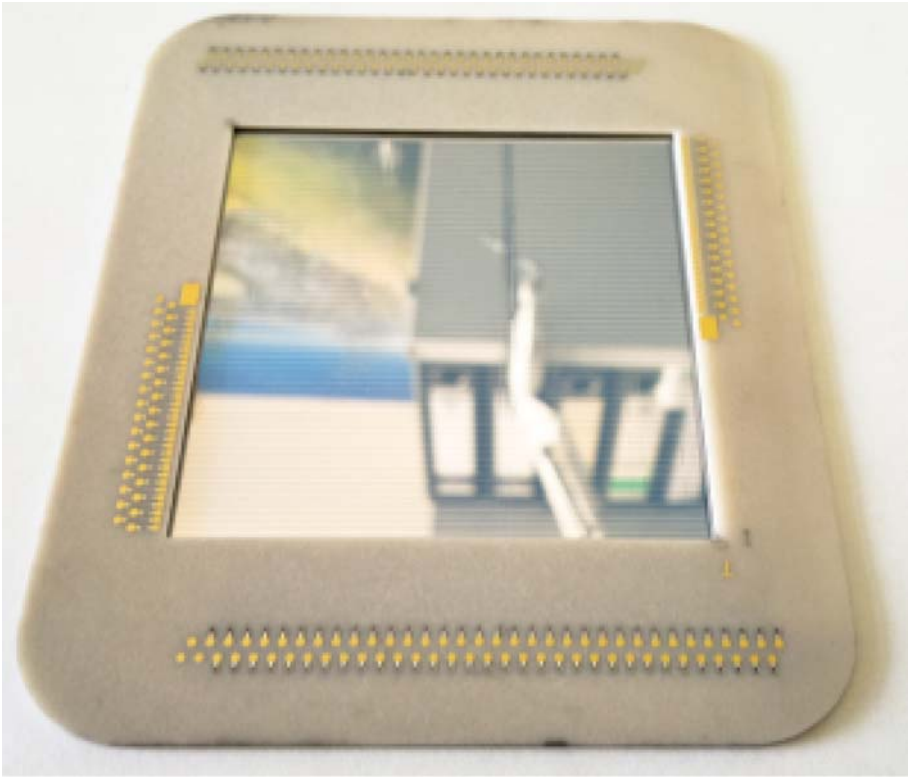
Standard PCB material is not bakeable ...

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



LUST HYBRID-TECHNIK

DSSSD as active window

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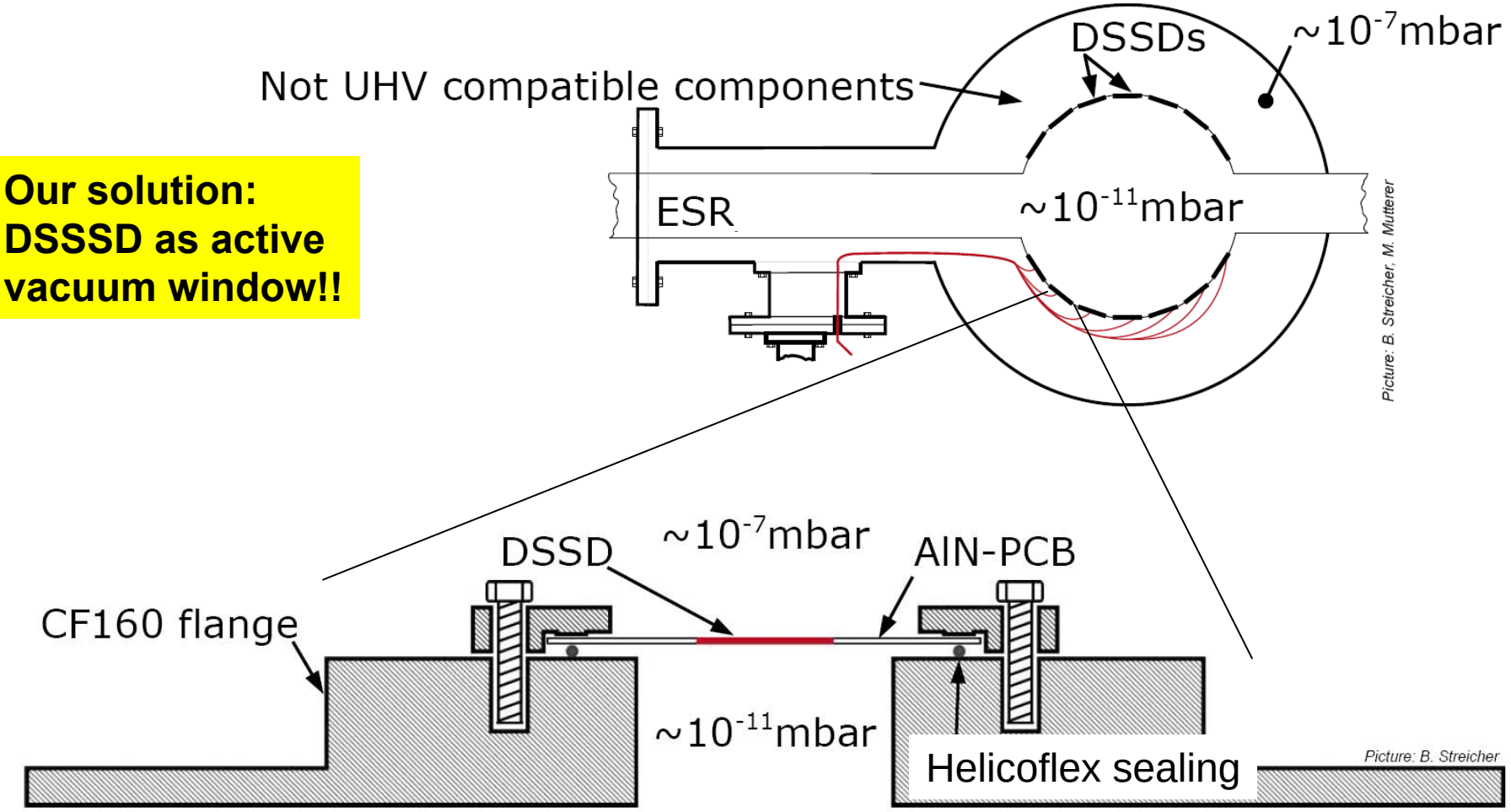
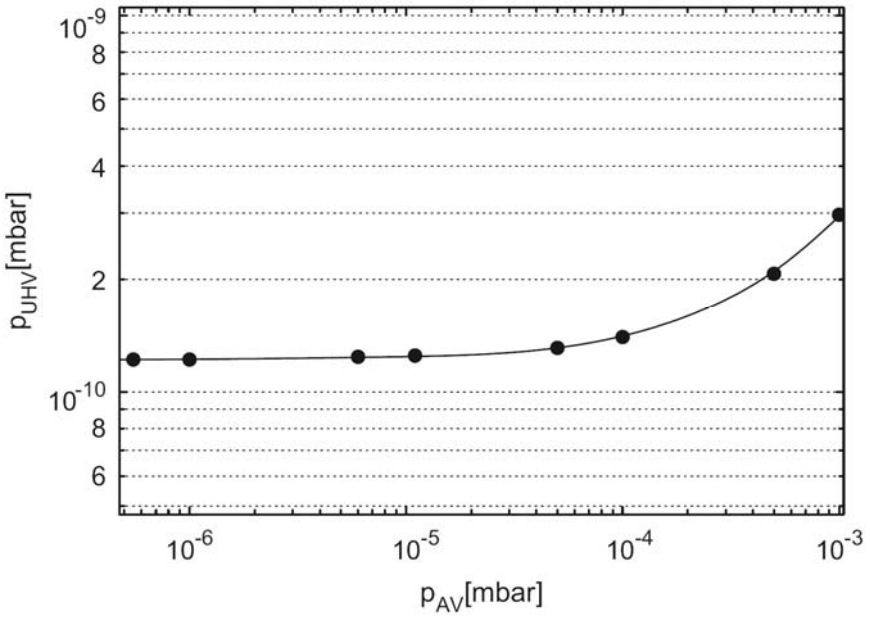
Our solution: DSSSD as active vacuum window!!



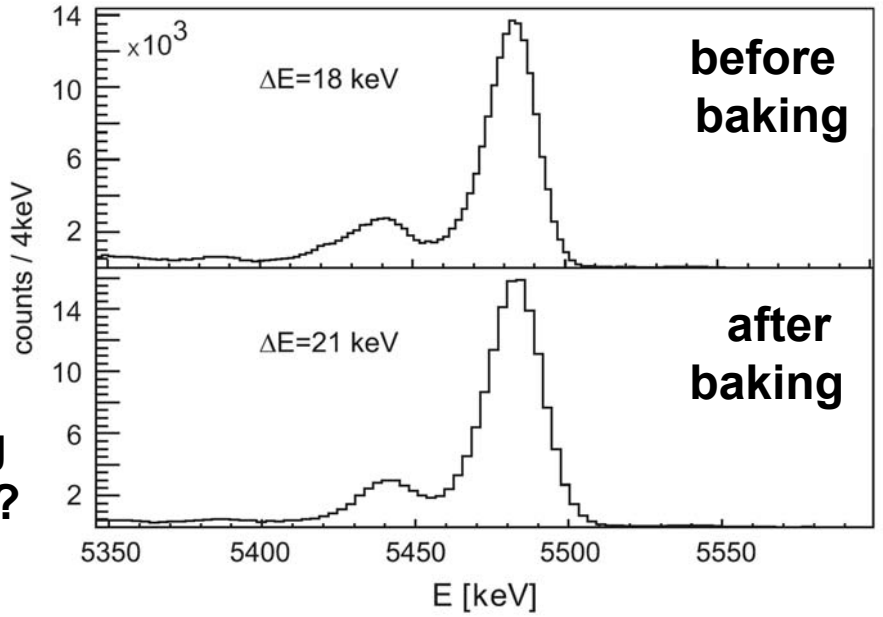
B. Streicher et al., NIM A 654, 604 (2011)

DSSSD as active window



Does the DSSSD keep the UHV?

YES ☺



Does the DSSSD survive the baking (150 °C for 2 days on the UHV side)?

YES ☺☺☺

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

EXL demonstrator

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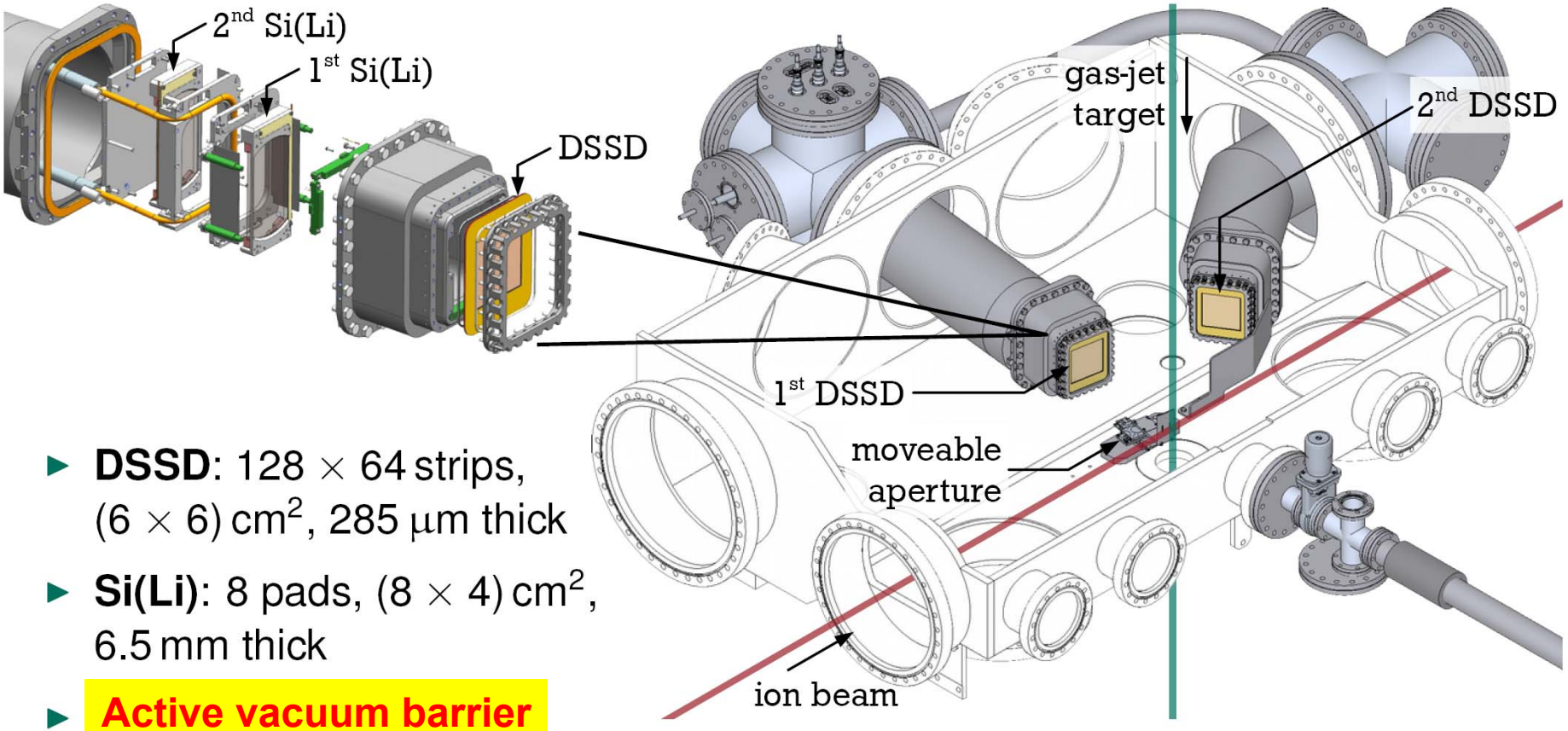

- **DSSD**: 128 × 64 strips, (6 × 6) cm^2, 285 μm thick
- **Si(Li)**: 8 pads, (8 × 4) cm^2, 6.5 mm thick
- **Active vacuum barrier**

B. Streicher et al., Nucl. Instr. and Meth. A 654, 604 (2011).

- **Aperture** to improve angular resolution (1 mm and 2 mm slits).

Pictures: M. Lindemulder

^{56}Ni(p,p) @ 390 MeV/u

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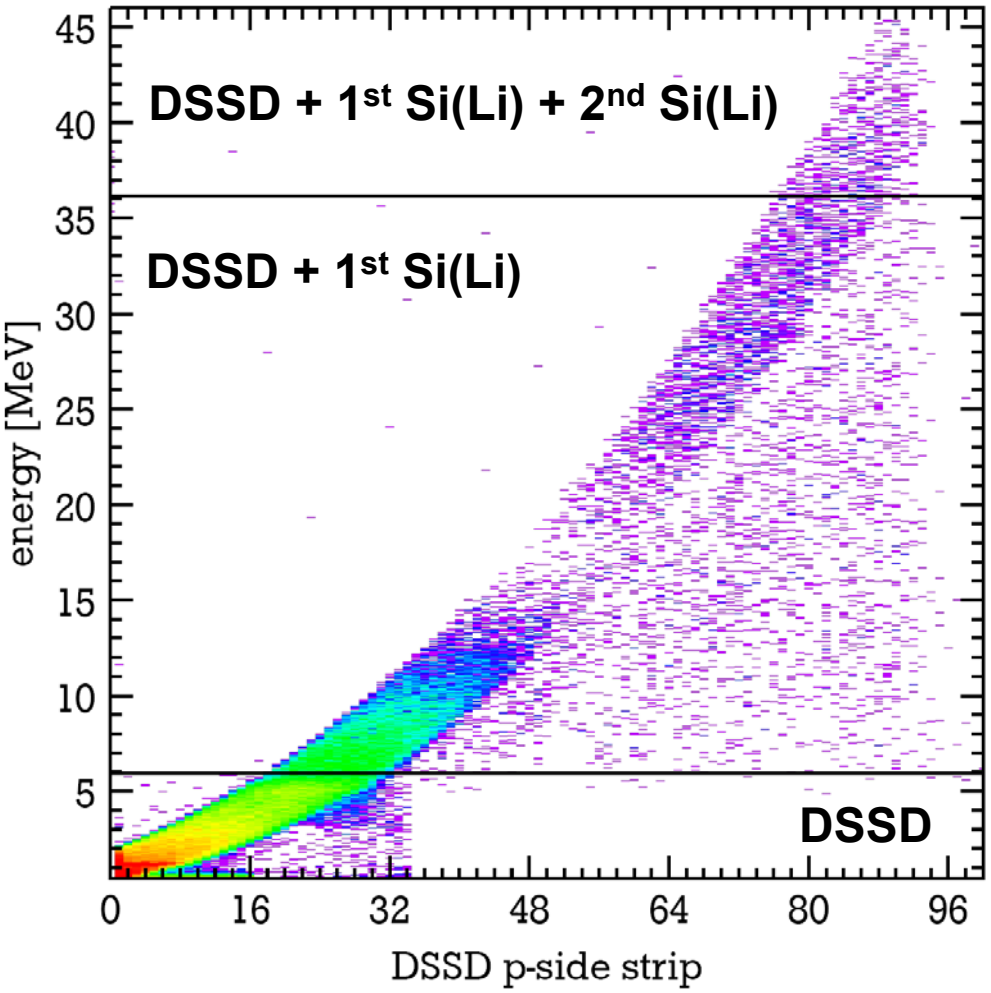

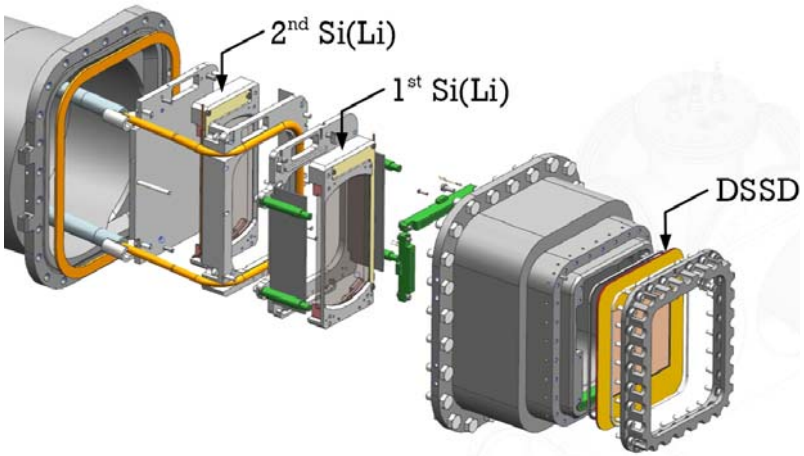

- σ of cooled beam: 0.6 mm ☺
- radius of target profile: 3.2 mm ☹

➔ limits angular / energy resolution

^{56}Ni(p,p) @ 390 MeV/u

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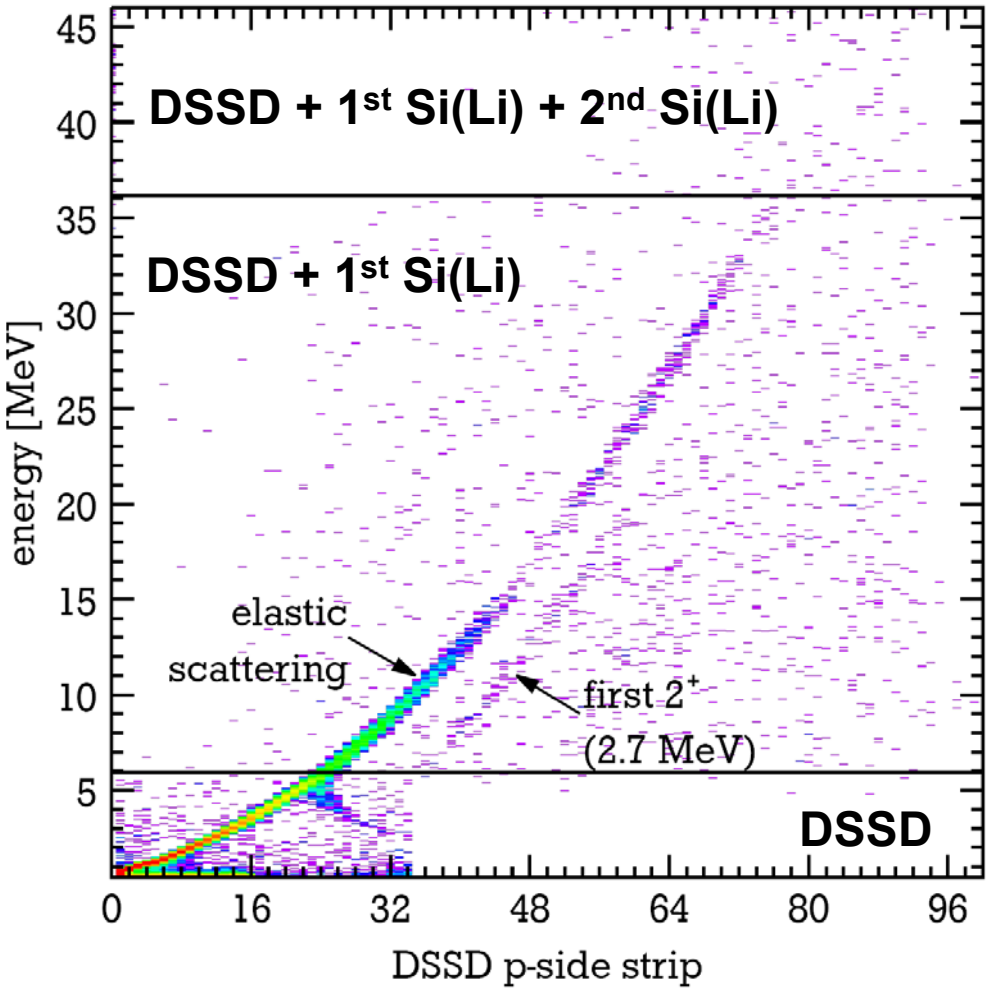

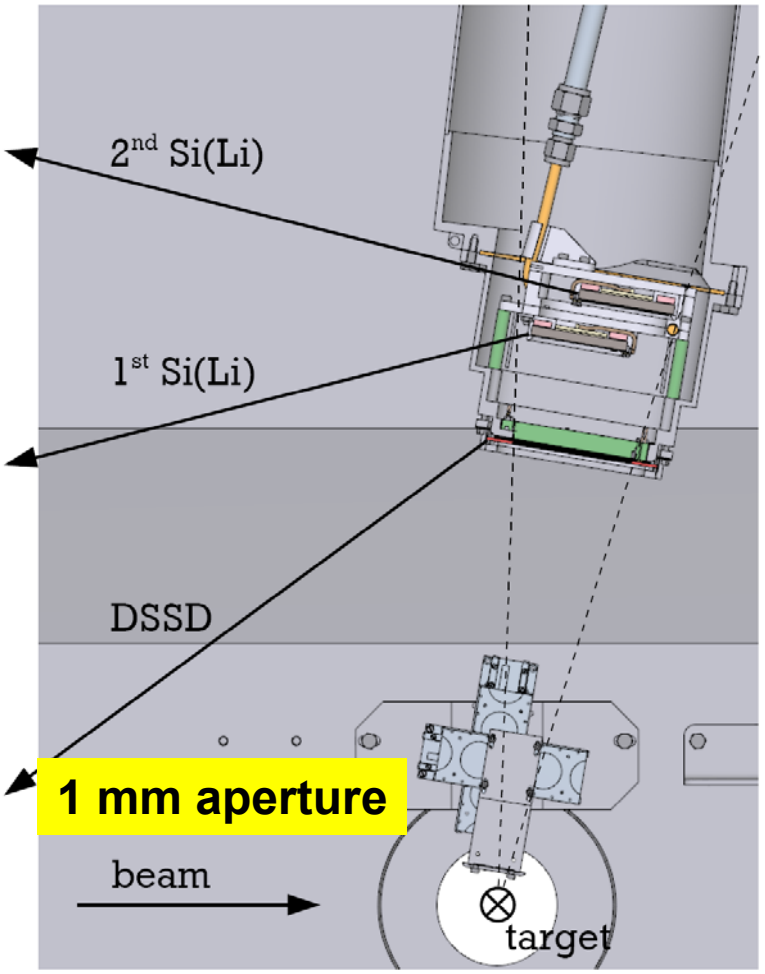

Differential cross section

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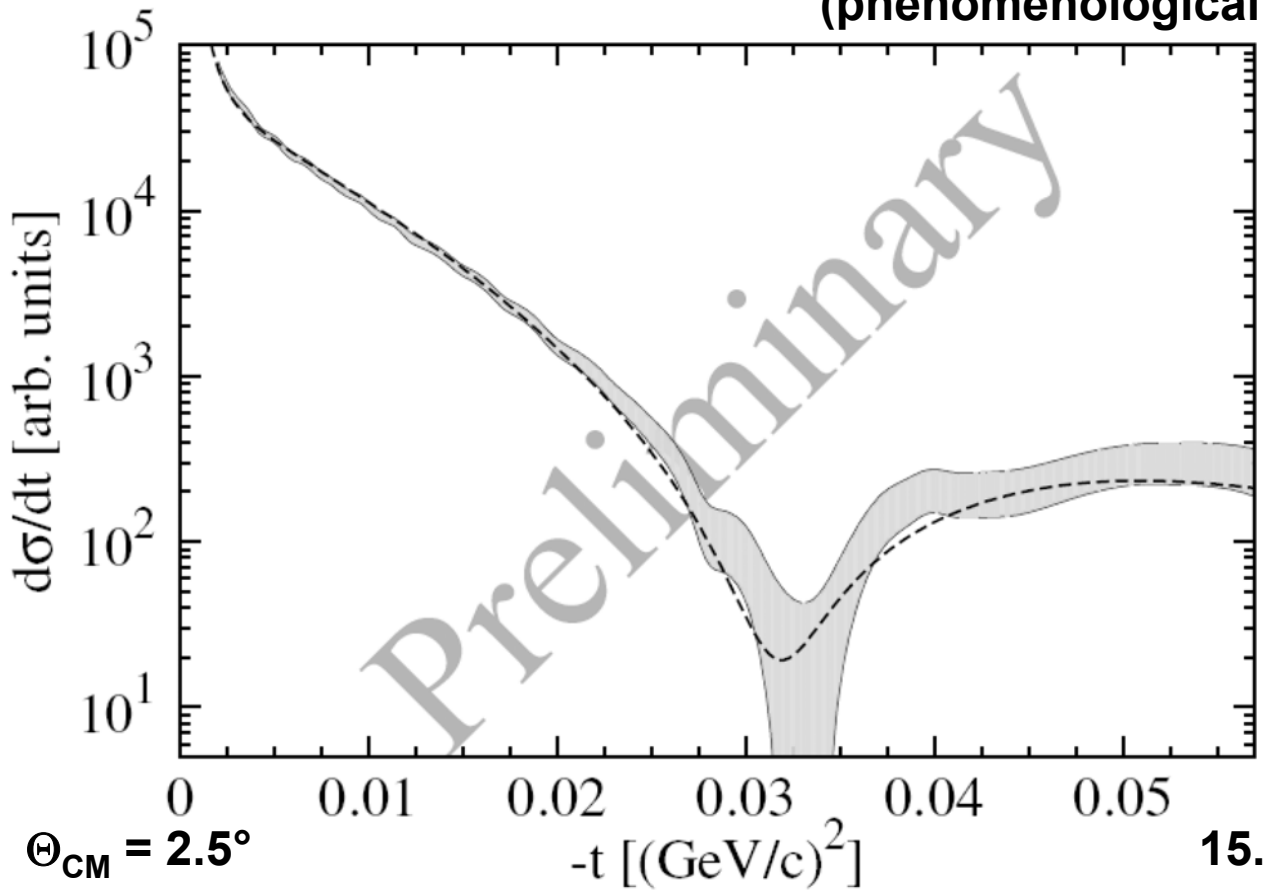
^{56}Ni(p,p) @ 390 MeV/u

- **Glauber fit**
- **symmetrised Fermi function (phenomenological distribution)**



Θ_{CM} = 2.5° 15.3°

Model dependence of matter distribution

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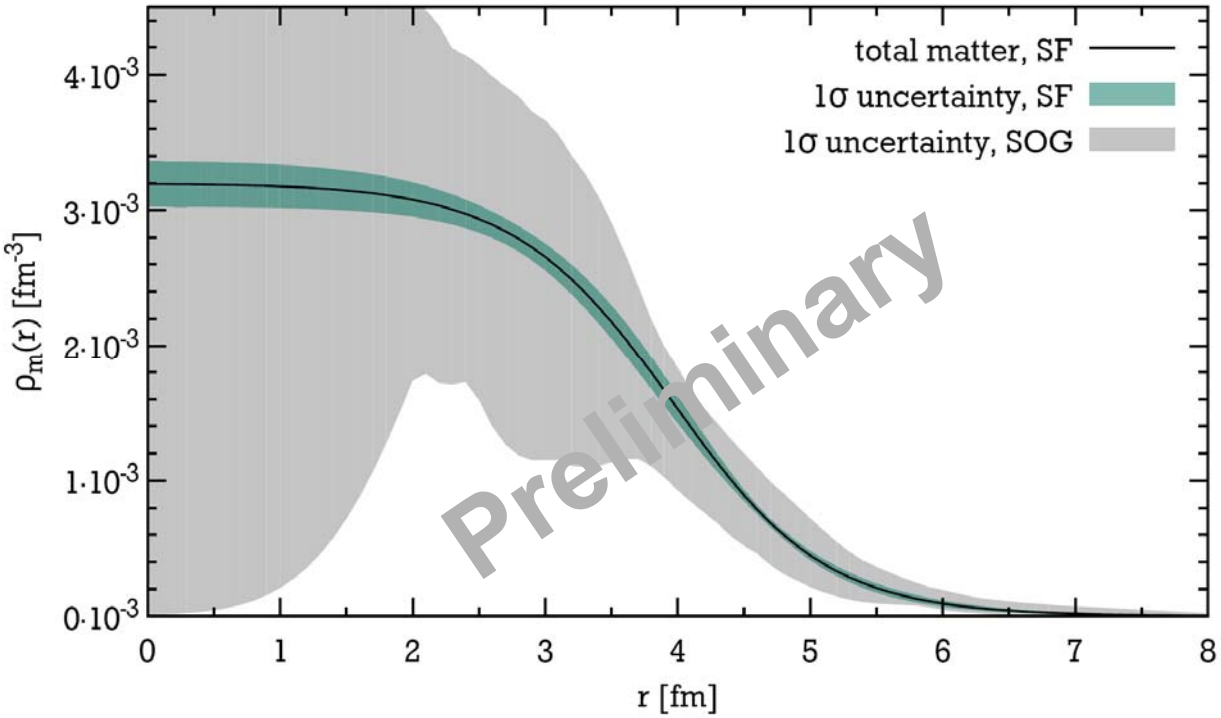
- **Symmetrised Fermi distribution (model dependent fit)**
- **Sum of Gaussians (model independent fit)**



RMS matter radius: $\langle r_m^2 \rangle^{1/2}$ = **3.7 - 3.8** fm

RMS matter radii of Ni isotopes

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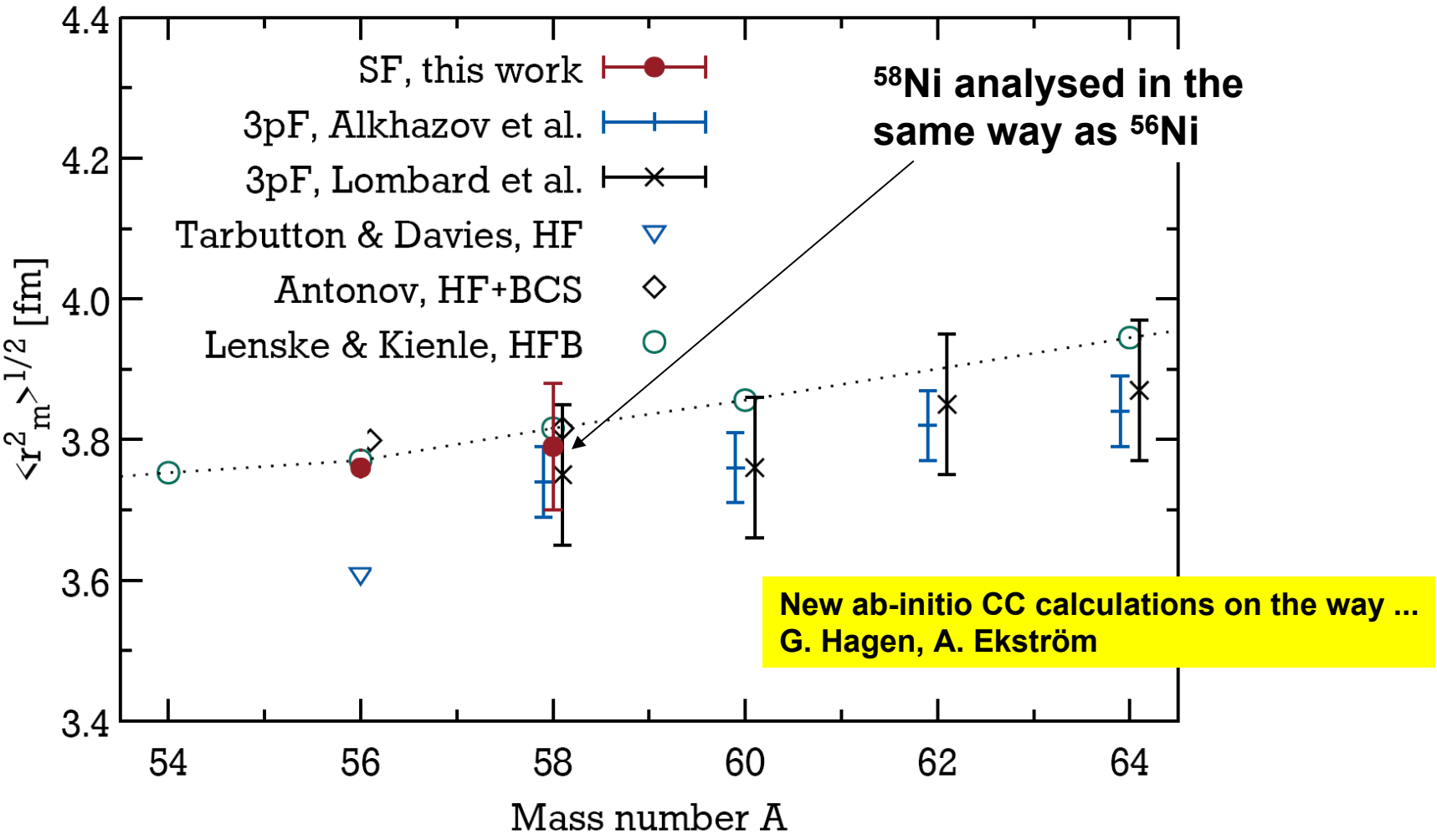

Excitation of IS giant resonances

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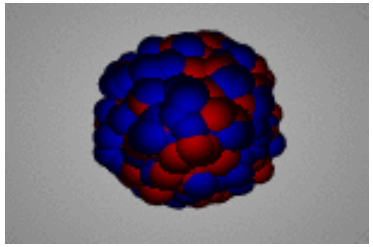
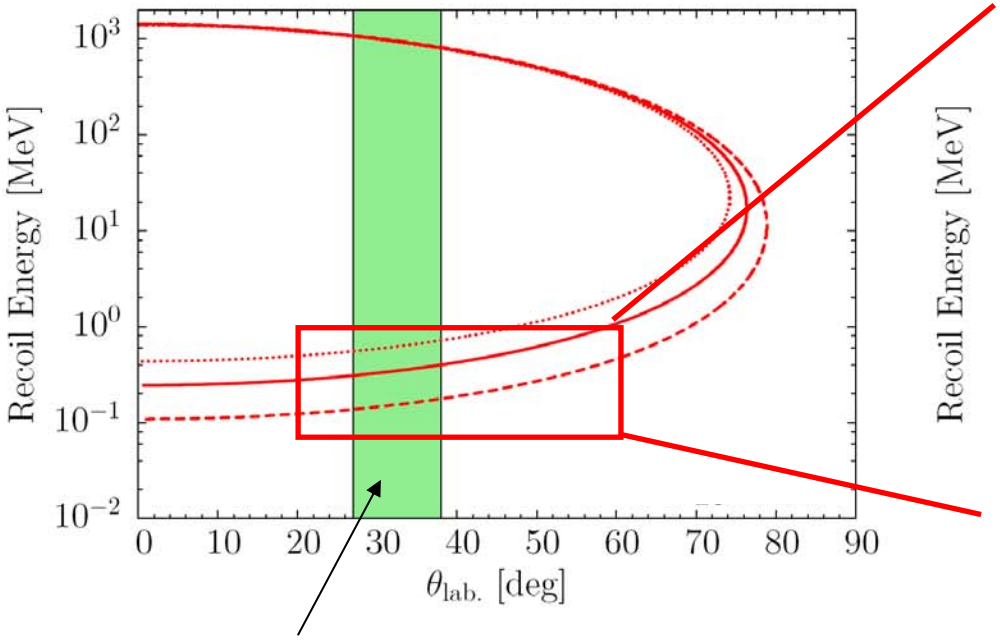
- IS GMR ("breathing mode")
  ... (in)compressibility in nuclear EoS
- ^{58}Ni(α,α') @ 100 MeV/u

  ^{4}He gas jet has an order of magnitude lower density
- Recoil energies of a few 100 keV

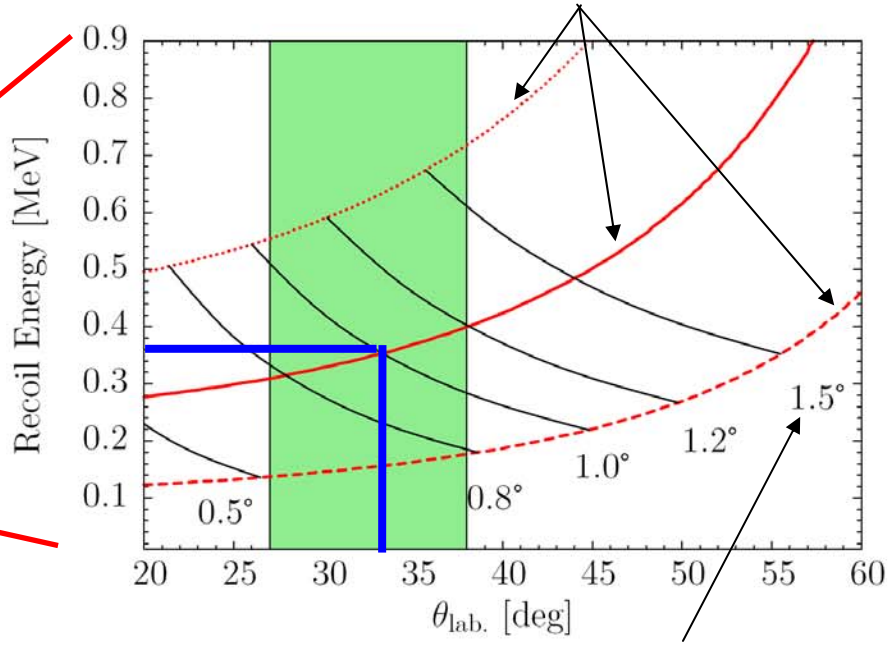


Animation by P. Adrich

E_x= 19 MeV ± 7 MeV

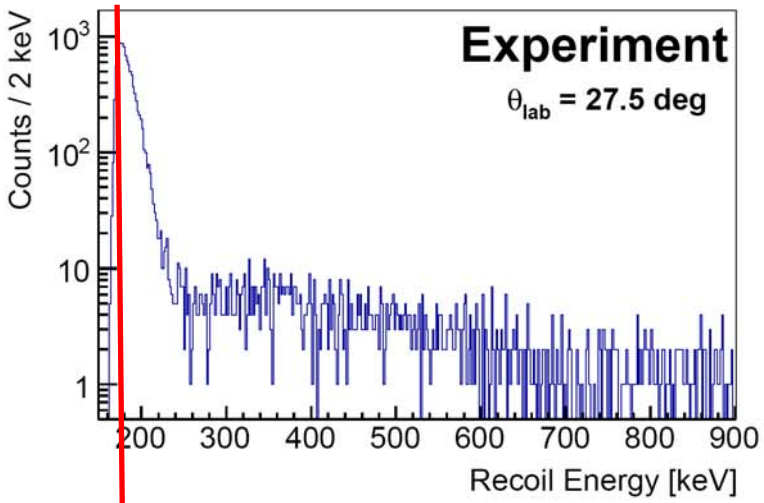


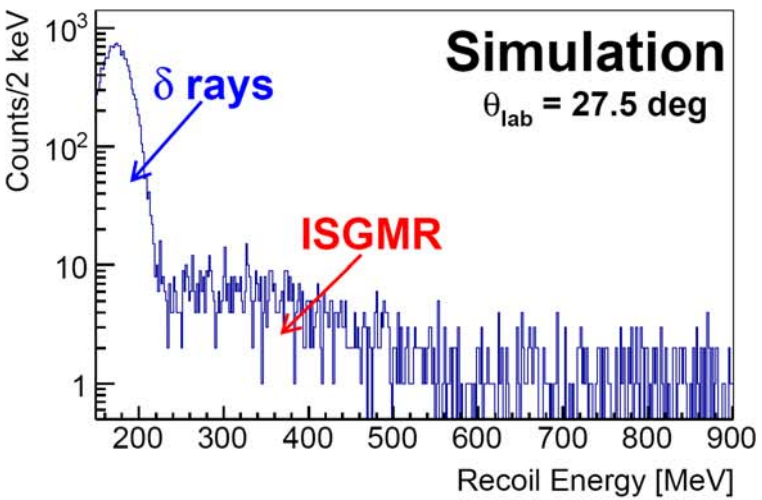
Region covered by DSSD2

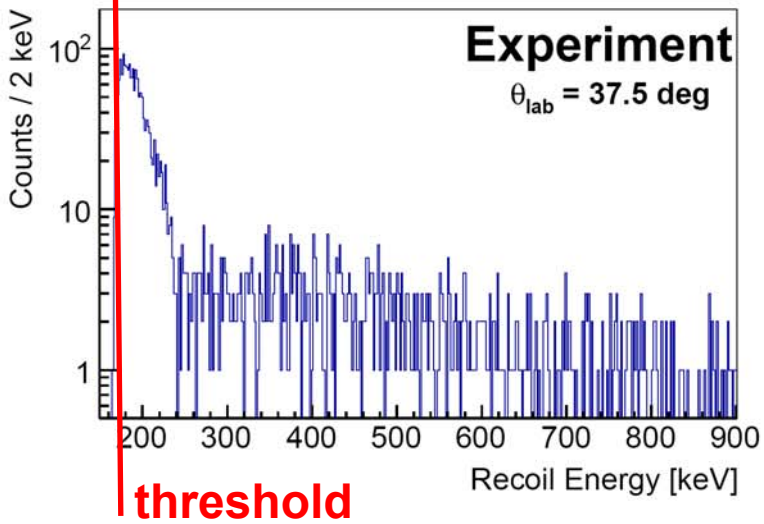


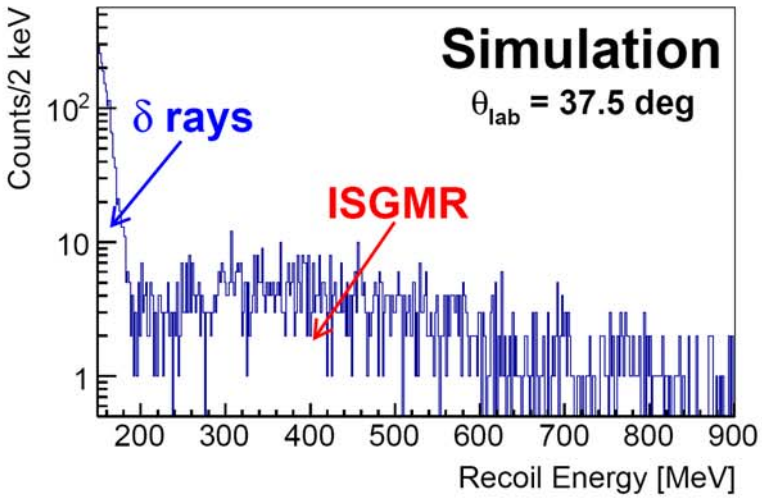
CMS scattering angle

Experimental / simulated spectra









IS giant monopole resonance in ^{58}Ni

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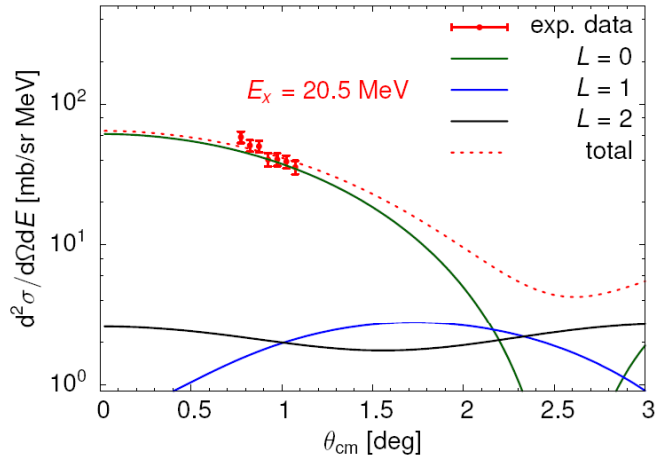
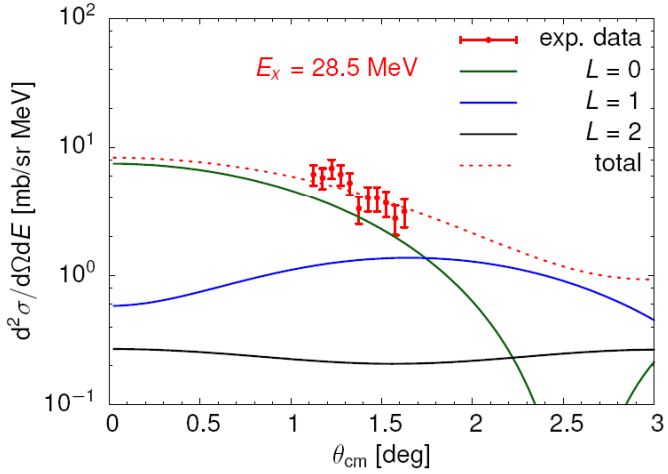
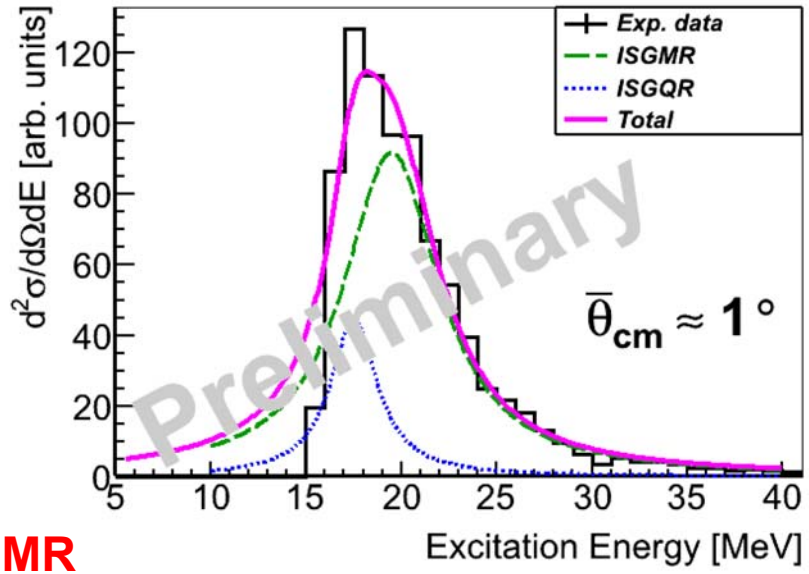




Multipole Decomposition Analysis

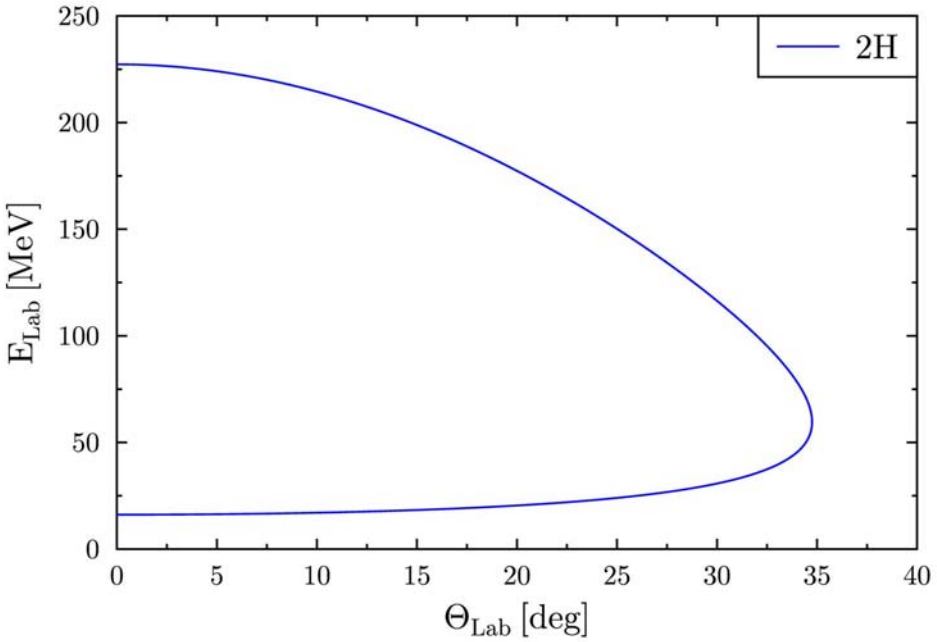


ISGMR

centroid [MeV]	EWSR [%]	
$21.9^{+0.8}_{-1.1}$	79^{+12}_{-11}	present data
$21.5^{+3.0}_{-0.3}$	74^{+22}_{-12}	PRC **61**, 067307 (2000)
$20.8^{+0.9}_{-0.3}$	85^{+13}_{-10}	PRC **73**, 014314 (2006)
21.1	94	RPA calculation [4]

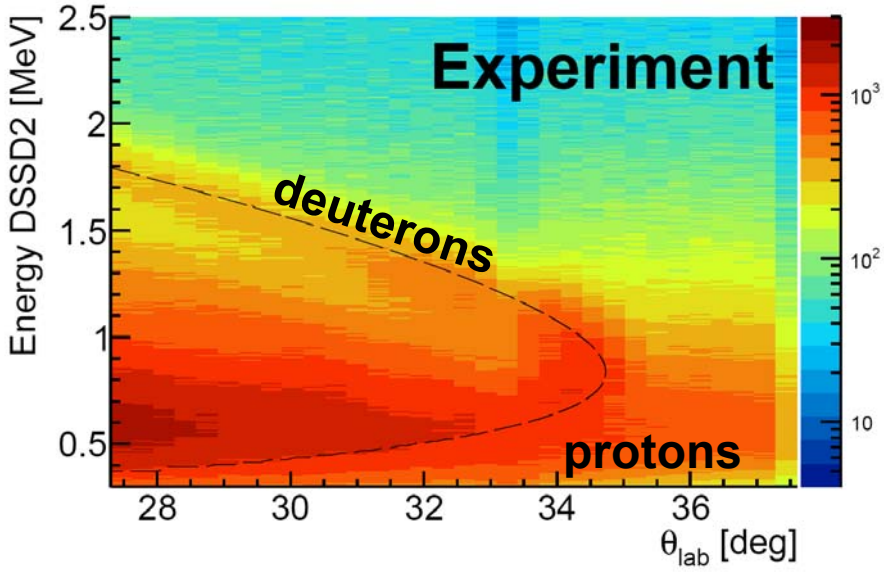
[4] G. Colò et al, Comput. Phys. Commun. 184 (2013)

^{20}Ne(p,d) @ 50 MeV/u



Parasitic user of ^{20}Ne beam (Exp. E087, P.J. Woods et al.)

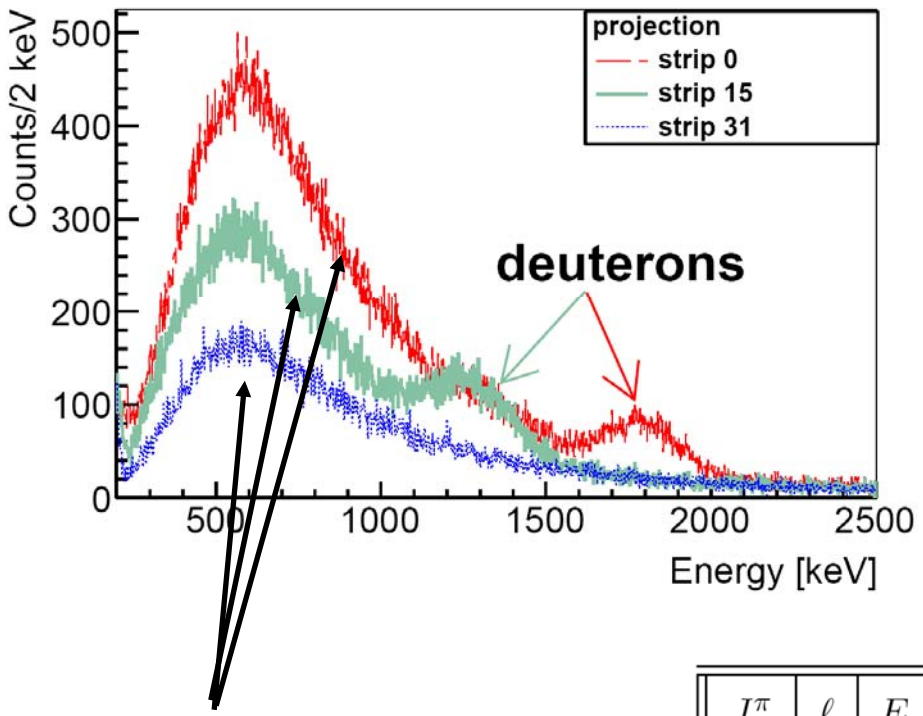
energy loss spectrum



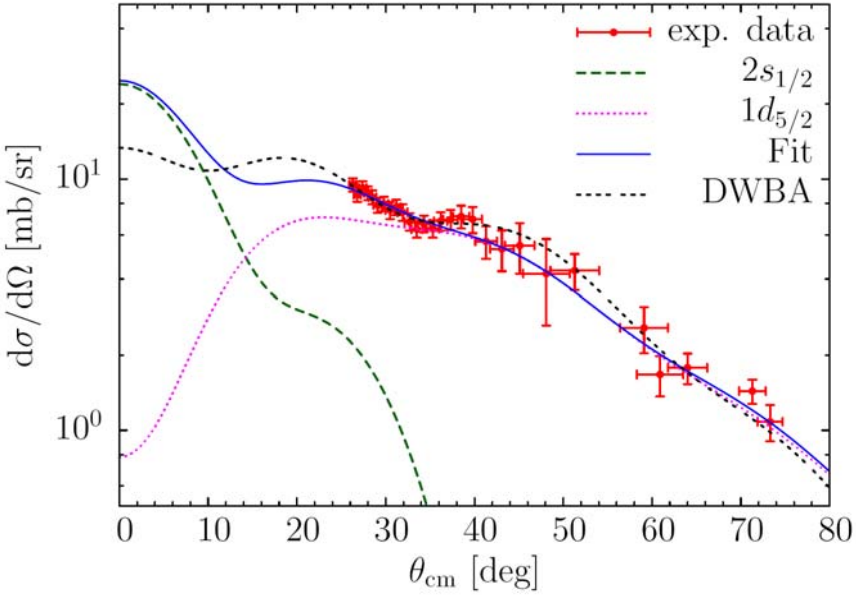
DSSD2

- **only one layer**
- **no PID**
- **different kinematics for p and d**

^{20}Ne(p,d) @ 50 MeV/u



elastically scattered protons



J^π	ℓ	E_x [keV]	$S_{\ell sj}$ (AWBA)	$S_{\ell sj}$ (SM)	$S_{\ell sj}$ (DWBA)
$\frac{1}{2}^+$	0	g.s.	0.44(17)	0.48	0.13(8)
$\frac{5}{2}^+$	2	238	1.57(12)	1.24	3.03(20)

... not resolved

… EXL at FAIR

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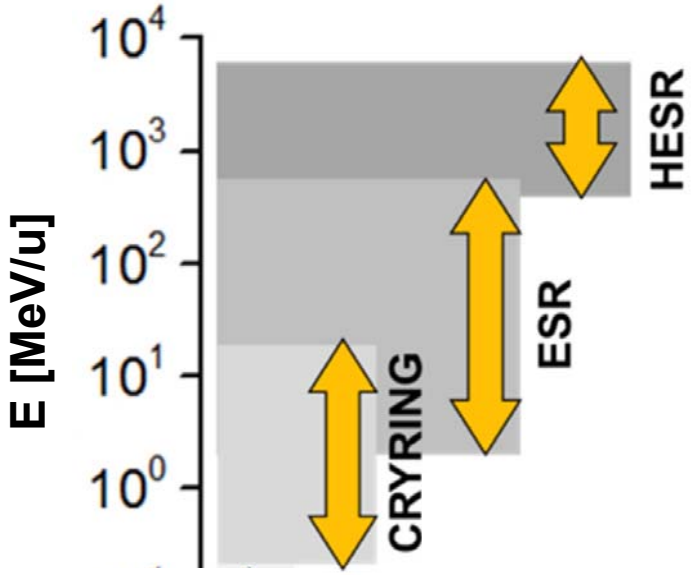
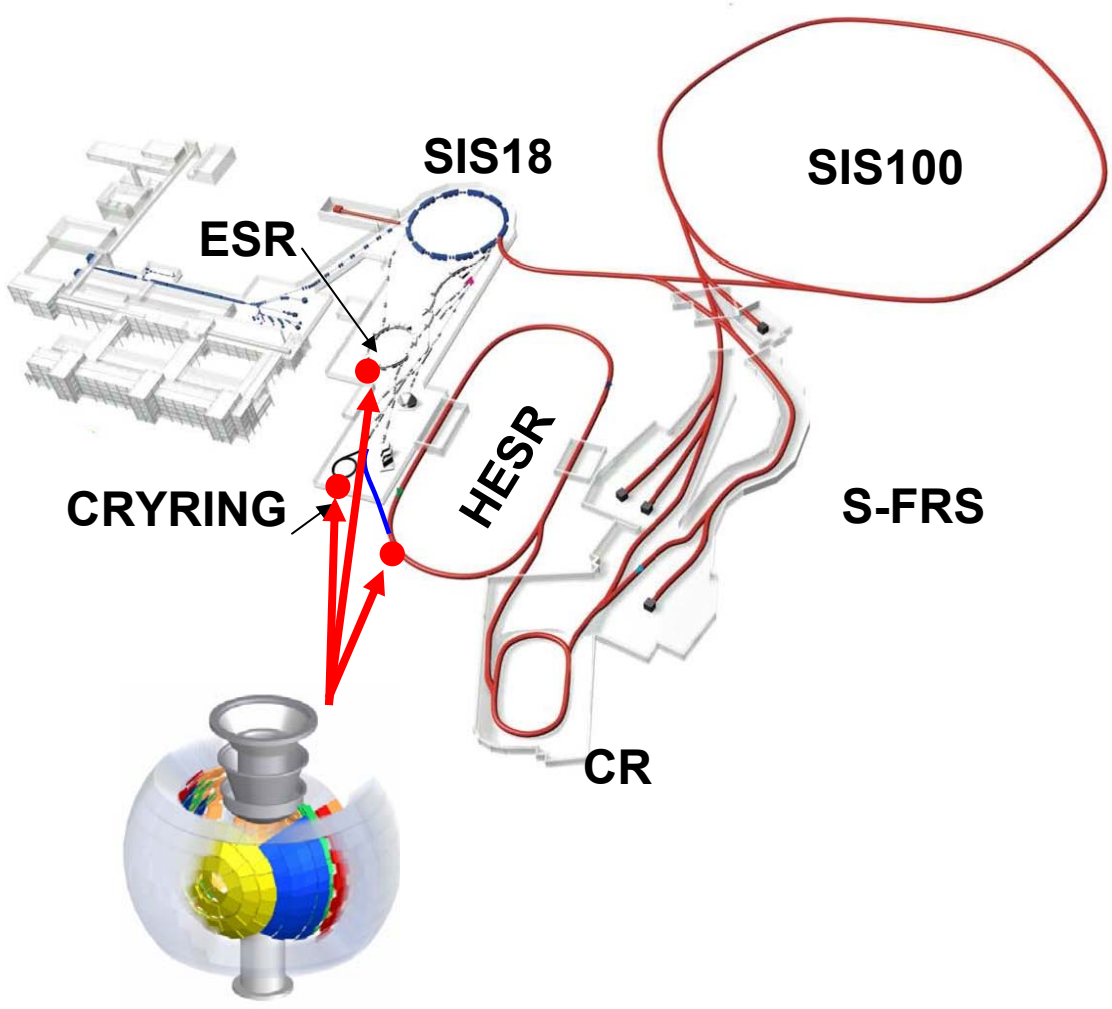
EXL is a versatile experimental set-up ... can profit from different storage rings at FAIR





TSR@MPI-K in Heidelberg

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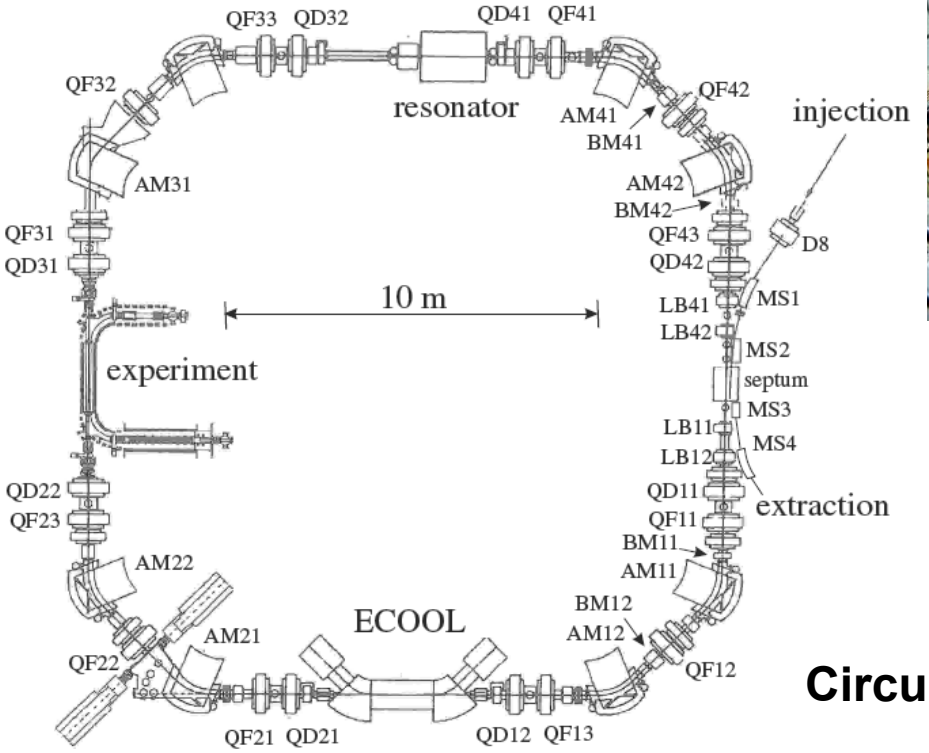

Circumference: 55.4 m

TSR@HIE-ISOLDE

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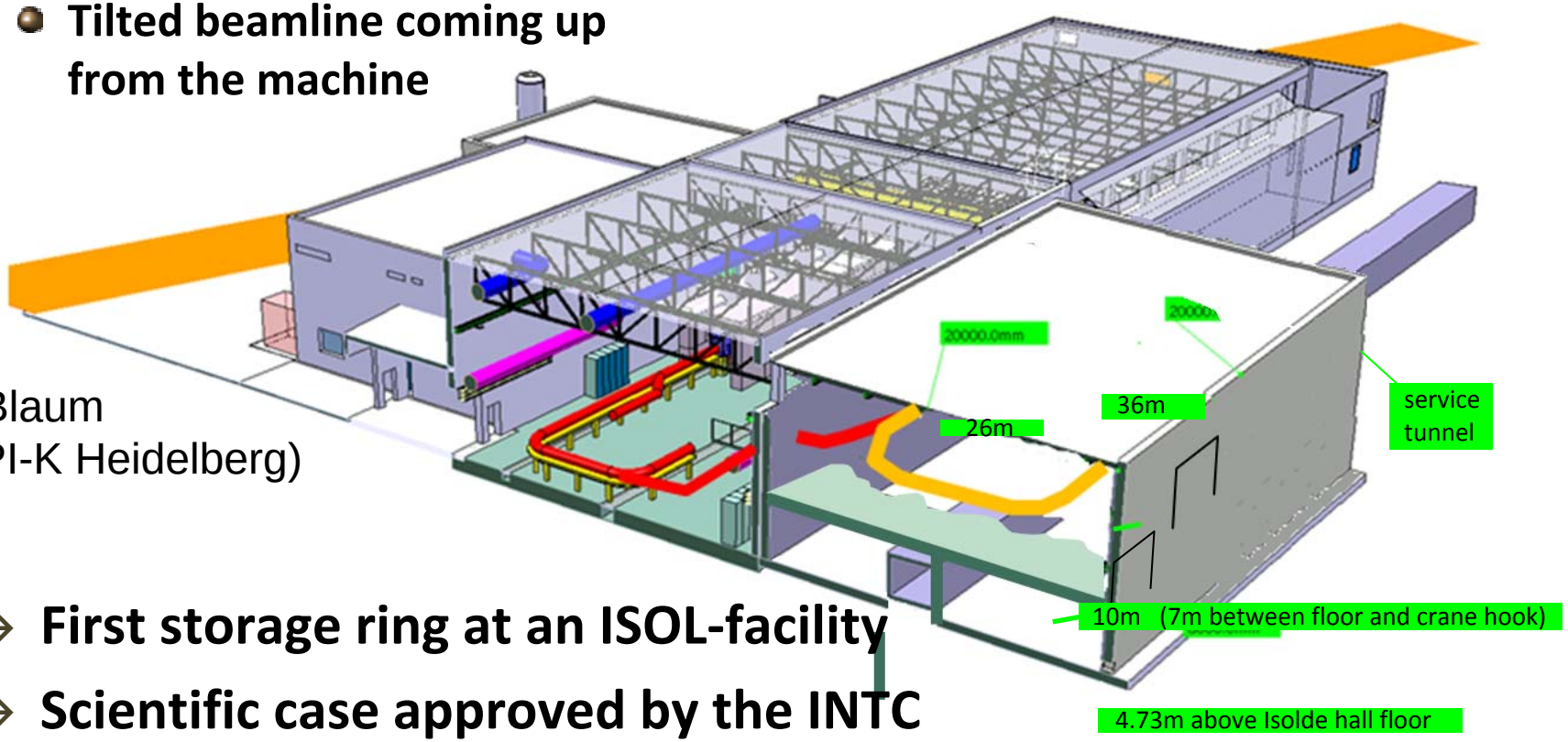
- **Possible TSR installation above the CERN service-tunnel**
- **Tilted beamline coming up from the machine**

M. Grieser et al., EPJST 207, 1-117 (2012)



K. Blaum
(MPI-K Heidelberg)

→ **First storage ring at an ISOL-facility**

→ **Scientific case approved by the INTC**

→ **... update 2016: not anymore in the mid-term plan of CERN ☹☹☹**

TSR@HIE-ISOLDE

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Nuclear physics at 10 MeV/u

Beam preparation
- purification of beams ... Isobaric contaminants
- preparation of isomeric beams
- cooling of beams

➔ **extract and send to external experiments**, e.g. MINIBALL, spectrometer, ACTAR or ISS

OR

➔ **reactions with internal targets**
- elastic and inelastic scattering
- transfer reactions, e.g. (d,p)
- capture reactions (p,γ) ... interesting for nuclear astrophysics

Example: ^{132}Sn(d,p)^{133}Sn

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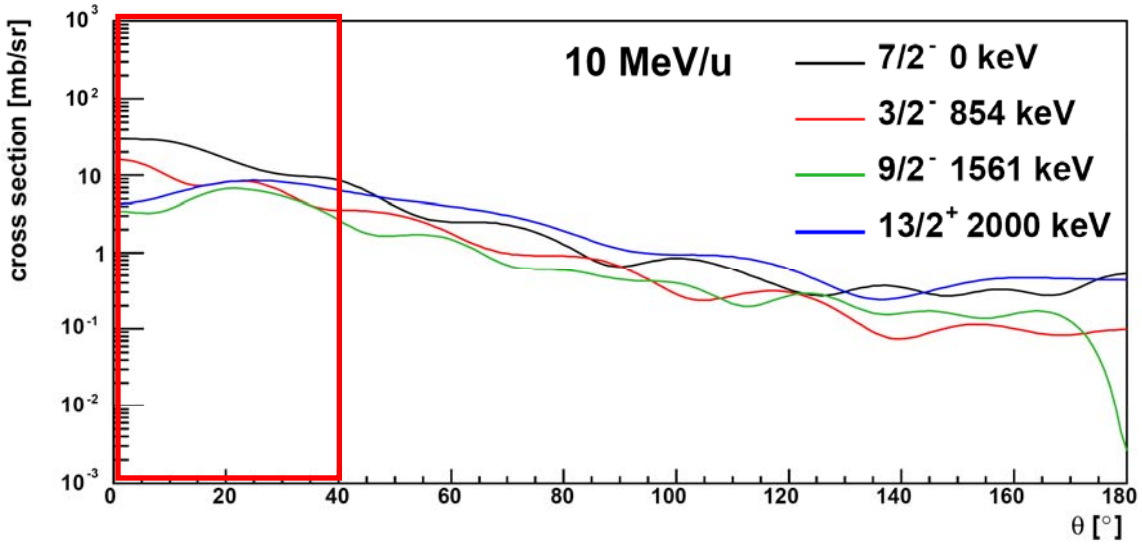
$T_{1/2}$: 40s
Rate: 10^6 pps
Cooling time: 0.2 s << $T_{1/2}$
... storage time much longer than nuclear lifetime



Target: 10^{14} atoms/cm^2 (D_2 gas, no background from carbon in CD_2)
Revolution frequency: 40 kHz

Luminosity L = 10^6 x 10^{14} x 4x10^4 x 40 ≈ 10^{26} cm^{-2} s^{-1}

Cross section: 10 mb/sr ➔ 10^{-26} x 10^{26} = 1 s^{-1} sr^{-1} ... looks feasible ☺☺☺

Example: ^{132}Sn(d,p)^{133}Sn

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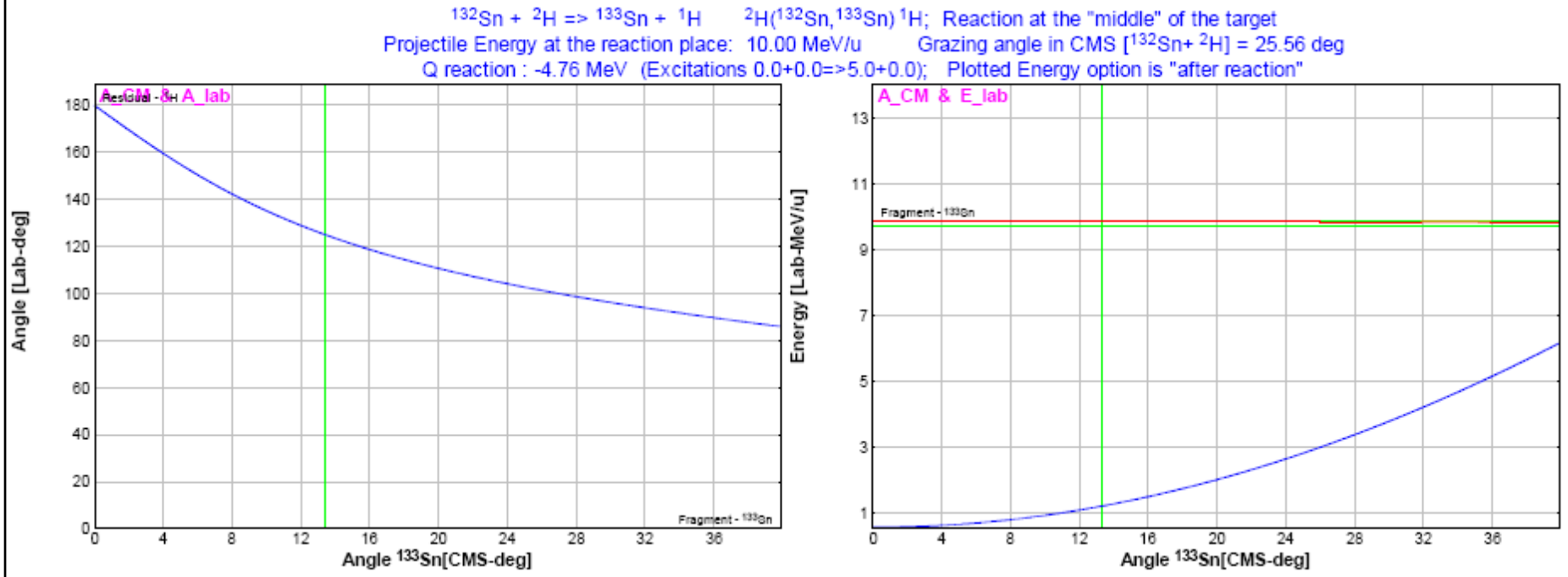
Q_{00} = 0.24 MeV
E*(^{133}Sn) = 5 MeV



Θ_{CM} < 40°
Protons are emitted in backward direction!!

Protons have low energies < 7 MeV ... detection needs windowless detectors inside the ring!!!

Example: ^{96}Ru(p,γ)^{97}Rh @ 9-11 MeV/u

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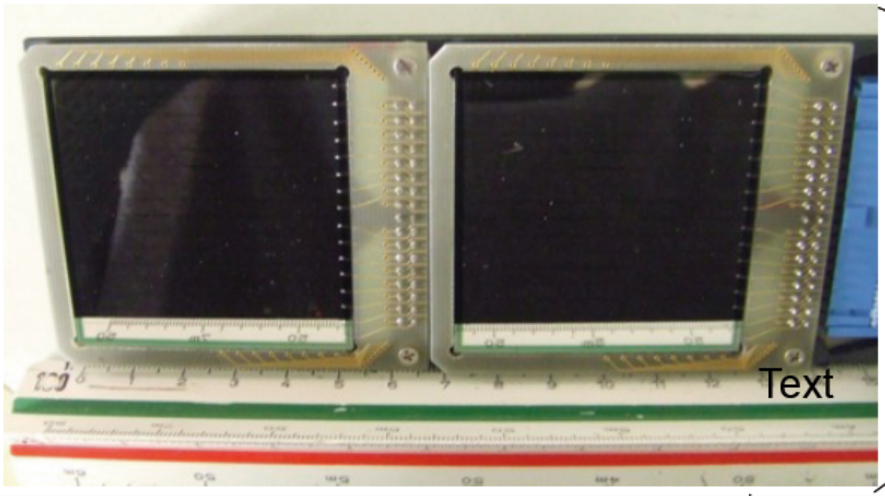
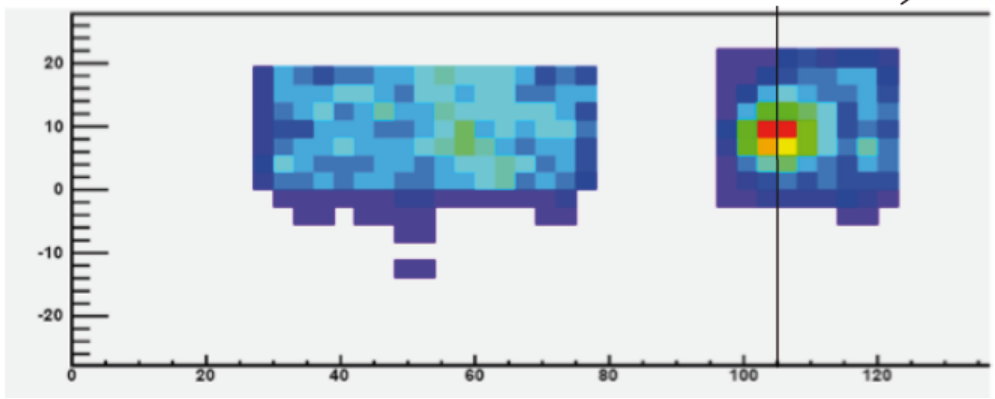
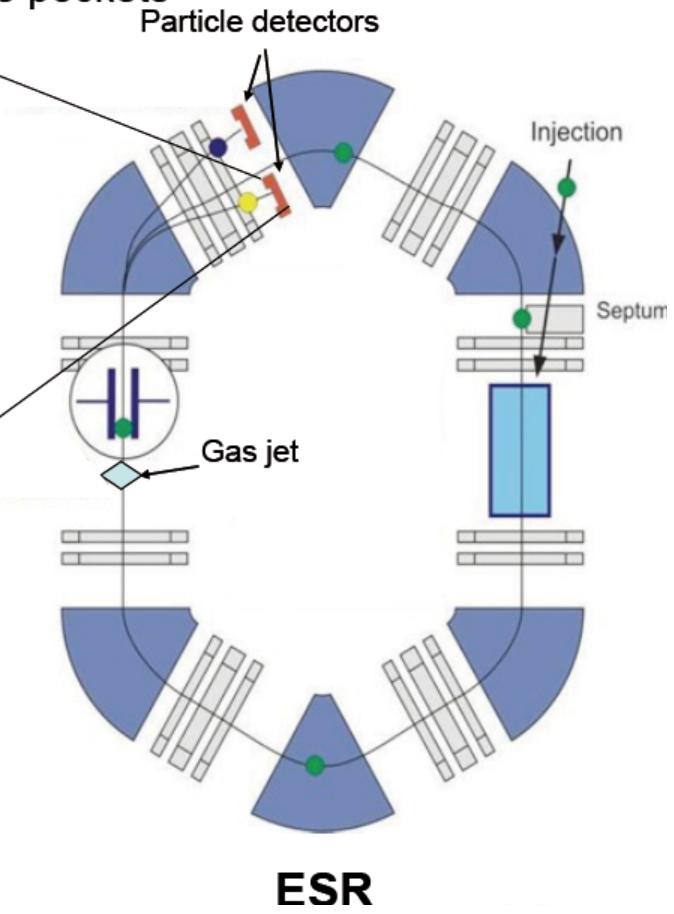
Particle detectors: Double sided silicon strip (16 x 16) inside pockets







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Summary

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

- **Detector concept developed and implemented at ESR (GSI)**

- **First experimental campaign (2012) ... with two detectors only!**

^{56}Ni(p,p) - first nuclear reaction experiment with a stored radioactive beam ever
➔ matter radius of ^{56}Ni measured for the first time

Feasibility studies
- **^{58}Ni(α,α') - isoscalar giant monopole resonance in ^{58}Ni**
- **^{20}Ne(p,d) - nucleon transfer reaction**

Looking forward to further experiments at GSI ... and later FAIR
... and maybe there's a future also at ISOLDE with the TSR

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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]

[1] KVI-CART, Groningen
[2] Technische Universität Darmstadt
[3] ATOMKI, Debrecen
[4] GSI, Darmstadt
[5] Ioffe Physico-Technical Institute, St.Petersburg
[6] Kyoto University
[7] Technische Universität München
[8] University of Tehran
[9] University of Tsukuba
[10] RIKEN Nishina Center
[11] The University of Edinburgh
[12] Saitama University
[13] Institute of Modern Physics, Lanzhou

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Thank you for your attention!!!!