First Nuclear Reaction Experiment with Stored Radioactive ^{56}Ni Beam and Internal Hydrogen and Helium Targets

Peter Egelhof
GSI Darmstadt, Germany
for the EXL Collaboration

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I. Introduction

II. The EXL* Project – an Overview

III. Feasibility Studies and First Experiments with RIB`s at the ESR Storage Ring

IV. Future Perspectives

V. Conclusions

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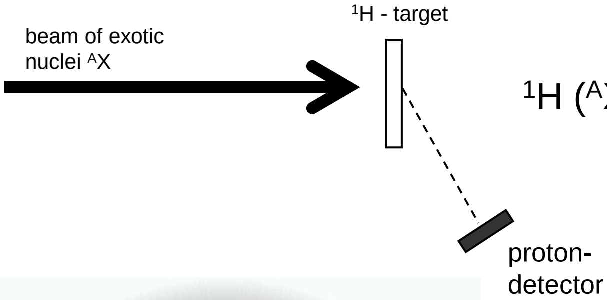
* **EXL**: **Ex**otic Nuclei Studied in **L**ight-Ion Induced Reactions at the NESR Storage Ring

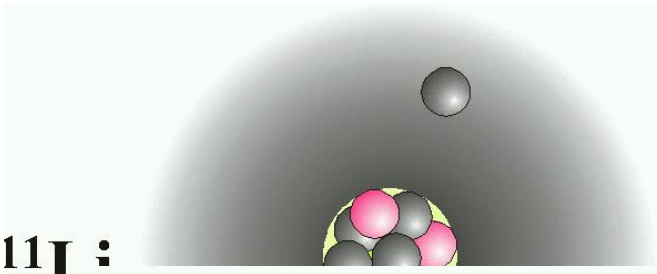
I. Introduction: Direct Reactions with Radioactive Beams in Inverse Kinematics



$^{1}H\ (^{A}X,\ ^{1}H)\ ^{A}X$

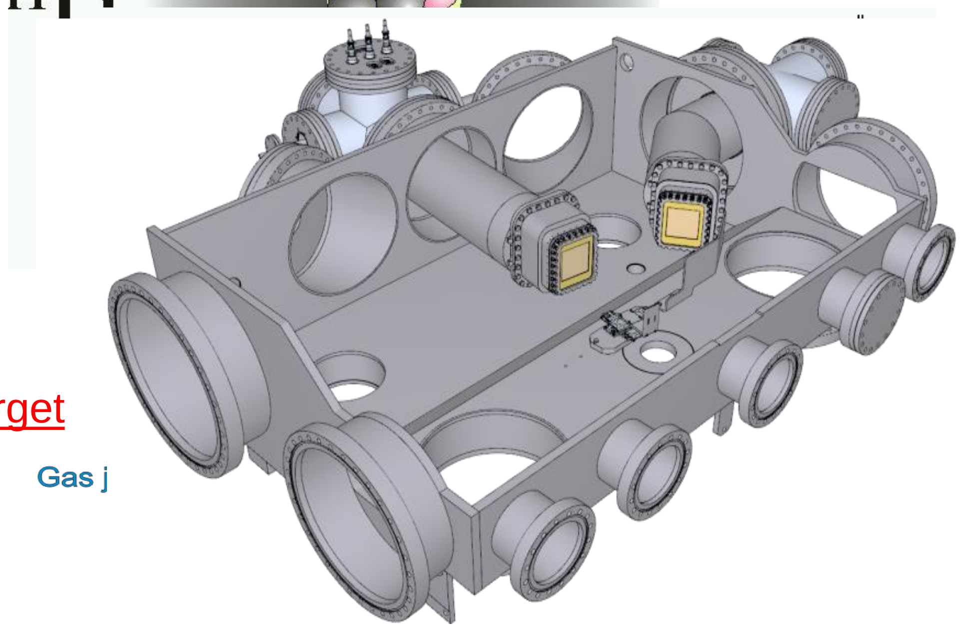
classical method of nuclear spectroscopy:

⇒ light ion induced direct reactions: (p,p), (p,p'), (d,p), ...
⇒ to investigate exotic nuclei: inverse kinematics
⇒ important information at low momentum transfer!



of particular interest:

⇒ radial shape of nuclei: skin, halo structures
⇒ doubly magic nuclei: ^{56}Ni, ^{132}Ni
⇒ giant resonances: nuclear compressibility



future perspectives at FAIR:

⇒ profit from intensity upgrade (up to 10^4 !!)
⇒ explore new regions of the chart of nuclides and new phenomena
⇒ use new and powerful methods:

EXL: direct reactions at internal storage ring target

⇒ high luminosity even for very low momentum transfer measurements

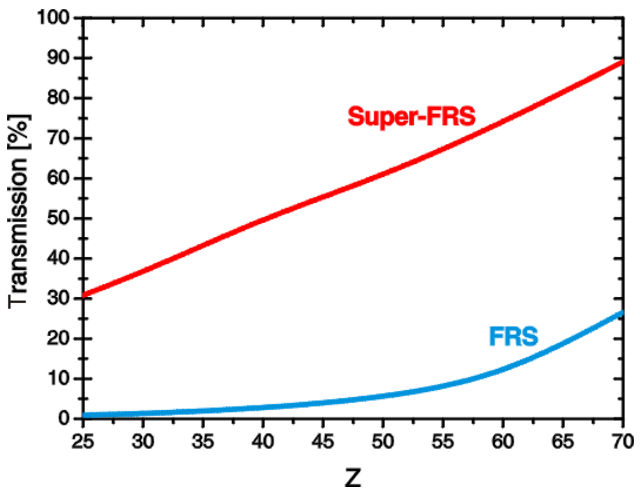
First Experiments at the ESR

Nuclear Physics with Radioactive Beams at FAIR: NUSTAR: NUclear STructure, Astrophysics and Reactions

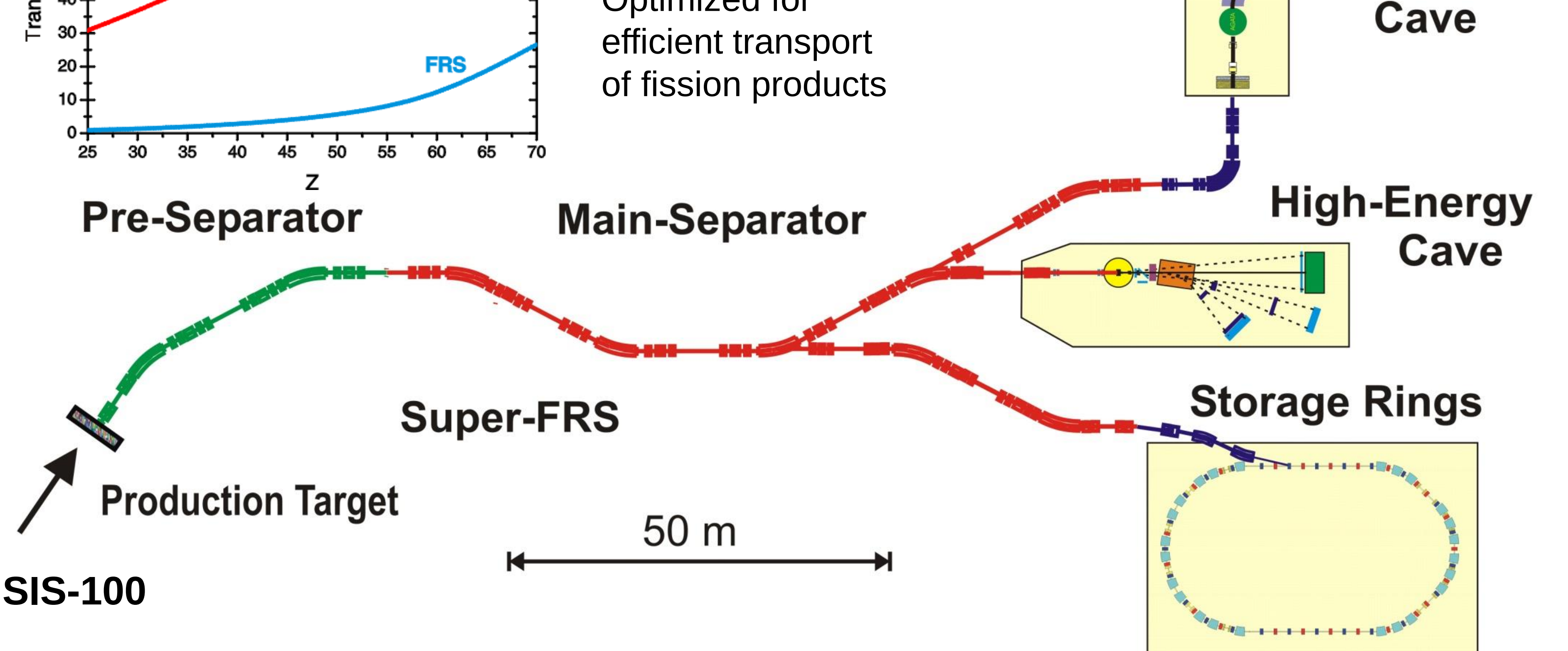
I High intensity primary beams from SIS 100 (e.g. 10^{12} ^{238}U / sec at 1 GeV/u)

II Superconducting large acceptance Fragmentseparator

III Three experimental areas



Optimized for efficient transport of fission products

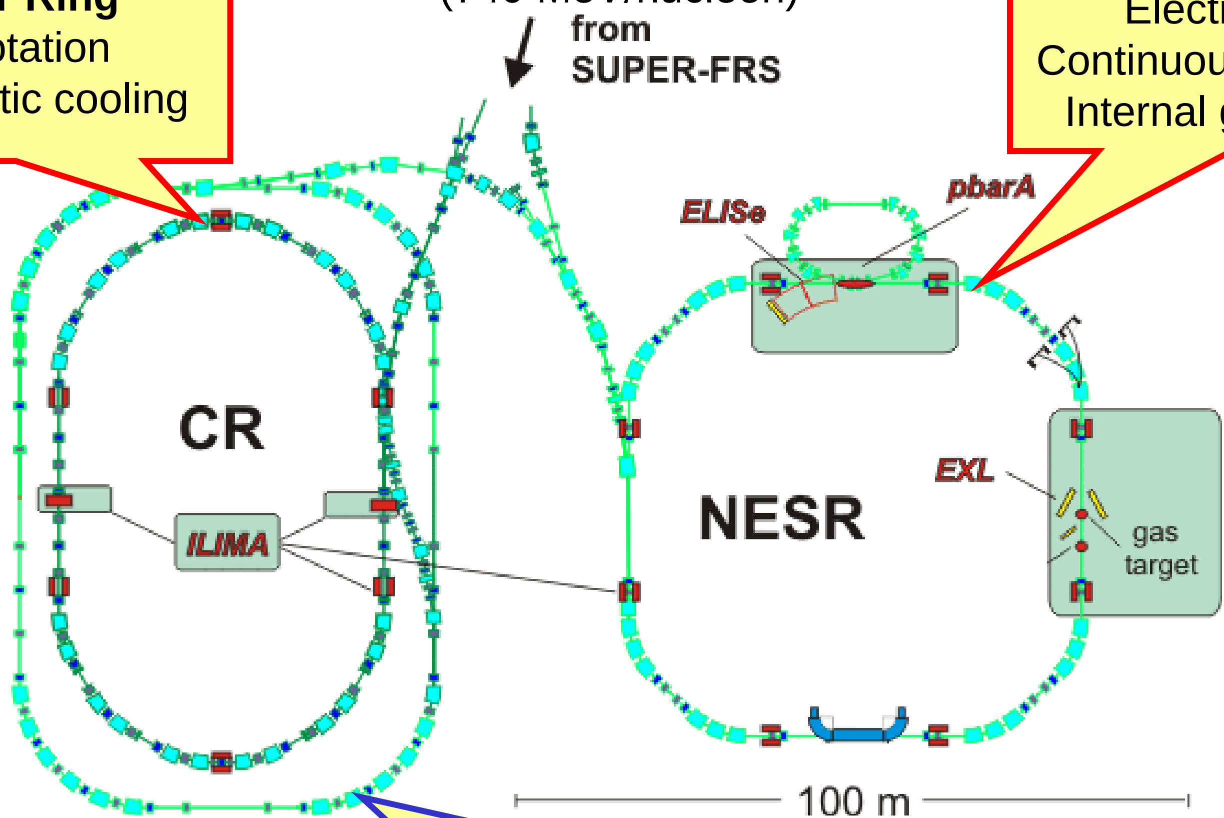


Experiments with Stored Exotic Nuclei

RIB
(740 MeV/nucleon)

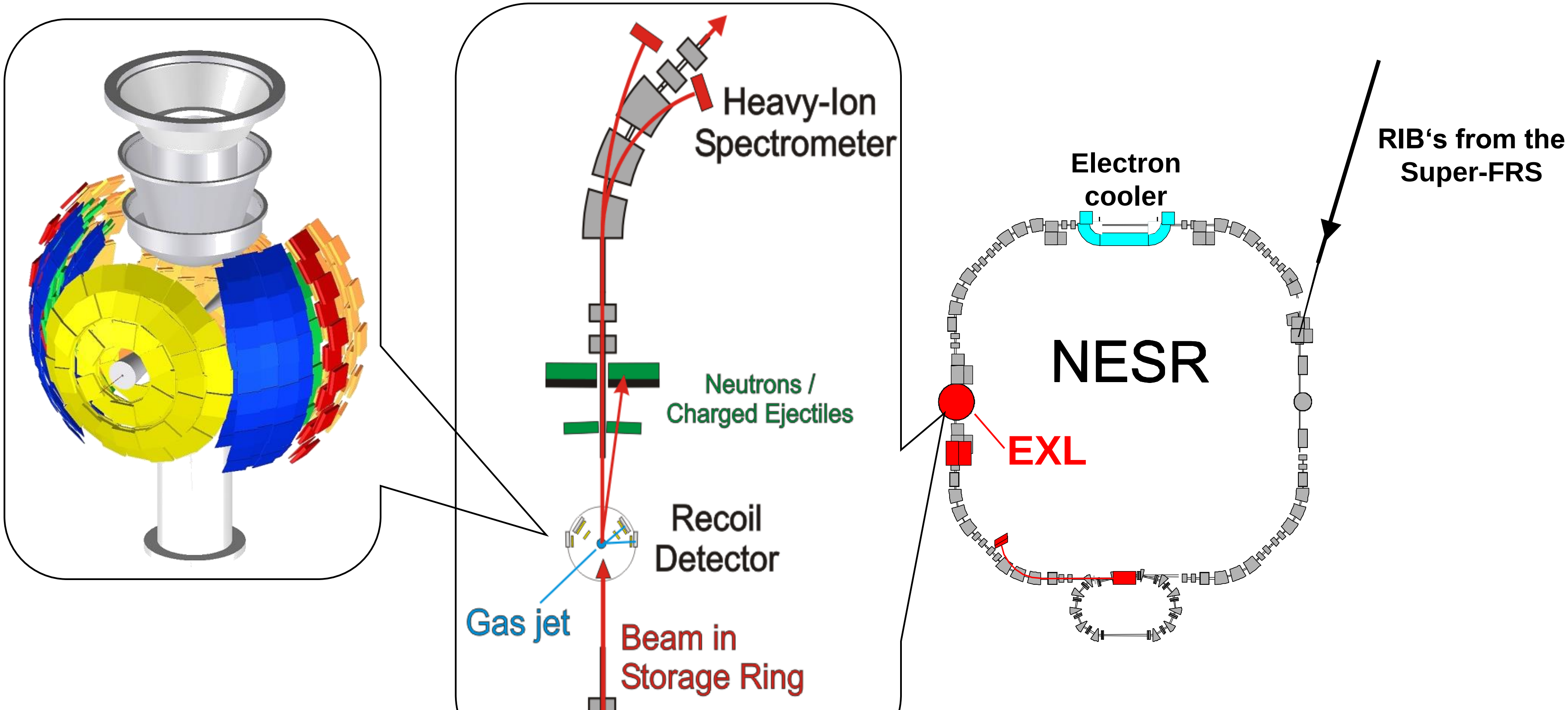
Collector Ring
Bunch rotation
Fast stochastic cooling

NESR
Electron cooling
Continuous accumulation
Internal gas jet targets



RESR
Deceleration (1T/s) to 100 - 400 MeV/nucleon

II. The EXL Project: EXotic Nuclei Studied in Light-Ion Induced Reactions at the NESR Storage Ring



Detection systems for:

- Target recoils and gammas (p,α,n,γ)
- Forward ejectiles (p,n)
- Beam-like heavy ions

Design goals:

- Universality: applicable to a wide class of reactions
- High energy resolution and high angular resolution
- Large solid angle acceptance
- Specially dedicated for low q measurements with high luminosity (> 10^{29} cm^{-2} s^{-1})

Light-Ion Induced Direct Reactions at Low Momentum Transfer

- elastic scattering (p,p), (α,α), …
  nuclear matter distribution ρ (r), skins, halo structures
- inelastic scattering (p,p'), (α,α'), …
  deformation parameters, B(E2) values, transition densities, giant resonances
- transfer reactions (p,d), (p,t), (p, ^{3}He), (d,p), …
  single particle structure, spectroscopic factors, spectroscopy beyond the driplines, neutron pair correlations, neutron (proton) capture cross sections
- charge exchange reactions (p,n), (^{3}He,t), (d, ^{2}He), …
  Gamow-Teller strength
- (knock-out reactions (p,2p), (p,pn), (p,p ^{4}He)…
  ground state configurations, nucleon momentum distributions)

for almost all cases:

region of low momentum transfer contains most important information

<u>Speciality of EXL:</u>

measurements at very low momentum transfer

$\Rightarrow$ complementary to R^{3}B !!!

Experiments to be Performed at Very Low Momentum Transfer – Some Selected Examples

- Investigation of Nuclear Matter Distributions:

  ⇒ halo, skin structure

  ⇒ probe in-medium interactions at extreme isospin (almost pure neutron matter)

  ⇒ in combination with electron scattering (ELISe project @ FAIR):

  separate neutron/proton content of nuclear matter (deduce neutron skins)

method: elastic proton scattering ⇒ at low q: high sensitivity to nuclear periphery

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- <u>Investigation of the Giant Monopole Resonance:</u>

  ⇒ gives access to nuclear compressibility ⇒ key parameters of the EOS

  ⇒ new collective modes (breathing mode of neutron skin)

method: inelastic α scattering <u>at low q</u>

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- Investigation of Nuclear Matter Distributions:

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method: inelastic α scattering at low q

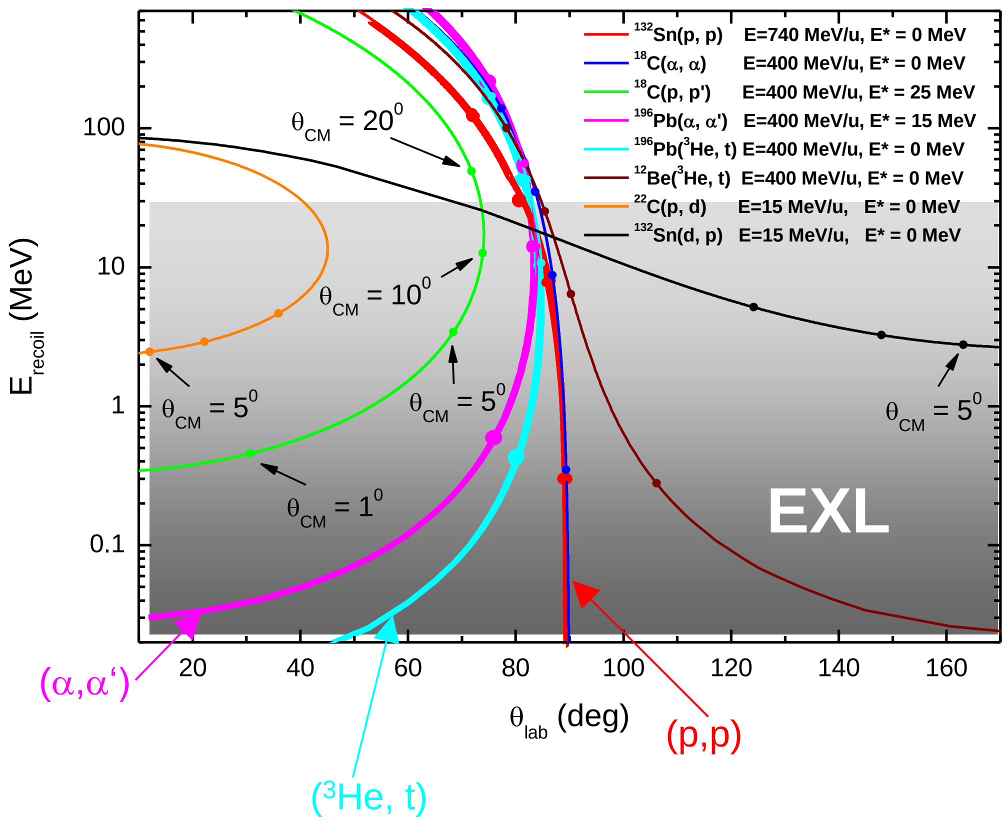
- Investigation of Gamow-Teller Transitions:

  ⇒ weak interaction rates for N = Z waiting point nuclei in the rp-process

  ⇒ electron capture rates in the presupernova evolution (core collaps)

method: (^{3}He,t), (d,^{2}He) charge exchange reactions at low q

Kinematical Conditions for Light-Ion Induced Direct Reactions in Inverse Kinematics



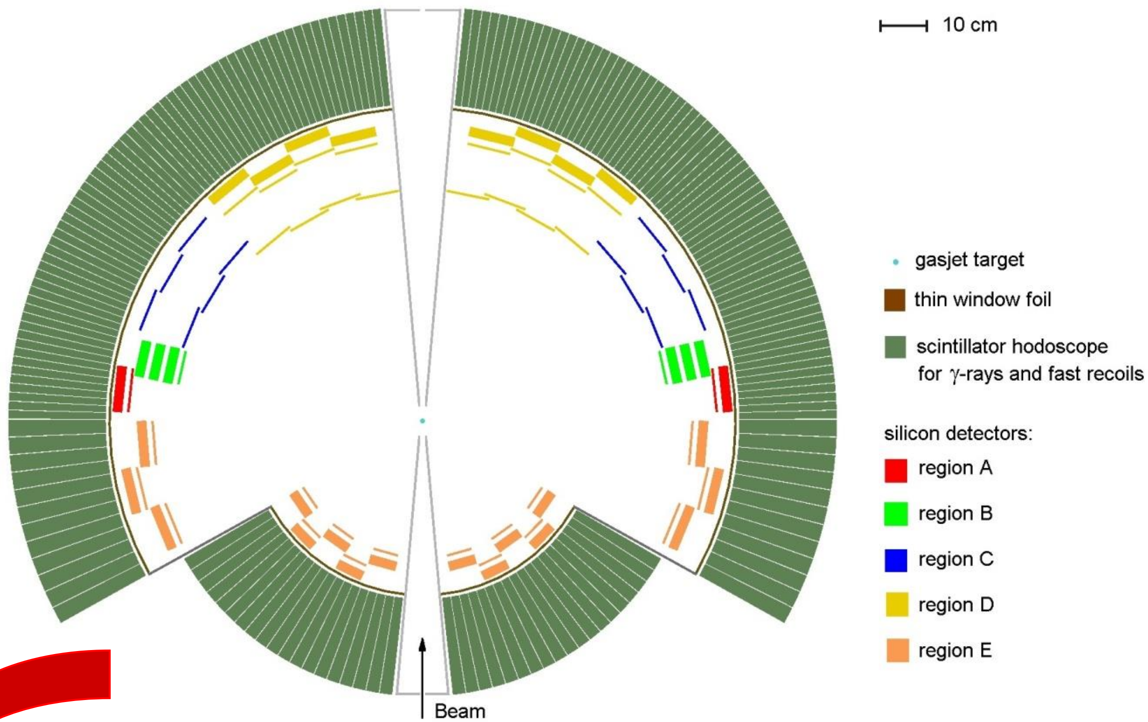
- required beam energies:
  E ≈ 200 … 740 MeV/u
  (except for transfer reactions)
- required targets: ^{1,2}H, ^{3,4}He
- most important information in region of low momentum transfer
  ⇒ low recoil energies of recoil particles
  ⇒ need thin targets for sufficient angular and energy resolution

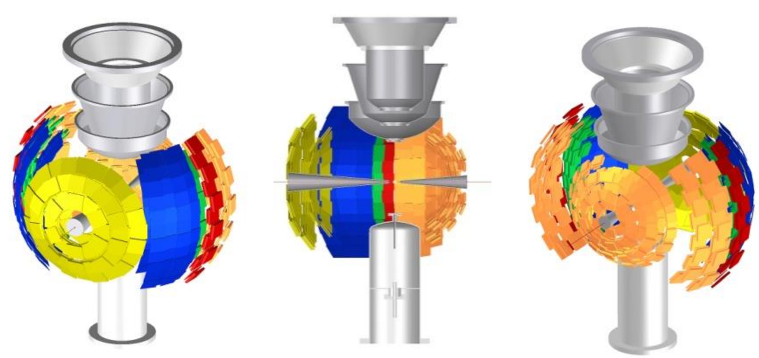
Advantage of Storage Rings for Direct Reactions in Inverse Kinematics

- low threshold and high resolution due to: beam cooling, thin target (10^{14}-10^{15} cm^{-2})
- gain of luminosity due to: continuous beam accumulation and recirculation
- low background due to: pure, windowless $^{1,2}H_2$, $^{3,4}He$, etc. targets
- experiments with isomeric beams

Experiments at very low momentum transfer can only be performed at EXL (except with active targets, but with substantial lower luminosity)

The EXL Recoil and Gamma Array





Si DSSD ⇨ **ΔE, x, y**
300 µm thick, spatial resolution better than 500 µm in x and y,
ΔE = 30 keV (FWHM)

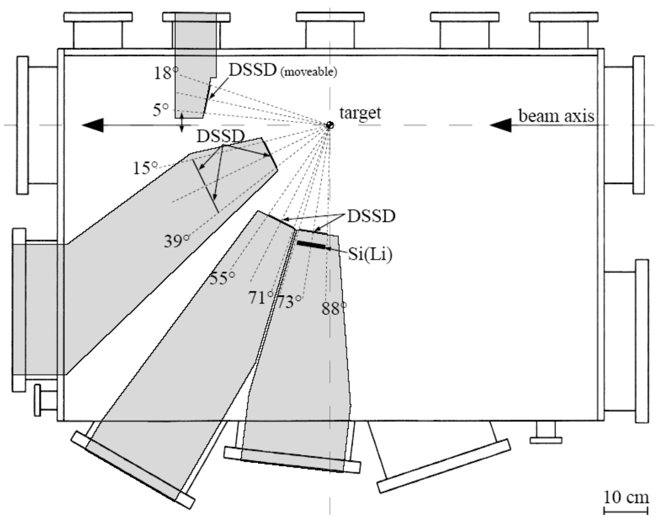
Thin Si DSSD ⇨ **tracking**
<100 µm thick, spatial resolution better than 100 µm in x and y,
ΔE = 30 keV (FWHM)

Si(Li) ⇨ **E**
9 mm thick, large area
100 x 100 mm^2,
ΔE = 50 keV (FWHM)

CsI crystals ⇨ **E, γ**
High efficiency, high resolution, 20 cm thick

III. Feasibility Studies and First Experiments with RIB`s at the ESR Storage Ring

specially designed scattering chamber for the ESR:



reactions with ^{58}Ni:

proof of principles and feasibility studies:

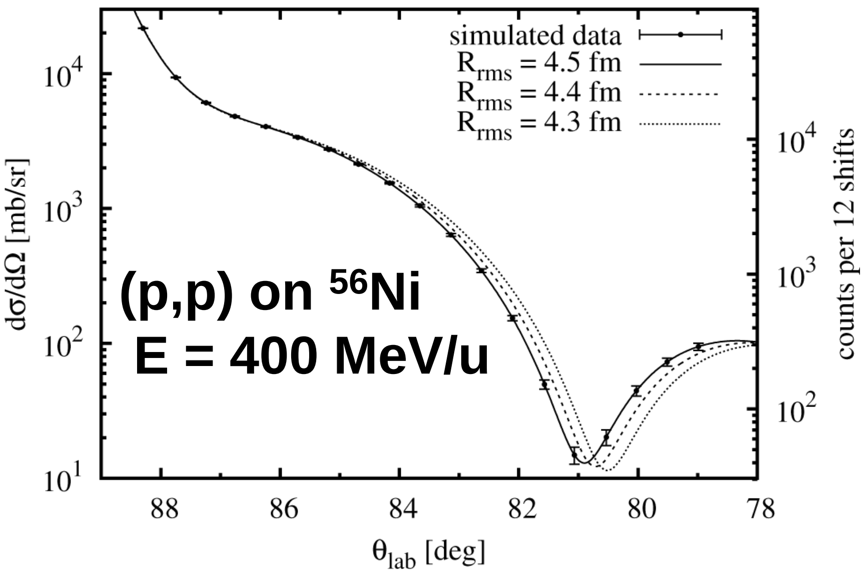
- UHV capability of detector setup
- background conditions in ESR environment at the internal target
- low energy threshold
- beam and target performance

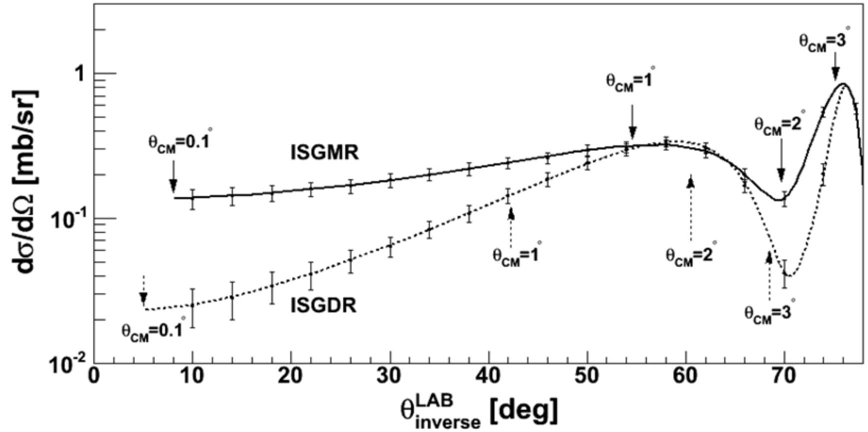
reactions with ^{56}Ni:

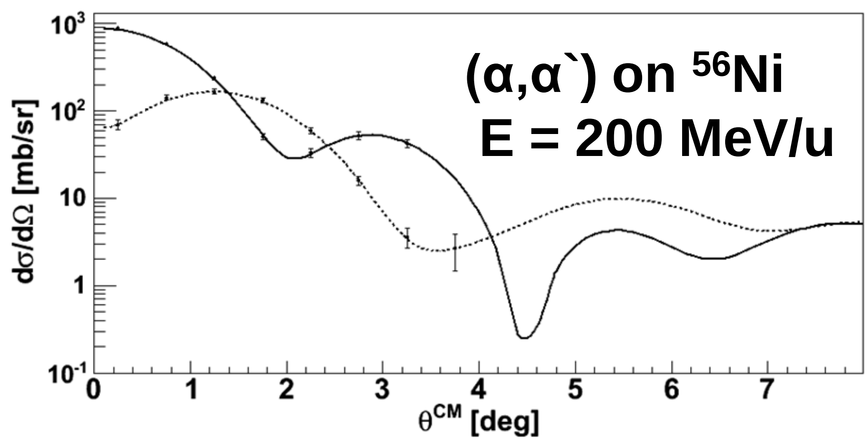
^{56}Ni: doubly magic nucleus!!

- (p,p) reactions: nuclear matter distribution
- (α,α`) reactions: giant resonances (GMR) EOS parameters (nucl. compressibility)
- (^{3}He,t) reactions: Gamow-Teller matrix elements, important for astrophys.

Theorectical Predictions





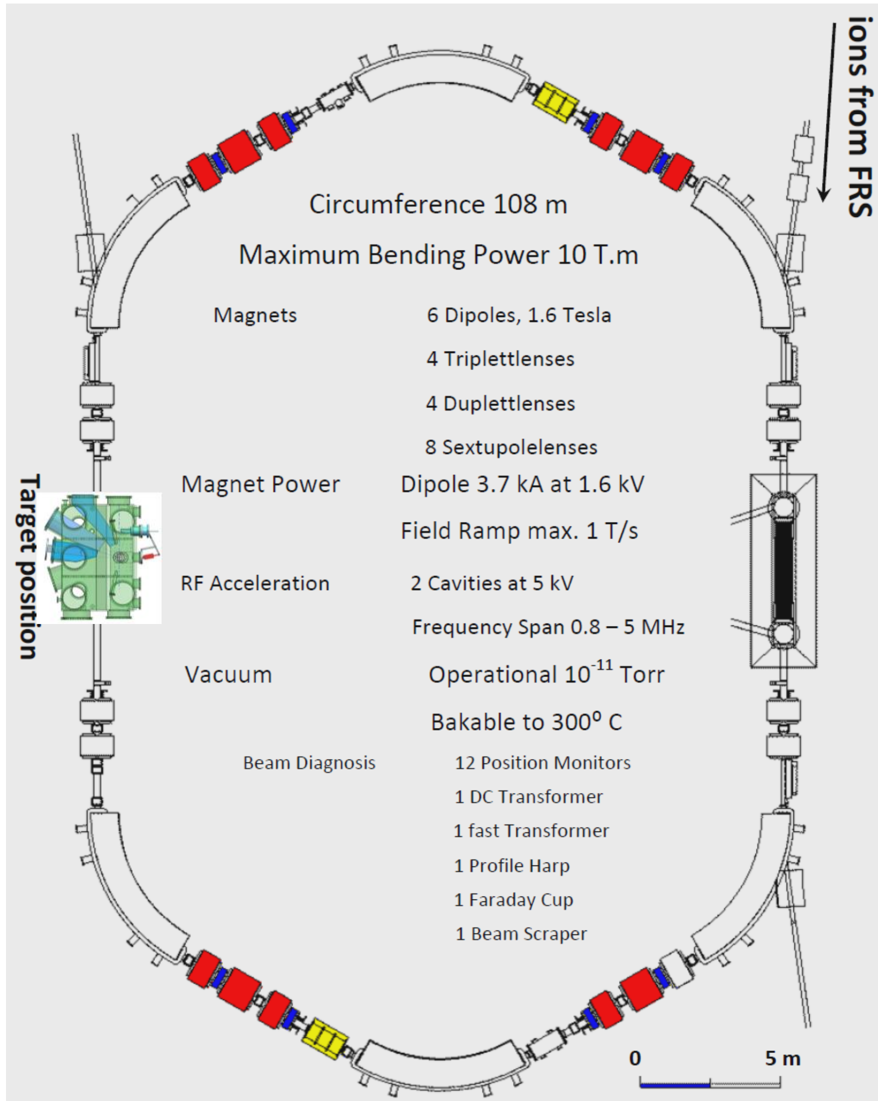


4 days with L = 10^{25} cm^{-2} sec^{-1}
recoil energies: 1 – 45 MeV

14 days with L = 10^{25} cm^{-2} sec^{-1}
recoil energies: 200 – 700 keV

<u>needed:</u> large solid angle detectors with low threshold and large dynamic range

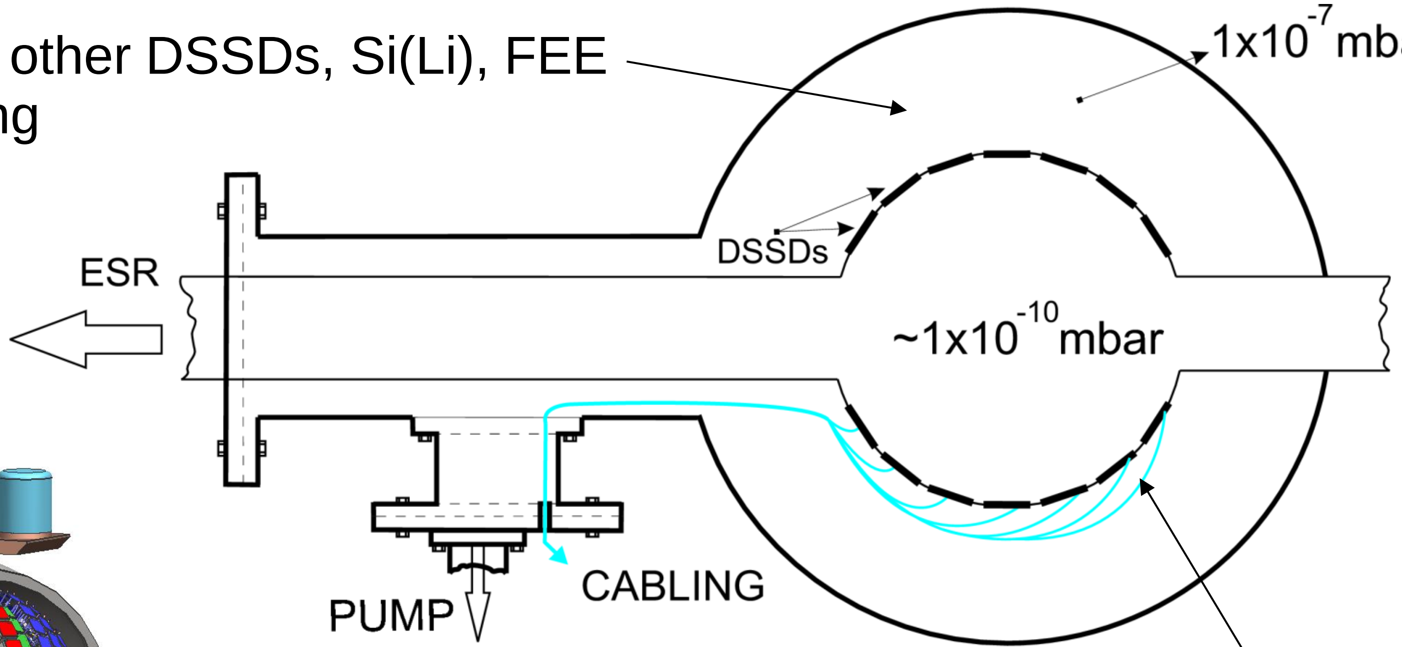
Setup at the ESR Storage Ring

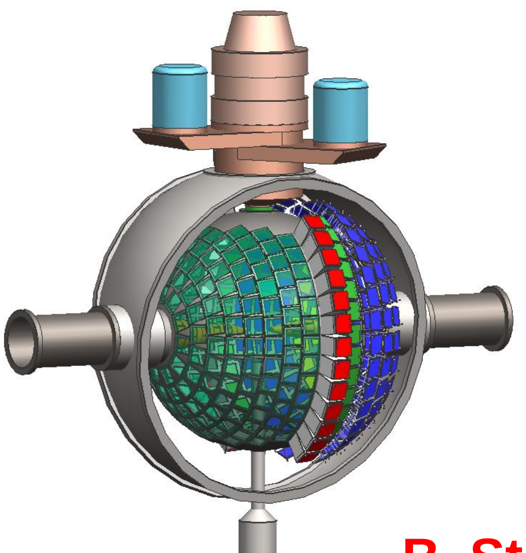


UHV Capability of the EXL Silicon Array:
Concept: using DSSD`s as high vacuum barrier

- Differential pumping proposed to separate (N)ESR vacuum from EXL instrumentation (cabling, FEE, other detectors)

Space for other DSSDs, Si(Li), FEE and cabling

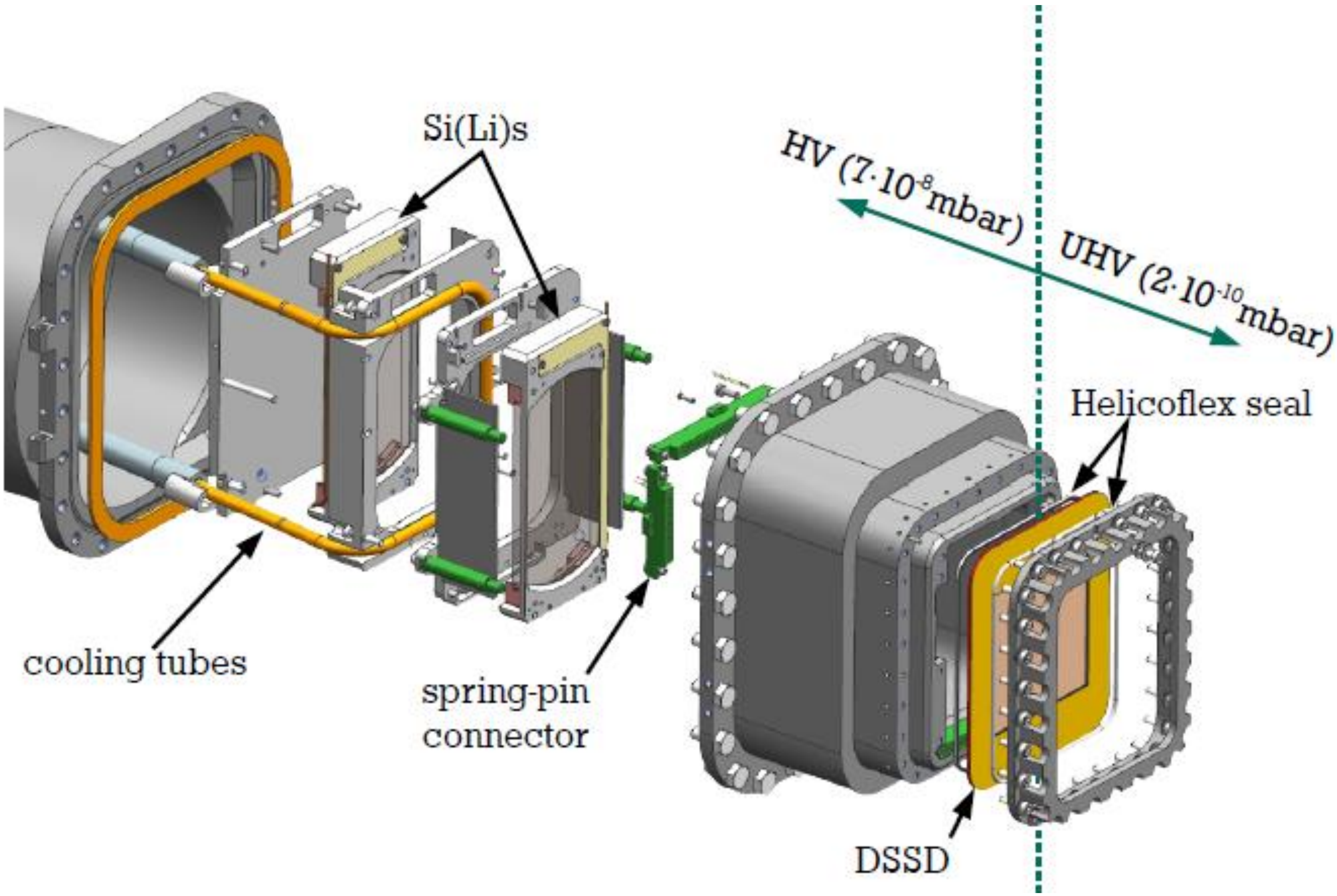




Inner shell of DSSDs on support frame forms (bakeable) vacuum barrier

B. Streicher et al., Nucl. Instr. Meth. A654 (2011) 604

Experimental Concept



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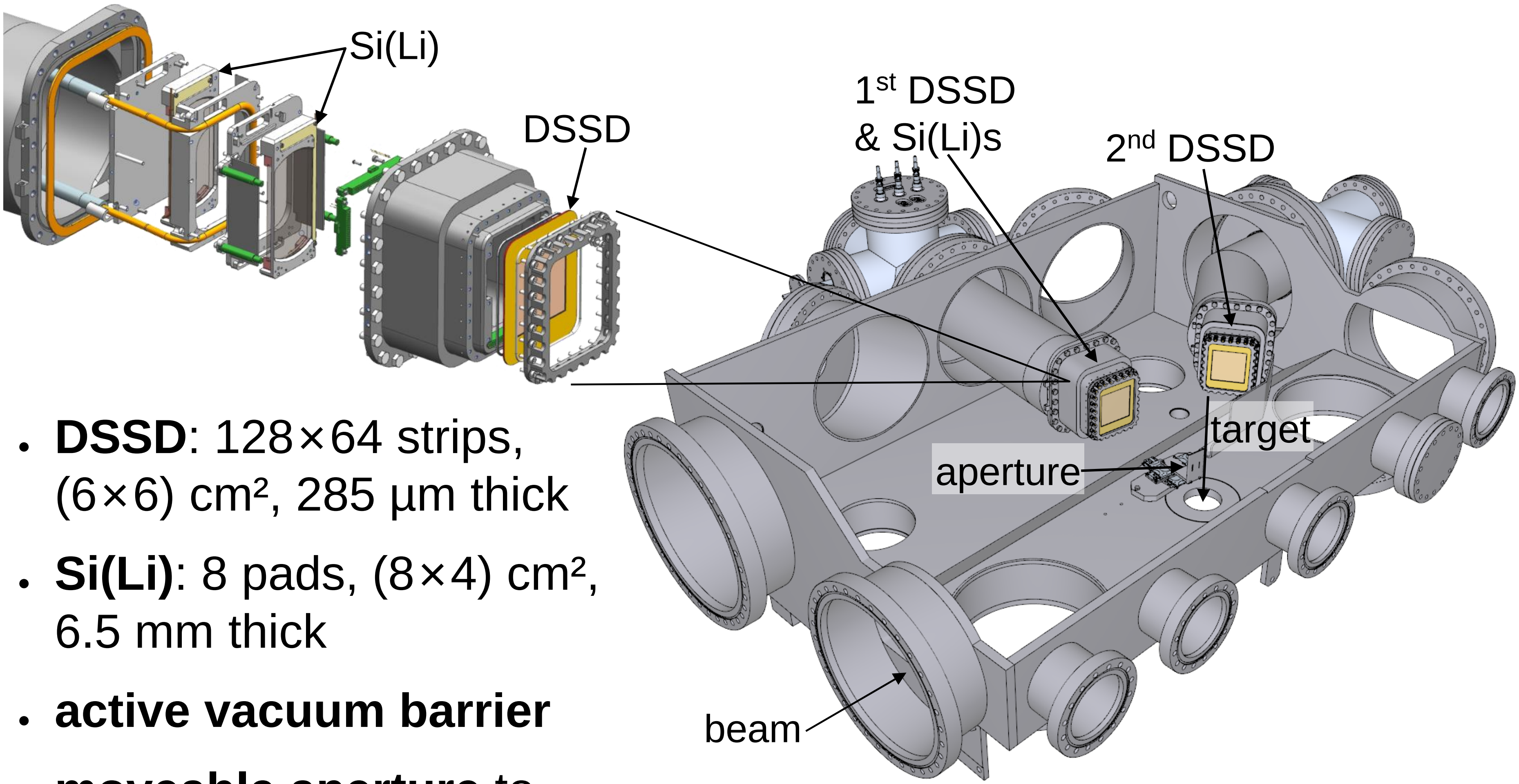
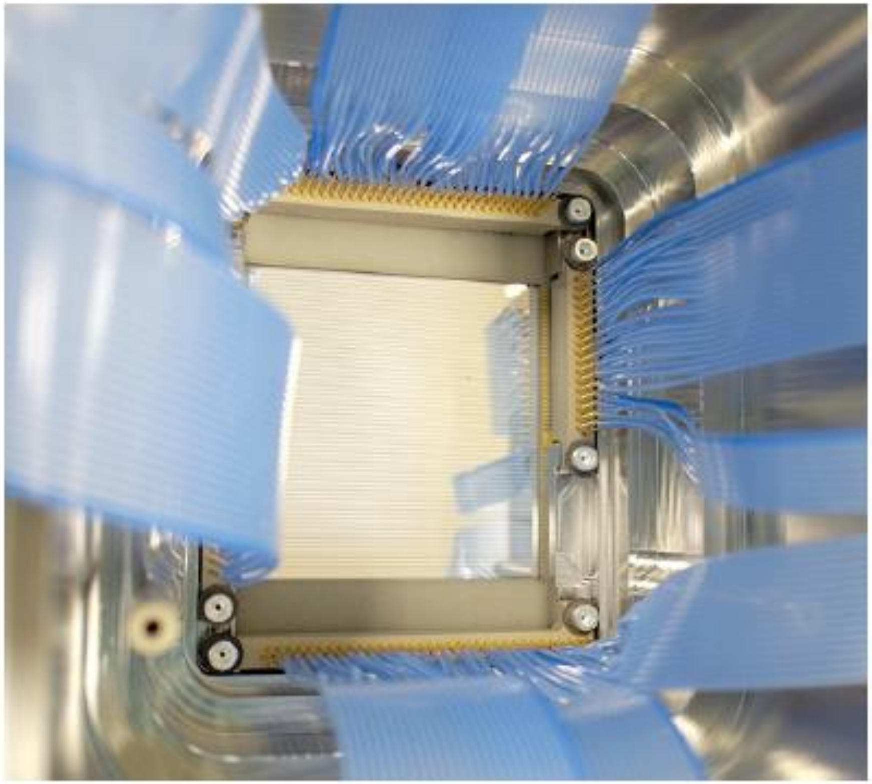


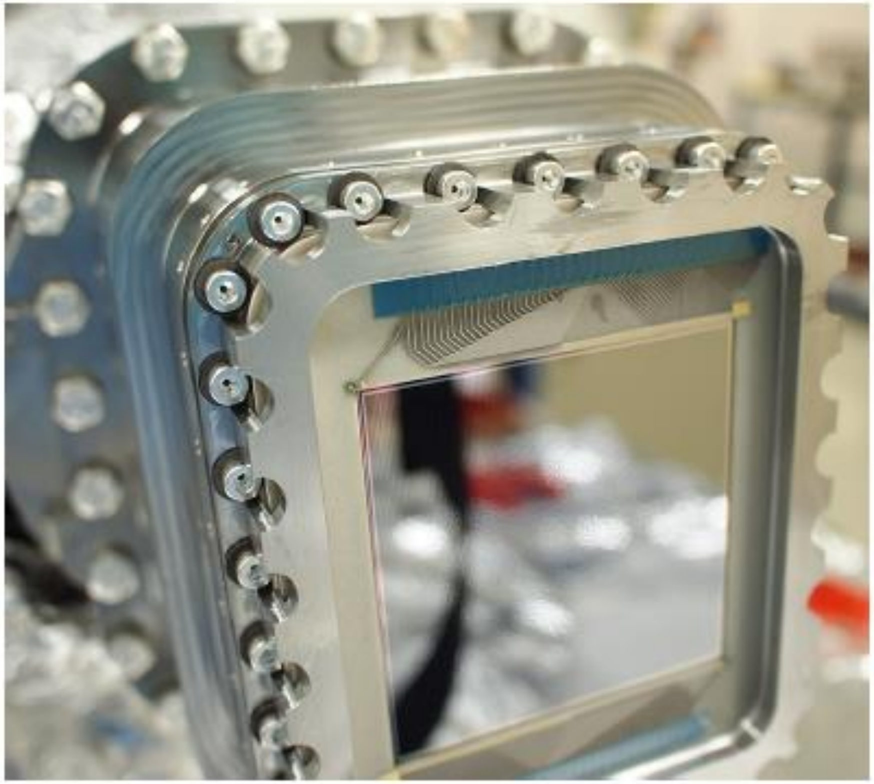
- **DSSD**: 128×64 strips, (6×6) cm², 285 µm thick
- **Si(Li)**: 8 pads, (8×4) cm², 6.5 mm thick
- **active vacuum barrier**
- **moveable aperture** to improve angular resolution

Experimental Concept for the E105 Experiment

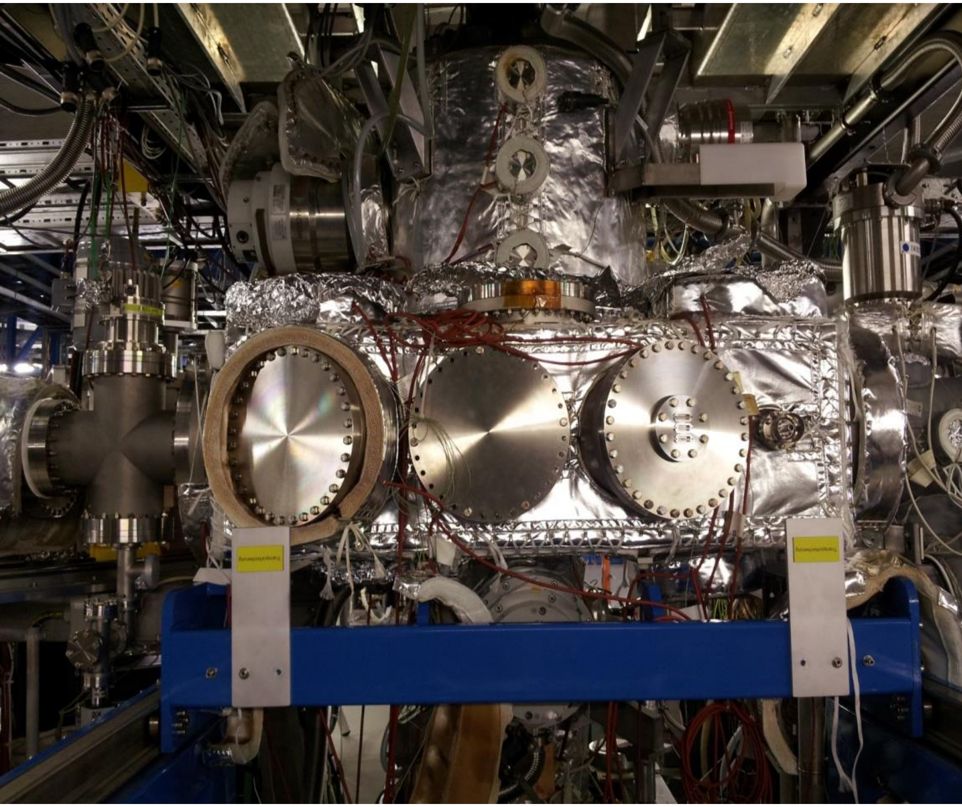
- Auxilliary vacuum side



- Ultra-high vacuum side

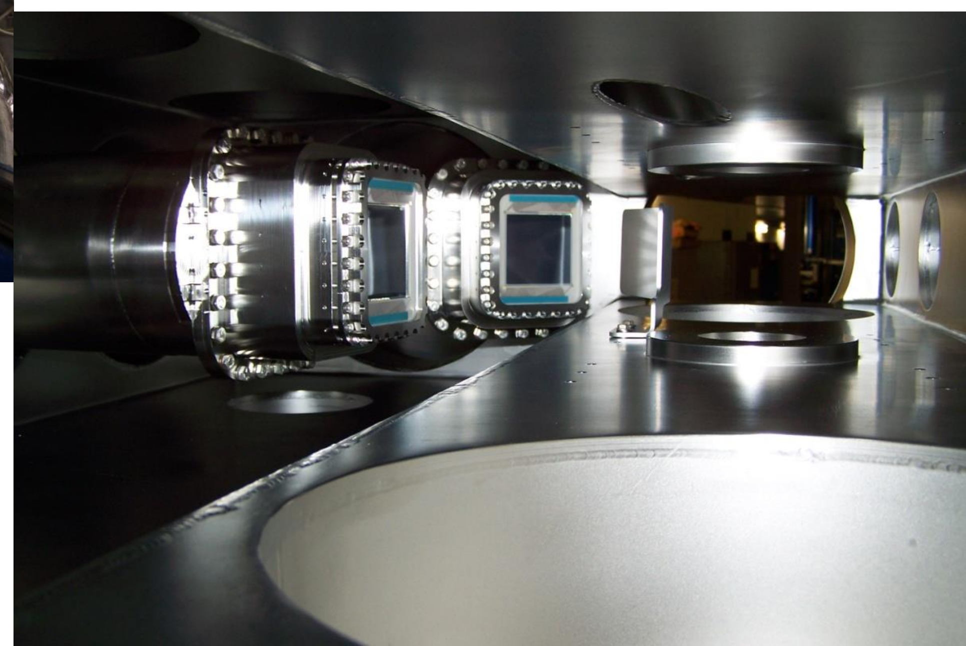


Experimental Setup at the ESR



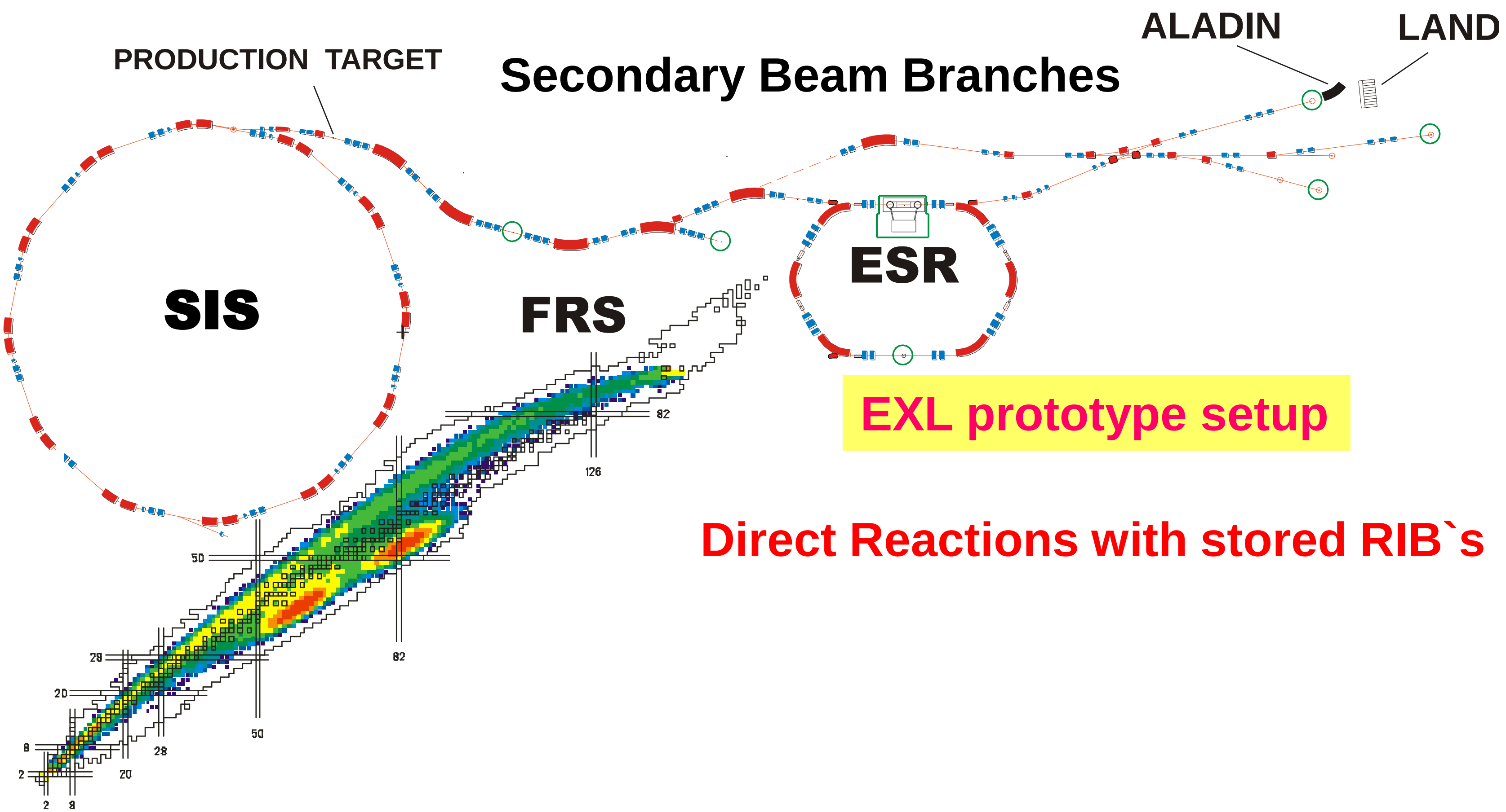
Scattering Chamber mounted at the Internal Target of the ESR

challenge:
UHV capable and bakeable DSSD and Si(Li) detectors



Preparation of the Stored Radioactive ^{56}Ni Beam

FRS: In-Flight Separator & High-Resolution Spectrometer



EXL prototype setup

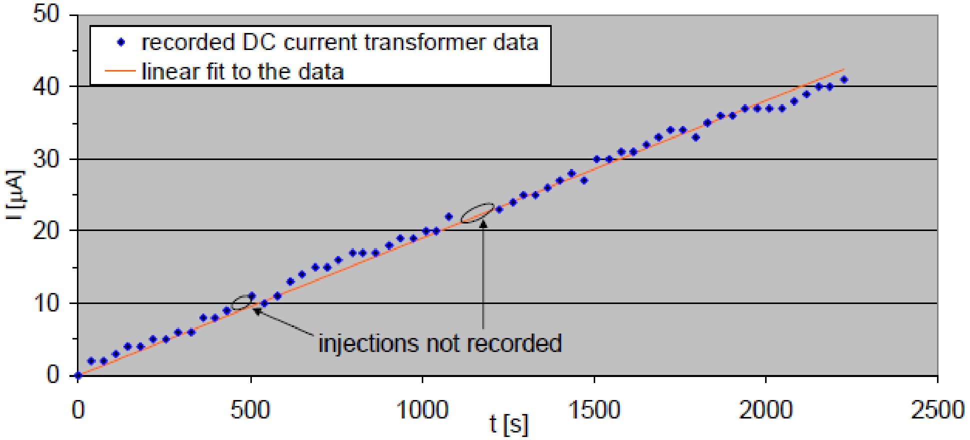
Direct Reactions with stored RIB`s

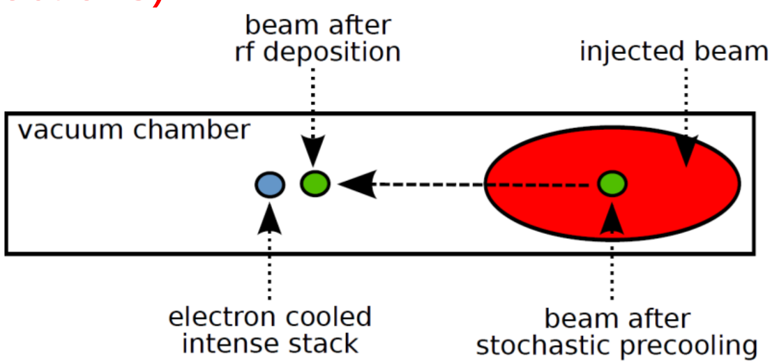
Preparation of the Stored Radioactive ^{56}Ni Beam

FRS: fragmentation of 600 MeV/u ^{58}Ni beam

injection to ESR: **7 x 10^4** ^{56}Ni per injection

stochastic cooling, bunching and stacking (60 injections):
4.8 x 10^6 ^{56}Ni in the ring

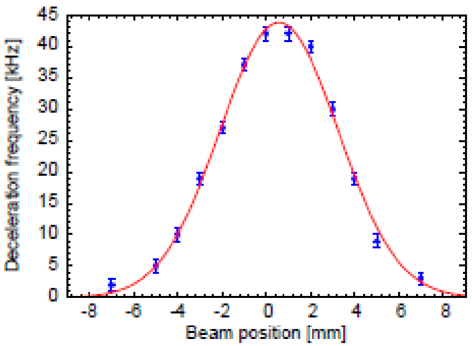




luminosity: H_2 target: 2 x 10^{13} cm^{-2}

$\Rightarrow$ **L = 2 x 10^{26} cm^{-2} sec^{-1}**
(reduced by aperture)

target profile

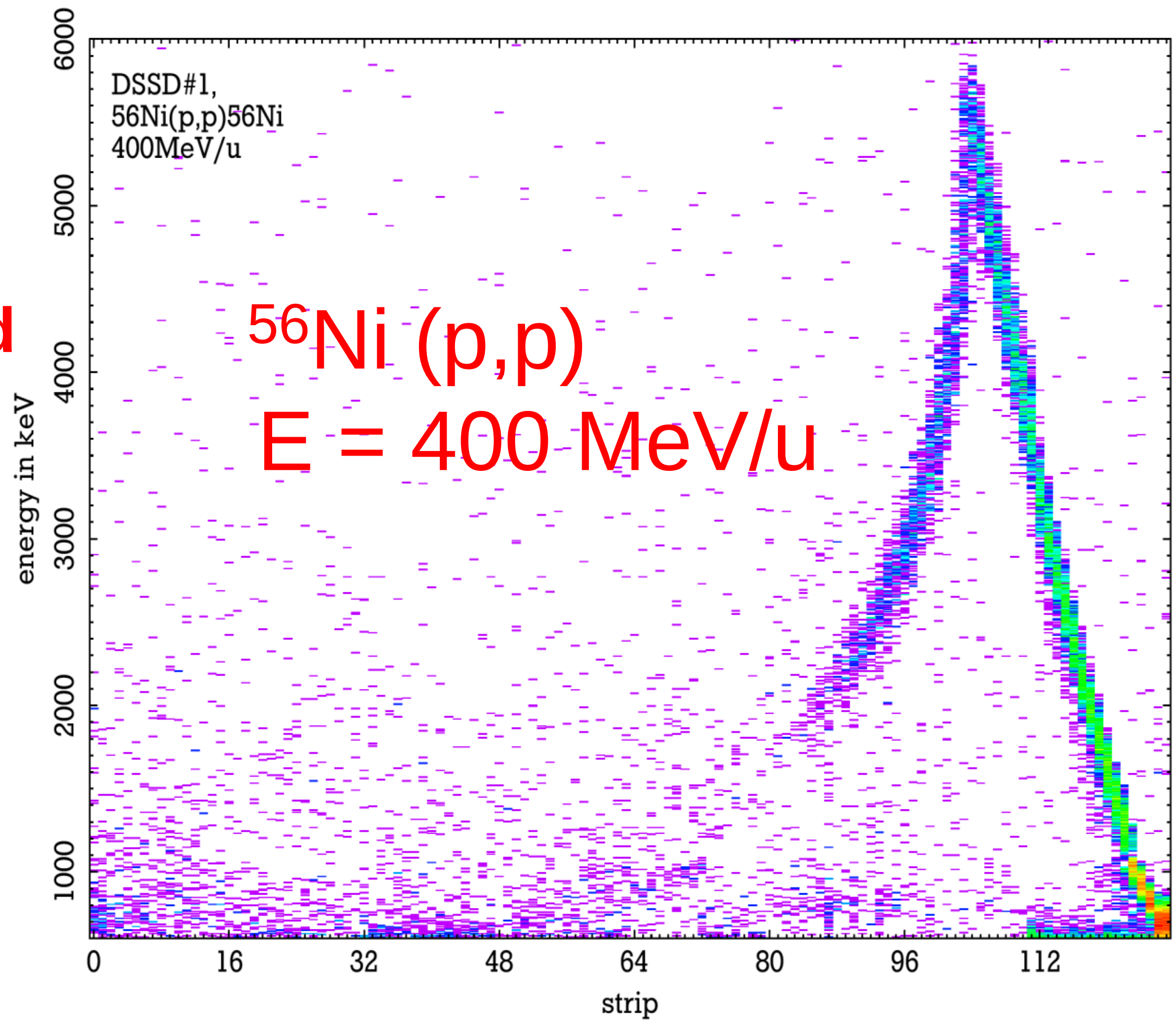


$\sigma = 3.78$ mm $\quad x_0 = 0.58$ mm

First Results with Radioactive Beam

25. 10. 2012:

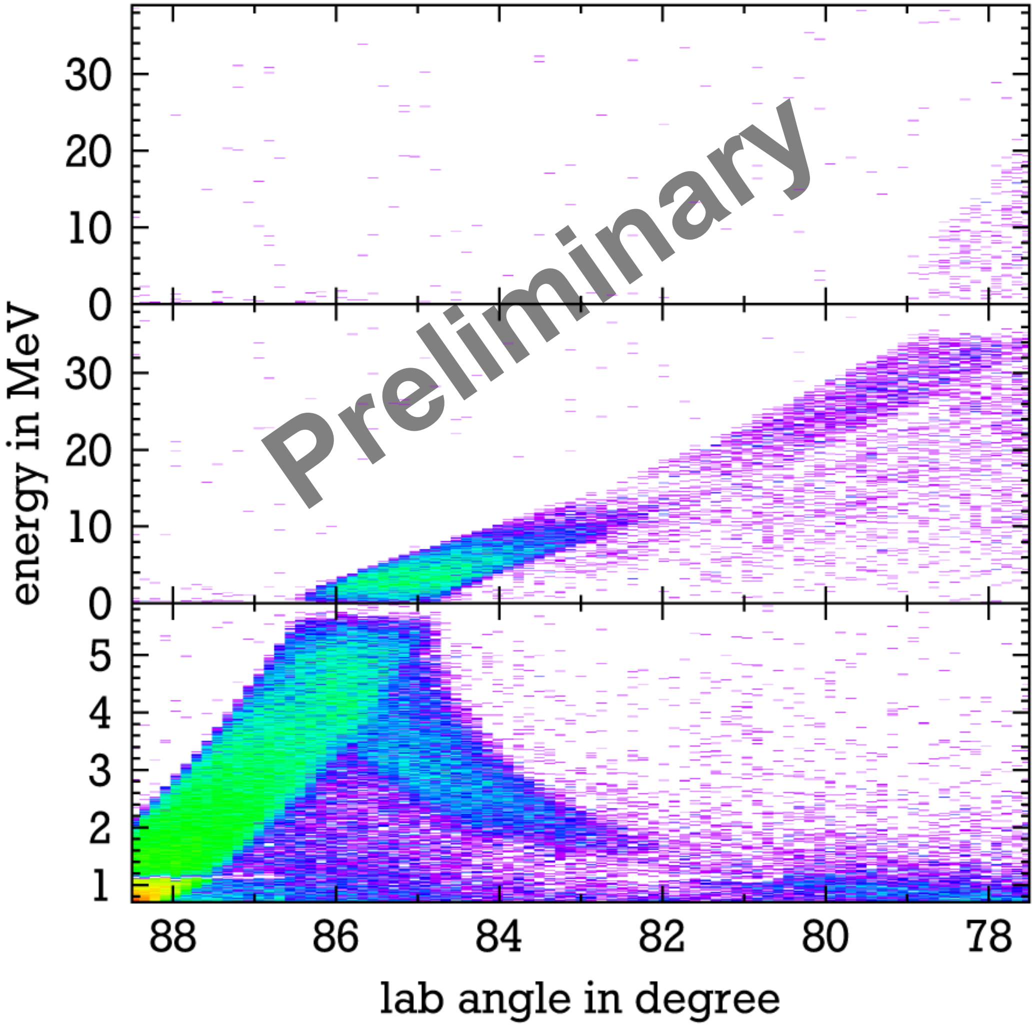
First Nuclear Reaction Experiment with Stored Radioactive Beam!!!!

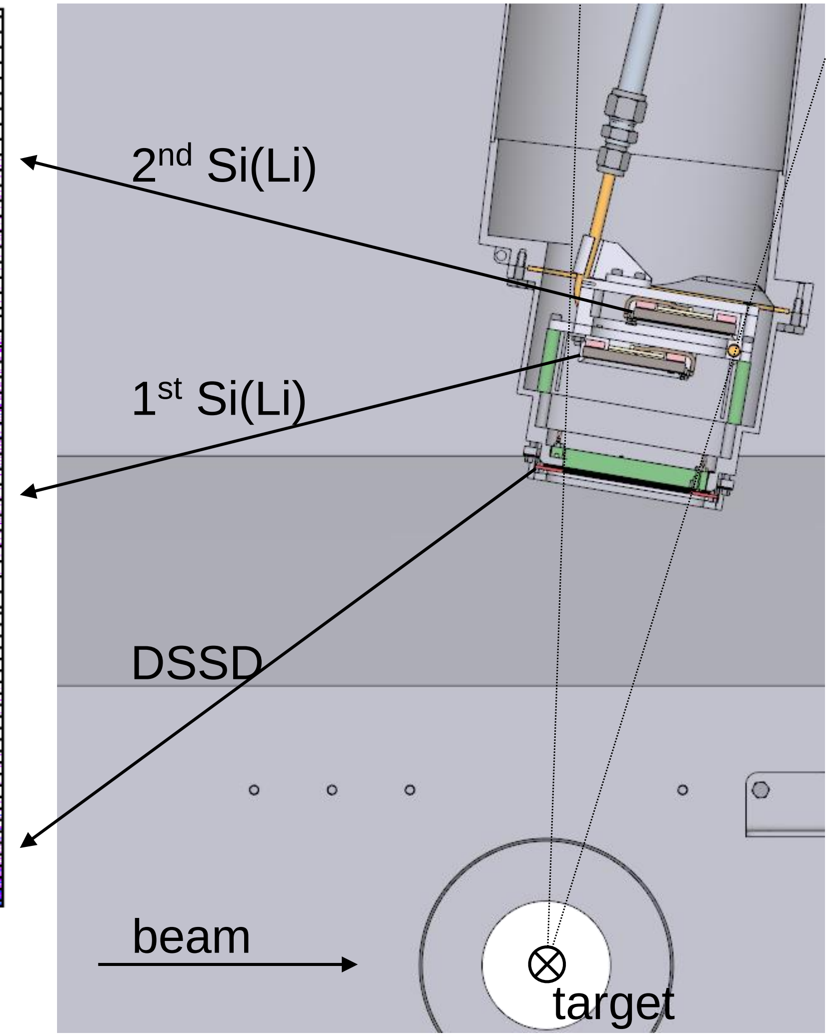


Θ_{Lab} = 72° .... 88°

First Results with Radioactive Beam

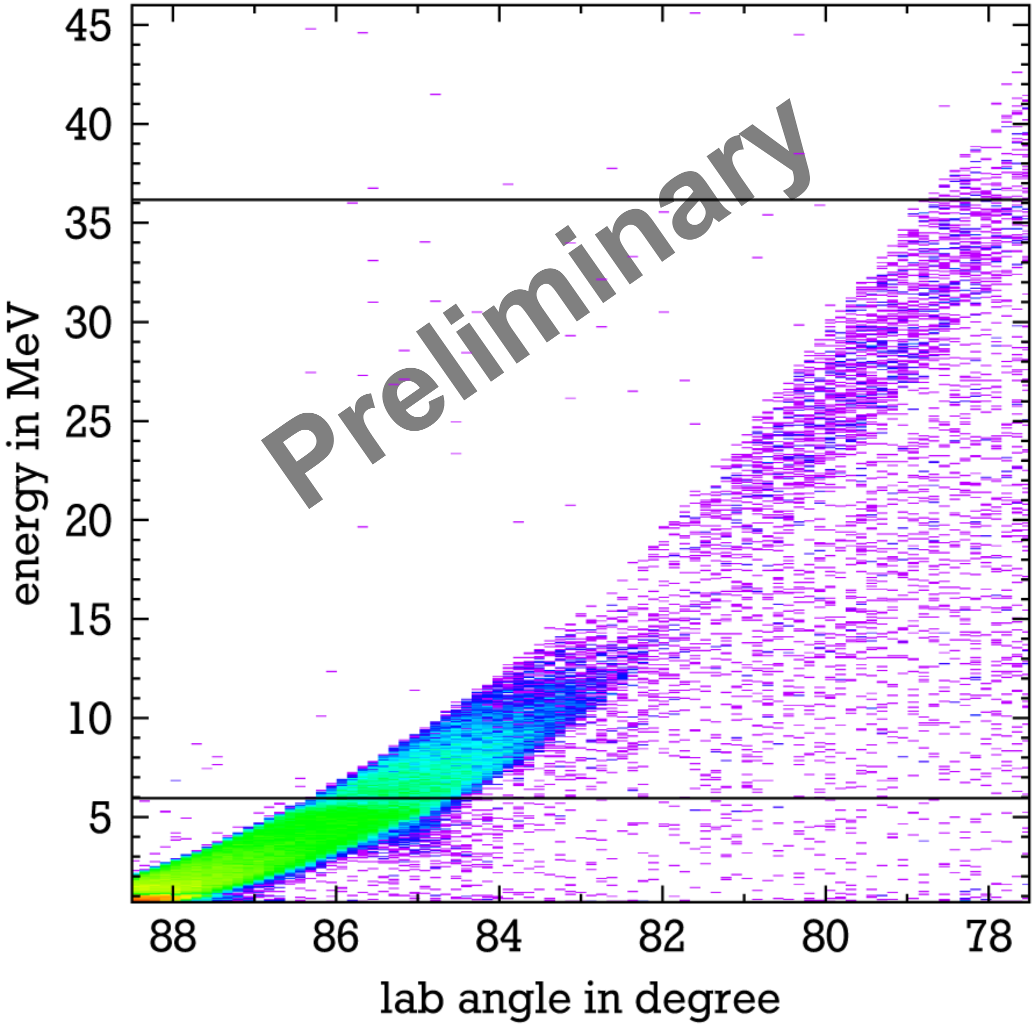
$^{56}Ni(p,p)$, E = 400 MeV/u   Response of Individual Detectors

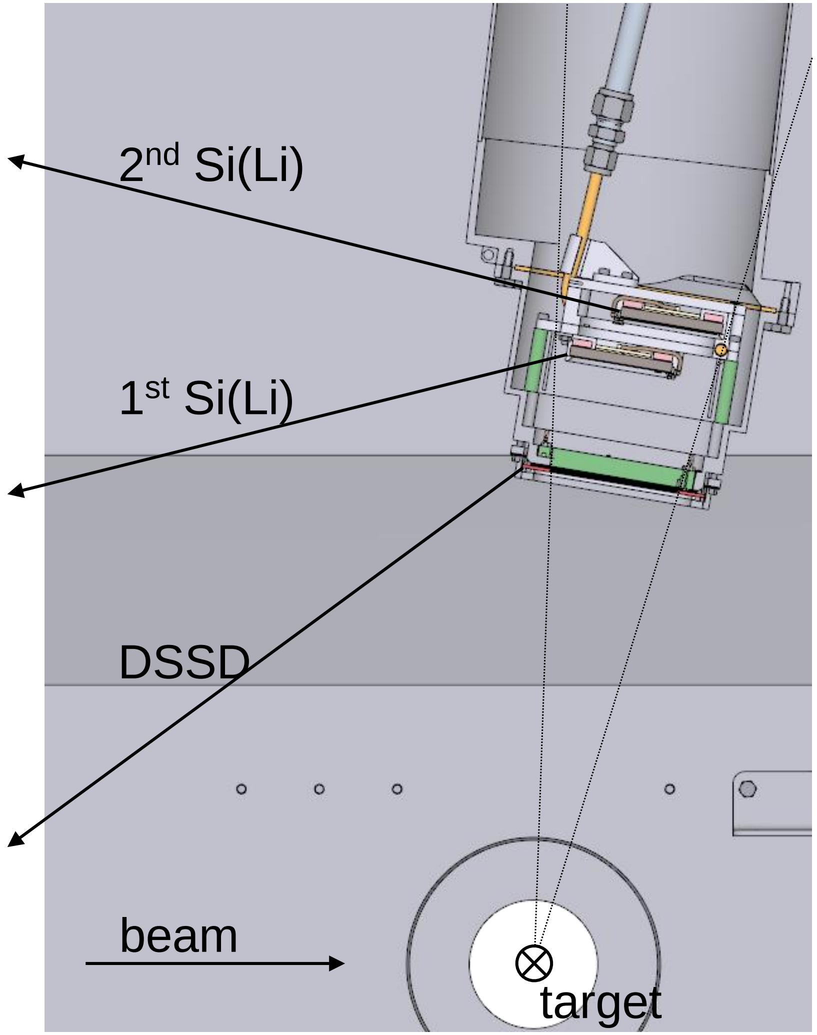




First Results with Radioactive Beam

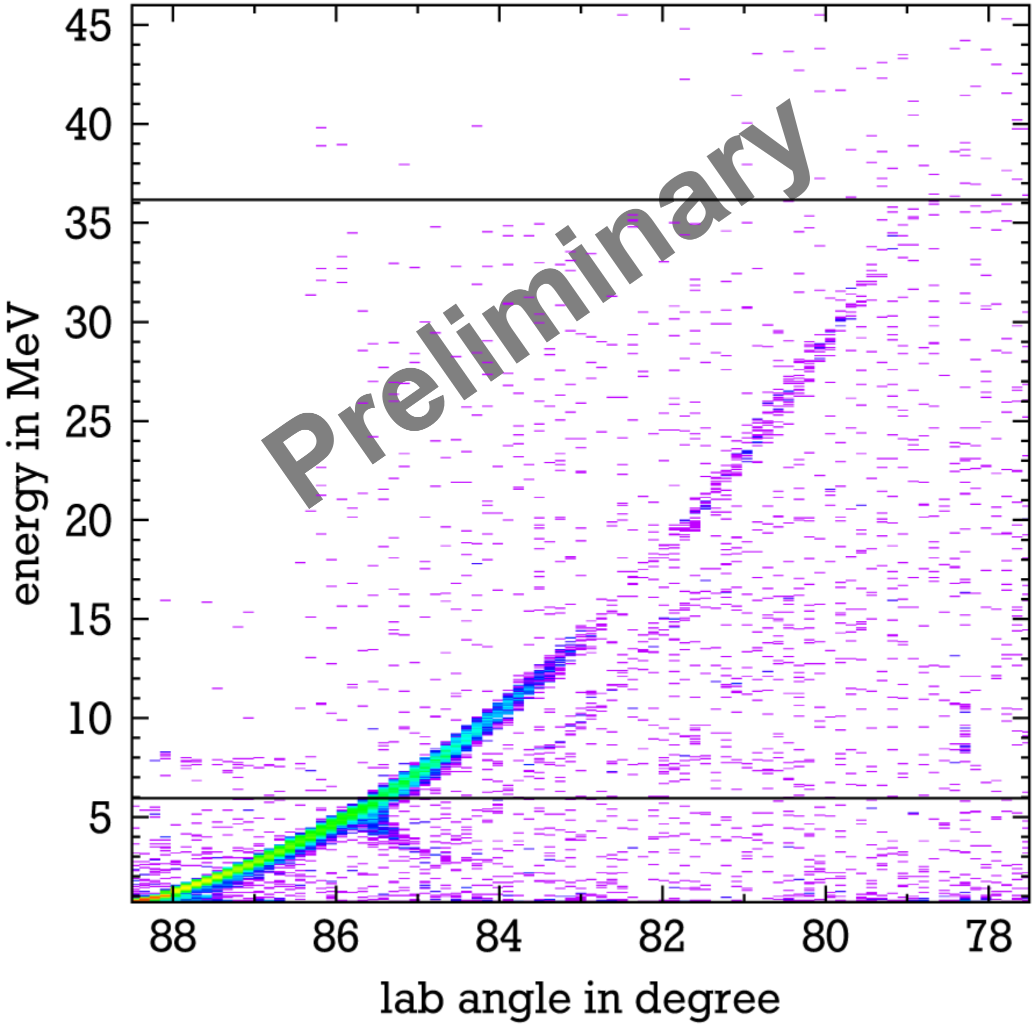
^{56}Ni(p,p), E = 400 MeV/u   Reconstructed Energy

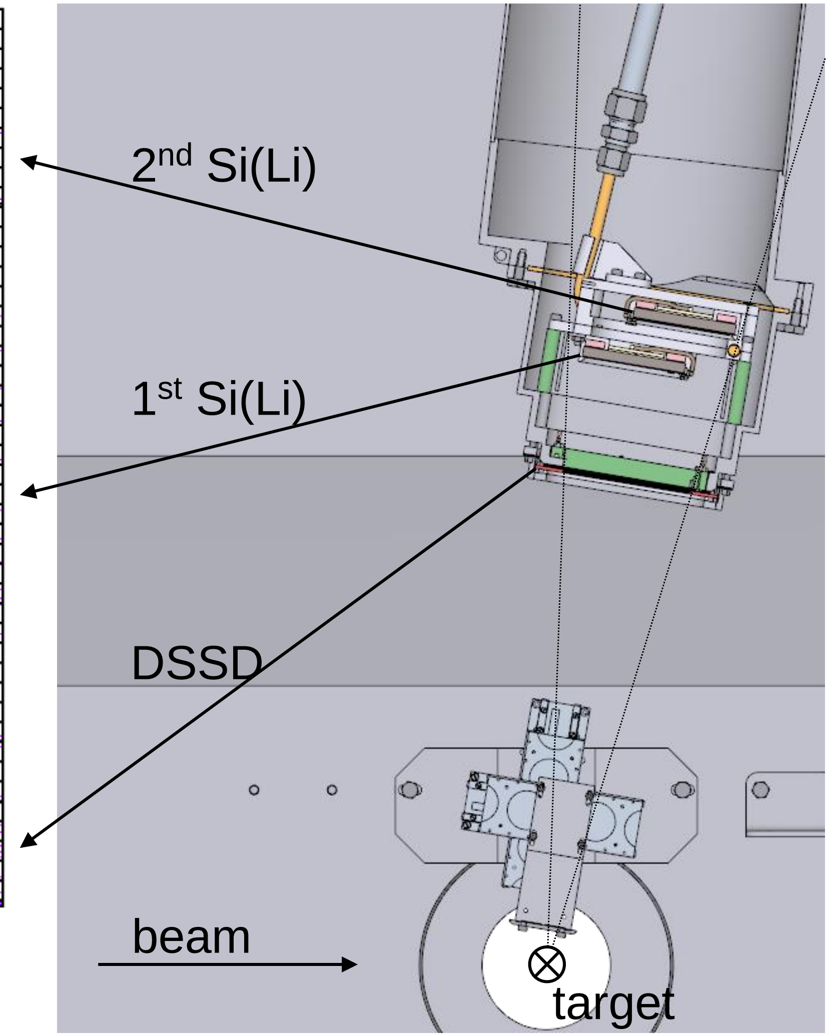




First Results with Radioactive Beam

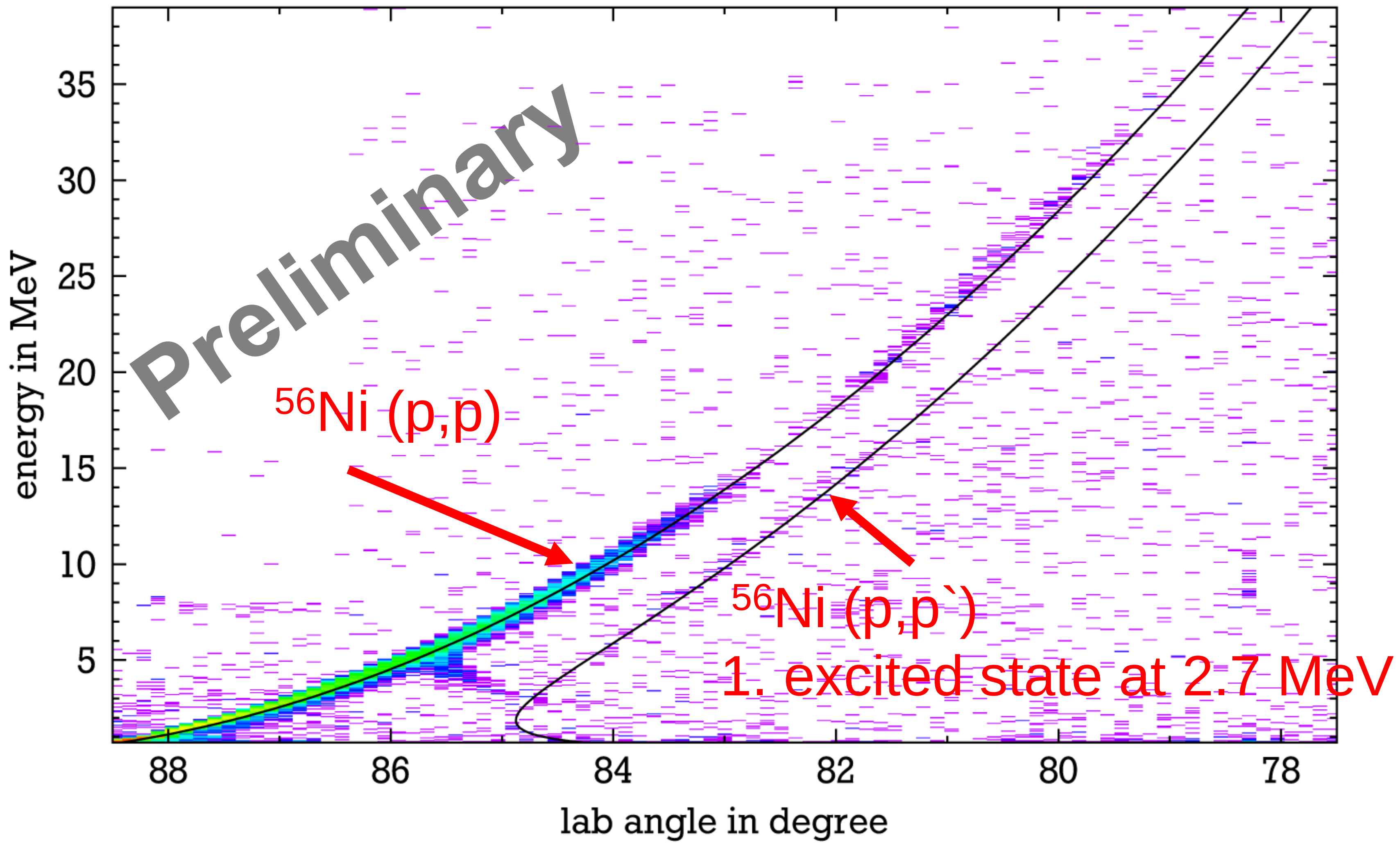
^{56}Ni(p,p), E = 400 MeV/u   Benefit of the 1mm Aperture





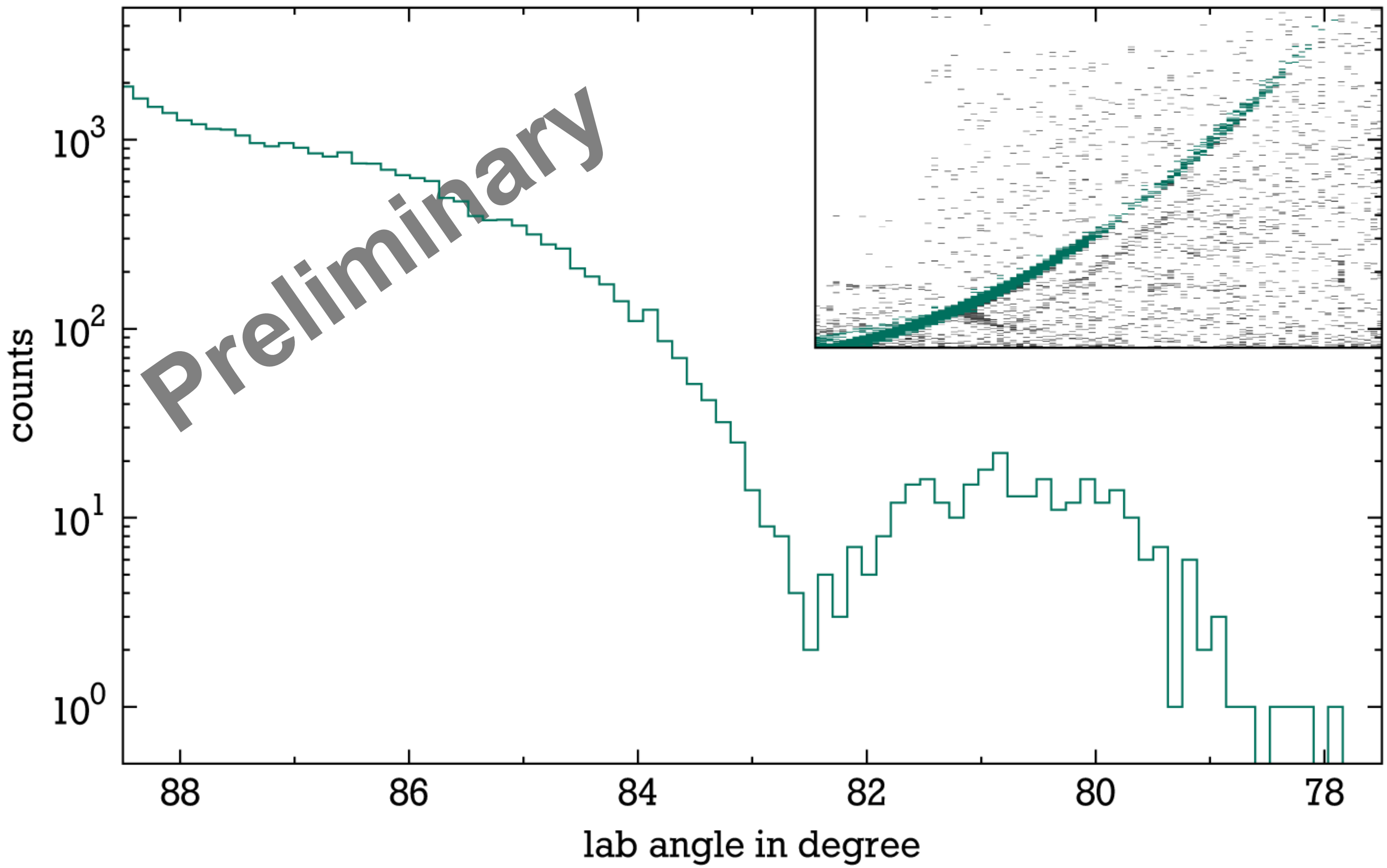
First Results with Radioactive Beam

^{56}Ni(p,p`), E = 400 MeV/u Identification of Inelastic Scattering



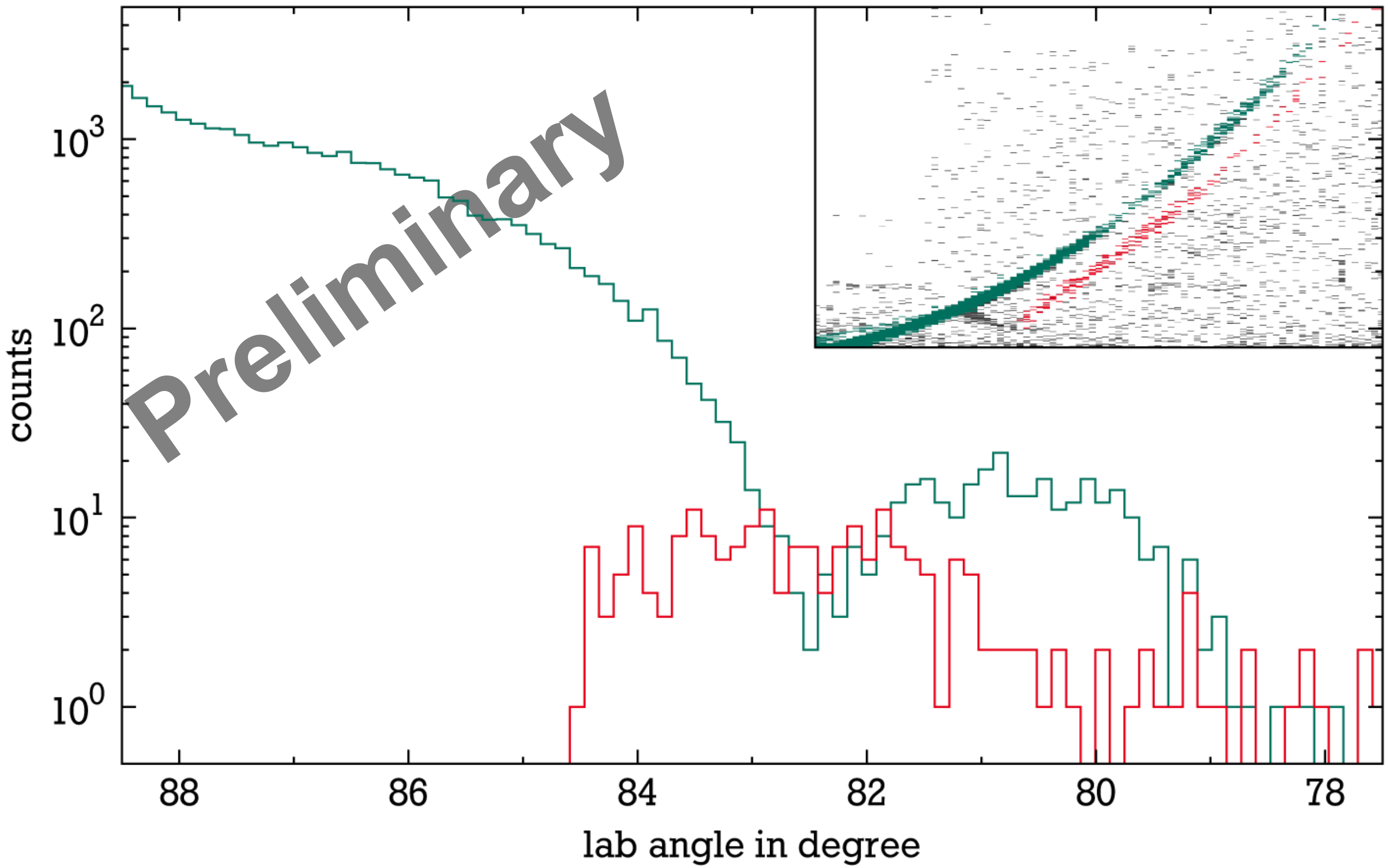
First Results with Radioactive Beam

^{56}Ni(p,p), E = 400 MeV/u Angular Distribution



First Results with Radioactive Beam

^{56}Ni(p,p), E = 400 MeV/u Angular Distribution (raw data!)



M. von Schmid et al., to be published

Investigation of the Giant Monopole Resonance in ^{58}Ni

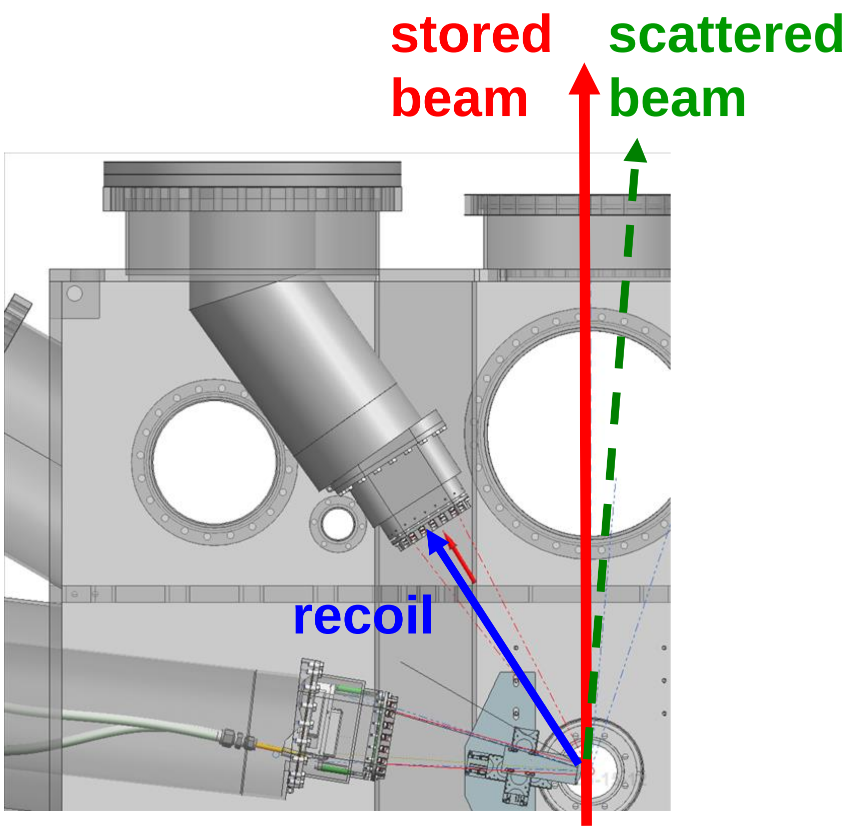
reaction: ^{58}Ni on He target

energy: 100 MeV/u

target: 8×10^{12} /cm^3

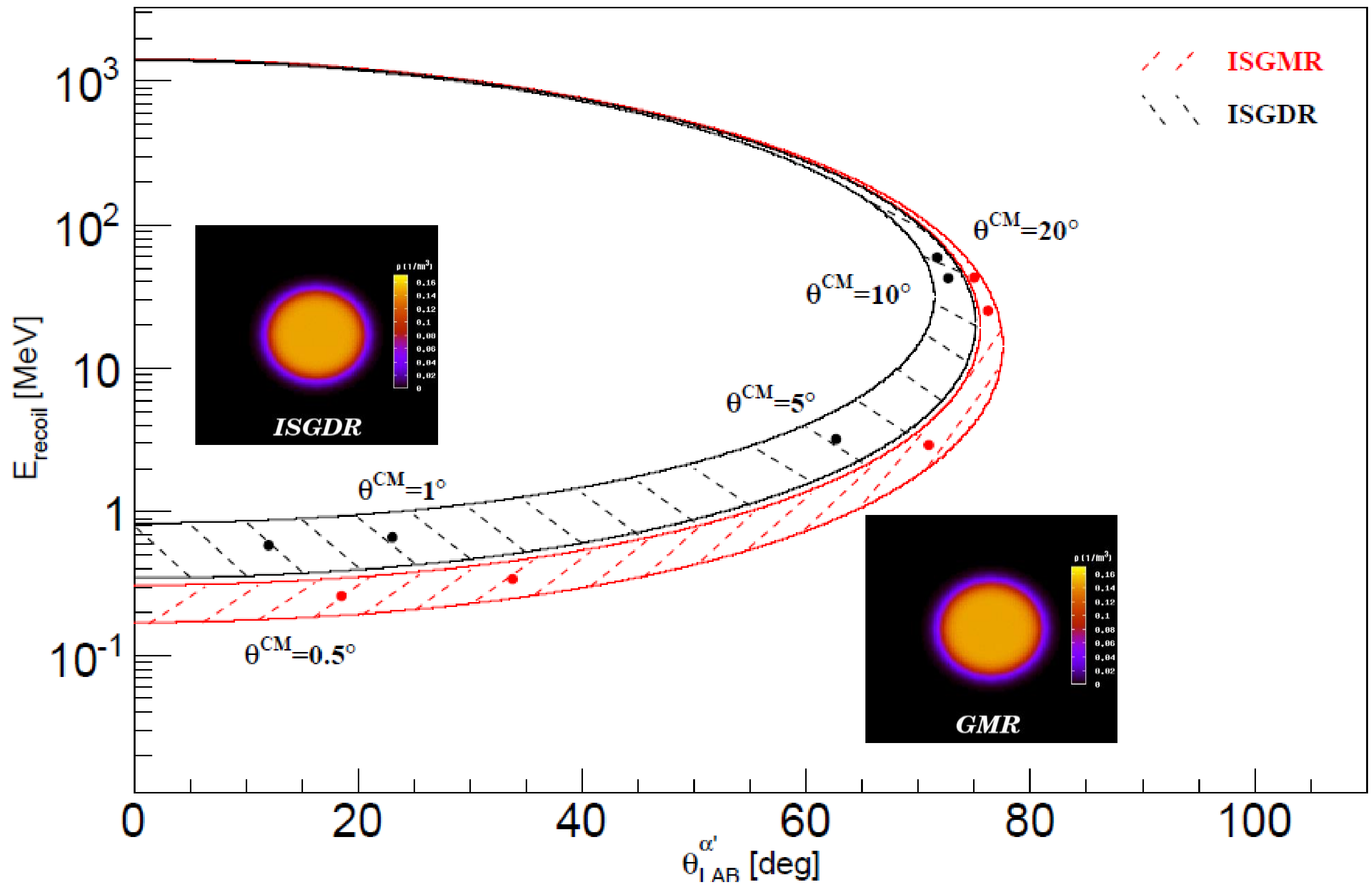
detectors: DSSD

$\Theta_{Lab} = 27° - 38°$



Investigation of the Giant Monopole Resonance in ^{58}Ni

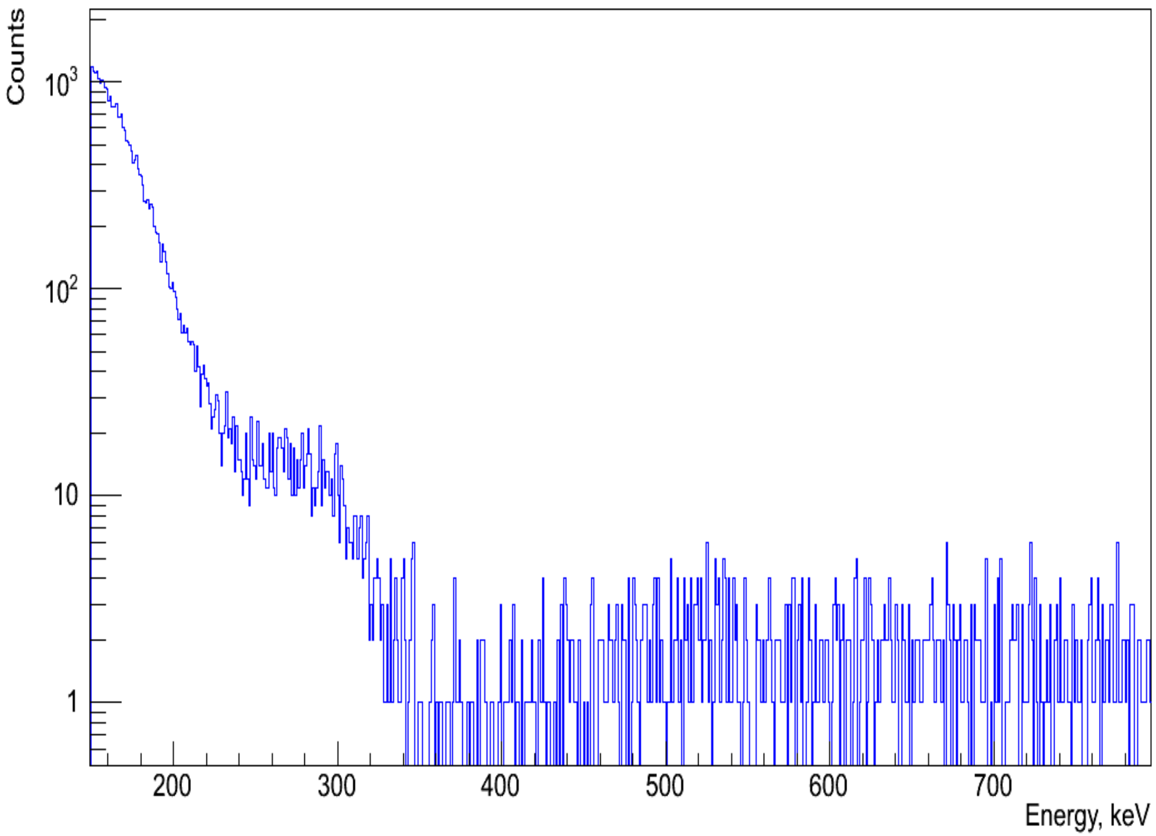
$^{58}Ni(\alpha,\alpha`)$, E = 100 MeV/u



challenge: detect and identify very low energy recoils

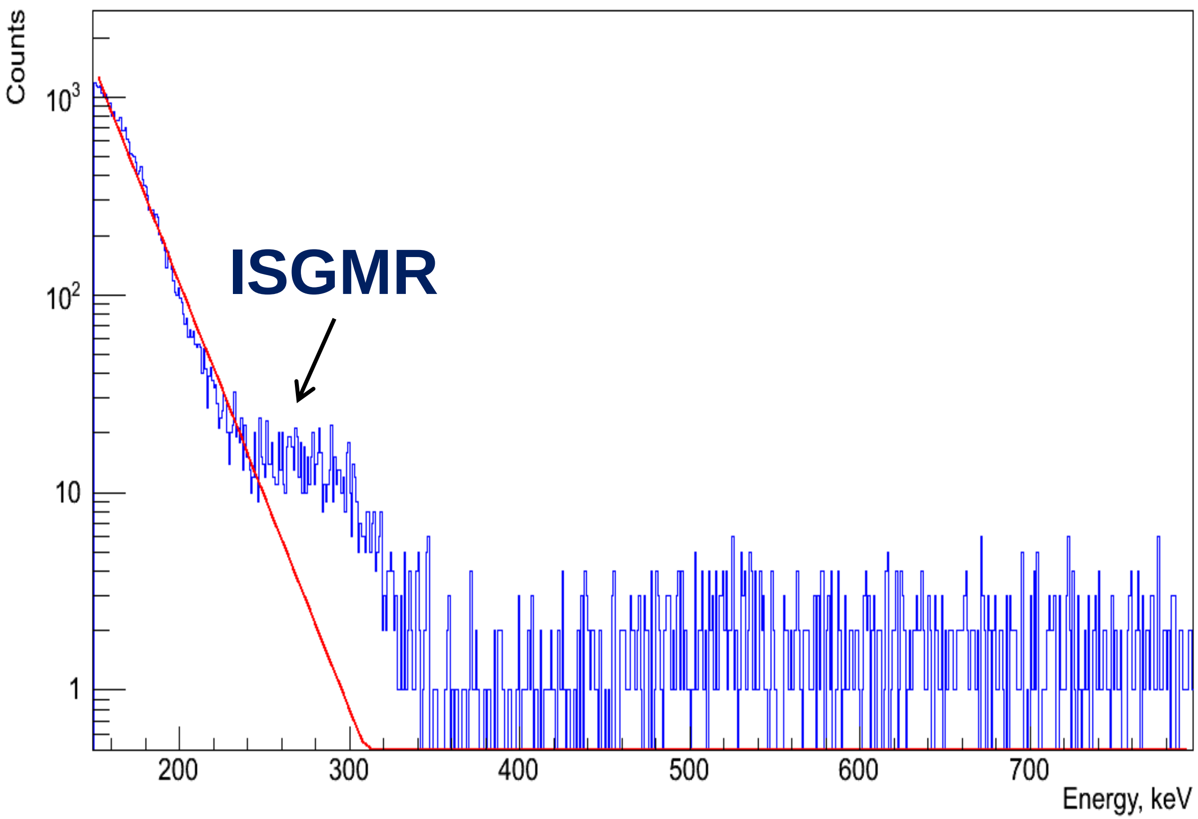
Investigation of the Giant Monopole Resonance in ^{58}Ni

$^{58}Ni(\alpha,\alpha`)$, E = 100 MeV/u, Θ_{lab} = 37 deg



Investigation of the Giant Monopole Resonance in ^{58}Ni

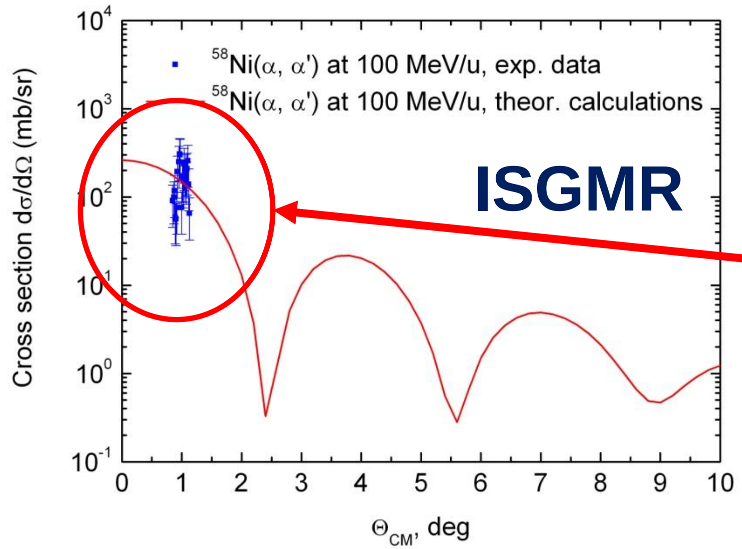
$^{58}Ni(\alpha,\alpha`)$, E = 100 MeV/u, Θ_{lab} = 37 deg



Investigation of the Giant Monopole Resonance in ^{58}Ni

comparison with theoretical prediction:

data preliminary



data down to $\Theta_{cm} < 1$ deg !

	Centroid [MeV]	RMS-width [MeV]
present data	20.5(5)	2.7(3)
PRC **73**, 014314 (2006)	18.4(2)	3.1(1)
"	$19.2^{+0.4}_{-0.2}$	$4.9^{+1.1}_{-0.3}$
Phys. Lett. B **637**, 43 (2006)	$19.9^{+0.7}_{-0.8}$	–

J. C. Zamora et al., to be published

Future Perspectives

short term perspectives:

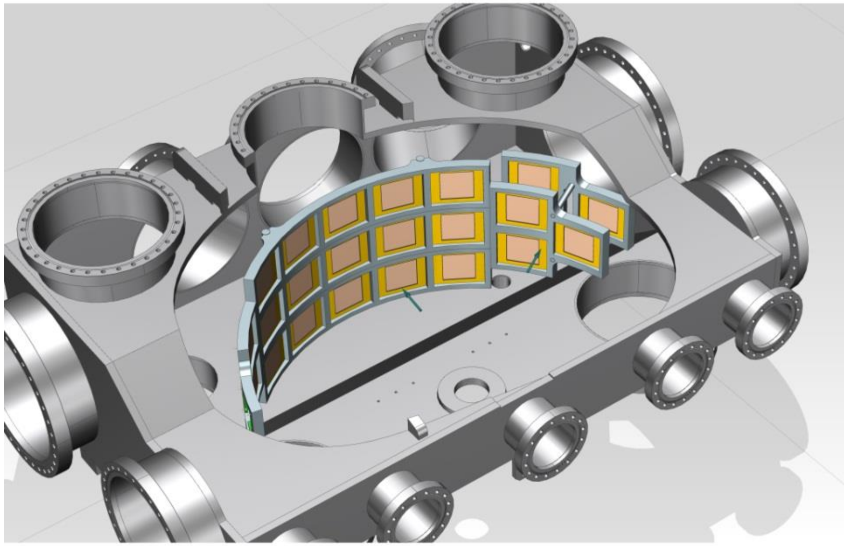
- (α,α`) on ^{56}Ni ⇒ investigate ISGMR and ISGDR
  ⇒ investigate the compressibility of nuclear matter

Future Perspectives

short term perspectives:

- (α,α`) on ^{56}Ni ⇒ investigate ISGMR and ISGDR

  needs upgrade of detector setup
  and readout (ASICS)



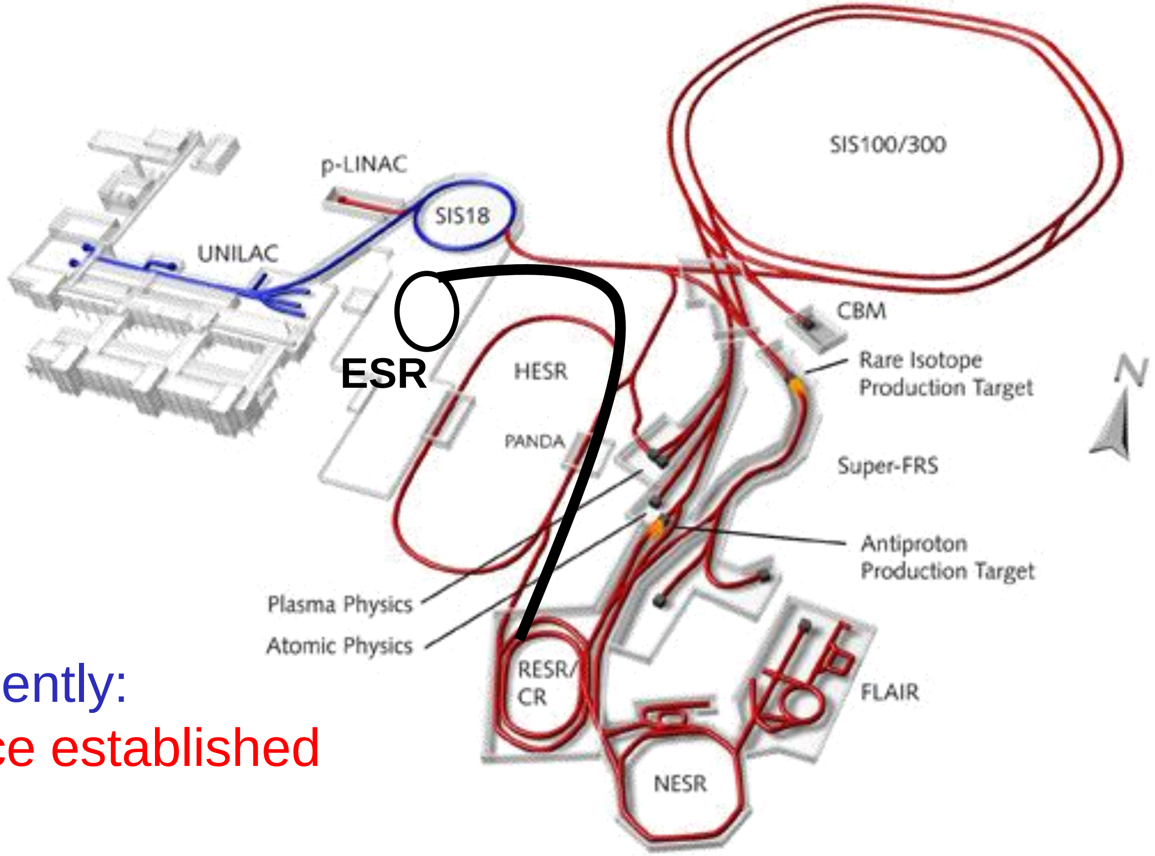
- (^{3}He,t) on ^{56}Ni ⇒ investigate Gamow – Teller strength
  needs upgrade of internal target

- transfer reactions at Cryring (GSI) and TSR@ISOLDE (CERN)

Future Perspectives

long term perspectives (EXL @ FAIR):

- for first phase of FAIR:
  transfer line from SUPER-FRS / CR to the ESR



- very recently:
  task force established

The E105 Collaboration

S. Bagachi[1], S. Bönig[2], M. Castlós[3], I. Dillmann[4], C. Dimopoulou[4], P. Egelhof[4], V. Eremin[5], H. Geissel[4], R. Gernhäuser[6], 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], M. Mutterer[4], D. Nagae[8], 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[9], H. Weick[4], J.S. Winfield[4], D. Winters[4], P.J. Woods[10], T. Yamaguchi[11], K. Yue[4,7], J.C. Zamora[2], J. Zenihiro[9]

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

V. Conclusions

- For the First Time (World Wide) a Nuclear Reaction Experiment with Stored Radioactive Beams was successfully performed.
- A “Proof of Principle” of the Experimental Concept with UHV capable Detectors and Infrastructure around the Internal Target was successful.
- A number of Important Physics Questions can be only addressed with the EXL Technique which is up to date World Wide unique.
- EXL@ESR and EXL@FAIR has a large Potential for Nuclear Structure and Nuclear Astrophysics.