Recent Results on Direct Reactions with Stored Radioactive Beams and with Active Targets

Peter Egelhof
GSI Darmstadt, Germany
for the EXL Collaboration

9th Int. Conference on Direct Reactions with Exotic Beams
DREB 2016

Halifax, Canada
July 11 – 15, 2016

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I. Introduction

II. Direct Reactions with RIB`s at Storage Rings –
A new Approach for Low Momentum Transfer Measurements

III. First Experiments and Feasibility Studies
at the ESR Storage Ring

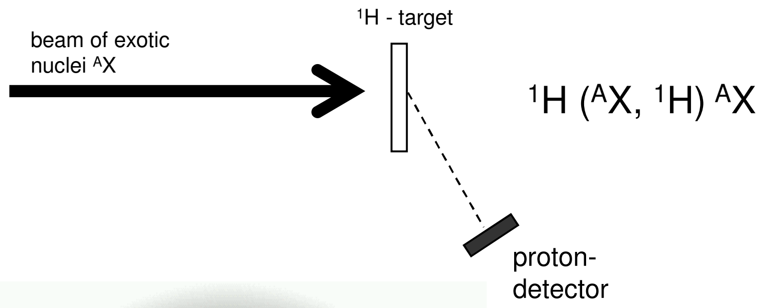
a) Elastic Proton Scattering on ^{56}Ni $\Rightarrow$ Nuclear Matter Distribution

b) Inelastic Alpha Scattering on ^{58}Ni $\Rightarrow$ Giant Monopole Resonance

IV. Future Perspectives

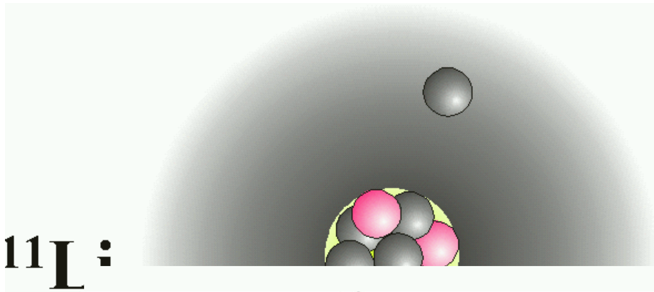
V. Conclusions

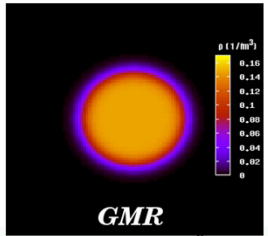
I. Introduction: Direct Reactions with Radioactive Beams in Inverse Kinematics



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!





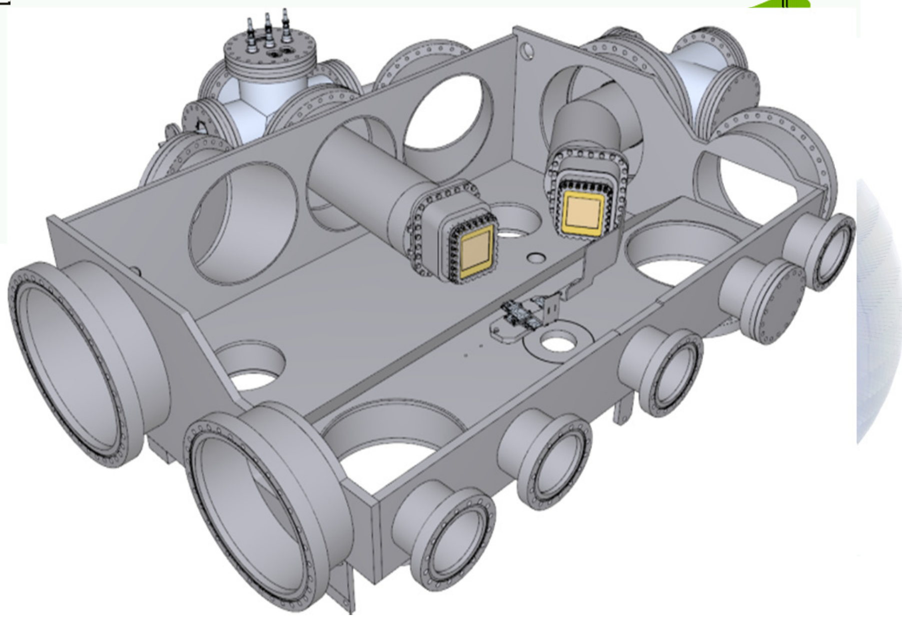
of particular interest:

⇒ 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:

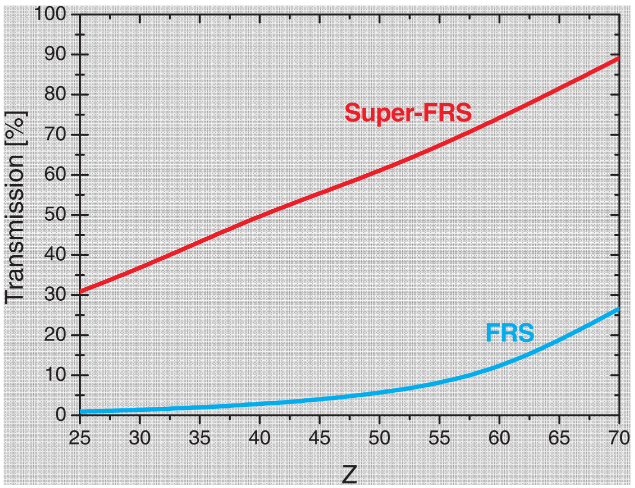
EXL: direct reactions at internal storage ring target
⇒ high luminosity even for very low momentum transfer measurements



First Experiments at the ESR

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

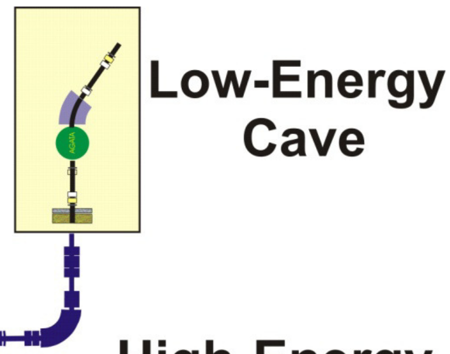
I High intensity primary beams from SIS 100 (e.g. 10^{12} ^{238}U / sec at 1 GeV/u)

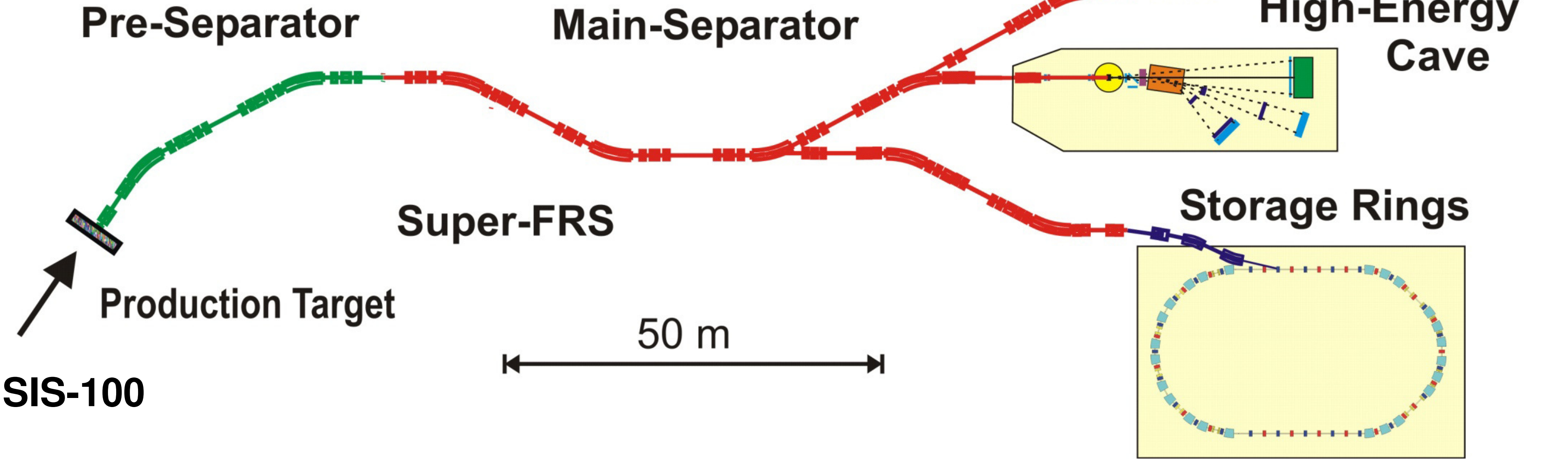


II Superconducting large acceptance Fragmentseparator

Optimized for efficient transport of fission products

III Three experimental areas



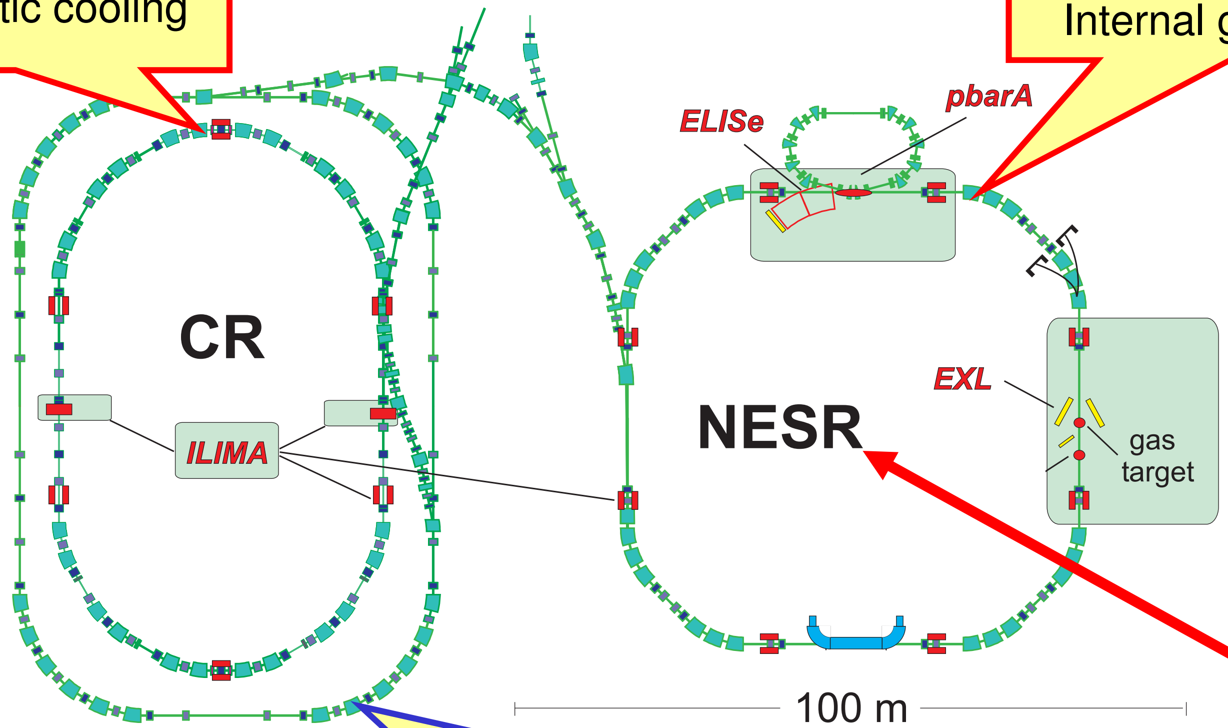


II. Direct Reactions with RIB`s at Storage Rings – A new Approach for Low Momentum Transfer Measurements

Collector Ring
Bunch rotation
Fast stochastic cooling

RIB
(740 MeV/nucleon)
from SUPER-FRS

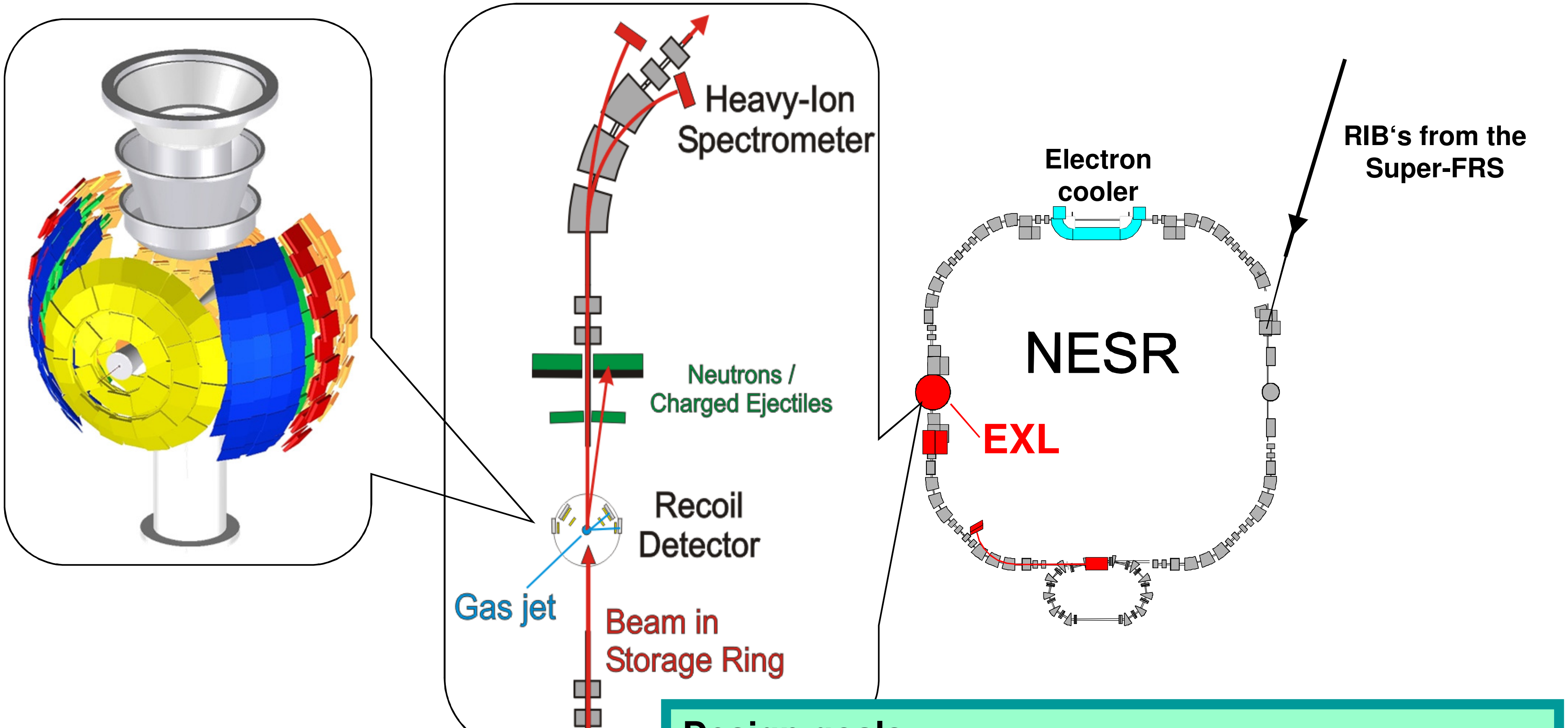
NESR
Electron cooling
Continuous accumulation
Internal gas jet targets



or ESR, HESR, CRYRING, etc.

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

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

Speciality of EXL:

measurements at very low momentum transfer

⇒ 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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- Investigation of the Giant Monopole Resonance:
  - ⇒ gives access to nuclear compressibility ⇒ key parameters of the EOS
  - ⇒ new collective modes (breathing mode of neutron skin)

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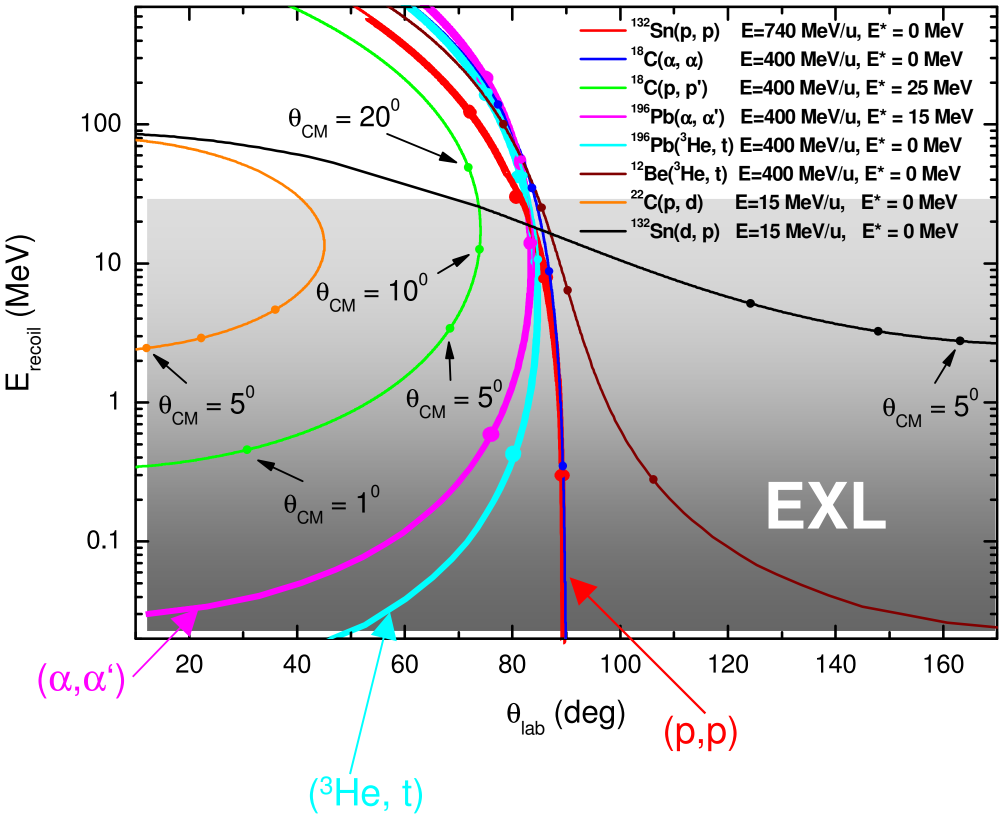
- Investigation of Gamow-Teller Transitions:
  - ⇒ weak interaction rates for N = Z waiting point nuclei in the rp-process
  - ⇒ electron capture rates in the presupernova evolution (core collaps)

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

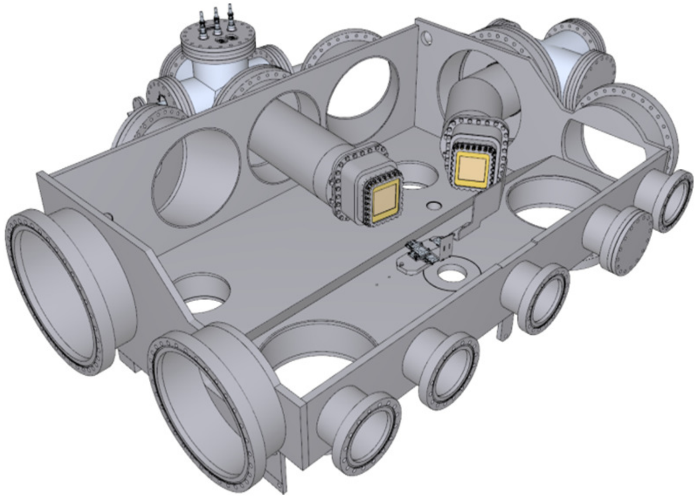
Advantage of Storage Rings for Direct Reactions in Inverse Kinematics

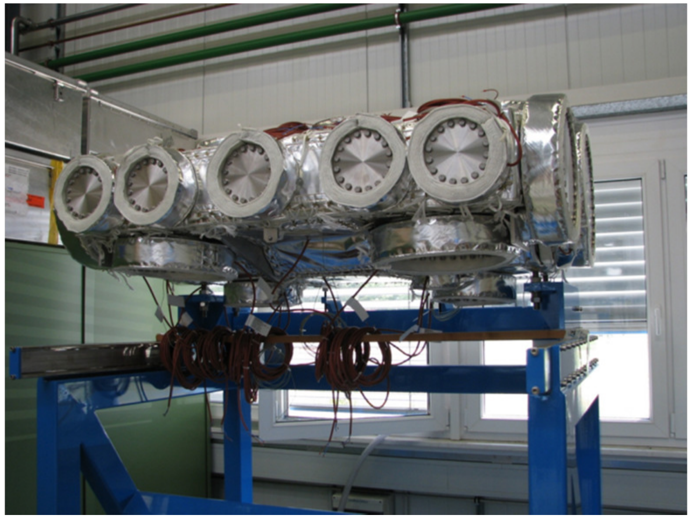
- low threshold and high resolution due to: beam cooling, thin target (10^{14}-10^{15} cm^{-2})
- gain of luminosity due to: continuous beam accumulation and recirculation
- low background due to: pure, windowless $^{1,2}H_2$, $^{3,4}He$, etc. targets
- experiments with isomeric beams

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

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

specially designed scattering chamber for the ESR:





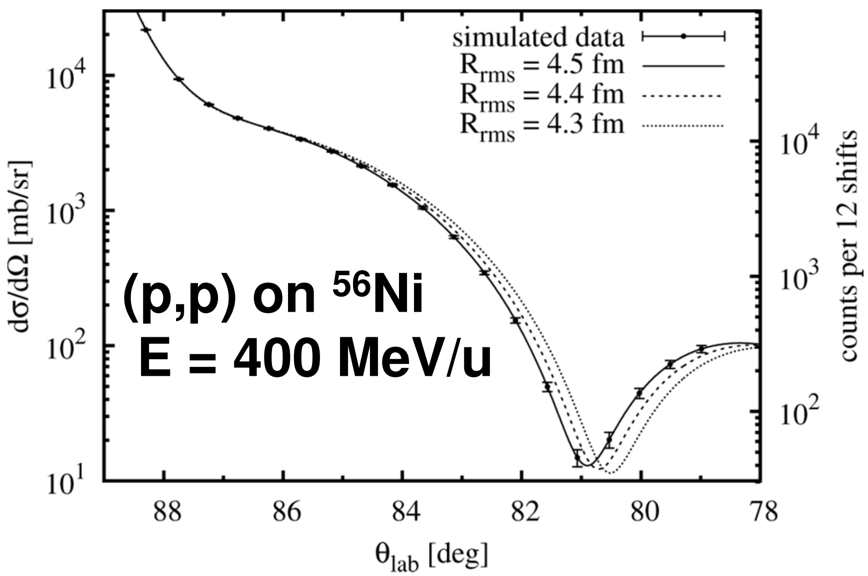
reactions with ^{58}Ni:

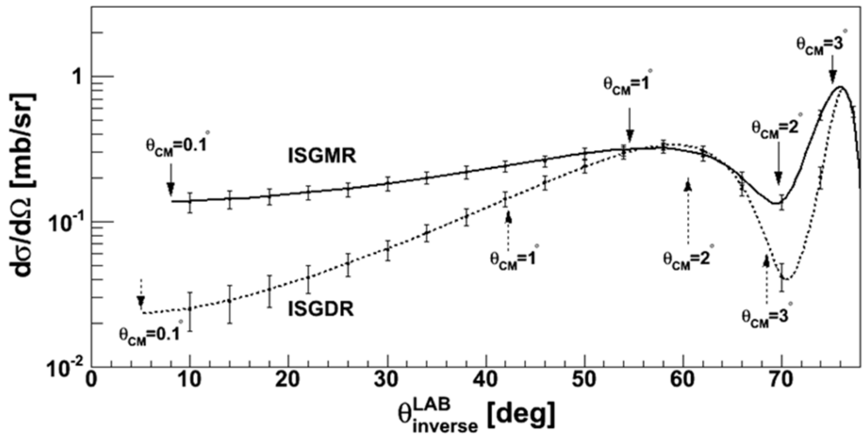
proof of principles and feasibility studies:
- UHV capability of detector setup
- background conditions in ESR environment at the internal target
- low energy threshold
- beam and target performance

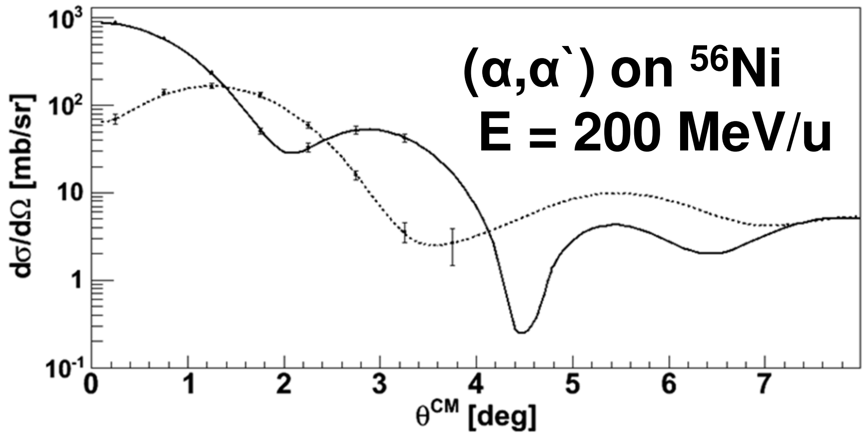
reactions with ^{56}Ni:

^{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







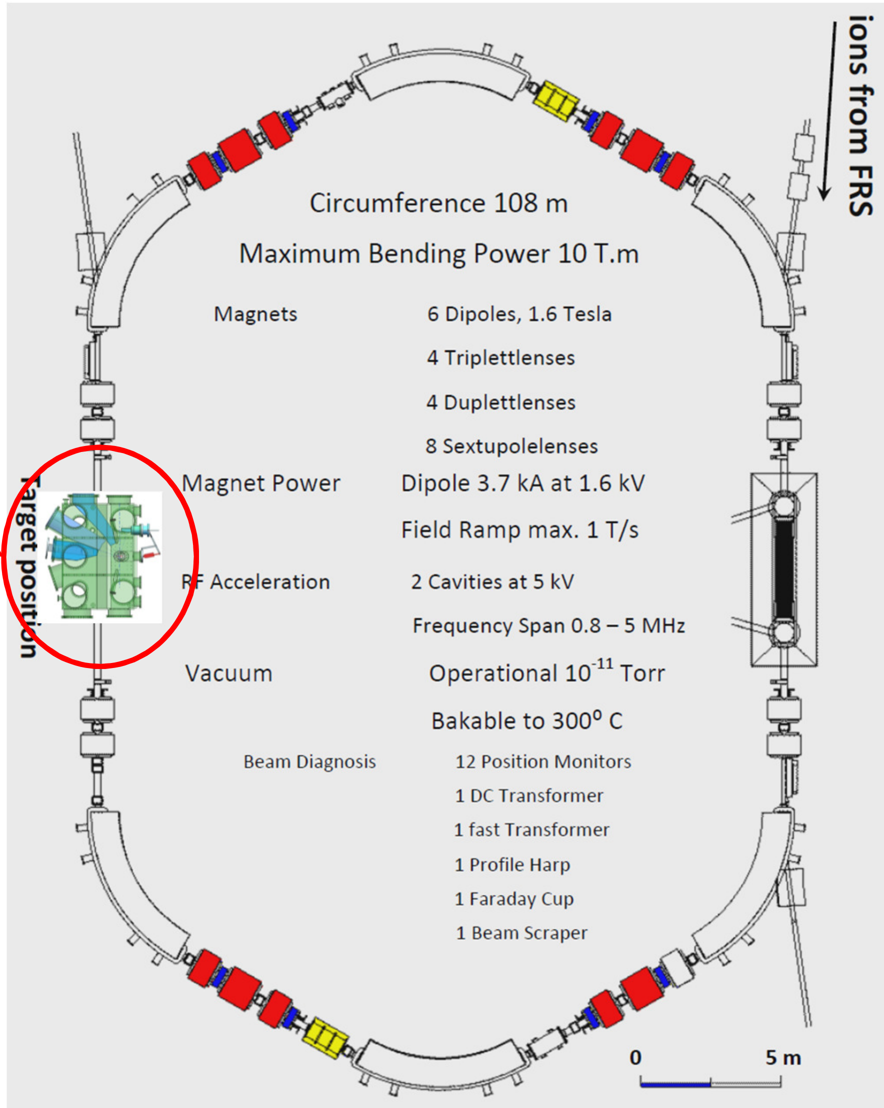
4 days with L = 10^{25} cm^{-2} sec^{-1}
recoil energies: 1 – 45 MeV

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

needed: large solid angle detectors with low threshold and large dynamic range

Setup at the ESR Storage Ring

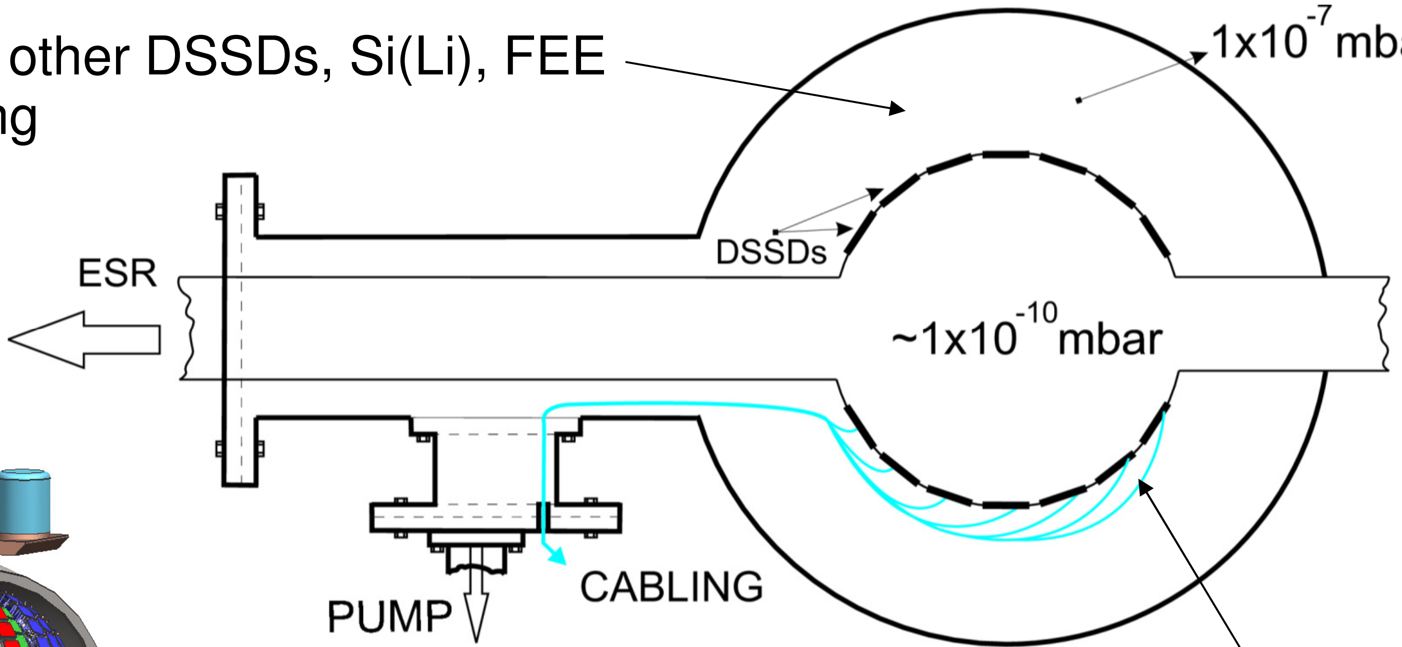
EXL setup

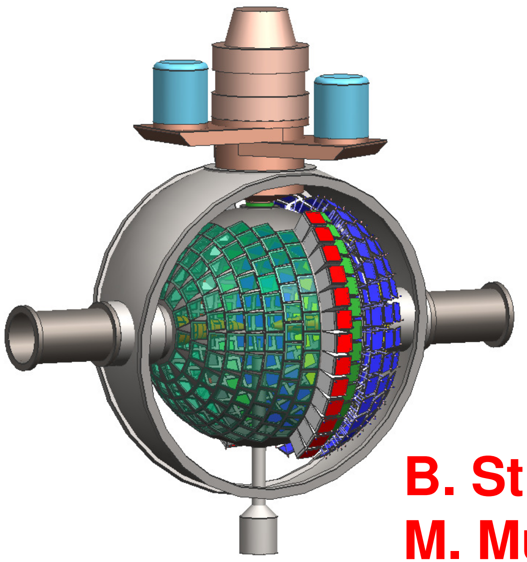


UHV Compatibility of the EXL Silicon Array:
Concept: using DSSD`s as High Vacuum Barrier

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

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

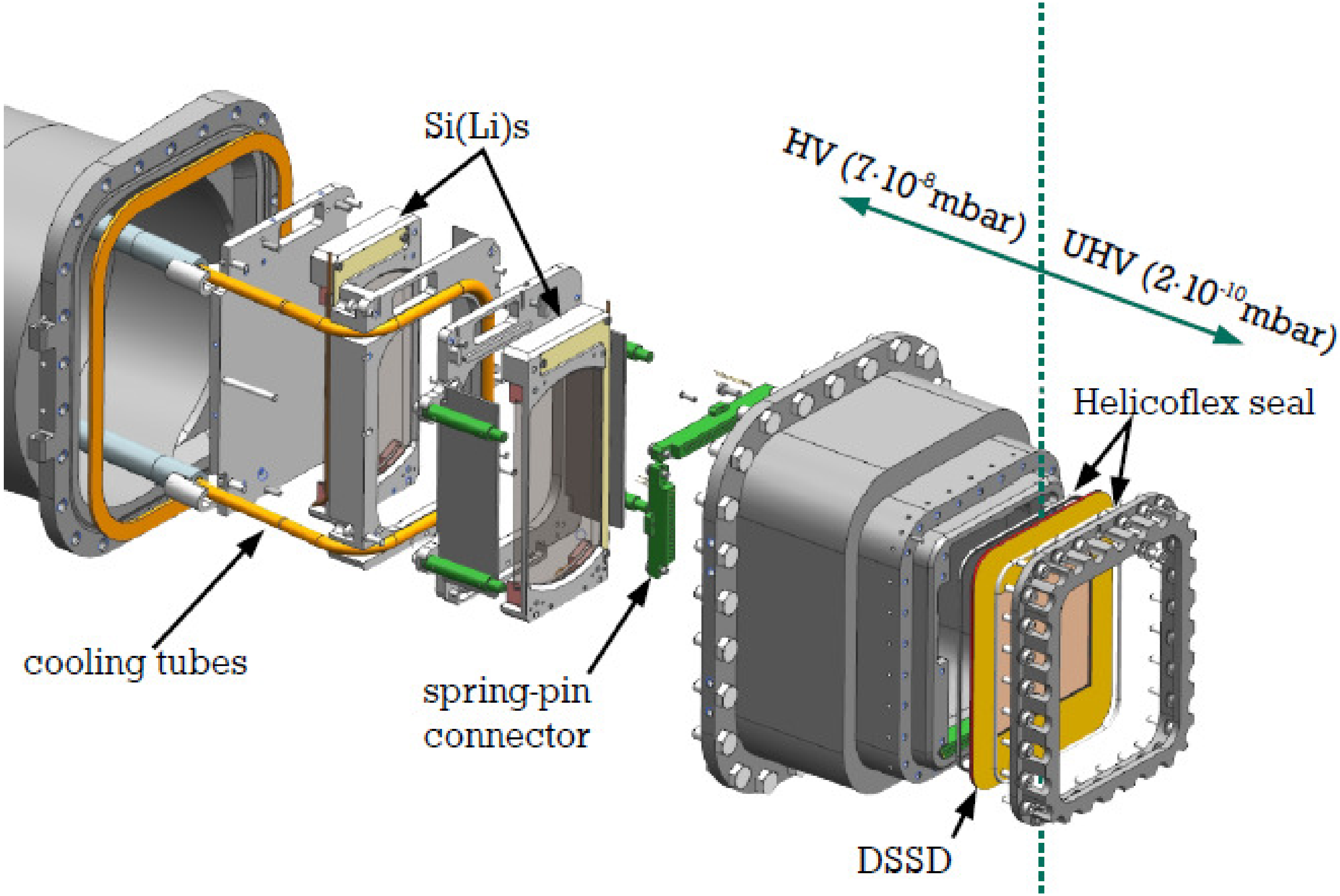




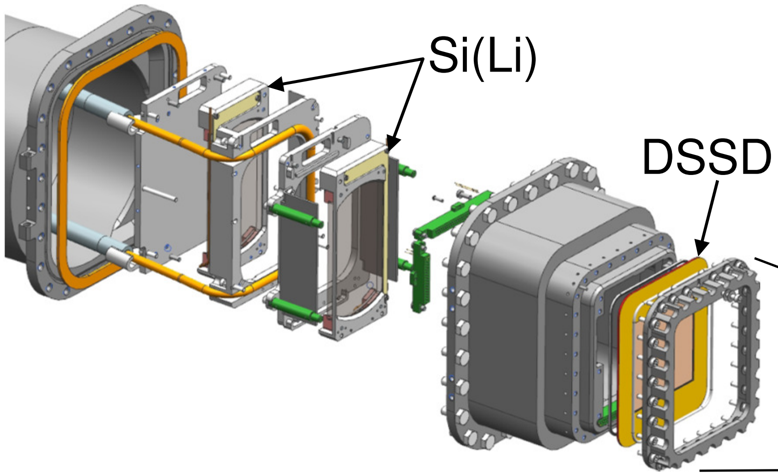
Inner shell of DSSDs on support frame forms (bakeable) vacuum barrier

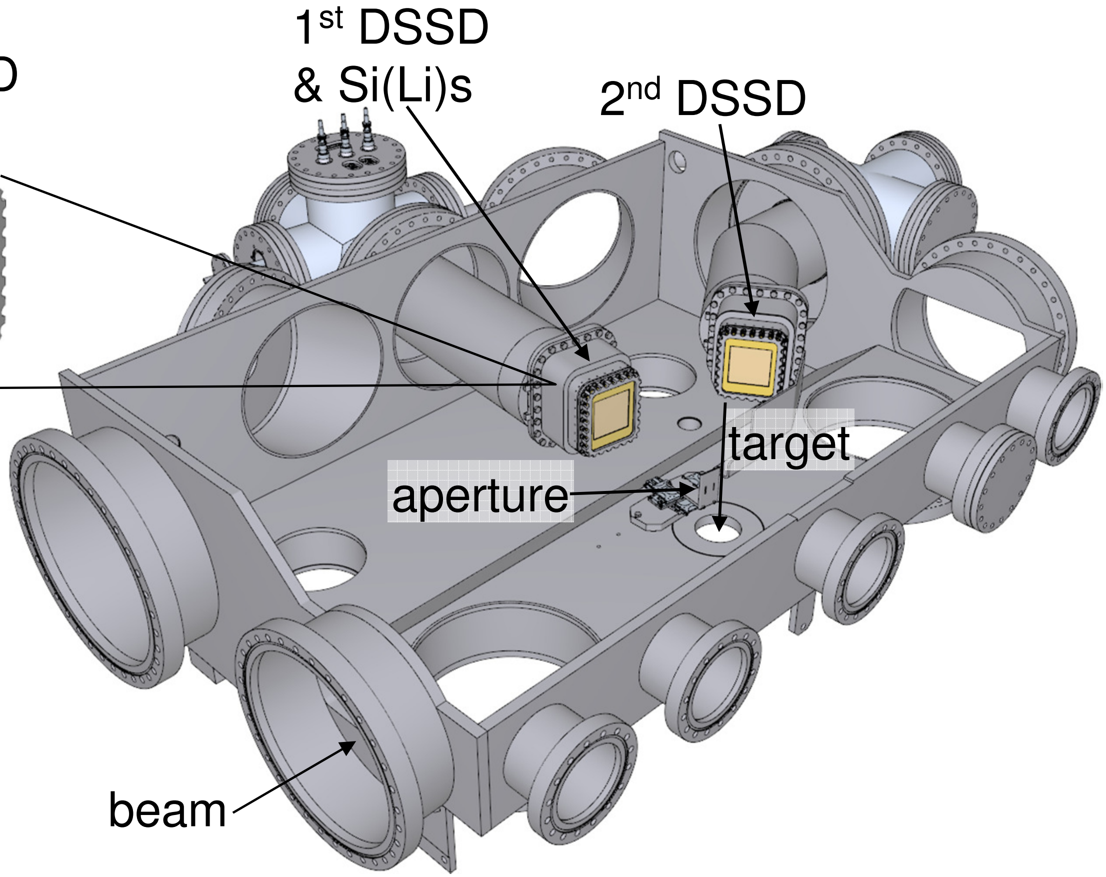
B. Streicher et al., Nucl. Instr. Meth. A654 (2011) 604
M. Mutterer et al., Phys. Scr. T166 (2015) 014053

Experimental Concept



Experimental Concept

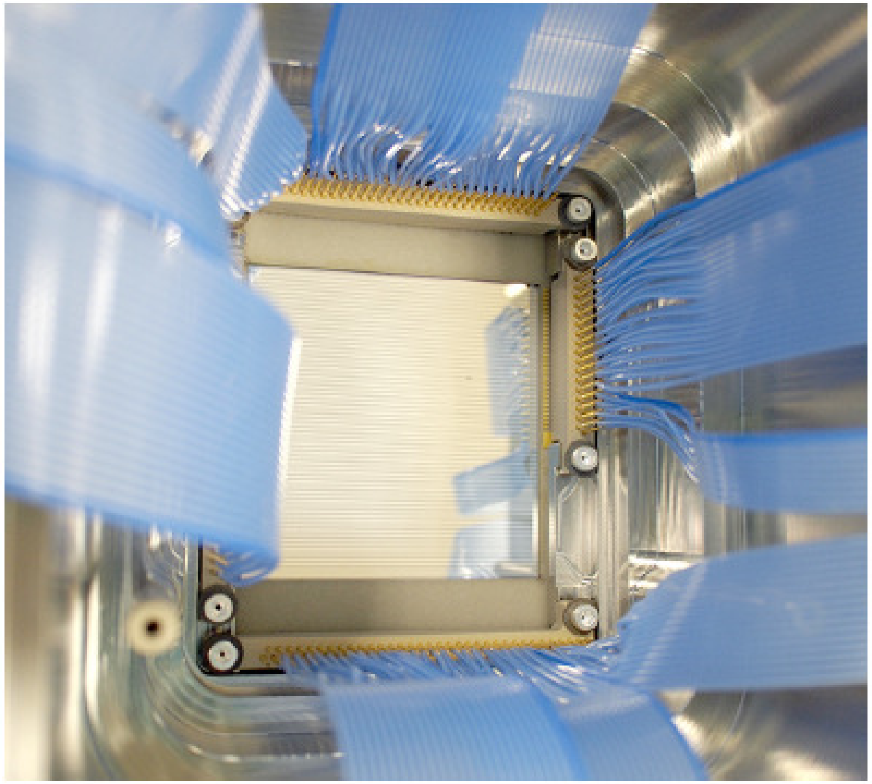




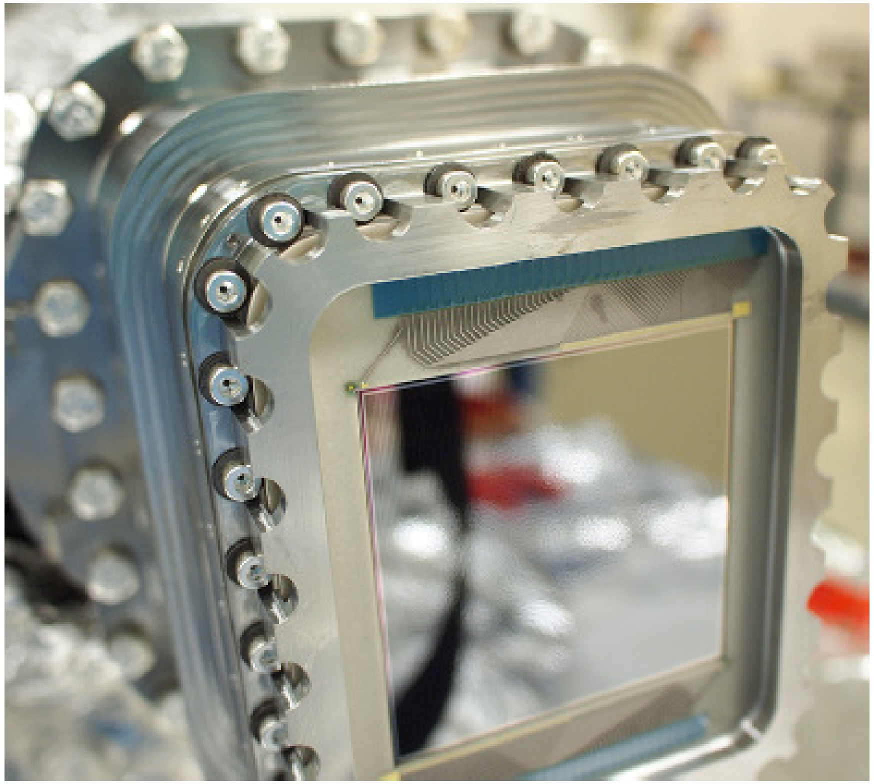
- **DSSD**: 128×64 strips, (6×6) cm², 285 µm thick
- **Si(Li)**: 8 pads, (8×4) cm², 6.5 mm thick
- **active vacuum barrier**
- **moveable aperture** to improve angular resolution

Experimental Concept

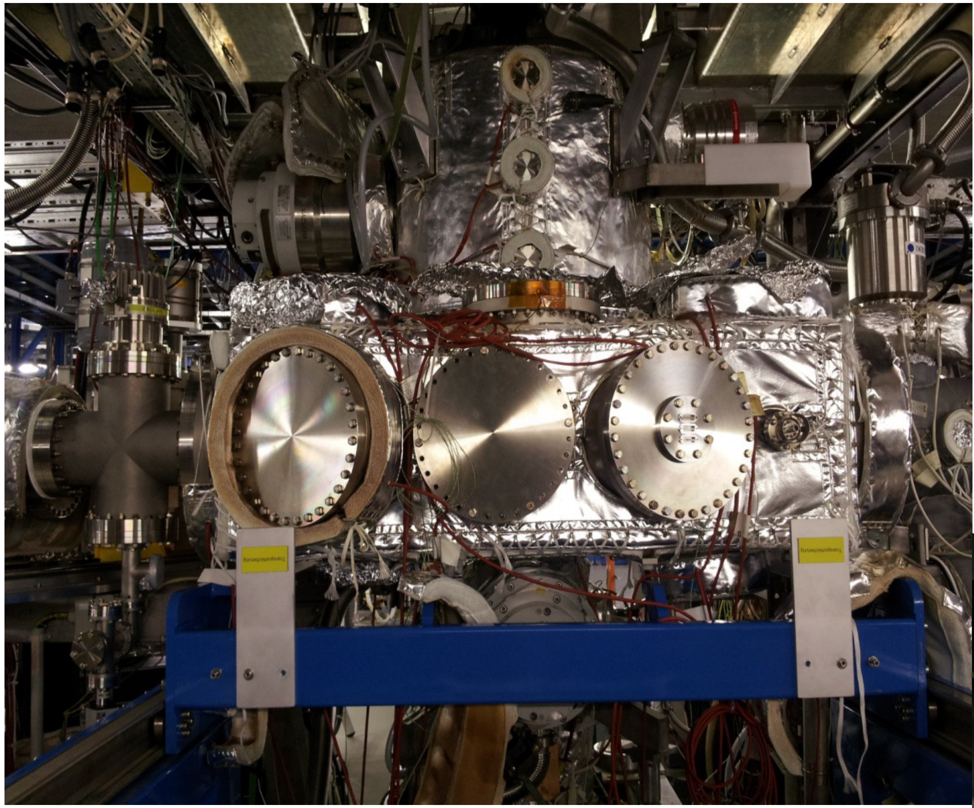
- Auxilliary vacuum side



- Ultra-high vacuum side

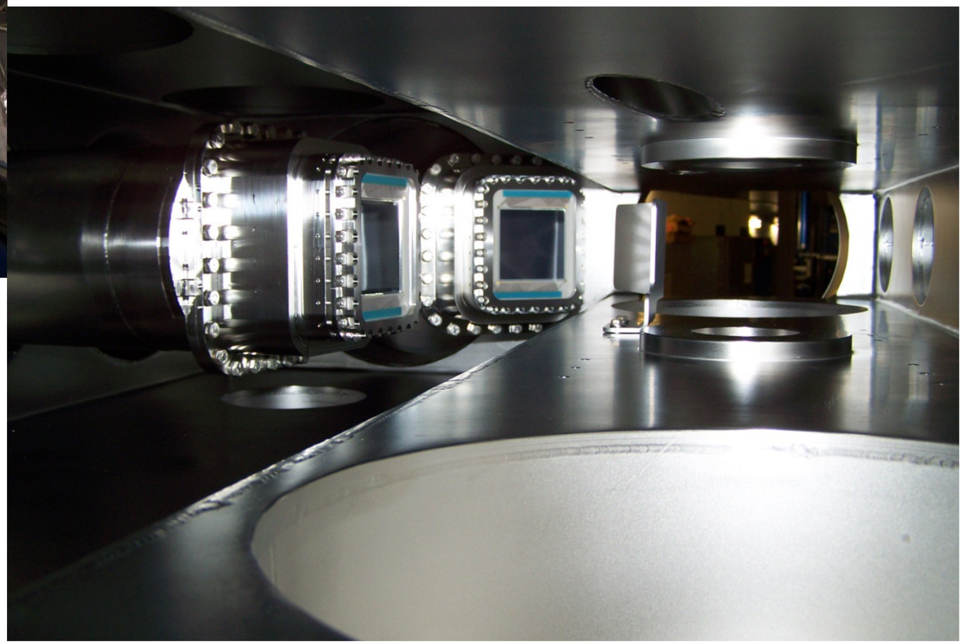


Experimental Setup at the ESR



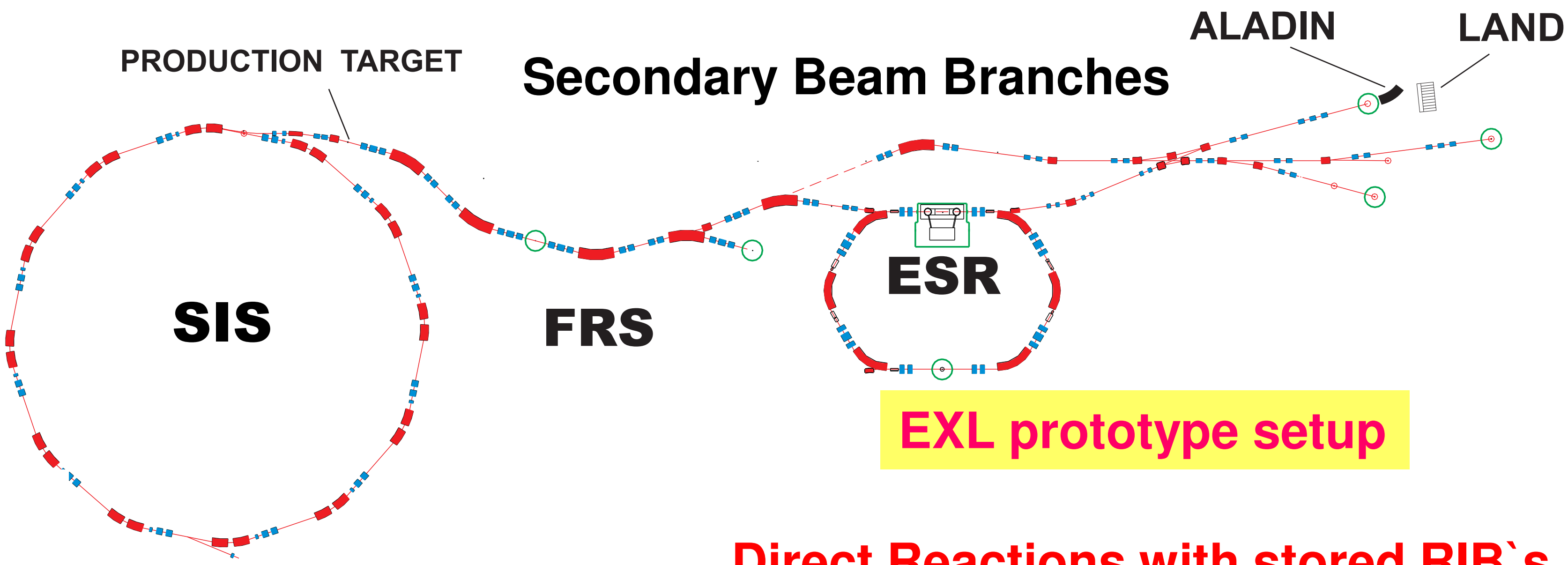
Scattering Chamber mounted
at the Internal Target of the ESR

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

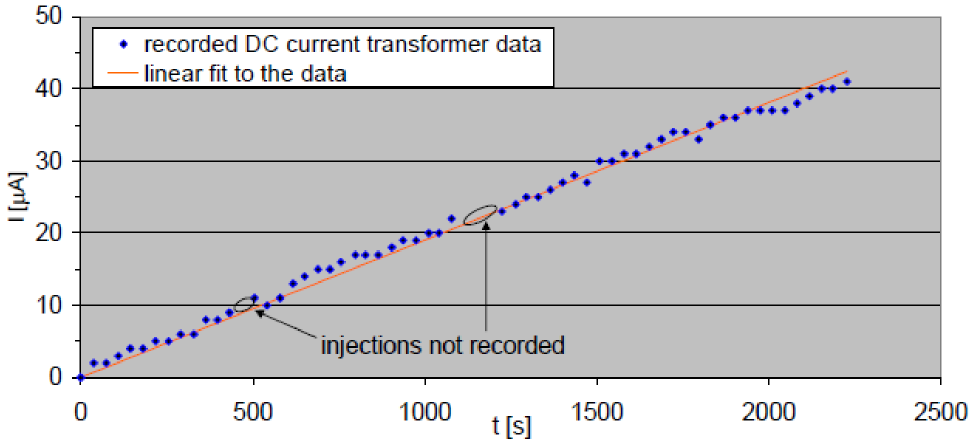
Direct Reactions with stored RIB`s

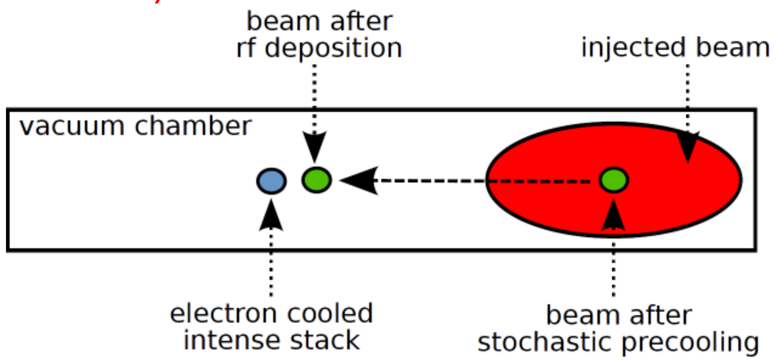
Preparation of the Stored Radioactive ^{56}Ni Beam

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

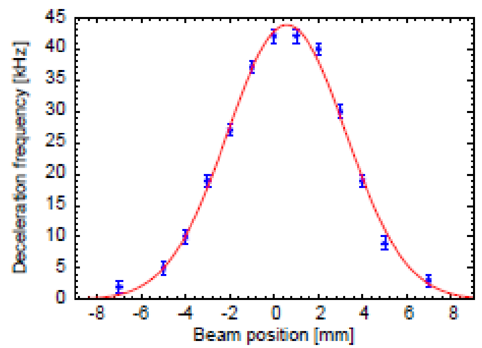
injection to ESR: **7 x 10^{4}** ^{56}Ni per injection

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





target profile



σ = 3.78 mm x_0 = 0.58 mm

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

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

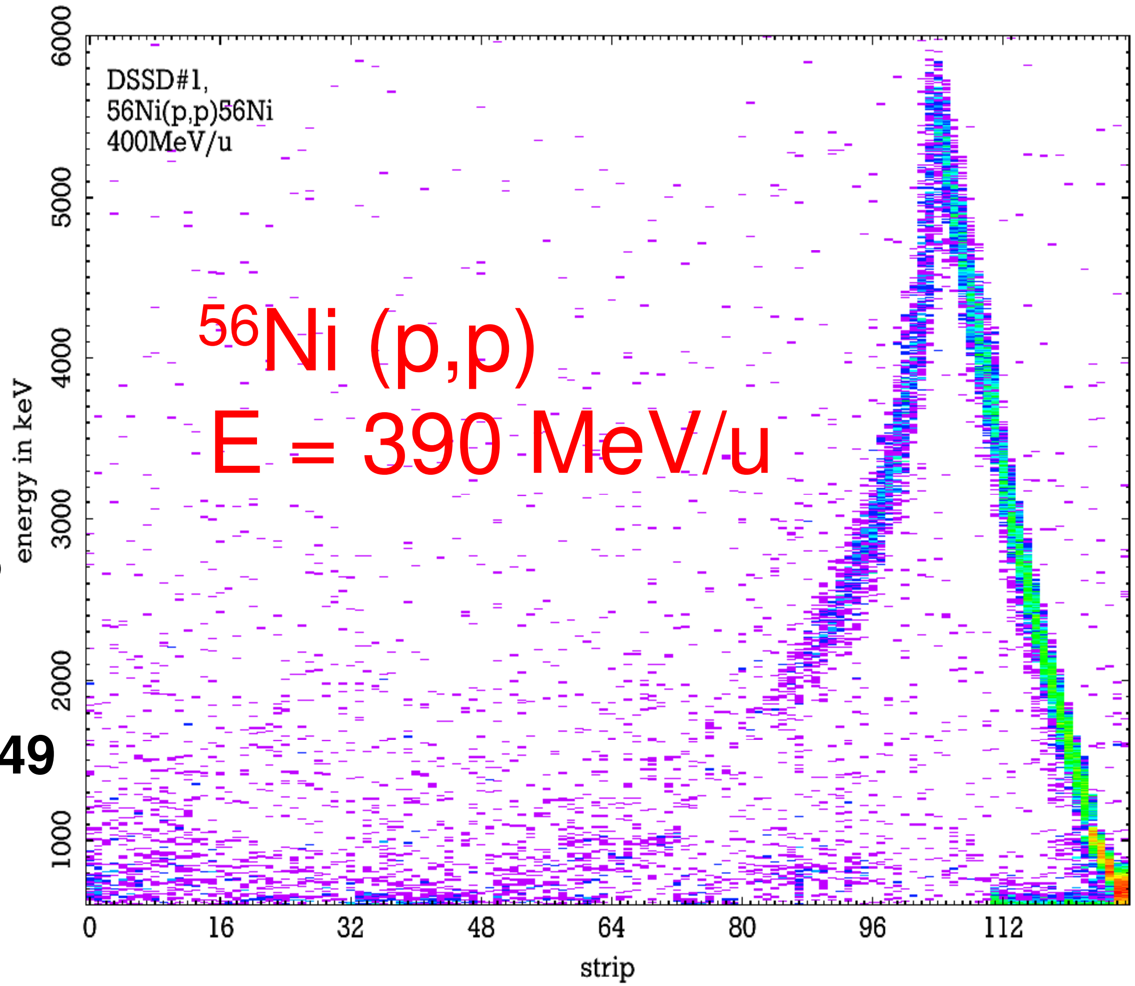
F. Nolden et al., Proc. IPAC2013 MOPEA013

First Results with Radioactive Beam: Elastic Proton Scattering on ^{56}Ni

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

M. von Schmid et al.,
Phys. Scr. T166 (2015) 014005

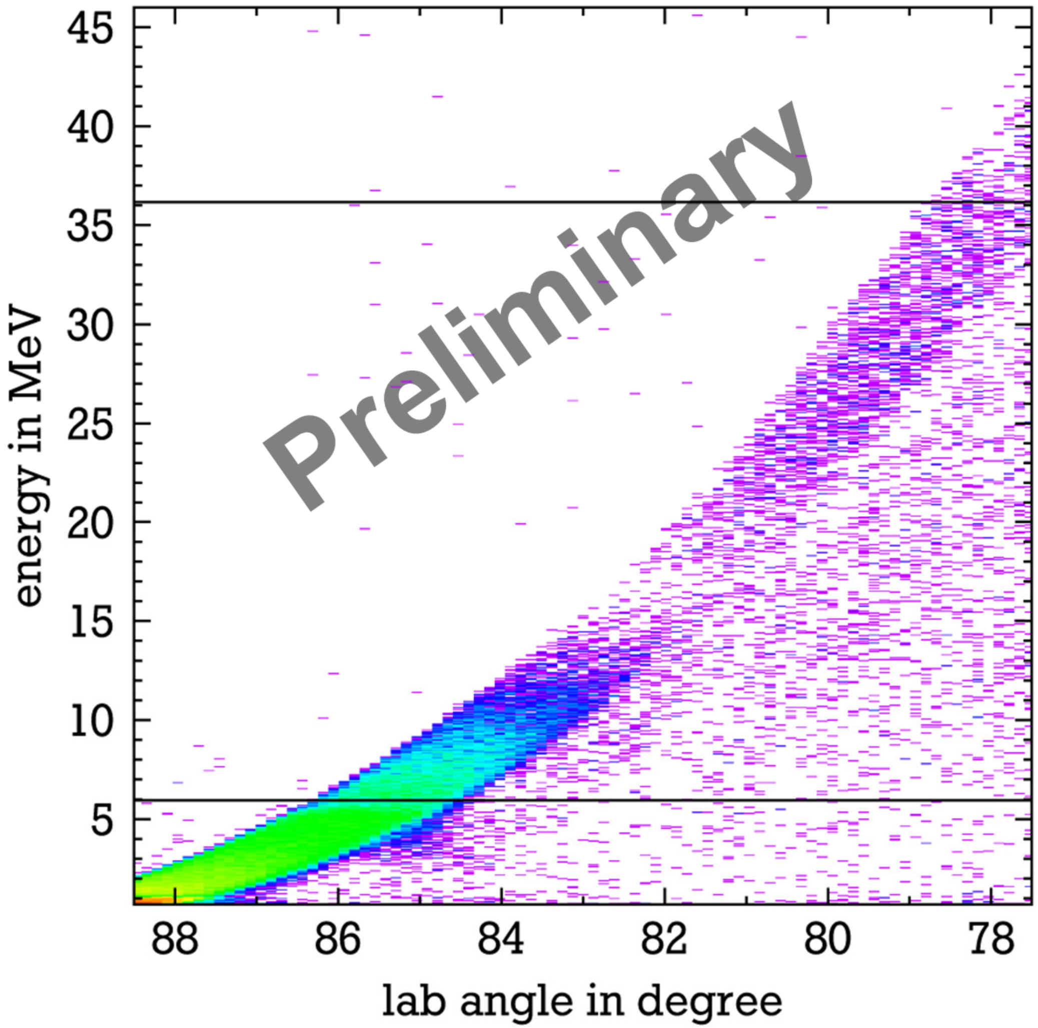
P. Egelhof et al.,
JPS Conf. Proc. 6 (2015) 020049

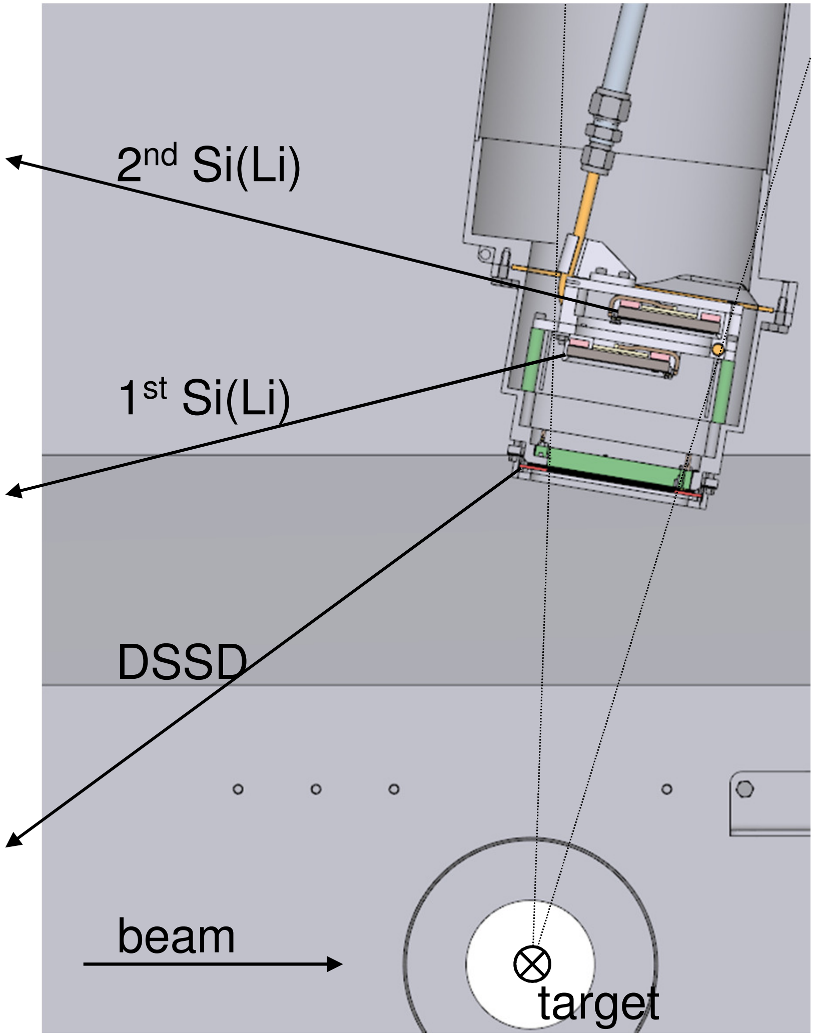


Θ_{Lab} = 72° .... 88°

First Results with Radioactive Beam: Elastic Proton Scattering on ^{56}Ni

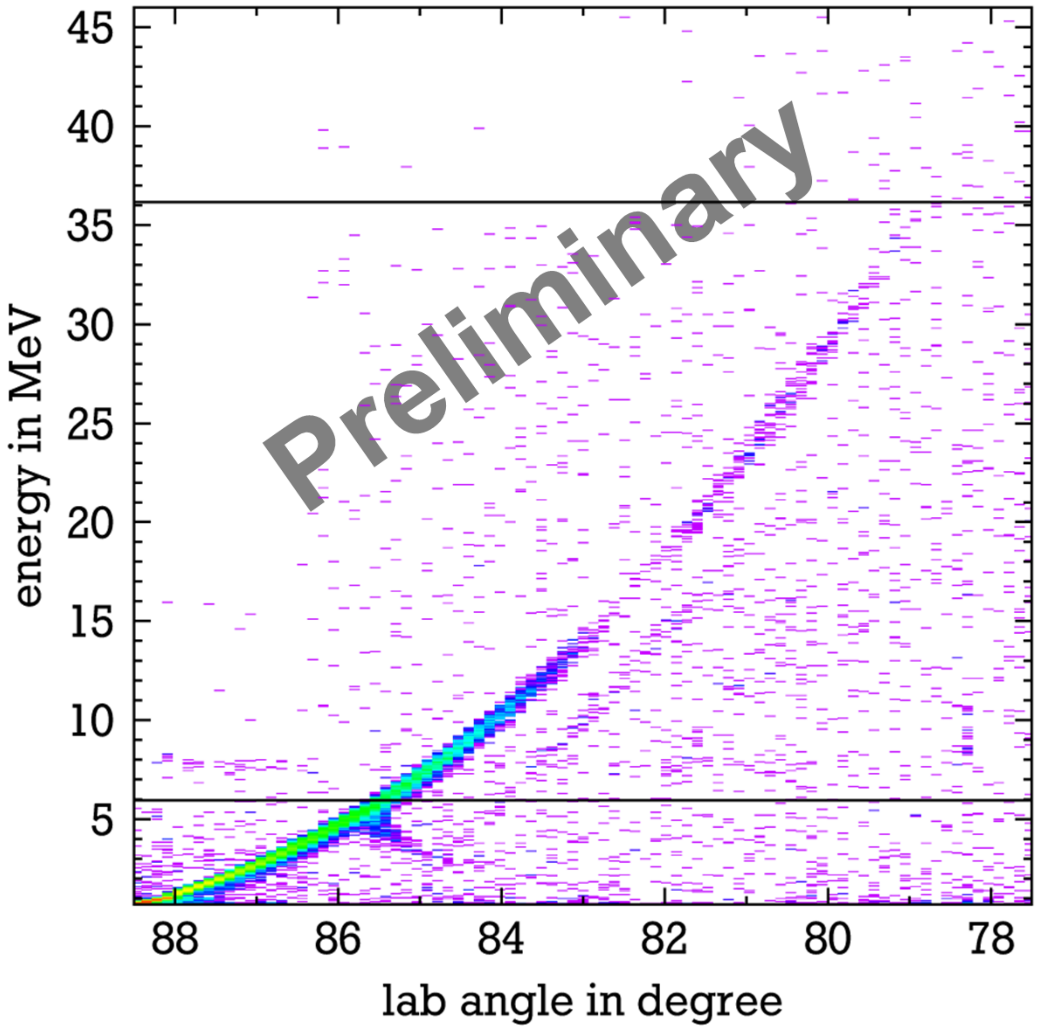
^{56}Ni(p,p), E = 390 MeV/u Reconstructed Energy

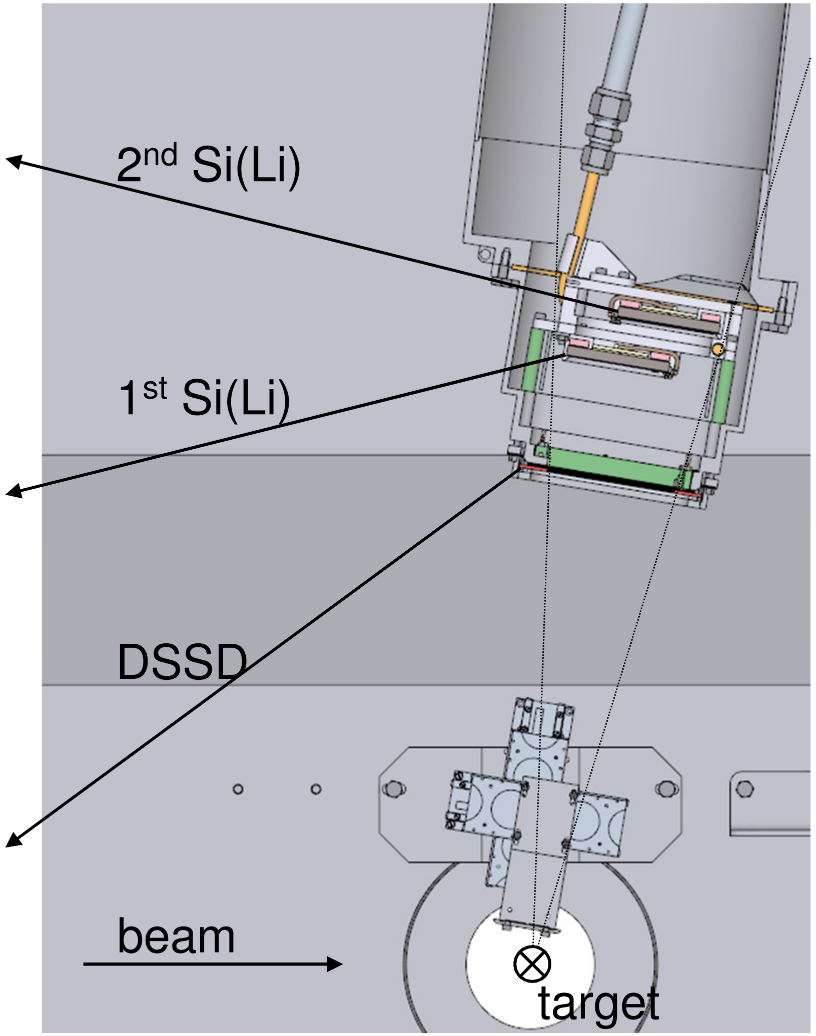




First Results with Radioactive Beam: Elastic Proton Scattering on ^{56}Ni

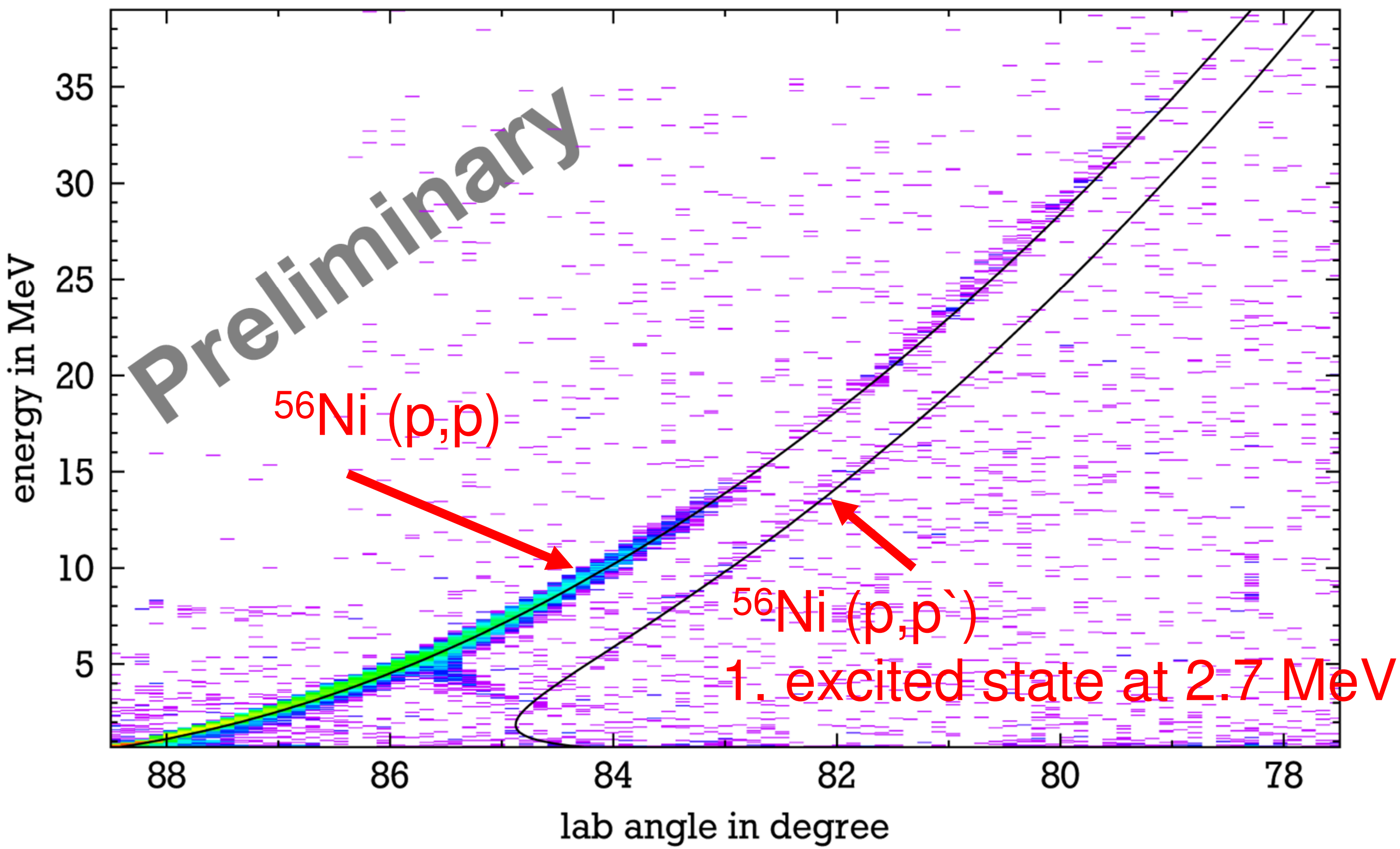
^{56}Ni(p,p), E = 390 MeV/u   Benefit of the 1mm Aperture





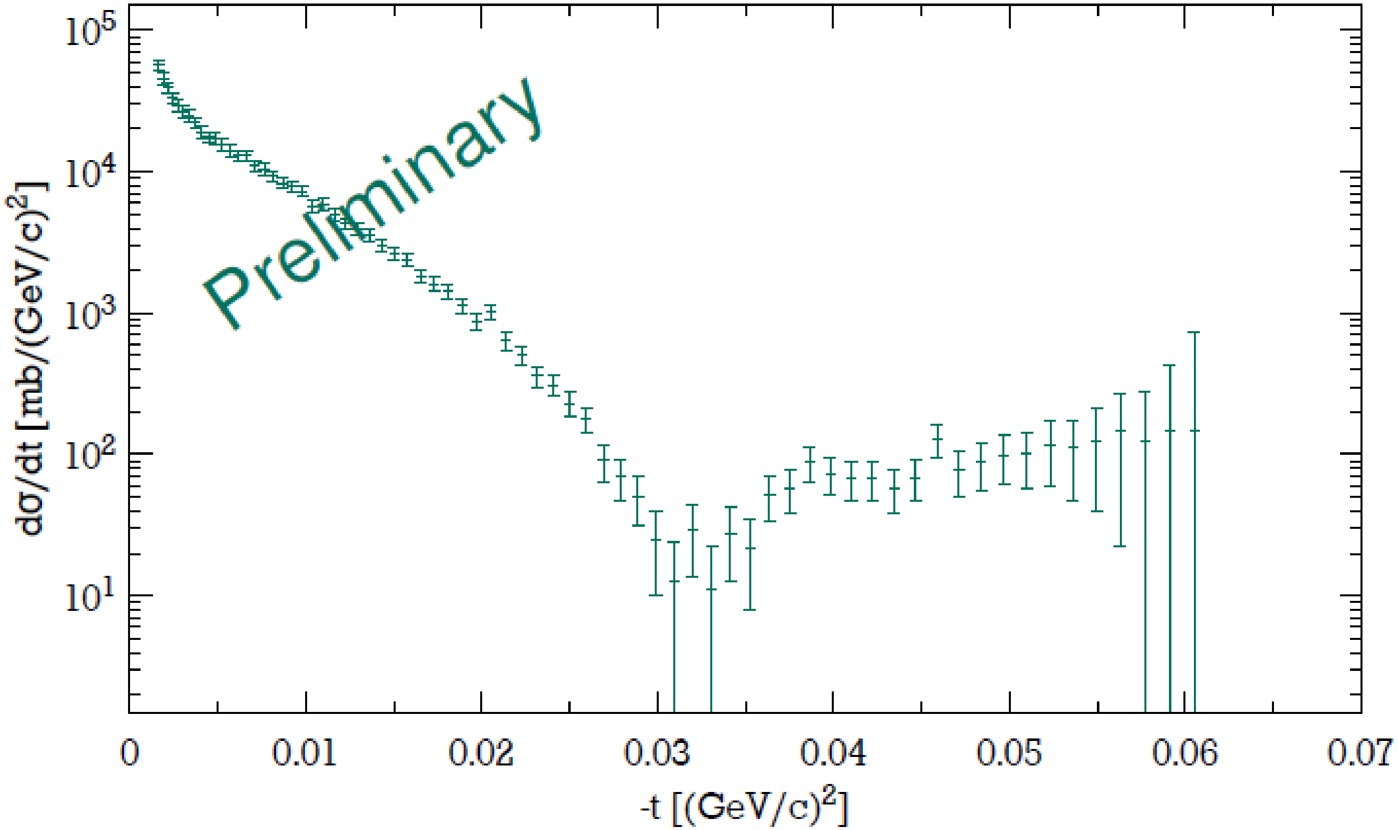
First Results with Radioactive Beam: Elastic Proton Scattering on ^{56}Ni

^{56}Ni(p,p\`), E = 390 MeV/u   Identification of Inelastic Scattering



First Results with Radioactive Beam: Elastic Proton Scattering on ^{56}Ni

^{56}Ni(p,p), E = 390 MeV/u Angular Distribution



M. v. Schmid, PHD thesis 2015

Concept of the Data Analysis

- Glauber multiple-scattering theory for calculation of cross sections:
  - use measured free pp, pn-cross sections as input (in medium effects negligible)
  - fold with nucleon density distribution
  - take into account multiple scattering (all terms!) (small for nuclear periphery)

- variation of the nuclear matter density distribution:

a) phenomenological parametrizations (point matter densities):

SF: Symmetrized Fermi

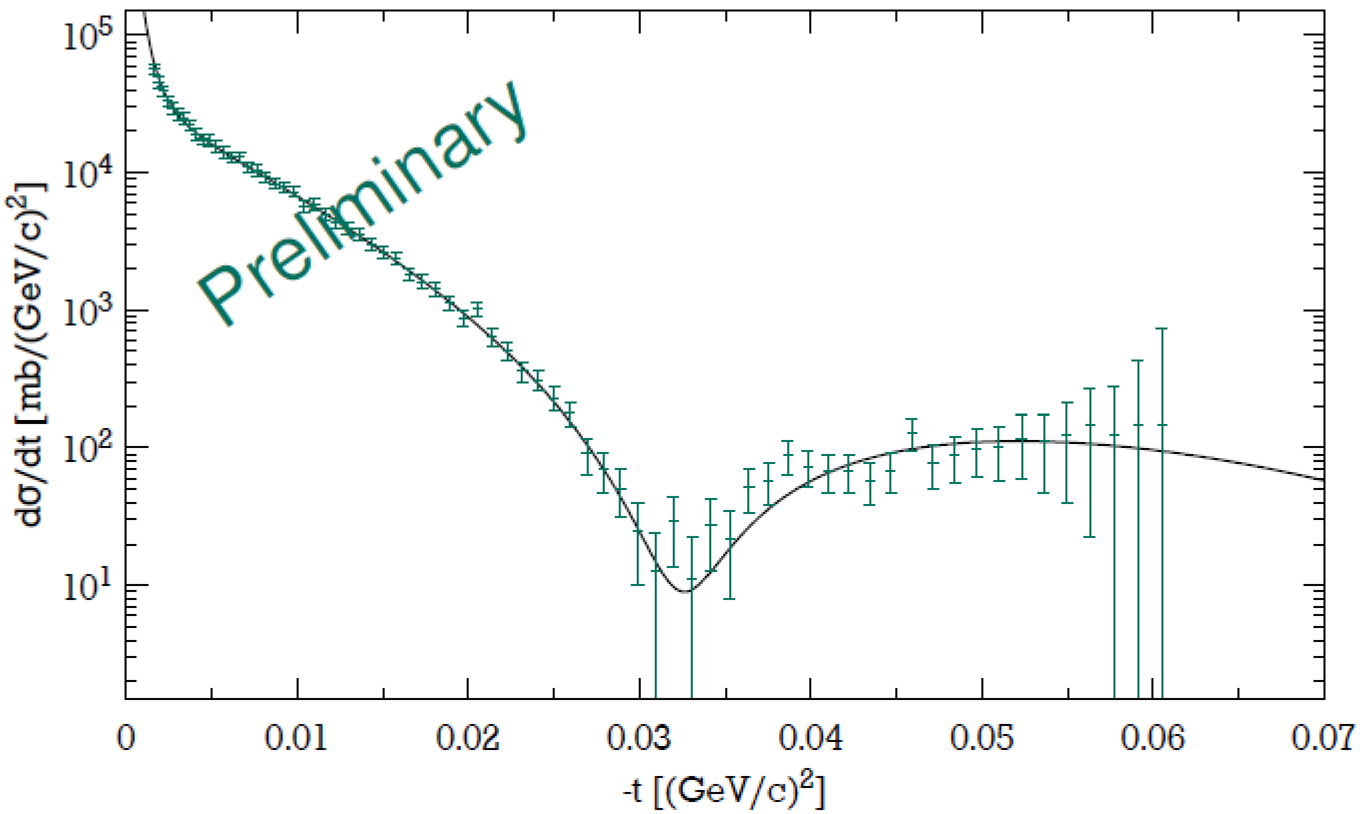
b) "model independent" analysis:

SOG: Sum Of Gaussians
(standard method for electron scattering data:
I. Sick, Nucl. Phys. A 218 (1974) 509)

Nuclear Matter Density Distribution of ^{56}Ni from Elastic Proton Scattering

$^{56}Ni(p,p)$, E = 390 MeV/u Angular Distribution

Cross Section fitted using the Glauber Theory



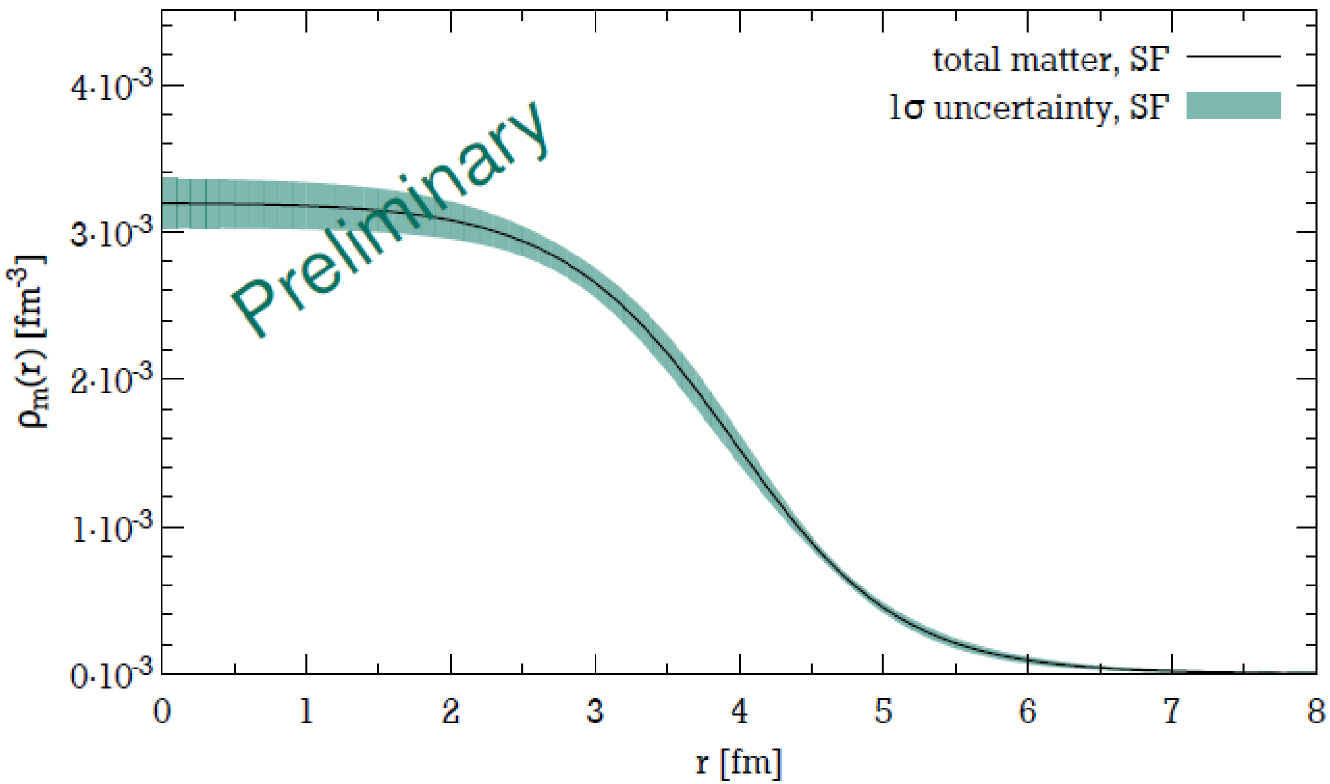
M. v. Schmid, PHD thesis 2015

Nuclear Matter Density Distribution of ^{56}Ni from Elastic Proton Scattering

Nuclear Matter Distribution of ^{56}Ni

Cross Section fitted using the Glauber Theory

- Symmetrised Fermi density parametrisation: $\rho_{SF}(r) = \rho_0 \frac{\sinh(\frac{R}{d})}{\cosh(\frac{r}{d})+\cosh(\frac{R}{d})}$



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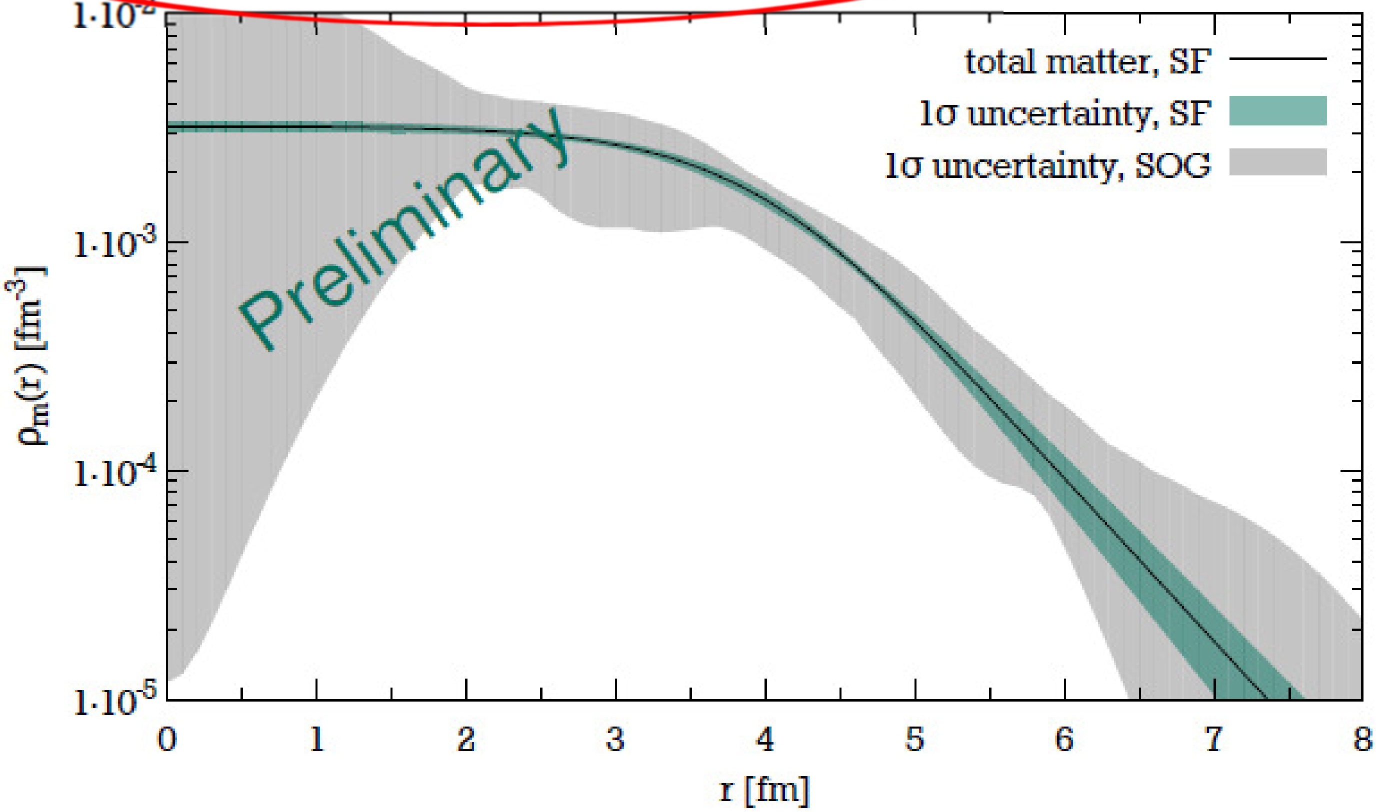
Nuclear Matter Density Distribution of ^{56}Ni from Elastic Proton Scattering

Nuclear Matter Distribution of ^{56}Ni

Cross Section fitted using the Glauber Theory

M. v. Schmid, PHD thesis 2015

- RMS matter radius: $\langle r_m^2 \rangle^{1/2} = (3.76 \pm 0.08)$ fm



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

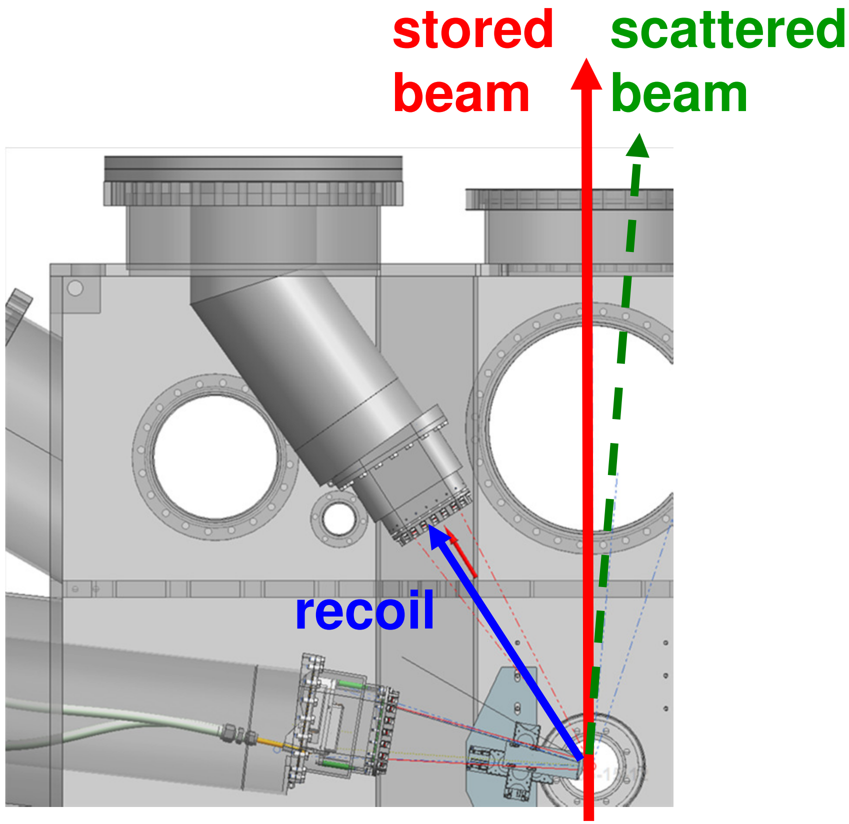
reaction: ^{58}Ni on He target

energy: 100 MeV/u

target: 8 X 10^{12} /cm^3

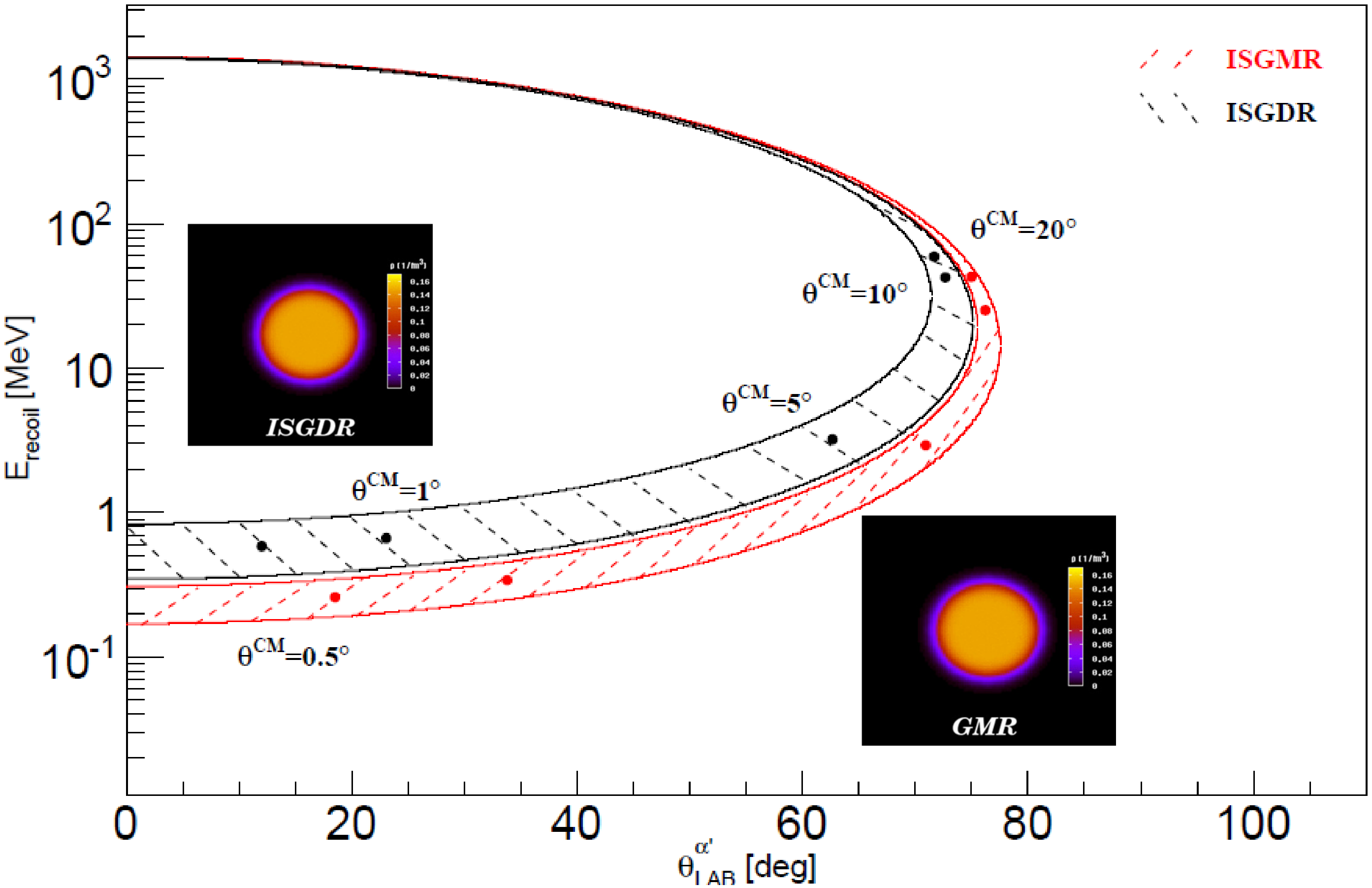
detectors: DSSD
Θ_{Lab} = 27° - 38°

PIN diodes
Θ_{Lab} = 0.2° - 1°



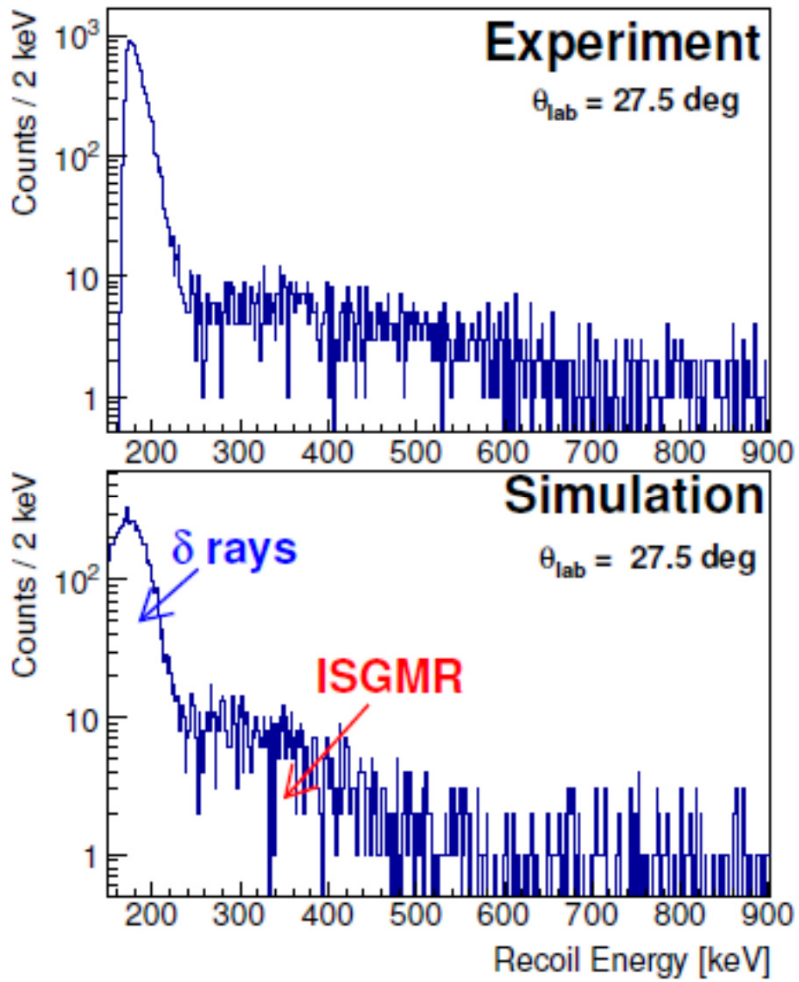
Feasibility Study:
Investigation of the Giant Monopole Resonance in ^{58}Ni

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



challenge: detect and identify very low energy recoils

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

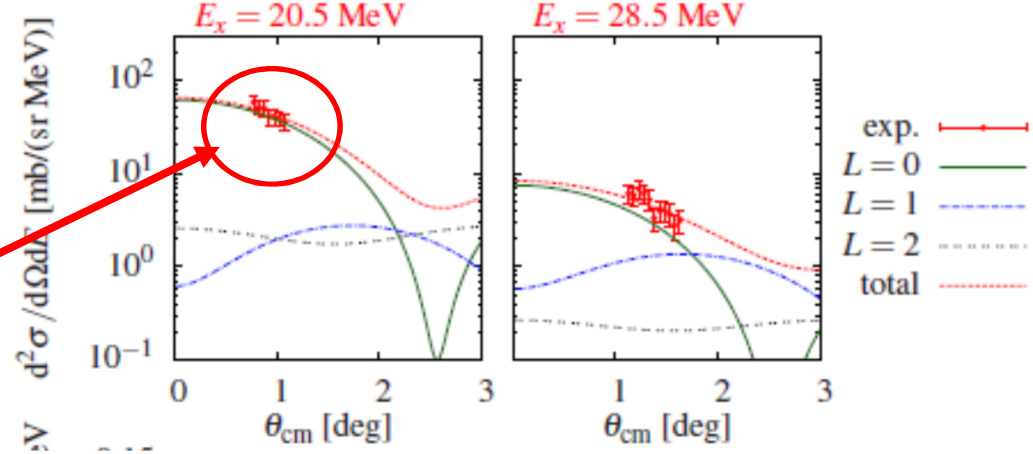


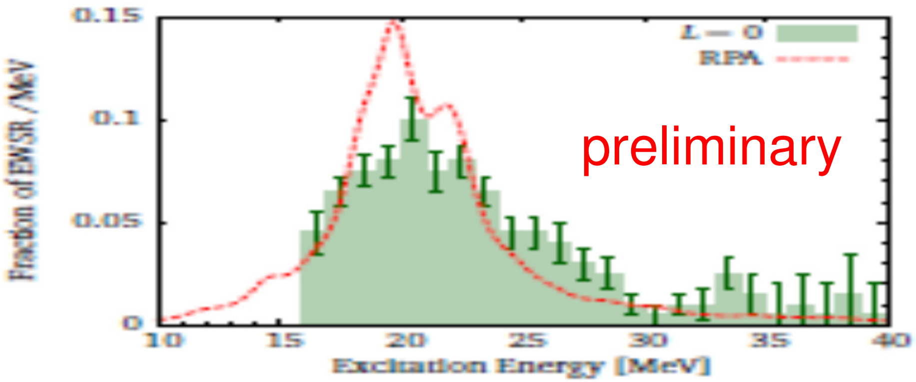
J. C. Zamora, PHD thesis 2015

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

J. C. Zamora,
PHD thesis 2015

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





comparison with data
obtained in normal kinematics
and with predictions

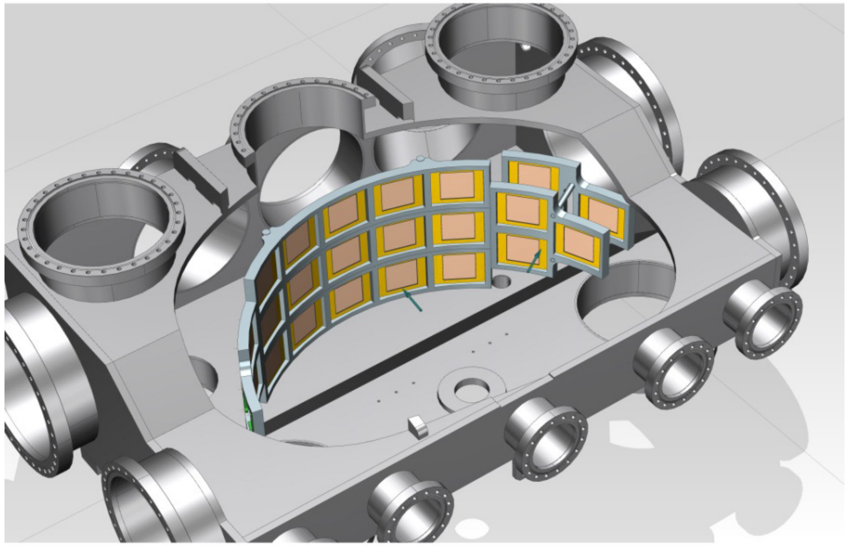
centroid [MeV]	EWSR [%]	
$21.9^{+0.8}_{-1.1}$	79^{+12}_{-11}	present data
$21.5^{+3.0}_{-0.3}$	74^{+22}_{-12}	PRC **61**, 067307 (2000)
$20.8^{+0.9}_{-0.3}$	85^{+13}_{-10}	PRC **73**, 014314 (2006)
21.2	109	RPA calculation

IV. Future Perspectives

short term perspectives:

- (α,α`) on ^{56}Ni ⇒ investigate ISGMR, compressibility of nuclear matter
- (^{3}He,t) and (d,^{2}He) on ^{56}Ni ⇒ investigate Gamow – Teller strength
- (p,p) on heavier Ni and Sn isotopes ⇒ nuclear matter distributions, skins
- transfer reactions at Cryring (GSI) and TSR@ISOLDE (CERN)

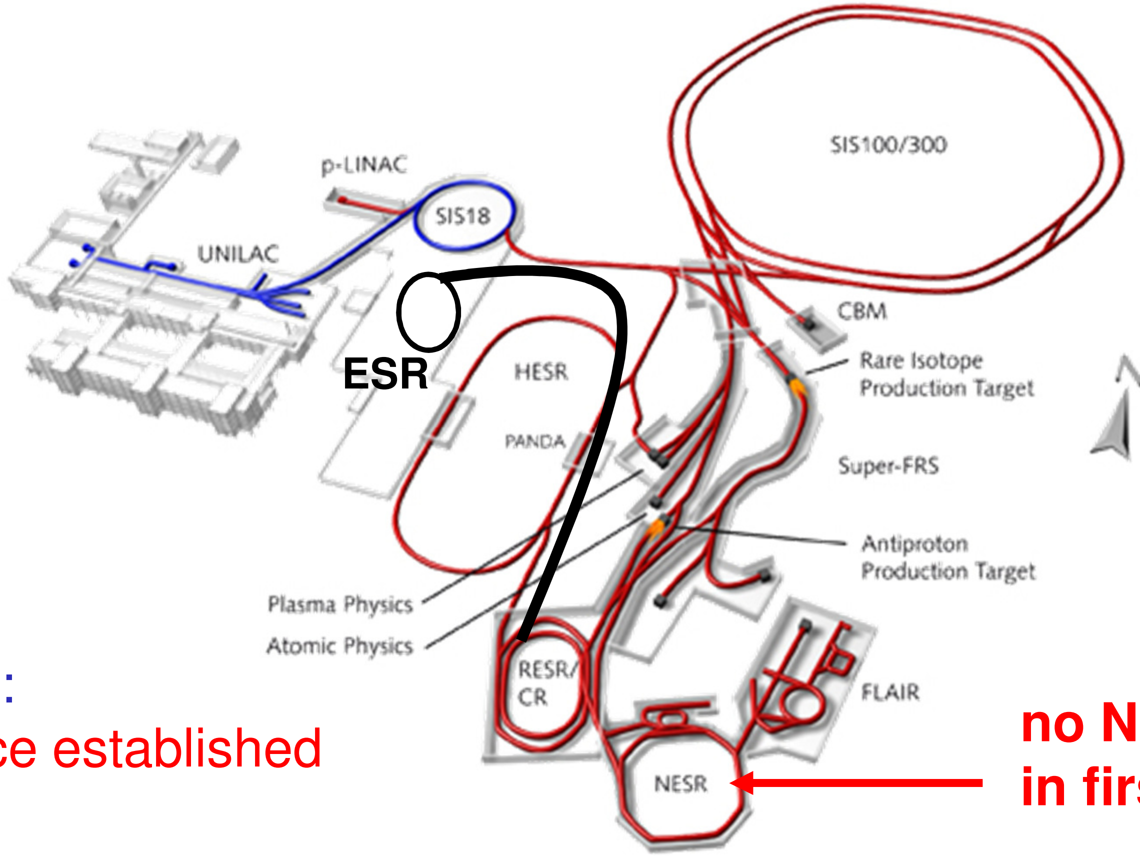
upgrade of detector setup and readout:



Future Perspectives

long term perspectives (EXL @ FAIR):

- for first phase of FAIR:
  ⇒ install EXL at the HESR
  ⇒ and/or install transfer line from SUPER-FRS / CR to the ESR



- recently:
  task force established

no NESR in first phase of FAIR!!!

The E105 Collaboration

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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 compatible Detectors and Infrastructure around the Internal Target was successfull.
- The Nuclear Matter Density Distribution of ^{56}Ni was determined with High Accuracy.
- A Feasibility Study for Investigations of the ISGMR was performed, the Cross Section was measured down to $\Theta_{cm} < 1$ deg.
- EXL@ESR and EXL@FAIR has a large Potential for Nuclear Structure and Nuclear Astrophysics.