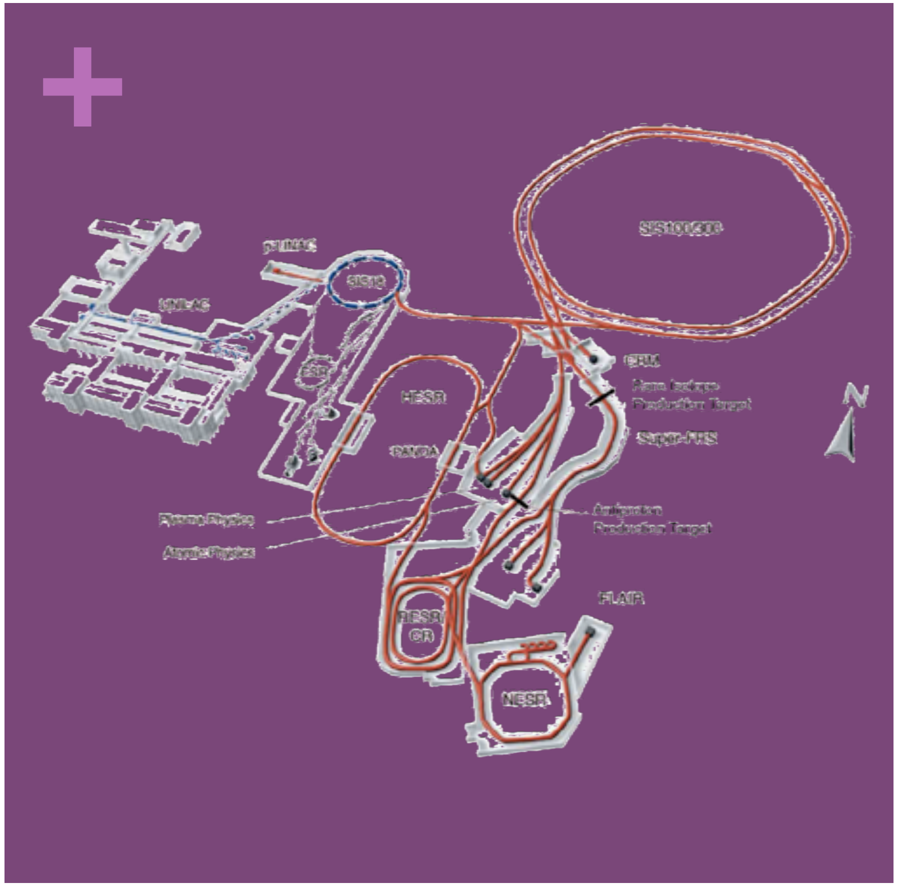
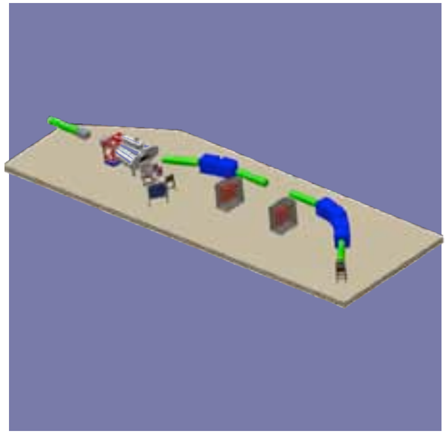
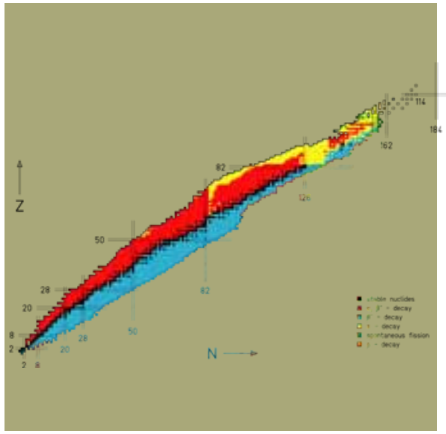






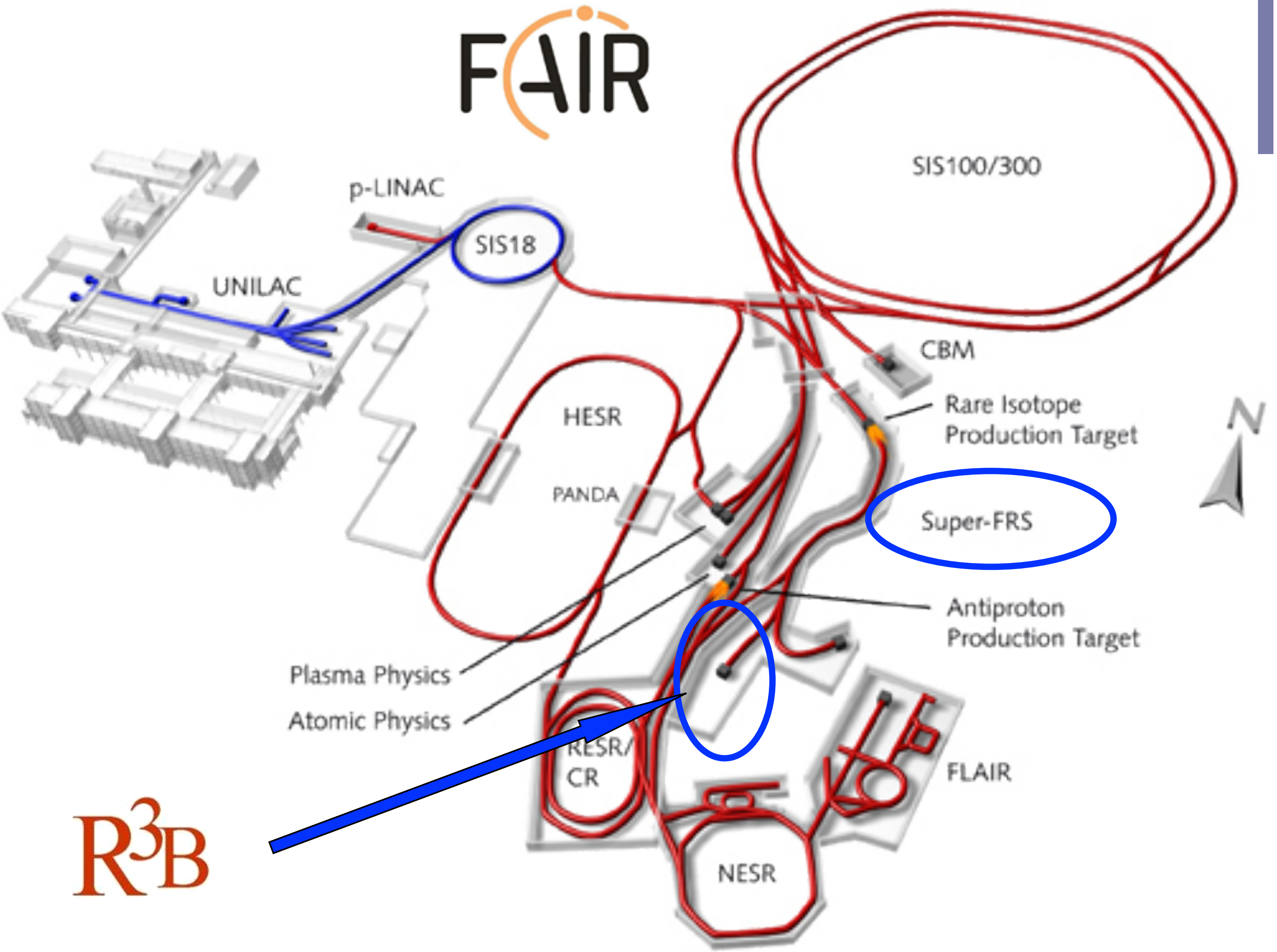
- FAIR
- NuSTAR programme
- Pre-R^{3}B experiments
- R^{3}B developments
- Complementary NuSTAR projects

Nuclear reactions with radioactive beams at FAIR

Thomas Nilsson
Chalmers University of Technology

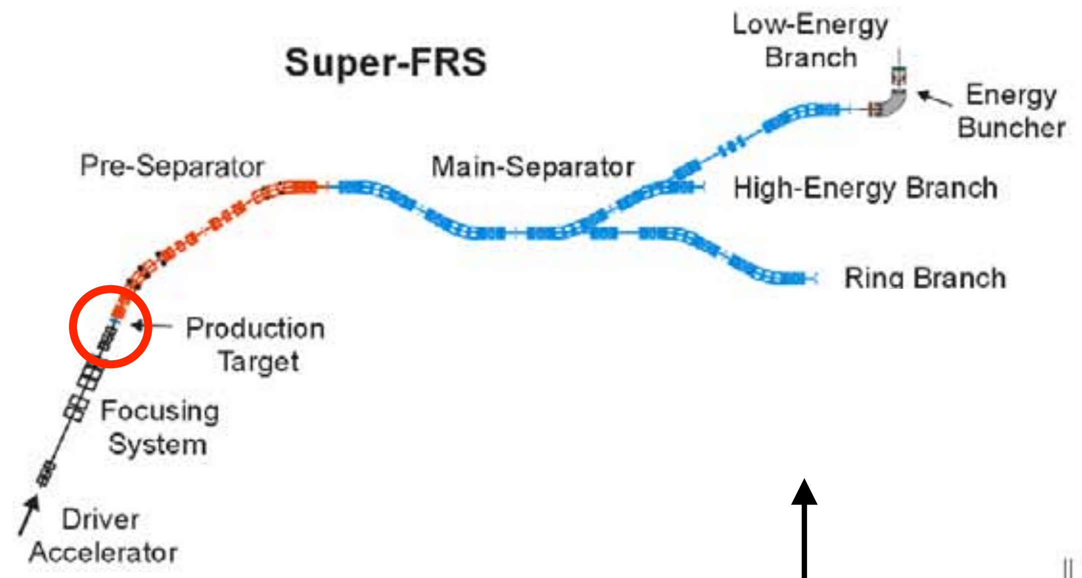
NORDIC WINTER MEETING ON PHYSICS @ FAIR – Mar. 23 2010

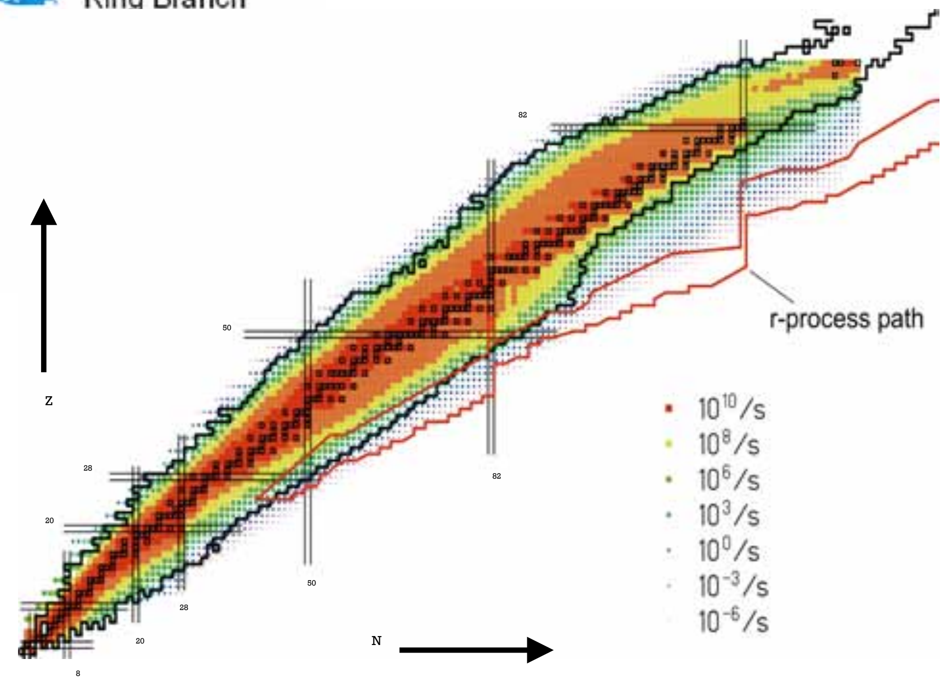
+



FAIR
p-LINAC
SIS18
UNILAC
SIS100/300
CBM
Rare Isotope
Production Target
HESR
PANDA
Super-FRS
N
Antiproton
Production Target
Plasma Physics
Atomic Physics
RESR/
CR
FLAIR
NESR
R3B

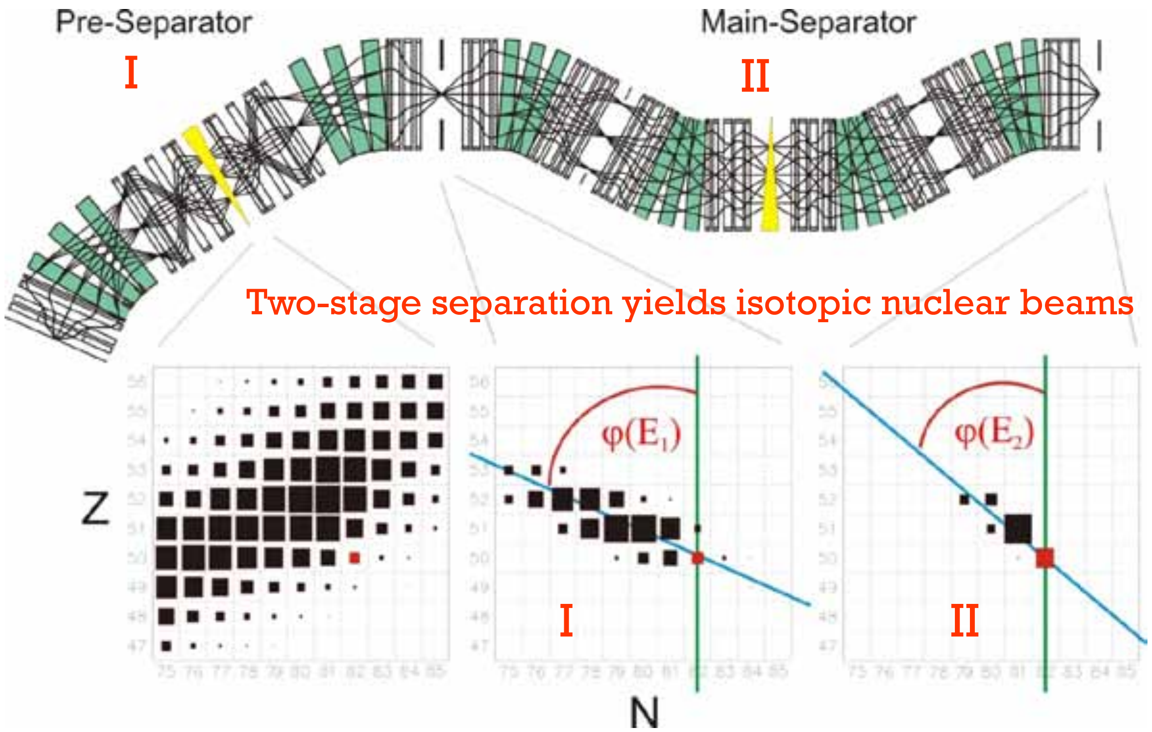
Super-FRS – radioactive beams at FAIR



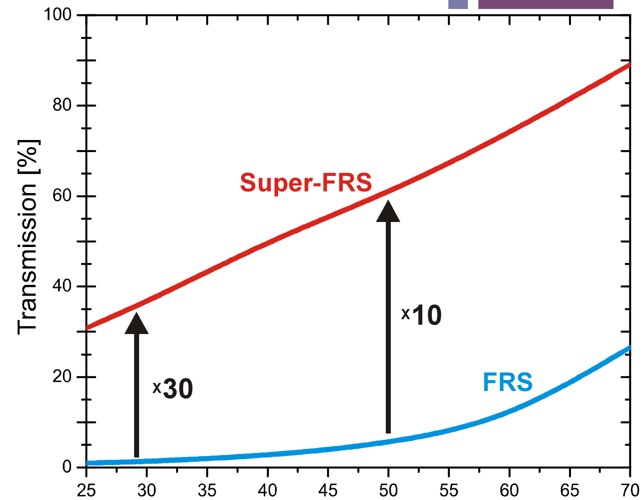


- Energy (0 – 1.5 GeV/u)
- Halflives (μs - >s)

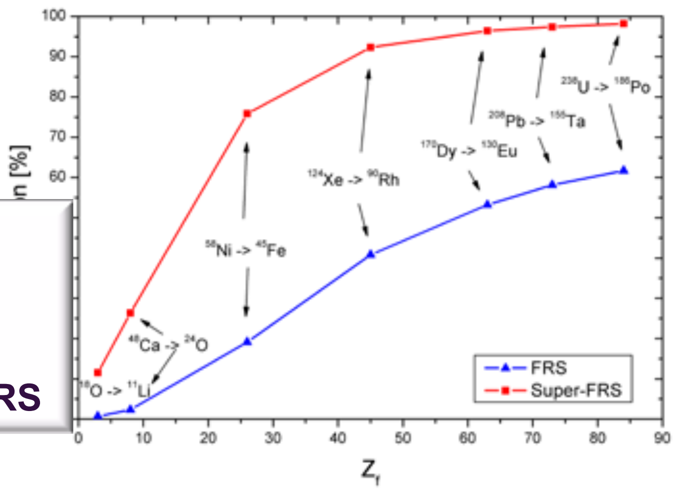
The Super-FRS



Fission



Fragmentation



- High acceptance for projectile fragments and fission products
- Two-stage separation absolutely needed for clean beams
- **More than one order of magnitude <u>transmission gain</u> relative to FRS**

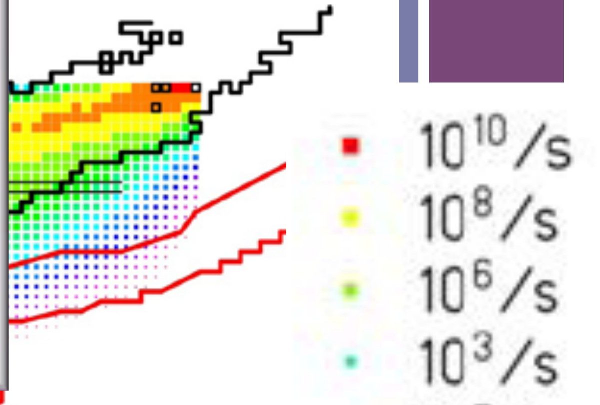
Nuclear STructure, Astrophysics and Reactions

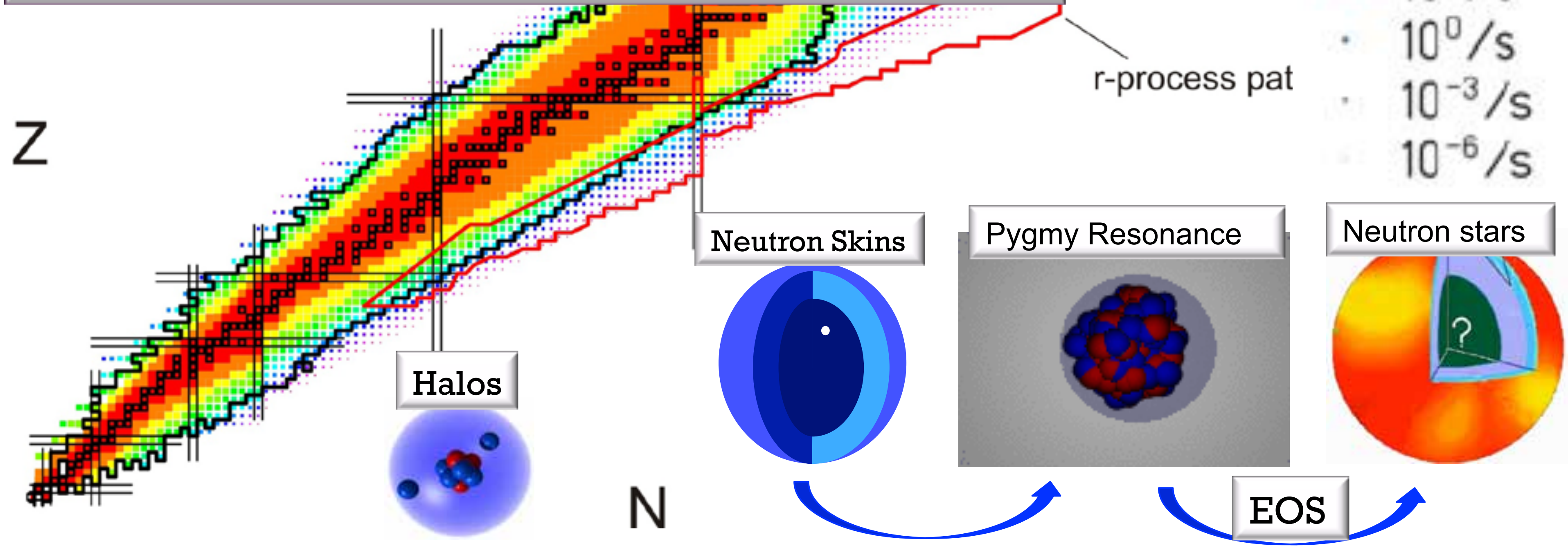
> 800 members from 37 countries and 146 institutions

Central Topics for NuSTAR at FAIR

- Quest for the limits of existence
- Halos, Open Quantum Systems, Few Body Correlations
- Changing shell structure far away from stability
- Skins, new collective modes, nuclear matter, neutron stars
- Phases and symmetries of the nuclear many body system
- Origin of the elements

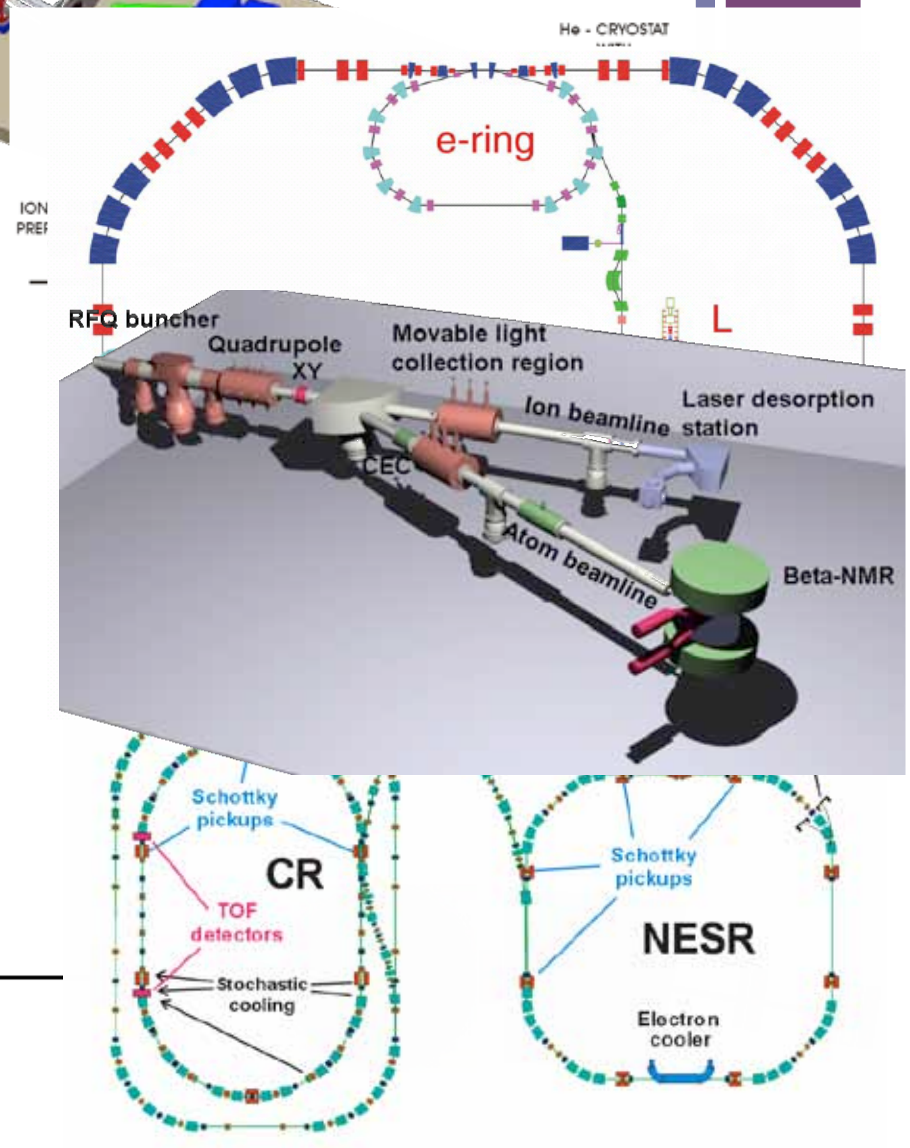
➔ **unified theory** (ab-initio, density functional, shell model)



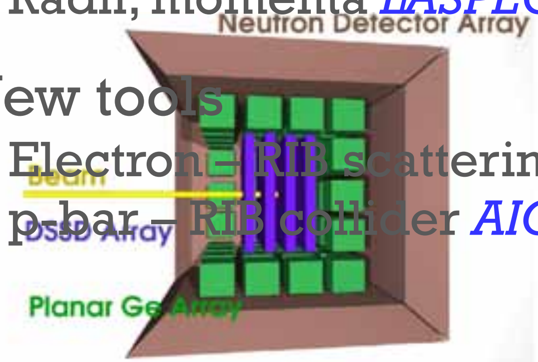


Similar for RIBF/FRIB/…-> T. Nakamura

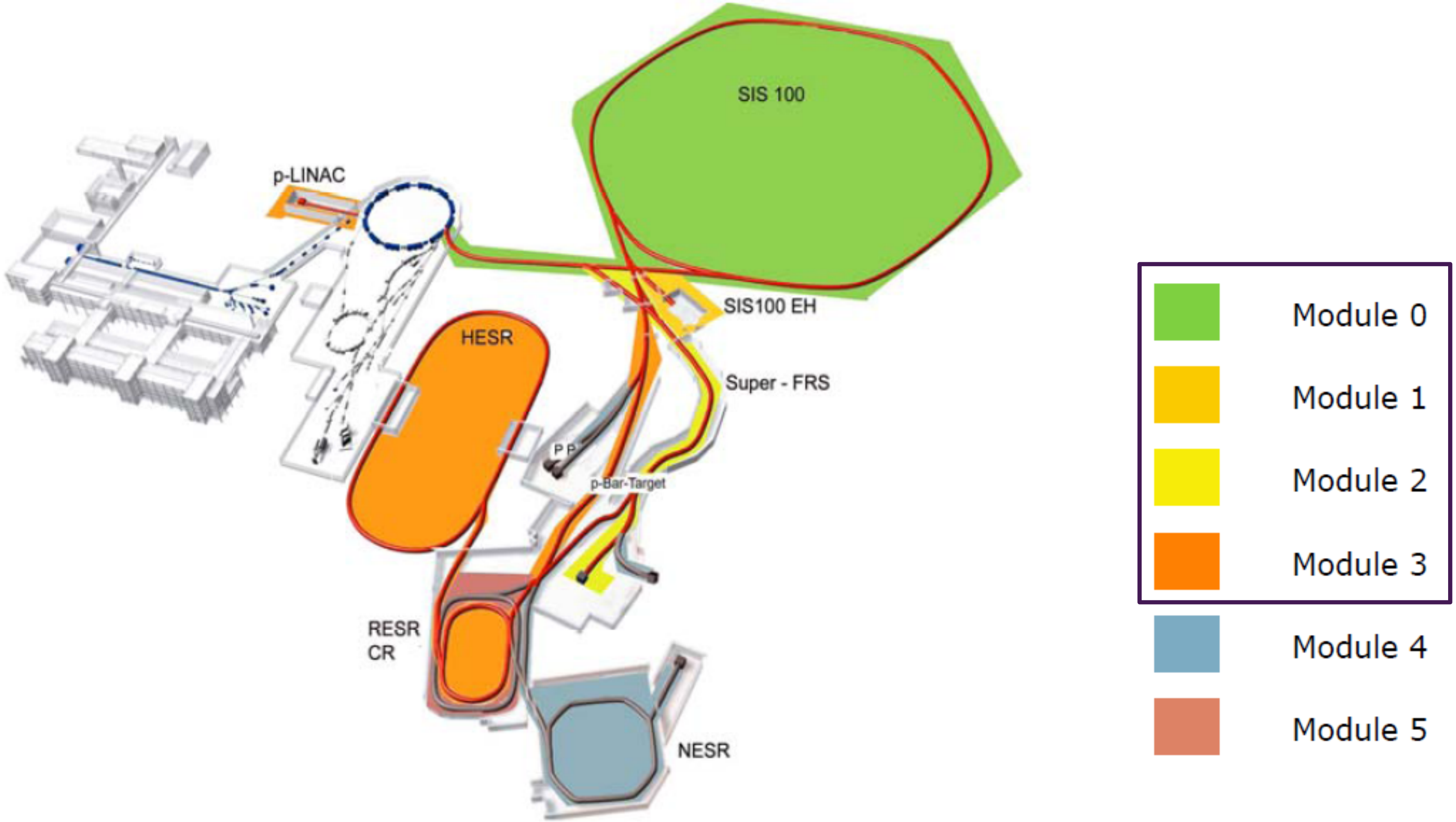
NuSTAR Experiments



- Nuclear reactions
  - Relativistic energies *R³B*
  - Cooled beams *EXL*
  - High-res. spectroscopy *HISPEC*
- Decay properties
  - Stopped beams *DESPEC*
- Ground state properties
  - Masses *MATS, ILIMA*
  - Radii, momenta *LASPEC*
- New tools
  - Electron – RIB scattering *ELISe*
  - p-bar – RIB collider *AIC*

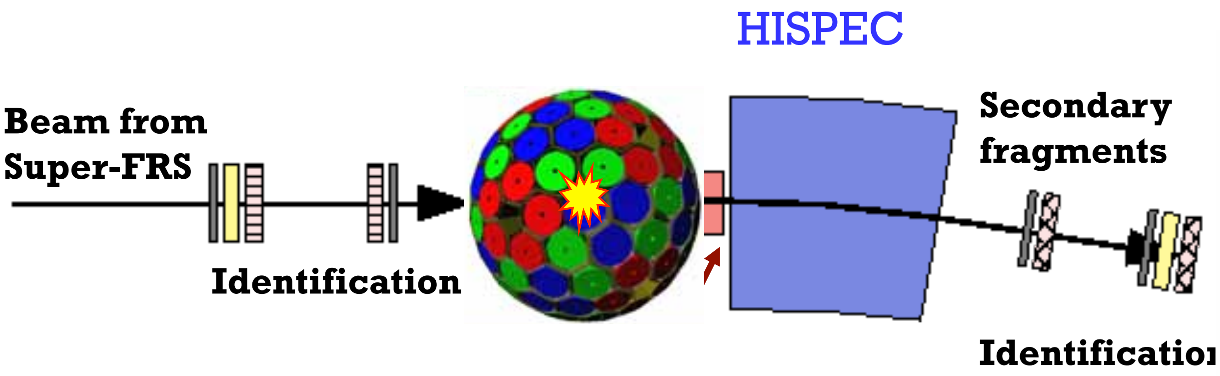


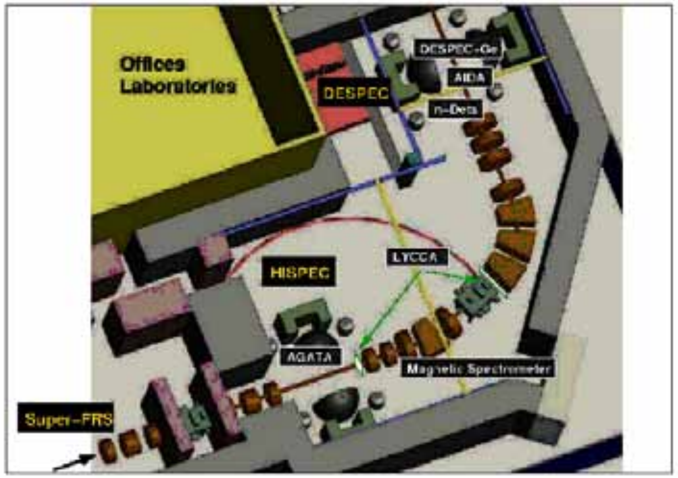
FAIR Modularized Start Version



-> Talk by Th. Beier

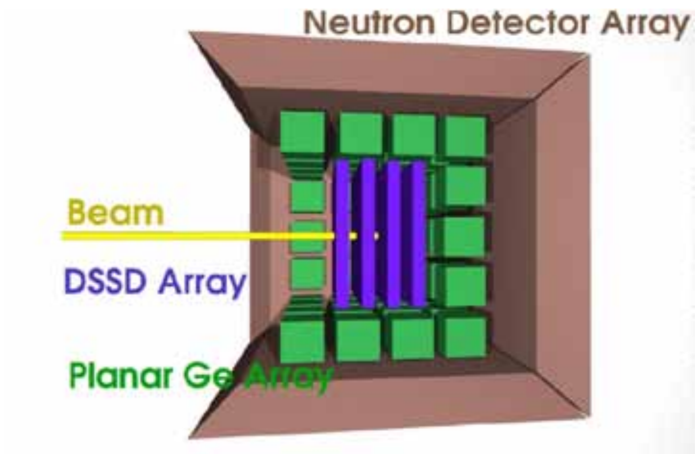
High-resolution in-flight and decay spectroscopy with RIBs (HISPEC/DESPEC)





AGATA - **A**dvanced **GA**mma **T**racking **A**rray

4π γ-array for experiments at European accelerators providing radioactive and high-intensity stable beams

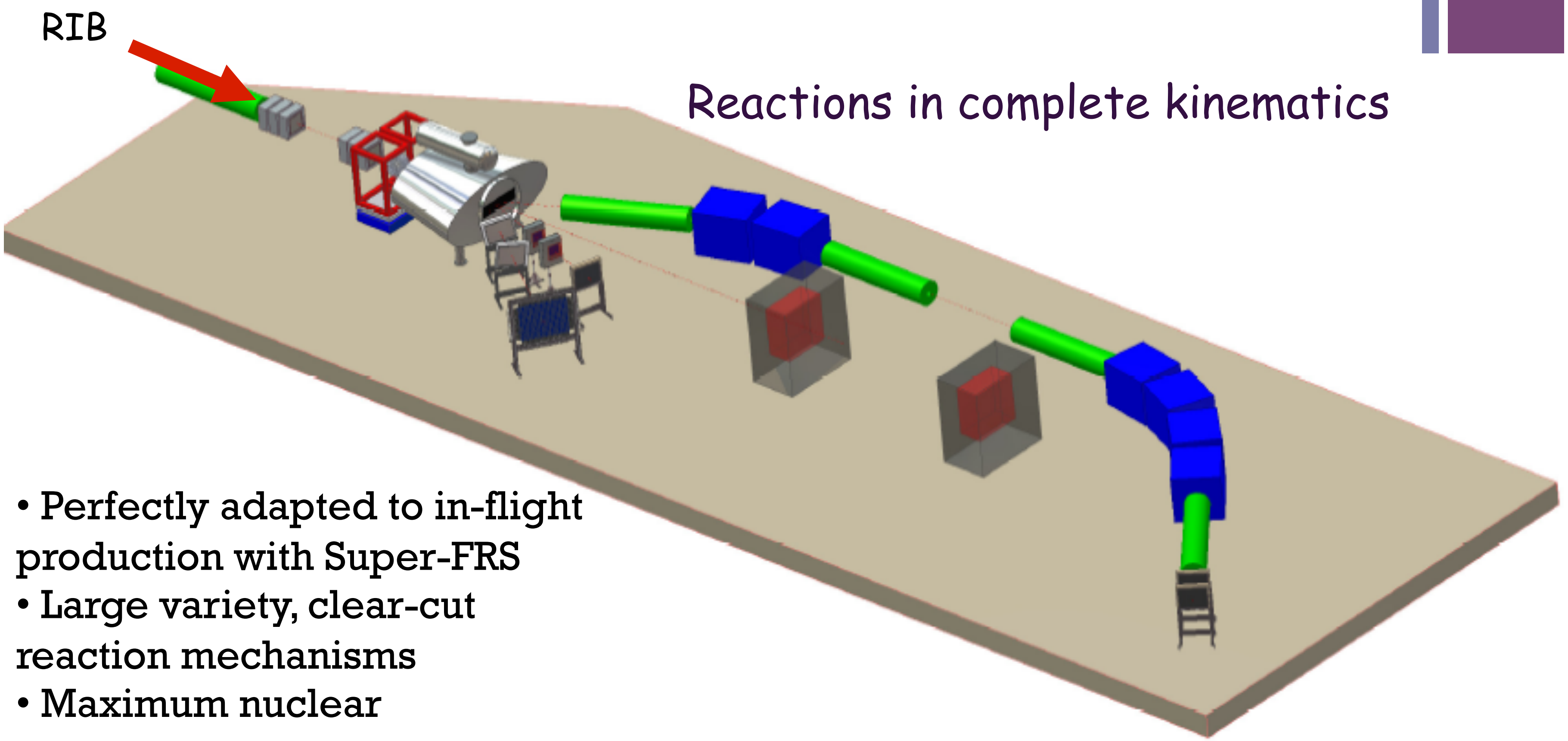


-> Talks by Z. Podolyak, R. Page

HISPEC/DESPEC physics

Research field	Experimental method (beam-energy range)	Physics goals and observables	Beam int. (particle/s)
Nuclear structure, reactions and astrophysics	Intermediate energy Coulomb excitation, In-beam spectroscopy of fragmentation products (E/A ~ 100 MeV)	Medium spin structure, Evolution of shell structure and nuclear shapes, transition probabilities, moments,	$10^{1}...10^{5}$
	Multiple Coulomb excitation, direct and deep-inelastic, fusion evaporation reactions (E/A ~ 5 MeV; Coulomb barrier)	high spin structure, single particle structure, dynamical properties, transition probabilities, moments,	$10^{4}...10^{7}$
	Decay spectroscopy (E/A = 0 MeV)	half-lives, spins, nuclear moments, GT strength, isomer decay, beta-decay, beta-delayed neutron emission, exotic decays such as two proton, two neutron.	$10^{-5}...10^{3}$

R³B Reactions with Relativistic Radioactive Beams



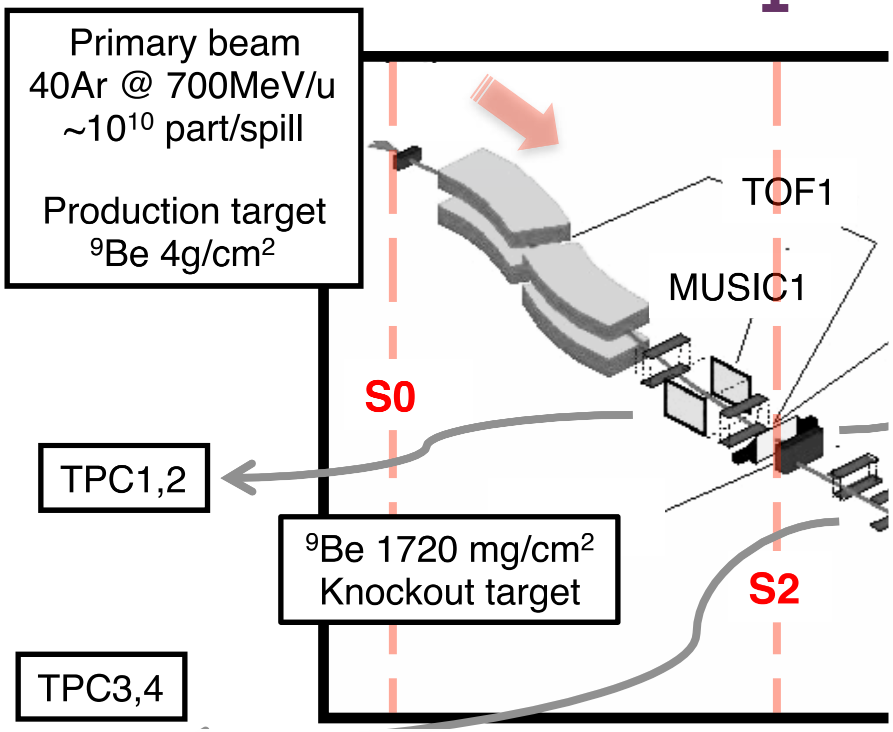
- Perfectly adapted to in-flight production with Super-FRS
- Large variety, clear-cut reaction mechanisms
- Maximum nuclear transparency
- Relativistic focussing
- Resolution

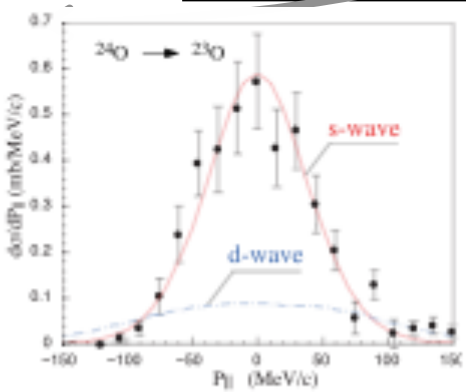
R^{3}B reaction types

Reaction type	*Physics goals*
Knockout	Shell structure, valence-nucleon wave function, many-particle decay channels unbound states, nuclear resonances beyond the drip lines
Quasi-free scattering	Single-particle spectral functions, shell-occupation probabilities, nucleon-nucleon correlations, cluster structures
Total-absorption measurements	Nuclear matter radii, halo and skin structures
Elastic p scattering	Nuclear matter densities, halo and skin structures
Heavy-ion induced electromagnetic excitation	Low-lying transition strength, single-particle structure, astrophysical S factor, soft coherent modes, low-lying resonances in the continuum, giant dipole (quadrupole) strength
Charge-exchange reactions	Gamow-Teller strength, soft excitation modes, spin-dipole resonance, neutron skin thickness
Fission	Shell structure, dynamical properties
Spallation	Reaction mechanism, astrophysics, applications: nuclear-waste transmutation, neutron spallation sources
Projectile fragmentation and multifragmentation	Equation-of-state, thermal instabilities, structural phenomena in excited nuclei, γ-spectroscopy of exotic nuclei

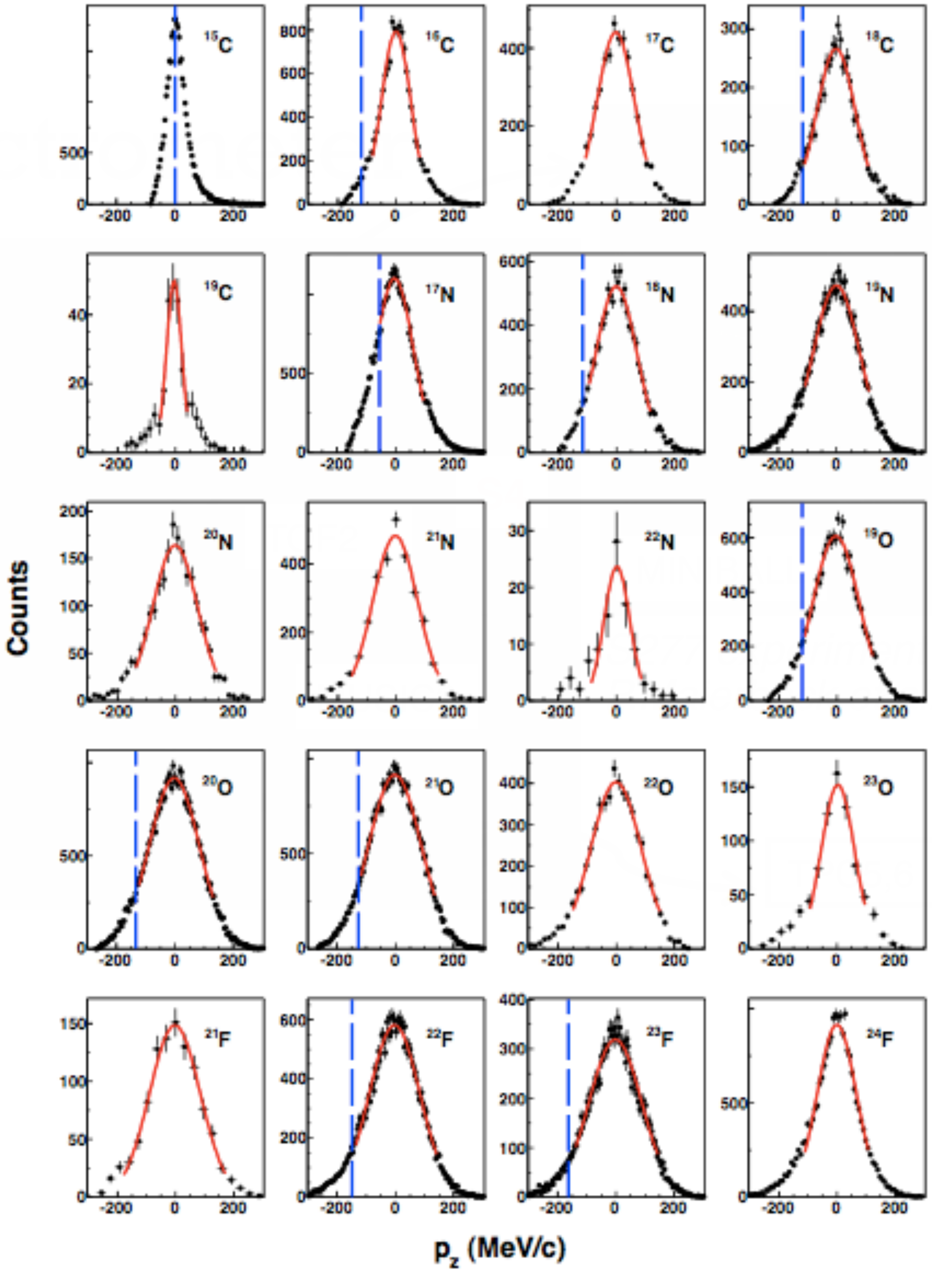
Astrophysics -> R.Reifarth

FRS used as a spe

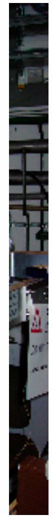




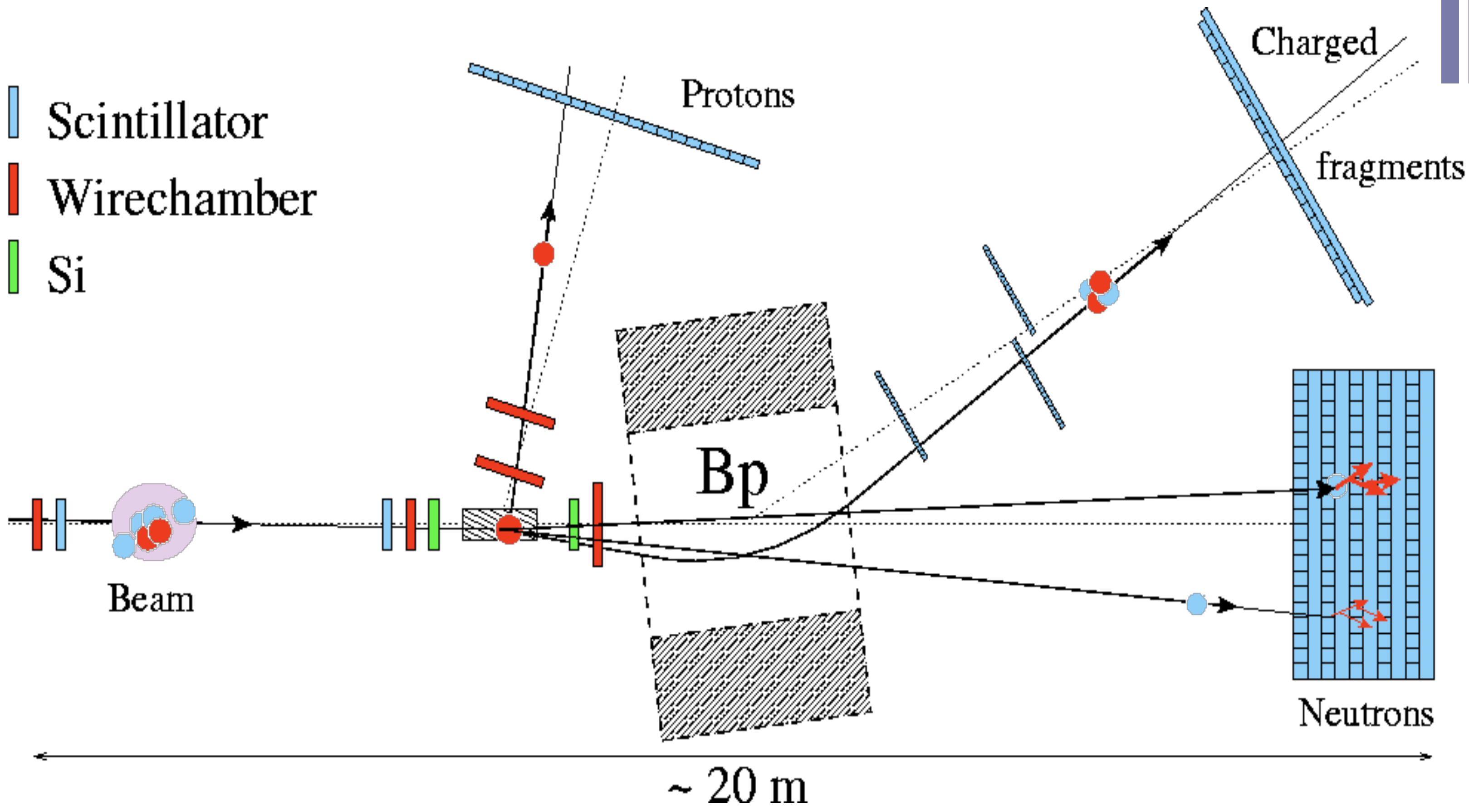
R. Kanungo et al, PRL 102 (2009) 152501



C.Rodríguez-Tajes et al, to be submitted to PRC



ALADIN/LAND@GSI



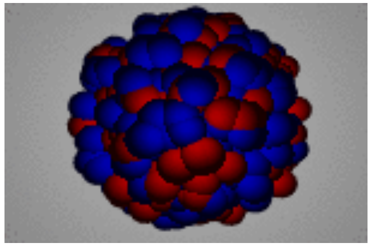
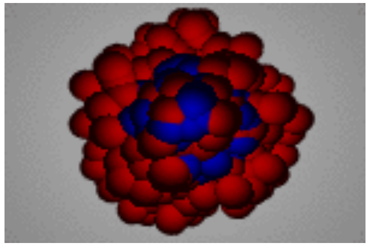
Data-taking since 1990

The collective response of the nucleus: Giant Resonances

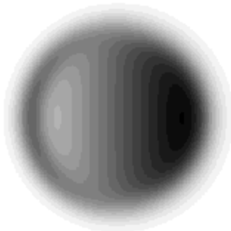
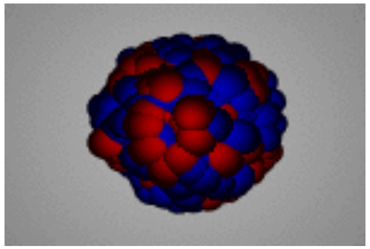
Electric giant resonances

Isoscalar | Isovector

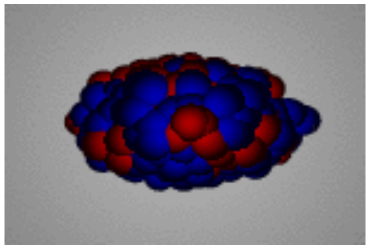
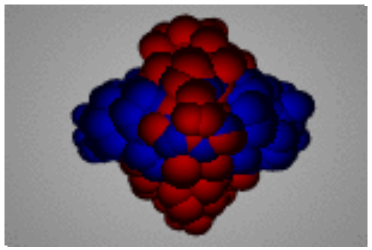
Monopole (GMR)

Dipole (GDR)

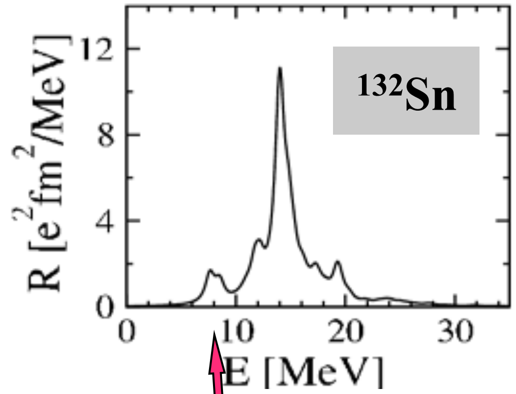
Quadrupole (GQR)

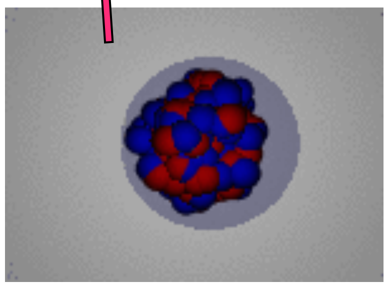



? new collective soft dipole mode

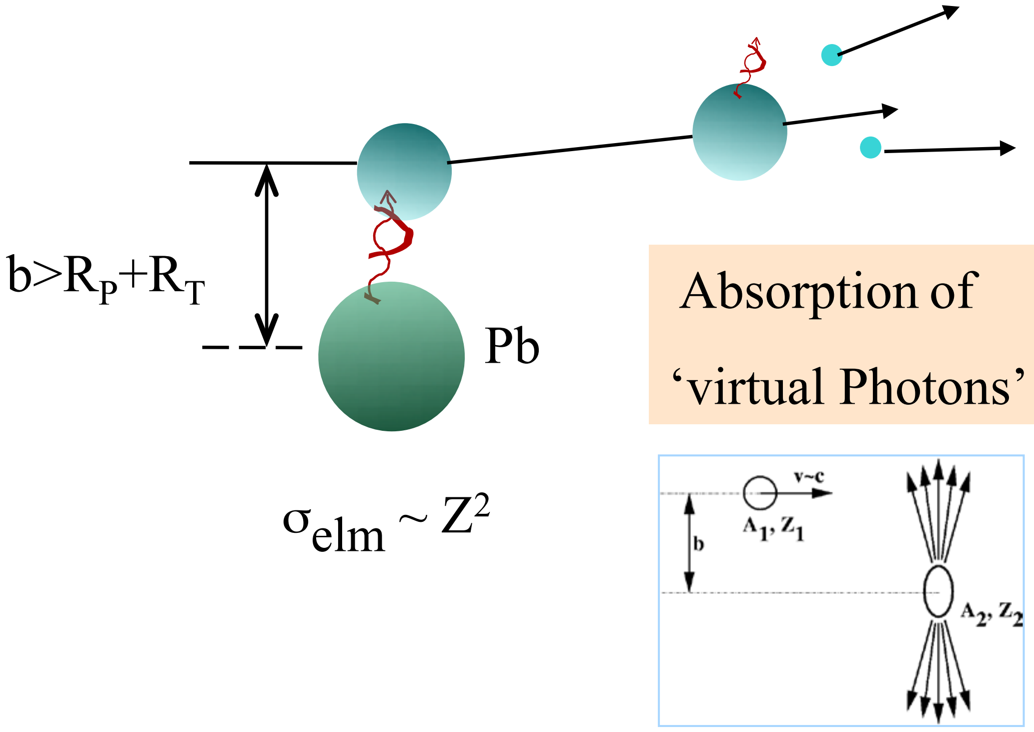
(Pygmy resonance)

Prediction: RMF (N. Paar et al.)





Electromagnetic excitation at high energies

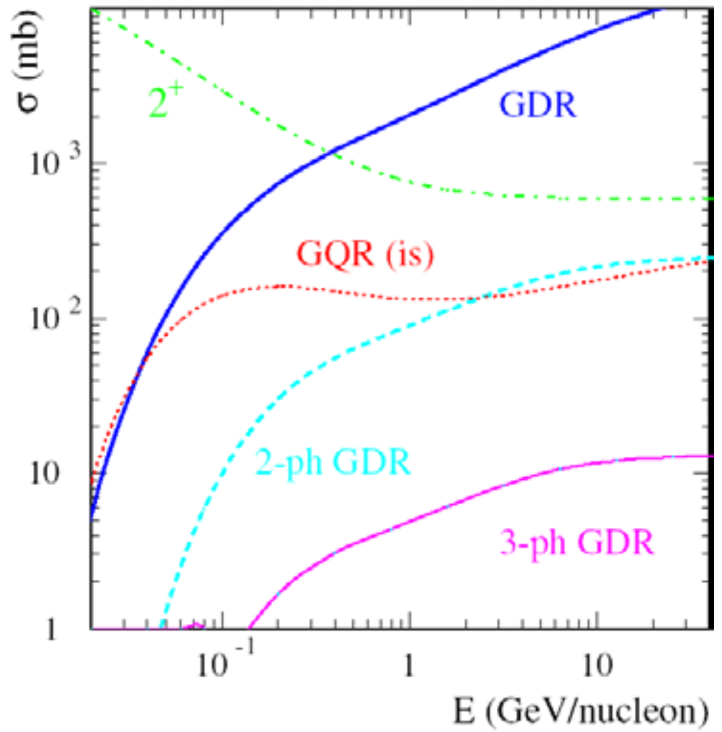


$\sigma_{elm} \sim Z^2$

Absorption of 'virtual Photons'

Semi-classical theory:

$$d\sigma_{elm} / dE = N_\gamma(E)\ \sigma_\gamma(E)$$



High velocities $v/c \approx 0.6$-0.9

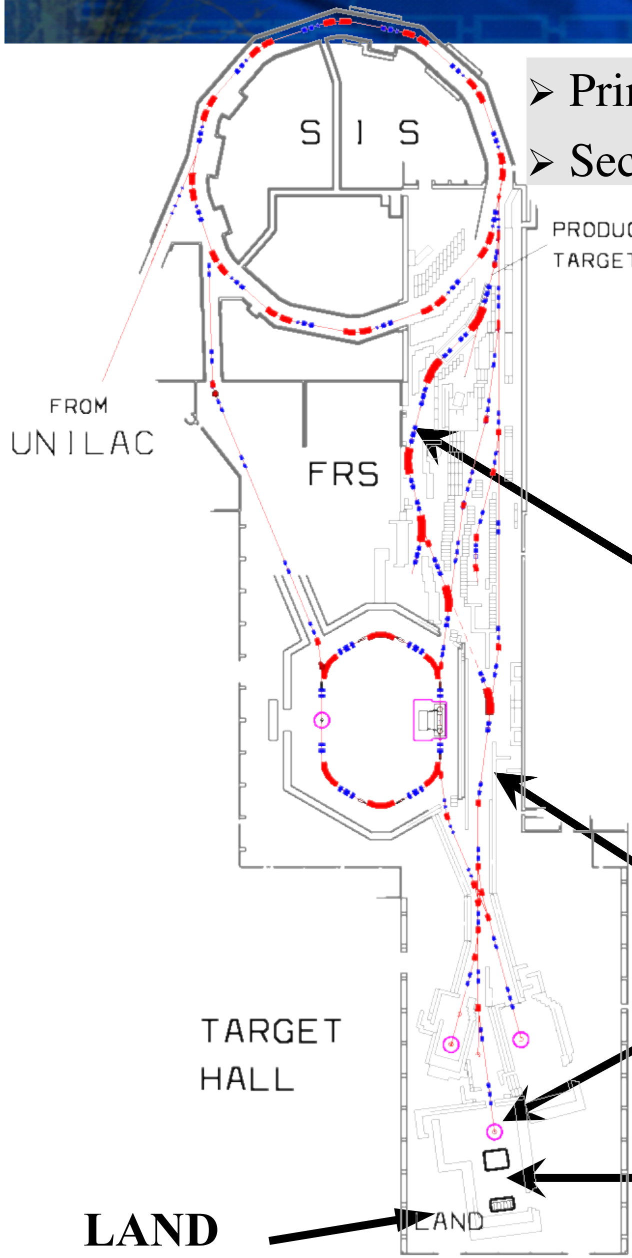
⇒ High-frequency Fourier components

$E_{\gamma,max} \approx 25$ MeV (@ 1 GeV/u)

Determination of 'photon energy' (excitation energy) via a kinematically complete measurement of the momenta of all outgoing particles (invariant mass)

Experimental Approach: Production of (fission-)fragment beams

- Primary: $3*10^8$ ^{238}U/spill @550MeV/u
- Secondary (mixed): 50 ions ^{132}Sn/spill (~10/sec @500 MeV/u)



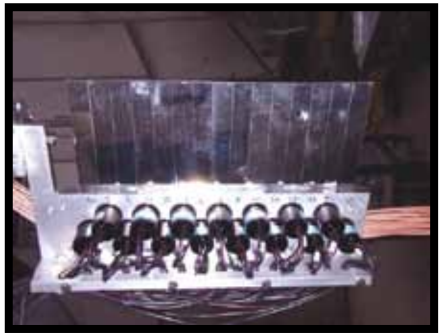
LAND

$$\frac{A}{Z} = \frac{e}{m_u c}\,\frac{B\rho}{\beta\gamma}$$

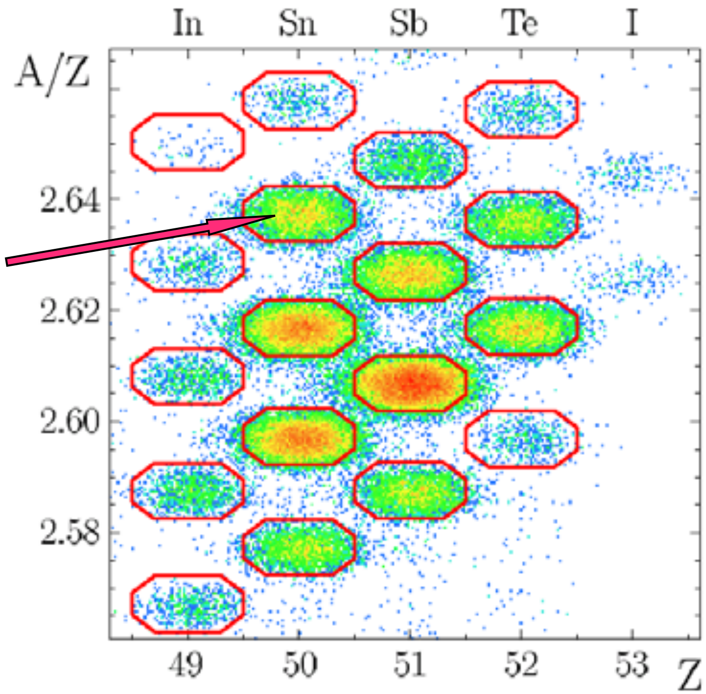
Bρ – from position at middle focal plane of the FRS

β – from TOF

Z – from ΔE

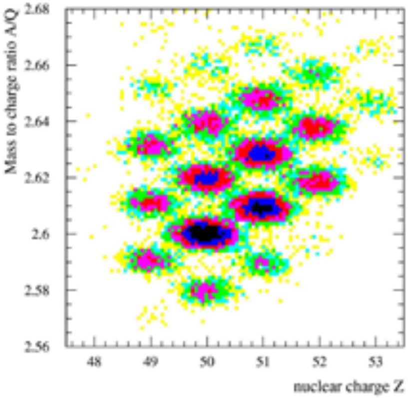


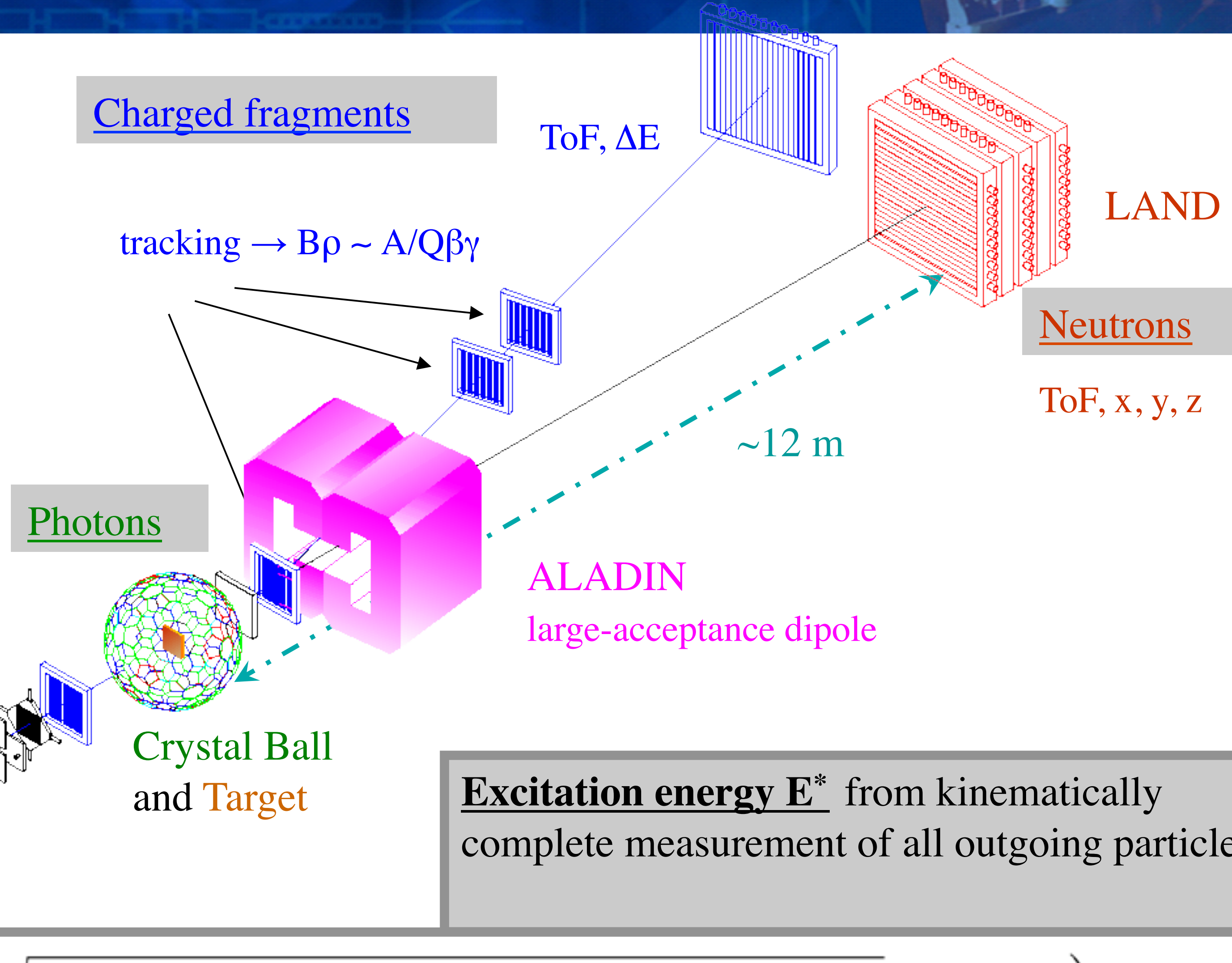
^{132}Sn



Experimental Approach II: The LAND reaction setup @GSI

Mixed beam





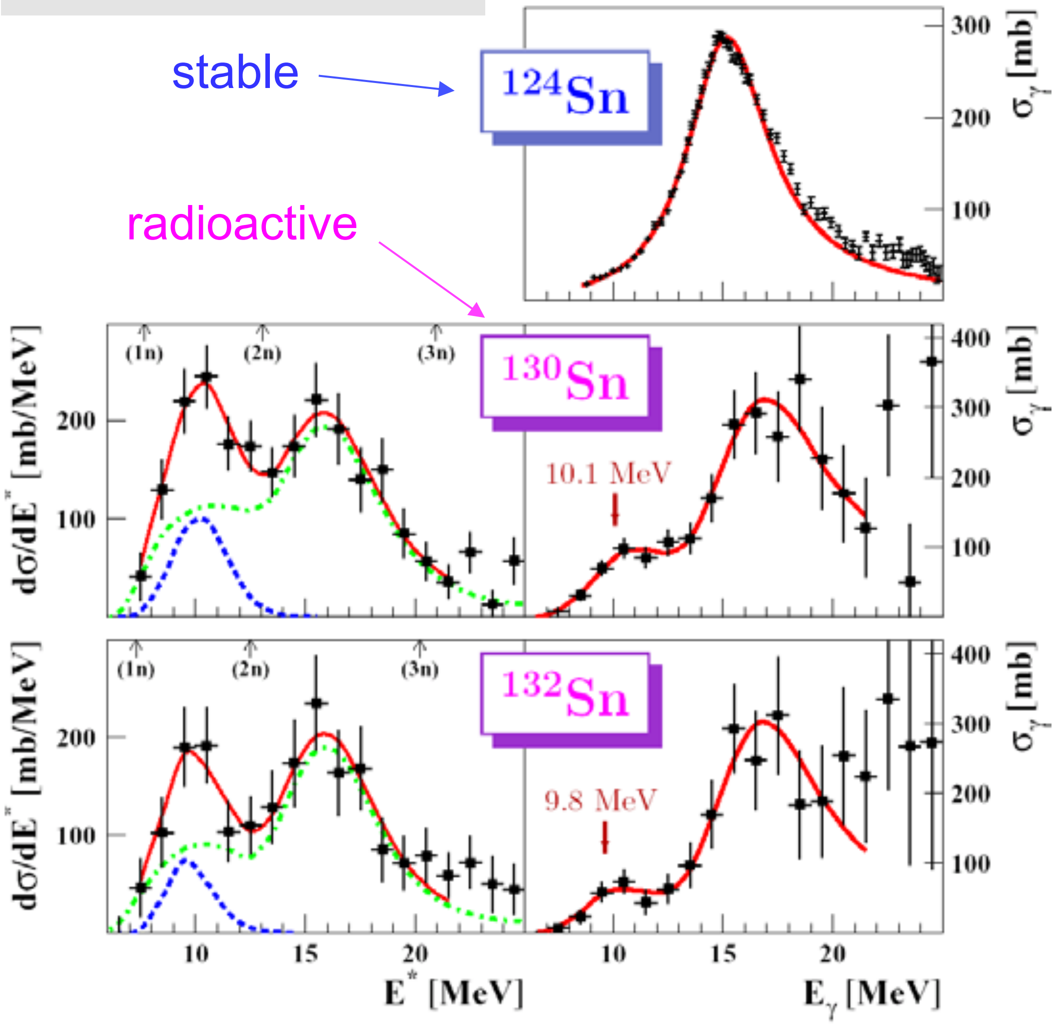
Excitation energy E* from kinematically complete measurement of all outgoing particles:

$$E^* = \left(\sqrt{\sum_i m_i^2 + \sum_{i \neq j} m_i m_j \gamma_i \gamma_j (1 - \beta_i \beta_j \cos\theta_{ij})} - m_{proj} \right) c^2 + E_\gamma$$

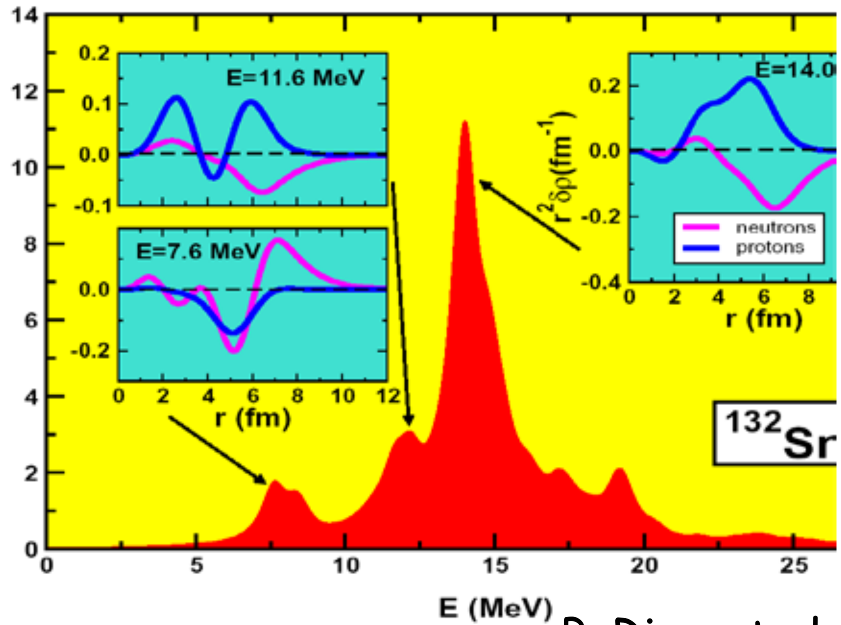
Dipole-strength distributions in neutron-rich Sn isotopes

Electromagnetic-excitation cross section

Photo-neutron cross section



P. Adrich et al., PRL 95 (2005) 132501



P. Ring et al.

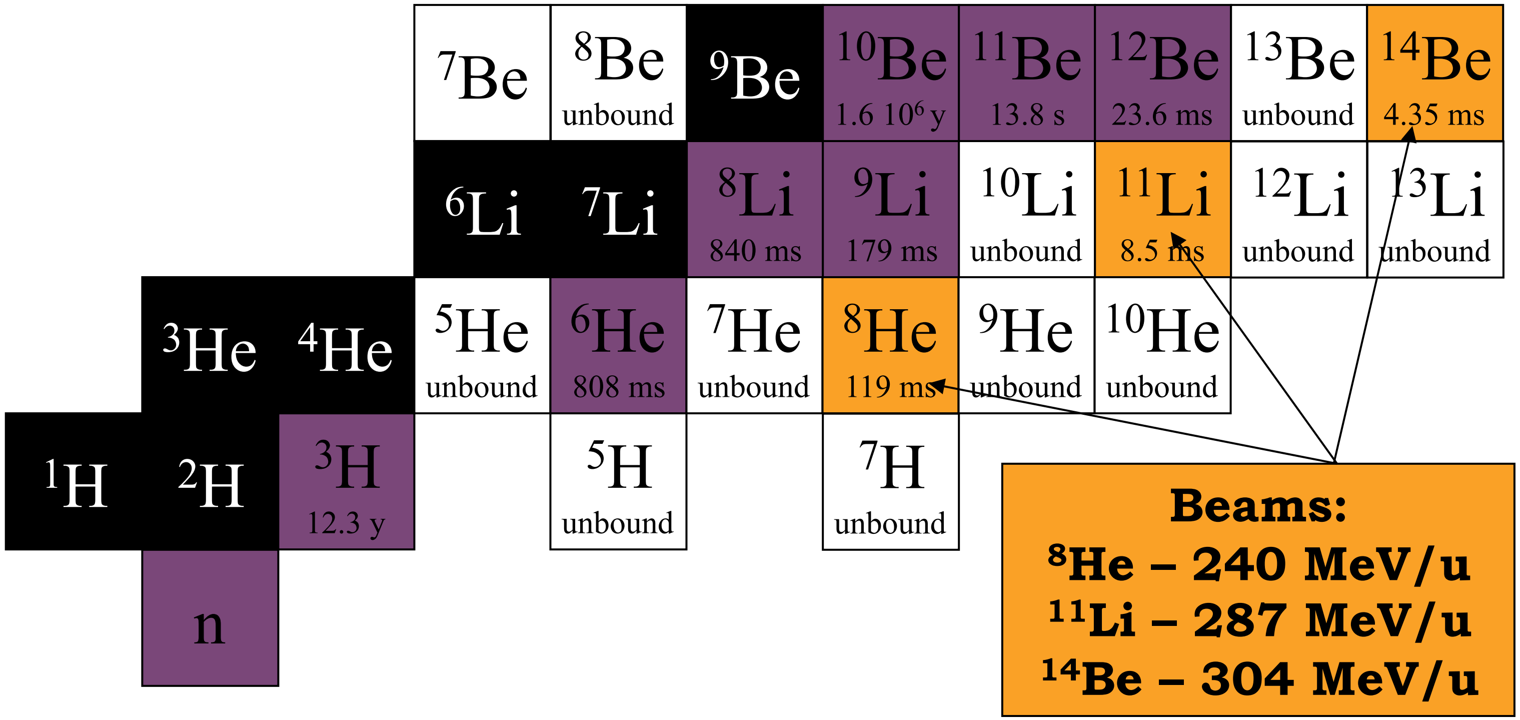
PDR

- located at 10 MeV
- exhausts a few % TRK sum rule
- in agreement with theory

GDR

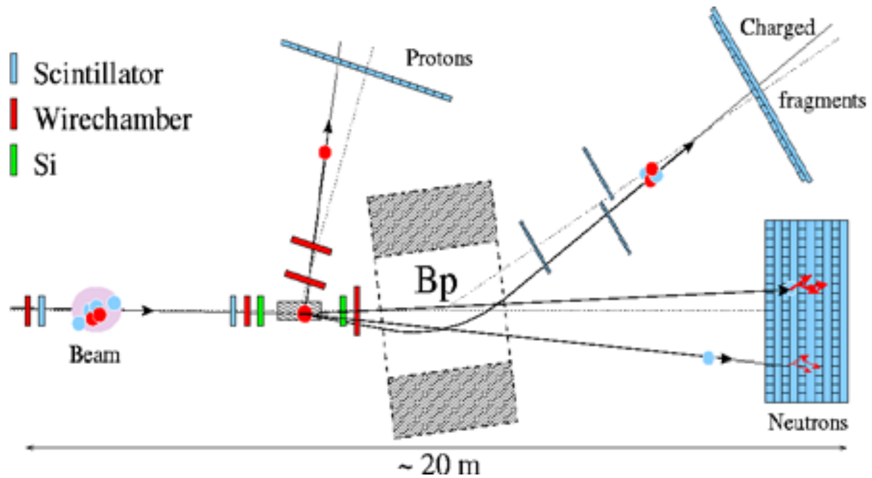
- no deviation from systematics

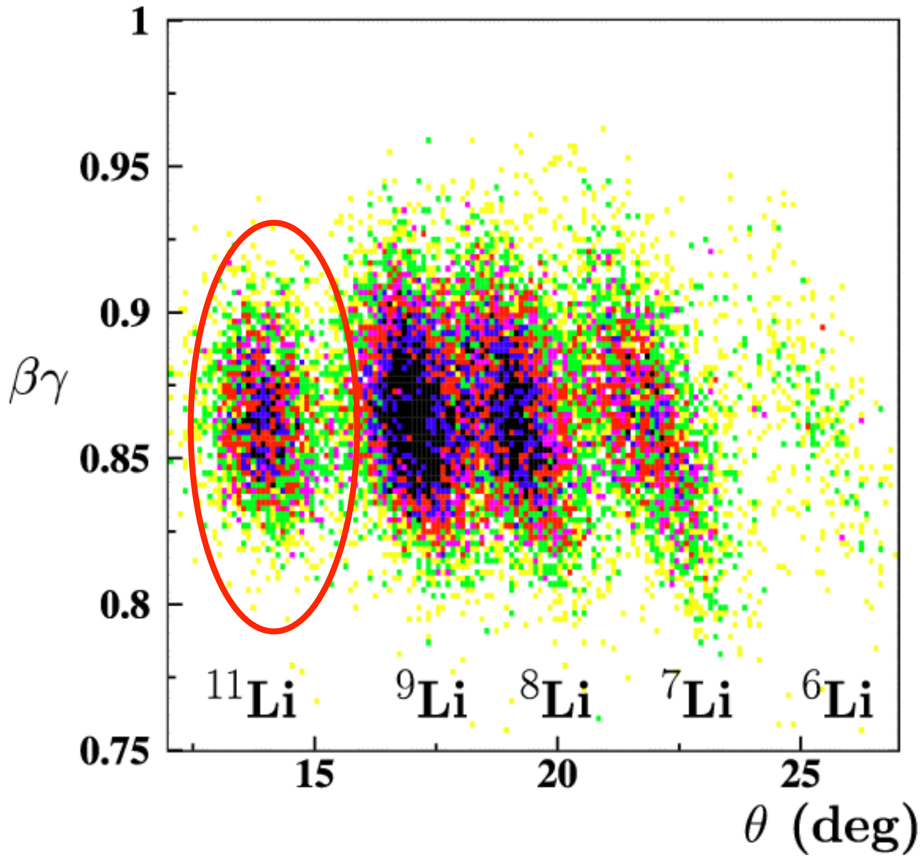
S245@GSI - Unbound Light Nuclei



Proton knockout from 304 MeV/u ^{14}Be

S245@GSI



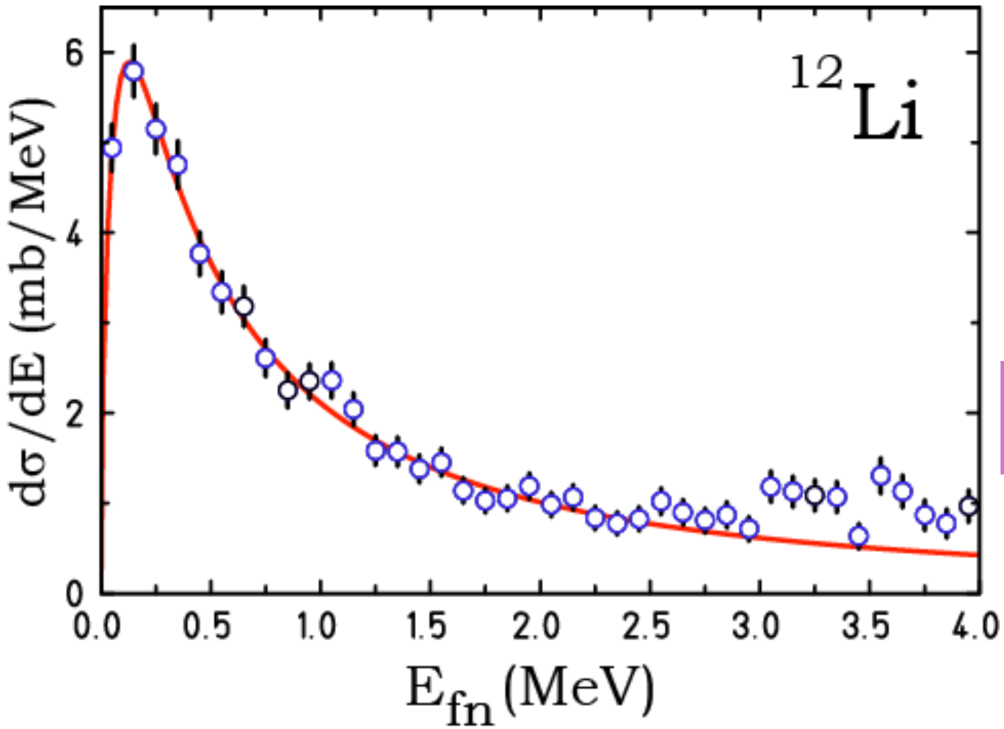


-> Talk by Yuliya Aksyutina

Yu. Aksyutina *et al.* PLB 666(2008)430

$^{1}H(^{14}Be,2pn)^{12}Li$

Going beyond the dripline…



ε =1.47(19)MeV

S_{2n} = 1.26(13) MeV

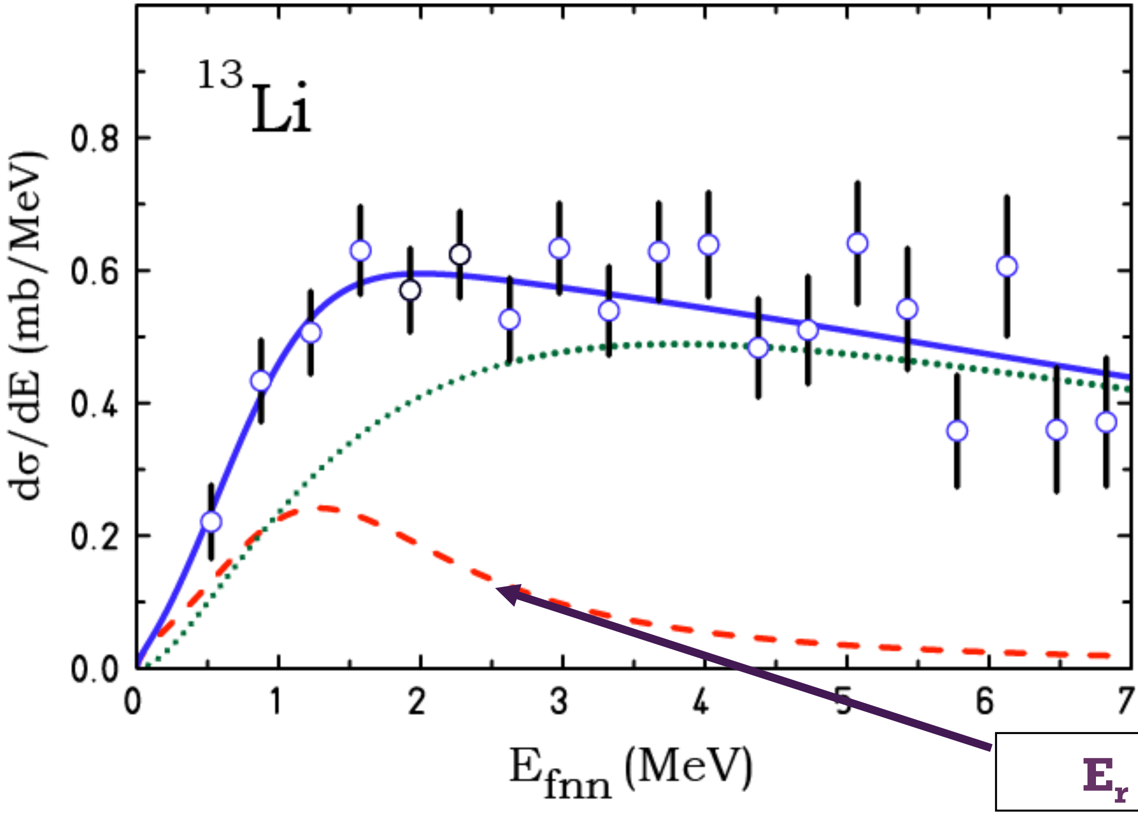
$$E_{fn} = \left|\vec{P}_f + \vec{P}_n\right| - M_f - m_n$$

$$a_s = -13.7(1.6)\, fm$$

Yu. Aksyutina *et al*. PLB 666(2008)430

$^{1}H(^{14}Be,2n)^{13}Li$

… and even further



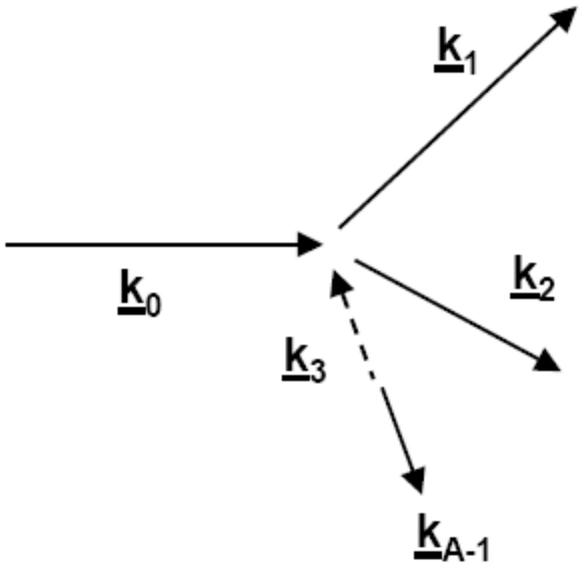
Yu. Aksyutina *et al*. PLB 666(2008)430

$$\frac{d\sigma}{dE_{f2n}} = \frac{E_{f2n}^{2}}{(2.21S_{2n} + E_{f2n})^{7/2}}$$

C. Forssén *et al*. NPA 673 (2008) 143

E_r = 1.47(31) MeV

Quasi-free scattering (QFS) –



Nuclear recoil momentum :

$$k_{A-1} = k_0 - k_1 - k_2 = -k_3$$

Separation energy of knocked-out nucleon

$$E_S = E_0 - E_1 - E_2 - \frac{k_{A-1}^2}{2(A-1)}$$

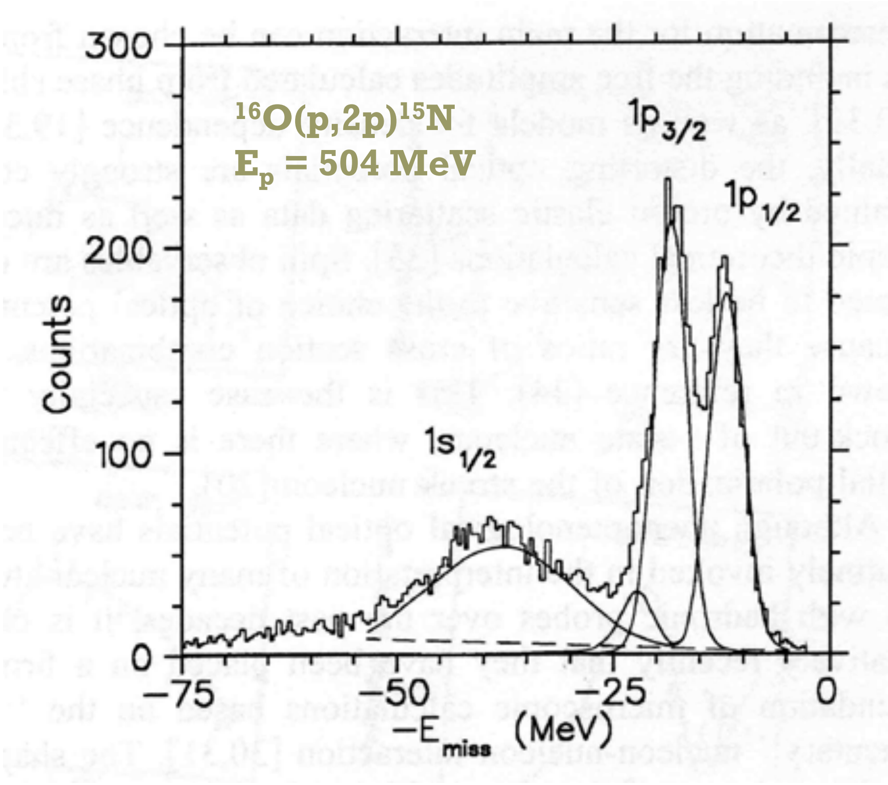
Coplanar geometry

Correlation cross-section in the factorized DWIA :

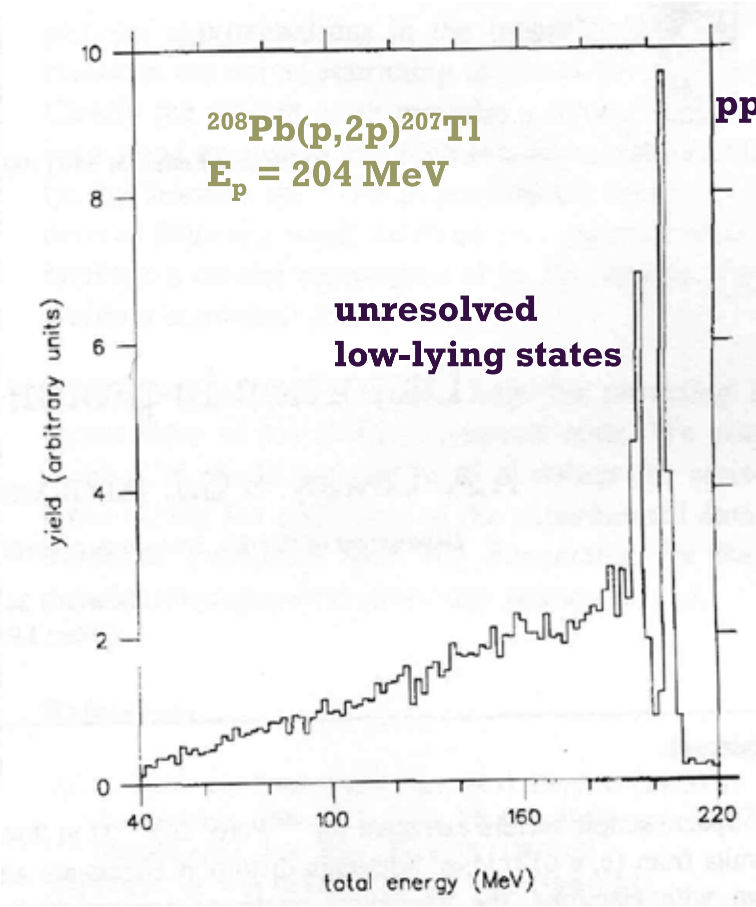
$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE} = \underbrace{S_3}_{\text{spectroscopic factor}} \underbrace{F_k \frac{d\sigma_{pp}}{d\Omega}(E_0, \theta, P_{eff})}_{\text{free n-n cross-section}} \underbrace{G(\vec{k}_3)}_{\text{distorted momentum distribution}}$$

spectroscopic factor — free n-n cross-section — distorted momentum distribution

QFS : Binding Energy Spectra



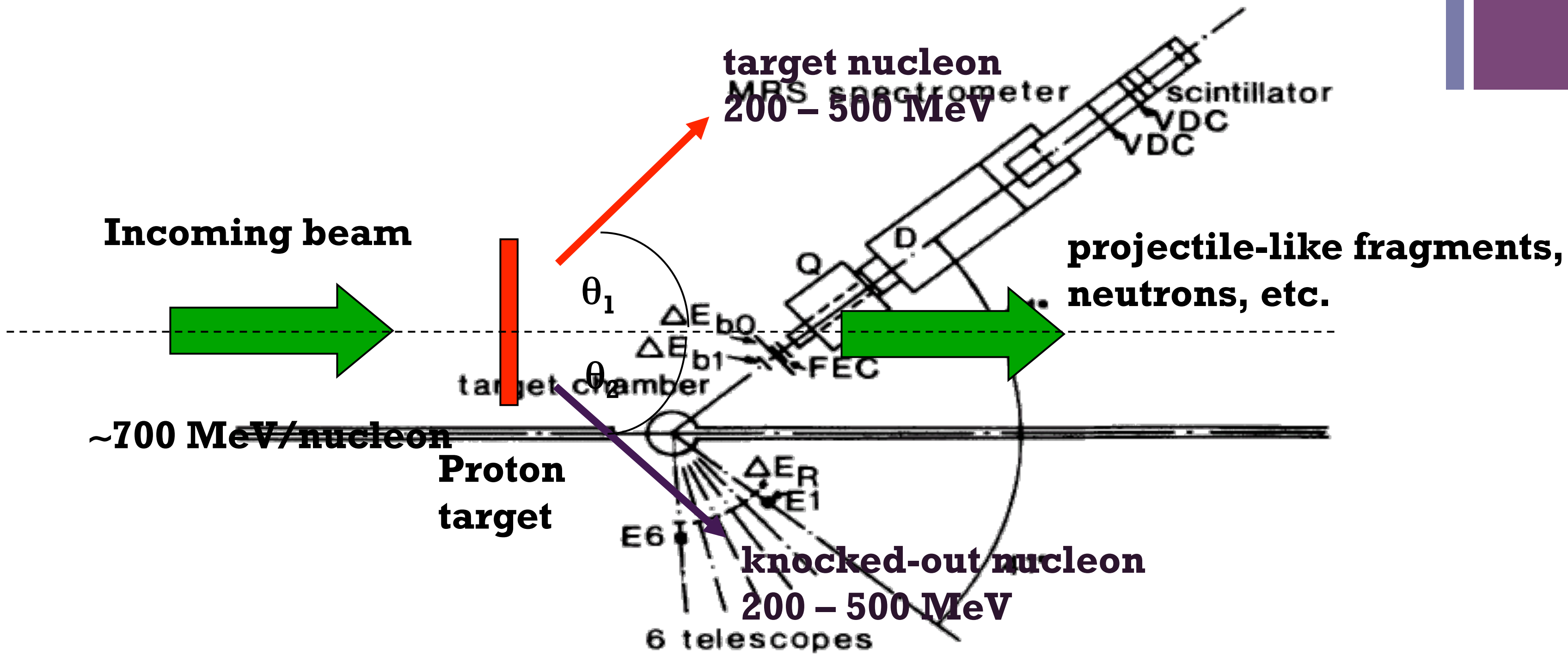
C.A. Miller et al., Phys. Rev. C 57 (1998) 1756.



A.A. Cowley et al., Phys. Lett. B 359 (1995) 300.

Energy resolution ~ few MeV

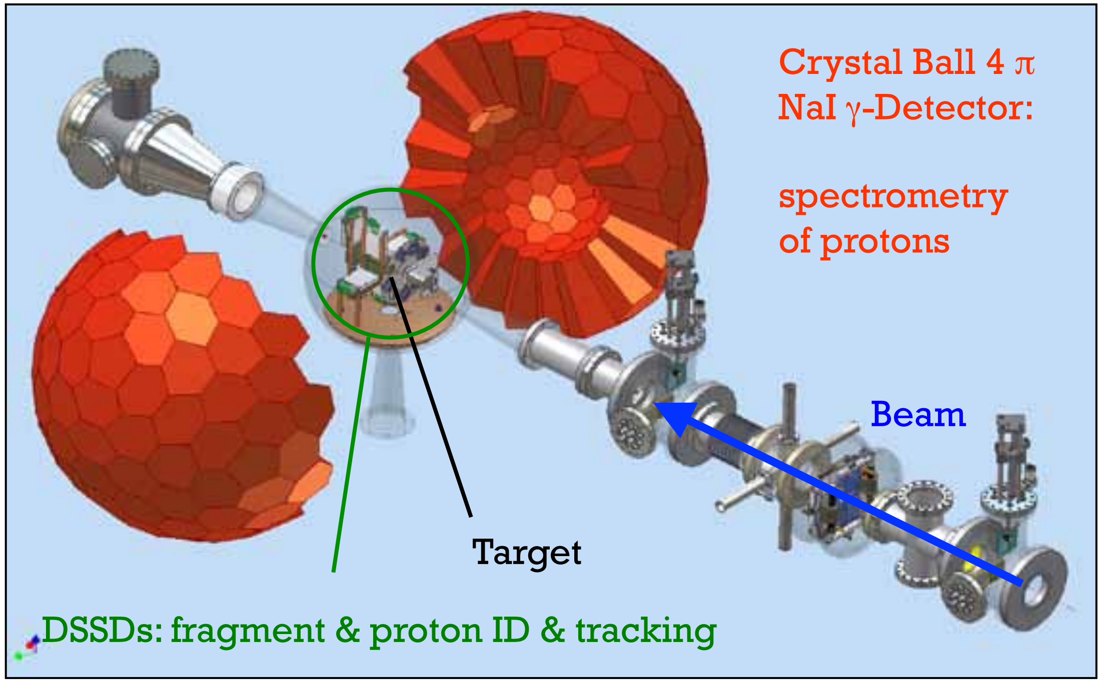
Experimental set-up



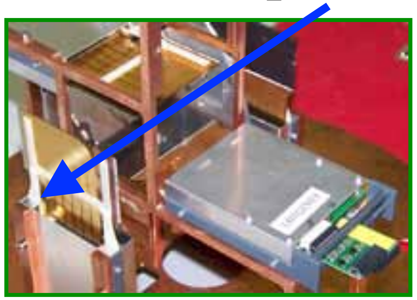
TRIUMF 1988

Upgrades for QFS pilot exp

LAND setup: Detectors around the target



DSSDs for proton tracking



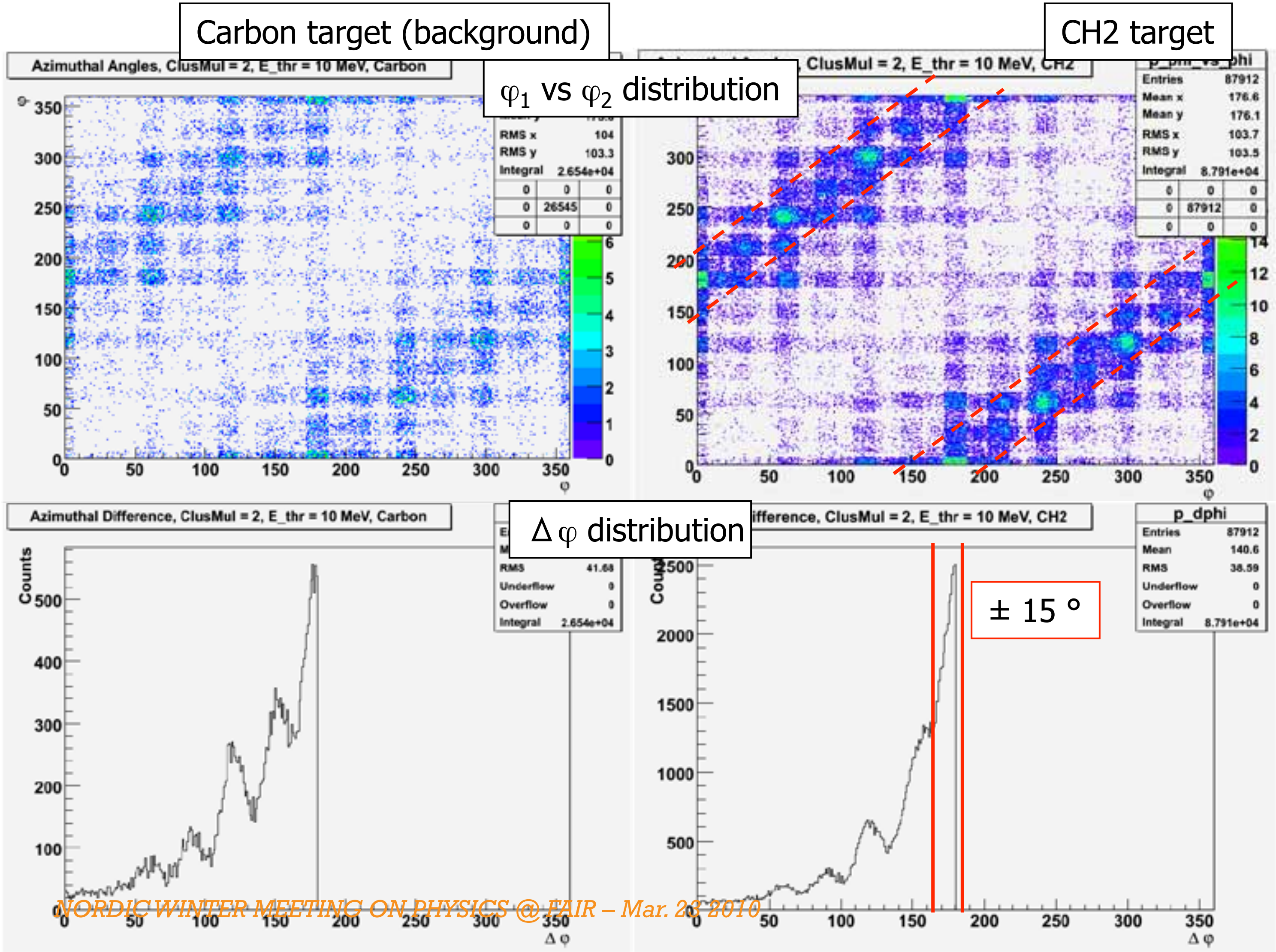
- 4 box detectors for proton tracking
- polar angle coverage ≈ $15° \leq \theta \leq 80°$
- resolution: $\Delta x \sim 100\ \mu m$; $\Delta E \sim 50$ keV
- range: 100 keV < E < 14 MeV
- 2 in-beam detectors for tracking & ID of fragments and protons

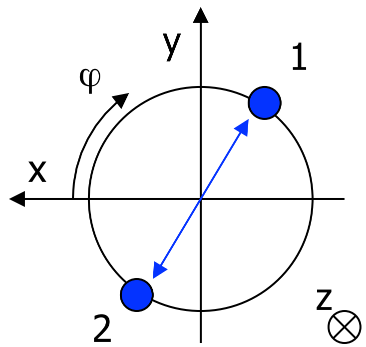
Crystal Ball for proton spectrometry

- 4π gamma detector (*1980 - ?)
- 162 NaI(Tl) crystals of 20 cm length
- New: Measure energy of recoil protons with additional readout of the forward 64 crystals (~ 2π) !

F. Wamers

2-proton events (≥ 10 MeV) in Crystal Ball: Azimuthal Distribution

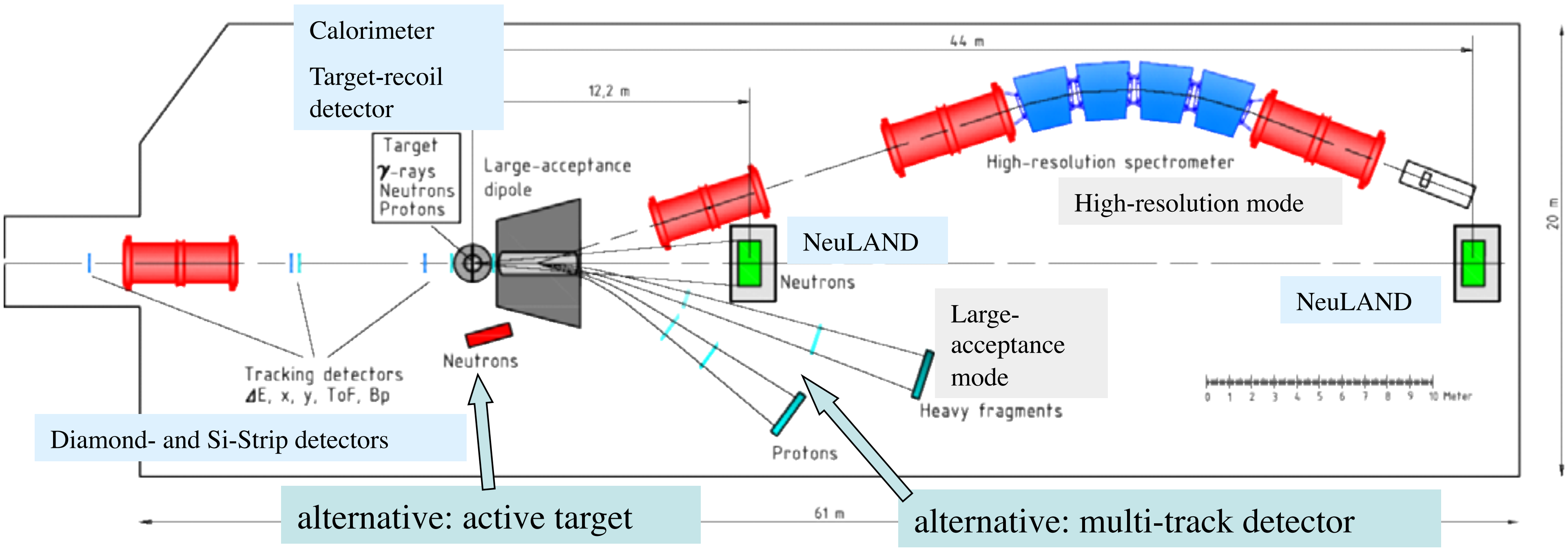




Correlation in $\Delta\varphi$:
$\Delta\varphi$ = 180°

F. Wamers

Reactions with Relativistic Radioactive Beams

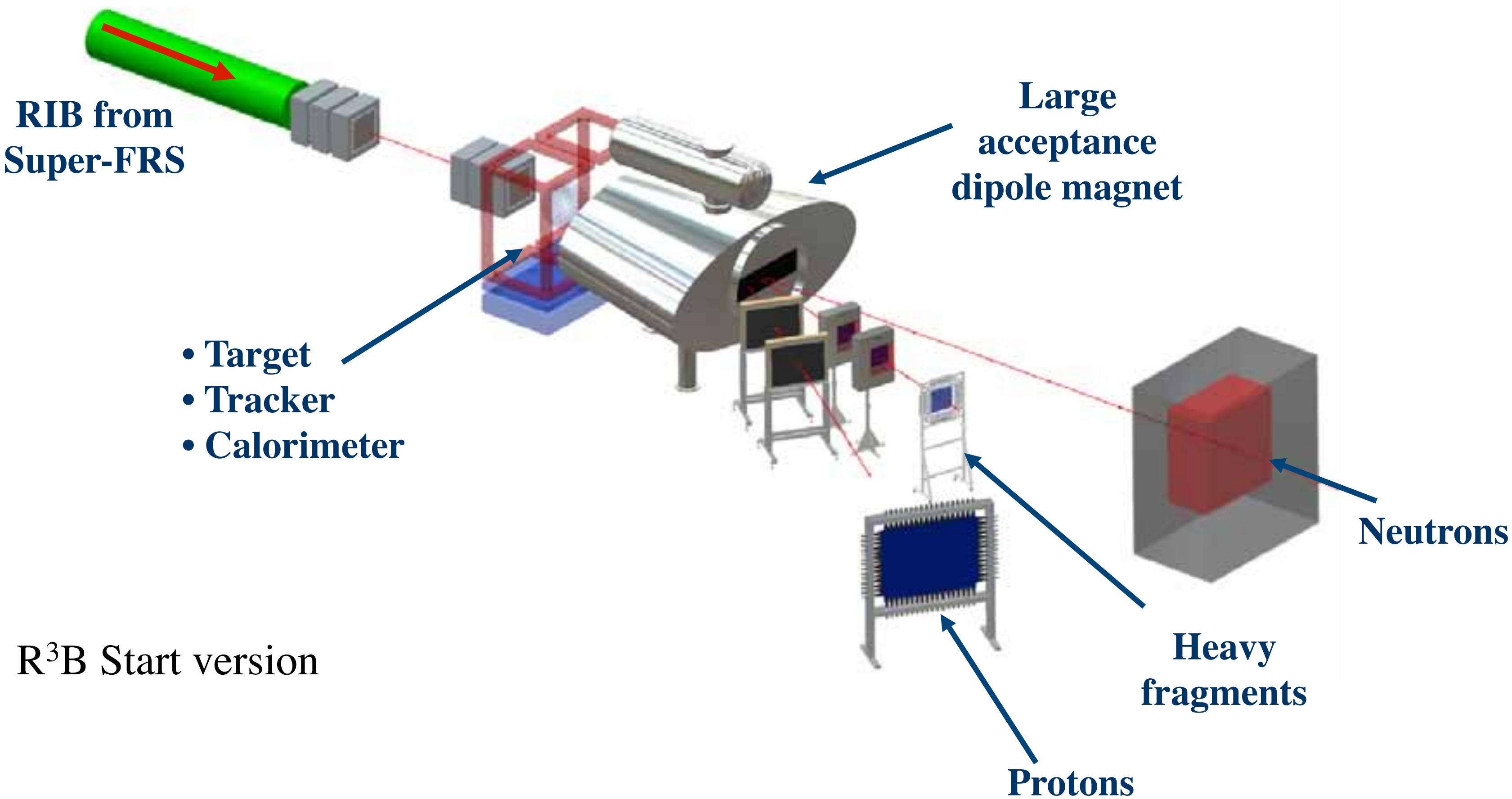


Kinematically complete measurement of reactions with high-energy secondary beams

Nuclear Astrophysics

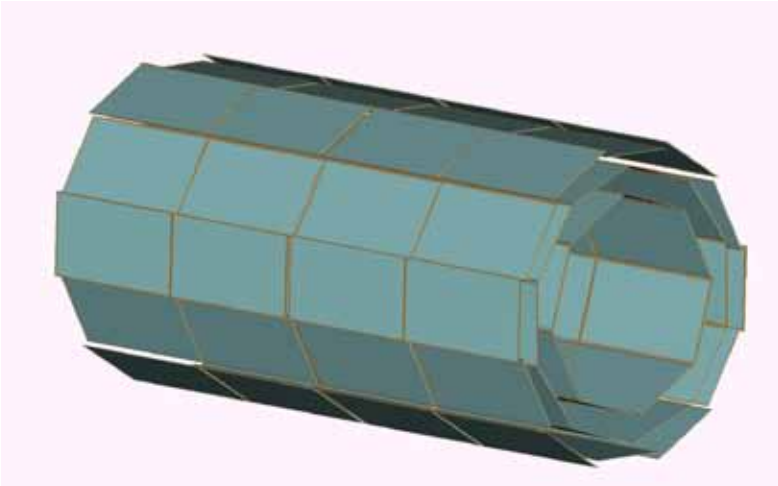
Structure of exotic nuclei

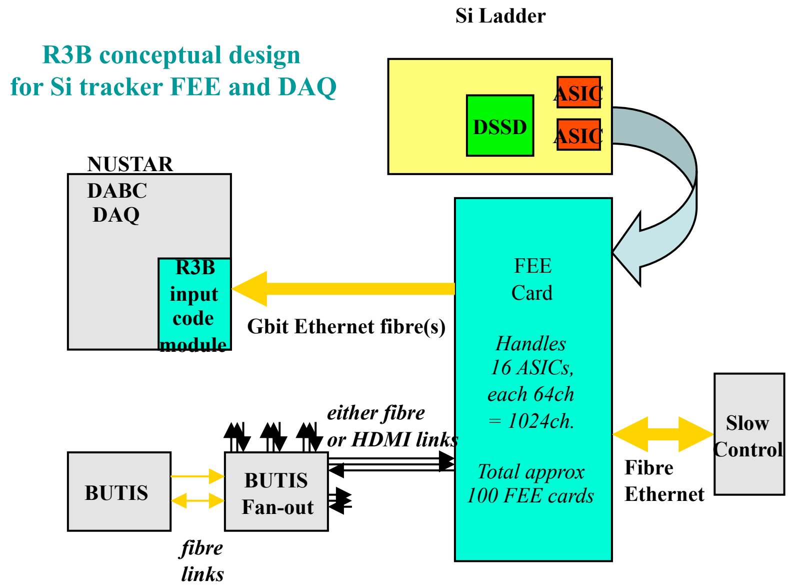
Neutron-rich matter



R^{3}B Start version

R³B Si Recoil Tracker WG





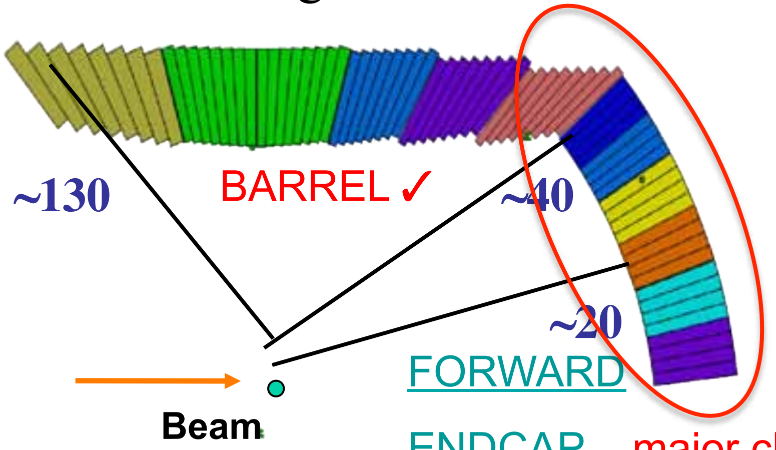
Tasks:

- **Simulations of target-recoil detector**
  - **elastic, inelastic, quasifree …**
- **Si-microstrip prototype testing**
  - **micro-strip, MAPS …**
- **Si tracker mechanical design**
- **Mechanical integration of target-recoil detector sub-systems**
  - **with LH2 target and calorimeter**
- **FEE and DAQ**
  - **100k channels, new ASIC design (low thresholds, self-triggering)**
- **Si-tracker construction, assembly and installation**
  - **Liverpool Semiconductor Centre (ATLAS, LHCb, etc)**
- **Si-ladder assembly testing**

WG Coordinator: Roy Lemmon – STFC Daresbury Laboratory, UK

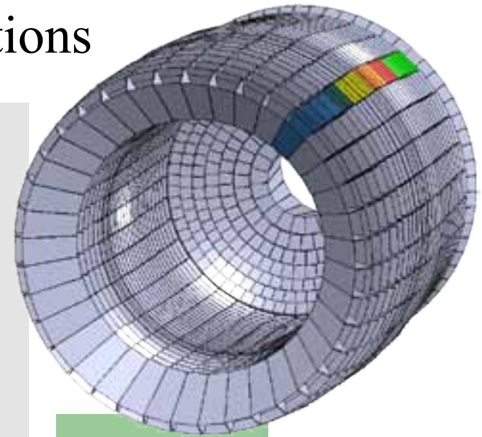
CALIFA/R³B R&D

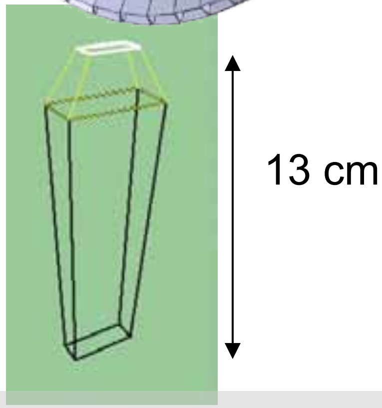
General design of the detector based on kinematical considerations



ENDCAP – major challenge!
LaBr/LaCl Phoswich?

"Egg" shape
Highly segmented
Thick detection volume
Scintillation based
performant photo-sensors

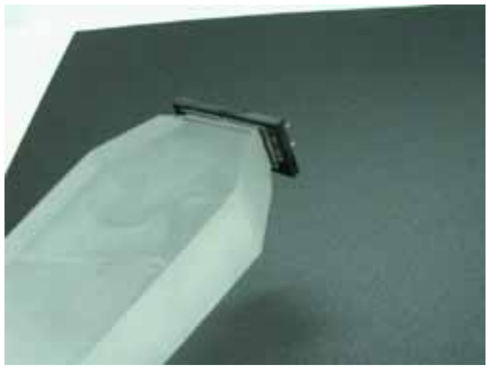




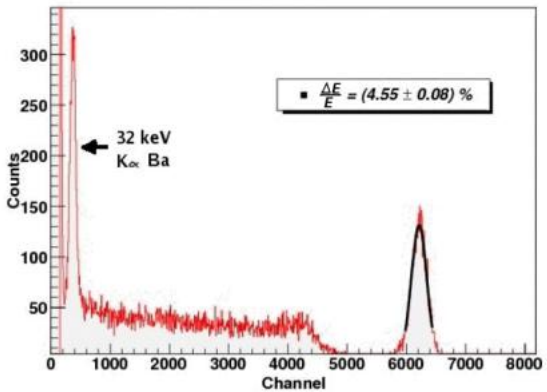
Real shape, 1MeV γ

◊ $\Delta E/E \sim 5$ %

Crystal and photosensors
Barrel → CsI+APD



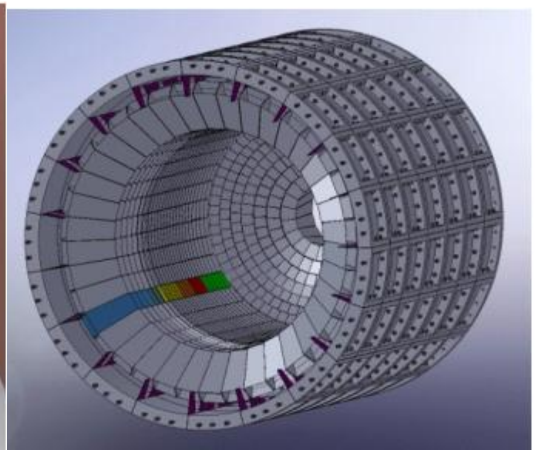
1cm³ and 662 keV γ

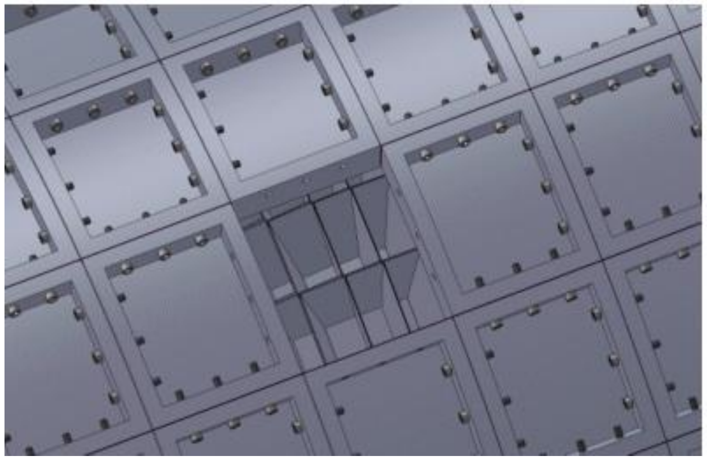


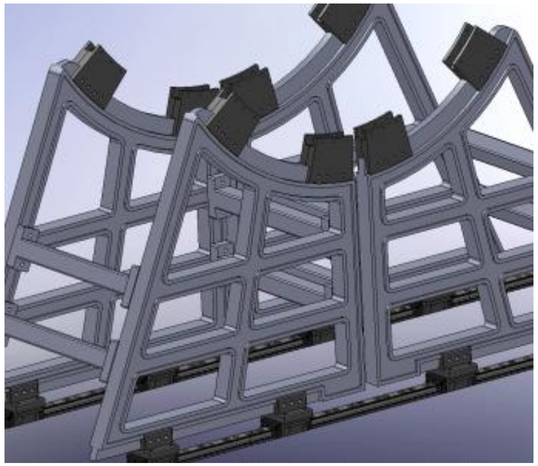
-> Talk by D. DiJulio

WG Coordinator: Dolores Cortina-Gil, Univ. Santiago de Compostela

Engineering design and Mechanical structure → based on carbon fibre alveolus







Large Area ToF-wall for heavy ions: iToF

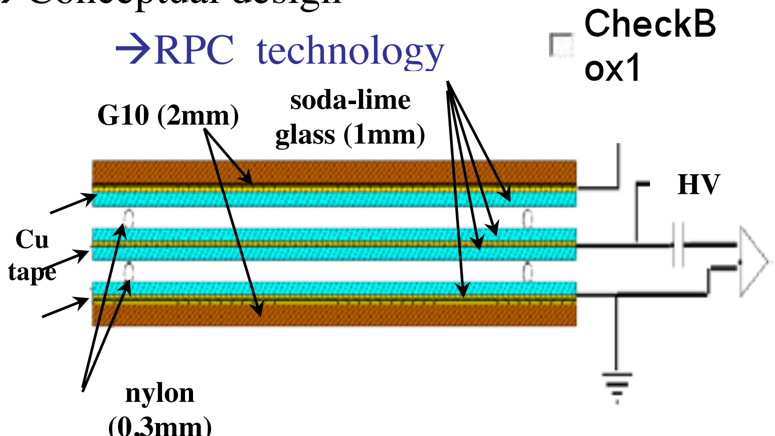
E. Casarejos, Santiago de Compostela

✓ Requirements:

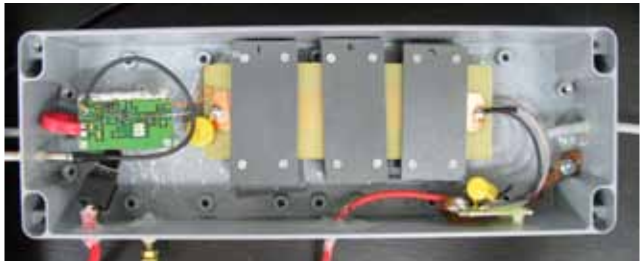
- adapted to heavy ions
- time resolution: <50 ps(sigma)
- surface ~1.5x1.5 m^2
- position resolution: <5mm
- multi-hit capabilities

→Conceptual design

→RPC technology



Design and construction of RPCs prototypes and front-end

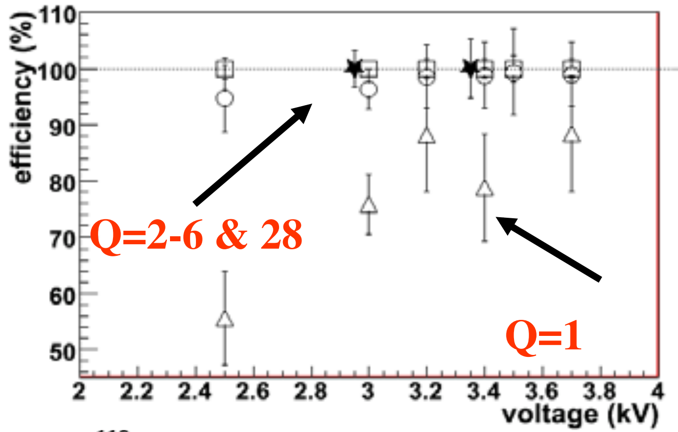


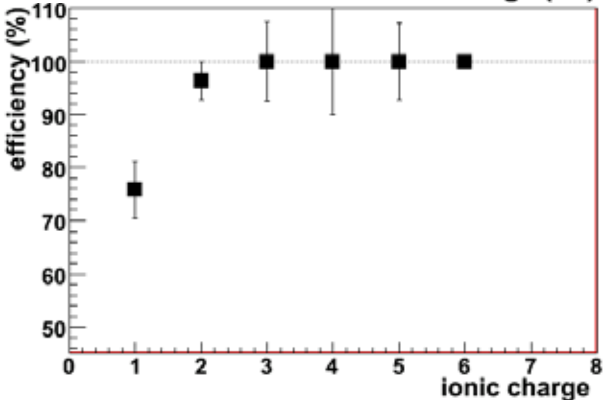
Results with prototypes

tested with relativistic heavy ions

pulse-shape analysis

✓ **study of efficiency of ion detection**





→ **good efficiency for heavy ions !!!!**

Neutron detector NeuLAND

Working group coordinator: K. Boretzky (GSI)

Existing LAND detector:
- $\sigma_t < 250$ ps
- $\sigma_{x,y,z} \approx 3$ cm
- Size: 2 x 2 x 1 m^3
- Plastic scintillator / Fe converter sandwich structure

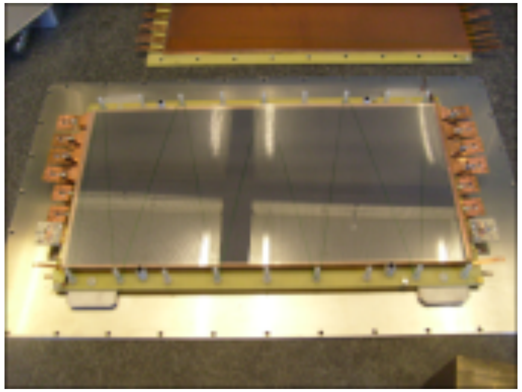
→

NeuLAND design goals:
- $\sigma_t < 100$ ps
- $\sigma_{x,y,z} \approx 1$ cm
- Size : approx. 2 x 2 x 0.8 m^3
- Efficiency > 90% for 1-n hits
- Improvement of multi-n recognition

↓

Timing RPC concept:
- Total of 140 m^2 RPC
- Approx. 10'000 channels
- Converter material: integrated in RPC structure

detection principle based on Resistive Plate Chambers plus iron converters



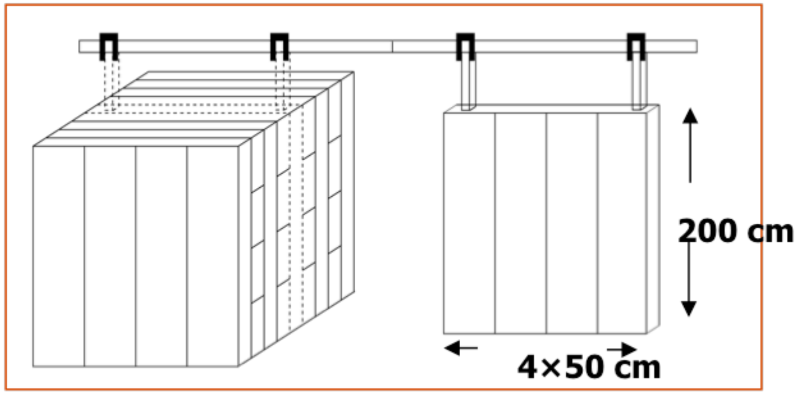
status:

✓ proof of principle: RPC excellent for slow protons

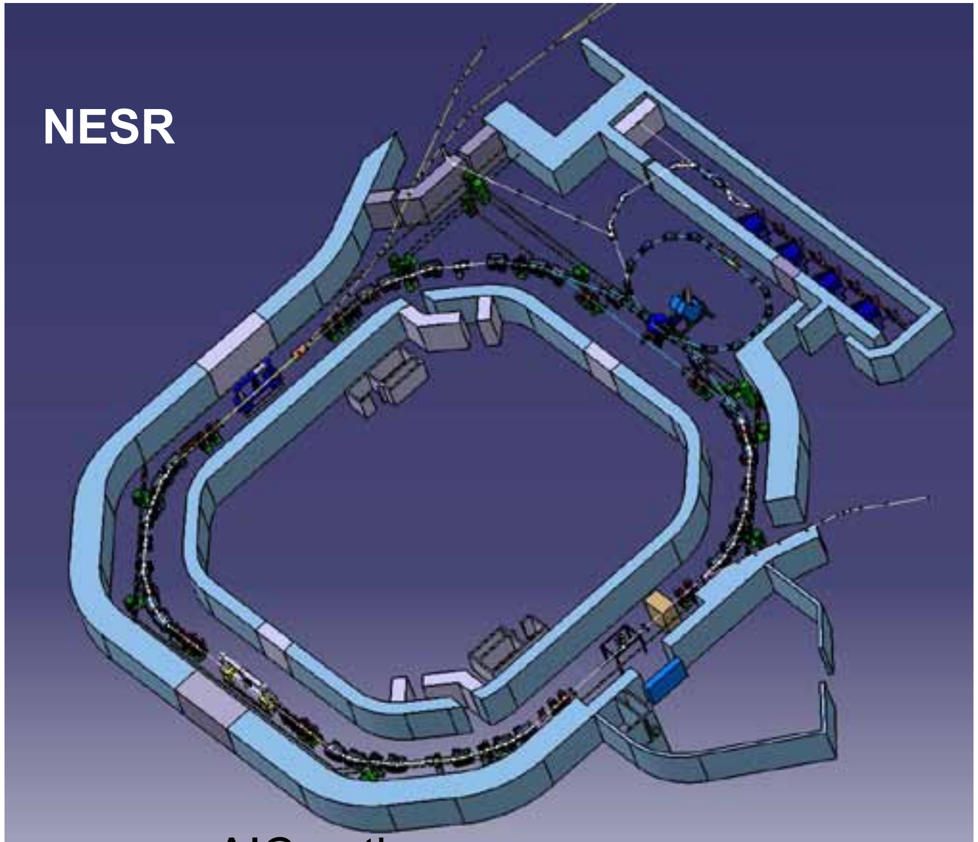
✓ prototypes with included converter as electrodes: efficiency of 99%, time resolution ~50 ps

next steps:

➢ test with neutrons in 2009, full size prototype in 2010



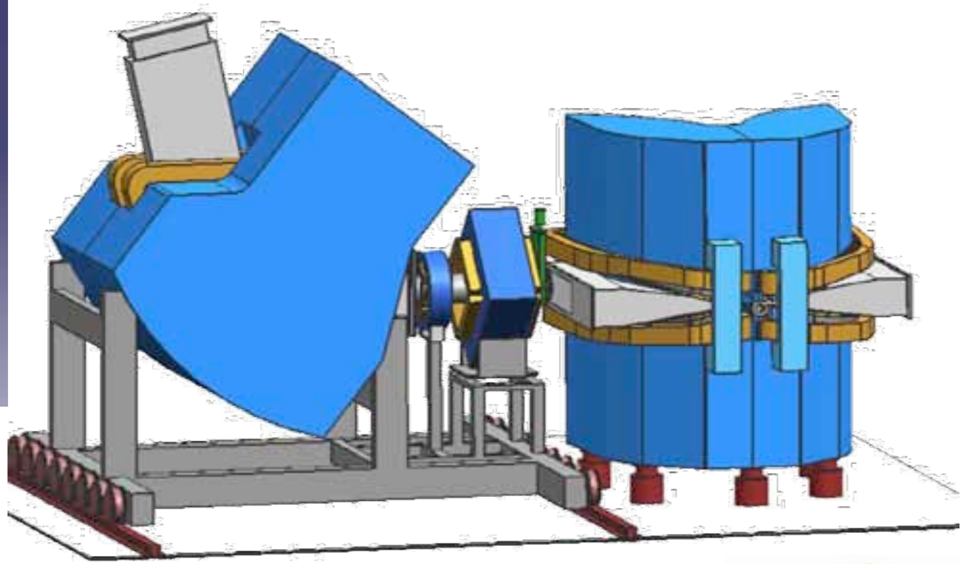
NUSTAR/**ELISe** experiment



- 125-500 MeV electrons
- 200-740 MeV/u RIBs

➔ up to 1.5 GeV CM energy

- spectrometer setup at the interaction zone & detector system in ring arcs



AIC option:

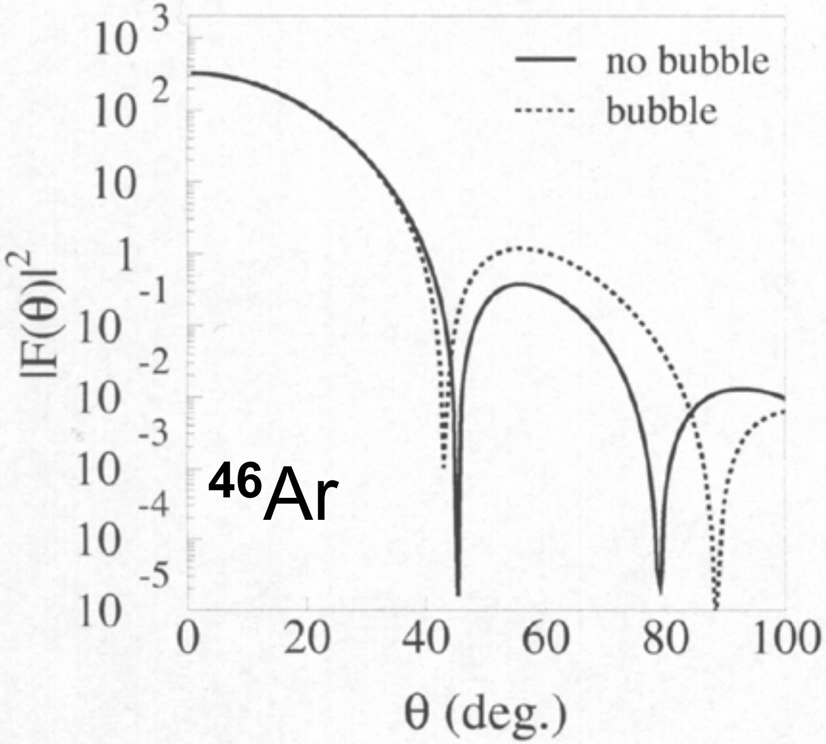
- 30 MeV antiprotons

- detector system in ring arcs
- schottky probes

Elastic Scattering

→ access to the interior ...

300 MeV e⁻ fixed target



Ar: inversion ($2s_{1/2}$, $1d_{3/2}$)

Accepted Manuscript

Detecting bubbles in exotic nuclei

E. Khan, M. Grasso, J. Margueron, N. Van Giai

PII: S0375-9474(07)00802-0
DOI: 10.1016/j.nuclphysa.2007.11.012
Reference: NUPHA 17421

To appear in: *Nuclear Physics A*

Received date: 3 July 2007
Revised date: 20 November 2007
Accepted date: 24 November 2007

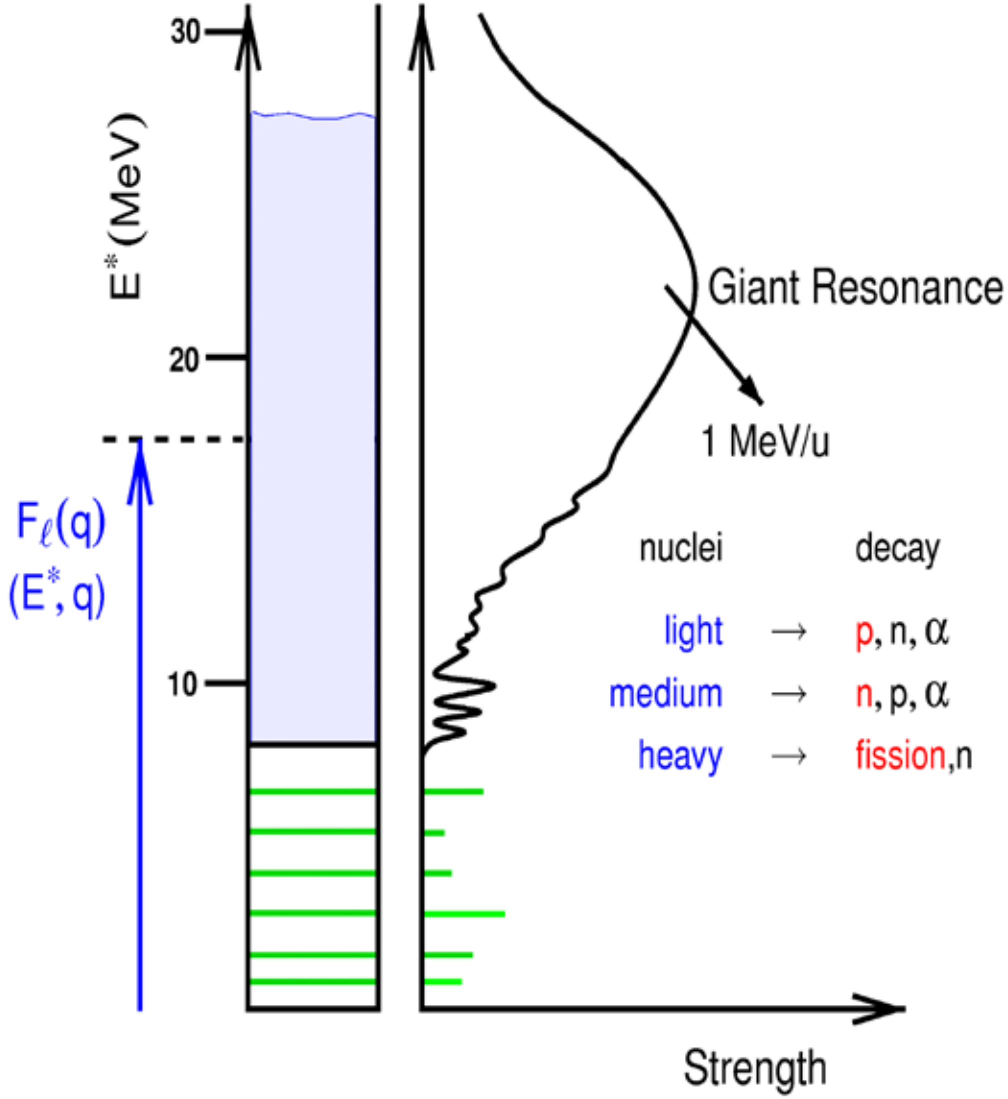
Please cite this article as: E. Khan, M. Grasso, J. Margueron, N. Van Giai, Detecting bubbles in exotic nuclei, *Nuclear Physics A* (2007), doi: 10.1016/j.nuclphysa.2007.11.012

Nucl. Phys. A800(2008)37
Phys. Rev. C79(2009)034318

L=2.7 × 10^{28} cm^{-2} s^{-1}

➔ complements other methods
e.g. GR studies

Inelastic scattering in the eA collider



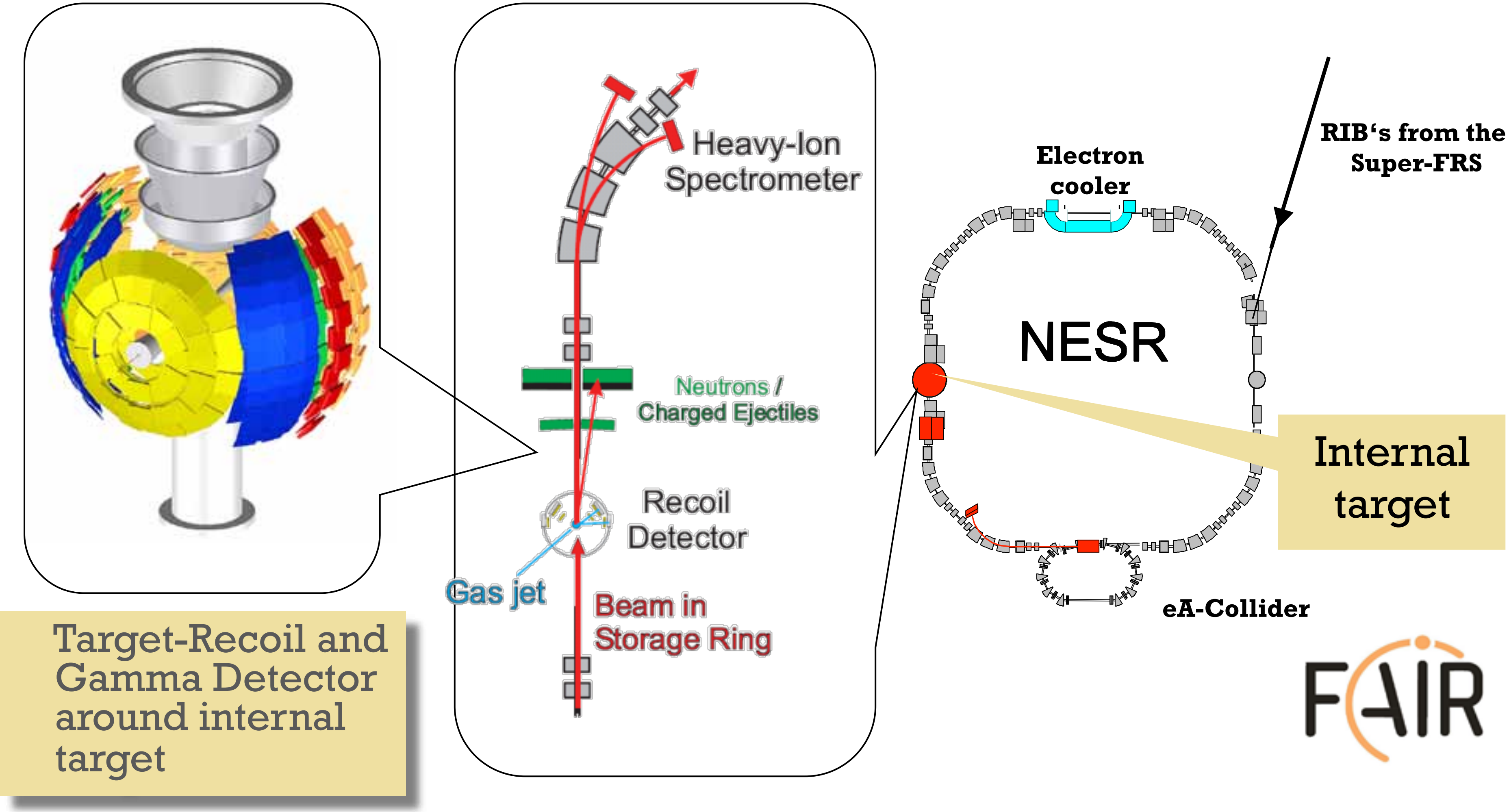
- Excitation energy is measured directly (below and above particle tresh.)
- momentum transfer dependence ➔ multipolarity of transition can be determined
- final state identification with unprecendented efficiency
  (e,e'X) ➔ (e,e' A') ➔ suppression of elastic radiative tail (no background)

➔ Low lying strength (structure)
E.g.: E1-Soft-Dipole mode:
transition density peaks in the interior.

Sagawa, Esbensen, NUPA693(2001)448

The EXL experiment

EXotic Nuclei Studied in Light-Ion Induced Reactions at the NESR Storage Ring



Light-ion scattering in the storage ring (EXL)

<u>Scattering in inverse kinematics</u>

Low-momentum transfer region often most important, e.g.,

- giant monopole excitation
- elastic scattering

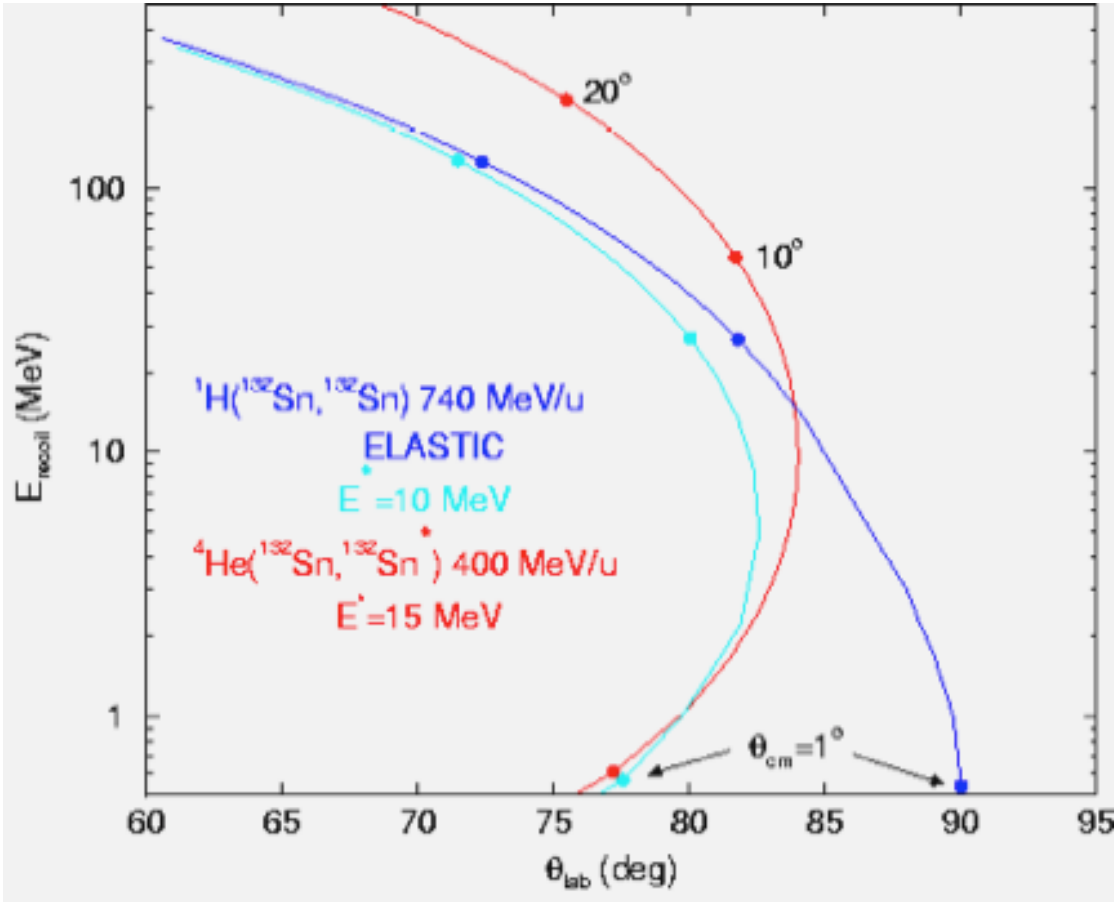
Experimental difficulty

- low recoil energies
- thin targets (low luminosity)

EXL solution:

in-ring scattering at internal gas-jet targets

gaining back luminosity due to circulation frequency of ~ 10^6



Conclusions

- R^3B - Reactions with relativistic radioactive beams yield unique possibilities for studies of nuclear systems at the extremes, based on a generic fixed-target set-up
  - Fully adapted to Super-FRS production method
- Developing and enlarging the experimental toolbox at R^3B requires cutting-edge instrumentation
  - Has to be accompanied by efficient and reproducible methods for data handling and analysis
- Complementary possibilities at EXL, ELISe and HISPEC
  - Ring branch unique for FAIR
- NuSTAR week in Lund Oct. 4-8