First Taste of HISPEC @ FAIR:
Experiences from the PreSPEC-AGATA Campaign

TECHNISCHE UNIVERSITÄT DARMSTADT

N. Pietralla for …

Campaign: D. Rudolph, W. Korten, M. Bentley, **et al. for PreSPEC-AGATA**

GSI: J. Gerl, M. Gorska, I. Kojouharov, H. Schaffner, N. Kurz et al.

FAIR@GSI: H.-J.Wollersheim, P. Boutachkov, S.Pietri et al.

TU Darmstadt: L. Cortes, A. Givechev, G. Guastalla, C. Louchard-Henning, M. Lettmann, E. Merchan, H. Pai, D. Ralet, **M. Reese**, P. Singh, **C. Stahl** et al.

Bundesministerium für Bildung und Forschung

BMBF

HIC for FAIR
Helmholtz International Center

Outline of Presentation

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- **Experimental challenges for HISPEC**
- **PreSPEC**
- **First (raw) data from PreSPEC-AGATA @ FRS 2014**
- **New experimental techniques (M1 Coulex)**
- **From PreSPEC to HISPEC**

HISPEC:
Central Instrument for NUSTAR at FAIR

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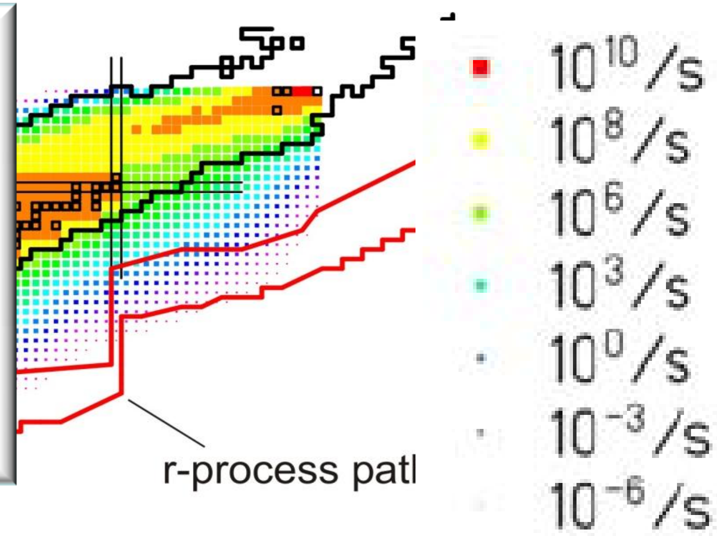
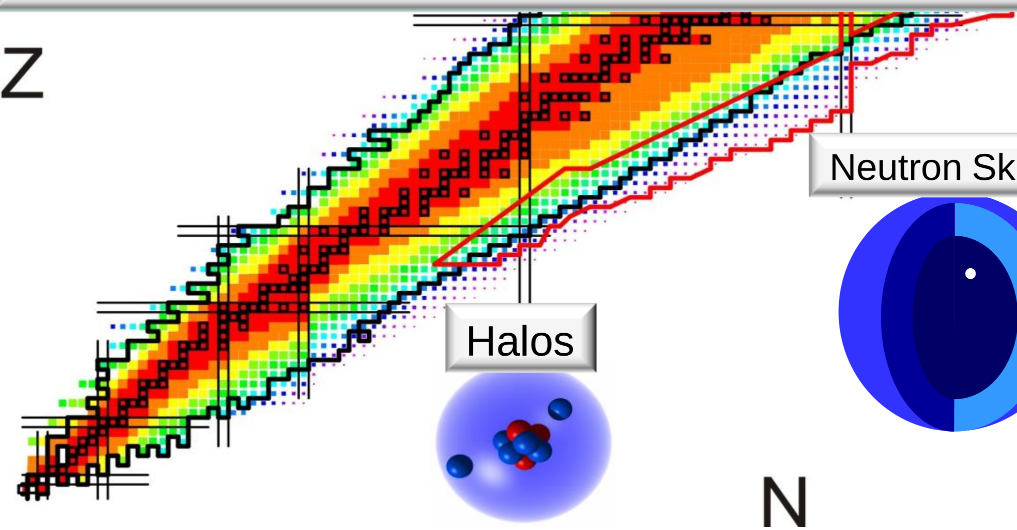
- Quest for the limits of existence
- Halos, Open Quantum Systems, Few Body Correlations
- Changing shell structure far away from stability
- Skins, new collective modes, nuclear matter, neutron stars
- Phases and symmetries of the nuclear many body system
- Origin of the elements
- unified QCD-based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

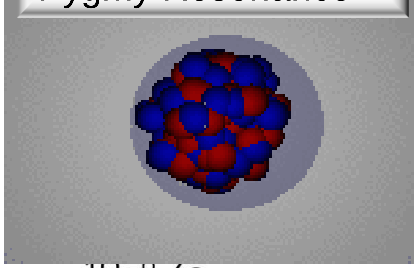




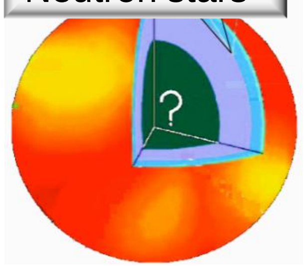
Halos

Neutron Skins

Pygmy Resonance

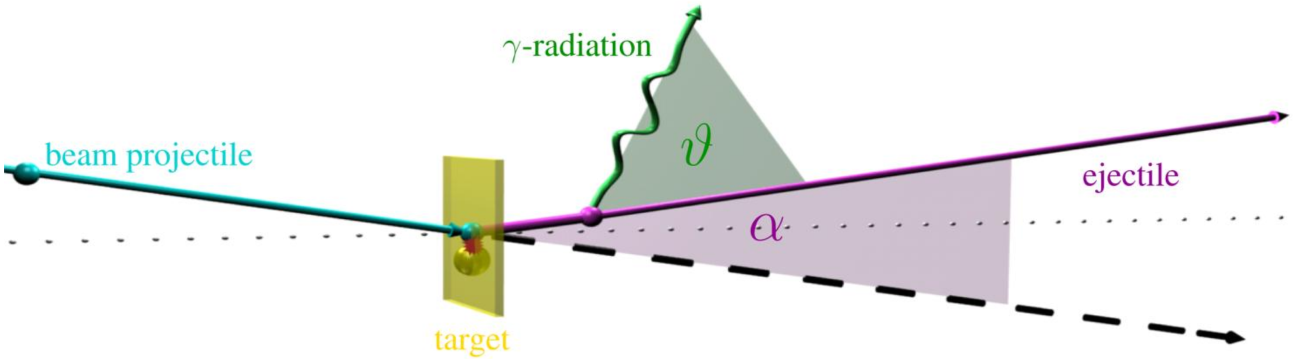


Neutron stars



Experimental Challenges

1. Relativistic secondary RI Beam from in-fight separator
2. Nuclear reaction in stationary target
3. Excited reaction products leave the target (flight direction changes)
4. Emission of Doppler-shifted γ-Radiation



- Need γ-energy in rest frame of emitting nucleus (Doppler-correction)
- → Need tracks of particle and γ-ray(s)
- Spectroscopic resolution depends on **accurate track reconstruction of both, γ-ray and particle!**

HISPEC – High Resolution Gamma-Ray Spectroscopy

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Purpose:

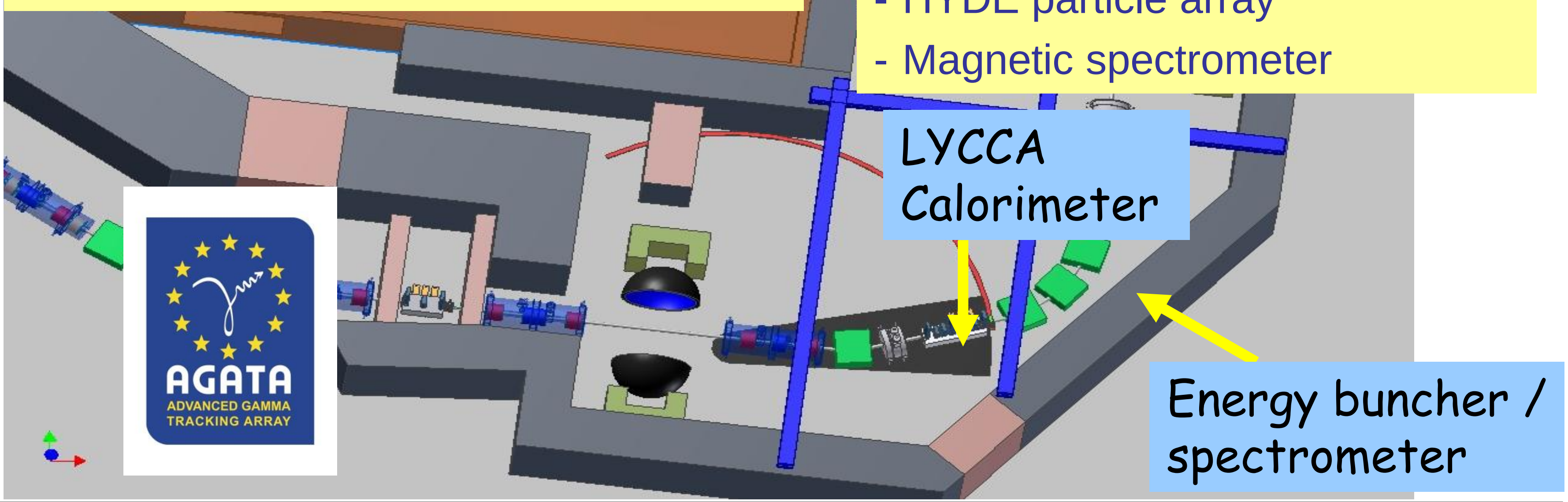
High-resolution in-flight spectroscopy of exotic nuclei using Super-FRS RIB beams at 3 – 400 A·MeV

Methods:

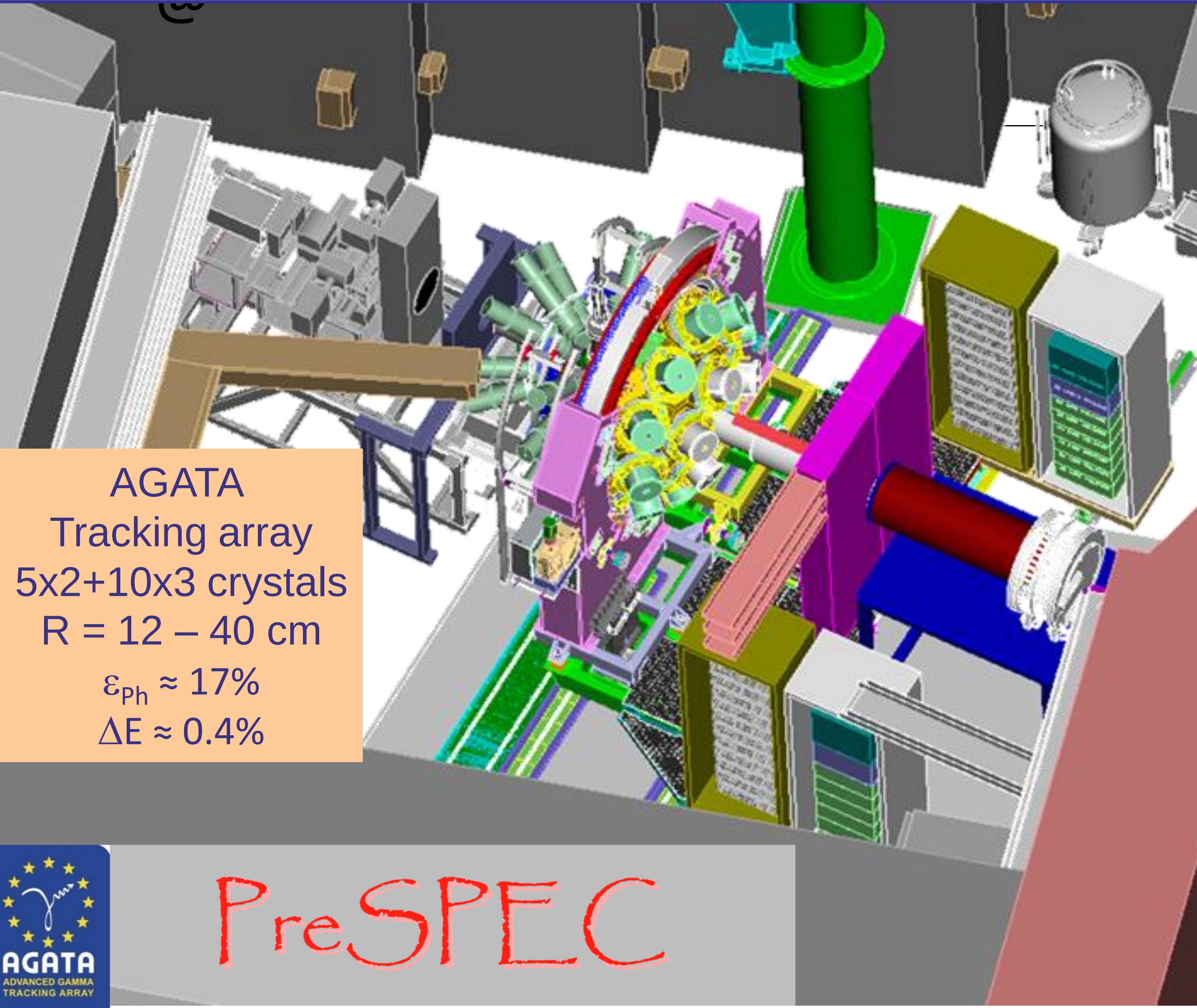
- Coulex, knock-out, fragmentation at relativistic energies, direct reactions,…

Set-up:

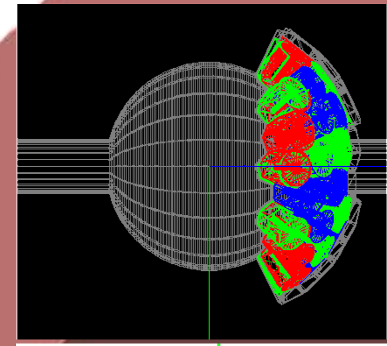
- Beam tracking and identification (LYCCA)
- Active target
- AGATA
- Fast timing
- HYDE particle array
- Magnetic spectrometer

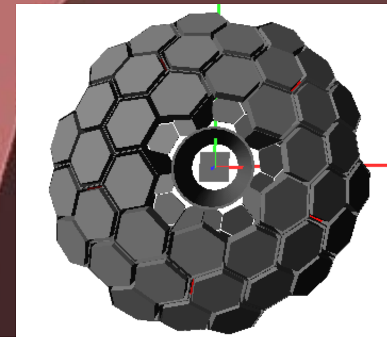


PRESPEC-AGATA Set-up = Early Implementation of HISPEC



AGATA
Tracking array
5x2+10x3 crystals
R = 12 – 40 cm
$\varepsilon_{Ph} \approx 17\%$
$\Delta E \approx 0.4\%$

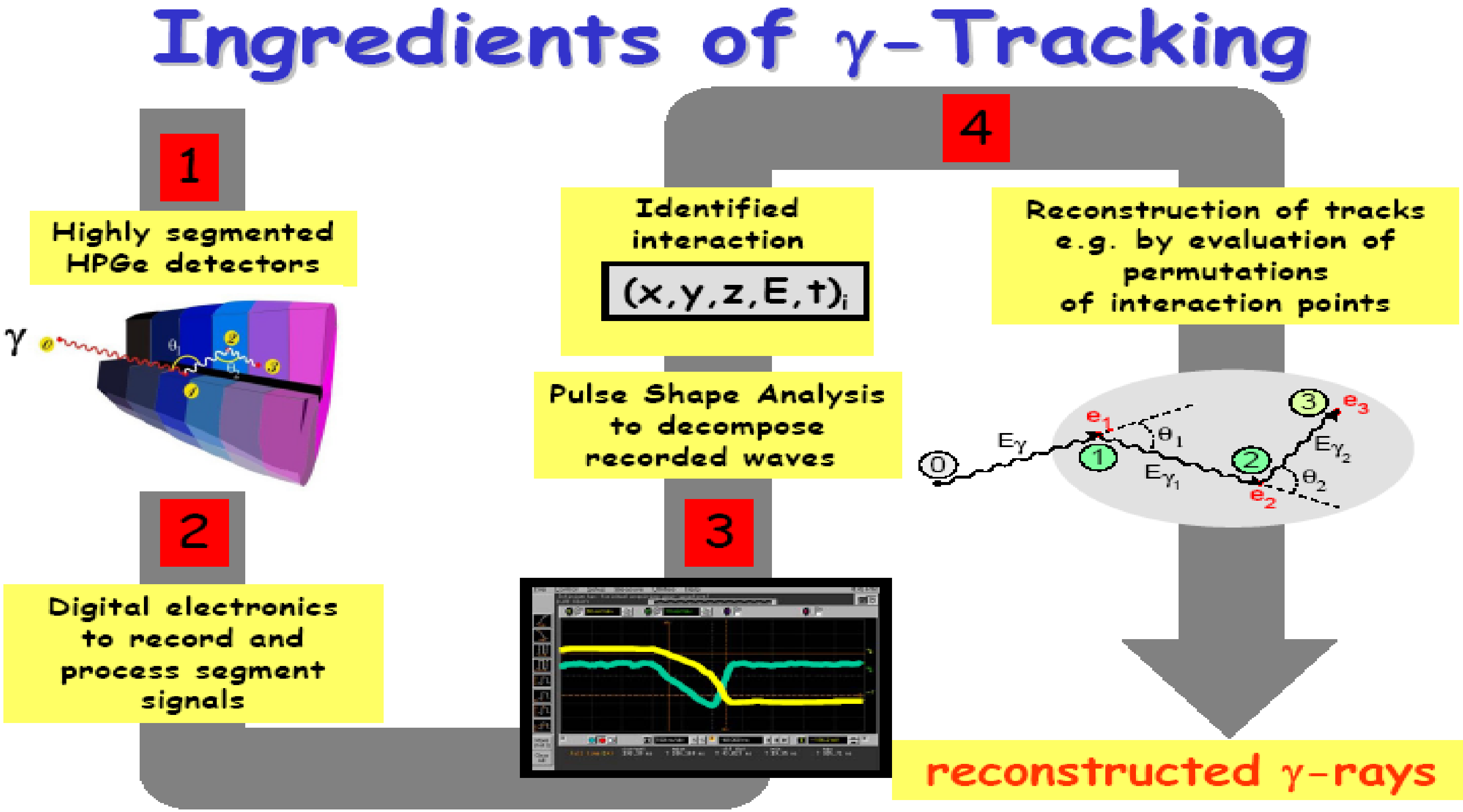




AGATA
ADVANCED GAMMA TRACKING ARRAY

PreSPEC

PSA and γ-Tracking in AGATA



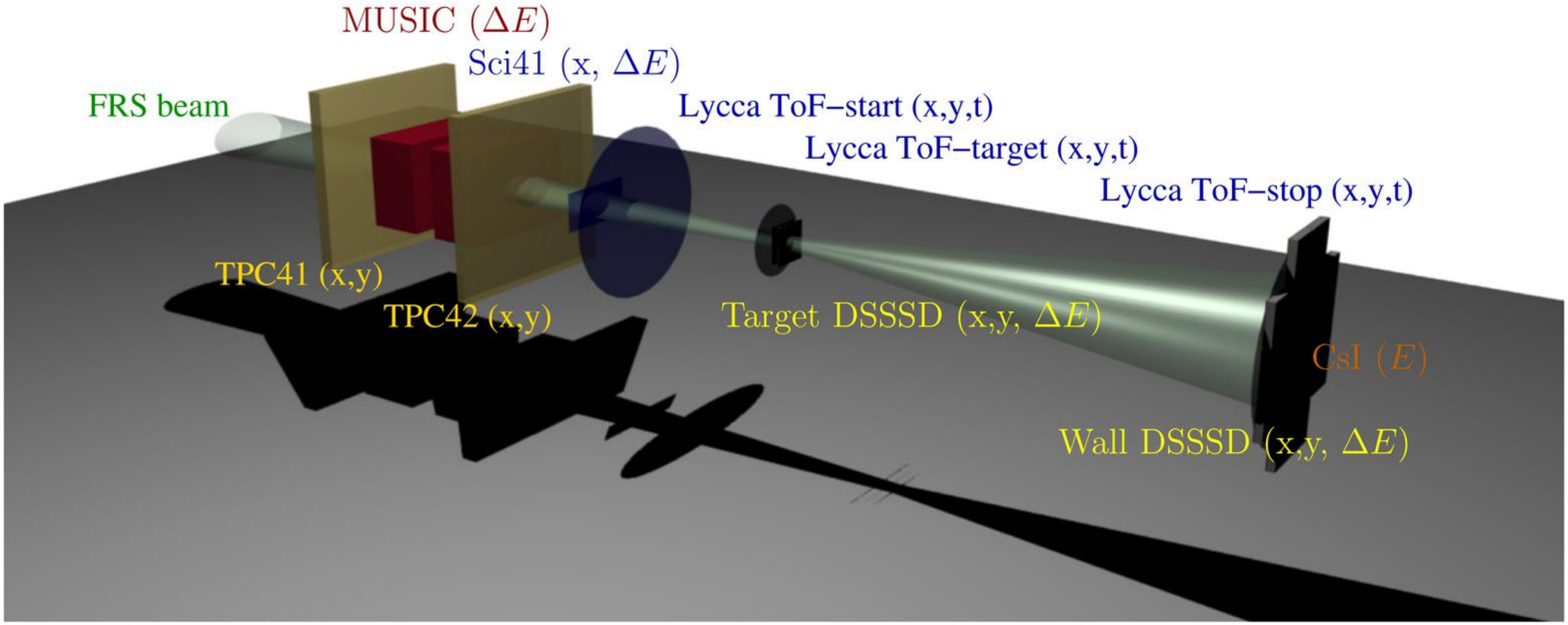
Particle Tracking & Identification

FRS detectors

- 2 TPCs for trajectory
- 2 Ionization chambers for Z identification

LYCCA detectors

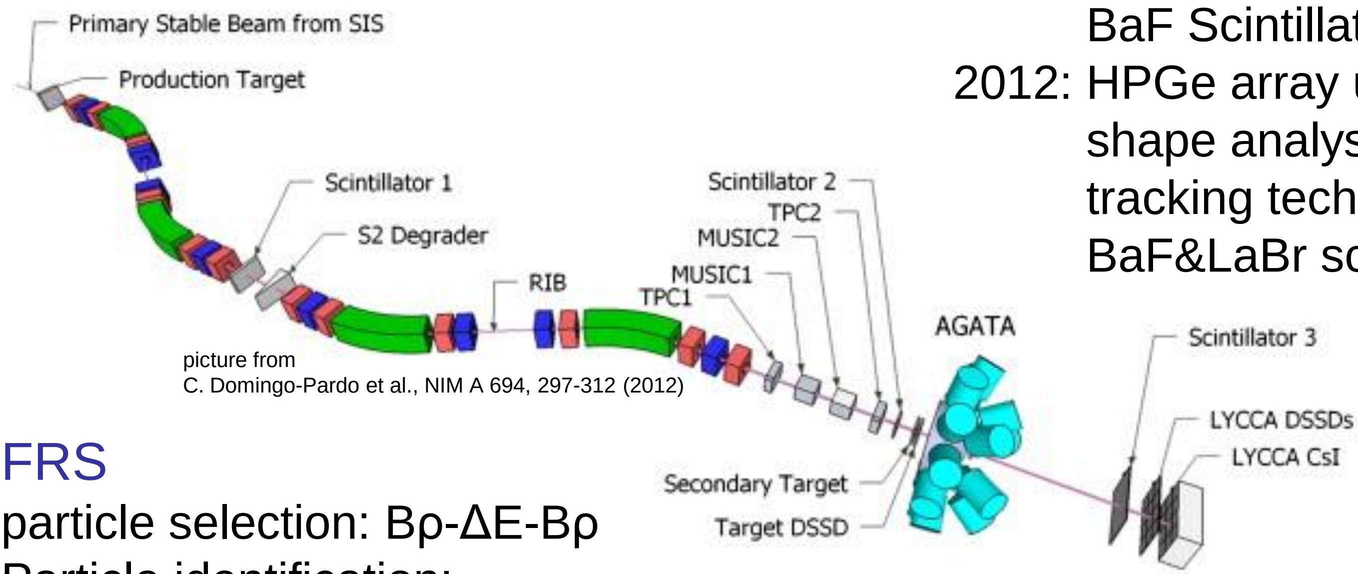
- **17 silicon DSSSD detectors for tracking and energy loss**
- **144 CsI scintillators for particle energy**
- **3 fast plastic scintillators for time of flight and tracking**



PreSPEC Schematic Setup

Gamma-ray detection

2011: 105 HPGe detectors (Euroball)
BaF Scintillators (HECTOR)
2012: HPGe array using pulse-shape analysis and γ-ray tracking techniques (AGATA)
BaF&LaBr scintillators (HECTOR+)



picture from
C. Domingo-Pardo et al., NIM A 694, 297-312 (2012)

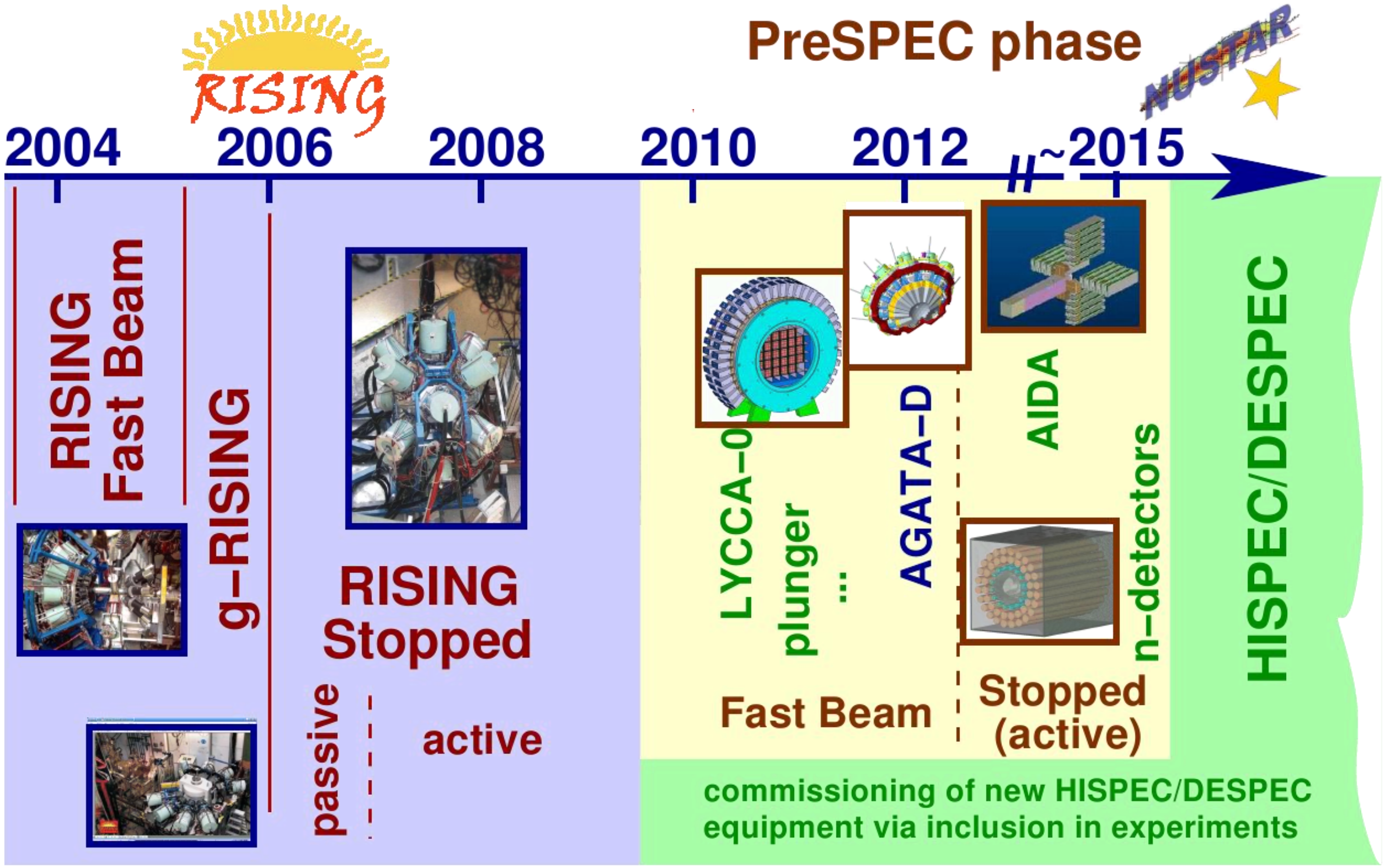
FRS

particle selection: Bρ-ΔE-Bρ
Particle identification:
- TPC tracking detectors
- ToF measurement
- Energy-loss measurement

LYCCA

Outgoing particle tracking and identification:
- Z identification via E-ΔE
- Mass identification via E-ToF

History of HISPEC



From PreSPEC to HISPEC

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2010 — 2011 — 2012 — 2013 — 2014 — 2015

RISING

PRESPEC In-beam
LYCCA-0 Commis.

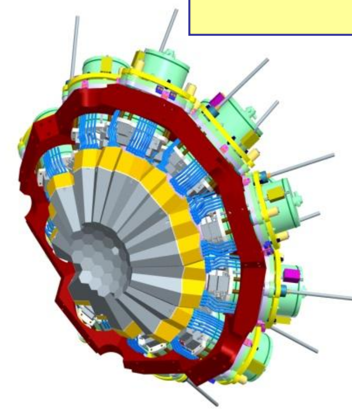
active stopper
g-factors

PRESPEC in-beam
with AGATA

Min. 25% bei
FAIR, GANIL,
Legnaro

AGATA Demonst.
Legnaro

AGATA .in GANIL

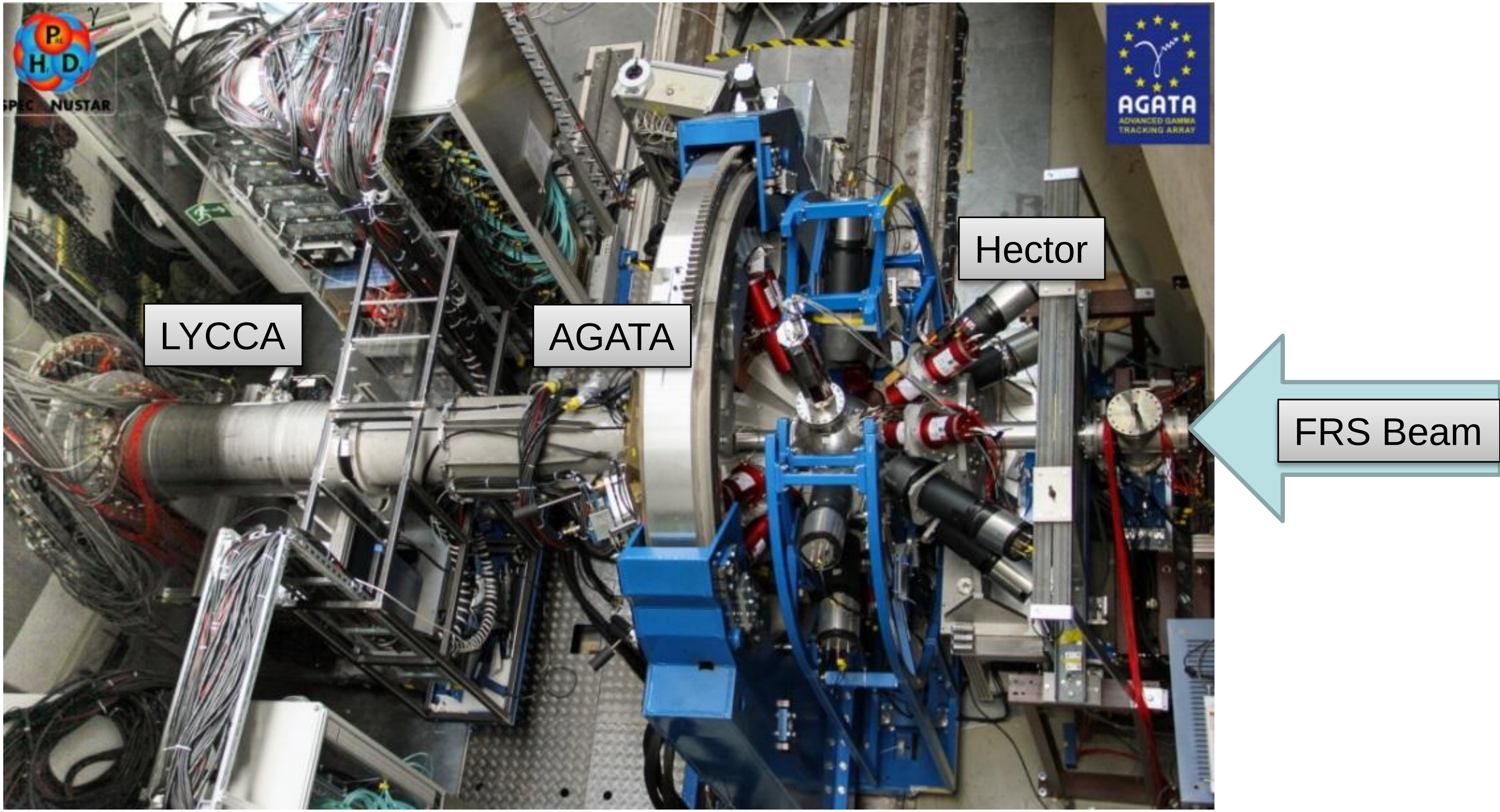


Experimental program 2010-2016: running!

- First experiments with AGATA Demonstr. at Legnaro (2010 – early 2012)

- PRESPEC Experiments at GSI-FRS (2012 - 2014 with AGATA)

PreSPEC in Operation March 2014

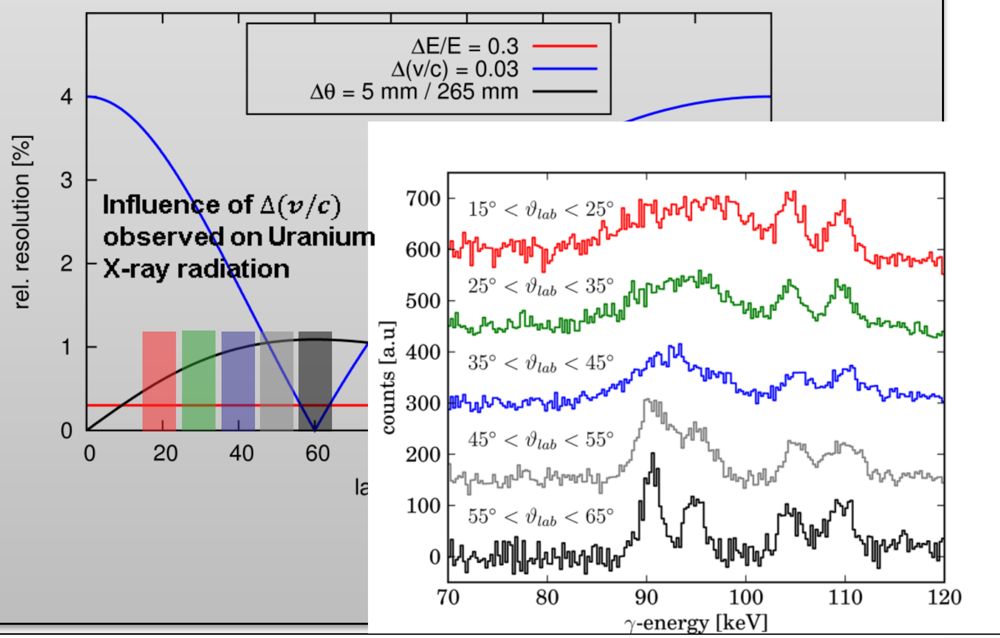


Doppler-Correction in PreSPEC

Doppler shift for photons emitted at $\beta = v/c$:

$$E_{\text{laboratory}} = E_{\text{rest}} \frac{\sqrt{1-\beta^2}}{1-\beta\cos(\vartheta_{\text{lab}})}$$

Achievable resolution for typical PreSPEC-AGATA conditions (analytic Gaussian error propagation):



More effects depend on half-life and J^π of excited state and geometry:

- peak shapes
- centroid shifts
- angular distribution

Discussion of these effects:
P. Doornenbal, et. al., NIM A, 613, 2, (2010), 218

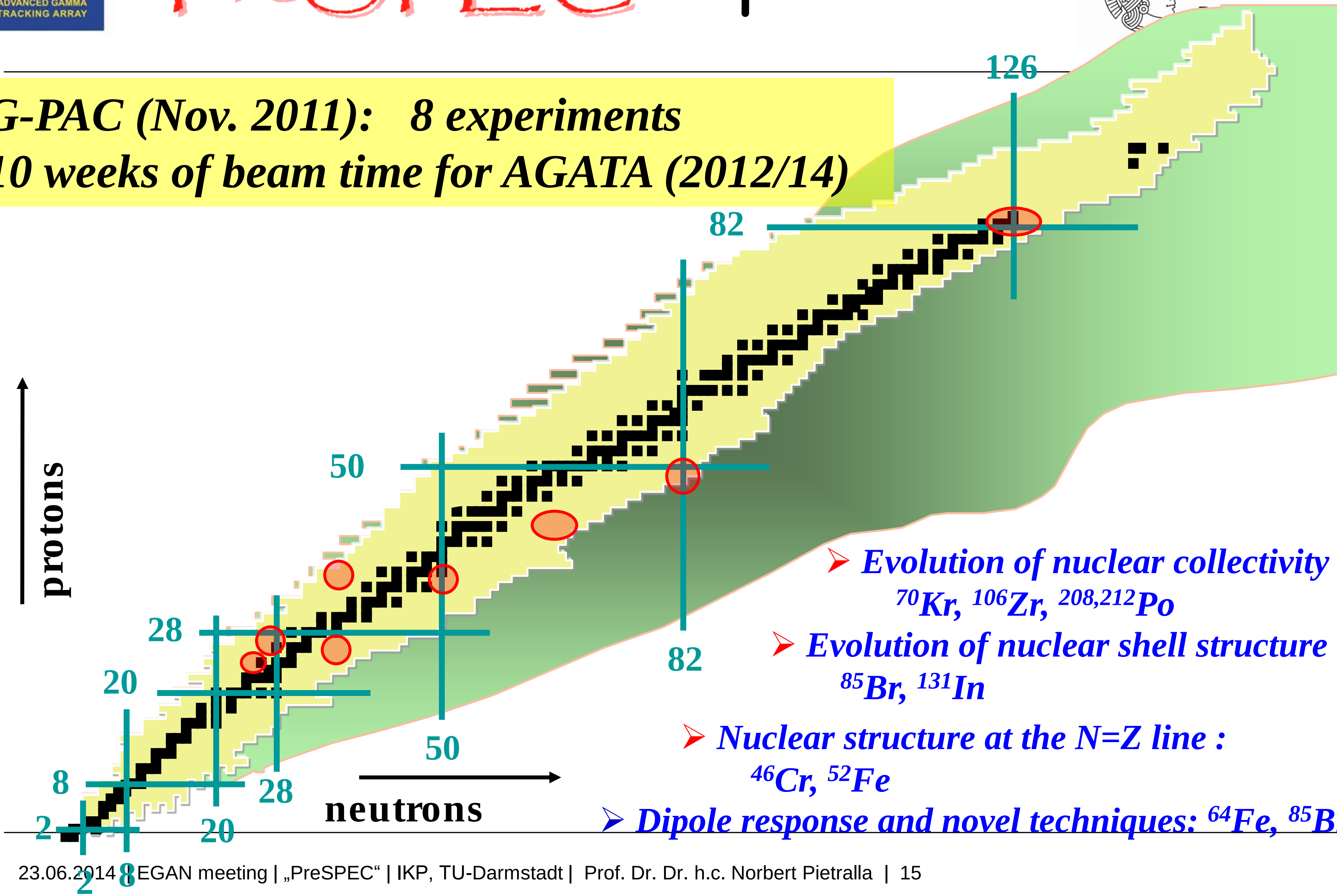
Peak shape from Doppler shift effects have been used to measure lifetimes:
A. Lemasson, et. al., Phys. Rev. C, 85, 041303, (2012)

Software for peak-shape calculation, fitting, and scientific usage is developed at TU-Darmstadt (C. Stahl / M.Lettmann) → C.Stahl

PreSPEC experiments

G-PAC (Nov. 2011): 8 experiments

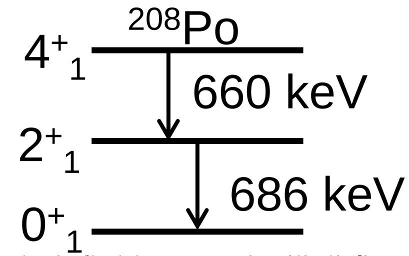
10 weeks of beam time for AGATA (2012/14)



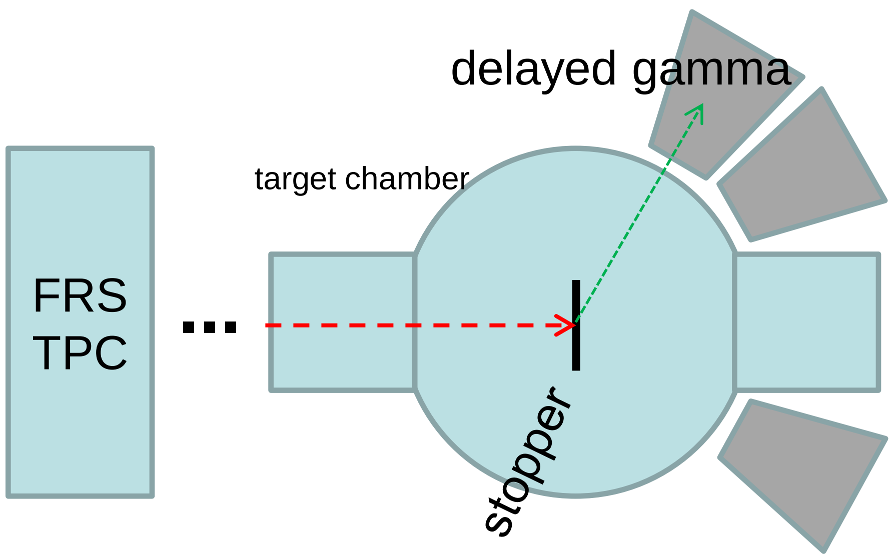
- *Evolution of nuclear collectivity* ^{70}Kr, ^{106}Zr, $^{208,212}Po$
- *Evolution of nuclear shell structure :* ^{85}Br, ^{131}In
- *Nuclear structure at the N=Z line :* ^{46}Cr, ^{52}Fe
- *Dipole response and novel techniques:* ^{64}Fe, ^{85}Br

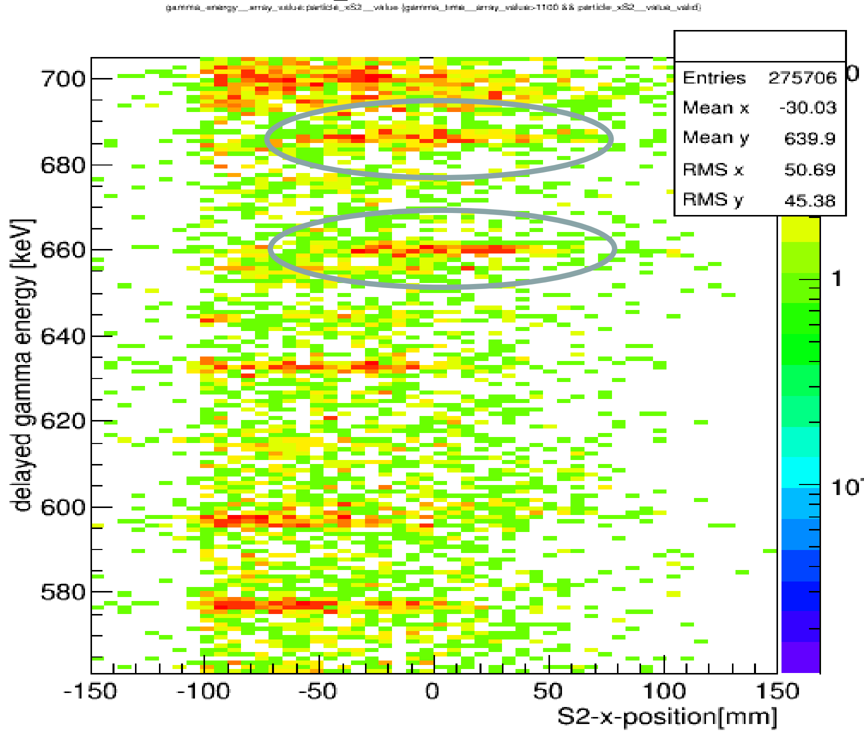
First Week of PreSPEC-AGATA 2014
Verify FRS setting using „isomer tagging“

- FRS setting on ^{208}Po
- e.g.: Is the isotope of interest centered in FRS?



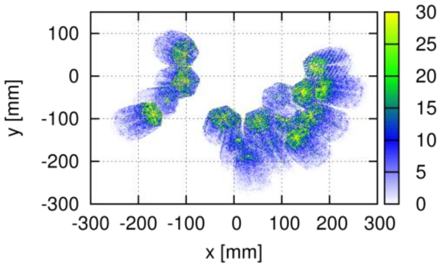
Use gamma-tagging of particles with delayed gamma radiation from isomers

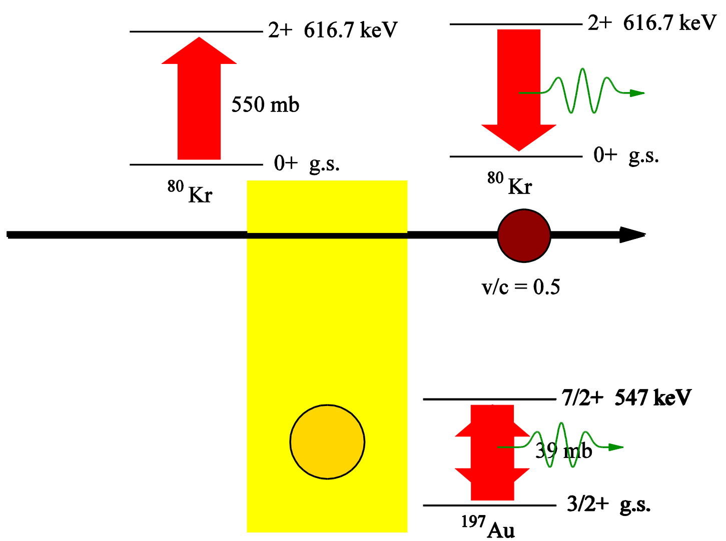


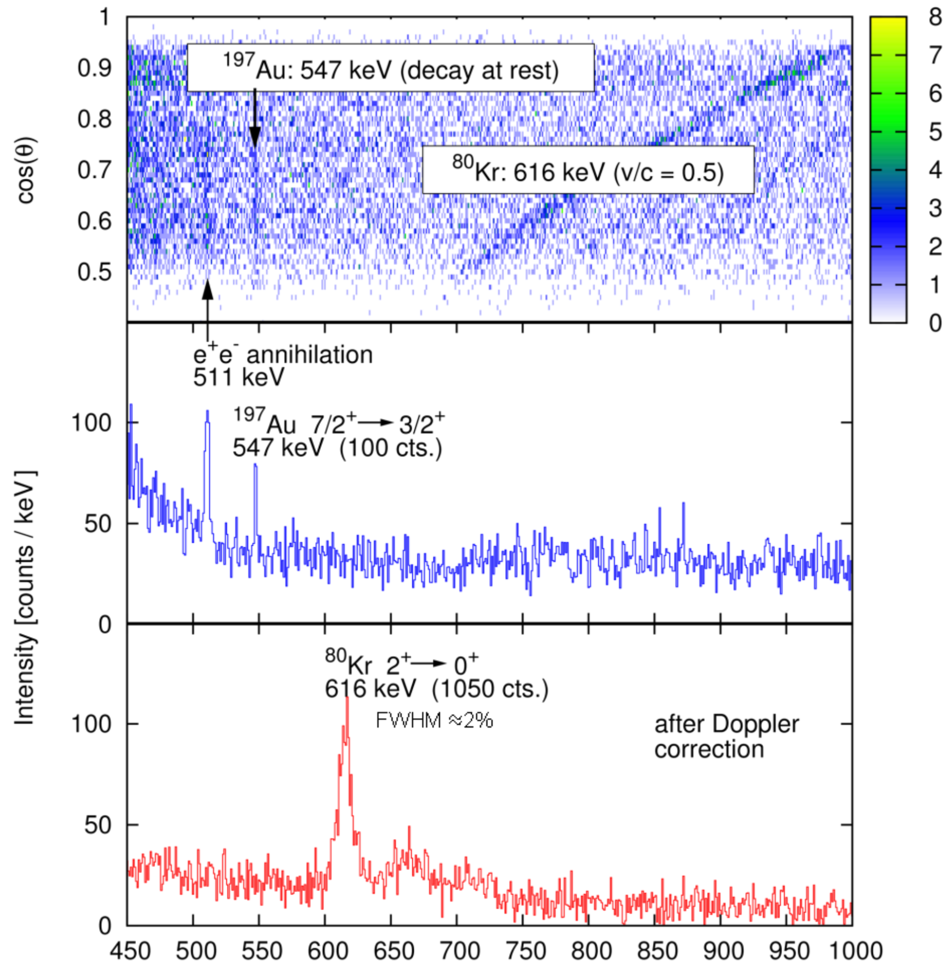


PreSPEC-AGATA Commissioning 2012: Coulomb Excitation of ^{80}Kr on Gold

Coulomb excitation of ^{80}Kr







data: M.Reese (TU Darmstadt) for PreSPEC

PreSPEC-AGATA Commissioning, 2012
(see M.Reese, Thu. morning)

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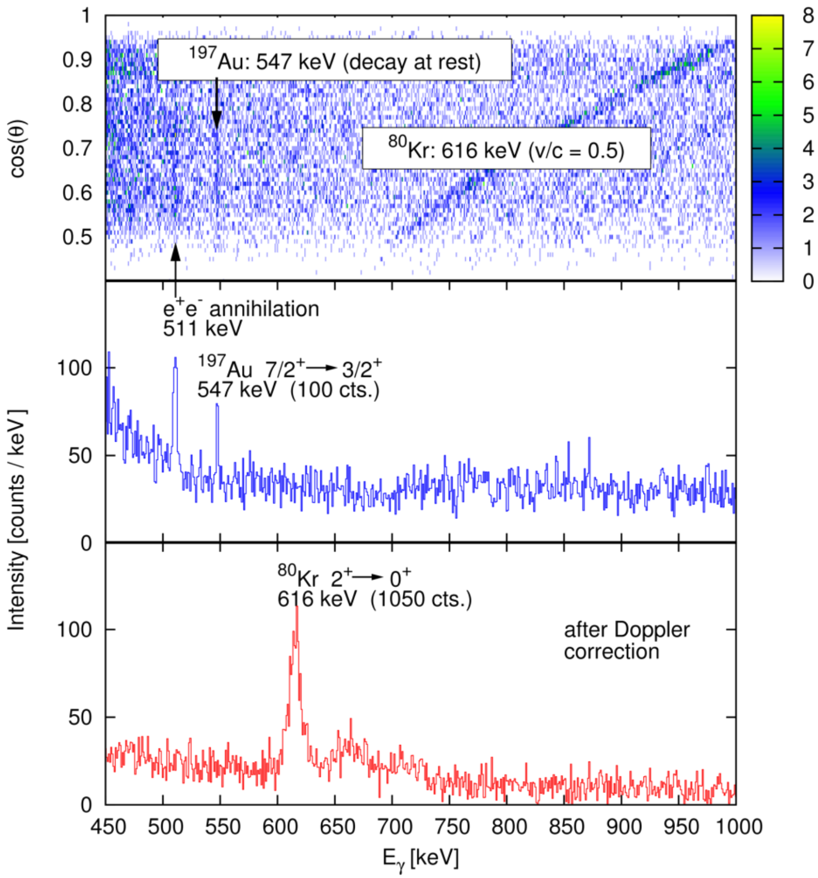
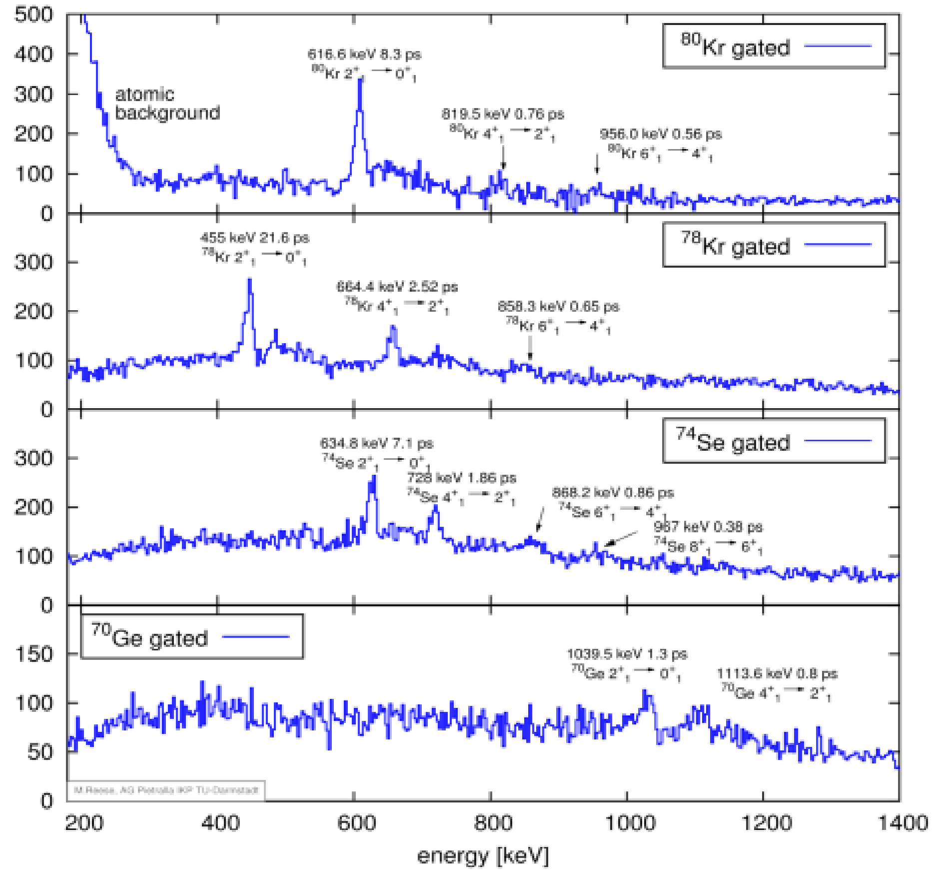
Coulomb excitation of ^{80}Kr



Secondary fragmentation of ^{80}Kr



Successful Commissioning of Liquid Hydrogen Target

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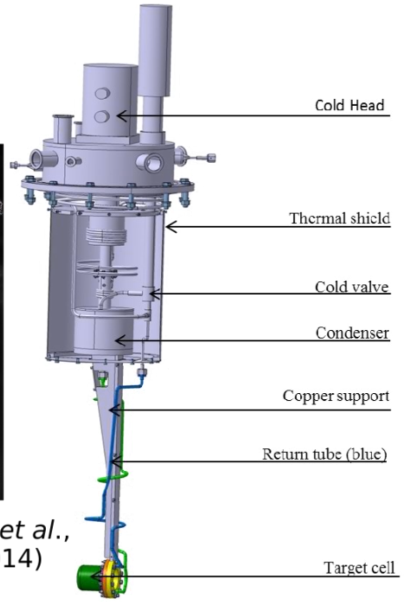
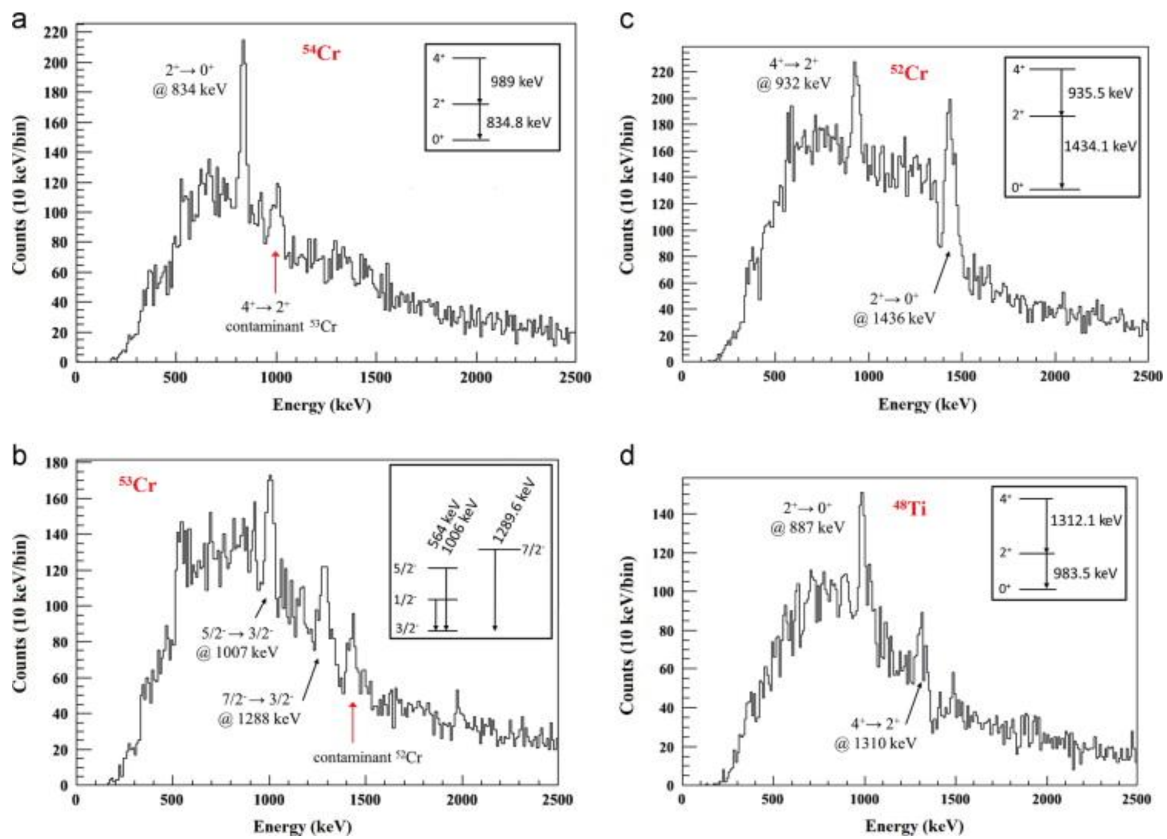


C. Louchart-Henning *et al.*, NIM A 736, 81-87 (2014)

Gamma spectra with gates on outgoing fragments, identified with LYCCA:



GSI in June 2012:

- ^{54}Cr beam with 130 MeV/u at the target position
- thickness of LH_2 target: 20mm

Physics Topics of PreSPEC

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- S426 ^{85}Br M1 spin-flip Coulomb excitation
- S427 ^{70}Kr energies
- S428 Zr shape evolution
- S429 B(E2) in the Pb region
- S430 ^{64}Fe Pygmy fine structure
- S433 ^{52}Fe isomer Coulex
- S434 $T_z = -2$ Lifetime measurements, ^{44,46}Cr

Direct Characterization of Spin-Orbit Splitting (Tensor Force): ^{85}Br as Test Case

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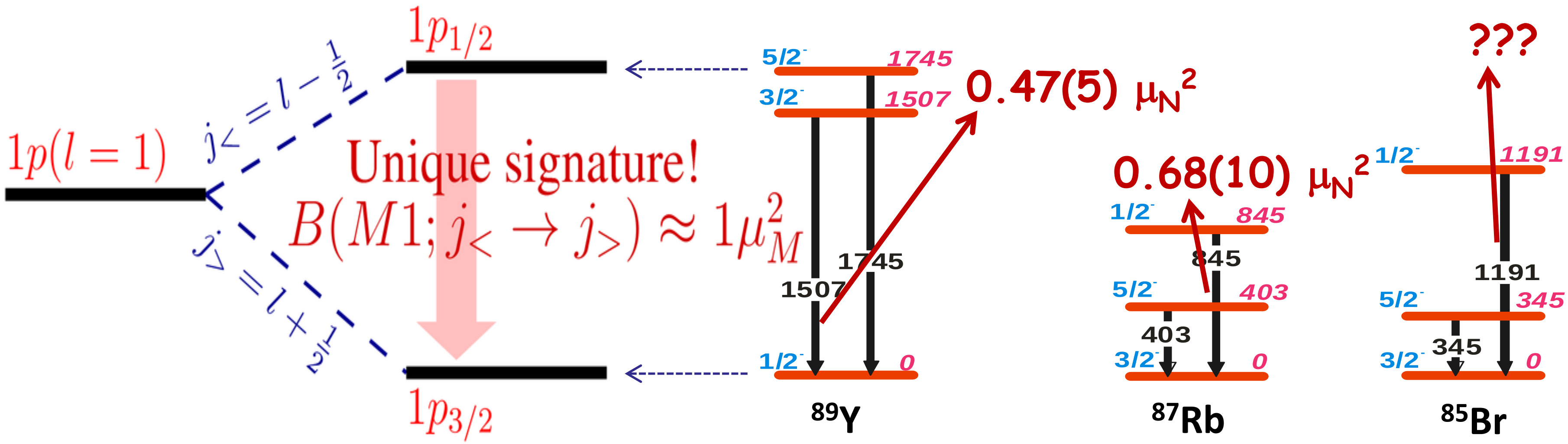

- Direct identification of spin-orbit partners via B(M1) strength measurement
- How to measure on exotic ions?
  - (γ,γ'), or (e,e')? No radioactive target !
  - Coulomb excitation ? E2 dominated !
  - But…

Spin-Flip M1: Coulex?

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Coulomb excitation only E2 dominated for low energy.

In-flight separation produces excotic ions with high velocity

M1 Coulomb excitation is small compared to E2 excitation for nonrelativistic beams.

$$\sigma_C(E2) \propto (1/\beta)^2$$

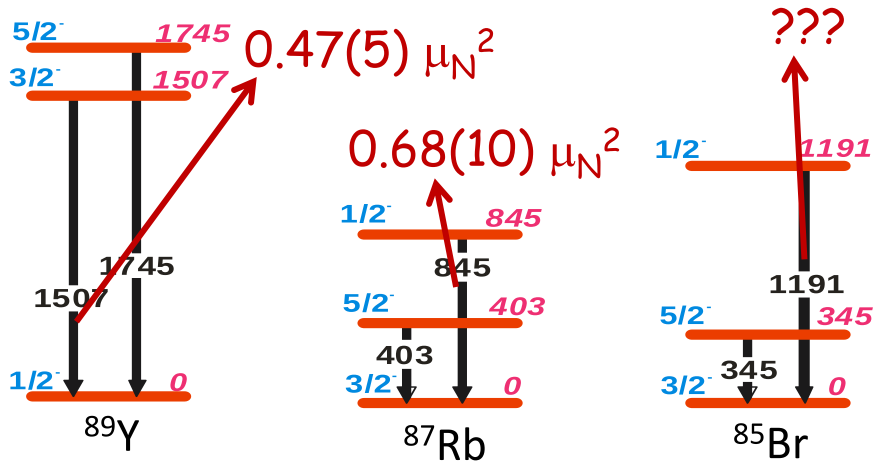
$$\sigma_C(M1) \text{ (independent)}$$

For high velocities, M1 can have significant contribution to the total cross-section!

$$\Rightarrow \quad \frac{\sigma_C(M1)}{\sigma_C(E2)} \propto \left(\frac{v}{c}\right)^2$$

Discriminate E2 vs M1-contribution?
I.e. how to measure the multipole mixing ratio?

Unique experimental signature of $\pi p_{1/2}$?



Relativistic Coulomb excitation reactions

$\sigma_c(E2) \propto (1/\beta)^2$

$\sigma_c(M1)$ – independent

$$\frac{\sigma_c(M1)}{\sigma_c(E2)} \propto \left(\frac{v}{c}\right)^2$$

➡ at high v/c large M1 matrix elements significantly contribute to total COULEX yield

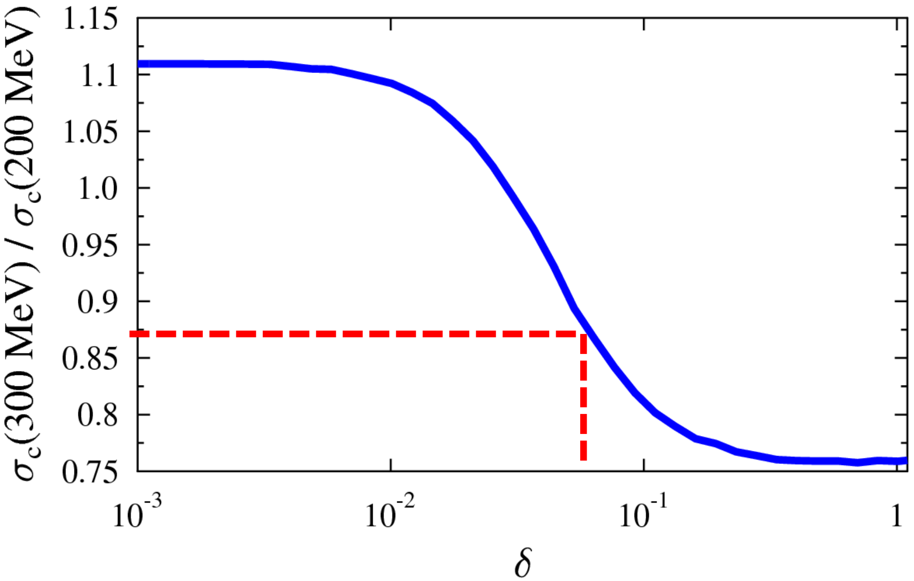
Relativistic beam energies $\beta \approx$ 50-70 % ➡ Possible at GSI

Huge Doppler spread in γ-ray spectrum ➡ need precise Doppler correction and reduce Doppler broadening ➡ PreSPEC-AGATA

Multipole-Mixing Ratio via 2 Beam Energies

- Energy dependence: decreasing E2 contribution for high energies
- Ratio of total cross-sections at different energies is sensitive to multipole mixing ratio

$$\delta \propto \frac{\langle f \| \hat{T}_{E2} \| i \rangle}{\langle f \| \hat{T}_{M1} \| i \rangle}$$



M1 Coulex test-shift in 2012

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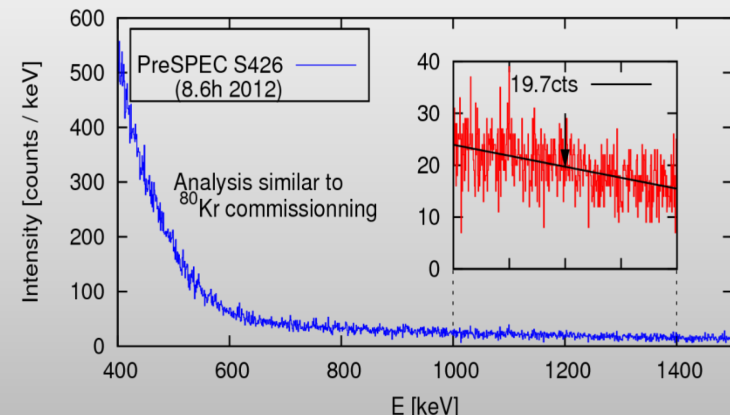
Neutron-rich ^{85}Br ideal test-case because of high rate of ^{86}Kr primary beam at GSI. Produce ^{85}Br by one proton knockout

One shift of data taking with ^{85}Br

- ^{85}Br beam: 300 MeV/u
- Mean particle rate: 26kHz (> 50kHz in spill)
- Target: 400 mg/cm^2 gold:



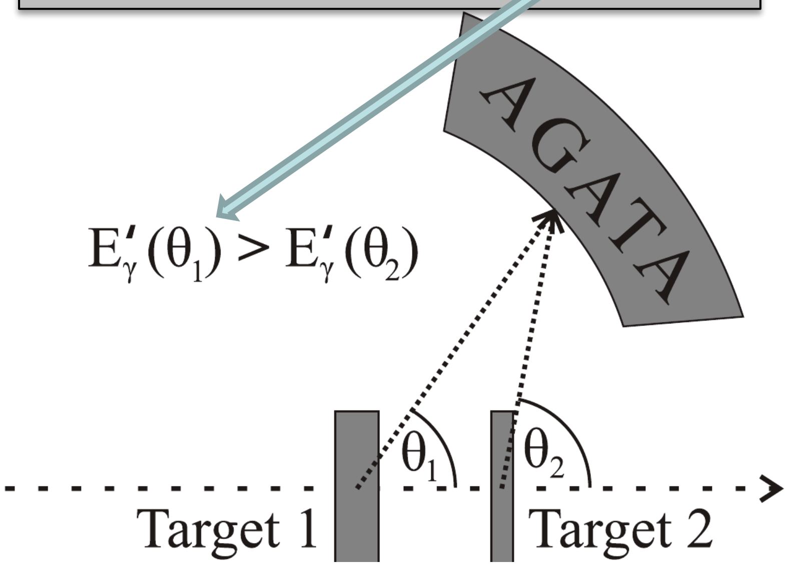
- Background higher than initially anticipated, consistent with commissioning
- Need two measurements at different energies
- Improvements: double-target solution: „Coulex-multipolarimetry by active degrader“

Two-Target Solution
(→ C. Stahl, Thu.)

Idea: 2 targets. First target thick enough to slow down beam from 300 to 200 MeV/u at the second target. All information in one measurement!

Reminder: Doppler effect

$$E_{\text{laboratory}} = E_{\text{rest}} \frac{\sqrt{1-\beta^2}}{1-\beta\cos(\vartheta_{\text{lab}})}$$

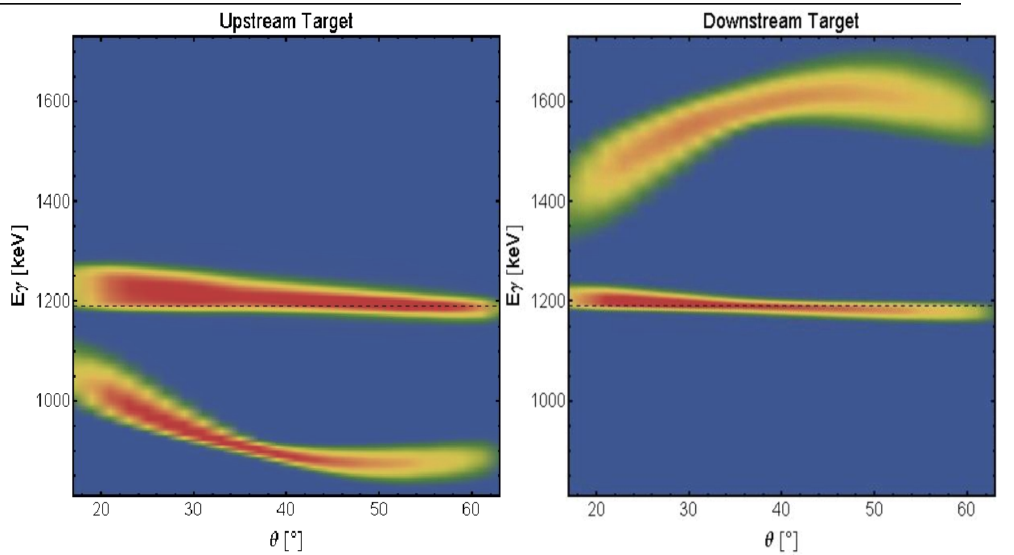


Working principle:

- Lifetime of excited state ~50 fs.
- Decay happens directly after excitation.
- Decay position equal to exitation position
- Two peaks will appear due to different detection angles (Doppler-effect)
- Excitation in first target happens at high energy (300 MeV/u)
- Exitation in second target happens at lower energy (200 MeV/u)

Two-Target Solution: Simulations

Simulated Peak shapes (Doppler-corrected Energy vs. detection angle):

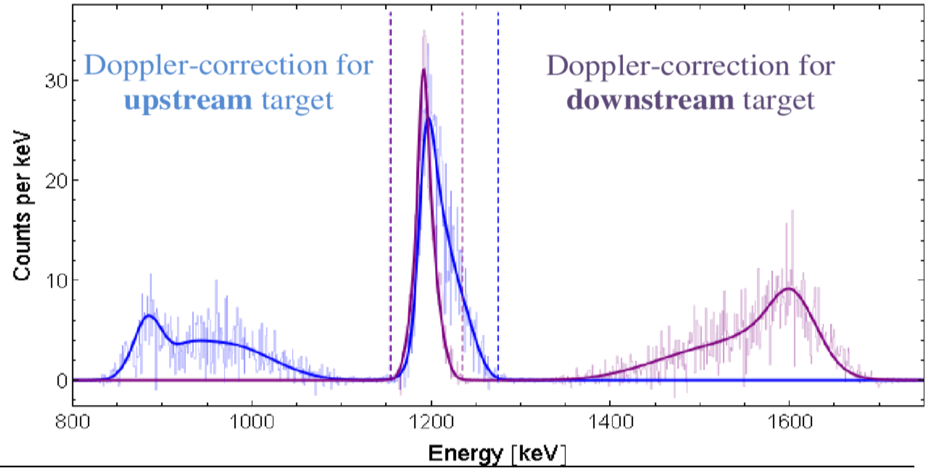


Pro's:

- one beam energy
  - one FRS setting
  - same conditions for both energies
- thick target
  - increased excitation prob.
  - better peak to background ratio

Con's:

- thick target
  - increased angular straggling
  - increased energy straggling
  - increaded velocity uncertainty



First data on Relativistic M1-Projectile COULEX

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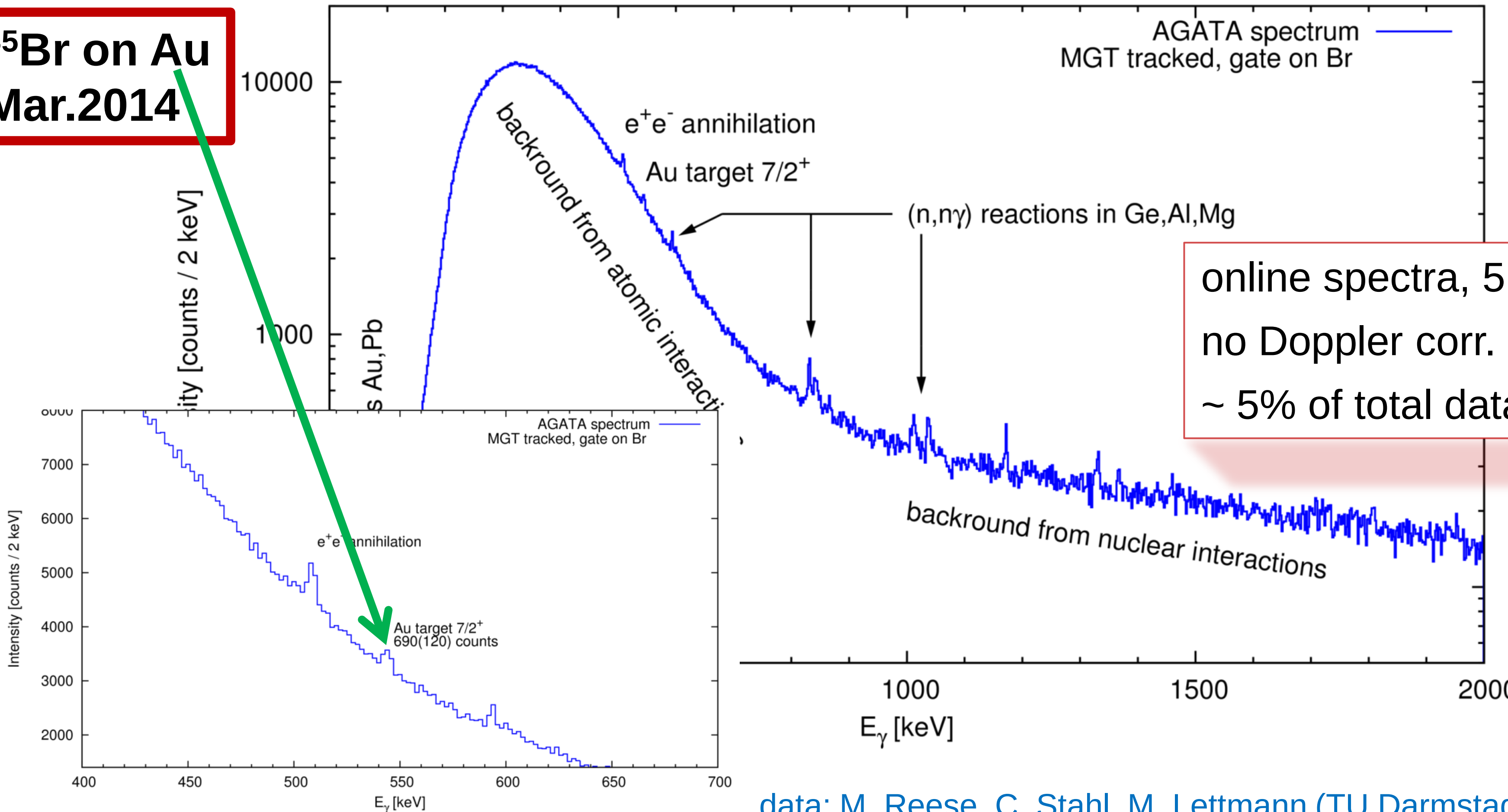
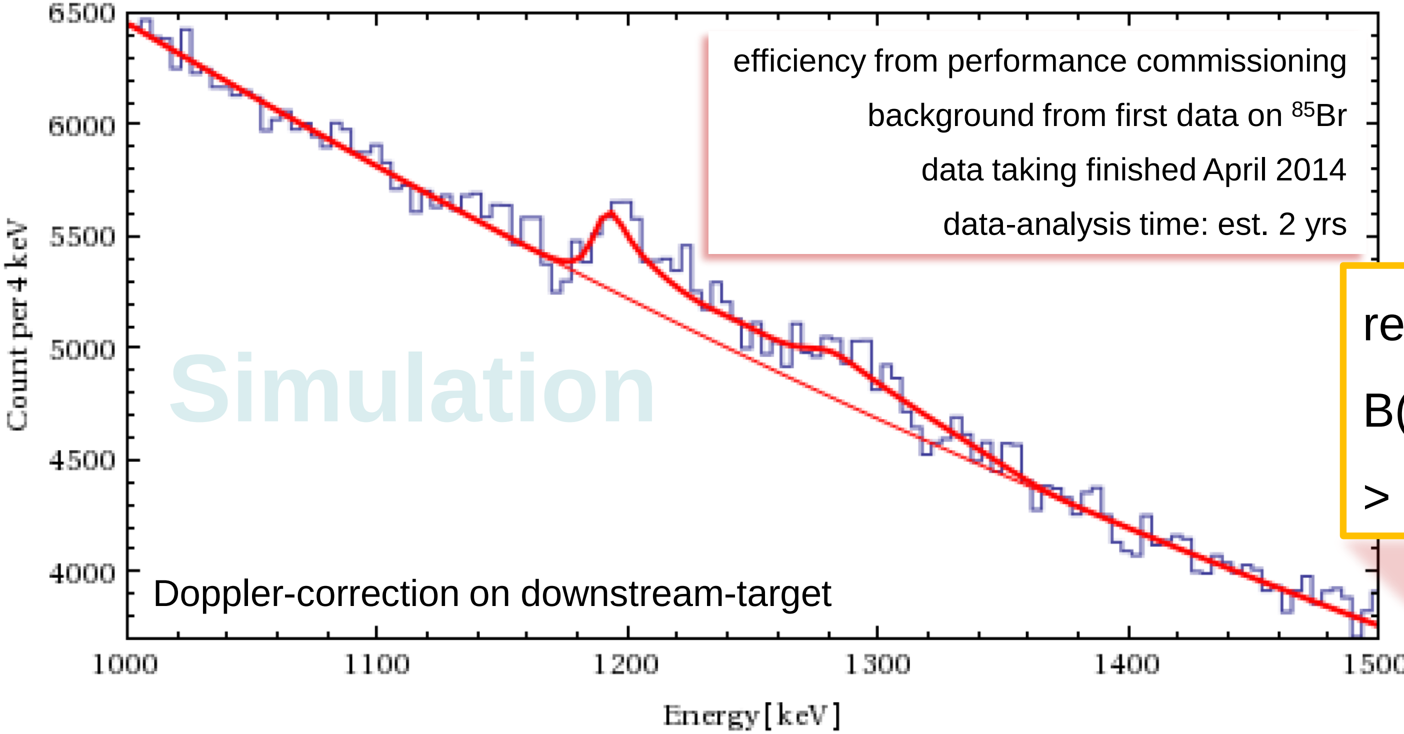
^{85}Br on Au
Mar.2014



online spectra, 5 h,
no Doppler corr.
~ 5% of total data

data: M. Reese, C. Stahl, M. Lettmann (TU Darmstadt)

Expected Data: Realistic Simulation



resulting sensitivity:

B(M1) = 0.6(2) μ_N^2

> 90% M1

Exciting new way for measuring spin-orbit splitting of exotic nuclei at FAIR !

Thanks to PreSPEC-, AGATA-collaborations, and M.Reese, C.Stahl, M.Lettmann et al.

Super-FRS Buildings (FAIR MSV version)

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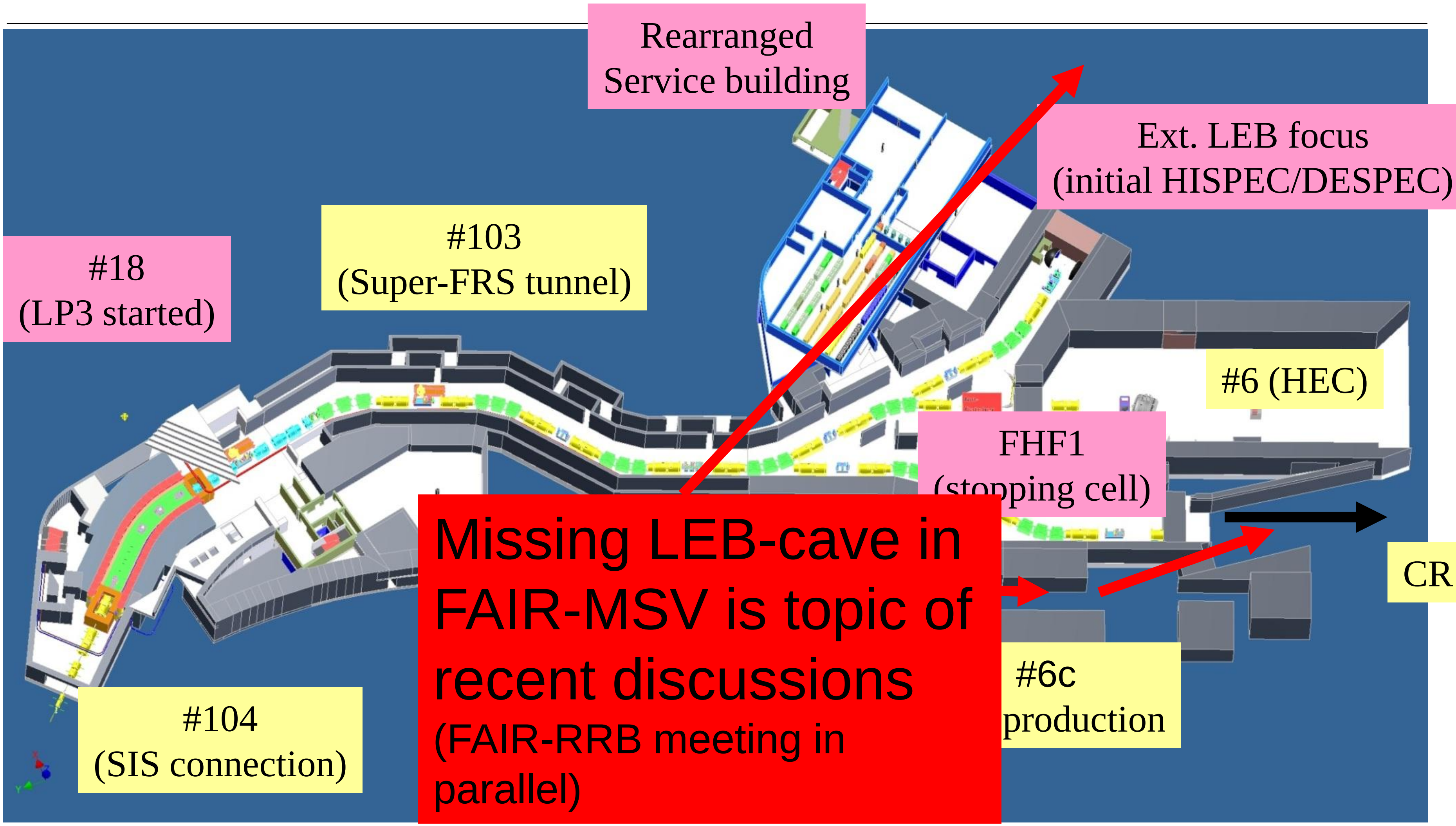

Summary

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HISPEC is ready, 1st phase (while waiting for the S-FRS)

evolution of nuclear collectivity

direct access to shell evolution (spin-orbit splitting)

several new ideas and methods

too little beam time!

Thanks to everyone who made PreSPEC a success !

Thank you for attention !