New developments for experiments with the three branches of the Fragment Separator FRS

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Super-FRS EC

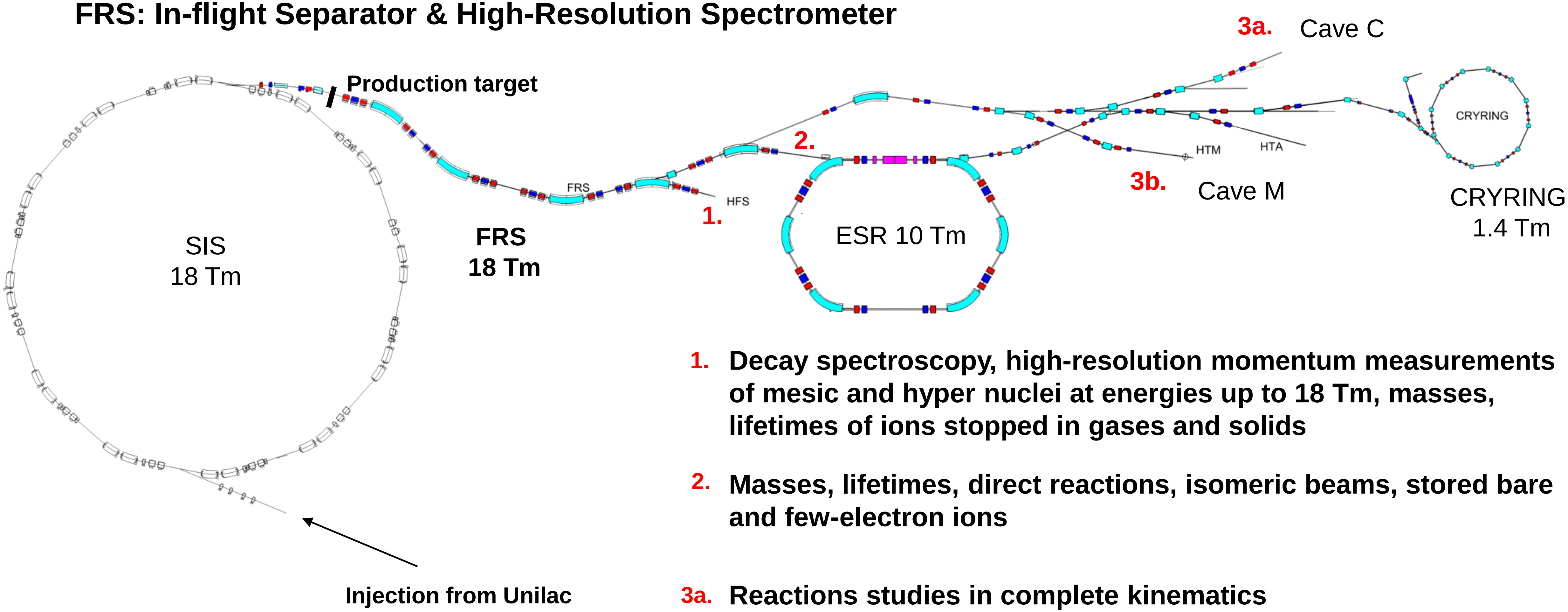
NUSTAR

FAIR Phase 0 Research Program

GSI

Exotic nuclear beams at GSI

FRS: In-flight Separator & High-Resolution Spectrometer



1. **Decay spectroscopy, high-resolution momentum measurements of mesic and hyper nuclei at energies up to 18 Tm, masses, lifetimes of ions stopped in gases and solids**

2. **Masses, lifetimes, direct reactions, isomeric beams, stored bare and few-electron ions**

3a. **Reactions studies in complete kinematics**

3b. **Bio-medical experiments with positron emitters**

Part 1: symmetric branch

Typical for experiments at the symmetric branch is a high level of flexibility at each focal plane

- Mechanical setup
- Targets, optics,
  degraders, primary beam energy

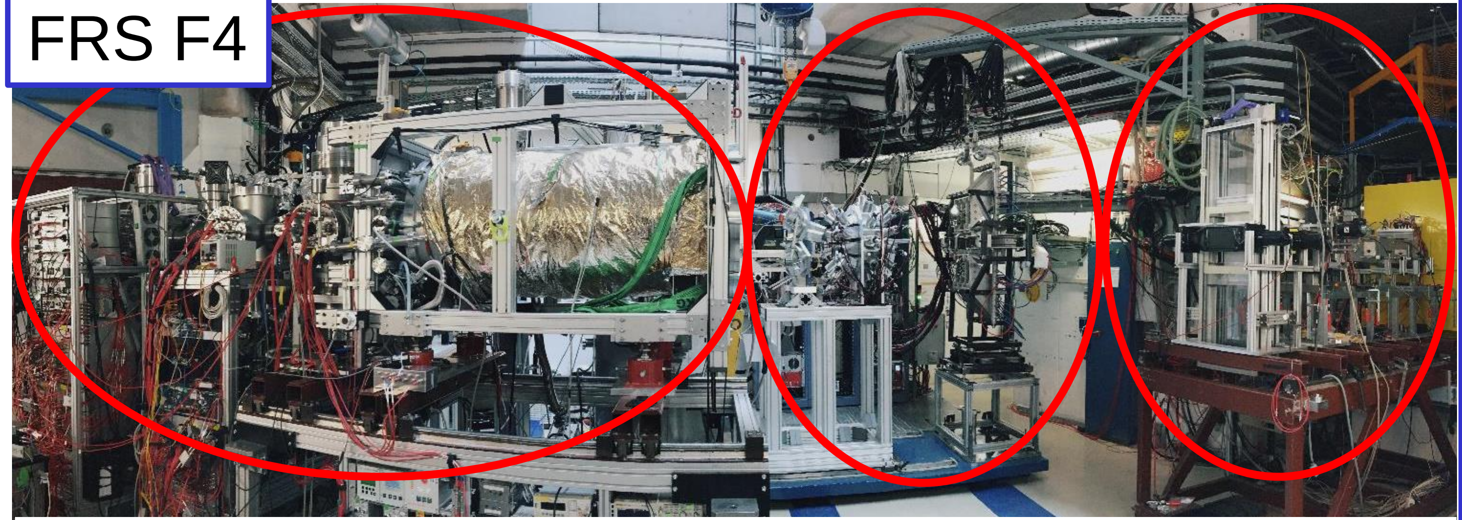
→ Optimized efficiency for each experiment

FRS F2

Standard setup

WASA setup

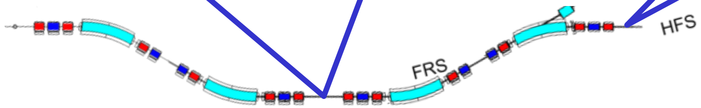
FRS F4



FRS Ion Catcher

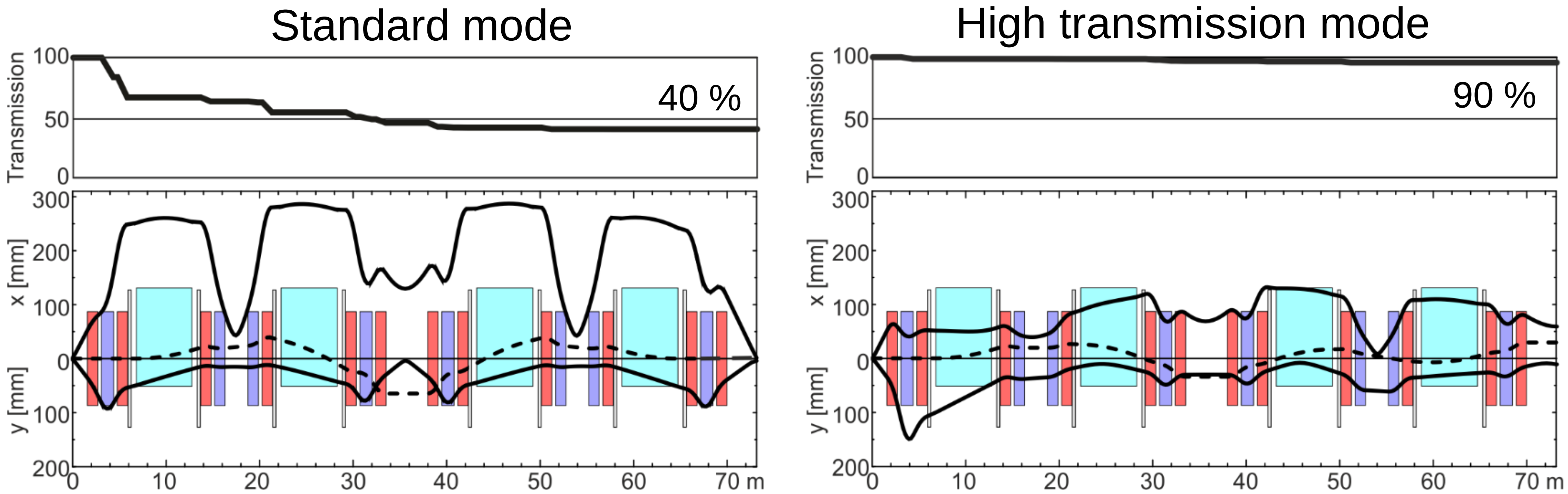
HISPEC/DESPEC and other user setups

FRS standard Equipment for particle ID



Different ion-optical modes

Goal: Change the optics to increase yields of ion of interest



ε_x=50 πmm mrad, ε_y=50 πmm mrad, x_0=1.5mm,y_0=2.2mm, $\Delta p/p$=2%

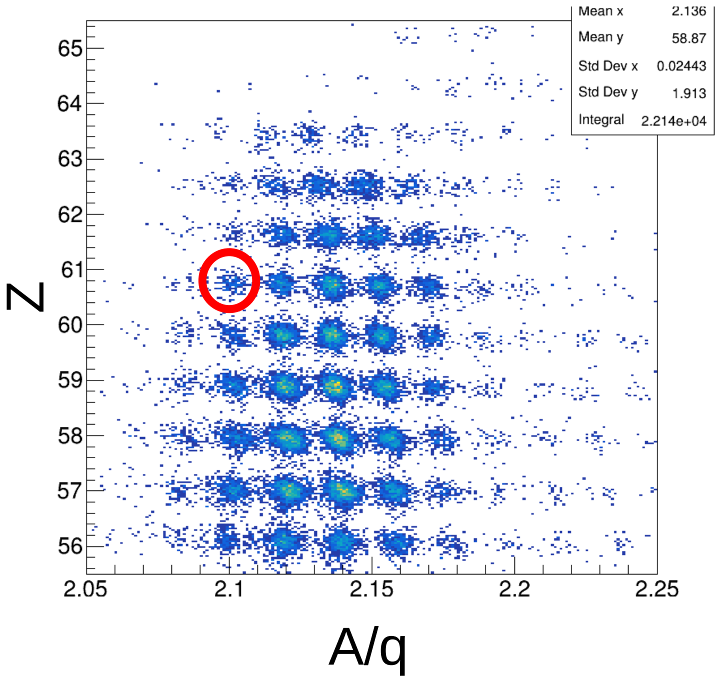
- **Two times higher transmission** by increased acceptance
- The increased momentum acceptance allows for e.g. **thicker targets (up to 16 g/cm^2 Be)**

E. Haettner et al., NIMB, 463 (2020) 455-459

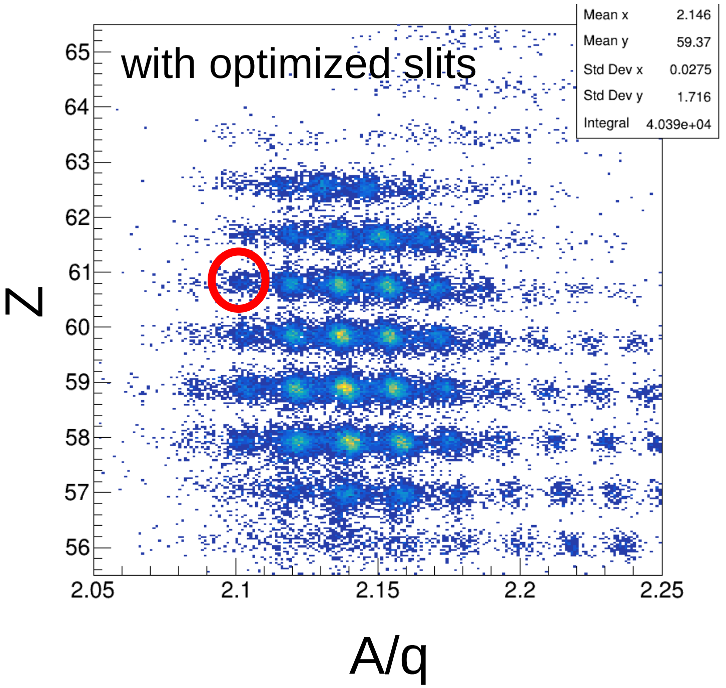
Comparision standard mode and high transmission mode

Test case: 1025 MeV/u ^{208}Pb on 4g/cm^2 Be

Standard mode



High transmission mode



- PID is possible
- With full acceptance (slits open)
  - Shift of rate towards stability
  - Rate increase of centered fragment: x2.3
  - Total rate of fragments increase by x7
- With optimized acceptance
  - Total rate of fragments increase by x2.2
  - **Rate increase of centered fragment: x1.9**

○ Centered fragment

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Experiment S511
C.Scheidenberger et al.

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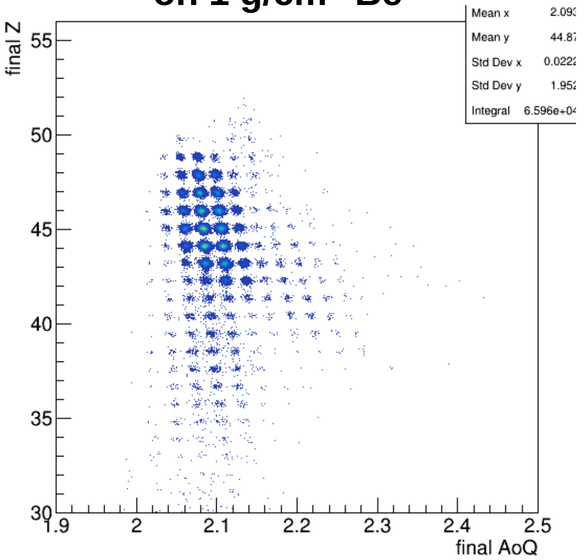
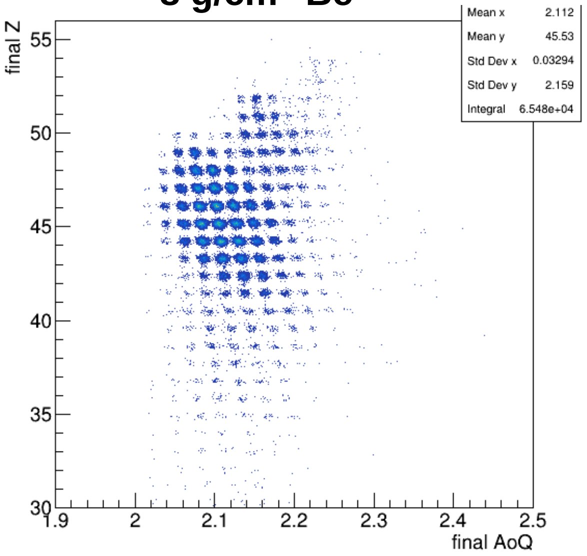
Experiment with secondary reactions in the production target

- ^{124}Xe beam on Be target of different thicknesses: 1, 8, 12, 16 g/cm^2 corresponding to 5, 22, 43, 87 mm!
- Centered fragment ^{98}Cd:
  - Similar A/Z^2 as the primary beam to minimize location straggling in the target
  - Far from primary beam secondary reactions can play a significant role to overall production
- Primary beam energy adjusted to preserve ion-optical conditions of FRS

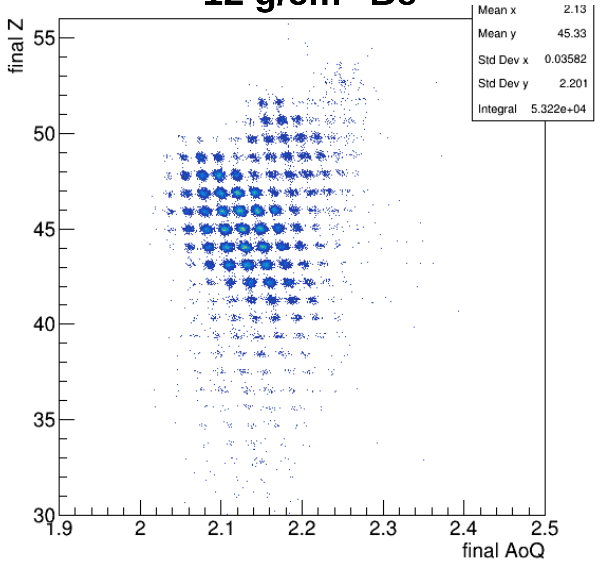
^{124}Xe (440 MeV/u) on 1 g/cm^2 Be



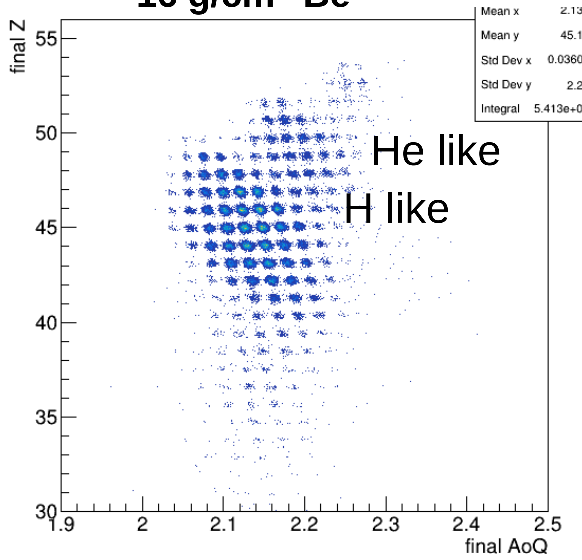
^{124}Xe (794 MeV/u) 8 g/cm^2 Be



^{124}Xe (982 MeV/u) 12 g/cm^2 Be

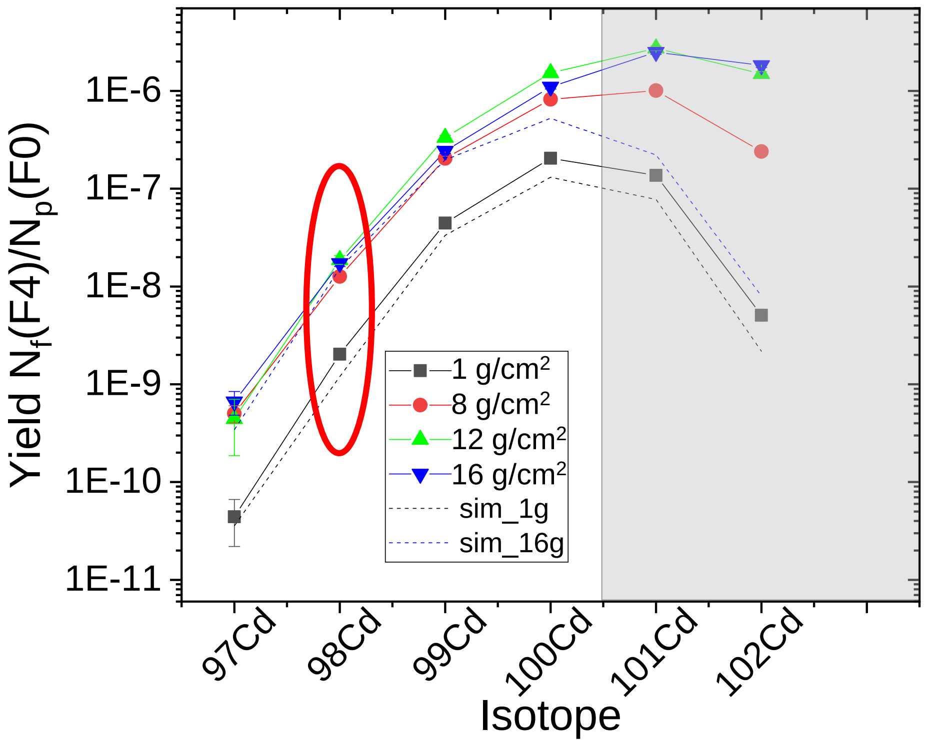


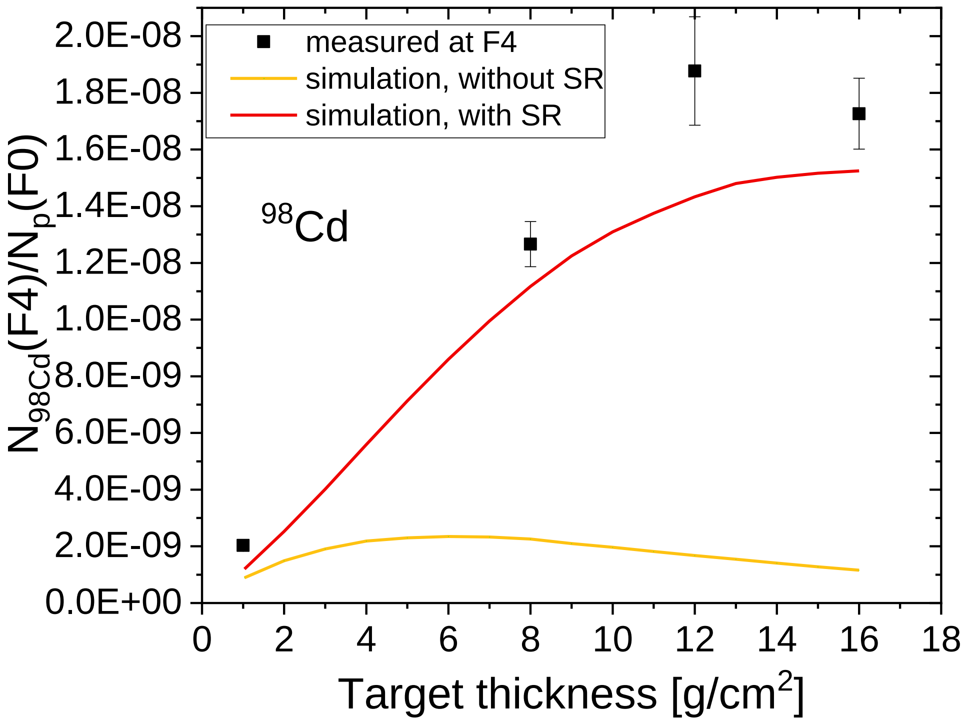
^{124}Xe (1156 MeV/u) 16 g/cm^2 Be



Experiment S474
W.R.Plaß et al.

Experiment with secondary reactions in the production target





Simulation: measured x-sections[1], epax 3.1[2], LISE++[3], MOCADI[4]

[1] H. Suzuki et al., Nucl. Instr. and Meth. in Phys. B 317 (2013) 756

[2] K. Sümmerer, Phys Rev.C86(2012)014601

[3] N. Iwasa, H. Weick, H. Geissel, Nucl. Instr. Meth. B269 (2011) 752

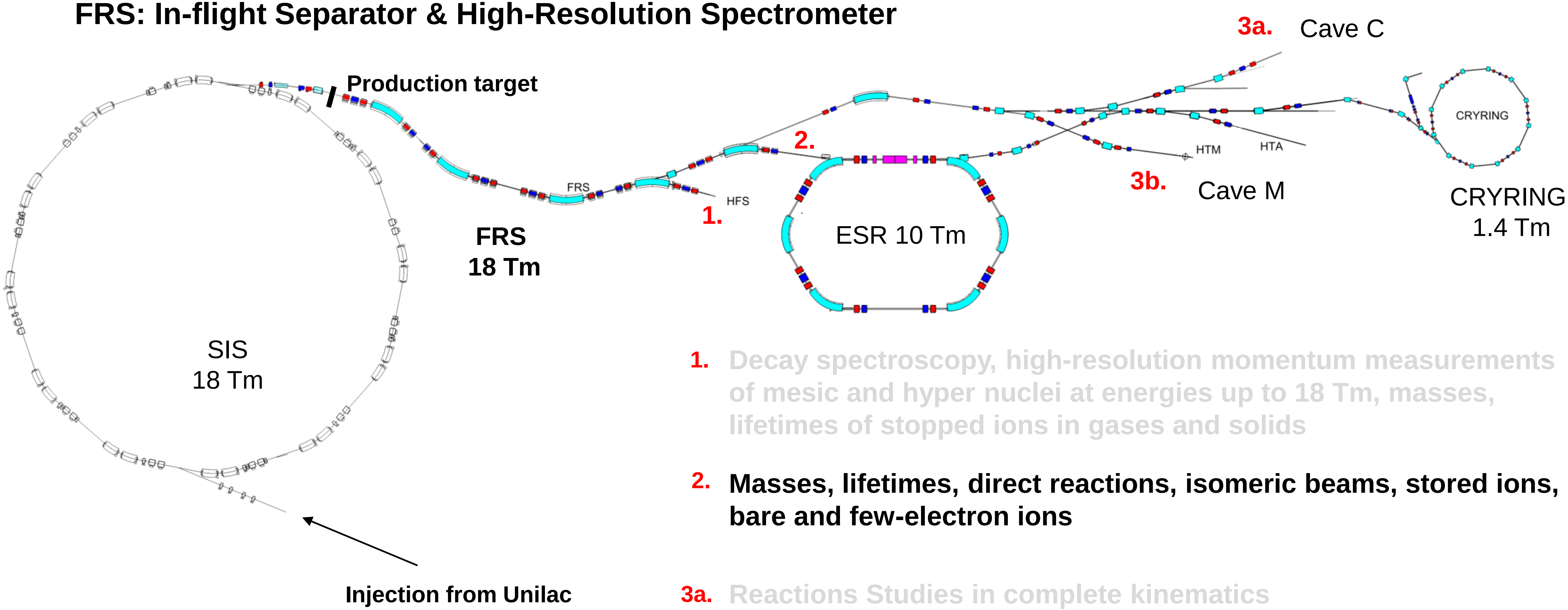
[4] O.B. Tarasov, D. Bazin NIMB 266 (2008) 4657–4664

Experiment S474
W.R.Plaß et al.

T.Dickel, H.Geissel, E.Haettner, C.Hornung, W.R.Plaß, R.Prajapat, J.Zhao

Part 2 : ESR branch

FRS: In-flight Separator & High-Resolution Spectrometer



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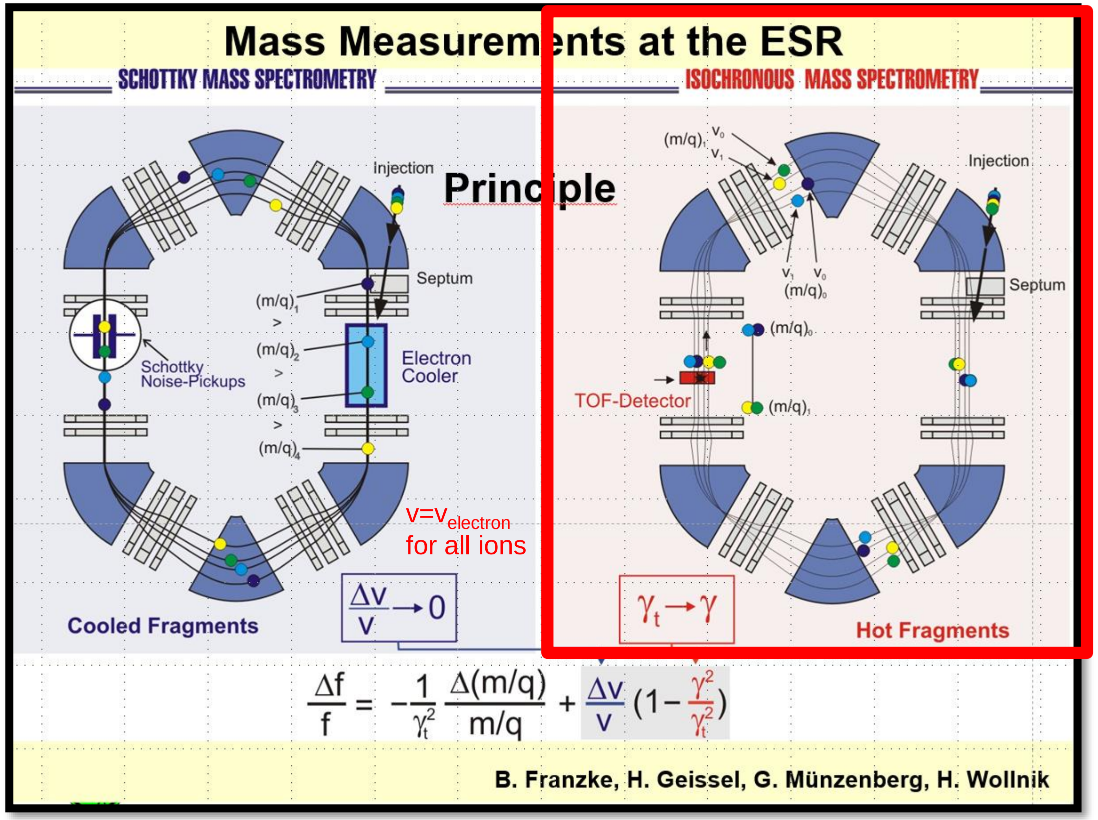
3a. Reactions Studies in complete kinematics

3b. Bio-medical experiments with positron emitters

Isochronous mass spectrometry at FRS-ESR



High accuracy and high resolution isochronous spectrometry require Bρ or velocity measurements in addition to revolution time.

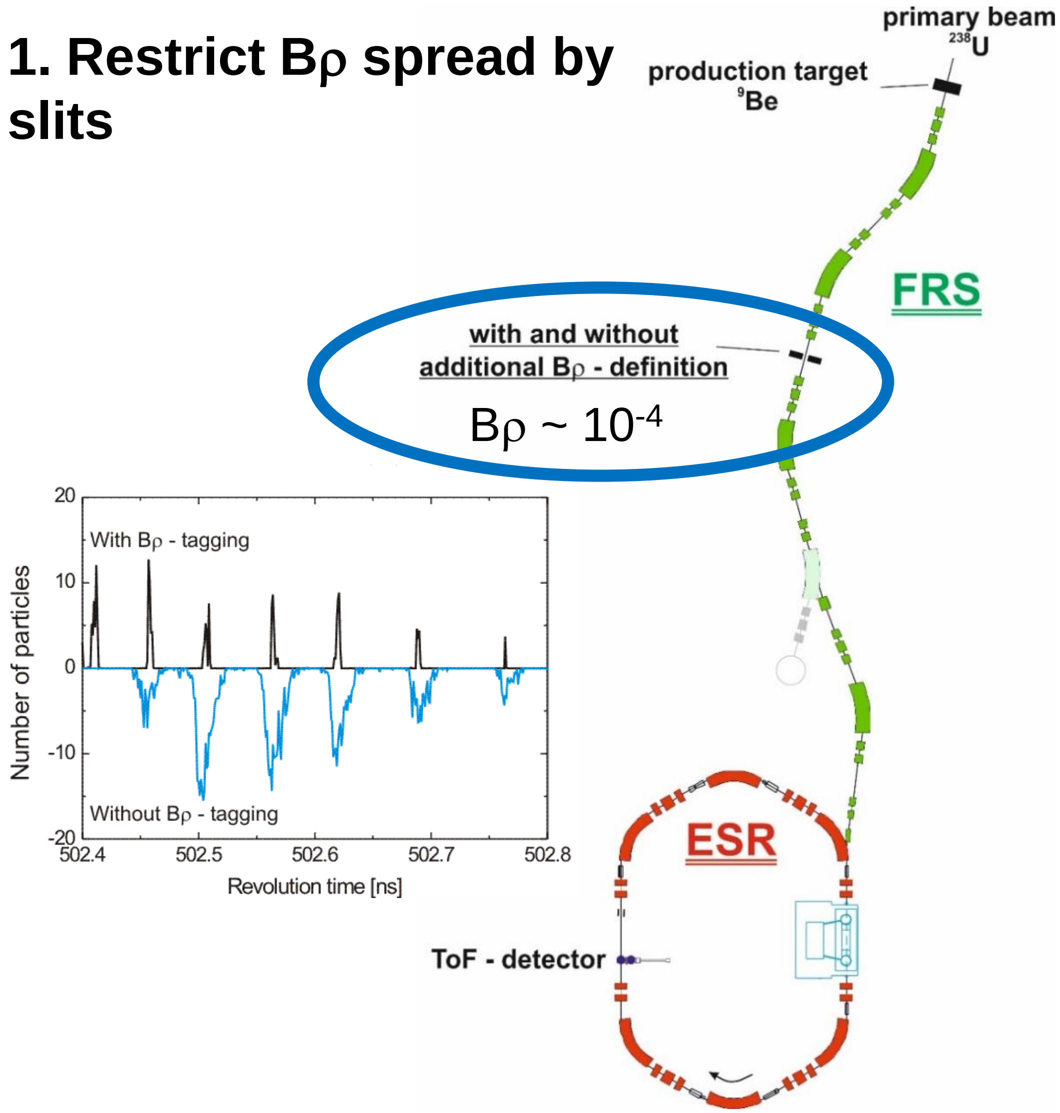
H. Geissel et al. Hyperfine Interact. (2006) 173:49–54

$$\frac{m_1}{q_1} = \left(\frac{m_0}{q_0}\right)\frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m_0}{q_0}\right)\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

A Ozawa et al. Prog. Theor. Exp. Phys, 03C009, 2012

Isochronous mass spectrometry - Bρ or velocity tagging

1. Restrict Bρ spread by slits

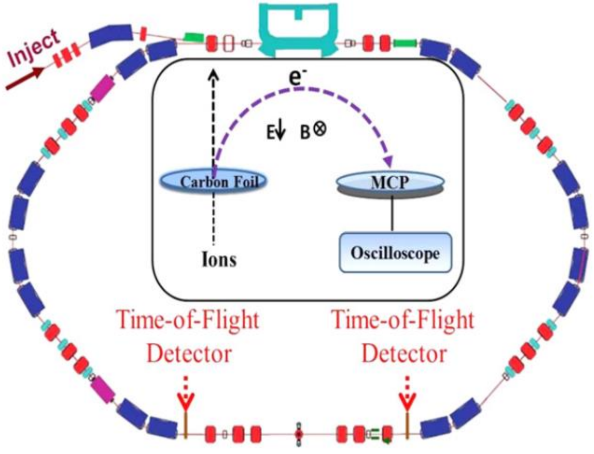


H. Geissel et al., Hyperfine Interact (2006) 173:49–54

2. Velocity determination by 2 ToF Detectors:

a) proposed ILIMA, CDR

b) implemented and in use in CSRe in Lanzhou,
Y M Xing et al., Phys. Scr. 2015 014010

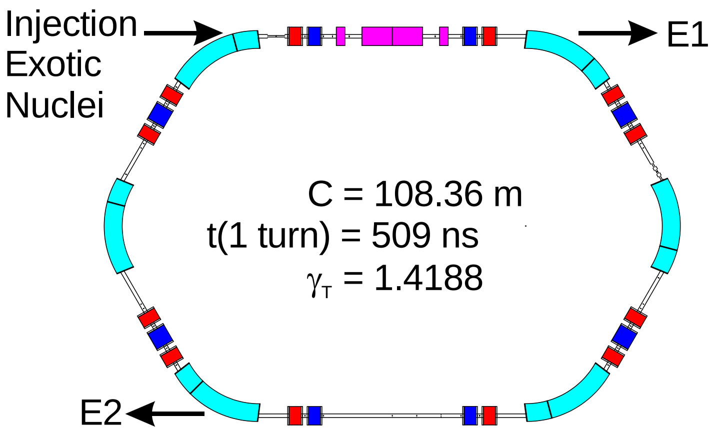


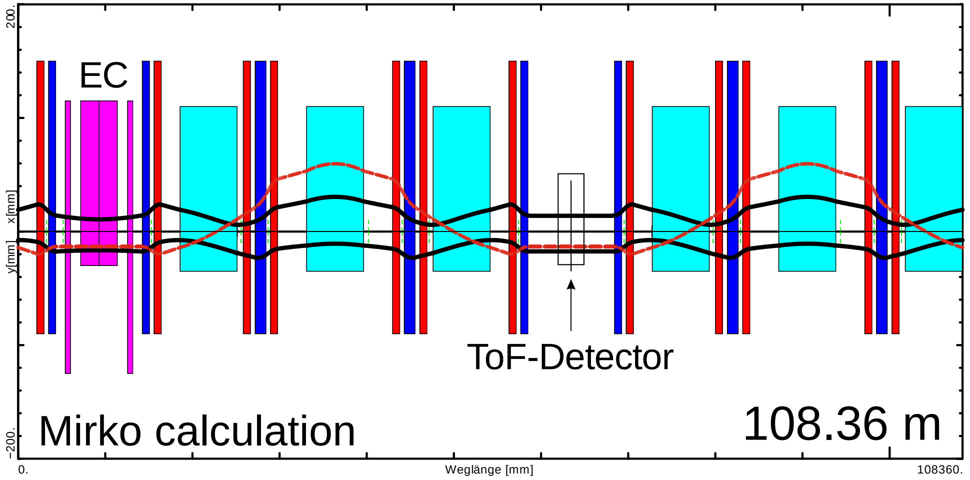
3. Bρ determination via recording the betatron oscillation at a dispersive ring section.

proposed for HIAF SRing
J.-H. Liu et al.,NUCL SCI TECH (2019) 30:152

→ What can be done at the ESR?

Isochronous ESR and its ToF detector



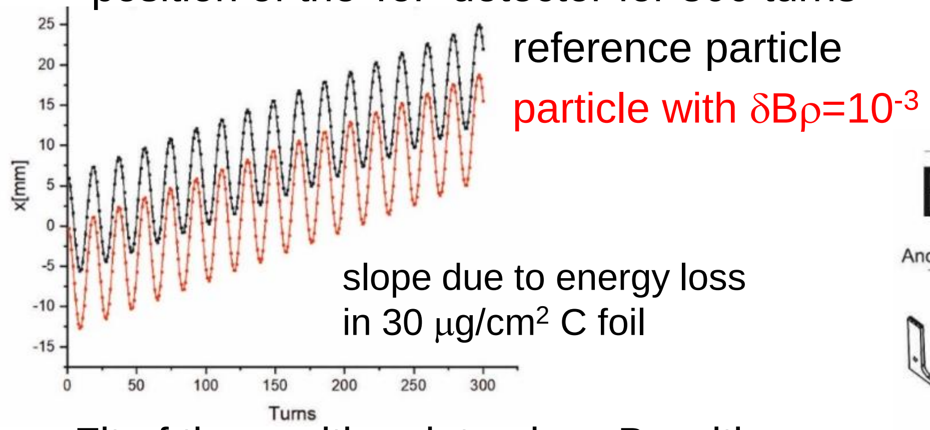


Isochronous lattice of ESR: Q_h=2.32 Q_v=2.26

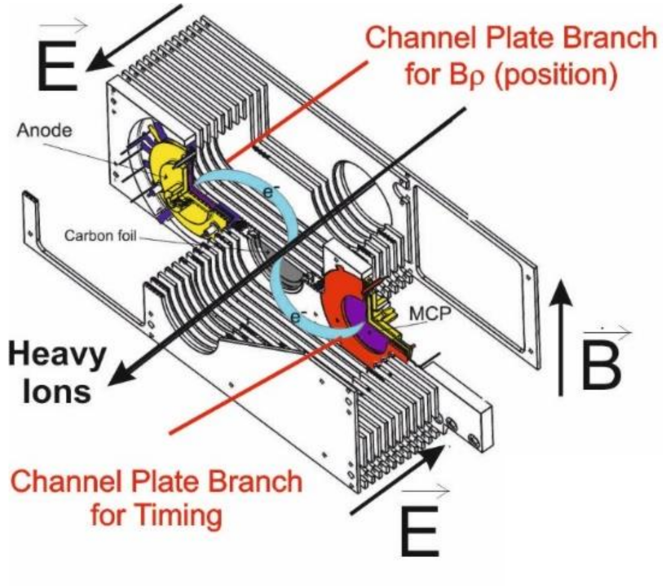
ε= 20 π mm mrad, dispersion line = 0.2 %

H. Geissel, B. Franczak

Simulation of the particle motion at the position of the ToF detector for 300 turns



Fit of the position data gives $B\rho$ with an accuracy of ~ 10^{-5}

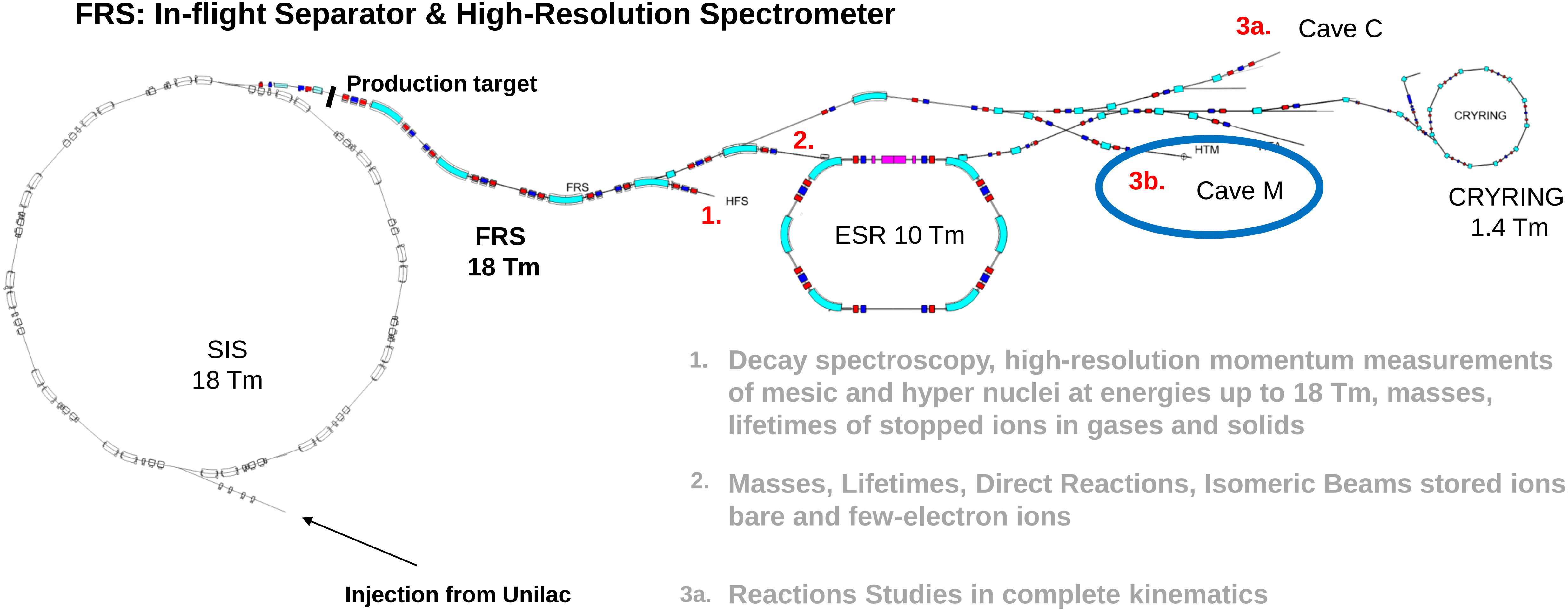


Simultaneous time and $B\rho$ determination could be realized by recording the betatron oscillation with a position sensitive anode in the second channel plate branch

H. Geissel and D. J. Morrissey, Handbook of Nuclear Physics in print

Part 3: Bio-medical experiments with positron emitters

FRS: In-flight Separator & High-Resolution Spectrometer



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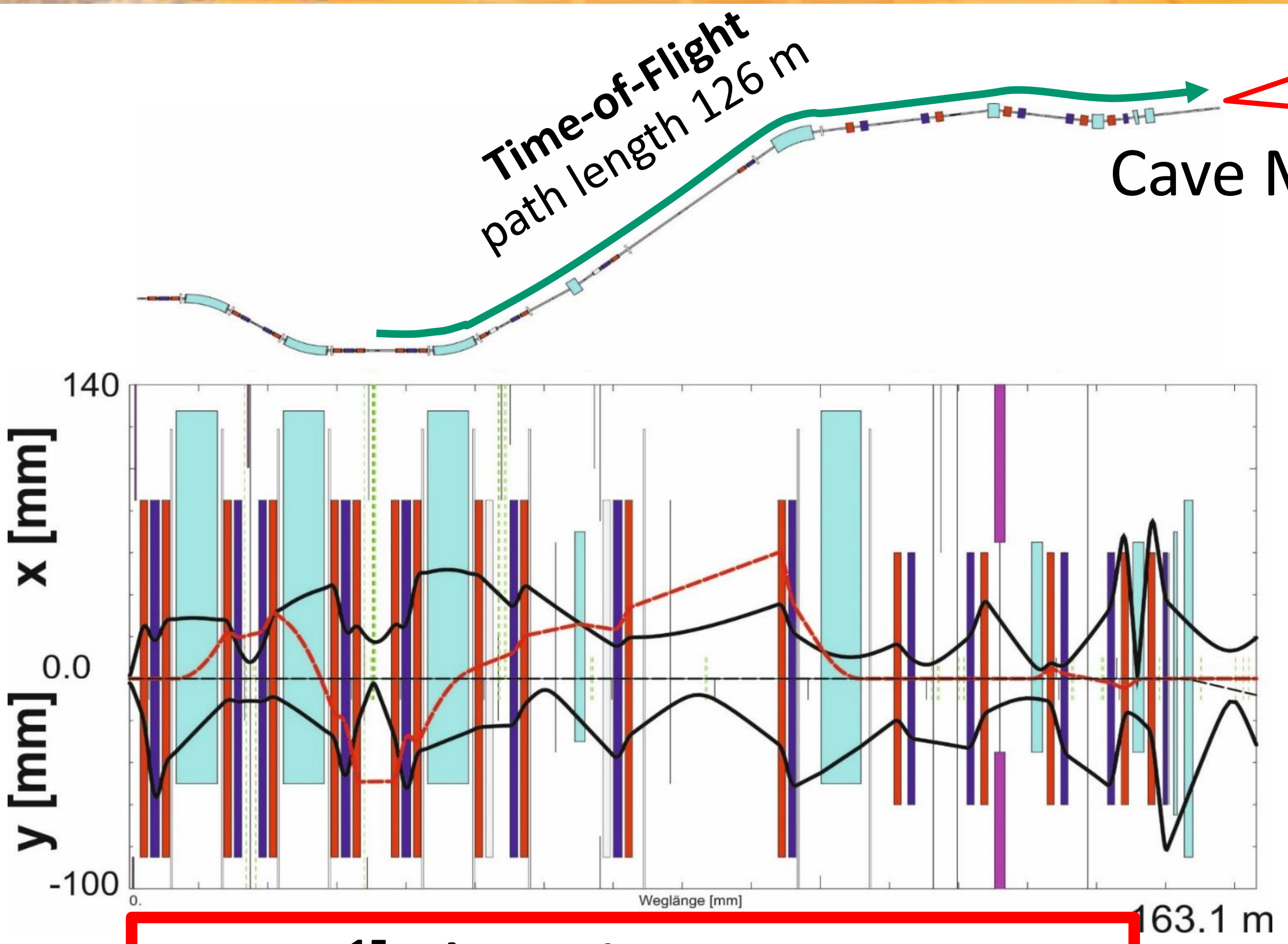
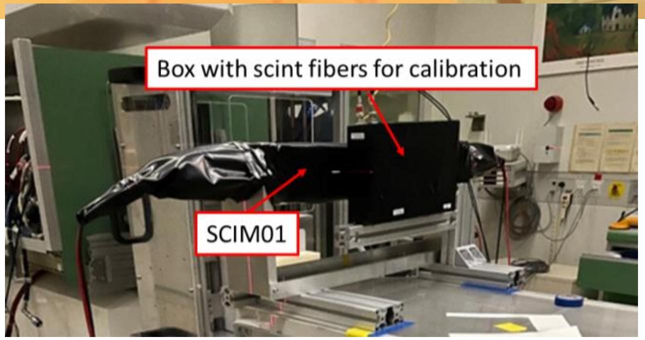
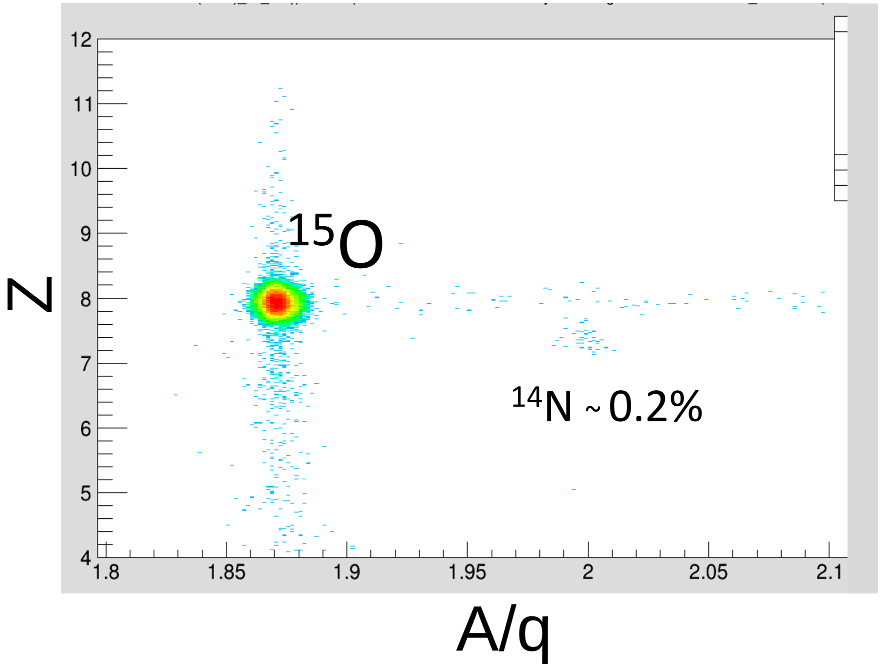
First experiments with FRS-CaveM using positron emitters







- **Pure ^{15}O beam in Cave M**
- **^{15}O in Cave M per ^{16}O in SIS: ~ $6\cdot10^{-4}$**
- **dp/p ~ 1.5% (FWHM)**

B.Franczak, H.Geissel, E.Haettner, D.Kostyleva, S.Purushothaman, C.Scheidenberger, Y.Tanaka et al.

Super-FRS EC

B · A · R · B

BIOMEDICAL APPLICATIONS OF RADIOACTIVE ION BEAMS

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Perspective for treatment?

- Carbon, Nitrogen and Oxygen beams of ~ 10^{11} particles/cycle in SIS18 has been reached
- Measured conversion factor of $6{\cdot}10^{-4}$ for SIS18-CaveM → $6{\cdot}10^{7}$ ^{15}O /cycle
- With ~1s acceleration and 1s extraction time

→ ~$3{\cdot}10^{7}$ ^{15}O /second on average

- **In-flight produced and separated positron emitters with intensities relevant for treatment are in reach**

Parameters for heavy ion tumor treatment
Heidelberg Ion Therapy (HIT) Center

Parameter	Steps	Protons	Carbon
Energy	255	48 – 221 MeV/u	88 – 430 MeV/u
Penetration	255	20 - 300 mm	20 - 300 mm
Beam Size	4	8 – 20 mm	4 – 12 mm
Intensity	10	$8{\cdot}10^{7}$ - $2{\cdot}10^{9}$ 1/s	$2{\cdot}10^{6}$ - $8{\cdot}10^{7}$ 1/s

D. Ondreka, U. Weinrich, “The Heidelberg Ion Therapy (HIT) Accelerator Coming into Operation”,
Proc. EPAC 2008, Genoa, Italy, 2008, pp. 979–981.

Summary

During FAIR phase-0 program at GSI many NUSTAR experiments are performed with all FRS branches. These experiments make use of new developments and the flexibility:

- Symmetric branch
    - High energies and thick target allows to make efficient use of secondary reactions in the production target
    - New high transmission mode was successfully applied and the rate increased by a factor 2
- ESR branch
    - The isochronous mode requires Bρ or velocity measurement in addition to the measurement of the revolution frequency for high accuracy mass measurements. This can be fulfilled by a position measurement at a dispersive ring section.
    - The existing ToF detector in the ESR can be modified to measure position and time simultaneously.
- Target hall branch
    - Biomedical research program with positron emitters for hadron therapy is started at GSI (www.gsi.de/BARB)
    - The GSI intensities for ^{11}C and ^{15}O ions can be similar to those routinely used for ^{12}C at Heidelberg Ion Therapy (HIT) Center

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Thanks to all collaborators and to you for your attention!