Isotope separation and particle identification at the Super-FRS

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Contents

- Introduction to in-flight production of rare isotope beams (RIBs)
- Introduction to Super-FRS

  separation method: FRS vs Super-FRS

  Super-FRS vs worldwide new-generation in-flight separators

- Particle identification of relativistic ions

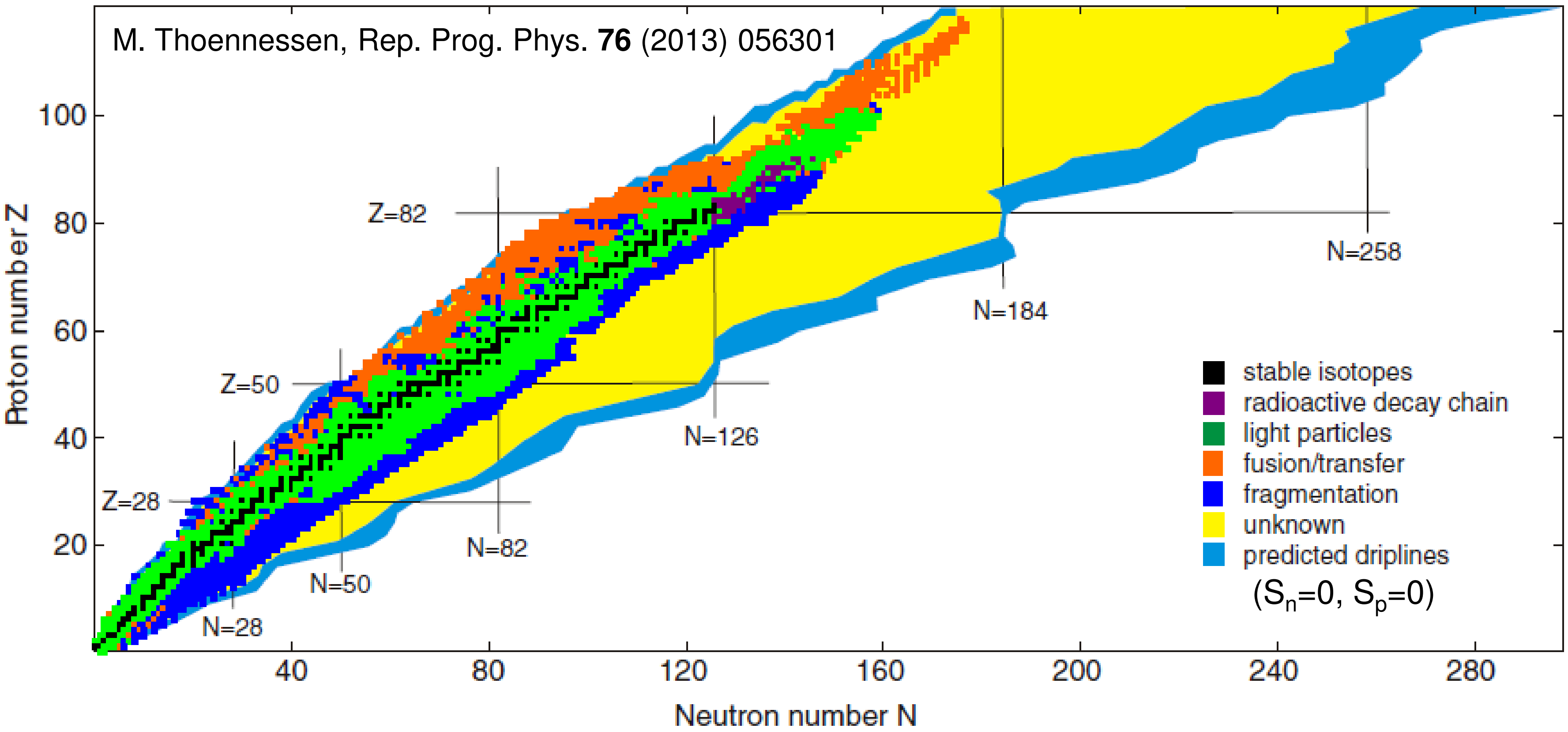
  standard PID detectors

  Super-FRS detector requirements & developments

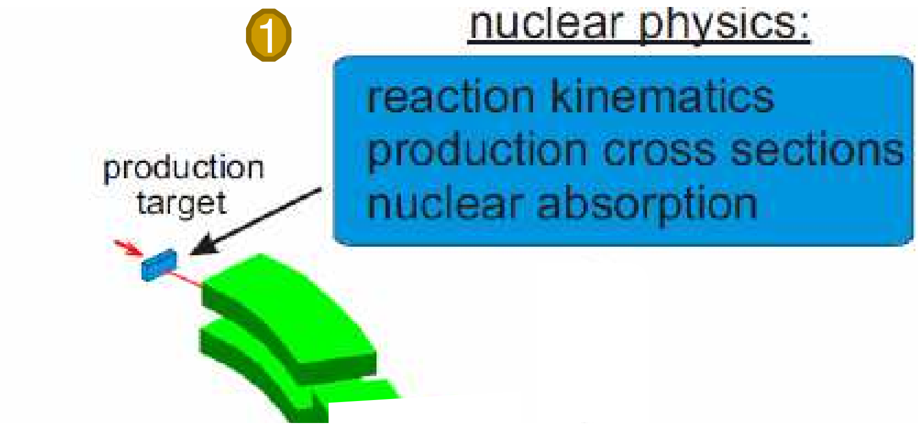
  Super-FRS unique experiments

Chart of nuclides

About 6000 nuclides are bound, only about half of them are known.
Most of the unobserved nuclides are neutron-rich.



Basic method: production



Nucler reactions to produce RIBs

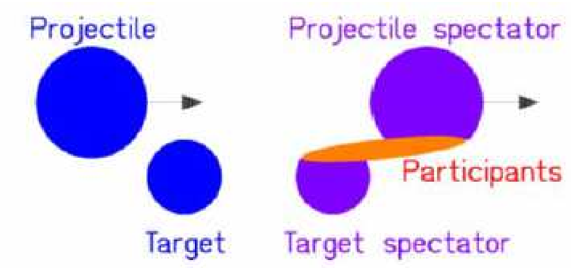
- fragmentation
- spallation
- fission
- fusion
- transfer

High Energy

High and Low Energy

E_{proj} ~ 100-1000 MeV/u , λ ~ 2-0.2 fm

Thick target (few g/cm^2) to increase the yields $Y(Z,A) = N_t \, I_{proj} \, \sigma(Z,A) \, \varepsilon$



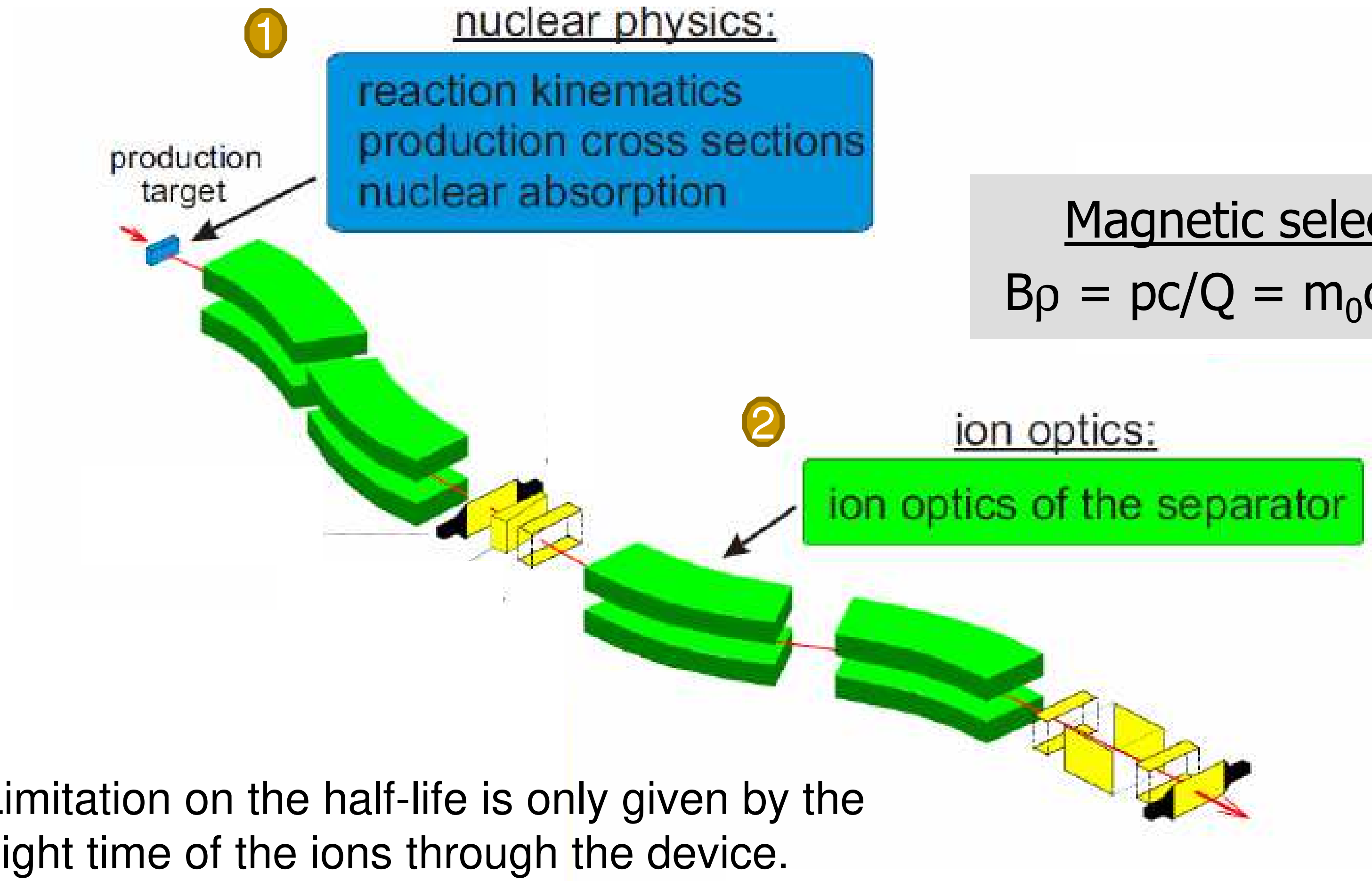
$v_{frag} \sim v_{proj}$

I_{proj} : N_{proj} / s

cross section

transmission, selection and efficency

Basic method: selection



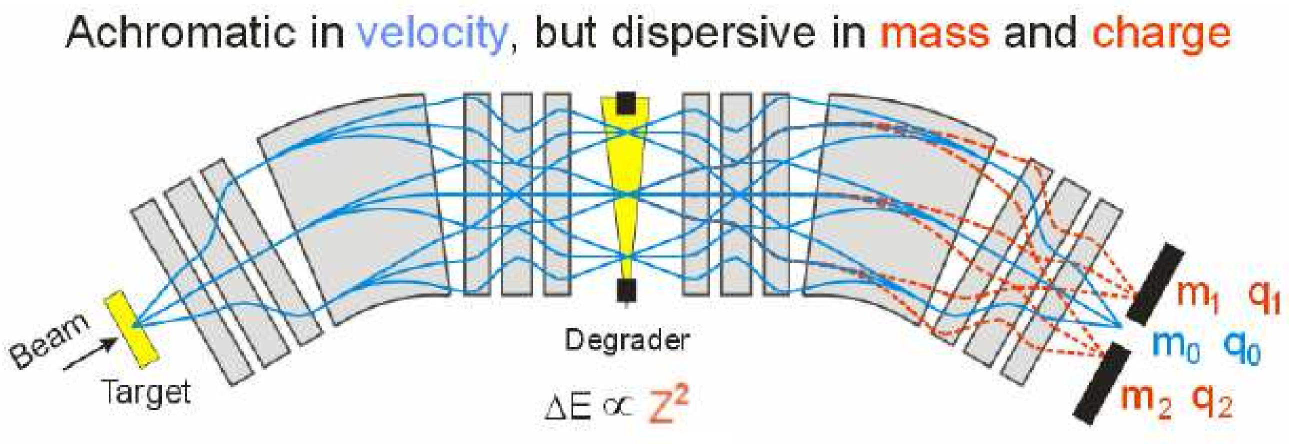
Magnetic selection

$B\rho = pc/Q = m_0c^2\beta\gamma/Q$

Limitation on the half-life is only given by the flight time of the ions through the device.

Separation method
momentum-loss-achromat

Because the fragments have approximately the same velocity they will loose different momenta in the degrader depending on their atomic number Z and will exit with different magnetic rigidity.

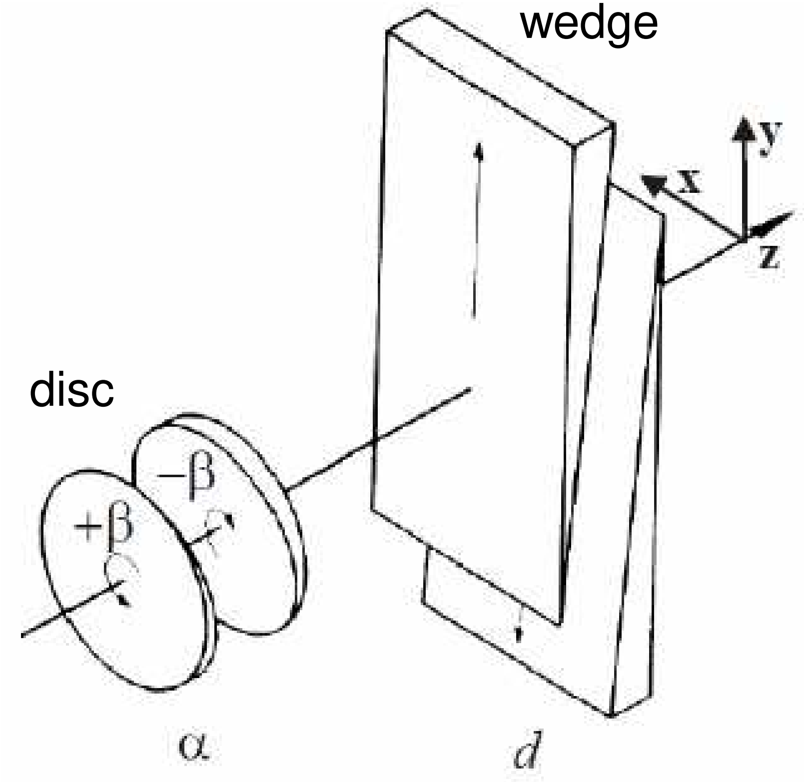


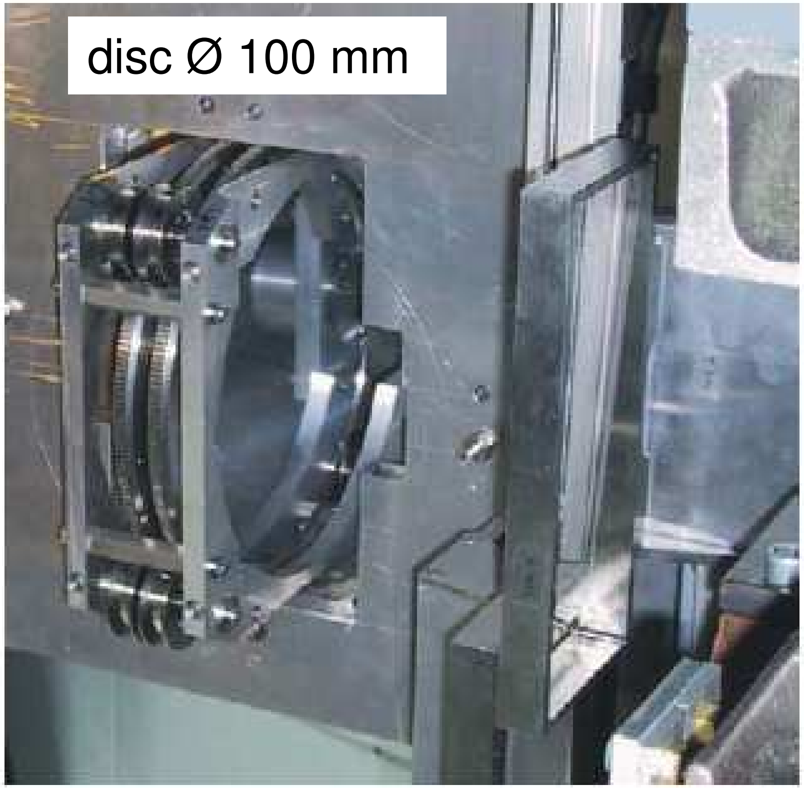
The final position and angle do not depend on momentum.

J.P. Dufour et al. *NIM A* 248 (1986) 267
K.-H. Schmidt et al. *NIM A* 260 (1987) 287

Degraders

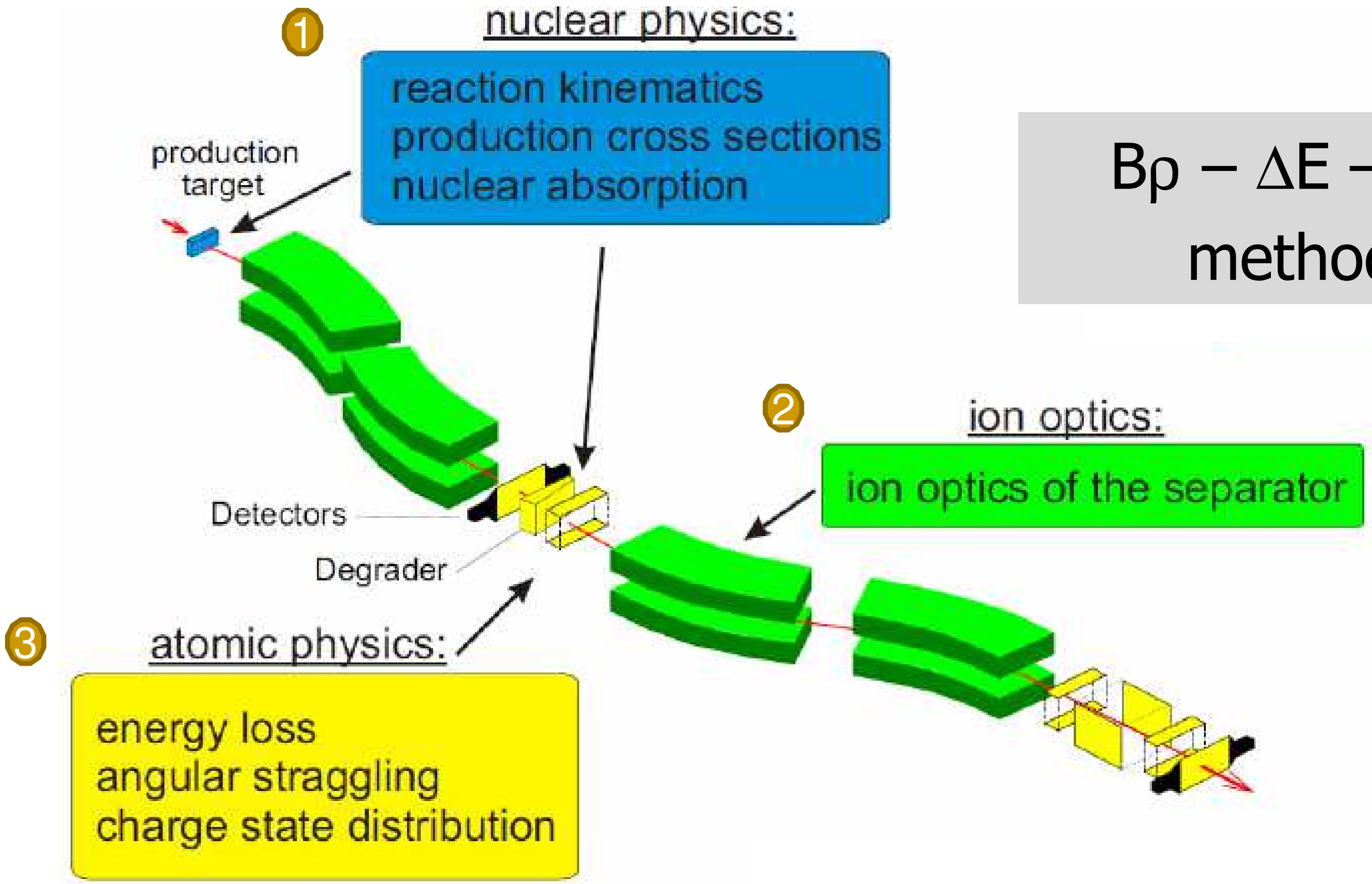
H. Folger et al., *NIM A* 303 (1991) 24





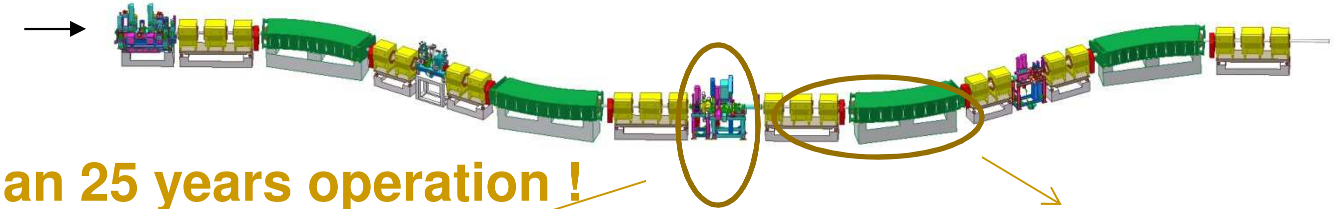
Wedge shaped disc and double-shaped wedge machined with μm precision.

Basic method: separation

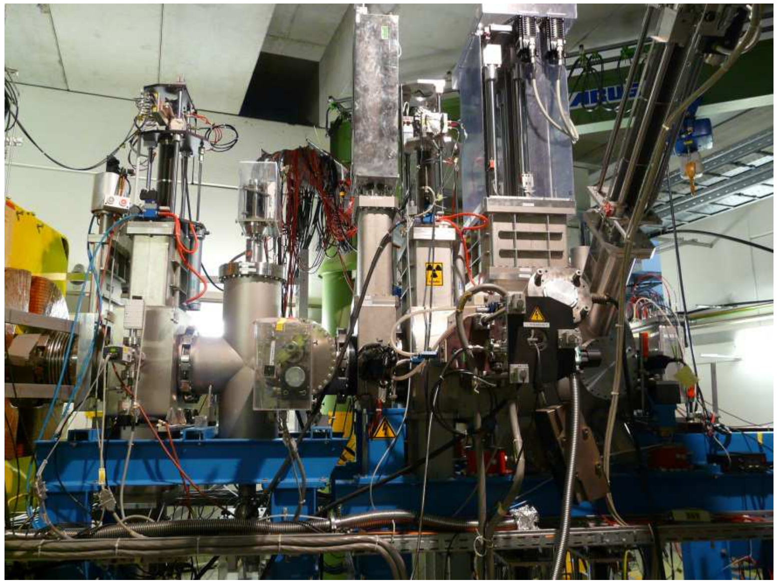


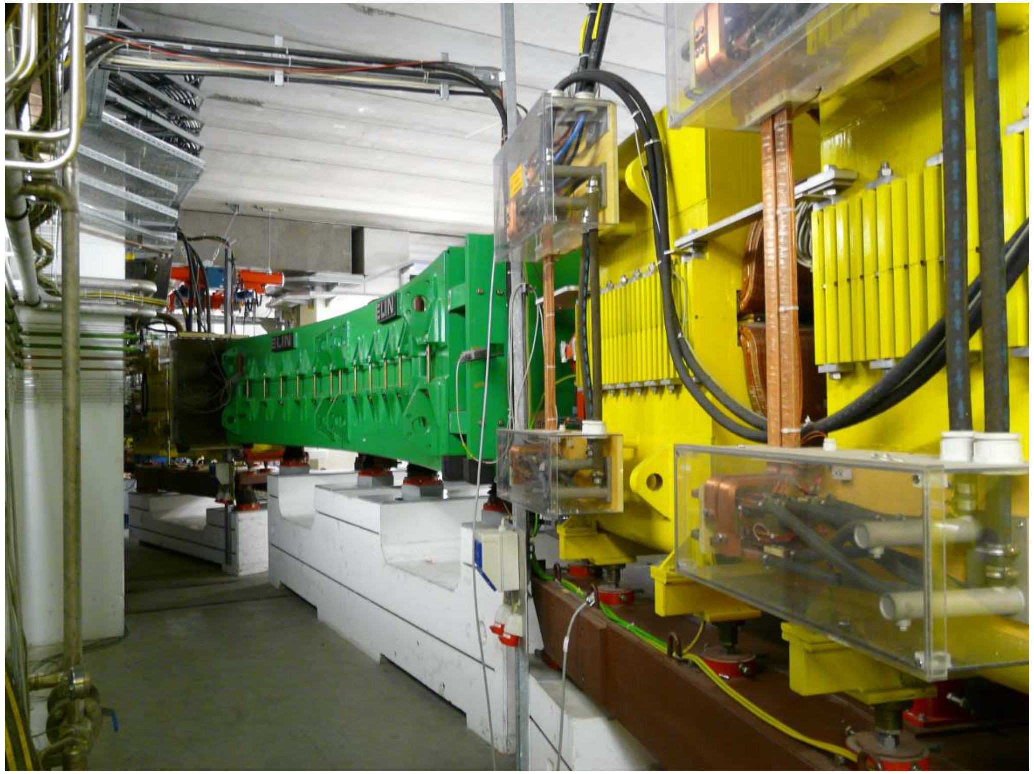
$B\rho - \Delta E - B\rho$ method

FRagment Separator



More than 25 years operation !





H. Geissel et al. *NIM B* 70 (1992) 286

Discovery of 60 new isotopes

Contents lists available at SciVerse ScienceDirect

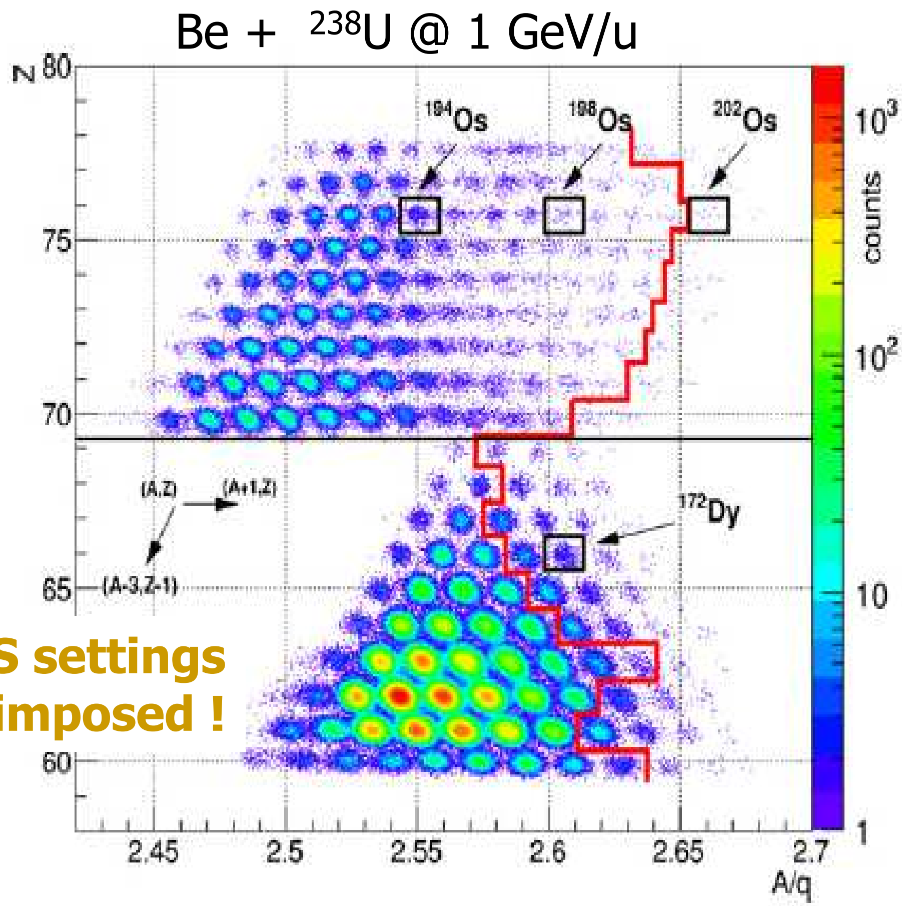
Physics Letters B

www.elsevier.com/locate/physletb

Discovery and cross-section measurement of neutron-rich isotopes in the element range from neodymium to platinum with the FRS

J. Kurcewicz[a,*], F. Farinon[a,b,1], H. Geissel[a,b], S. Pietri[a], C. Nociforo[a], A. Prochazka[a,b], H. Weick[a], J.S. Winfield[a], A. Estradé[a,c], P.R.P. Allegro[d], A. Bail[e], G. Bélier[e], J. Benlliure[f], G. Benzoni[g], M. Bunce[h], M. Bowry[h], R. Caballero-Folch[i], I. Dillmann[a,b], A. Evdokimov[a,b], J. Gerl[a], A. Gottardo[j], E. Gregor[a], R. Janik[k], A. Kelić-Heil[a], R. Knöbel[a], T. Kubo[l], Yu.A. Litvinov[a,m], E. Merchan[a,n], I. Mukha[a], F. Naqvi[a,o], M. Pfützner[a,p], M. Pomorski[p], Zs. Podolyák[h], P.H. Regan[h], B. Riese[a,b], M.V. Ricciardi[a], C. Scheidenberger[a,b], B. Sitar[k], P. Spiller[a], J. Stadlmann[a], P. Strmen[k], B. Sun[b,q], I. Szarka[k], J. Taïeb[e], S. Terashima[a,l], J.J. Valiente-Dobón[j], M. Winkler[a], Ph. Woods[r]

- $T_{1/2}$ long enough to survive for 300 ns ToF
- measured production cross sectons down up to 1 pb



4 FRS settings superimposed !

J. Kurcewicz et al., *PLB* 717 (2012) 371

^{100}Sn study

ARTICLE C.B. Hinke et al., *Nature* 486 (2012) 341

doi:10.1038/nature11116

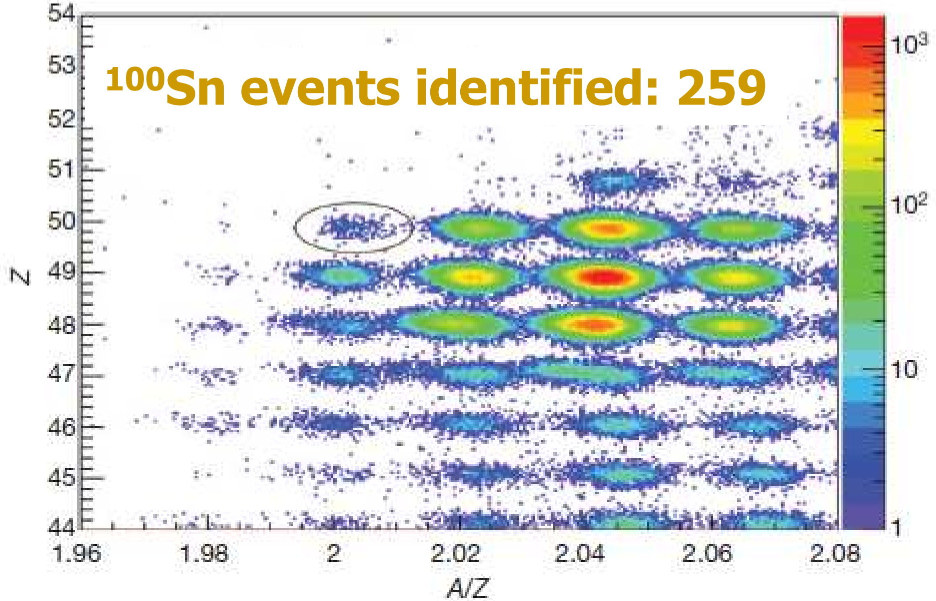
Superallowed Gamow–Teller decay of the doubly magic nucleus ^{100}Sn

C. B. Hinke[1], M. Böhmer[1], P. Boutachkov[2], T. Faestermann[1], H. Geissel[2], J. Gerl[2], R. Gernhäuser[1], M. Górska[2], A. Gottardo[3], H. Grawe[2], J. L. Grębosz[4], R. Krücken[1,5], N. Kurz[2], Z. Liu[6], L. Maier[1], F. Nowacki[7], S. Pietri[2], Zs. Podolyák[8], K. Sieja[7], K. Steiger[1], K. Straub[1], H. Weick[2], H.-J. Wollersheim[2], P. J. Woods[6], N. Al-Dahan[8], N. Alkhomashi[8], A. Ataç[9], A. Blazhev[10], N. F. Braun[10], I. T. Čeliković[11], T. Davinson[6], I. Dillmann[2], C. Domingo-Pardo[12], P. C. Doornenbal[13], G. de France[14], G. F. Farrelly[8], F. Farinon[2], N. Goel[2], T. C. Habermann[2], R. Hoischen[2], R. Janik[15], M. Karny[16], A. Kaşkaş[9], I. M. Kojouharov[2], Th. Kröll[17], Y. Litvinov[2], S. Myalski[4], F. Nebel[1], S. Nishimura[13], C. Nociforo[2], J. Nyberg[18], A. R. Parikh[19], A. Procházka[2], P. H. Regan[8], C. Rigollet[20], H. Schaffner[2], C. Scheidenberger[2], S. Schwertel[1], P.-A. Söderström[13], S. J. Steer[8], A. Stolz[21] & P. Strmeň[15]

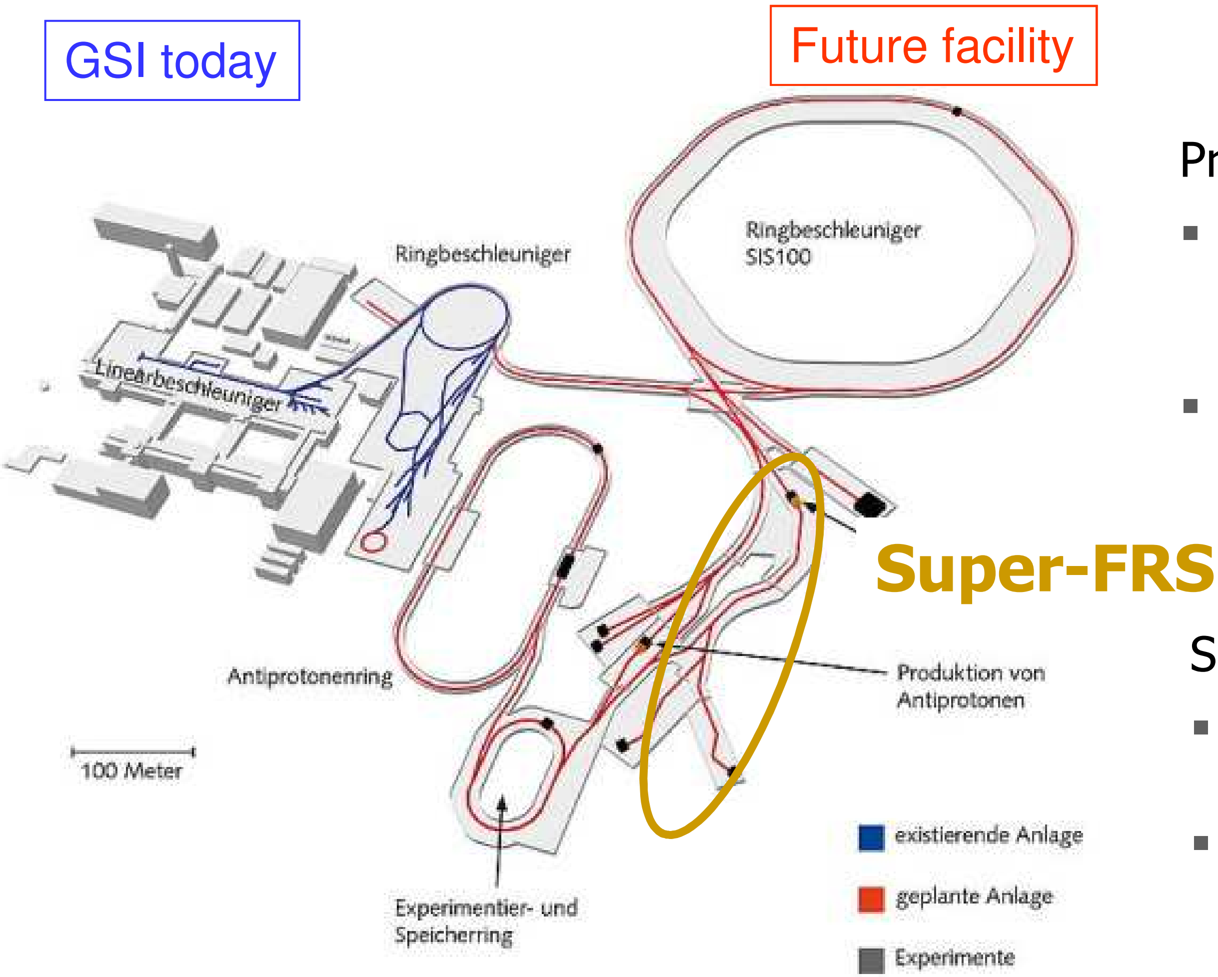
Be + ^{124}Xe @ 1 GeV/u

≤ 1 ^{100}Sn/hour !

- measured $T_{1/2}$, β-decay end-point energy, GT strength, the largest so far measured in allowed nuclear β-decay, establishing the 'superallowed' nature of this pure spin-flip ^{100}Sn $(0^+) \rightarrow$ ^{100}In $(1^+(\pi g_{9/2}^{-1}, \nu g_{7/2}))$ transition



NUSTAR facility at FAIR



Primary Beams

- 5×10^{11} $^{238}U^{28+}$ (pulse) 3.5×10^{11} $^{238}U^{28+}$/s (DC) @1.5 GeV/u
- factor **100** in intensity over present

Secondary Beams

- broad range of RIBs up to 1-2 GeV/u
- up to factor **10000** in intensity over present

The Super-FRS at FAIR

(H. Geissel et al. NIMB 204(2003)71)

Based on experience and successful experimental program at the FRS :

- Multi-stage separation (high resolution spectrometer)
- Multi-branch system serving experimental areas and storage-rings

Technical Design Report (version submitted on April 24th 2008)

H. Geissel, M. Winkler, H. Weick, K.-H. Behr, G. Münzenberg, H. Simon, K. Sümmerer, B. Achenbach, D. Acker, D. Ackermann, T. Aumann, J. Äystö, R. Baer, M. Berz, D. Boutin, C. Brandau, A. Brünle, P. Dendooven, G. Fehrenbacher, E. Floch, M. Gleim, W. Hüller, H. Iwase, A. Kalimov, C. Karagiannis, M. Kauschke, A. Kelic, B. Kindler, G. Klappich, E. Kozlova, A. Kratz, T. Kubo, N. Kurz, K. Kusaka, H. Leibrock, J. Lettry, S. Litvinov, Y. Litvinov, B. Lommel, S. Manikonda, A. Marbs, G. Moritz, C. Mühle, C. Nociforo, J. A. Nolen, H. Penttilä, W. Plass, Z. Podolyak, A. Prochazka, I. Pschorn, T. Radon, H. Ramakers, J. Saren, G. Savard, C. Scheidenberger, P. Schnizer, M. Schwickert, B.M. Sherrill, B. Sitar, A. Stafinak, R. Stieglitz, M. Svedentsov, N.A. Tahir, An. Tauschwitz, O. Tarasov, M. Tomut, P. Vobly, H. Welker, R. Wilfinger, Ch. Will, J.S. Winfield, Y. Xiang, M. Yavor, A. Yoshida, A.F. Zeller.

Layout of the Super-FRS

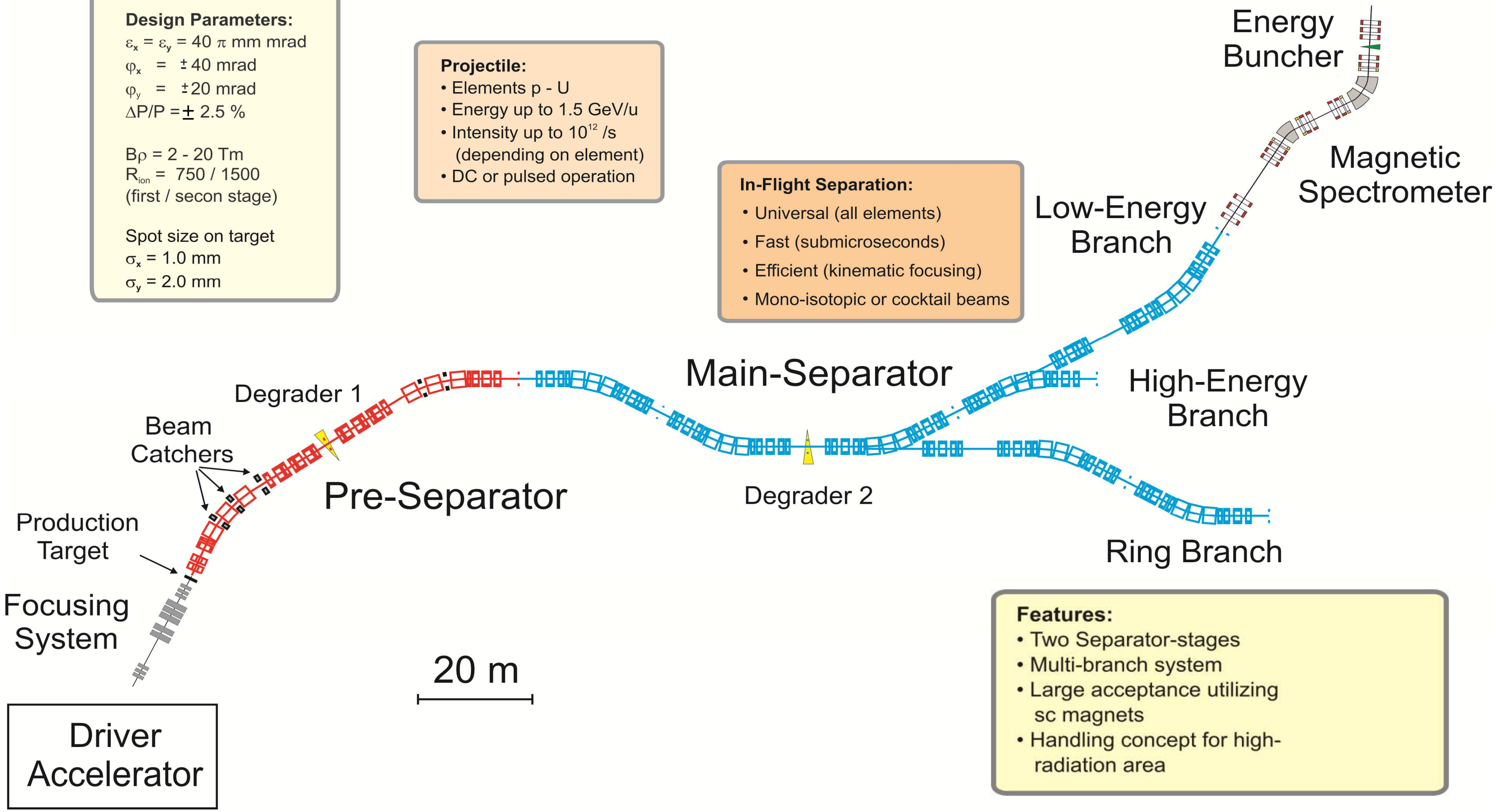
Design Parameters:
$\varepsilon_x = \varepsilon_y = 40\ \pi$ mm mrad
φ_x = ±40 mrad
φ_y = ±20 mrad
$\Delta P/P = \pm 2.5$ %

$B\rho$ = 2 - 20 Tm
R_{ion} = 750 / 1500
(first / secon stage)

Spot size on target
σ_x = 1.0 mm
σ_y = 2.0 mm

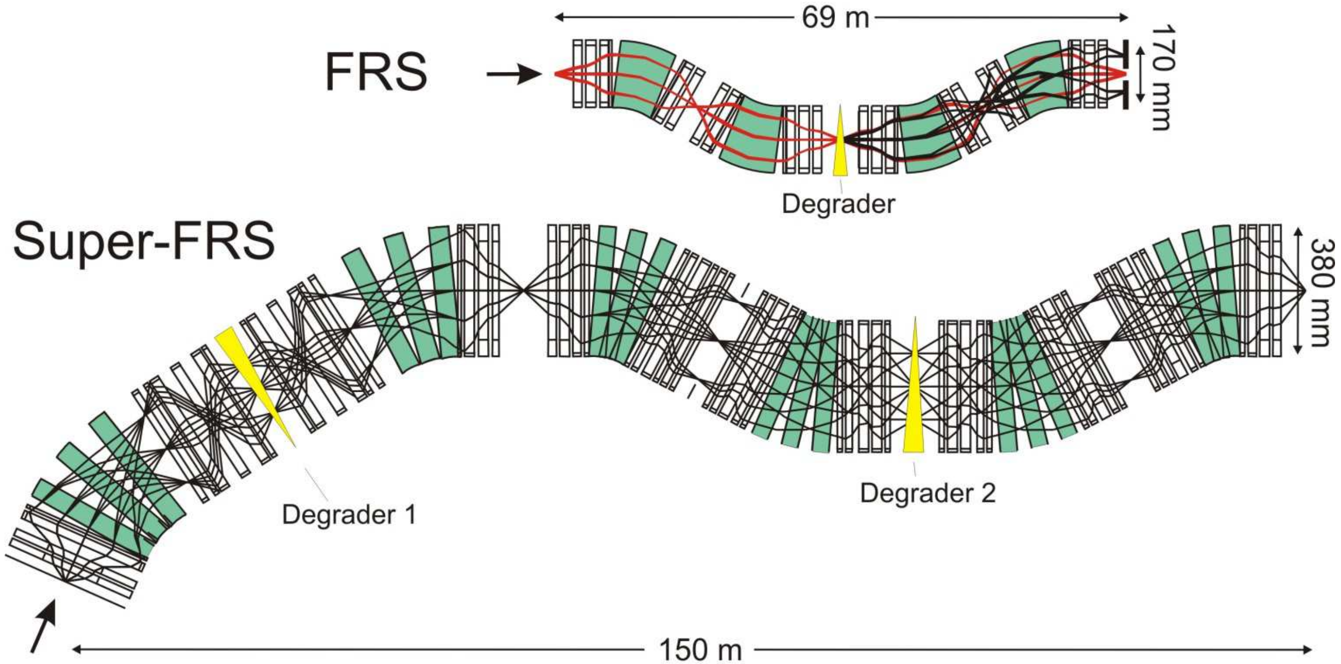
Projectile:
- Elements p - U
- Energy up to 1.5 GeV/u
- Intensity up to 10^{12} /s (depending on element)
- DC or pulsed operation

In-Flight Separation:
- Universal (all elements)
- Fast (submicroseconds)
- Efficient (kinematic focusing)
- Mono-isotopic or cocktail beams



Features:
- Two Separator-stages
- Multi-branch system
- Large acceptance utilizing sc magnets
- Handling concept for high-radiation area

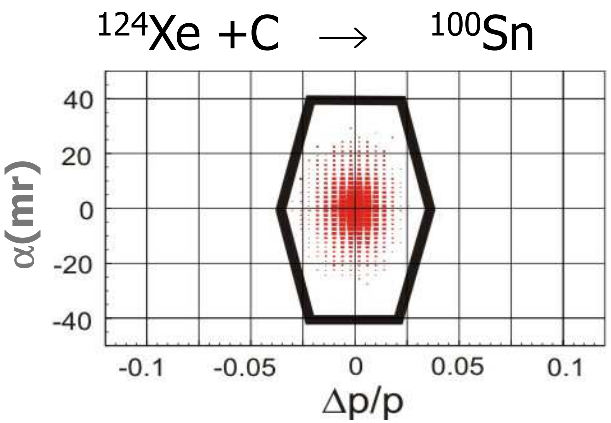
Parameters of the Super-FRS

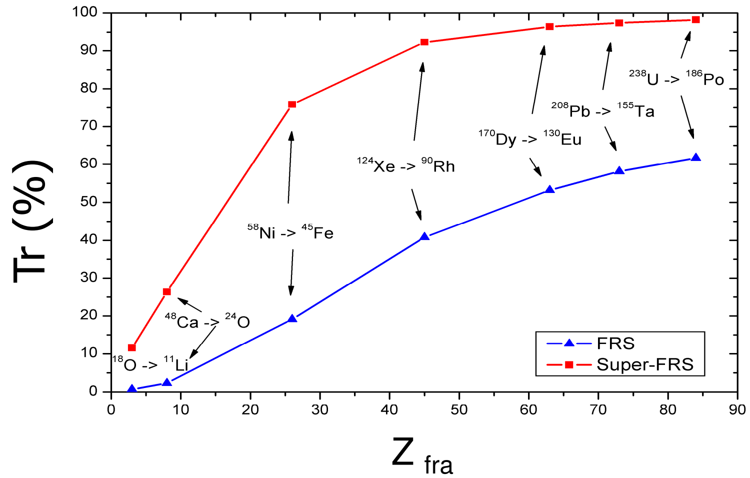


	$B\rho_{max}$	$\Delta p/p$	$\Delta\theta/\theta$, $\Delta\phi/\phi$	Resolving Power
Super-FRS	20 Tm	±2.5 %	±40, ±20 mr	1500 (40πmm mr)
FRS	18 Tm	±1%	±7.5, ±7.5 mr	1500 (20πmm mr)

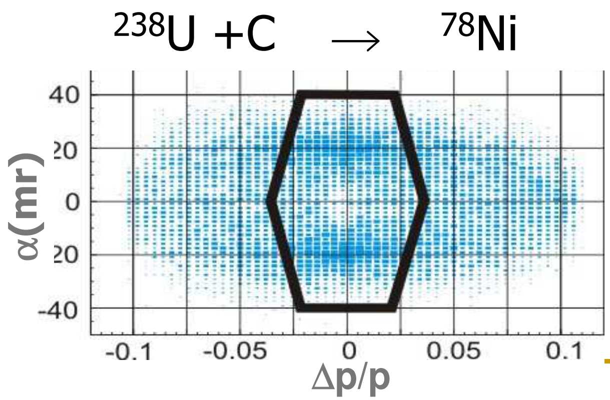
Comparison FRS – Super-FRS
Transmission gain

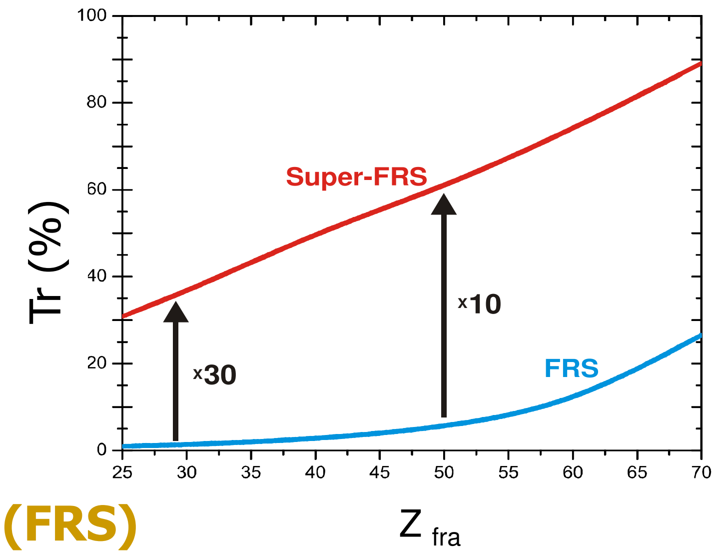
- Fragmentation





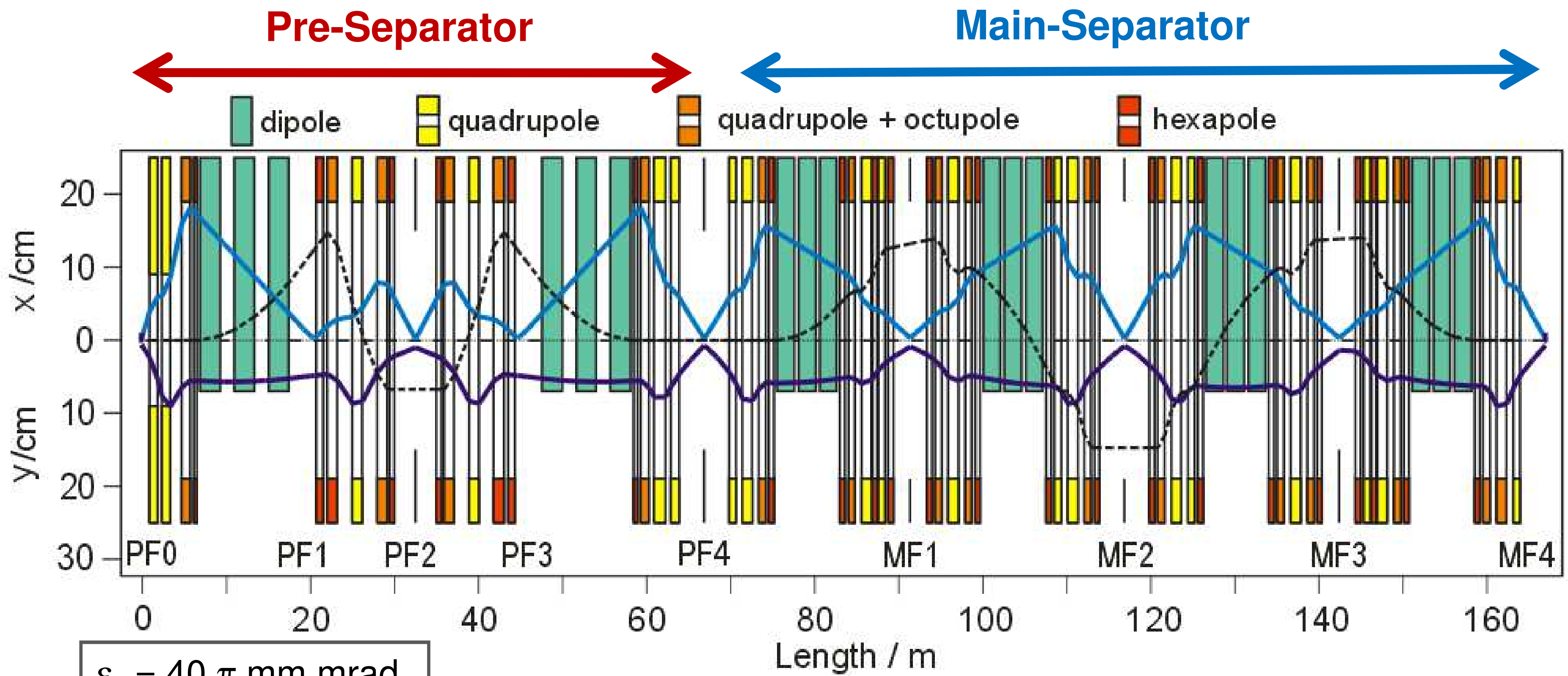
- Fission





Apertures (Super-FRS) ≈ 2 x Apertures (FRS)

Ion optics design (HEB)



ε_x = 40 π mm mrad
φ_x = ±40 mrad

ε_y = 40 π mm mrad
φ_y = ±20 mrad

$\Delta p/p$ = ±2.5 %

Main magnet requirements:

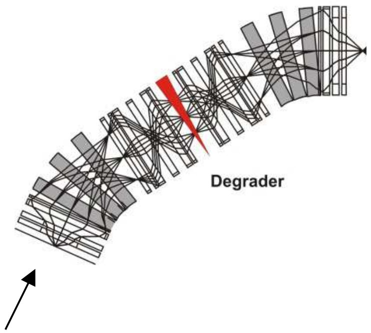
Dipole (unit): r = 12.5 m, f = 9,75°, G = ±85 mm, B = 1.6 T

Quadrupole: L = 0.8/1.2m, **G = ±190 mm, g_{Max} = 10 T/m**

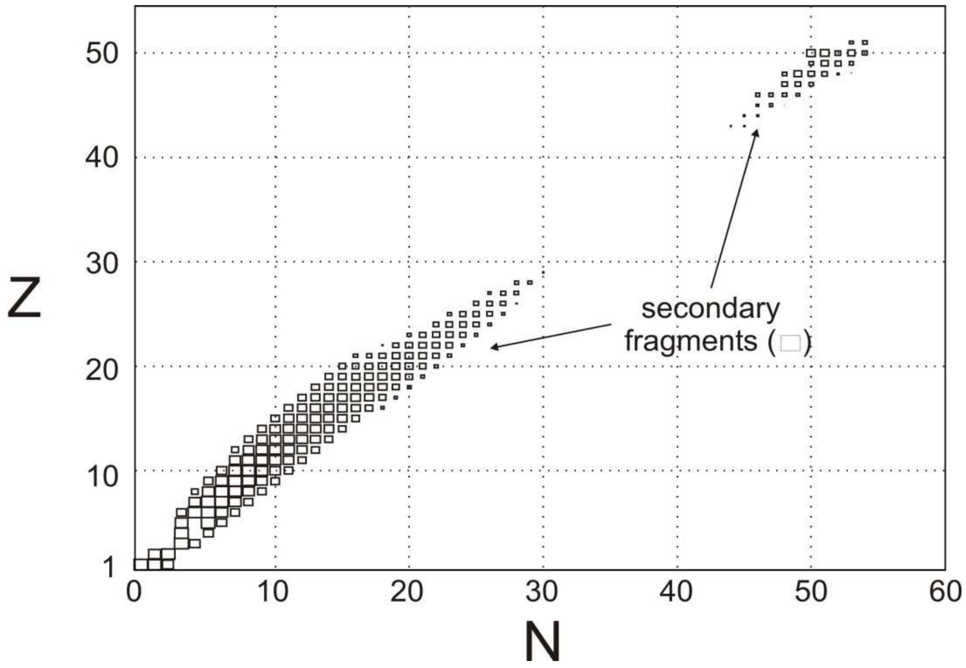
+ Sextupole Magnets and Octupole correction coil

2-stage separation
e.g. ^{100}Sn

1-stage separator



Fragmentation of ^{124}Xe @ 1 GeV/u

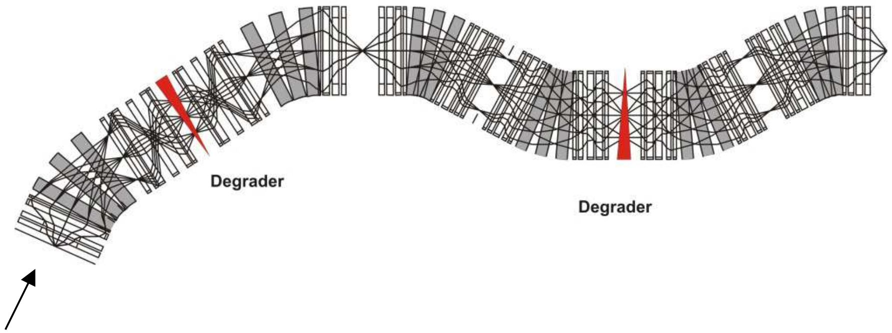


- Strong reduction of contaminants
- Optimization of fragment rate
- Main separator used for secondary reaction studies

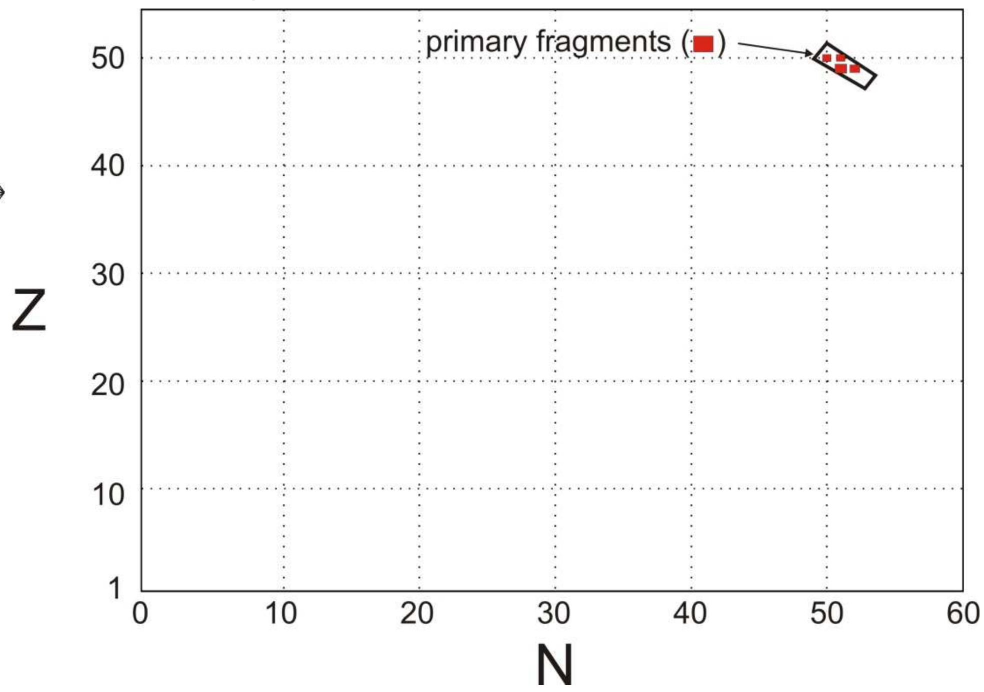
2-stage separation

e.g. ^{100}Sn

1-stage separator 2-stage separator



Fragmentation of ^{124}Xe @ 1 GeV/u



- Strong reduction of contaminants
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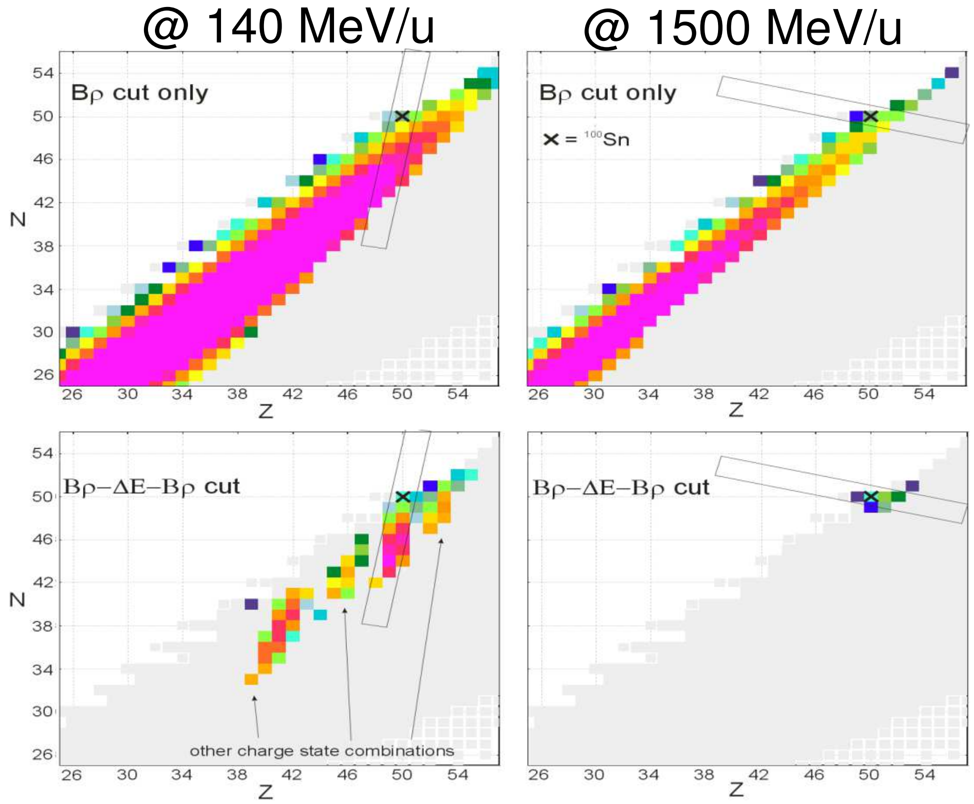
Advantages of high-energy RIBs



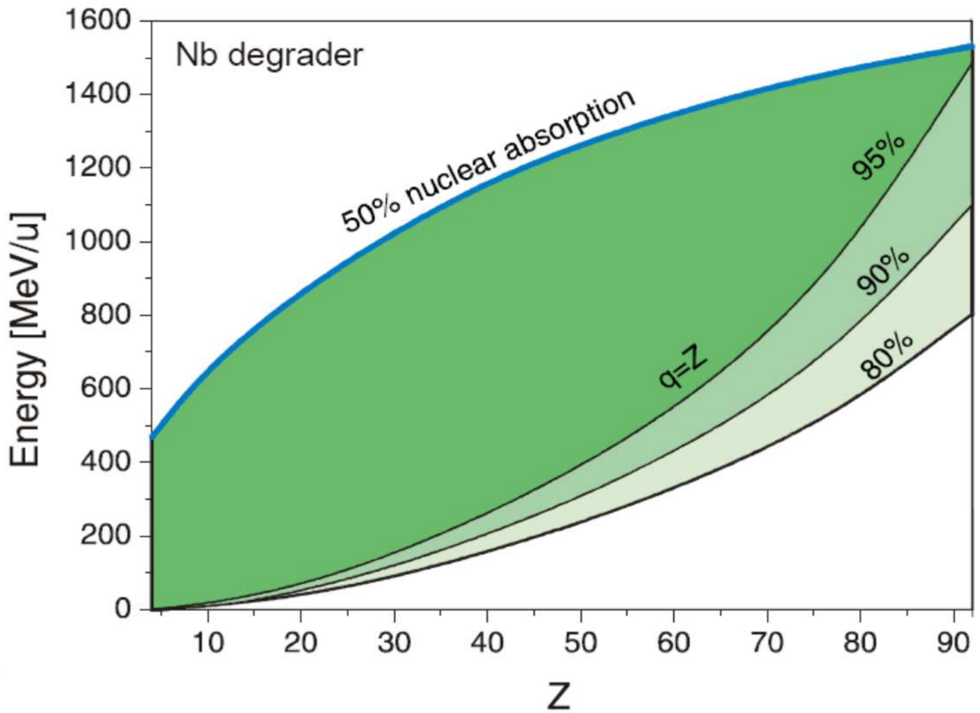
- Thick production target – very exotic RIBs
- Pure incoming RIBs incident on secondary target
- Fully stripped reaction products after secondary target
- Strong kinematical forward focusing of reaction products
- High luminosity – thick reaction target

Particle interaction with matter

The LS correction gives perfect agreement with the experimental data for bare projectiles. At lower energies the heavy ions are no longer completely stripped. Therefore, *z* is replaced by the effective charge

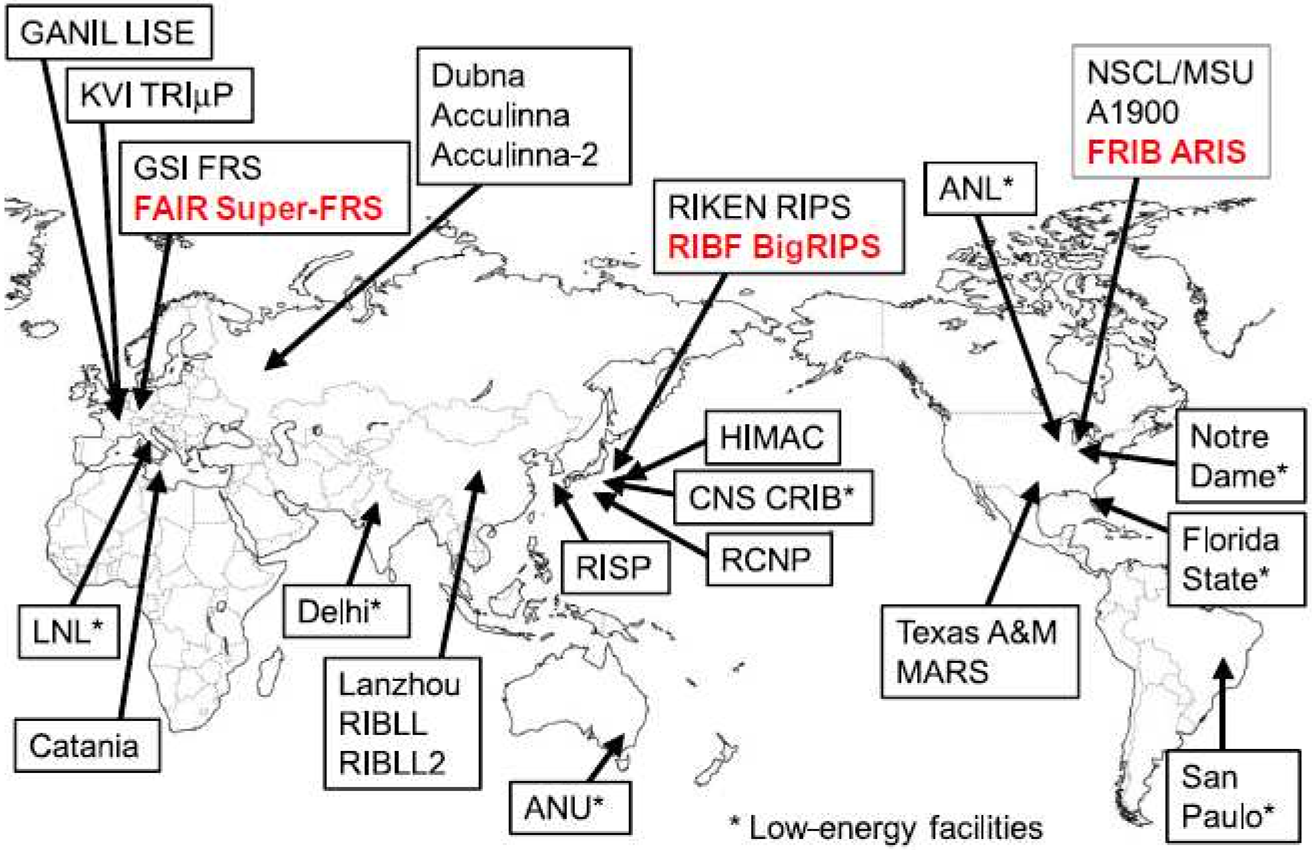
$$q_{eff} = z\left[1 - exp\left(\frac{-0.95v}{z^{\frac{2}{3}}v_0}\right)\right]$$

where v_0 is the Bohr velocity.



C. Nociforo, GSI AccSeminar 2017

World map of in-flight RIB facilities



T. Kubo, *NIM B* 376 (2016) 102

Comparison

Table 1
Main parameters of the Super-FRS, ARIS, and BigRIPS separators.

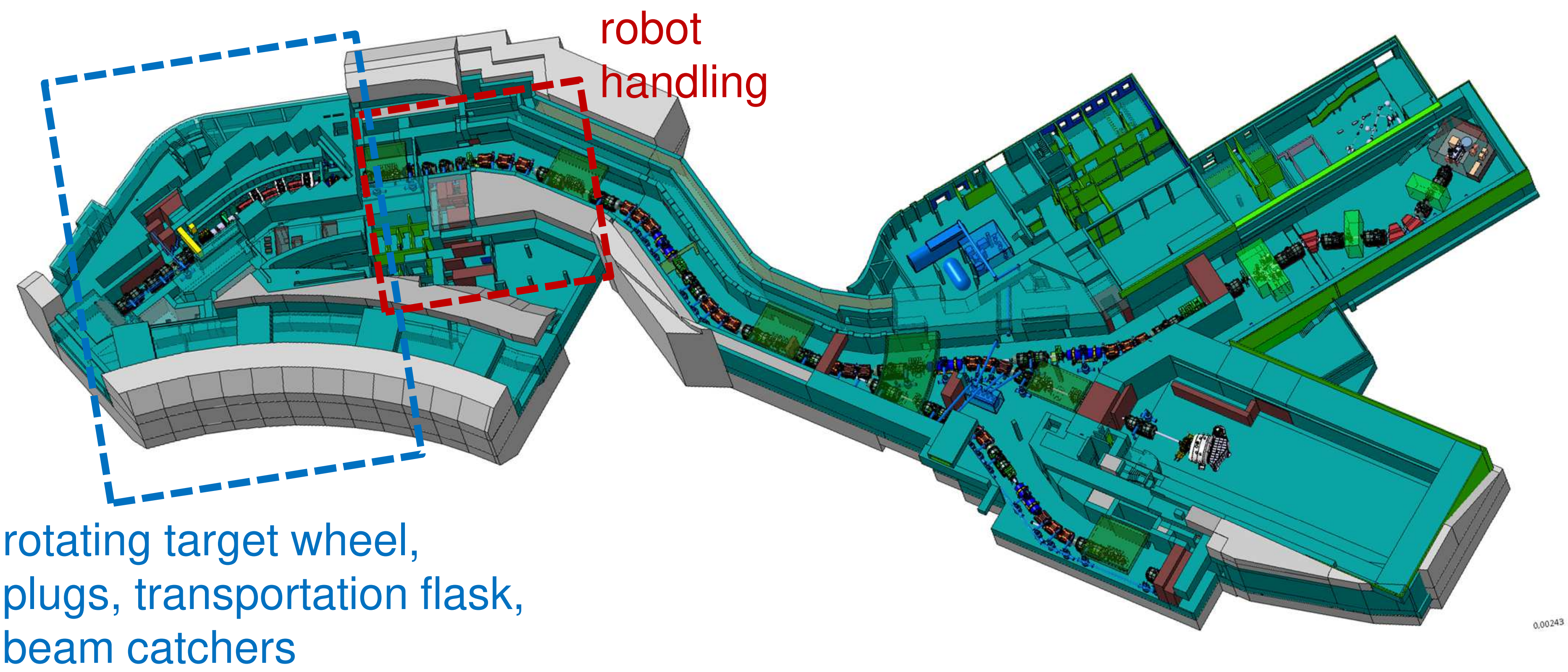
Separator	Super-FRS	ARIS	BigRIPS
Facility	FAIR at GSI	FRIB at MSU	RIBF at RIKEN
Primary beams	Up to U	Up to U	Up to U
Beam energy	1.5 GeV/u	⩾200 MeV/u[f]	345 MeV/u
Beam intensity[a]	3.5×10^{11} ^{238}U/s	5×10^{13} ^{238}U/s (8 pμA)[g]	6.24×10^{12}/s (1 pμA)
Beam power[a]	20 kW for ^{238}U	400 kW for all	82 kW for ^{238}U
Mode	CW (also pulse)	CW	CW
Acceptances $\Delta\theta$	±40 mrad	±40 mrad	±40 mrad
$\Delta\phi$	±20 mrad	±40 mrad	±50 mrad
$\Delta p/p$	±2.5%	±5%	±3%
Max. rigidity (Bρ)	20 Tm	8 Tm	9.5 Tm
Number of stages	2+	2(3)	2+
Resolution $P/\Delta P$[b]	1766/3532[d]	1720/3000–4000	1270/3420
Length	176.2 m[e]	86.5 m	78.2 m
Energy degraders at 1st/2nd stages[c]	Achromatic/achromatic	Momentum compression/achromatic	Achromatic/achromatic
References	[6,7]	[9]	[10–12]

[a] Goal values.
[b] First-order momentum resolution for an object size of 1 mm at the first and second stages, respectively.
[c] Type of degraders.
[d] 750/1500 ~~for an object size of $\sigma(x) = 1$ mm.~~
[e] High-energy branch.
[f] 310 MeV/u for low-Z ions.
[g] 1 pμA (particle micro Amps) corresponds to 6.24×10^{12} particles/s.

T. Kubo, *NIM B* 376 (2016) 102

High intensity and radiation level

The Super-FRS operation needs totally new concepts.



High intensity and radiation level

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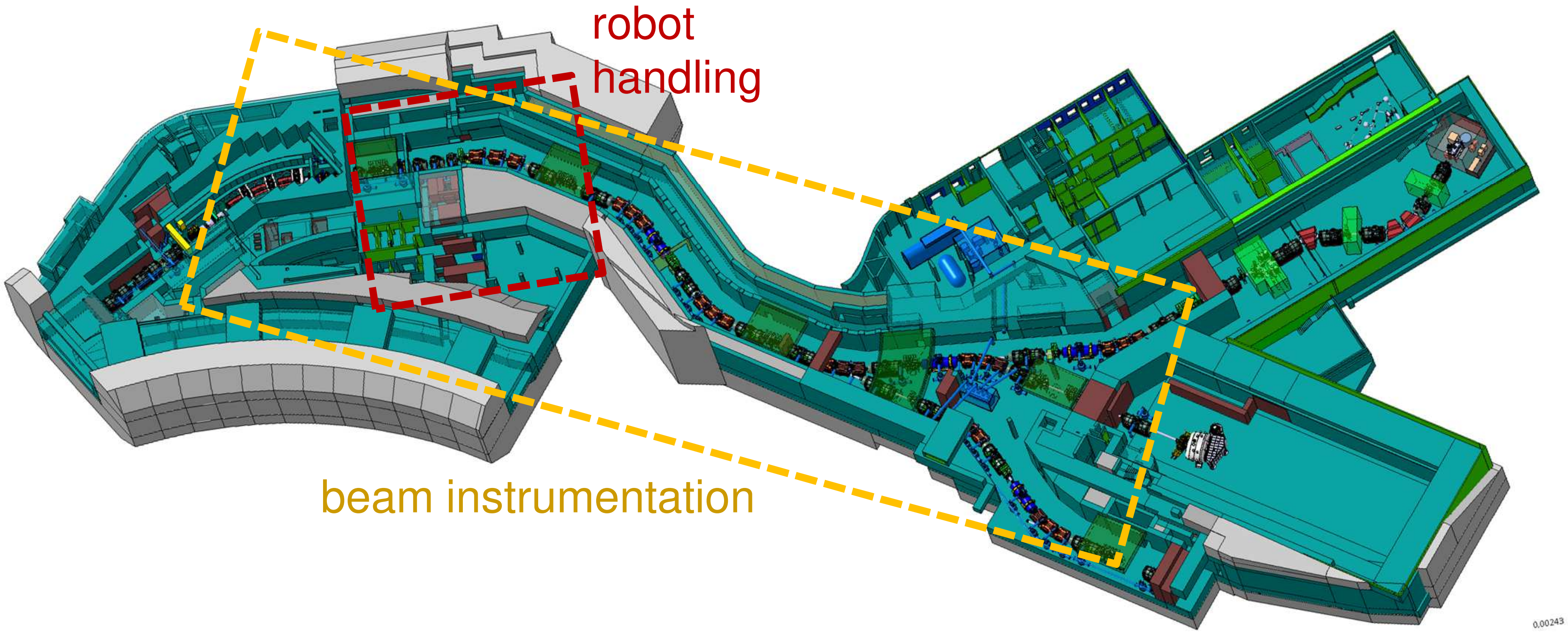
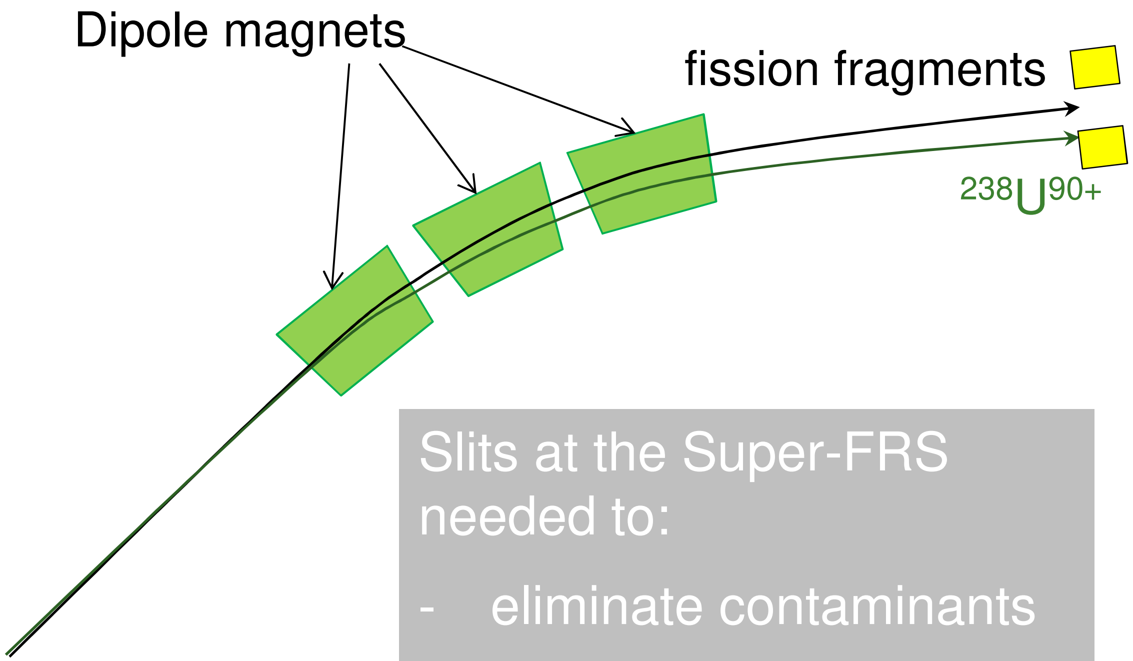


The Super-FRS takes well established FRS detecting system concept to its operation limit.

Slit system requirements



Slits at the Super-FRS needed to:

- eliminate contaminants
- define phase space
- protect devices (e.g. during magnet setting)

- High stopping power
- Vacuum compatible
- Heat resistant

DENSIMET®
97% tungsten,
3% iron and nickel
Density: 18.5 g/cm^3

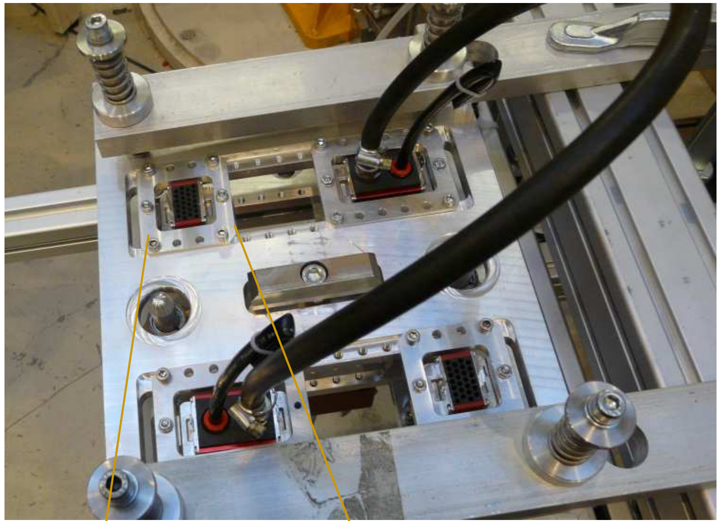
- Precision
- Endurance
- Reproducibility

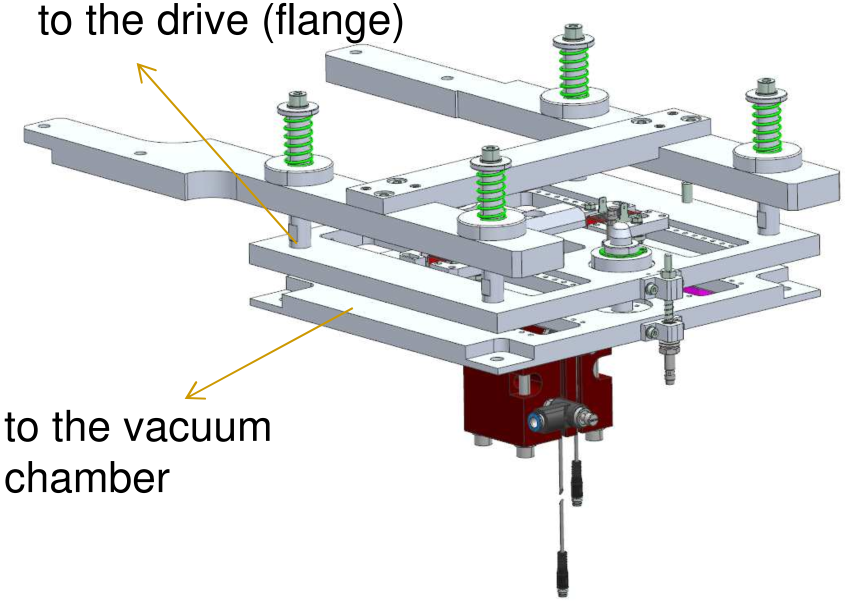
X-Slit pre-series

Pre-series FAT passed

Specification	Test result
Integral leakage rate	6×10^{-10} mbar.l/s
Minimum gap	50 µm uniformly over the surface
Movement precision	0.1 mm
Stop switch activation	0.1 mm
Endurance	6600 open-close cycles
Heat resistance	500 W beam power absorption

Interface compatible with robot handling





to the drive (flange)

to the vacuum chamber

Modular self-aligned connectors

- plates for gas, water and electrical connections (interface)
- at all insertions of the Pre-Separator vacuum chambers
- scalable and modular
- designed and tested by Super-FRS group (T. Blatz, C. Karagiannis, C. Schlör)

In-flight PID

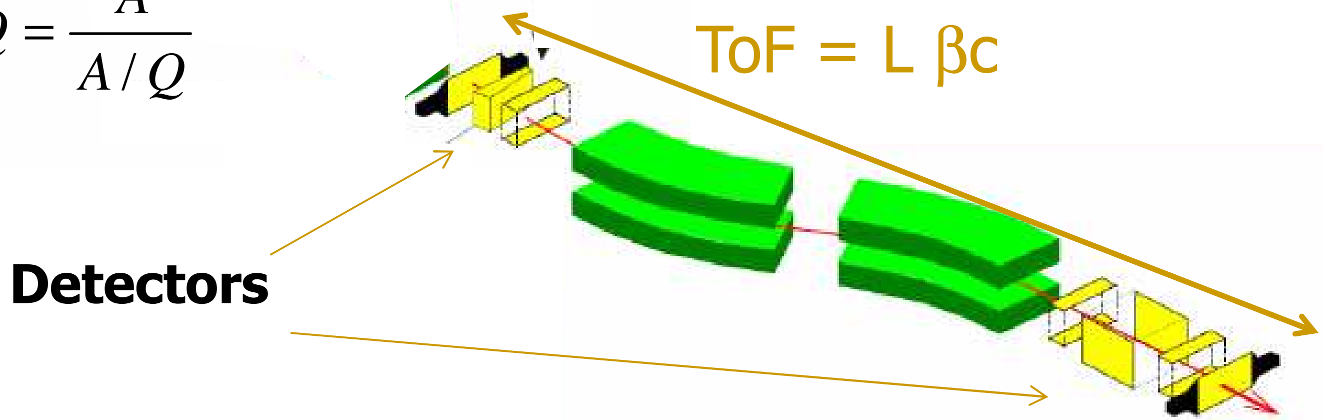
$$Z \leftarrow -dE/dx = f(Z, \beta)$$ atomic number

$$A/Q = \frac{B\rho}{\gamma\beta m_u}$$ $Z \neq Q$ charge state

Bρ – ToF – ΔE method

$$A = \frac{T_{KE}}{(\gamma - 1) m_u}$$ mass number, T_{KE} kinetic energy

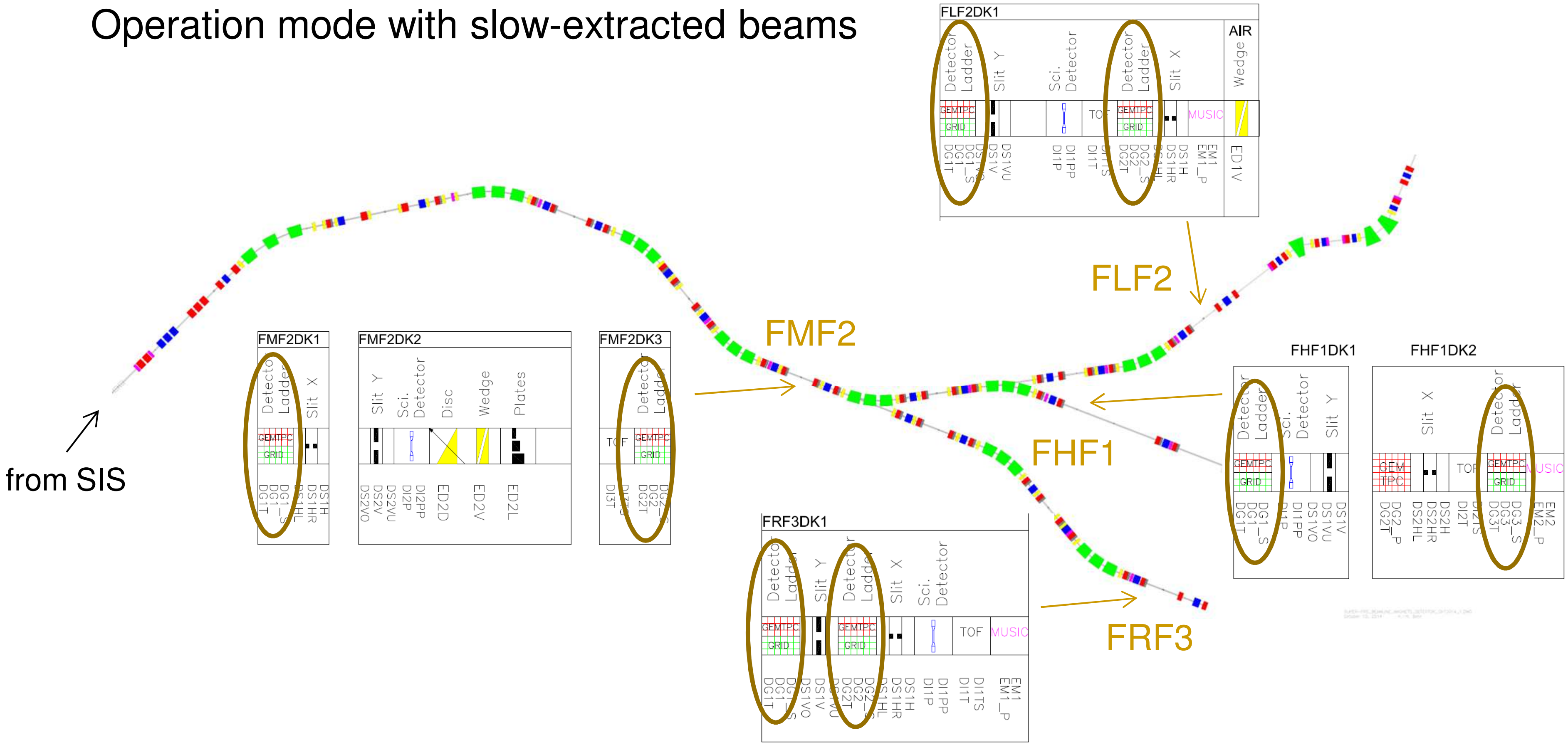
$$Q = \frac{A}{A/Q}$$



- Clean full isotope identification on event-by-event basis (PID)

Tracking detector

Operation mode with slow-extracted beams



Intensity 10¹¹/s <10¹⁰/s <10⁹/s <10⁷/s <10⁵/s

C. Nociforo, GSI AccSeminar 2017

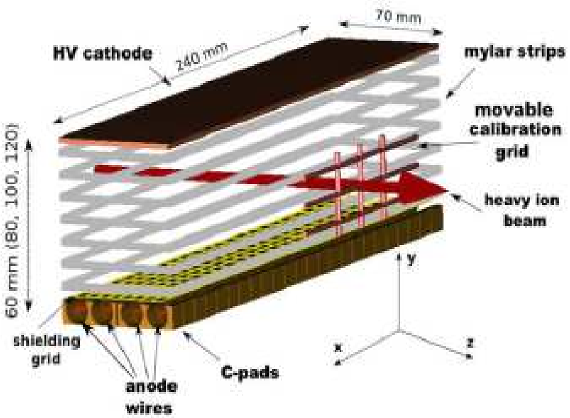
Tracking requirements
Bρ reconstruction

- momentum resolution (1st order)

D ~ 6 cm/% , Δx < 1mm → Δp/p ~ 10^{-4}

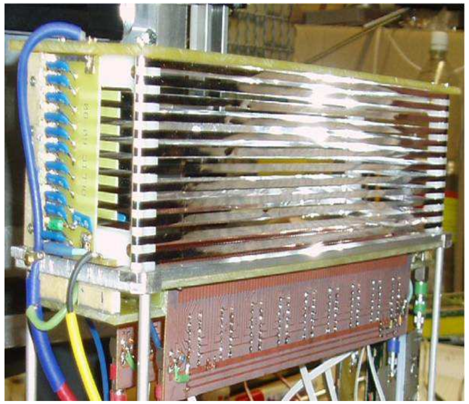
$$B\rho = B\rho_0 \left(1 - \frac{x_{FHF1} - M\, x_{FMF2}}{D}\right) + \Delta(B\rho)$$

where Δ(Bρ) includes corrections for additional momentum spread due to additional matter and reaction



Time Projection Chamber (TPC)

FRS TPC: R. Janik et al., *NIM A* 640 (2011) 54

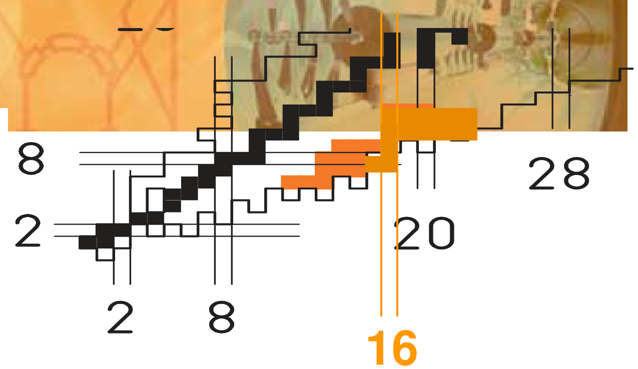


^{24}O study

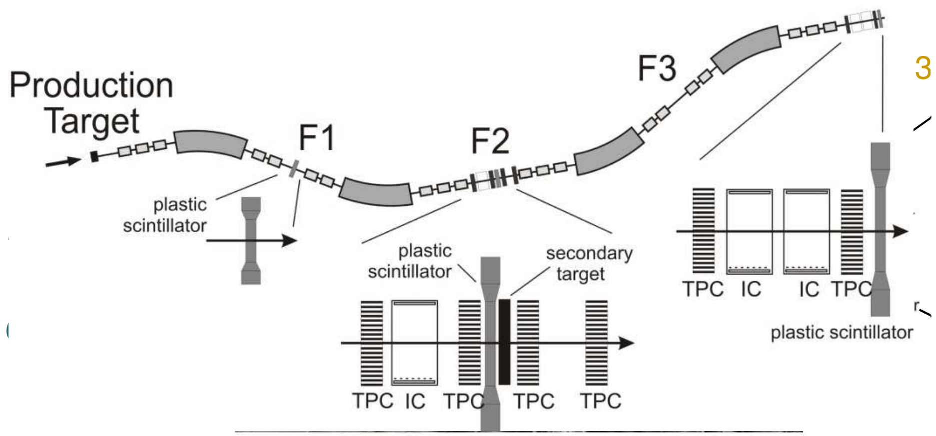
PRL 102, 152501 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

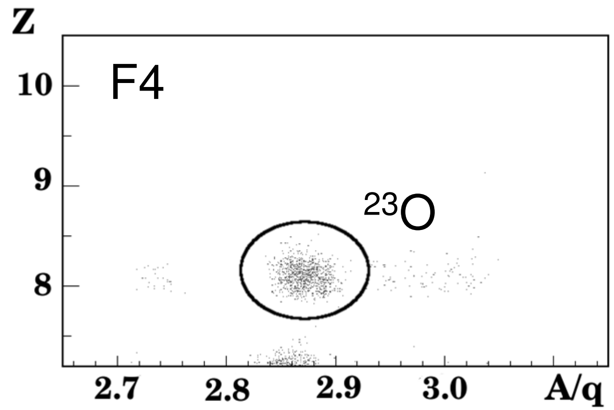
One-Neutron Removal Measurement Reveals ^{24}O as a New Doubly Magic Nucleus

R. Kanungo,[1,*] C. Nociforo,[2] A. Prochazka,[2,3] T. Aumann,[2] D. Boutin,[3] D. Cortina-Gil,[4] B. Davids,[5] M. Diakaki,[6] F. Farinon,[2,3] H. Geissel,[2] R. Gernhäuser,[7] J. Gerl,[2] R. Janik,[8] B. Jonson,[9] B. Kindler,[2] R. Knöbel,[2,3] R. Krücken,[7] M. Lantz,[9] H. Lenske,[3] Y. Litvinov,[2] B. Lommel,[2] K. Mahata,[2] P. Maierbeck,[7] A. Musumarra,[10,11] T. Nilsson,[9] T. Otsuka,[12] C. Perro,[1] C. Scheidenberger,[2] B. Sitar,[8] P. Strmen,[8] B. Sun,[2] I. Szarka,[8] I. Tanihata,[13] Y. Utsuno,[14] H. Weick,[2] and M. Winkler[2]

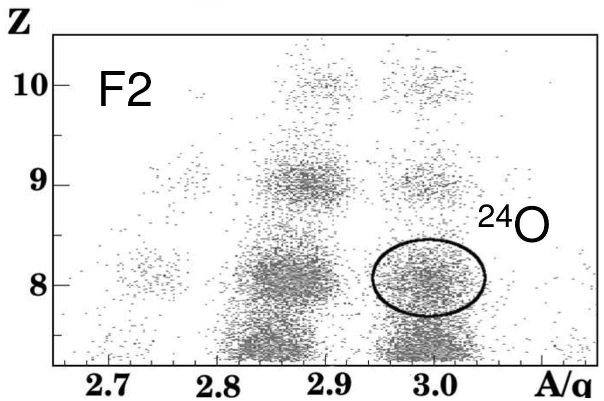


FRagment Separator (FRS)





node "



High-resolution momentum (~$1.5 \cdot 10^{-4}$) in 1*n* removal channel

$$P_f^{lab} = (1 + \frac{x_4 - M x_2}{D_{24}}) z_f B\rho$$

Tracking requirements

- momentum resolution (1st order)

  D ~ 6 cm/% , $\Delta x < 1$mm → $\Delta p/p \sim 10^{-4}$

$$B\rho = B\rho_0 \left(1 - \frac{x_{FHF1} - M\, x_{FMF2}}{D}\right) + \Delta(B\rho)$$

  where $\Delta(B\rho)$ includes corrections for additional momentum spread due to additional matter and reaction

- large acceptance, e.g. Super-FRS $\Delta p/p = \pm\ 2.5\%$ (higher order corrections)

  operation in vacuum, thin & low Z windows to minimize angular spread

- higher rate (~2 kHz/mm^2), large area (~10^3 mm^2), large dynamic range

Tracking requirements

- momentum resolution (1st order)

D ~ 6 cm/% , Δx < 1mm → Δp/p ~ 10^{-4}

$$B\rho = B\rho_0 \left(1 - \frac{x_{FHF1} - M\, x_{FMF2}}{D}\right) + \Delta(B\rho)$$

where Δ(Bρ) includes corrections for additional momentum spread due to additional matter and reaction

Time Projection Chamber (TPC)

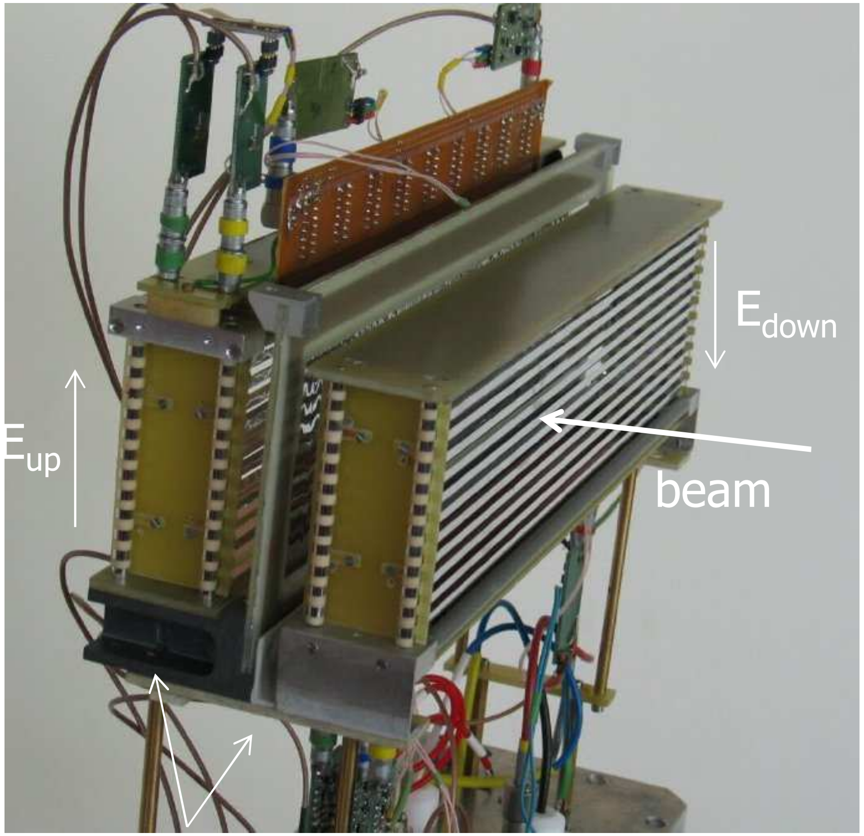
FRS TPC: R. Janik et al., *NIM A* 640 (2011) 54

´Twin´ Gas Electron Multiplication (GEM)-TPC

F. Garcia et al., GSI Scientific Report (2014)

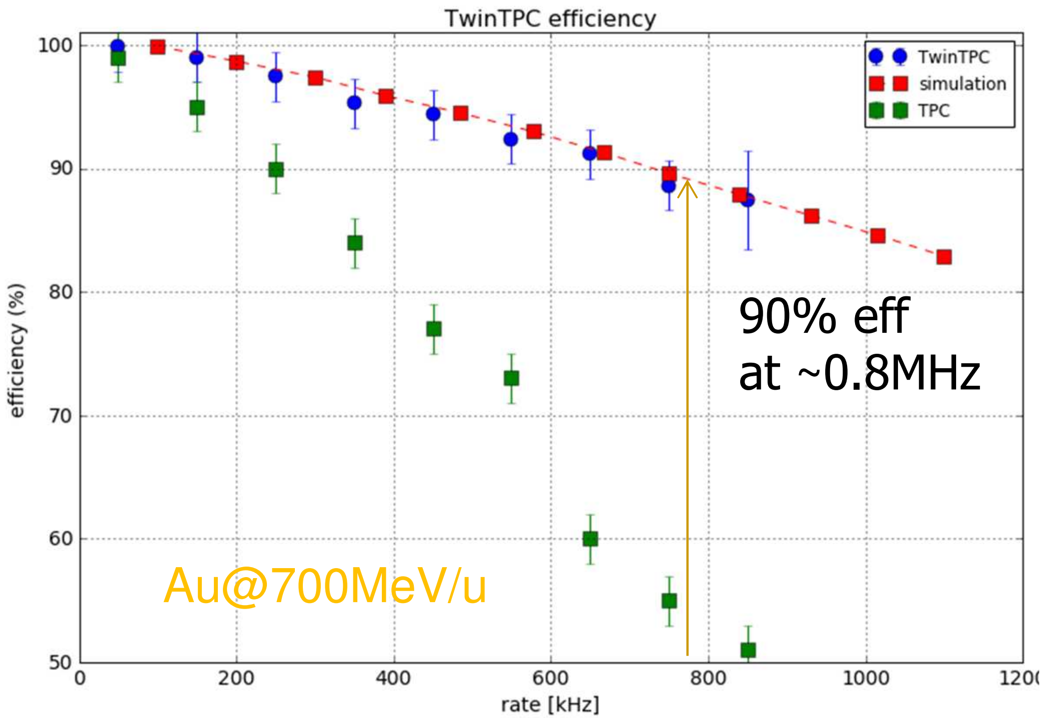
FRS Twin TPC

Built at CUBratislava



200x70x30 mm^3

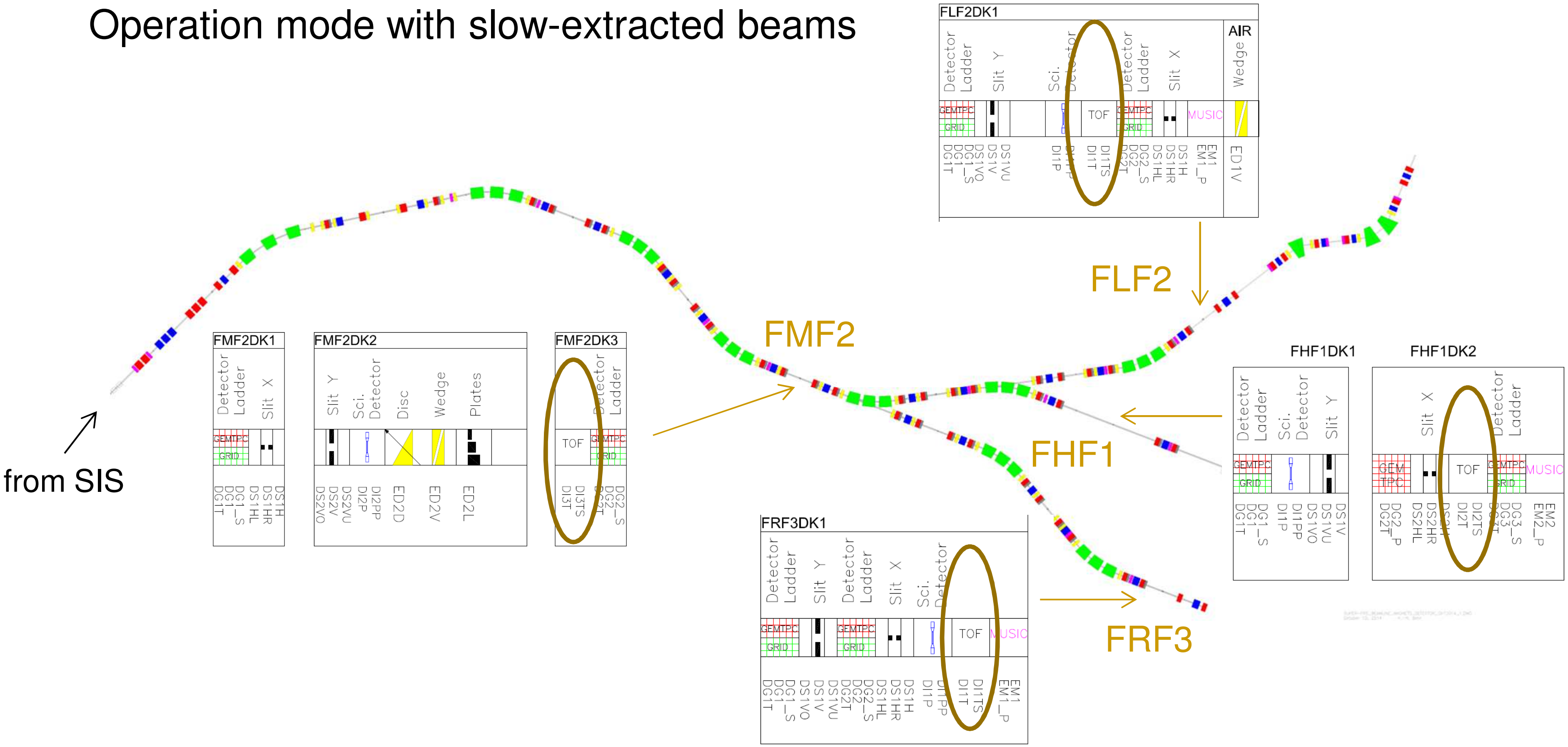
- Delay line, multi-hit TDC (V1290) readout



A. Prochazka et al., GSI Scientific Report (2014)

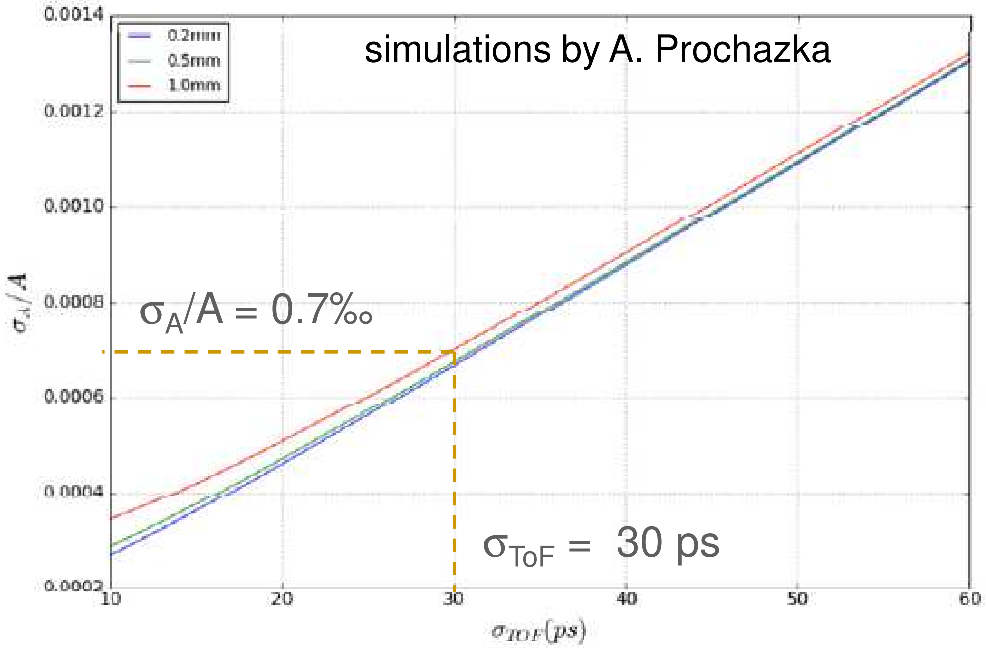
ToF detector

Operation mode with slow-extracted beams



Intensity 10^{11}/s $<10^{10}$/s $<10^{9}$/s $<10^{7}$/s $<10^{5}$/s

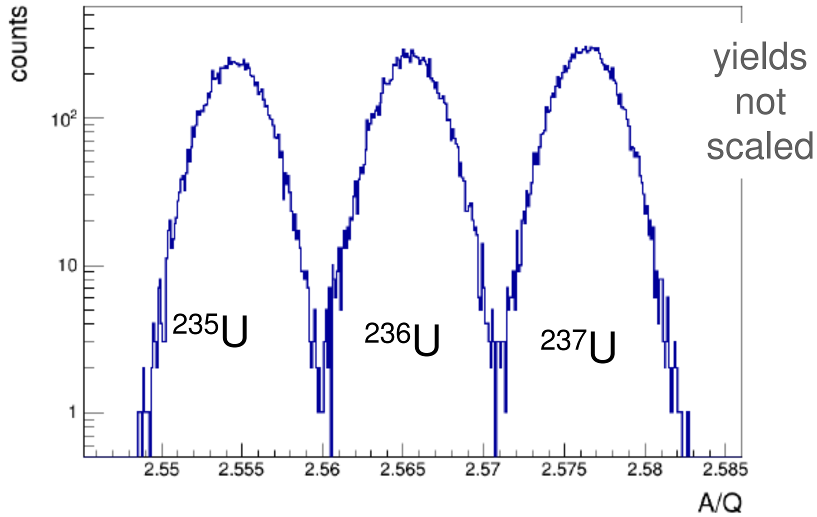
ToF requirements
A/q reconstruction



$$\frac{\Delta A}{A} \approx \frac{\Delta B\rho}{B\rho} + \gamma^2 \frac{\Delta ToF}{ToF}$$

β = 0.8, L = 55 m

Monte Carlo simulations (MOCADI)



σ_x = 0.5 mm, σ_t = 20 ps

ToF requirements

- homogeneous and large-area material
  (at the Super-FRS in total 70000 mm^2)

- start/stop fast (triggering) signals

  → **Plastic scintillators** (0.5 – 3 mm) readout by PMTs

  best FRS ToF measurements (FWHM= 17 ps)

  A. Ebran et al., *NIM A* 728 (2013) 40

- higher rate (>10^6 Hz)

  → segmented plastics scintillator, optical scintillating fibers

  cheap but material get quickly damaged,
  not simple to be replaced in vacuum

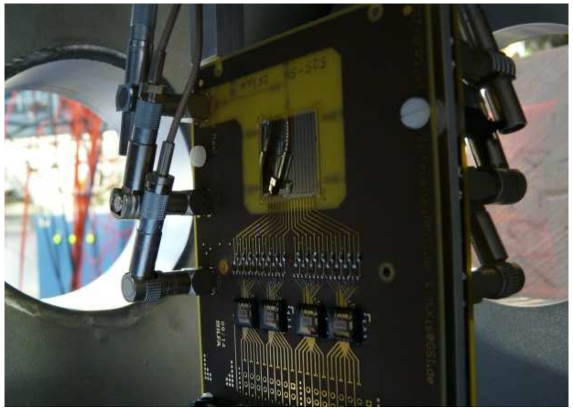
ToF detector requirements

- radiation-hard material

  → ToF silicon/diamond strip detectors arranged in planar geometry

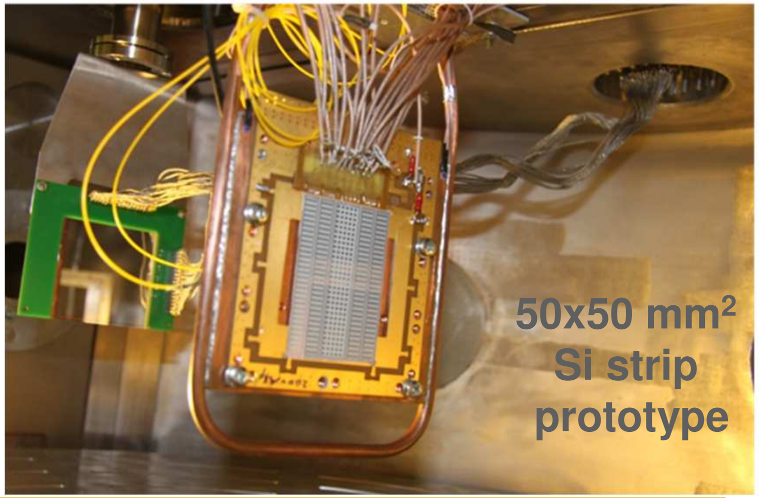
  - total channels (strips): 1400 chs
  - timing resolution (full): $\sigma_t < 35$ ps, $\sigma_t = 20$ ps for U
  - rate capability: 0.5 kHz/mm^2 , < 15 kHz/strip
  - activity: < 1 kGy/year

2 x **pcCVD -DD 20x20x0.3 mm^3**



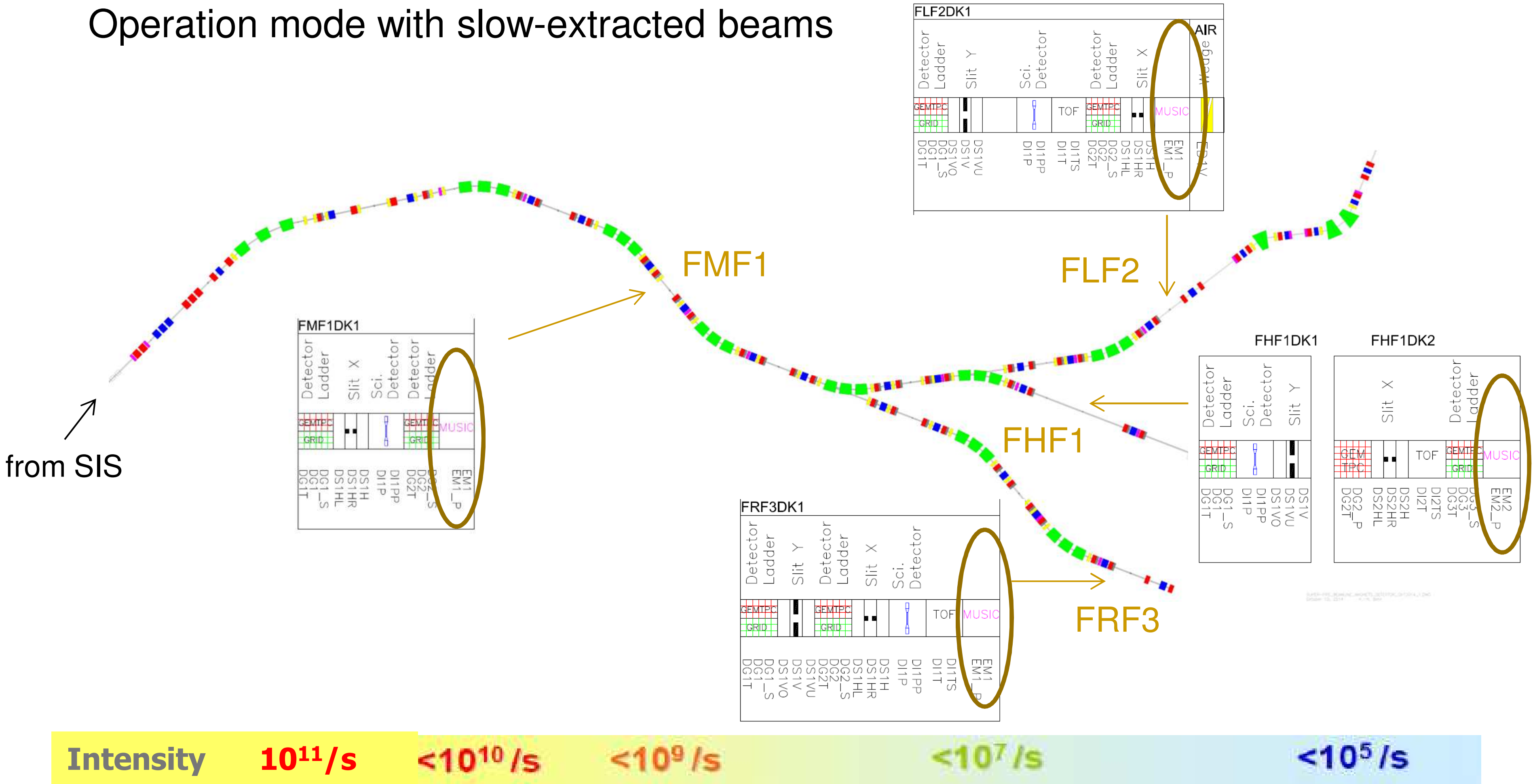
F. Schirru et al., *J. Phys. D: Appl. Phys.* 49 (2016) 215105

V. Eremin et al., *NIM A* 796 (2015) 158



ΔE detector

Operation mode with slow-extracted beams



ΔE requirements

A suitable ΔE detector needs to have

- good energy resolution ($\Delta Z < 0.4$)
- high counting rate capability (pile-up correction)
- robustness against beam bombardment

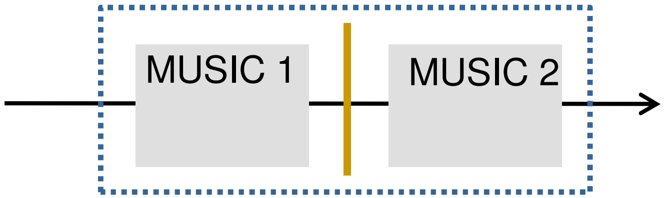
Gas ionization chambers are

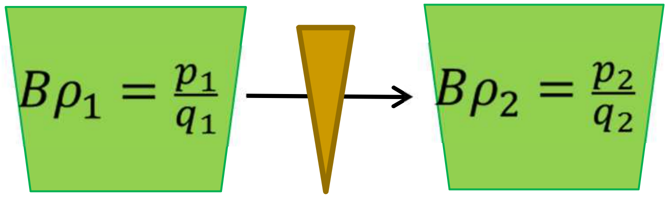
- extremely stable if equipped with gas flow system
- can provide energy resolution as good as that of semiconductor detectors
- charge-state selective
- large-scale detector easy to fabricate

Multiple Sampling Ionization Chamber (MUSIC)

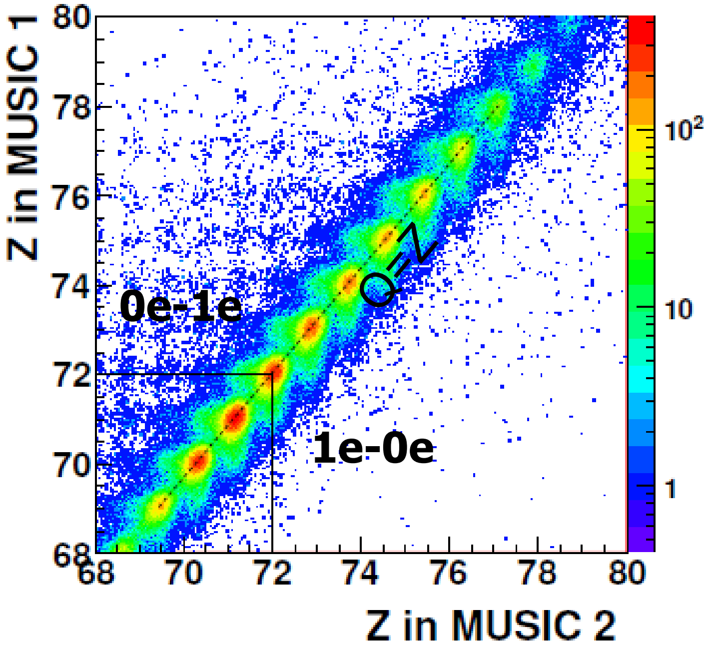
FRS MUSIC: A. Stolz, et al., GSI Scientific Report (1998)

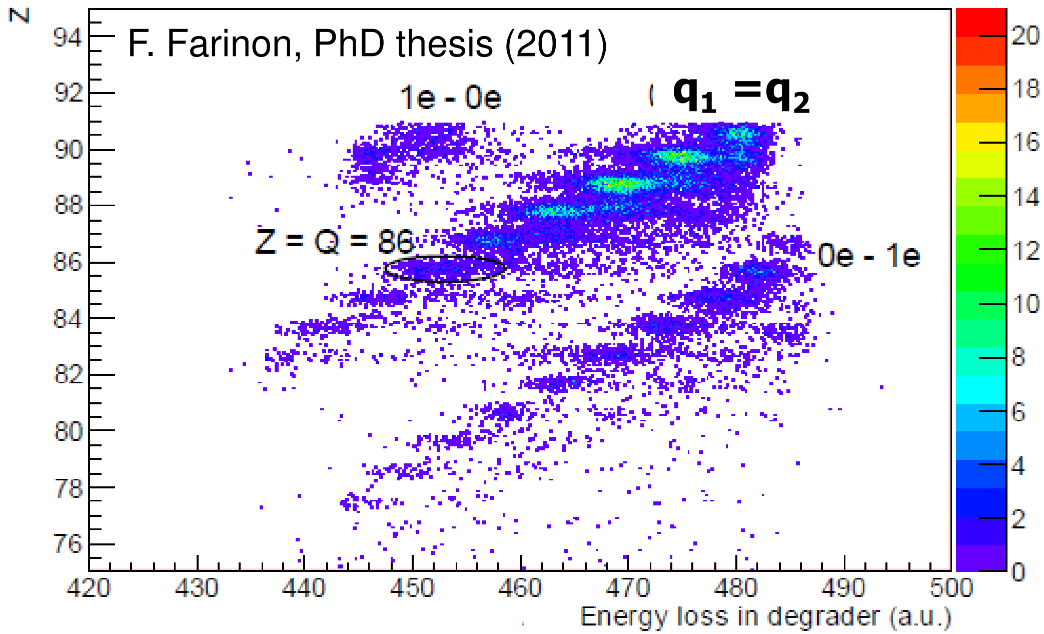
Charge state selection





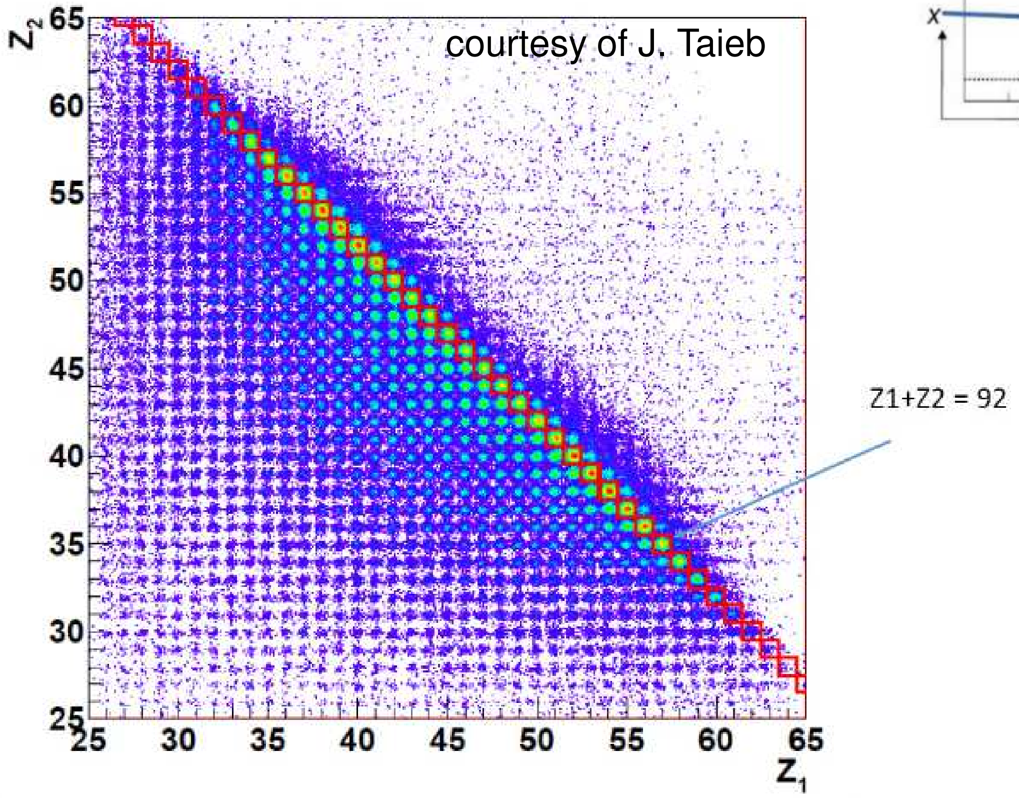
Stripper between two MUSIC stages

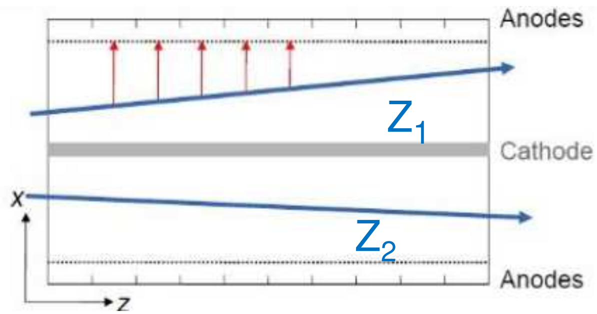




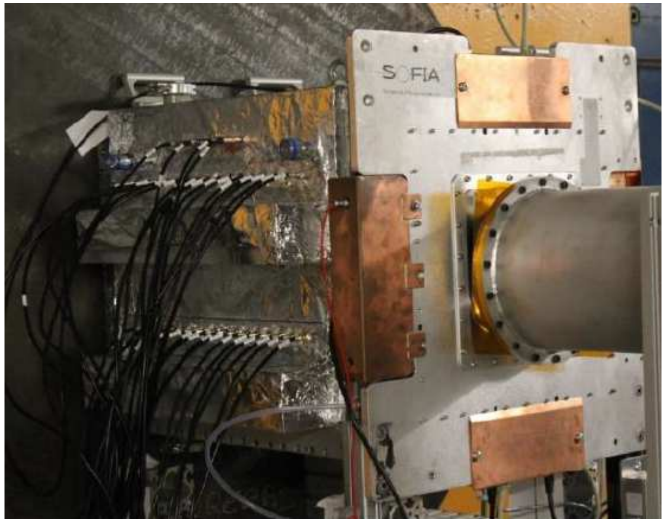
MUSIC for fission fragment detection

Fragment charge correlations
(SOFIA exp. 2014)





SOFIA
Twin MUSIC
designed by
CEA - GSI



Summary

- Overview of in-flight separation method of RIBs

- The Super-FRS at FAIR and its PID detecting system

  challenges: high intensity & high precision

- New discovery have been closely linked to new technical developments of accelerators and detectors

The Super-FRS is well suited to nuclear experiments at the forefront of science.