End-to-end rare isotope beam and particle ID simulations for FRIB

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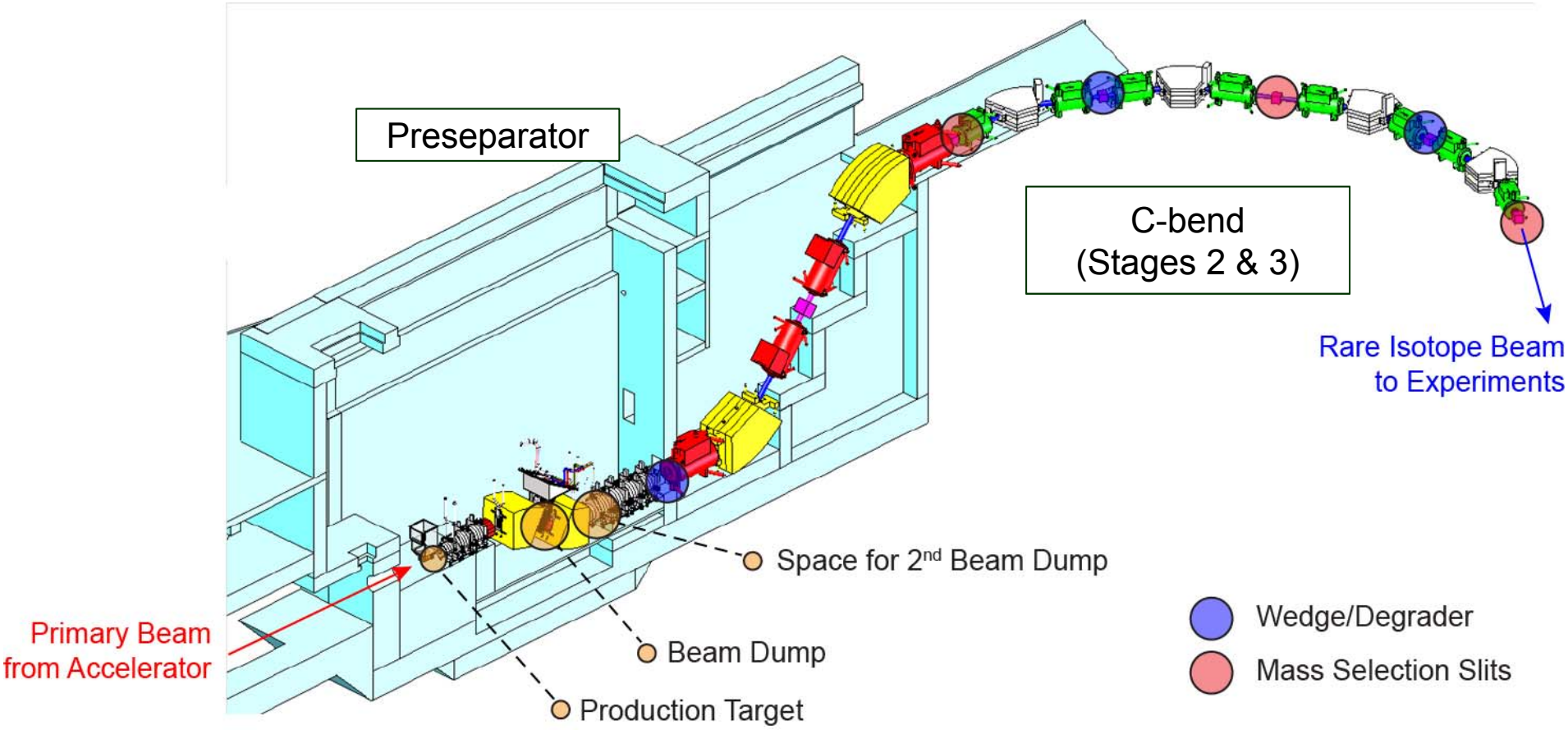
Introduction

- End-to-end simulations to predict transmission and purity
  - Field analysis techniques are being applied to determine the best parameters to use in the beam physics code
  - Description of optics and some examples of difficult cases
- Particle identification (PID) techniques are needed for positive identification of desired product(s)
- Simulations tools adopted for FRIB
  - LISE/COSY model: **ARIS and HEBT** (high energy beam transport lines)
  - Monte Carlo methods to simulate PID
    - » Deduce detector requirements needed for difficult cases

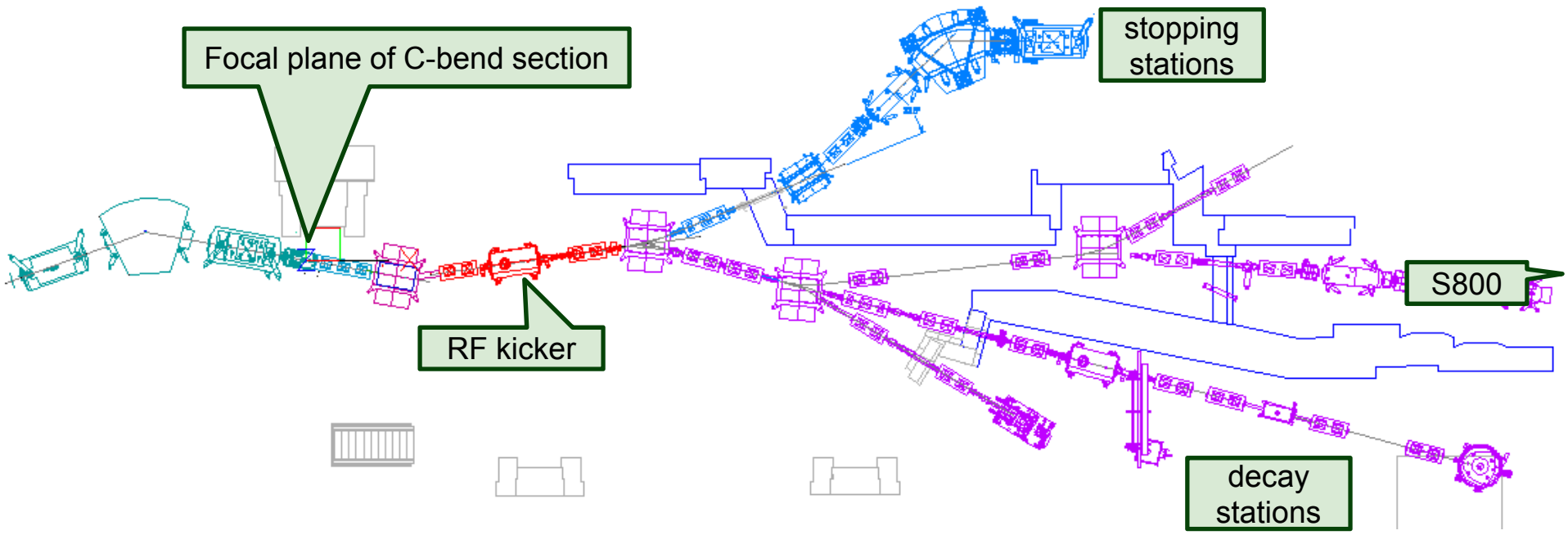
Simulations start at target of ARIS separator

- Up to three stage fragment separator
  - vertical preseparator consists of new magnet designs
  - C-bend layout of existing A1900 magnets



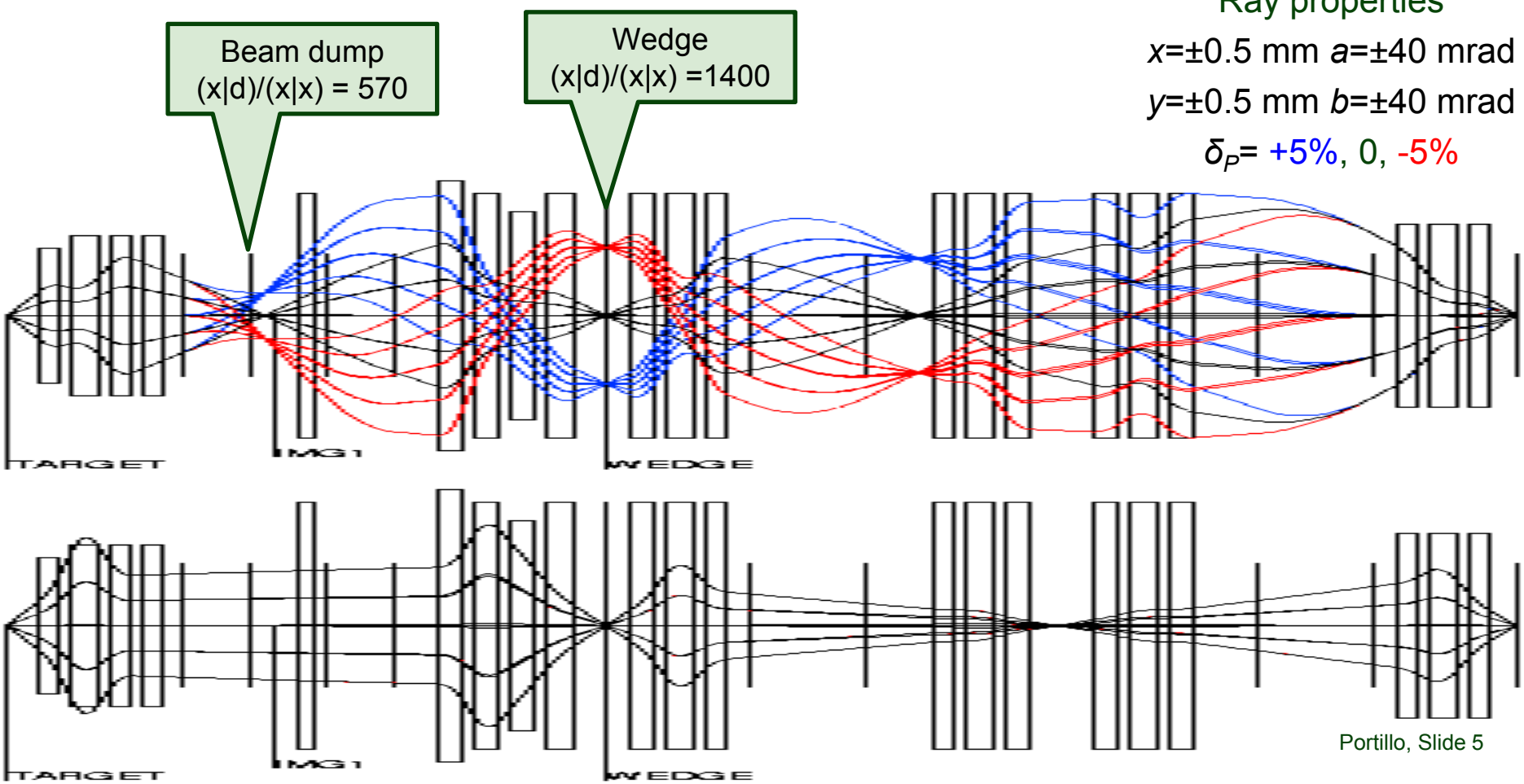
Simulations needed up through HEBT up to end stations

- Beams are distributed to various devices
  - The baseline layout uses all of the existing NSCL beam lines
    - » Examples to stopping station (N4S) and S800 object will be shown
  - Considering future additions or upgrades



Optics through preseparator section: Order 1

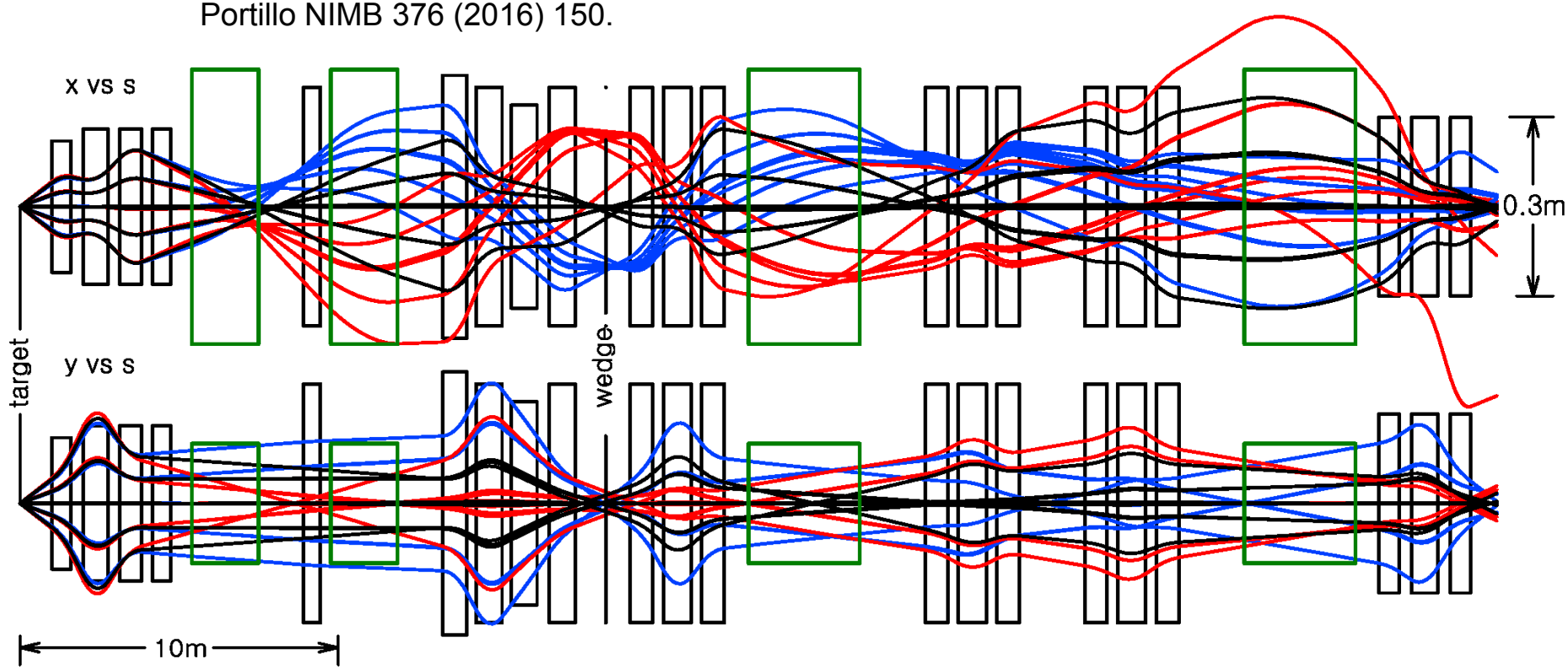
- Designed to have momentum compression in standard operational mode
  - Compression factor *k*=3.5 requires wedge d/R~0.2
  - Using special version of COSY 9.1 with ATIMA to emulate degrader effects



Preseparator higher order optics with corrections

- Simulated field parameters have been included into COSY model
  - All preseparator magnets are new designs for FRIB project
    - » Most focusing magnets have nested sextupole and octupole excitation coils
  - Field analysis used to extract magnet parameters from TOSCA field simulations
  - Parameters include up to 5th order terms

Induced *n*=6 terms from quadrupole included in simulations,
Portillo NIMB 376 (2016) 150.



Postseparator optics

- Preseparator (or C-Bend) can operate in single- or two-stage separation modes
  - Two-stage provides full acceptance from preseparator (with compression)
  - Single-stage (illustrated below) has higher resolving power at reduced acceptance

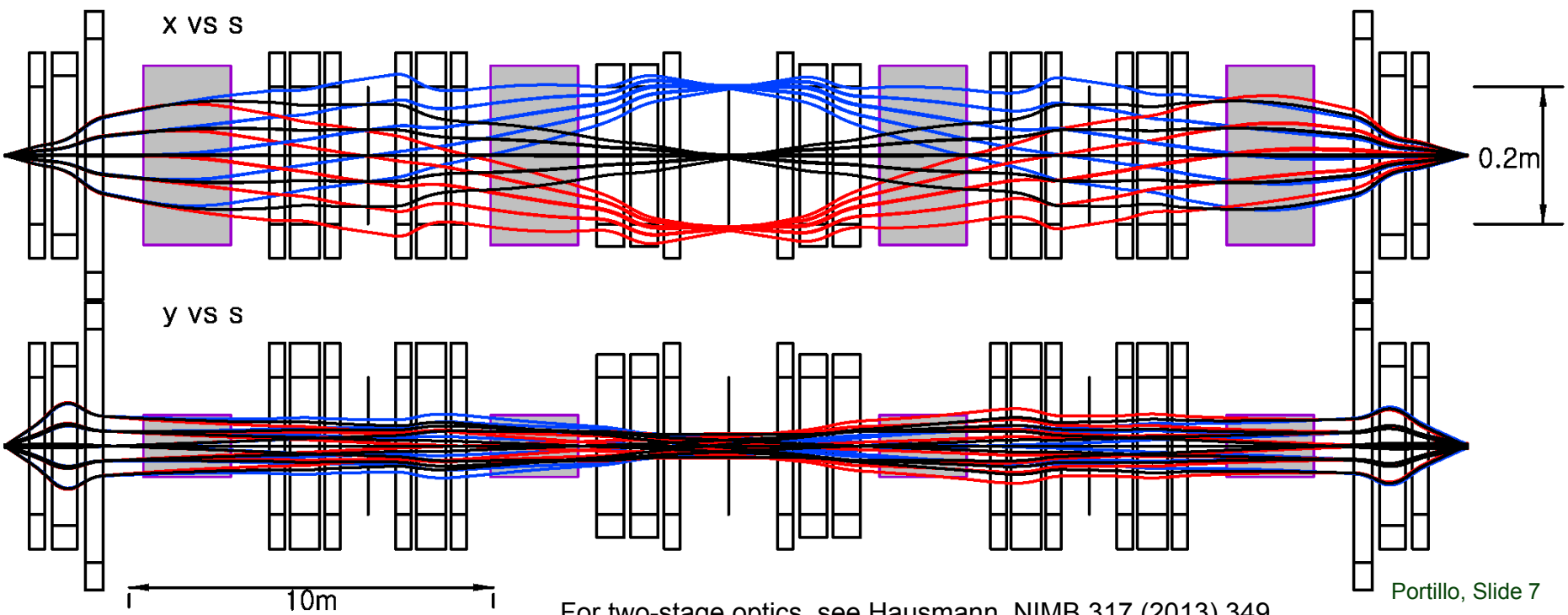
5th order COSY model of single-stage mode of operation
* For enhancing PID, provides large resolving power
  R=(x|d)/(x|x)=4100 for enhancing PID
* Low aberrations due to symmetry

Ray properties

x=±0.7 mm a=±15 mrad

y=±2.4 mm b=±35 mrad

δ_P= +1.5%, 0, -1.5%

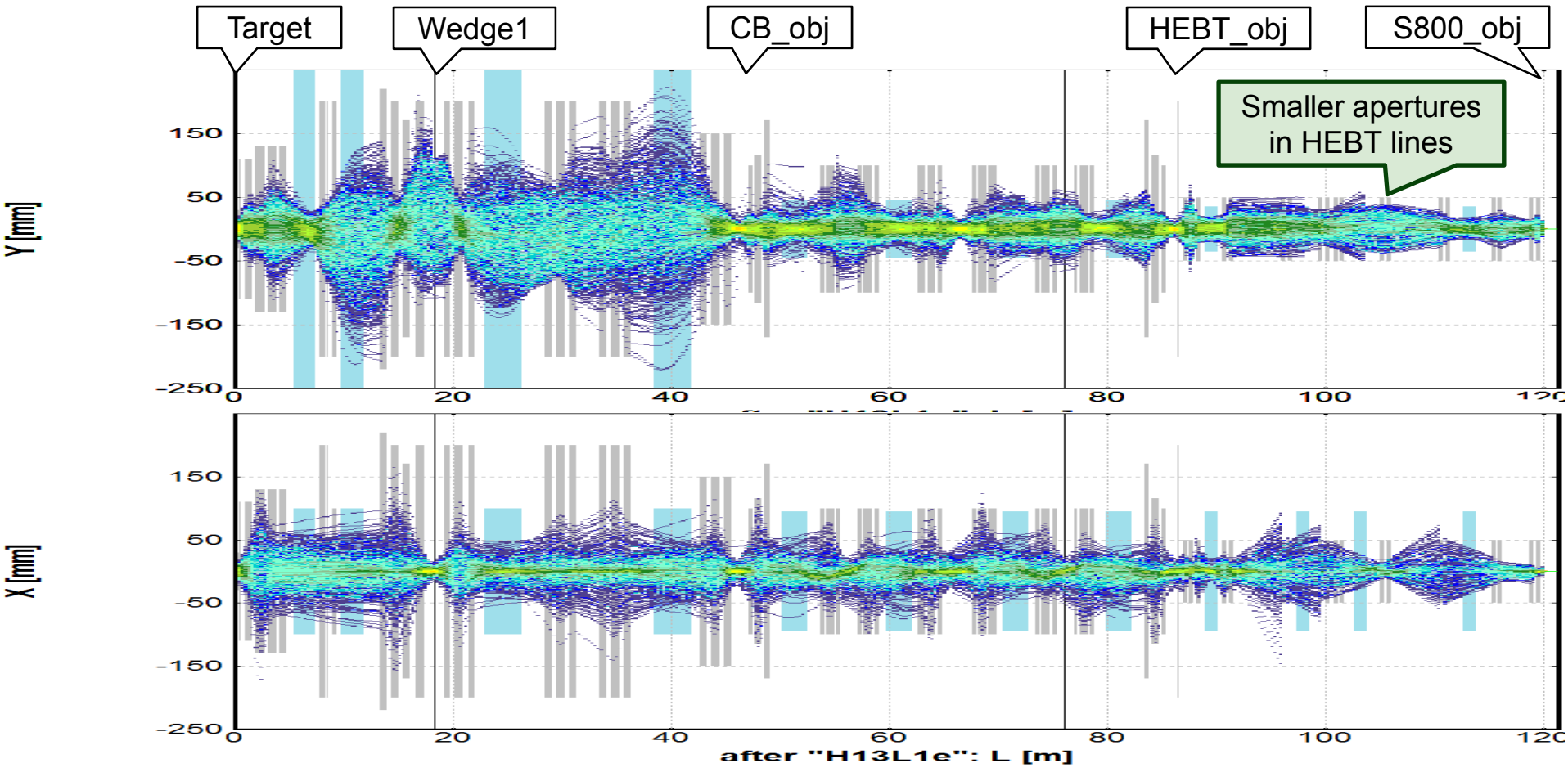


For two-stage optics, see Hausmann, NIMB 317 (2013) 349.

Example of Monte Carlo End-to-end Simulation in Higher Order:

- LISE++ Monte Carlo simulation using 5th order maps from COSY
- Using two-stage C-Bend mode for fragment with large phase space

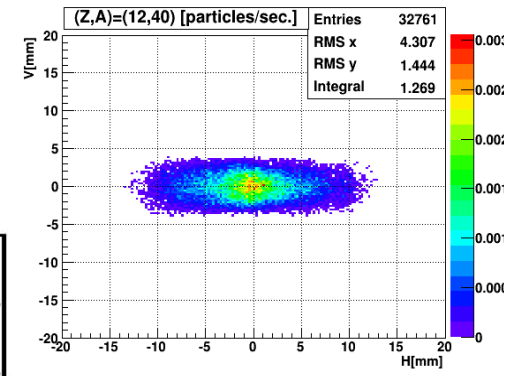
Example: 261 AMeV ^{48}Ca -> d/R=0.35 carbon target (EPAX 2.15) -> ^{40}Mg -> d/R=0.16 Al wedge

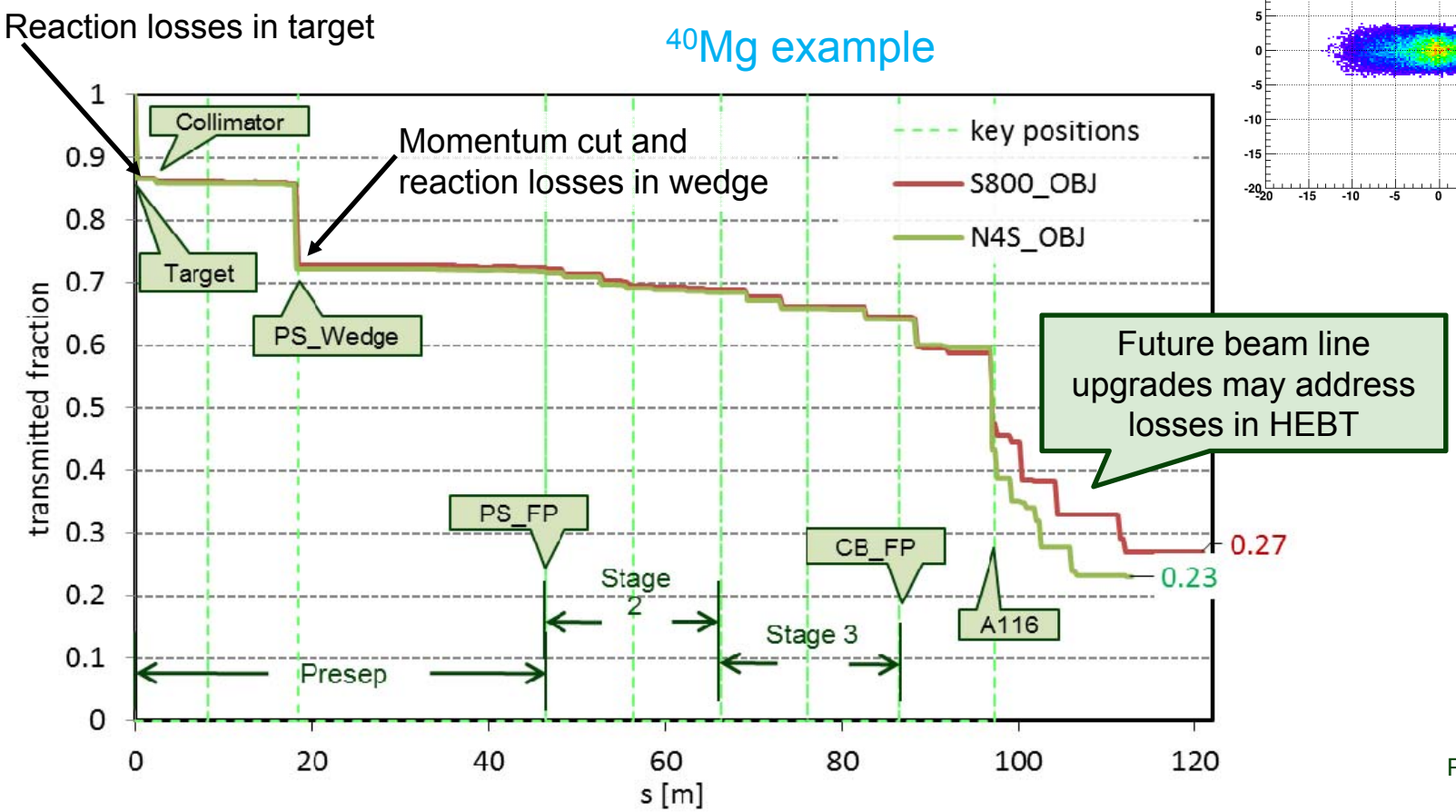


Challenging cases for FRIB: Large phase space products

- End-to-end simulations show good transmission through fragment separator but some transmission losses in existing beam lines
  - Example below is a transmission plot of transport to
    - » object of S800 (spectrograph experiments)
    - » object of N4-South (stopping station)

beam spot at s800obj

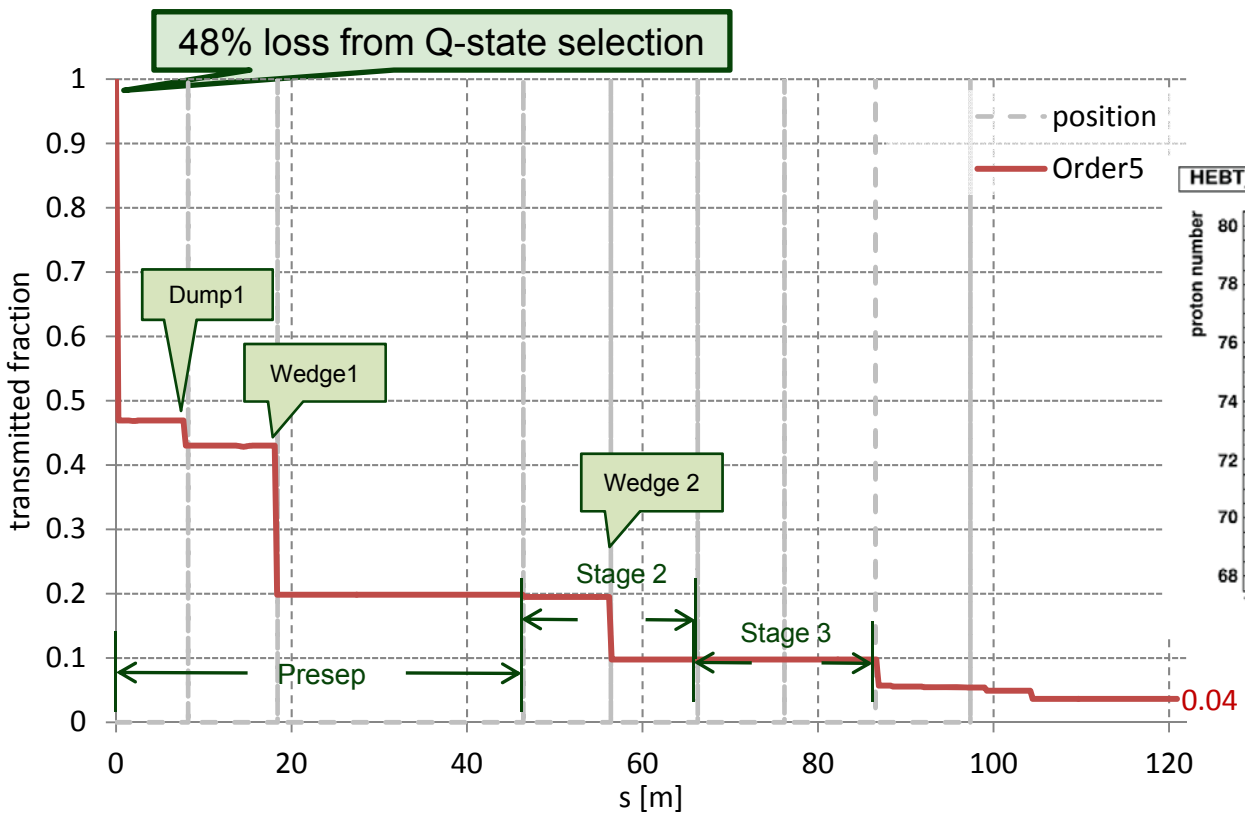


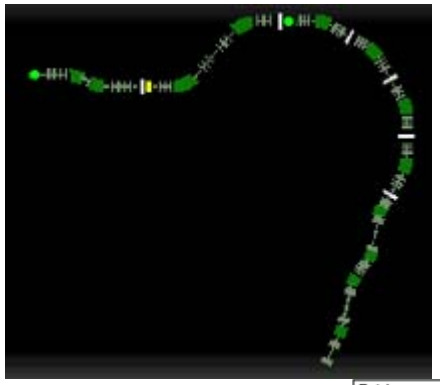


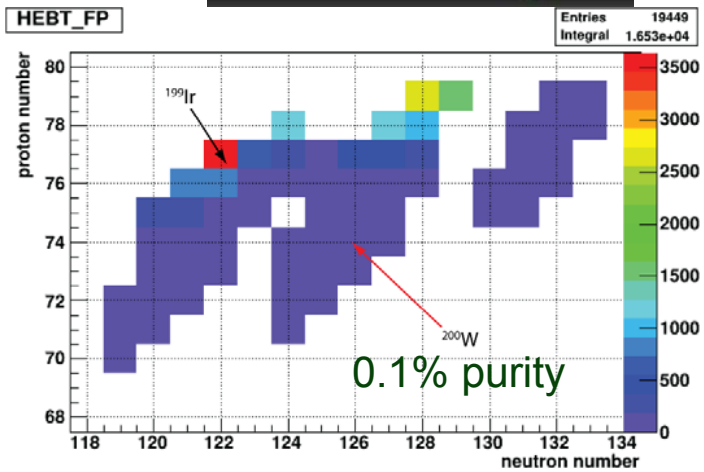
Challenging cases for FRIB: Charge exchange losses

- Unavoidable losses from charge exchange limit the achievable transmission for high-Z fragments at FRIB energies
  - Optimizing degrader thicknesses can help reduce losses in some cases

Example: 202 AMeV ^{238}U -> d/R=0.25 carbon target -> ^{200}W -> d/R=0.2 wedge1 -> d/R=0.34 wedge2 -> S800obj



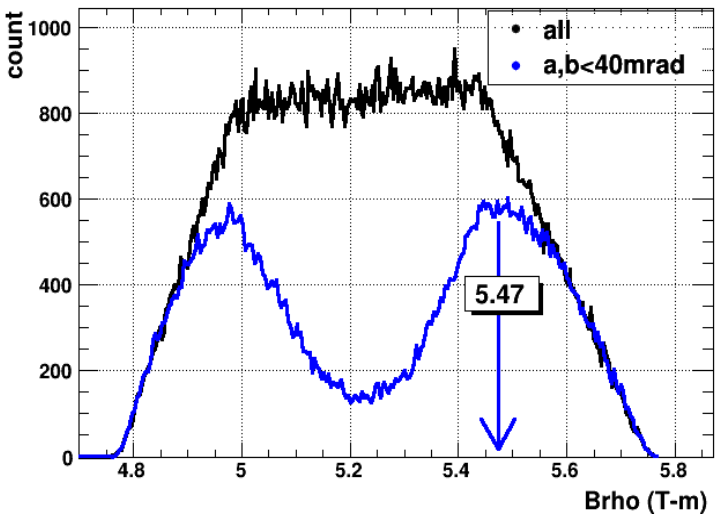




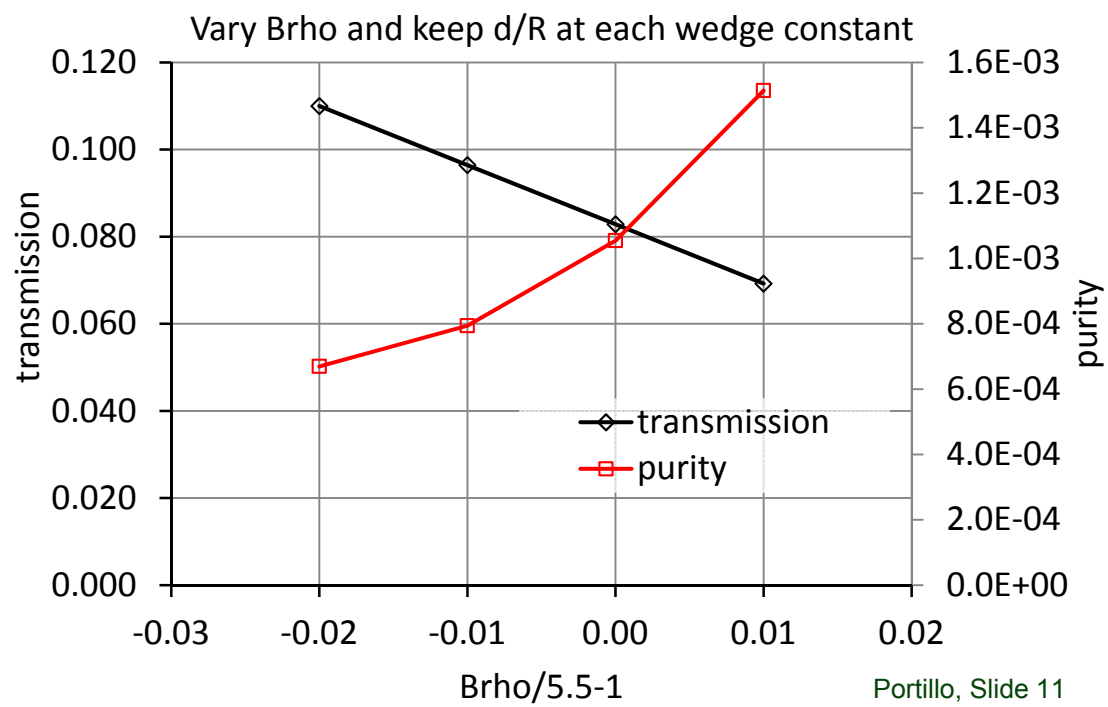
Challenging cases for FRIB: ^{238}U fission products

- Fission products from ^{238}U offer a special challenge
  - Phase space of all products are large
  - Selecting optimum Brho setting requires extra considerations

Simply using peak method of optimum Brho



One must also regard what is more important; e.g. purity vs transmission



In-Flight PID for FRIB
Fundamentals

- Event based tagging at detectors is needed
  - *TOF-Bρ-ΔE* method

$$B\rho = \frac{A}{Q}\frac{uc^2}{ec}\beta\gamma$$

$$\beta = \frac{S}{t \cdot c}$$

S = path length
t = time of flight (*TOF*)
$\gamma^2 = 1/(1-\beta^2)$

- Momentum tagging is necessary
  - Large *Δp/p* acceptances

ARIS	$\pm 5\%$
BigRIPS	$\pm 3\%$
SuperFRS	$\pm 2.5\%$

$B\rho$ determined from position measurement at large dispersive plane

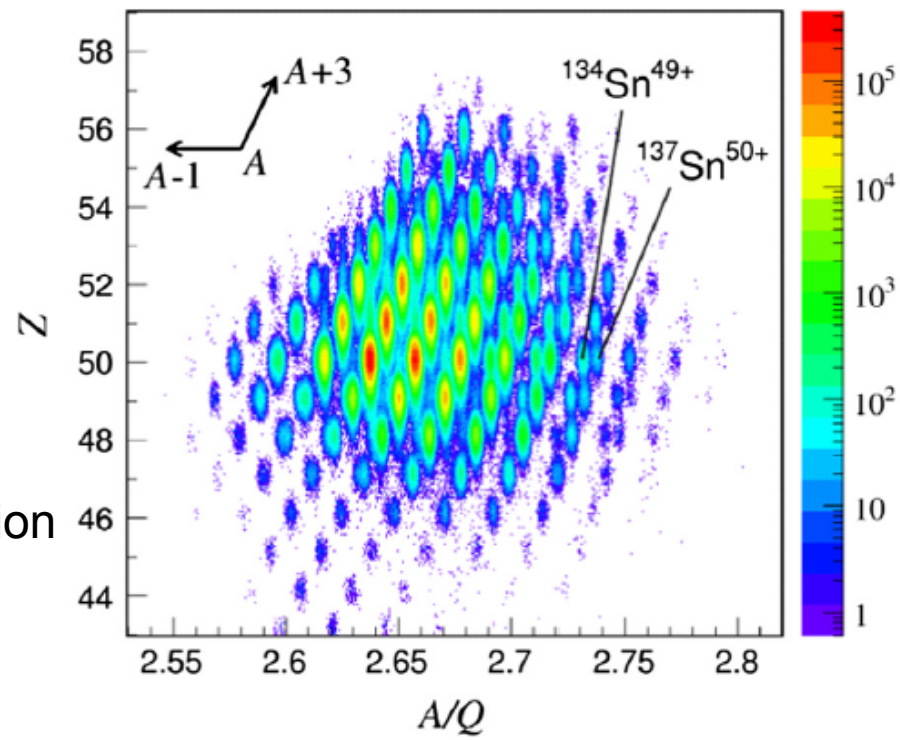
$\frac{A}{Q}$ is solved for, then A, Z, Q need to be resolved

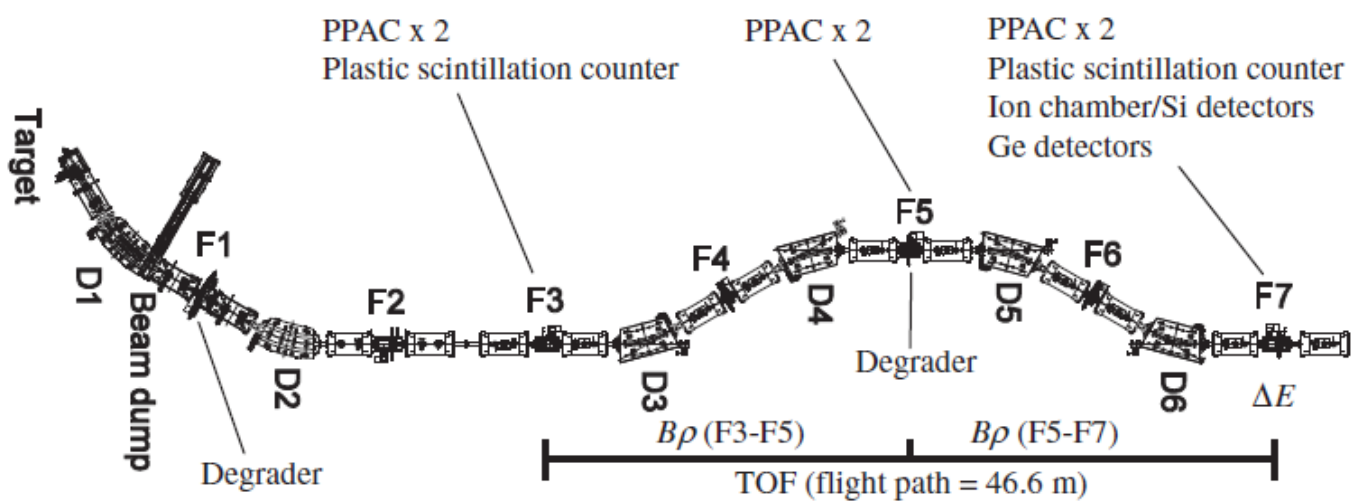
- *ΔE* needed for determination of *Z*

Useful current example in literature

- Identification of ^{238}U fission products at BigRIPS
  - Demonstrates the challenging aspects due to **charge exchange**

Fukuda NIMB 317 (2013) 323.
- G3 setting
- Technique requires high A/Q resolution



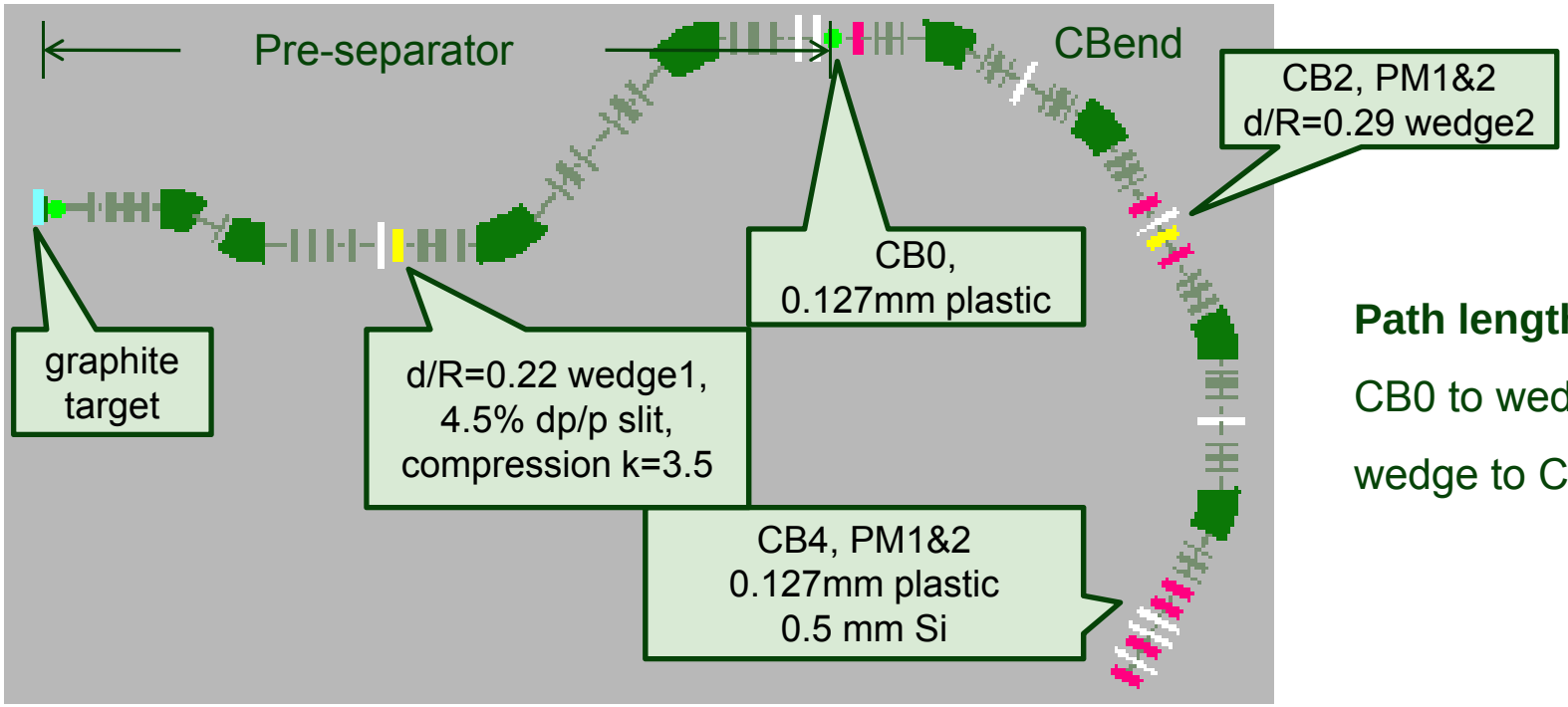


PID case considered here

- Similar to BigRIPS method. Apply to **ARIS** separator layout
  - Have used a fragmentation case to demonstrate resolving of overlapping of products due to charge-exchange effects

218 MeV/u ^{160}Gd -> 1.8 mm C (d/R=0.23)

-> $^{152}Ce_{58+}$ 5.38 T-m 4.5% dp/p
-> 4.90 T-m **CB-4000** -> 1.2 mm Al wedge -> 4.35 T-m



Path lengths

CB0 to wedge: 19.7 m

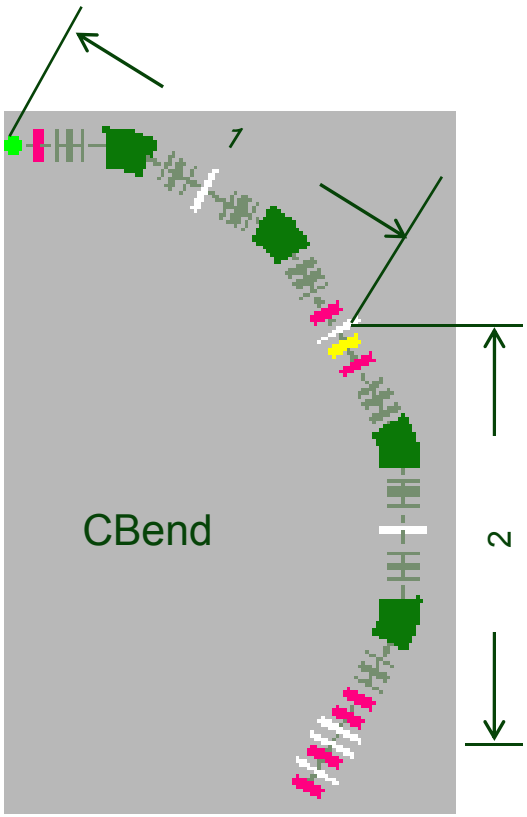
wedge to CB4: 20.2 m

Adopted method for *Bρ* determination

- Use 1st order approximation for $B\rho$ determination
  - Assuming negligible spot size at object position

$$B\rho_1 \approx B\rho_{r,1}\left(1 + \frac{x_1}{(x|\delta)_1}\right)$$

» $B\rho_{r,1}$ is the set spectrometer rigidity before wedge
» $(x|\delta)_1$ is momentum dispersion at wedge position



- Validity of this approximation
  - Poor resolution results if higher order effects are not well corrected
  - Otherwise, trajectory reconstruction methods are needed to compensate for aberration effects
    » Demonstrated by Fukuda et al.

Adopted method for *Z* determination

- Use *Z* extraction from *ΔE* prescribed by Fukuda et al. using the Bethe form of energy loss

$$\frac{dE}{dw} = \frac{4\pi e^4 Z^2}{m_e c^2 \beta^2} N z L_B$$

$$L_B = \ln \frac{2 m_e c^2 \beta^2}{I} - \ln(1-\beta^2) - \beta^2$$

S. Ahlen, *Rev. Mod. Phys.*, vol. 52, p. 121, 1980.

- In the approximation that change in *β* is small over the thickness *w*

$$Z = k_c D \beta \sqrt{\frac{\Delta E}{L_B \Delta w}}$$

  - I =mean ionization potential; adopted values from ATIMA at *β*=0.5
  - k_c is a correction factor
  - Δw is material thickness
  - $1/D^2 = N \times 5.131 \times 10^{-19} \quad [eV \cdot cm]$ in CGI units
  - N = electron density in material

Q state identification method

- Total kinetic energy *K* can help deduce *A* and *Q*

$$A = \frac{K}{uc^2(\gamma - 1)} \qquad Q = \frac{A}{B\rho}\frac{uc^2}{ec}\beta\gamma$$

  - Requires stopping of products in E-loss detectors and
  - Careful calibration of each detector layer (e.g. each layer from Si telescope)

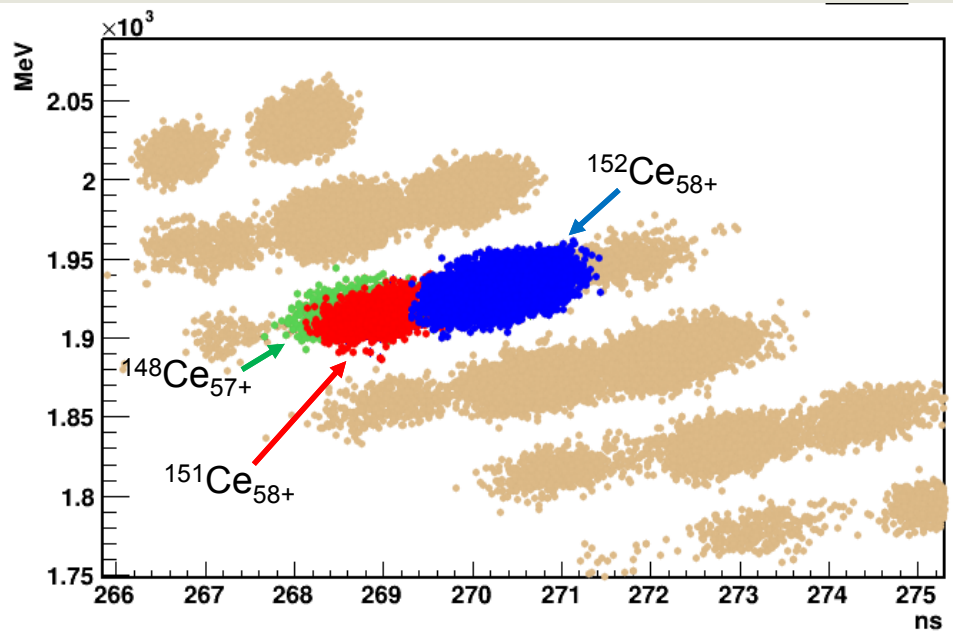
- Here, we assume *K* is unknown and instead,
  - Rely on accurate *TOF* (i.e. β) measurement(s)
  - Use high resolving power to enhance *A/Q* (i.e. $B\rho$) resolution
  - Untangle *A* and *Q* without depending on *K* measurement

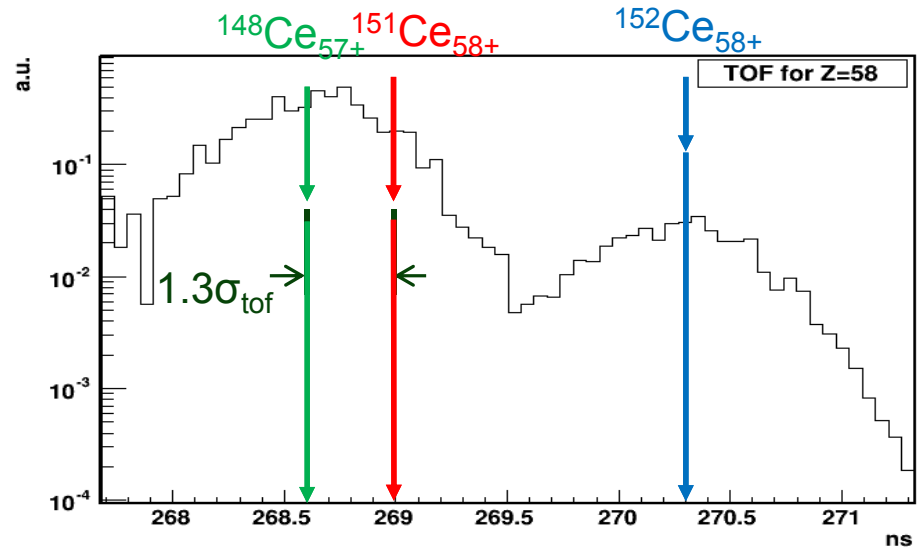
$$\Lambda = \frac{A}{Q} = \frac{B\rho}{\beta\gamma}\frac{ec}{uc^2}$$

Situation when accurate *Bρ* is not known

"World without *Bρ* correction"

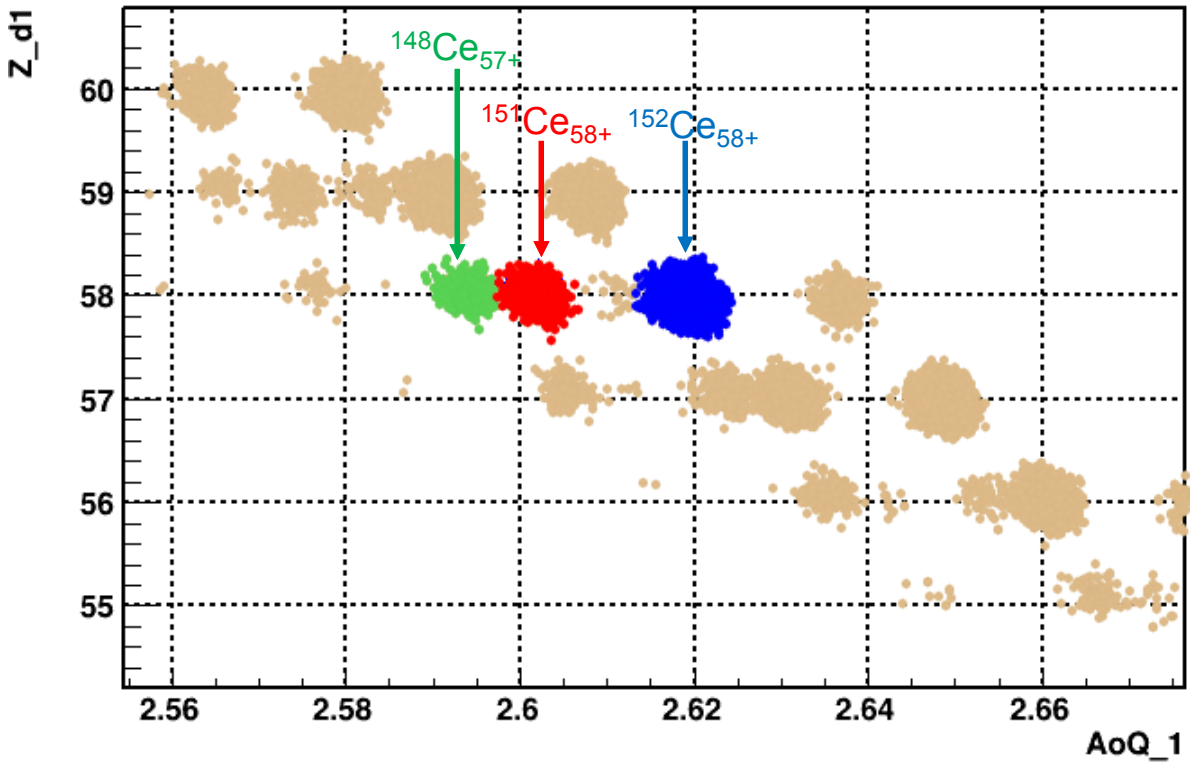
- Assuming perfect *ΔE* and *TOF* detectors
- Positive identification is difficult at higher *Z*
  - Example of setting with $^{152}Ce_{58+}$ (*Z*=*Q*) centered
  - $^{148}Ce_{57+}$ (*Z*=*Q-1* at target)





PID based on determined *Bρ* and *β*

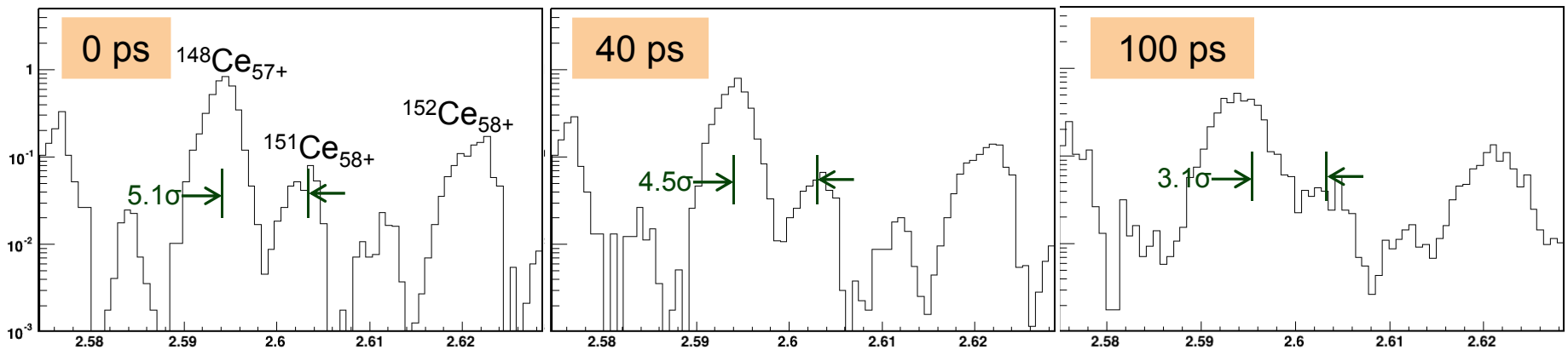
- Simulations with the adopted PID method shows that good Q-state separation is possible
  - Ideal simulation is based on time-of-flight (***TOF***) and ***ΔE*** detectors with perfect resolution (i.e. zero sigma uncertainty)
  - Assuming perfect position resolution of **tracking** detectors at degrader and focal-plane positions to determine $B\rho_1$ and $B\rho_2$



FP slit settings ±25 mm

Effect of *TOF* resolution [1]

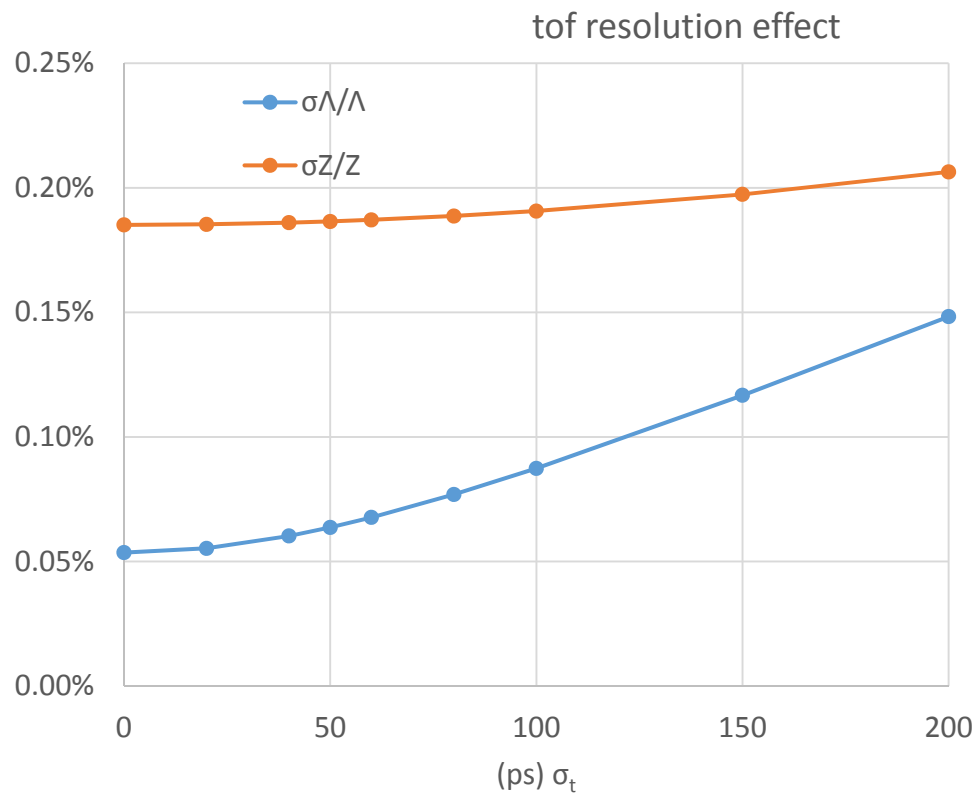
- Simulated *A/Q* histograms for three different detector intrinsic *TOF* resolution values (sigma)
  - products at *Z*=58
  - Adopt figure of merit as separation between $^{148}Cs_{57+}$ and $^{151}Cs_{58+}$



Effect of *TOF* resolution [2]

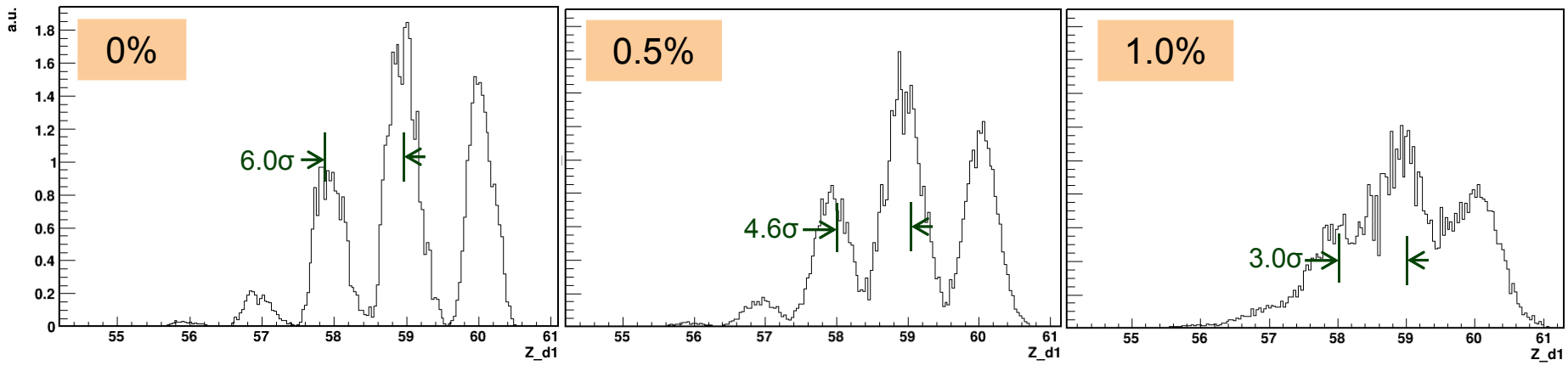
- Trend of *Z* and *A/Q* resolution versus *TOF* resolution

σ_t (ps)	σ_Z/Z	σ_Λ/Λ
0	0.185%	0.054%
20	0.185%	0.055%
40	0.186%	0.060%
50	0.187%	0.064%
60	0.187%	0.068%
80	0.189%	0.077%
100	0.191%	0.087%
150	0.197%	0.117%
200	0.206%	0.148%



Effect of *ΔE* resolution [1]

- Simulated *Z* histograms for three different *intrinsic ΔE* detector resolution values (sigma)
  - For figure of merit, include all products for FP slits at ±25 mm



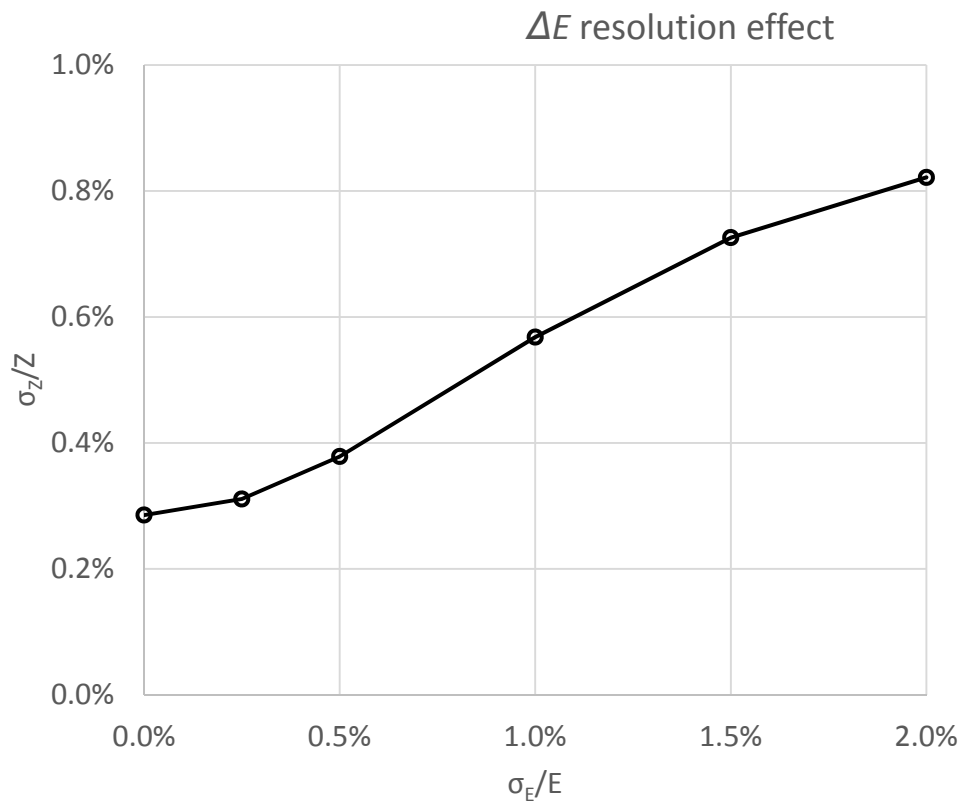
Effect of *ΔE* resolution [2]

- Trend of *Z* determination versus *ΔE* detector resolution

σ_{dE}/E	σ_Z/Z
0	0.29%
0.25%	0.31%
0.50%	0.38%
1.00%	0.57%
1.50%	0.73%
2.00%	0.82%

About what is obtained at BigRIPS for Z=46

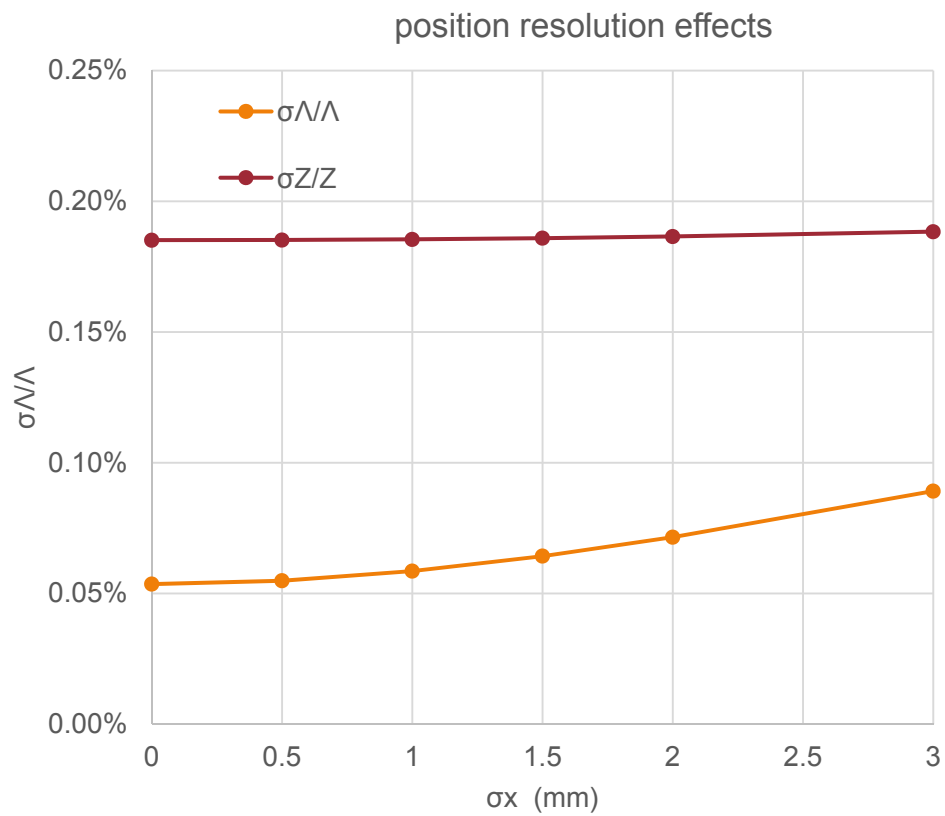
Ohnishi JPSJ 77 (2008) 080201



Effect of position resolution

- Trend of *Z* and A/Q determination versus *x* resolution at wedge and FP positions

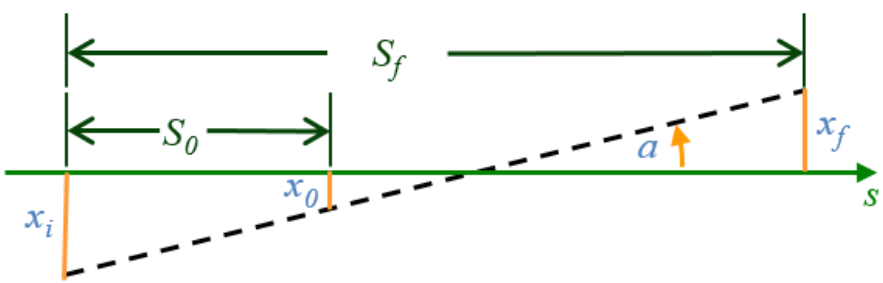
σ_x (mm)	σ_Z/Z	σ_Λ/Λ
0	0.185%	0.054%
0.5	0.185%	0.055%
1	0.185%	0.059%
1.5	0.186%	0.064%
2	0.187%	0.072%
3	0.188%	0.089%



Tracking detectors

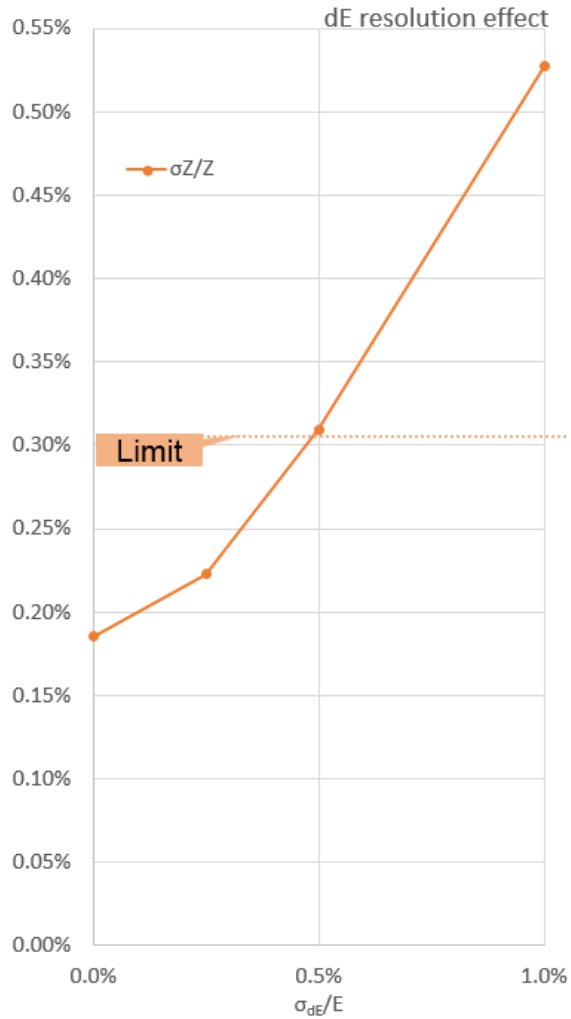
S_f = 1.000 m, DP detectors

S_f = 0.431 m, FP detectors

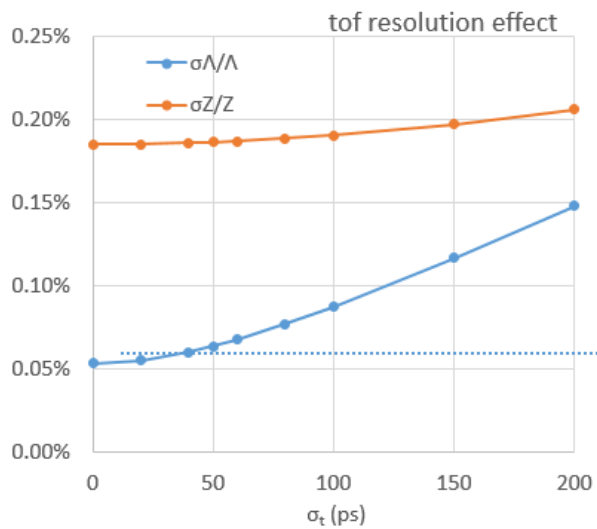


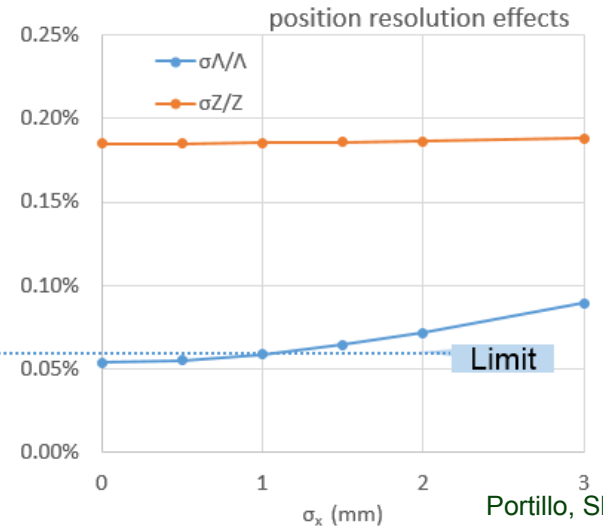
Summary of effects

- σ_E has by far the strongest effect on Z resolution
  - The next strongest effect is σ_t
  - Conclusion:
    - » σ_E is critical to Z resolution and having $\frac{\sigma_E}{E} < 0.5\%$ is important



- σ_t has the strongest effect on A/Q resolution
  (Relative to σ_x ~1mm and σ_t ~ 50ps)
  - Conclusions:
    - » Timing resolution is critical to mass resolution
    - » Relying on higher order tracking may impose more dependence on position resolution
- A/Q affects Q identification the most





Conclusions

- End-to-end simulations are ongoing for FRIB
  - using the latest field parameters for all (existing and future) magnets
- Have simulated the performance of diagnostics in separators
  - Relies on postseparator (C-bend) for *TOF-Bρ-ΔE* method
  - Demonstrated that adequate Q-state resolution is feasible
- Adopted an in-flight PID scheme that can be used by experimenters
- Have determined resolution specifications for the detectors
  - Based on difficult PID cases expected at high Z
  - Specifications are challenging but have been shown to be achievable
- More accurate trajectory reconstruction methods can be considered to improve PID resolution
  - Example: Tracking detectors at preseparator focal plane position