



Particle Identification with the S800 Spectrograph – Present and Future

Jorge Pereira

MICHIGAN STATE
UNIVERSITY



U.S. DEPARTMENT OF
ENERGY

Office of
Science

The S800 in Figures

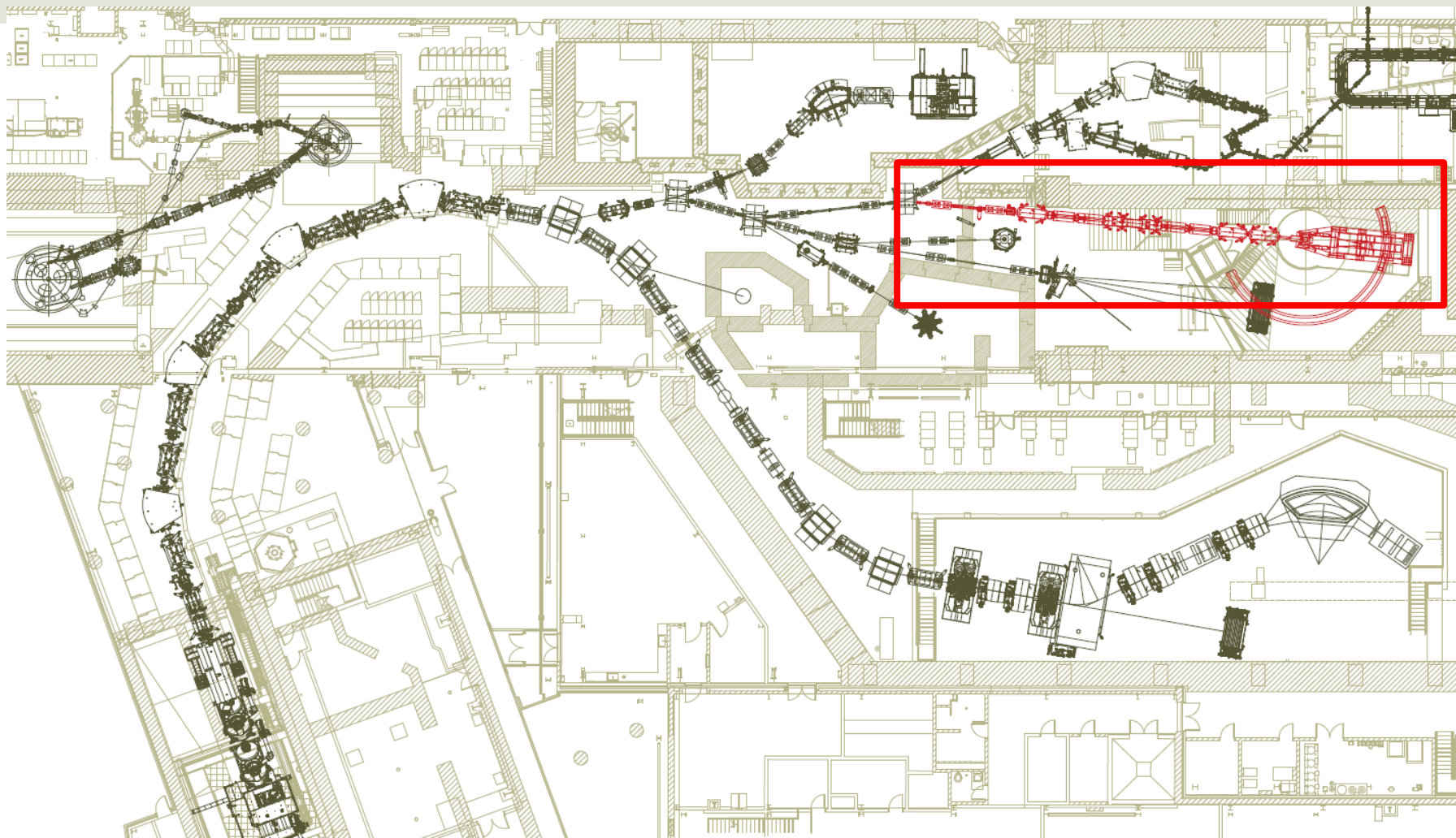


Facility for Rare Isotope Beams
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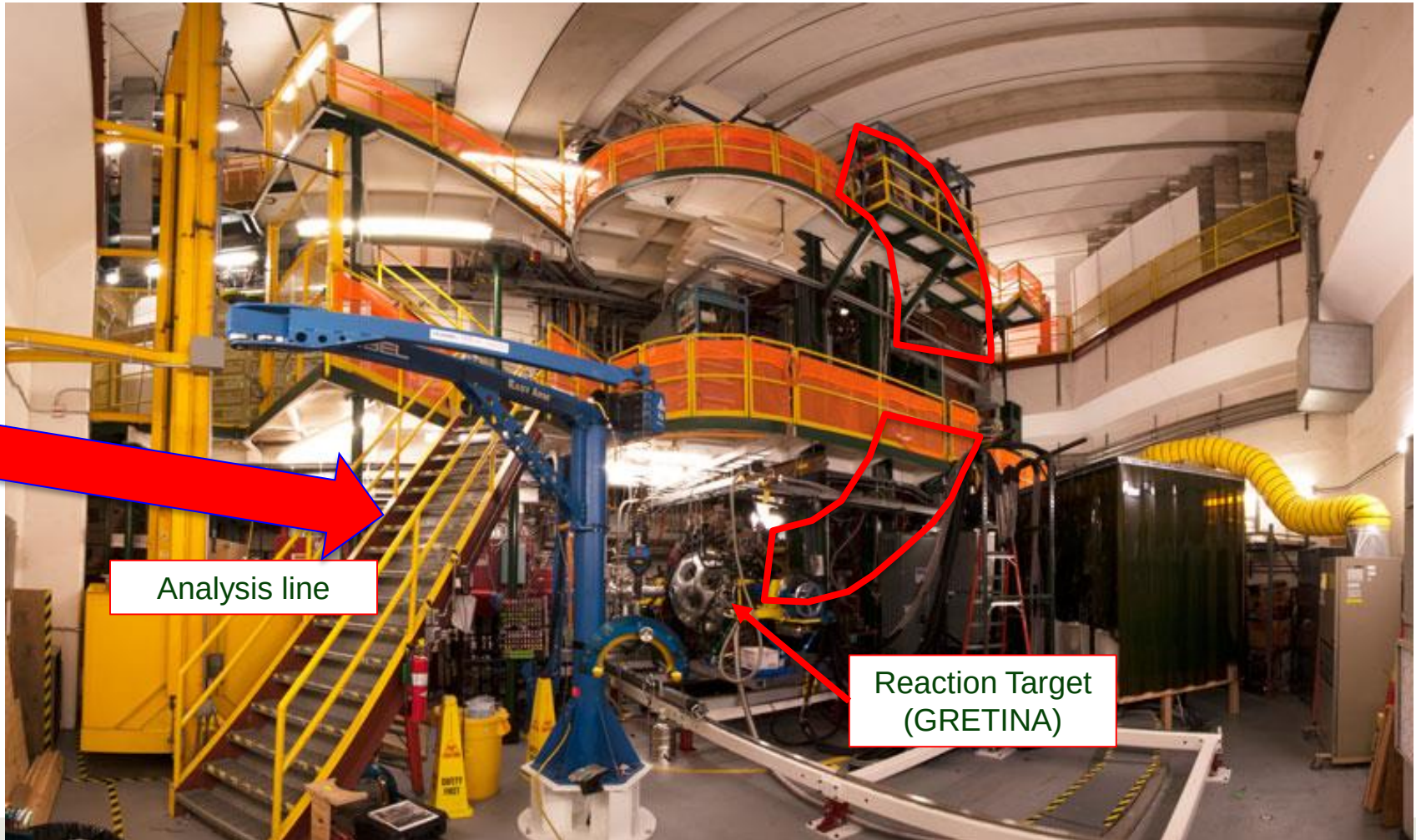
Jorge Pereira, Dec 2020, Particle Identification With the S800 Spectrograph

, Slide 2

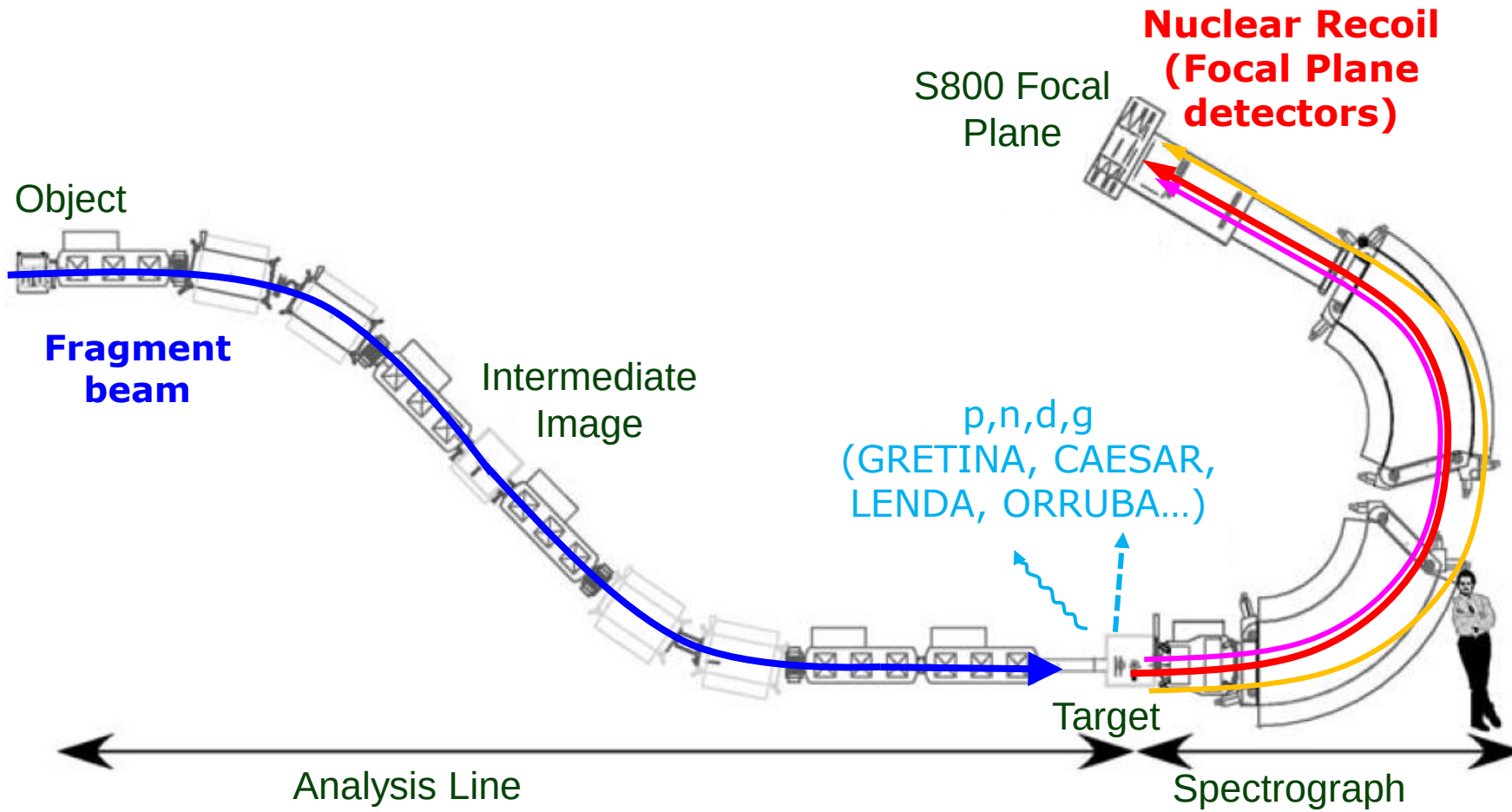
The S800 and FRIB



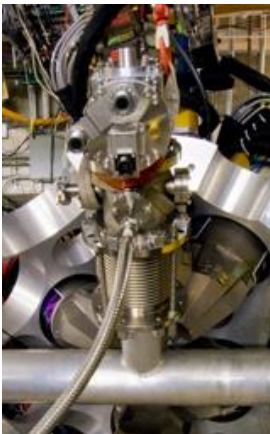
The S3 Vault (Home of S800)



The S800



The S800



Liquid H/D target



gammas

GRETINA



neutrons

LEND



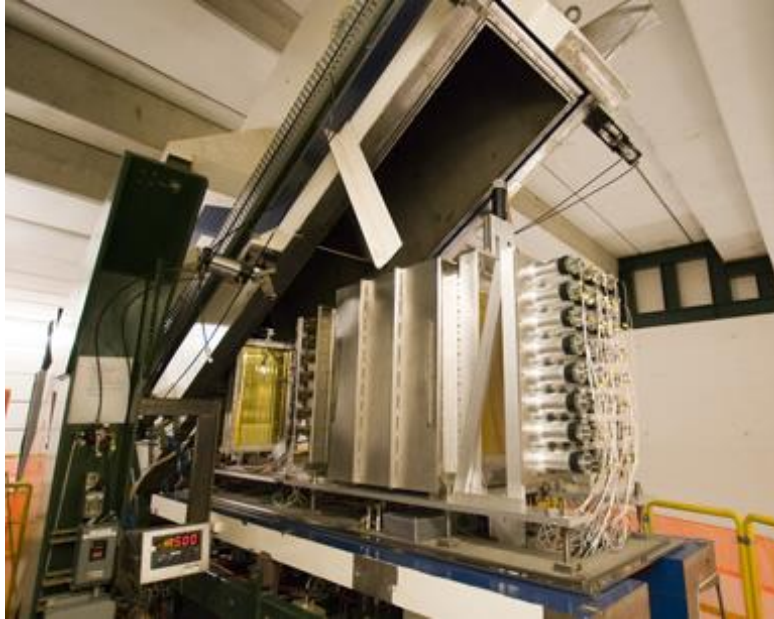
Charged-
particles

ATTPC

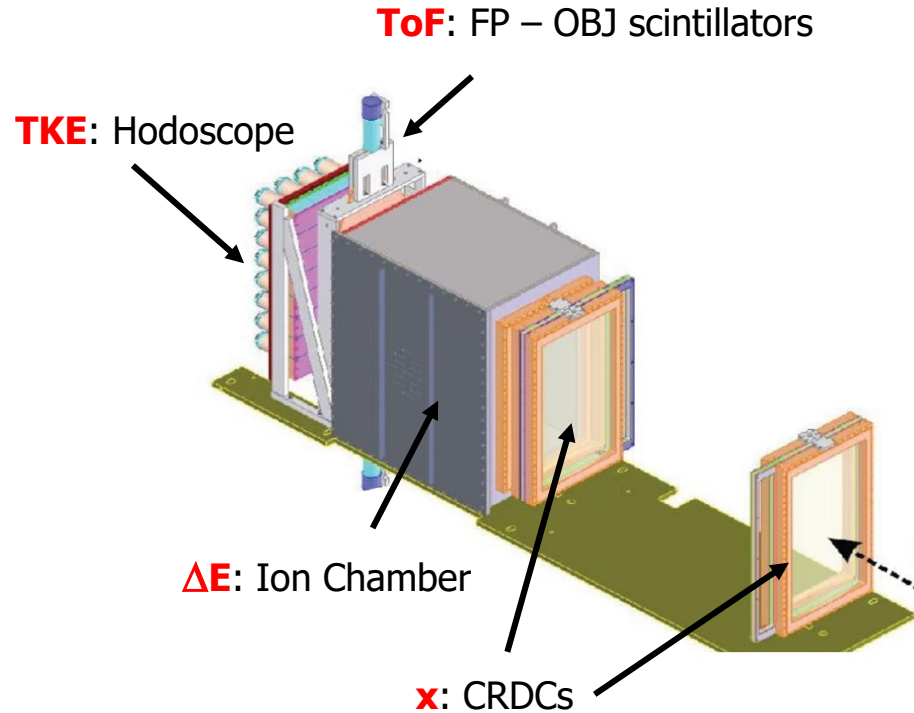


ORRUBA

Separation, and Identification of Recoil Nuclei in the S800 Focal Plane



Courtesy Shumpei Noji



Particle Identification and Separation with the S800. Current Status



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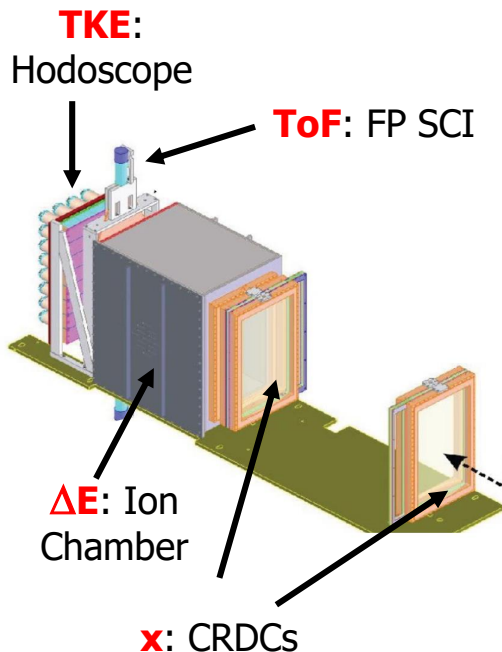
, Slide 8

Particle Separation and Identification

Separation and Identification in terms of Z and A

Case I: Fully-stripped nuclei ($Z=Q$) $\sim$ ($Z < 35$, $E > 50$ MeV/u)

Based on $\underline{Z}$, and $(\underline{A/Q})$:

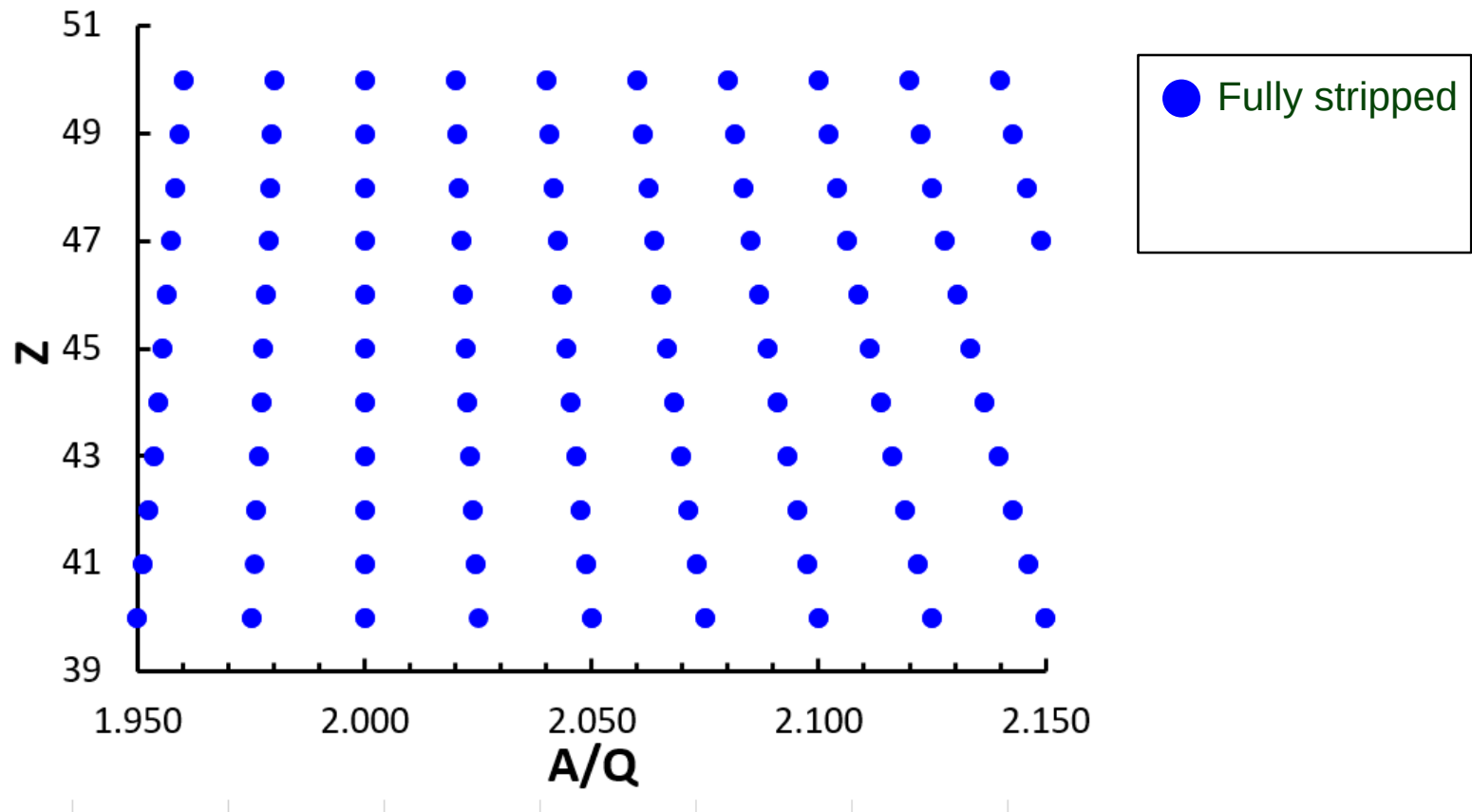


$$1) \quad Z \sim \sqrt{\Delta E \cdot \beta^2} \rightarrow \sqrt{\Delta E \cdot (L/cToF)^2}$$

$$2) \quad \frac{A}{Q} = \frac{e}{uc} \frac{B\rho}{\beta\gamma} = \frac{e}{uc} (B\rho)_0 \left(1 + \frac{x - Mx_0}{D} \right) \left(\frac{ToF^2}{c^2 L^2} + 1 \right)^{1/2}$$

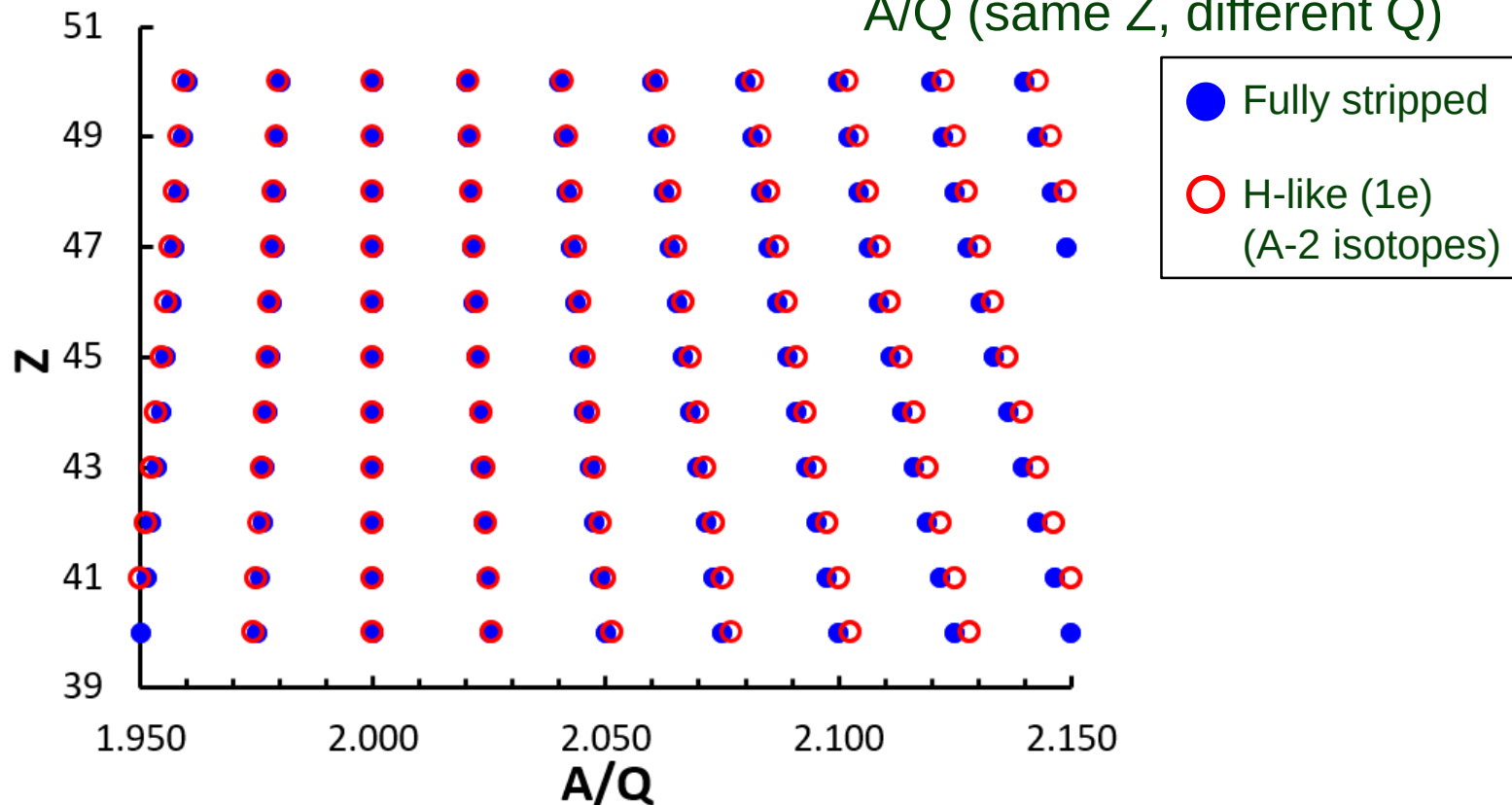
3) Assumption $Z=Q$. Then, from Identified Z (integer) and $(\underline{A/Q}) \rightarrow A$

Particle Separation and Identification



Particle Separation and Identification

Case II: Multiple charge-state ($Z \neq Q$) $\rightarrow$ Different isotopes, same A/Q (same Z , different Q)

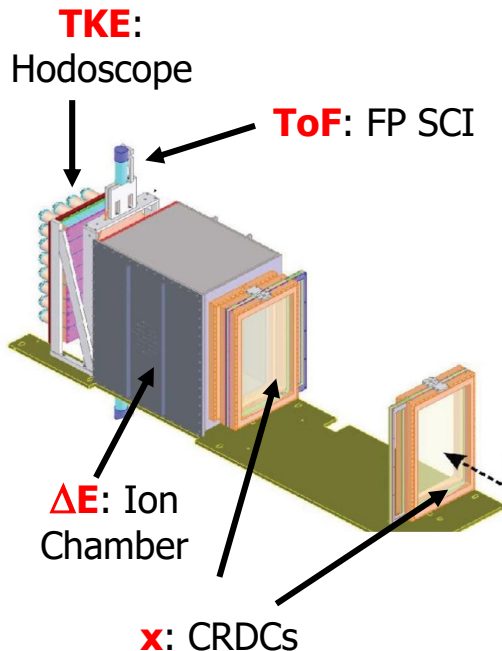


Particle Separation and Identification

Separation and Identification in terms of Z and A

Case II: Multiple charge-state ($Z \neq Q$)

Based on $\underline{Z}$, $\underline{(A/Q)}$, and $\underline{Q}$



$$1) \quad Z \sim \sqrt{\Delta E \cdot \beta^2} \rightarrow \sqrt{\Delta E \cdot (L/cToF)^2}$$

$$2) \quad \frac{A}{Q} = \frac{e}{uc} \frac{B\rho}{\beta\gamma} = \frac{e}{uc} (B\rho)_0 \left(1 + \frac{x - Mx_0}{D} \right) \left(\frac{ToF^2}{c^2 L^2} + 1 \right)^{1/2}$$

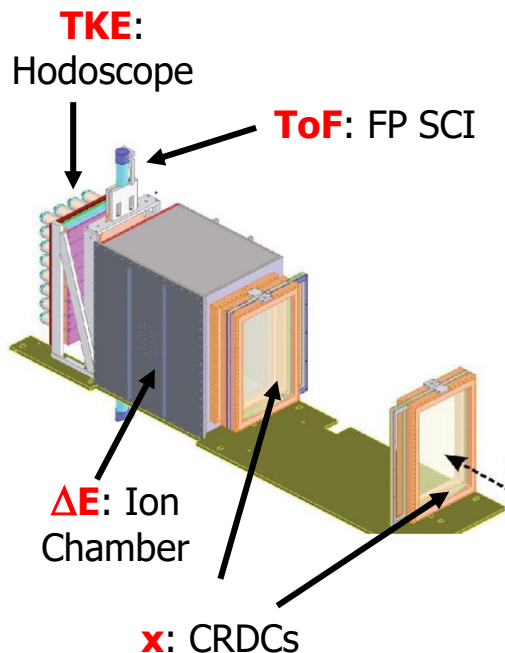
3) ~~Assumption $Z=Q$. Then, from Identified Z (integer) and $\underline{(A/Q)} \rightarrow A$~~

Particle Separation and Identification

Separation and Identification in terms of Z and A

Case II: Multiple charge-state ($Z \neq Q$)

Based on $\underline{Z}$, $\underline{(A/Q)}$, and $\underline{Q}$



$$1) \quad Z \sim \sqrt{\Delta E \cdot \beta^2} \rightarrow \sqrt{\Delta E \cdot (L/c \cdot \text{ToF})^2}$$

$$2) \quad \frac{A}{Q} = \frac{e}{uc} \frac{B\rho}{\beta\gamma} = \frac{e}{uc} (B\rho)_0 \left(1 + \frac{x - Mx_0}{D} \right) \left(\frac{\text{ToF}^2}{c^2 L^2} + 1 \right)^{1/2}$$

$$3) \quad Q = A \frac{uc}{e} \frac{\beta\gamma}{B\rho} = \frac{\text{TKE}}{ec \cdot (B\rho)_0} \left(1 + \frac{x - Mx_0}{D} \right)^{-1} \times \frac{L/c \cdot \text{ToF}}{1 - \sqrt{1 - (L/c \cdot \text{ToF})^2}}$$

$$4) \quad \text{From identified } Q \text{ (integer) and } (A/Q) \rightarrow A$$

Particle Separation and Identification

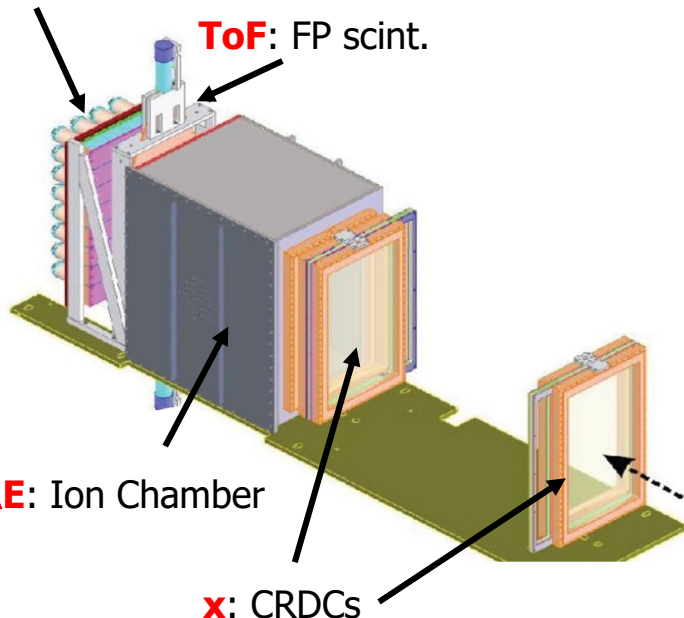
	ΔE (MeV)	X (mm)	ToF (ps)	TKE (%)	D (cm/%)	M	Δx (mm)	L (m)
Resolutions (sigma)	1.2	0.5	170	0.85	9.5	2	1	14

TKE: Hodoscope

ToF: FP scint.

ΔE : Ion Chamber

X: CRDCs



$$\frac{\delta A o Q}{A o Q} = \left[\left(\frac{\delta x}{D} \right)^2 + \left(\frac{M \Delta x_0}{D} \right)^2 + \gamma^2 \left(\frac{\delta T o F}{T o F} \right)^2 \right]^{1/2}$$

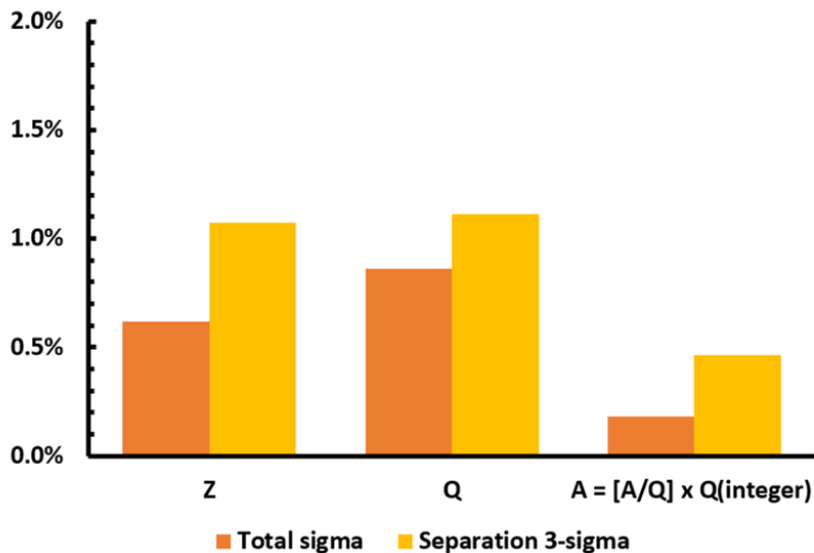
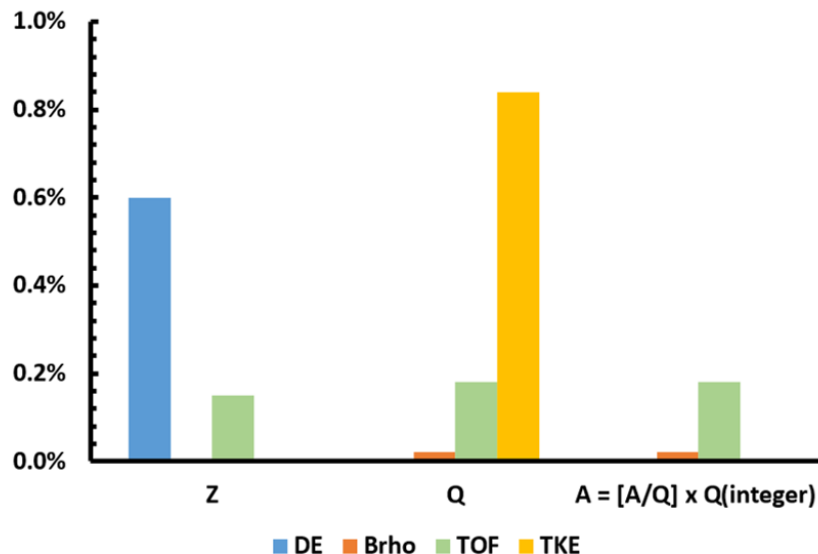
$$\frac{\delta Q}{Q} = \left[\left(\frac{\delta T K E}{T K E} \right)^2 + \left(\frac{\delta x}{D} \right)^2 + \left(\frac{M \Delta x_0}{D} \right)^2 + \gamma^2 \left(\frac{\delta T o F}{T o F} \right)^2 \right]^{1/2}$$

$$\frac{\delta Z}{Z} = \left[\left(\frac{1}{2} \frac{\delta \Delta E}{\Delta E} \right)^2 + \left(\frac{\delta T o F}{T o F} \right)^2 \right]^{1/2}$$

Separation Capabilities with the S800

	ΔE (MeV)	X (mm)	ToF (ps)	TKE (%)	D (cm/%)	M	Δx (mm)	L (m)
Resolutions (sigma)	1.2	0.5	170	0.85	9.5	2	1	14

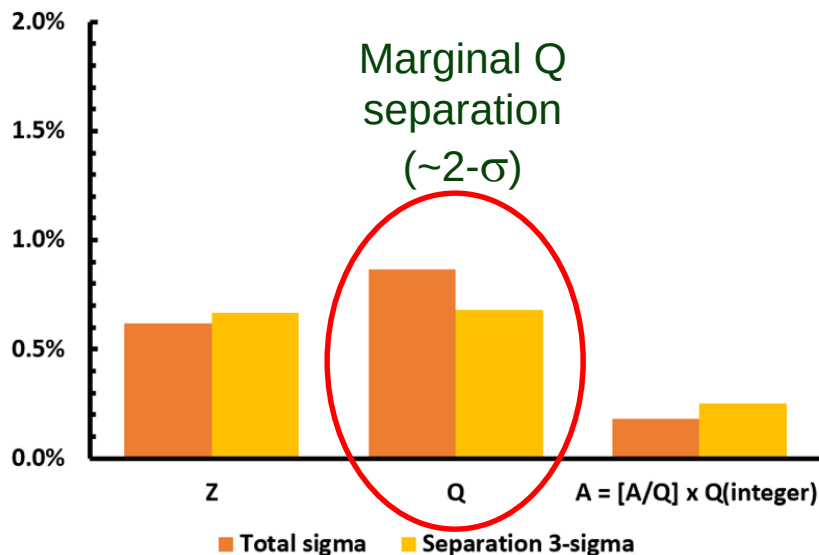
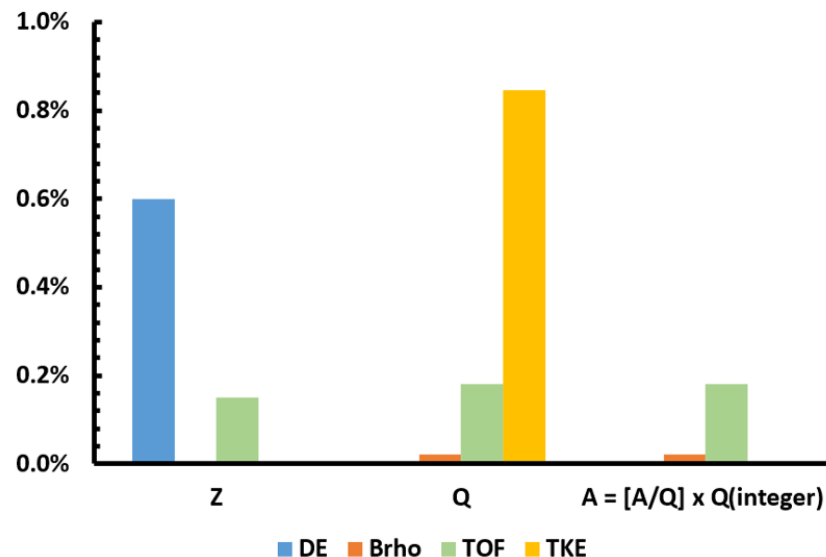
Case (1): Region of nuclei around $^{76}\text{Ge}^{32+}$ @ $E \sim 90 \text{ MeV/u}$



Separation Capabilities with the S800

	ΔE (MeV)	X (mm)	ToF (ps)	TKE (%)	D (cm/%)	M	Δx (mm)	L (m)
Resolutions (sigma)	1.2	0.5	170	0.85	9.5	2	1	14

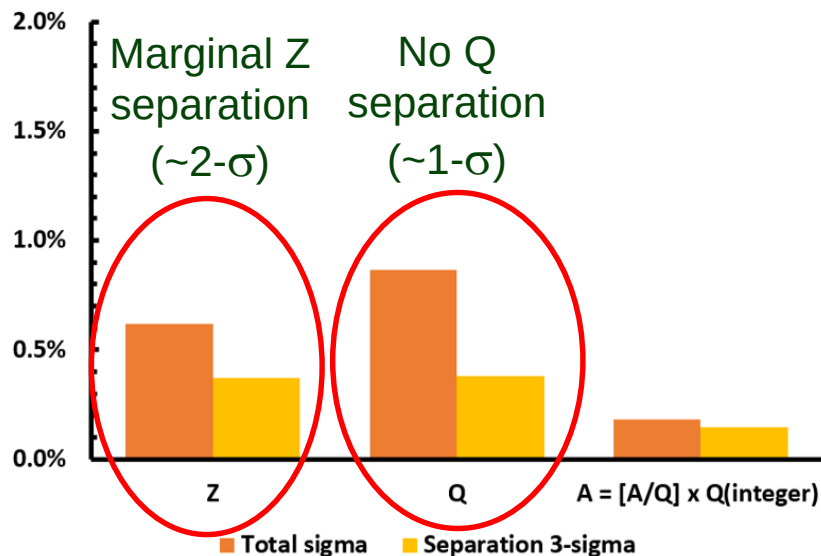
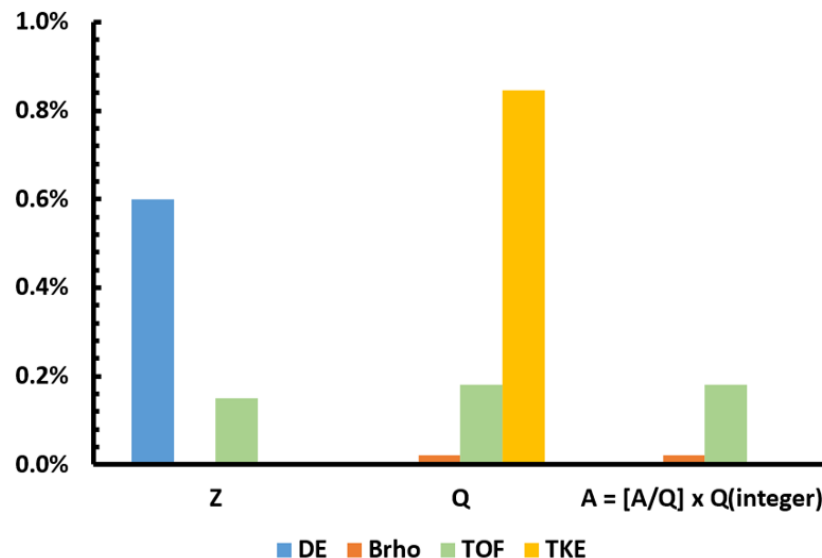
Case (2): Region of nuclei around $^{132}\text{Sn}^{50+}$ @ $E \sim 90 \text{ MeV/u}$



Separation Capabilities with the S800

	ΔE (MeV)	X (mm)	ToF (ps)	TKE (%)	D (cm/%)	M	Δx (mm)	L (m)
Resolutions (sigma)	1.2	0.5	170	0.85	9.5	2	1	14

Case (3): Region of nuclei around $^{228}\text{Th}^{88+}$ @ $E \sim 90$ MeV/u



Improving the Separation Capabilities of the S800: Detector Upgrades



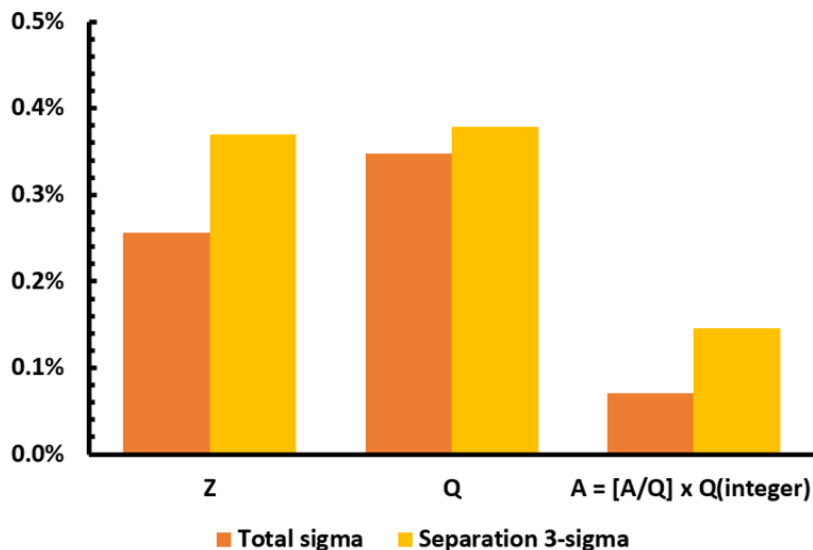
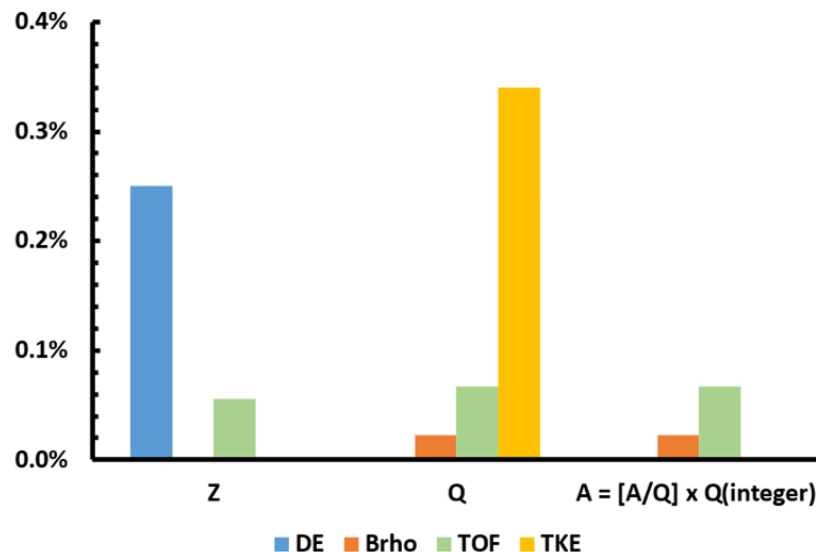
Facility for Rare Isotope Beams
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Jorge Pereira, Dec 2020, Particle Identification With the S800 Spectrograph

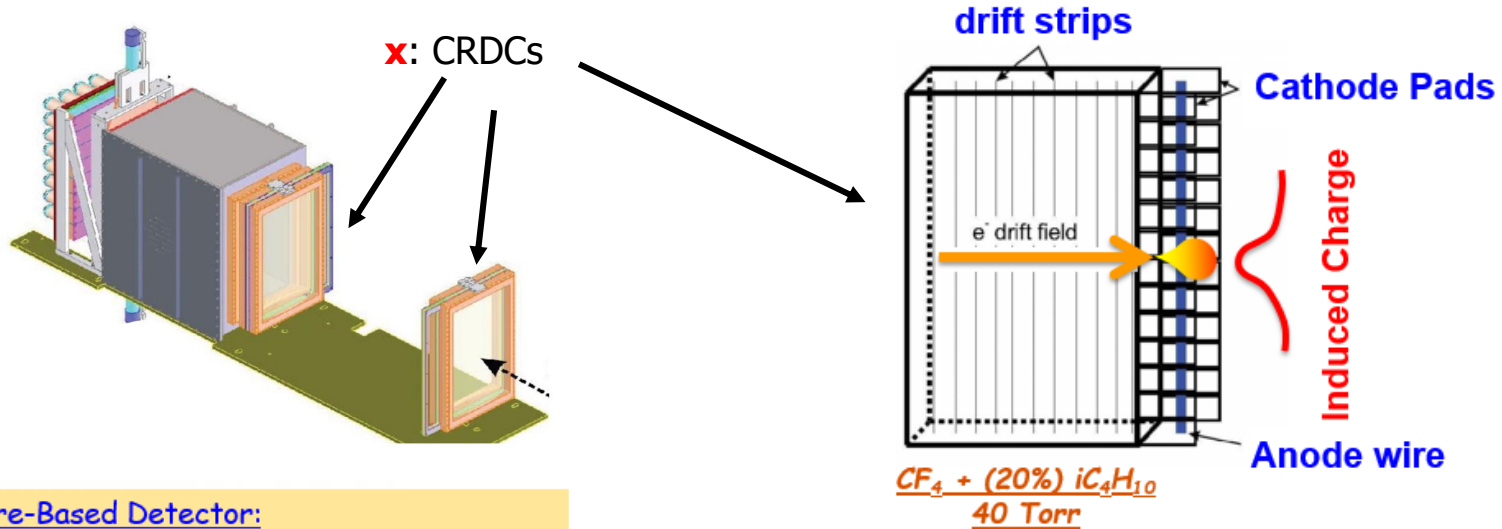
Separation Capabilities with the S800

	ΔE (MeV)	X (mm)	ToF (ps)	TKE (%)	D (cm/%)	M	Δx (mm)	L (m)
Resolutions (sigma)	1.2	0.5	170	0.85	9.5	2	1	14
New Resolutions	0.5	0.5	65	0.35				

Case (3): Region of nuclei around $^{228}\text{Th}^{88+}$ @ $E \sim 90$ MeV/u

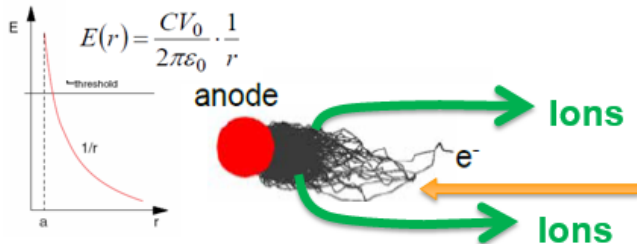


Current S800Tracking system: Cathode Readout Drift Chamber (CRDC)



Wire-Based Detector:

"Mechanics", Economic but
Secondary effects → Gain limits
Space charge → Counting-rate limits
Aging → Damage after long-term operation



Cathode Readout Drift Chamber (CRDC):

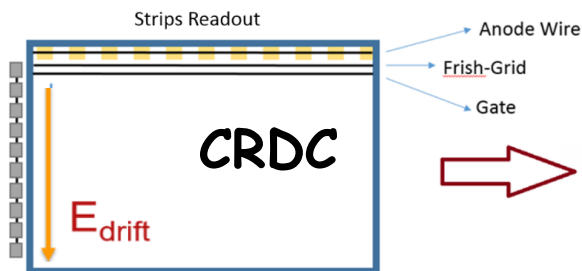
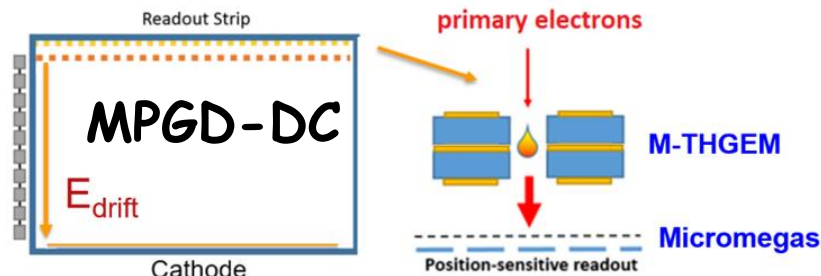
Position and angles

Two CRDCs, 1 m apart, with 30x60 cm² effective area filled with CF₄/(20%)iC₄H₁₀

-) Slow detector → low rate (<5KHz)
-) Position resolution → <1mm FWHM
-) Aging problems



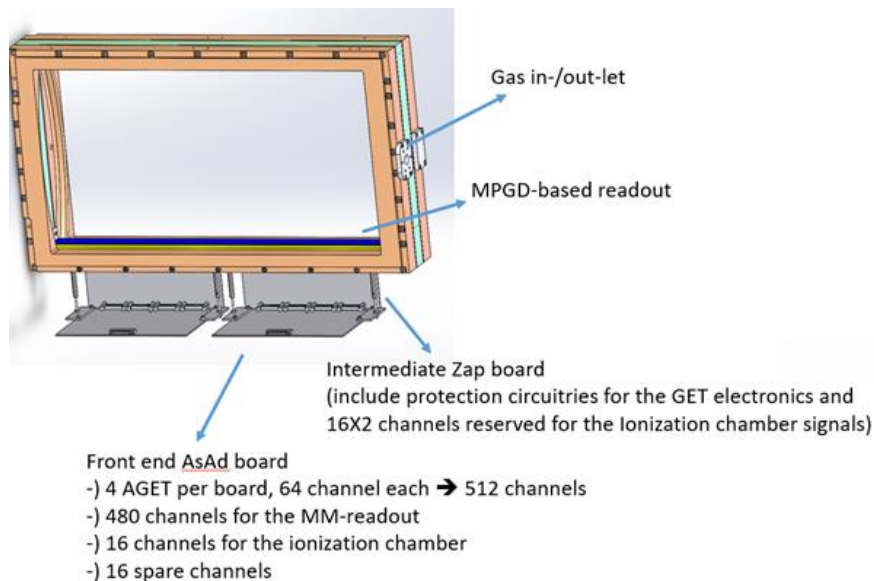
New S800 Tracking System



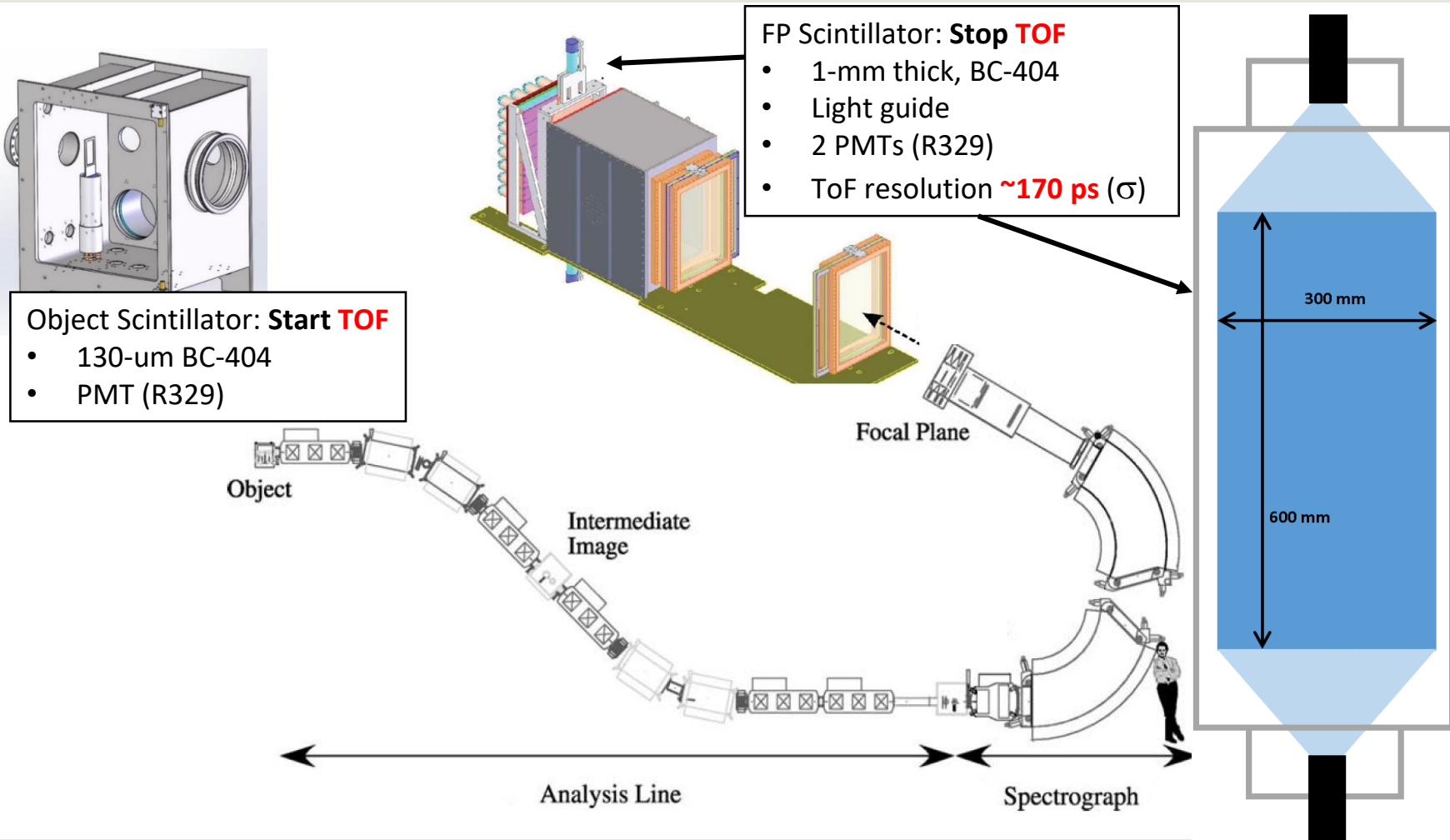
Cortesi *et al.*, Rev. Sci. Ins. 88, 013303 (2017)

-) No loss of charge → high gain @ low voltage
-) Robust avalanche confinement
 - lower secondary effects
-) Long avalanche region
 - high gain @ low pressure
-) Field geometry stabilized by inner electrodes
 - reduced charging-up

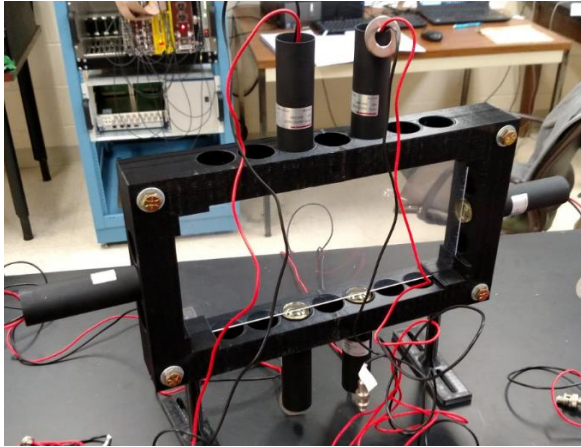
-) Prototype fabricated/tested (May 2019)
-) Optimum results (Cortesi *et al.*, JINST, 2020):
 - Very good X resolutions **0.25 mm, sigma** (goal was 0.5 mm)
 - Efficiencies ~100%, even for very light Z
 - Good performance of GET electronics



Current S800 Time-of-Flight System



New S800 Plastic Scintillator detector for Time-of-Flight (ToF) Measurement

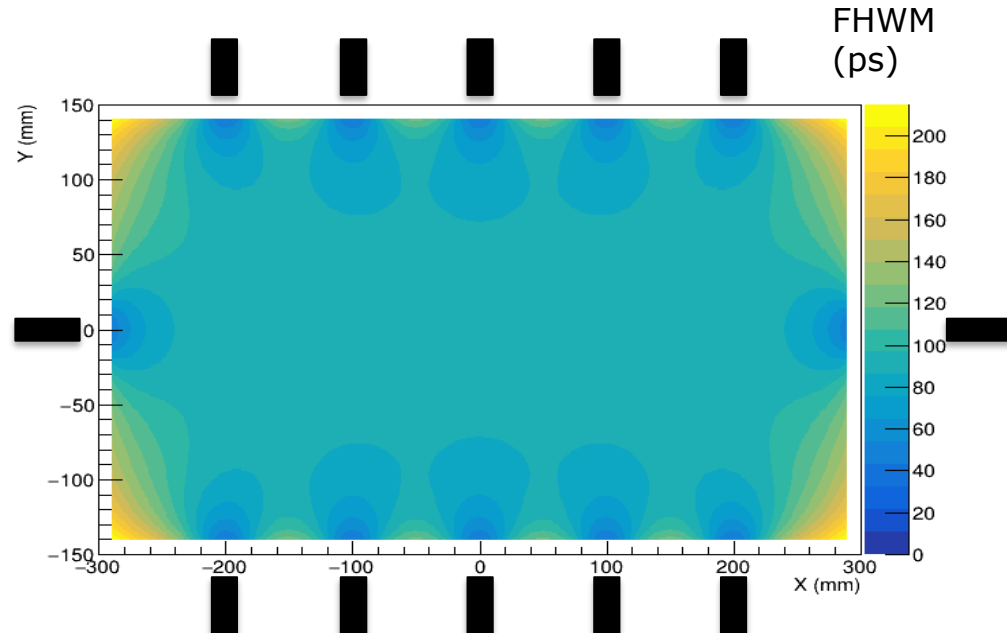


Prototype studies at CMU

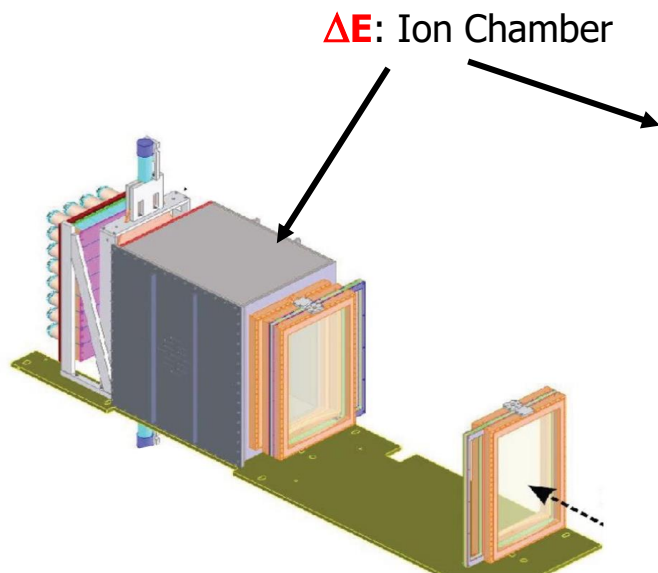
- EJ-230: 300 mm x 150 mm (Half-size S800)
- 6 PMTs H6533: TTS ~ 160 ps
- Optimum resolutions with LASER beam (~ 17 ps, sigma)

Projections S800

- EJ-230: 600 mm x 300 mm
- 12 PMTs H6533
- Optimum resolutions: ~ 38 ps, sigma (goal was 64 ps)



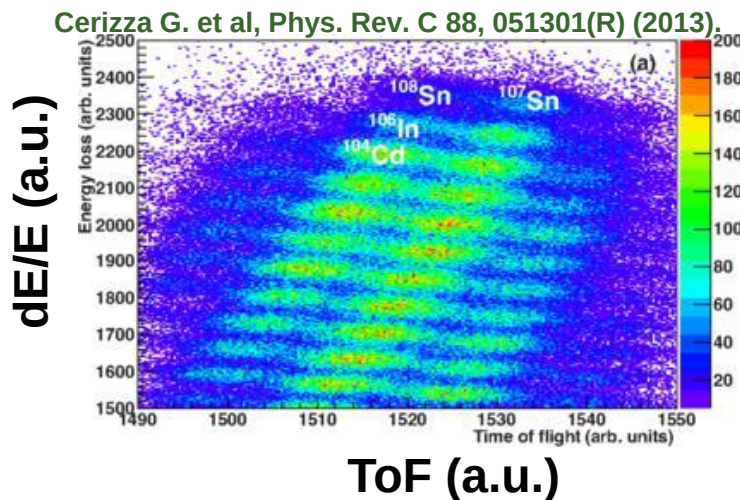
Current Energy-Loss Detector: S800 Ionization Chamber



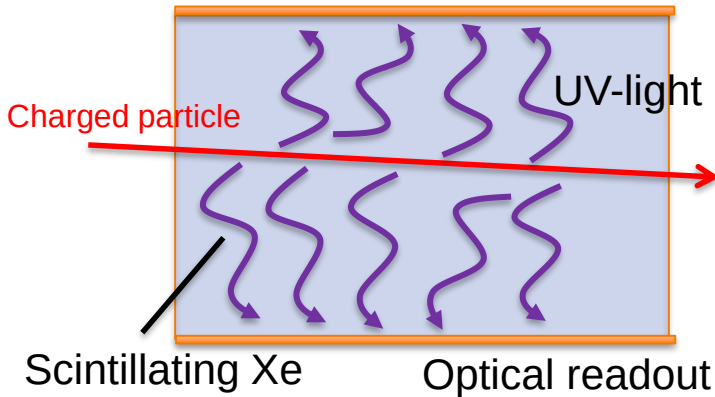
Ionization Chamber (IC):

16 stacked-parallel plate ion chambers (each 1" long). Filled with P10 (300-600 Torr)

- Typical resolutions $\sim 1.2\%$ (sigma)
- Slow detector $\rightarrow$ Low rate (~ 6 KHz)
- High SNR

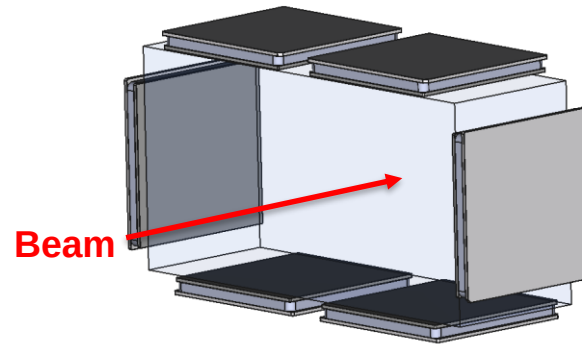


New S800 ELOSS Detector



Operational principle:

-) Volume filled with high-scintillation yield gas (Xe)
-) Incident nucleus excites gas molecules
-) De-excitation with emission of intense, prompt scintillation light (UV) (*) *Optionally: stimulated emission of electro-luminescence light*



Energy-loss detector based on Xe scintillation

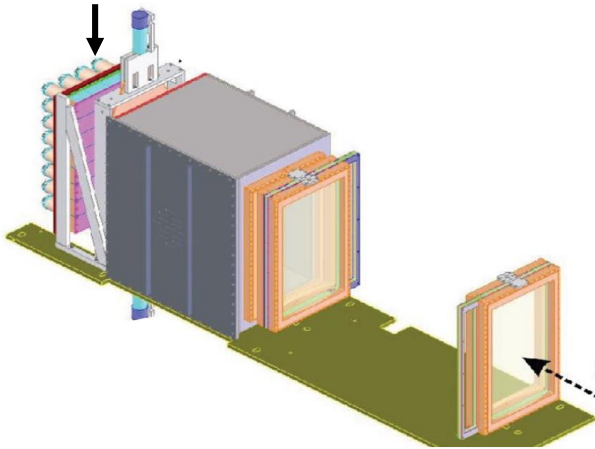
-) High yield → 28 photons/keV - 70% of NaI(Tl)
-) Fast process → photons emitted within 10's ns
-) Self-transparency
-) Increase resolution → stimulated electroluminescence
-) Emission peaks at ~170 nm (different optical readout options available)

MRI project to develop ELOSS (PI M. Cortesi)

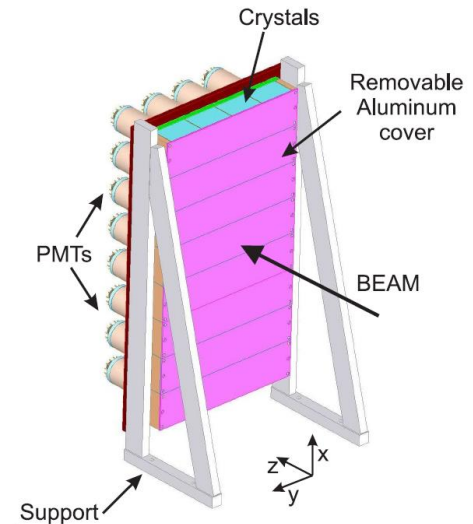
-) Test with prototype (2020)
 - E resolution for different gases
 - Time resolution / localization capability
-) Validation MC simulation → extrapolations to full scale design study
-) **Goal:** Energy resolution **0.5% σ**

S800 Total Kinetic Energy Detector: CsI(Na) Hodoscope

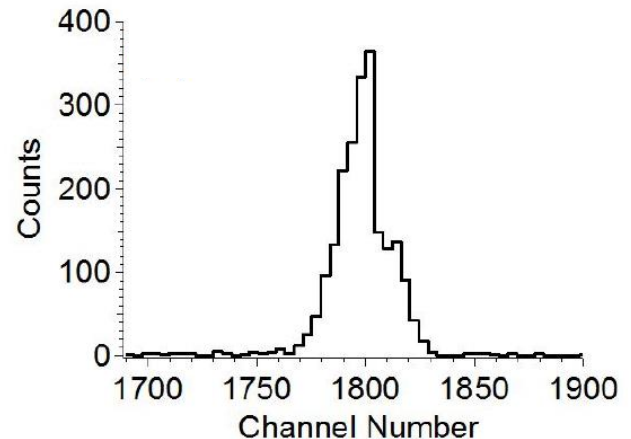
TKE: Hodoscope



-) 32 CsI(Na) crystals
-) High light output yield
-) Peak emission 420 nm (Bi-alkali photocathodes)
-) Robust, easy to cut/shape
-) Slightly hygroscopic

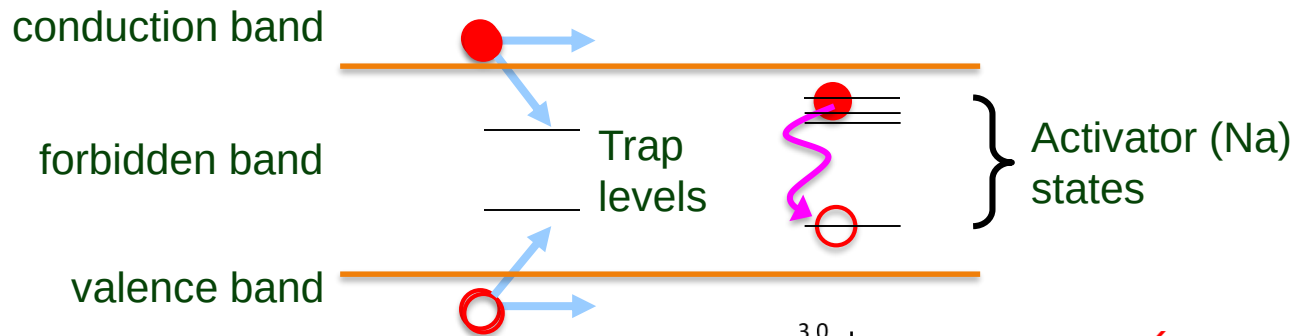


-) Installed and commissioned in 2010 (K. Meierbachtol, PhD. MSU 2012)
-) Analysis of light-output response using ^{76}Ge primary beam @ 130 MeV/u
-) Extraction of **Light-output resolution** for each crystal (average **0.34%, sigma**)
-) Conversion of Light-output into TKE requires complex calibration



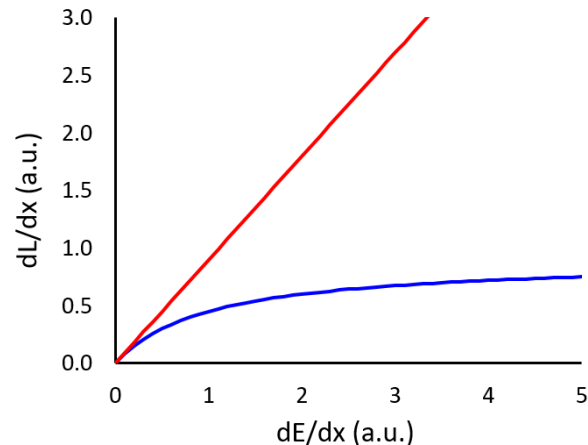
Light Response from CsI(Na) Crystals

-) Light output in Scintillators ~~LINEAR~~ Energy deposited (ΔE)
-) Light output in Scintillator depends on ΔE , Z , A



Birks “Quenching” effect
(J.B. Birks, Pergamon Press, 1960)

$$\frac{dL}{dx} = S \frac{dE}{dx} \cdot \left(1 + k B \frac{dE}{dx} \right)^{-1}$$



Characterization of Light Response of CsI(Na) Crystals in S800 Hodoscope

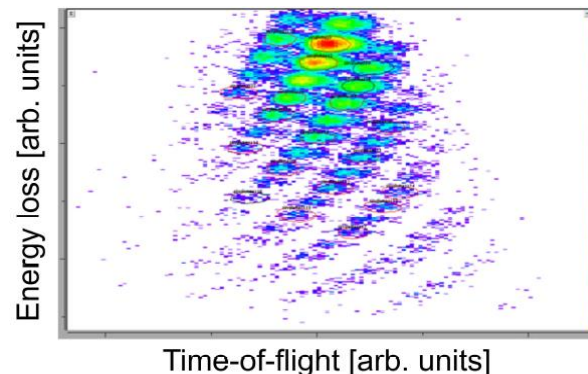
(Horn *et al.*, NIM A 320, 1992)

$$\frac{dL}{dx} = S \frac{dE}{dx} \cdot \left(1 + k B \frac{dE}{dx}\right)^{-1} \longrightarrow L = a_0 + a_1 \left[TKE - a_2 AZ^2 \ln \left(\frac{TKE + a_2 AZ^2}{a_2 AZ^2} \right) \right]$$

***L* vs. *TKE* function obtained for each crystal** from global fit:

- Fragmentation nuclei from ^{76}Ge
- TKE range ~4200–7900 MeV

(K. Meierbachtol, PhD. MSU 2012.)



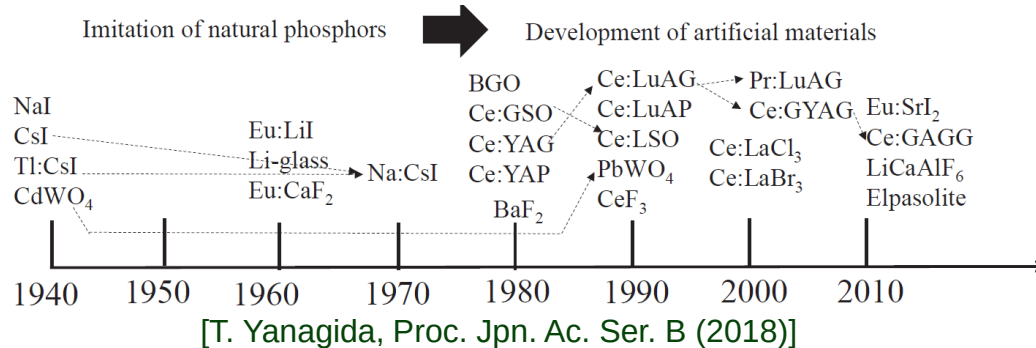
***L* resolution 0.34% (σ)**



TKE intrinsic resolution 0.85% (σ)
Not sufficient for heavy nuclei $\sim {}^{238}\text{U}$ (0.35%)

TKE detector based on Scintillating Crystals

-) Are inorganic scintillator good for TKE measurement of heavy nuclei (^{238}U)?



^{18}O @ 70 A MeV

[Suda *et al.*, RIKEN Prog. Re. 2002]

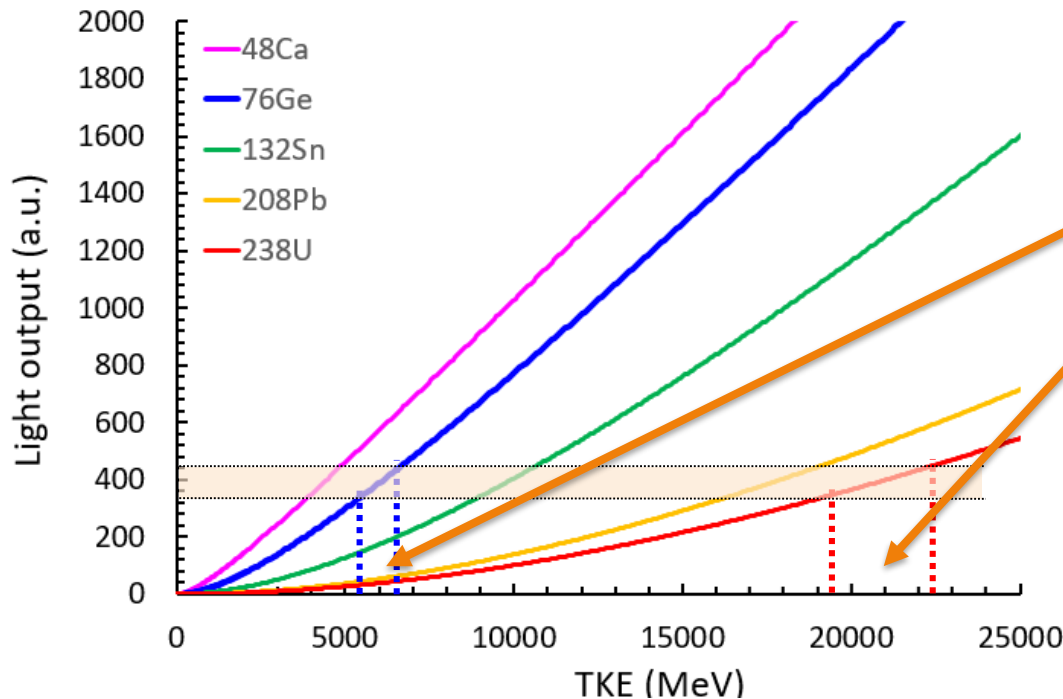
- Light-output intrinsic resolution
→ Not clear “winner”
- Response to Heavy Ions? (Quenching)
→ Not much is known

Crystal	Res. % (FWHM)
NaI(Tl)	0.95
CsI(Tl)	1.5
GSO	1.8

TKE detector based on Scintillating Crystals

What can we expect for heavy ions using coefficients obtained by Krista (in the region around ^{76}Ge)?

$$L = a_0 + a_1 \left[TKE - a_2 AZ^2 \ln \left(\frac{TKE + a_2 AZ^2}{a_2 AZ^2} \right) \right]$$



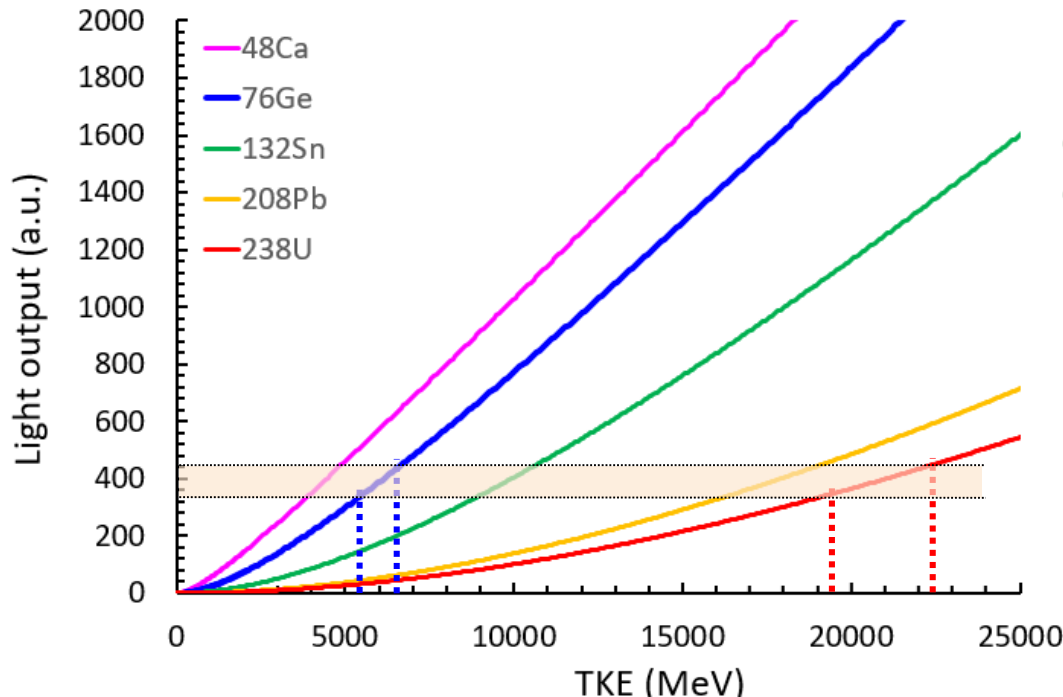
For the same intrinsic L resolution:
Quenching effects degrade TKE
resolution for heavier nuclei

TKE detector based on Scintillating Crystals

What can we expect for heavy ions using coefficients obtained by Krista (in the region around ^{76}Ge)?

(Parlog *et al.*, NIM 2002)

$$L = a_0 + a_1 \left[TKE - a_2 AZ^2 \ln \left(\frac{TKE + a_2 AZ^2}{a_2 AZ^2} \right) \right] + a_4 a_2 AZ^2 \ln \left(\frac{TKE + a_2 AZ^2}{a_3 A + a_2 AZ^2} \right)$$



HOWEVER:

delta-electrons reduce effect of quenching (Meyer-Murray model) (more important for heavier nuclei)

-) Could delta-e compensate quenching?
-) Need more data for heavier nuclei

Conclusions

- The S800 spectrograph is expected to play critical role in the scientific program at FRIB
- Current detection system provides separation capabilities (including charge-states) in regions of nuclei as high as $\sim Z=50$.
- Future detector development will improve position, energy-loss, and time-of-flight resolutions by more than a factor 2.
- Alternative solutions to improve the TKE separation needed for Q separation of heavy nuclei near ^{238}U are currently under consideration.
- Further studies on the response of scintillators to heavy nuclei are needed: particularly, role of quenching effects and delta electrons.

Thanks!

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Alexandra Gade, Shumpei Noji, Yassid Ayyad,
Andreas Stolz, Alfredo Estrade, Kailong Wang,
Dirk Weisshaar, Brad Sherrill, Oleg Tarasov,
Antonio Villari, Georg Bollen