Introduction on the HIRIBL separator at HIAF

He Wang

Institute of Modern Physics, CAS

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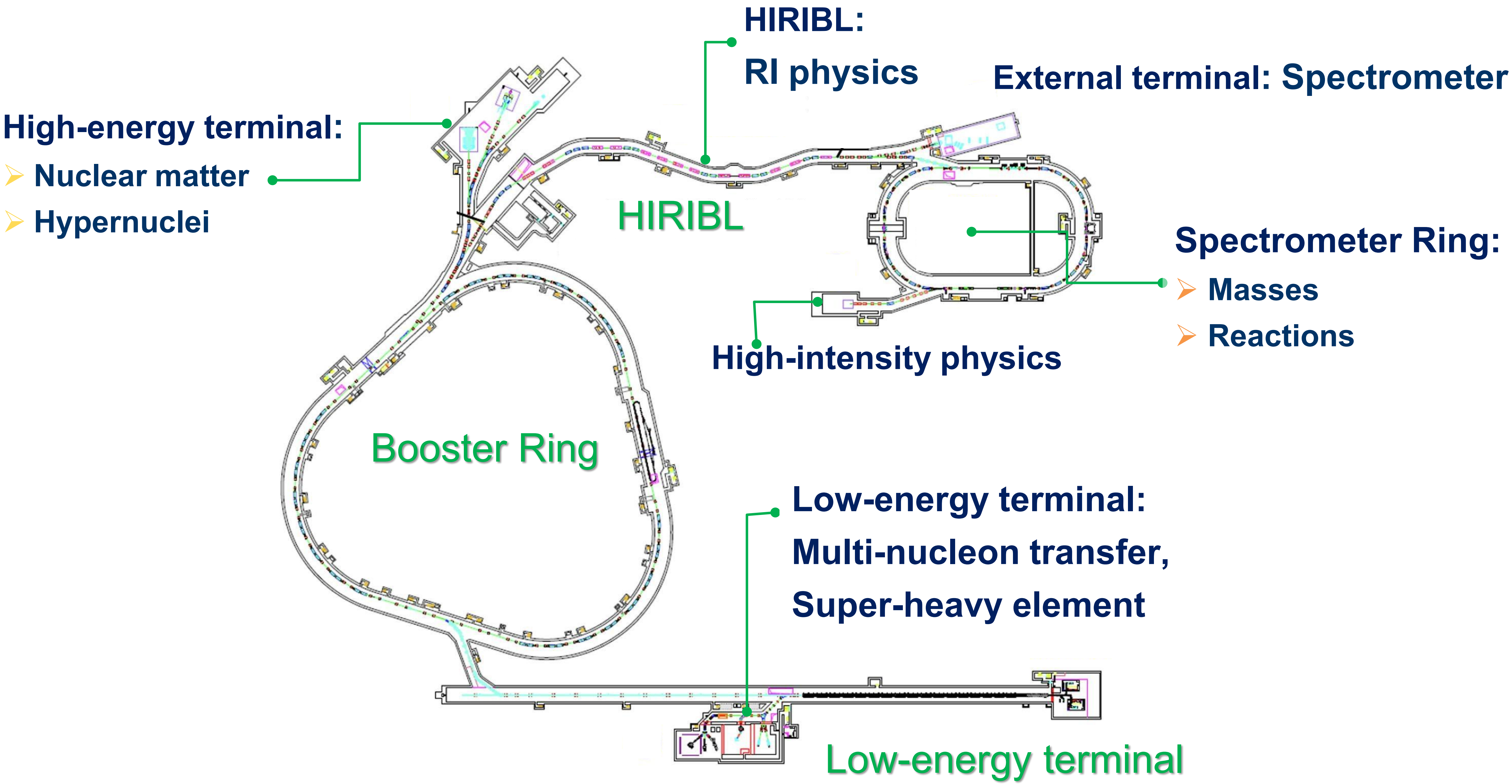
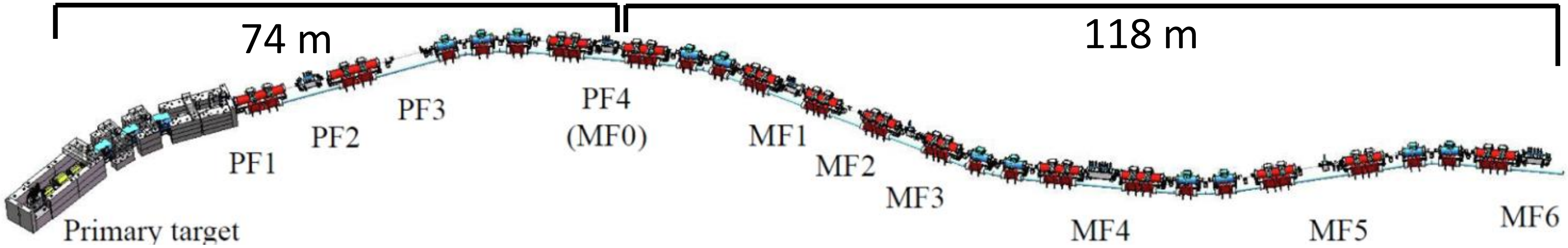
Content

- Concept of HIRIBL (HFRS)
  - Operation modes
- Beam-line devices
  - PID detectors
- Production scenario for astrophysics
- Summary

Experimental terminals



HIRIBL: HIgh-rigidity Radioactive Ion Beam Line



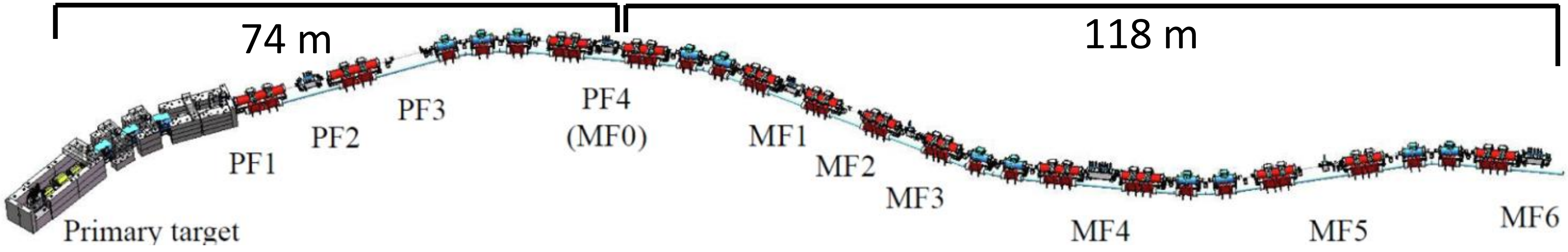
HIAF beam

Ion species	Energy (GeV/u)	Intensity (ppp)
p	9.3	5.0×10^{13}
$^{12}C^{6+}$	4.2	6.0×10^{12}
$^{78}Kr^{19+}$	1.7	2.5×10^{12}
$^{209}Bi^{31+}$	0.85	3.0×10^{11}
$^{238}U^{35+}$	0.835	2.0×10^{11}

HIRIBL

- Pre-separator： 74m
- Main separator： 118m
- Beams： H~U
- Max. beam rate： ~10^7 pps
- Bρ max: 15 Tm

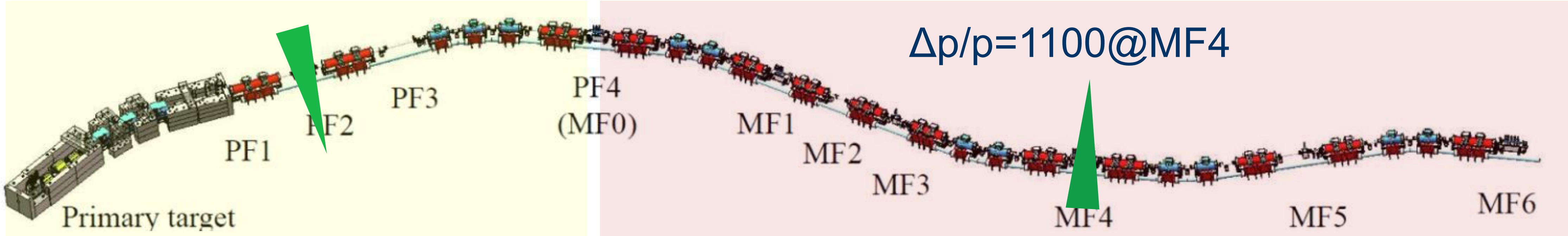
HIRIBL: HIgh-rigidity Radioactive Ion Beam Line

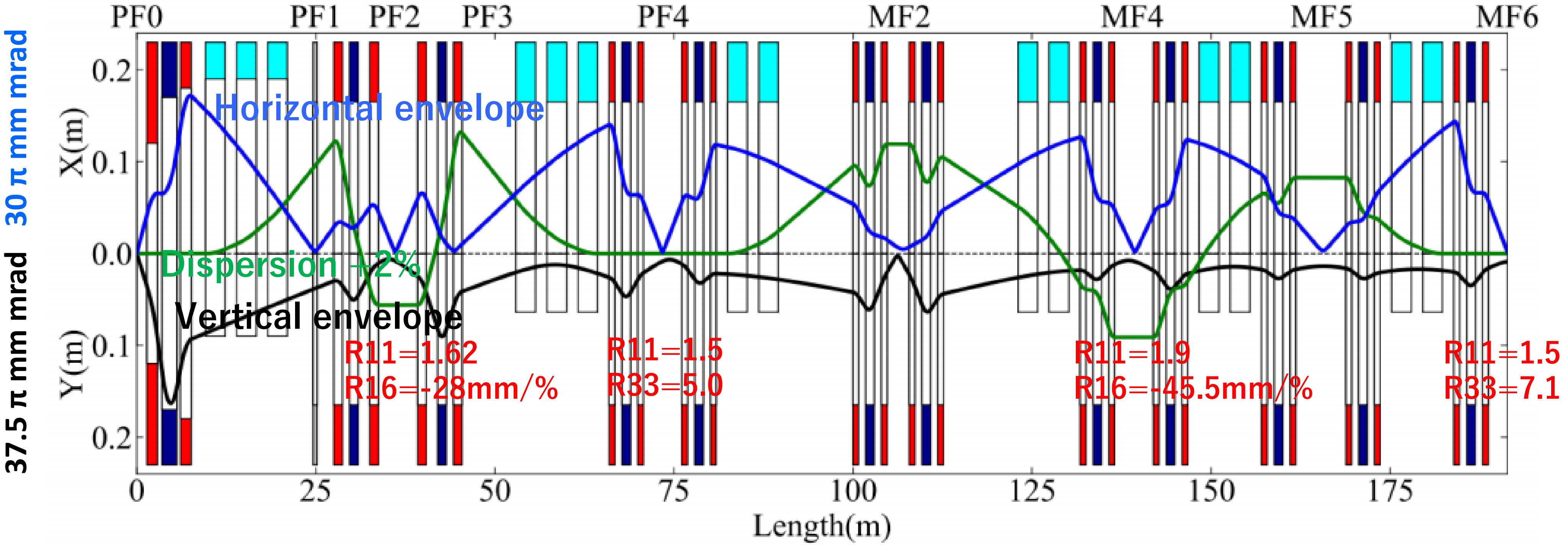


	Length (m)	Beam size at target (mm)	Angular acceptance(mrad)	Momentum acceptance	Resolving power	Max. Bρ (Tm)
HIRIBL (HFRS) NIM.B 547(2024),165214	191.38	±1/±1.5	±30 (X); ±25 (Y)	±2.0	850/1100 (ΔX=±1mm)	**15 / 25**
SuperFRS NIM.B 204(2003),71	182.2	±1/±2	±40 (X); ±20 (Y)	±2.5	750/1500 (ΔX=±1mm)	20
BigRIPS PTEP 2012,03C003	78.2	±0.5/±0.5	±40 (X); ±50 (Y)	±3	1260/3420 (ΔX=±0.5mm)	9.5
ARIS NIM.B 317(2013), 349	86.8	±0.5/±0.5	±40 (X); ±40 (Y)	±5	1720/3000 (ΔX=±0.5mm)	8

Operation mode I: Achromatic

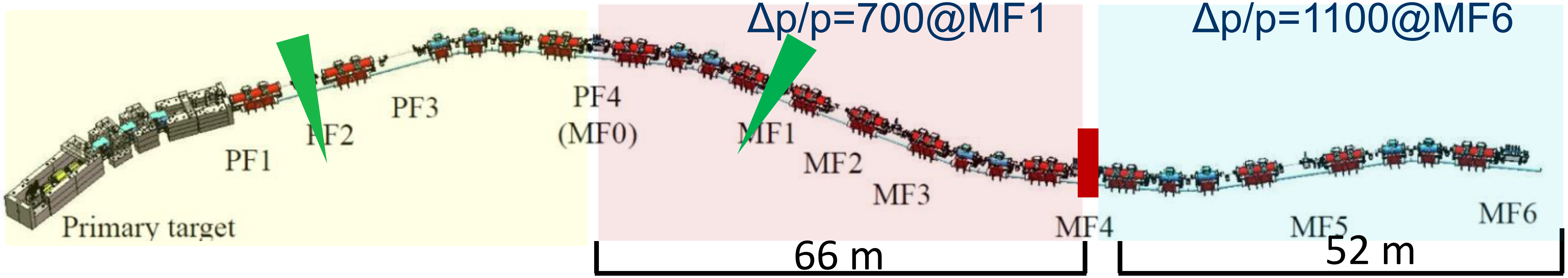
pre-separator + separator

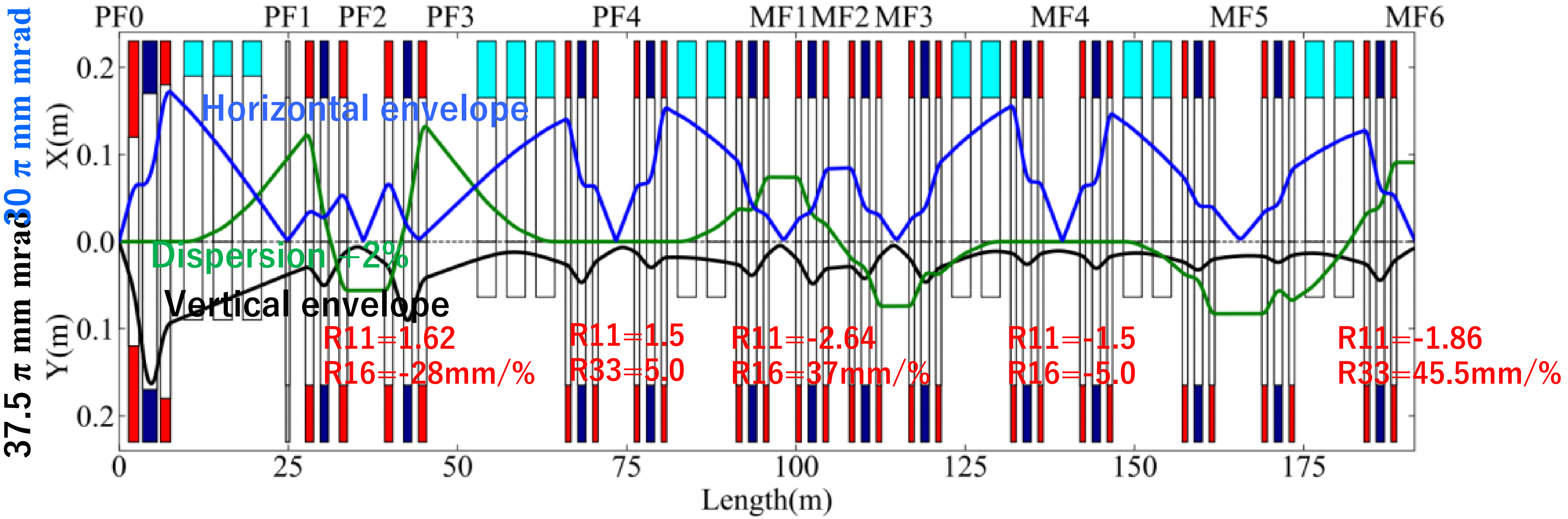




Operation mode II: Dispersive

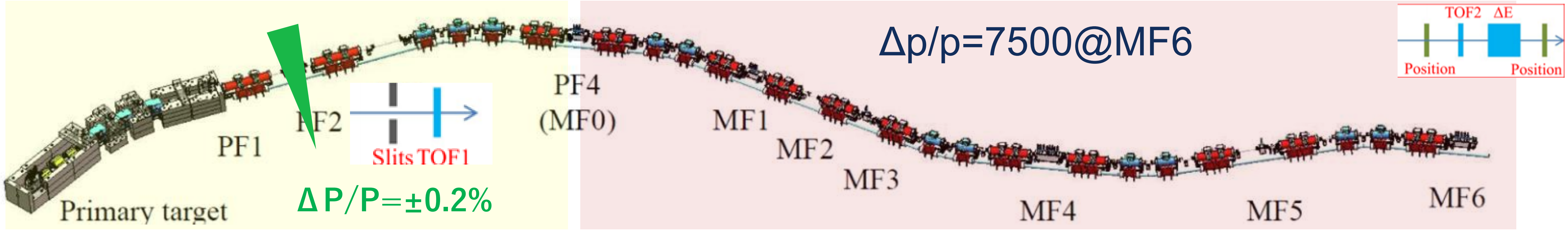
pre-separator + separator + spectrometer

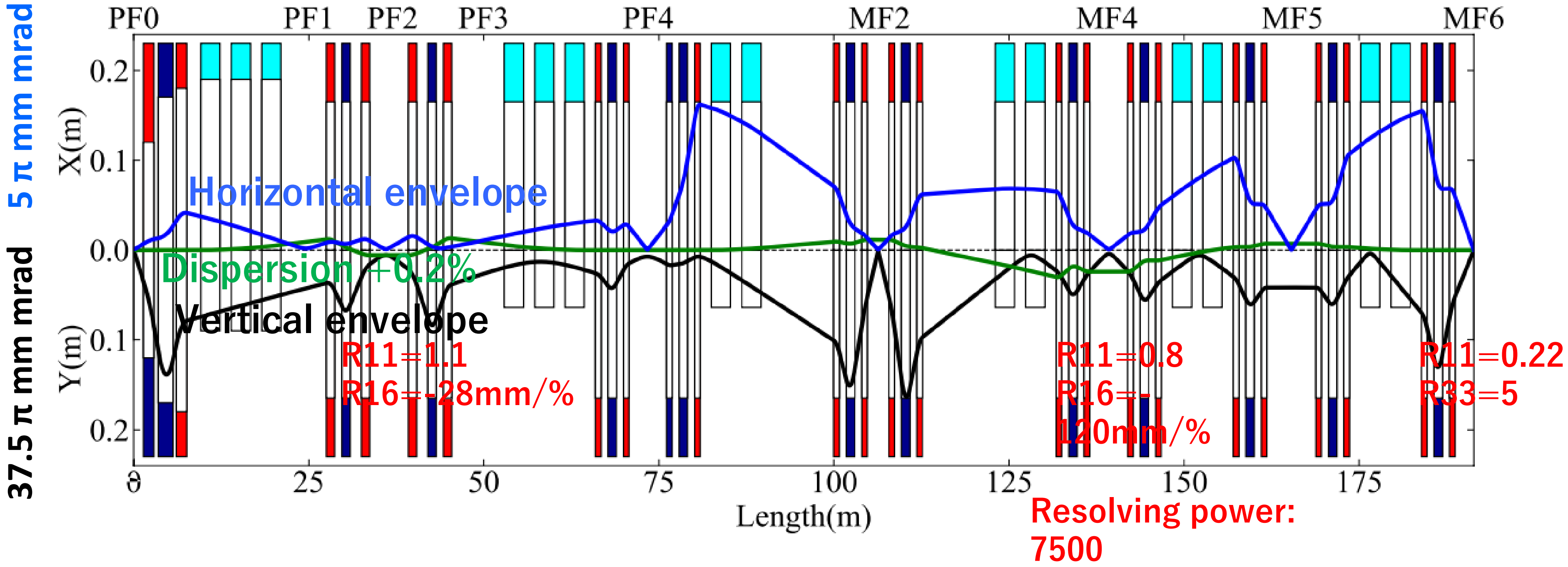




Operation mode III: High-resolution

pre-separator + separator

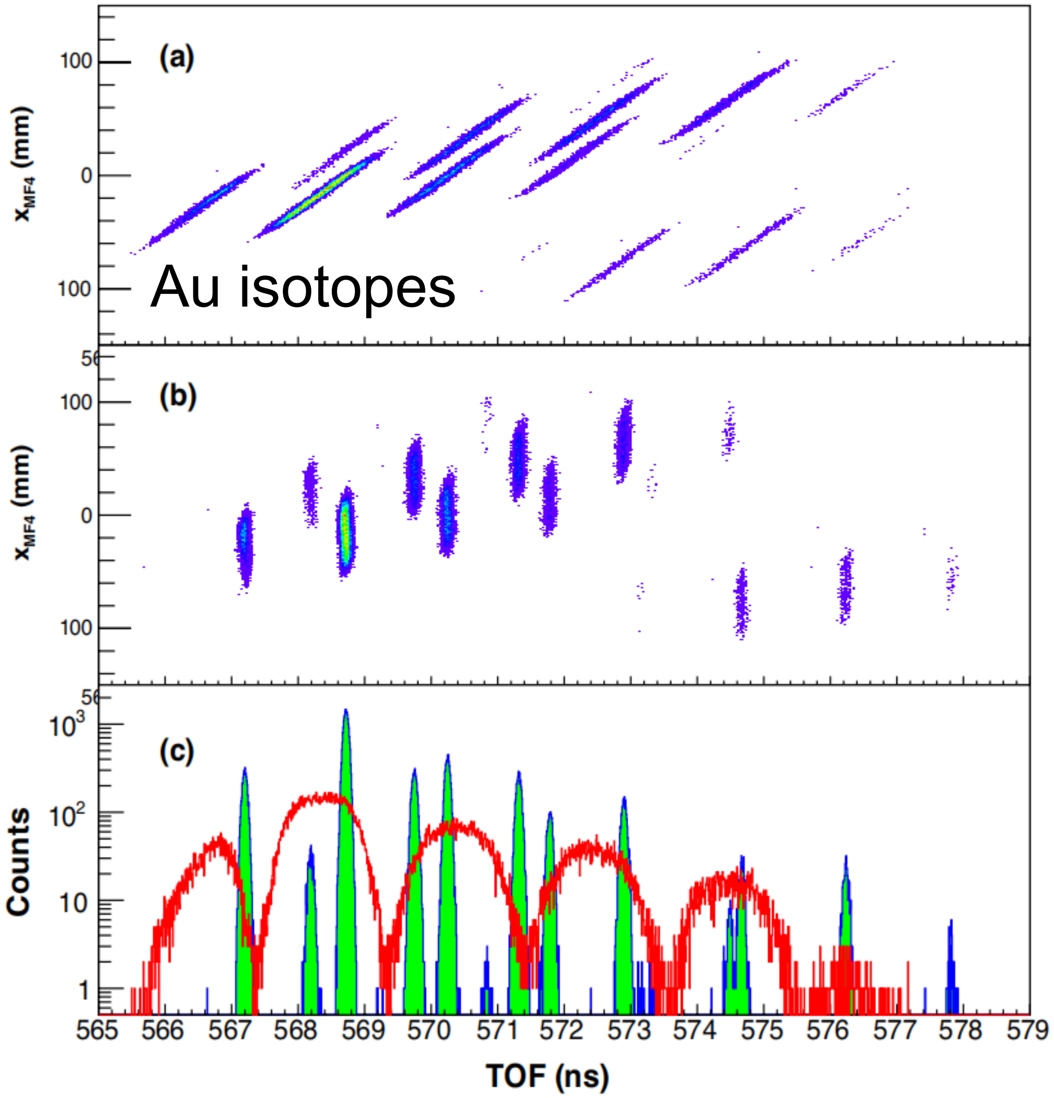


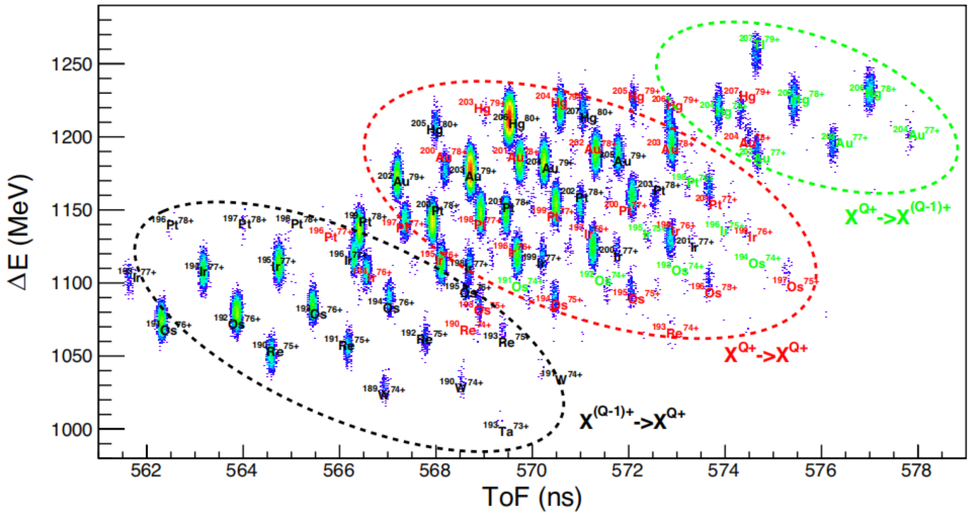


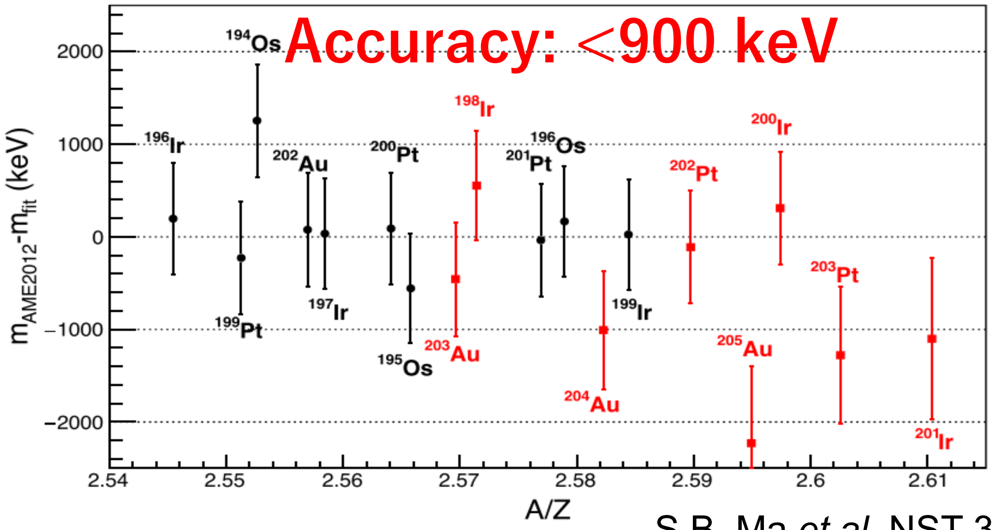
Operation mode III: High-resolution Bρ-TOF for mass

^{208}Pb(850.74 MeV/u, 1.1e+11 ppp)+C(4.4 g/cm^2)->^{204}Au

σ_{TOF}=30 ps; $\sigma_{Position}$=0.5 mm; $\sigma_{\Delta E}$=0.4%

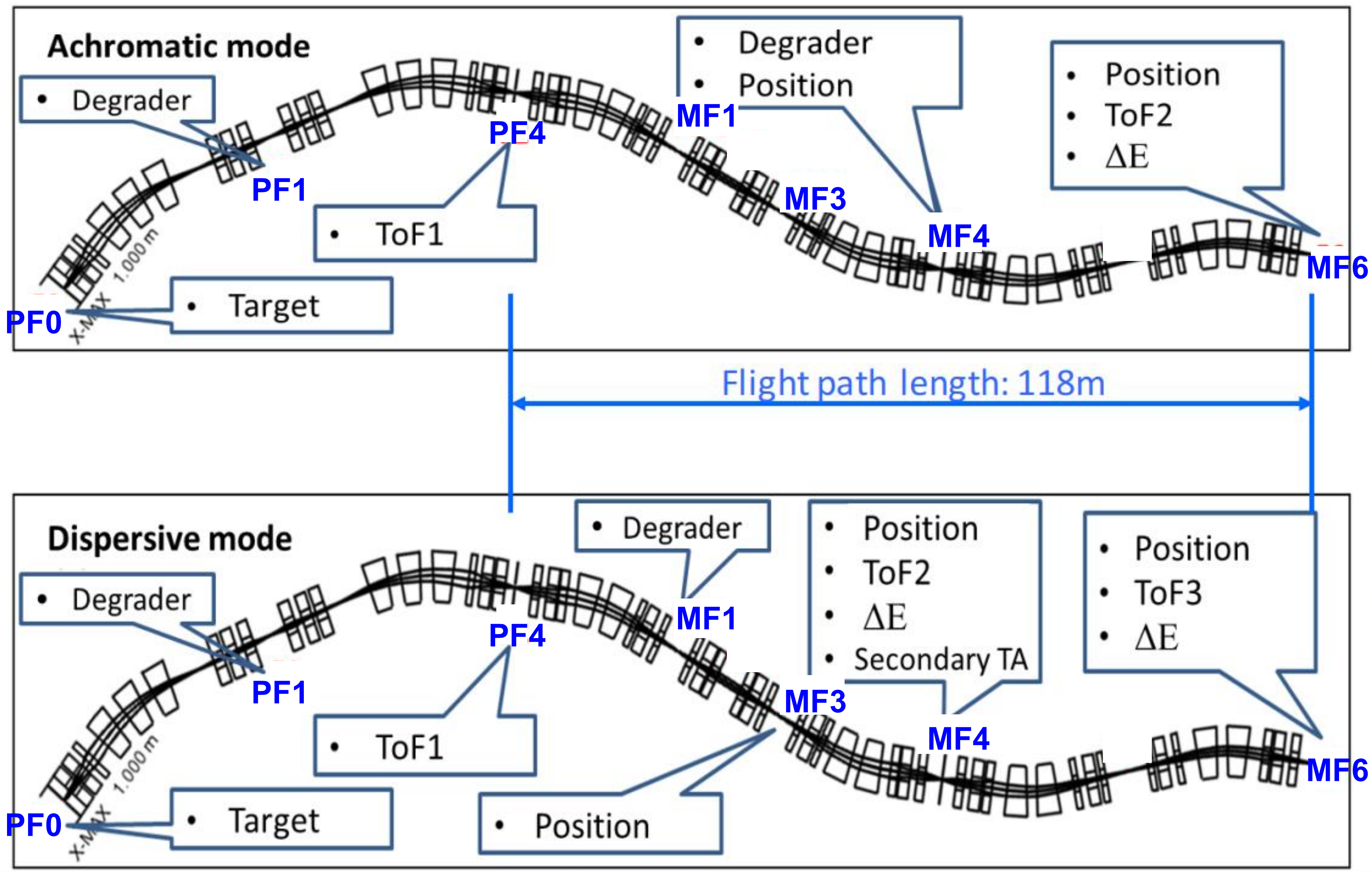






S.B. Ma *et al*. NST 35(2024) 97

Beam-line detectors and devices



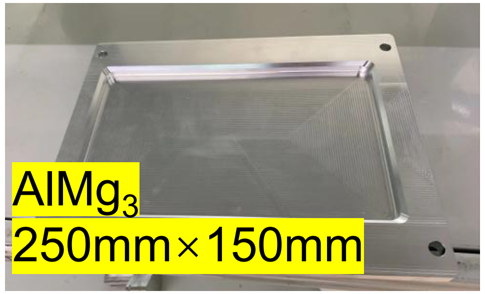
- **Production and purification of RIBs**
  - Target
  - Degrader
  - Slits
- **PID, Bρ-TOF-ΔE**
  - TOF detectors
  - Tracking detector
  - ΔE detector

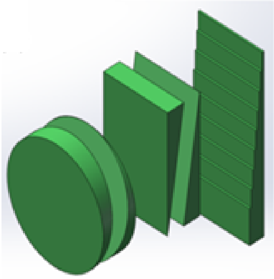
Beam-line devices

Graphite Target

slow (U, 3.16 kW)
fast (U, 9.5 kW)
extraction modes

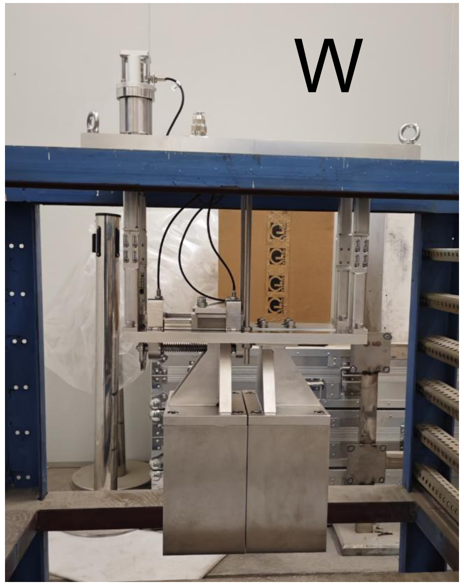
Degrader





-
- PF2,MF3,MF4

Slit



- Volume: 140mm(X)*100mm(Y)*190mm(Z)
- Weight: ~51 kg
- Repetitive motion accuracy: <0.1mm

Courtesy: Z. Yang, et al

PID detectors requirement

- TOF Detector

Position	Dimension	Resolution(σ)	Counts	Particles	Quantity
PF4	~40(x)×40(y) mm^2	<50 ps	~7e+6 ppp	H ~ U	1
MF4	~40(x)×60(y) mm^2	<50 ps	~5e+6 ppp	H ~ U	1
MF6	~250(x)×70(y) mm^2	<50 ps	~5e+6 ppp	H ~ U	1

- Position Detector

Position	Dimension	Resolution(σ)	Counts	Particles	Quantity
MF3	~200(x)×60(y) mm^2	<0.5 mm	Total：~7e+6 ppp	H ~ U	2
MF4	~220(x)×80(y) mm^2	<0.5 mm	Total：~7e+6 ppp	H ~ U	2
MF6	~250(x)×60(y) mm^2	<0.5 mm	Total：~5e+6 ppp	H ~ U	2

- *ΔE* Detector

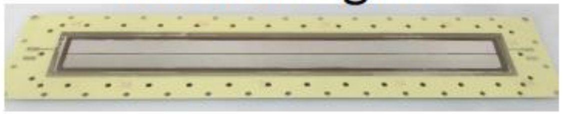
Position	Dimension	Resolution(σ)	Counts	Particles	Quantity
MF4	~70(x)×60(y) mm^2	<0.5%	~5e+6 ppp	H ~ U	1
MF6	~250(x)×60(y) mm^2	<0.5%	~5e+6 pps	H ~ U	1

PID resolution requirements

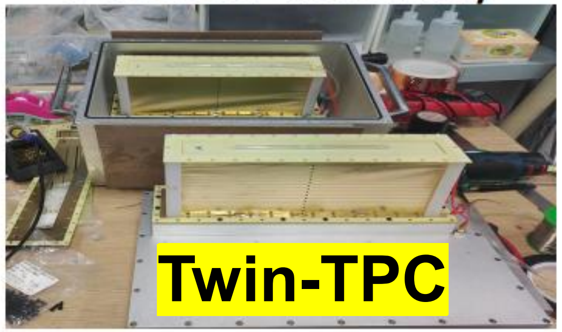
PID detectors: Tracking

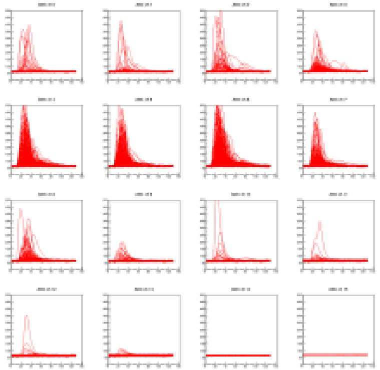
Courtesy of X.H. Zhang and H.J. Ong

Micromegas

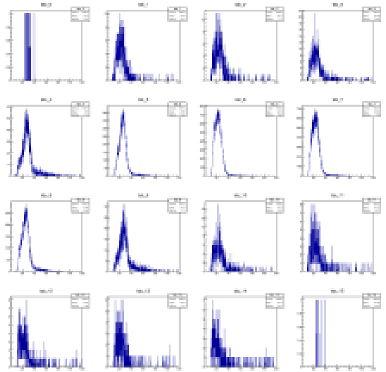


Detector assembly



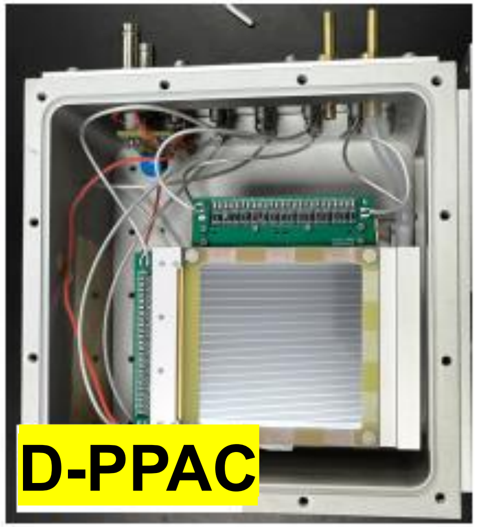


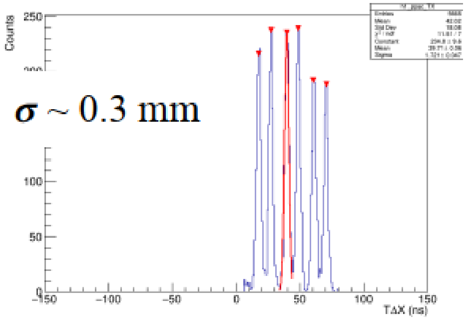
Pulse shape



Drift time

Z.X. Ma and E.Q. Liu et al.



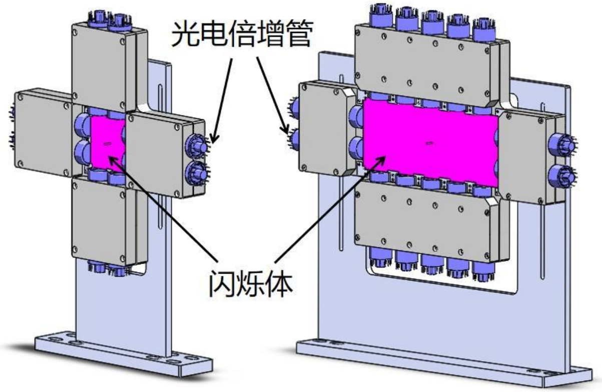


Position

C. Yuan, F.S. Shi et al.

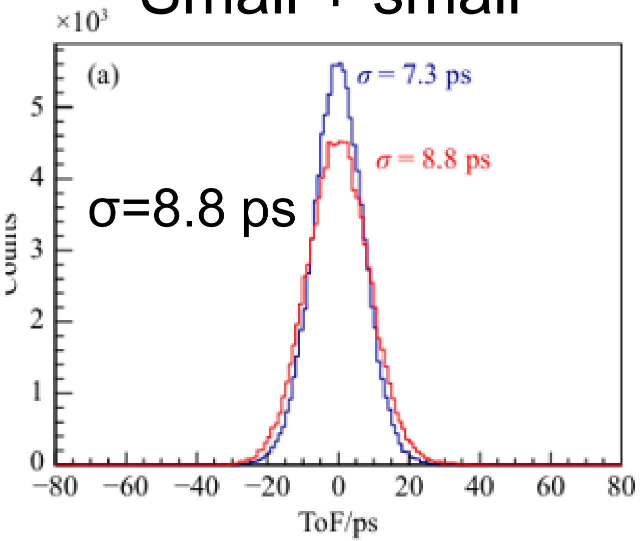
PID detectors: TOF

H6533

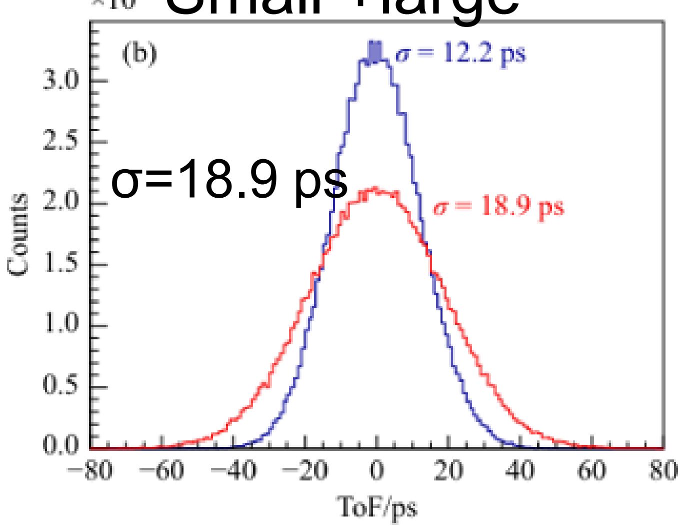


70x70 260x100

Small + small

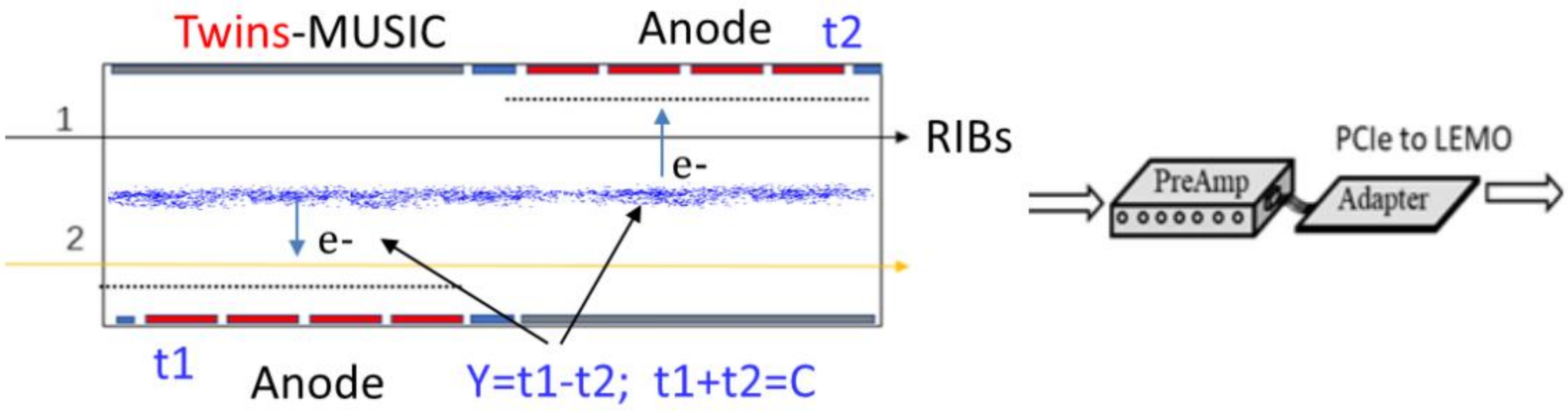


Small +large

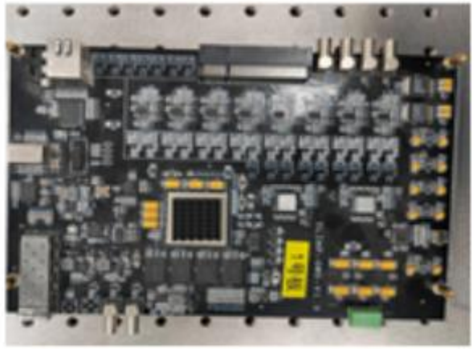


X.T. Wu et al., Nuclear Physics Review 41(2), 670—677 (2024)

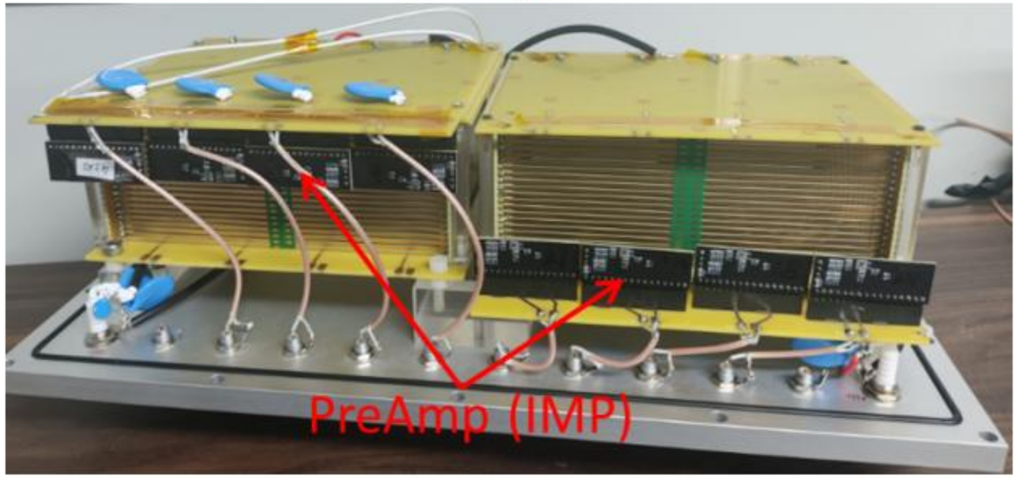
PID detectors: Twins MUSIC



Waveform digitizer



Prototype



W.D.Zhang, F.H.Lu, S.W.Tang *et al.*

PID detectors: HIRIBL DAQ

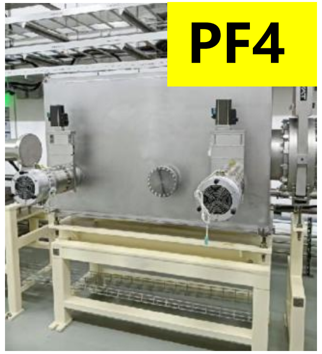
Challenges

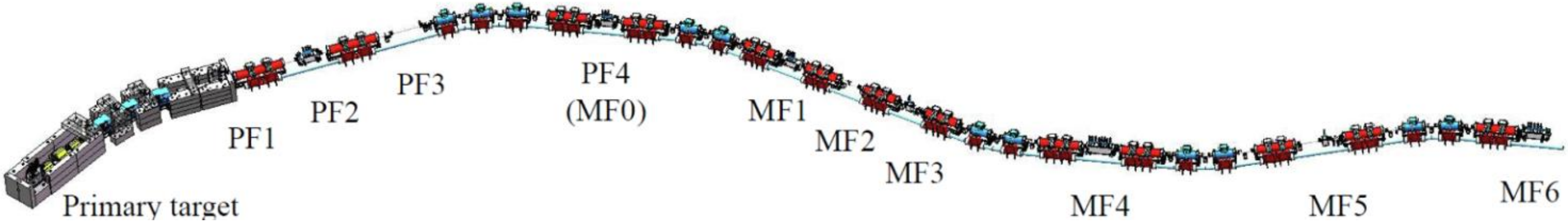
- High data rate:
  Average 9 GB/s, peak 18 GB/s
- Large spatial scale: 100m~200m, fiber
- Compatibility between new and old electronic systems
- Triggerless
- Time-stamp based

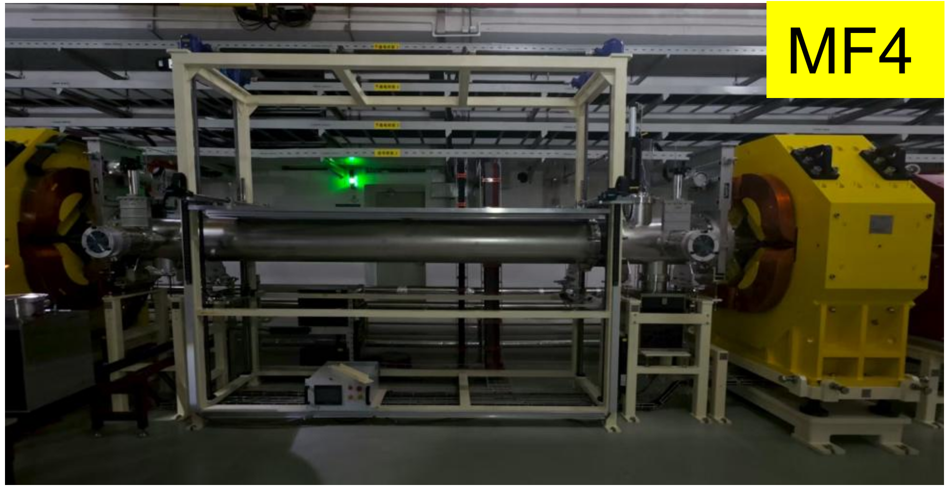
CROB-PCIe (bandwidth 32Gbps/4GB/s)

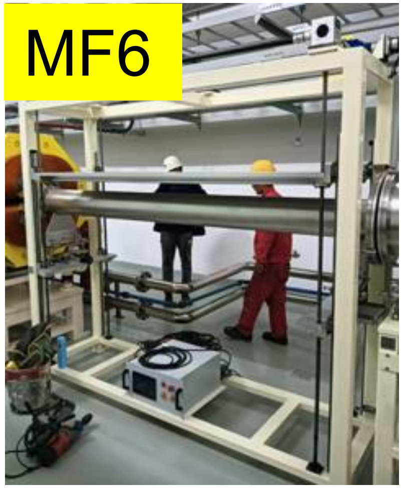
Courtesy: J.F Yang, et al

HIRIBL: Facility tour on 9/4

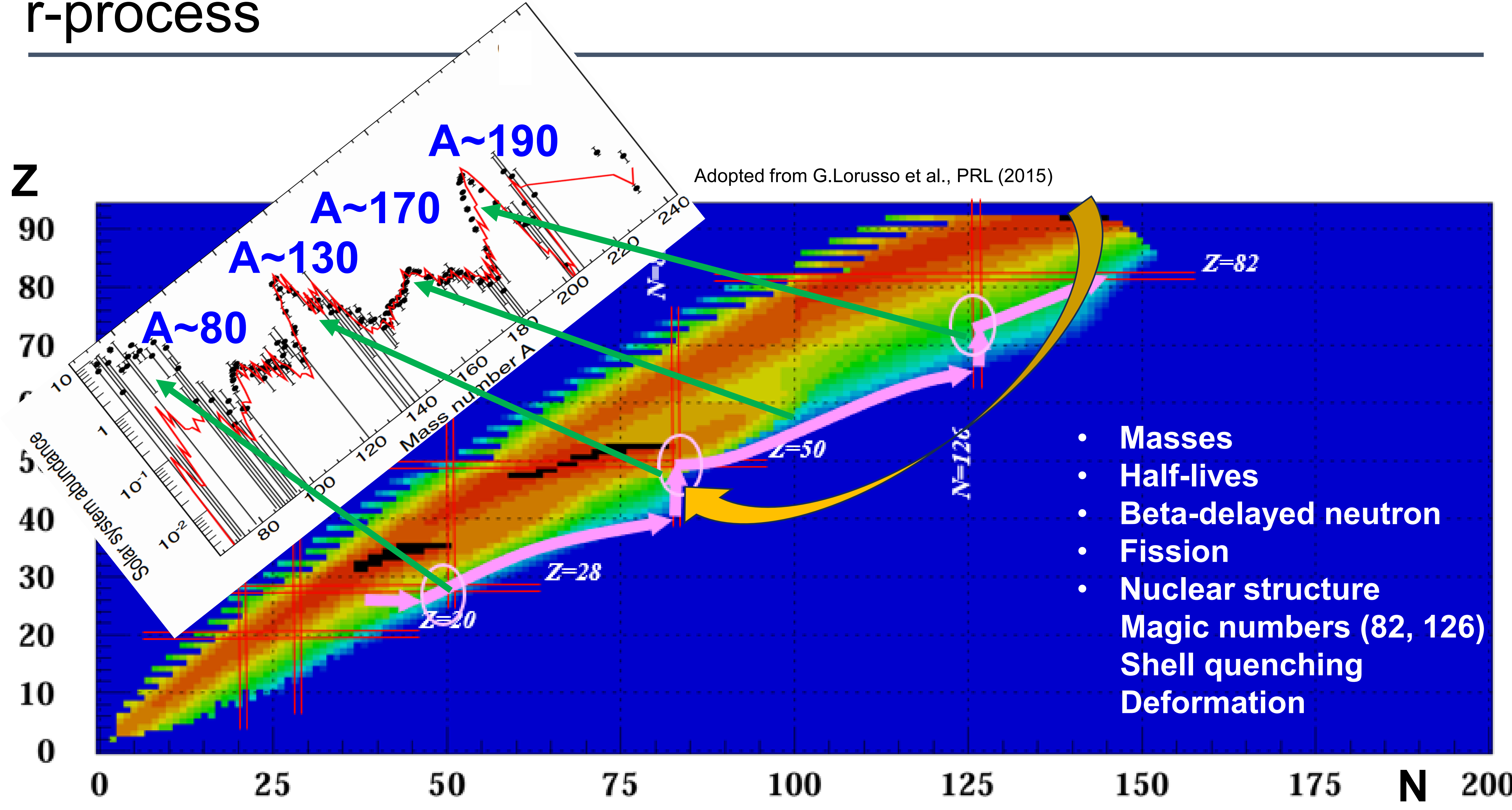








r-process



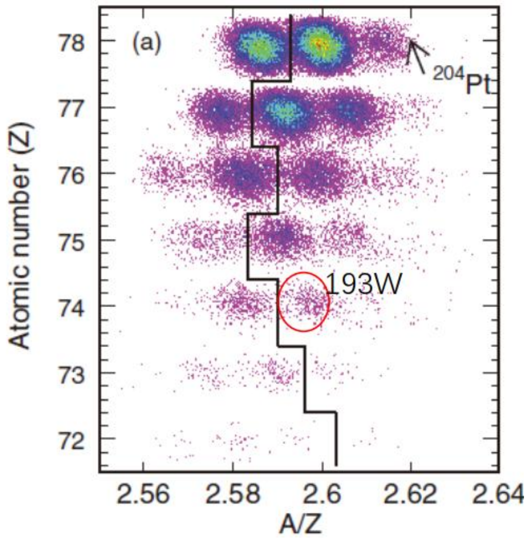
- Masses
- Half-lives
- Beta-delayed neutron
- Fission
- Nuclear structure
  Magic numbers (82, 126)
  Shell quenching
  Deformation

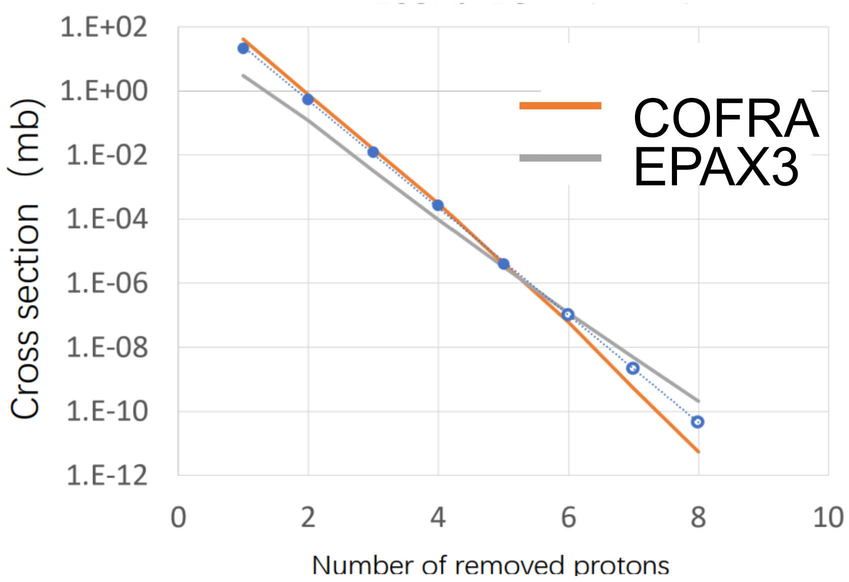
1st and 2nd peaks: *N* = 50 and *N* = 82

	HIAF	RIBF	FRIB
^{238}U intensity [pnA]	10^{11} ppp→1.6	100	356
Target [mm]	100-mm C	4-mm Be	1.8-mm Be
Energy after target [MeV/u]	270	250	140
Charge state	99%	99%	99%
Factor	1	2.5	2.4

3^{rd} peak: N=126

^{208}Pb+^{9}Be→N=126 isotopes





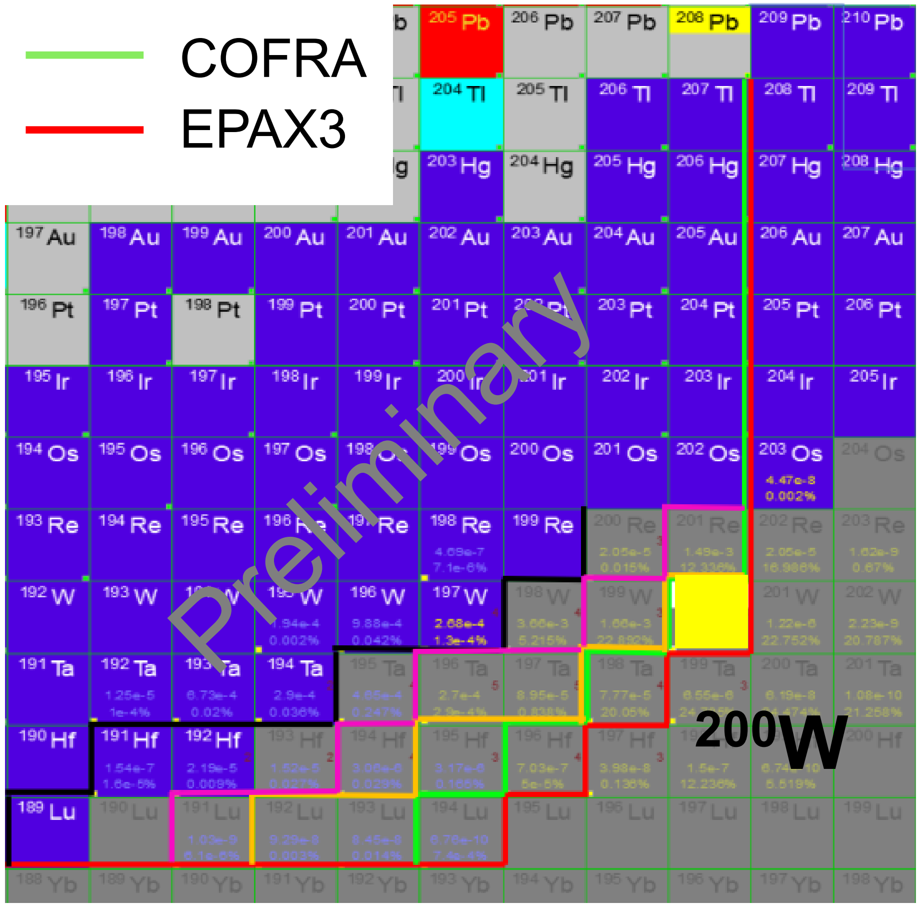
T. KURTUKIAN-NIETO *et al.*, PRC 89, 024616 (2014)

^{238}U+4mm-^{9}Be→^{213,215}Tl

70pnA, 4000/2000 ions

T.T. Yeung et al., PRL 133, 072501 (2024)

^{208}Pb+C (0.5g/cm^{2})@HIAF

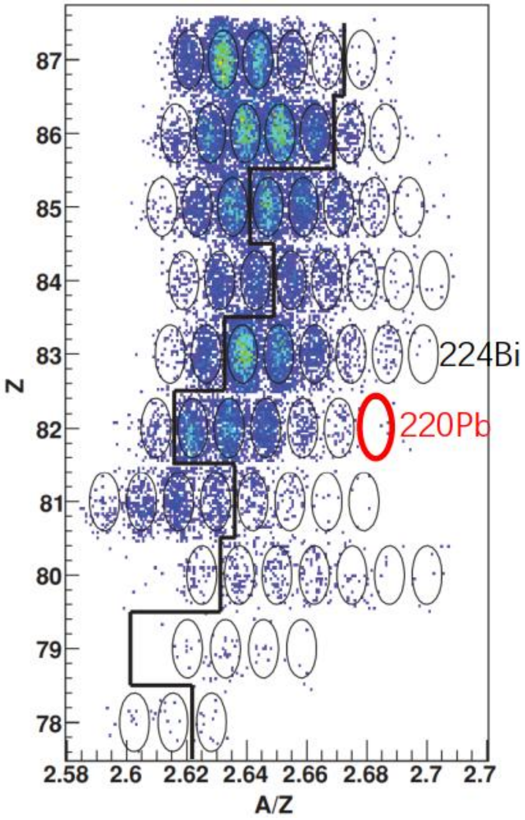


20 New isotopes

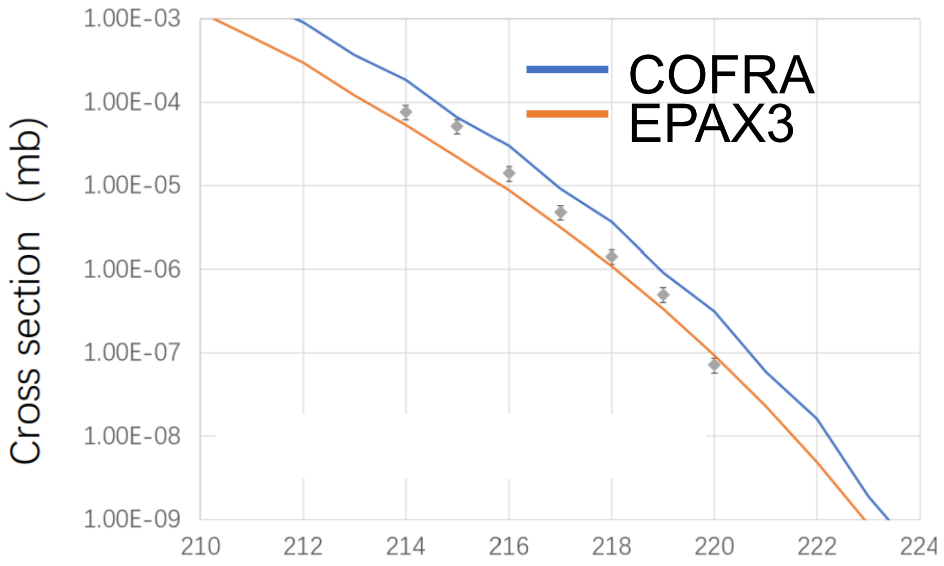
^{189,190}Lu-^{194}Lu, ^{191,192,193}Hf-^{196}Hf

^{195}Ta-^{198}Ta, ^{198}W-^{200}W, ^{200}Re-^{201}Re

3rd peak: Beyond ^{208}Pb

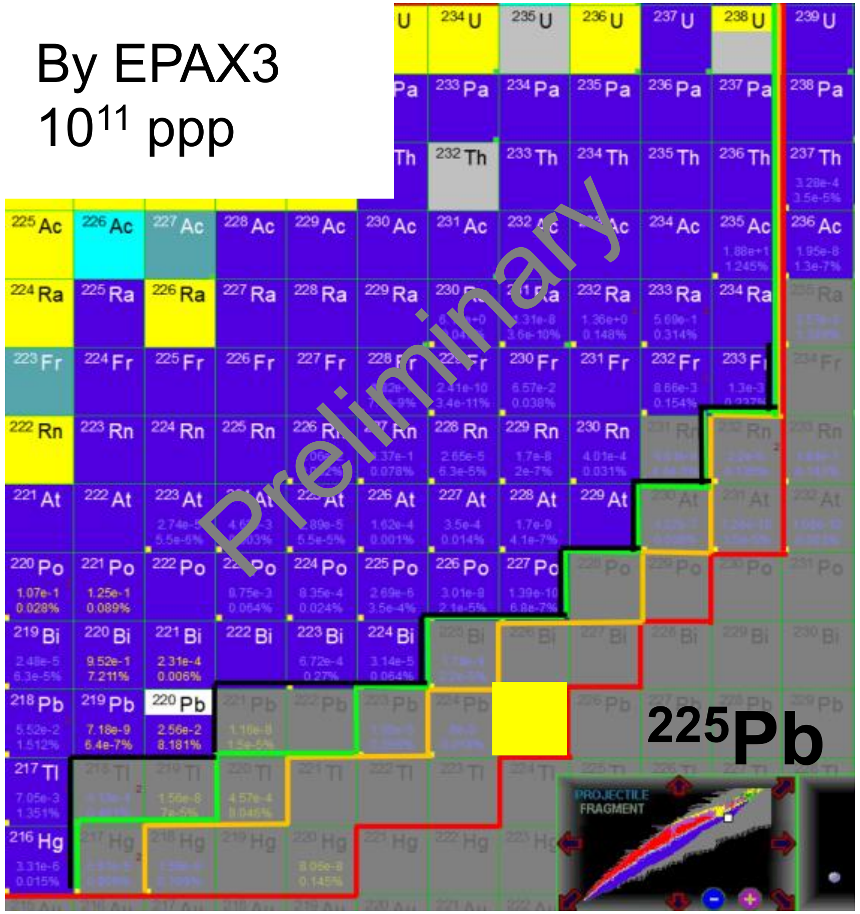


^{238}U+^{9}Be (2.5 g/cm^{2})→Pb



H. ALVAREZ-POL, PRC 82, 041602(R) (2010)

^{238}U+C (0.5g/cm^{2})@HIAF

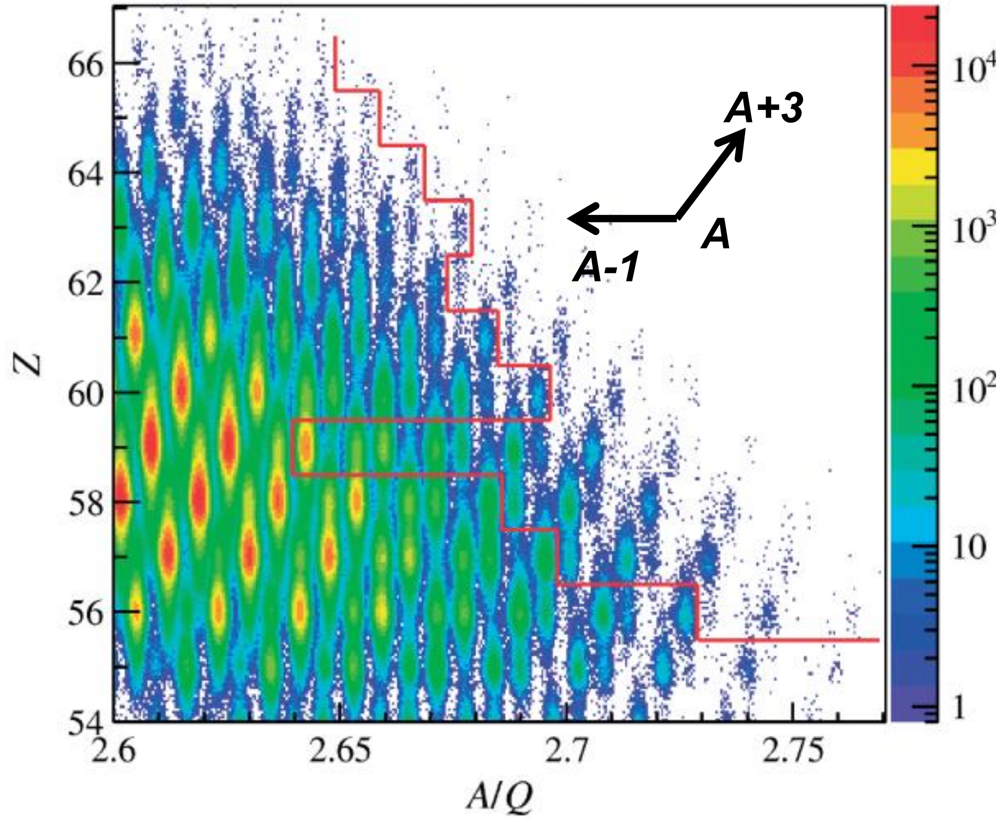


23 New isotopes

^{232}Rn, ^{230,231}At, ^{228,229}Po, $^{225-227}$Bi, $^{221-225}$Pb, $^{218-223}$Tl, $^{217-220}$Hg

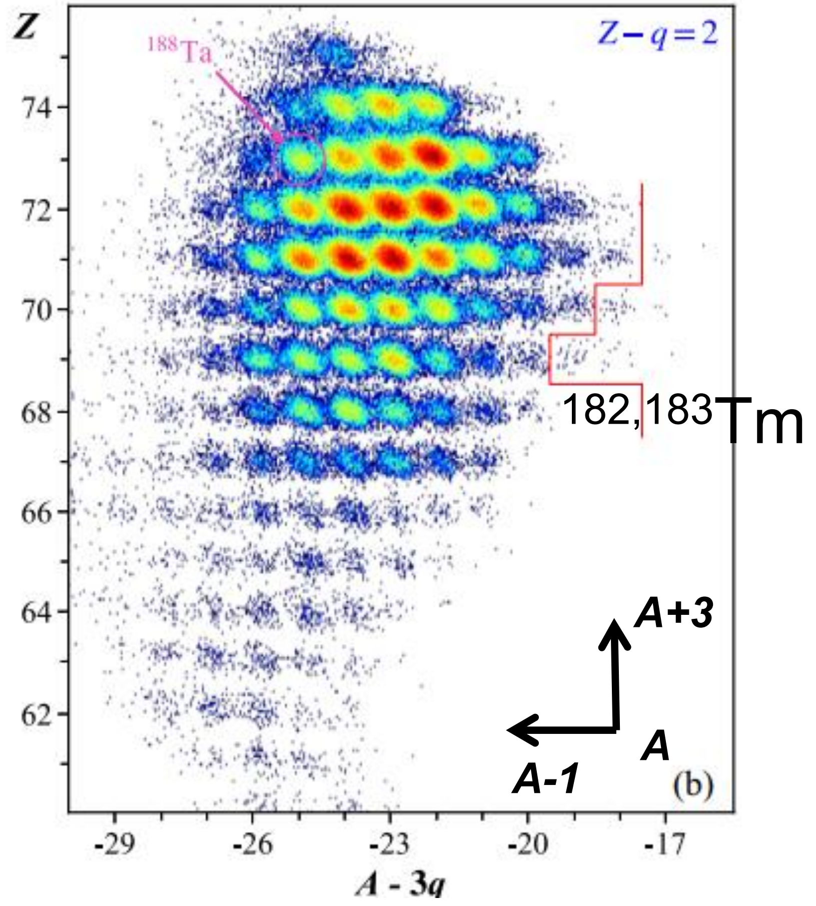
Rare-earth region: Fission and fragmentation

$^{238}U+^{9}Be$ (4/4.9 mm)@345 MeV/u



N. Fukuda et al., JPSJ 87, 014202 (2018)

$^{198}Pt+C$ (3.54 mm)@186 MeV/u



O.B. Tarasov et al., PRL132, 072501 (2024)

Rare-earth region: Projectiles

- Fragmentation of ^{198}Pt, ^{197}Au, ^{208}Pb
- Fission of ^{238}U

Rare-earth region: how to access?

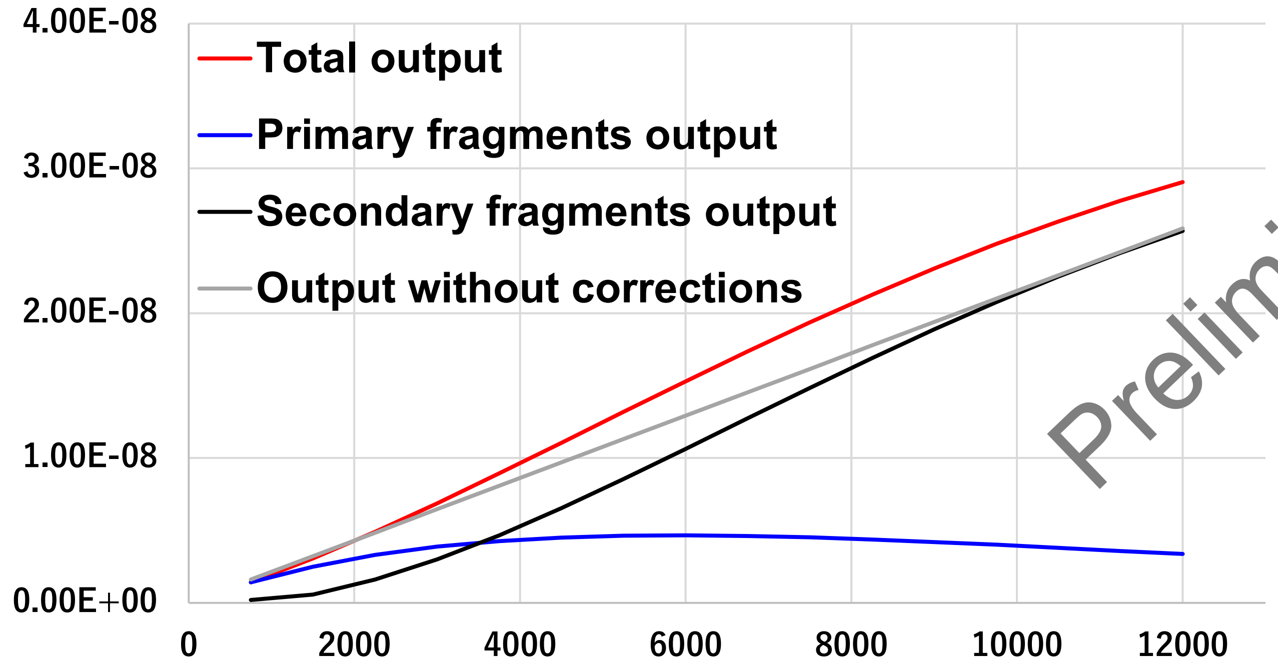
- $^{198}Pt + C \rightarrow ^{181}Er$ @ 850 MeV/u
- Thick target effect
  - Number of target nucleus (T_{tar})
    - Increase
  - Survival probability (P_{sur})
    - Production vs reaction loss
  - Charge-state distribution (R_{FS})
    - Energy dependence
- Production = T_{tar} x R_{FS} x P_{sur}

Preliminary

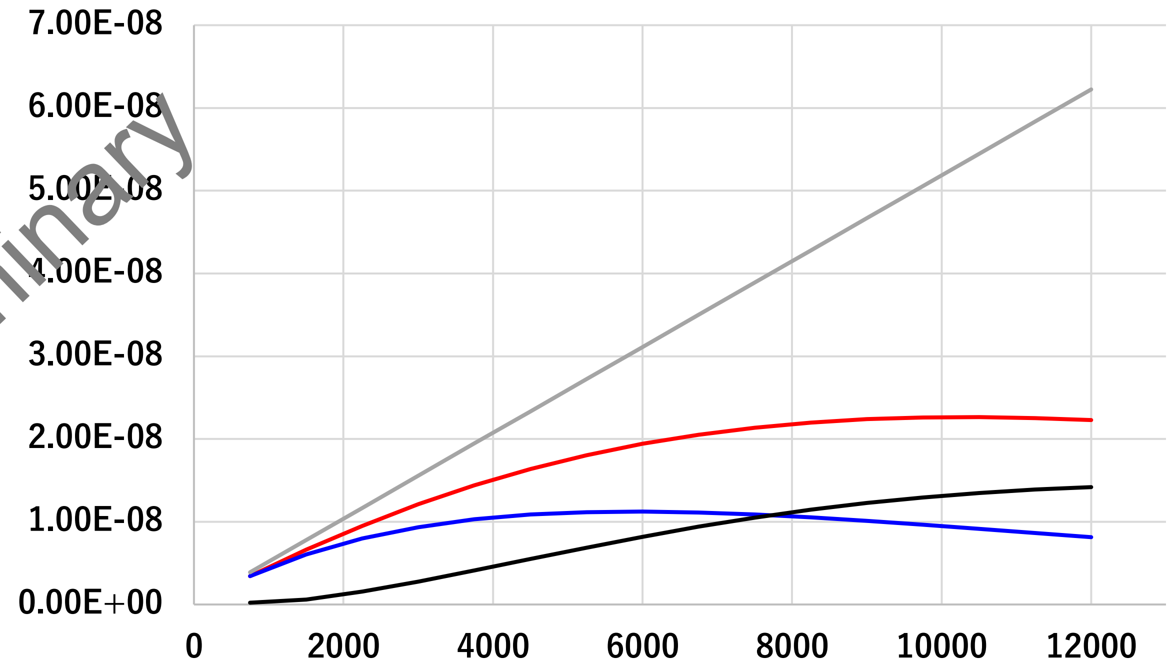
rp-process: thick-target effect

$^{124}Xe + C \rightarrow {}^{98}Cd$

EPAX3:
multi-reaction **enhances** production



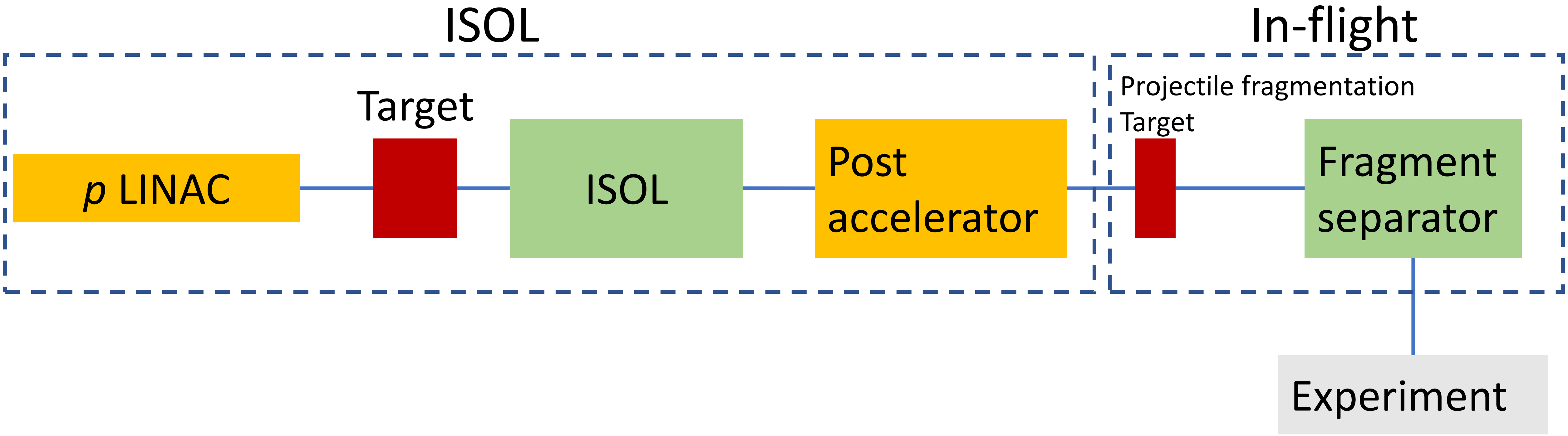
EPAX2:
multi-reaction **reduces** production



Be thickness (mg/cm^2)

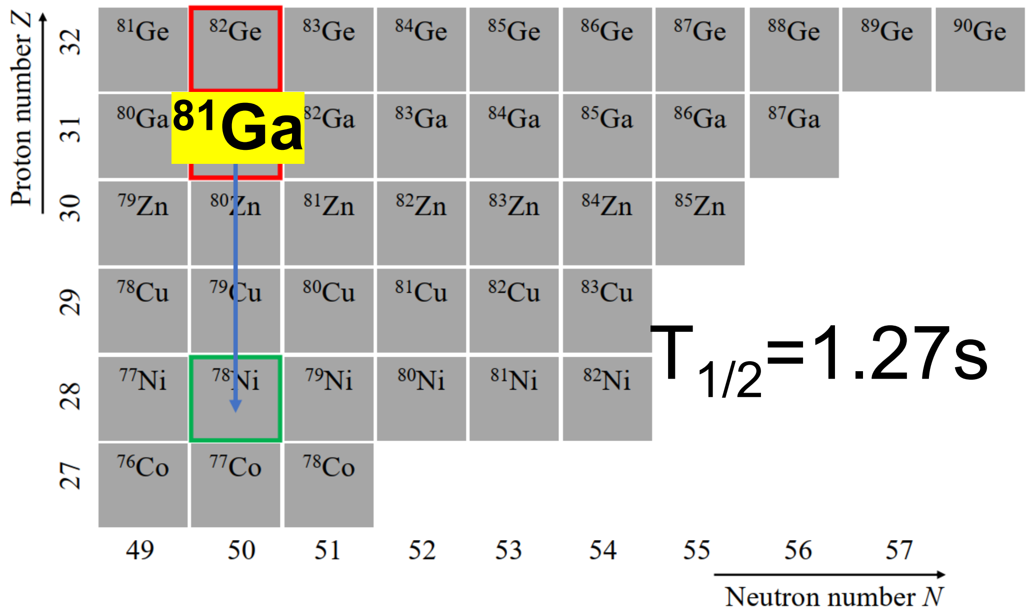
Two-step scheme

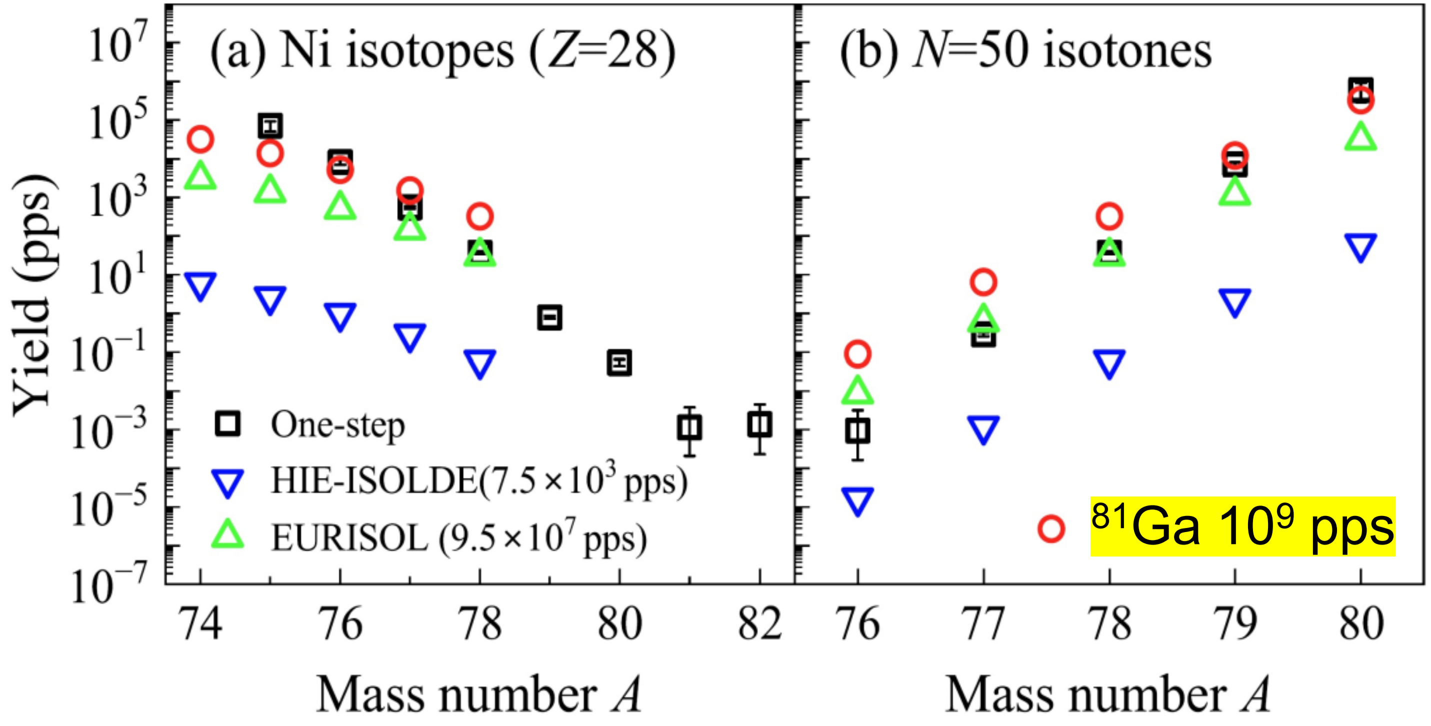
- ISOL + In-flight
- Fission + Projectile fragmentation of unstable nuclei



Two- vs one-step

- 8pμA ^{238}U + 0.35-g/cm^2 Be @150MeV/u
- Fission + Projectile fragmentation of ^{81}Ga





X.H. Sun, HW et al., PLB 858 (2024) 139081

Summary

- Opportunities at HIRIBL for heavy radioactive isotopes
  - Devices and PID detectors
  - Decay station at MF6

- Possible scenarios to access r- and rp-process path
  - Fission, projectile fragmentation, thick-target effect

- Collaboration for astro-nuclear physics
  - Decay station? Ge array? Triggerless?

    Request to accelerator division for beam species

Welcome to HIAF

SUNFLOWER workshop on 9/2~9/4