JYVÄSKYLÄN YLIOPISTO
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Mass measurements of N=Z nuclei and the vicinity at RIKEN with the Rare-RI Ring for the study of rp- and νp processes

Zhuang Ge

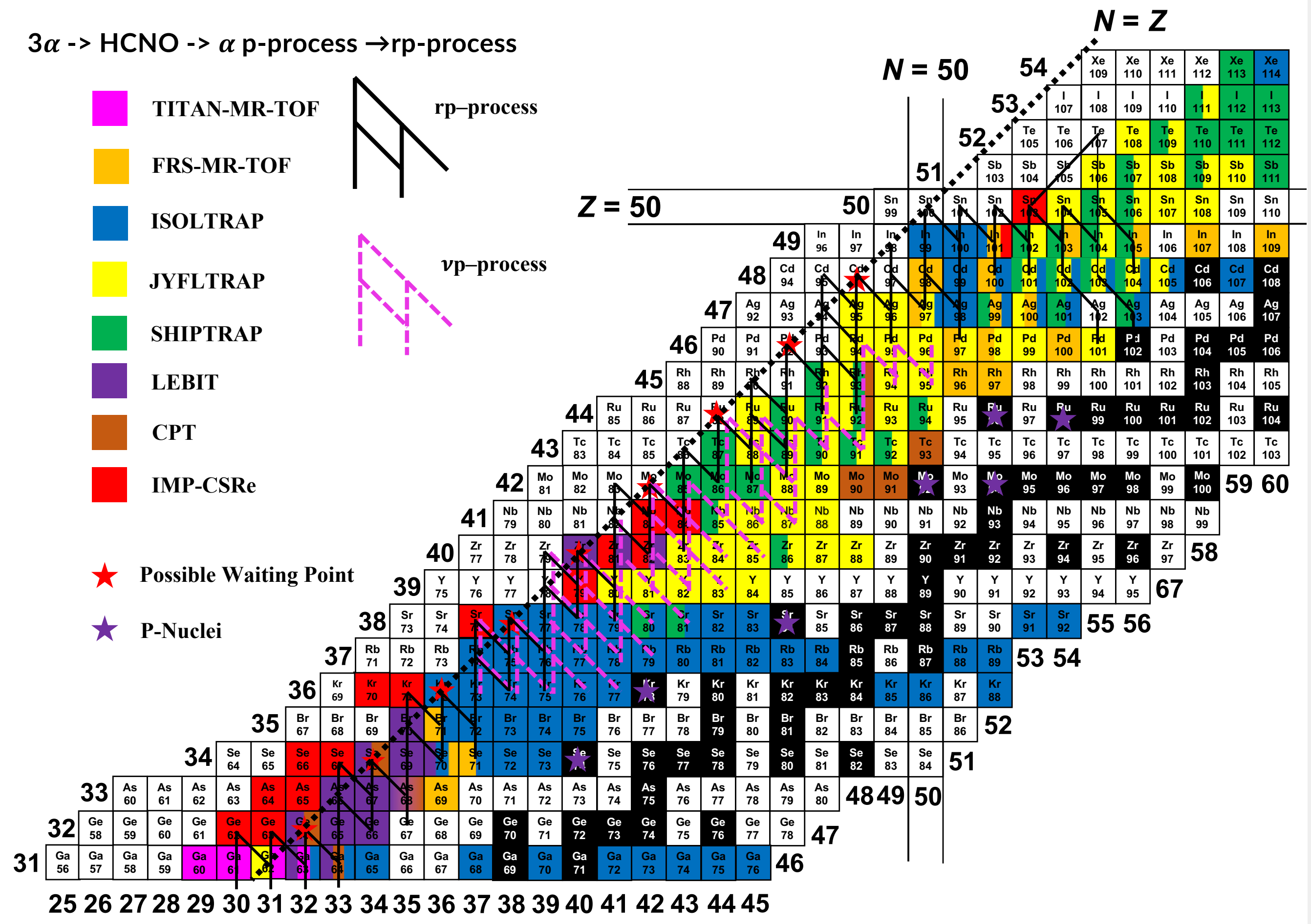
Academy research follow

University of Jyväskylä

Motivation

Nuclear mass ↔ nuclear binding energy:

$$M(N,Z) = Z \cdot m_p + N \cdot m_n - B(N,Z)/c^2$$



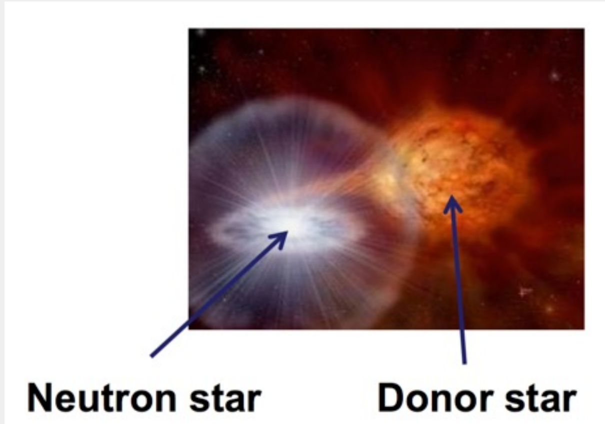
Nuclear Astrophysics

vp-, rp-process

(waiting point, Zr-Nr cycle)

abundance of P-nuclei

($^{92;94}$Mo and $^{96;98}$Ru,^{84}Sr isotopes)



C. Weber et al., Phys. Rev. C 78, 054310 (2008)

V.-V. Elomaa et al., Phys. Rev. Lett. 102, 252501 (2011)

E. Haettner et al., Phys. Rev. Lett. 106, 122501 (2011)

F. Herfurth et al., Eur. Phys. J. A, 47,75 (2011)

X. Tu et al., Phys. Rev. Lett. 106, 112501 (2011)

Y.M. Xing, et al., Physics Letters B 781 358–363 (2018)

C. Hornung et al., Physics Letters B 802, 135200 (2020)

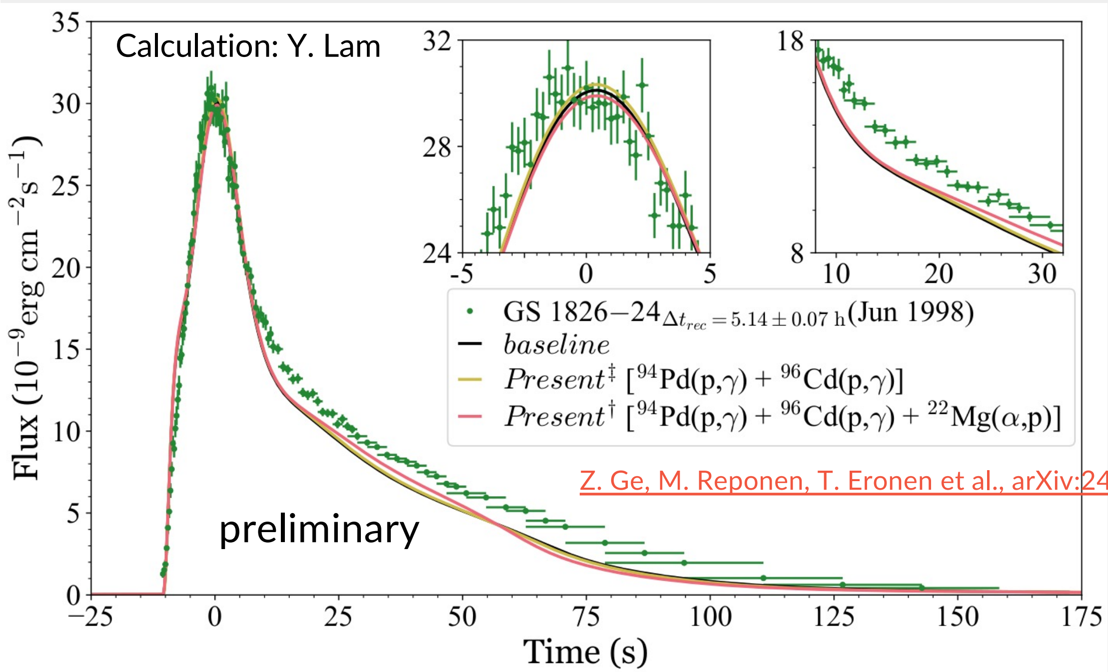
M. Mougeot et al., Nature Physics 17, 1099 (2021)

A. Hamaker, et al., Nat. Phys. 17, 1408–1412 (2021).

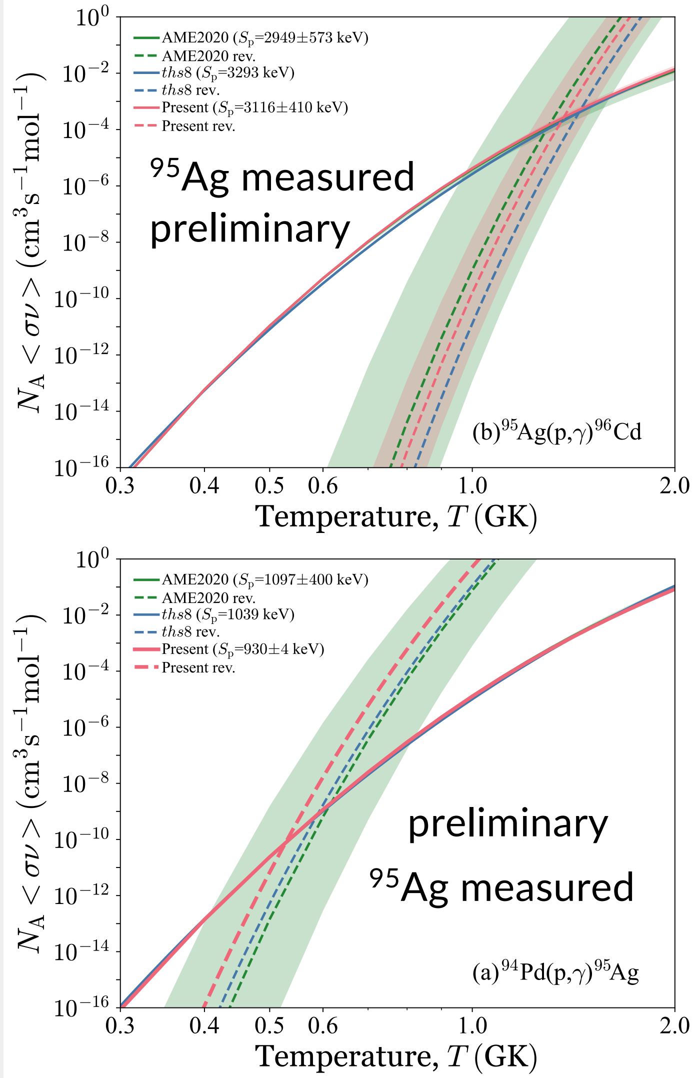
Impacts on the X-ray burst

Exponential dependence on masses!

time−scale $\propto e^{(Q/kT)} / A(Q)$
isotope production $\propto A(Q) \cdot e^{(Q/kT)}$
energy production $\propto A(Q) \cdot Q \cdot e^{(Q/kT)}$
Common parameter:
Q (mass difference)



Z. Ge, M. Reponen, T. Eronen et al., arXiv:2401.07976



96Cd needed

Impact on *νp*-process and rp-process

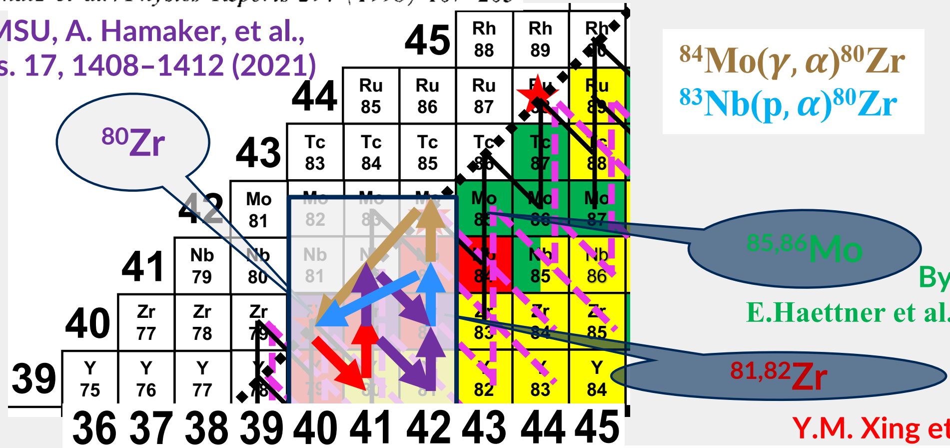
rp process:

1. Finalize flow branching into the Zr–Nb cycle (exist or not ?)
2. Waiting point: Degree of waiting? Light curve –^{84}Mo, ^{88}Ru, ^{92}Pd, ^{96}Cd
3. Final composition/time scale/energy production or light curve shape of X-ray bust ashes

Zr–Nb cycle: $^{83}\mathrm{Nb}(p,\alpha)\,^{80}\mathrm{Zr}(\beta^+)\,^{80}\mathrm{Y}(p,\gamma)\,^{81}\mathrm{Zr}\begin{Bmatrix}(\beta^+)^{81}\mathrm{Y}(p,\gamma)\\(p,\gamma)^{82}\mathrm{Nb}(\beta+)\end{Bmatrix}{}^{82}\mathrm{Zr}(p,\gamma)\,^{83}\mathrm{Nb}$

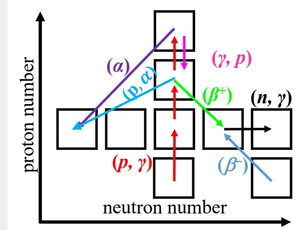
H. Schatz et al. / Physics Reports 294 (1998) 167–263

LEBIT/MSU, A. Hamaker, et al., Nat. Phys. 17, 1408–1412 (2021)



$^{84}\mathrm{Mo}(\gamma,\alpha)^{80}\mathrm{Zr}$

$^{83}\mathrm{Nb}(p,\alpha)^{80}\mathrm{Zr}$



By SHIPTRAP
E.Haettner et al., PRL 106, 122501 (2011)

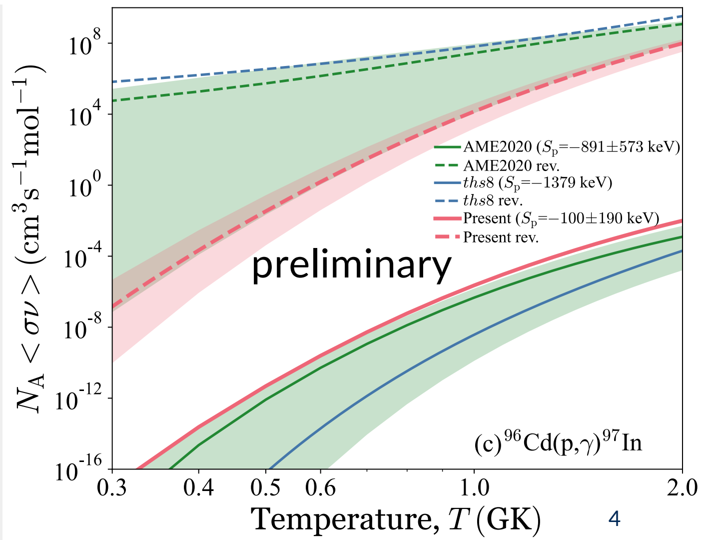
By CSR/IMP
Y.M. Xing et al., PLB 781, 358 (2018)

low alpha separation island:
α separation energy of ^{84}Mo

***νp*-process:**

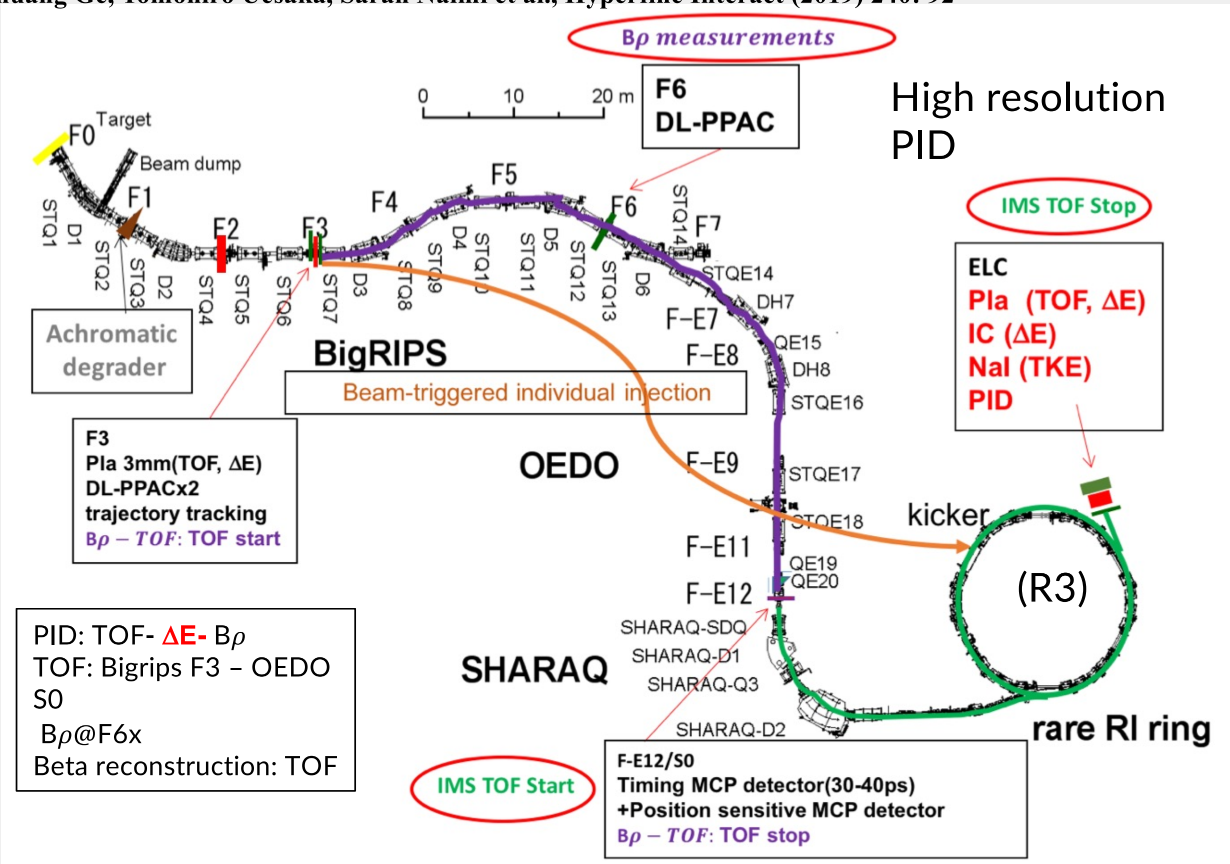
1. finalize the path/flow
2. source of p-nuclei (^{84}Sr,^{92,94}Mo)
3. ^{84}Mo :precursor of ^{84}Sr

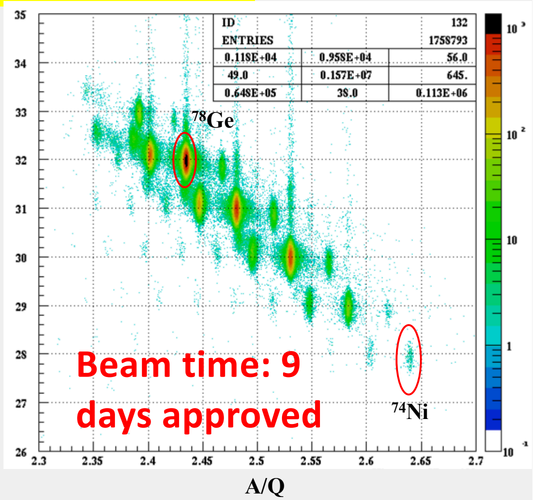
Key masses: ^{84}Mo,^{82,83}Nb, ^{88}Ru,^{92}Pd, ^{93}Pd, ^{96}Cd,^{94}Ag, ^{98}In, ^{100}Sn



Setup for Mass measurements by $B\rho - TOF$ & *IMS* (Isochronous mass spectrometry)

Zhuang Ge, Tomohiro Uesaka, Sarah Naimi et al., Hyperfine Interact (2019) 240: 92





$B\rho - TOF$ mass:
By-product part of IMS runs

F3-S0:
Efficiency 70-90%
Momentum acceptance $\pm 0.5\%$
Rare-RI Ring:
Efficiency 1 %
Momentum acceptance $\pm 0.3\%$

IMS **(Isochronous mass spectrometry) method.**
Revolution time Correction by beta/ $B\rho$ measurements:

$$\left(\frac{m}{q}\right)_1 = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

Mass measurements by $B\rho - TOF$ **, TOF (F3-S0) and** $B\rho$ **measurements at F6/F5:**

$$\frac{m_0}{q} = \frac{B\rho}{\gamma L/t} = B\rho\sqrt{\left(\frac{t}{L}\right)^2 - \left(\frac{1}{c}\right)^2}$$

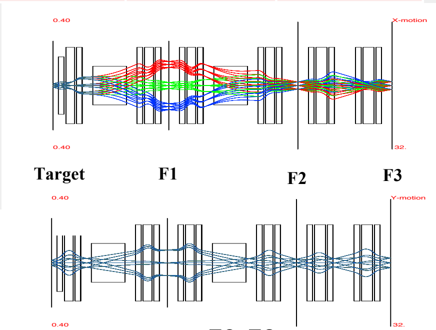
Ion optics design (beam-line and storage ring)

Zhuang Ge et al., Nuclear Physics Review, 2019, 36(3): 294-304 (2019)

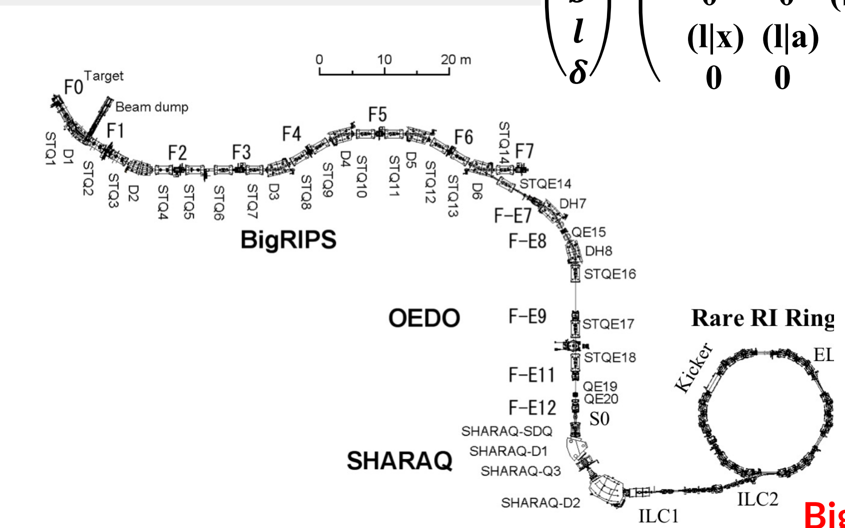
	(x|x)	(x|a)	(a|x)	(a|a)	(y|y)	(y|b)	(b|y)	(b|b)	(x|dp)	(a|dp)	(l|dp)	L|dEk
F3F4	-0.966	0	0	-1.03	-3.88	0	-0.04	-0.26	-1.86	-1.89	4.04	2.187439
F3F5	-0.01	-9.6	0.1	0	1.298	0	-0.06	0.77	0.108	0.505	8.81	4.771546
F3F6	0.965	0	0	1.036	-3.88	0	0	-0.257	7.54	0.368	11.62	6.296793
F3FE7	-0.394	9.7	-0.1	0.016	1.17	-2.386	0.438	-0.039	0.316	-0.803	17.21	9.323857
F3FE9	-0.854	0	-0.14	-0.527	2.67	0	-0.55	0.373	0	0.297	26.94	14.59592
F3S0	2.18	0	0.58	0.46	-2.27	0	0	-0.44	0	0.258	36.09	19.54942
F3ILC1	1.38	-0.58	1.87	-0.06	3.34	0.02	0.76	0.304	-4.15	0.66	44.26	23.98
F3ILC2	-6.18	0	0.83	-0.16	-2.6	0.48	0.476	-0.465	-5.78	-0.66	54.08	29.2974
F3KC	-9.1	1.04	-0.3	-0.07	-2.53	3.71	-0.42	0.22	-7	0	58.43	31.65375

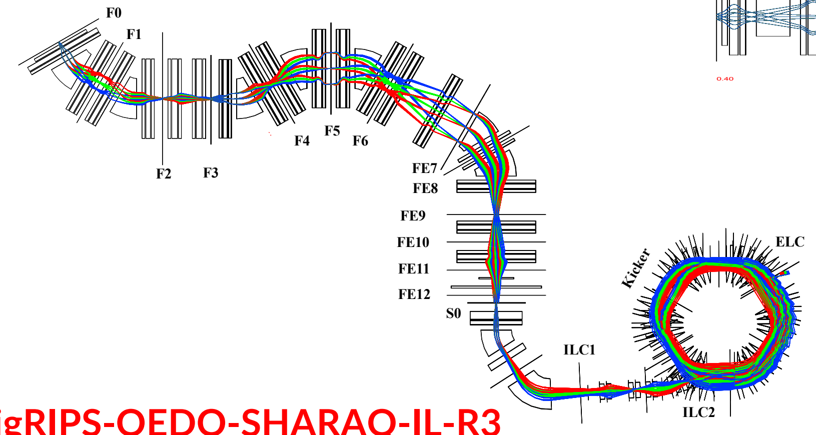
Transfer matrix :

$$\begin{pmatrix} x \\ a \\ y \\ b \\ l \\ \delta \end{pmatrix} = \begin{pmatrix} (x|x) & (x|a) & 0 & 0 & 0 & (x|\delta) \\ (a|x) & (a|a) & 0 & 0 & 0 & (a|\delta) \\ 0 & 0 & (y|y) & (y|b) & 0 & 0 \\ 0 & 0 & (b|y) & (b|b) & 0 & 0 \\ (l|x) & (l|a) & 0 & 0 & 1 & (l|\delta) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} x_0 \\ a_0 \\ y_0 \\ b_0 \\ l_0 \\ \delta_0 \end{pmatrix}$$



F0-F3





BigRIPS-OEDO-SHARAQ-IL-R3

Isochronous design for all N=Z nuclei

Zhuang Ge, Tomohiro Uesaka et al., Hyperfine Interact (2019) 240: 92

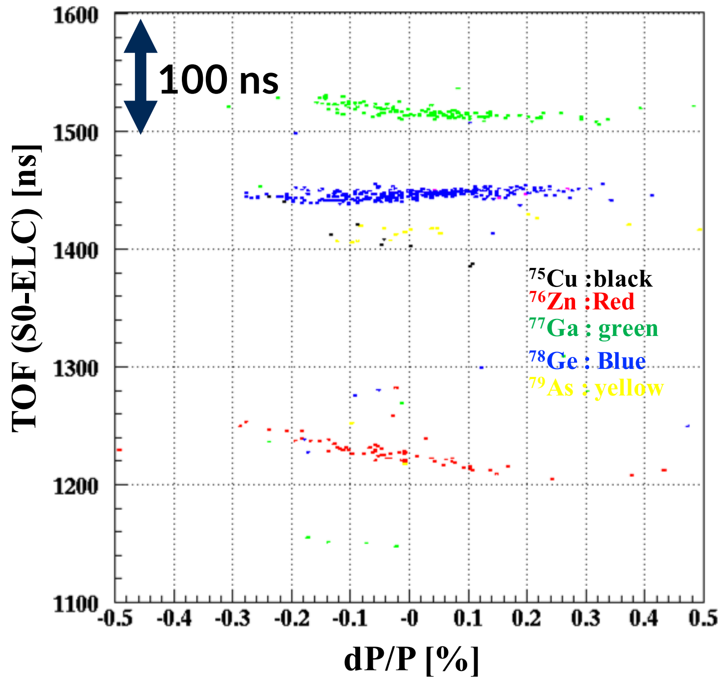
Isochronous optics not on N=Z nuclei

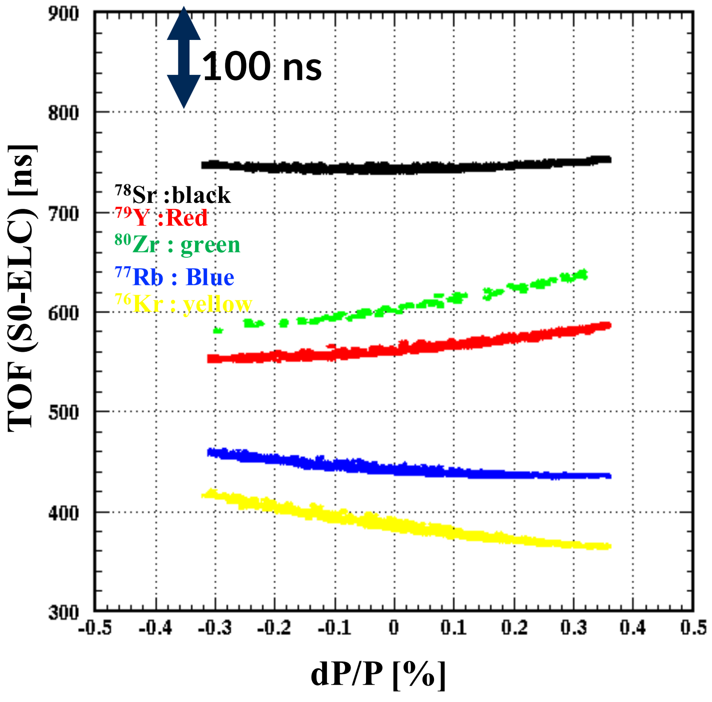
Isochronous on N=Z nuclei

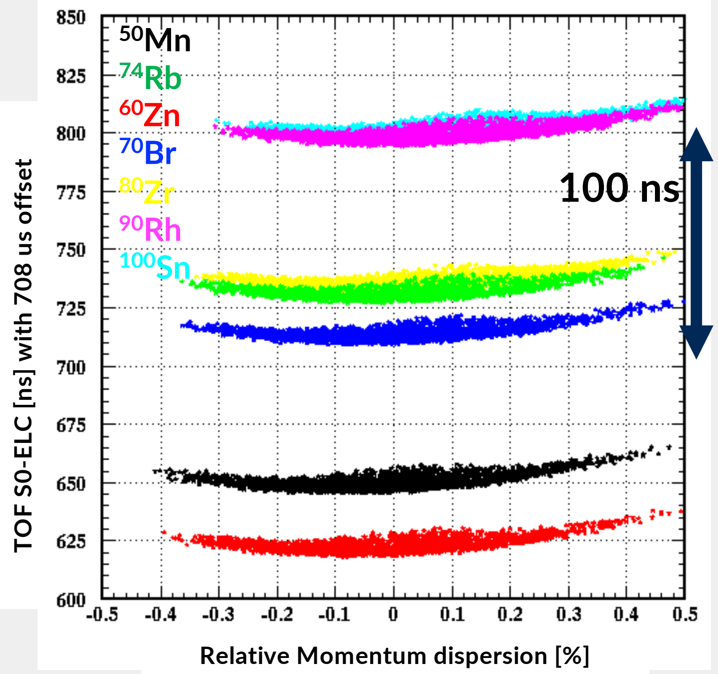
Online

simulation

simulation







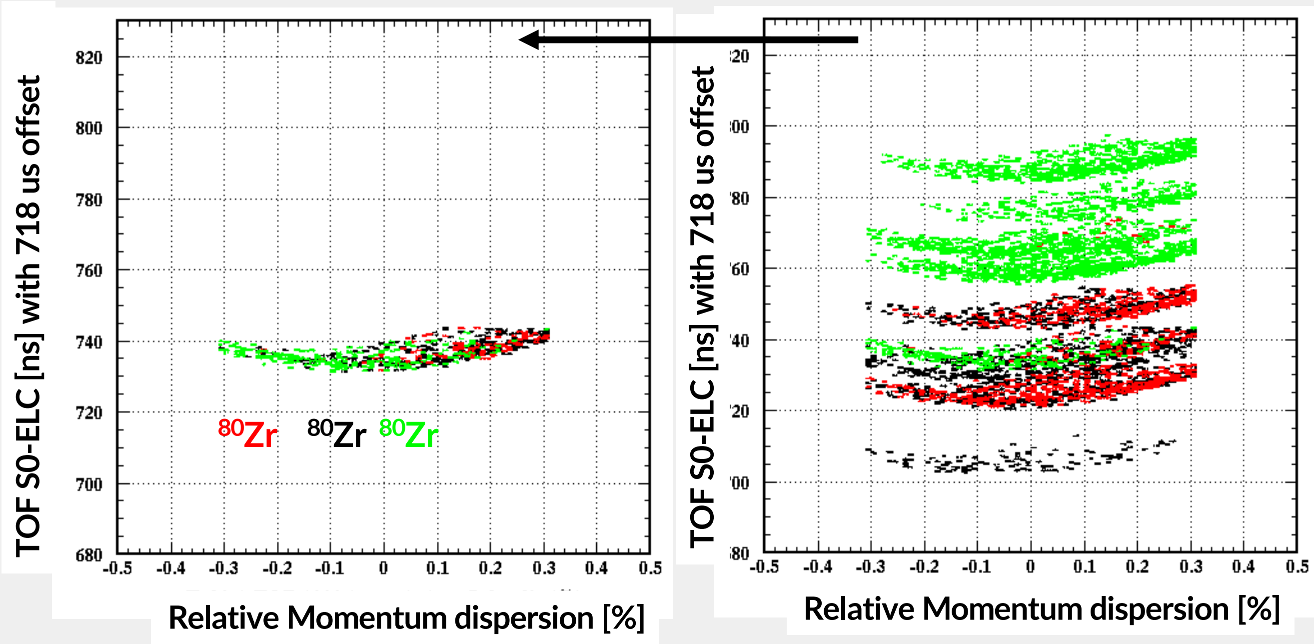
Only One ion species has isochronous condition

All N=Z nuclei ion species has isochronous condition

Isochronous condition confirmation

primary beam ^{124}Xe
Simulation starting from F0

Isochronous condition confirmation can be done by:
Check same species of ion at different settings



Setting on 76Sr:

Setting on 80Zr:

Setting on 84Mo:

Only change variable degrader thickness and varying Dipole before F3

Emittance-dependent Isochronism

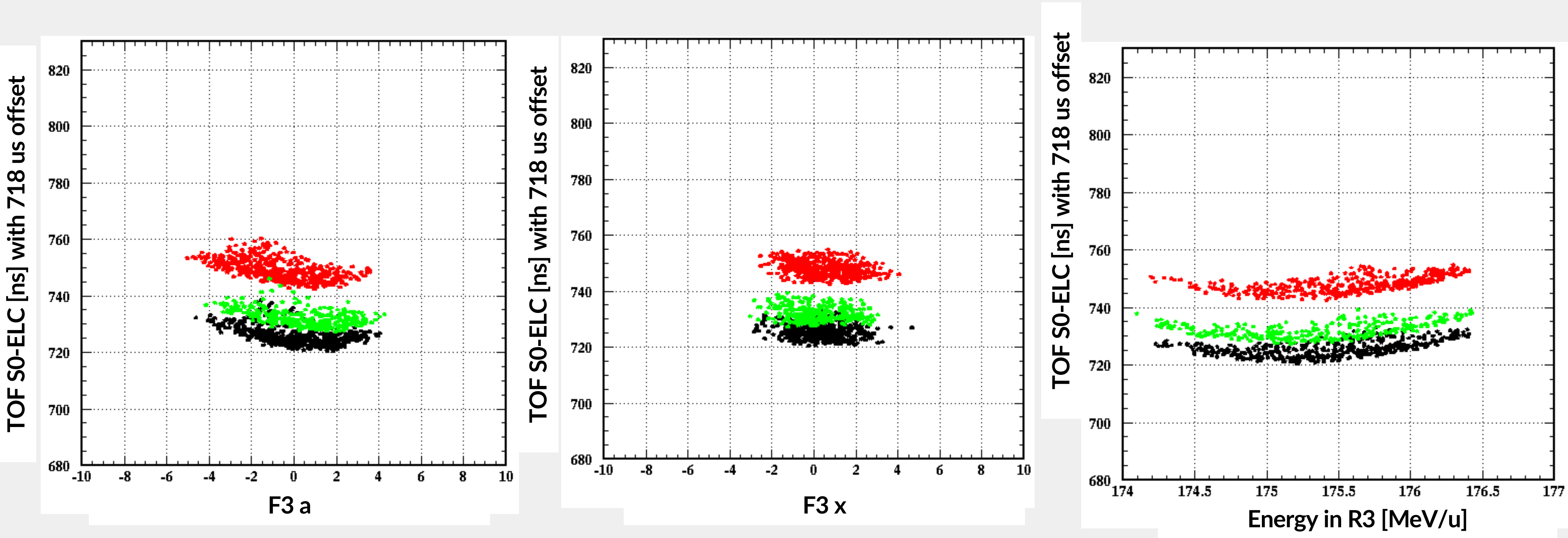
^{76}Sr: black
^{78}Y :Red
^{74}Rb: green

F3 Pla: 1mm^{t}
F3 IC in
F3 PPAC in

primary beam ^{124}Xe (345MeV/u)
Target: 8mm^{t} ^{9}Be
Simulation starting from F0

Setting on 76Sr:
Brho centering

1900 turns circulation in R3



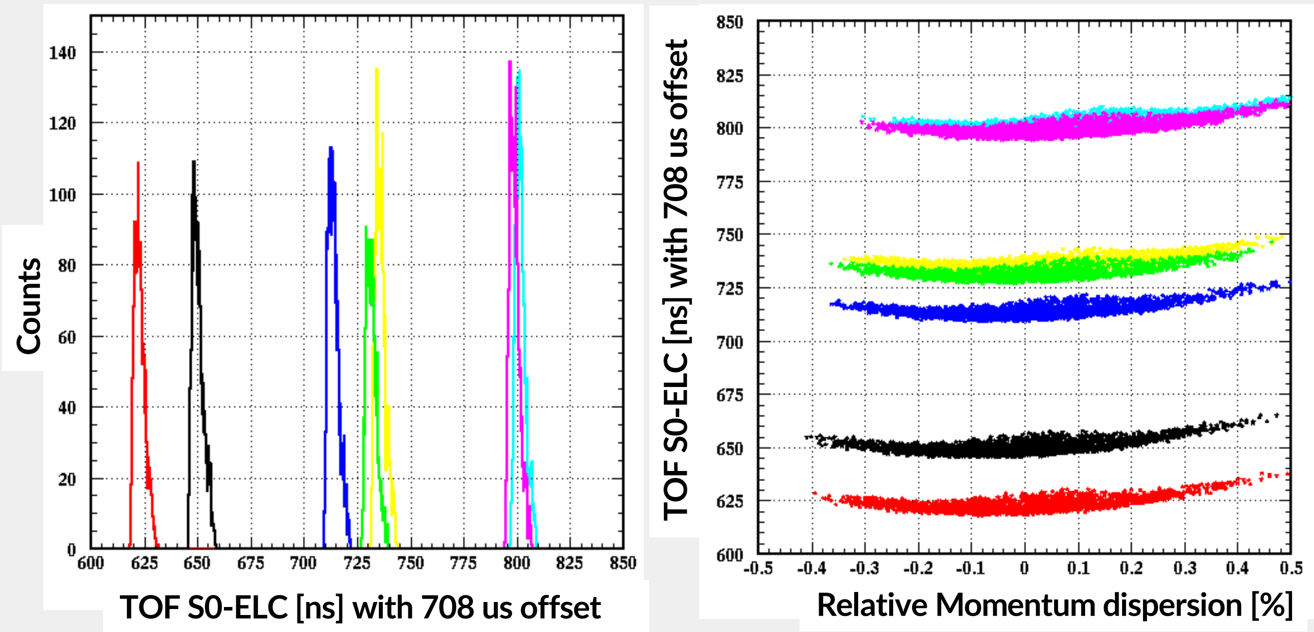
N=Z simulation (Z=25-50): all in isochronous

Varying the primary beam species and energy only,

Keeping settings from F3 to ELC

All N=Z is in isochronous condition

Simulation starting from F3



^{50}Mn
^{74}Rb
^{60}Zn
^{70}Br
^{80}Zr
^{90}Rh
^{100}Sn

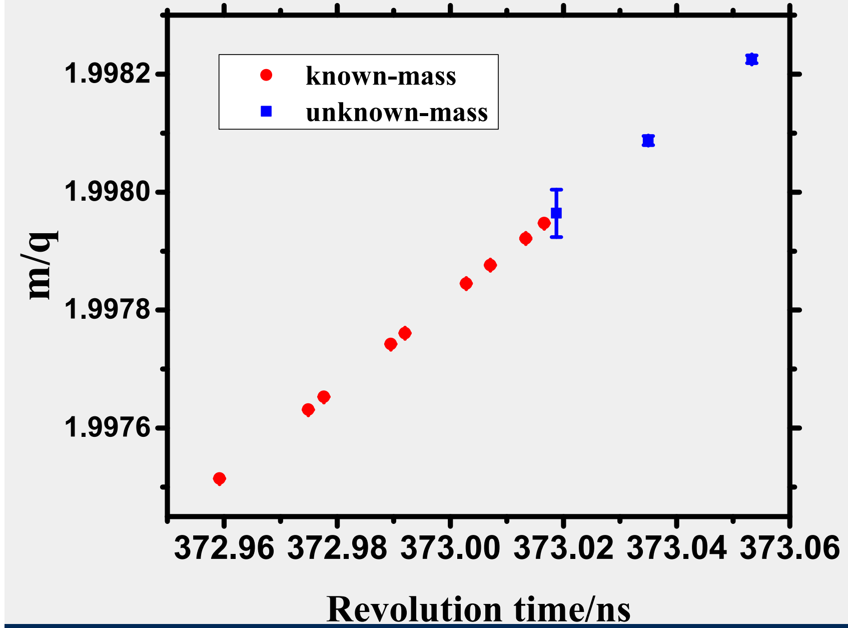
Mass Determination

1. Masses of bare ions

$$m = m_a - Zm_e + B_e(Z)$$

$$B_e(Z) = 14.4381 Z^{2.39} + 1.55468 \times 10^{-6} Z^{5.35} [eV]$$

2. Mass Calibration



Polynomial Fit:

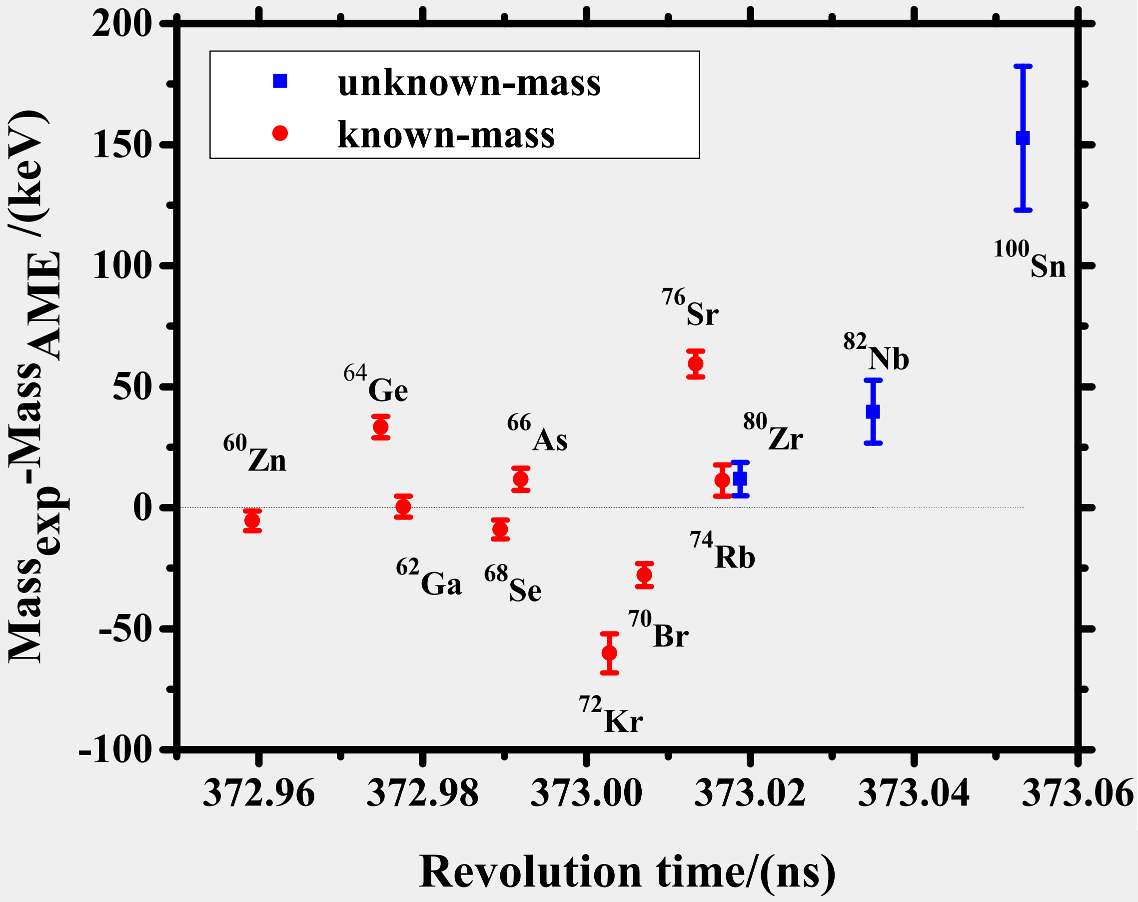
$$\frac{m}{q}(T) = \sum_{i=0}^{k} a_i T^i.$$

Least square method:

$$\chi^2 = \sum_{i=1}^{n} \frac{\left[\left(\frac{m}{q}\right)_i - \sum_{j=0}^{k} a_j T_i^j\right]^2}{\sigma_i^2\left(\frac{m}{q}\right) + \sigma_{meas,i}^2\left(\frac{m}{q}\right)}$$

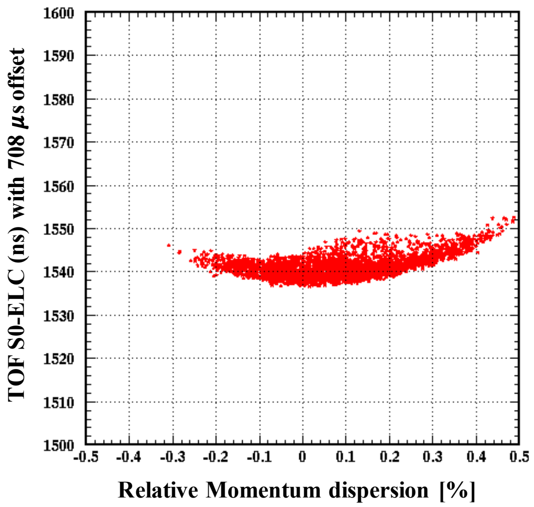
$$\boxed{\mathcal{A} = (\mathcal{T}^t \mathcal{P} \mathcal{T})^{-1} \mathcal{T}^t \mathcal{P} \mathcal{M}}$$

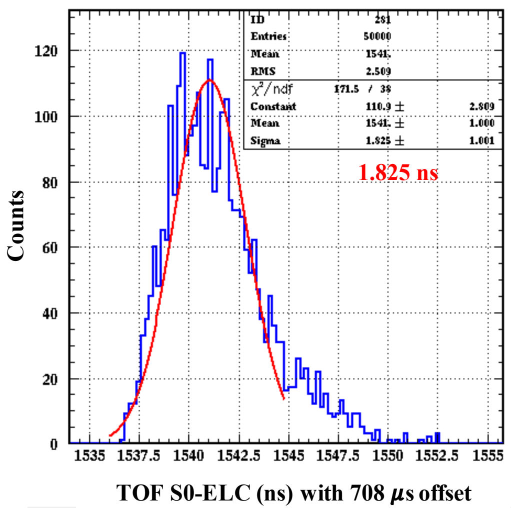
Mass calibration results



Nuclide	ME(exp-AME) (keV)	ME(exp) (keV)	Error(exp) (keV)	Error(AME) (keV)
^{60}Zn	-5.363	-54179	4.040	0.6
^{70}Br	-28.157	-51453	4.749	14.9
^{74}Rb	11.067	-51905	6.510	3.0
^{72}Kr	-60.596	-54001	8.022	8.0
^{76}Sr	59.119	-54189	5.331	34.5
^{62}Ga	0.077	-51986	4.359	0.7
^{64}Ge	32.909	-54283	4.424	3.7
^{66}As	14.322	-52011	4.557	5.7
^{68}Se	-9.476	-54199	3.965	0.5
^{80}Zr*	11.772	-55505	6.858	1490.4
^{82}Nb*	40.336	-52160	12.989	298.0
^{100}Sn*	155.250	-57127	29.737	301.5

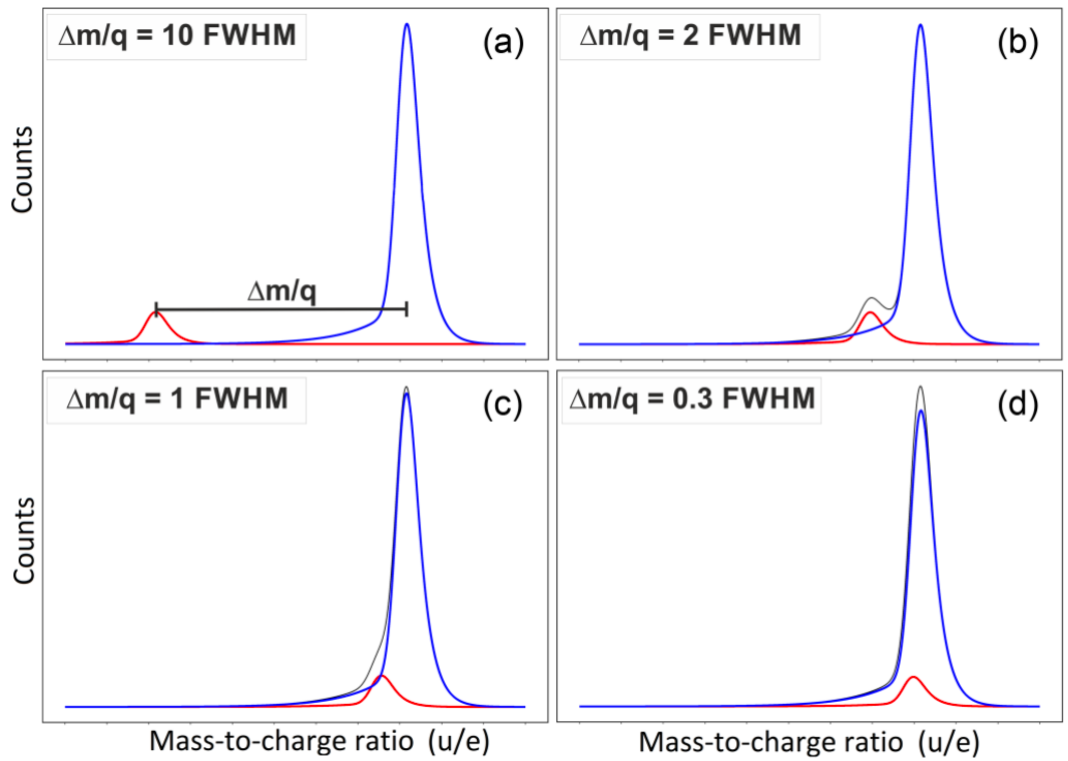
Technique development for analysis





Designed isochronism: ~$2.5\text{x}10^{-6}$

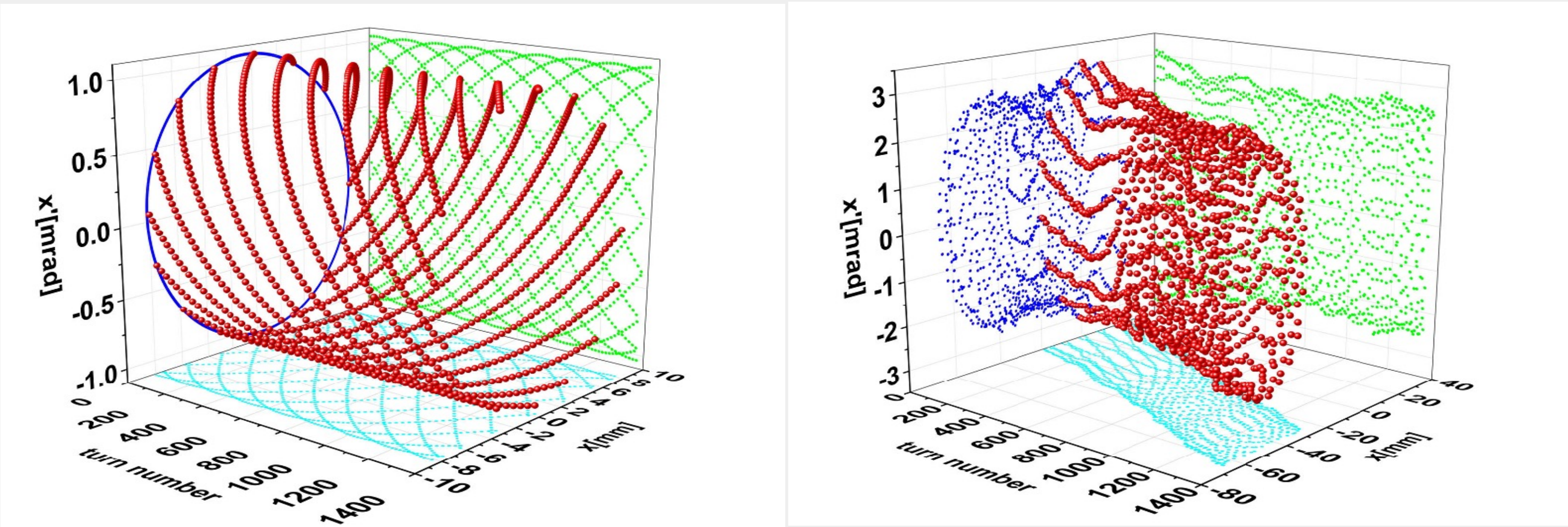
S. Ayet et al., Physical Review C 99, 064313 (2019)



Will employ the Hyper-EMG method developed for GSI MR-TOF
to addressing
higher order optics effect and close-lying isomeric states

Simulation of detection of ions circulating in Ring

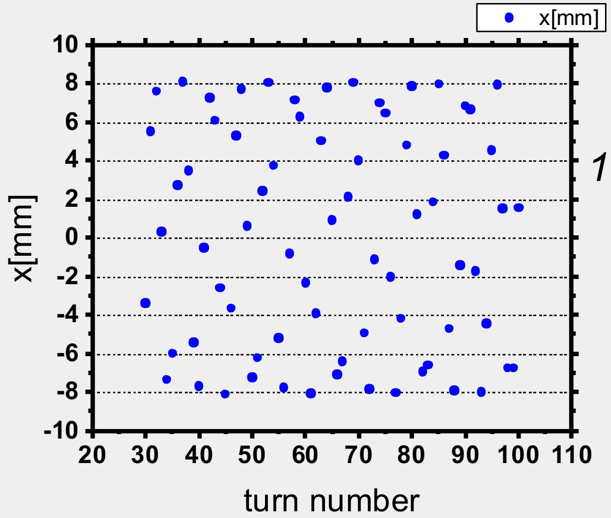
(phase space of XX' as a function of turn number)



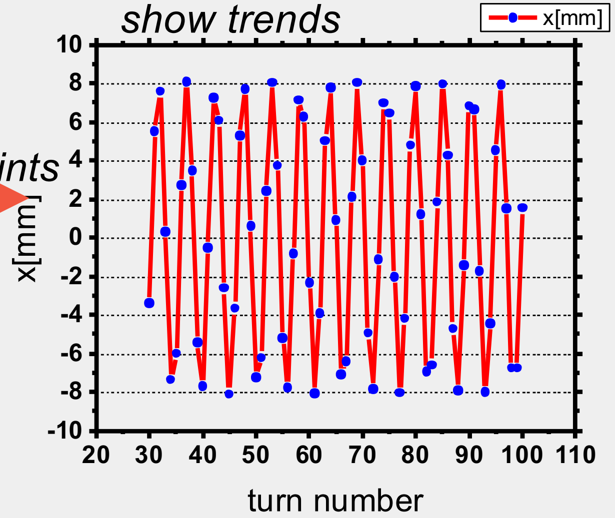
- *No energy loss detector in ring (like Position-sensitive Schottky)*
- *40 $\mu g/cm^2$ carbon foil MCP detector (matter angular and energy staggling in)*

Monitoring of ion's lateral position and angular distribution by in-ring detector with/without energy loss

No energy loss: X-position as a function of turn number

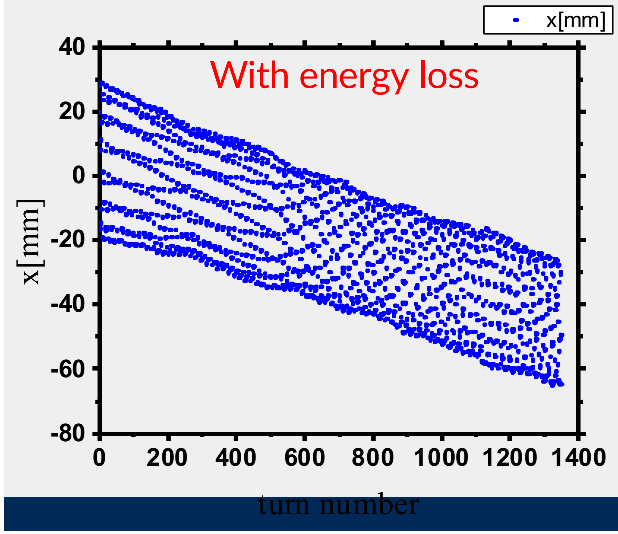


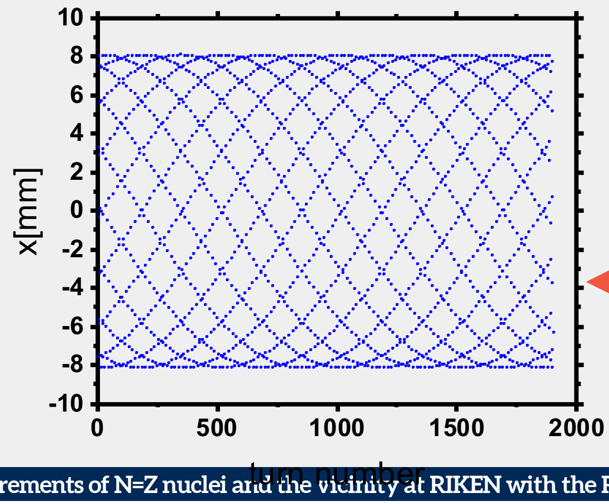
Red lines for connection to show trends



100 turns in blue points

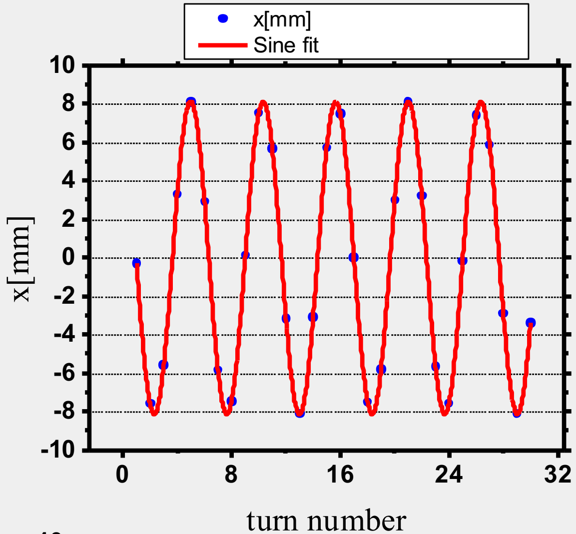
(^{38}K)

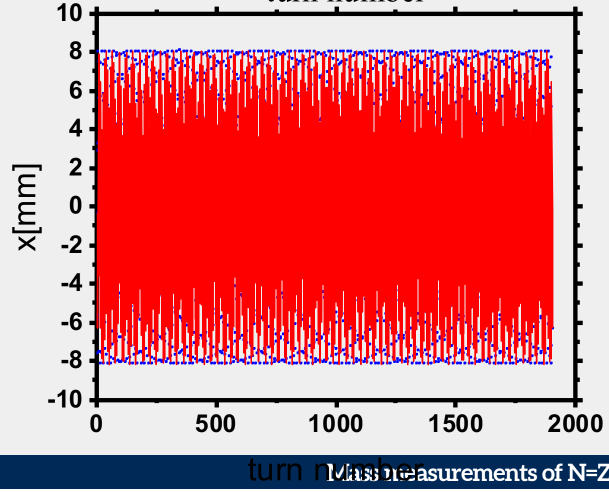




1900 turns in blue points

Fitting with betatron function





$$X_i = X_0 + \sqrt{\beta_i \varepsilon}\ \cos(2\pi Qn+\mu_i)$$
$$= X_0 + \sqrt{\beta_i \varepsilon}\ \sin(2\pi Qn+\mu_i+0.5\ \pi)$$
$$= X_0 + \sqrt{\beta_i \varepsilon}\ \sin[\pi(2Qn-(-\mu_i/\pi-0.5))$$
$$= X_0 + \sqrt{\beta_i \varepsilon}\ \sin[2Q\pi(n-(-\mu_i/\pi-0.5)/2Q)$$

$$\left.\begin{array}{l} Xc = (-\mu_i/\pi-0.5)/2Q \\ Y0 = X_0 \\ W = 1/2Q \\ X = n \\ A = \sqrt{\beta_i \varepsilon} \end{array}\right\}\ \textbf{Parameters}$$

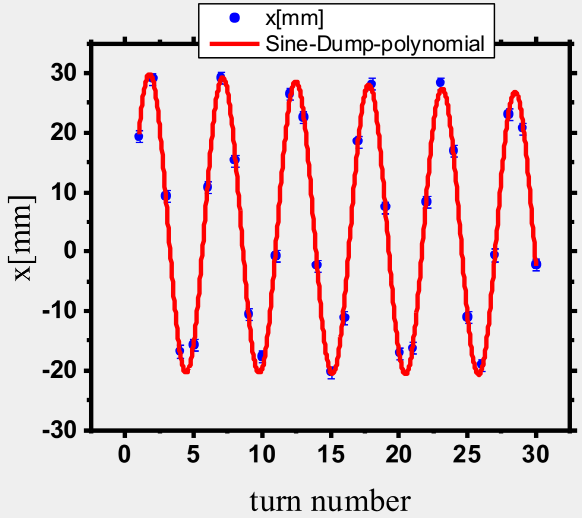
$$Q = 1/(2W) = 0.187$$
$$\mu_i = -\pi\ (Xc/W+0.5) = 0.426$$
$$\sqrt{\beta_i \varepsilon} = A = 8.11116$$

Model	*Sine*	
Fitting Equation	*y=y0+A*sin(pi*(x-xc)/w)*	
Reduced Chi-Sqr	*4E-5*	
Adj. R-Square	*1*	
	Value	*Standard Error*
y0	*0.014689*	*1.5E-4*
xc	*-1.69847*	*5E-5*
w	*2.67198*	*1.104E-7*
A	*8.11116*	*2.2E-4*

Betatron function parameters can be reconstructed

Detector position resolution dependence of in-ring position measurements

Fitting equation:
*Equationy=y0+A*exp(-x*t0)*sin(pi*(x-xc)/w)+b*x*

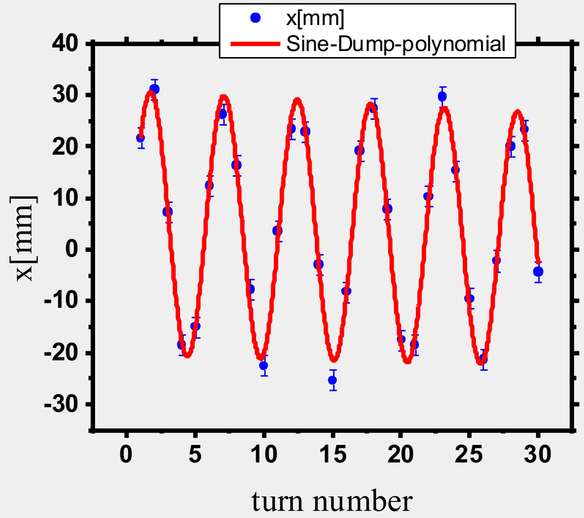


1mm resolution

y0 = 4.88761+-0.40679

Fitting center

Fitting center uncertainty



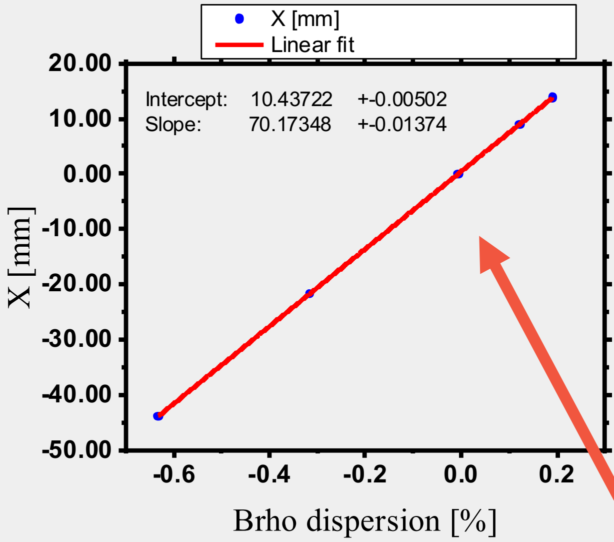
2mm resolution

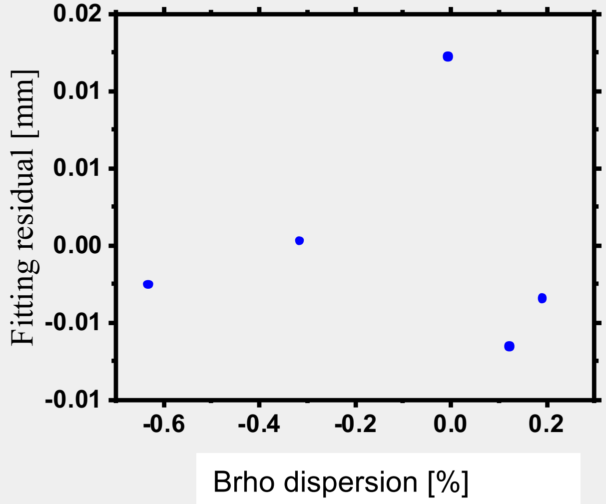
y0 =5.2032 +-0.76486

Fitting center

Fitting center uncertainty

Dispersion function deduction and momentum measurements





After getting the a, b parameters, we can use the function: x=1/b(y-b) for momentum deduction from position measurements

*Equation: y = a + b*x*

Weight No Weighting

Residual Sum of Squares 1.5E-4

x: momentum dispersion; y:position

	Value	*Standard Error*
Intercept	*10.43722*	*0.00502*
Slope	*70.17348*	*0.01374*

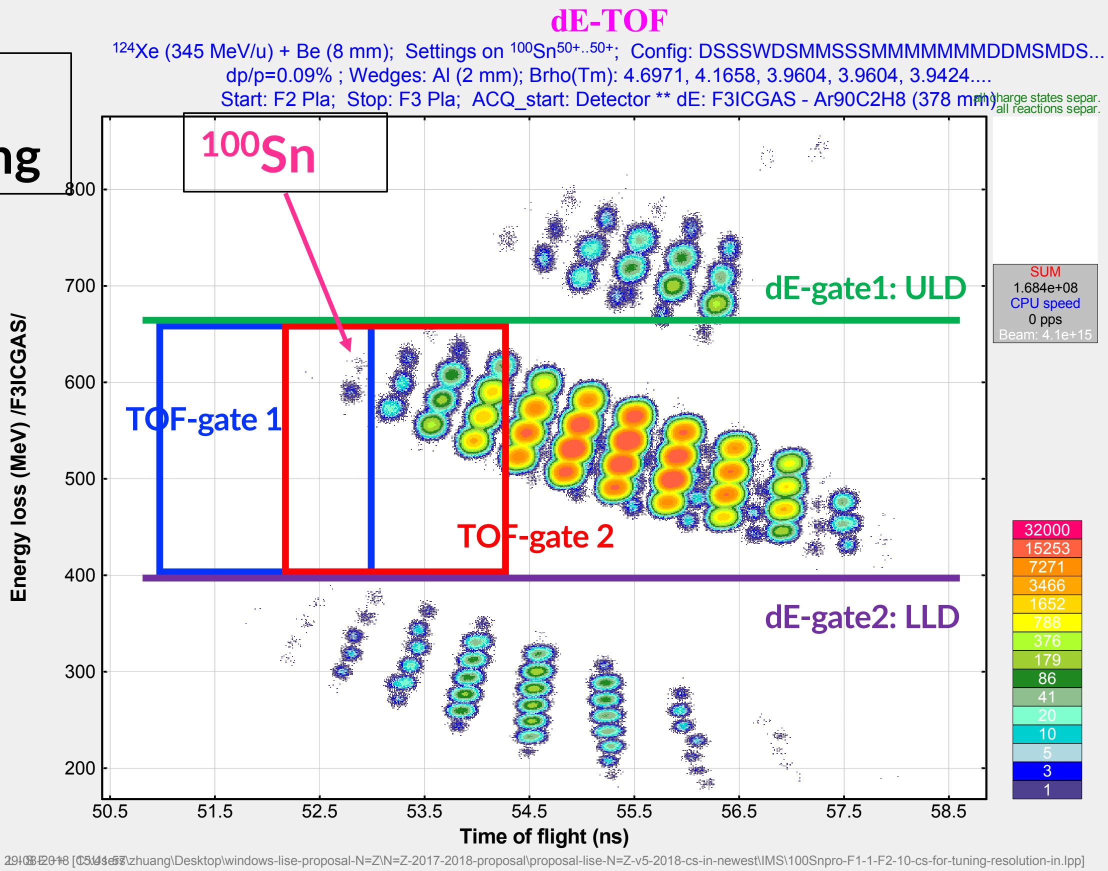
Points in figure for fitting

Designed: ~70 mm/%

$\delta(B\rho)/(B\rho)$	***center position (from fitting)***
0.19026	***23.78104***
-0.31533	***-11.69109***
-0.00658	***9.98512***
-0.63179	***-33.8995***
0.12169	***18.967***

TOF-dE gate selection

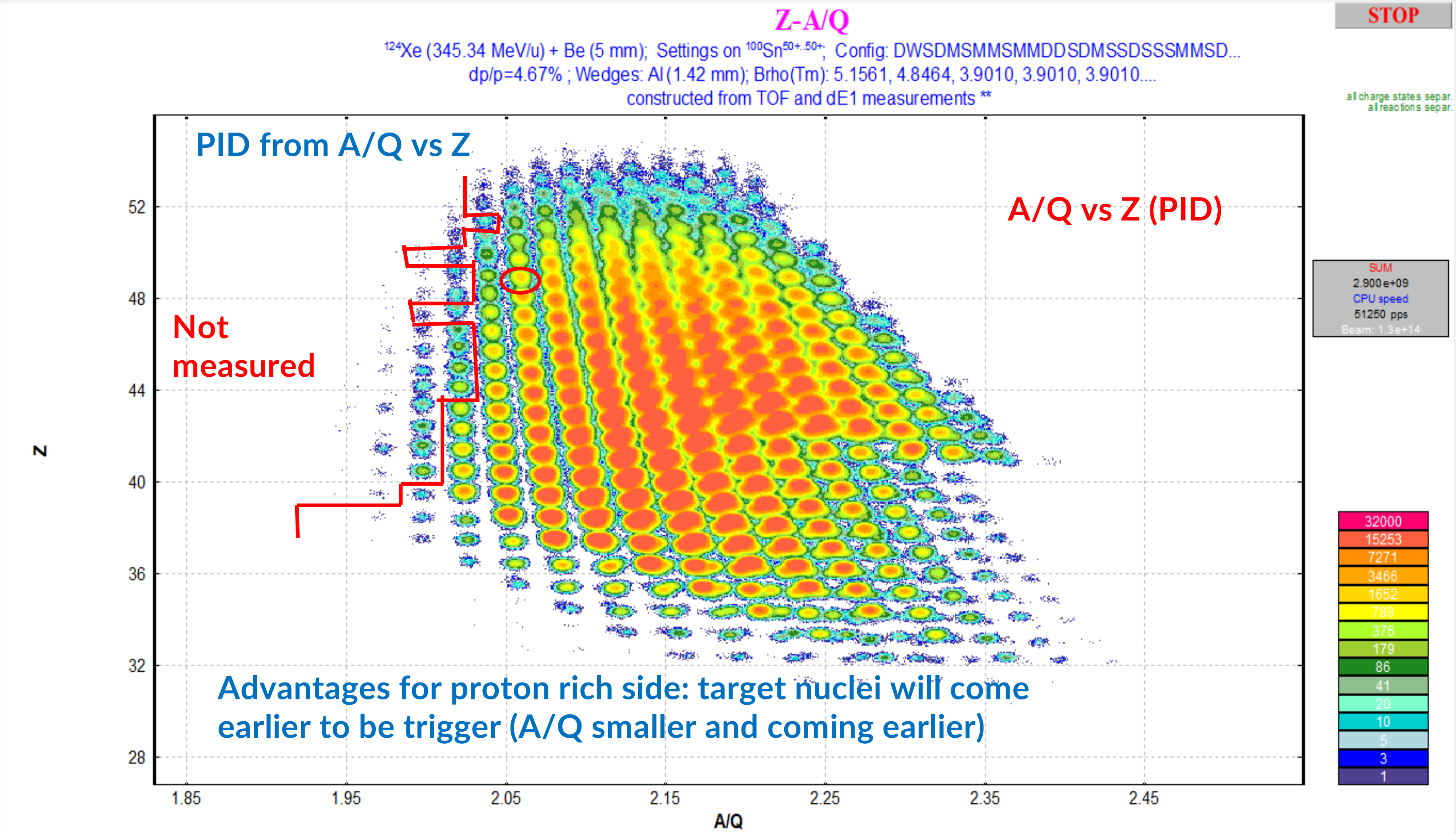
^{100}Sn setting



Tuning setting:
F1 slit:
+- 1 mm
F2 slit:
+- 10mm

Setting TOF-grate1 and TOF-gate2 rates ratio to be 4:1
The two TOF gates set in 'or'logic (for example, 'N=Z and more exotic area'for TOF-gate 1 in 80 Hz
and additional reference in TOF-gate 2 to be 20 Hz)

scan the chart of nuclides for mass measurements using N=Z as reference for future IMS



Summary and outlook

- Status and Motivation of Mass measurement of N=Z nuclei and the vicinity for nuclear astrophysics
- Influence of masses on rp-process and νp-process
- Proposed experiment in RIKEN (9 days approved)
- IMS and bro-TOF methods for Mass measurements
- Optics design for mass measurements
- Unique isochronous design for N=Z nuclei
- Simulation study of TOF sprctum related to momentum dispersion and experiemental design
- Mass determination of N=Z nuclei with the proposed new method
- Future developments for higher order optics effct
- Simulation of in-ring detector for momentum (magnetic regidity) reconstuction
- Long range plan for nuclei to be measured

Thank you for your attention

Advantages of combining the two TOF methods (Bρ-TOF and IMS) for direct mass measurements of N=Z and the vicinity:

(a). By combining two complementary methods to make full use of the beam time. When measuring masses with high precision with R3, the Bρ-TOF method by the beam-line can simultaneously accept nuclei with relatively larger momentum dispersion to reach a larger range of chart of nuclides at the proton rich side. We can measure the most exotic nuclei (proton unbound, like ^{93}Ag, ^{89}Rh) even with a half-lives of ~1 us.

(b). By taking full advantages of the Isochronous condition, it will be the first time to realize mass measurements in isochronous condition for all the target and reference nuclei (N=Z) in storage ring, of which the in-ring TOF are all independent of momentum dispersion.

(c). As all the N=Z nuclei are independent of momentum dispersion in-ring, we do not need Bρ/velocity correction for N=Z nuclei, thus making full liberation of the beam-line for the Bρ-TOF measurements and we can use more detectors in beam-line for trajectory reconstruction, which in return will help with the beam monitoring for in-ring mass measurements.

(d). We can achieve ever good resolution even with few counts for N=Z nuclei all in Isochronous mode. Besides, we can resolve most of the N=Z isomeric states due to the high resolving power for N=Z nuclei.

(e). More isochronous nuclei with precise known mass can be used as reference in the IMS method. We can use the mass measured in-ring directly for the mass calibration for the Bρ-TOF method to avoid far away extrapolation.

(f). R3 condition can be kept for the same for all reference and target N=Z nuclei in one same IMS setting (extraction time difference to the reference nuclei in 100 ns after 700 μs), thus saving a large amount of beam turning time.

(g). As we measure the proton rich ions possessing the smallest m/q, which corresponds to the shortest TOF from F0 to F3 compared to other produced secondary ions in the same run, the target nuclei will arrive earlier than other secondary ions to be trigger signals. For this reason, we can largely open the slits at F1, F2 to accept more nuclei for the IMS and Bρ-TOF mass measurements.

(h). It will be a good way to minimize systematic errors for measuring the N=Z lines, as the reference nuclei from the extra reference runs can cover a large range of Z. During the reference runs we can also pick up un-measured nuclei beyond N=Z line by the beam-lines to deduce the masses by the Bρ-TOF method.