Slowed-down RI beam produced from fast projectile fragment at RIBF

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Low energy RI beam

- Reaction with low-energy beam

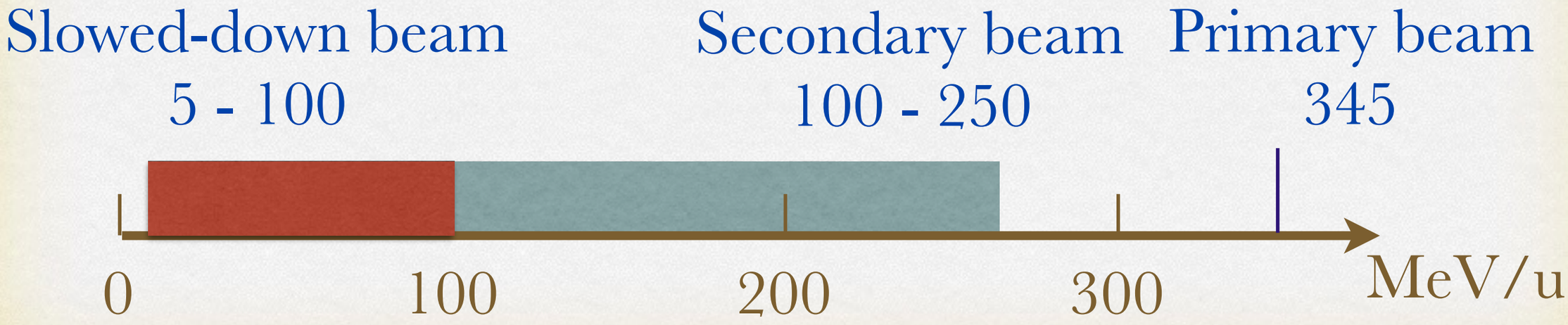
  transfer reaction, fusion reaction, multi-nucleon transfer reaction

- Re-acceleration of RI
  - HIE-ISOLDE (ISOL + re-acceleration)
  - FRIB (Fragment Separator + re-acceleration)

Small emittance
Same apparatus as stable beam

- Slowed-down beam – RIBF
  - Fragment Separator + (energy degrader+Optics Optimization)

Intense RI beam



Slowed-down RI beam of ^{82}Ge

Optimization to RI-beam intensity

T. S. et al, NIMB 376 (2016) 180.

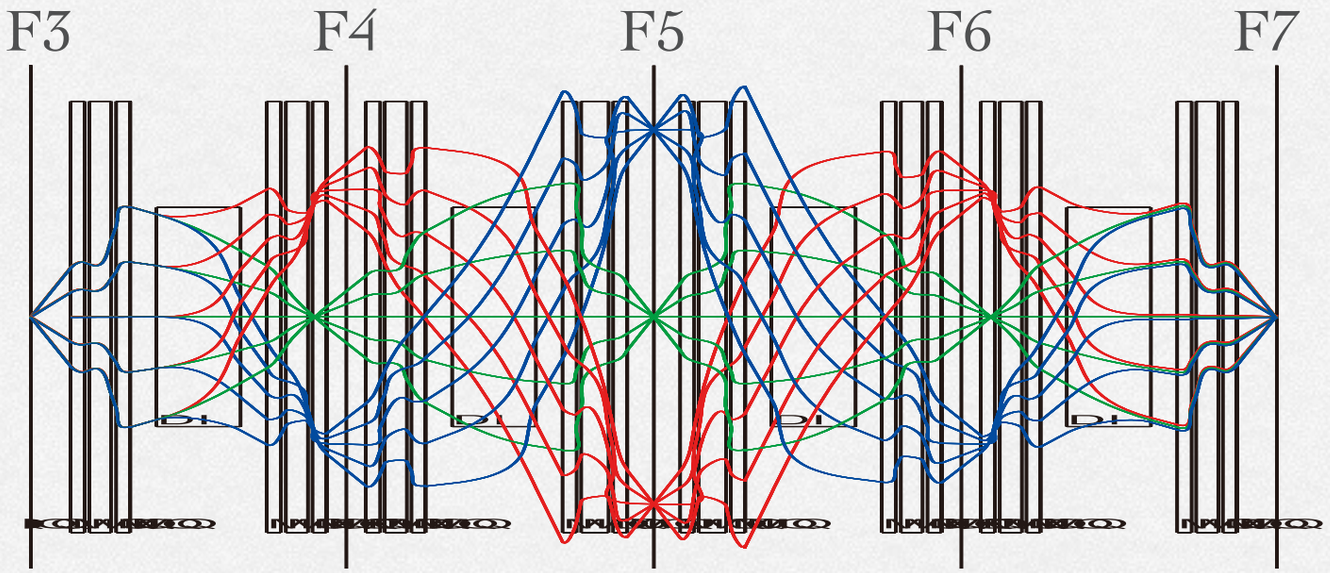
Is it possible to provide a slowed-down RI beam with 5-20 MeV/u for experiments?

Momentum compression mode

T.S. et al, Proposed at RNB8 (2009)

- Standard optics mode

COSY INFINITY



X direction

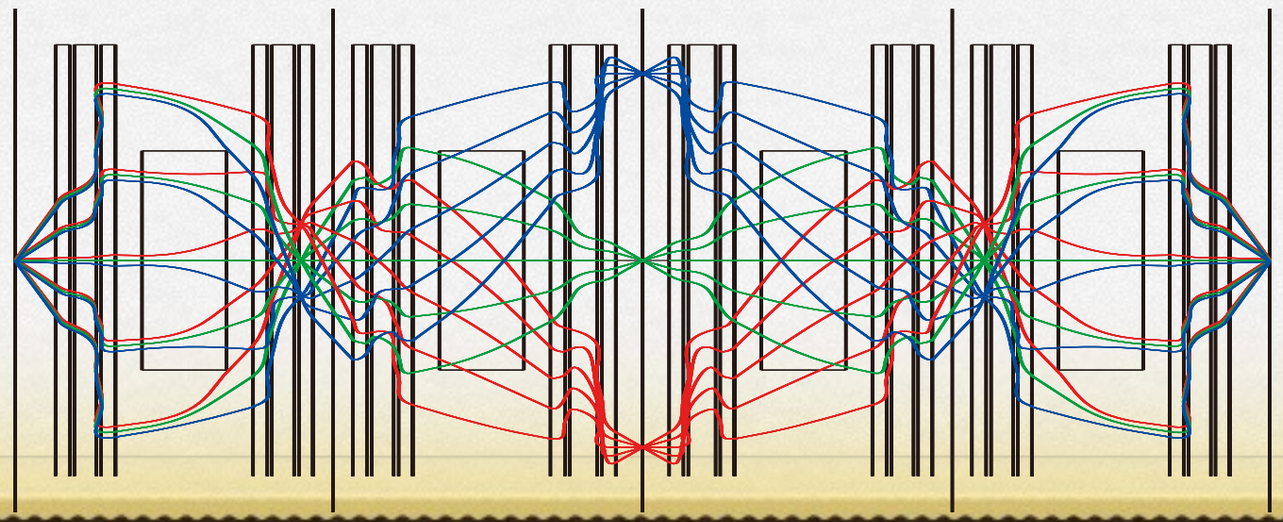
δp/p

Blue: + 3 %,

Green: 0 %,

Red: - 3 %

- New optics mode



δp/p

Blue: +1.2 %,

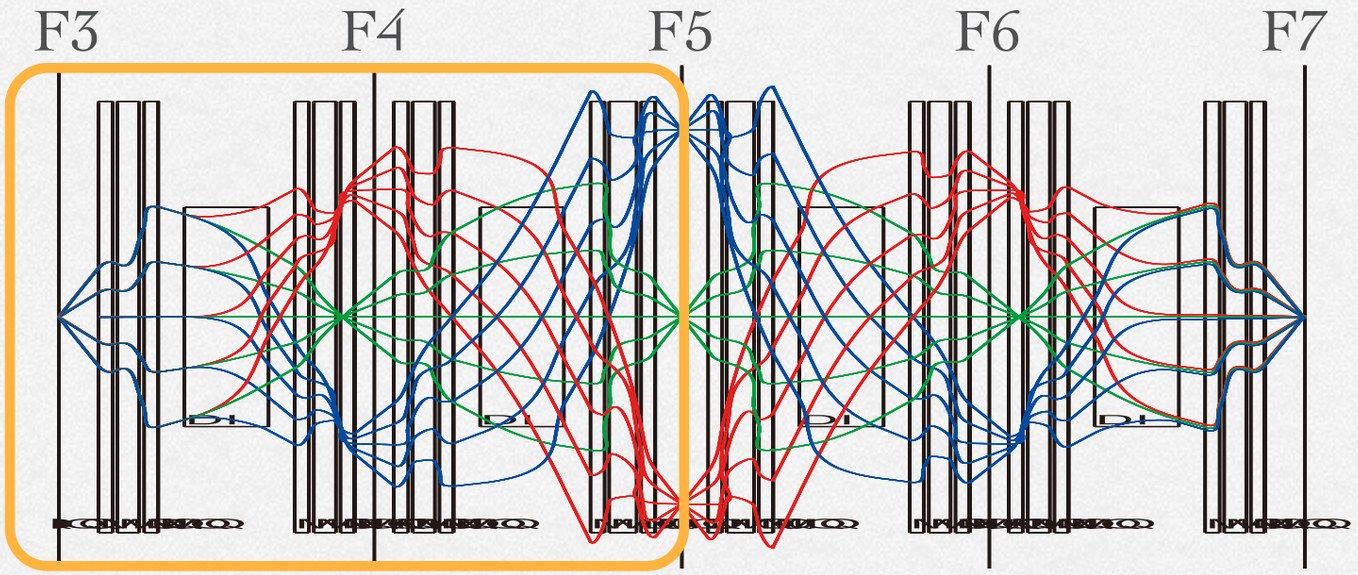
Green: 0 %,

Red: -1.2 %

Momentum compression mode

T.S. et al, Proposed at RNB8 (2009)

- Standard optics mode

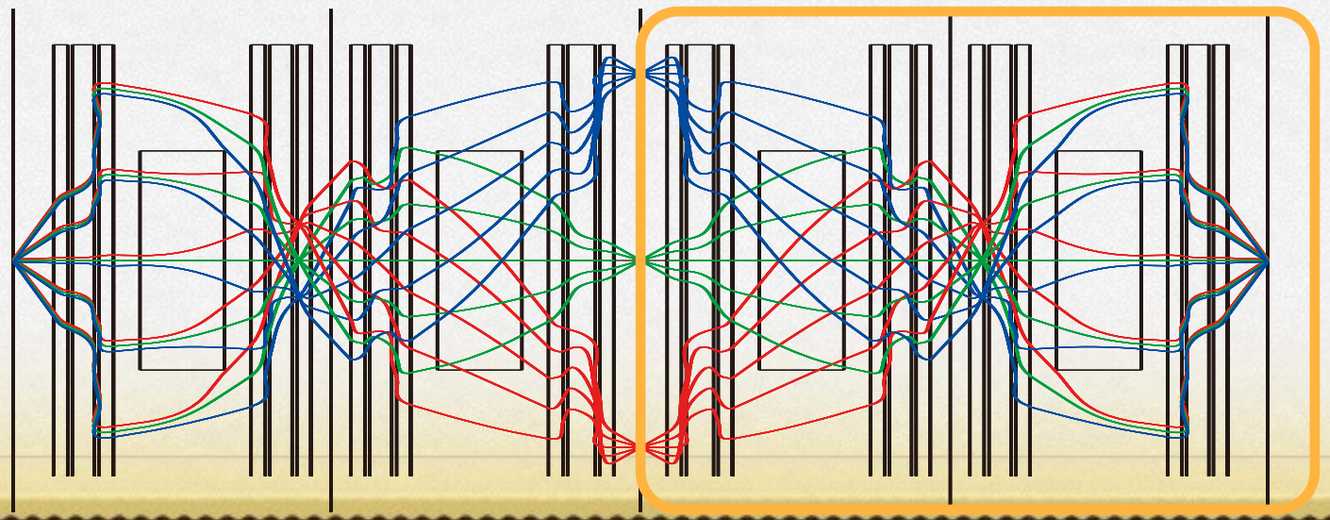


X direction

	δp/p
Blue:	+ 3 %,
Green:	0 %,
Red:	- 3 %

- New optics mode

$\delta p/p$ ± 3 % → ± 1.2 %



	δp/p
Blue:	+1.2 %,
Green:	0 %,
Red:	-1.2 %

Production test of ^{82}Ge (~15MeV/u)

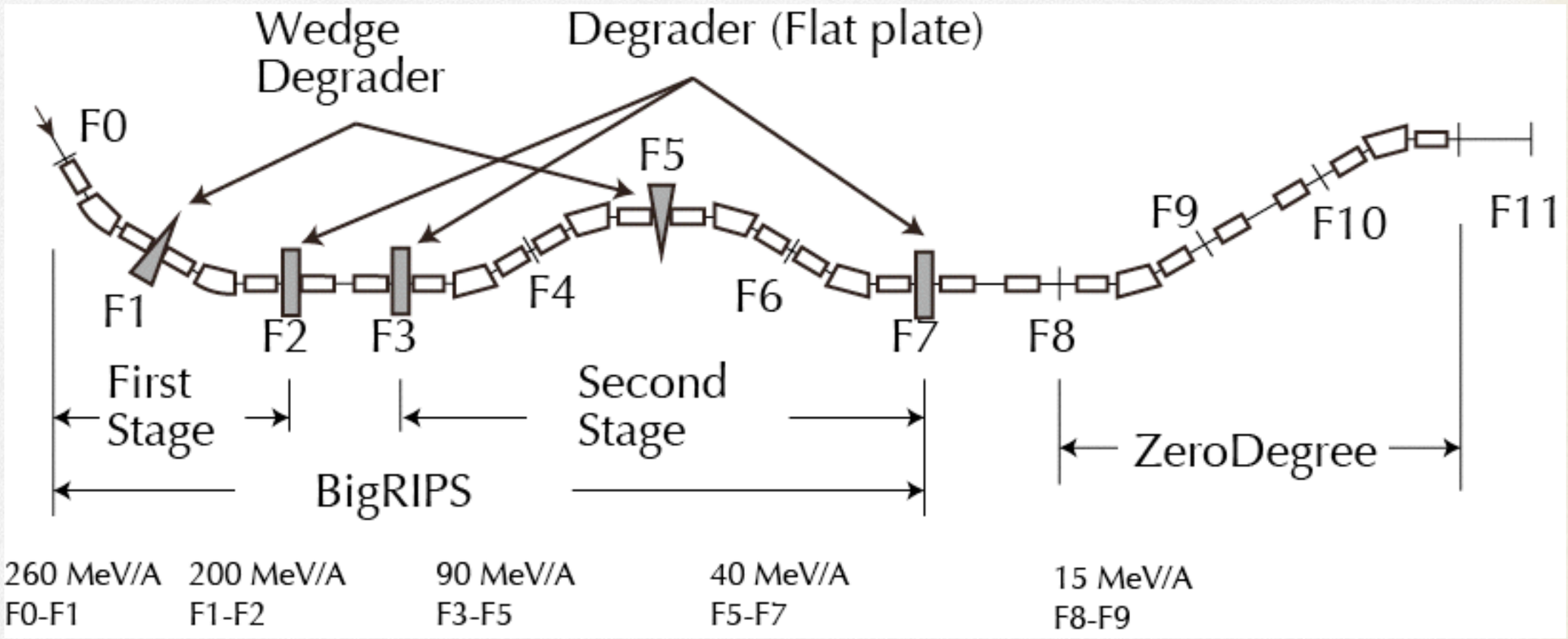
- Primary Beam, ^{238}U (345 MeV/A)

Oct. 25-26 (24h), 2014

- Secondary Beam, ^{82}Ge (40 MeV/A after F5 deg., 15 MeV/A @ F8)

Target: Be 7mm

For energy adjustment



5mm

7.5mm 0.4mm 2mm 0.24mm

Momentum compression mode

- Ion optics of p compression and many degraders

$$\mathcal{M}_{F0F7} = \mathcal{M}_{F5F7}\mathcal{D}_{F5}\mathcal{M}_{F3F5}\mathcal{D}_{F3}\mathcal{M}_{F2F3}\mathcal{D}_{F2}\mathcal{M}_{F1F2}\mathcal{D}_{F1}\mathcal{M}_{F0F1}$$

$$\mathcal{M}_{F0F1} = \begin{pmatrix} (x|x)_{F0F1} & 0 & (x|\delta)_{F0F1} & 0 & 0 \\ 0 & (a|a)_{F0F1} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathcal{D}_{F1} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ (\delta|x)_{F1} & (\delta|a)_{F1} & (\delta|\delta)_{F1} & (\delta|\delta_z)_{F1} & (\delta|\delta_m)_{F1} \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\begin{aligned} (x|x)_{F0F7} &= (x|x)_{F0F1}(x|x)_{F1F2}(x|x)_{F2F3} \\ &\quad \times (x|x)_{F3F5}(x|x)_{F5F7}\frac{(\delta|\delta)_{F1}(\delta|\delta)_{F5}}{c_{F1}c_{F5}}, \\ (a|a)_{F0F7} &= \frac{1}{(x|x)_{F0F1}(x|x)_{F1F2}(x|x)_{F2F3}} \\ &\quad \times \frac{1}{(x|x)_{F3F5}(x|x)_{F5F7}}, \\ (\delta|\delta)_{F0F7} &= c_{F1}c_{F5}(\delta|\delta)_{F2}(\delta|\delta)_{F3}(\delta|\delta)_{F7}. \end{aligned}$$

$$c_{F1} = \frac{\delta_{F1F2}}{\delta_{F0F1}},$$

$$c_{F5} = \frac{\delta_{F5F7}}{\delta_{F3F5}}$$

$$\det\mathcal{M}_{F0F7} = (\delta|\delta)_{F1}(\delta|\delta)_{F2}(\delta|\delta)_{F3}(\delta|\delta)_{F5}(\delta|\delta)_{F7}.$$

$$\sim \frac{1}{1 - d_{\text{total}}/R}$$

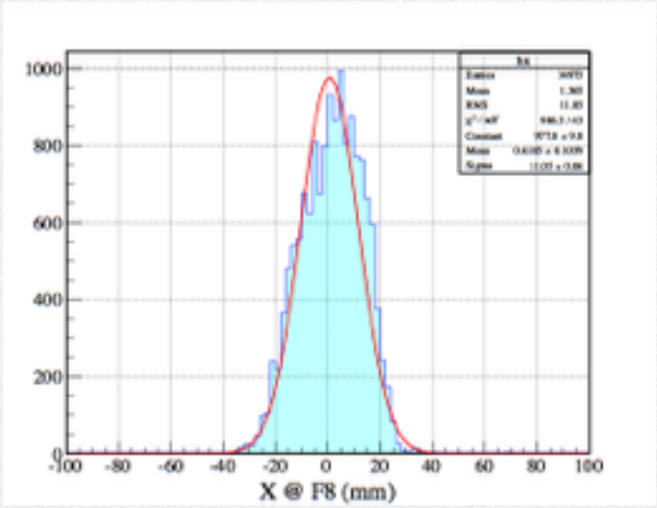
- Rebalance of (x|x), (a|a), (δ|δ)

  $\det M_{\text{F0F7}} = (\text{x}|\text{x})(\text{a}|\text{a})(\delta|\delta) = \text{constant}$

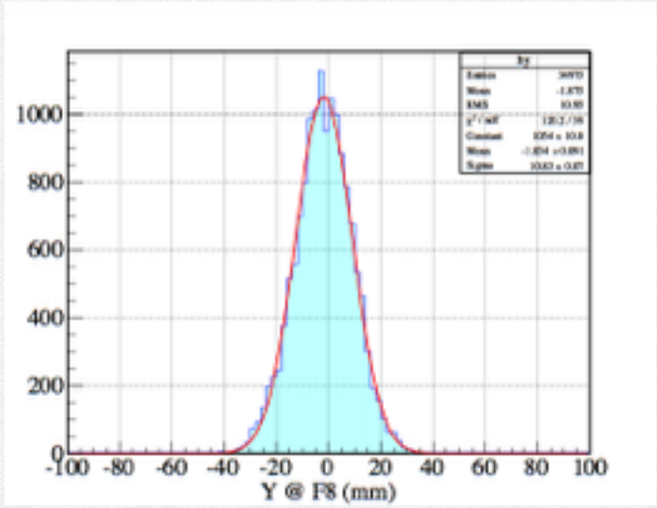
First Slowed-down Exotic RI Beam

- Beam spot @ F8

σ(X) = 11 mm

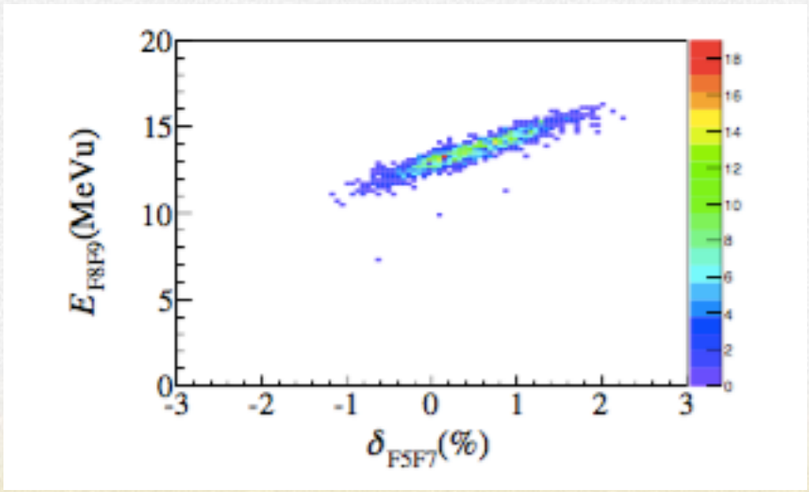


σ(Y) = 11 mm



- Energy distribution

E @ F8 = 13 ± 2.5 MeV/A



Beam quality is fine.

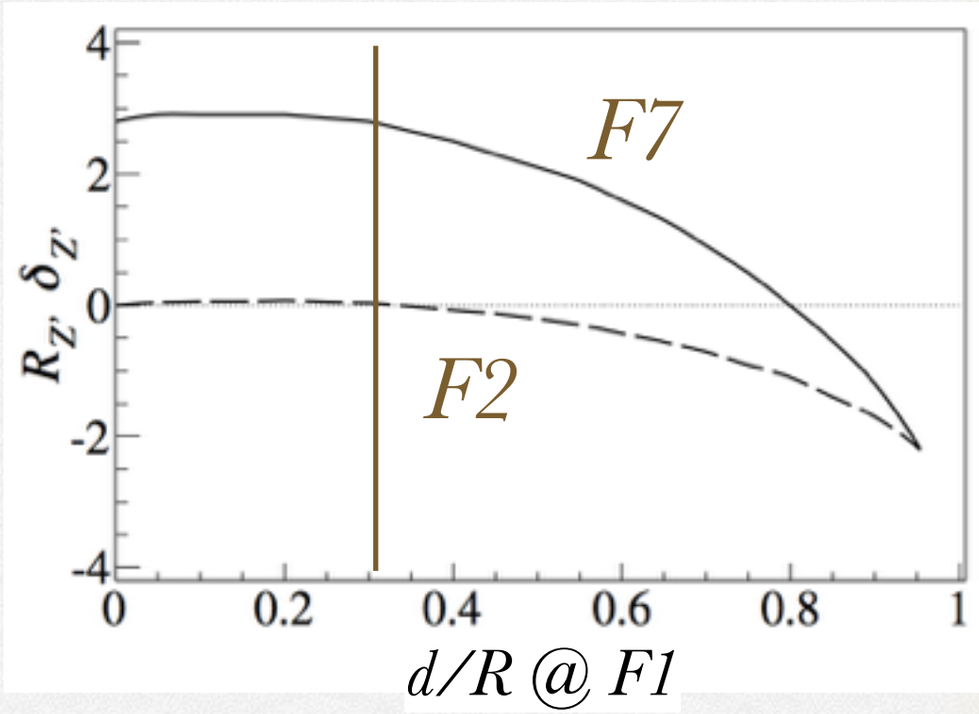
PURIFICATION

- Mass resolving power

$$R_{m(F2)} = \left| \frac{(x|\delta_m)_{F0F2}}{(x|x)_{F0F2}\, x_{F0}} \right| = \left| -\frac{(\delta|\delta_m)_{F1}}{(\delta|\delta)_{F1}} \frac{(x|\delta)_{F0F1}}{(x|x)_{F0F1}\sigma_{x_0}} \right|$$

$$R_{m(F7)} = \left| \frac{(x|\delta_m)_{F0F7}}{(x|x)_{F0F7}\sigma_{x_0}} \right|$$

$$= \left| -\frac{(\delta|\delta_m)_{F1}}{(\delta|\delta)_{F1}} \frac{(x|\delta)_{F0F1}}{(x|x)_{F0F1}\sigma_{x_0}} - \frac{(\delta|\delta_m)_{F5}}{(\delta|\delta)_{F1}(\delta|\delta)_{F5}} \times \frac{c_{F1}}{(x|x)_{F0F1}(x|x)_{F1F2}(x|x)_{F2F3}} \times \frac{(x|\delta)_{F3F5}}{(x|x)_{F3F5}\sigma_{x_0}} \right|.$$



Resolving power of isotone

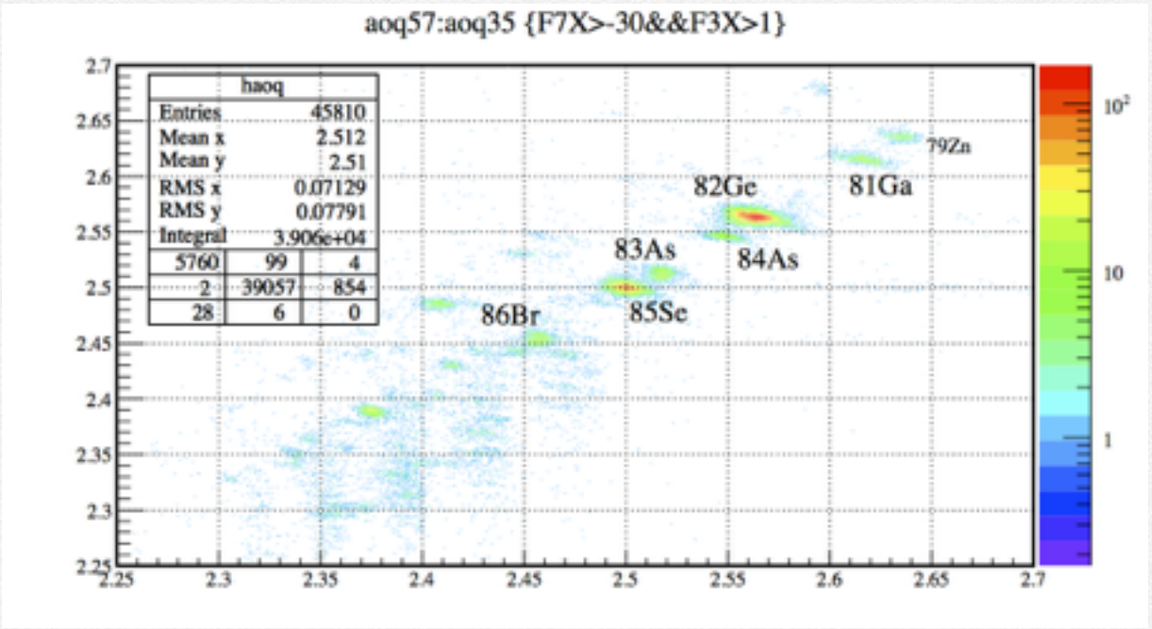
$E_{F0F1} = 266$ *MeV/u,*

$E_{F5F7} = 40$ *MeV/u*

$d_{F1} + d_{F5} \sim 15$*mm (const.)*

Purity of ^{82}Ge

- Purity using software cut
  - 40% was achieved for yield-optimized momentum selection.



Problem

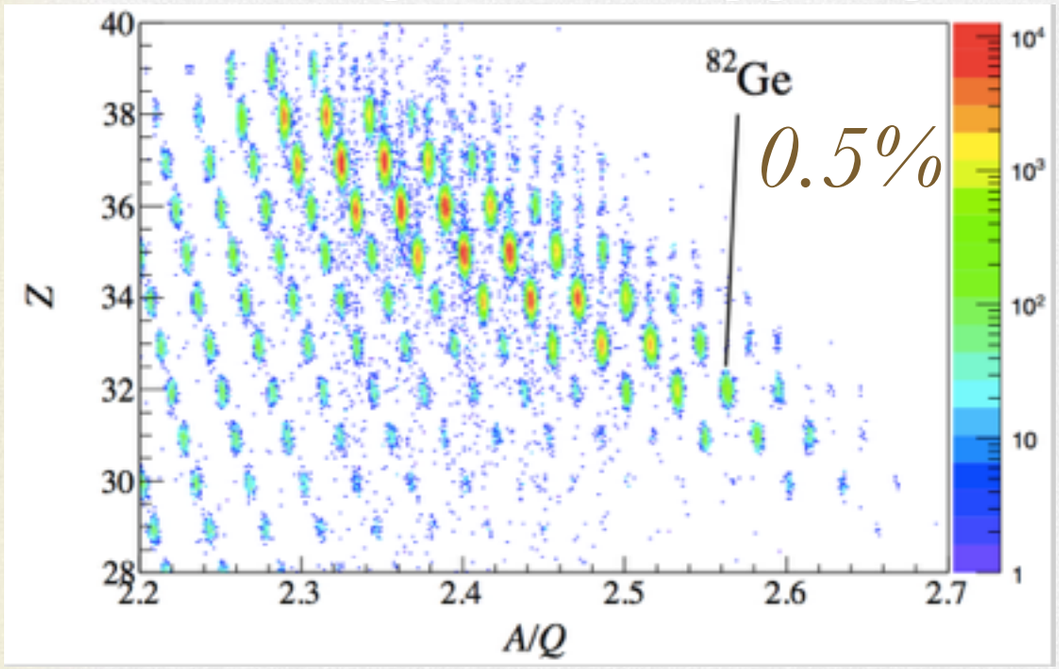
- Yield peak of momentum distribution

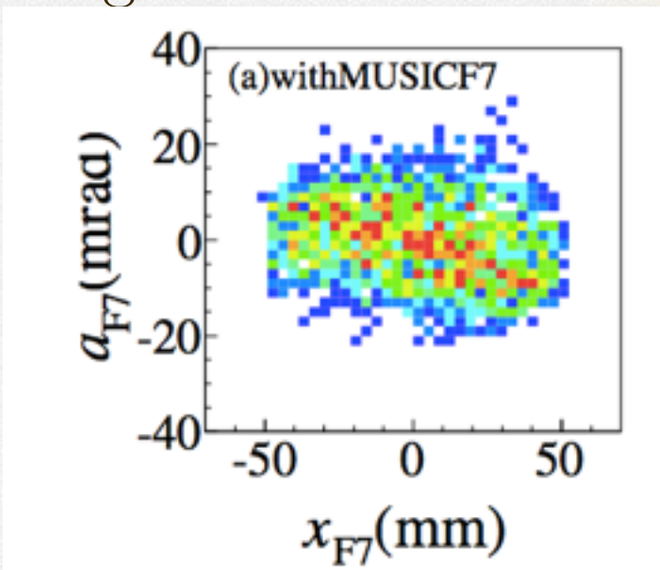
  Purity at F7 is fine, but low purity after 1st stage

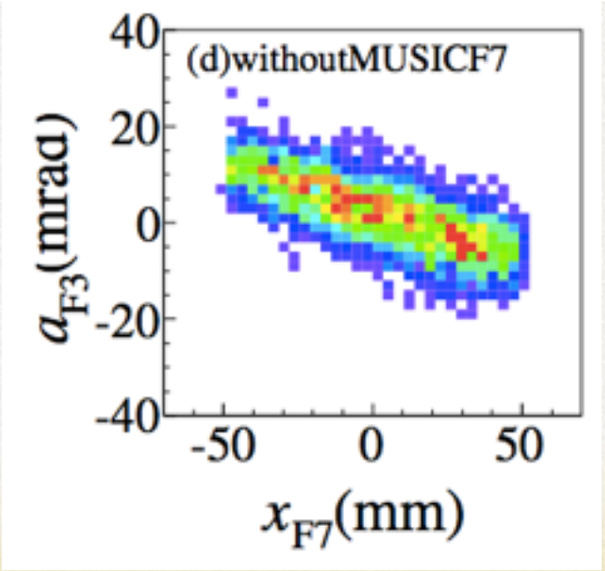
  Total intensity limitation (10^7pps) after 1st stage about radiation safety

- Focus at F7

  Angular straggling in IC at F7







Slowed-down beam of ^{93}Zr with 50 and 20 MeV/u

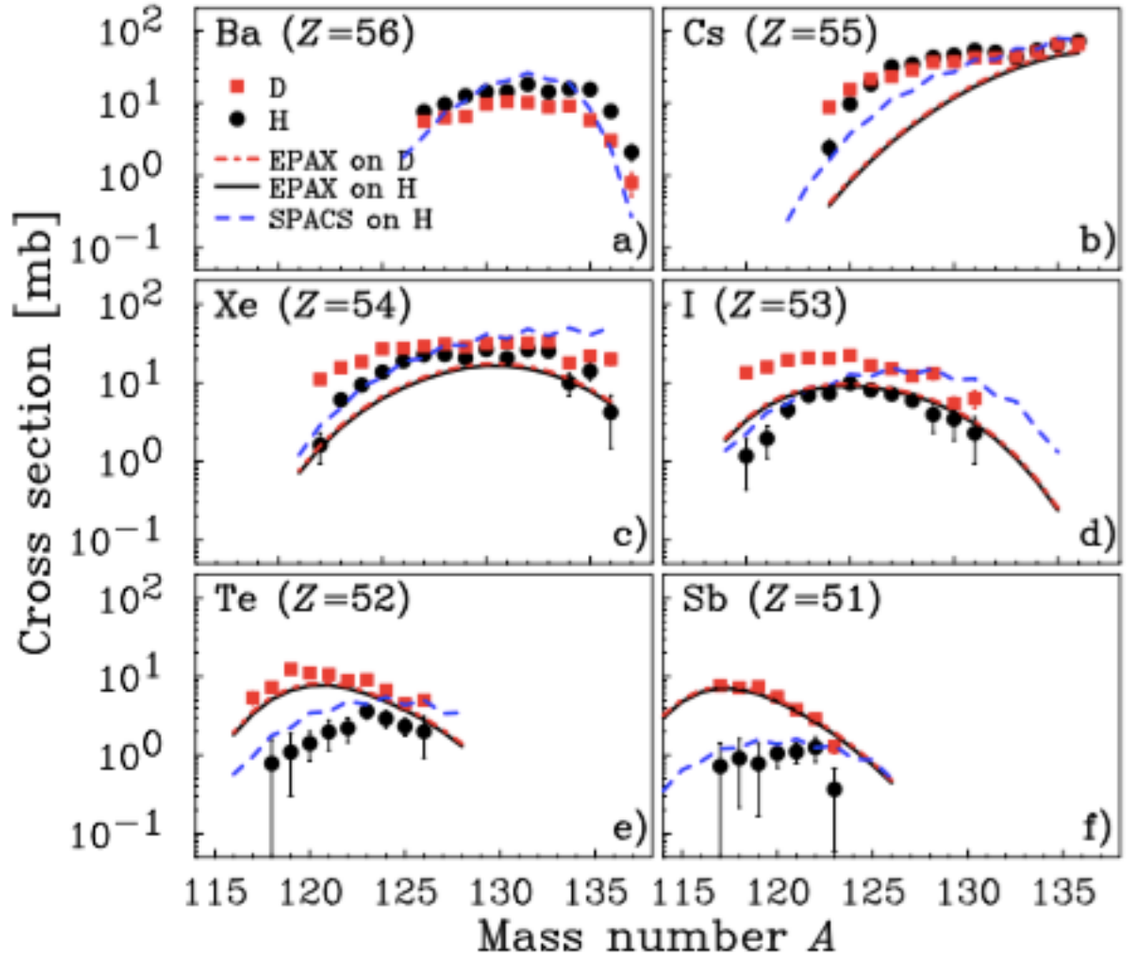


Fig. 2. (Color online.) Isotopic distributions of the measured cross sections for $51 \leq Z \leq 56$ elements produced by ^{137}Cs on proton (circle) and deuteron (square) at 185 MeV/nucleon. The solid and dot-dashed lines indicate EPAX [22] calculations on proton and deuteron, respectively, and these two EPAX calculations are close to each other. The SPACS [23] calculations on proton (dashed) is also displayed for comparison.

Wang et al, PLB

1. Reaction cross section for transmutation of LLFP
2. Optimization for the projectile fragmentation reaction on proton and deuteron
3. High purity after 1st stage
4. High transmission for ZeroDegree spectrometer
5. Minimize a material thickness in a F7-F8 straight line: secondary target is at F8.

Slowed-down Beam of LLFP ^{93}Zr

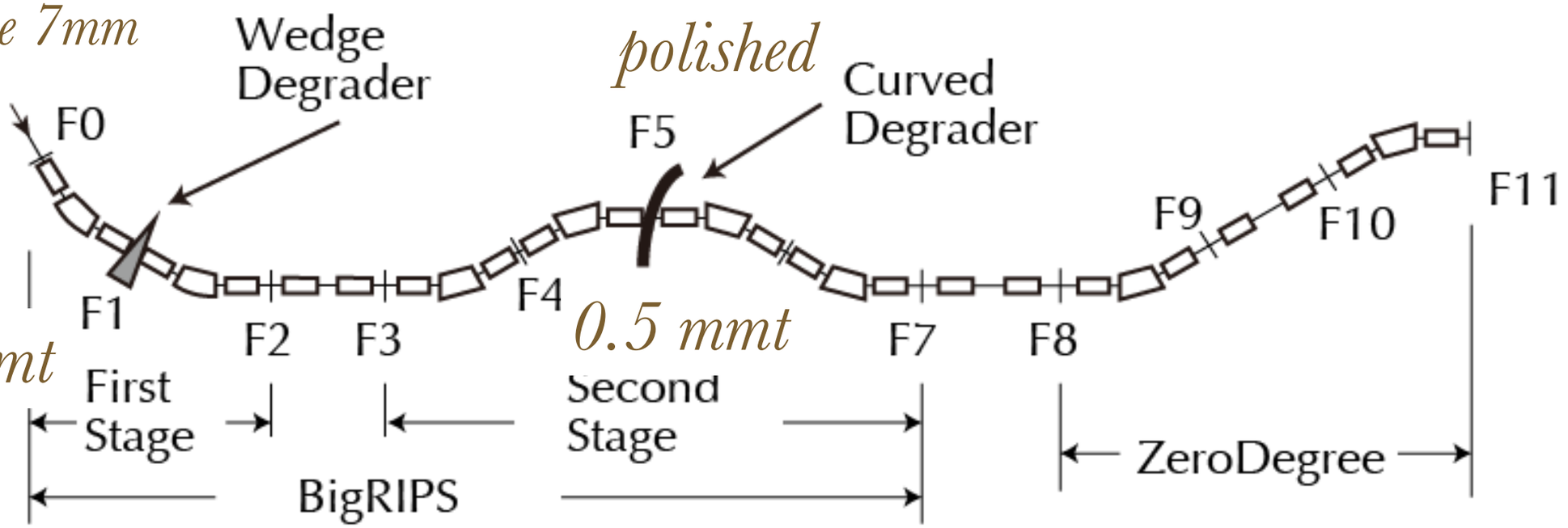
- Primary Beam, ^{238}U (345 MeV/A)

June 1-3 (2 days), 2016

- Secondary Beam, ^{93}Zr (50 MeV/u, 20 MeV/u @ F8-Target center)

Remove of degraders for energy adjustment

Target: Be 7mm



4, or 5mmt

0.5 mmt

Dispersive mode
no detecters at F9 and F10
no change of charge state

Energy Adjustment to 50MeV/u

- Goal: 50 MeV/u (center of secondary target),
  40 MeV/u (Secondary target), 60 MeV/u (no target)

- Procedure

  - 1. Measure energy by ZeroDegree:
    51.5 MeV/u (no secondary target)

  - 2. Change Bρ of 1st stage
    keeping 2nd stage: good for PID in 2nd stage

  - 3. Change Bρ of 2nd stage
    Same RI beam after 1st stage

- There was difficulty. Time consuming procedure!
  small change of 1st stage —> lost of ^{93}Zr beam at 2nd stage
  A very small change by +0.4% for D1 was acceptable.

Energy Adjustment to 50MeV/u

- Goal: 50 MeV/u (center of secondary target),
  40 MeV/u (Secondary target), 60 MeV/u (no target)

- Another procedure

  - 1. Prepare a relation between $\Delta B\rho_{01}$ and ΔE after secondary target

  - 2. Measure energy by using TOF at ZeroDegree:
    51.5 MeV/u (no secondary target)

  - 3. Calculate $B\rho_{01}$ from the prepared relation, and other $B\rho$'s

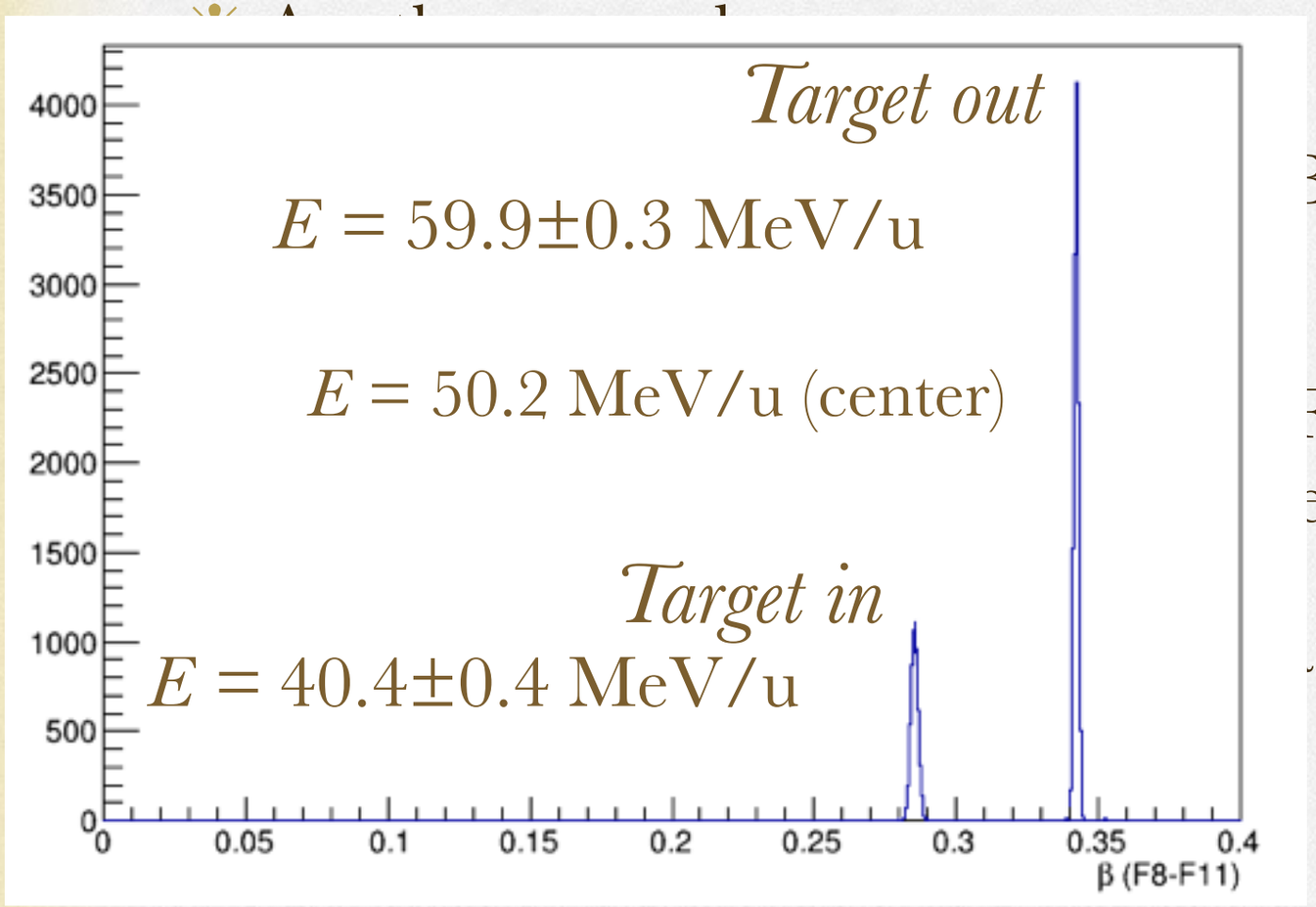
20 min. *+1.24% up*

  - 2nd E: 45.6 MeV/u (target in) 60.4 MeV/u (target out)

  - 3rd E: 40.4 MeV/u (target in), 59.9 MeV/u (target out)
    50.2 MeV/u (average)

Energy Adjustment to 50MeV/u

- Goal: 50 MeV/u (center of secondary target),
  40 MeV/u (Secondary target), 60 MeV/u (no target)



$B\rho_{01}$ and ΔE after secondary

F at ZeroDegree:
et)

red relation, and other Bρ's

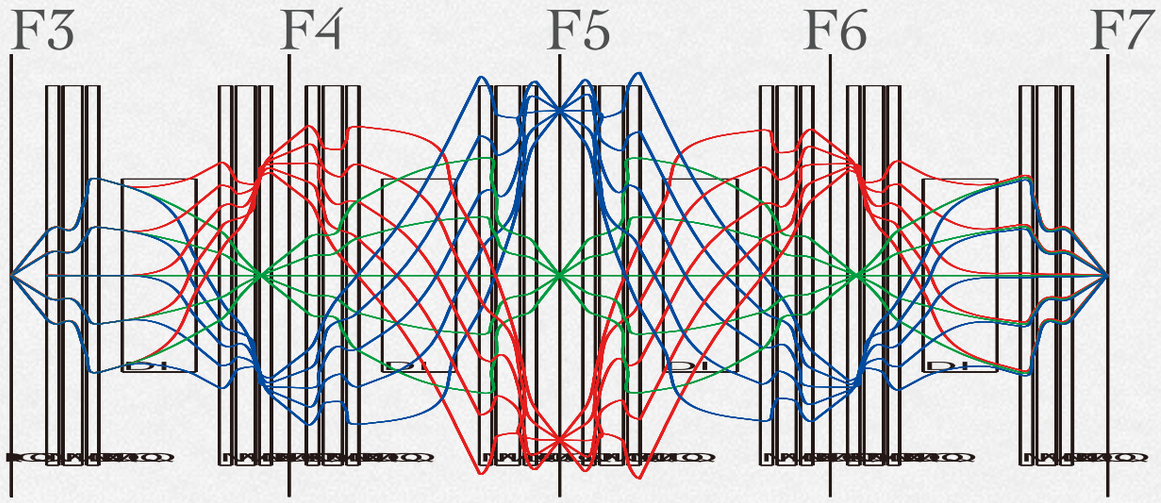
MeV/u (target out)

- 3rd E: 40.4 MeV/u (target in), 59.9 MeV/u (target out)
  50.2 MeV/u (average)

SLOWED-DOWN BEAM (SMALL EMITTANCE)

- Yield of LLFP is enough high to make small emittance by slit

- Standard optics mode



X direction

δp/p

Blue: + 3 %,

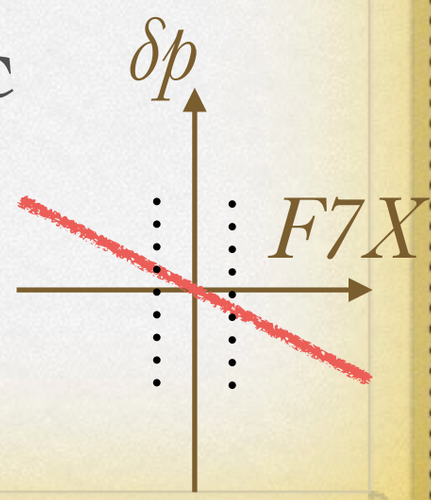
Green: 0 %,

Red: - 3 %

- Mono energetic degrader: For high transmission of ZeroDegree Spectrometer

δp/p<±0.1% @ F5-F7

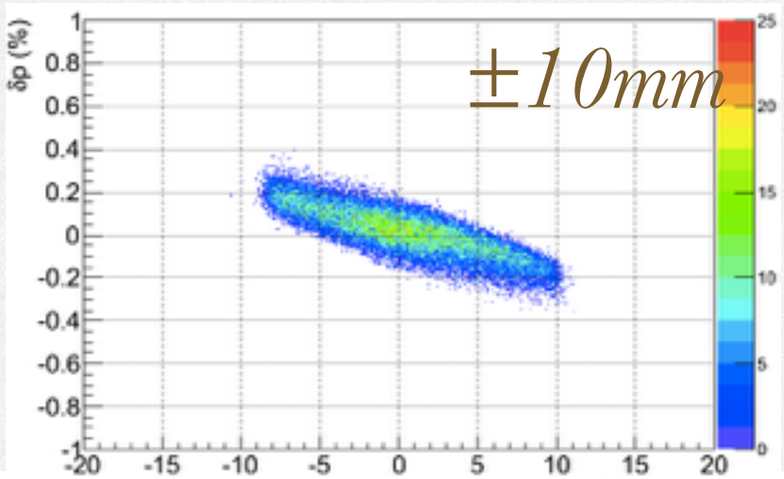
$\delta p/p$ ± 3 % → Mono Energetic

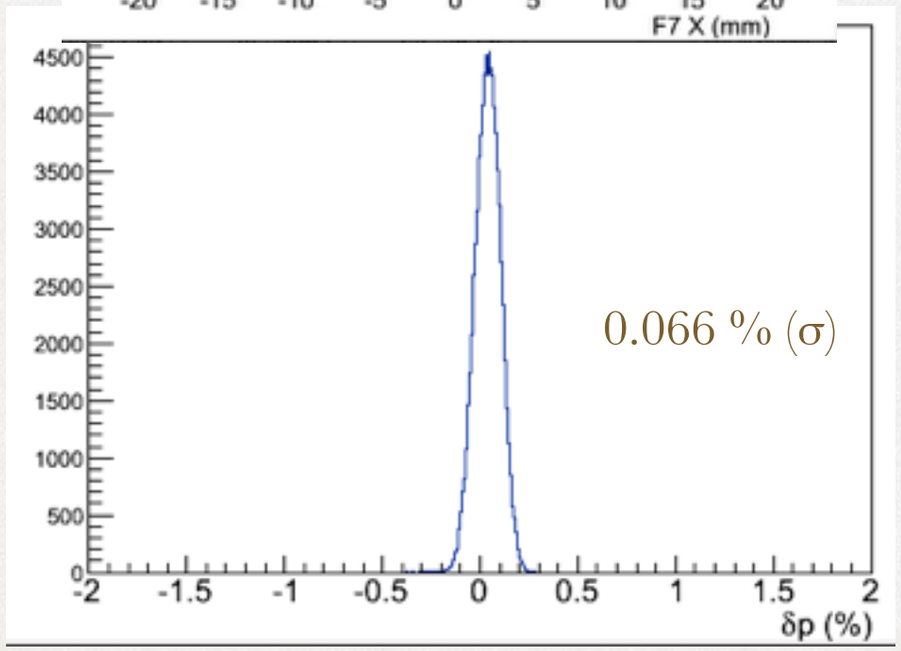


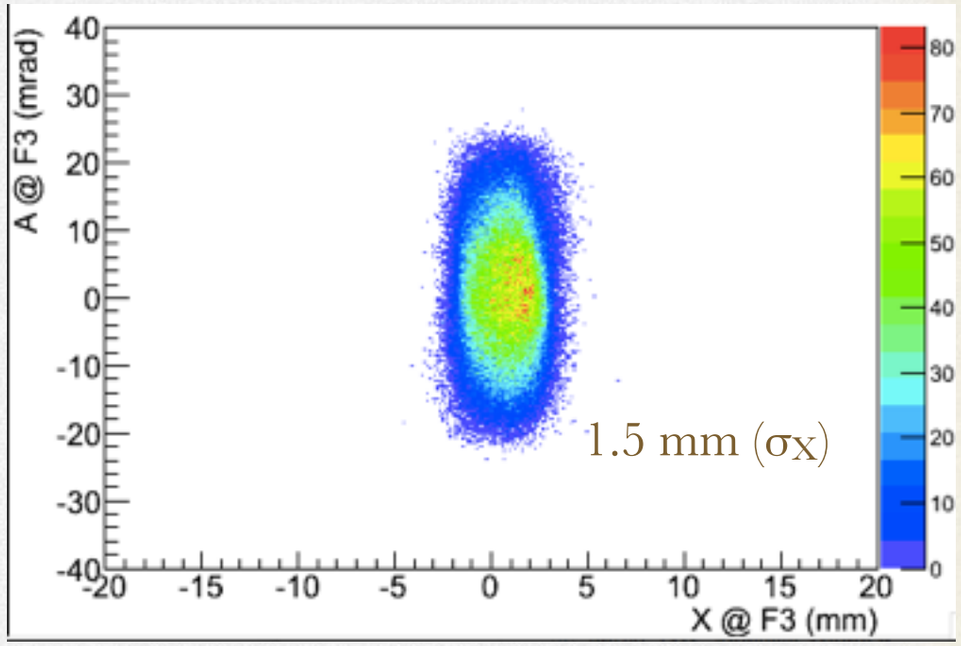
- High purity after 1st stage separation: > 40%
  for detectors and for radiation safety limit (10^7pps)

Small Emittance

- Narrow momentum distribution: narrow F1 X slit (±1mm)
- Narrow X distribution: X slit @ F2 (±2mm)



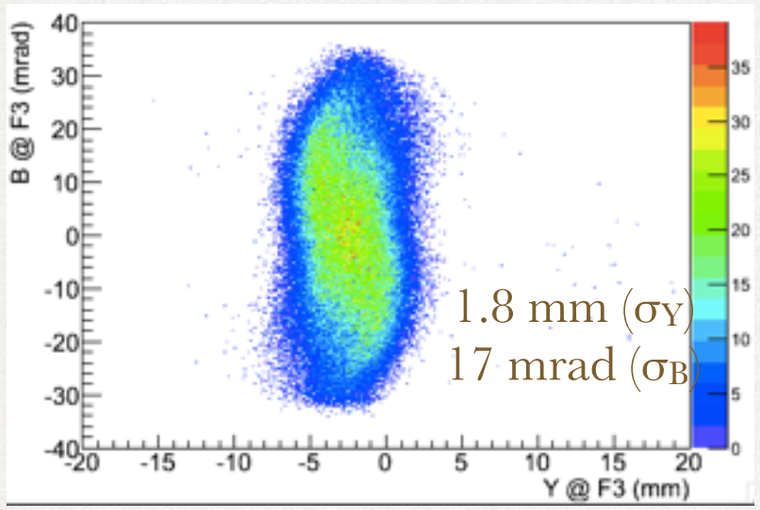




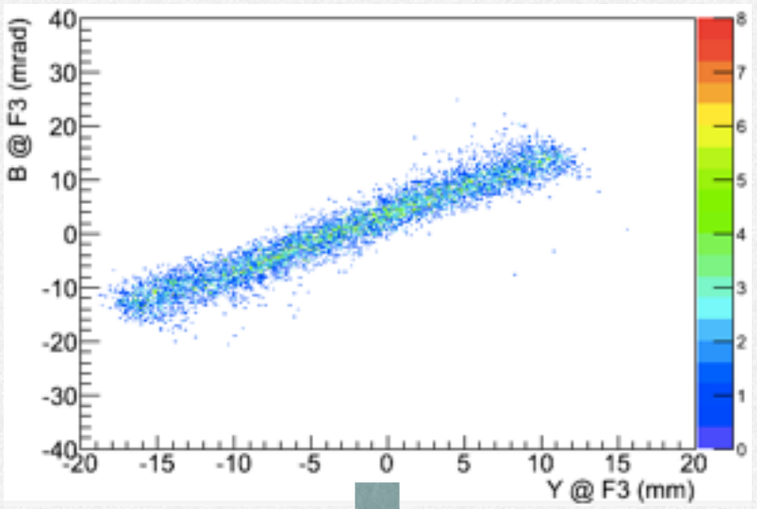
Momentum between F5-F7

Small Emittance

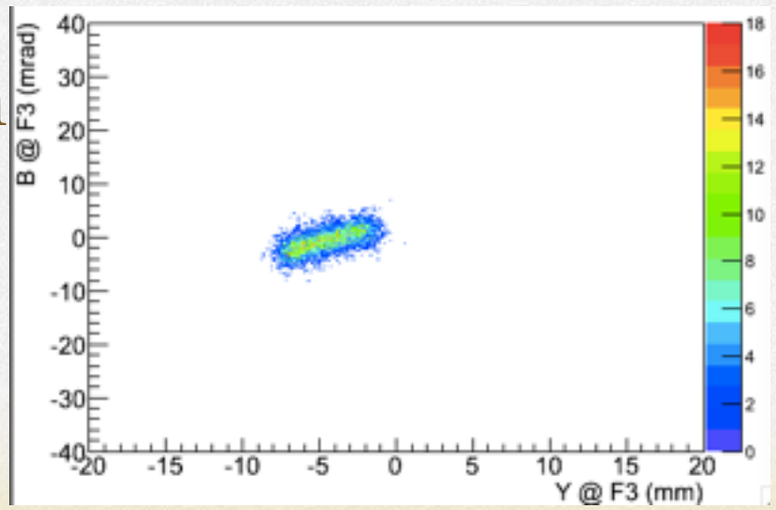
- Small emittance of Y: out of focus at Y slit @ F2



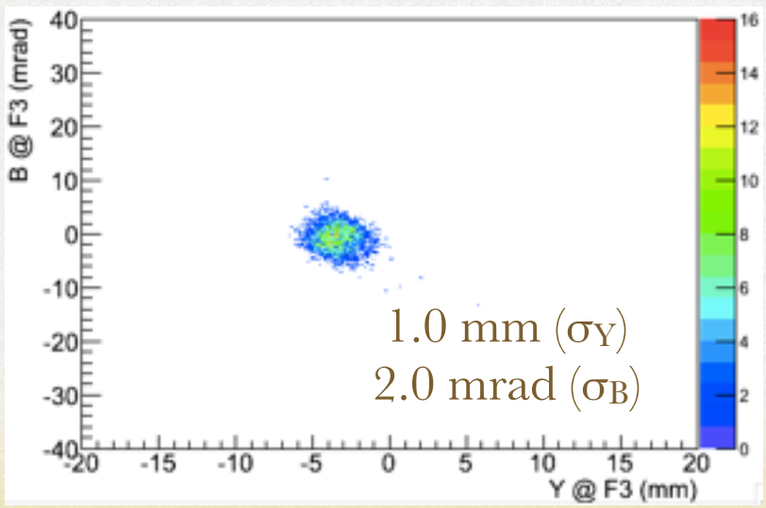
out of focus



cut by Y slit ±2 mm

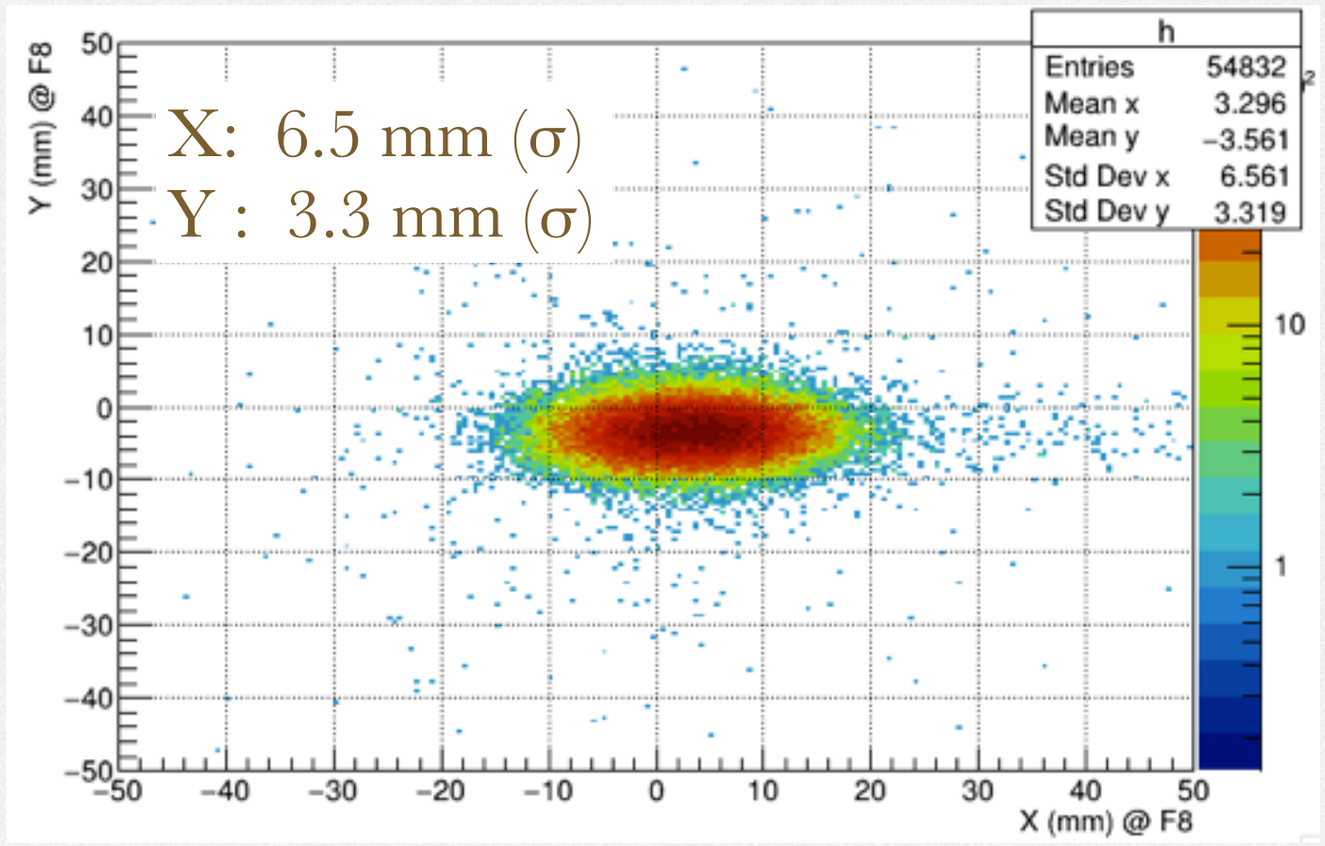


focus between F2 and F3



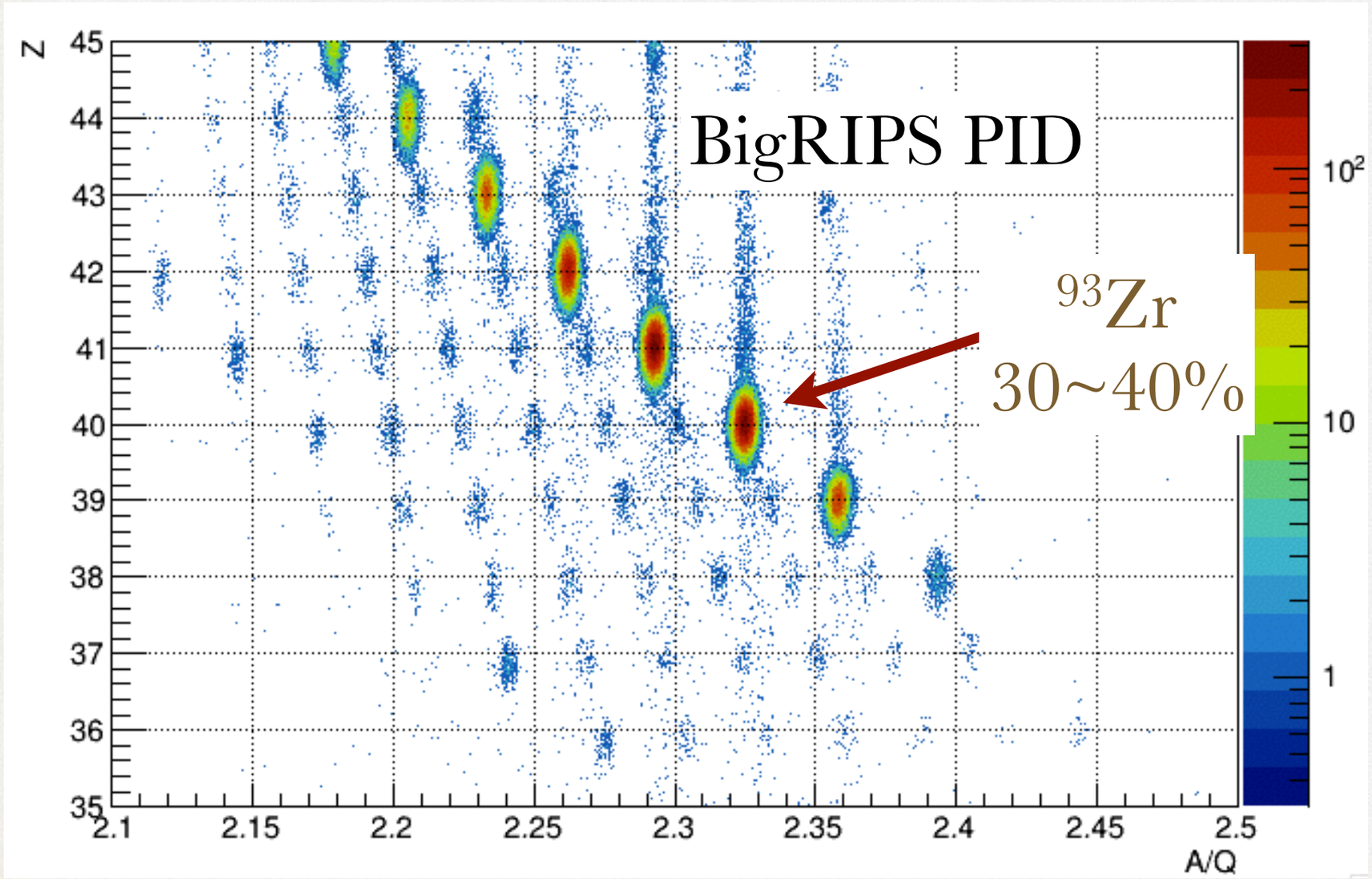
Beam size

- Secondary Beam, ^{93}Zr (50 MeV/u)



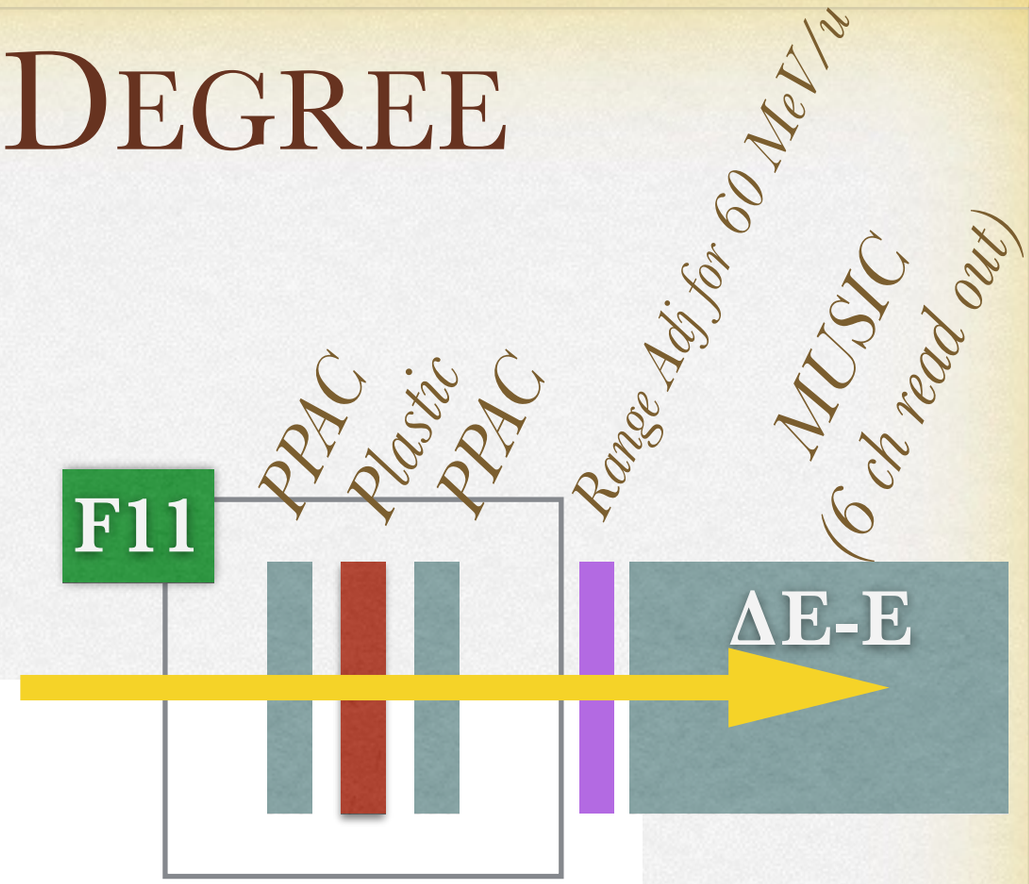
PID AND PURITY

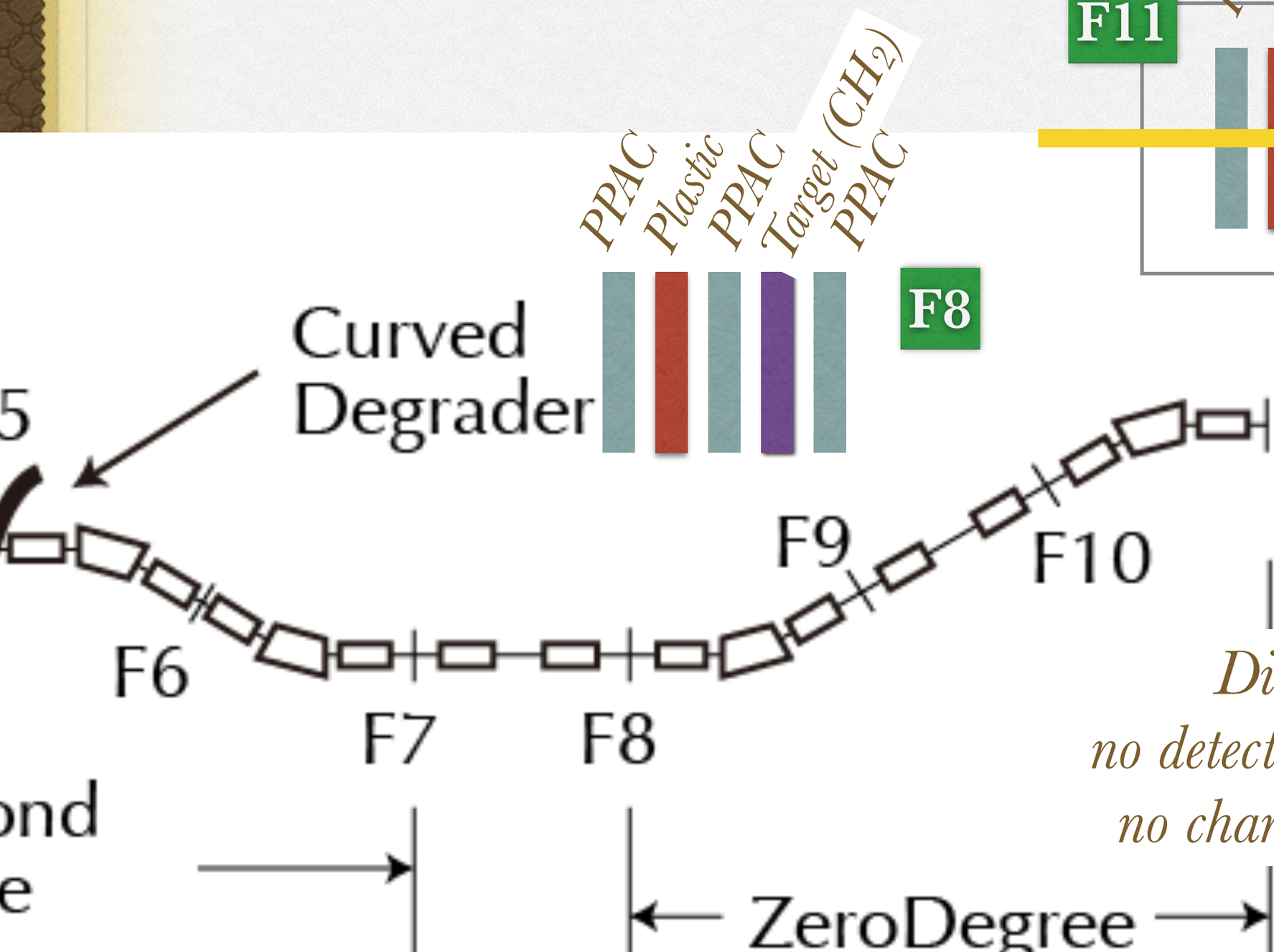
- Secondary Beam, ^{93}Zr (50 MeV/u)



PID in ZeroDegree

- Dispersive mode
  - Bρ - TOF - ΔE - E: (A/Q, Z, Q)





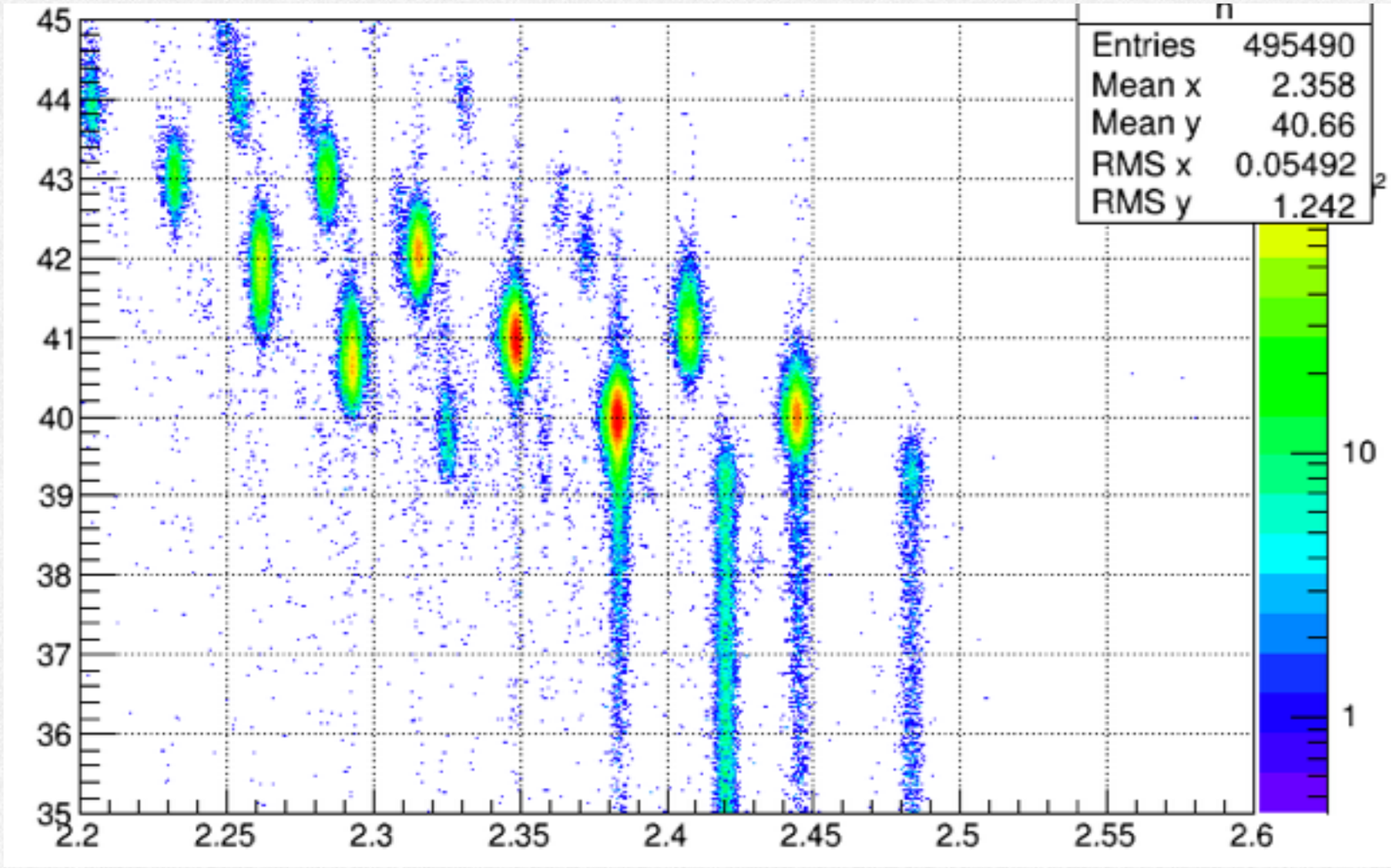
Dispersive mode
no detecters at F9 and F10
no change of charge state

Transport to ZeroDegree

- Secondary Beam, ^{93}Zr (50 MeV/u)

Tail: Stopped in first/beginning of second ch

ΔE-E in MUSIC



Z

A/Q

Q determination: in progress

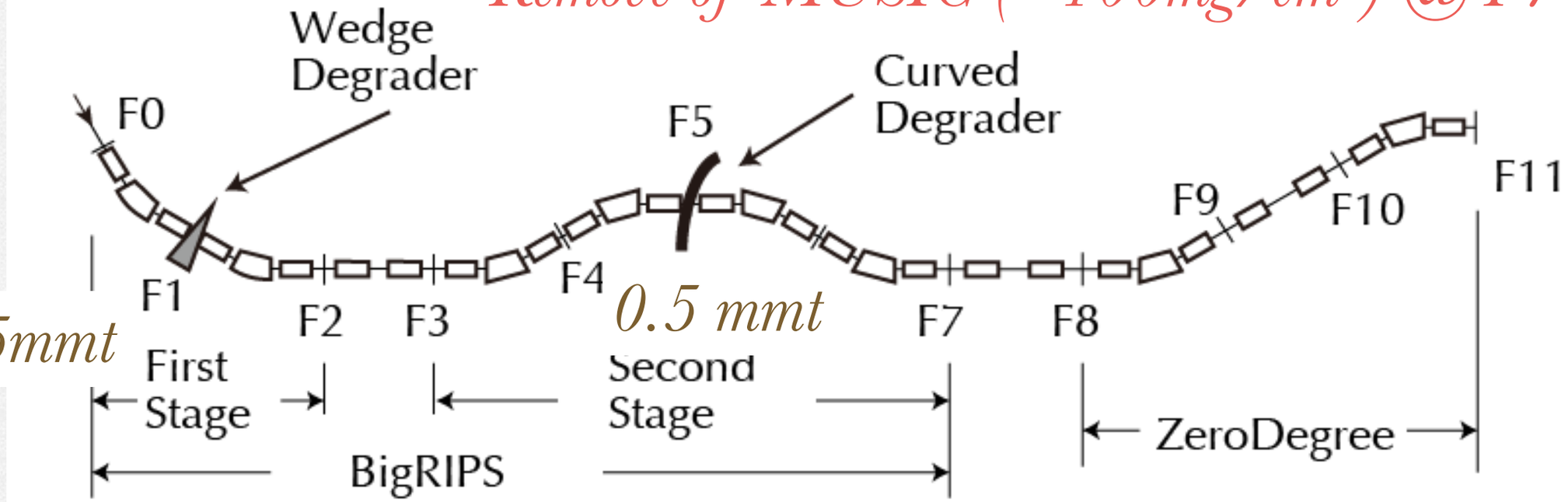
20 MeV/u (^{93}Zr beam)

- Secondary Beam, ^{93}Zr (20 MeV/u @ F8-Target center)

June 1-3, 2016

Remove of degraders for energy adjustment
Remove of MUSIC (~100mg/cm^2) @ F7

Target: Be 7mm



4, or 5mmt

0.5 mmt

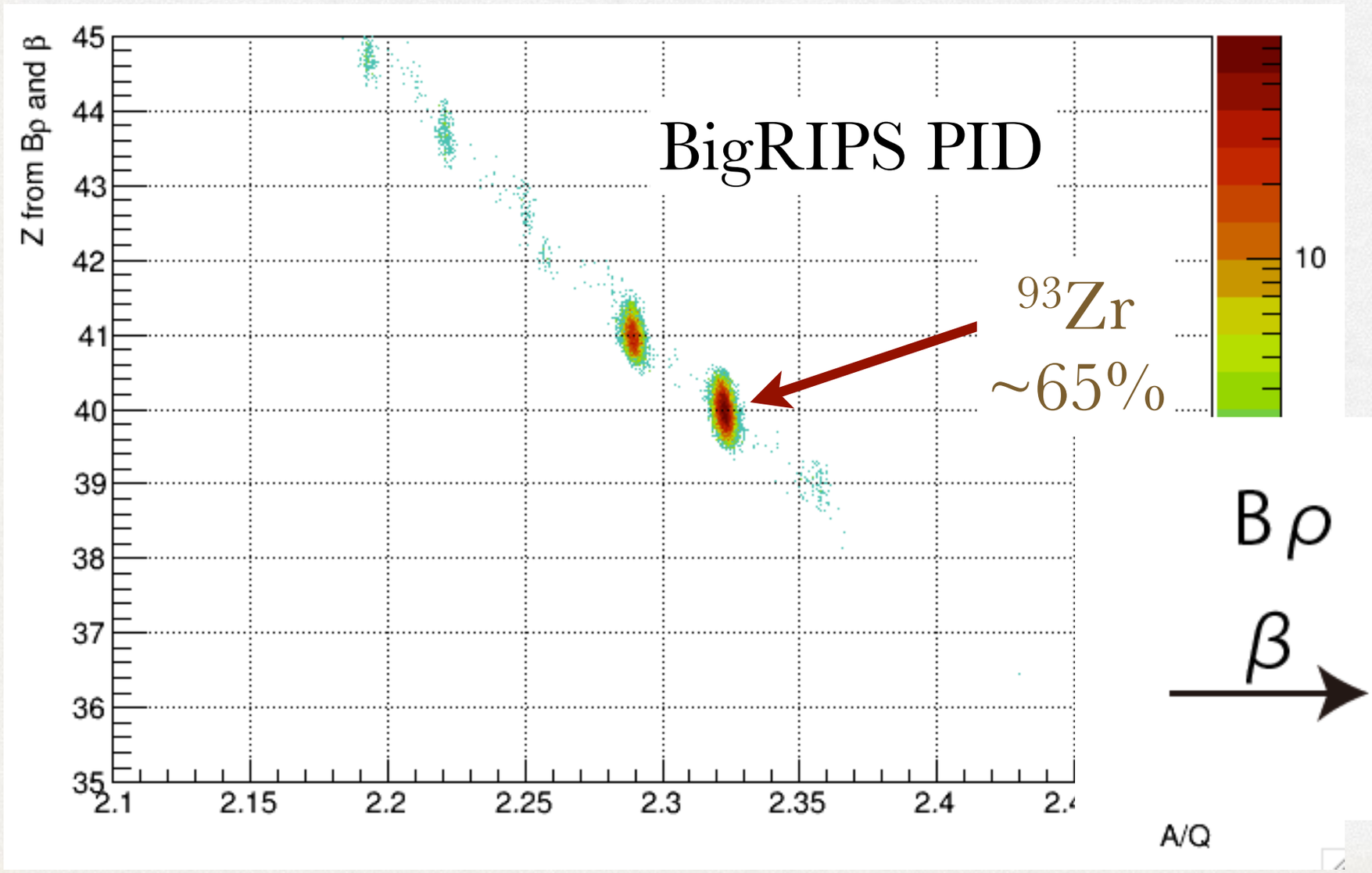
no MUSIC@F7
20 MeV/u

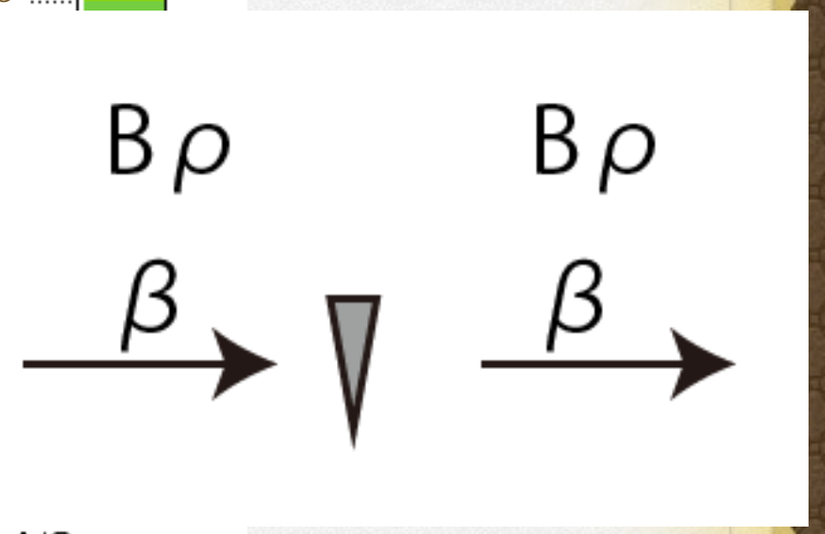
Dispersive mode
no detecters at F9 and F10
no change of charge state

Slowed-down Beam of LLFP ^{93}Zr

- Secondary Beam, ^{93}Zr (20 MeV/u)

  Z from E-loss F5 in degrader, (no IC @ F7)





Energy Adjustment to 20 MeV/u

- Goal: 20 MeV/u (center of secondary target, 20mg/cm^2),
  15 MeV/u (Secondary target), 25 MeV/u (no target)

- Procedure

  - 1. Prepare a relation between $\Delta B\rho_{01}$ and ΔE after secondary target

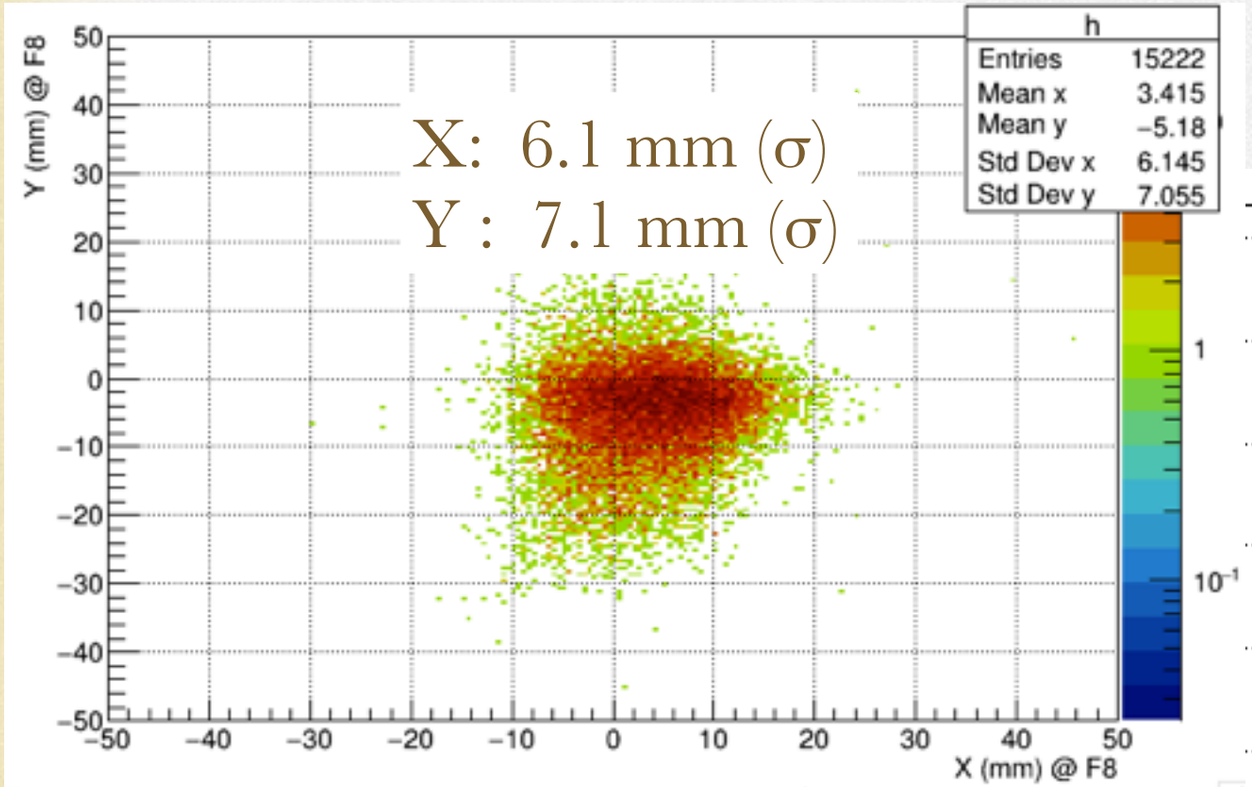
  - 2. Measure energy by ZeroDegree:
    29.5 MeV/u (Target in), 24.3 MeV/u (Target out)

  - 3. Calculate $B\rho_{01}$ from the prepared relation and other $B\rho$'s

- 2nd E tuning: 16.9 MeV/u (target in) 23.6 MeV/u (target out)
  20.3 MeV/u (average)

Slowed-down Beam of LLFP ^{93}Zr

- Secondary Beam, ^{93}Zr (20 MeV/u)



2nd Energy measurement

E = 23.6±0.2 MeV/u

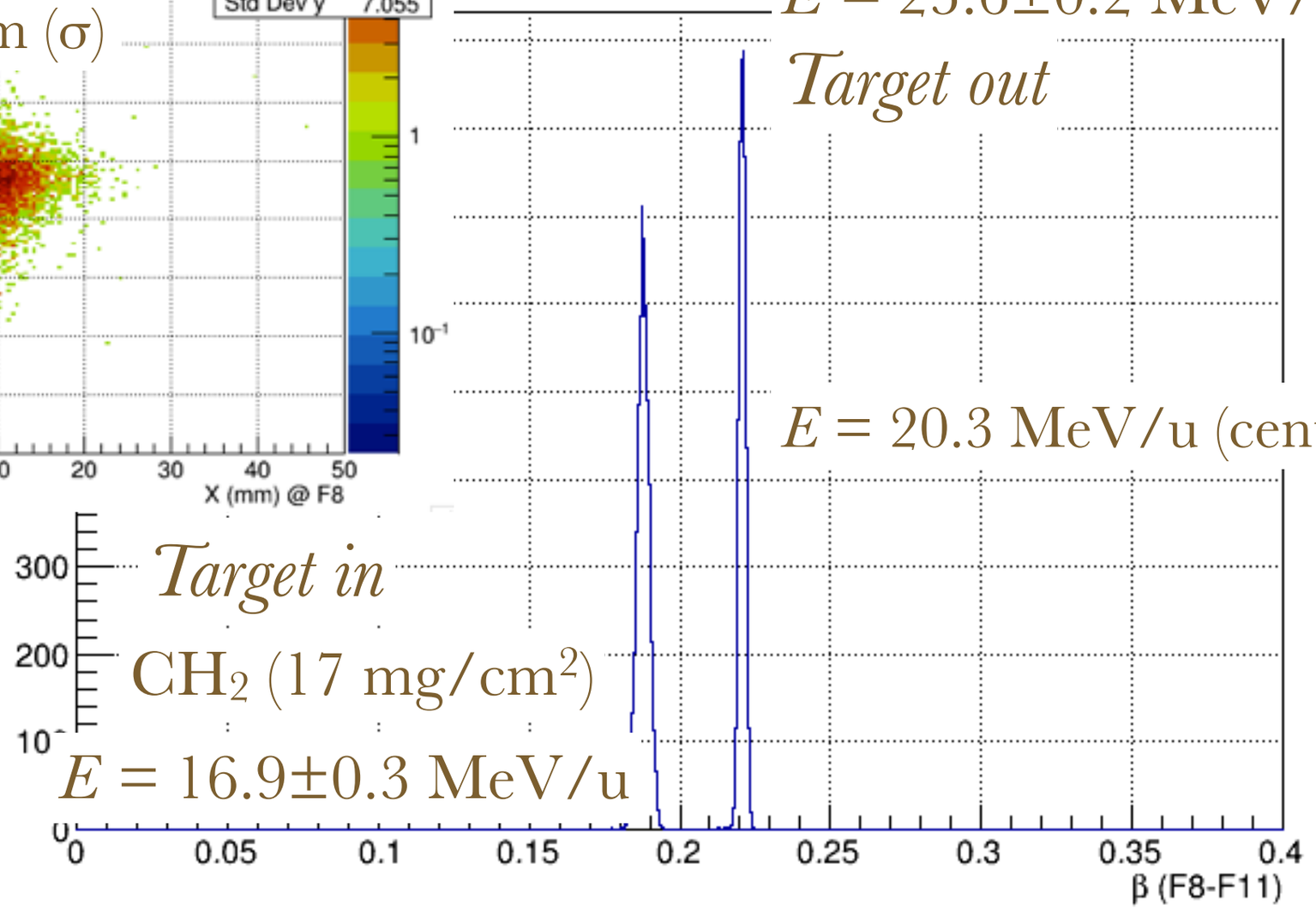
Target out

E = 20.3 MeV/u (center)

Target in

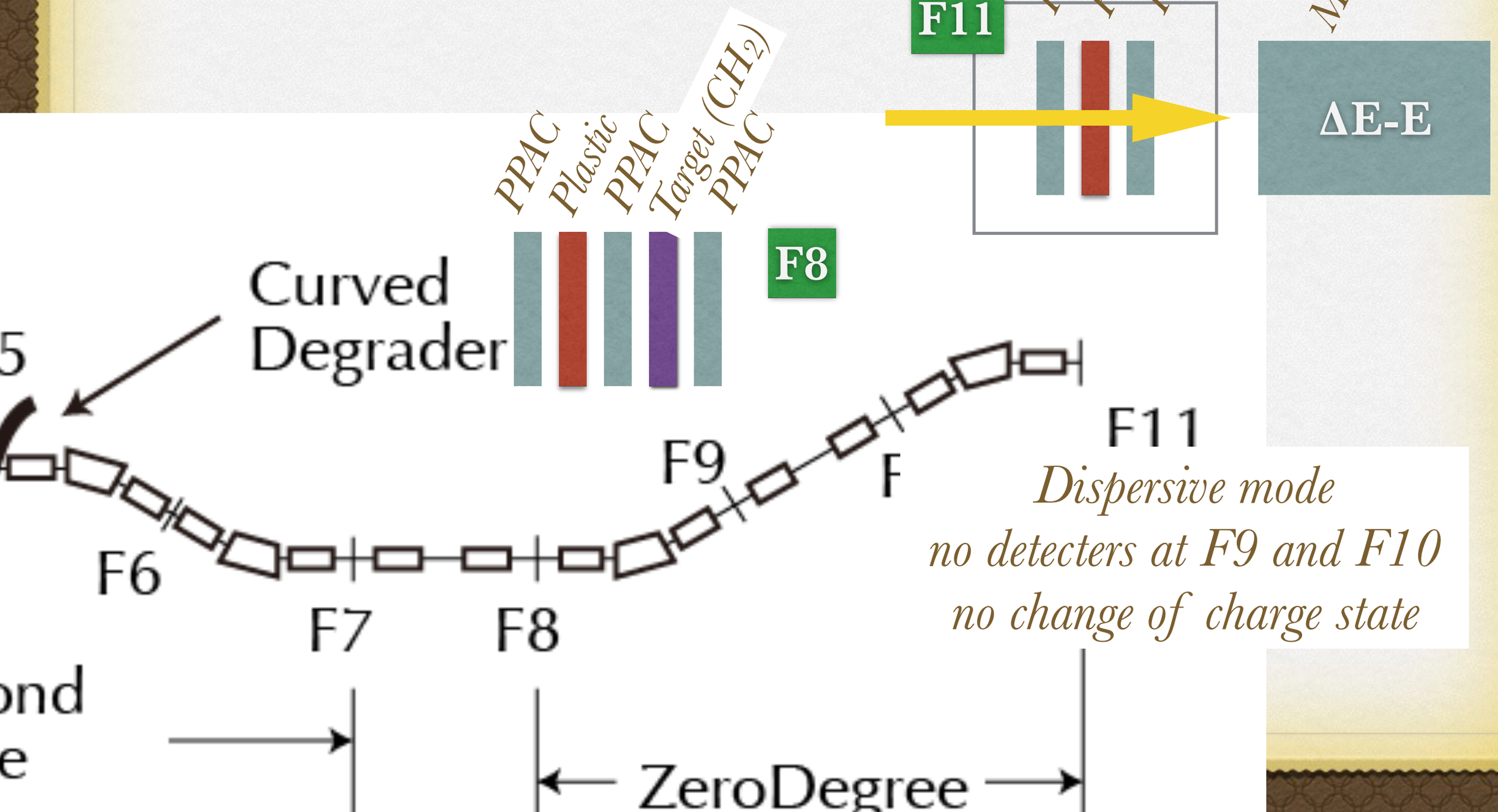
CH_2 (17 mg/cm^2)

E = 16.9±0.3 MeV/u



PID in ZeroDegree

- Dispersive mode
  - Bρ - TOF - ΔE - E: (A/Q, Z, Q)



Dispersive mode
no detecters at F9 and F10
no change of charge state

SUMMARY

Slowed-down RI beam was produced.

Energy-control method was established.

1. Yield optimization for ^{82}Ge beam

   Remaining issues: Purity after 1st stage,

   Improve transmission (focus tuning)

2. Small-emittance optimization of ^{93}Zr beam

   Remaining issues:

   Remove detectors: F7 IC, @ 50 MeV/u

   all F7 detectors @ 20 MeV/u

   Particle identification at ZeroDegree,

   especially @ 20 MeV/u

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