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Animation of a neutron star X-ray burst.
Credit: NASA/Dana Berr.

First detection of the rp-process nucleus ^{96}Cd

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Type I X-ray bursts


Neutron star EXO 0748-676. Image credit: NASA.

Artist's conception of neutron star EXO 0748-676 (blue sphere). It is part of a binary star system, and its neighboring star (yellow-red sphere) supplies the fuel for the thermonuclear bursts.

(Image Credit: NASA)

Type I X-ray bursts are thermonuclear explosions on the surface of a neutron star accreting matter from a companion in a binary system.

Fuel: H and He.

Energy release: 10^{39}-10^{40}ergs. Time scale: 10-100 s

Temp. range: 0.2 to 2.0 GK Density: $\rho \approx 10^5$ g/cm^3

Mechanisms: 3α, αp-process and rp-process

Recent observations from X-ray satellites

+ understanding of underlying nuclear physics

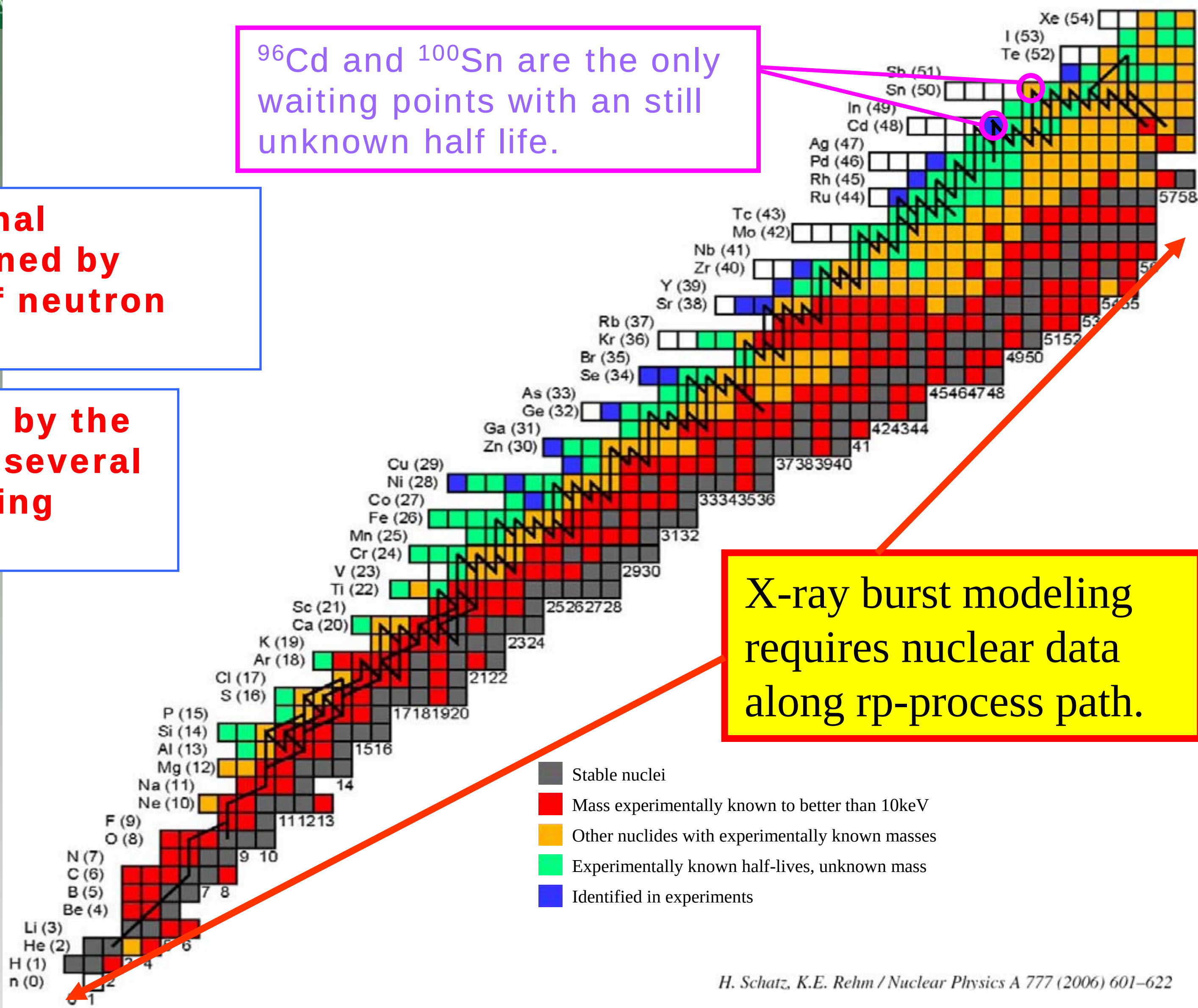
$\Rightarrow$ constraint astrophysical models

rp-process

^{96}Cd and ^{100}Sn are the only waiting points with an still unknown half life.

Reaction path and final abundances determined by nuclear properties of neutron deficient nuclei.

Time scale governed by the β-decay half-lives of several even-even N=Z waiting point nuclei.



X-ray burst modeling requires nuclear data along rp-process path.

rp-process studies at the NSCL: looking for ^{96}Cd

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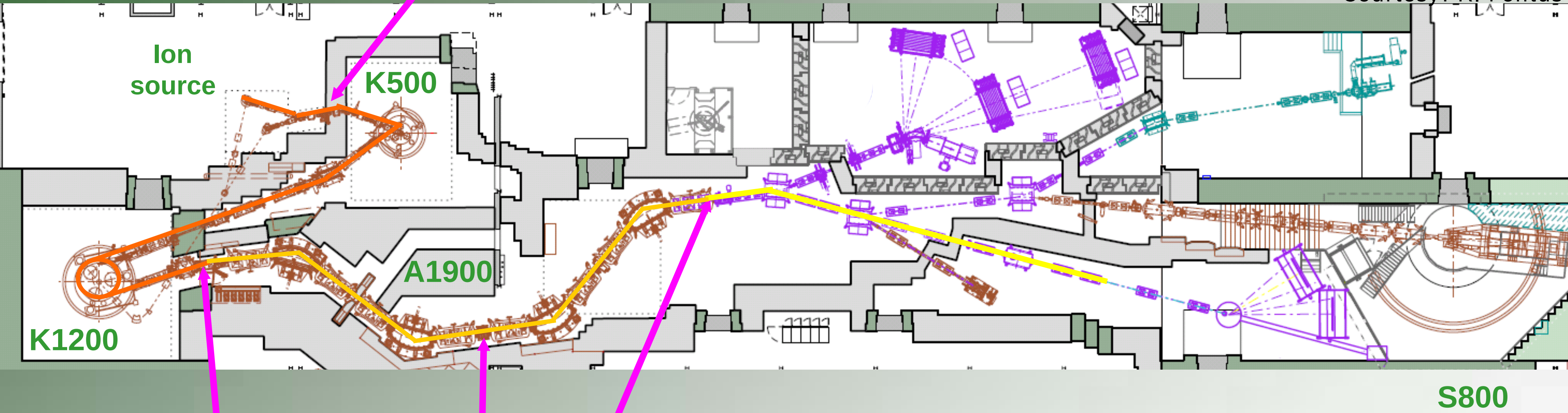
Primary beam: ^{124}Xe at 140 MeV/u.

Courtesy: R. Fontus



Be target 188mg/cm^2.

^{96}Cd cocktail sent to vault

Al wedge 180 mg/cm^2

A1900 settings:

$B\rho_{1,2}$=3.1675 T·m; $B\rho_{3,4}$=2.7965 T·m

Momentum acceptance = 1 %

Average beam current = 5.6 pnA

Experimental challenges in rp-process studies at NSCL

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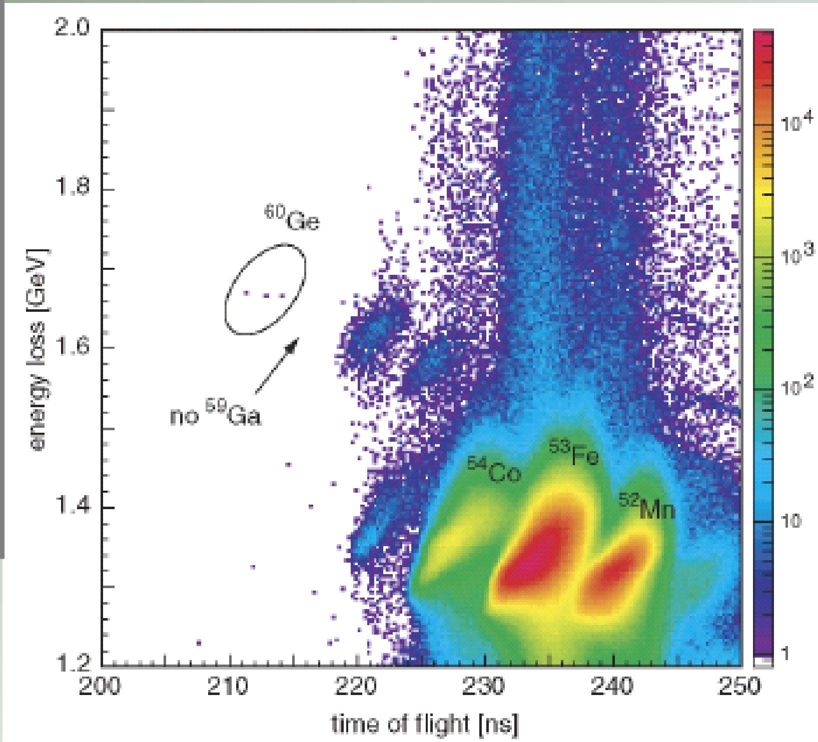
First observation of ^{60}Ge and ^{64}Se

Stolz, et. al. Phys. Let. B. 627 (2005) 32.

- The existence of ^{60}Ge and ^{64}Se was demonstrated for the first time.
- Difficulties:

  Lack of beam purity limited the total beam intensity to about 1/10 of what would have been available.

  Total beam intensity ~ 10^3 pps, did not allow β-decay measurements.



A. Stolz et al,. Phys. Let. B 627 (2005) 32.

Proper correlation of events imposes a limit on the implant rate.

Example: ^{96}Cd

Estimated half-life = 1s

Assuming beam spot covering ~1200 pixels

Wait 5 half-

⇒ Average

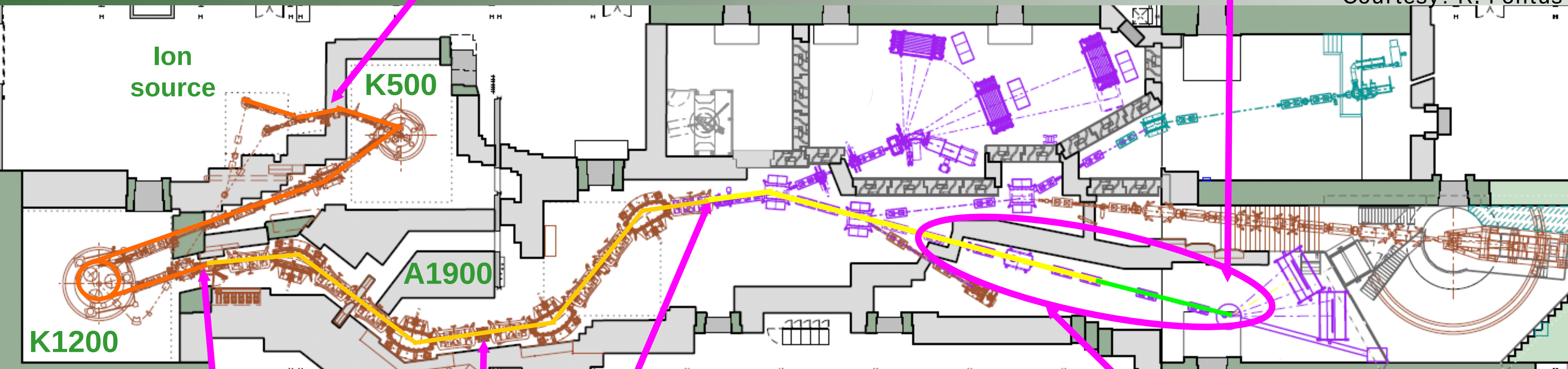
We need to add a velocity filter to the A1900 configuration

rp-process studies at the NSCL: looking for ^{96}Cd

Primary beam: ^{124}Xe at 140 MeV/u.

Experimental station

Courtesy: R. Fontus



S800

Be target 188mg/cm^2.

^{96}Cd cocktail sent to vault

RFFS: Additional purification of secondary proton-rich beams

Al wedge 180 mg/cm^2

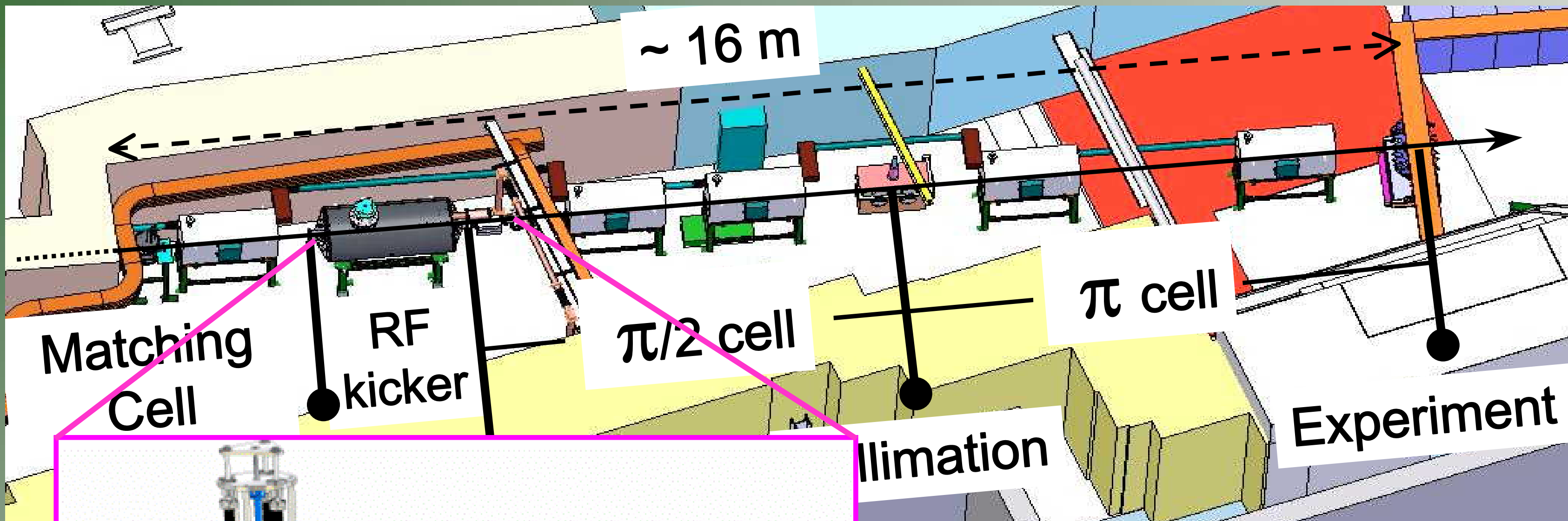
A1900 settings:

$B\rho_{1,2}$=3.1675 T·m; $B\rho_{3,4}$=2.7965 T·m

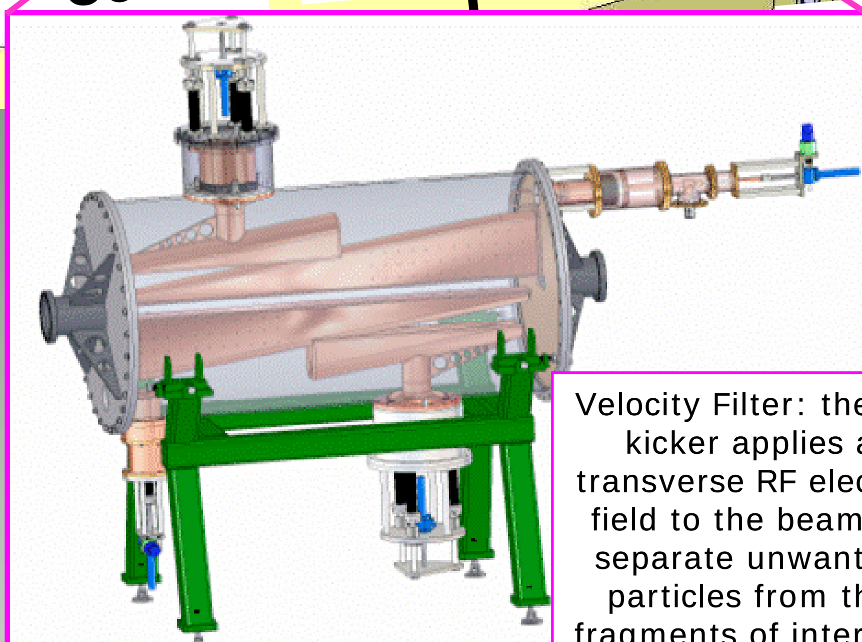
Momentum acceptance = 1 %

Average beam current = 5.6 pnA

The Solution: The Radio Frequency Fragment Separator



M. Doleans et al., “Status Report on the NSCL RF Fragment Separator” Proc. of PAC, Albuquerque, NM, to be published (2007)

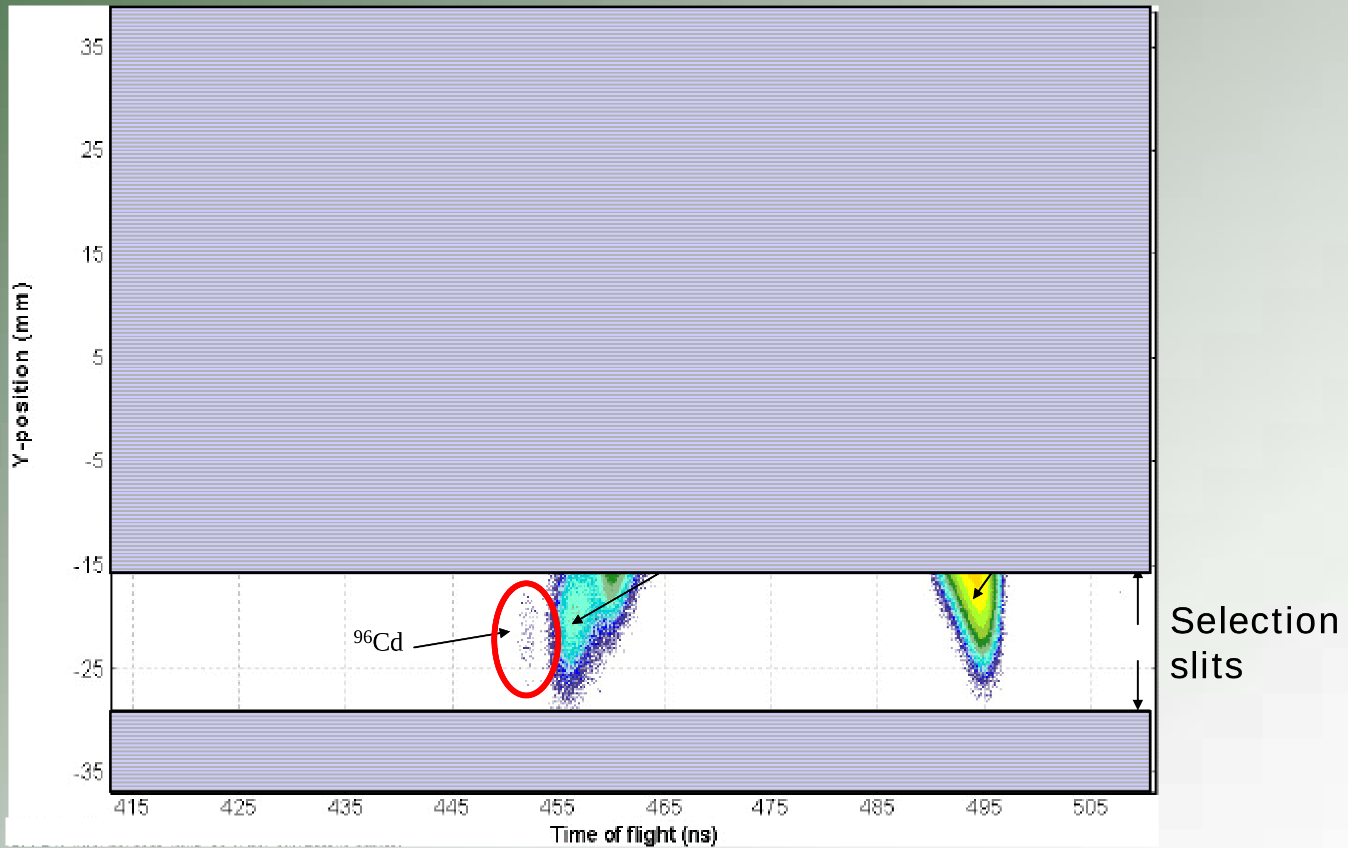


Velocity Filter: the RF kicker applies a transverse RF electric field to the beam to separate unwanted particles from the fragments of interest.

- The various species in the beam cocktail arrive with different rf phases and experience different transverse deflections.
- Contaminants are eliminated by collimation

The enhanced signal to background ratio translates into at least a factor of ten in efficiency for experiments.

RFFS simulated in LISE++



Example of beam purification using RFFS. Settings on ^{96}Cd.

RFFS Commissioning. May 2007.

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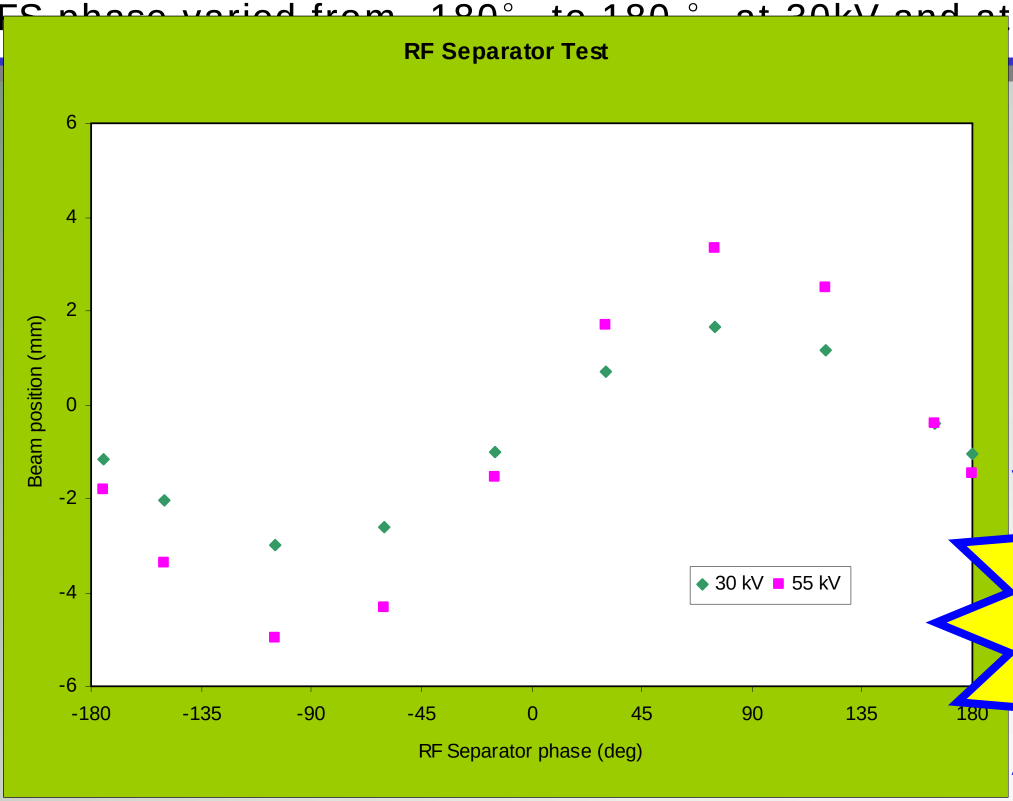
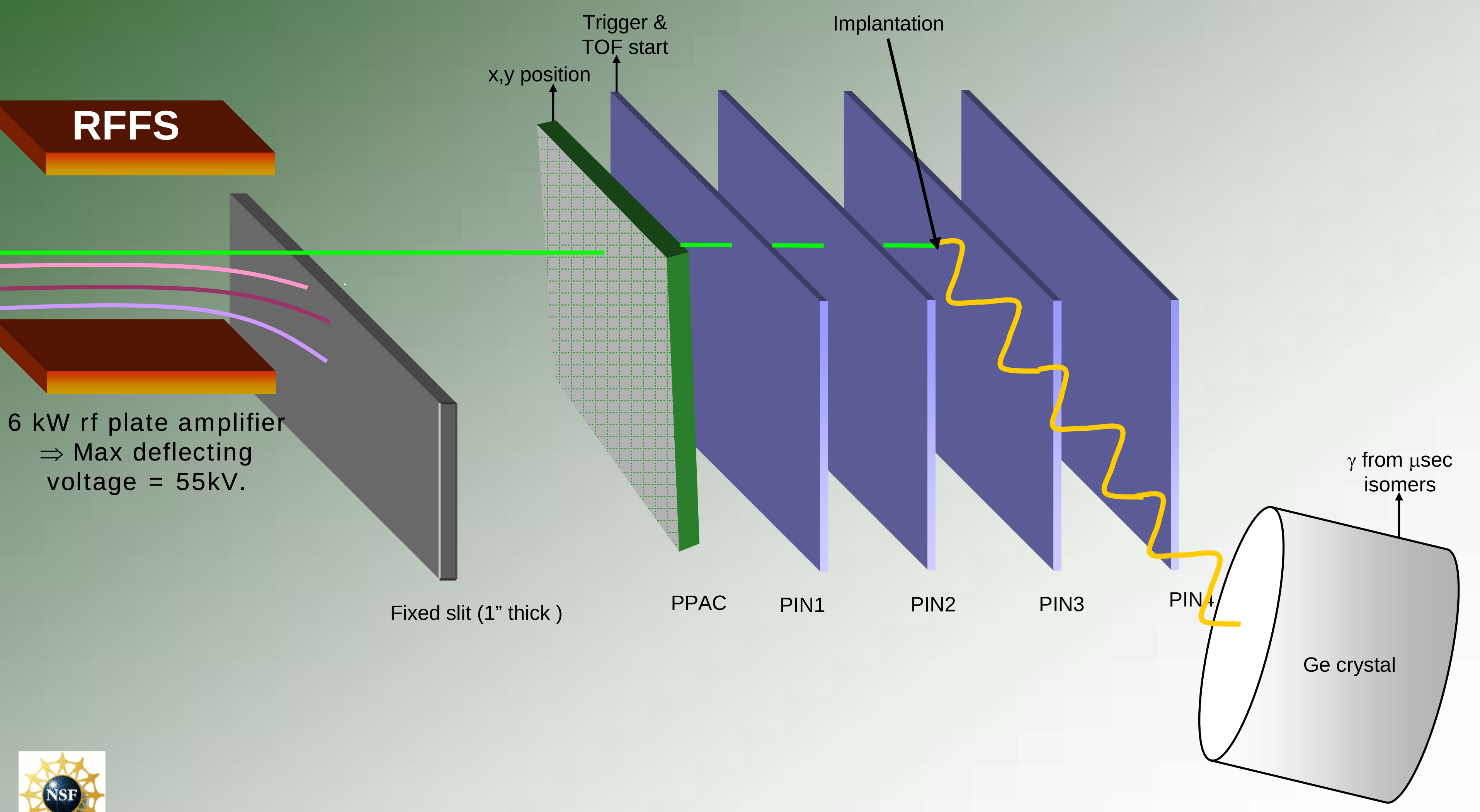
- Exp00362 RF Separator Test, May 2007
  - Settings:
    - Primary beam: ^{124}Xe at 140 MeV/u.
    - RFFS phase varied from -180° to 180 ° at 30kV and at 55kV



The kicker works!

Expected deflection as a function of RF phase and voltage observed.

RFFS Commissioning Run Experimental Setup



^{96}Cd: Particle Identification

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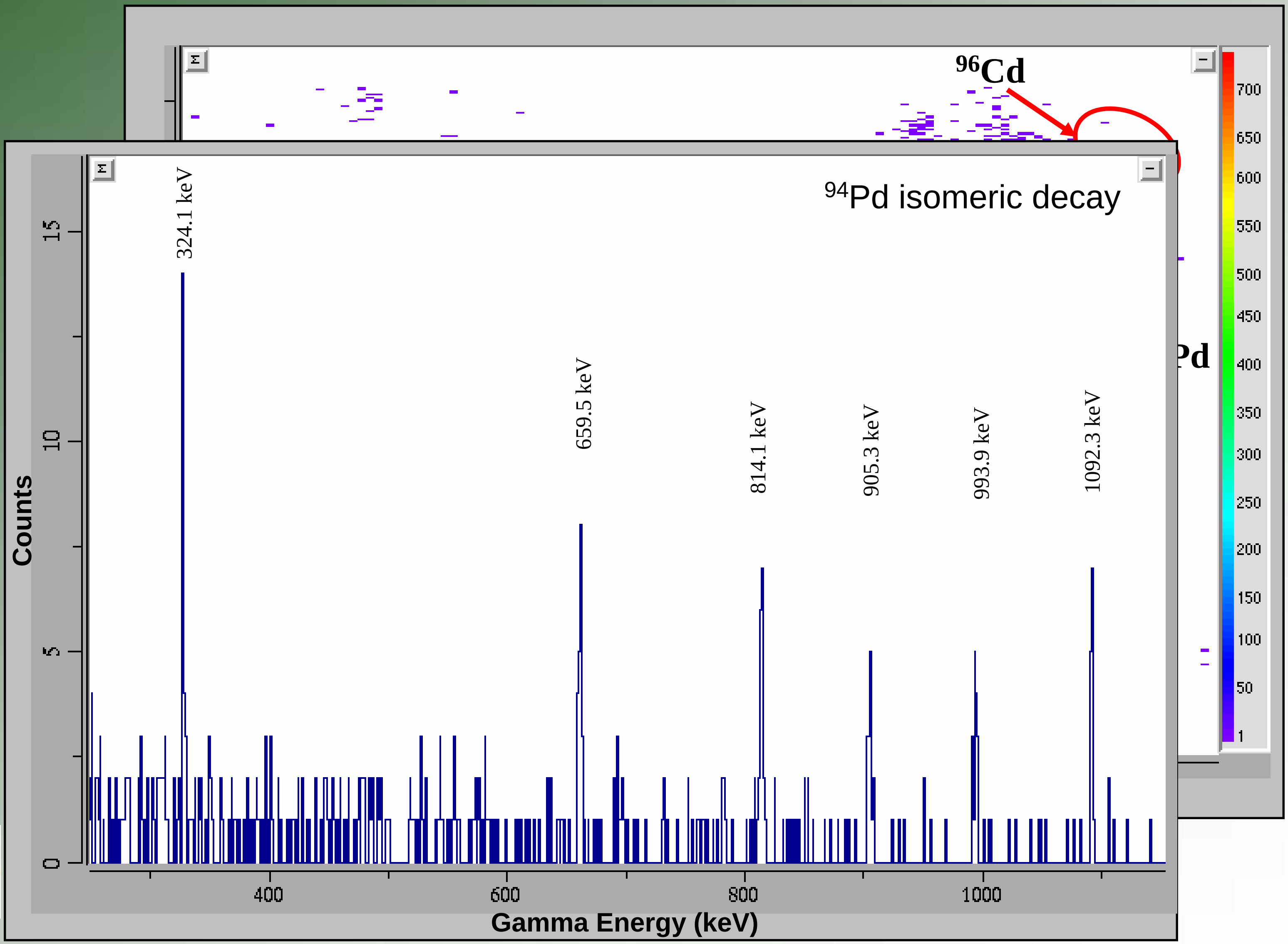

^{96}Cd: Particle Identification

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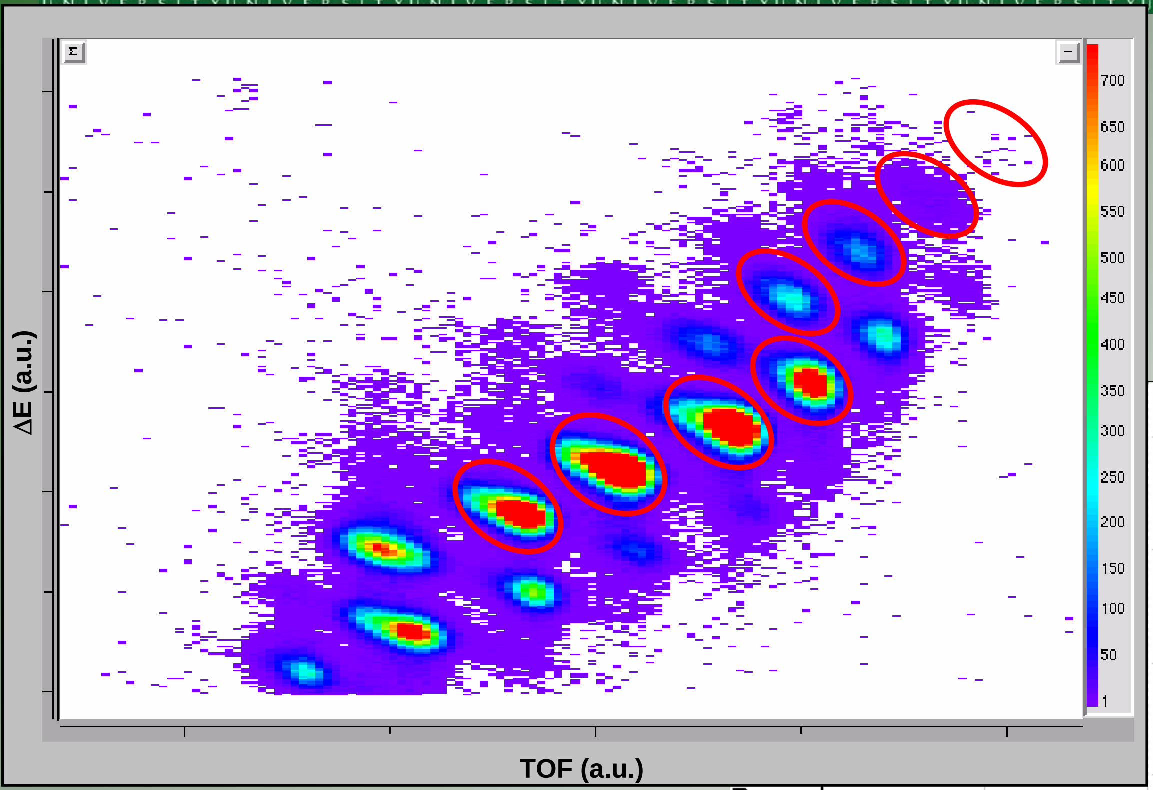

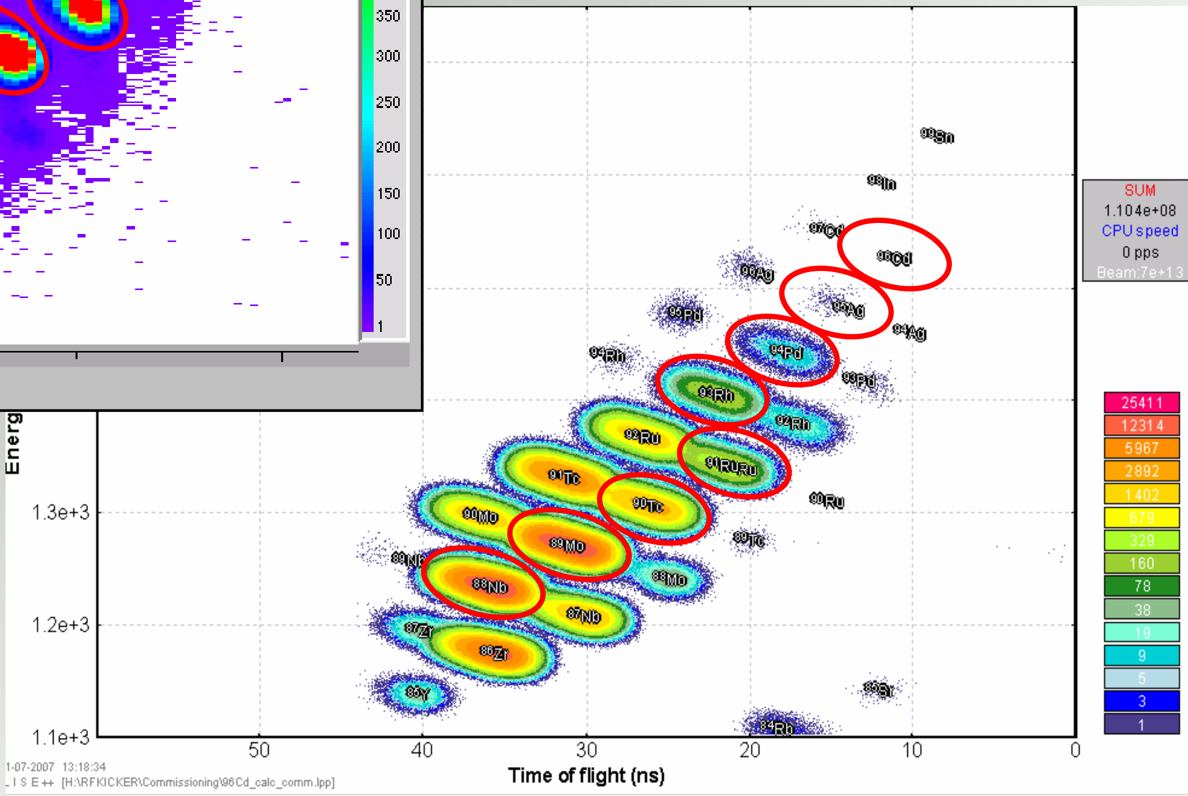

^{96}Cd. Observed yields.

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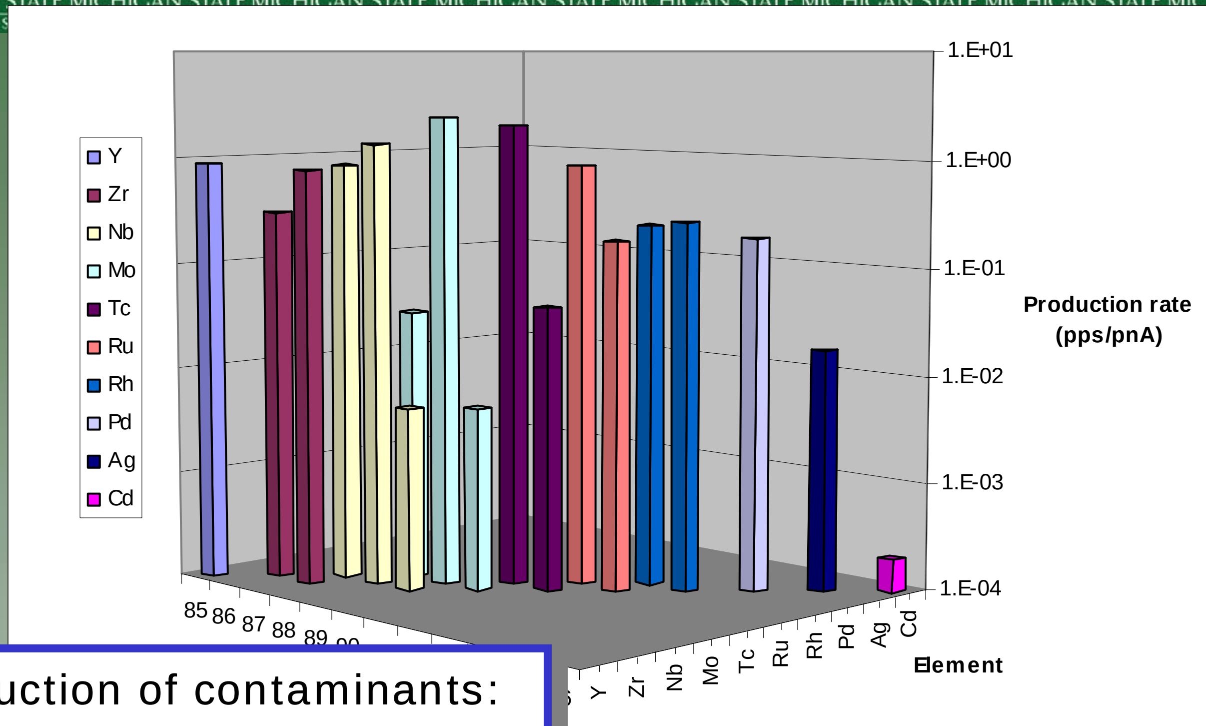

Significant reduction of contaminants:

Total count rate

without selection slits = 167 pps/pnA.

with selection slits = 11 pps/pnA

$\Rightarrow$ **purification factor ≈15**

Total live time = 15842.8 s

18 ^{96}Cd events observed

^{96}Cd rate = $(2.03 \pm 0.48) \times 10^{-4}$ pps/pnA

Lower limit of 95 ns for the half-life of ^{96}Cd.

(Predicted $T_{1/2} \approx 1$s)

Final Remarks

- The proton rich N=Z=48 nucleus ^{96}Cd has been observed for the first time and it has a half-life longer than 95 ns. Our measurement therefore paves the way for direct studies of the decay of this nucleus, which will constitute important pieces of information for the rp-process models.

- The efficiency of this measurement was greatly improved by the additional purification of the cocktail beam provided by the RFFS.

- Three experiments that will make use of the RFFS have been approved by the NSCL PAC31:
    - Beta-decay Half-life Measurement of ^{84}Mo
    - Beta-Delayed Proton Emission of ^{69}Kr
    - Study of the Beta-Decay of ^{100}Sn

- The measurement of production rates of nuclei far from stability with existing facilities is crucial for the prediction of rates achievable with future rare isotope acceleration facilities.

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