

A Large Acceptance Spectrometer for Deep-Inelastic Scattering with re-accelerated Radioactive Beams

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A Large Acceptance Spectrometer for DIC with RIBs at $E/A \sim 6-15$ MeV:

Research objectives:

- **structure studies** of neutron-rich nuclei (at high spin states) around the projectile
- **reaction dynamics** (e.g. peripheral collisions, N/Z equilibration, symmetry energy, EOS)
- **additional research topics** of interest to the community...

Present work:

- Preliminary design of a large acceptance spectrometer for above-barrier energies: $E/A = 6-15$ MeV/u

Requirements :

- design specific for binary reactions
- large angular acceptance ($\Delta\Omega > 20$ msr) and high momentum resolving power (> 1000) via trajectory reconstruction [“Raytracing spectrometer”]
- Z, A identification of projectile residues up to $Z \sim 60$, $A \sim 150$
- flexibility in target and focal plane detector setups:
 - target location: accommodate a 4π Gamma Array (and charged particle array)
 - focal plane: accommodate a decay setup
- spectrograph and associated detectors must be rotatable ($\theta = -20-120$ degrees)
- further suggestions ...

Large Acceptance Spectrometers in Europe:

VAMOS: RNBs from SPIRAL,
combined with
EXOAM and TIARA

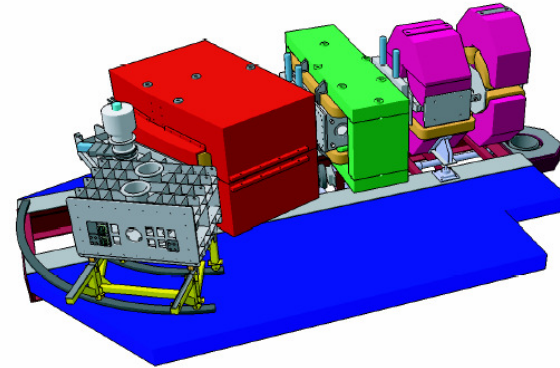


Fig. 6.5: Three-dimensional drawing of the VAMOS spectrometer at GANIL.

E-71

PRISMA (combined with CLARA)

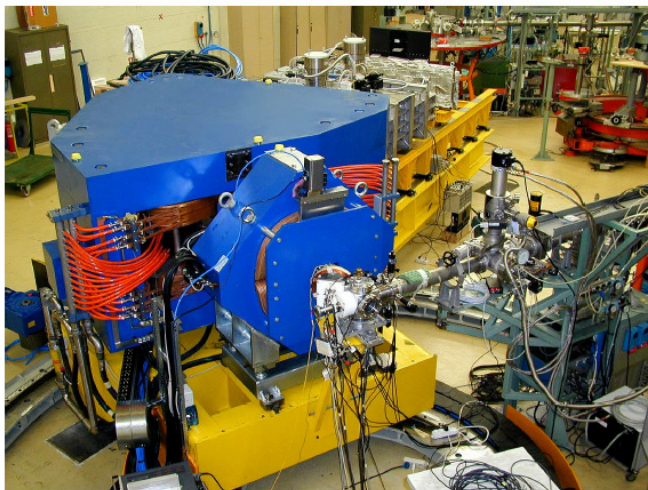
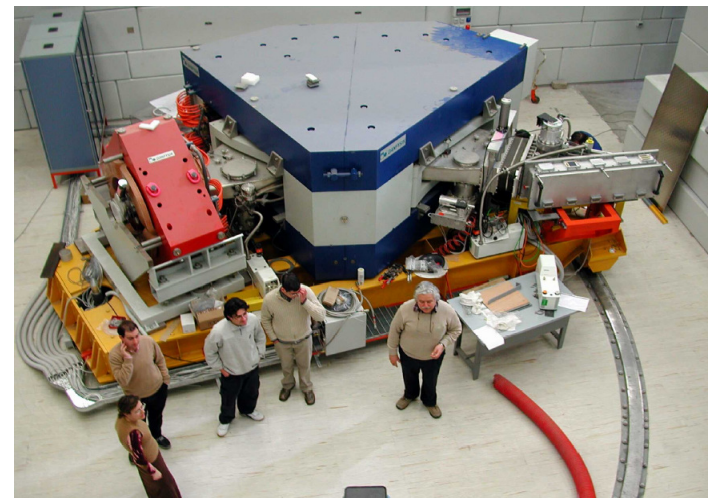


Fig. 6.6: The PRISMA spectrometer at LNL, Legnaro, in Italy.

MAGNEX (RNBs from EXCYT or FRIBs)



Example of nuclide production in DIC with RIBs:

^{94}Kr (15 MeV/u) + ^{64}Ni

○ Calculations*:

DIT: (interaction, nucleon exchange)

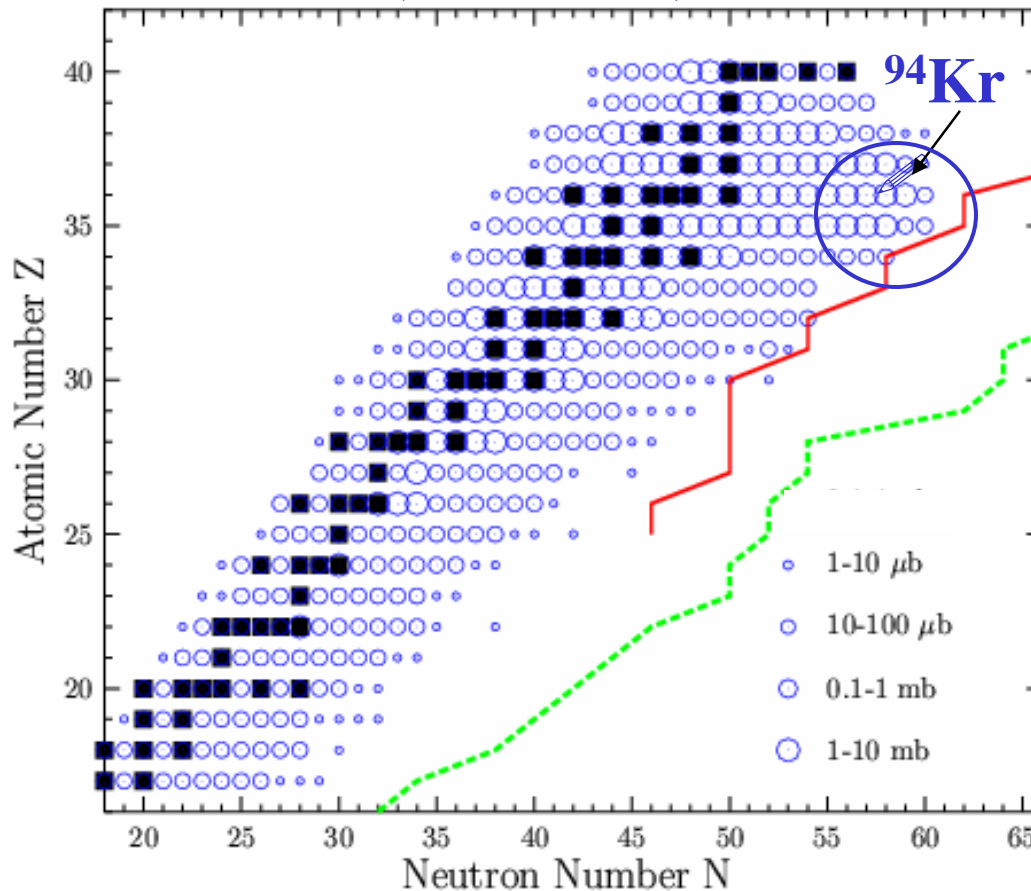
GEMINI :
de-excitation

■ stable nuclides

---- r-process

----- n-drip line

Work in progress
to improve DIT code
and make it
appropriate for very
low cross sections
with very n-rich
projectiles



Rate estimates: ^{94}Kr from “RIA” at $\sim 10^8$ pps, ^{64}Ni (20mg/cm²) :
1mb => 200 pps

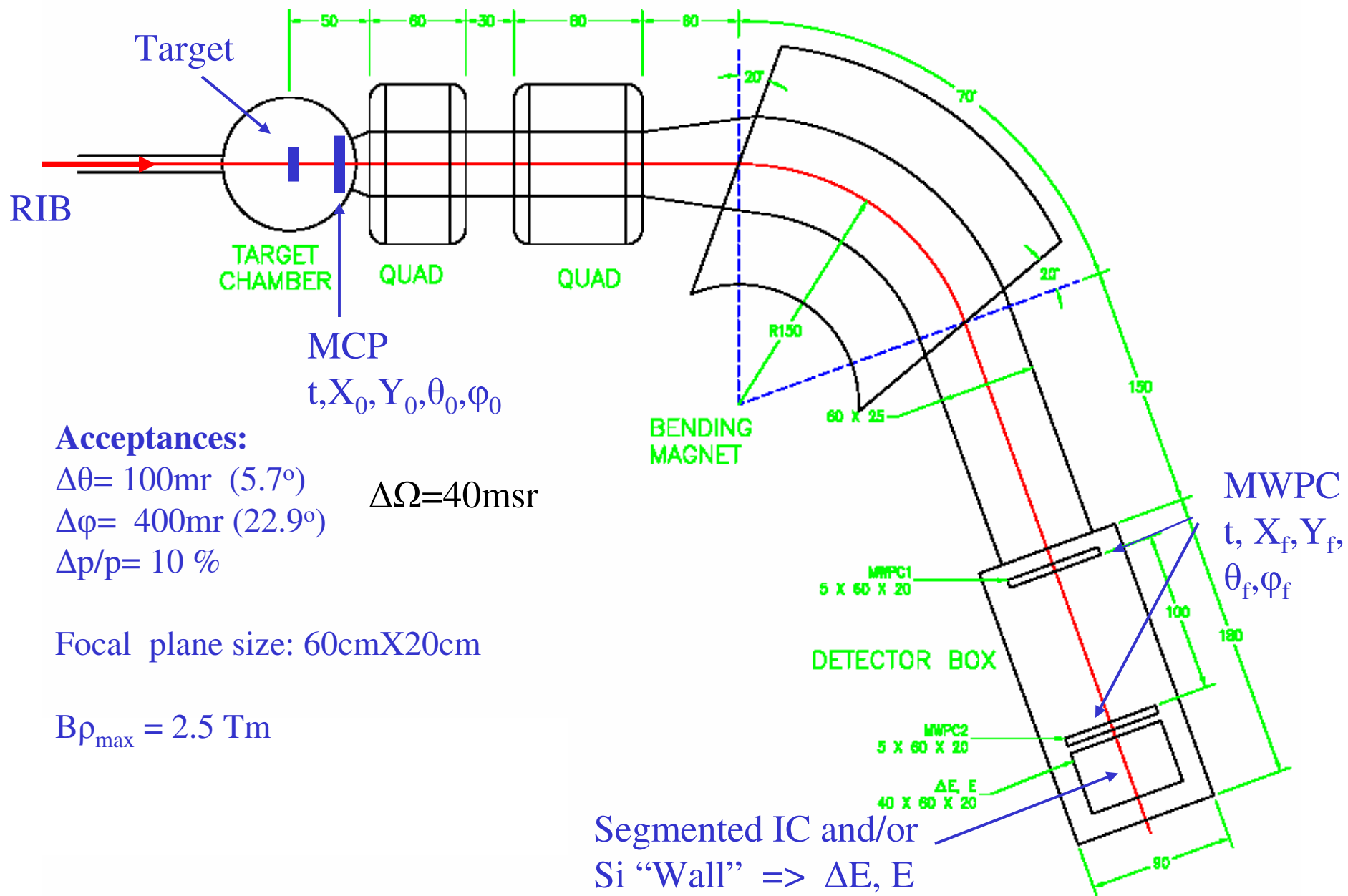
*References: **DIT:** L. Tassan-Got and C. Stephan, Nucl. Phys. A524 121 (1991)
GEMINI: R. Charity et al., Nucl. Phys. A483 391 (1988)

Calculated
nuclide
cross sections:

Very important:

Neutron-pickup
channels !!!
along with
proton stripping

Large Acceptance Spectrograph : preliminary layout



LAS prelim. specifications: QQD type, $B_{p_{\max}}=2.5\text{Tm}$

Large Bore Quadrupoles (30-40cm diameter). Large Gap Dipole magnet (20-25cm)
Room temperature vs superconducting magnets (to be decided)

Target - Q1 distance: 30-120cm. “Nominal”: 50cm

Quadrupole Q1: aperture: 30cm, length 60cm, $B_{\max, \text{tip}} = 1.5\text{T}$ (Y focusing)

Quadrupole Q2: aperture: 40cm, length 80cm, $B_{\max, \text{tip}} = 0.5\text{T}$ (X focusing).

Collins type (elliptical aperture) can also be used (e.g. VAMOS)

Superposition of higher multipoles is also considered

Dipole: bending radius: 150cm, bending angle: 70° , gap: 25cm, $B_{\max} = 1.7\text{T}$

Entrance and exit pole face rotation: $+20^\circ$ (Y-focusing)

Entrance and exit pole face curvatures ($1/R_1=0.2$, $1/R_2=0.0$) to be optimized
(along with inclusion of possible higher-order profiling etc.)

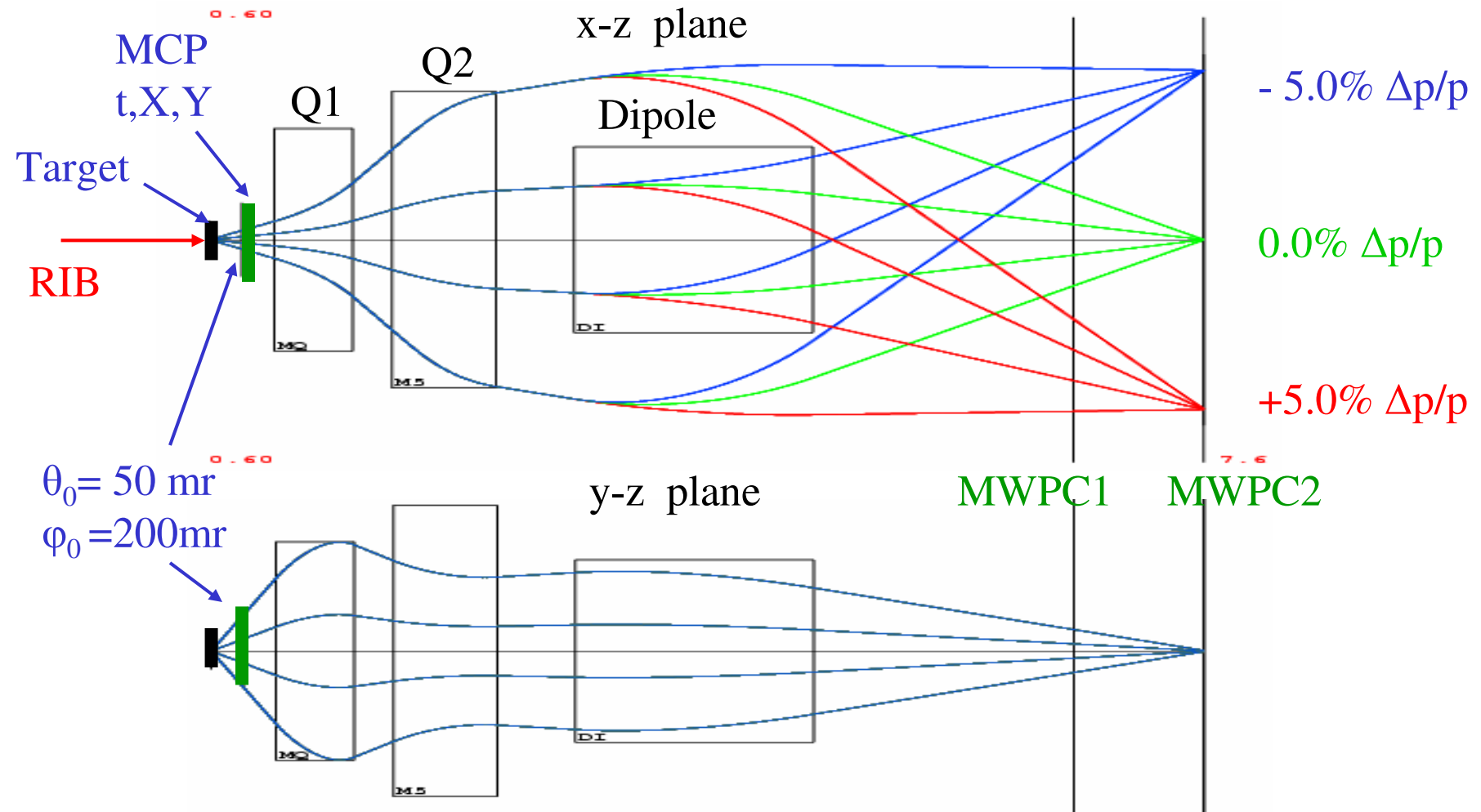
Dipole - MWPC1: 2.0m, MWPC 1- MWPC2: 1.0m (this version, can be shorter also)

Length of **central trajectory:** 7.6 m

Appropriate for mass A determination via TOF: 130ns at 15MeV/u,

160ns at 10MeV/u, 210ns at 6 MeV/u

RIA Large Acceptance Spectrograph: 1st order optics



Rays through LAS: $^{94}\text{Kr}^{34+}$ (15 MeV/u) $B\rho=1.54$ Tm

Ion Optics calculations with COSY-Infinity

Large Acceptance Spectrograph : optics summary:

First-order optics (point-to-point focusing in x,y at MWPC2):

Dispersions: $(x/\delta) = 4.6\text{cm}/\%$, $(\theta/\delta) = 12\text{ mr}/\%$

Magnifications: $M_x = (x/x) = -0.80$, $M_y = (y/y) = -7.0$

$M_\theta = (\theta/\theta) = 1.24$, $M_\phi = (\phi/\phi) = -0.14$

Path length dependences: $(l/\delta) = 3.5\text{cm}/\%$, $(l/\theta) = -0.3\text{cm}/\text{mr}$

The most important **higher-order aberrations in x,y (cm)**

at full acceptable phase space: $\Delta\theta = \pm 50\text{mr}$, $\Delta\phi = \pm 200\text{mr}$, $\Delta p/p = \pm 5\%$

Horizontal (X)

Vertical(Y)

2nd order:

$(x/\theta\delta) \Rightarrow 4.5\text{cm}$

$(y/\theta\phi) \Rightarrow -2.2\text{cm}$

$(x/\delta^2) \Rightarrow -2.1\text{cm}$

$(y/\phi\delta) \Rightarrow 6.8\text{cm}$

3d order:

$(x/\theta^3) \Rightarrow 1.5\text{cm}$

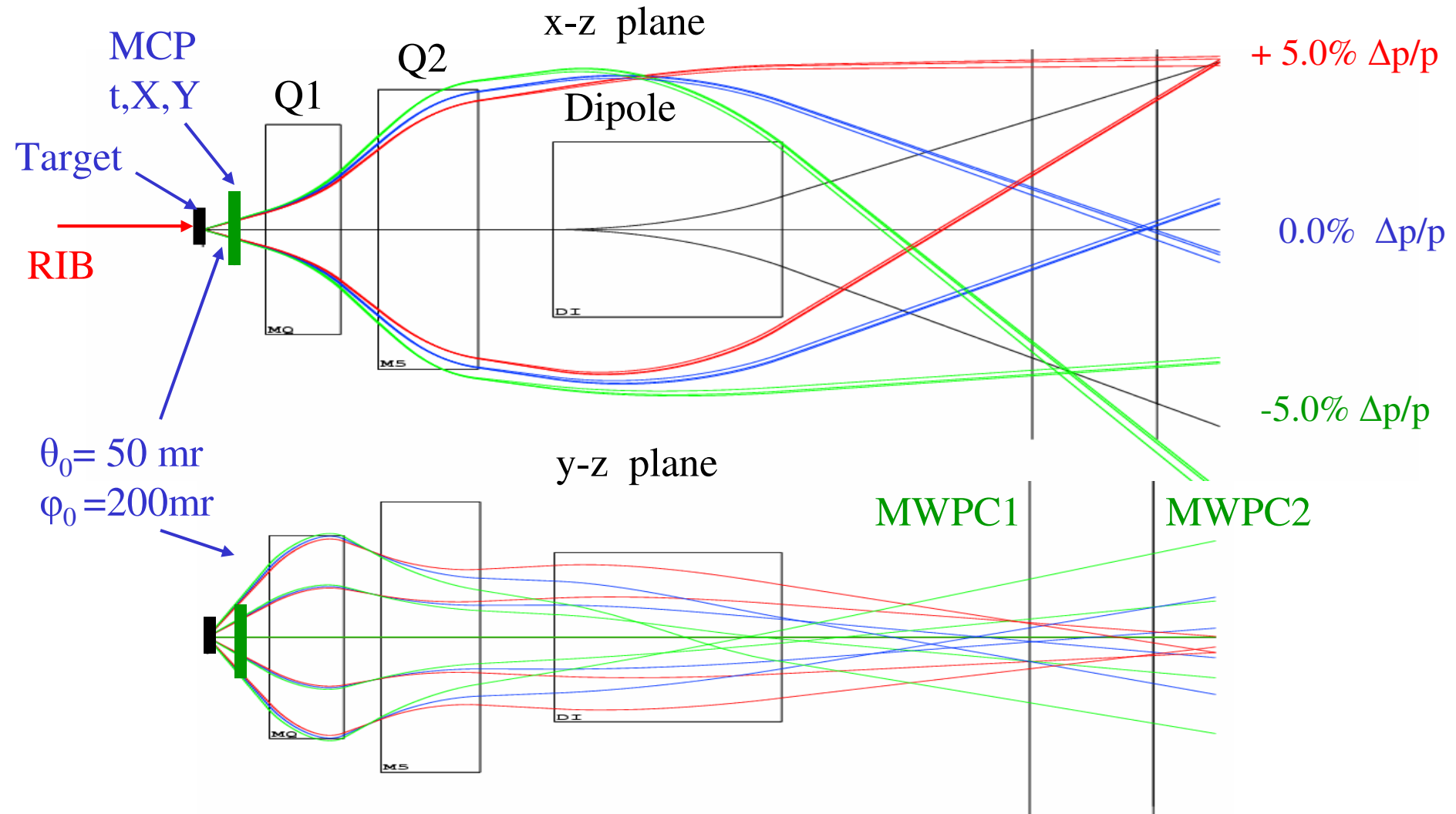
$(y/\phi^3) \Rightarrow -4.0\text{cm}$

$(x/\theta\delta^2) \Rightarrow -0.8\text{cm}$

$(y/\theta^2\phi) \Rightarrow 0.6\text{cm}$

$(y/\theta\phi\delta) \Rightarrow -0.5\text{cm}$

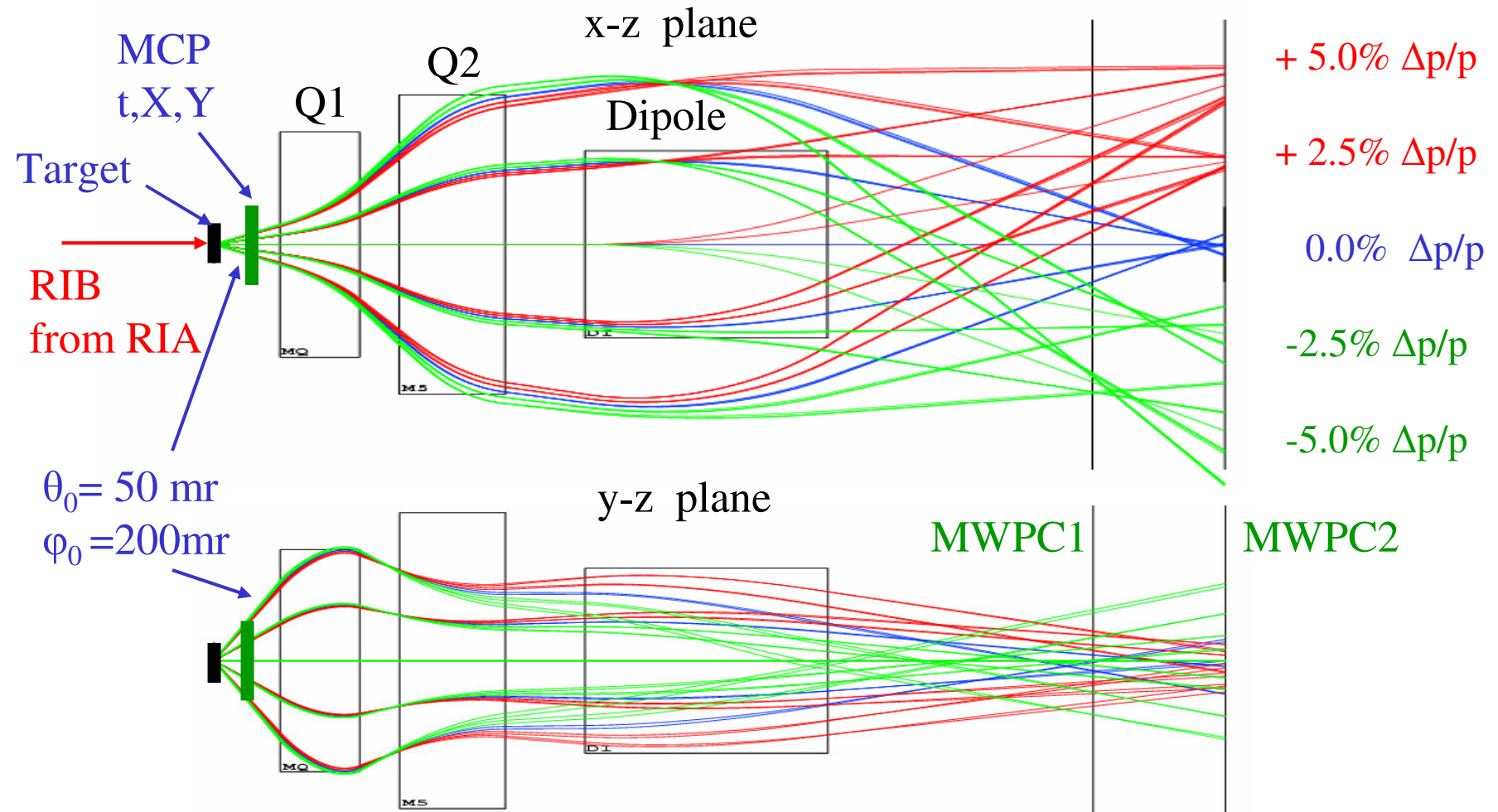
Large Acceptance Spectrograph: 5th order optics



Rays through LAS: $^{94}\text{Kr}^{34+}$ (15 MeV/u) $B\rho = 1.54 \text{ Tm}$

Ion Optics calculations with COSY-Infinity

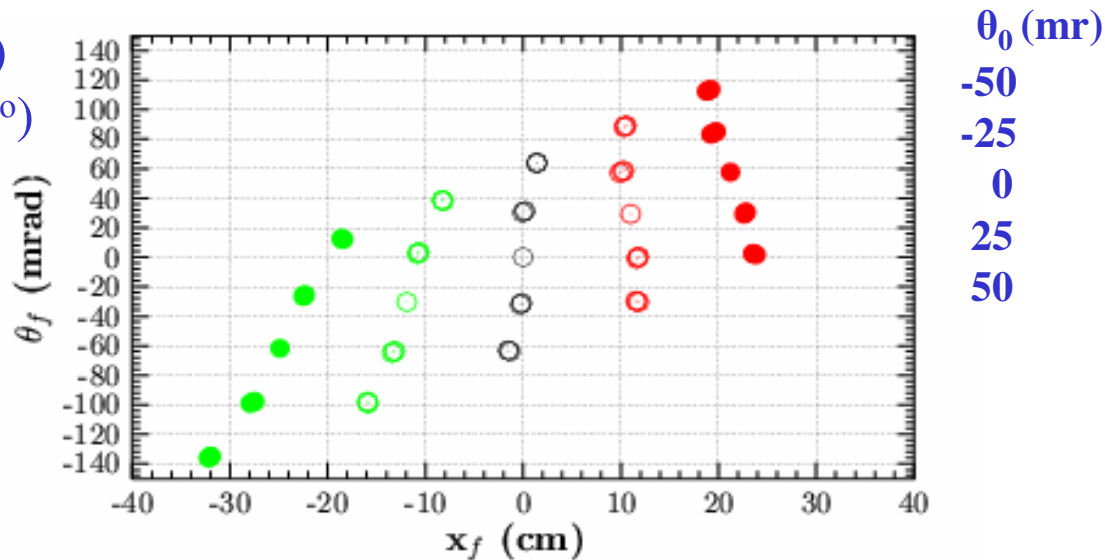
LAS: 5th order optics, multipoles (H,O,D,DD) included



Rays through LAS: $^{94}\text{Kr}^{34+}$ (15 MeV/u) $B\rho = 1.54 \text{ Tm}$
 Multipoles (O,D,DD) superimposed on Q2,
 Entrance pole face of dipole curved with $R = +5\text{m}$ (convex)

LAS: Relations at the Focal Plane

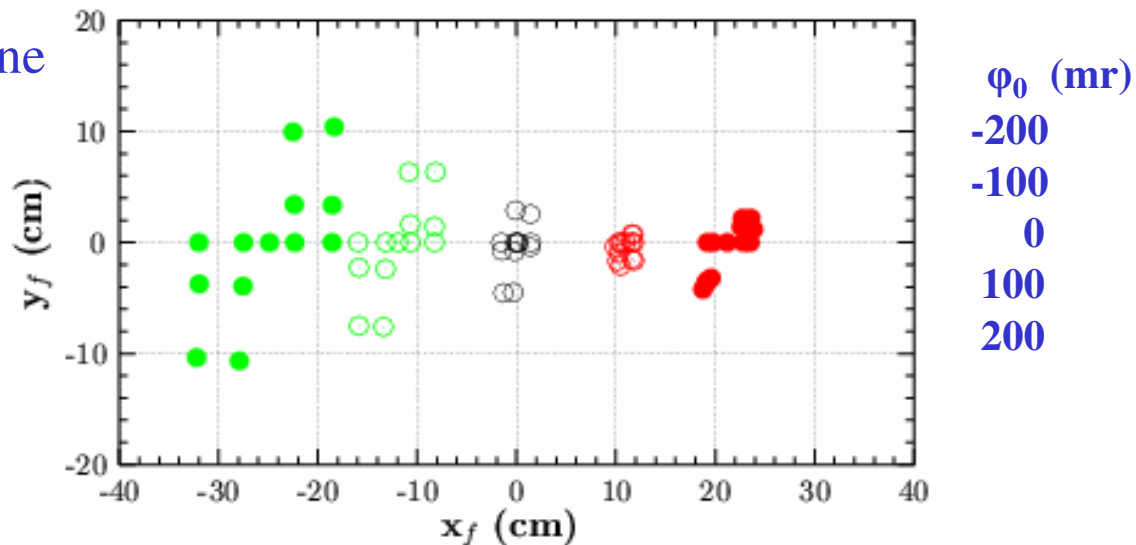
$\Delta\theta_0 = 100$ mr (5.7°)
 $\Delta\phi_0 = 400$ mr (22.9°)



$\Delta p/p$ range: -5.0% -2.5% 0.0% +2.5% +5.0%

Effective Focal Plane
and Detector size:

60cm x 25cm



5th order ion optics calculations with COSY-I

Details of Experimental Procedures:

Momentum ($\Rightarrow B\rho$) reconstruction:

Measured quantities: after target: (MCP): θ_0, φ_0
At the focal plane detectors: (MWPC1,2): $x_f, y_f, \theta_f, \varphi_f$

Assuming 1.5mm beam spot on target, x,y position resolutions of 1mm,
and final angle resolution of 2mrad:

momentum can be reconstructed with **resolution 1/2000**

using calculated inverse **transfer maps** (determined to 5th order or higher with COSY)
and accurate description of the fields of the magnets.

Summary of measured and extracted quantities:

Velocity (from TOF), Energy loss (from IC), Total Energy (IC+Si wall)

Mass-to-charge ratio: A/Q $B\rho \sim A/Q \times v$

Atomic Number Z $Z \sim v \Delta E^{1/2}$

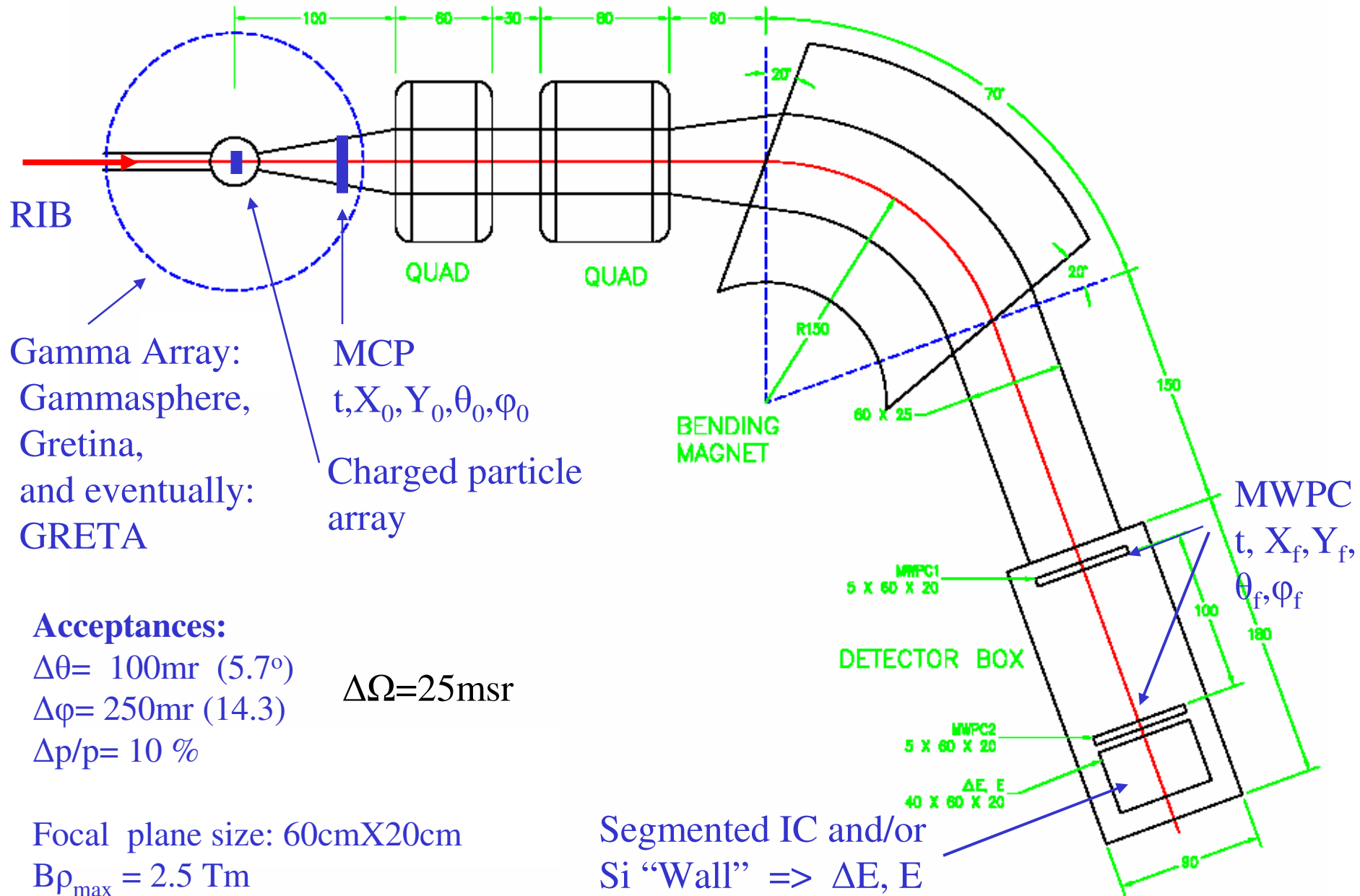
Ionic charge Q $Q \sim f(E, v, B\rho)$

Mass number A $A = Q_{\text{int}} \times A/Q$

Complete Identification of heavy residues in Z, Q, A, v, θ_r

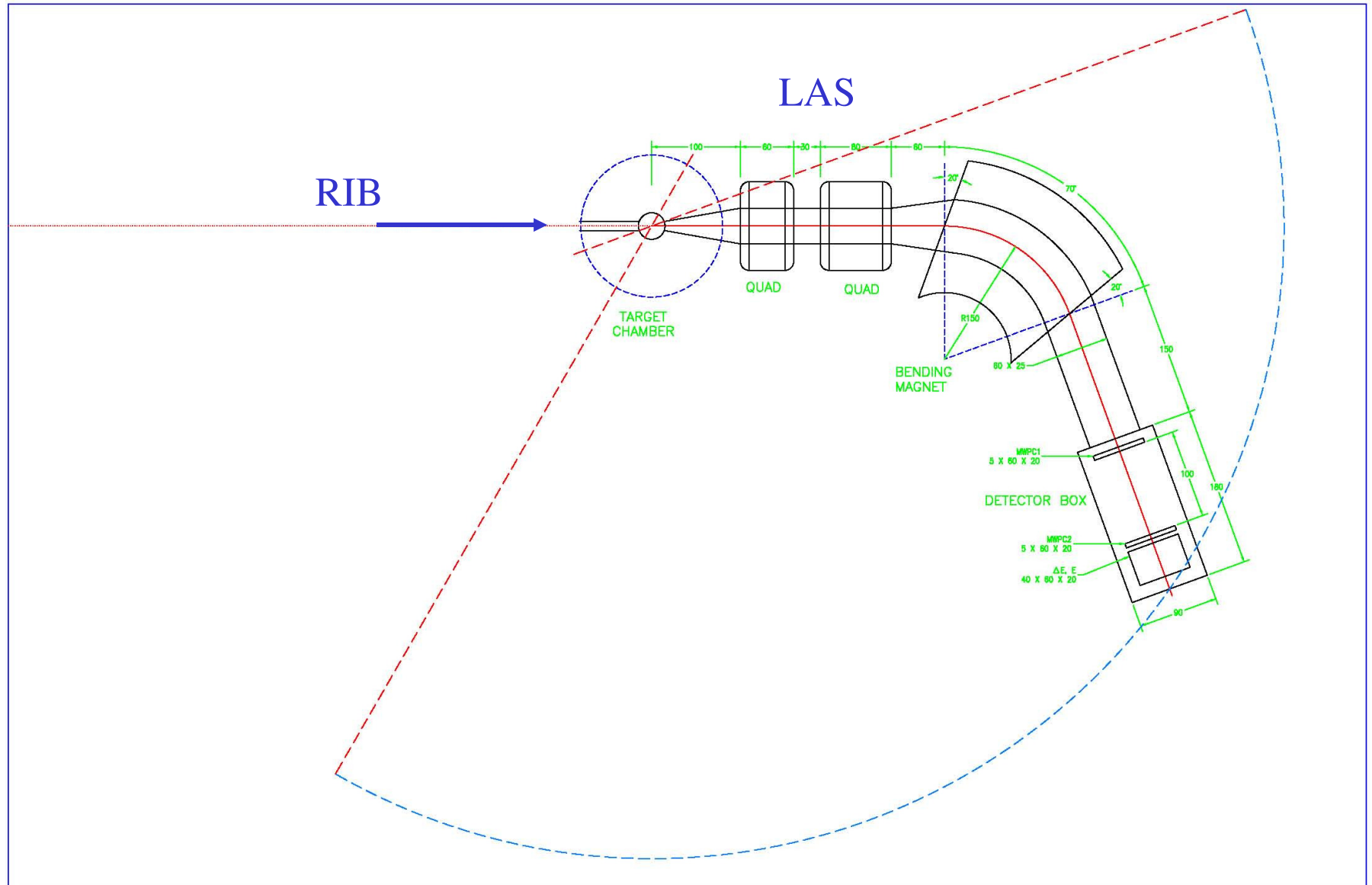
Residue yield distributios in Z, A, v and θ_r can be obtained

Layout of “LAS” + Gamma and Charged Particle Arrays:



LAS : preliminary layout of experimental room:

The room dimensions are: ~10m x 15 m, arc is ~7m radius; angular range -20 to 120 degrees



Overview of “LAS” tasks (partial list) :

- Detailed definition of the spectrograph specifications
- Detailed design of the spectrograph according to these specifications
- Magnets (superconducting ?)
- Detectors: need state of the art detector systems:
 - tracking-MCP, MWPC/drift chambers
 - segmented IC
 - large area (+high uniformity) Si detectors for ΔE , E (“Si walls”)
- Target chamber (s)
- Electronics, data acquisition
- Many more things to be added in the list and to be discussed ...

Representative results from recent cross section measurements of neutron-rich products at 15MeV/nucleon with ^{40}Ar and ^{86}Kr beams at Texas A&M with the MARS recoil separator:

G.A. Souliotis et al, in preparation

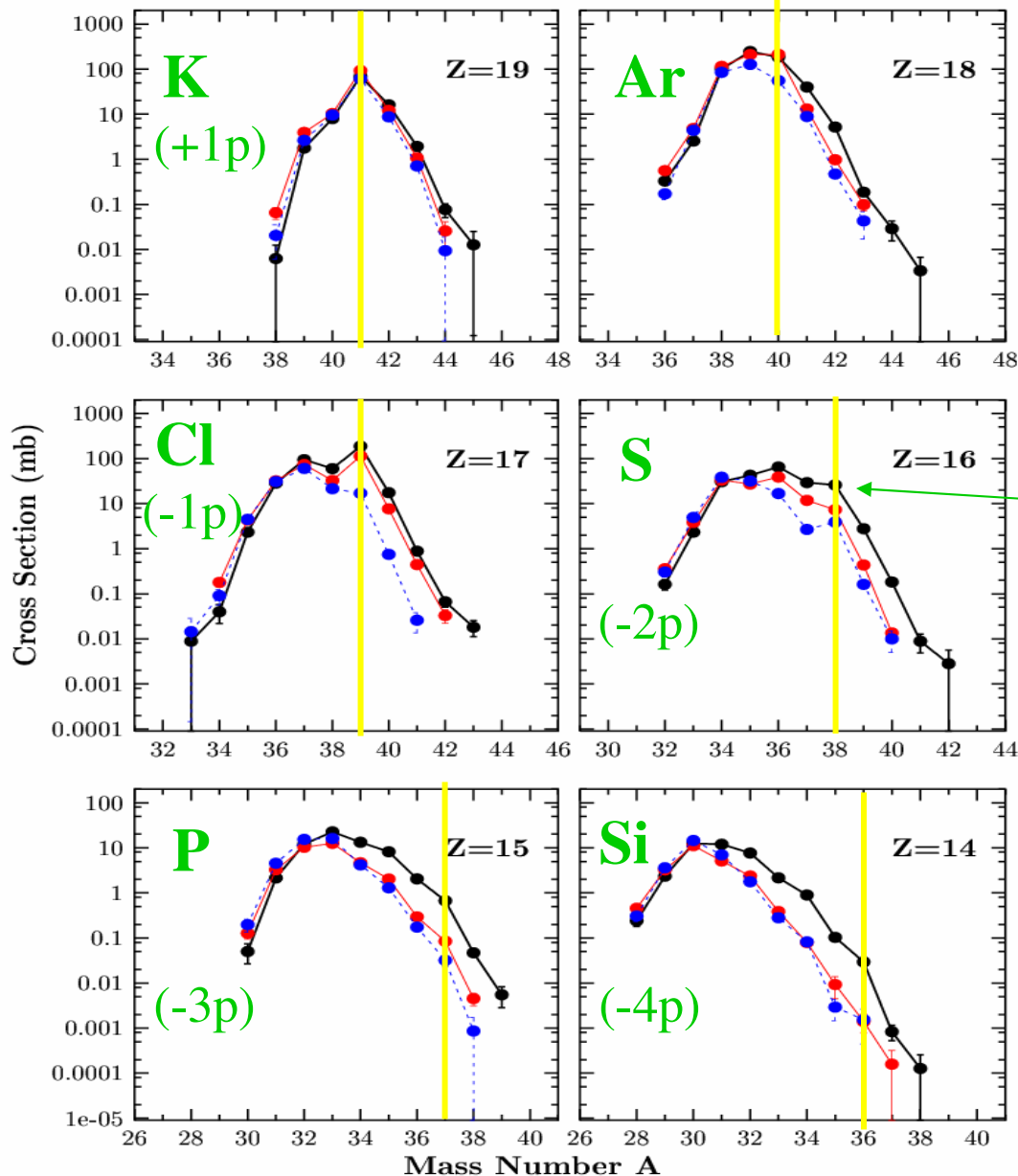


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Nuclide cross sections from: ^{40}Ar (15MeV/nucleon) + ^{64}Ni , ^{58}Ni , ^{27}Al



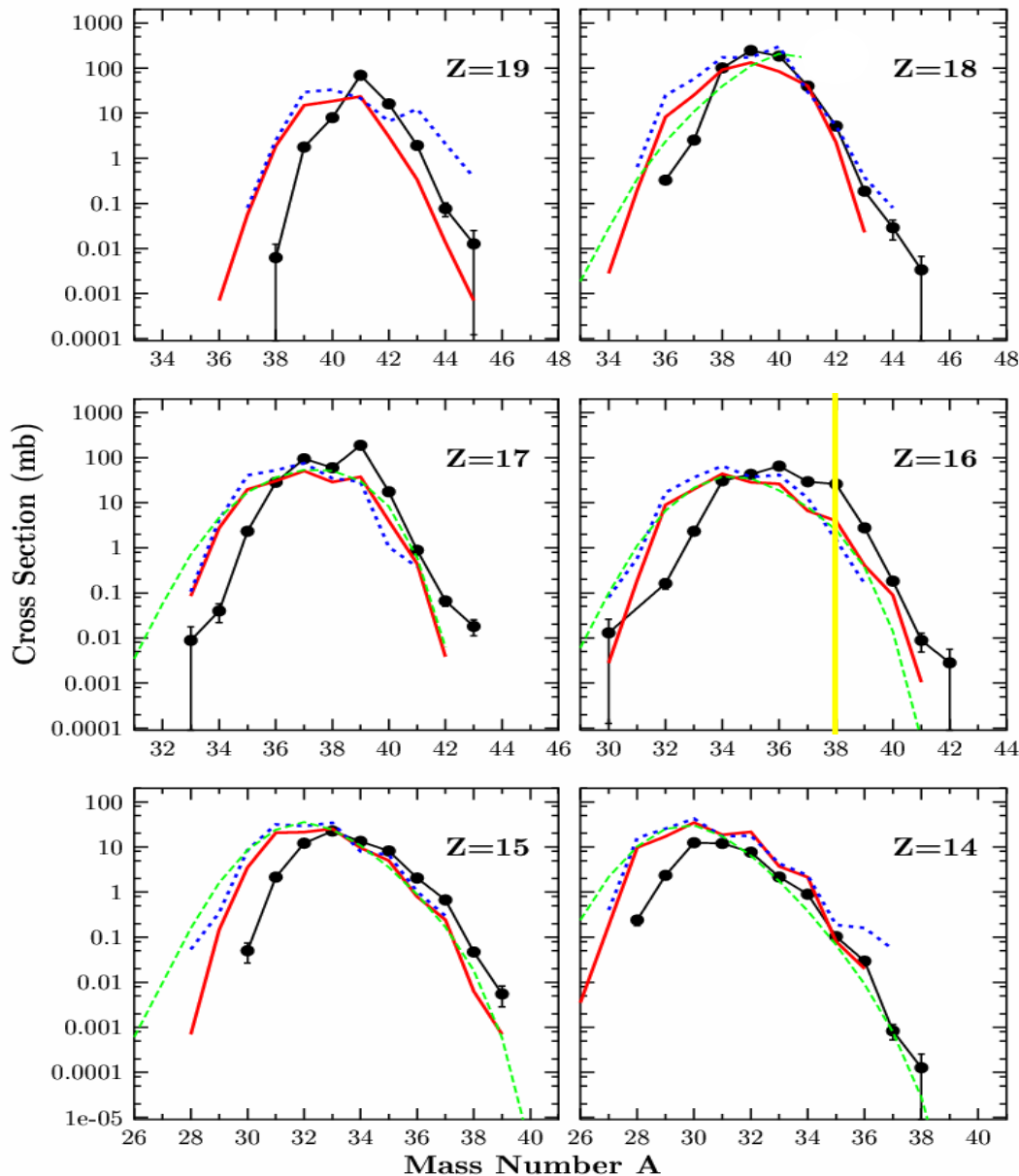
● $^{40}\text{Ar} + ^{64}\text{Ni}$

● $^{40}\text{Ar} + ^{58}\text{Ni}$

● $^{40}\text{Ar} + ^{27}\text{Al}$

largest cross sections
with the n-rich ^{64}Ni target

Comparison: Data, Calculations: ^{40}Ar (15MeV/nucleon) + ^{64}Ni



• MARS data

— DIT/GEMINI

..... CoMD/GEMINI

..... EPAX

Data show enhanced cross sections of n-rich nuclides close to the projectile *

Model Calculations underestimate the cross sections on the neutron-rich side

DIT: Deep Inelastic Transfer:

L. Tassan-Got, Nucl. Phys. A 524, 121 (1991)

CoMD: Constraint Molecular Dynamics:

M. Papa et al., Phys. Rev. C 64, 024612 (2001)

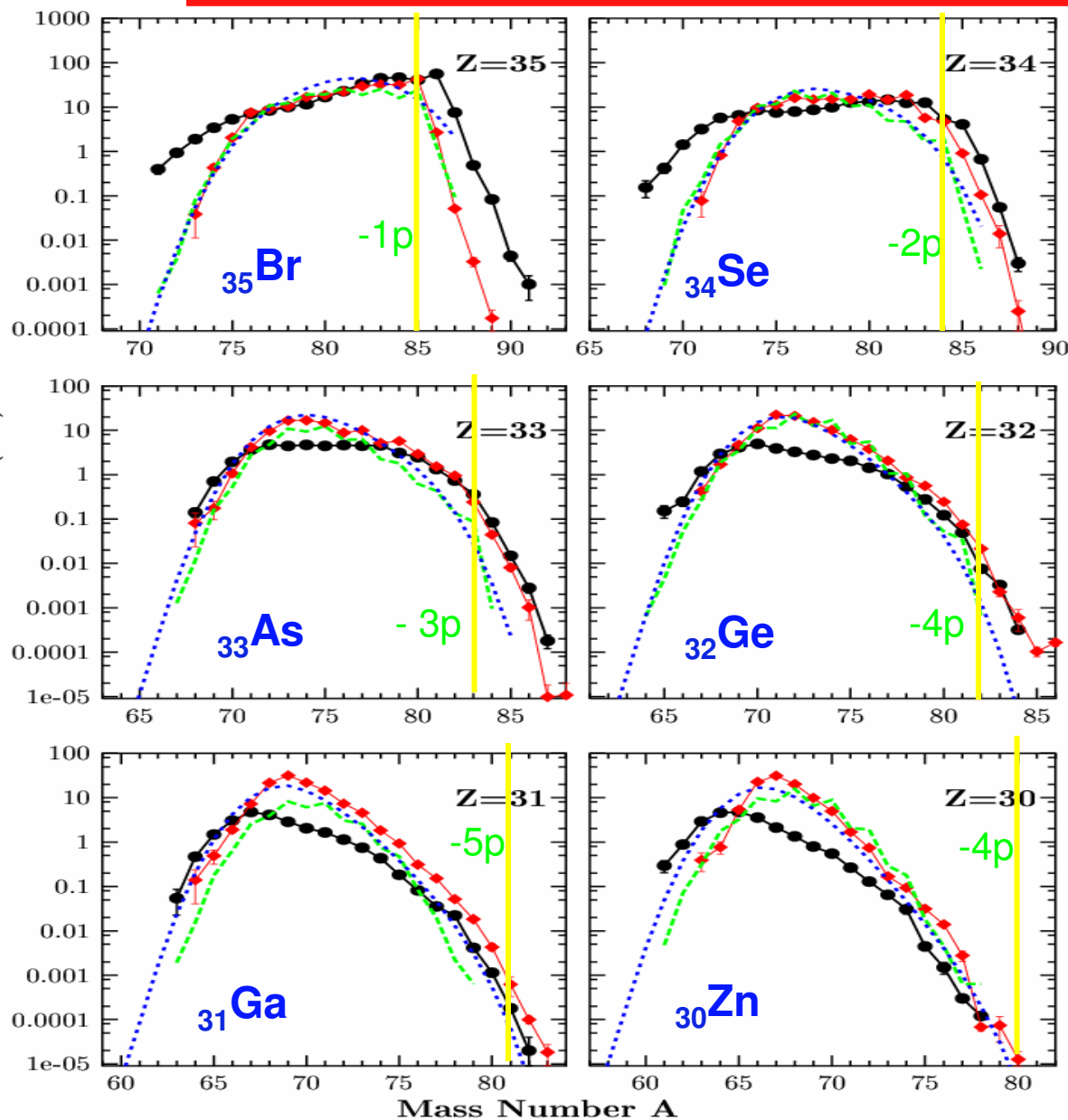
GEMINI: Binary decay code:

R. Charity, Nucl. Phys. A 483 391 (1988)

EPAX: Cross Section parametrization (high-energy)

K. Suemmerer et al, Phys. Rev. C 61, 034607 (2000)

Cross section measurements: ^{86}Kr (15 MeV/u) + ^{64}Ni



● $^{86}\text{Kr} + ^{64}\text{Ni}$ (15 MeV/u)
 ● $^{86}\text{Kr} + ^{64}\text{Ni}$ (25 MeV/u)*
 ----- DIT/GEMINI
 ----- EPAX

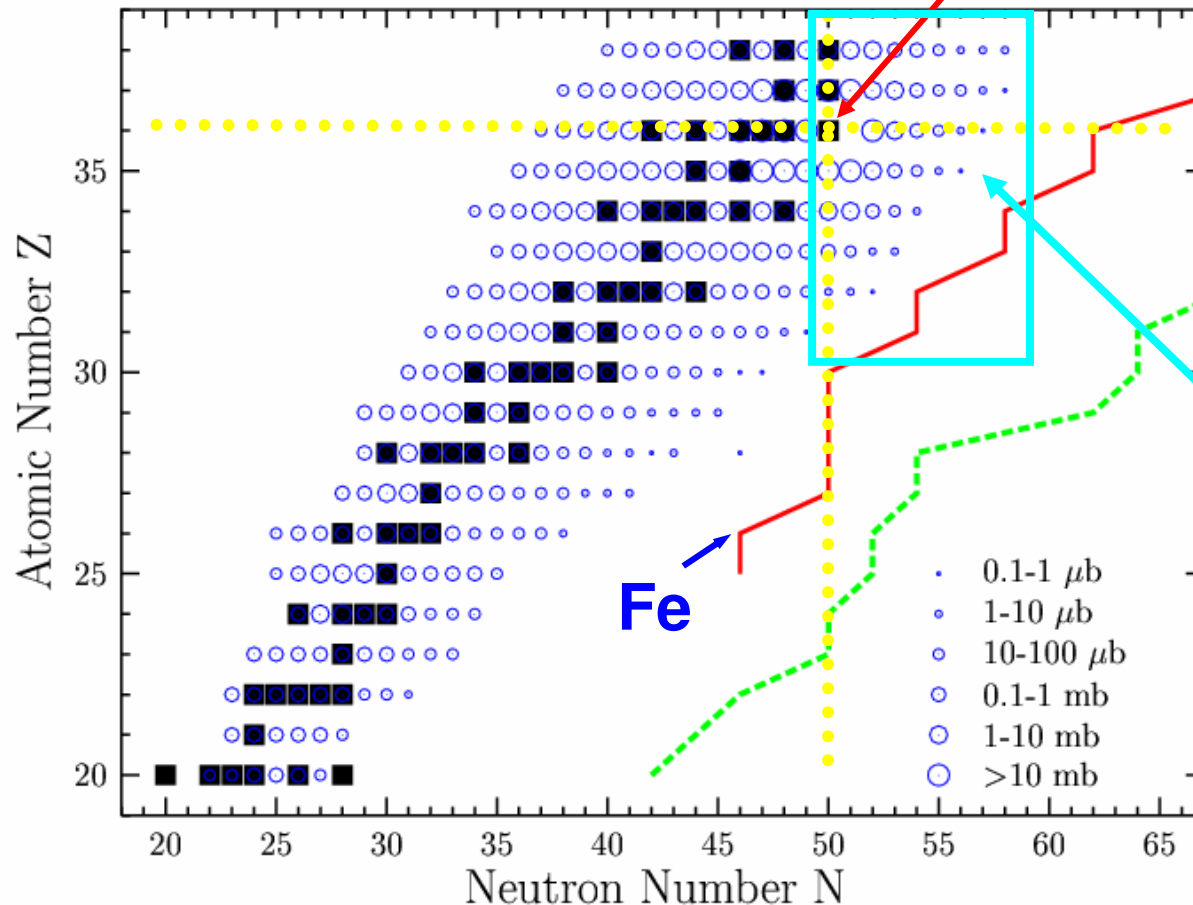
Large cross sections of neutron-pickup products near the projectile

*25 MeV/nucleon data: G. A. Souliotis et al., Phys. Lett. B 543, 163 (2002)

Rare Isotope Production at 15MeV/nucleon :

^{86}Kr (15 MeV/nucleon) + ^{64}Ni

^{86}Kr
36 50



○ MARS Data:*

■ stable nuclei

— r-process

- - - n-drip line

Neutron-
pickup
products

Neutron-Rich Rare Isotopes near and above the Fe-Ni region

*G. A. Souliotis et al., in preparation

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