The recoil mass spectrometer MARA at JYFL

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Outline

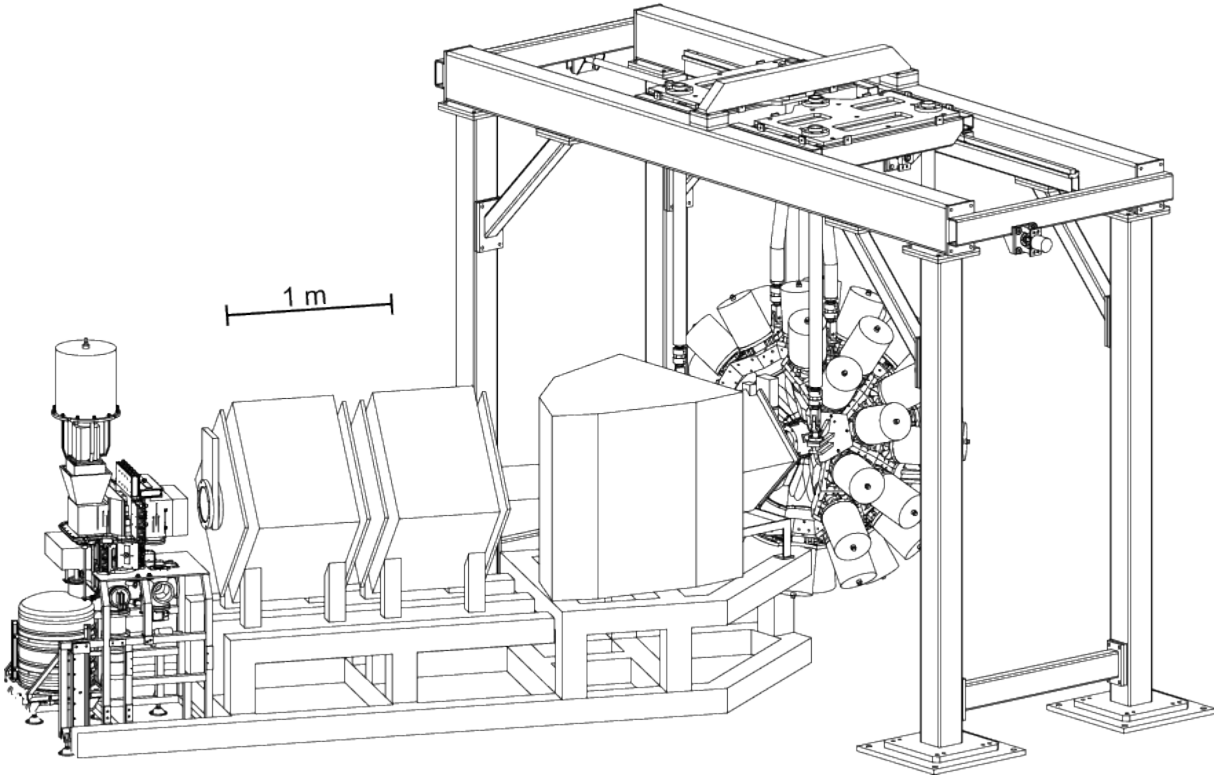
- MARA (***M**ass **A**nalysing **R**ecoil **A**pparatus*) overview
  - Motivation and history of the MARA project
  - Optics of charged particles
  - MARA working principle and its optical elements
    - quadrupole triplet,
    - electrostatic deflector and
    - magnetic dipole
- Instrumentation
  - Vacuum system,
  - Slits and apertures
  - Possible detector setups in the target area and at the focal plane
- Simulated performance in a test reaction
- Summary and outlook

Motivation to build MARA

- The gas-filled separator RITU has been used extensively over almost 2 decades to study neutron deficient heavy elements close to the proton drip line and transfermium nuclei.
- In recent years interest has been increasingly pointed to the lighter nuclei in the ^{100}Sn region and below.

Problems with gas-filled separator in lighter mass region:

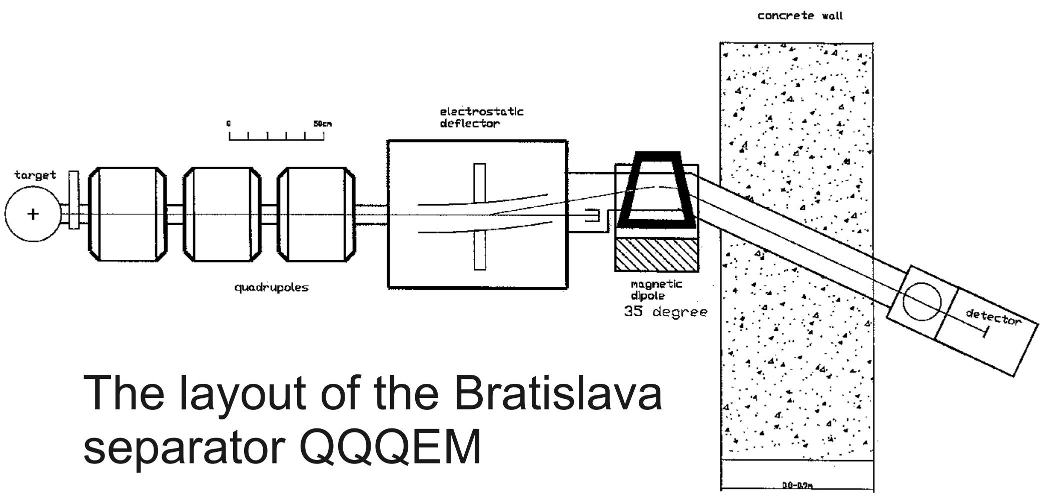
- beam is difficult to separate in symmetric reactions (impossible in inverse kinematics)
- no mass resolution -> needs often a tag (alpha, beta, isomer,...)
- high counting rates at a focal plane due to other evaporation channels



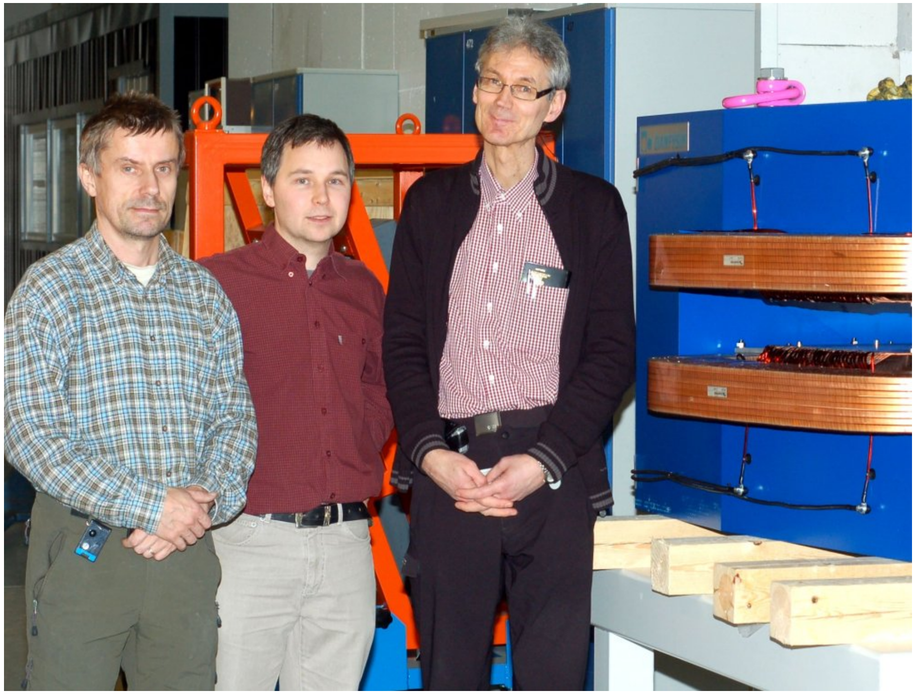
RITU gas-filled separator

History of the MARA project

- About 8 years ago, before starting to design a new vacuum separator the construction of a new gas filled separator was considered
- The idea of a new vacuum mode separator at JYFL was initiated by the Bratislava separator plan
- The deflector were extended to 20 degrees and the dipole to 40 degrees in order to achieve a physical mass separation at the focal plane. The configuration of MARA was born
- The quadrupole triplet arrived on spring 2007
- The magnetic dipole arrived on summer 2008
- Last part (deflector) should arrive summer 2012
- Construction of the MARA cave has been started on January this year



The layout of the Bratislava separator QQQEM



Arrival of the MARA dipole

Optics of charged particles

In a presence of an electric and magnetic field the force acting on a charged particle (mass *m*, momentum *p*, velocity *v* and kinetic energy E_k) is the Lorentz force:

$$F = q\boldsymbol{E} + q\boldsymbol{v} \times \boldsymbol{B}$$

A rigidity is the product of a field strength and a bending radius. Thus it tells how strong field is needed to bend charged particle with given radius of curvature. The electric rigidity and the magnetic rigidity of an ion describes the trajectory of the ion through the spectrometer.

Electric rigidity:

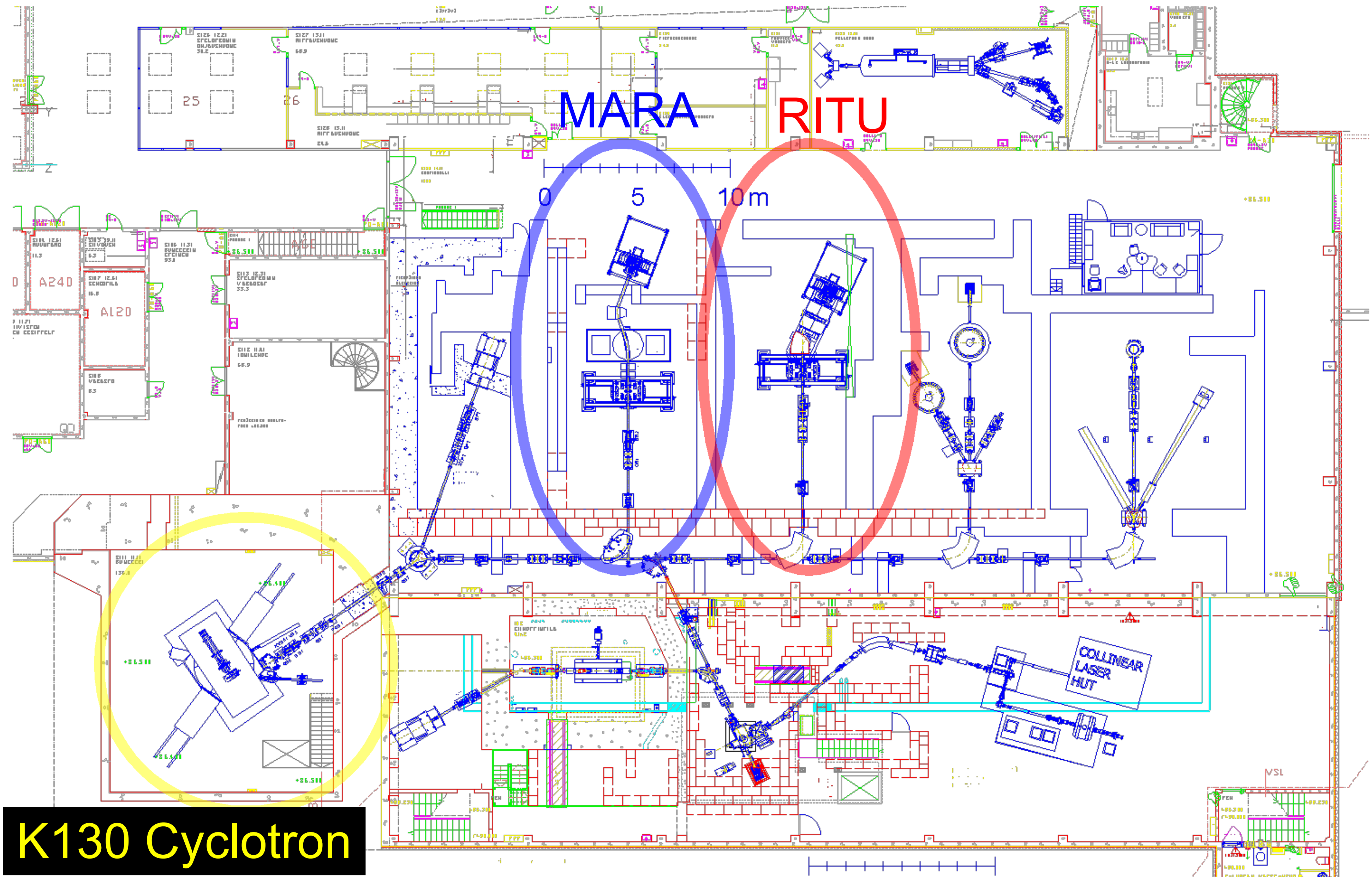
$$\chi_E = E\rho_E = \frac{pv}{q} \approx \frac{2E_k}{q}$$

Magnetic rigidity:

$$\chi_B = B\rho_B = \frac{p}{q} \approx \frac{\sqrt{2E_k m}}{q}$$

The electric and magnetic field can be designed so that the energy dispersion cancels (E_k in both χ_E and χ_B) and only the mass dispersion remains (*m* only in χ_B) → RECOIL MASS SPECTROMETER (FMA, EMMA, CAMEL, HIRA, MARA, ...)

Position of MARA at JYFL accelerator laboratory



MARA (*M*ass *A*nalysing *R*ecoil *A*pparatus)

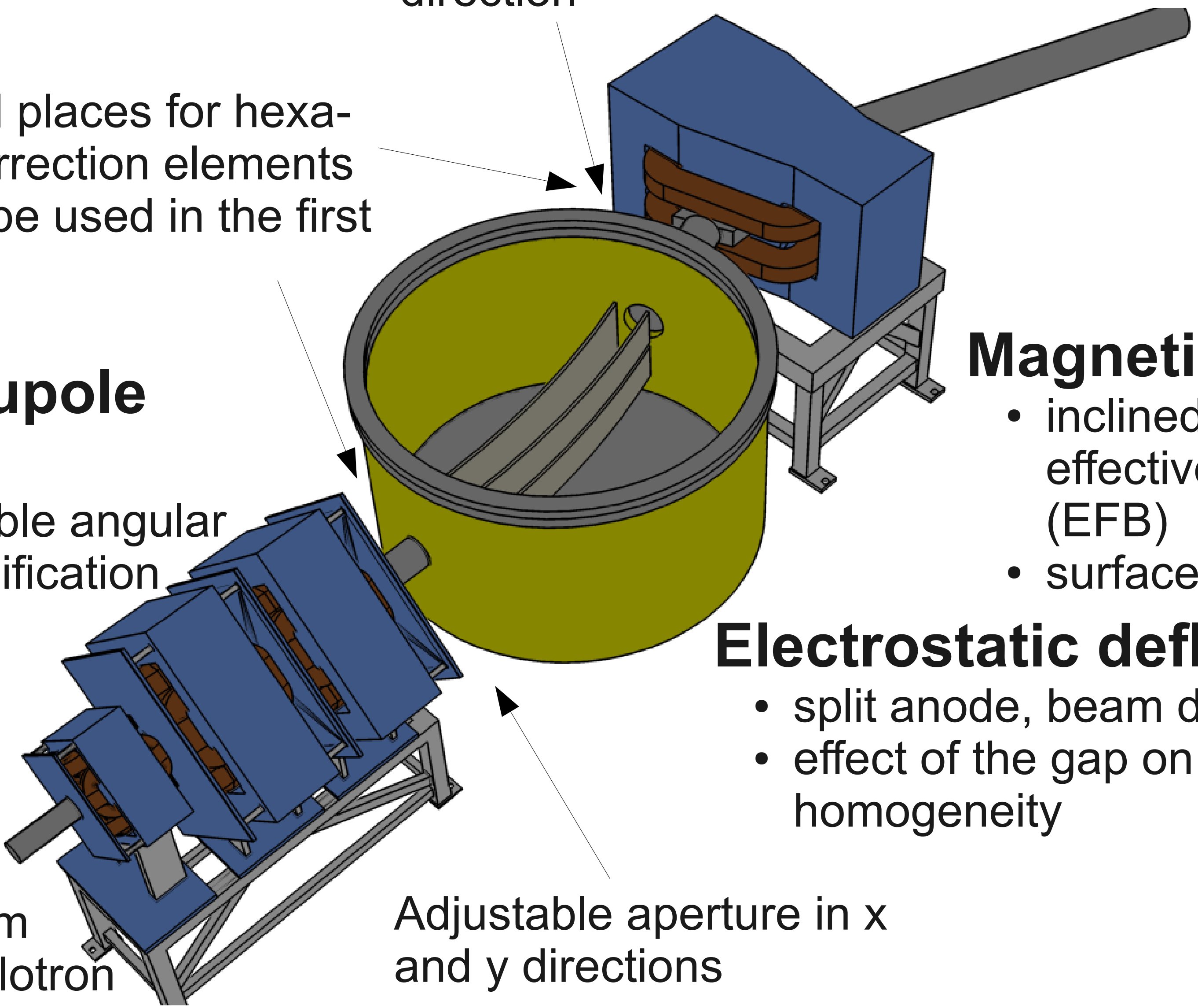
Schematic view of MARA

Adjustable aperture in x direction

Focal plane

- after 2.0 m long drift length
- slit system
- two position sensitive detect-ors → tracking

Optimal places for hexa-pole correction elements (not to be used in the first phase)



Quadrupole triplet

- scalable angular magnification

Magnetic dipole

- inclined and rounded effective field boundaries (EFB)
- surface coils

Electrostatic deflector

- split anode, beam dump
- effect of the gap on the field homogeneity

Target

beam from K130 cyclotron

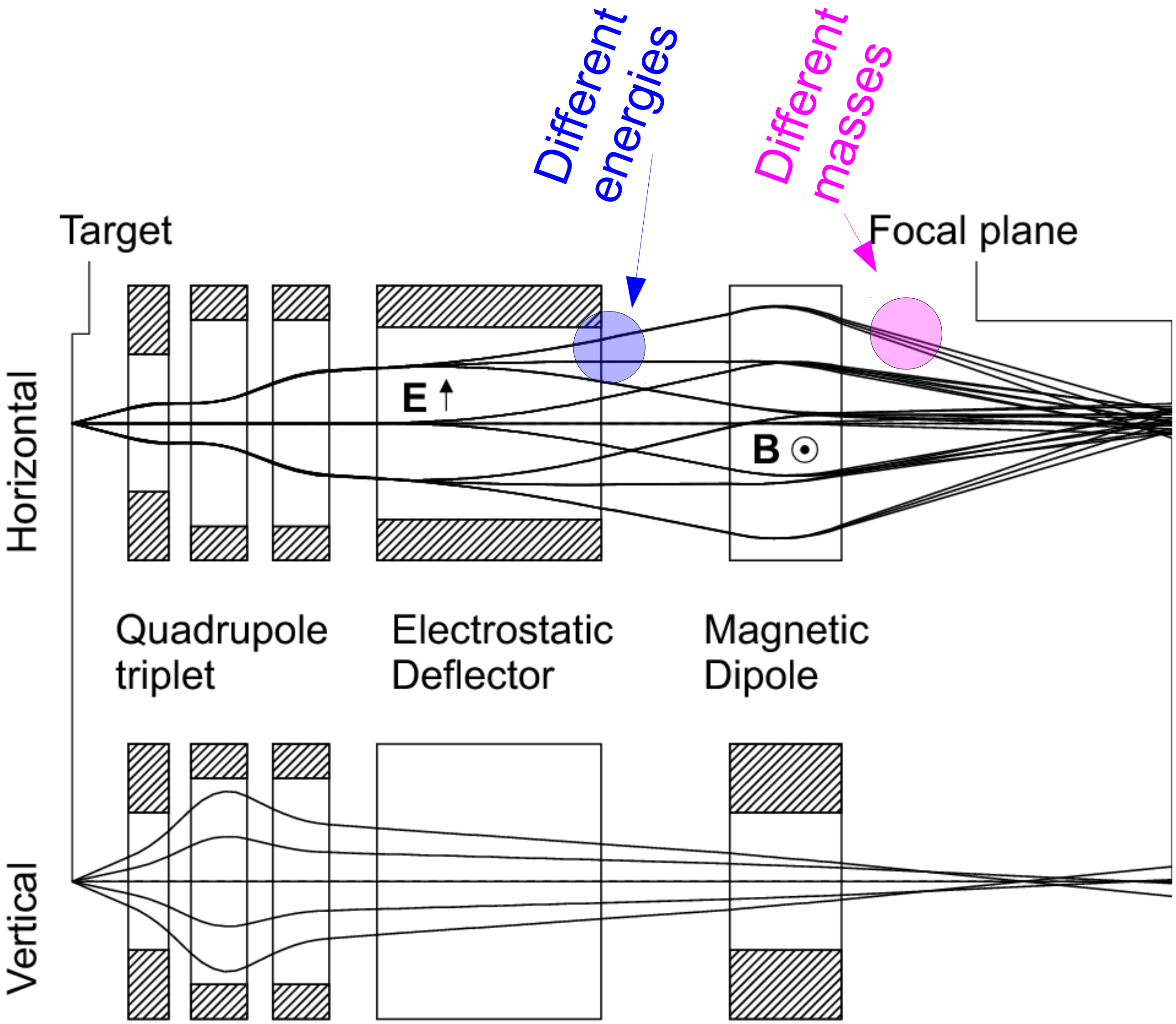
Adjustable aperture in x and y directions

The MARA working principle

Quadrupole triplet:
- point-to-parallel focus from target to the deflector
- point-to-point focus from target to the focal plane

Deflector:
- separates primary beam and products
- separates according to energy (per charge)

Magnetic dipole
- separates masses and cancels the energy dispersion at the focal plane



MARA specification

Some comparison to other RMS with physical mass separation:

- MARA has asymmetric ion optical configuration with one electrostatic deflector (E): QQQEM
- Fixed energy focus (due to missing second deflector)
- Tilted focal plane angle
- Shorter than other recoil mass separators
- Typical angular acceptance of 10 msr
- Typical m/q and energy acceptance
- Typical resolving power

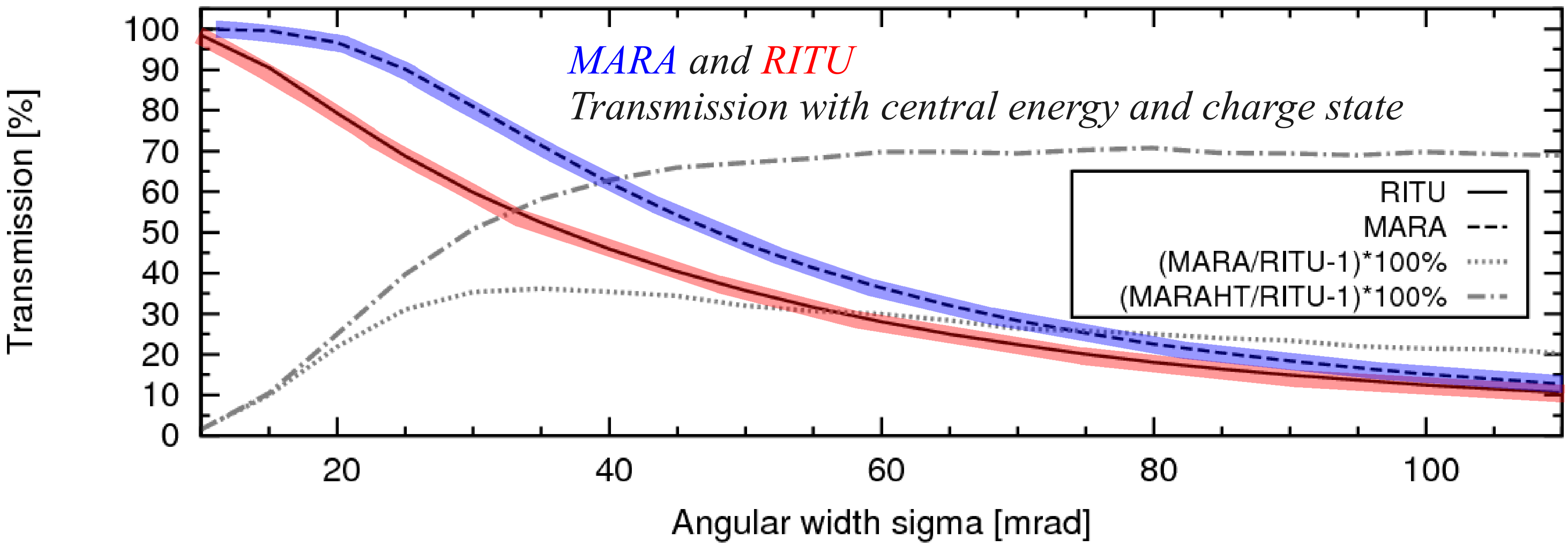
Total length along the optic axis	6.85 m
Angular acceptance (horiz., vert.)	45 mrad, 55 mrad
Energy acceptance	-15 – +20%
First order resolving power	250
Dispersion	8.1 mm/(% in mass)
Magnification (horiz., vert.)	-1.6, -4.7
First order resolving power with ±1 mm horizontal beam spot	250
Mass focal plane angle from optic axis	13°

MARA specification

Quadrupole triplet	$\mathbf{Q_1}$	$\mathbf{Q_{2,3}}$
Optical length	25 cm	35 cm
Bore diameter	10 cm	15 cm
Maximum field gradient	10 T/m	10 T/m
Nominal field relative to $B\rho$	0.4698 T/$B\rho$	0.5859, 0.2387 T/$B\rho$
Sector fields	**Electrostatic**	**Magnetic**
Radius of curvature, ρ	4.000 m	1.000 m
Bending angle, ϕ	20°	40°
Vertical gap	14 cm	20 cm (active)
Horizontal gap	10 cm (active)	10 cm
Maximum rigidity	14.2 MV	1 Tm
Inclination of EFB (entrance and exit)		8°
EFB curvature radii (entrance and exit)		2.0 m
Height of the gap in the anode	1.5 cm (extending from ≈10° to ≈19°)	
Drift lengths	**Length [cm]**	
Target – Q_1	35	
$Q_1 - Q_2$	14	
$Q_2 - Q_3$	16	
Q_3 – Deflector EFB	30	
Deflector EFB – Dipole EFB	80	
Dipole EFB – Focal plane	205.8	

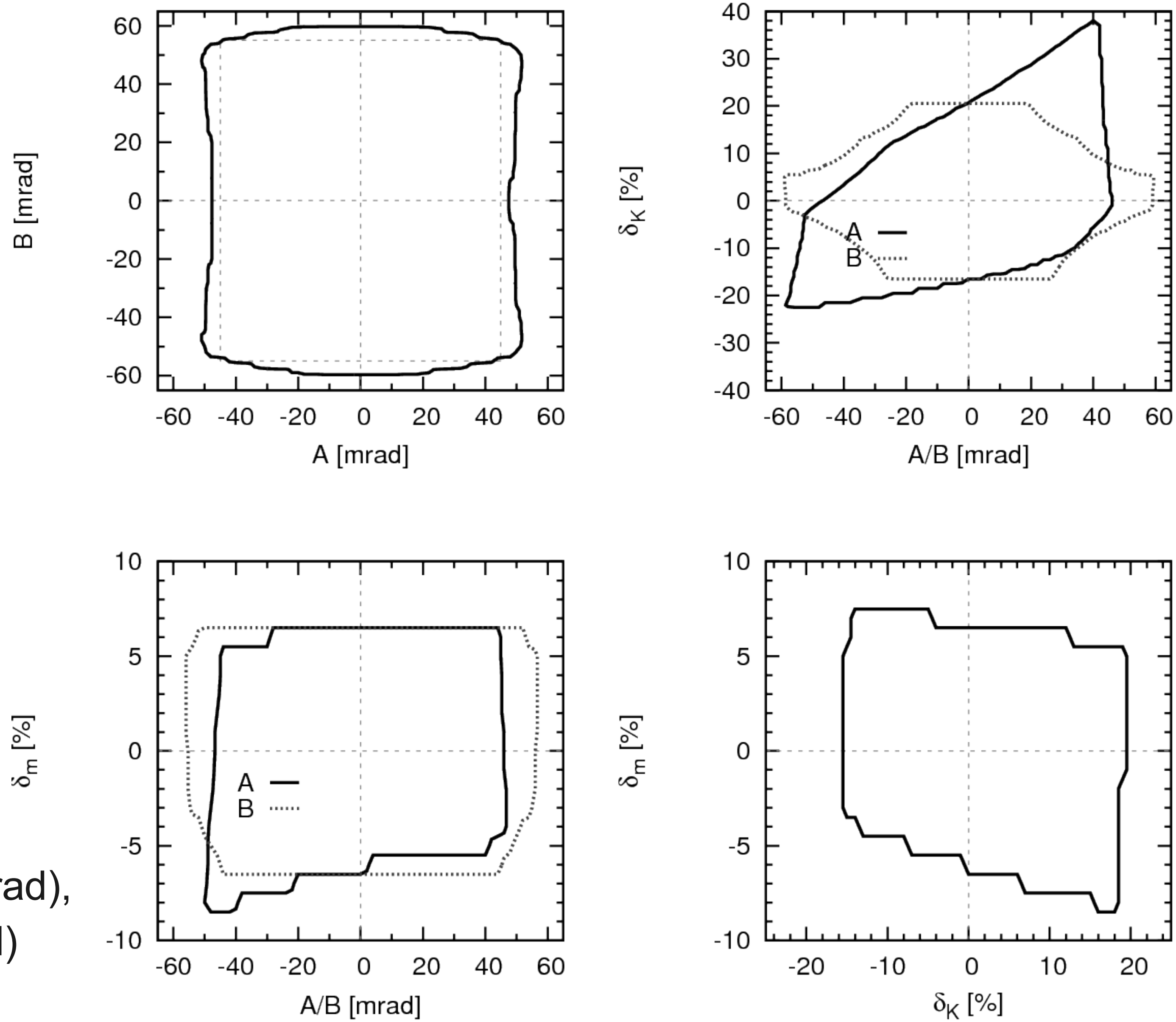
Transmission and acceptance studies of MARA

- MARA has about 20% larger solid angle acceptance than RITU.
- Angular acceptance is almost symmetric: ~45x55 $mrad^2$ while RITU acceptance is asymmetric ~25x85 $mrad^2$.
- MARA can collect only 2 or 3 charge states representing 30-45% of total.
- The figure below shows transmission as a function of the width of the angular distribution of products. Real transmission is smaller due to energy spread and charge distribution.



Transmission and acceptance studies of MARA

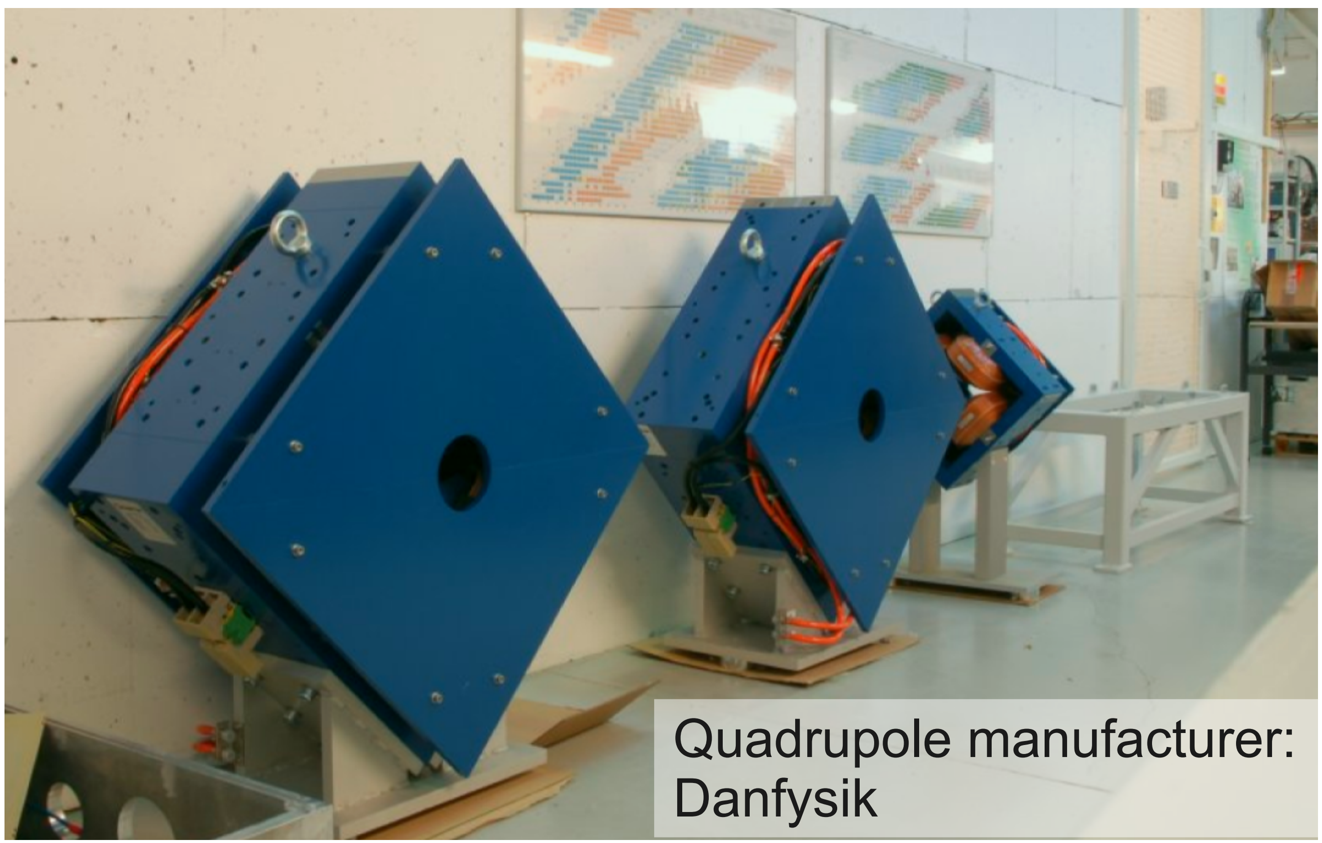
- No strong coupling between horizontal and vertical angles (*A* and *B* in the figure)
- Strong coupling between energy deviation and angle in both x and y



horizontal "angle": $A = p_x/p_z$ (~rad),
vertical "angle": $B = p_y/p_z$ (~rad)

The quadrupole triplet

- Allows flexible transformation of trajectories from the target area to the entrance of the deflector
- 3 fields → 3 parameters, stigmatic focus at the focal plane binds 2 parameters → continuum of solutions giving stigmatic focus
- → variable angular magnifications can be obtained which leads to variable first order resolving power

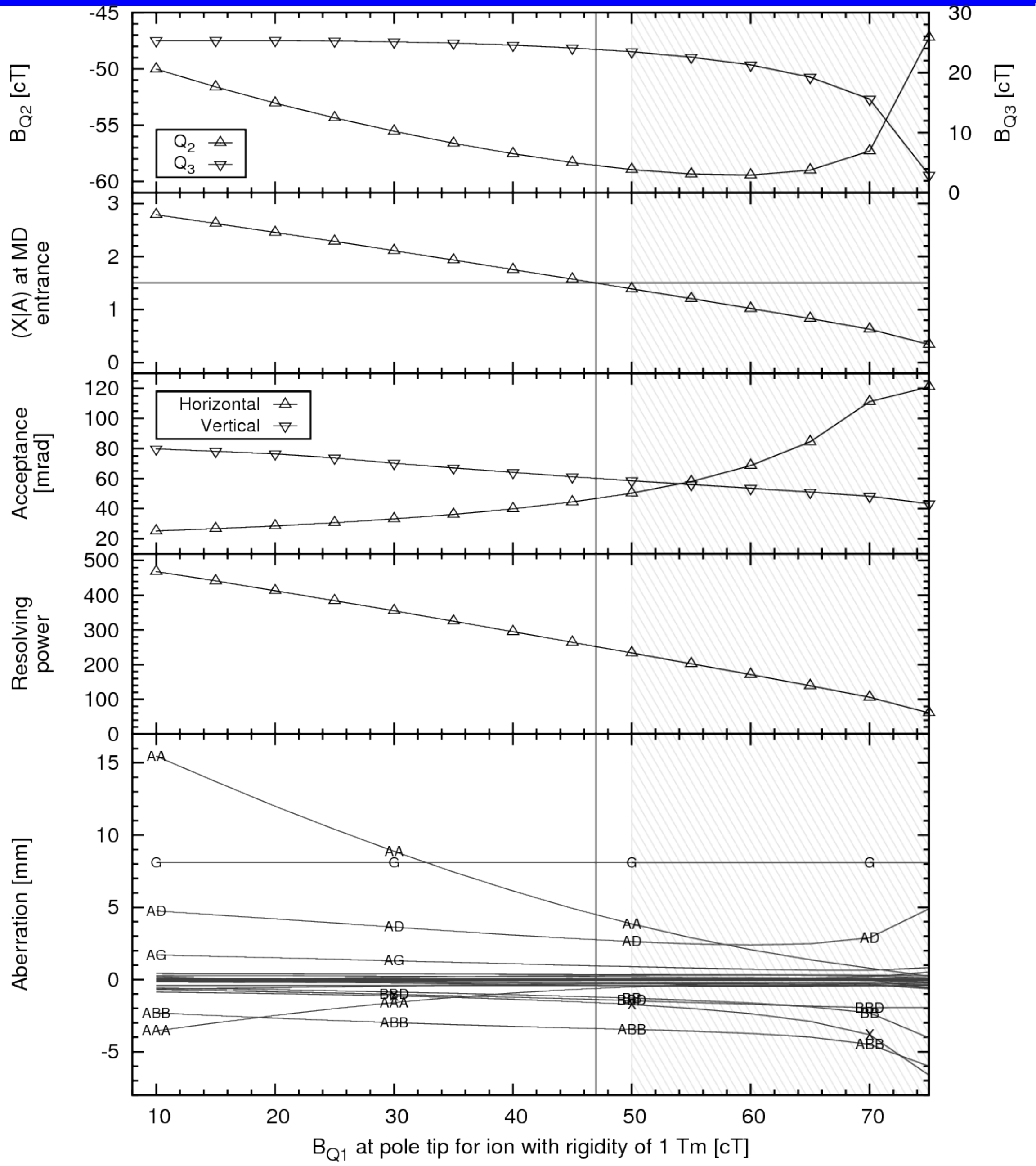


Quadrupole manufacturer: Danfysik

The quadrupole triplet

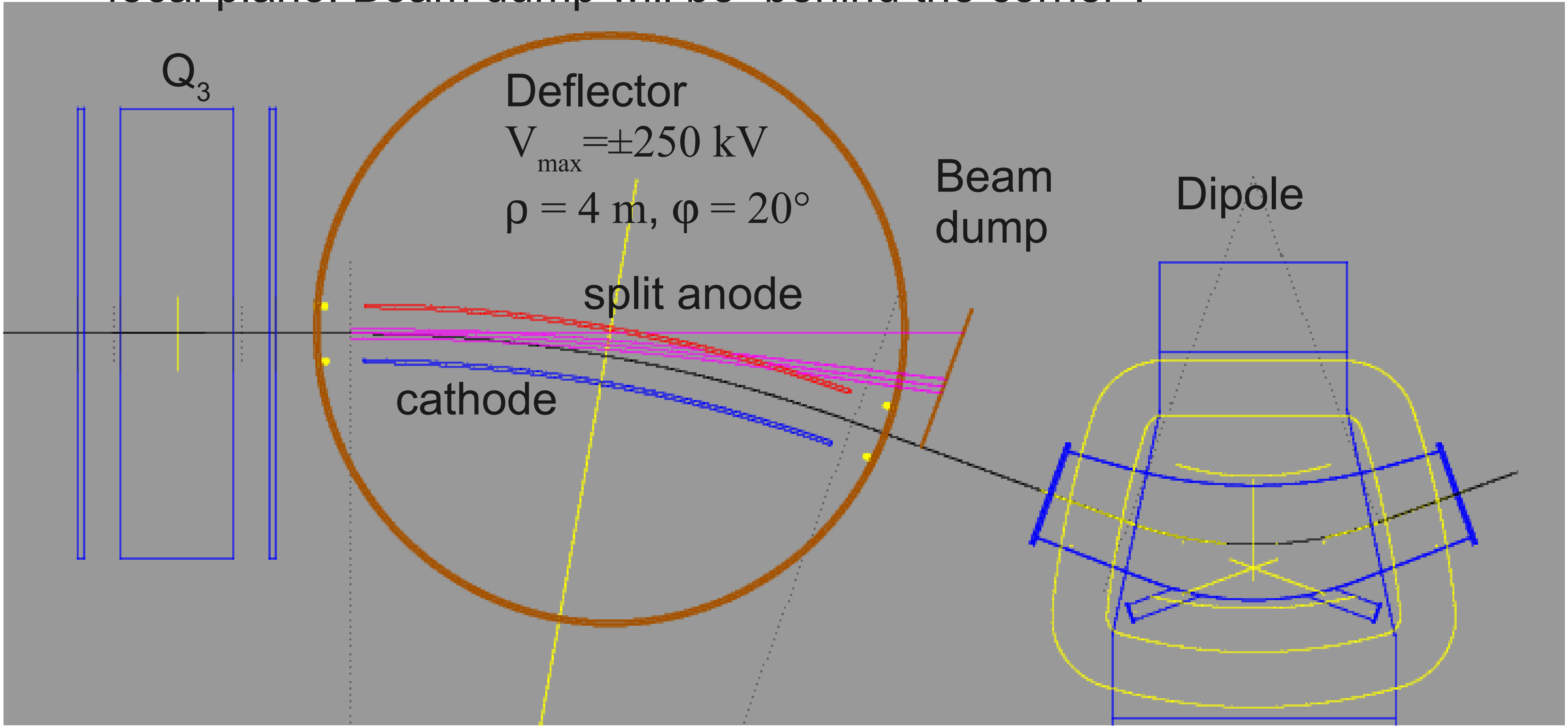
There is a continuum of solutions producing a stigmatic focus.

- All values of the first quadrupole results a solution
- Higher than nominal maximum relative fields can be used in Q_1 since $B\rho < 1.0$ Tm for typical products
- Some aberrations (especially $(X|A^2)$) depend on solution (However, the acceptance changes as well)
- First order resolving power is proportional to Q_1 field
- Changes in horizontal and vertical angular acceptances



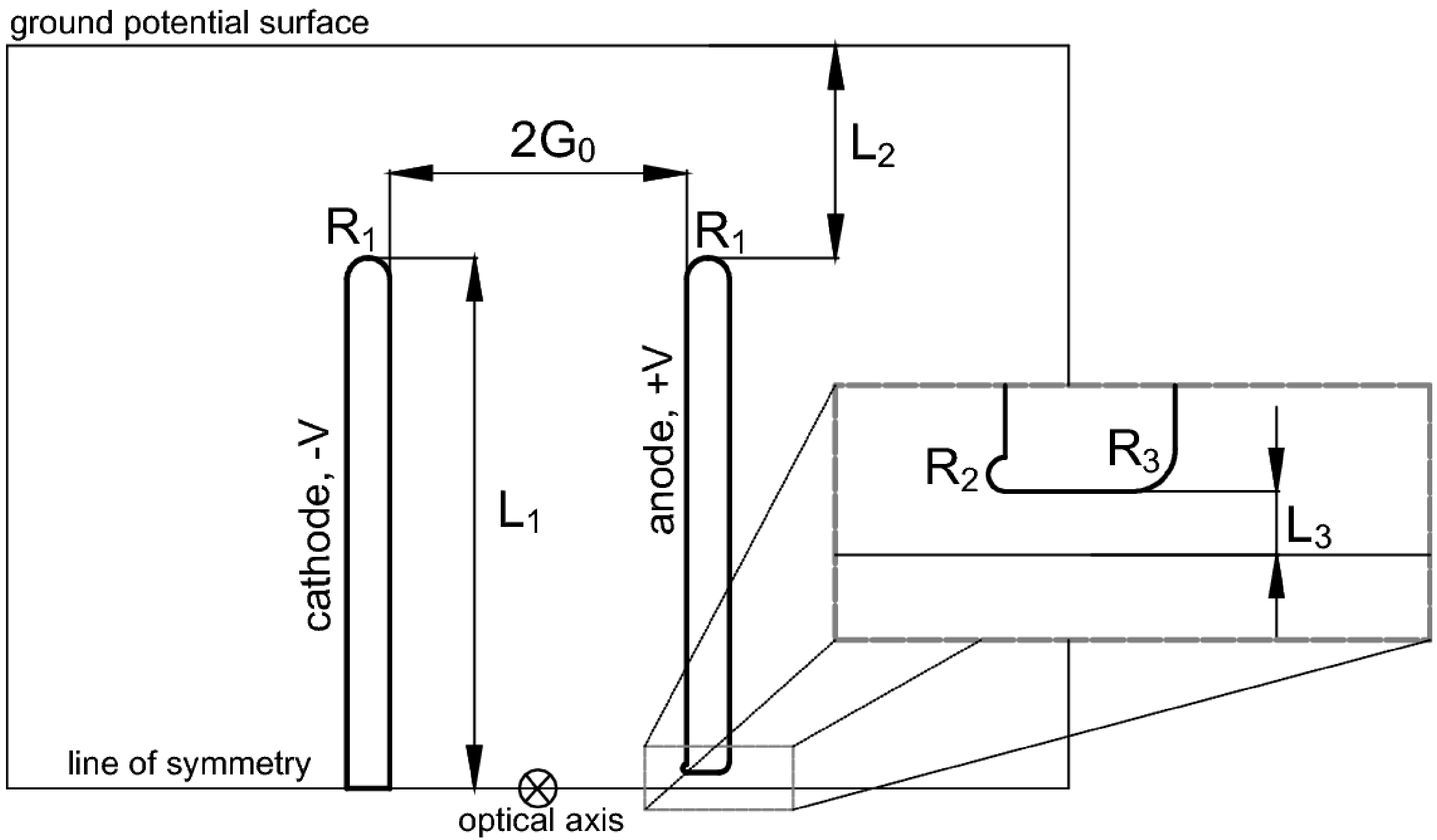
The electrostatic deflector

- Most complicated ion optical element of MARA
- Required high precision machine-tooling and careful design of the split anode (total gap height is 15 mm)
- The split anode reduces the amount of scattered primary beam at the focal plane. Beam dump will be “behind the corner”.



The electrostatic deflector: the split anode

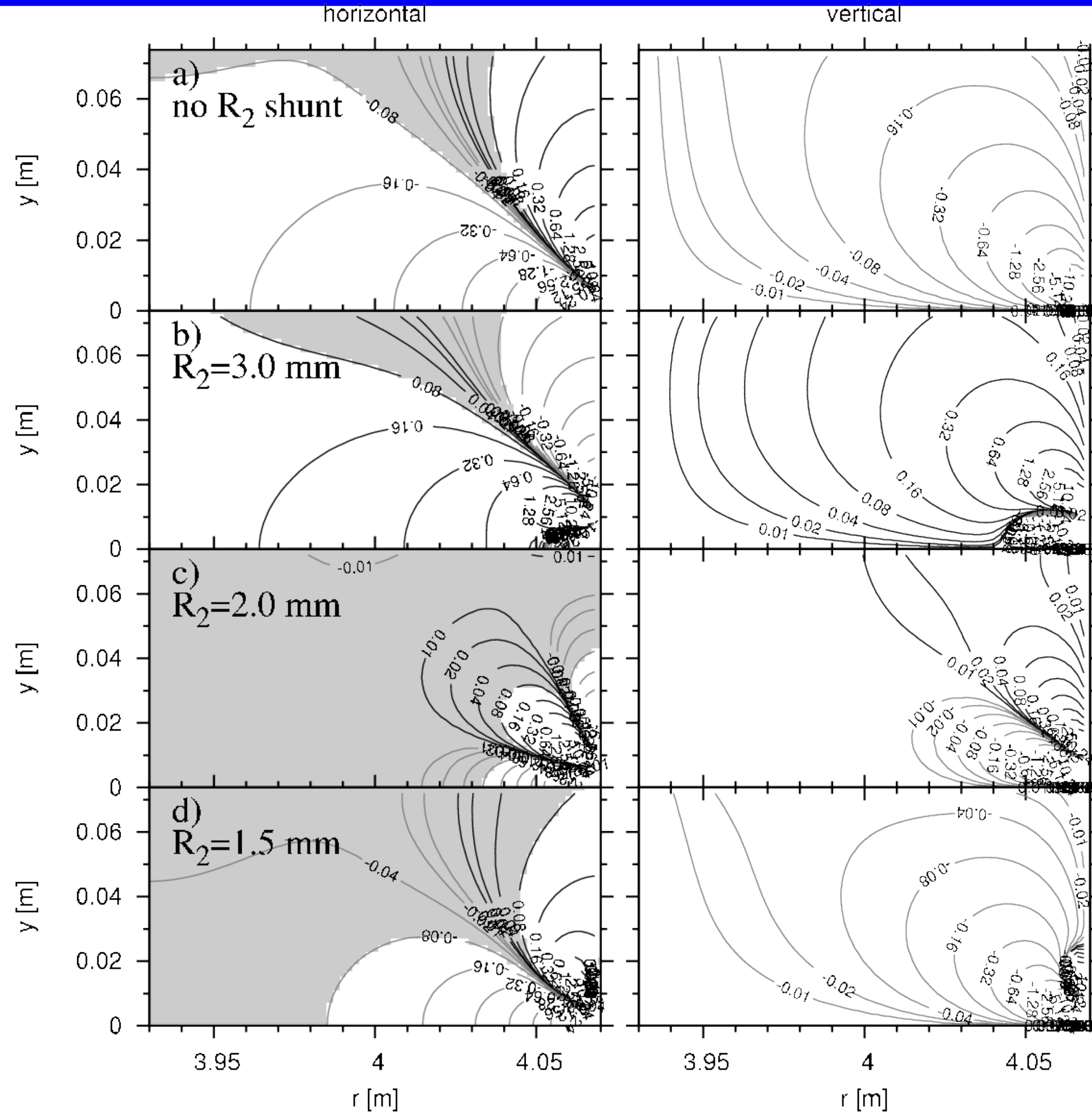
A cross-section of the upper half of the deflector below. The final specification of the geometry will be made this spring in co-operation with a manufacturer. The effects of different shim sizes have been studied.



The electrostatic deflector: the split anode

Acceptable field region: the horizontal electric field component must deviate less than 0.08% from the ideal in order to retain the mass resolution. In reality limit is around 0.16% since only the second half of the anode will be split.

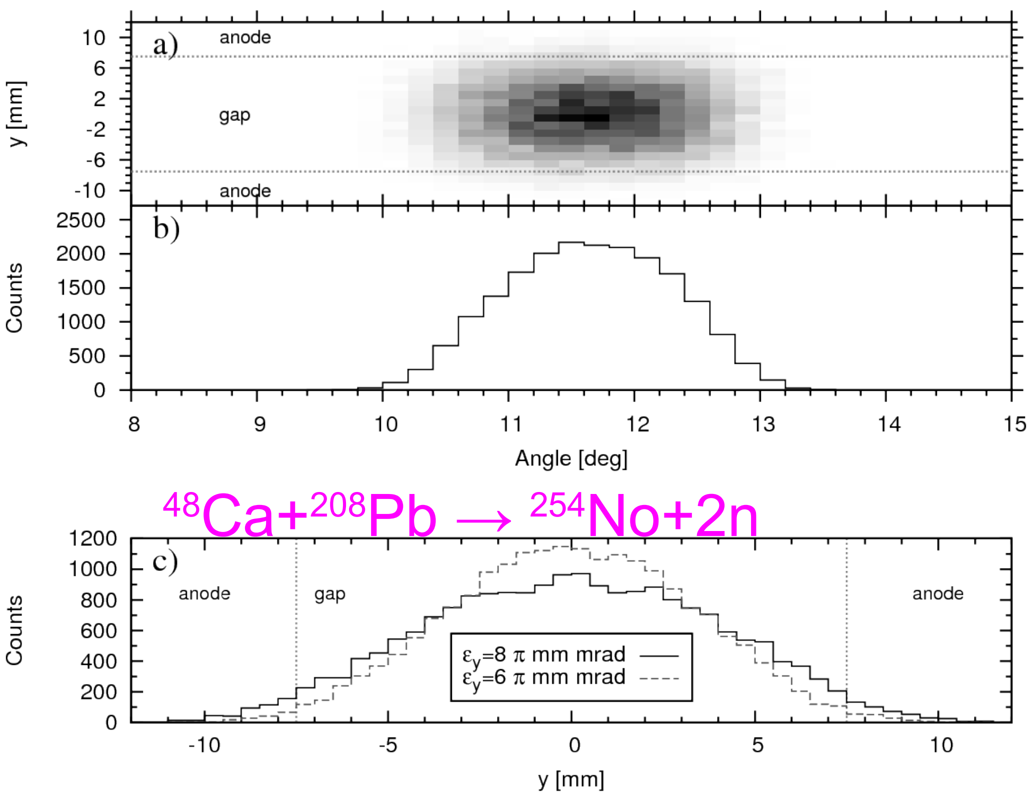
To avoid tails of other fusion channels in a m/q spectrum the bad field region will be shadowed. This will reduce acceptance little bit.

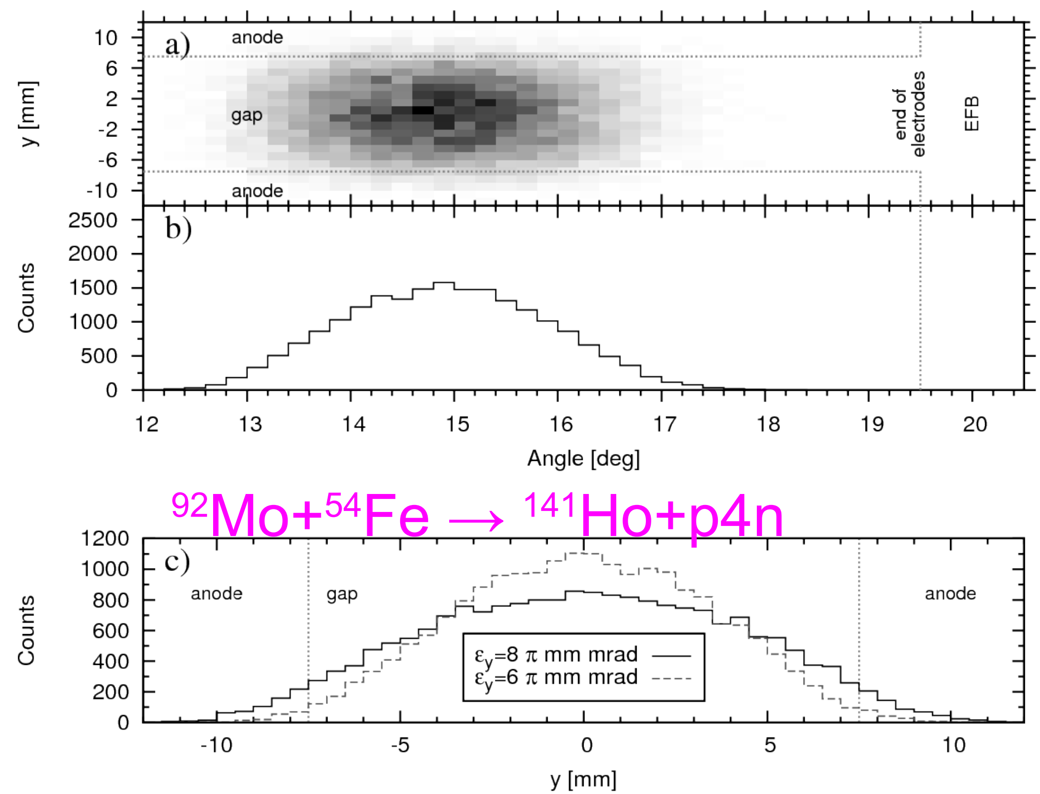


The electrostatic deflector: primary beam

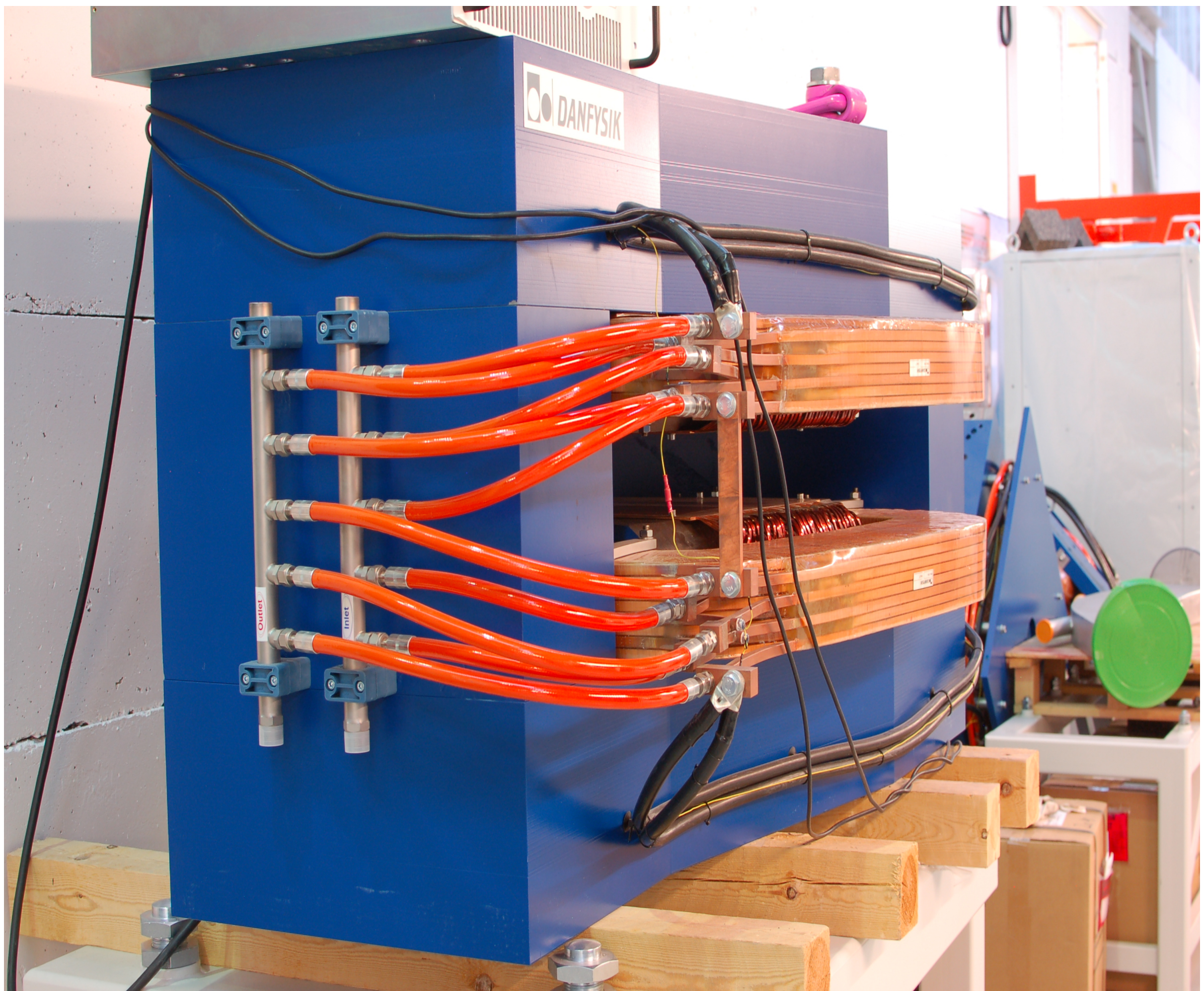
The primary beam has 2—6 times as large electric rigidity than fusion products. The spatial distribution of primary beam particles have been calculated for to extreme (in rigidity ratio) reactions.

Most of the beam (~95) fits through the gap. The gap can be also closed before the end of the deflector to add mechanical strength.





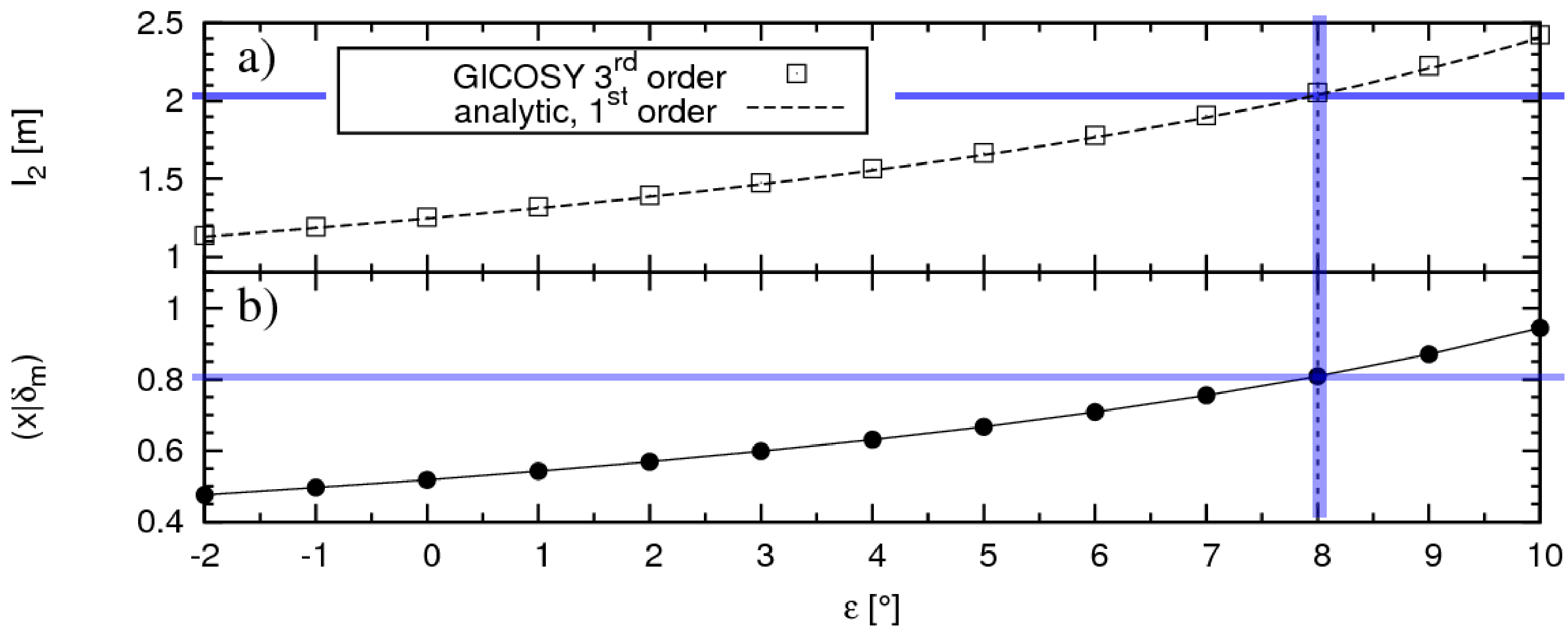
The magnetic dipole



- The masses are separated in the magnetic dipole.
- The specification of the MARA dipole is very similar to the other RMS: 40° deflection angle, 1.00 m radius of curvature, 10 cm horizontal gap, 1.0 T maximum field
- Maximum rigidity: 1 Tm
- EFBs have been tilted 8° and have 2.0 m radii of curvature
- Surface coils can be used to produce max. ±1% quadrupole component
- Manufacturer: Danfysik

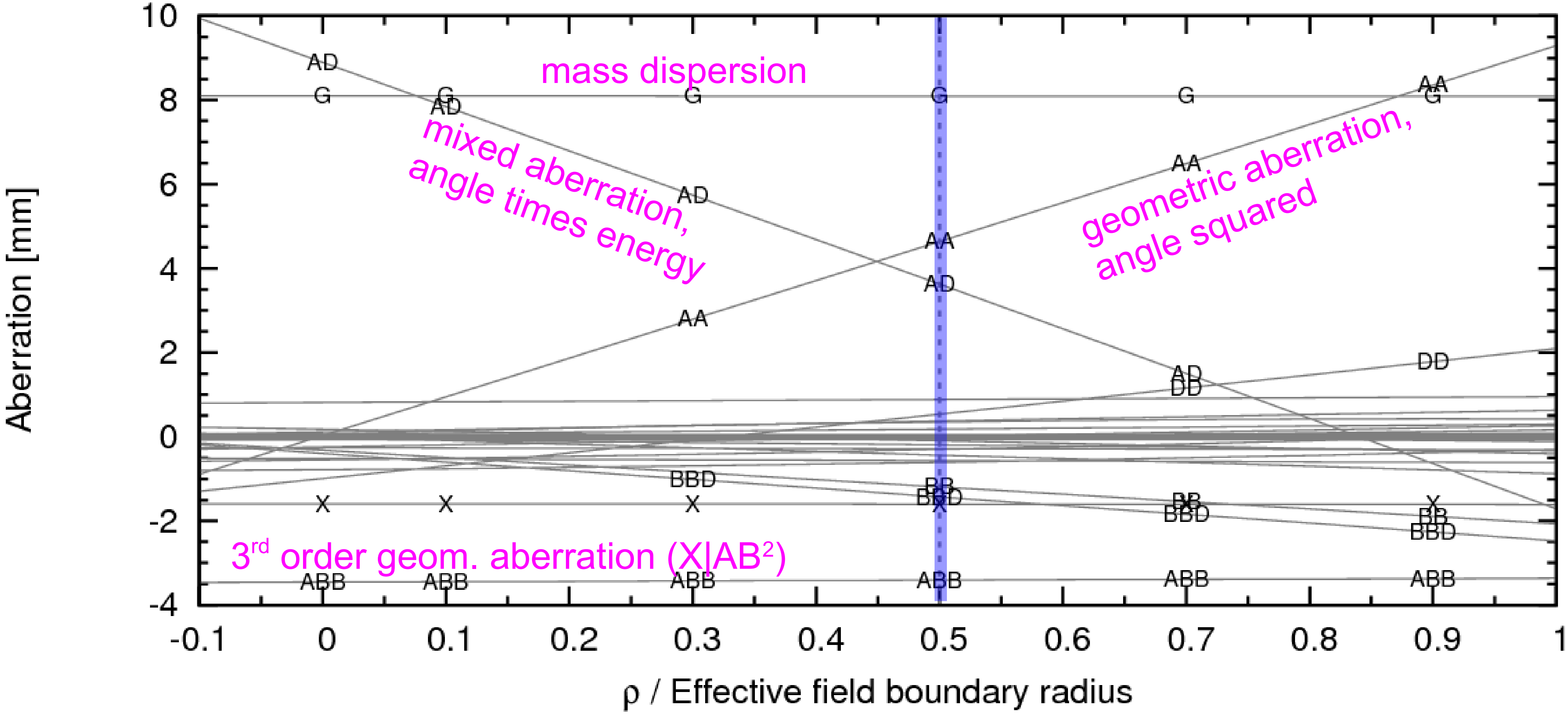
The inclined EFB of the dipole

- The distance from the dipole to the energy focus (l_2 in the figure below) can be changed by tilting the effective field boundary (EFB) of the dipole.
- l_2 needs to be long enough in order to achieve a sufficient mass dispersion.
- The inclination angle of $\varepsilon=8°$ has been adopted for the entrance and exit of the dipole symmetrically. This results $l_2=2.058$ m and $(x|\delta_m)=0.81$.



Aberrations, adding curvature to the dipole EFB

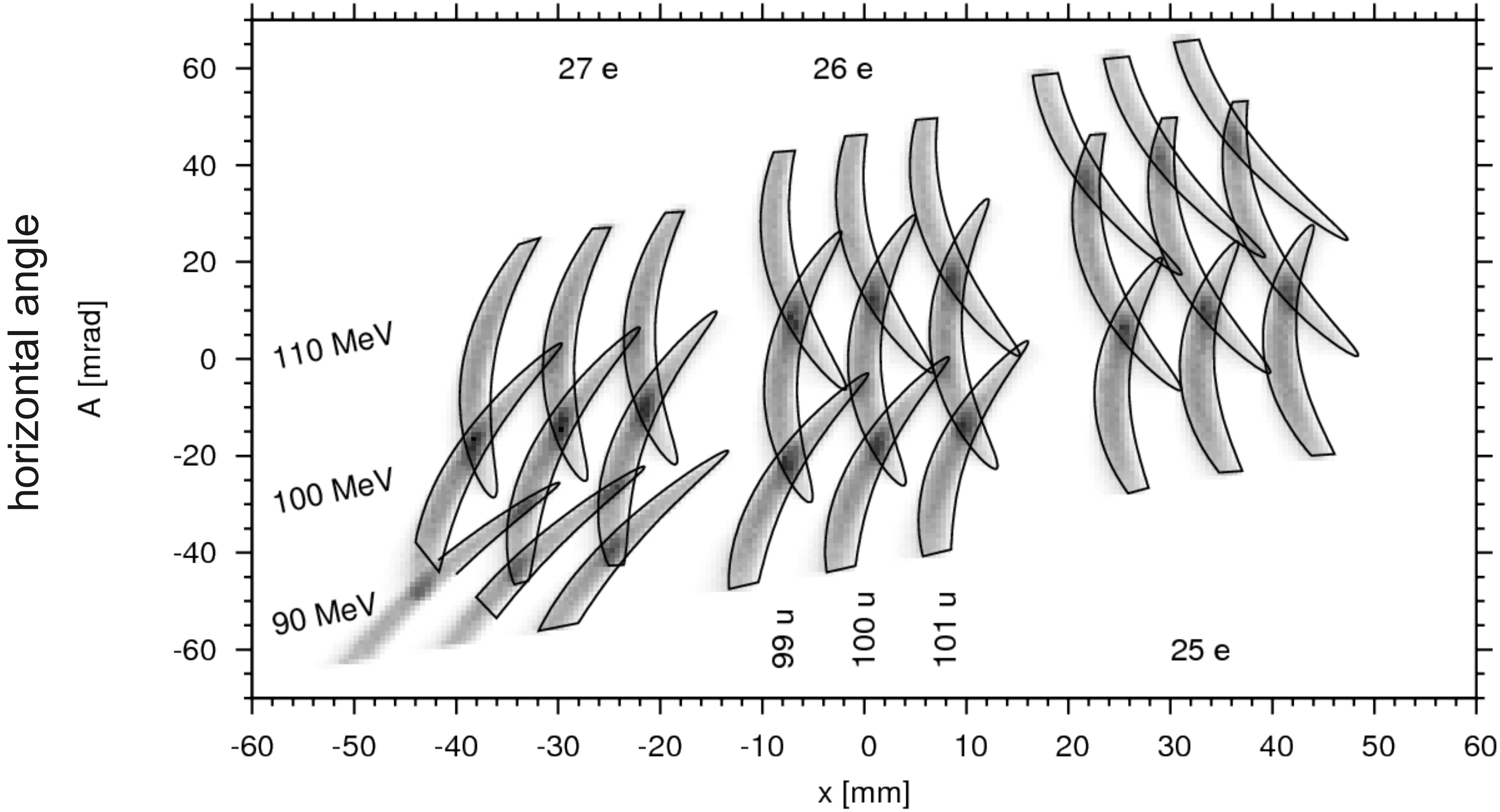
- A curvature of 2 m has been adopted symmetrically. This is a comprom-ise between (X|AA) and (X|AD) aberrations.



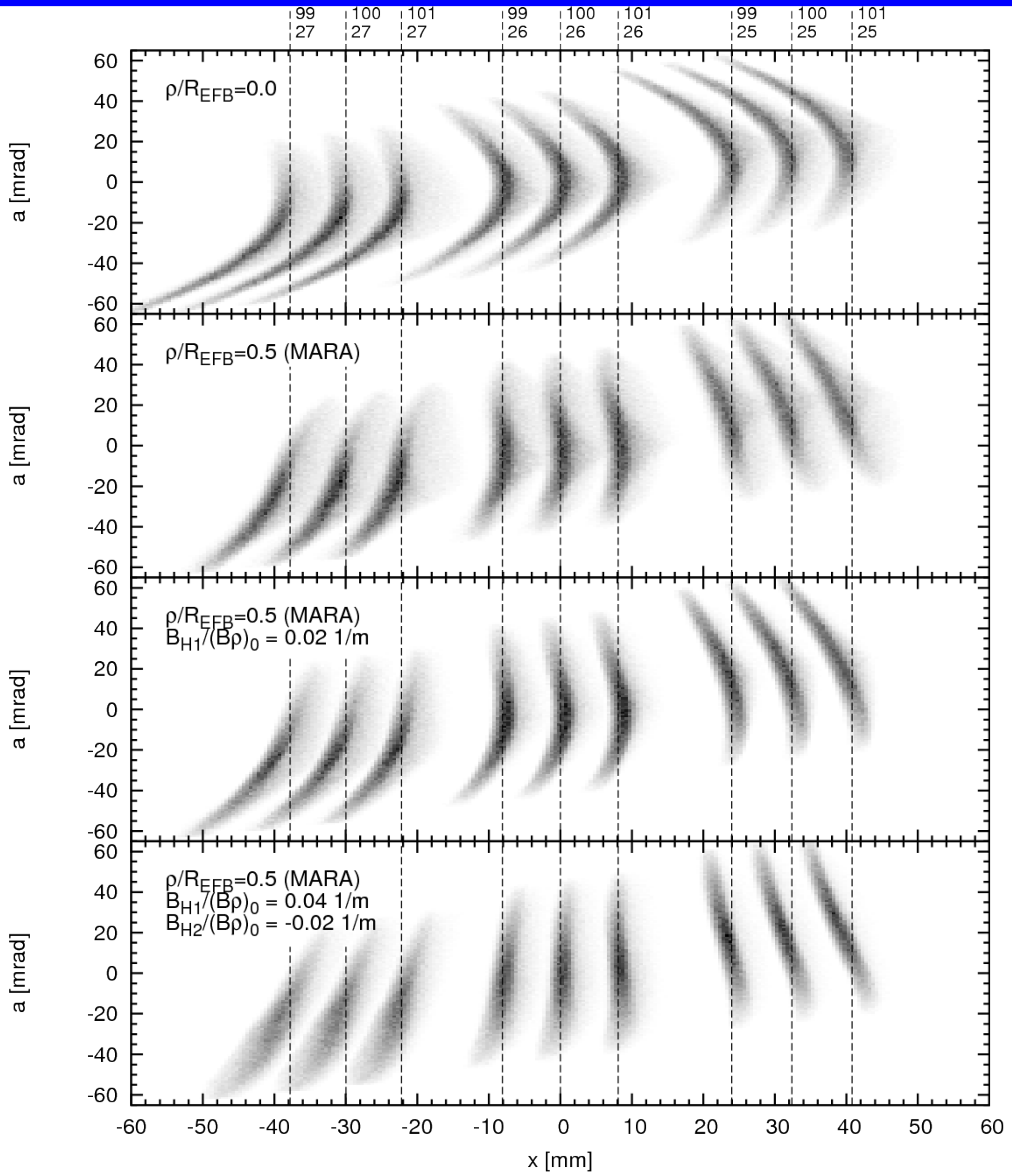
AD ↔ $a_{00}\delta_{K00}(x|A\delta_K)$, horizontal angle $A = p_x/p_z$, vertical angle: $B = p_y/p_z$, mass: $m=m_0(1+G)$, kinetic energy: $E_k=E_{k0}(1+D)$, x_{00}= 1 mm, a_{00}= 45 mrad, y_{00}= 1.5 mm, b_{00}= 55 mrad, δ_{K00}= 0.07 and δ_{m00}=0.01.

Aberrations

- Simulation of three different masses, energies and charges (with wide angular distribution) through MARA show the main aberrations in action (figure below).
- Energy/ToF and angle information can be used to improve mass resolution.



Aberrations: rounded dipole EFB and hexapoles



No rounded EFBs in the dipole

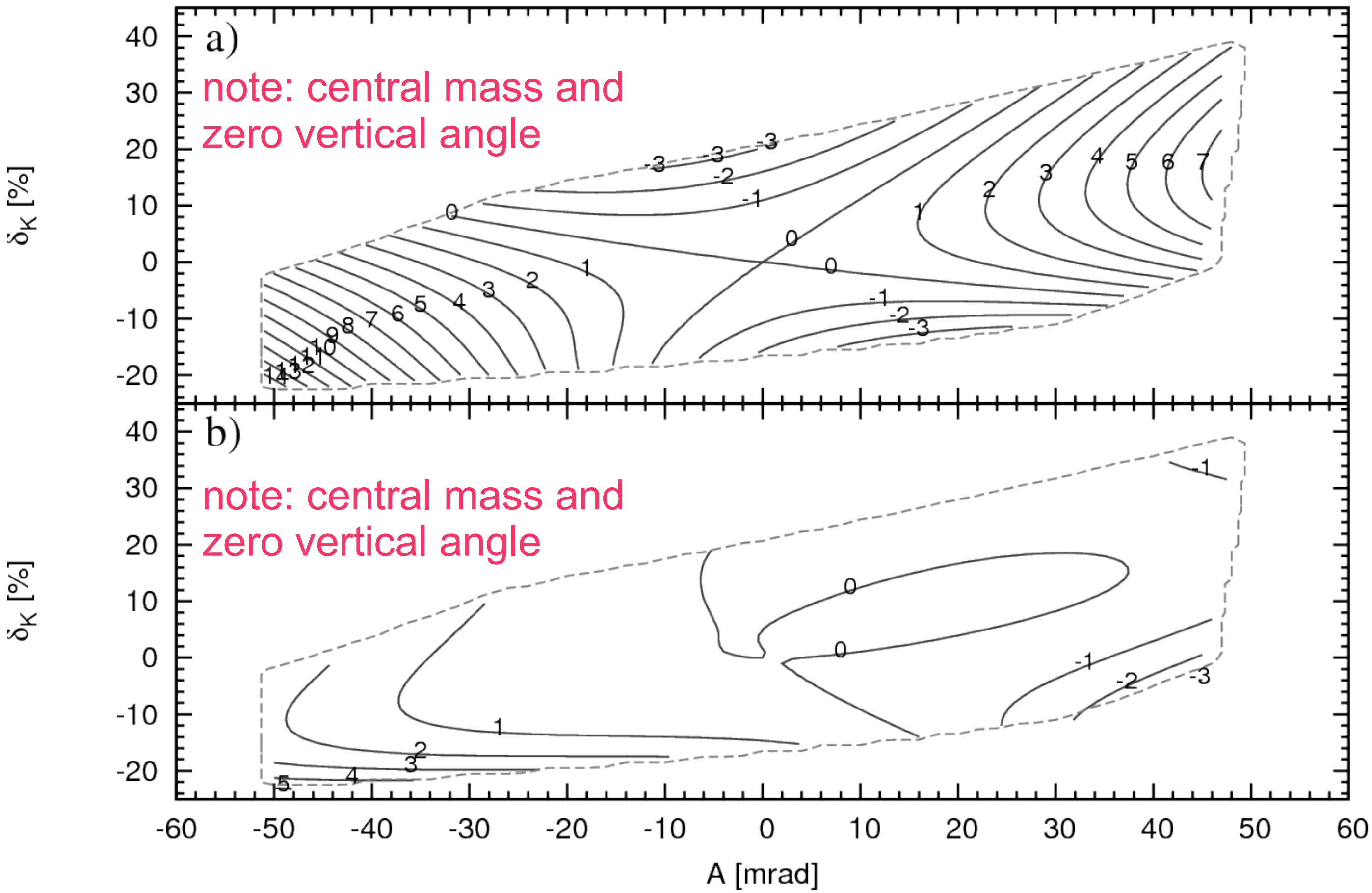
EFB radius 2.0 m (MARA)

Adding one hexapole between Q_3 and the deflector (requires more space)

Adding second hexapole between the deflector and the dipole

Aberrations: Closer look to $(X|AA)$ and $(X|\delta_K{}^2)$

The main aberrations are illustrated here as horizontal shifts [mm] at the focal plane due to horizontal initial angle, A, and energy deviation δ_K. in the case of a) MARA and b) MARA with two hexapoles.

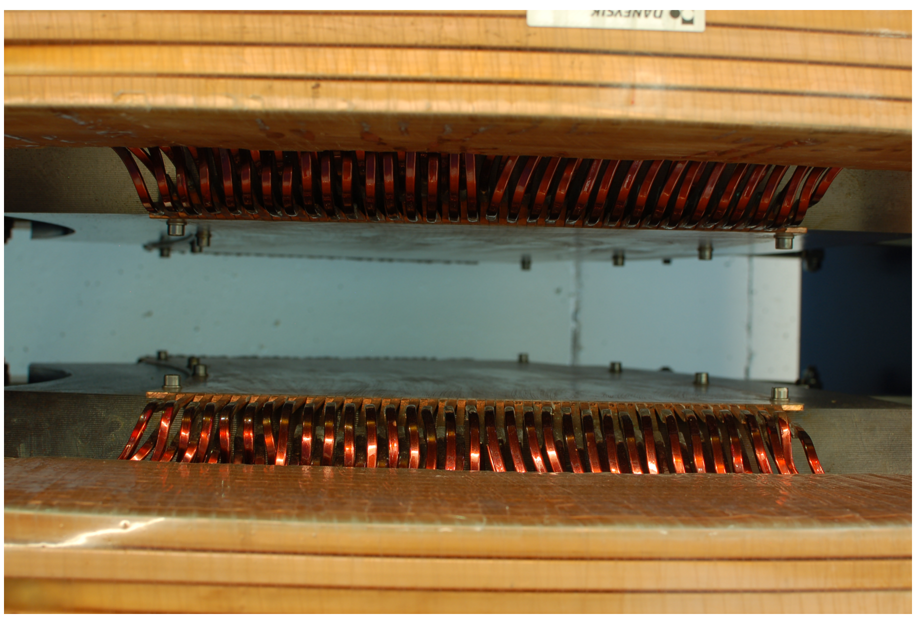


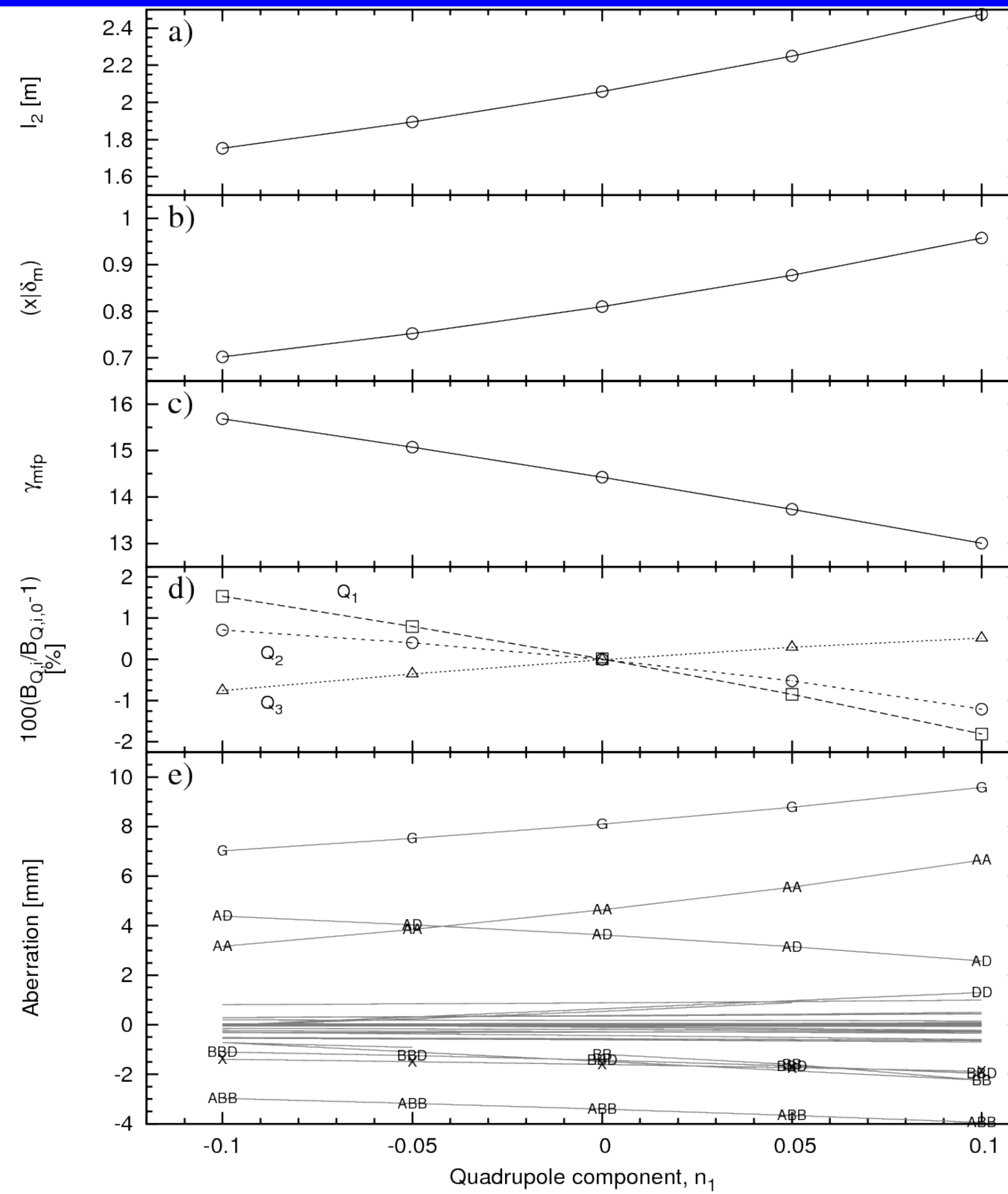
The maximum absolute size of the $(X|\delta_K{}^2)$ is less than $(X|\delta_m)/2$. Real resolution can be improved by limiting angular acceptance in horizontal direction if needed in an experiment.

Clearly, the hexapoles can correct aberrations remarkably. These can be added later to MARA with small modifications.

Surface coils in the magnetic dipole

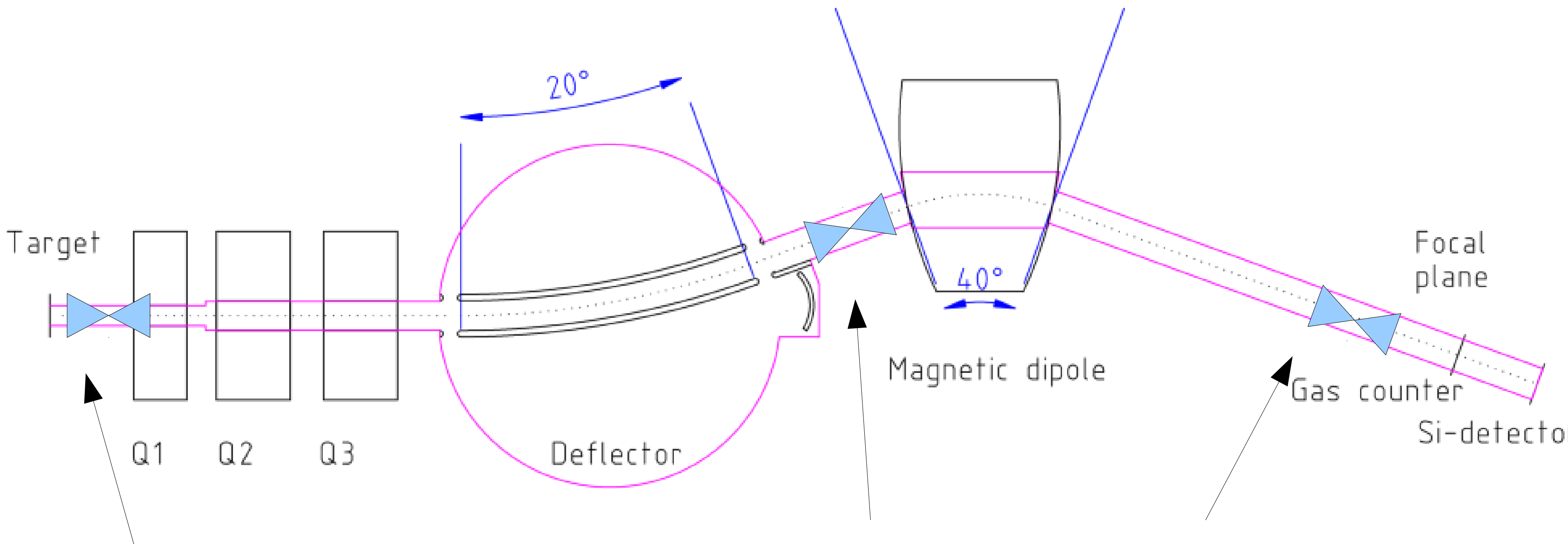
The last drift length between the dipole and the focal plane can be changed between 1.75—2.06—2.45 m by energising the surface coils in the dipole. This corresponds to variable mass dispersion between 7.0—9.5 mm/(% in m/q).





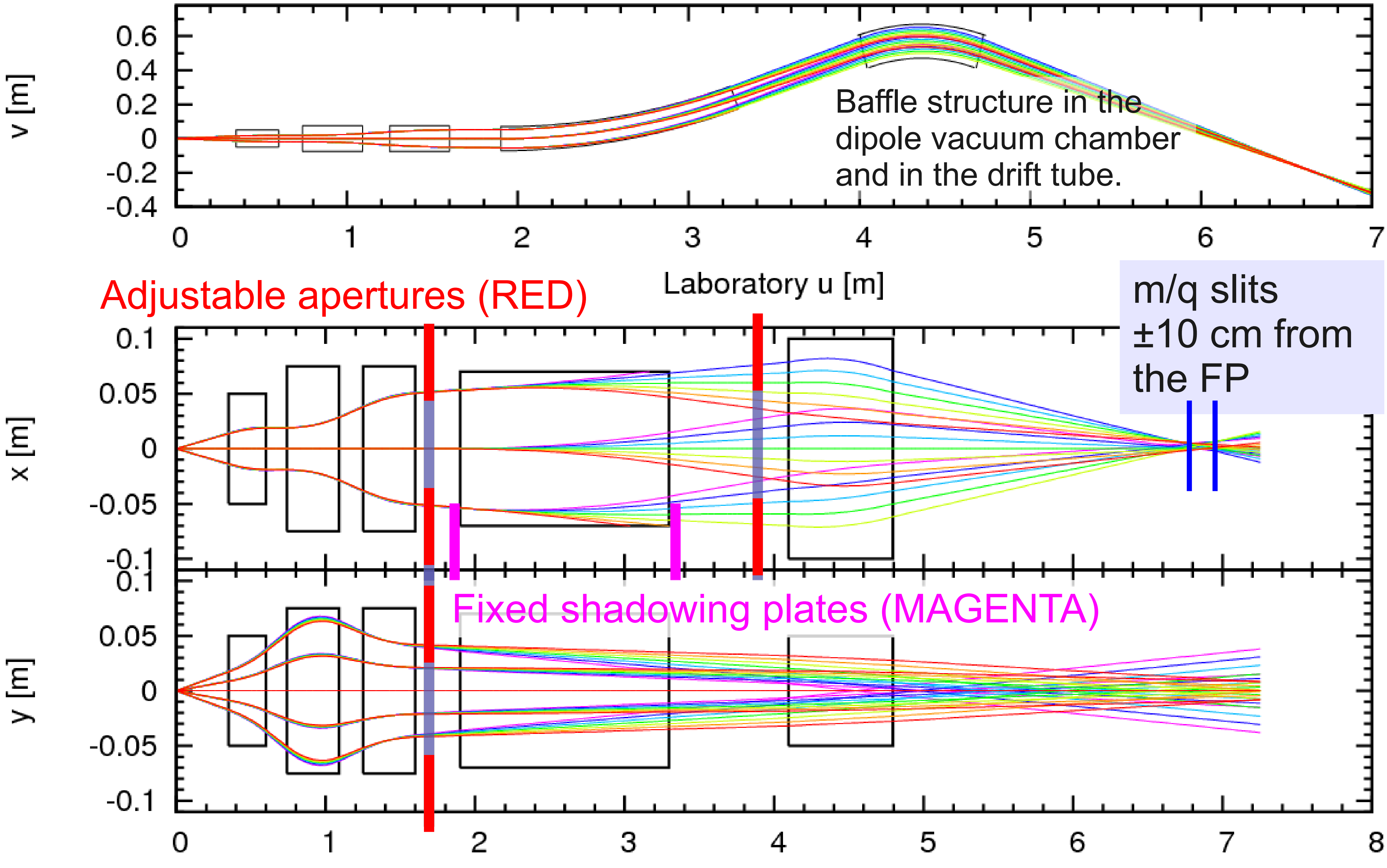
Instrumentation: vacuum system

The high voltages of the deflector requires high vacuum. Since there are very limited space between Q_3 and the deflector the triplet and the deflector will form one vacuum section. The second section is formed by the dipole and part of the tube towards the focal plane. Turbo molecular pumps and a cryo pump will be used for pumping.



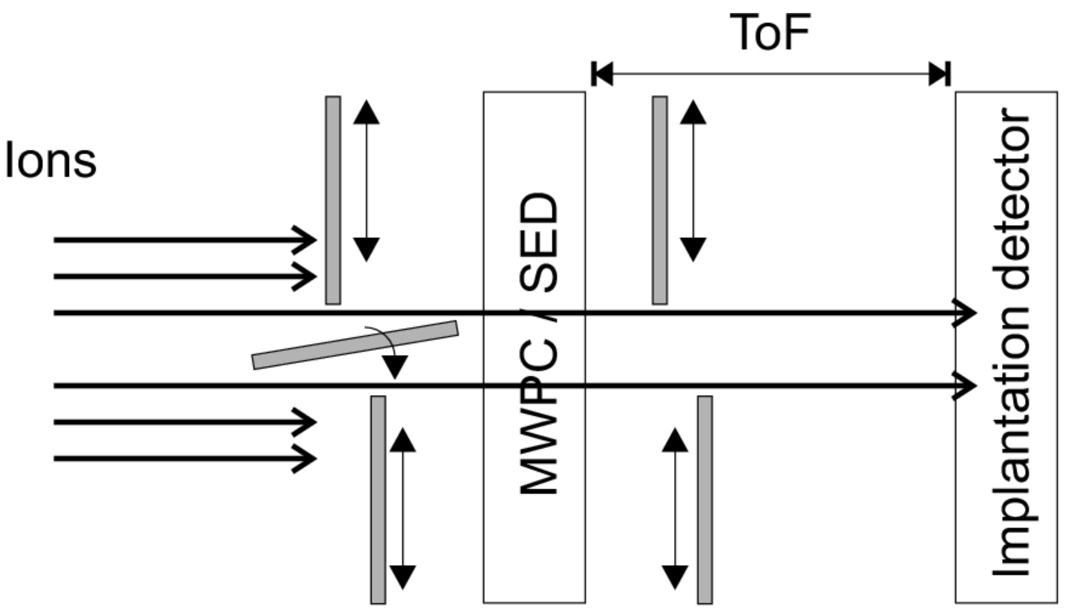
Gate valves (x3): after target, between deflector and the dipole and before focal plane chamber.

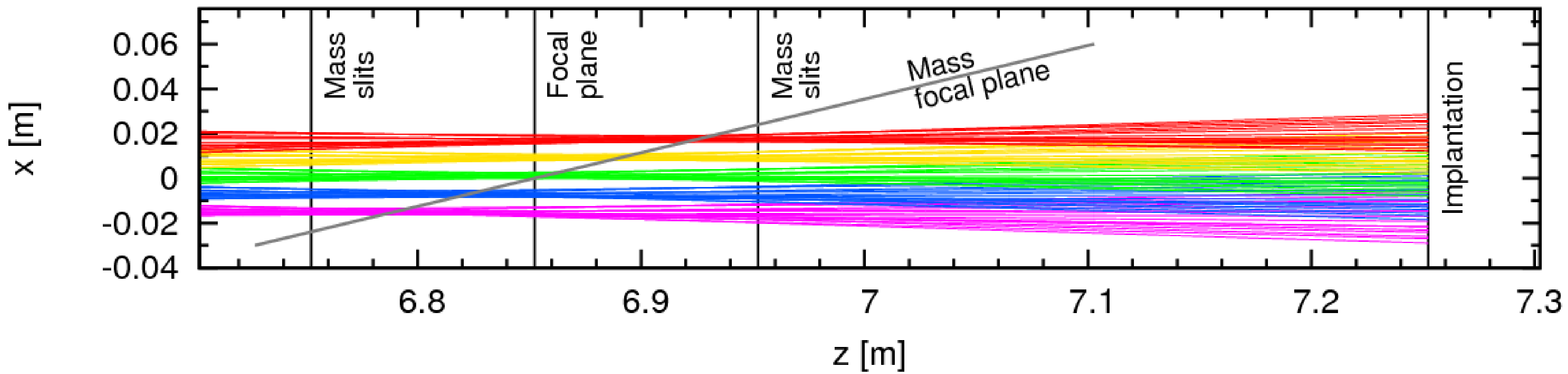
Instrumentation: apertures and slits



Instrumentation: Apertures and slits

Due to tilted focal plane in MARA it is preferable to have two m/q slit systems before and after the focal plane.

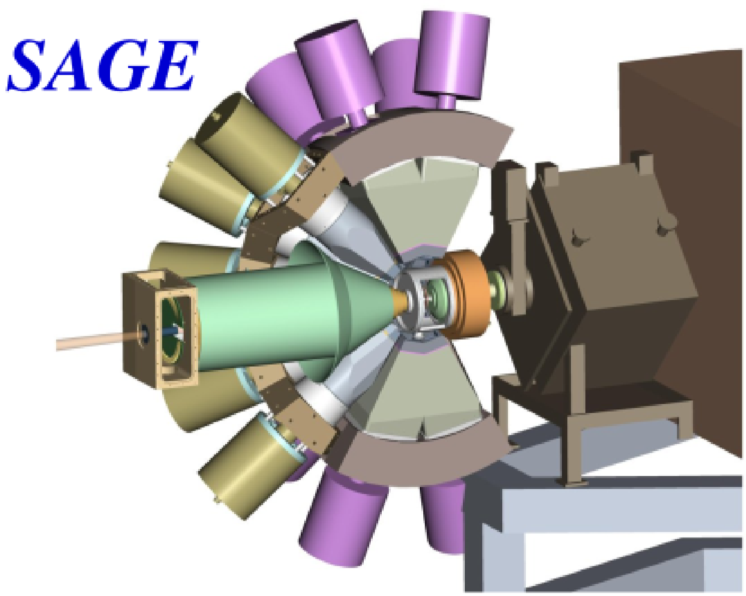




Ideas for the detector setup: the target area

In principle all detector setups used or planned to be used with RITU could be used also in conjunction with MARA. These are for example:

- JUROGAM II Ge-detector array
- SAGE electron spectrometer
- LISA charged particle spectrometer. In the case of pure neutron evaporation channel under study LISA or other similar detector can be used to veto channels comprising charged particles.



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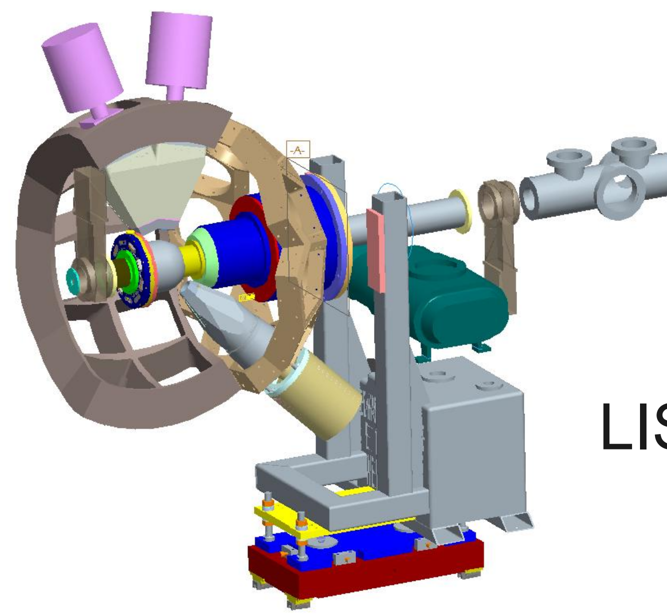
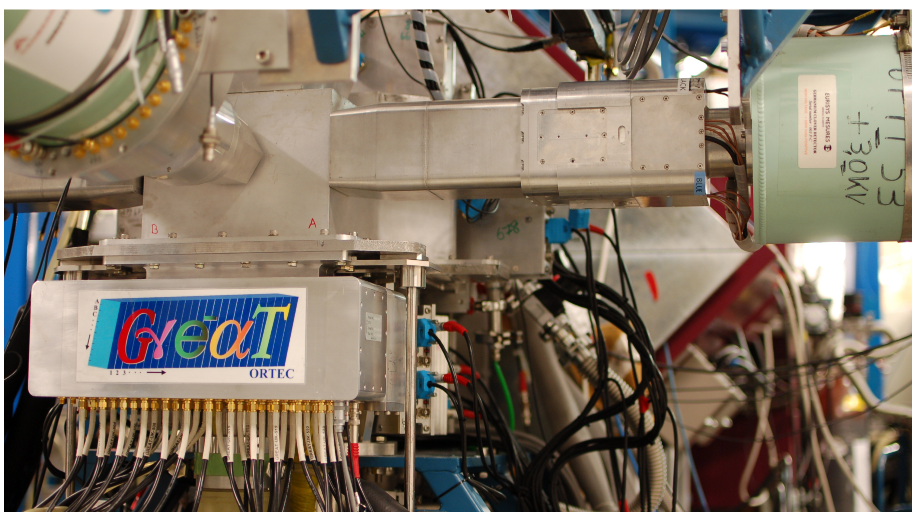


LISA

Ideas for the detector setup: the focal plane

Following detectors would be useful:

- Transmission detector at the FP:
  - SED or MWPC
  - position sensitive → m/q
  - good timing resolution
- Implantation detector
  - Energy, time, position (→ angle together with transmission det.)
  - Two DSSDs parallel
- Box detector for electrons/charged particles



GREAT spectrometer at the focal plane of RITU

- Germanium detectors for detecting isomers and prompt gammas after particle decay
- Scintillator for recoil-beta tagging
- Ion chamber for Z identification
- Double-ToF system including degrader foil and a second transmission detector

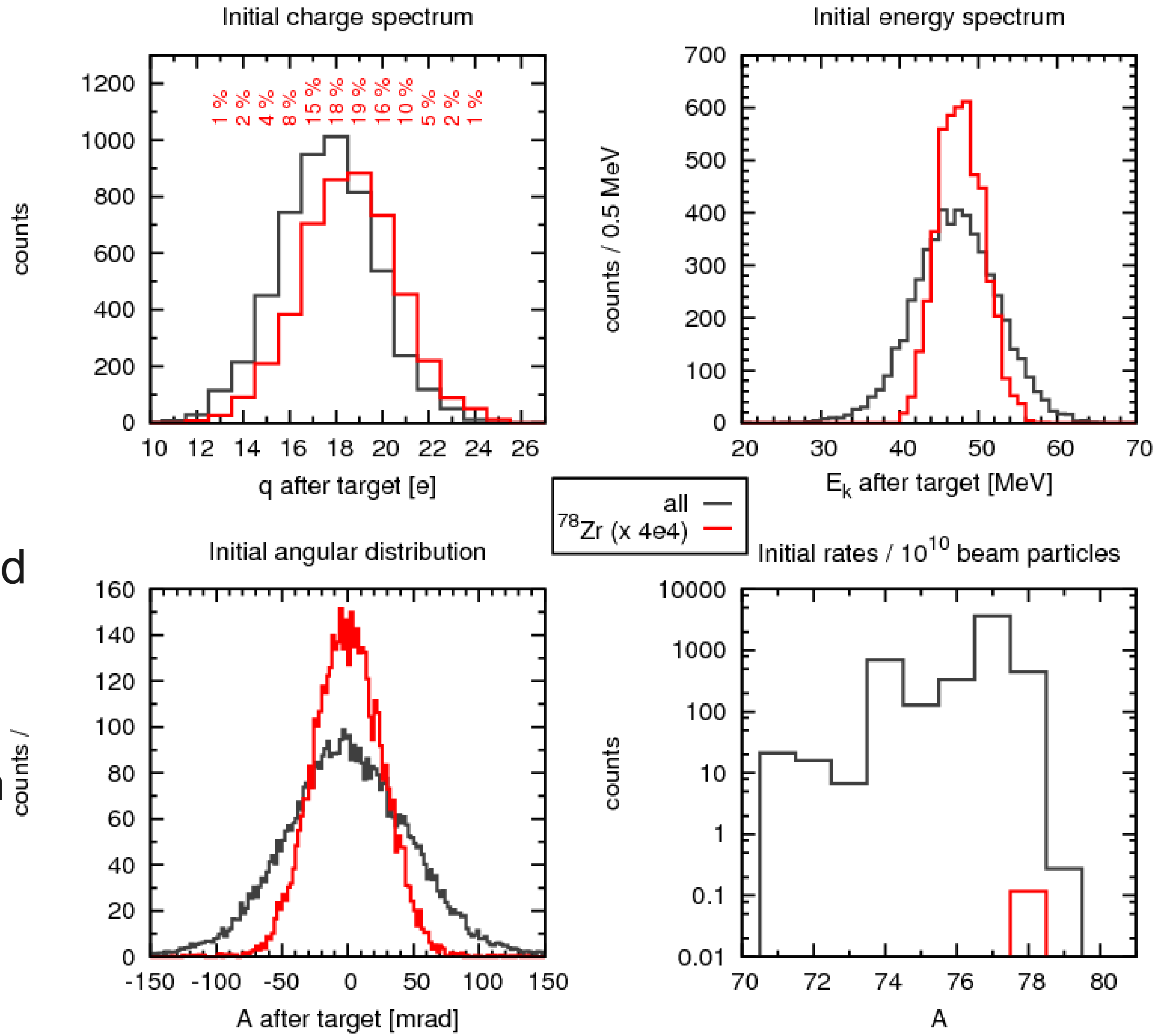
Simulation of a fusion evaporation reaction and MARA

The following scheme has been used in fusion evaporation reaction simulations:

1) Generating a primary beam particle
2) Slowing down the primary beam particle to the sampled reaction postion using TRIM code or some distribution
3) Evaporating light particles independently and isotropically in CM frame using the kinetic energy distribution given by PACE4 code. The weight of the product is calculated from beam intensity, total number of events, target thickness, cross section and position weight
4) Slowing down the product out from the target (TRIM or a suitable distribution)
5) Using transfer matrices from GICOSY code to transfer over optical elements. Between elements the apertures and slits are evaluated.
6) Analysing results

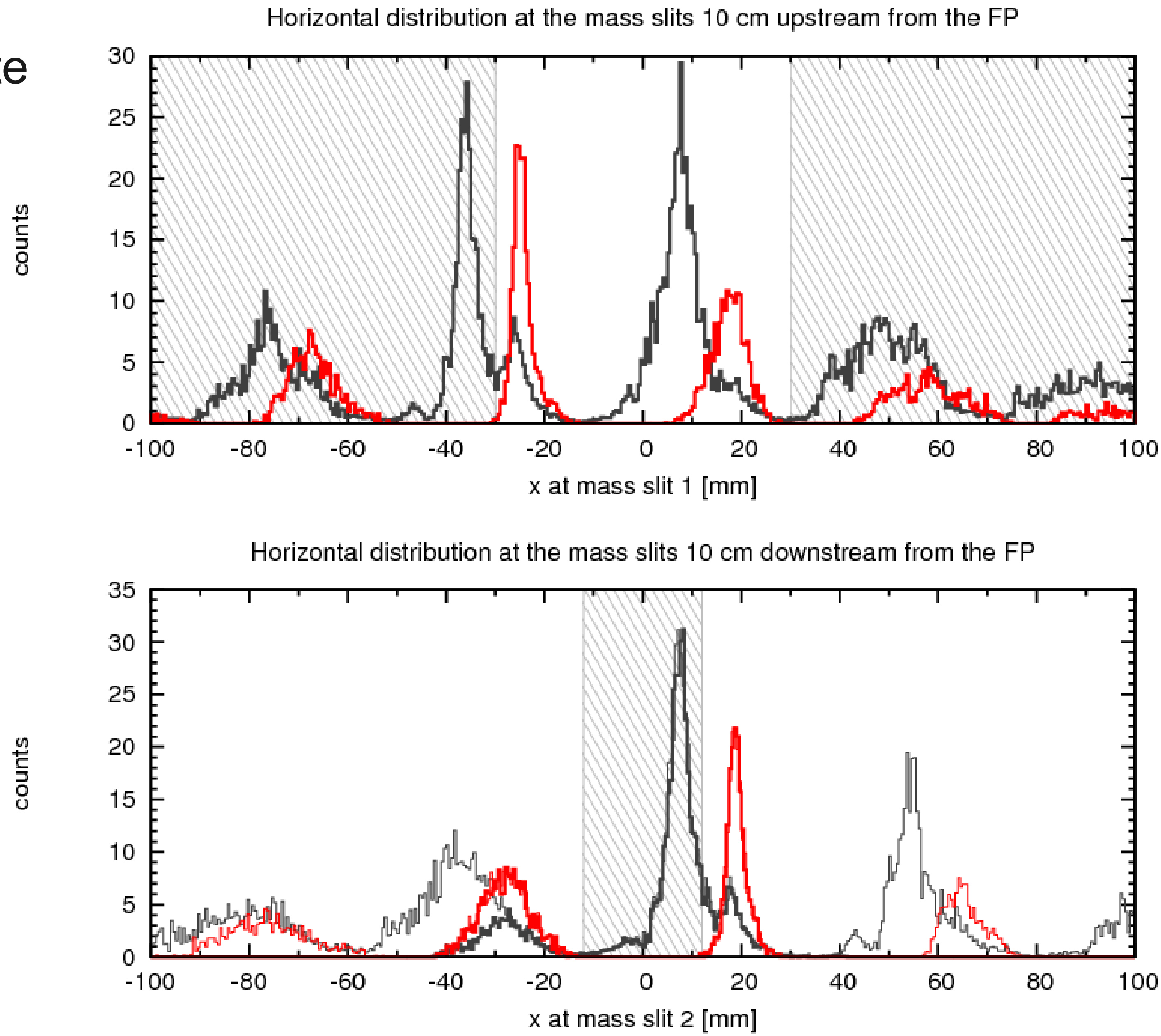
Example reaction: $^{40}Ca+^{40}Ca \rightarrow ^{78}Zr+2n$

- Symmetric reaction
- target 300 μg/cm²
- Beam energy 117 MeV
- Cross sections from PACE4
- almost 40% of products in two most abundant charge states
- pure neutron channel has narrower energy and angle distribution
- other channels produce around 6 orders of magnitudes more fusion products in total



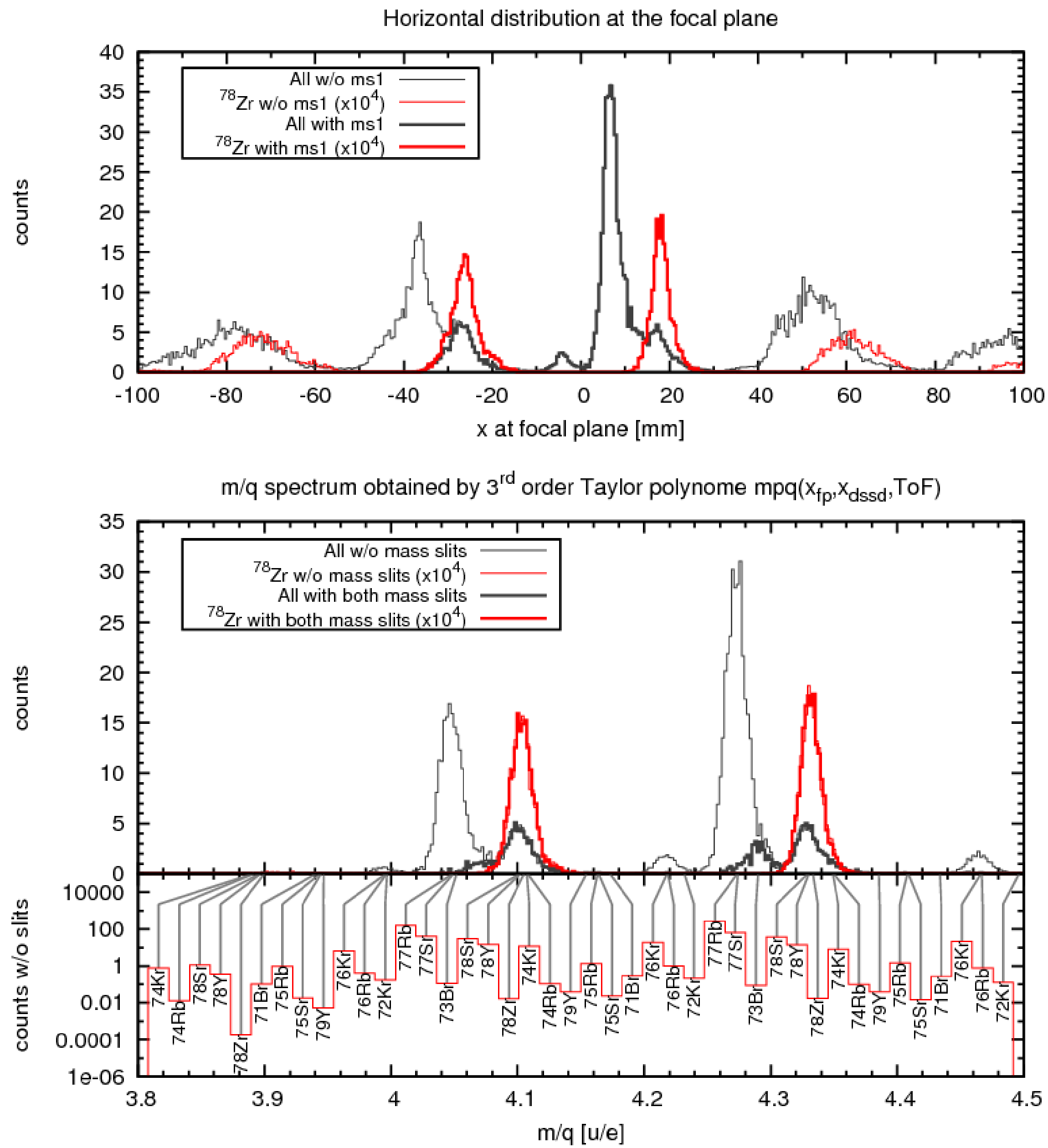
Example reaction: $^{40}Ca+^{40}Ca\rightarrow^{78}Zr+2n$

- Most of the counting rate can be cut by one aperture (10 cm before the FP) and one barrier (10 cm after the FP)
- Products (RED) has been multiplied by 10^4.



Example reaction: $^{40}Ca + ^{40}Ca \rightarrow ^{78}Zr + 2n$

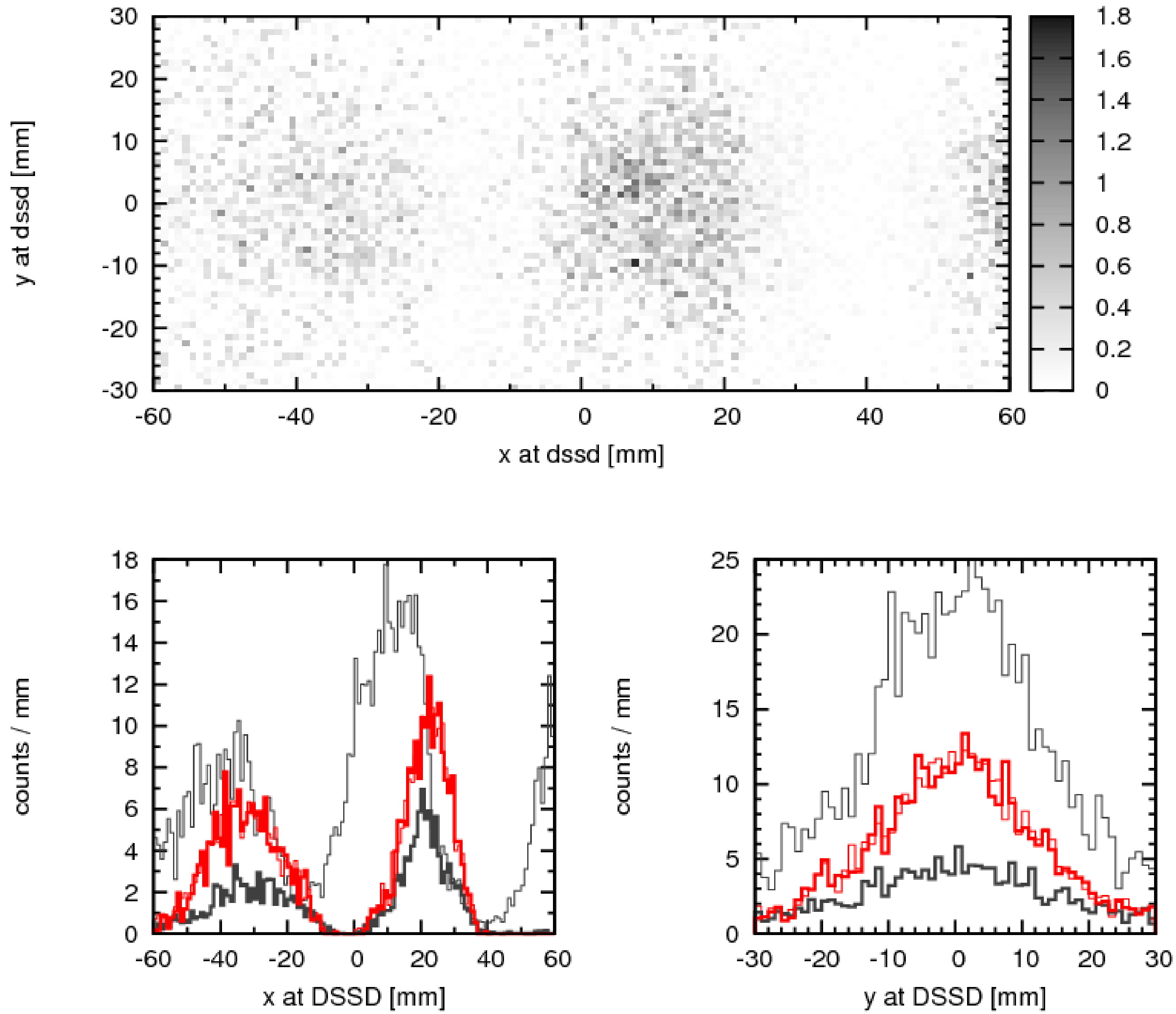
- m/q spectrum calculated from realistic focal plane information (scattering and limited resolution in detectors) (bottom figure)
- The biggest problem is to separate isobars and other peaks which have almost the same m/q ratio
- The double-ToF method has been simulated for this reaction (not shown) and seems to work for ^{78}Zr but requires relatively thick degrader and larger stop detector



Example reaction: $^{40}Ca+^{40}Ca \rightarrow ^{78}Zr+2n$

Spatial distribution at the implantation detector 40 cm after the FP.

The minimum implantation detector size is 10x4 cm^2.



Summary and outlook

- The simulations show that MARA project is promising and there are some possibilities for improvements if needed.
- Lot of work and design are to be done
  - vacuum system: pumps, valves and chambers
  - apertures and slits
  - control system for slits and apertures and also for vacuum, magnets and deflector HV
- The electrostatic deflector of MARA recoil-mass separator is now funded and the commissioning of MARA should take place spring 2013.
- MARA opens the door to the studies of N~Z nuclei at JYFL. Some experiments have been carried out around and below the neutron deficient tin region using RITU and it is clear that these experiments would have benefited from MARA.
- MARA and RITU are complementary to each other.