Optica Iónica & Espectrómetros

1era Clase: 21/01/2025, 09:30 - 10:30
Definiciones; Formalismo; Principales elementos de óptica iónica

2da Clase: 28/01/2025, 09:30 - 10:30
Higher Orders ; Ejemplos

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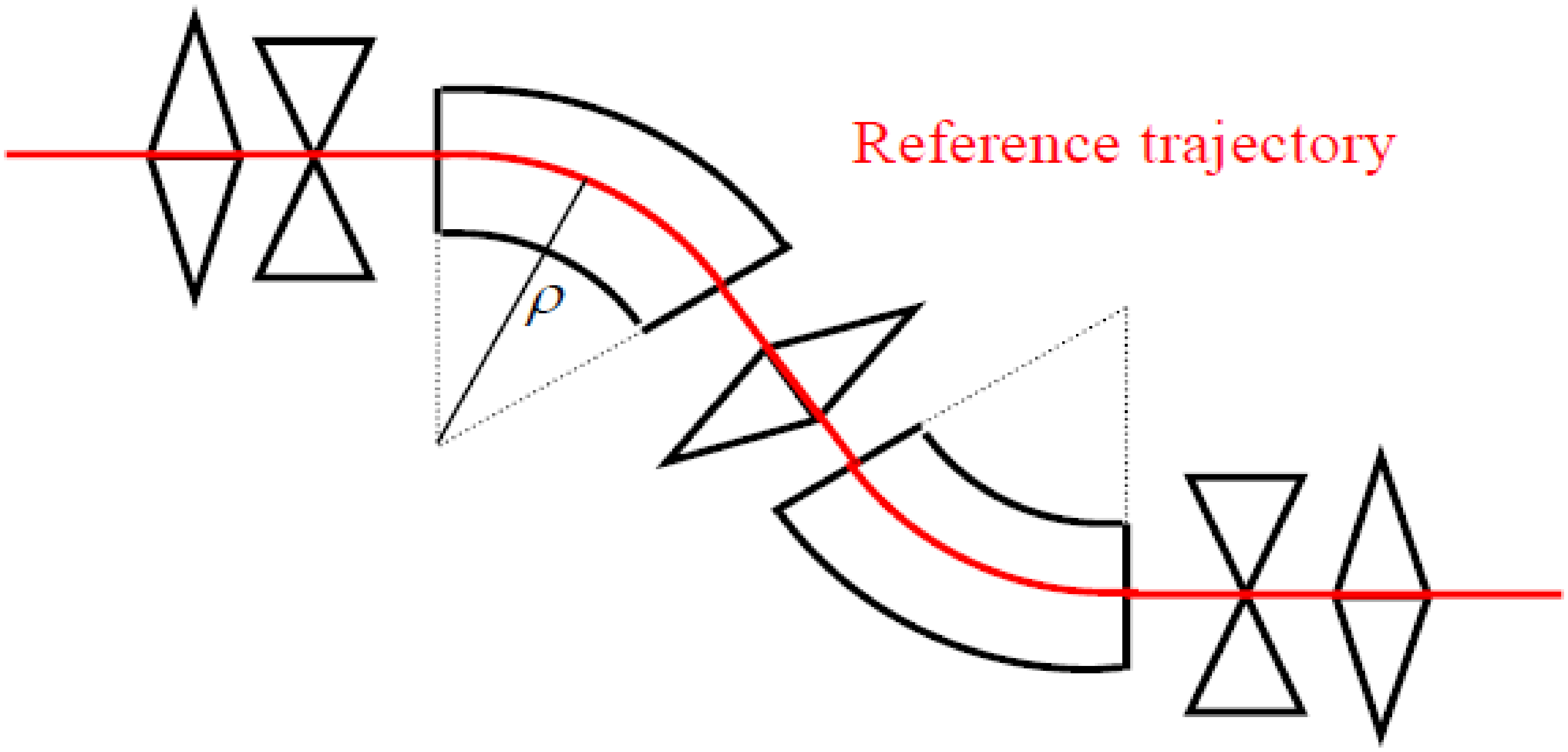
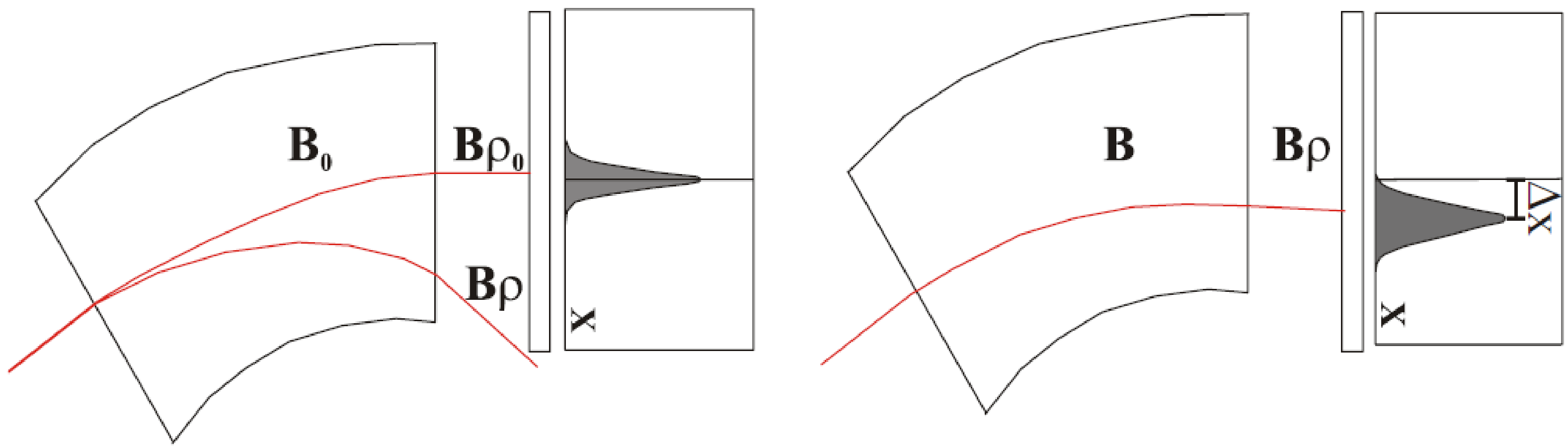
Ion optics



What we learned yesterday?



For a beam ellipse

Resolving power (95%) $= \dfrac{(x|\delta)}{\Delta x\ (2.45\ \sigma)}$

Why it works?

Thanks to the Lorentz force F and Newton's second law

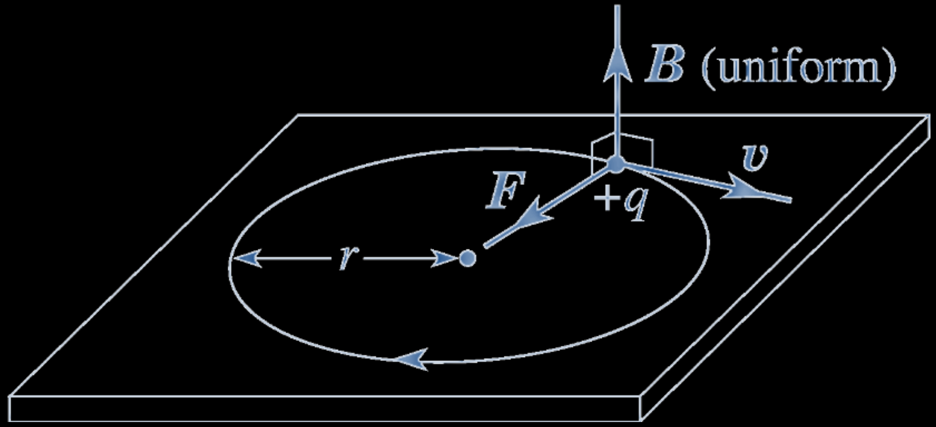
1. Lorentz force: A charged particle moving in an electromagnetic field experiences a force.

$$\frac{d\boldsymbol{p}}{dt} = \boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Electic Force Magnetic Force

This force causes a centripetal acceleration and consequently a circular motion of the particle in the medium based on the equations described below.

2. **Newton's second law**



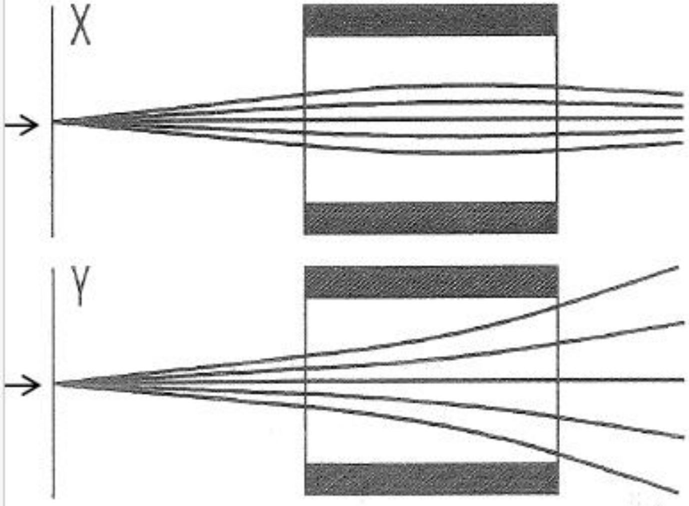
$$\boldsymbol{F} = m\,\boldsymbol{a}$$

$$F_{centripetal} = \frac{mv^2}{r}$$

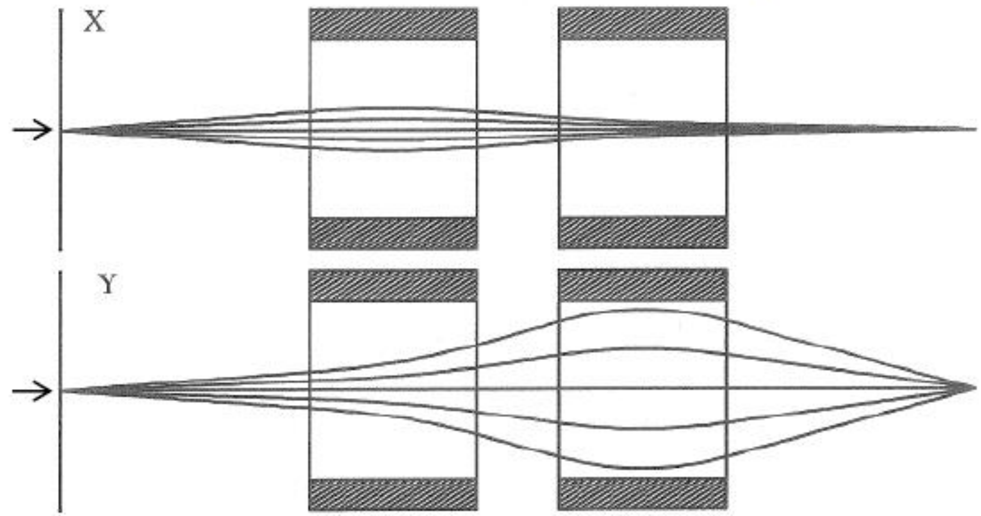
Radius r → ρ

Focusing Elements

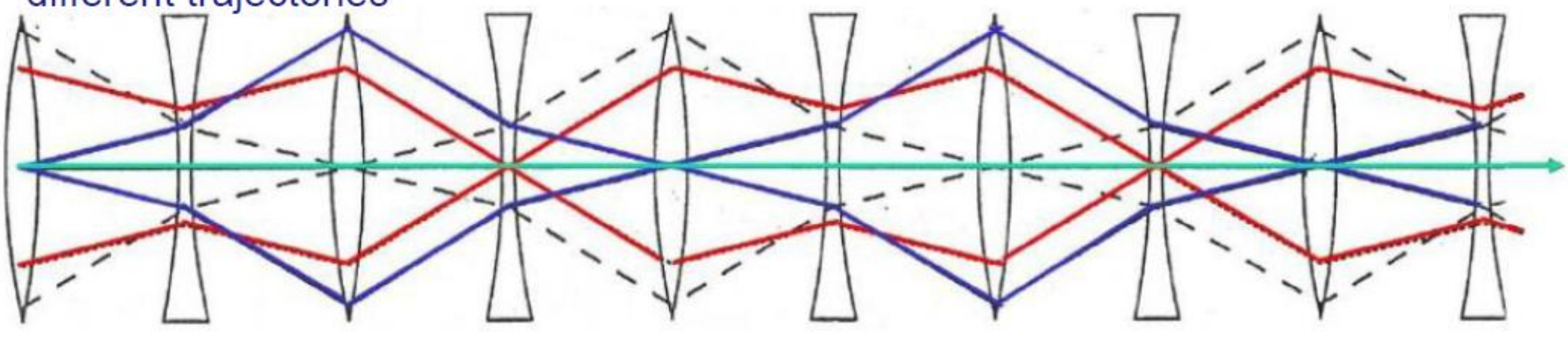
one quadrupole does not solve the problem



many quadrupole magnets combined can focus in x and y



quadrupole channel with different trajectories



Ion optics

Taylor expansion in x, a, y, b and δ

$$x_1 = (x|x)\ x_0 + (x|a)\ a_0 + (x|\delta)\delta + (x|x^2)x_0^2 + (x|xa)\ x_0 a_0 + (x|a^2)a_0^2$$

$$(x|x\delta)\ x_0 + (x|a\delta)\ a_0\delta + (x|\delta^2)\delta^2 + (x|y^2)y_0^2 + (x|yb)\ y_0 b_0 + (x|b^2)b_0^2$$ + higher orders

First order

$$(x|\ \ldots) = \frac{\partial}{\partial x}$$

$$Higher\ orders : e.g.\ (x|a^2) = \frac{\partial x}{\partial a \partial a} = T_{122}$$

Transfer matrix formalism

Following Taylor expansion the trajectory component Xi after propagation through an ion optical element can be calculated from

$$X_i = \sum_j Y_j \left\{ (X_i \mid Y_j) + \sum_k \frac{Y_k}{2} \left\{ (X_i \mid Y_j Y_k) + \sum_l \frac{Y_l}{3} \{ (X_i \mid Y_j Y_k Y_l) + \cdots \} \right\} \right\},$$

where Yi are the components of the trajectory before the ion optical element, and (Xi | Yj), (Xi | YjYk), (Xi | YjYkYl), . . . are the first-order, second-order, third-order, . . . transfer coefficients

This can be described as matrix–vector multiplication with :

6×6 matrix in first order
6×6^2 matrix in second order,
6×6^3 matrix in third order, etc.

Transfer matrix formalism

$$\begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix} = \begin{pmatrix} T_{11} & T_{12} & T_{13} & T_{14} & T_{15} & T_{16} \\ T_{21} & T_{22} & T_{23} & T_{24} & T_{25} & T_{26} \\ T_{31} & T_{32} & T_{33} & T_{34} & T_{35} & T_{36} \\ T_{41} & T_{42} & T_{43} & T_{44} & T_{45} & T_{46} \\ T_{51} & T_{52} & T_{53} & T_{54} & T_{55} & T_{56} \\ T_{61} & T_{62} & T_{63} & T_{64} & T_{65} & T_{66} \end{pmatrix} \begin{bmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \\ l_0 \\ \delta_0 \end{bmatrix}$$

$$\mathrm{T} = \begin{pmatrix} (x|x) & (x|a) & (x|y) & (x|b) & (x|l) & (x|\delta) \\ (a|x) & (a|a) & (a|y) & (a|b) & (x|l) & (a|\delta) \\ (y|x) & (y|a) & (y|y) & (y|b) & (x|l) & (y|\delta) \\ (b|x) & (b|a) & (b|y) & (b|b) & (x|l) & (a|\delta) \\ (l|x) & (l|a) & (l|y) & (l|b) & (x|l) & (l|\delta) \\ (\delta|x) & (\delta|a) & (\delta|y) & (\delta|b) & (x|l) & (\delta|\delta) \end{pmatrix}$$

Transfer matrix formalism

Most crucial parameters :

$$
\mathrm{T} = \begin{pmatrix}
(x|x) & (x|a) & (x|y) & (x|b) & (x|l) & (x|\delta) \\
(a|x) & (a|a) & (a|y) & (a|b) & (x|l) & (a|\delta) \\
(y|x) & (y|a) & (y|y) & (y|b) & (x|l) & (y|\delta) \\
(b|x) & (b|a) & (b|y) & (b|b) & (x|l) & (a|\delta) \\
(l|x) & (l|a) & (l|y) & (l|b) & (x|l) & (l|\delta) \\
(\delta|x) & (\delta|a) & (\delta|y) & (\delta|b) & (x|l) & (\delta|\delta)
\end{pmatrix}
$$

$$T_{11} = magnification\ in\ horizontal$$

$$T_{16} = dispersion\ in\ momentun = dispersion\ in\ B\rho$$

$$T_{33} = magnification\ in\ vertical$$

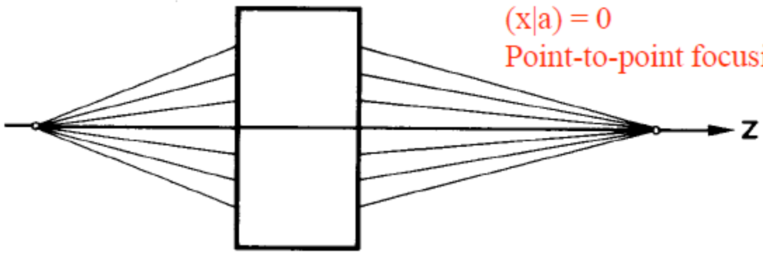
$$T_{12} = angular\ dependance\ in\ horizontal$$

$$T_{34} = angular\ dependance\ in\ vertical$$

Focal points

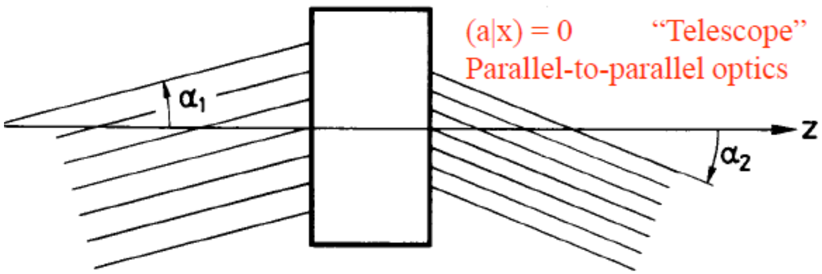
Achromatic system:
T16= T26= 0
(x|δp) = (a|δp)

(x|a) = 0
Point-to-point focusing



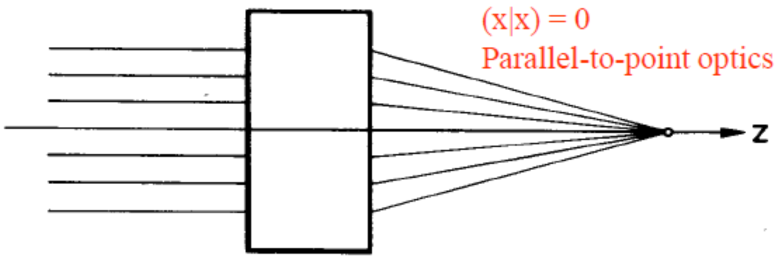
(a)

(a|x) = 0 “Telescope”
Parallel-to-parallel optics



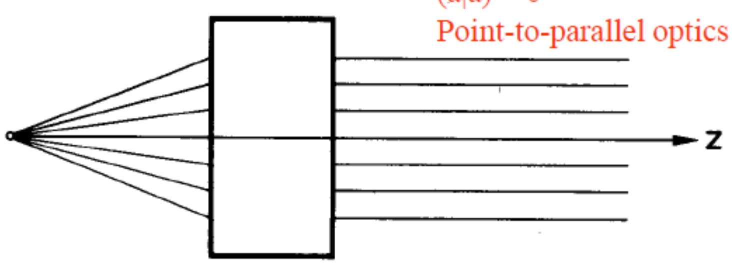
(b)

(x|x) = 0
Parallel-to-point optics

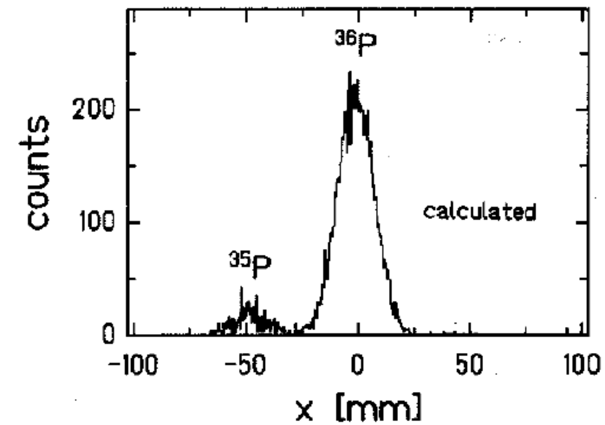


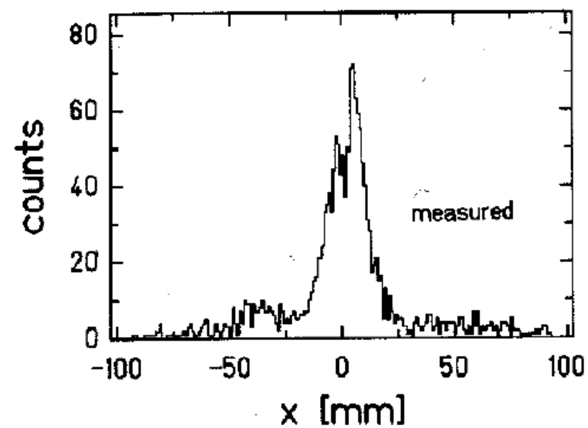
(c)

(a|a) = 0
Point-to-parallel optics

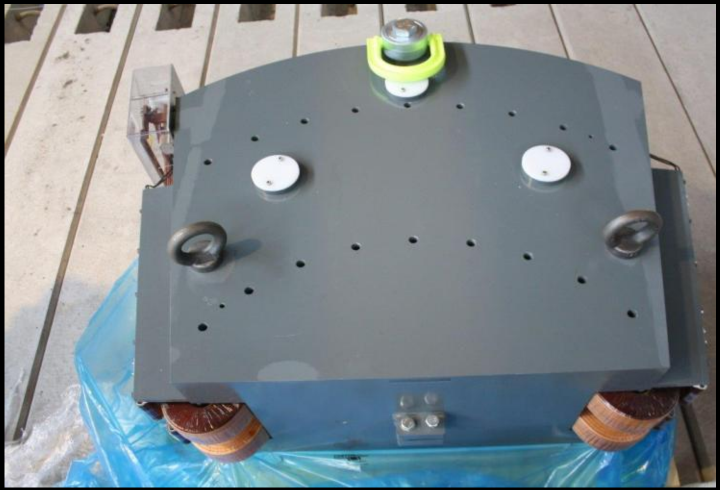


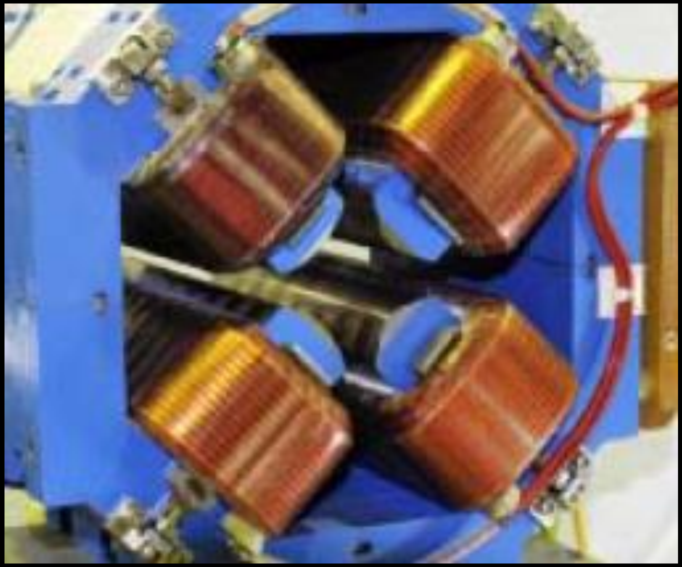
(d)





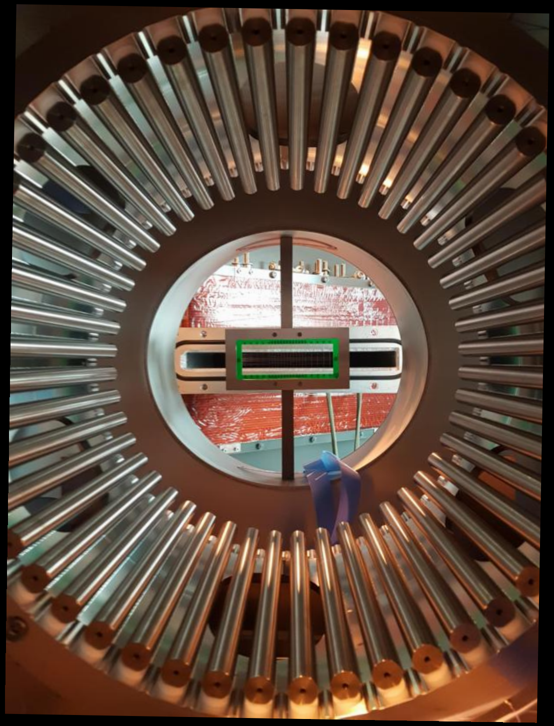
MAGNETIC DIPOLE





M. QUADRUPOLE

M. SEXTUPOLE

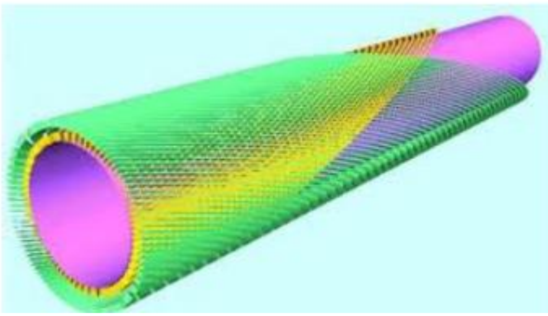


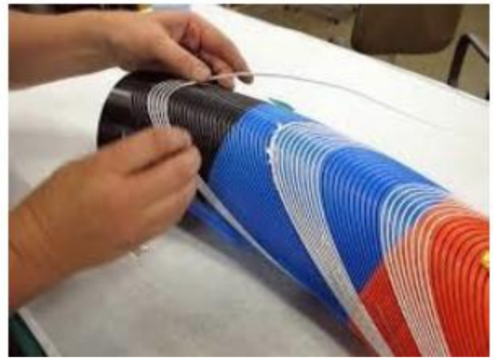
$$\frac{d\boldsymbol{p}}{dt} = \boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Electric
MULTIPOLE

Advanced Magnet Design

- Canted Cosine Theta Design

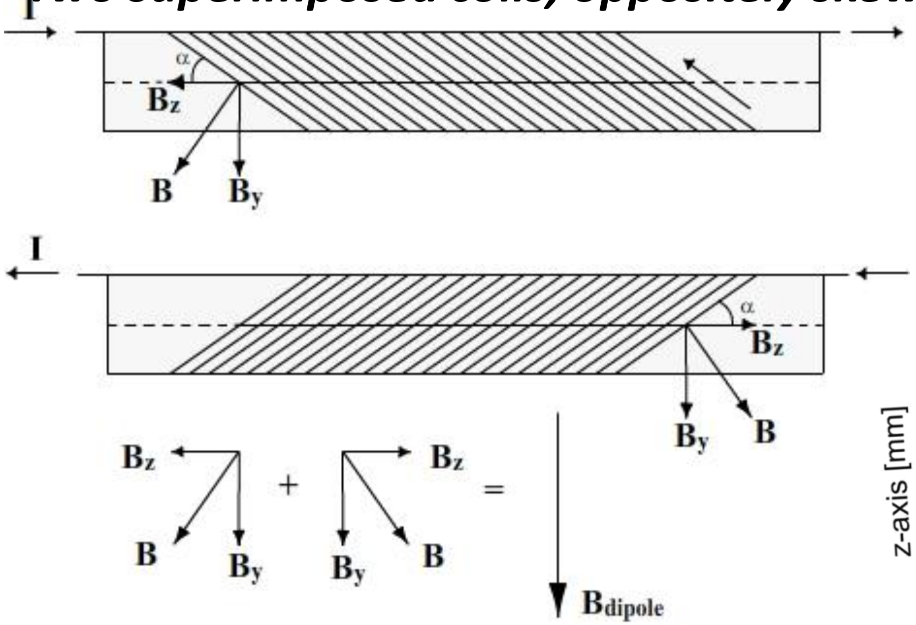




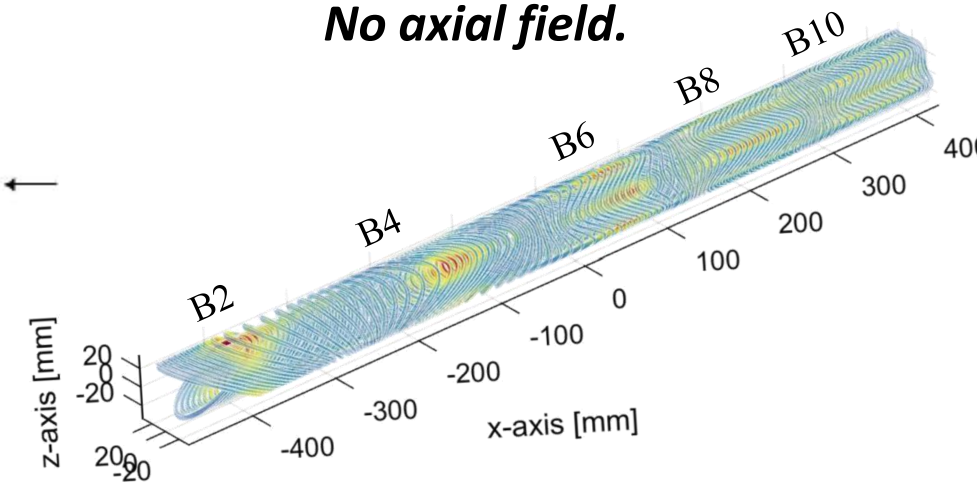
nested arrangement of canted coils can possibly reach fields up to 16-20 T

LBNL

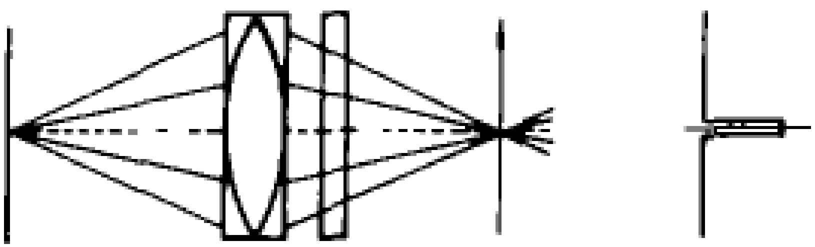
Two superimposed coils, oppositely skewed



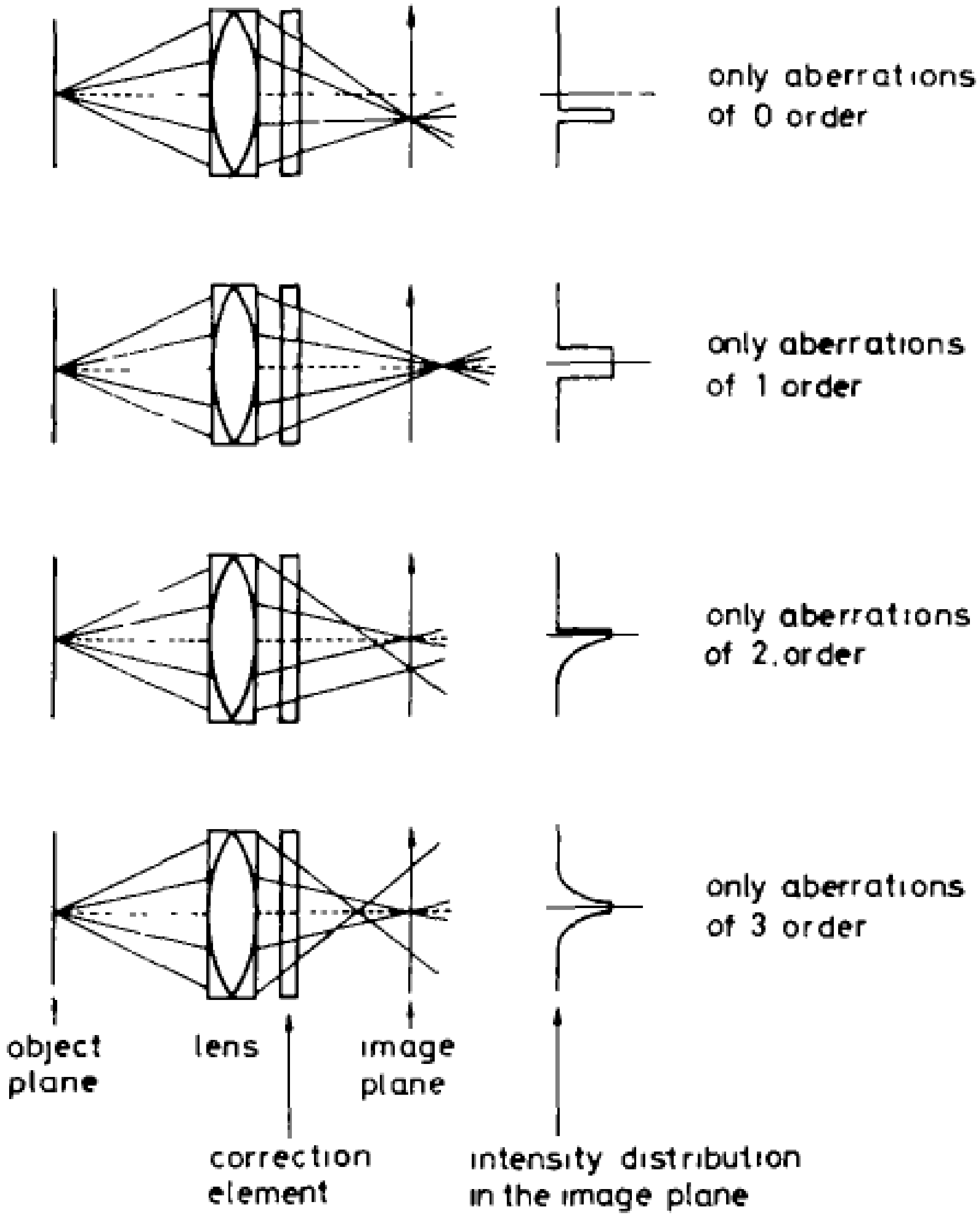
pure cosine-theta field
No axial field.



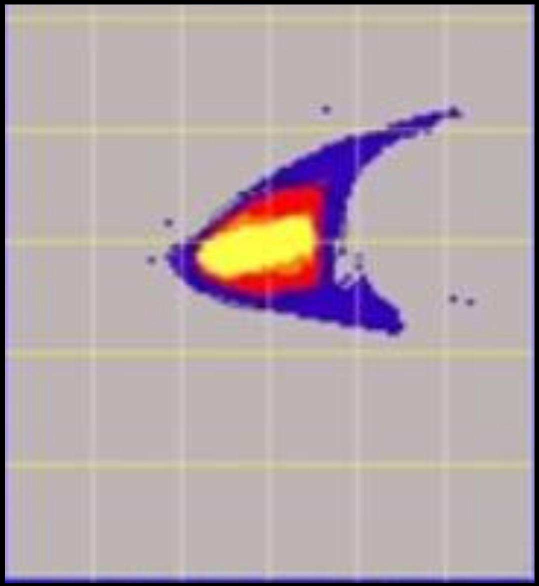
Aberrations and ith order counterpart



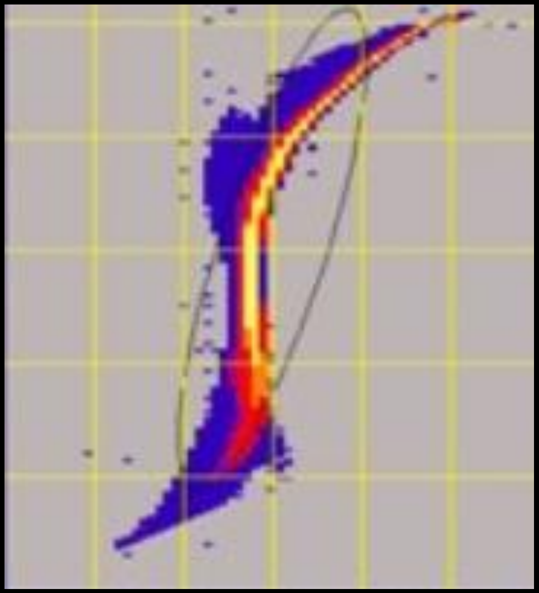
No aberrations



Aberrations and i^{th} order counterpart

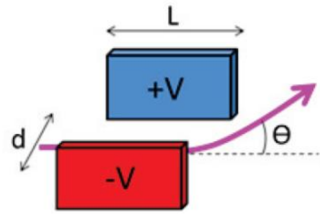


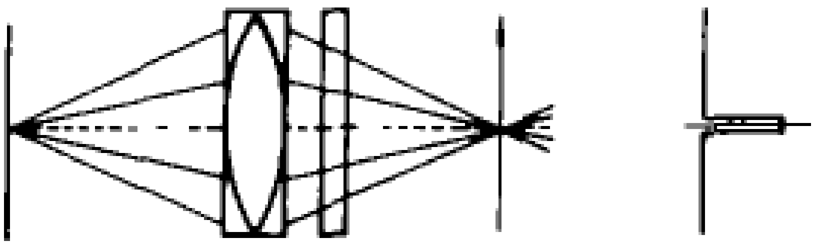
C-shape
2nd order



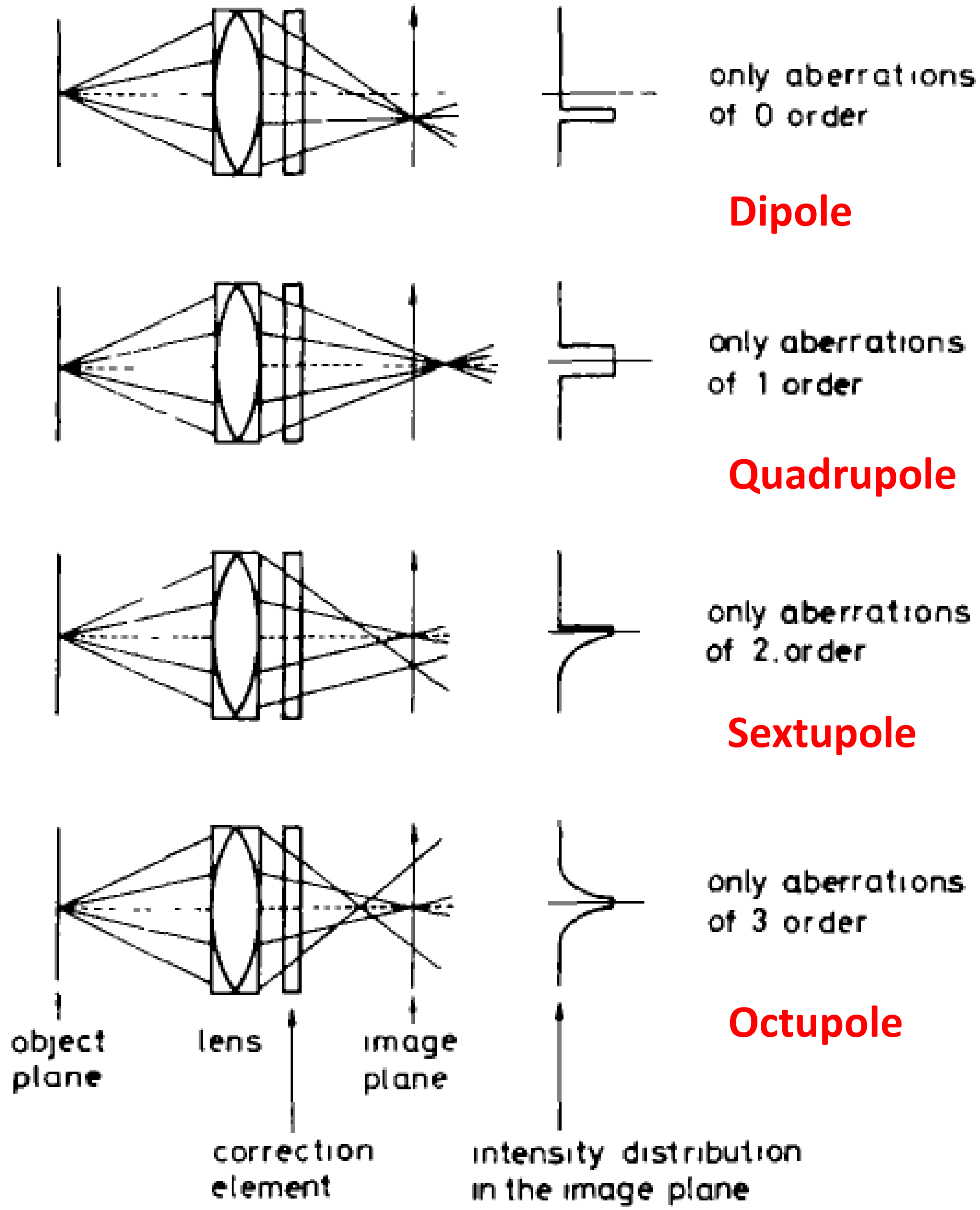
S-shape
3rd order

Aberrations and i^{th} order counterpart





No aberrations

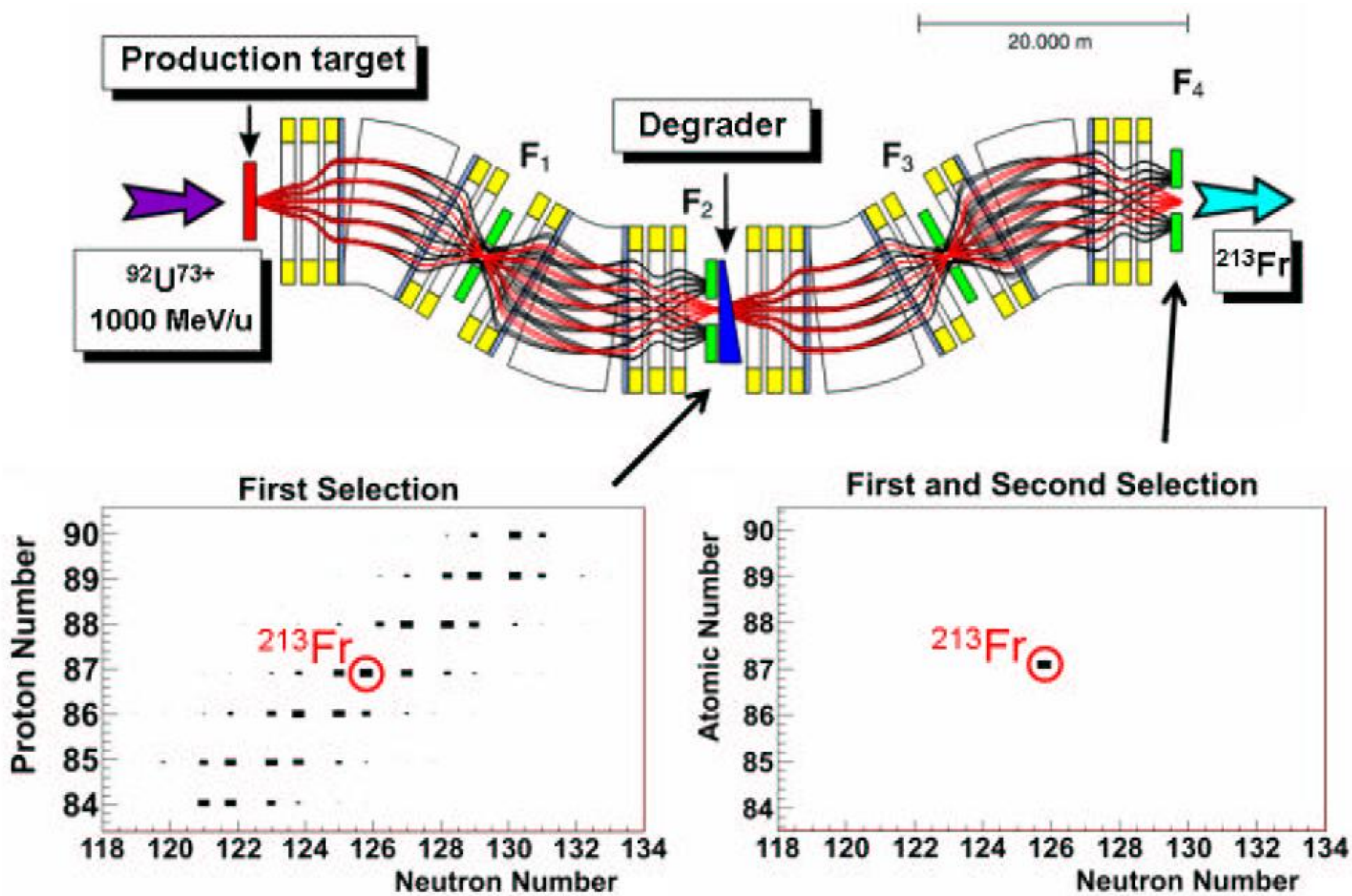


Influence on m-pole elements on the aberrations up to fifth order.

A symbol ◯ indicates that multipole elements can not influence aberrations o the indicated order

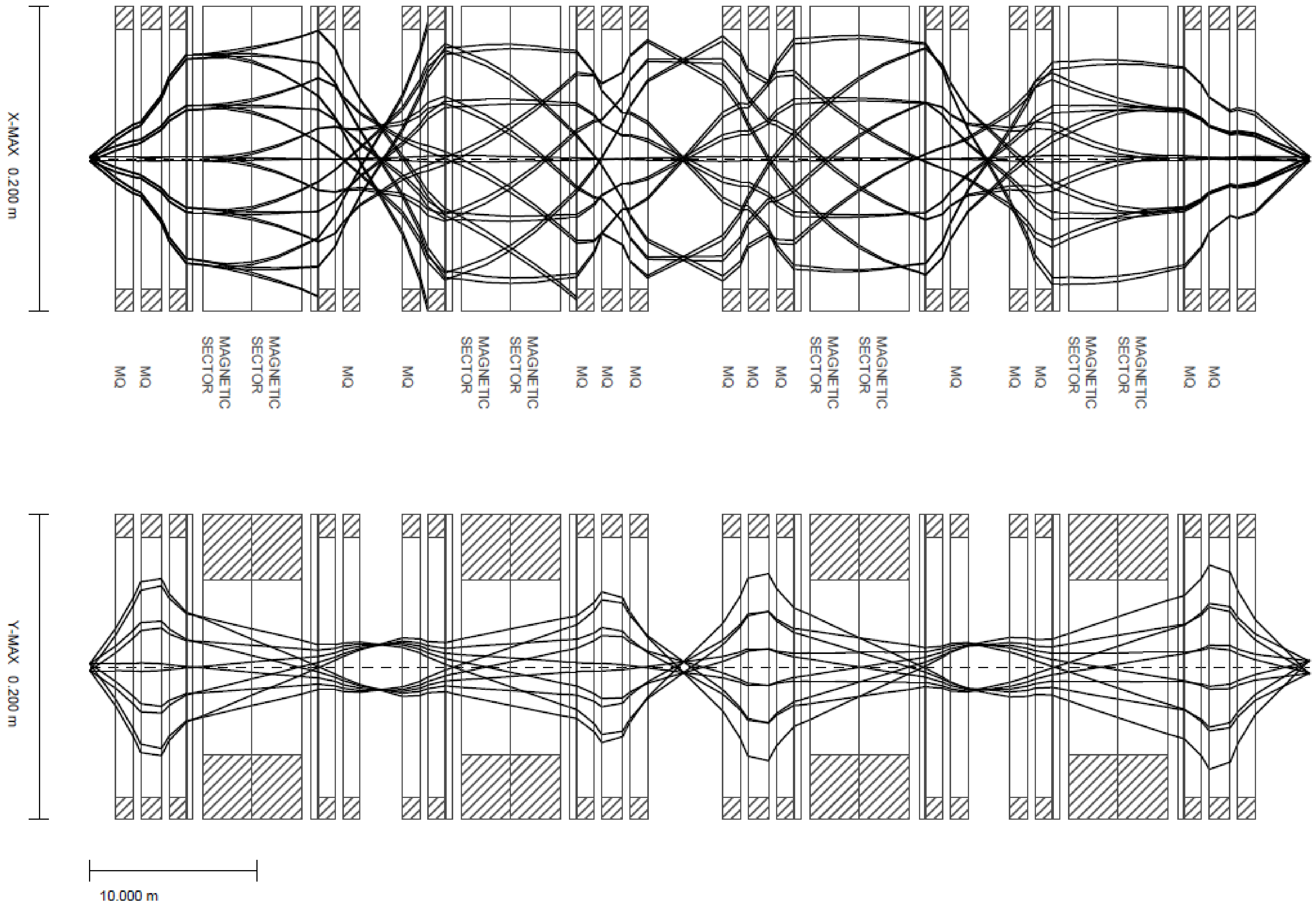
	Zeroth Order	First Order	Second Order	Third Order	Fourth Order	Fifth Order
Dipole	x	x	x	x	x	x
Quadrupole	◯	x	x	x	x	x
Sextupole	◯	◯	x	x	x	x
Octupole	◯	◯	◯	x	x	x
Decapole	◯	◯	◯	◯	x	x
Dodecapole	◯	◯	◯	◯	◯	x

GSI FRAGMENT SEPARATOR FRS



GSI FRAGMENT SEPARATOR FRS

GICOSY



Nuclear Instruments and Methods in Physics Research B70 (1992) 286–297
North-Holland

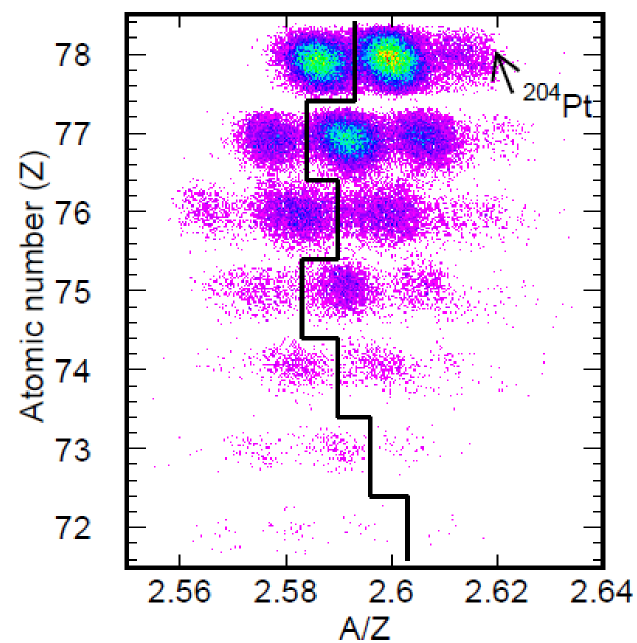
NIM B
Beam Interactions with Materials & Atoms

The GSI projectile fragment separator (FRS): a versatile magnetic system for relativistic heavy ions

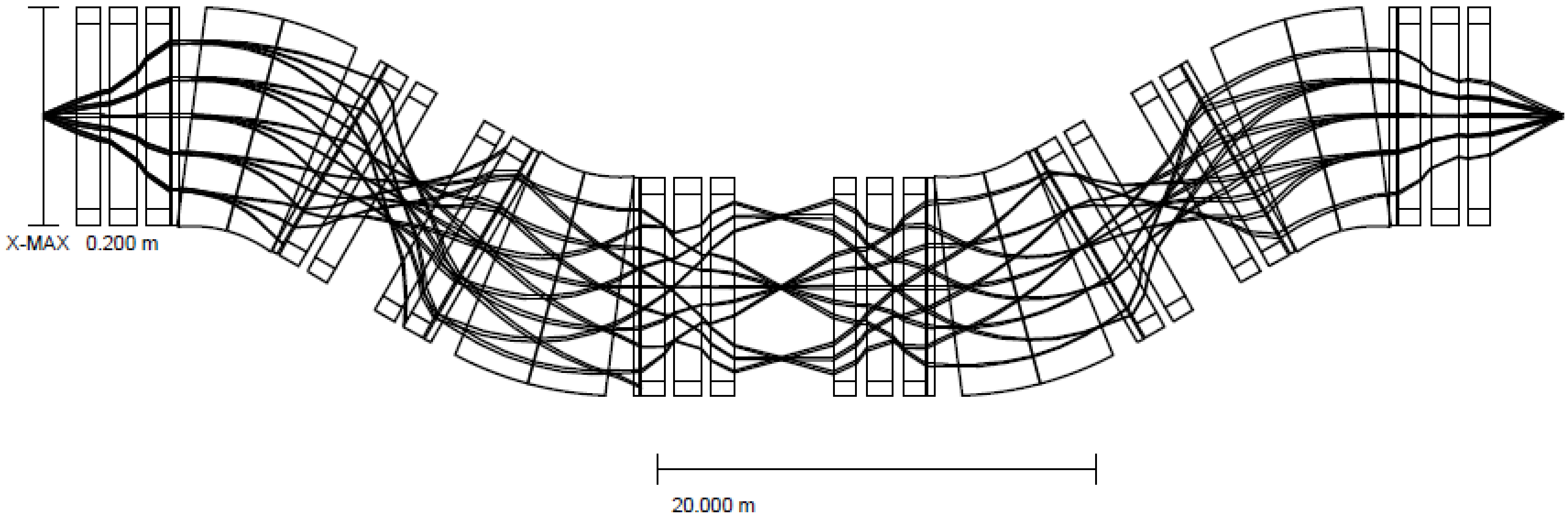
H. Geissel, P. Armbruster, K.H. Behr, A. Brünle, K. Burkard, M. Chen [1], H. Folger, B. Franczak, H. Keller, O. Klepper, B. Langenbeck, F. Nickel, E. Pfeng, M. Pfützner [2], E. Roeckl, K. Rykaczewski [2], I. Schall, D. Schardt, C. Scheidenberger, K.-H. Schmidt, A. Schröter, T. Schwab, K. Sümmerer, M. Weber and G. Münzenberg
Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Germany

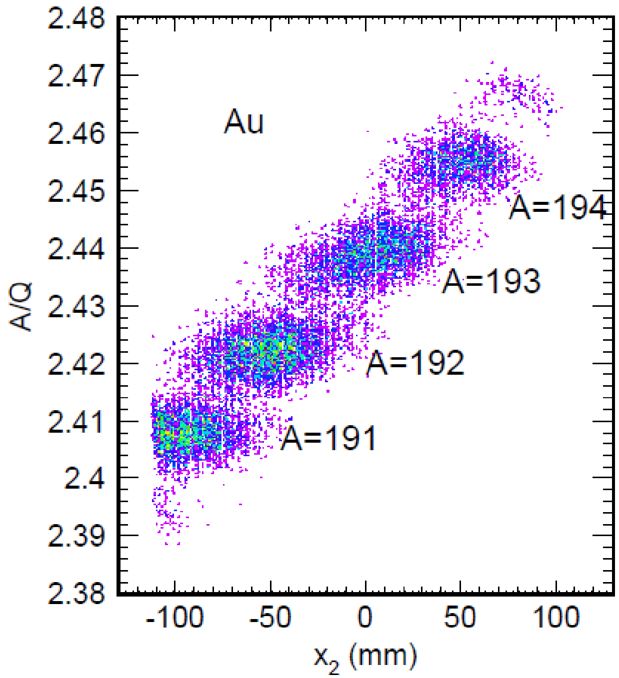
Table 2
Calculated ion-optical matrix elements of the standard high-resolution achromatic mode at the central and final focal planes

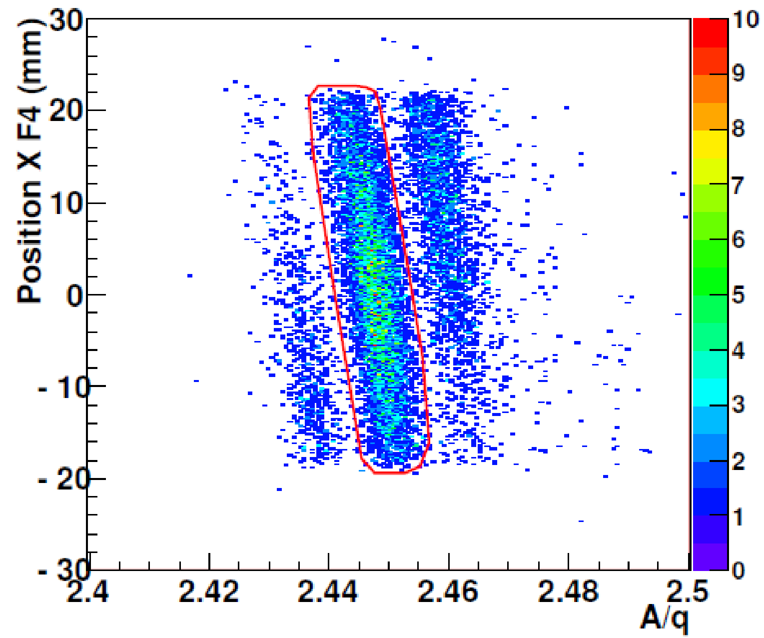
Matrix element	At F_2	At F_4
$(x\|x)$	0.79	1.00
$(x\|x')$ [cm/mrad]	0	0
$(x\|\delta p)$ [cm/%]	−6.81	0
$(x'\|x)$ [mrad/cm]	1.21	1.92
$(x'\|x')$	1.27	1.00
$(x'\|\delta p)$ [mrad/%]	0	0
$(y\|y)$	−1.13	0.83
$(y\|y')$ [cm/mrad]	−0.007	0.011
$(y'\|y)$ [mrad/cm]	12.32	−27.84
$(y'\|y')$	−0.81	0.83



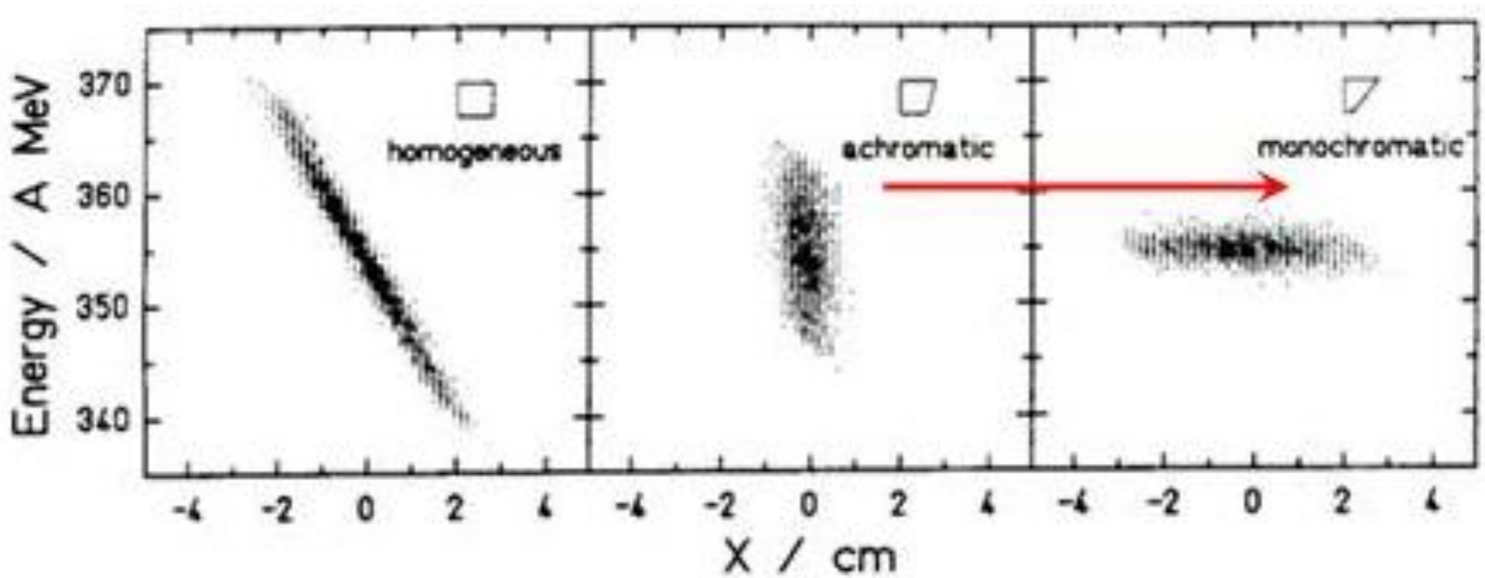
GSI FRAGMENT SEPARATOR FRS

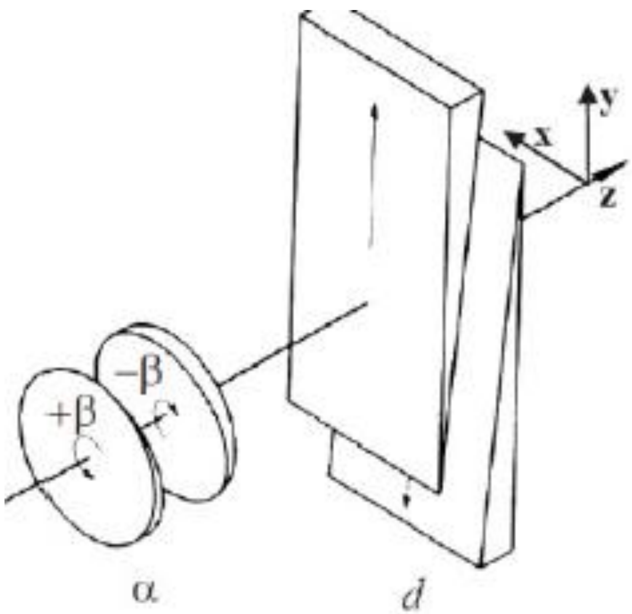




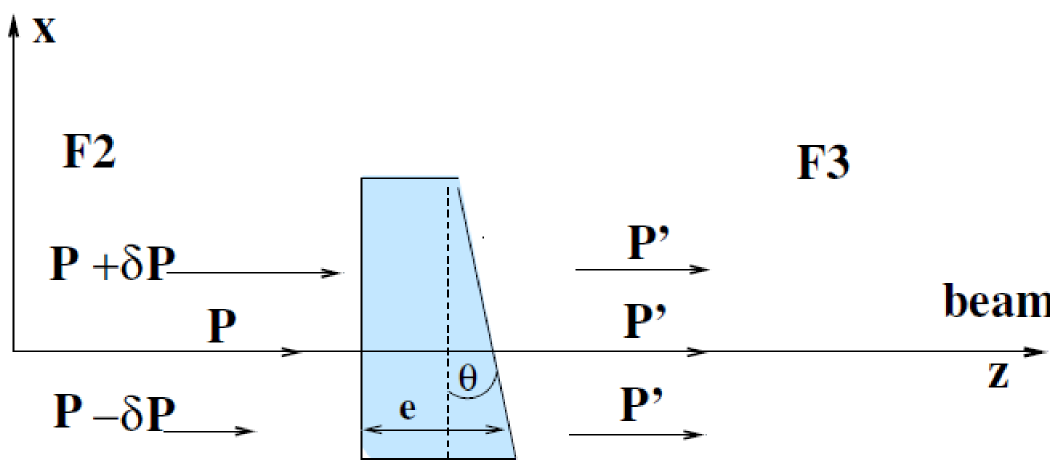


GSI FRAGMENT SEPARATOR FRS degrader

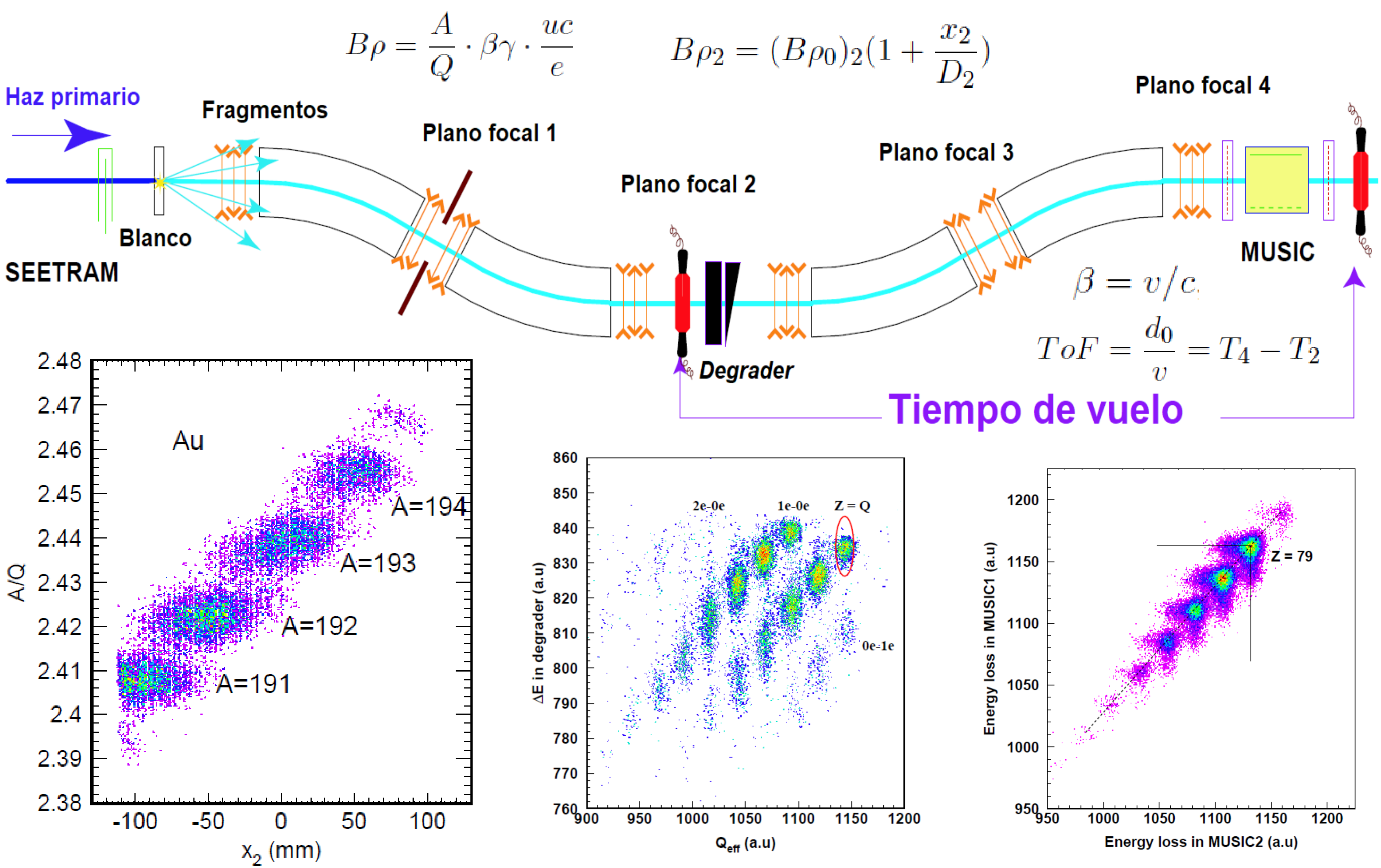




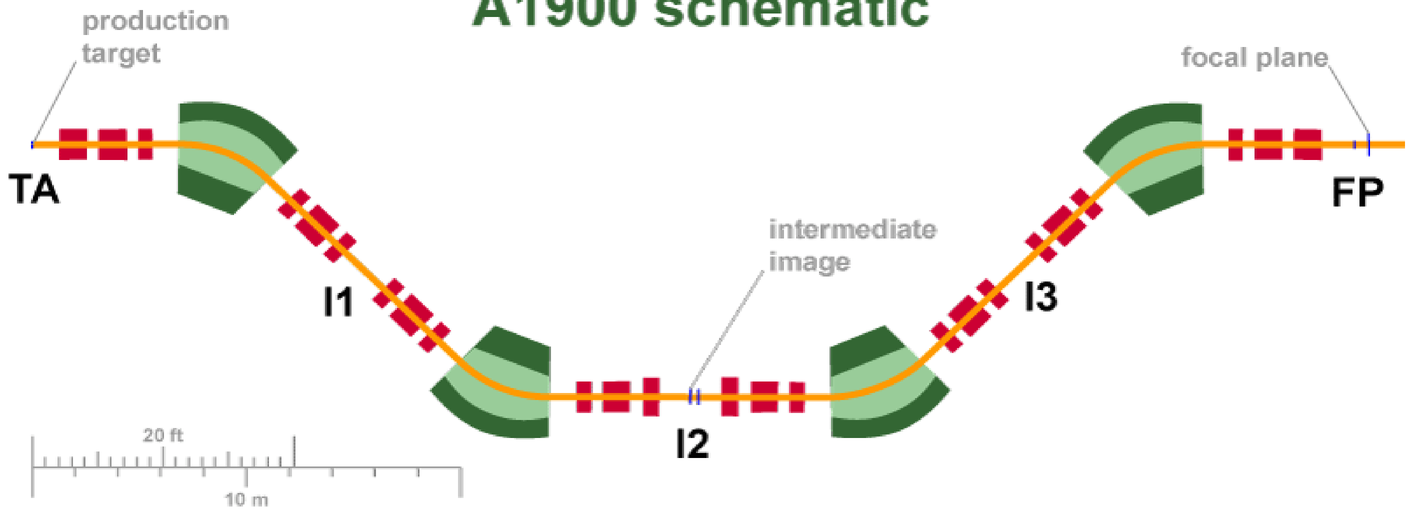
$$\frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_e v^2} Nz \left[\ln \frac{2m_e v^2}{I} - \ln\left(1-\beta^2\right) - \beta^2 \right]$$

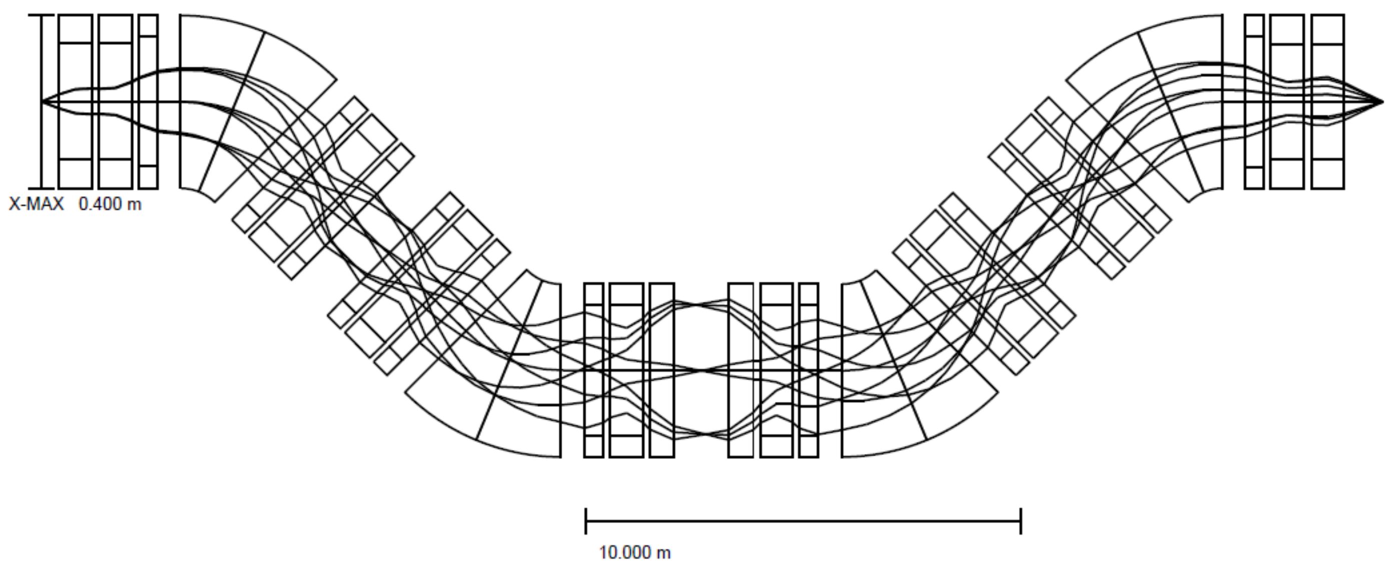


GSI FRAGMENT SEPARATOR FRS

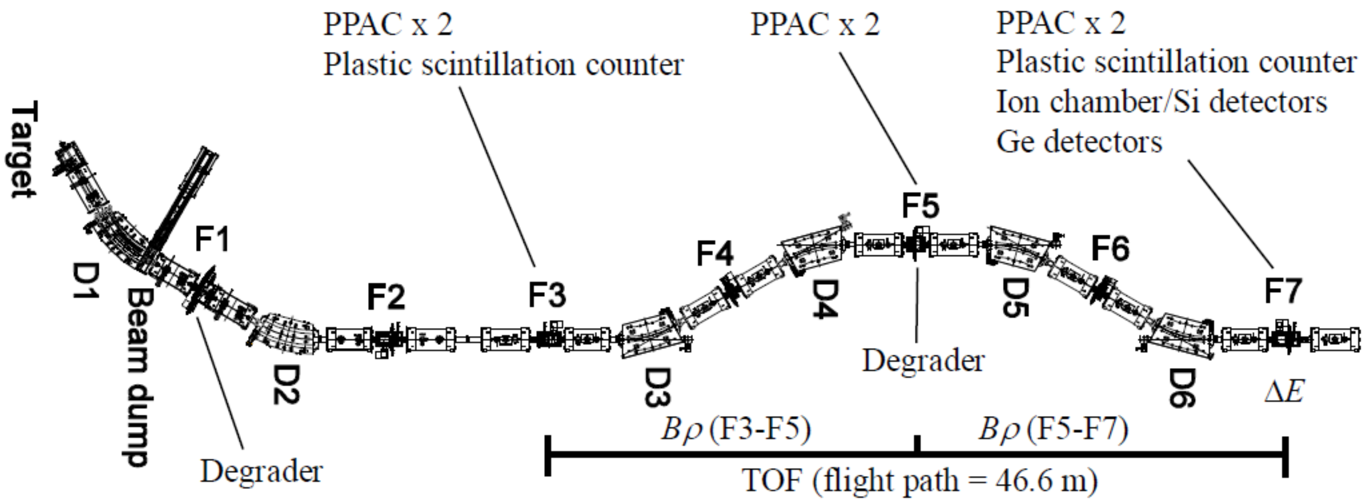


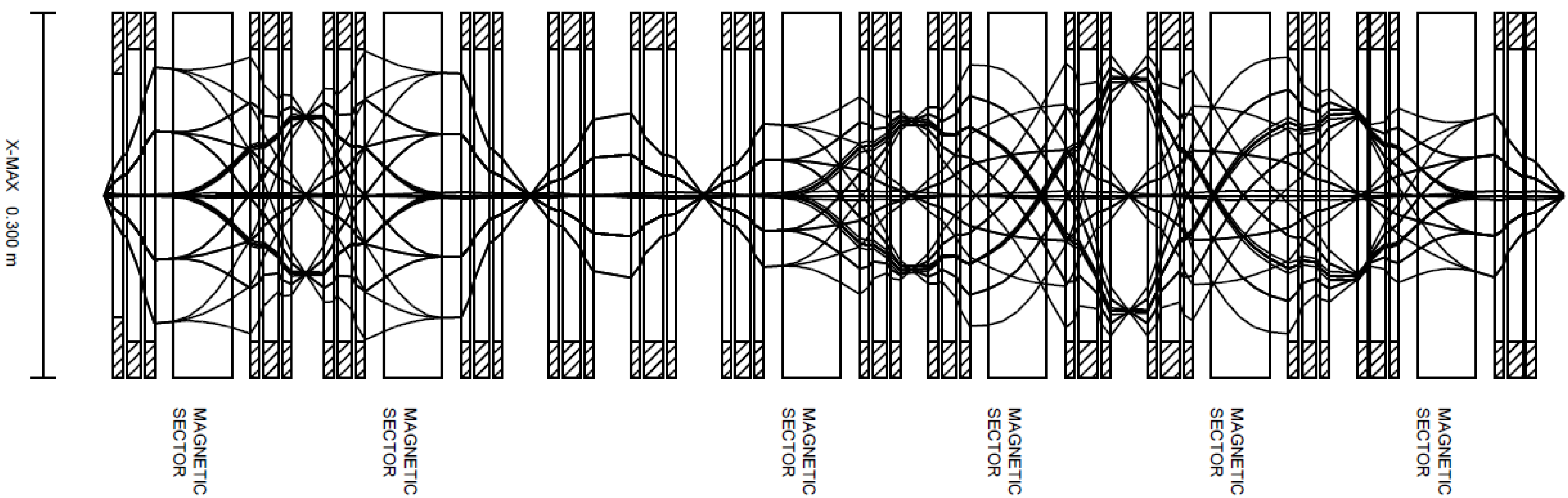
A1900 schematic





BIGRIPS RIKEN

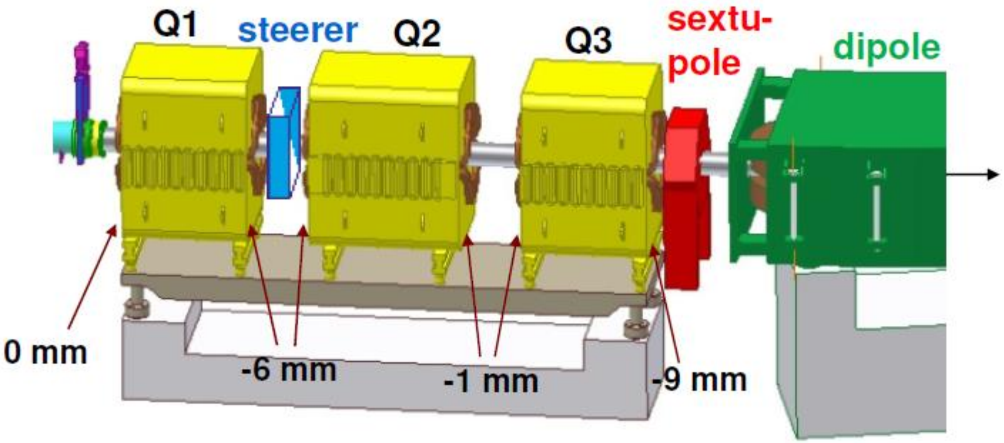




Comparison of Fragment Separators

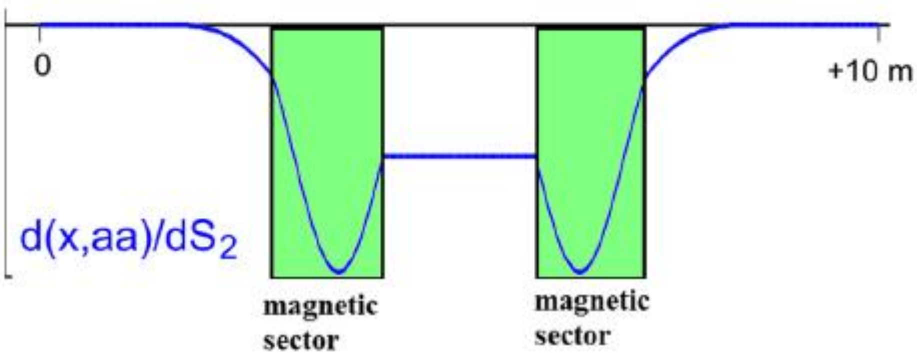
device	Ω (msr)	$\Delta p/p$ (%)	$B\rho$ (T-m)	resolving power†	length (m)	reference
A1200	0.8/4.3	3.0	5.4	700/1500	22.	Sherrill 1992
A1900	8.0	5.4	6.0	~2900	35	Morrissey 2003
COMBAS	6.4	20.	4.5	4360	14.5	Artukh 1993
LISE	1.0	5.0	3.2	800	18.	Mueller 1991
FRS	0.2	2.0	18.	1500	73.	Geissel 1992
super-FRS‡	0.8	5.0	18.	1500	~140	Geissel 2003
RIPS	5.0	6.0	5.76	1500	21.	Kubo 1990
big-RIPS‡	8.0	6.0	9.0	1290/3300	77	Kubo 2003
RCNP	1.1	8.0	3.2	2000	14.8	Shimoda 1992

GSI FRAGMENT SEPARATOR FRS: high-order



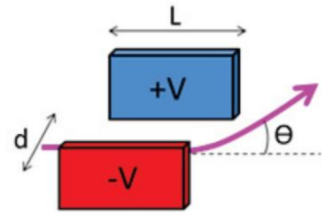
Assume a short sextupole of strength S2 at some point in the system. Then the influence on the 2nd order coefficients can be expressed by the size of the 1st order. The influence of the coupling coefficient (x,aa) is given by (See table p. 108 in SLAC 75) :

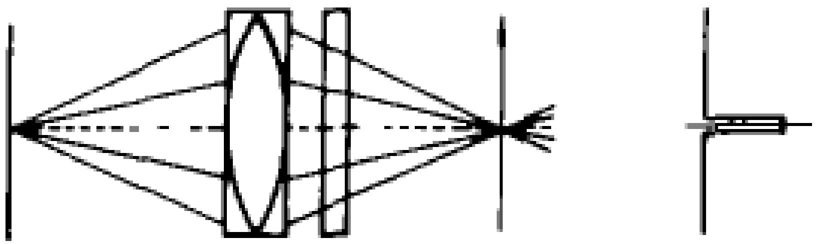
$$d(x,aa)/dS_2 = 2(((x,a)_f(x,x) - (x,x)_f(x,a))\ (x,a)(x,a))$$



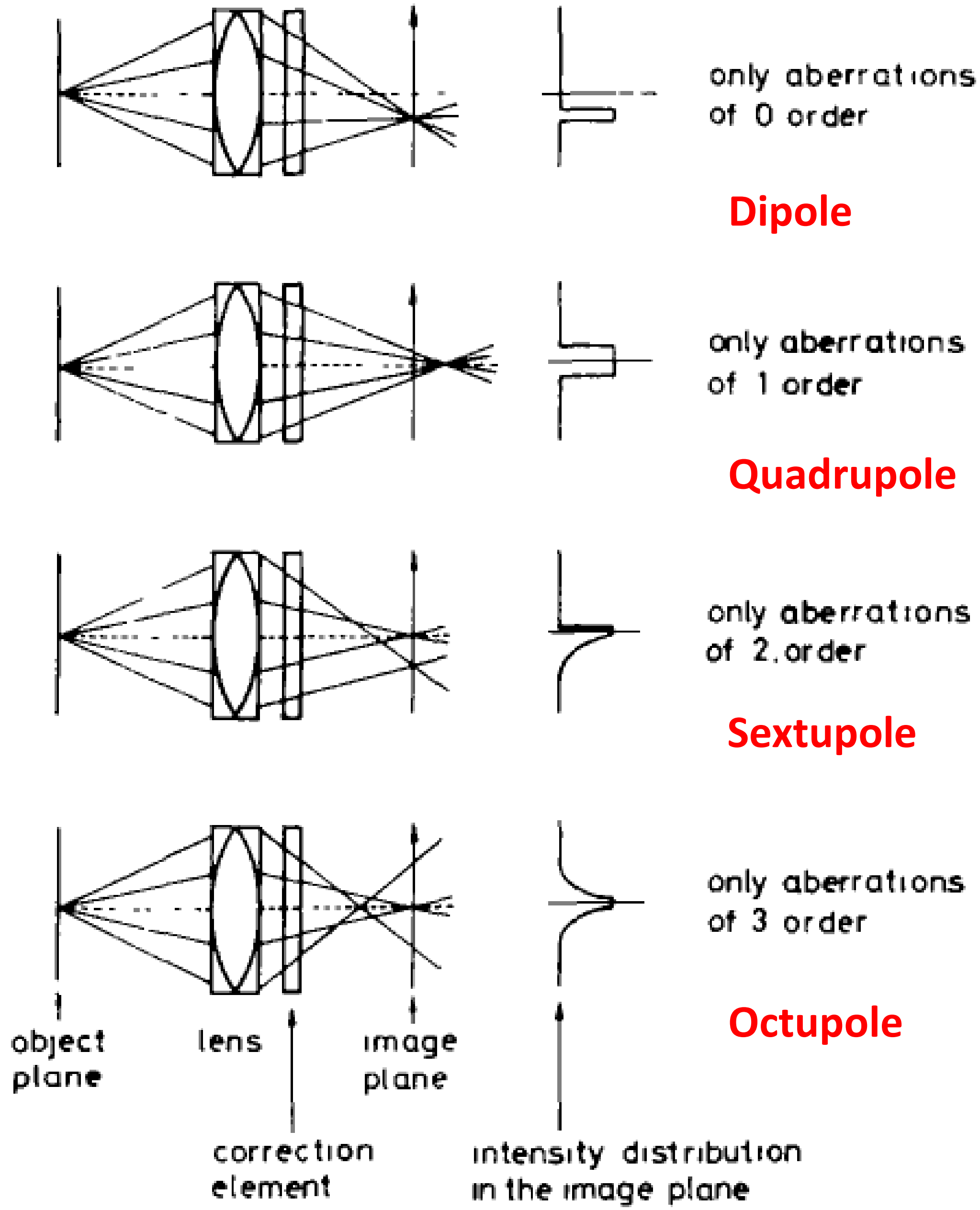
where $(x,a)_f$ and $(x,x)_f$ are taken at the end of the system and the other terms at the position of the sextupole.

Aberrations and ith order counterpart





No aberrations



Influence on m-pole elements on the aberrations up to fifth order.

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Sextupole	◯	◯	x	x	x	x
Octupole	◯	◯	◯	x	x	x
Decapole	◯	◯	◯	◯	x	x
Dodecapole	◯	◯	◯	◯	◯	x

Then End