Dipole spectrometer for LAMPS experiments at RAON

Nuclear
Physics
Laboratory

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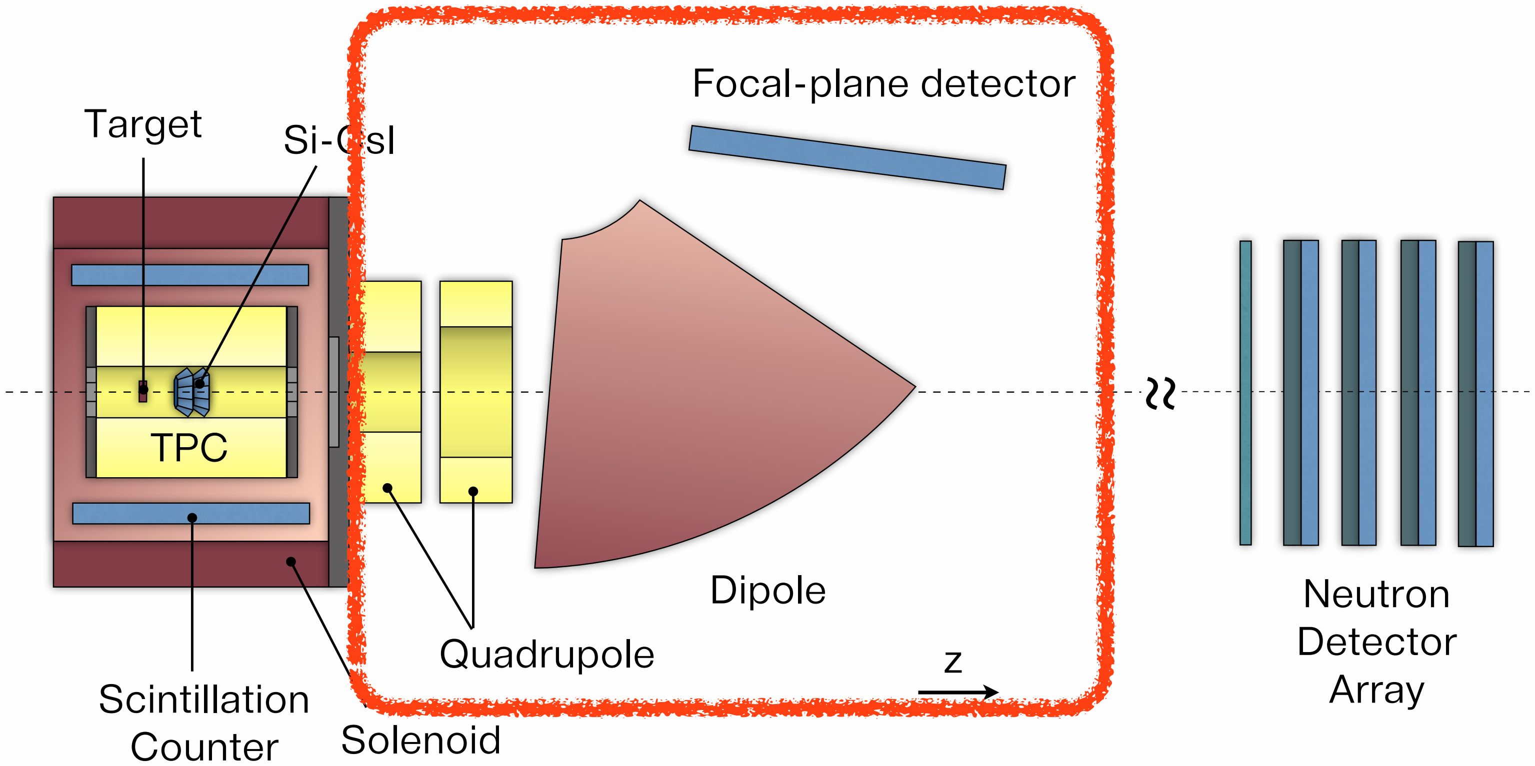
Outline

- **Introduction**
  - Dipole spectrometer
- **Beam Optics**
- **Simulation Results**
  - GICOSY simulation – QQD system, QD system
  - K-trace simulation – QD system
  - Geant4 simulation – QD system with fringe function
- **Summary & Plan**

Introduction

- **Dipole spectrometer for High-Energy LAMPS**



- **Requirement**
  - high momentum resolution ⇔ large acceptance

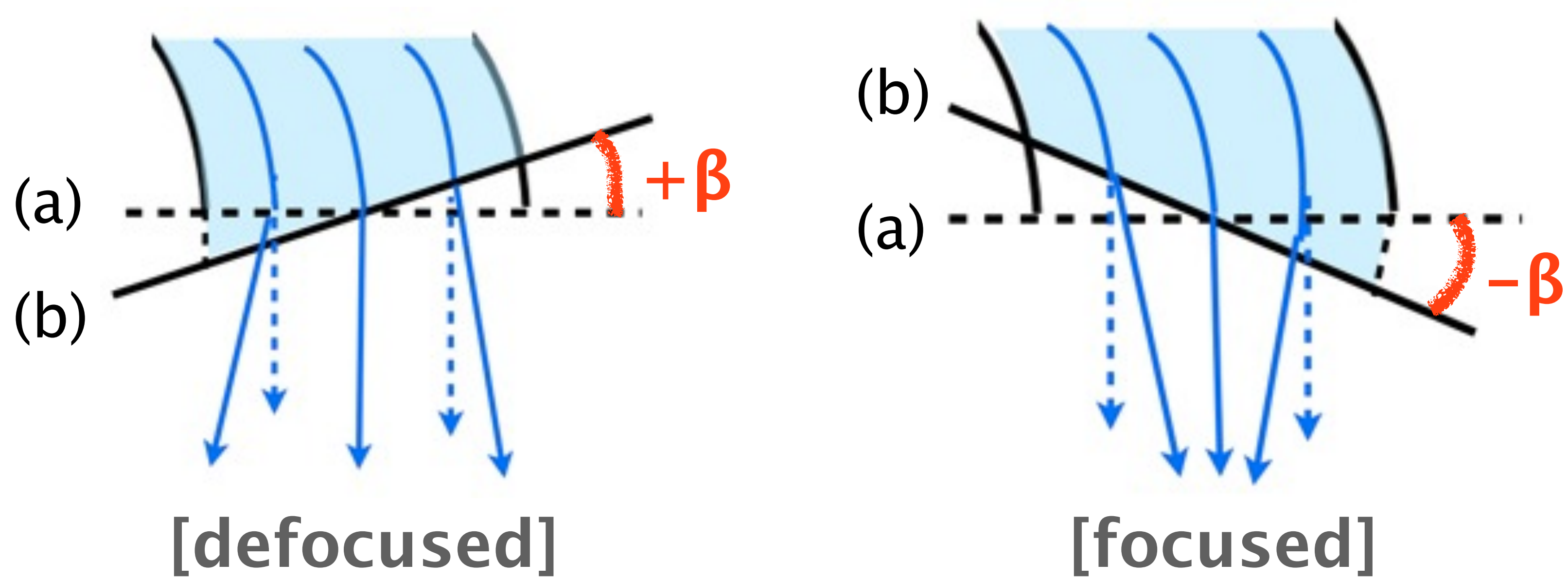
- **Difficulties**
  - Momentum acceptance is inversely proportional to dispersion.
  - Large angular acceptance increases the aberration and deteriorate the momentum resolution.

Introduction

Optimization of focal points.

$$R = \frac{D}{2x_0(x|x)} = \frac{\text{Dispersion}}{\text{Beam image size}}$$

- Different configurations : QD, QQD, etc.
- Various designs and scales : deflection angle, gap diameter, etc.
  e.g.) shim angle β



(a) perpendicular to central trajectory
(b) actual pole face

Simulation Tools

- TRANSPORT, K-trace, and GICOSY for beam optics
- Geant4 for detector simulation

Beam Optics

Matrix approach to calculate beam transport

BEAM
- charged particles
- expressed as a column vector X

$$X = \begin{pmatrix} x \\ x' \\ y \\ y' \\ \ell \\ \delta \end{pmatrix}$$

x : the horizontal beam extent (cm)
x′ : the horizontal beam divergence (mrad)
y : the vertical beam extent (cm)
y′ : the vertical beam divergence (mrad)
ℓ : the longitudinal beam extent (cm)
δ : the momentum spread (%) ΔP/P

ELEMENTS
- Q-magnet, Dipole, drift space, etc.
- expressed as a 6×6 Transfer Matrix R

1st order calculation

$$X(1) = R(Ln)R(Mn)\cdots R(L4)R(M2)R(L3)R(Q2)R(L2)R(M1)R(L1)X(0)$$

$$X(1) = RX(0)$$

TRANSPORT
GICOSY
...

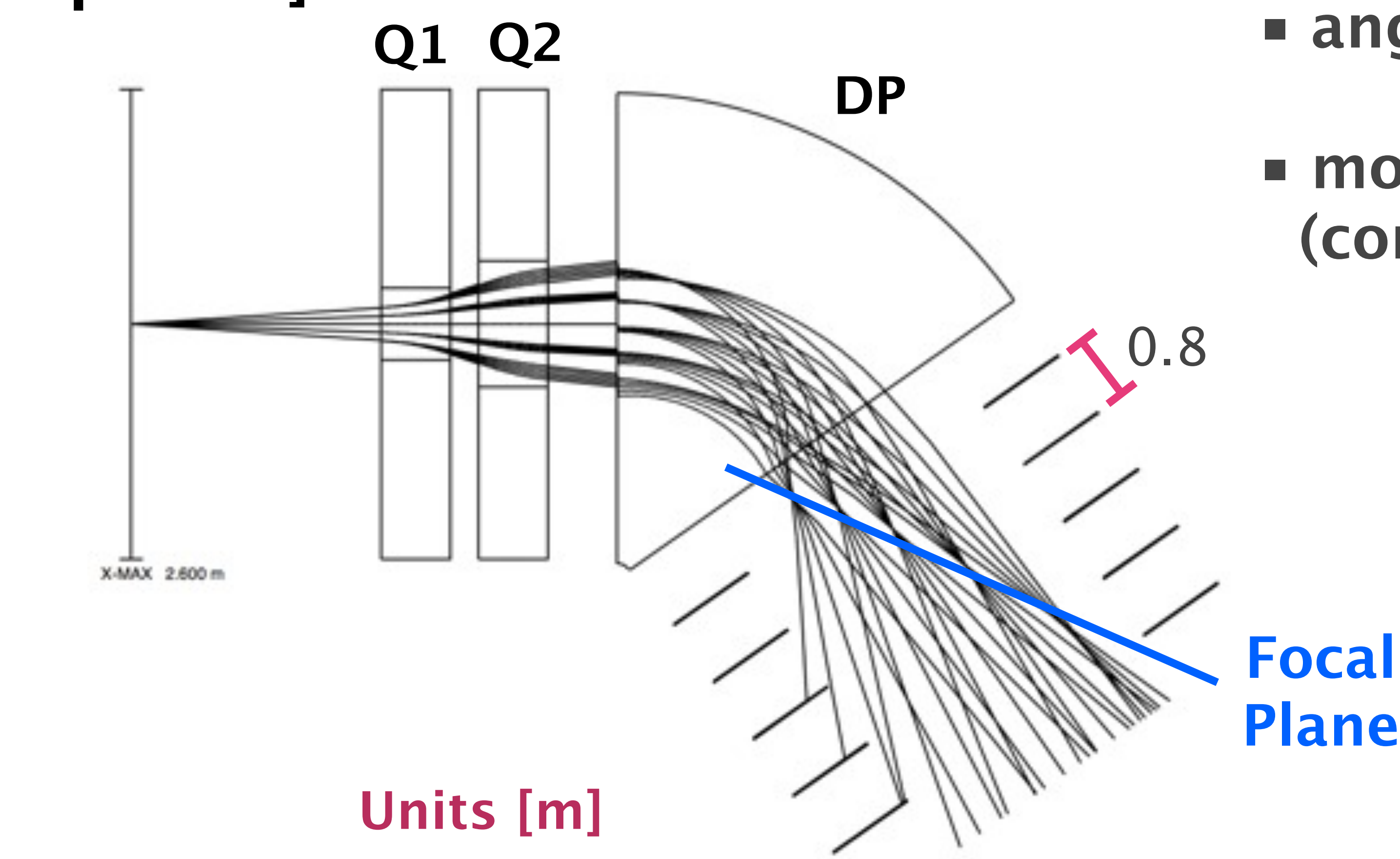
Higher order calculation

$$x_j(f) = \sum_k R_{jk}x_k(i) + \sum_{k,l} T_{jkl}x_k(i)x_l(i) + \cdots$$

K-trace

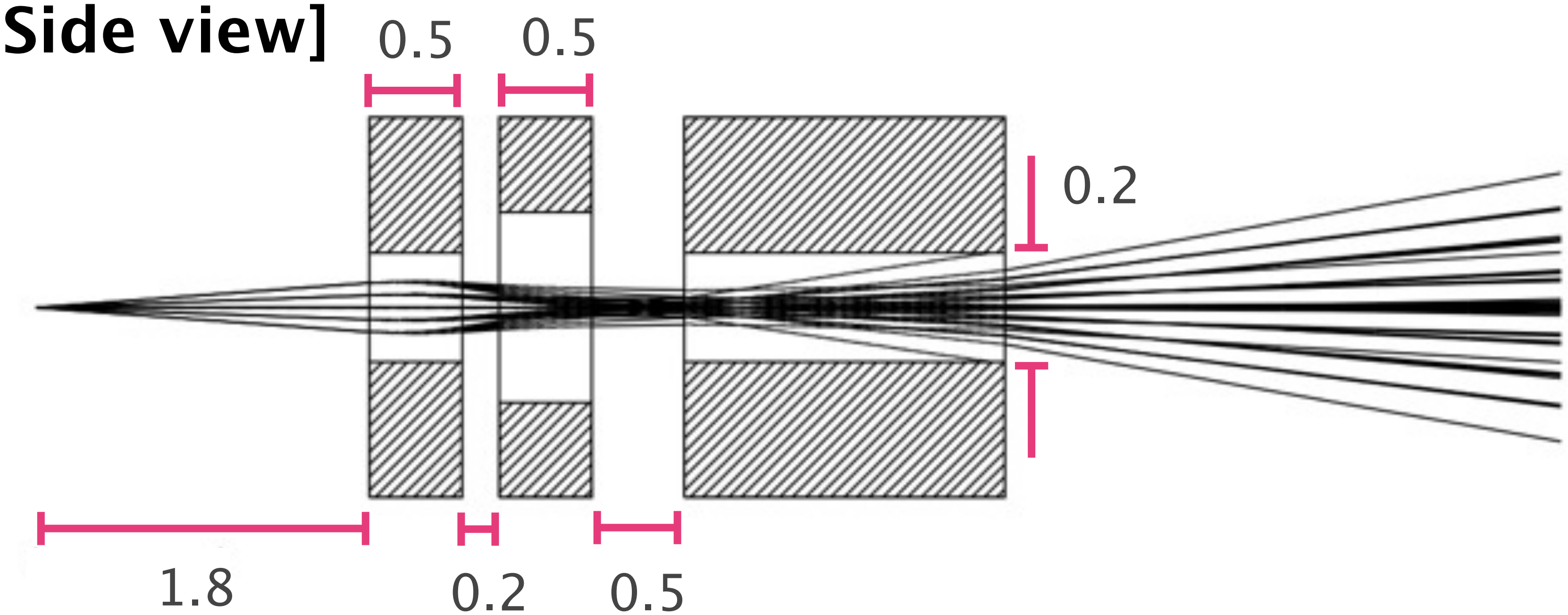
GICOSY simulation [QQD]

[Top view]



- 2nd order calculation
- angular acceptance = 50 mr (horizontal)
  50 mr (vertical)
- momentum Range = ±30 %
  (corresponding KE Range ~ ±58 %)

[Side view]

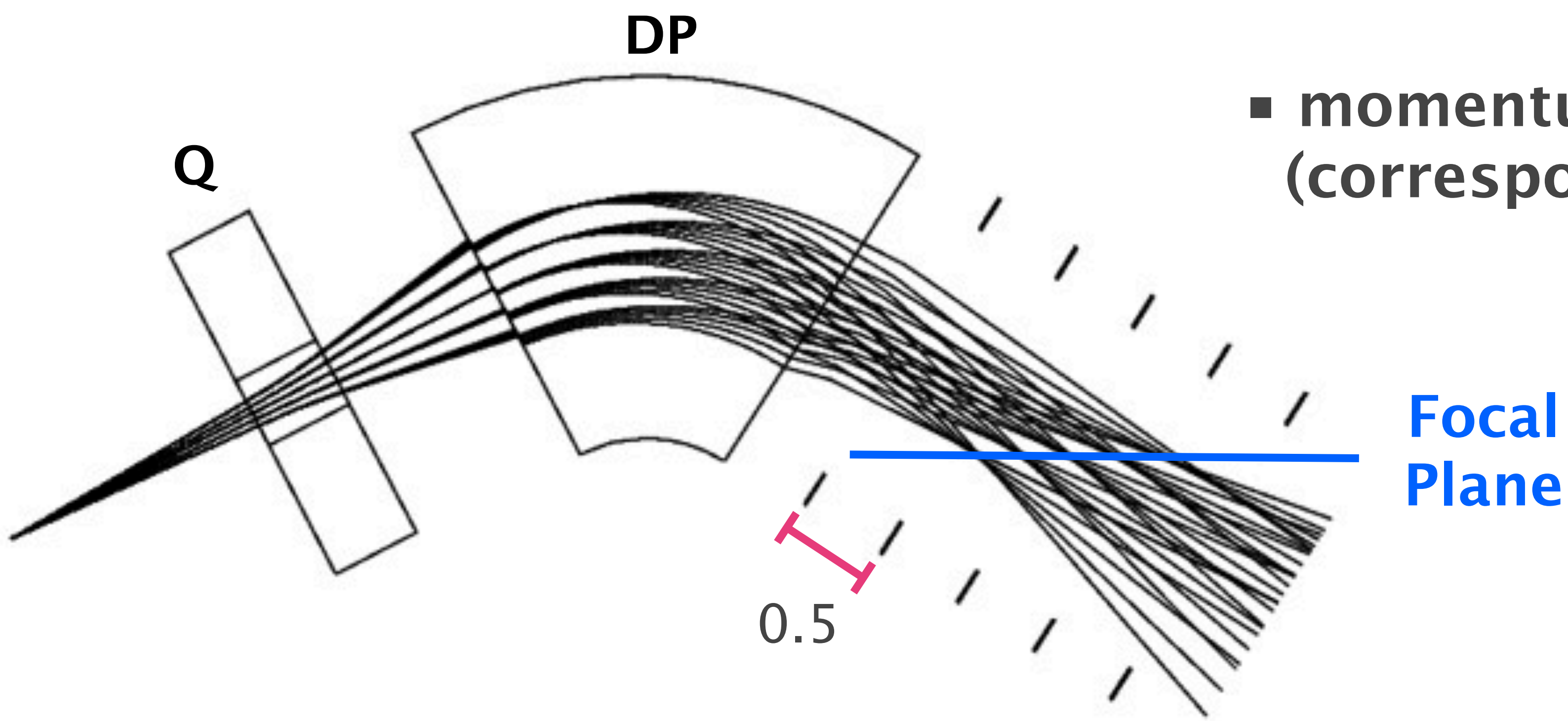


- **Q1** : diameter of gap =0.4 m,
  B=−1.88 T/m
- **Q2** : diameter of gap =0.7 m,
  B=+0.81 T/m
- **DP** : deflection angle θ=55°
  deflection radius=1.8 m,
  $\beta_{upstream}$=−25°,
  $\beta_{downstream}$=−25°
  B =−0.36 T

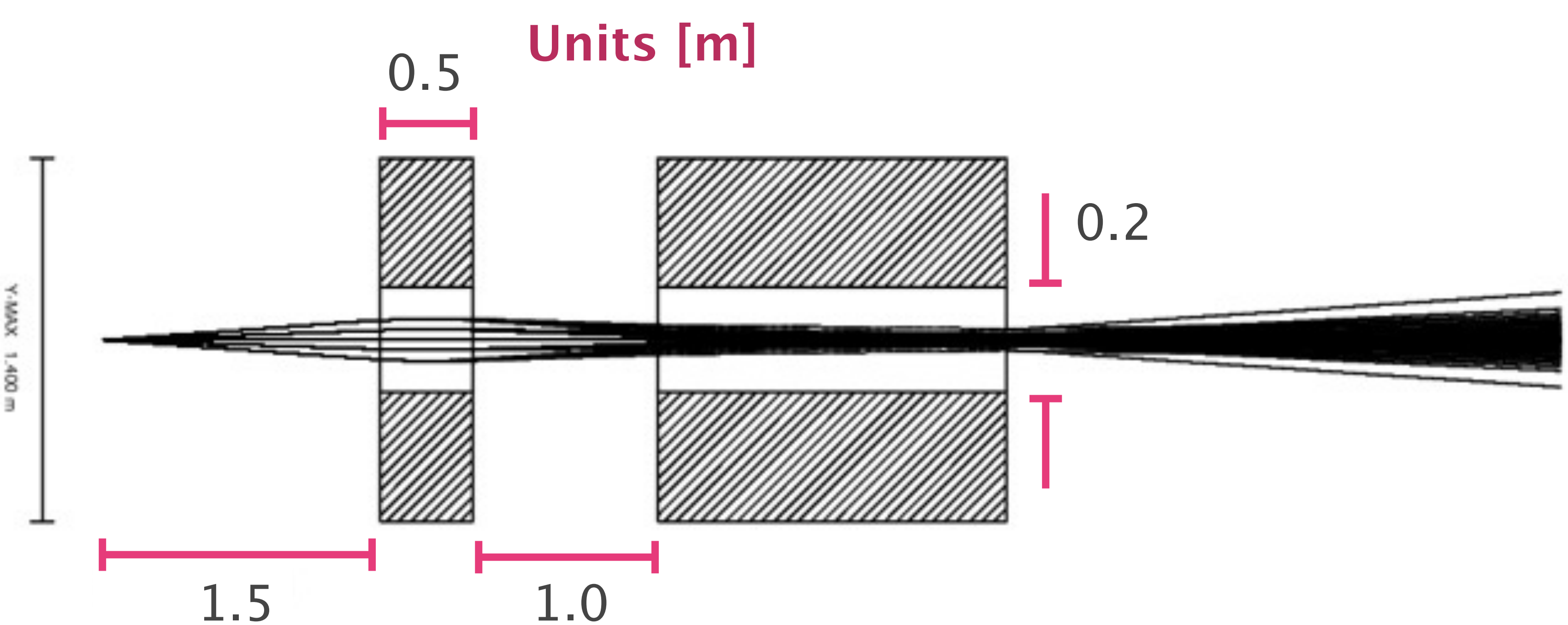
GICOSY simulation [QD]

- 2nd order calculation
- angular acceptance = 50 mr (horizontal)
  50 mr (vertical)
- momentum Range = ±15 %
  (corresponding KE Range ~ ±30 %)

[Top view]



[Side view]

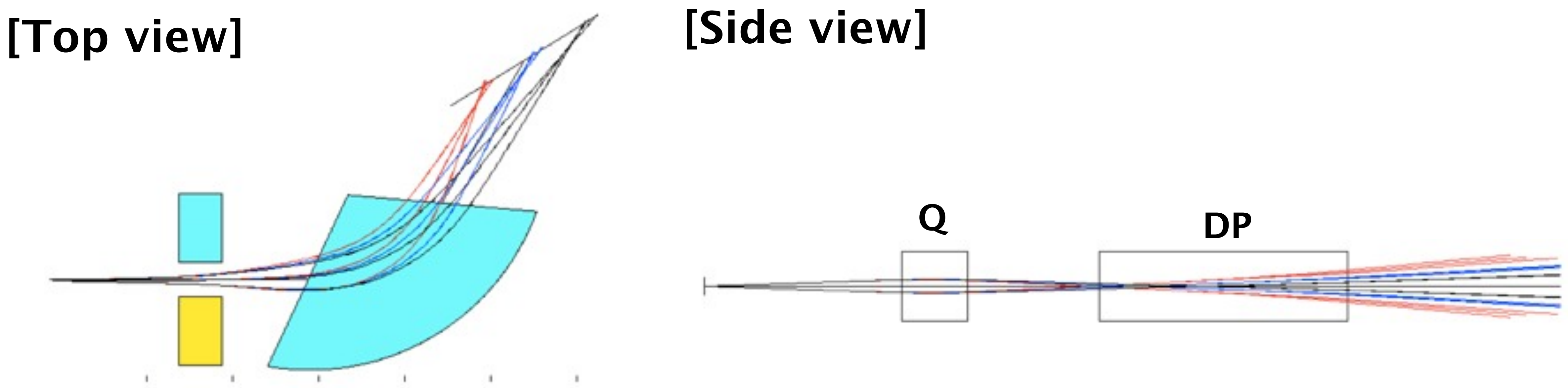


- **Q** : diameter of gap =0.4 m,
  B=-1.42 T/m
- **DP** : deflection angle θ=60°
  deflection radius=1.8 m,
  $\beta_{upstream}$=-25°,
  $\beta_{downstream}$=-25°
  B =-0.36 T

K-trace simulation [QD]

K-trace simulation

- Higher-order beam optics calculation
- Graphic reflects real geometric shape



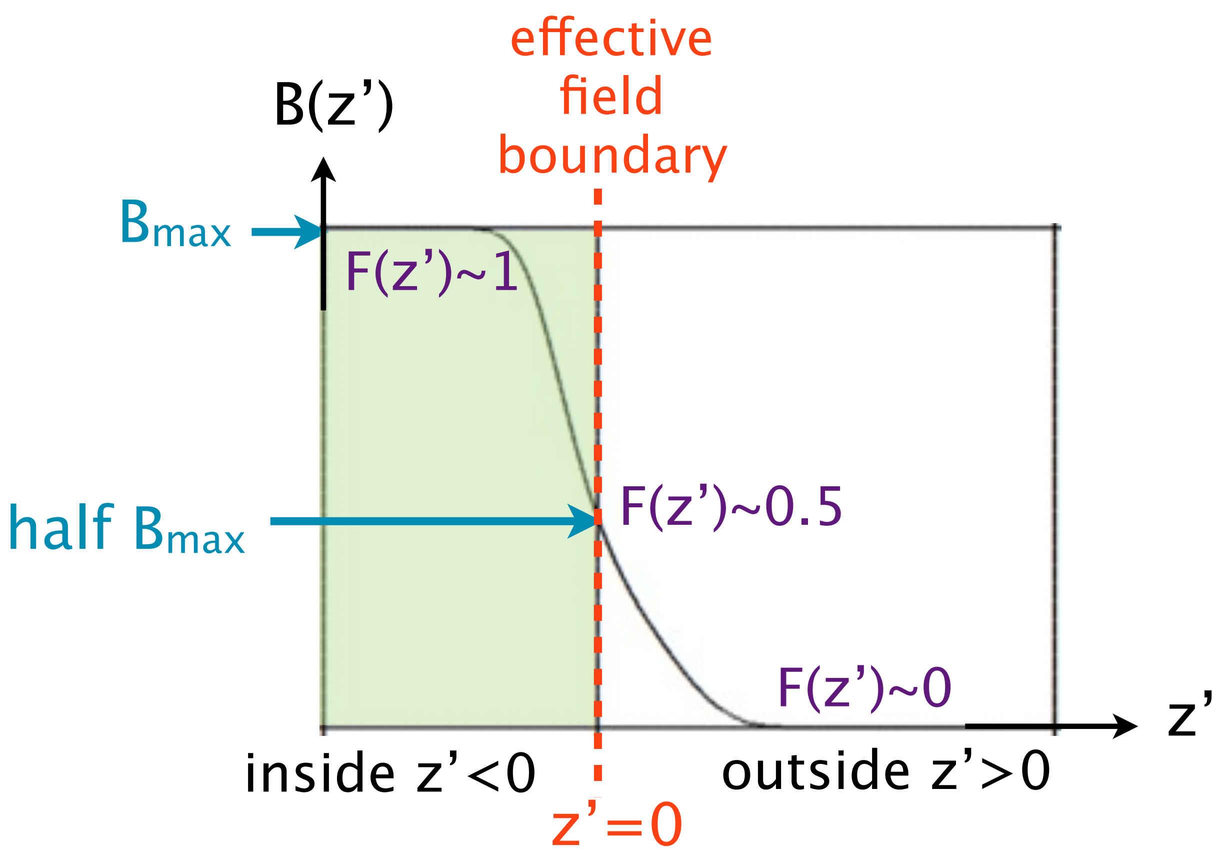
- Same design and scale with GICOSY QD system in the previous slide.
- Results from GICOSY and K-trace simulations agree well.

Fringe Function

- **Enge Function**
  - describes fringe effects at boundary
  - applying more realistic B-field to Geant4 simulation

$$F(z') = \frac{1}{1 + \exp(a_1 + a_2 \cdot (z'/D) + ... + a_6 \cdot (z'/D)^5)},$$

D = radius of the gap
z' = distance from the effective field boundary
a_n = parameter for the n_{th} order polynomial (extracted from GICOSY)

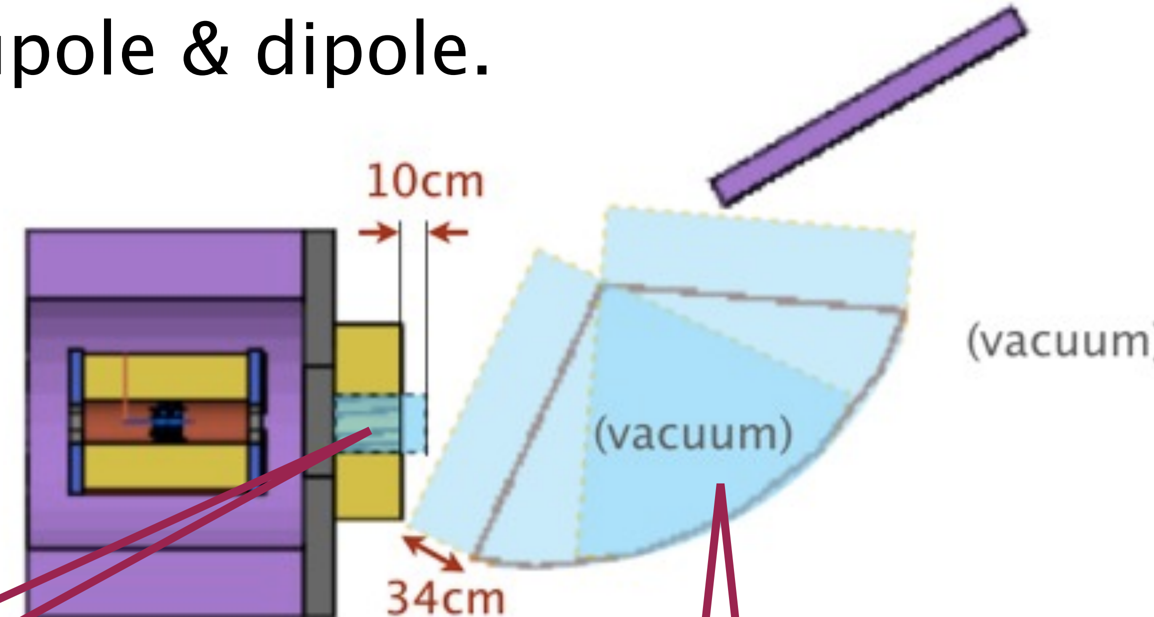


- B-field is defined by $B(z') = B_{max} \times F(z')$

Fringe Function

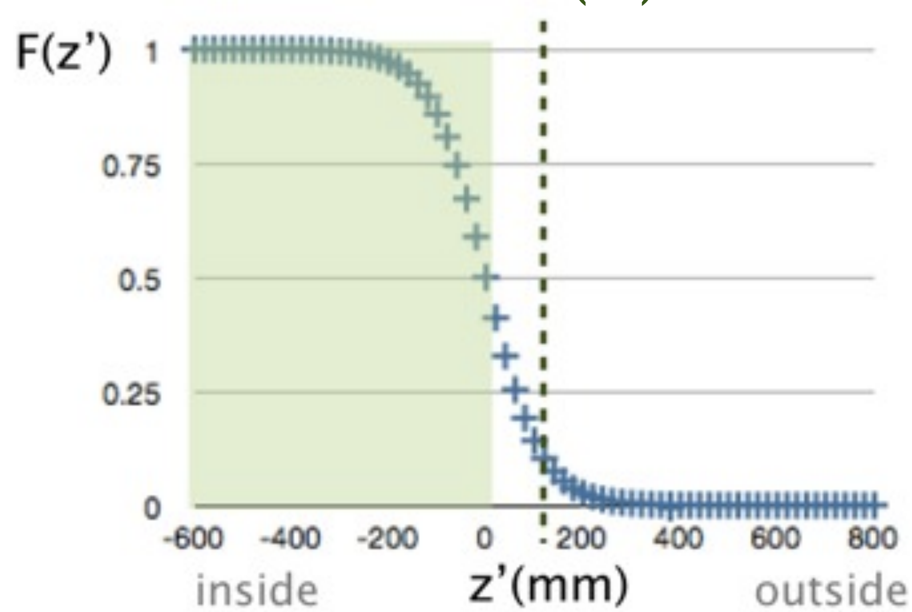
Apply to Geant4 simulation

- Shapes of F(z') are different for quadrupole & dipole.
- cuts are determined according to F(z') values of quadrupole & dipole.



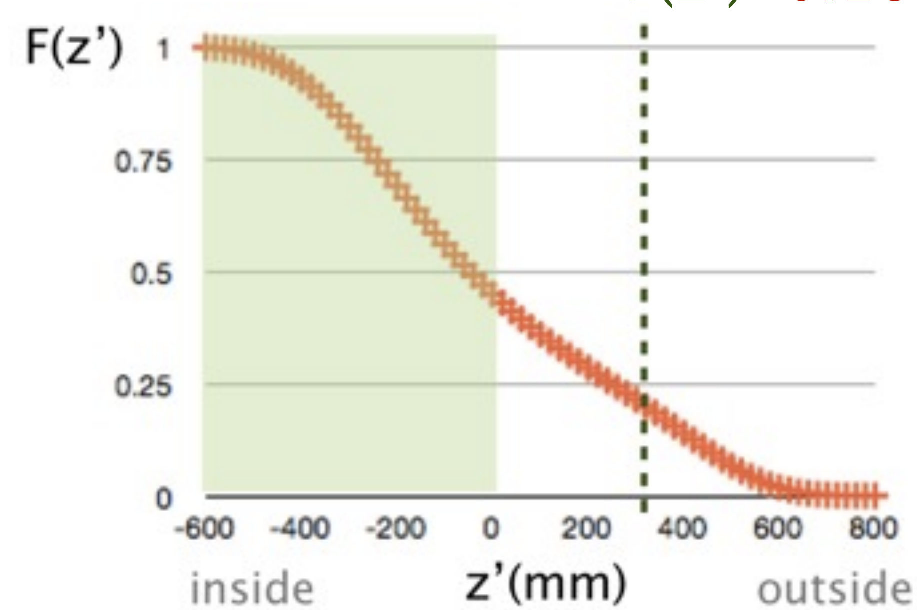
Quadrupole

z'=10cm
F(z')~0.14



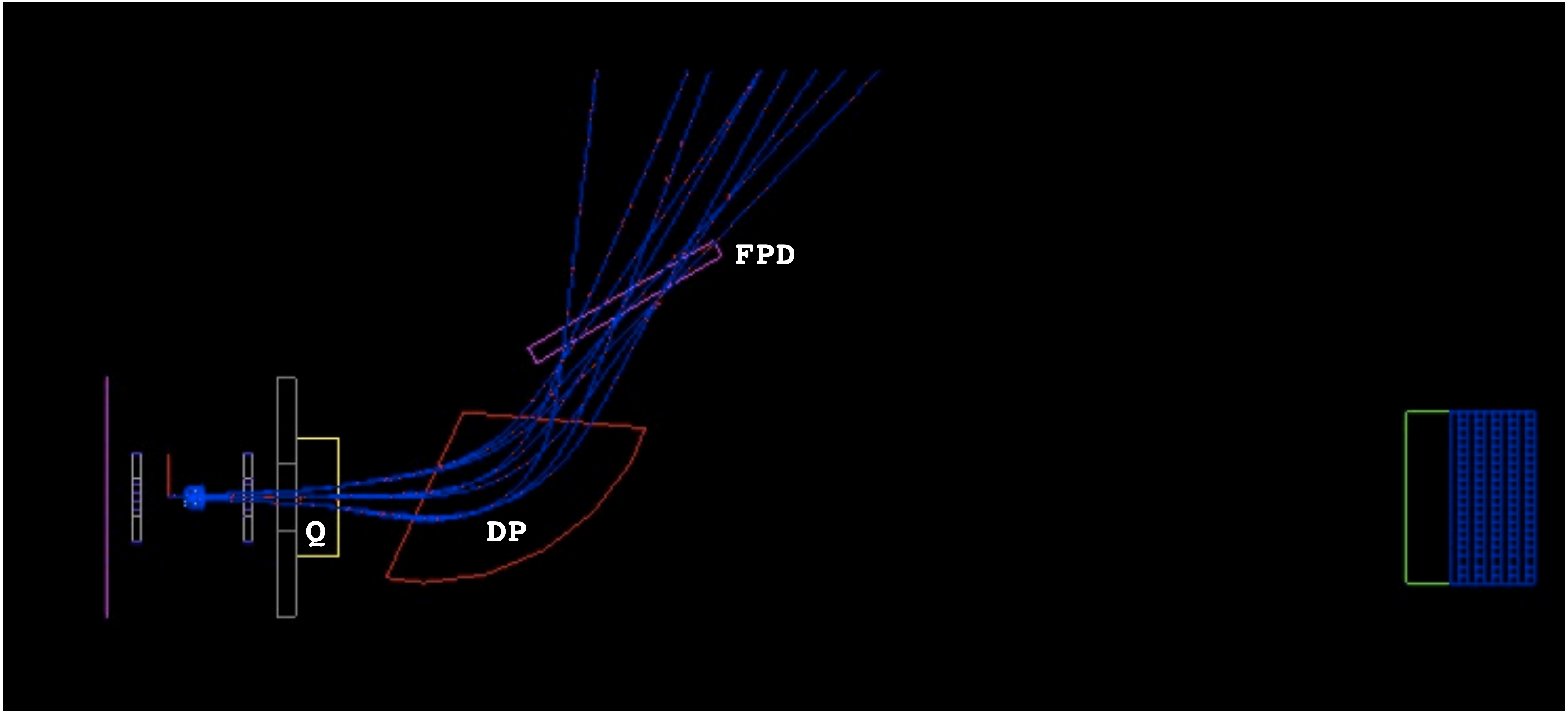
Dipole

z'=34cm
F(z')~0.18



Geant4 simulation [QD]

- **Geant4 simulation with fringe function applied**
  - Trajectories of 3 different momentum (δ = −15, 0, +15 %)
  - For each momentum, trajectories of 3 divergence (x' = −50, 0, 50 mr)



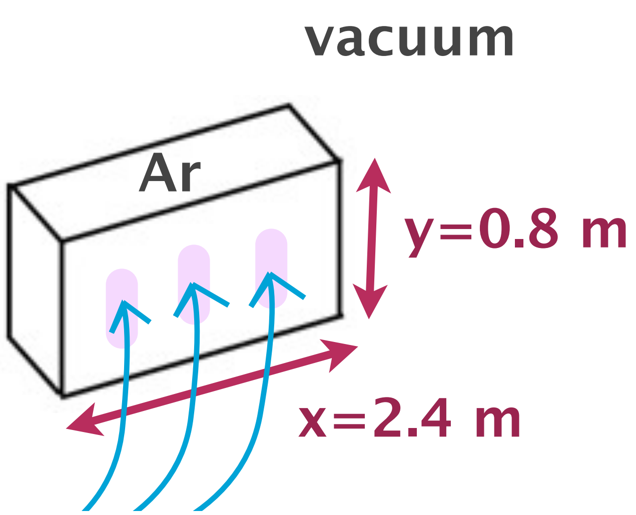
Geant4 Simulation Results

Beam condition

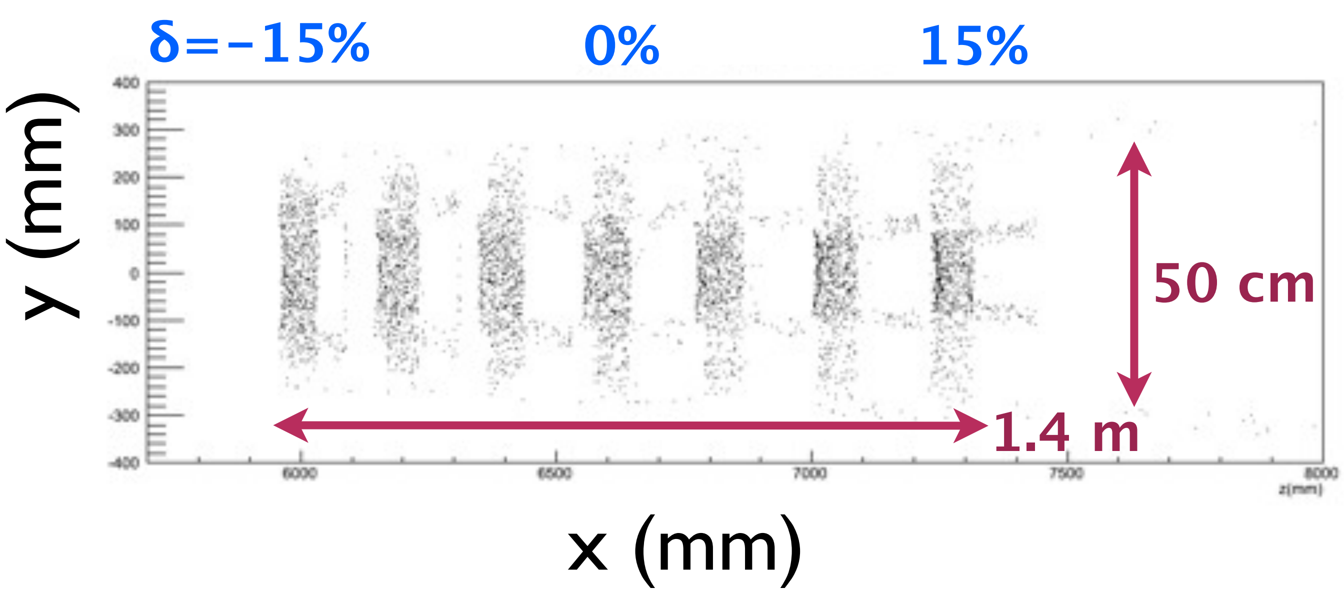
- central trajectory : proton with KE = 20 MeV (p=194.7 MeV/c)
- 1000 protons for each δ (Δδ=5% within δ ≤ ±15%)
- random momentum direction (x'≤50 mrad, y'≤50 mrad)
- plot for the fastest hits on FPD only

Focal plane detector

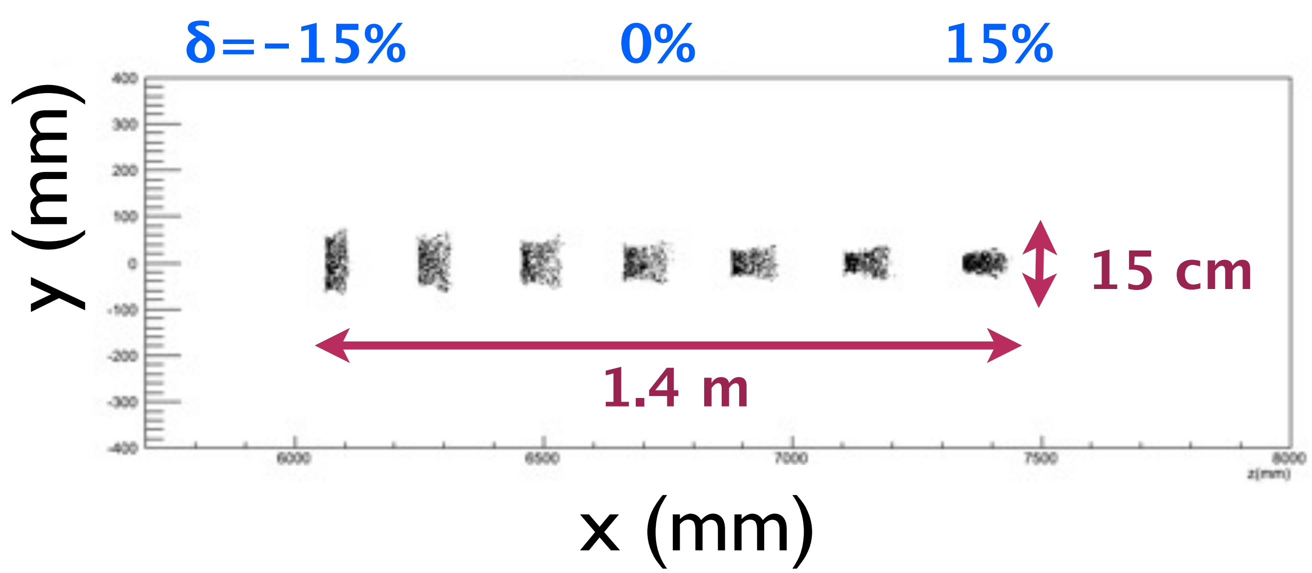
- Simple box with Argon gas
- 2.4 m × 0.8 m × 0.2 m (not scaled)
- angle tilted from the exit pole face of DP = 33°



[Before fringe function]



[After fringe function]



Summary & Plan

- **Optimizing focal points is on-going**
  - narrower focal plane's width (within ~1m)
  - tune the beam size for higher momentum resolution

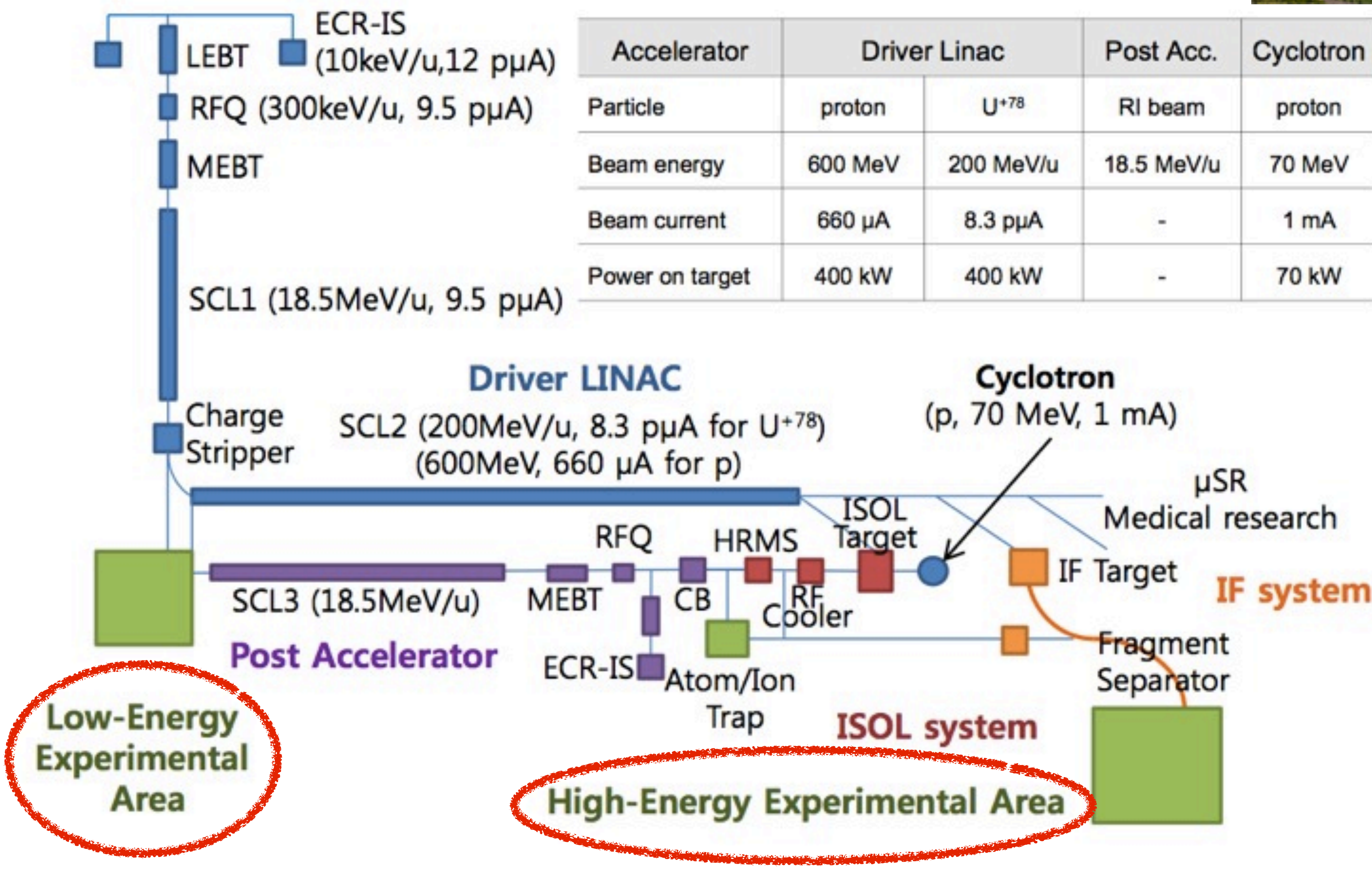
- **R&D for Focal Plane Detector**
  - correlation between initial and final parameters (angle, position, etc.)
  - multi-layer for the angular information

BACK-UP

RAON

- **RAON (RI beam accelerator)**
  - Meaning ‘delightful’, ‘joyful’, ‘happy’
  - Multi-purpose for the basic and applied science

Accelerator	Driver Linac		Post Acc.	Cyclotron
Particle	proton	U^{+78}	RI beam	proton
Beam energy	600 MeV	200 MeV/u	18.5 MeV/u	70 MeV
Beam current	660 μA	8.3 pμA	-	1 mA
Power on target	400 kW	400 kW	-	70 kW



Basic concepts

Lorentz force and Magnetic Rigidity [Tm]

$$\boxed{B\rho} = \frac{\gamma m v}{q|e|} = \frac{p}{q|e|} = \frac{\boxed{p}}{0.3q}$$

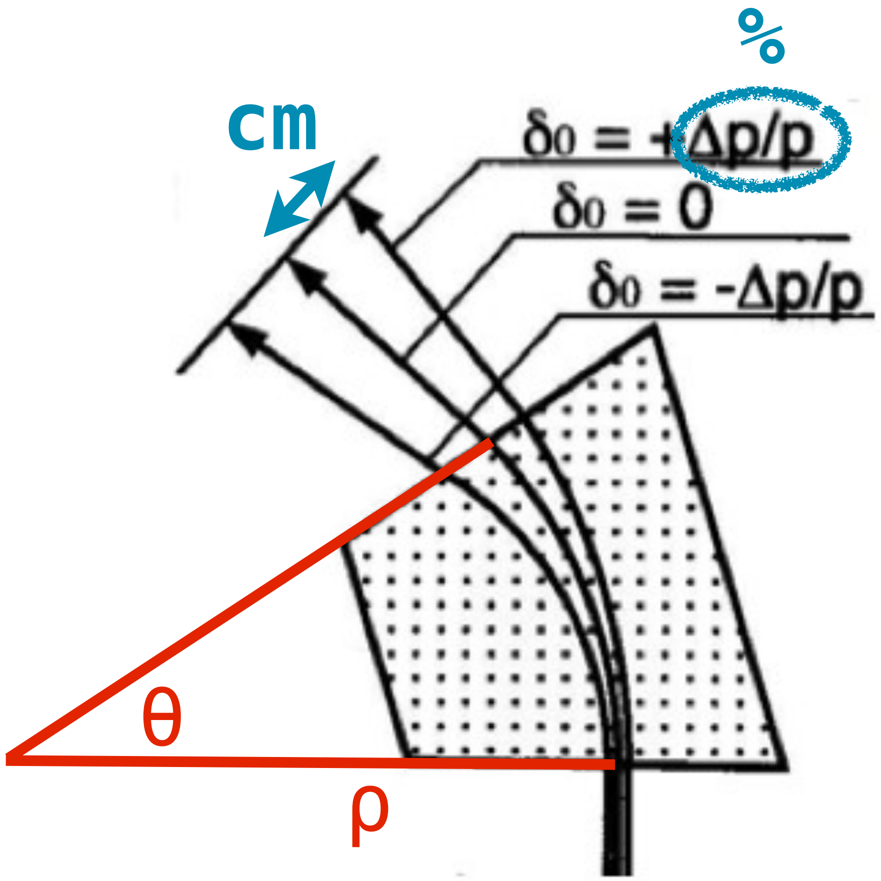
- When B-field is fixed, Curvature radius is proportional to momentum.
  ⇨ Position sensitive detector gives momentum information

Dispersion

- **Dispersion [cm/%]**
  - Quality to estimate the momentum separation
  - depend on the geometrical shape of dipole

$$D = \rho(1-\cos\theta)$$

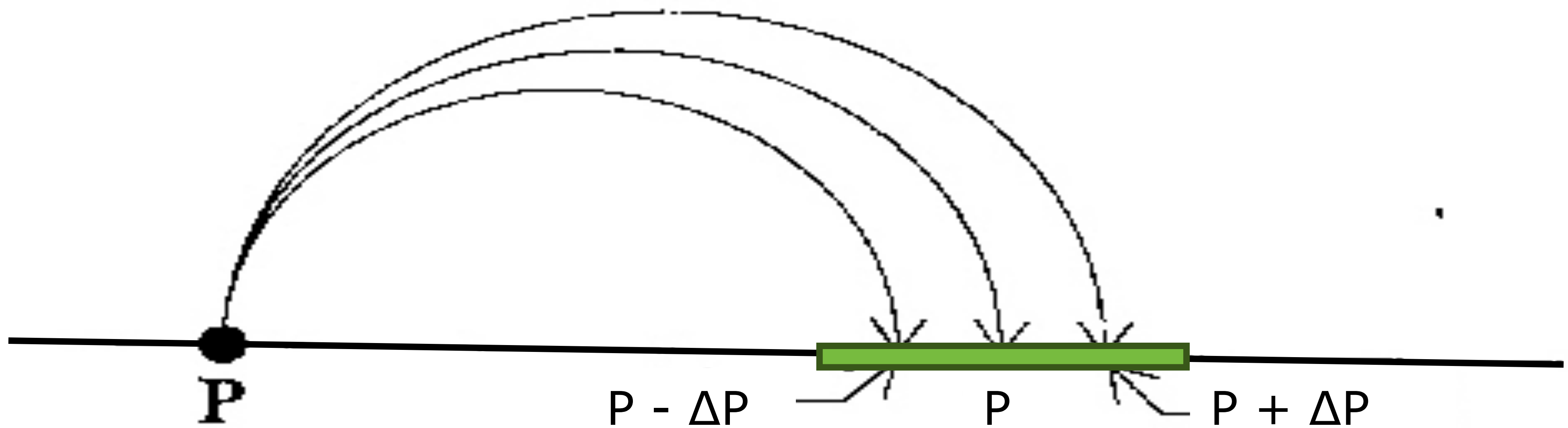
ρ : radius of central trajectory
θ : deflection angle



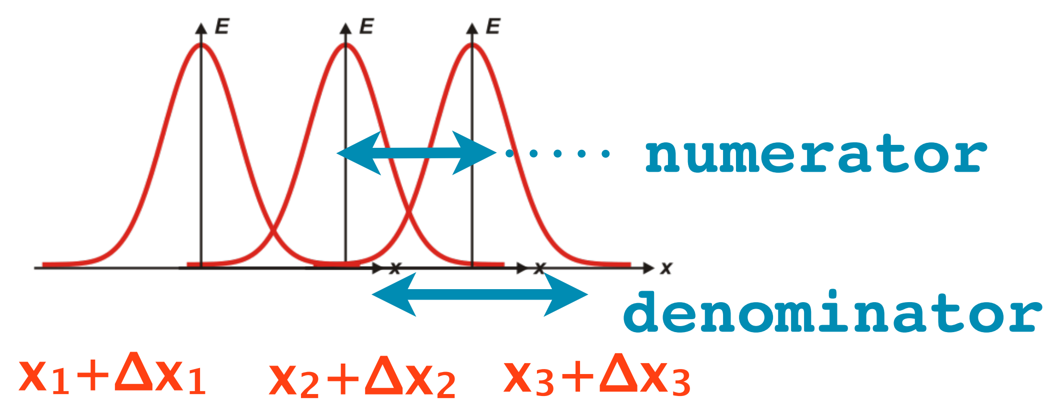
- If we design the dipole with large ρ and θ, effective path length (=ρ· θ) becomes longer and we can achieve <u>large dispersion</u>.

Resolving Power

- **Resolving power R**
  - directly related to the momentum resolution
  - Not only the separation, size of the beam image at counter is considered.



$$R = \frac{D}{2x_0(x|x)} = \frac{\text{Dispersion}}{\text{Beam image size}}$$

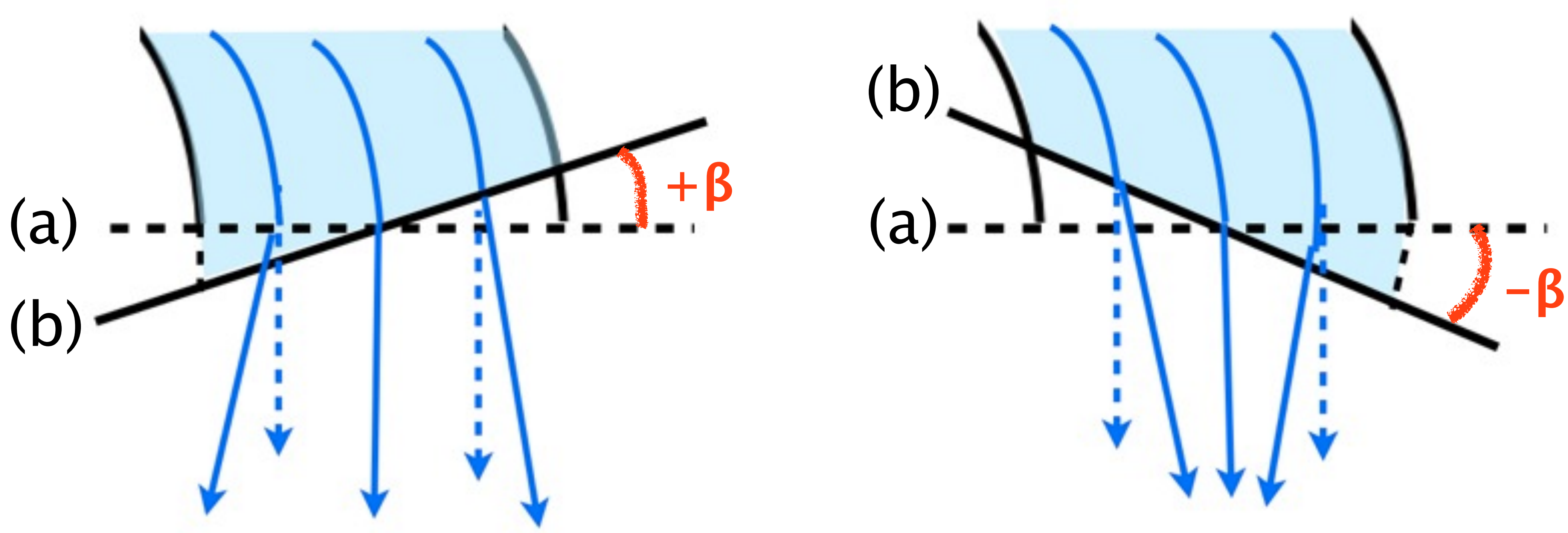


- **For high resolving power, design of precise focusing system required**

Shim angle

- **Shim angle β**
  - Rotation of pole face for additional focusing
    - We apply shim angles to focus in horizontal direction for entrance and exit surface

(a) perpendicular to central trajectory
(b) actual pole face of dipole

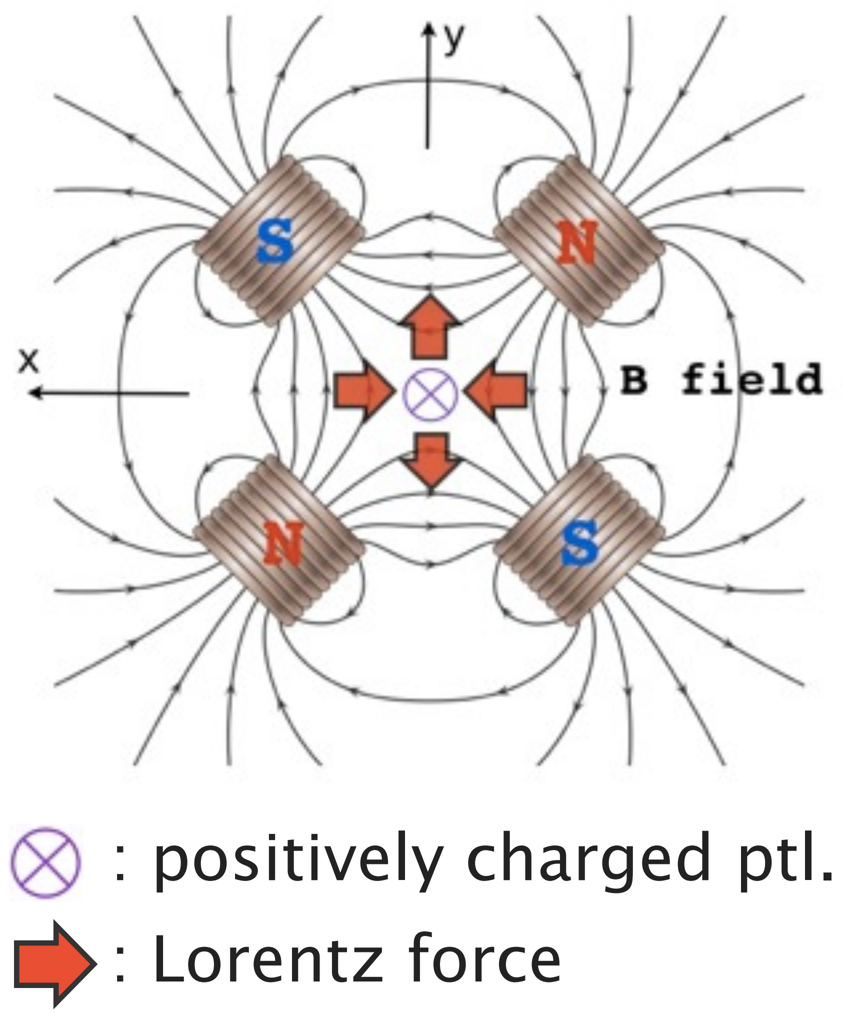


[defocused] [focused]

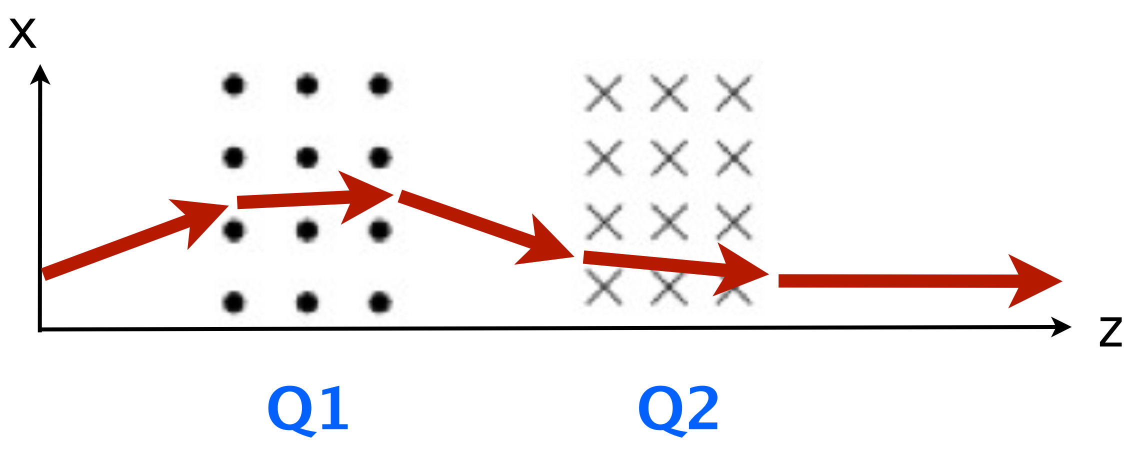
Quadrupole Magnet

Quadrupole magnet

- Used for more precise focusing
- Horizontal focusing leads to vertical defocusing. (vice versa)

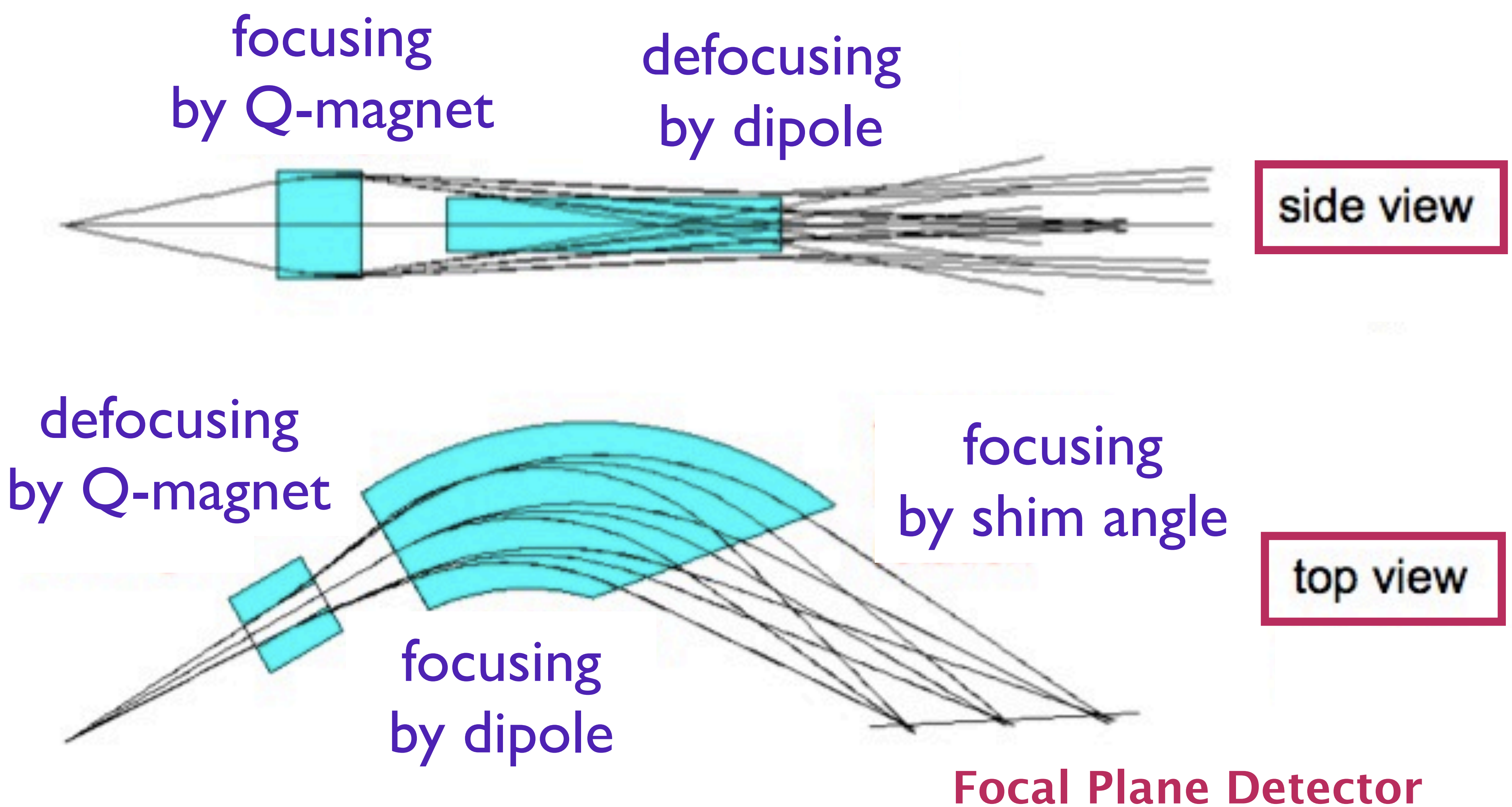


- Increase angular acceptance



QD system

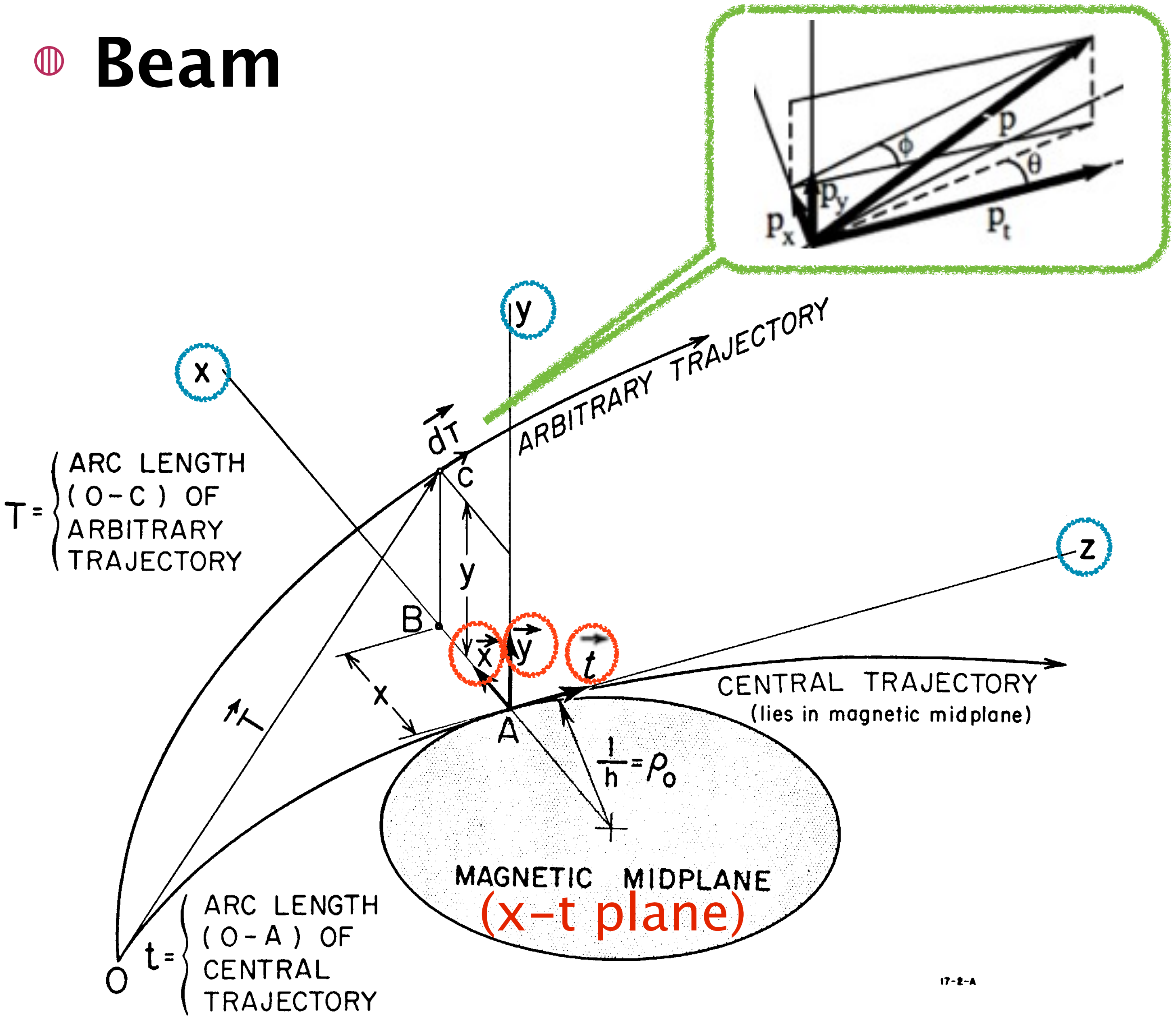
- **Example of the whole focusing system**



- **Various configurations are ongoing to optimize focal points**
- **Simulation by TRANSPORT, GICOGY, and GEANT4.**

Coordinate system

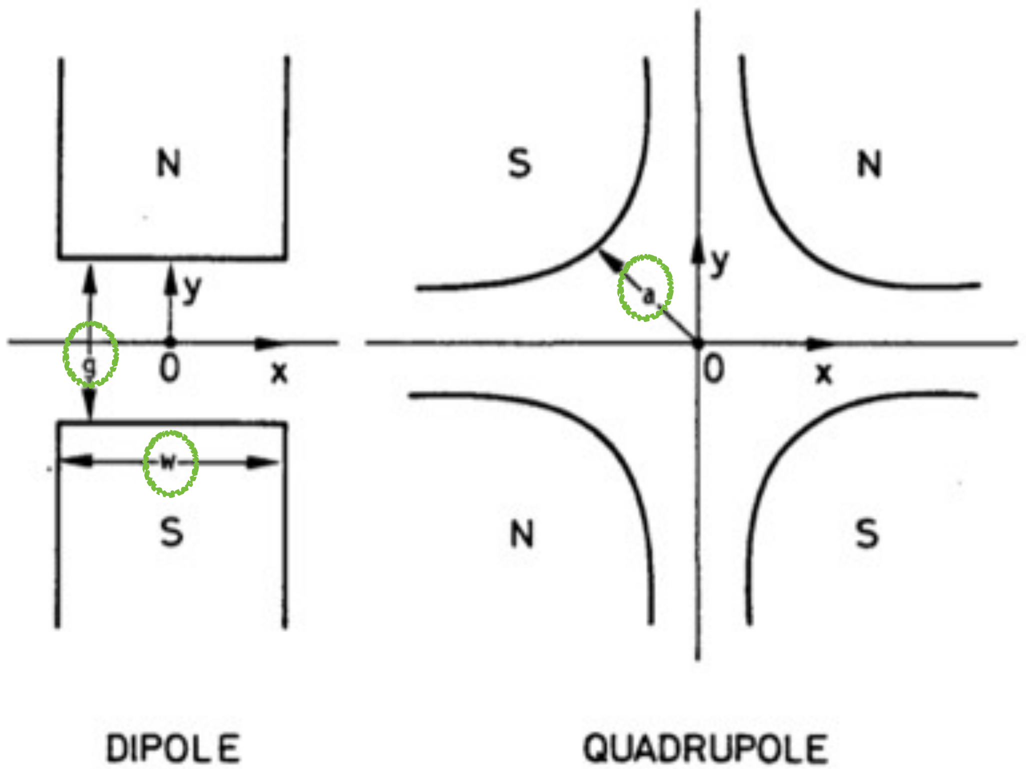
◍ Beam



◯ : laboratory frame

◯ : optical reference frame

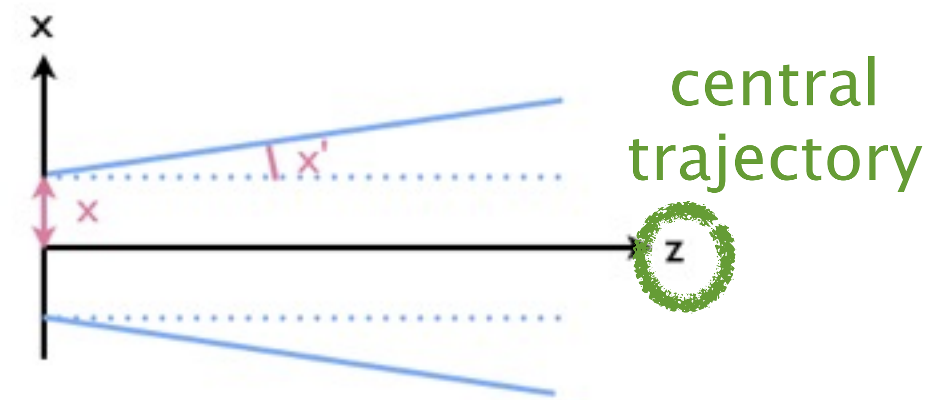
◍ Magnet elements



w : width
g : gap
a : aperture radius

Beam Optics Matrix

- assume ℓ=0
- x & y independent to each other
- $\delta_1=\delta_0$ and $(x|\delta)$=D



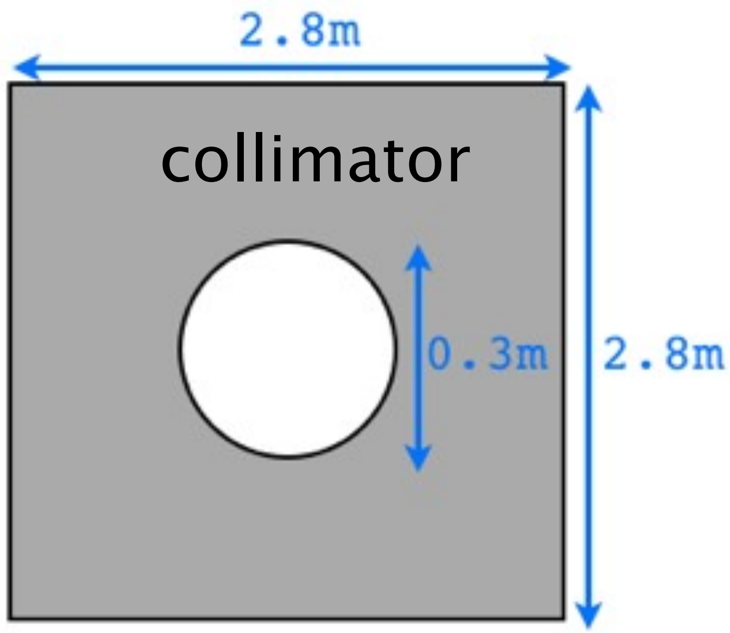
$$X(1) = RX(0)$$

=D

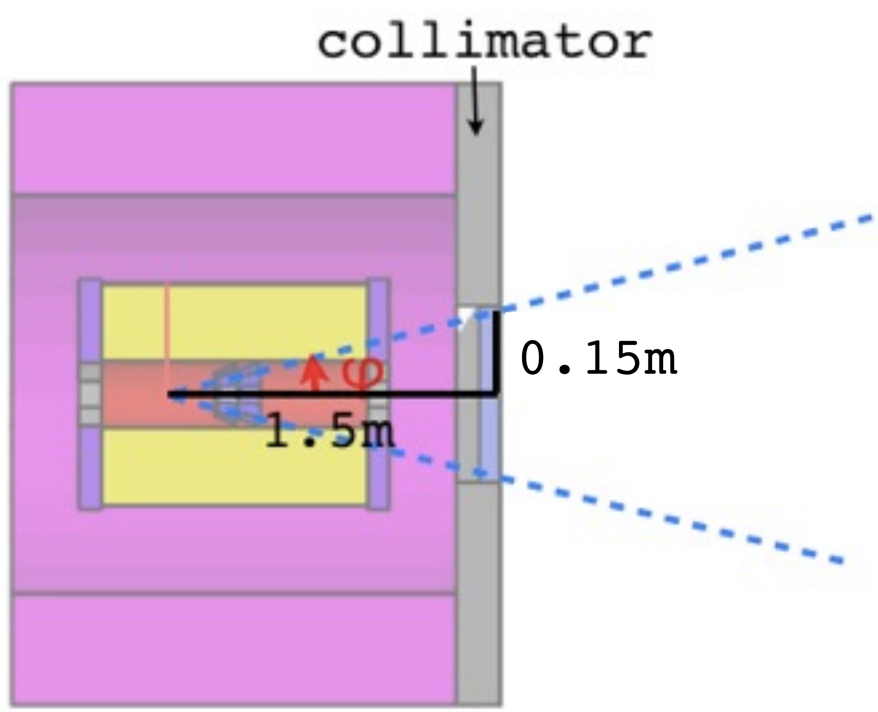
$$\begin{pmatrix} x_1 \\ x_1' \\ y_1 \\ y_1' \\ l_1 \\ \delta_1 \end{pmatrix} = \begin{pmatrix} (x|x) & (x|x') & (x|y) & (x|y') & (x|l) & (x|\delta) \\ (x'|x) & (x'|x') & (x'|y) & (x'|y') & (x'|l) & (x'|\delta) \\ (y|x) & (y|x') & (y|y) & (y|y') & (y|l) & (y|\delta) \\ (y'|x) & (y'|x') & (y'|y) & (y'|y') & (y'|l) & (y'|\delta) \\ (l|x) & (l|x') & (l|y) & (l|y') & (l|l) & (l|\delta) \\ (\delta|x) & (\delta|x') & (\delta|y) & (\delta|y') & (\delta|l) & (\delta|\delta) \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ y_0 \\ y_0' \\ l_0 \\ \delta_0 \end{pmatrix}$$

=1

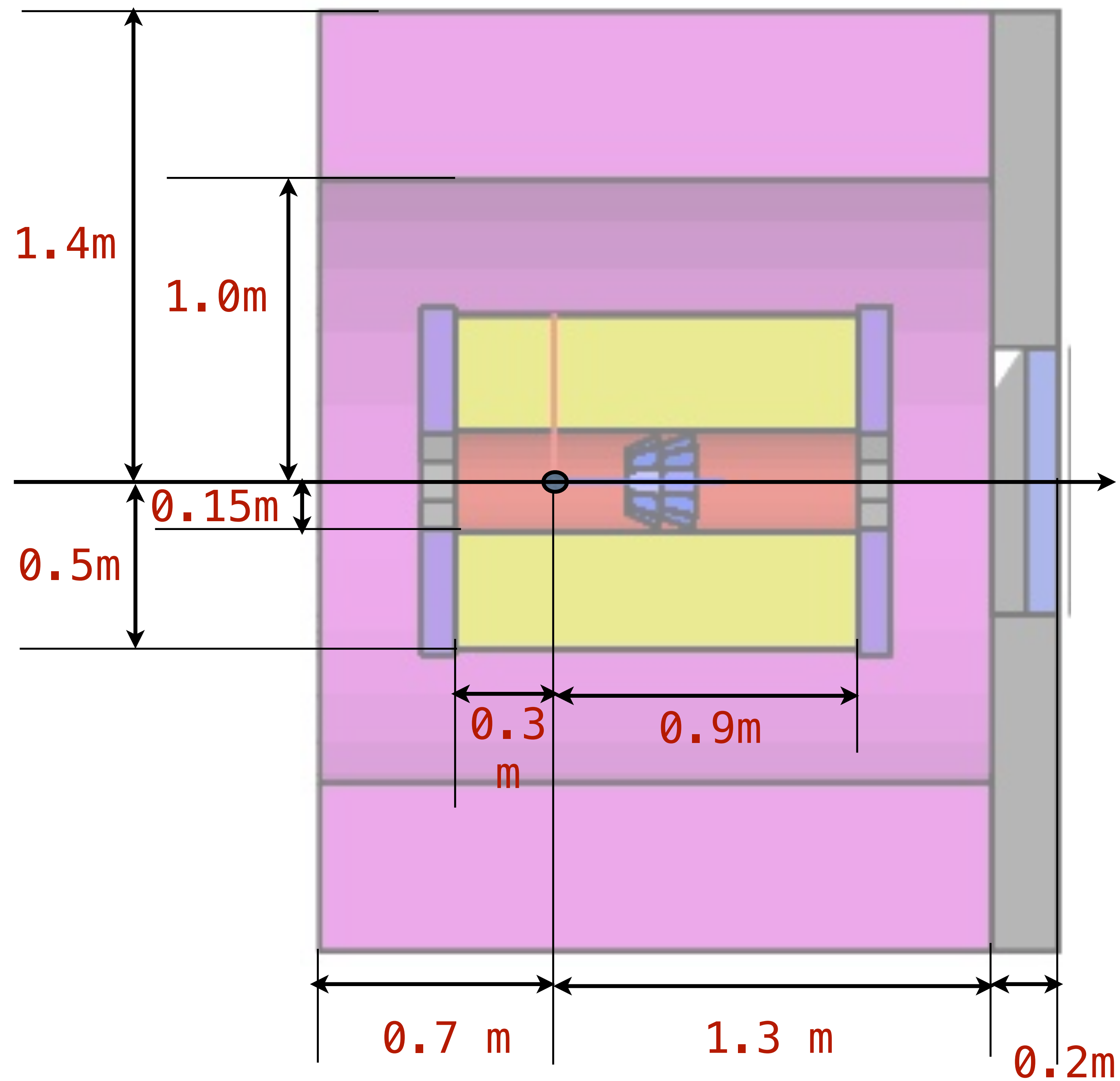
SCALE



[front view]

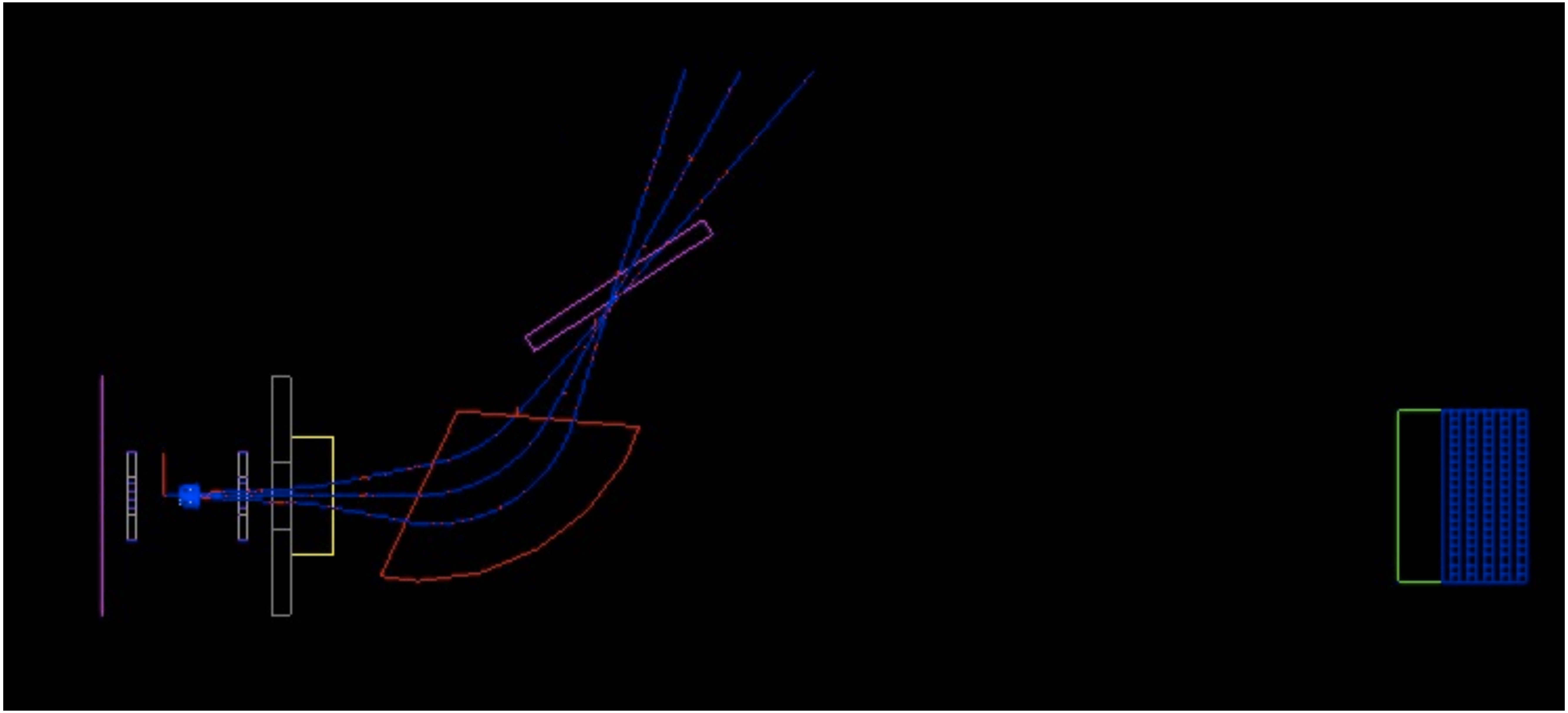


[side view]



Geant4 simulation

- Trajectories of central momentum
  with 3 divergence (x’ = −50, 0, 50 mr)

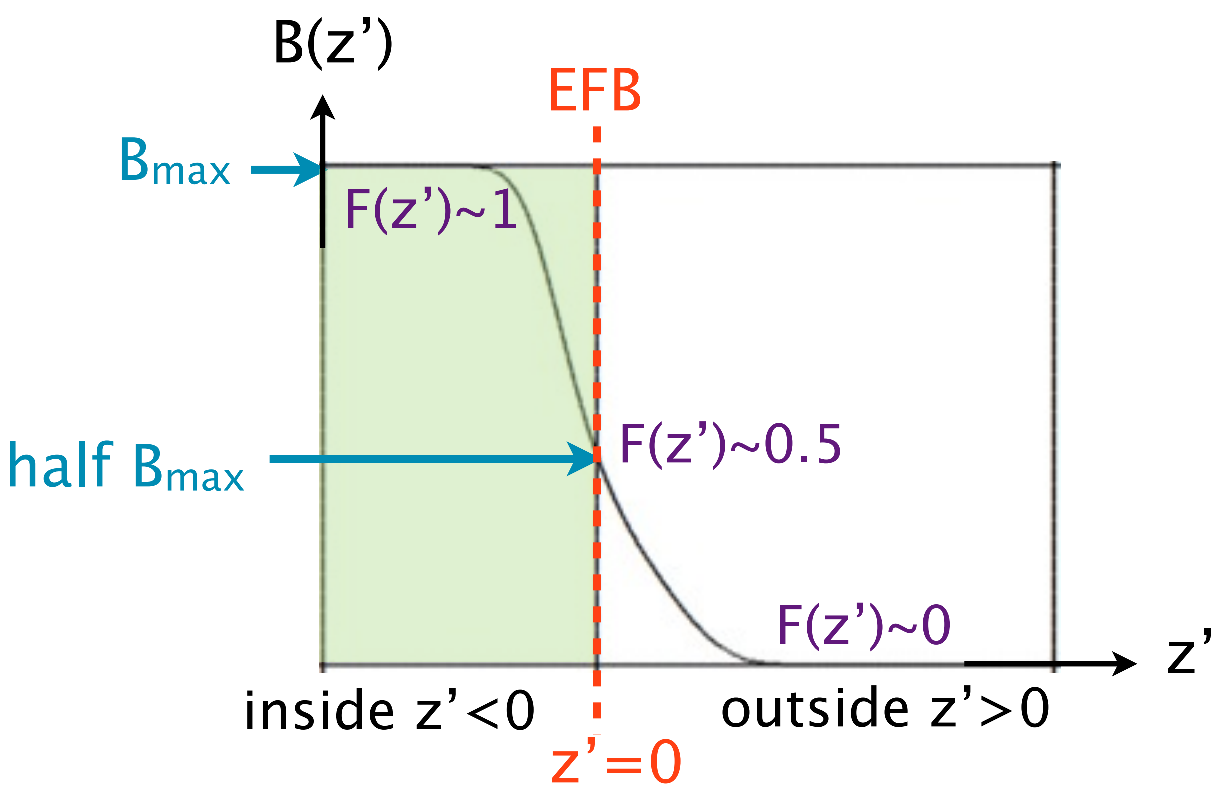


Fringe Function

- **Enge Function :** $$F(z') = \frac{1}{1 + \exp(a_1 + a_2 \cdot (z'/D) + \ldots + a_6 \cdot (z'/D)^5)},$$

where D = gap parameter (=half-aperture)
z' = distance from the effective field boundary
a_n = parameter for the n_{th} order polynomial

- B-field is defined by $B(z')=B_{max}\times F(z')$



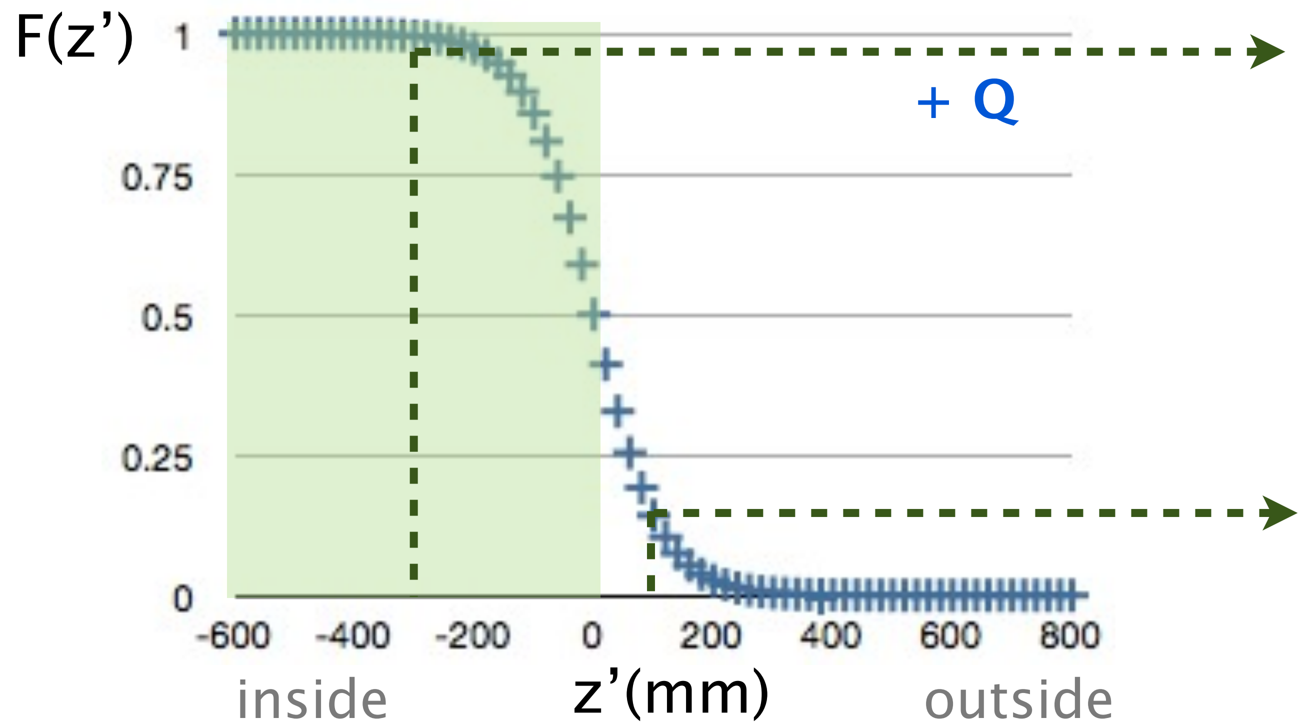
1. D = 200 mm for Q and DP both
2. a_n = extracted from the GICOSY (default value)

For dipole magnet
a1=0.205133
a2=0.840972
a3=-0.141308
a4=0.050050
a5=0.000076
a6=0.005197

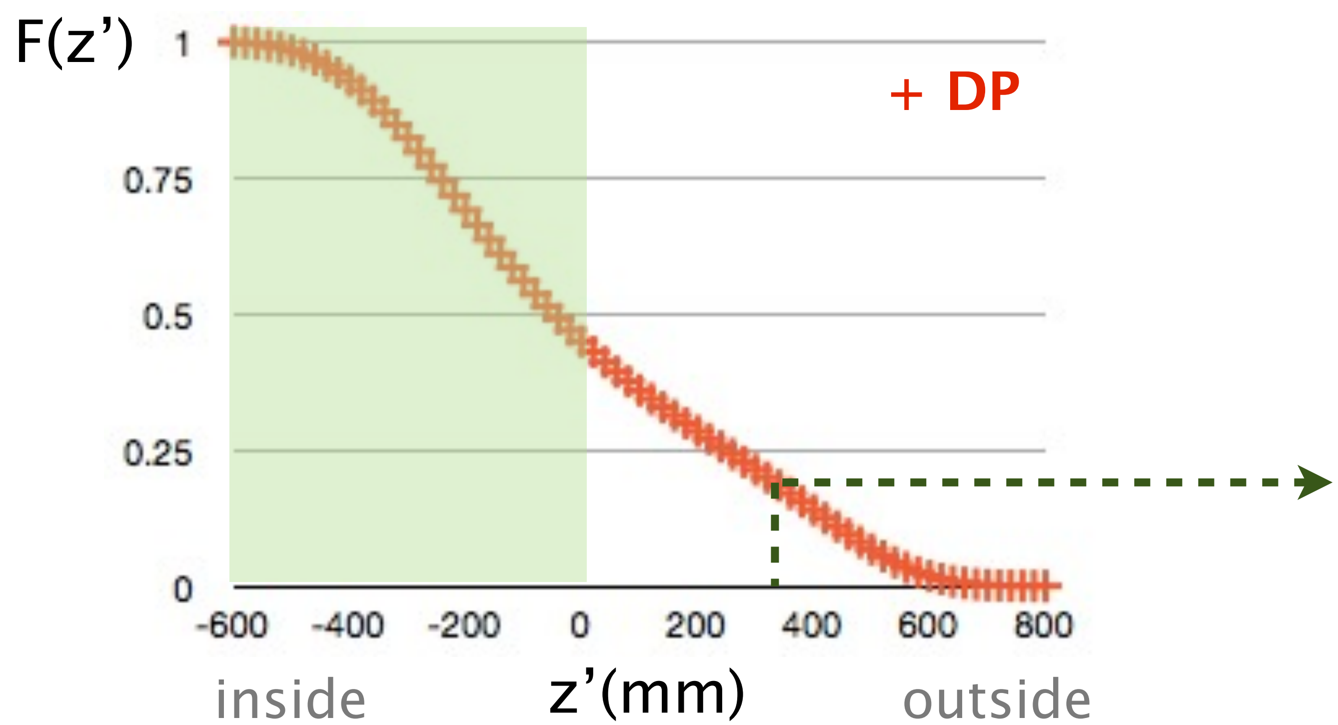
For Q-magnet
a2=3.59463

Introduction

◍ for Q :



◍ for DP :



F(z') comparable

[130513_engeFunction]