Magnetic fields of BigRIPS magnet

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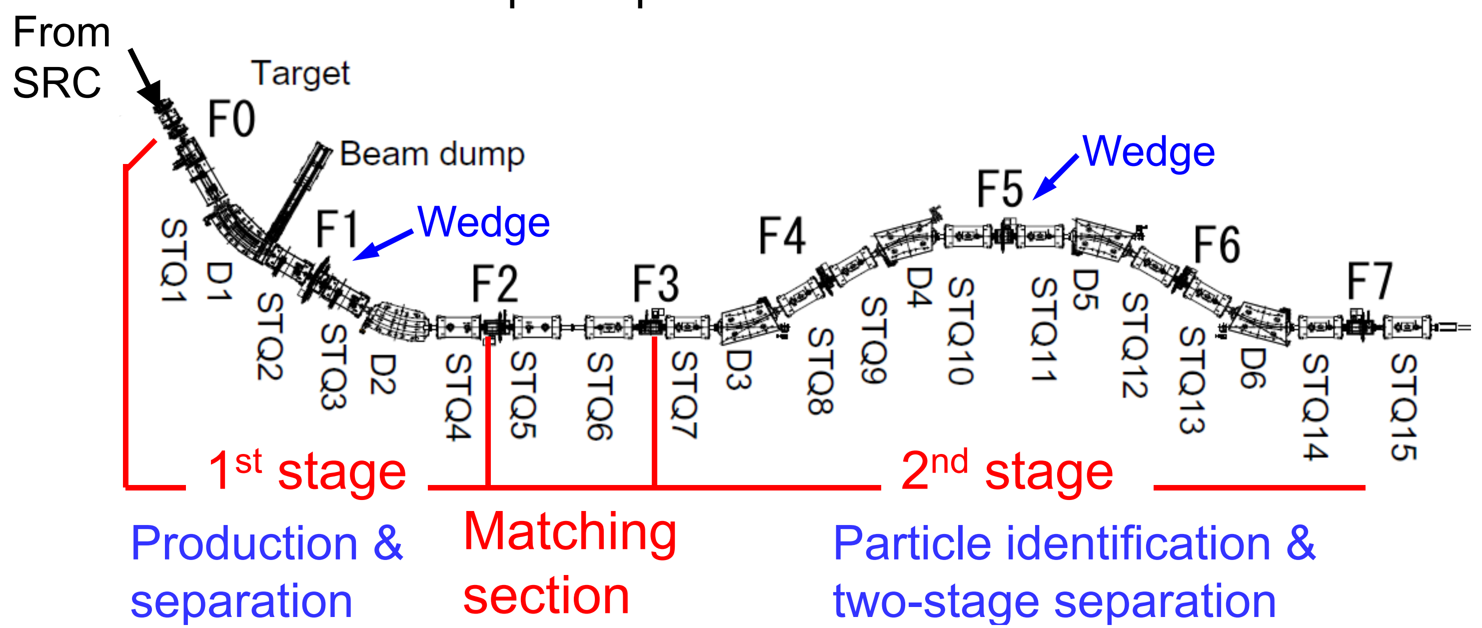
Features of BigRIPS magnet

For efficient transmission of RI beams even when the in-flight fission of uranium beams is employed as a production reaction,
BigRIPS magnets have following features:

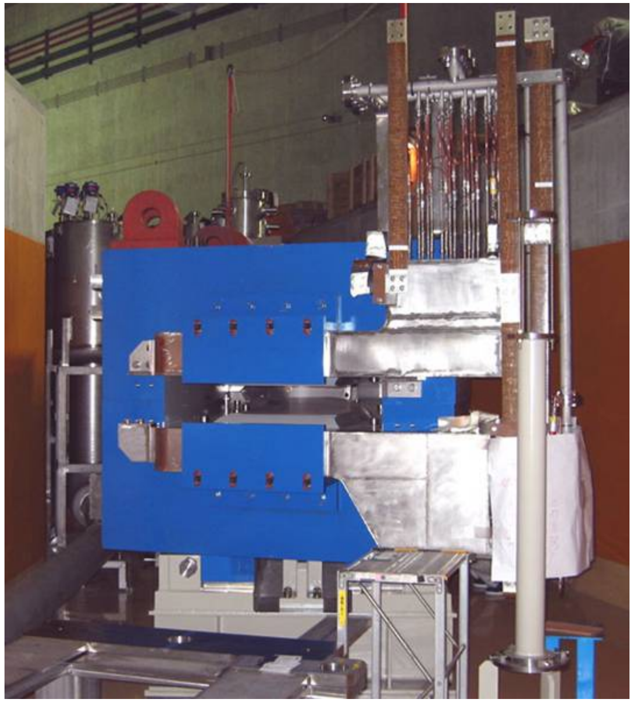
1) Large acceptances
   - Comparable with angular / momentum spreads of in-flight fission at RIBF energy (+/-50 mrad, +/-5%)

2) Superconducting quads with a large aperture, and strong field
   - Pole tip radius: 170 mm
   - Maximum pole tip field: 2.4 T



Parameters:
Δa = +/-40 mrad
Δb = +/-50 mrad
$\Delta p/p$ = +/-3 %
$B\rho$ = 9 Tm
L ~ 78 m

Room-temperature Dipole (D1-D6)

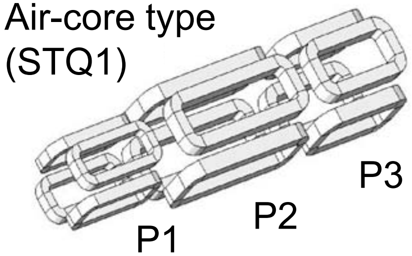


H-type, ρ=6 m, 30deg bend
pole gap=140 mm
weight=56 tons
maximum field=1.75 T (10.5Tm)

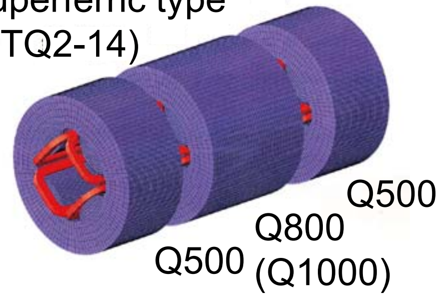
Superconducting triplet quadrupole and sextupole (STQ1-14)

pole tip radius=170 mm
bore radius=120 mm
(90mm for STQ1-P1)
effective length
～500mm (STQ1-P1/3,Q500)
～800mm (STQ1-P2,Q800)
～1000mm (Q1000)
maximum field gradient
24T/m for STQ1-P1
20T/m for STQ1-P2,3
14.1T/m for STQ2-14

Air-core type
(STQ1)



Superferric type
(STQ2-14)



Sextupole magnet is superimposed on one of the Q500 magnet

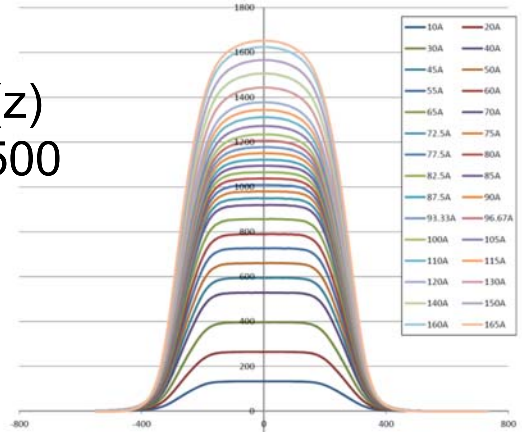
Our goal: accurate ion-optical setting *without any tuning*

Various problems concerning
short-length, large-aperture, and strong field magnets.

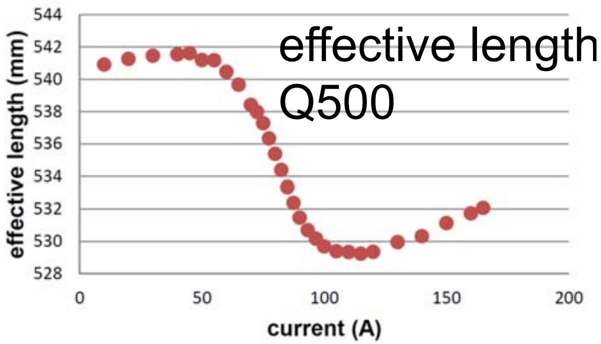
- **Large fringing field region**
  - Entire region must be treated as fringe.
- **Large saturation effect**
  - Shape and effective length vary drastically with the magnet excitation.
- **Existence of pseudo terms**
  - originate from the changes of the magnetic field along the beam axis

→ The effects of the varying field maps should be included in the ion-optical simulation.

$B_r(z)$
Q500



z position (mm)



Surface map analysis of 3D magnetic field

obtained by solving Laplace's eq. in cylindrical coordinate system

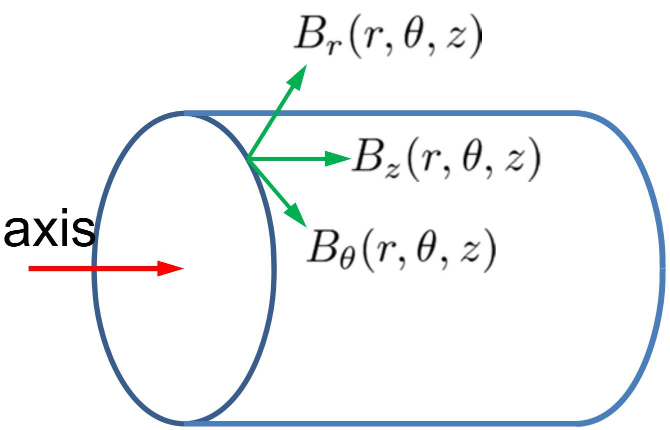
$$(\vec{\nabla}^2\Phi = 0,\ \text{where } \vec{B} = \vec{\nabla}\Phi)$$

see Takeda et al., NIM B317 (2013) 798

surface measurement

Fourier analysis

$$\begin{cases} B_r(r,\theta,z) &= \sum_{n=1}^{\infty} B_{r,n}(r,z)\sin n\theta, \\ B_\theta(r,\theta,z) &= \sum_{n=1}^{\infty} B_{\theta,n}(r,z)\cos n\theta, \\ B_z(r,\theta,z) &= \sum_{n=1}^{\infty} B_{z,n}(r,z)\sin n\theta. \end{cases}$$



(without skew terms for simplicity)

Extraction of $b_{n,0}$

$$\begin{cases} B_{r,n}(r,z) &\equiv \left(\frac{r}{r_0}\right)^{n-1} \sum_{m=0}^{\infty} b_{n,m}(z)\left(\frac{r}{r_0}\right)^{2m}, \\ B_{\theta,n}(r,z) &\equiv \left(\frac{r}{r_0}\right)^{n-1} \sum_{m=0}^{\infty} \frac{n}{n+2m} b_{n,m}(z)\left(\frac{r}{r_0}\right)^{2m}, \\ B_{z,n}(r,z) &\equiv \left(\frac{r}{r_0}\right)^{n} \sum_{m=0}^{\infty} \frac{r_0}{n+2m}\frac{\partial}{\partial z} b_{n,m}(z)\left(\frac{r}{r_0}\right)^{2m}. \end{cases}$$

3D magnetic field (B_r, B_θ, B_z) is expressed by $b_{n,0}(z)$ only.
It can be extracted from measured surface map.

$$b_{n,m}(z) = -\frac{r_0^2}{4m(n+m)}\frac{n+2m}{n+2(m-1)}\frac{\partial^2}{\partial z^2} b_{n,m-1}(z).$$

($b_{n,0}$: leading term, $b_{n,m>0}$: pseudo terms)

Advantages of this method

- **only one component (B_r or B_θ) is sufficient**
- **$b_{n,0}(z)$ depends only on z**
  - 3D field map which satisfies Maxwell's eq. is obtained by $b_{n,0}(z)$ function
  - easy to parameterize full 3D map
    - desirable for ion-optical calculation (COSY)
- **Measurement errors are averaged during the integration process of Fourier transform**

(cf. traditional surface data method)

based on Helmholtz's theorem

$$\vec{B}(\vec{x}) = \vec{\nabla}\phi(\vec{x}) + \vec{\nabla} \times \vec{A}(\vec{x})$$

where

$$\phi(\vec{x}) = \int_{\partial V} \frac{\hat{n}(\vec{x}') \cdot \vec{B}(\vec{x}')}{4\pi |\vec{x} - \vec{x}'|} dS - \int_V \frac{\vec{\nabla} \cdot \vec{B}(\vec{x}')}{4\pi |\vec{x} - \vec{x}'|} dV$$

$$\vec{A}(\vec{x}) = \int_{\partial V} \frac{\hat{n}(\vec{x}') \times \vec{B}(\vec{x}')}{4\pi |\vec{x} - \vec{x}'|} dS + \int_V \frac{\vec{\nabla} \times \vec{B}(\vec{x}')}{4\pi |\vec{x} - \vec{x}'|} dV$$

in the case of $\nabla \cdot B = \nabla \times B = 0$

⇒ volume integral term=0

3D field map is described by surface data.

shape of the surface is arbitrary.

all the three components are necessary.

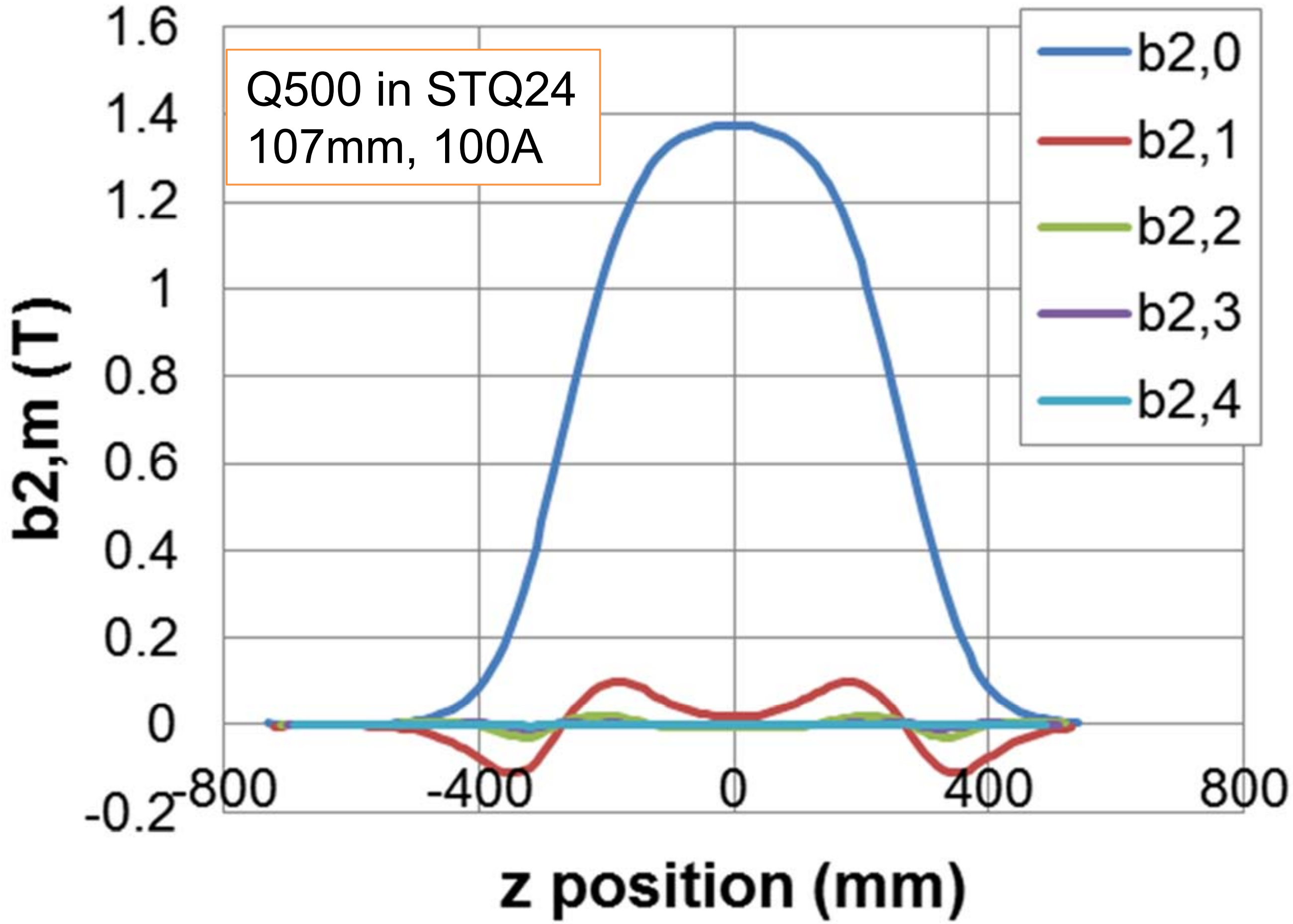
⟺

Our method

cylinder shape

only one component is sufficient

extracted $b_{2,0\sim4}$



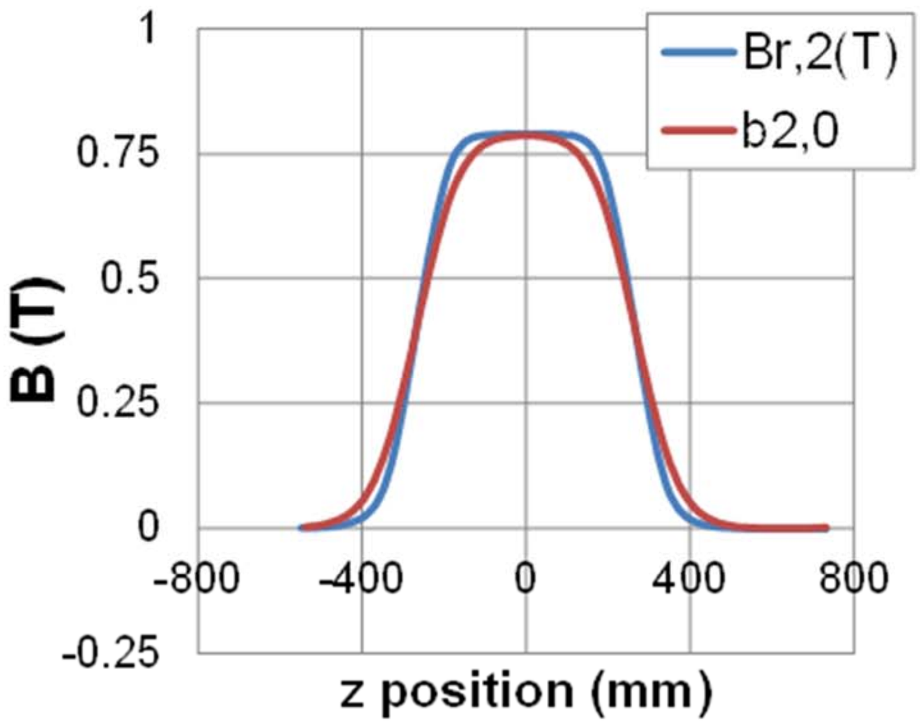
ratio to b2,0
- b2,1…7～8%
- b2,2…1～2%
- b2,3…0.3～0.5%
- b2,4…0.1～0.2%

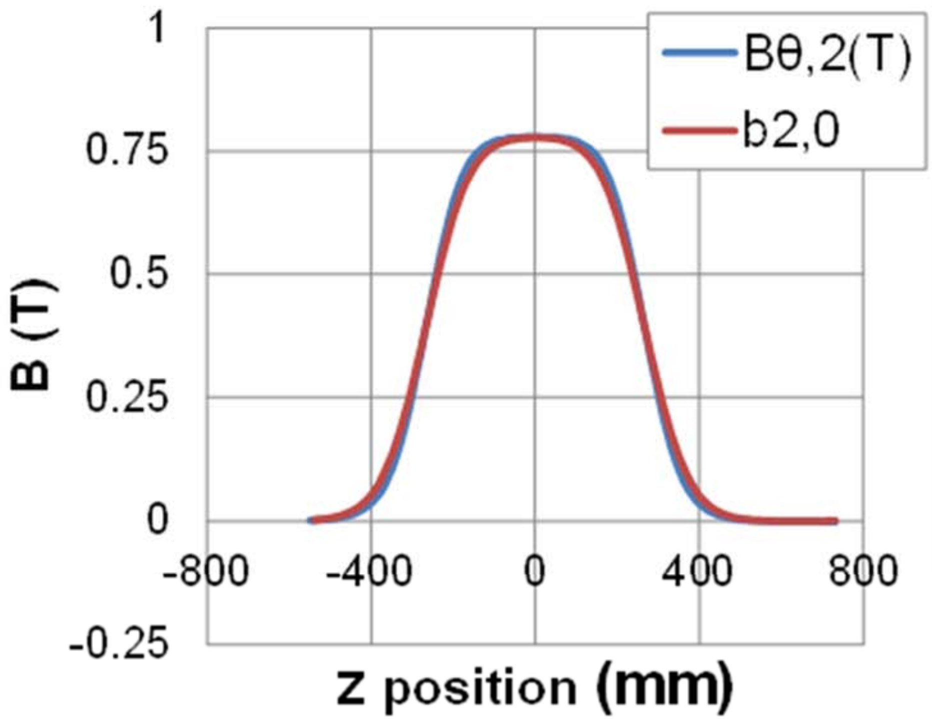
$$b_{n,m}(z) = -\frac{r_0^2}{4m(n+m)}\frac{n+2m}{n+2(m-1)}\frac{\partial^2}{\partial z^2}b_{n,m-1}(z).$$

Comparison between $B_{r,2}$, $B_{\theta,2}$ and $b_{2,0}$

$$B_{r,2}(r,z) = b_{2,0}(z)\left(\frac{r}{r_0}\right) + b_{2,1}(z)\left(\frac{r}{r_0}\right)^3 + b_{2,2}(z)\left(\frac{r}{r_0}\right)^5 + \cdots$$

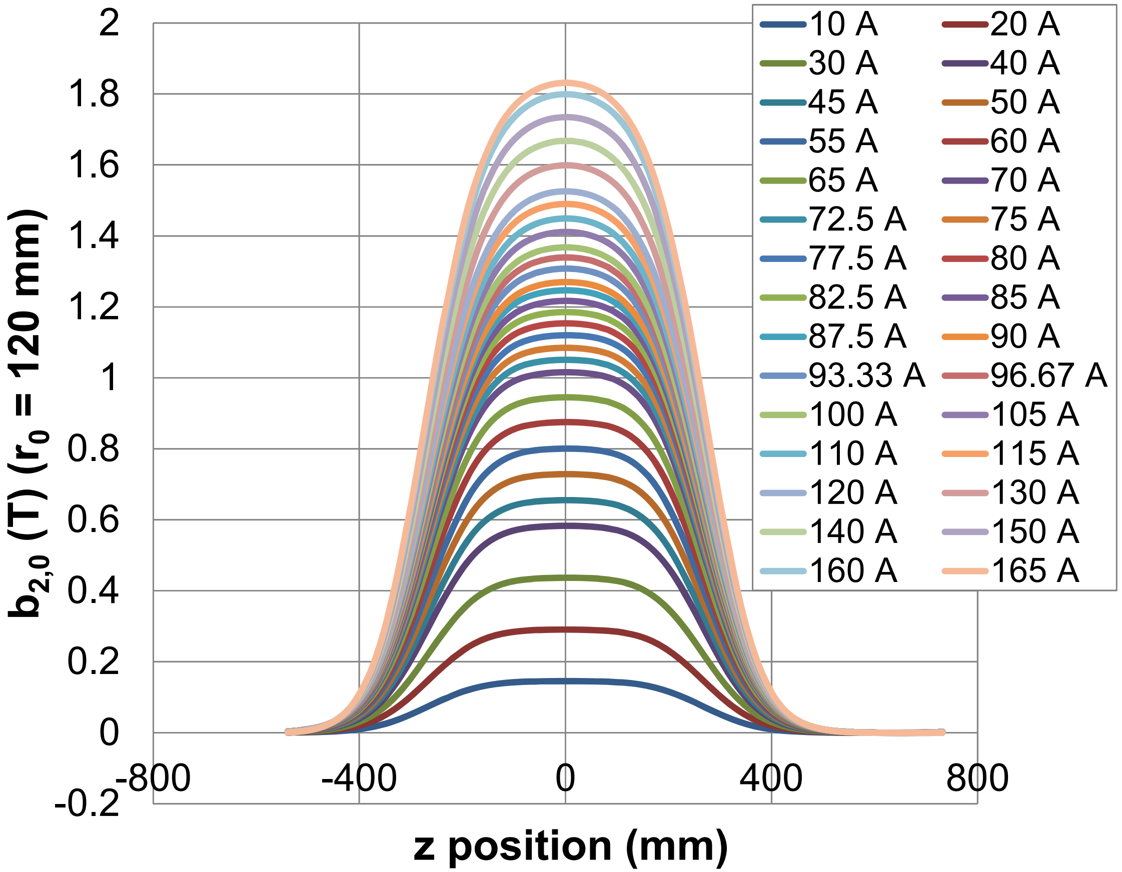
$$B_{\theta,2}(r,z) = b_{2,0}(z)\left(\frac{r}{r_0}\right) + \frac{2}{2+2}b_{2,1}(z)\left(\frac{r}{r_0}\right)^3 + \frac{2}{2+4}b_{2,2}(z)\left(\frac{r}{r_0}\right)^5 + \cdots$$





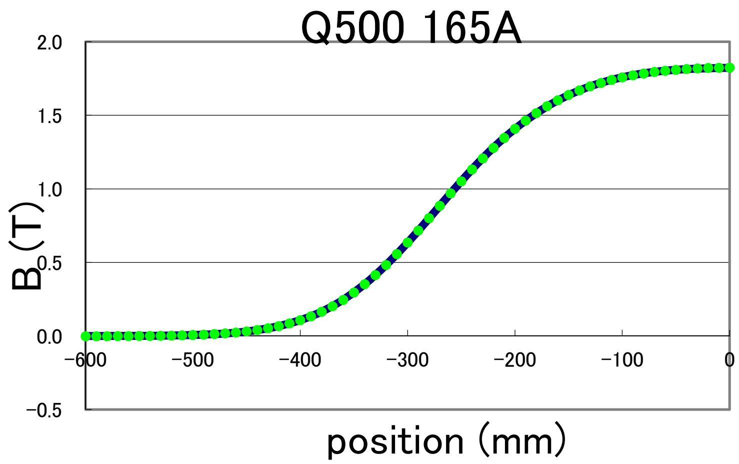
Q500 in STQ24, 107mm, 60A

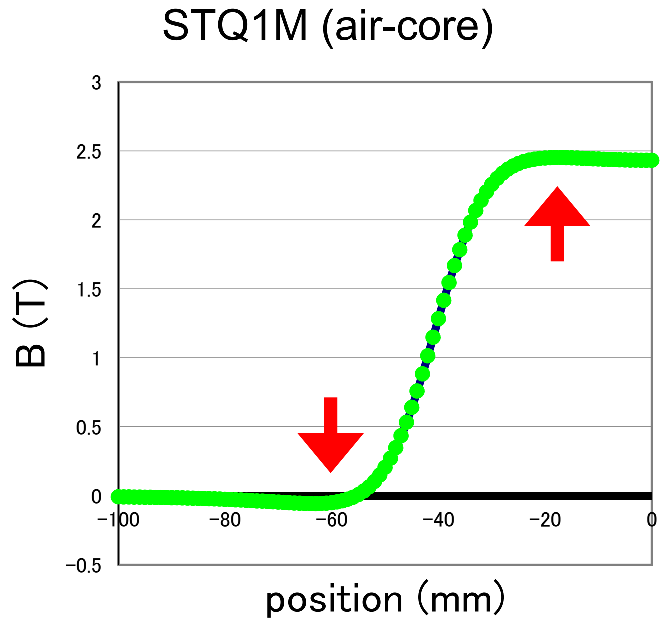
$b_{2,0}$ at different excitation currents



Fringing field fitting

Enge coefficients a_i are freely searched to minimize $\Sigma_i [b_{2,0}(z_i)-Enge(z_i)]^2$.





$$F(z)=\frac{1}{1+\exp\left[a_1+a_2(z/D)+\cdots+a_6(z/D)^5\right]}$$

(D : full aperture)

$$F(z)=\frac{1}{1+\exp\left[a_1+a_2(z/D)+\cdots+a_6(z/D)^5\right]}$$
$$+a_7\tanh\left(a_8+a_9(z/D)\right)\cdot\exp\left[-\left(\frac{z/D+a_{10}}{a_{11}}\right)^2\right]$$

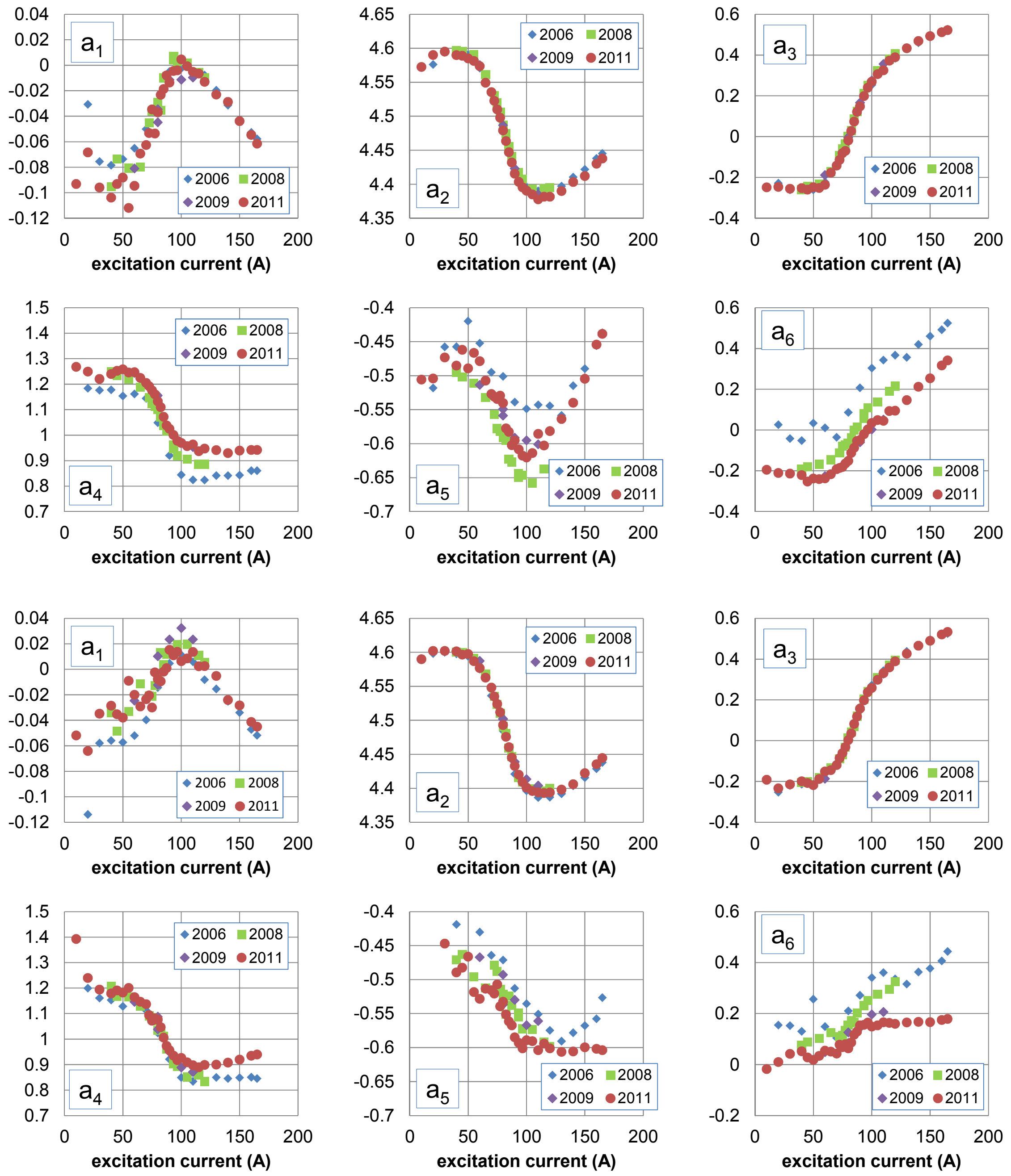
Folded expression
$b_{2,0}(z)=B_c$*Fin*Fout

→ implemented in COSY

Second term is introduced to express under- & overshooting shaped fields.

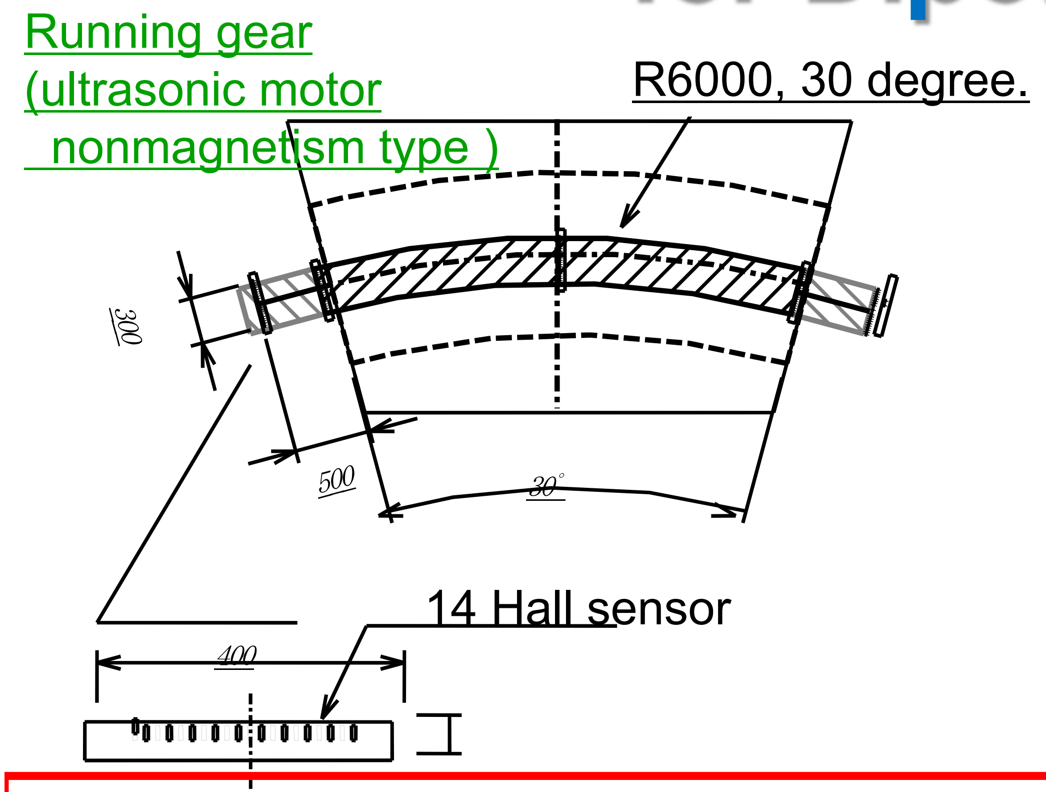
Q500 entry side

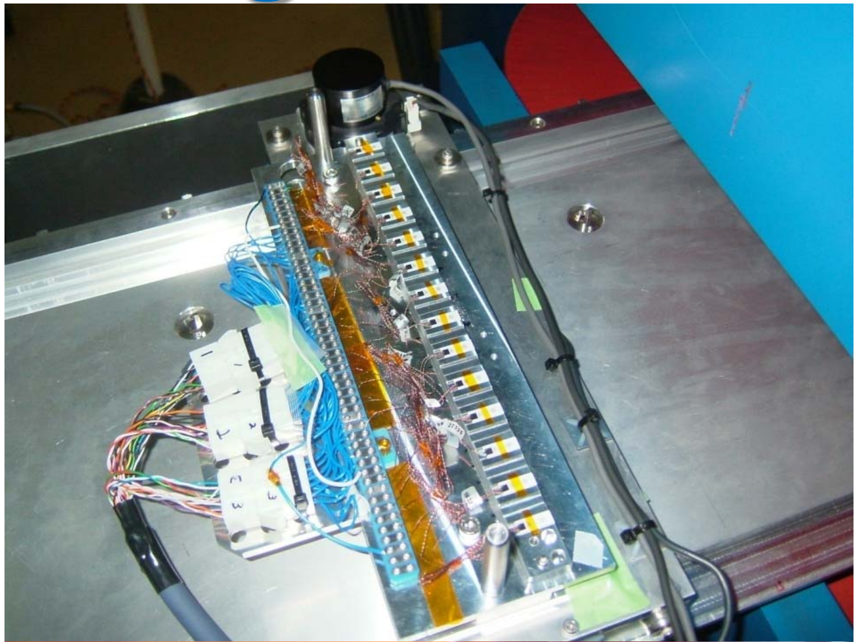
Q500 exit side

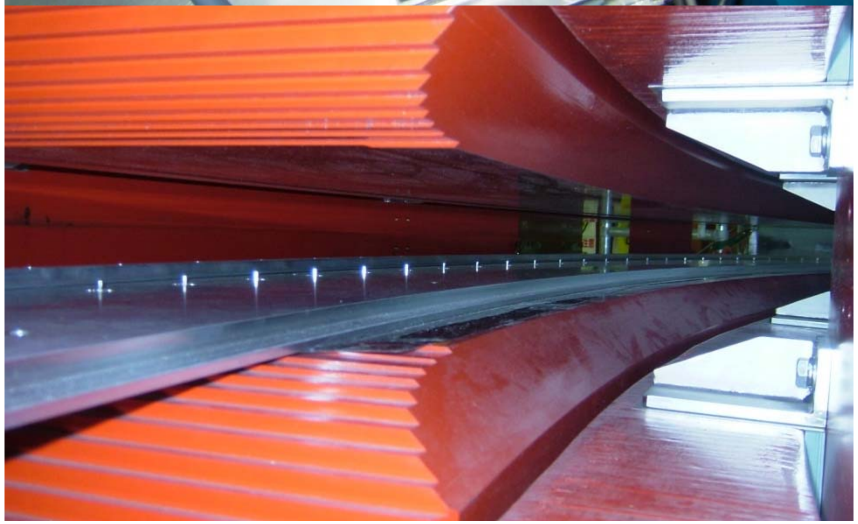


$b_{2,0}$ at any excitation current can be obtained by interpolating these Enge coefficients.

Magnetic field measurement for Dipole magnet



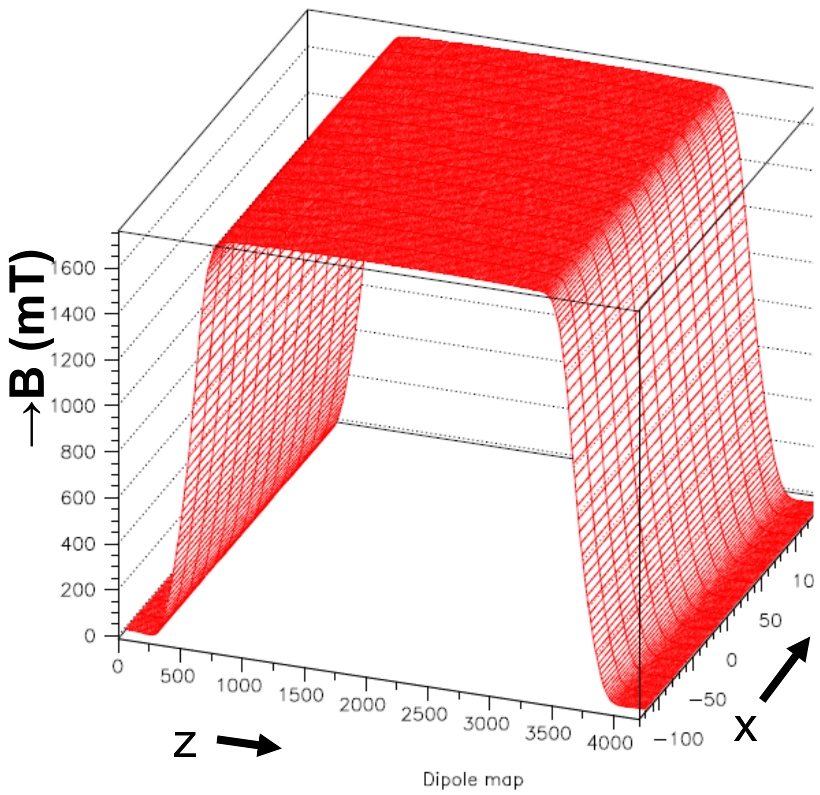




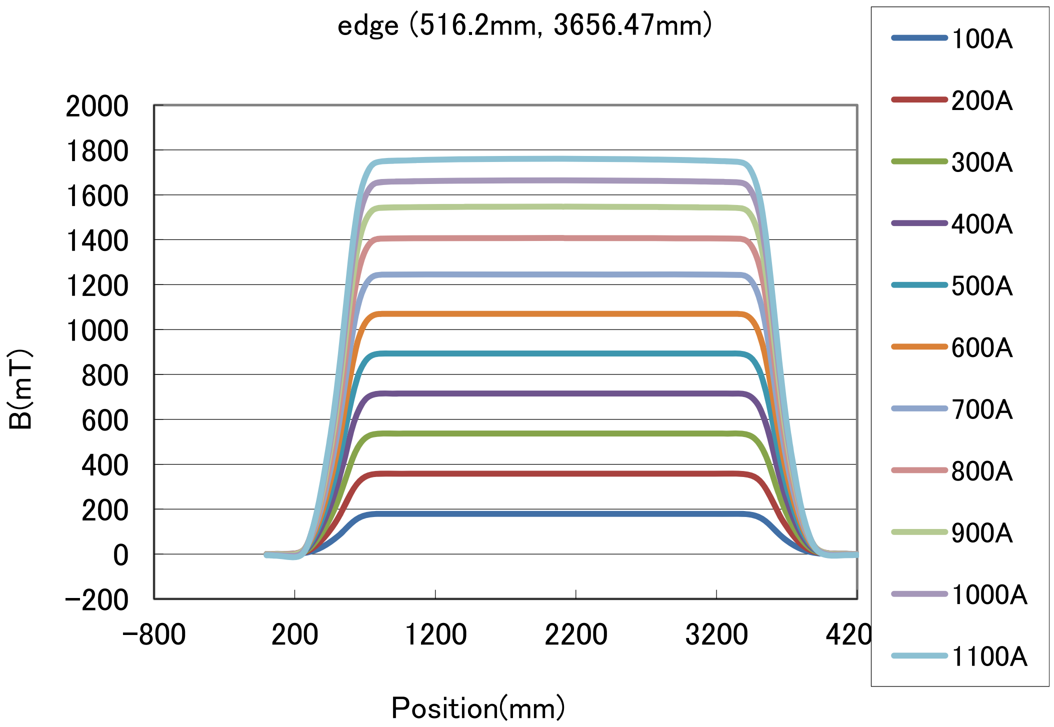
Measurement range : size of dipole ± 500mm
Interval of cross direction : 20mm (center 10mm)
Measurement plane : center, ±10mm, 20mm,
(Gap ±70mm) 30mm. 40mm
Measurement Magnetic field
100A to 1100 A interval to 100A

(by Y. Yanagisawa)

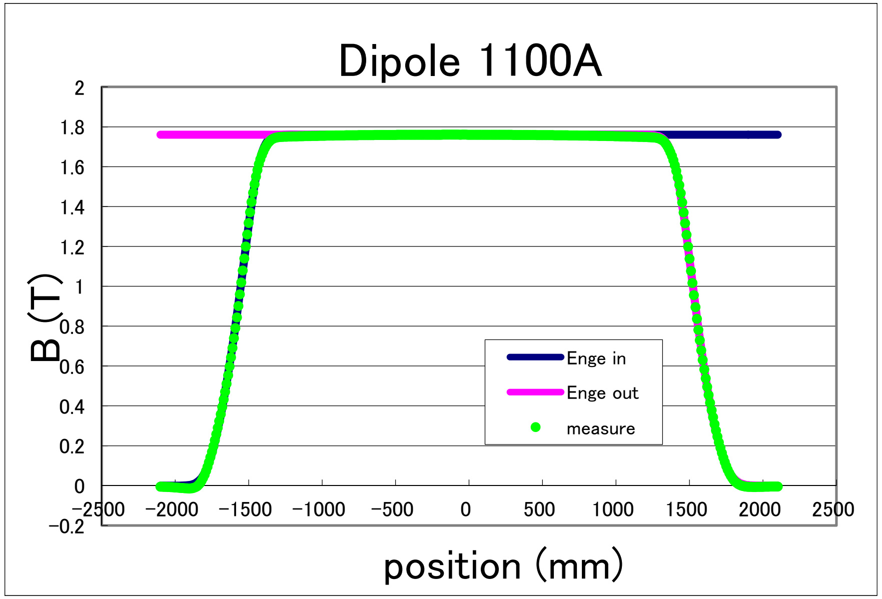
Dipole map

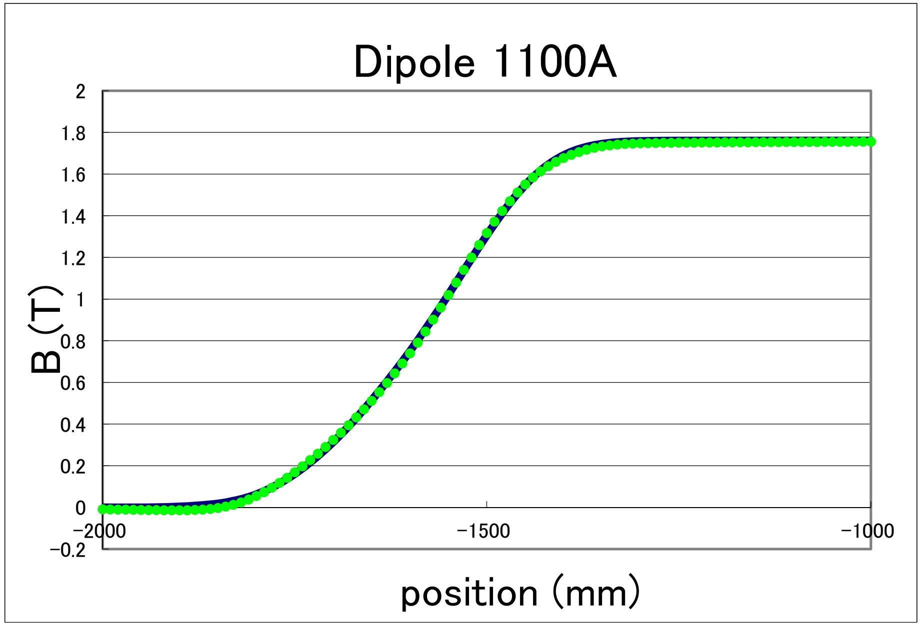


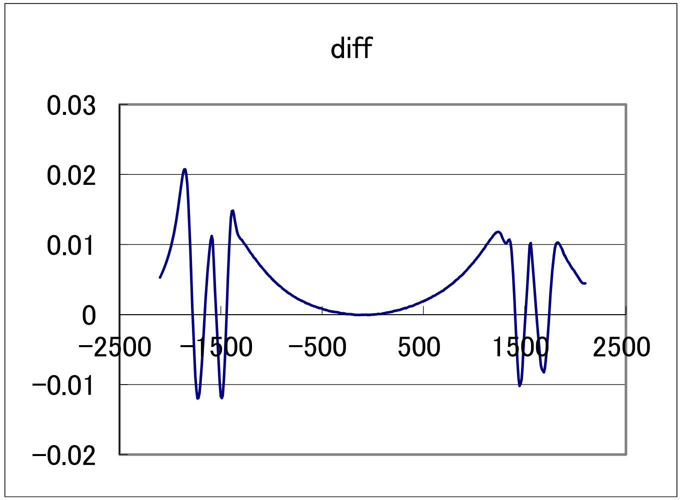
1100A



Fitting by Enge function



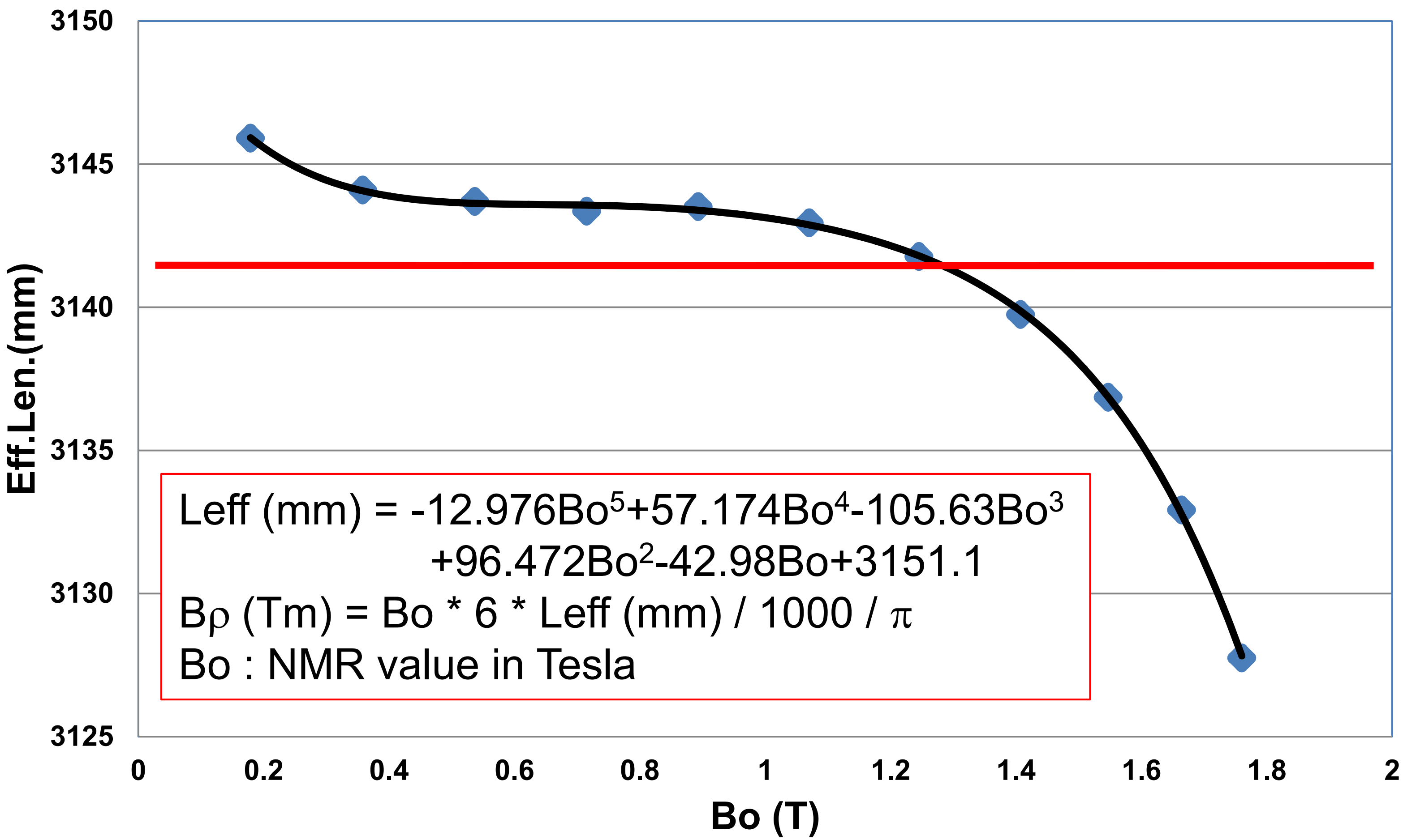




$$F(z) = \frac{1}{1 + \exp\left[a_1 + a_2 (z/D) + \cdots + a_6 (z/D)^5\right]}$$

→ implemented in COSY

Effective length of dipole

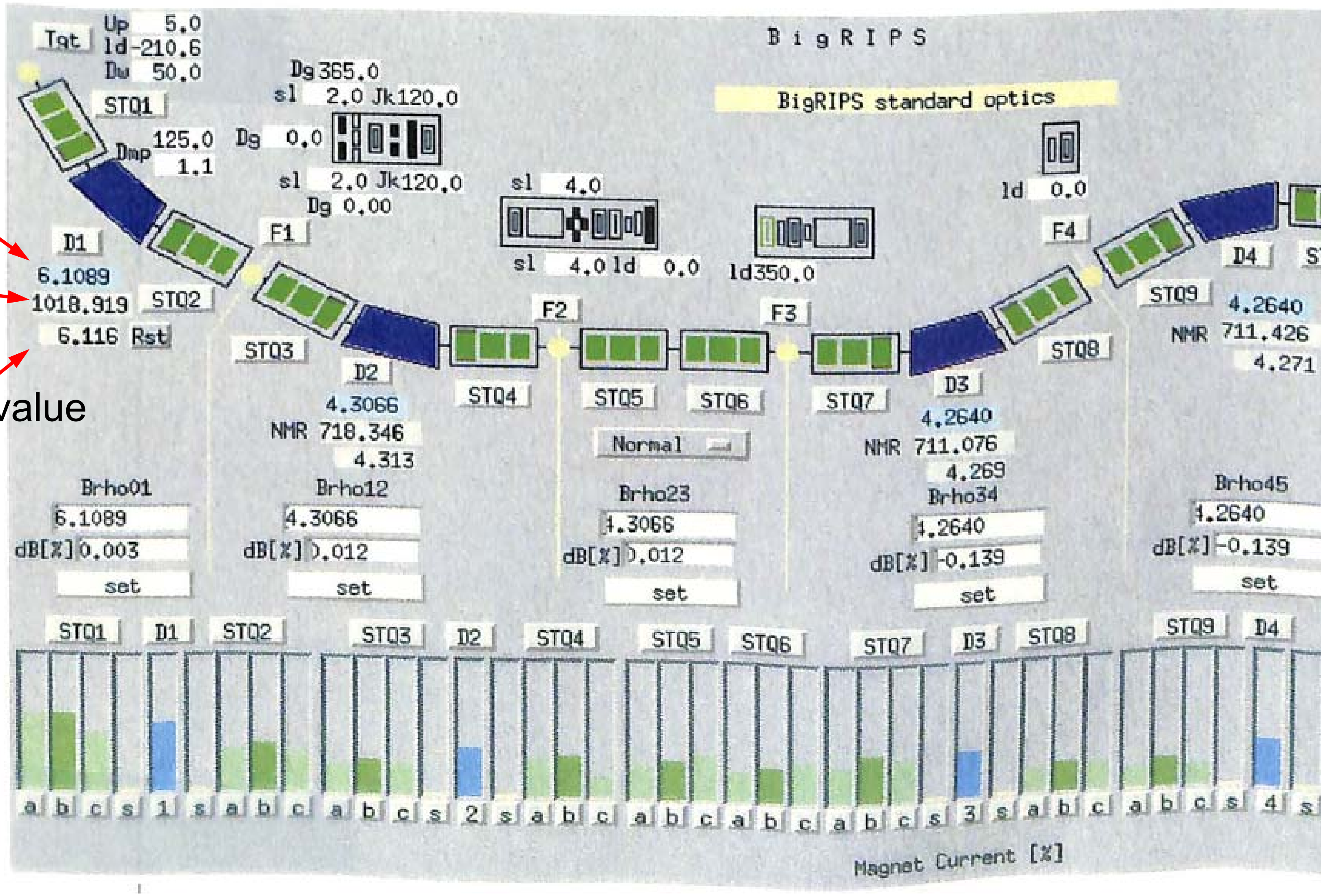


Bρ correction by effective length is important for absolute value determination of A/Q

Bρ set value

NMR value

corrected Bρ value



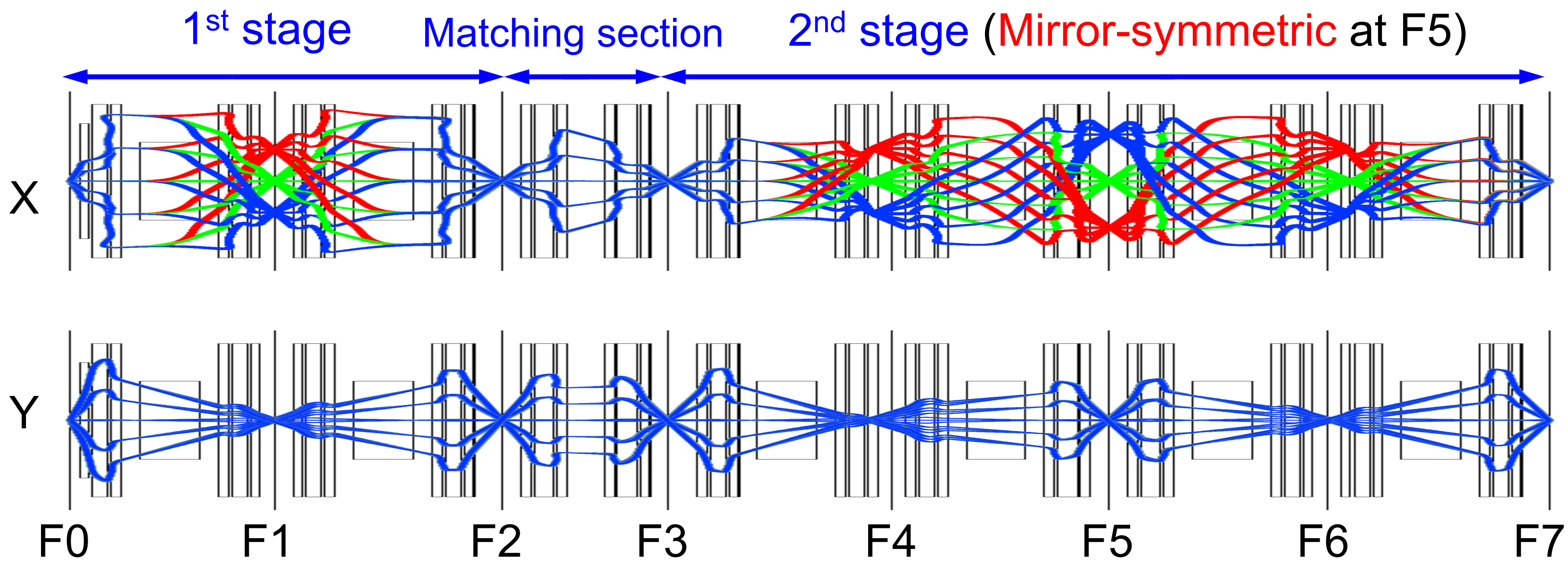
Magnet current settings for STQ

Set Bρ → field strength (B_{COSY})→ set current (I_{COSY})
↑ COSY fitting ↑ B-I curve

Repeat in 0.5Tm steps to find Bρ-B function for each quadrupole.
These functions are prepared for each optical mode.
B-I curves are implemented in magnet control system (EPICS).
Thus currents of all magnets are set by just putting Bρ value.

Quality of Bρ-B function is very important.
Sometimes Bρ-B function results in uneven behavior, which causes unexpected optical conditions (out of focus, etc).
Disagreement between experiment and COSY becomes large in such cases.

Required conditions for the standard BigRIPS mode



F0F1

(x|x)=-1.7, (x|a)=0,
(y|y)=-5.0, (y|b)=0,
(x|δ)=-21.4 mm/%, (a|δ)=0

F0F2

(x|x)=2.0, (x|a)=0,
(y|y)=1.6, (y|b)=0,
(x|δ)=0 mm/%, (a|δ)=0

F2F3

(x|x)=-1.08, (y|y)=-1.18,
(x|a)=(y|b)=(a|x)=(b|y)=0

F3F4

(x|x)=-1.40, (x|a)=-0.791,
(y|y)=-3.45, (y|b)=-0.272,
(x|δ)=-22.1 mm/%, (a|δ)=0

F3F5

(x|x)=0.92, (x|a)=0,
(y|y)=1.06, (y|b)=0,
(x|δ)=31.7 mm/%, (a|δ)=0

P/ΔP =
1260 (1st stage)
3420 (2nd stage)

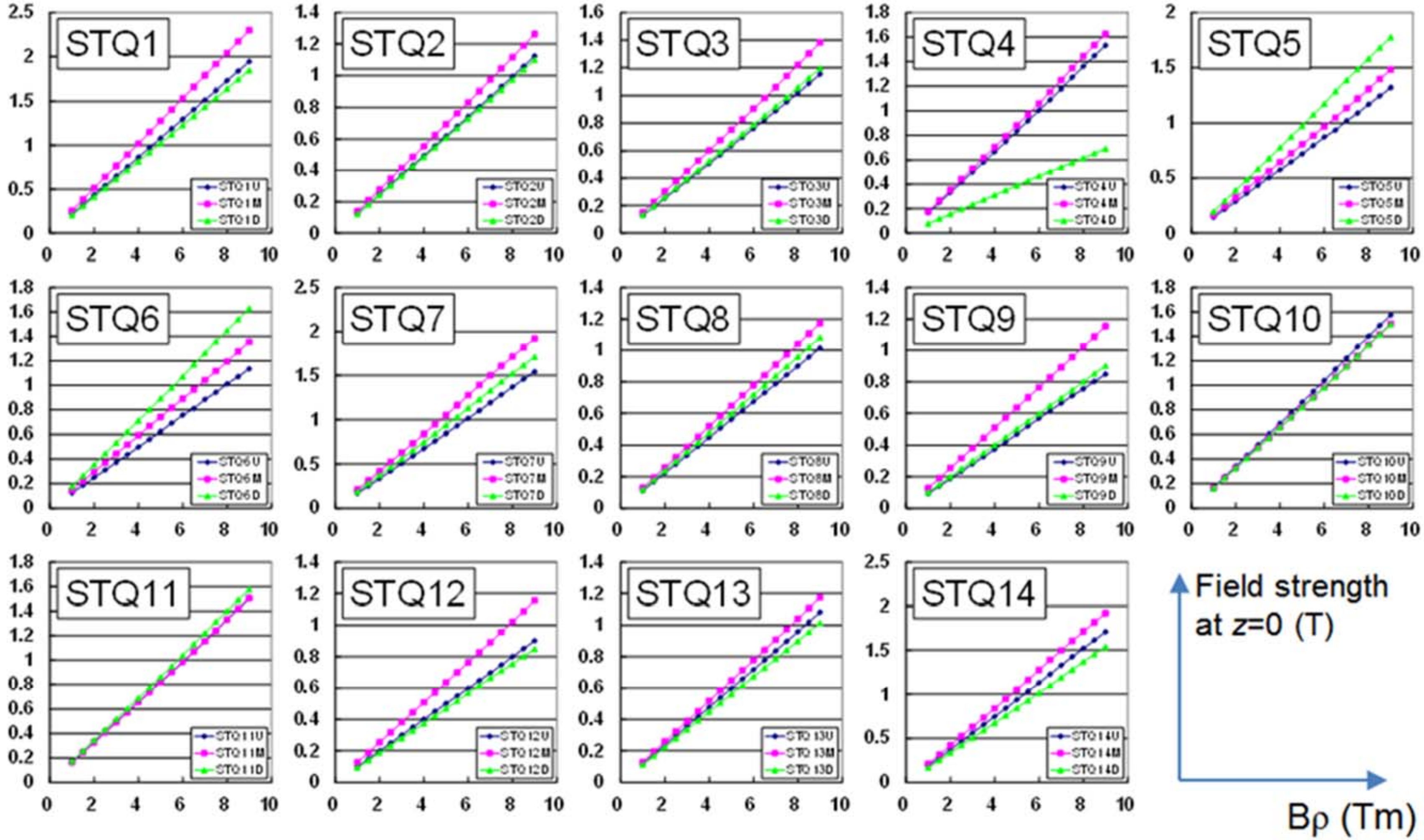
Mirror-symmetric setting of F3-F5

F7F6 ←

F7F5 ←

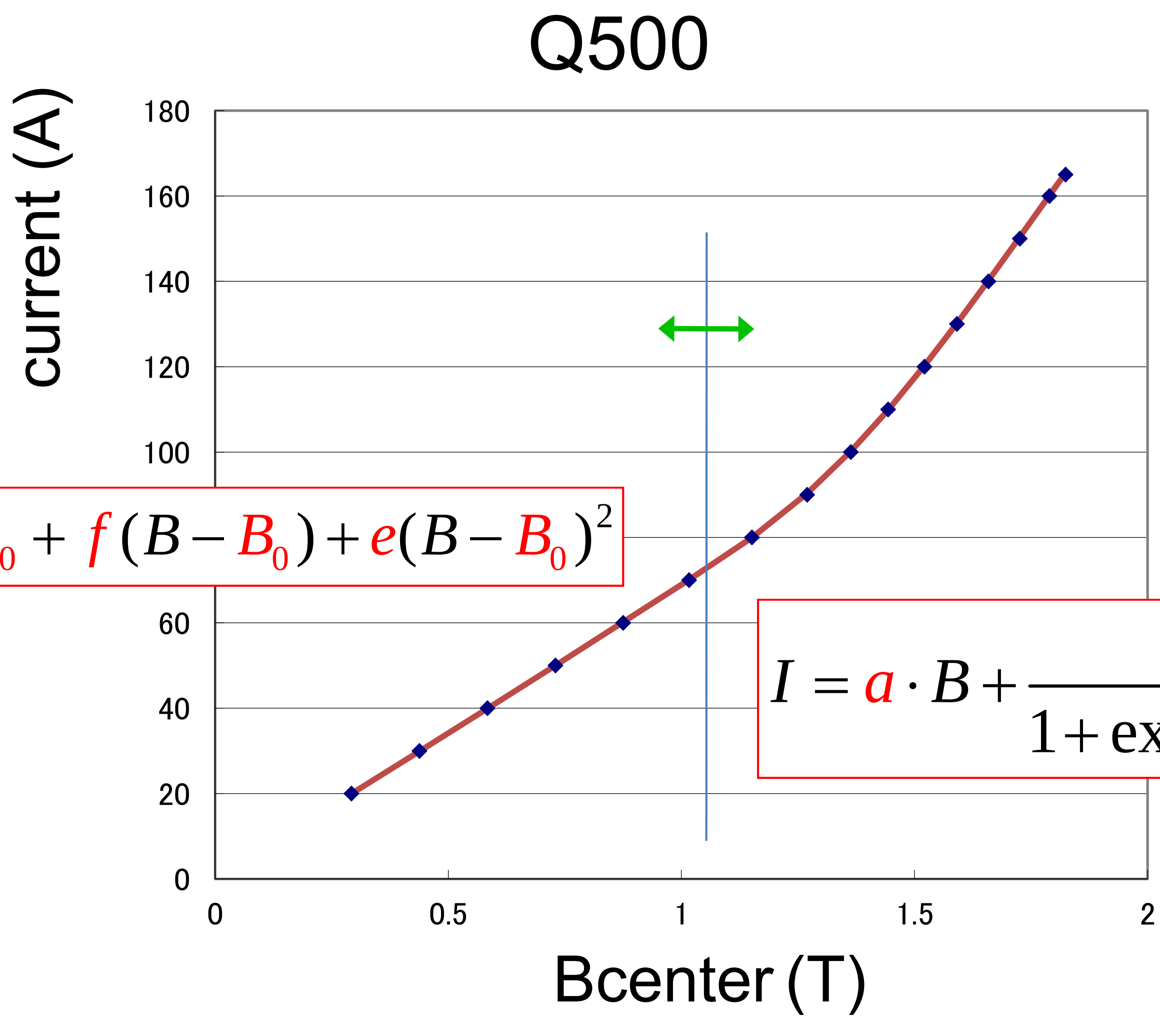
Field strengths of the three quadrupoles in each STQ

(BigRIPS standard mode)



Slope and offset parameters are implemented in the magnet control system (EPICS)

B-I curve



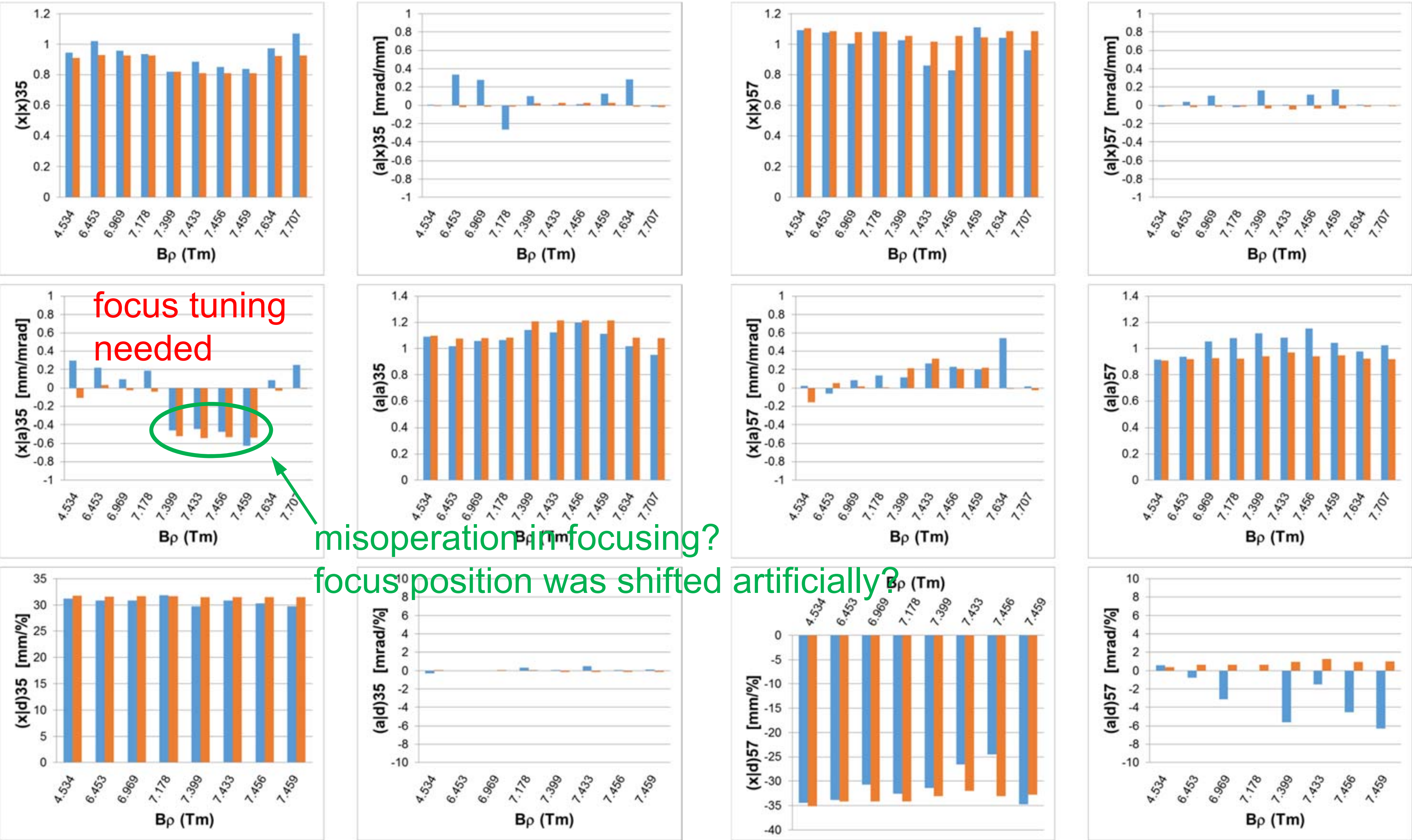
$$I = I_0 + f(B - B_0) + e(B - B_0)^2$$

$$I = a \cdot B + \frac{b \cdot (B - c)}{1 + \exp[-d \cdot (B - c)]}$$

- same for other super-ferric quadrupoles and dipoles
- linear functions are used for air-core quads

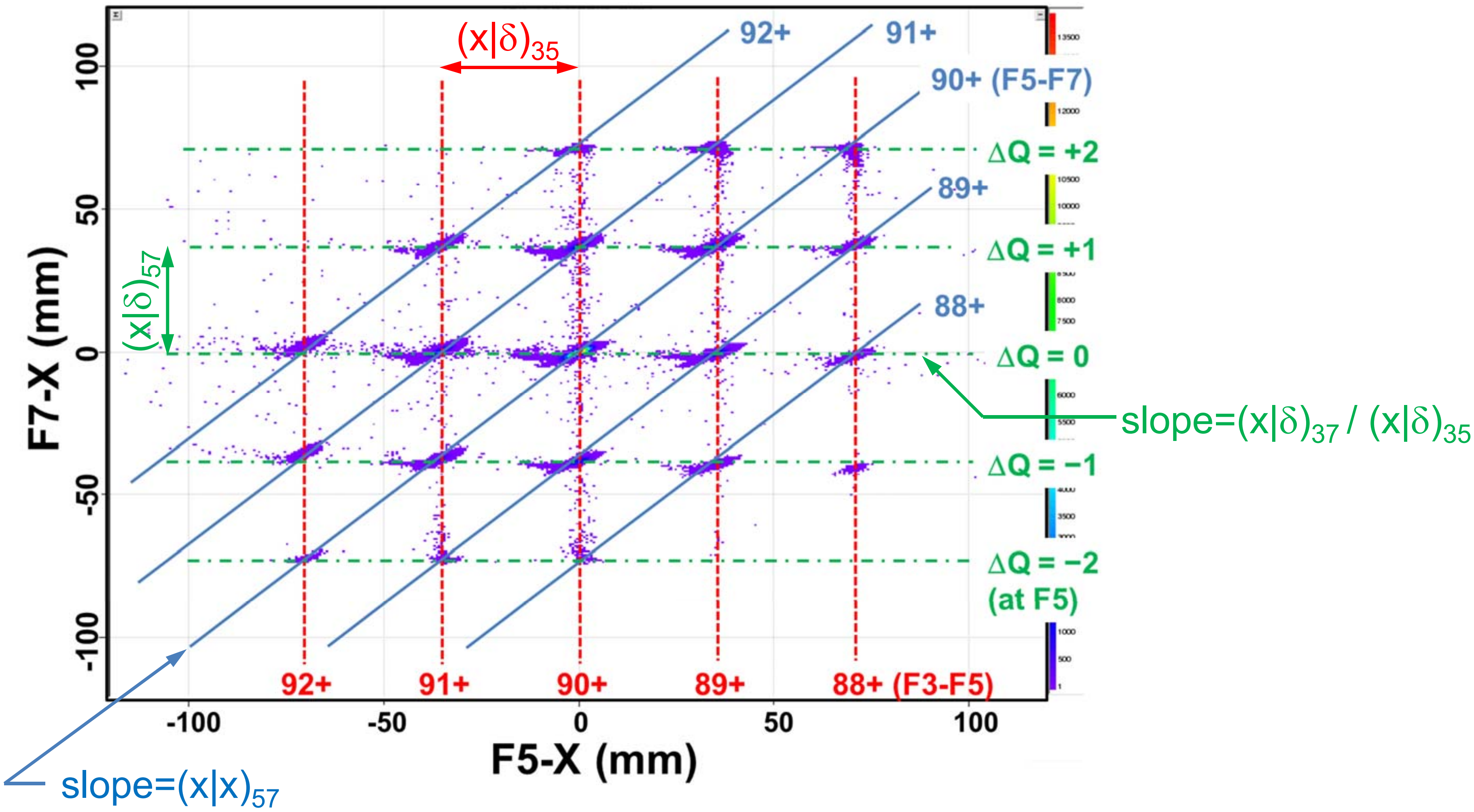
Transfer matrix elements

F3-F5 F5-F7

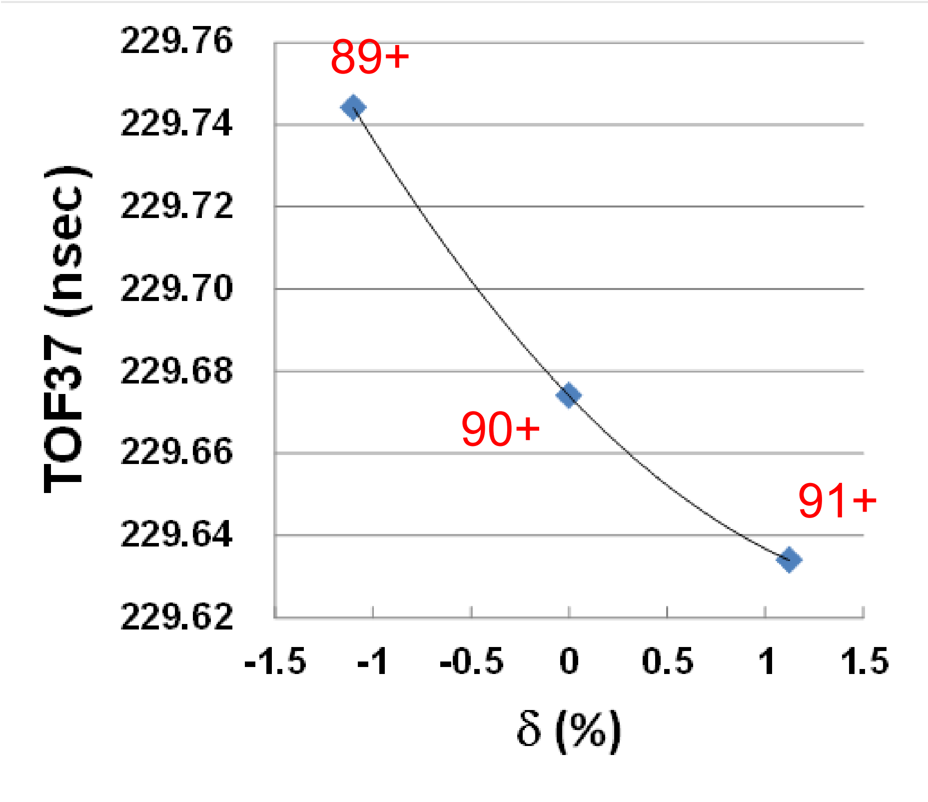


measured COSY

transfer matrix measurement with ^{238}U primary beam



(L|δ) measurement with primary beam



All the charge states have the same velocity.
Flight-path-length difference can easily be deduced by the TOF measurements.

(TOF|δ) = -0.0498ns/%
→ (L|δ) = -10.2mm/%
(COSY: -6.5mm/%)

Summary & Issues

- Large aperture, short length, strong field magnets are used in BigRIPS
- 3D magnetic field is successfully extracted from 2D surface data on a cylinder
  - quadrupole and higher multipoles
- successfully applied to ion-optics of BigRIPS
- room for further improvement in focusing
- similar procedure for dipole?
  - curved reference orbit