Hardware Magnet

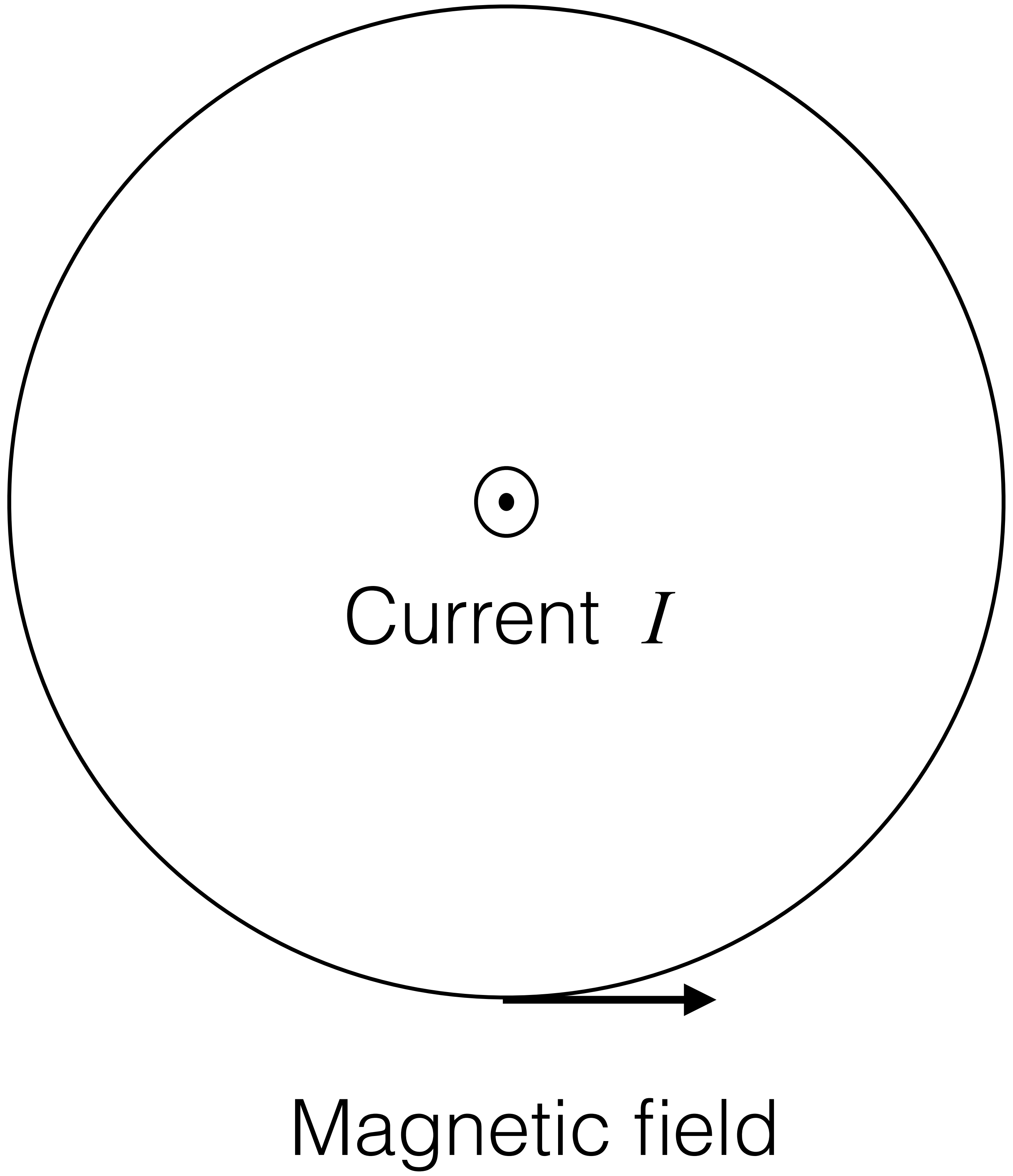
practical examples and some stories at KURNS

Ishi, Yoshihiro 27 Sep. 2022

outline

- Basics of magnet designing
  - you can find many excellent references in OHO, CAS, etc.
  - e.g. CAS 2006 S. Russenschuck p410
- FFA magnet
- Practical examples at KURNS
- Learnings from the Commissioning and Operations

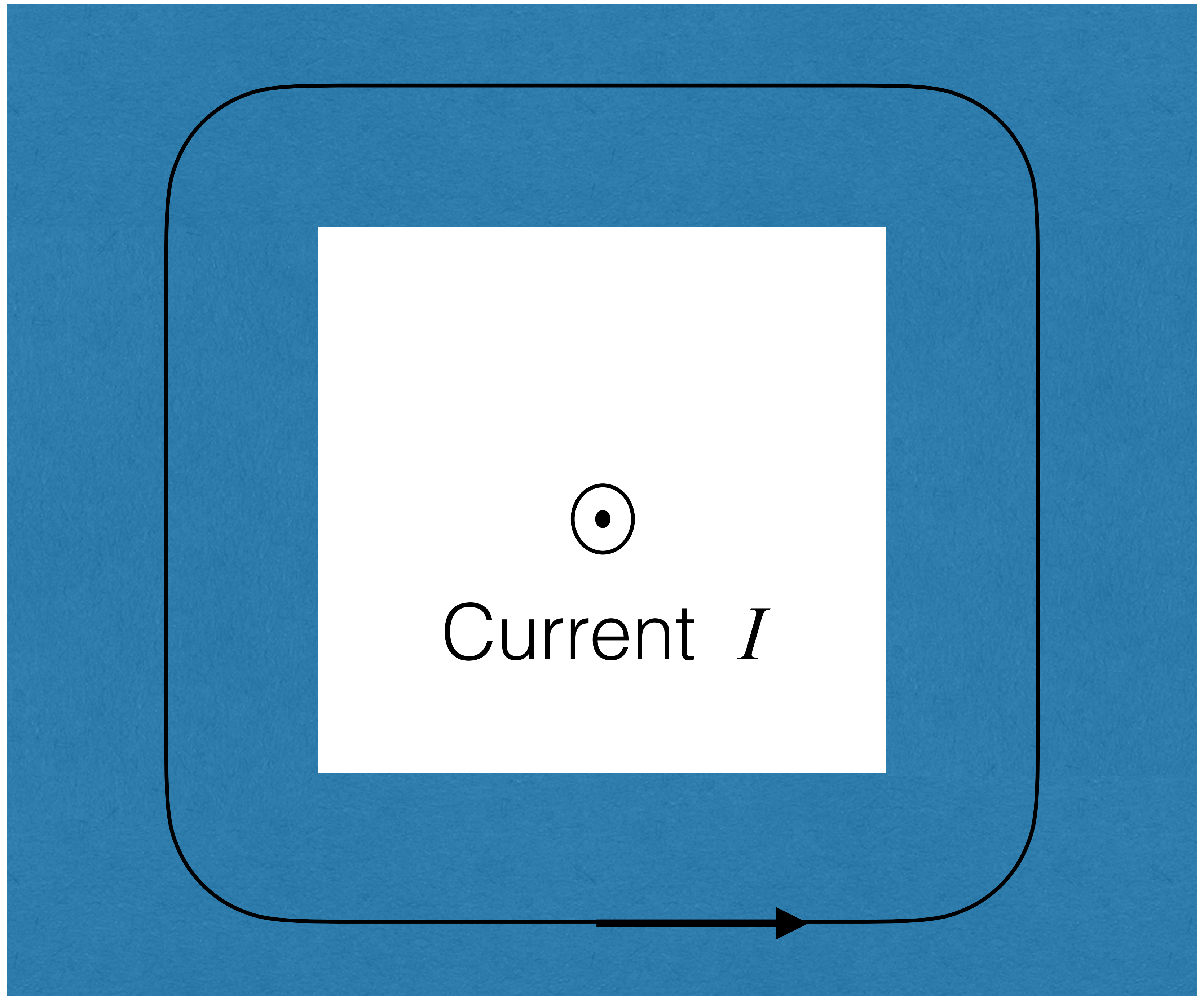
Basics of magnet designing



$$
\begin{aligned}
\boldsymbol{J} &= \mathrm{rot}\boldsymbol{H} \\
I &= \int_S \mathrm{rot}\boldsymbol{H}\cdot d\boldsymbol{s} \\
I &= \oint \boldsymbol{H}\cdot d\boldsymbol{l}
\end{aligned}
$$

$$I = \int_S \boldsymbol{J}\cdot d\boldsymbol{s}$$

Basics of magnet designing

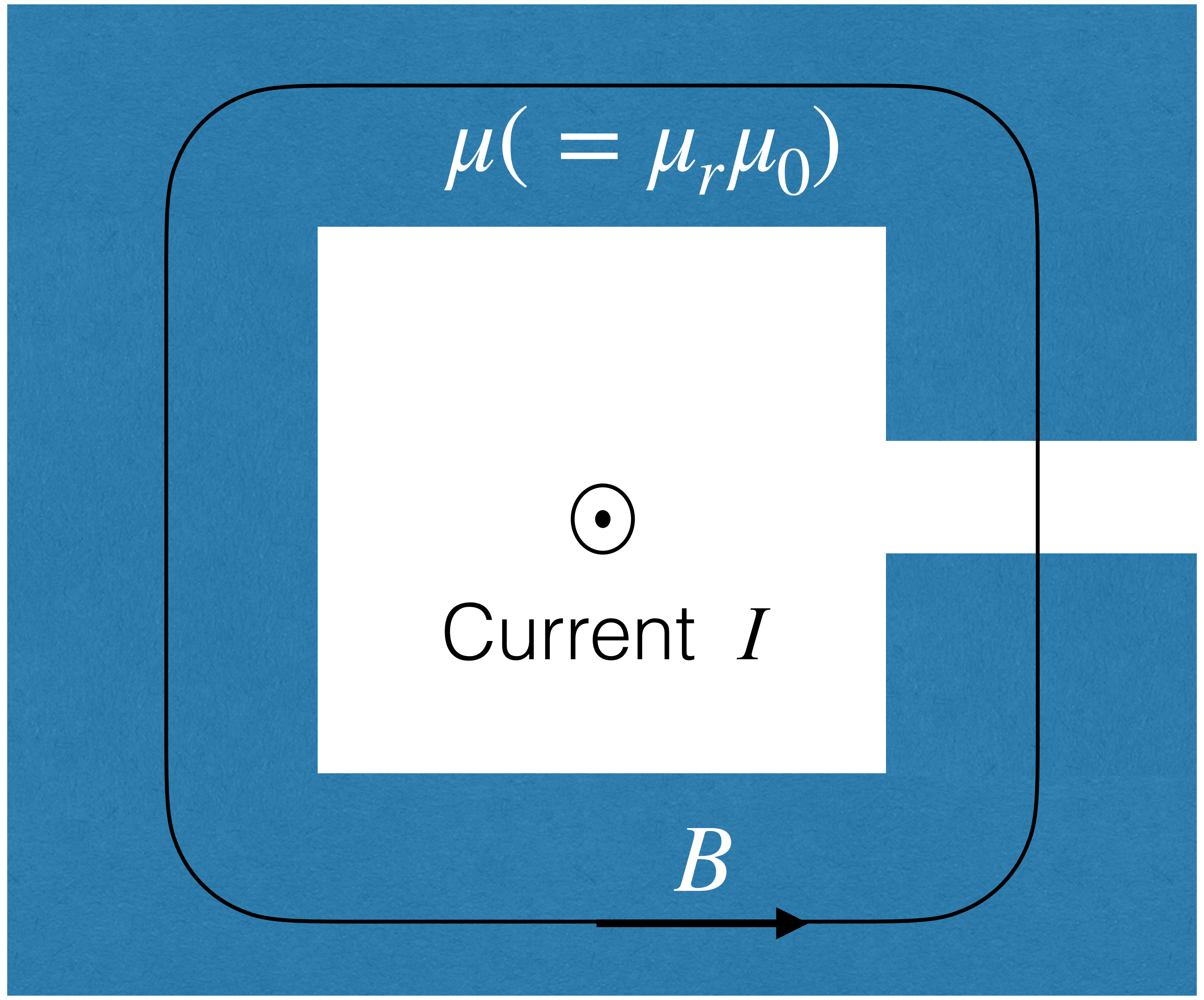


Magnetic field

$$\begin{aligned} \boldsymbol{J} &= \mathrm{rot}\,\boldsymbol{H} \\ I &= \int_S \mathrm{rot}\,\boldsymbol{H} \cdot d\boldsymbol{s} \\ I &= \oint \boldsymbol{H} \cdot d\boldsymbol{l} \end{aligned}$$

$$I = \int_S \boldsymbol{J} \cdot d\boldsymbol{s}$$

Basics of magnet designing



Magnetic field

$$\boldsymbol{J} = \mathrm{rot}\,\boldsymbol{H} \qquad I = \int_S \boldsymbol{J}\cdot d\boldsymbol{s}$$

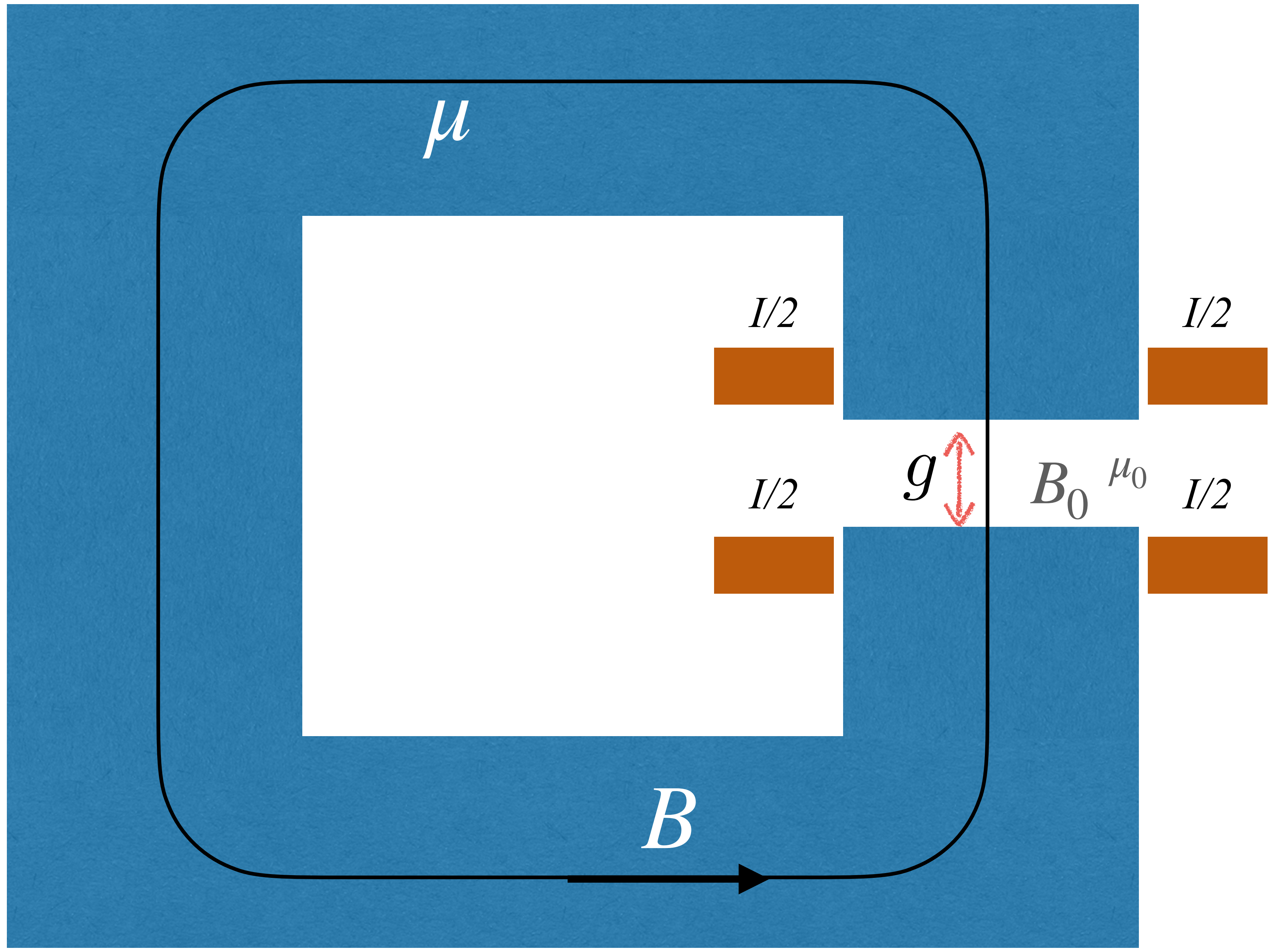
$$I = \int_S \mathrm{rot}\,\boldsymbol{H}\cdot d\boldsymbol{s}$$

$$I = \oint \boldsymbol{H}\cdot d\boldsymbol{l}$$

$$= \cancel{\int_{\mathrm{iron}} \frac{\boldsymbol{B}}{\mu}\cdot d\boldsymbol{l}} + \int_{\mathrm{air}} \frac{\boldsymbol{B}_0}{\mu_0}\cdot d\boldsymbol{l}$$

$$\mu >> \mu_0 \qquad \frac{\mu}{\mu_0} \sim 10^2 - 10^4$$

Basics of magnet designing



Magnetic field

total current

$$I = Ni = \frac{B_0}{\mu_0} h$$

coil turn number

gap height

B_0 : 1.0 T

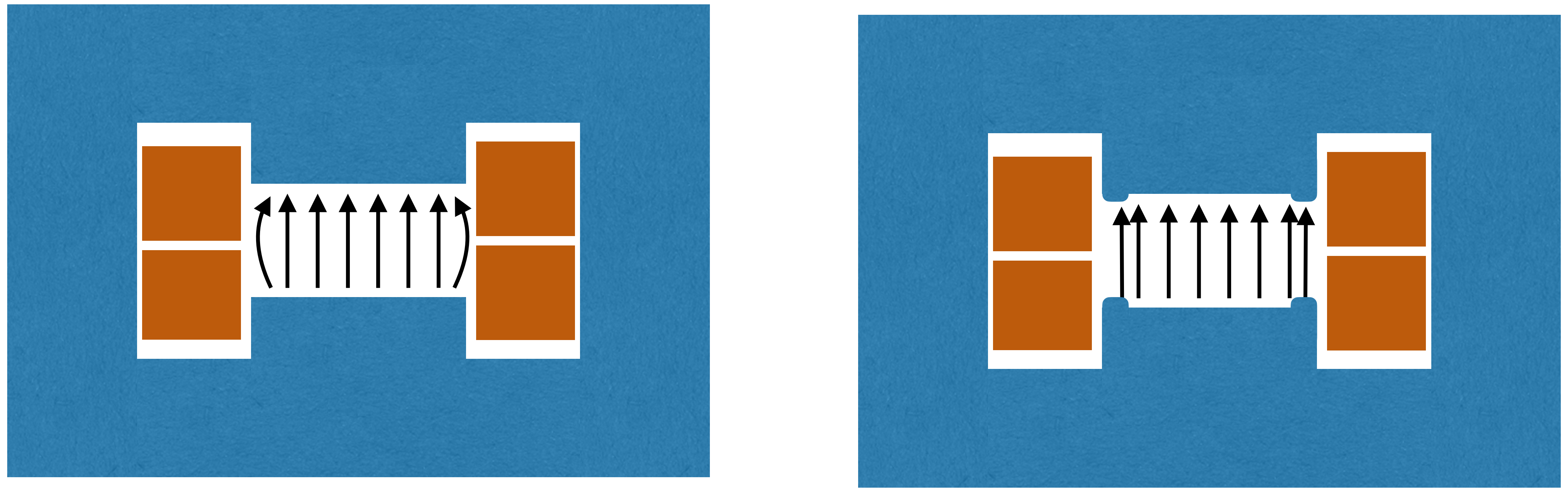
h : 0.1 m

μ_0 : $4\pi \times 10^{-7}$ H/m

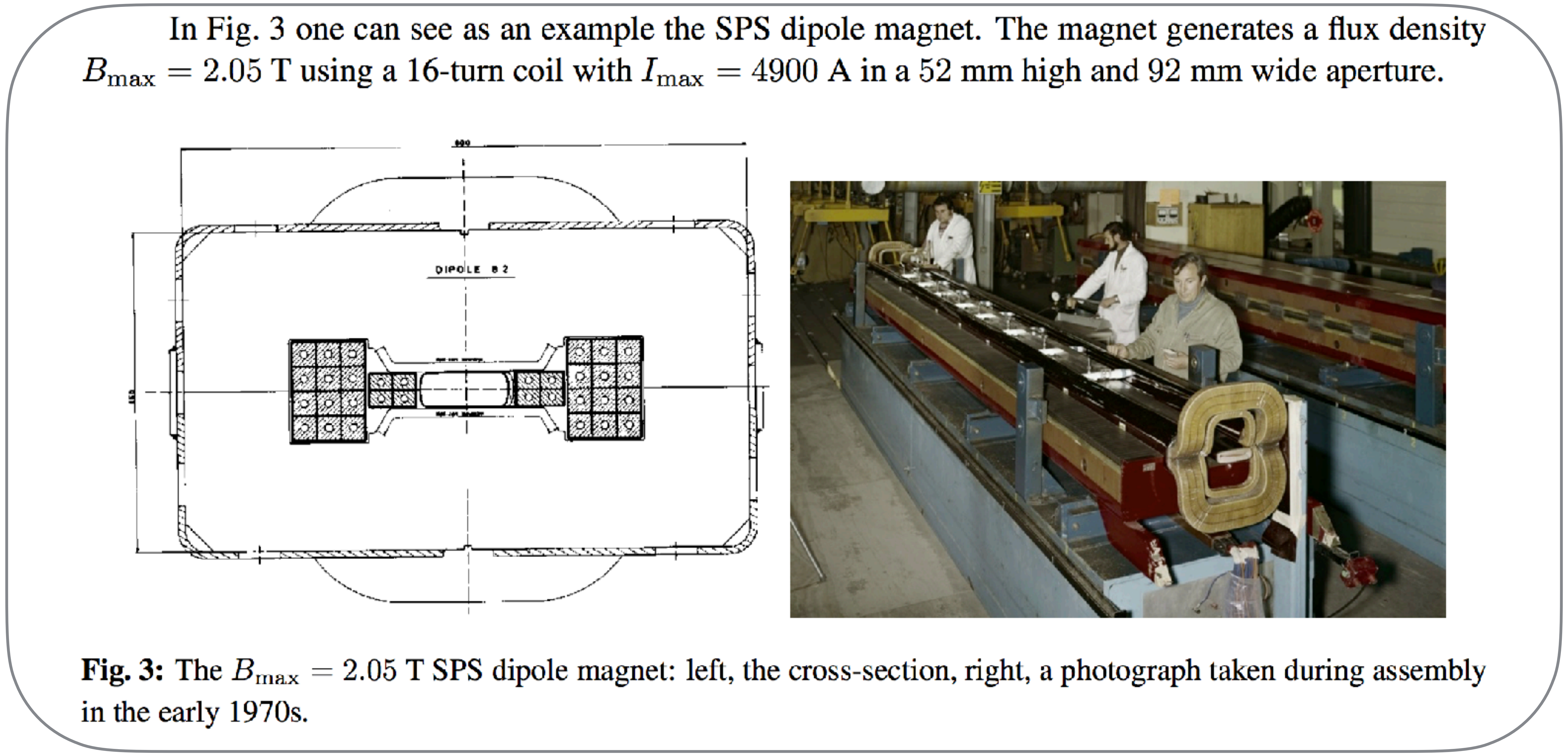
I : 8×10^4 A

Bending Magnet

H型



$$\frac{\Delta B}{B} \sim 1.0 \times 10^{-4}$$



In Fig. 3 one can see as an example the SPS dipole magnet. The magnet generates a flux density $B_{\mathrm{max}} = 2.05$ T using a 16-turn coil with $I_{\mathrm{max}} = 4900$ A in a 52 mm high and 92 mm wide aperture.

Fig. 3: The $B_{\mathrm{max}} = 2.05$ T SPS dipole magnet: left, the cross-section, right, a photograph taken during assembly in the early 1970s.

銅ホローコンダクター

G. de Rijk “High-field Accelerator Magnets “Published by CERN in the Proceedings of the CAS-CERN Accelerator School: Advanced Accelerator Physics, Trondheim, Norway, 19–29 August 2013, edited by W. Herr, CERN-2014-009 (CERN, Geneva, 2014)

Quadrupole Magnet

function：focus or defocus the beam
field distribution：linear (ideally)

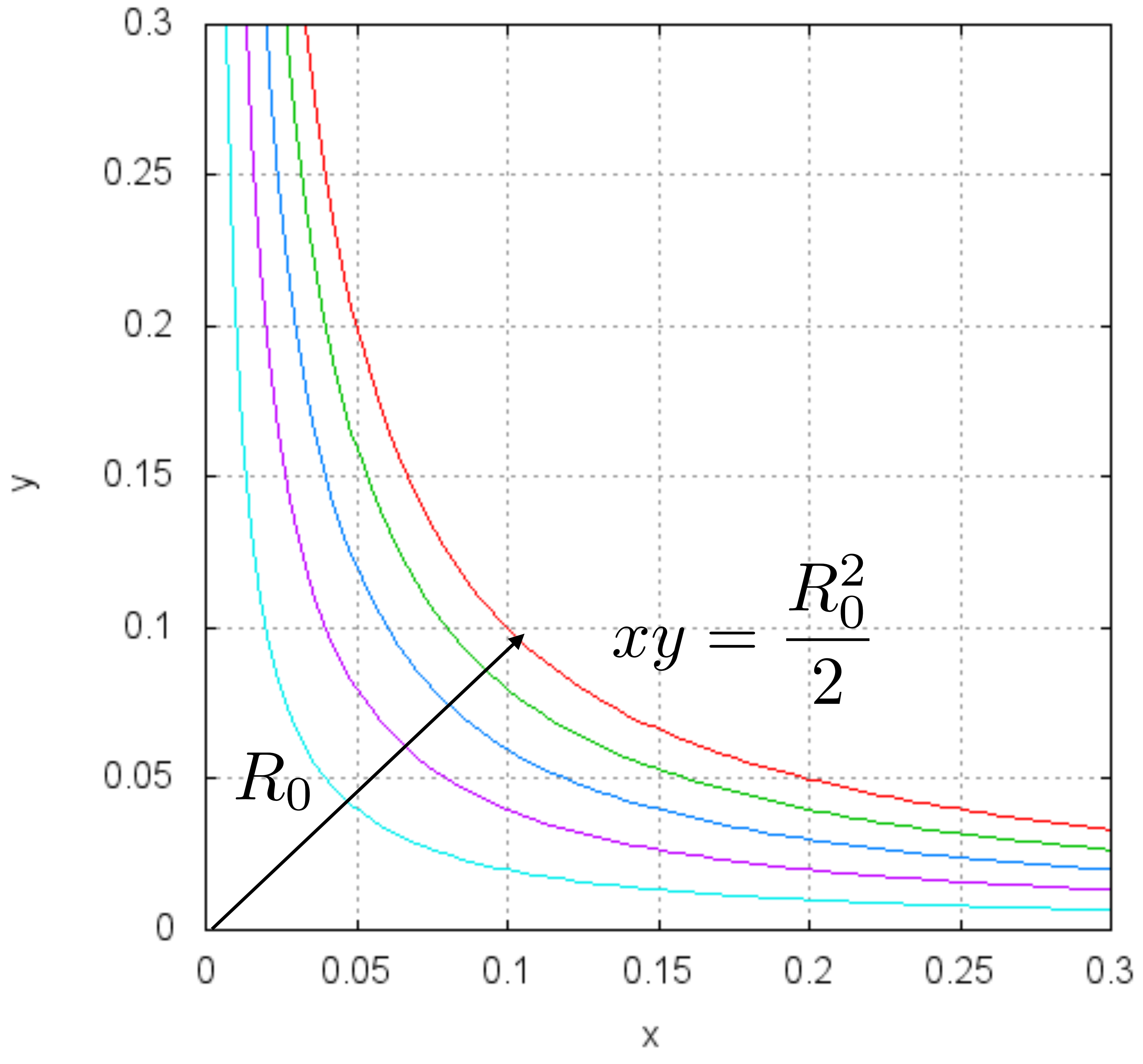
$$B_y(x,y,s) = ax$$
$$B_x(x,y,s) = ay$$

Fields which does not have divergence can be expressed by the rotation of any vector fields(vector potential), while fields without rotation can be expressed as the gradient of any scaler filed $\Phi(x,y)$ (scaler potential).

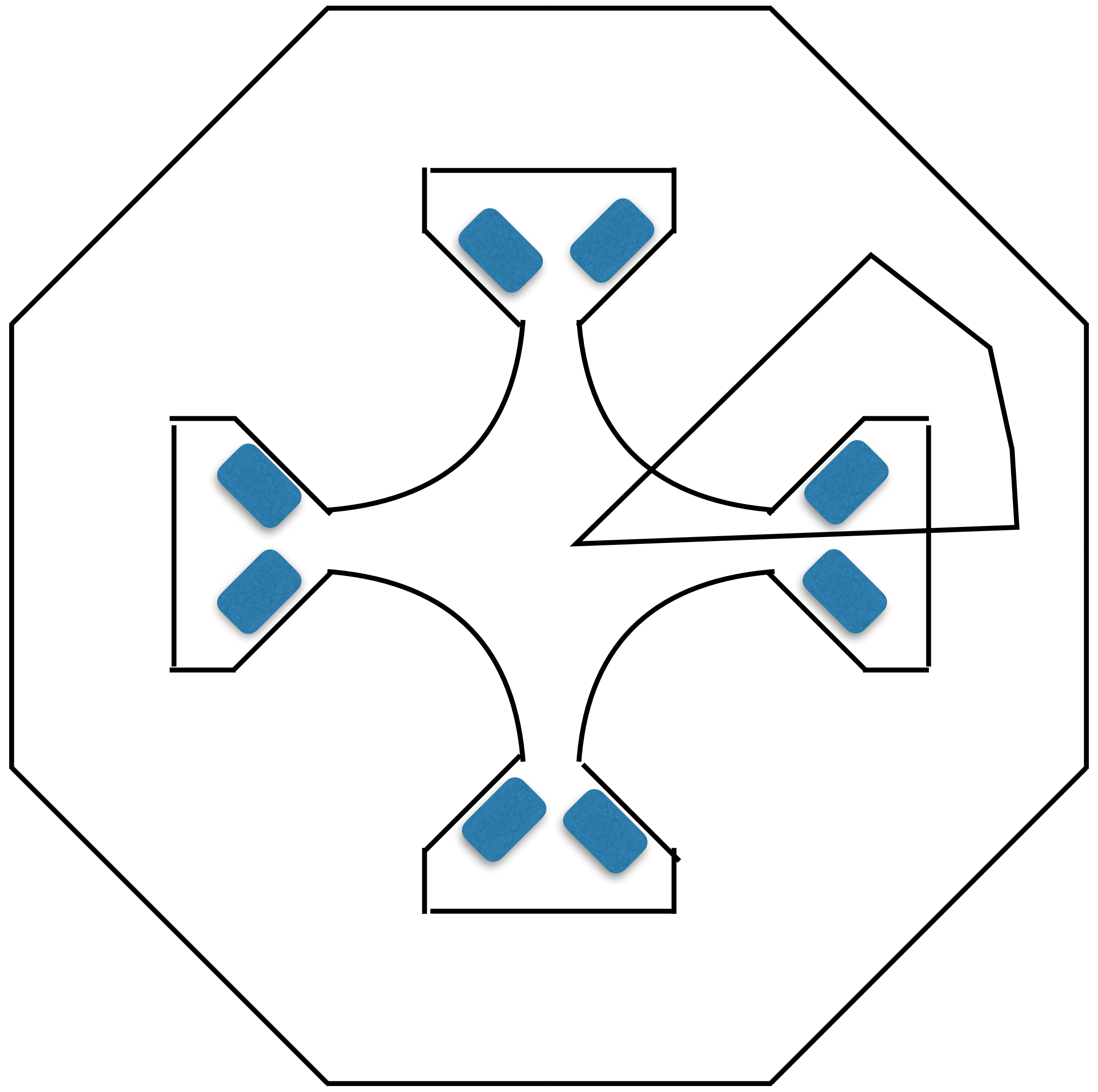
$$\Phi = -axy$$

$$B_x(x,y) = -\frac{\partial\Phi(x,y)}{\partial x}$$
$$B_y(x,y) = -\frac{\partial\Phi(x,y)}{\partial y}$$

pole surface should be set to one of the equipotential surface.



Quadrupole Magnet



$$I = \int_S \boldsymbol{J} \cdot d\boldsymbol{s}$$

$$\begin{aligned} \boldsymbol{J} &= \mathrm{rot}\boldsymbol{H} \\ I &= \int_S \mathrm{rot}\boldsymbol{H} \cdot d\boldsymbol{s} \\ I &= \oint \boldsymbol{H} \cdot d\boldsymbol{l} \\ I &= \int_{\mathrm{iron}} \frac{\boldsymbol{B}}{\mu} \cdot d\boldsymbol{l} + \int_{\mathrm{bore}} \frac{\boldsymbol{B}}{\mu_0} \cdot d\boldsymbol{l} \end{aligned}$$

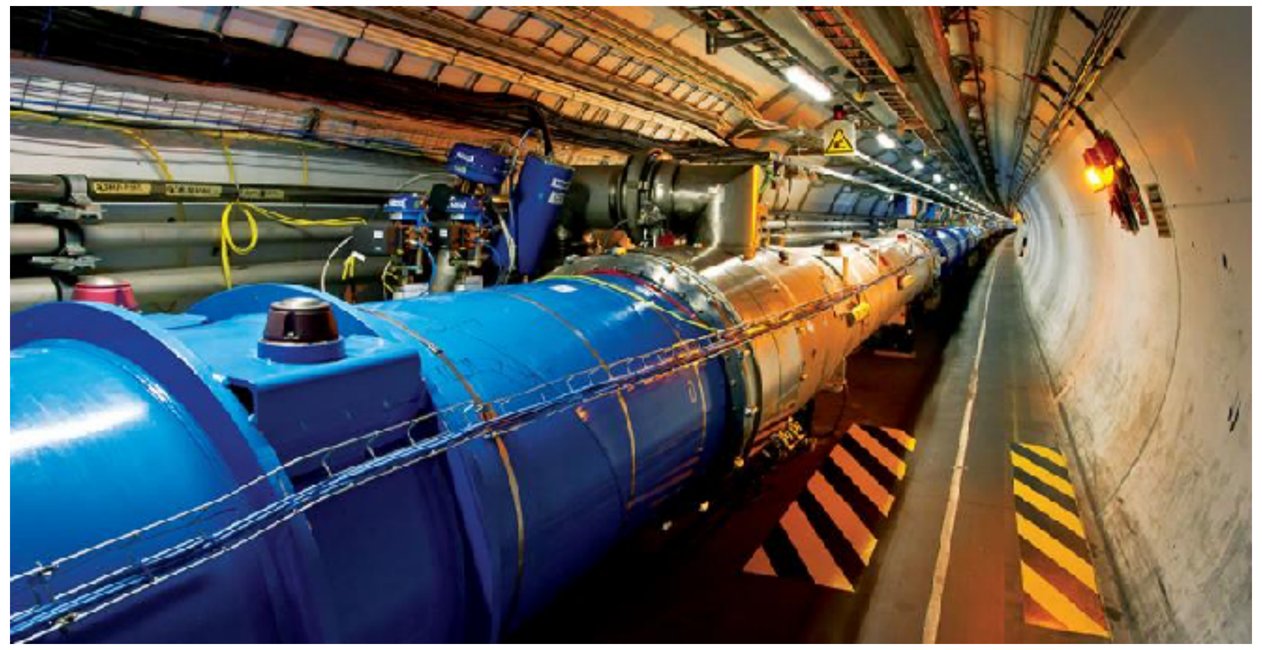
$$\int_{\mathrm{bore}} \frac{\boldsymbol{B}}{\mu_0} \cdot d\boldsymbol{l} = \int_0^{R_0} \frac{B_r}{\mu_0} \cdot dr$$

$$B_r = \sqrt{B_x^2 + B_y^2} = \sqrt{B_1^2 y^2 + B_1^2 x^2} = B_1 r$$

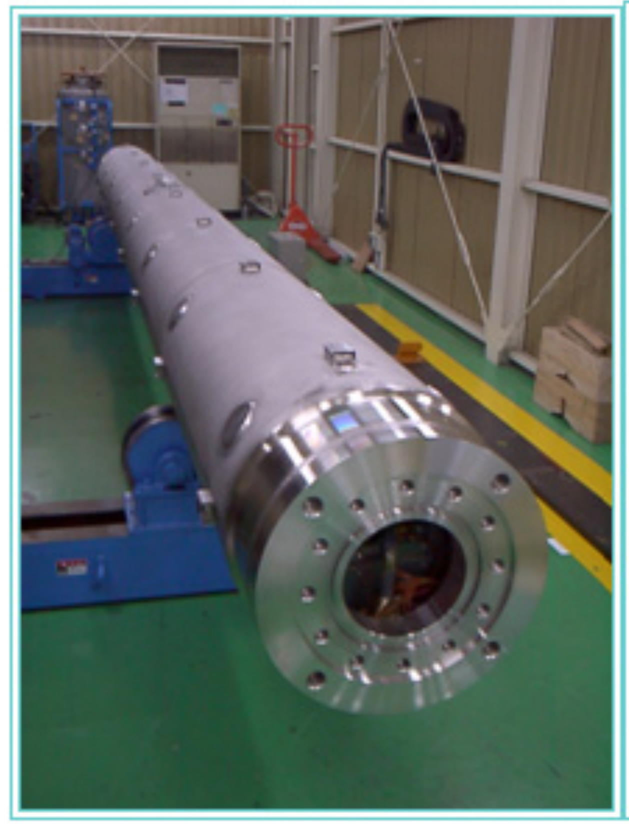
$$I = Ni = \int_0^{R_0} \frac{B_r}{\mu_0} \cdot dr = \frac{B_1 R_0^2}{2\mu_0}$$

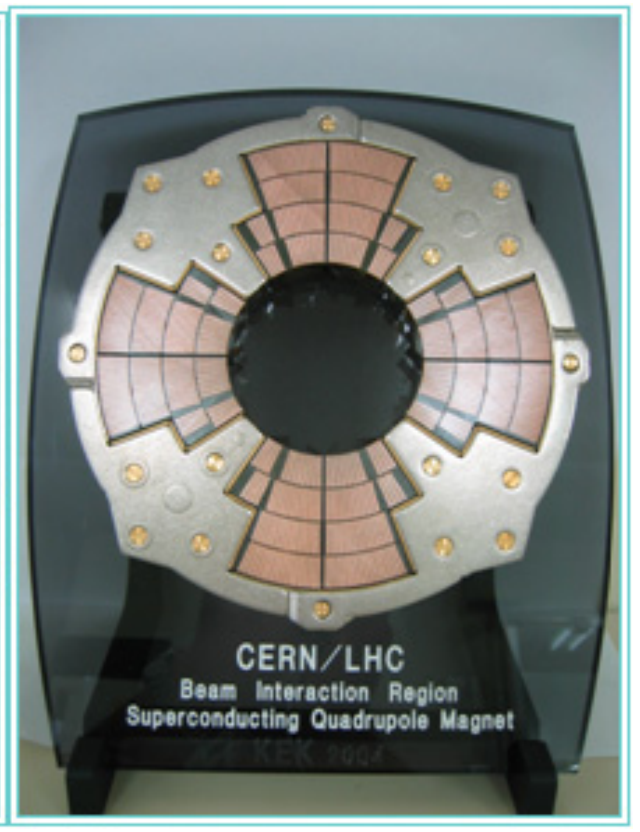
Super conducting magnet

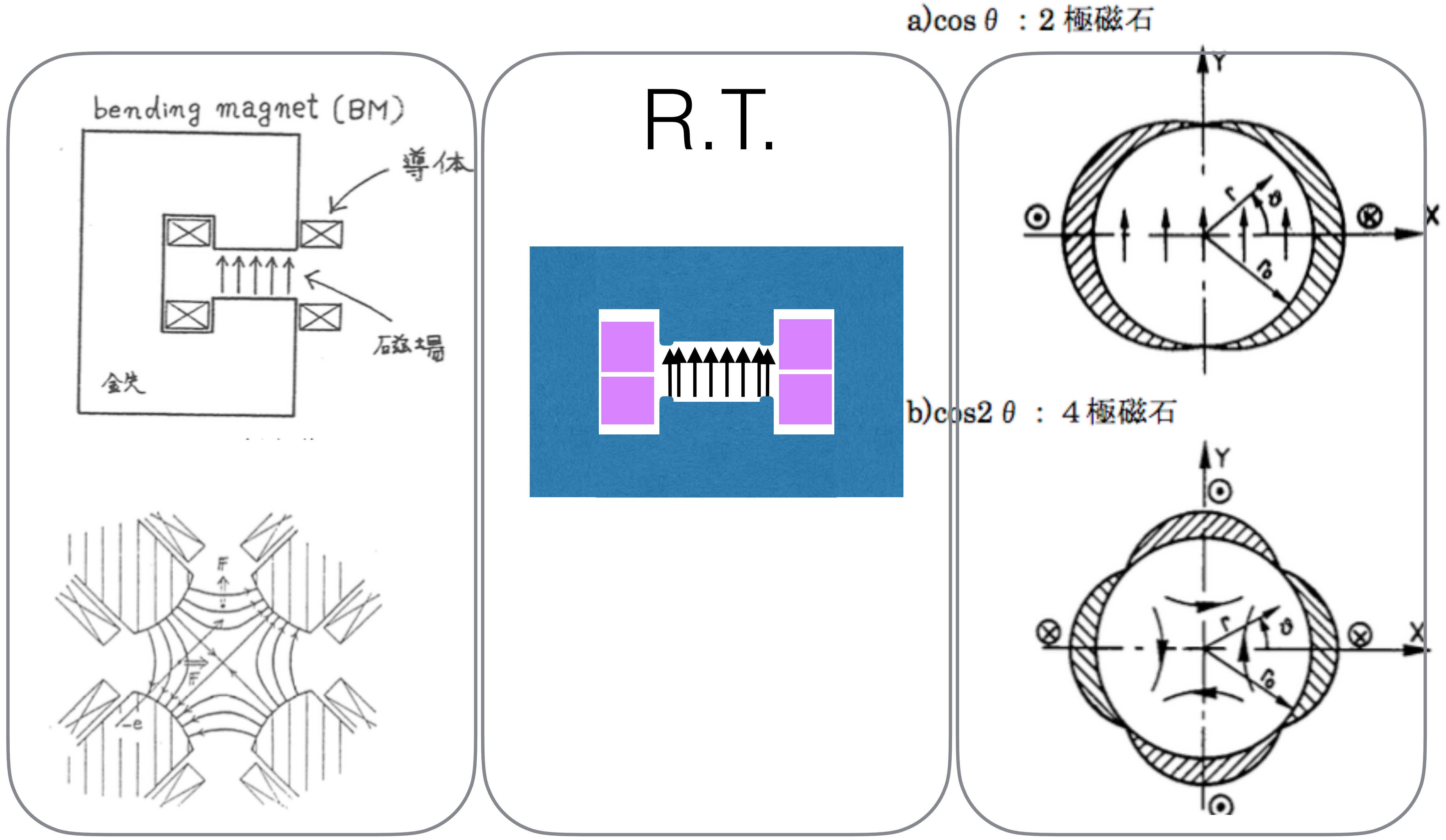
The field limit of R.T magnet is about 2T because of the permeability of iron. Super conducting magnet i.e. LHC can generate 8T.



https://home.cern/topics/large-hadron-collider







R.T.

super ferric

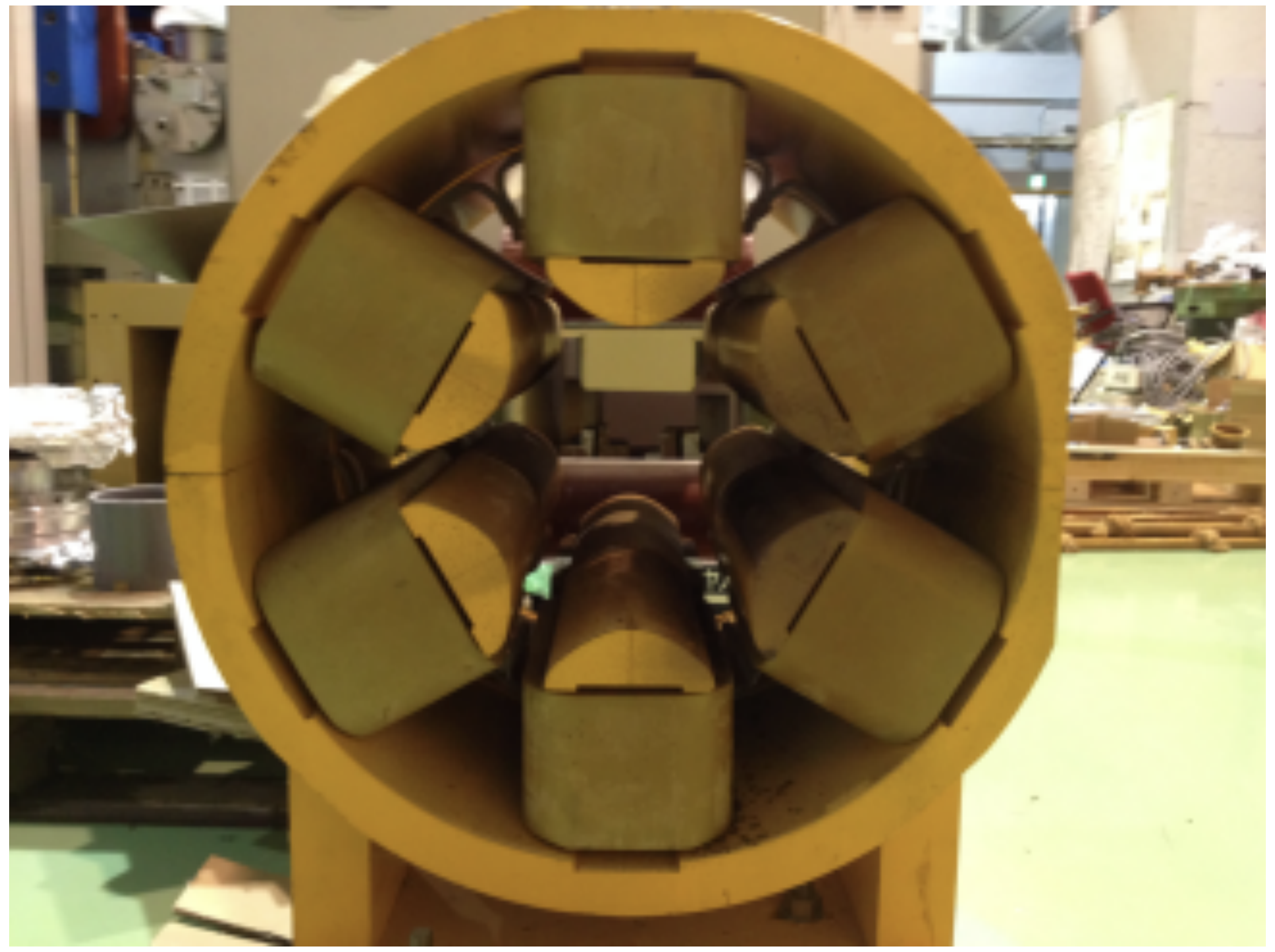
super con.

sextuple magnet

function：chromaticity correction,

resonance excitation for slow beam extractions

field distribution：quadratic(ideally)



# poles	Φ	B_x	B_y
2	$B_0 y$	0	B_0
4	$B_1 xy$	$B_1 y$	$B_1 x$
6	$\frac{1}{6}B_2(3x^2y - y^3)$	B_2xy	$\frac{1}{2}B_2(x^2 - y^2)$

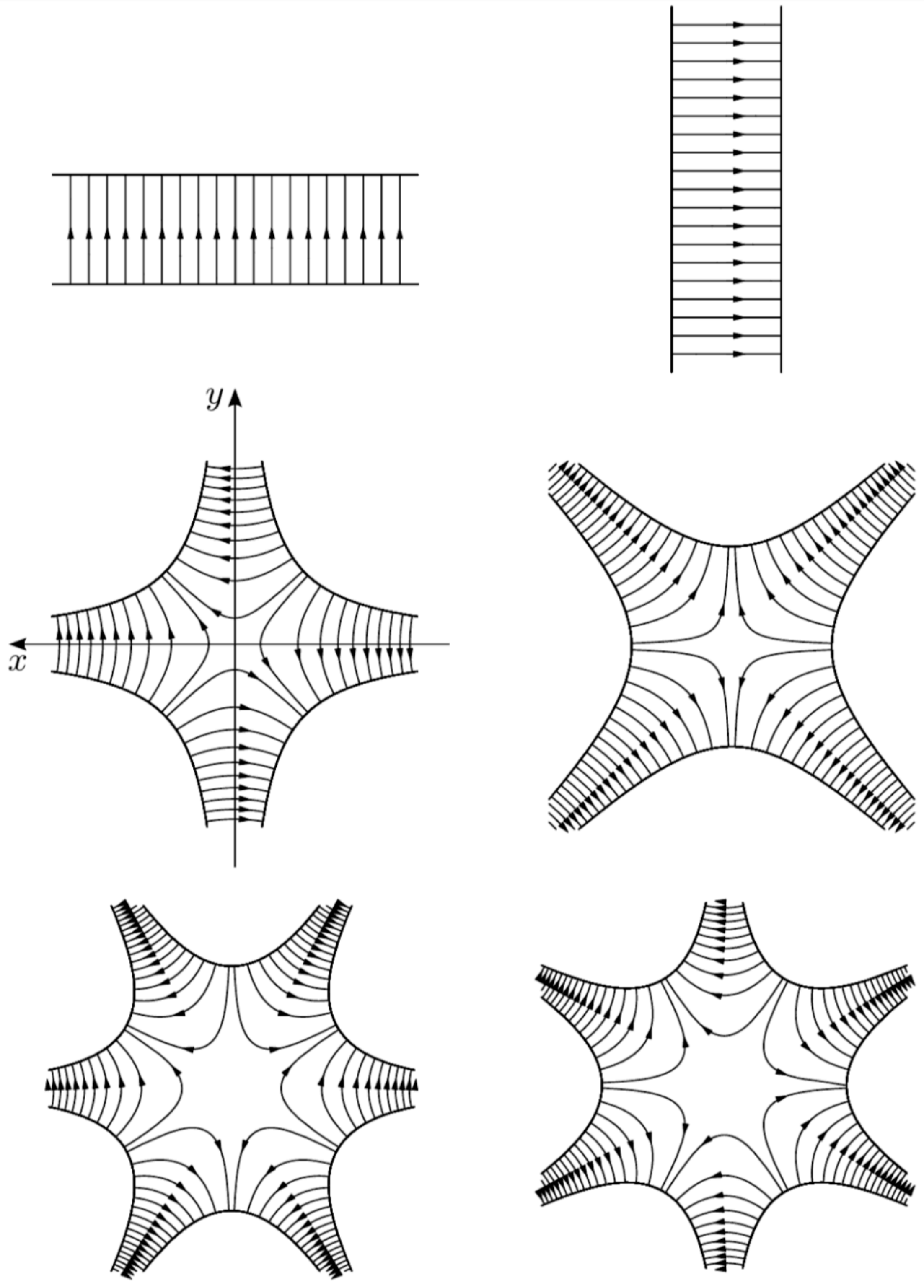
$$B_x(x,0,s) = 0, \qquad B_y(x,0,s) = B_0 + B_1\frac{x}{1!} + B_2\frac{x^2}{2!} + B_3\frac{x^3}{3!} + \dots \qquad B_s(x,0,s) = 0.$$

normal skew

Dipole

Quadrupole

Sextupole



$$B_s = 0$$ hard edge model

$$\mathrm{div}\mathbf{B} = 0$$
$$\mathrm{rot}\mathbf{B} = 0$$

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} (b_n + ia_n)(x+iy)^n$$

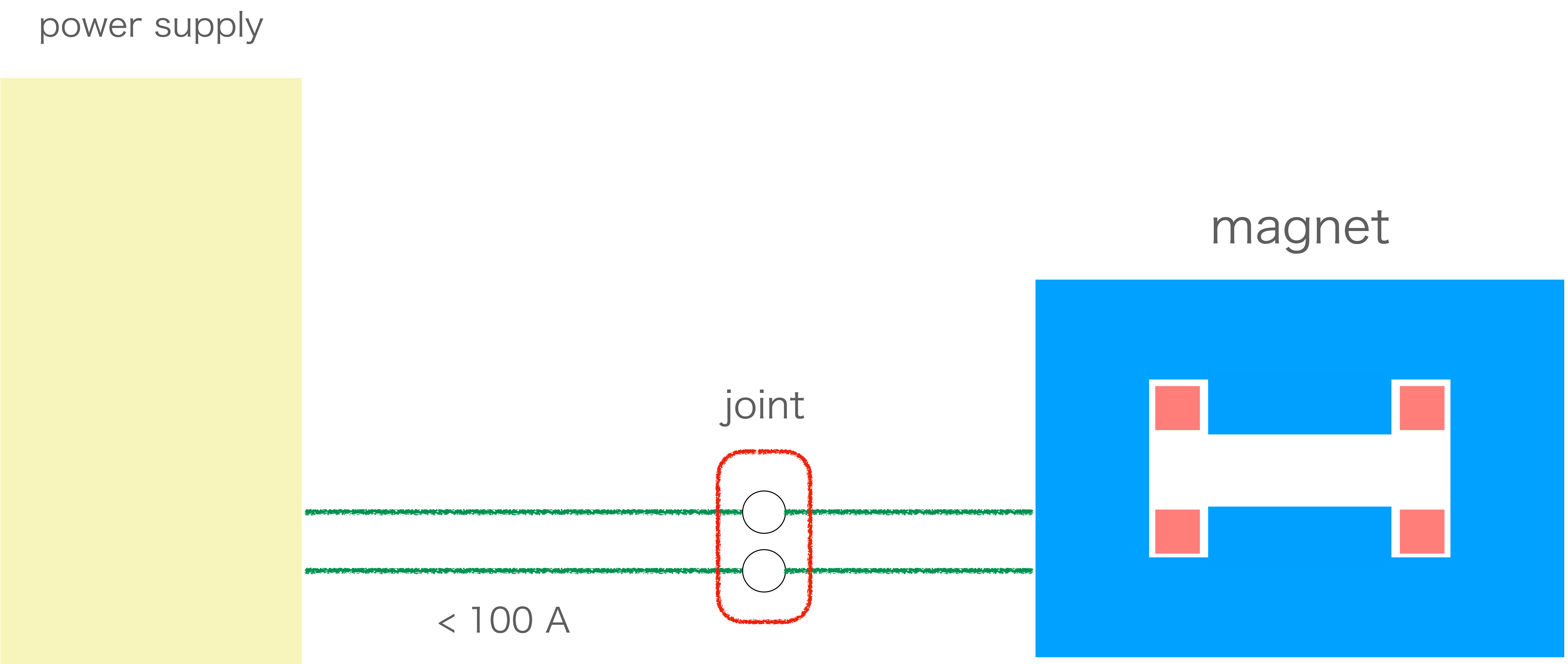
$$\Phi = -B_0 Im \left[\sum_{n=0}^{\infty} \frac{b_n + ia_n}{n+1} (x+iy)^{n+1} \right]$$

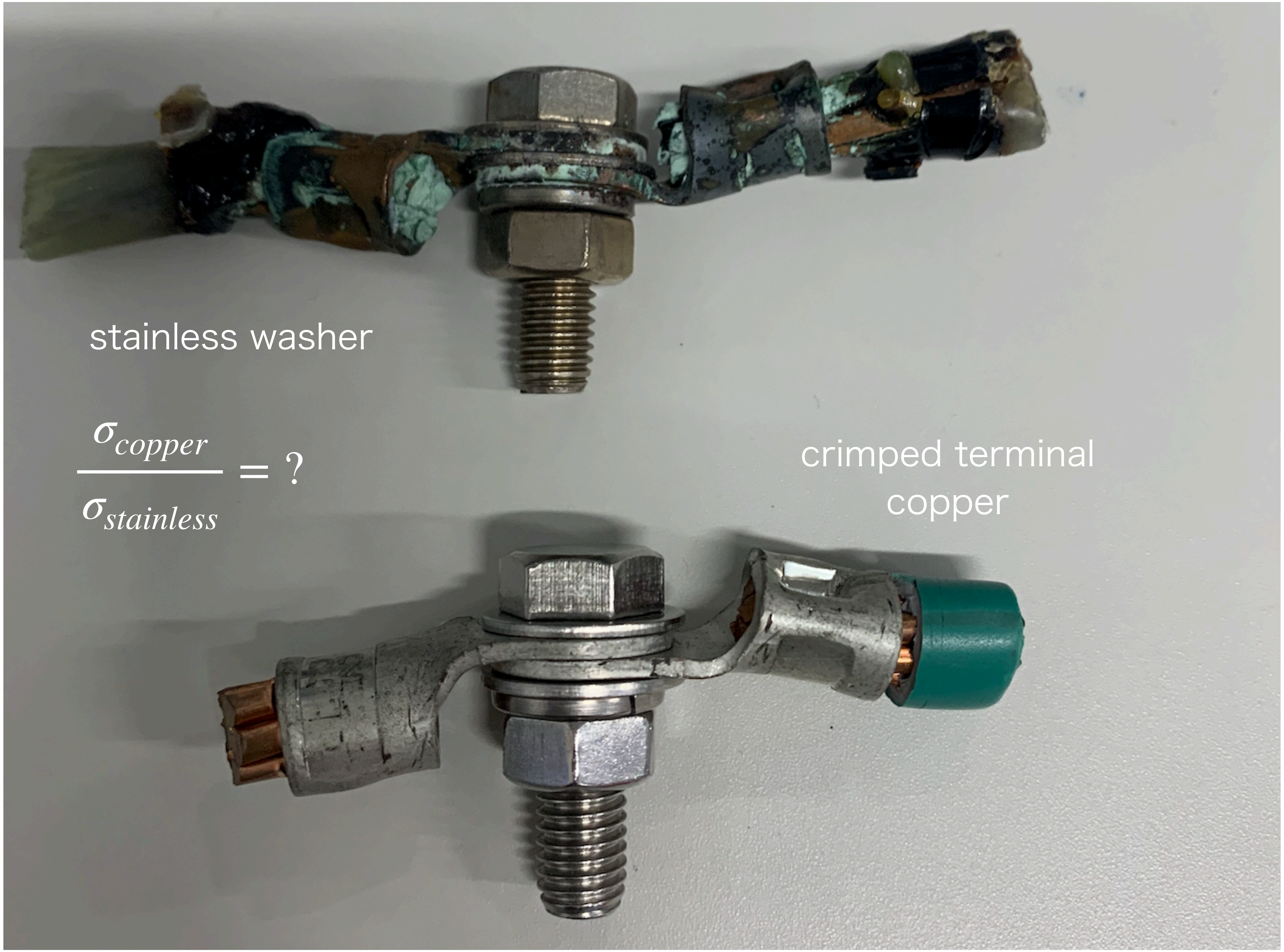
$$A_s = -B_0 Re \left[\sum_{n=0}^{\infty} \frac{b_n + ia_n}{n+1} (x+iy)^{n+1} \right]$$

$$b_n = \frac{1}{B_0 n!} \frac{\partial^n B_y}{\partial x^n} \bigg|_{x=y=0} a_n = \frac{1}{B_0 n!} \frac{\partial^n B_x}{\partial x^n} \bigg|_{x=y=0}$$

Quiz 1

What is the difference between the two?


power supply
magnet
joint
< 100 A



stainless washer

$$\frac{\sigma_{copper}}{\sigma_{stainless}} = ?$$

crimped terminal
copper

Advantage of FF(fixed field)

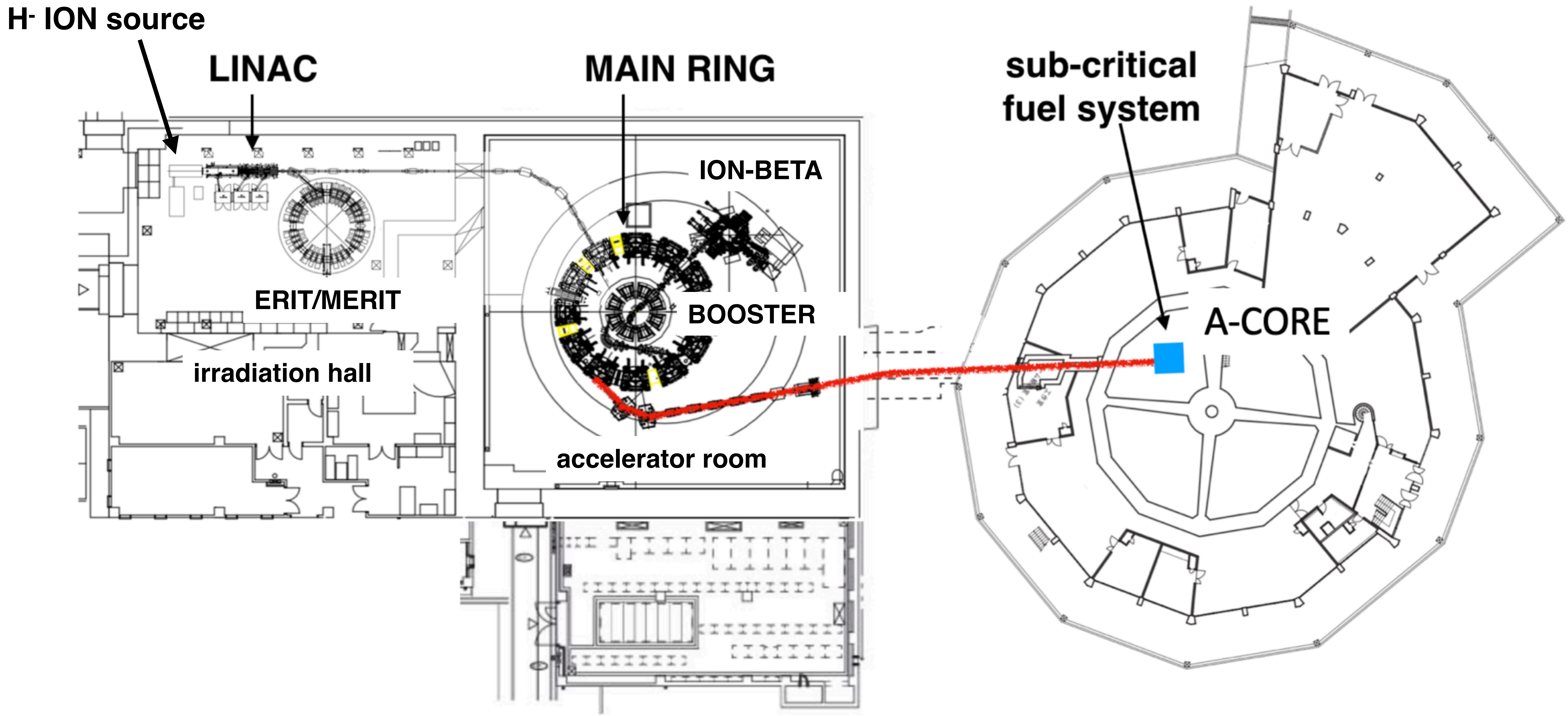
★Needs no ramping

- Rapid cycling
- Easy to use super conducting coil
- Also permanent magnets can be used
- Block iron can be used
  - precise machining → high accuracy of pole shape

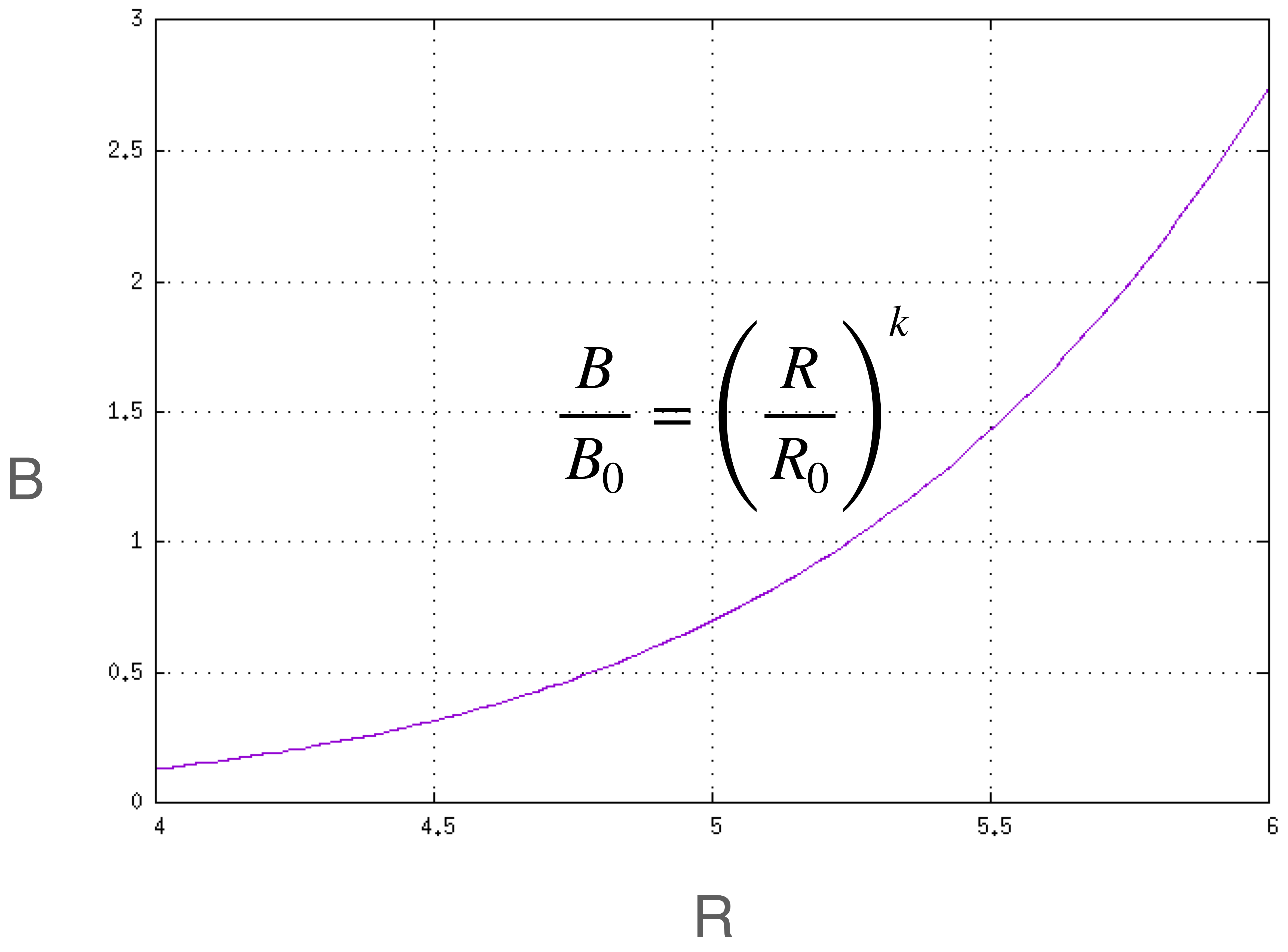
FFA magnets

- Horizontal FFA
  - permanent magnet
  - electro magnet
    - room temp. magnet (radial/spiral, single-coil/multi-coil)
    - super conducting magnet
- Vertical FFA

Layout of the accelerator complex

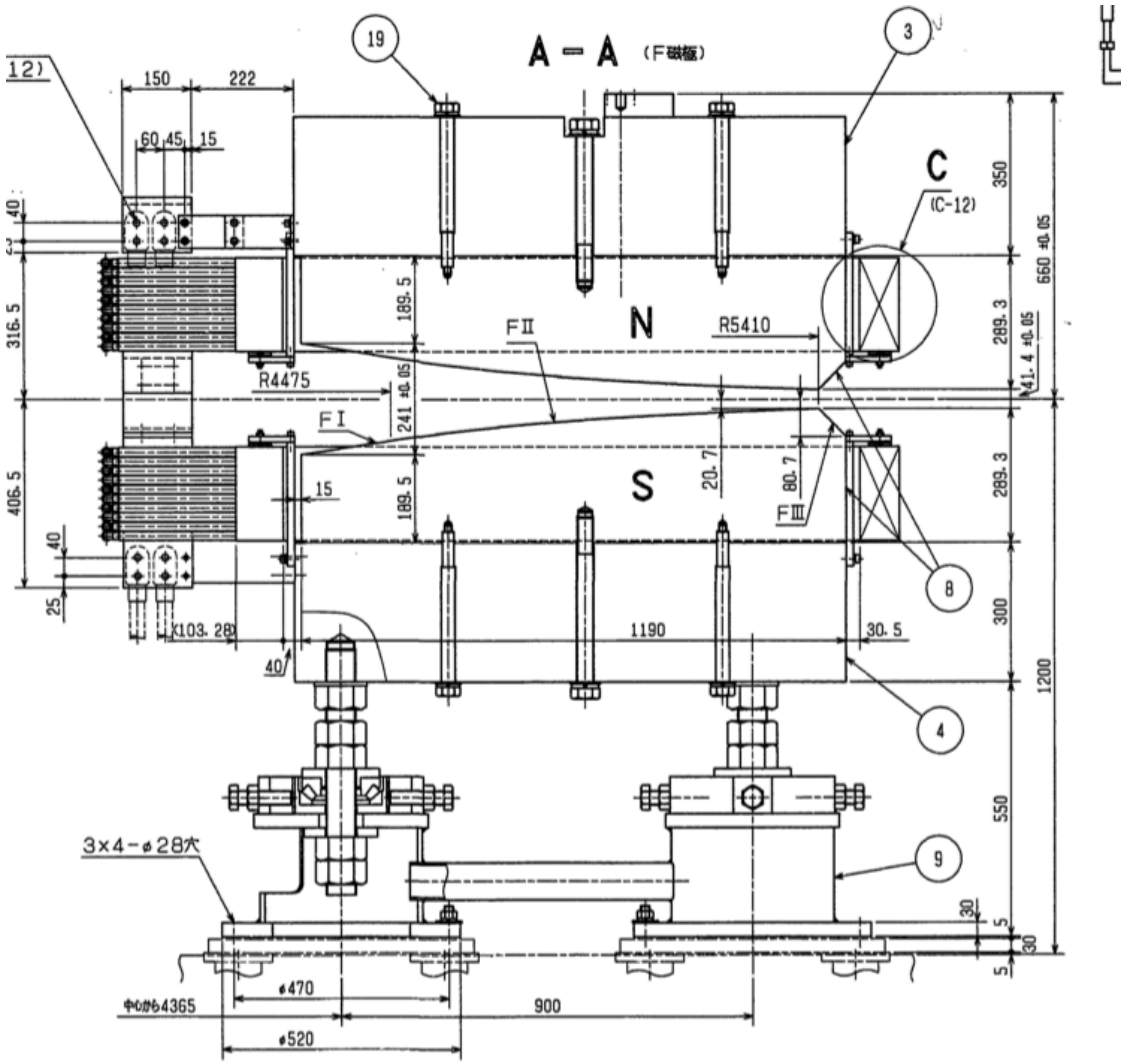


B field shaping with pole shape



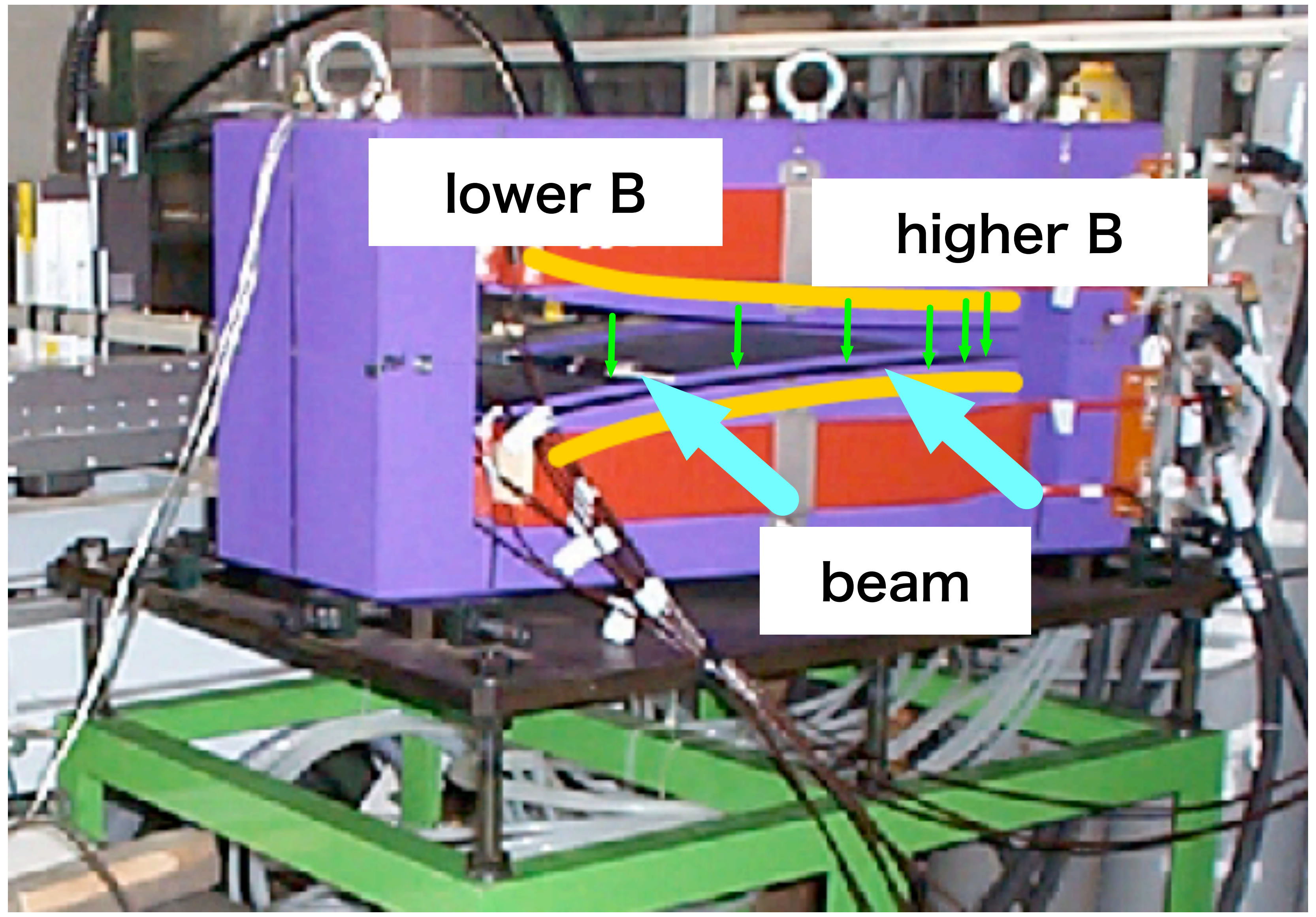
$$\frac{B}{B_0} = \left(\frac{R}{R_0}\right)^k$$

FII) 4475≤R≤5410 Fg=21x(5400/R)$^{7.75}$

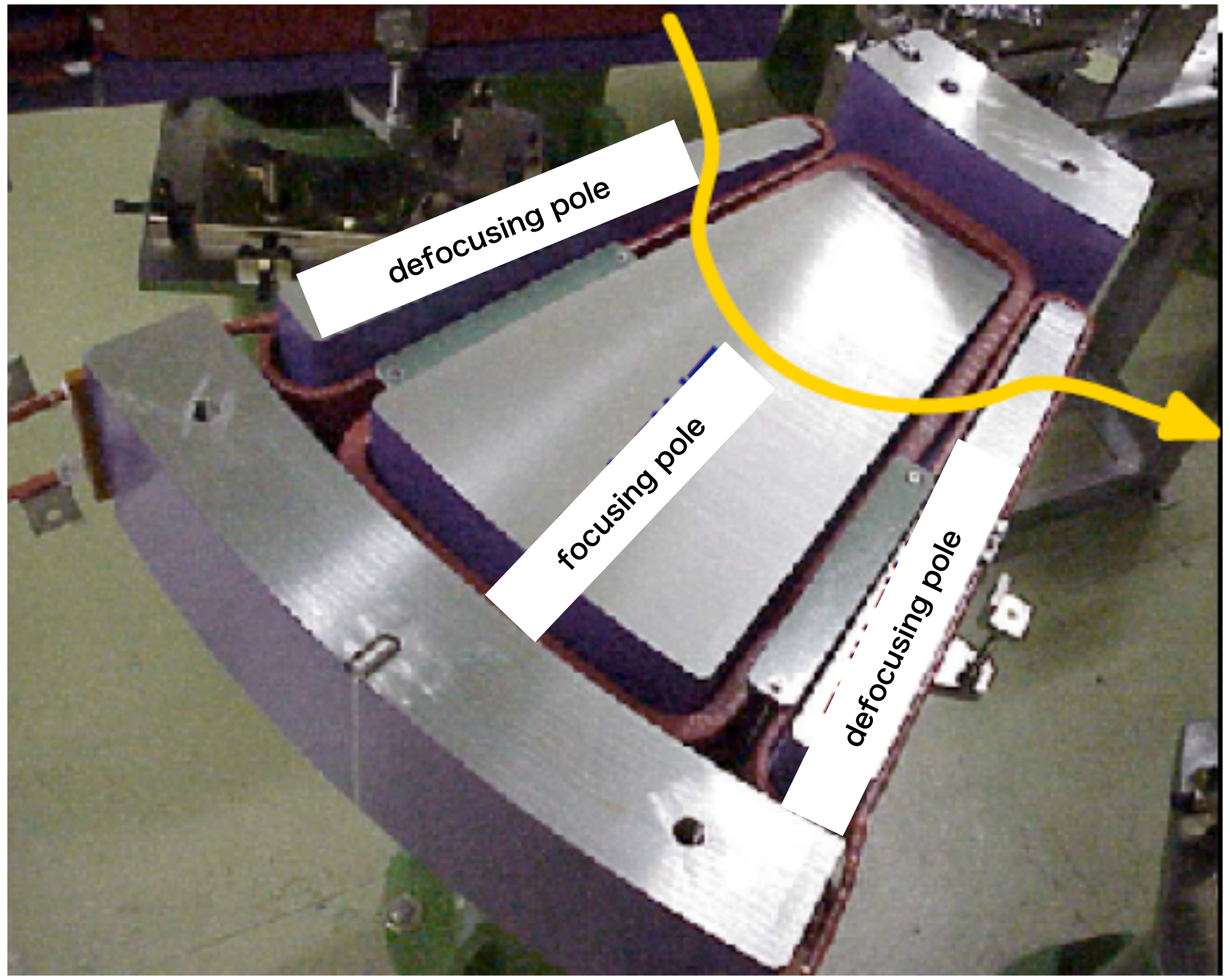


B field shaping with pole shape

If you want to use fixed field in strong focusing, you need reverse bending.

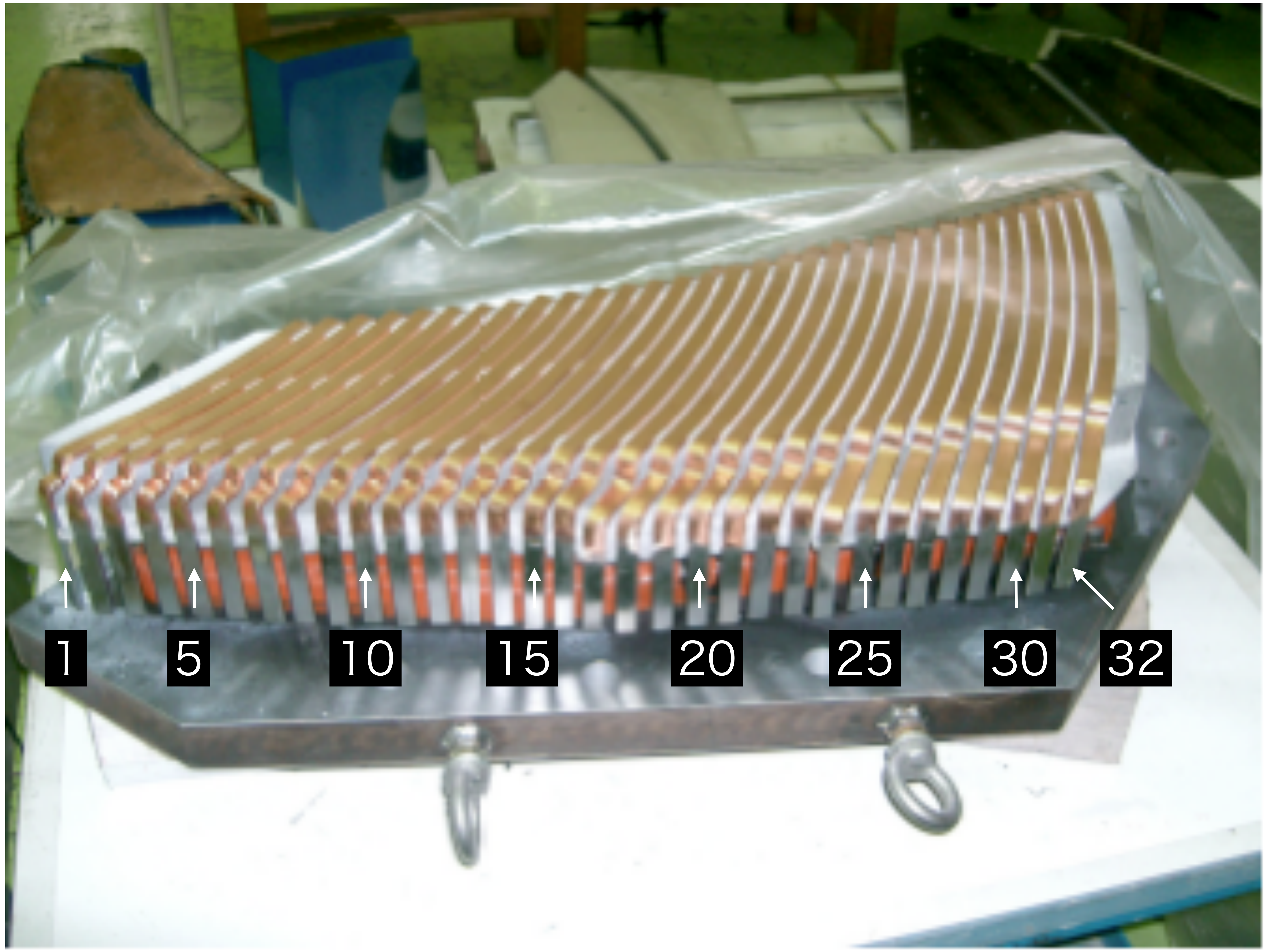


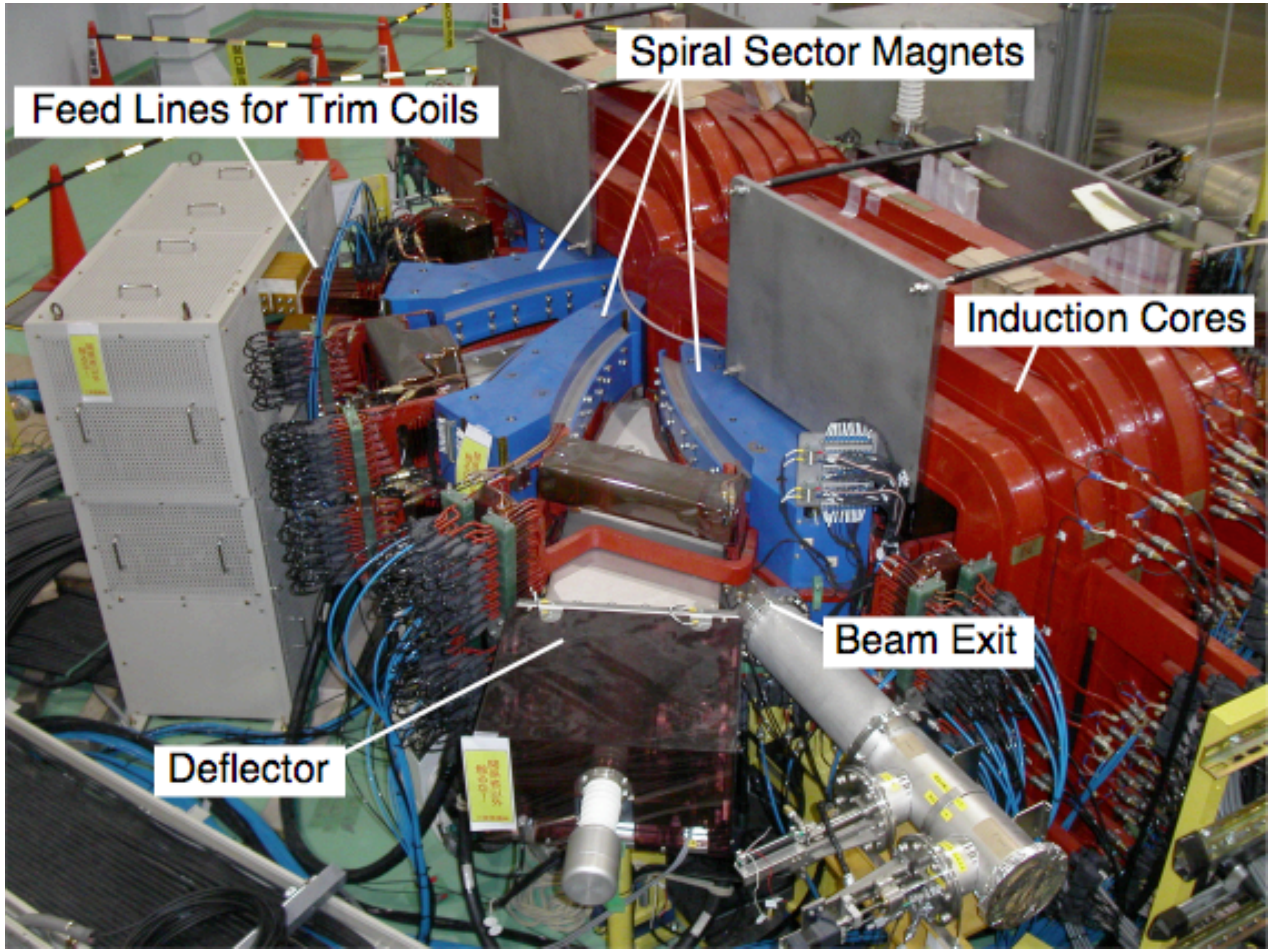
Outer radii the stronger B field

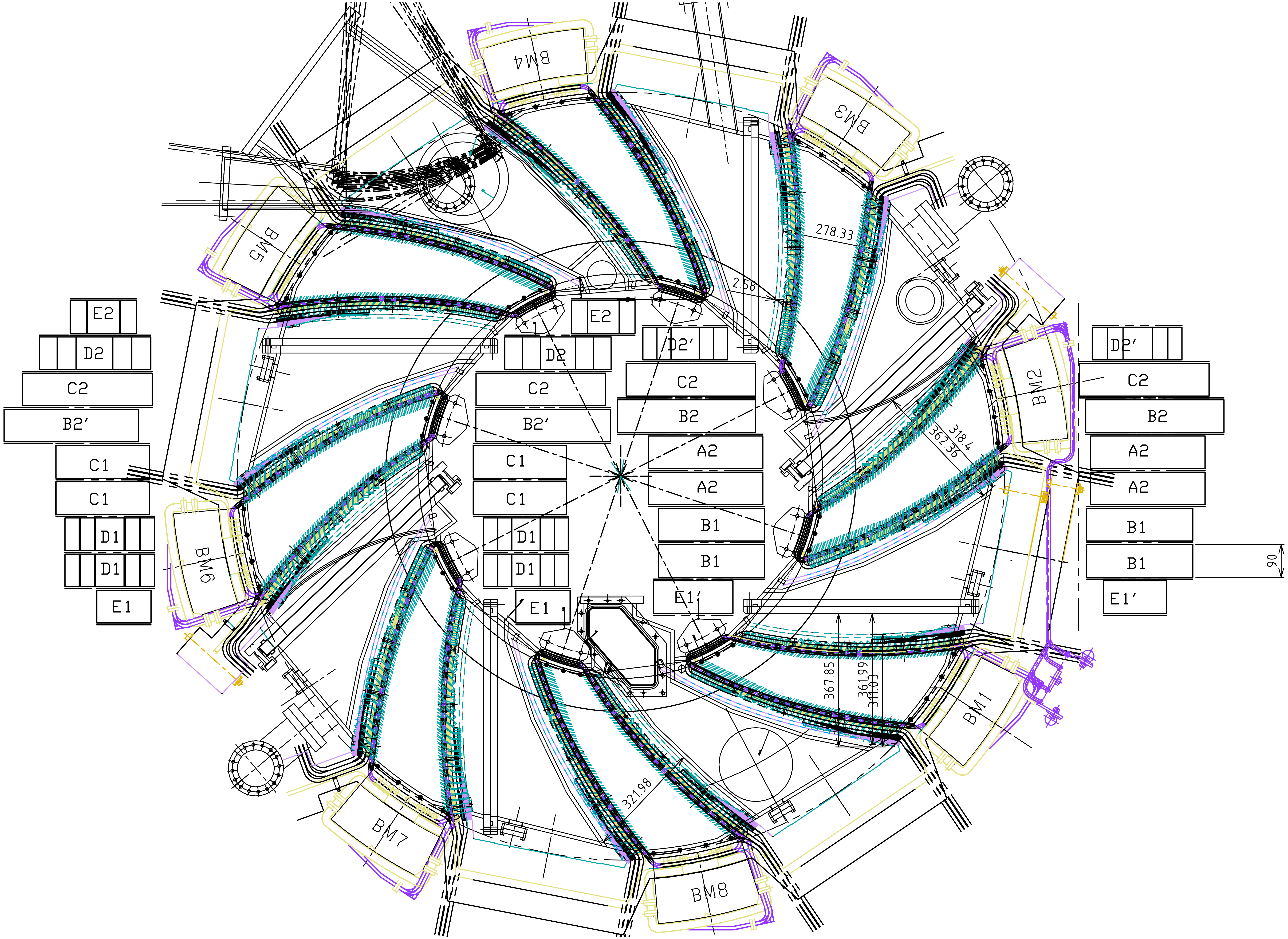


Reverse bend generates focusing force in vertical direction.

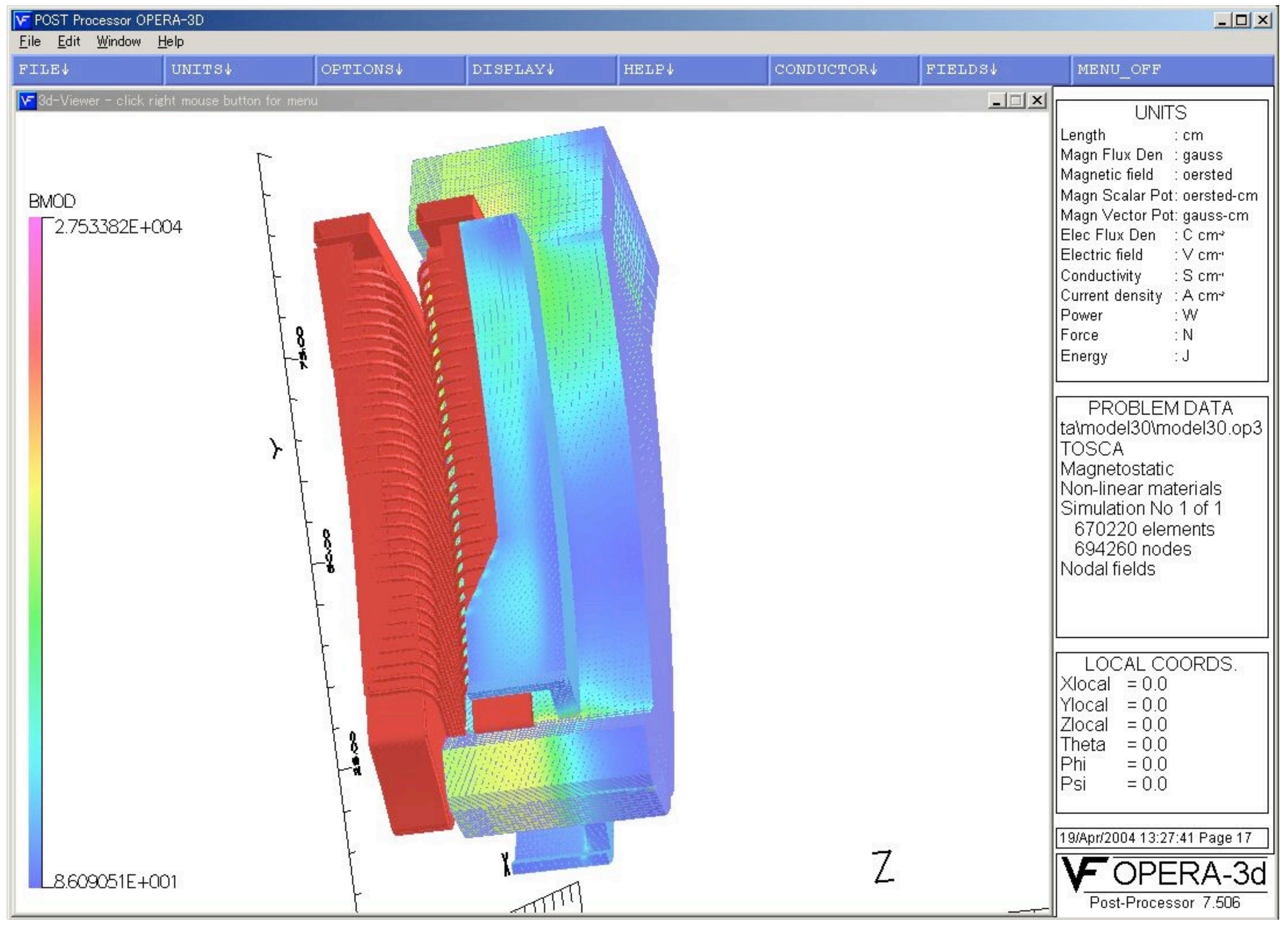
B field shaping with multi coils






BM4
BM3
BM5
BM2
BM6
BM1
BM7
BM8
E2
D2
C2
B2′
C1
C1
D1
D1
E1
E2
D2
C2
B2′
C1
C1
D1
D1
E1
D2′
C2
B2
A2
A2
B1
B1
E1′
D2′
C2
B2
A2
A2
B1
B1
E1′
278.33
2.58
318.4
362.36
367.85
361.99
311.03
321.98
90

B field shaping with multi coils



UNITS

Length : cm
Magn Flux Den : gauss
Magnetic field : oersted
Magn Scalar Pot: oersted-cm
Magn Vector Pot: gauss-cm
Elec Flux Den : C cm^{-2}
Electric field : V cm^{-1}
Conductivity : S cm^{-1}
Current density : A cm^{-2}
Power : W
Force : N
Energy : J

PROBLEM DATA

ta\model30\model30.op3
TOSCA
Magnetostatic
Non-linear materials
Simulation No 1 of 1
670220 elements
694260 nodes
Nodal fields

LOCAL COORDS.

Xlocal = 0.0
Ylocal = 0.0
Zlocal = 0.0
Theta = 0.0
Phi = 0.0
Psi = 0.0

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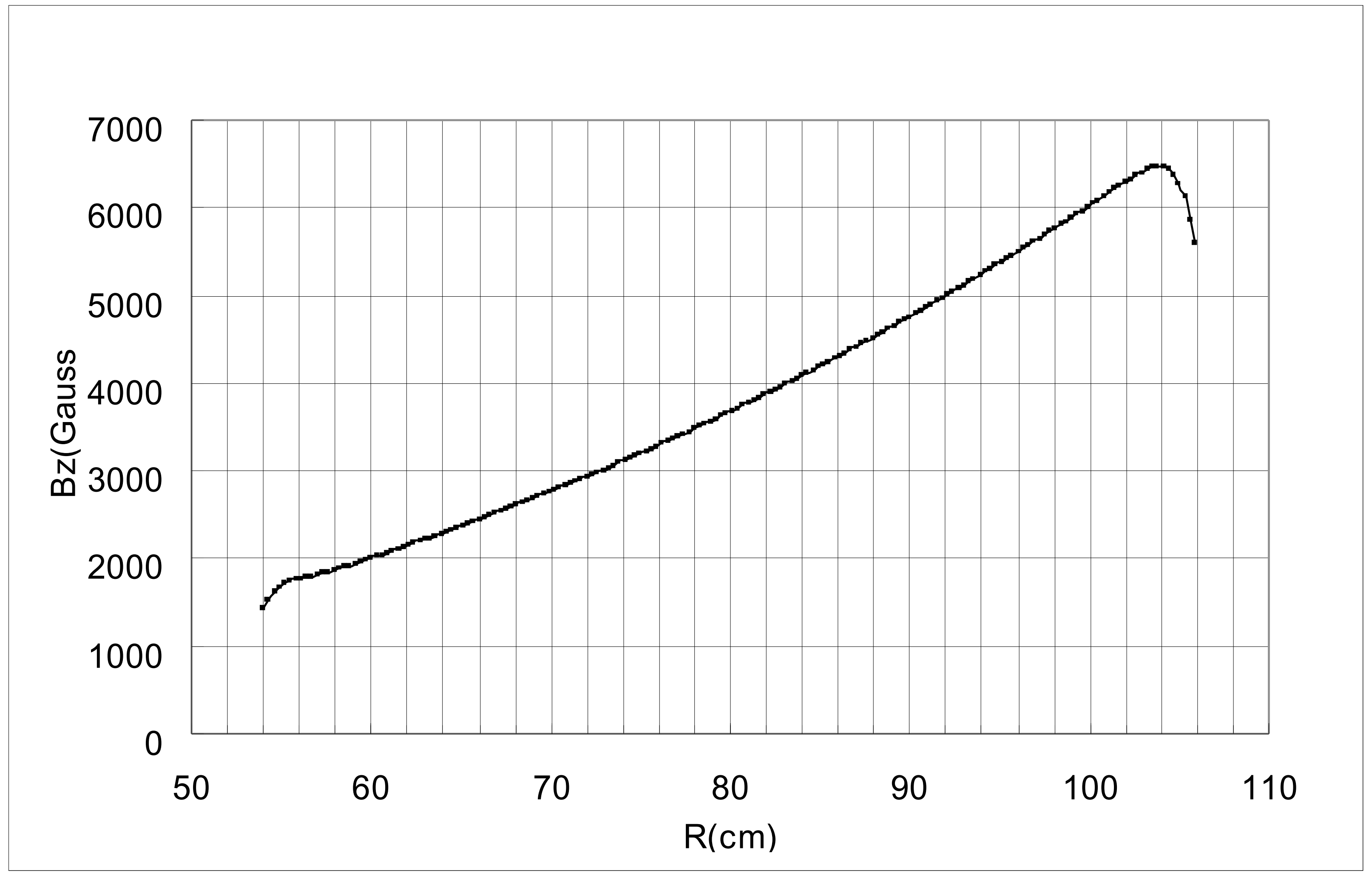
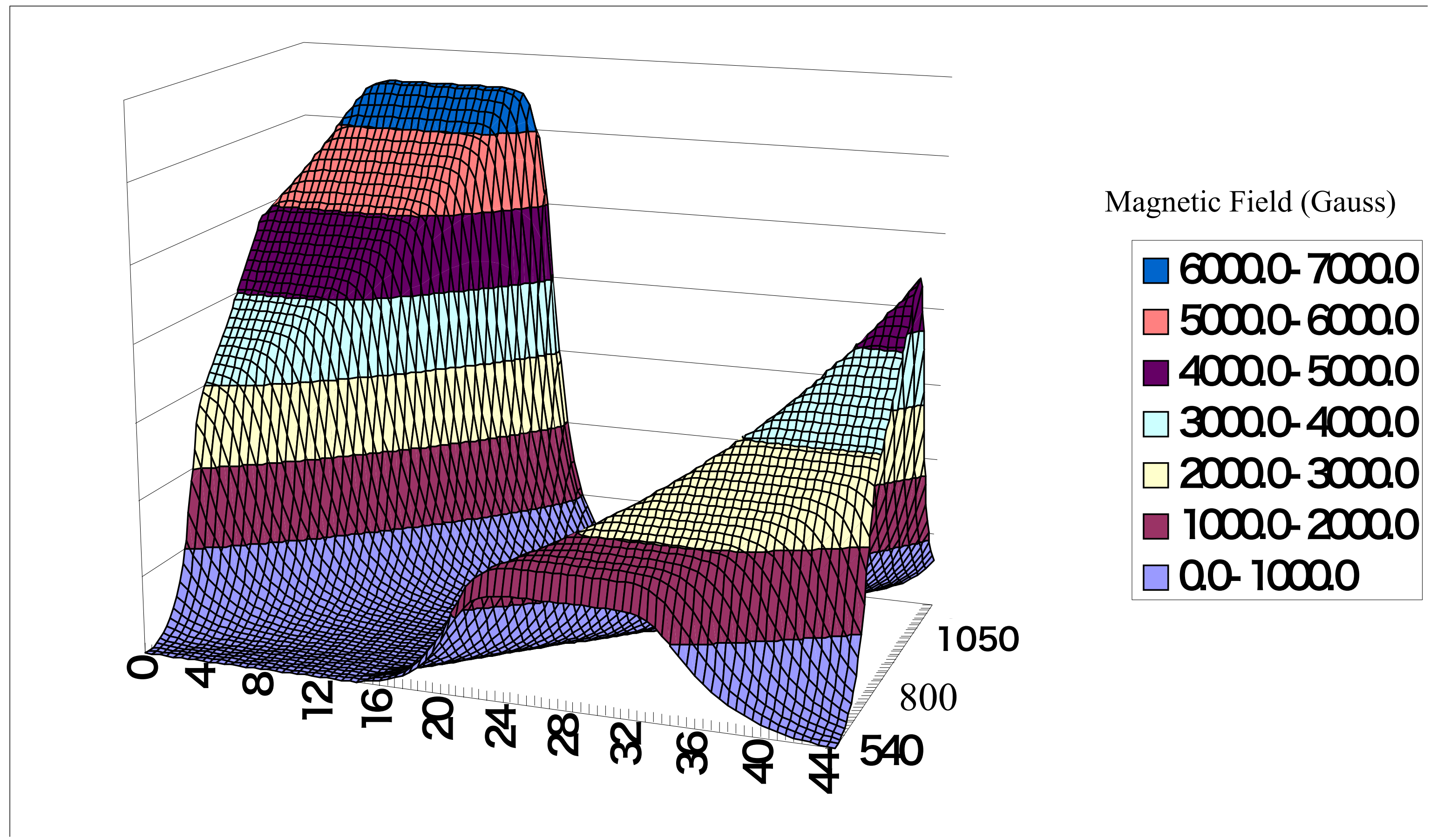




Quiz 2

What is the difference between the main magnet of the main ring and the booster.

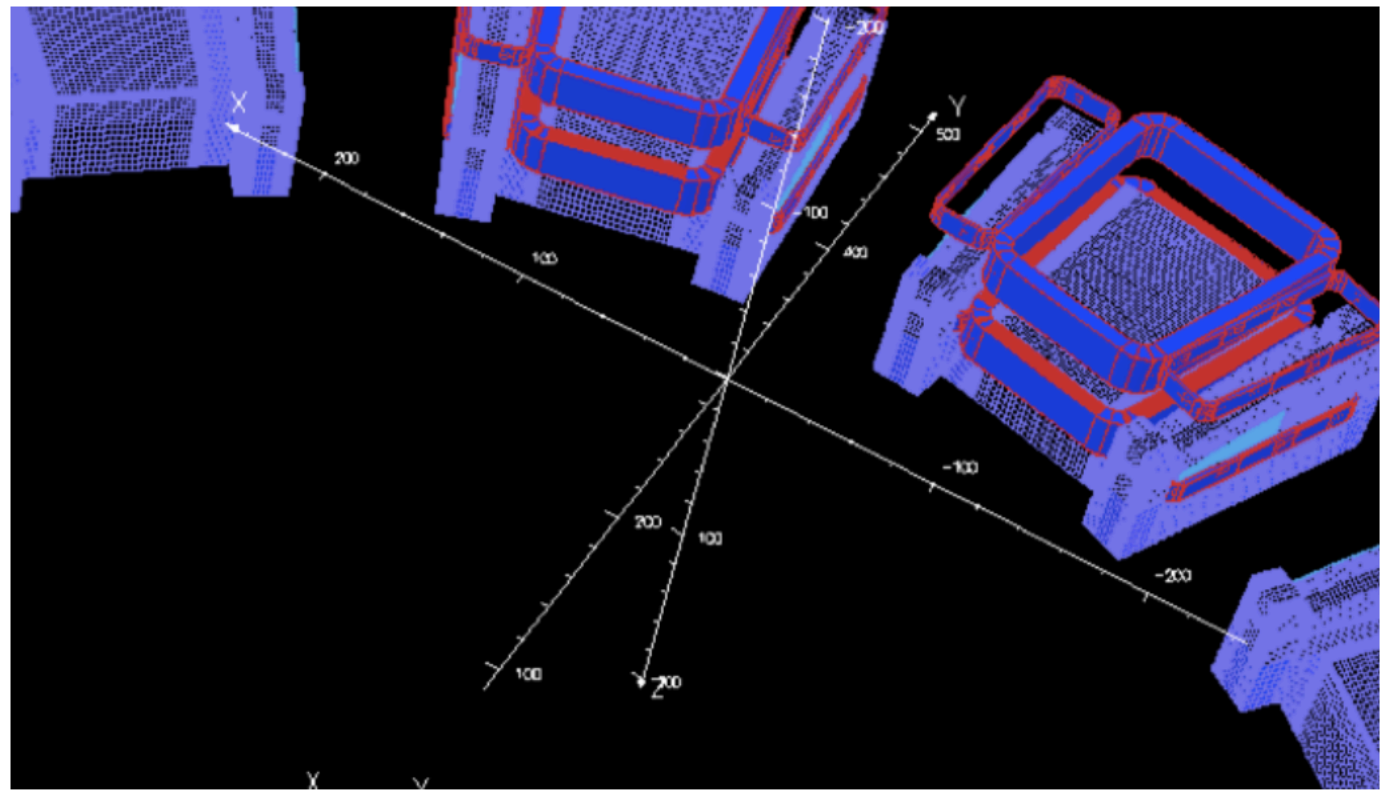


Figure 1: The input model of the main magnet in MAIN RING for the magnetic field calculation by TOSCA. Return yokes are not installed to make energy variable beam extractions easy. No field clamps are adopted.

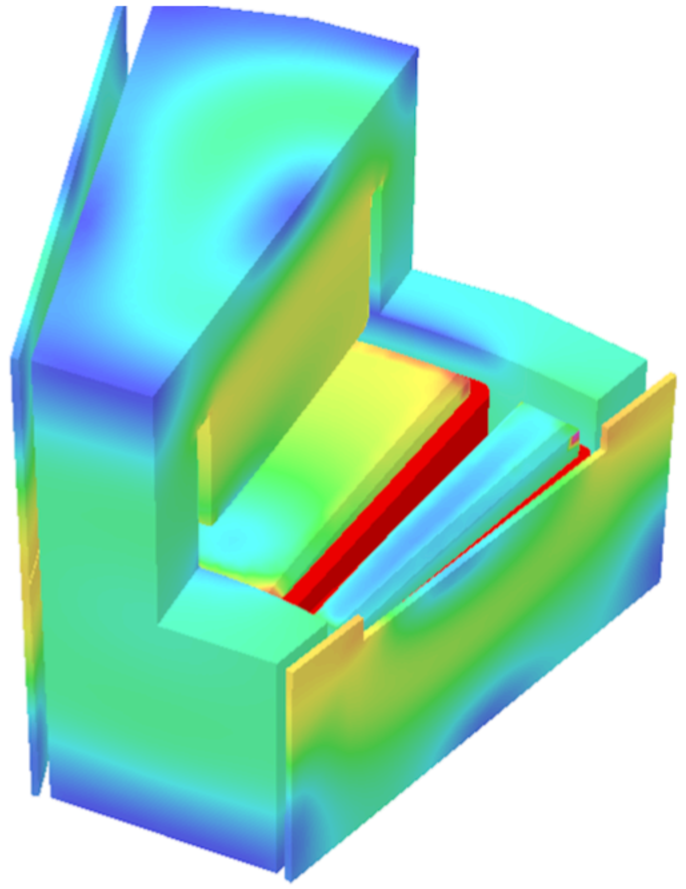
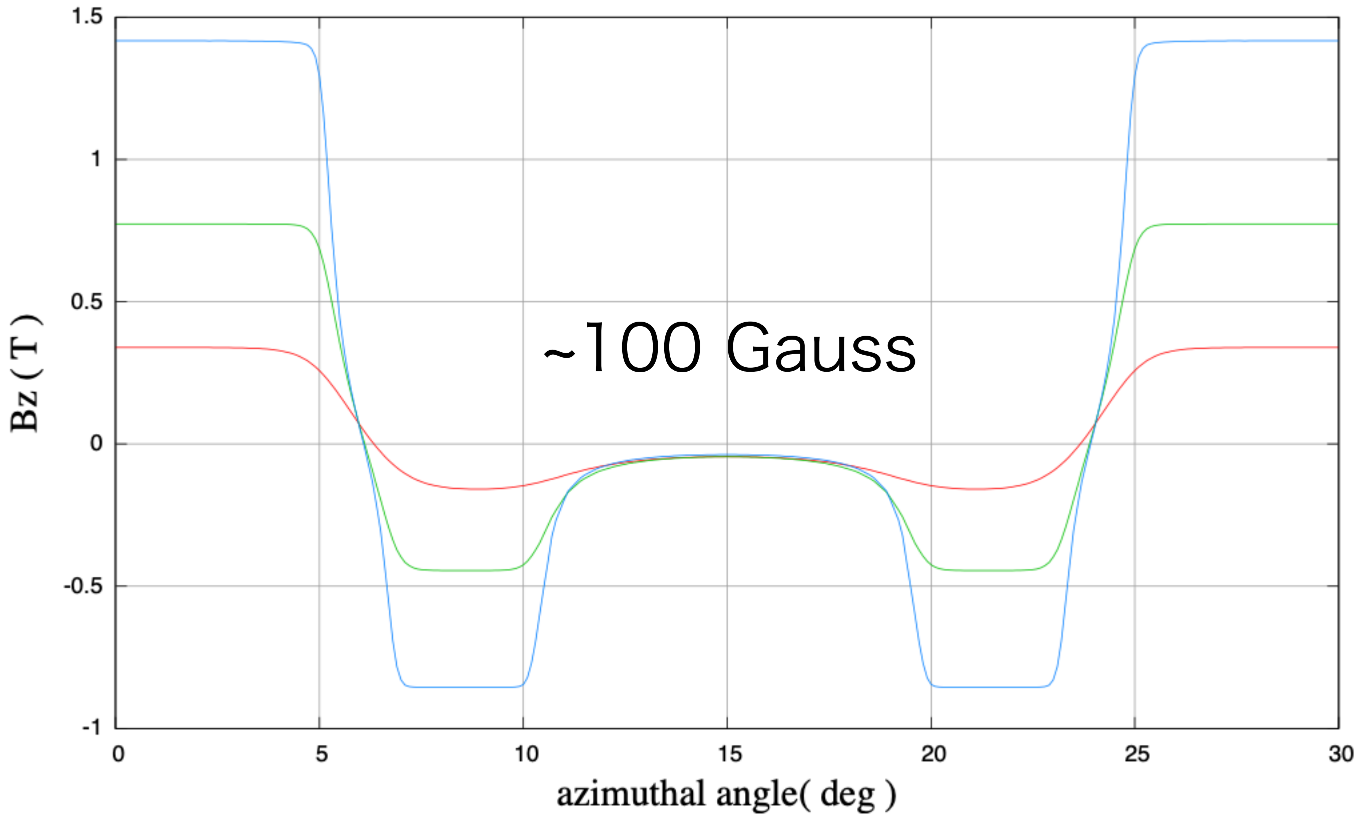
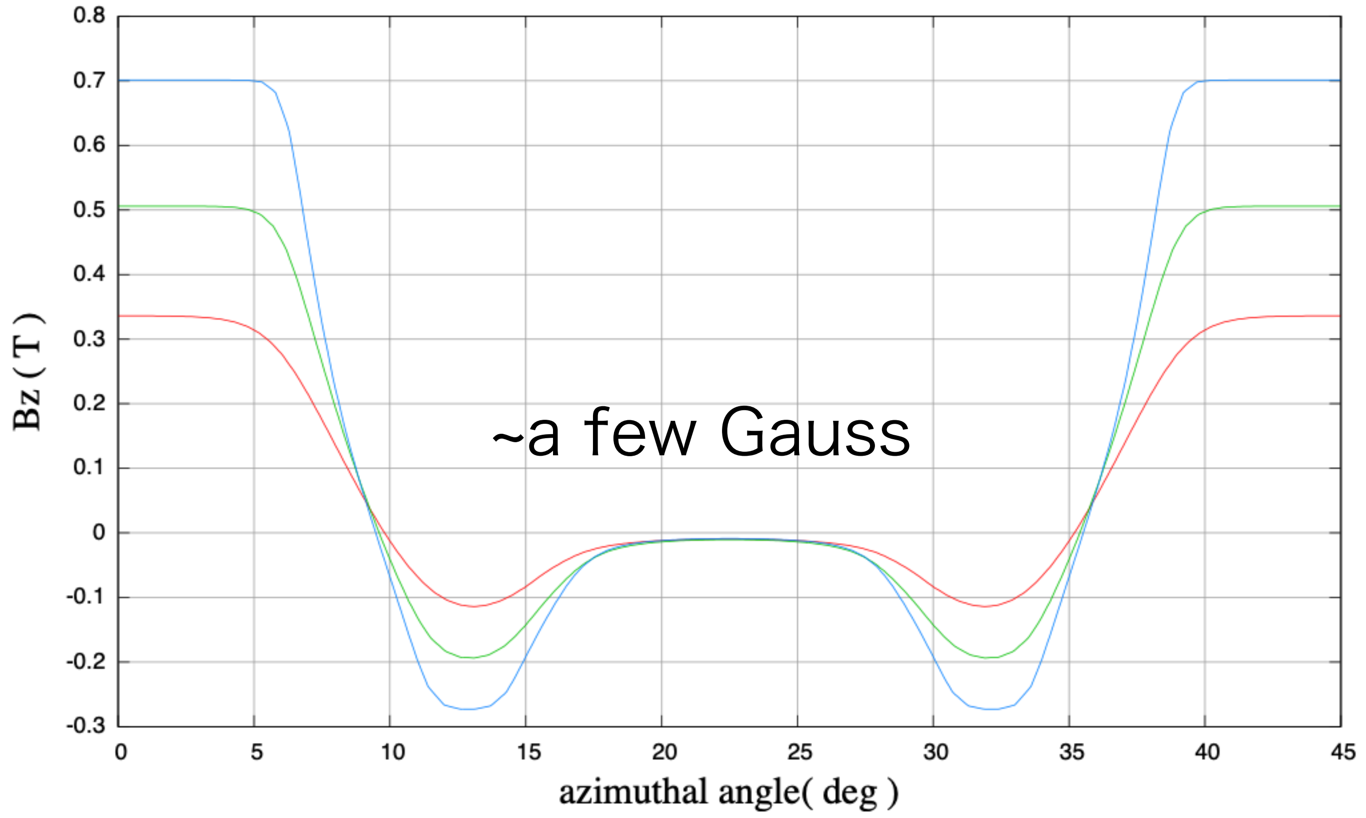


Figure 3: The input model of the main magnet in BOOSTER for the magnetic field calculation by TOSCA. Return yokes and field clamps are adopted.



~100 Gauss

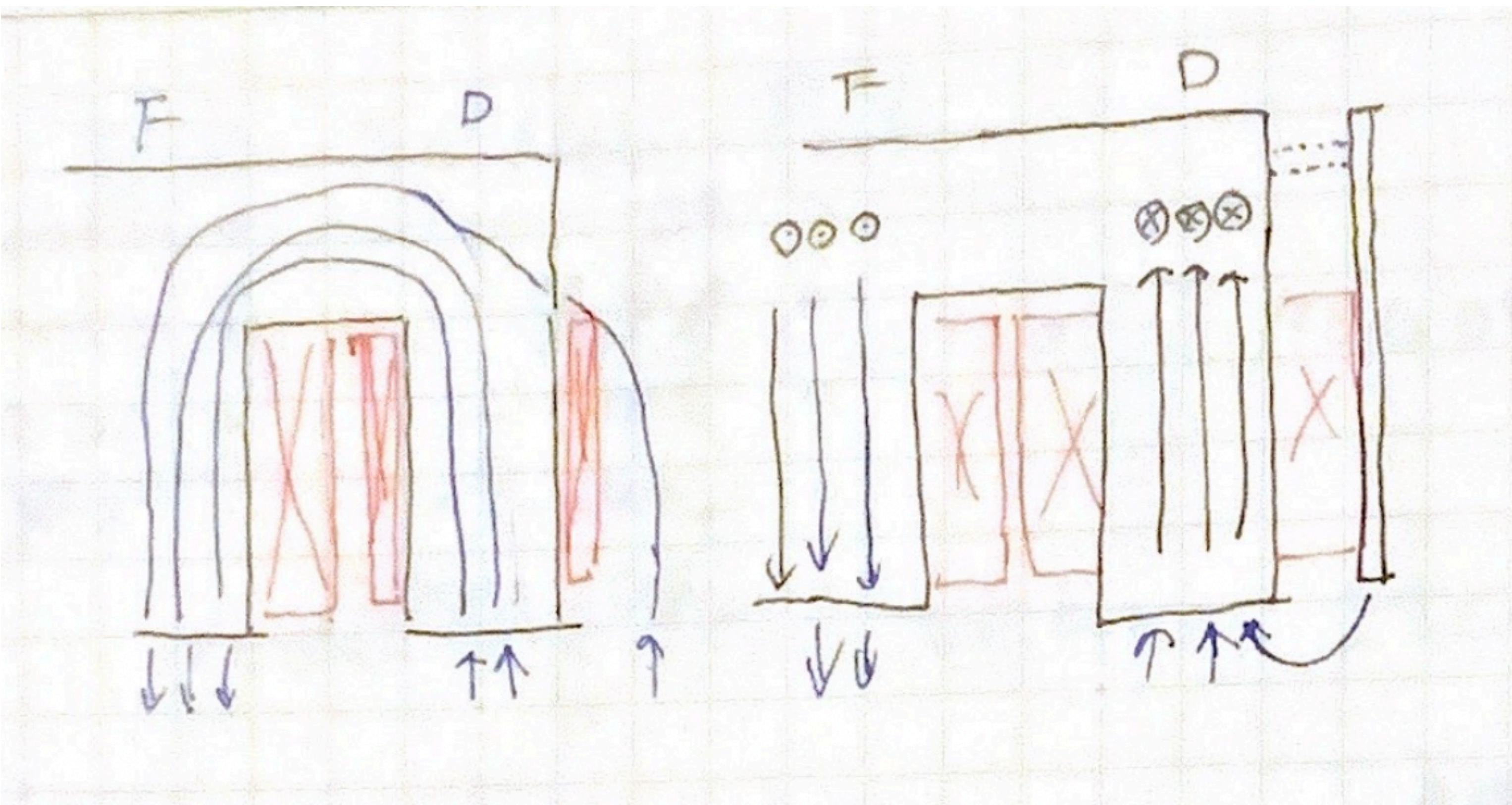
Figure 2: B_z vs θ along different radii for the unit cell in MAIN RING. Red, green and blue lines correspond to radius of 4.4 m, 4.9 m and 5.3 m, respectively.



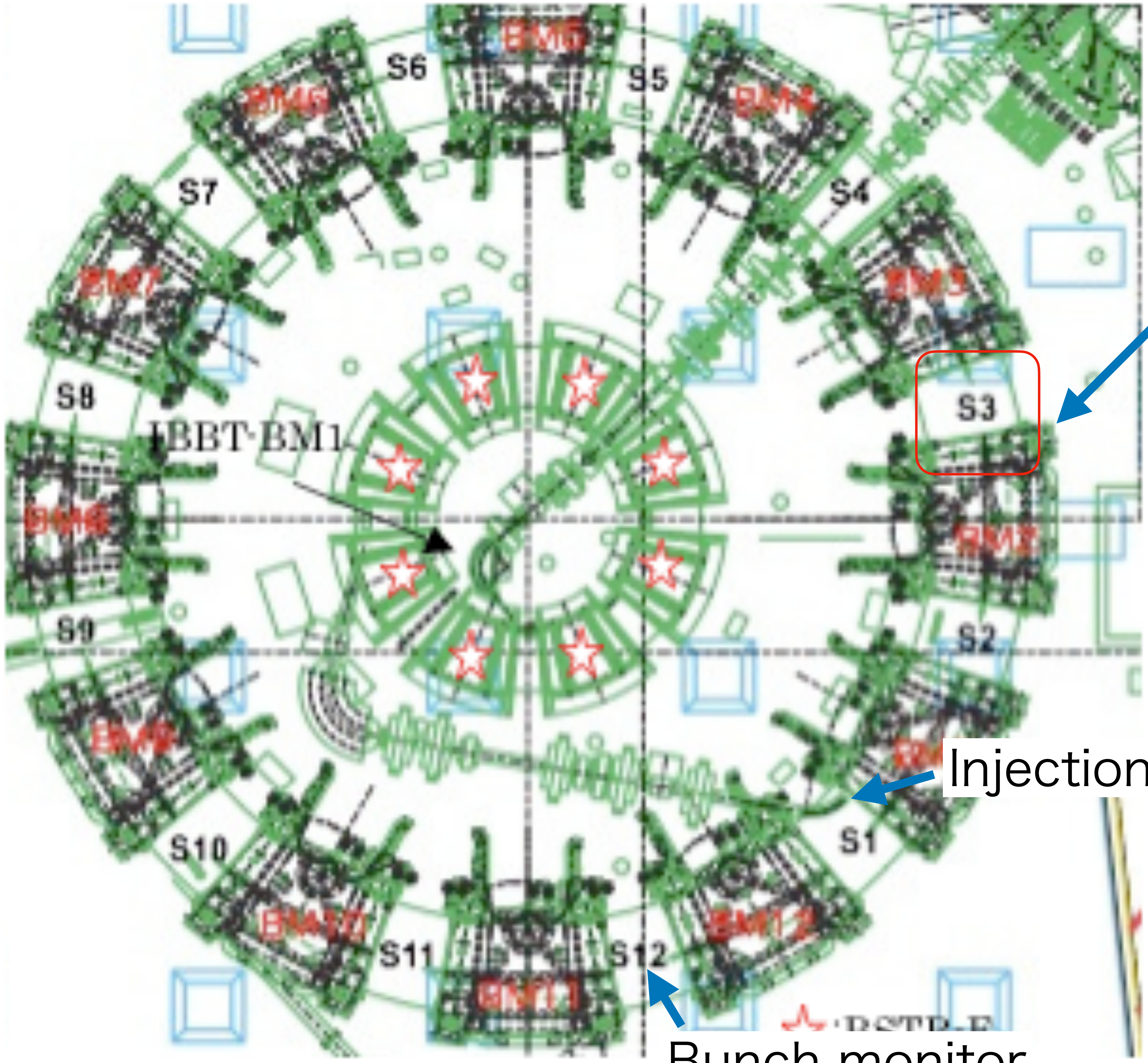
~a few Gauss

Figure 4: B_z vs θ along different radii for the unit cell in BOOSTER. Red, green and blue lines correspond to radius of 1.2 m, 1.4 m and 1.6 m, respectively.

main ring booster



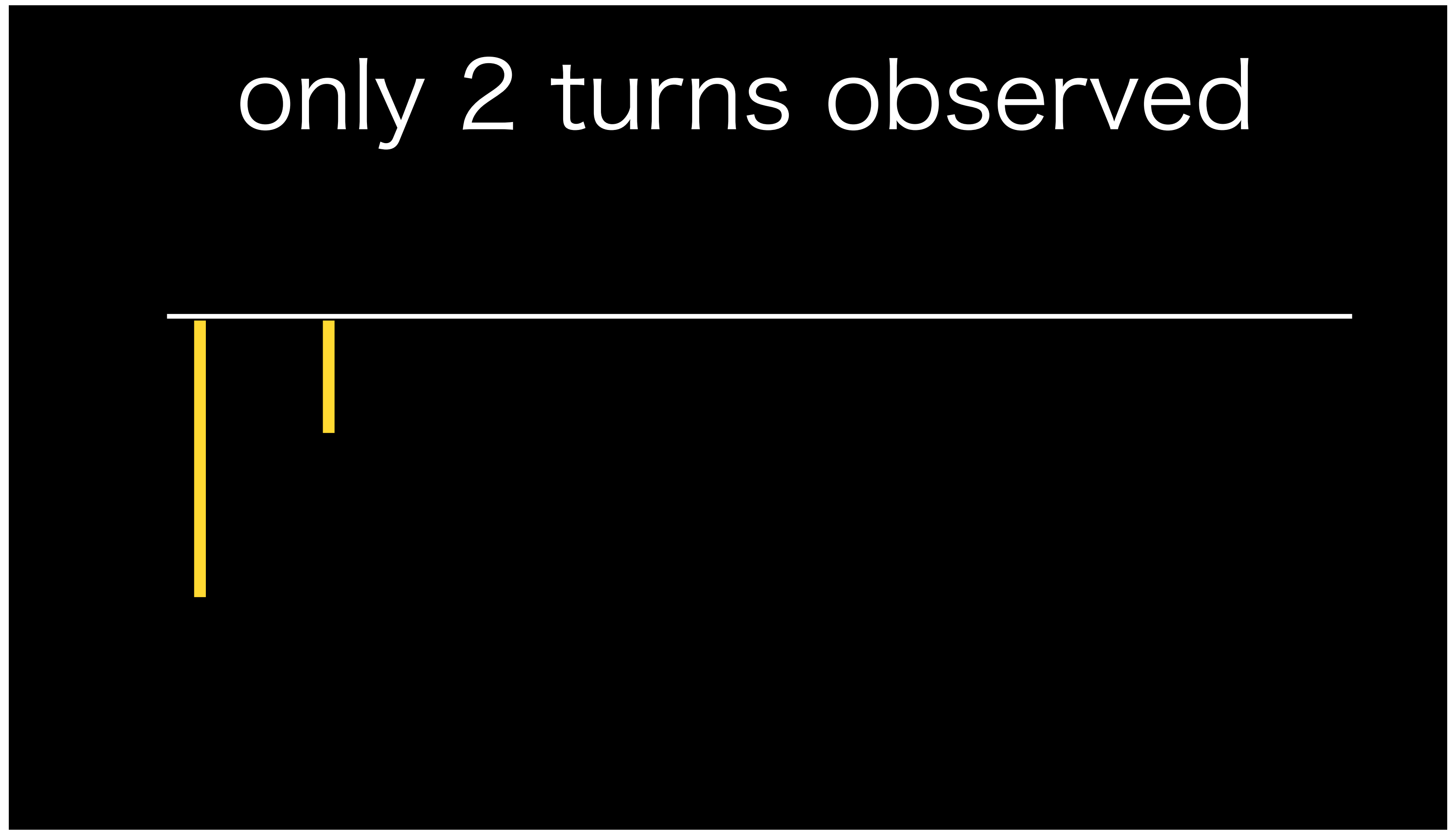
Field clamps rather attract leakage fields for the yoke-free magnet.

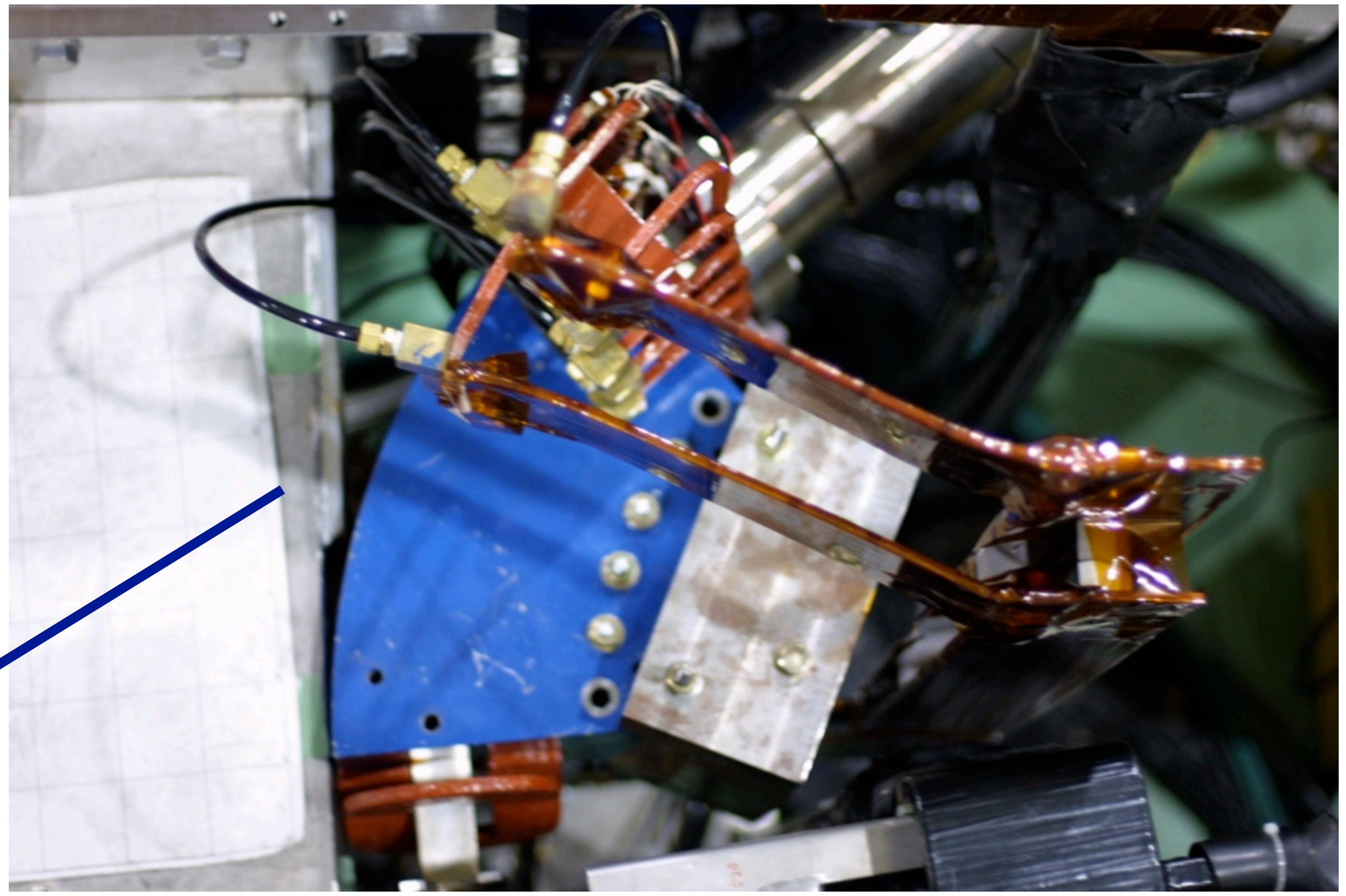


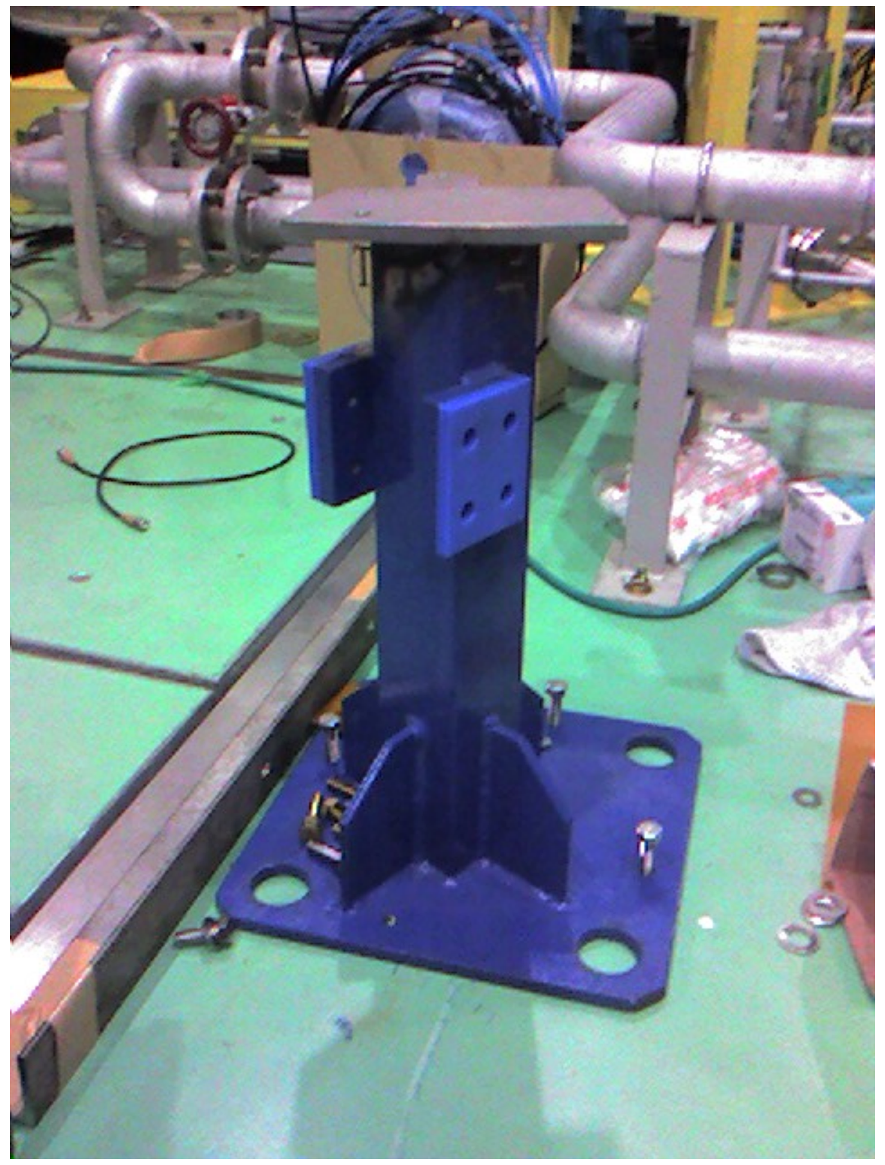
Beam loss at 2nd turn seams to occur around this section

Injection point

Bunch monitor

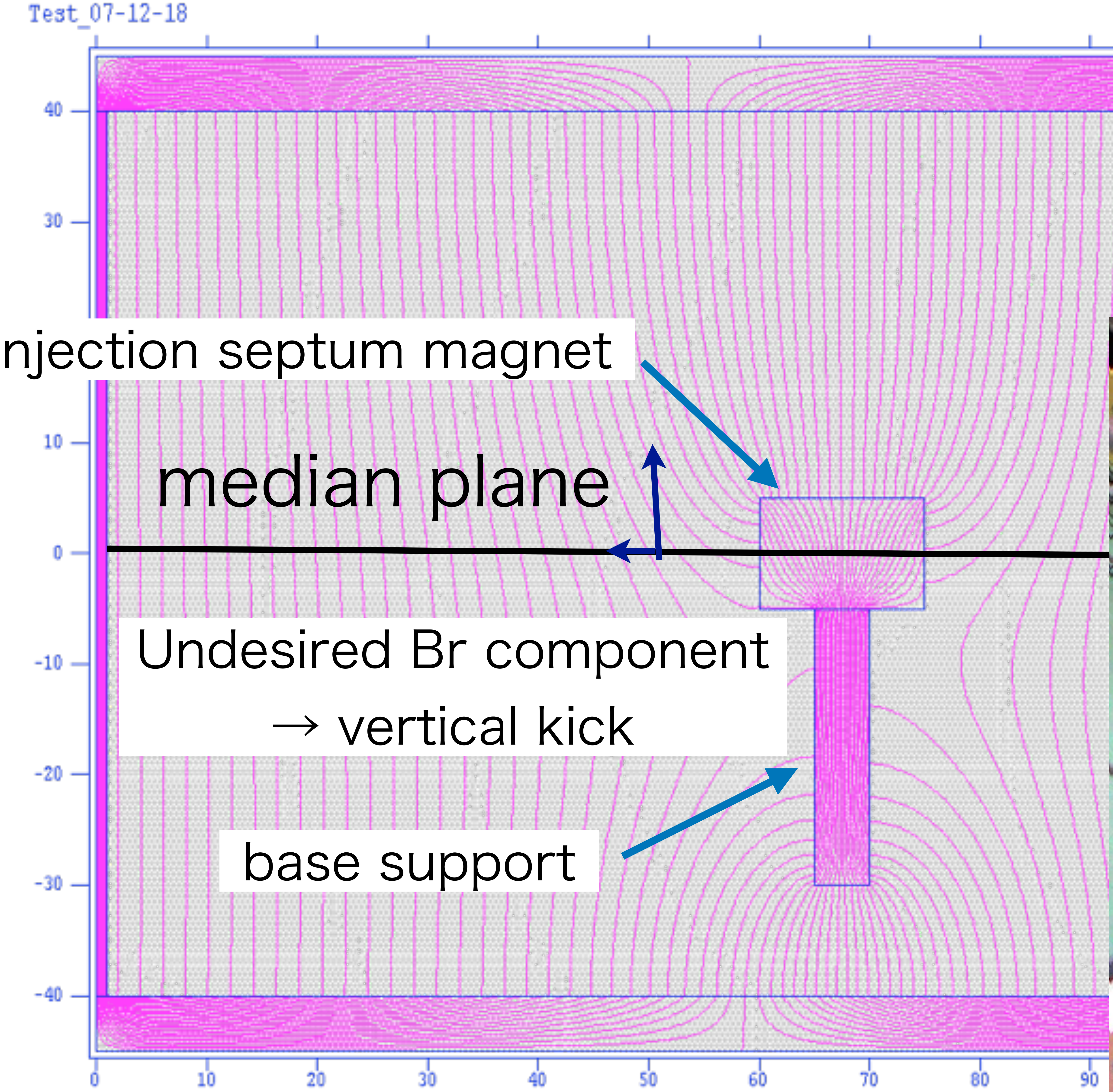

only 2 turns observed





injection septum
magnet

Iron support disturbed leakage field distribution

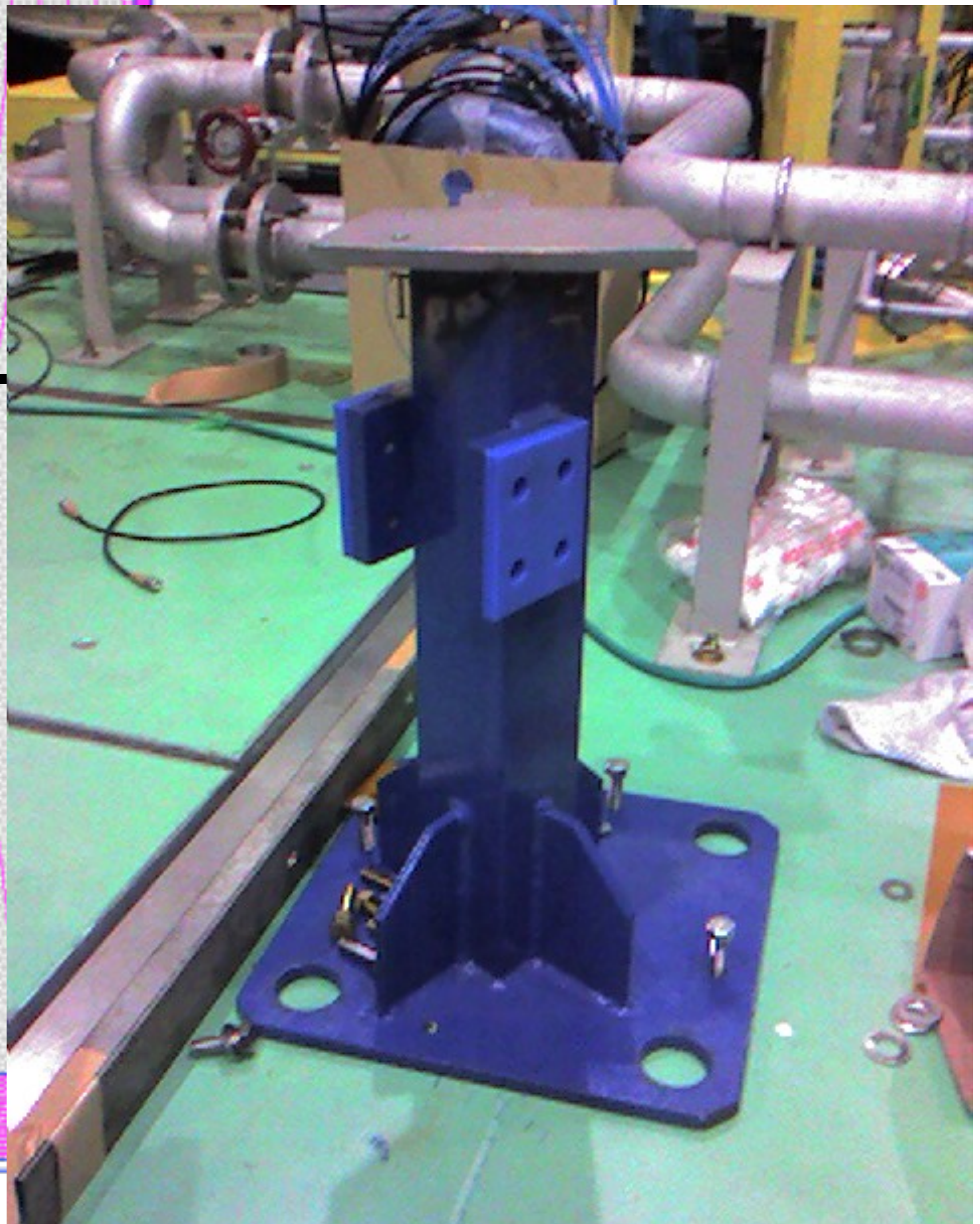


injection septum magnet

median plane

Undesired Br component
→ vertical kick

base support



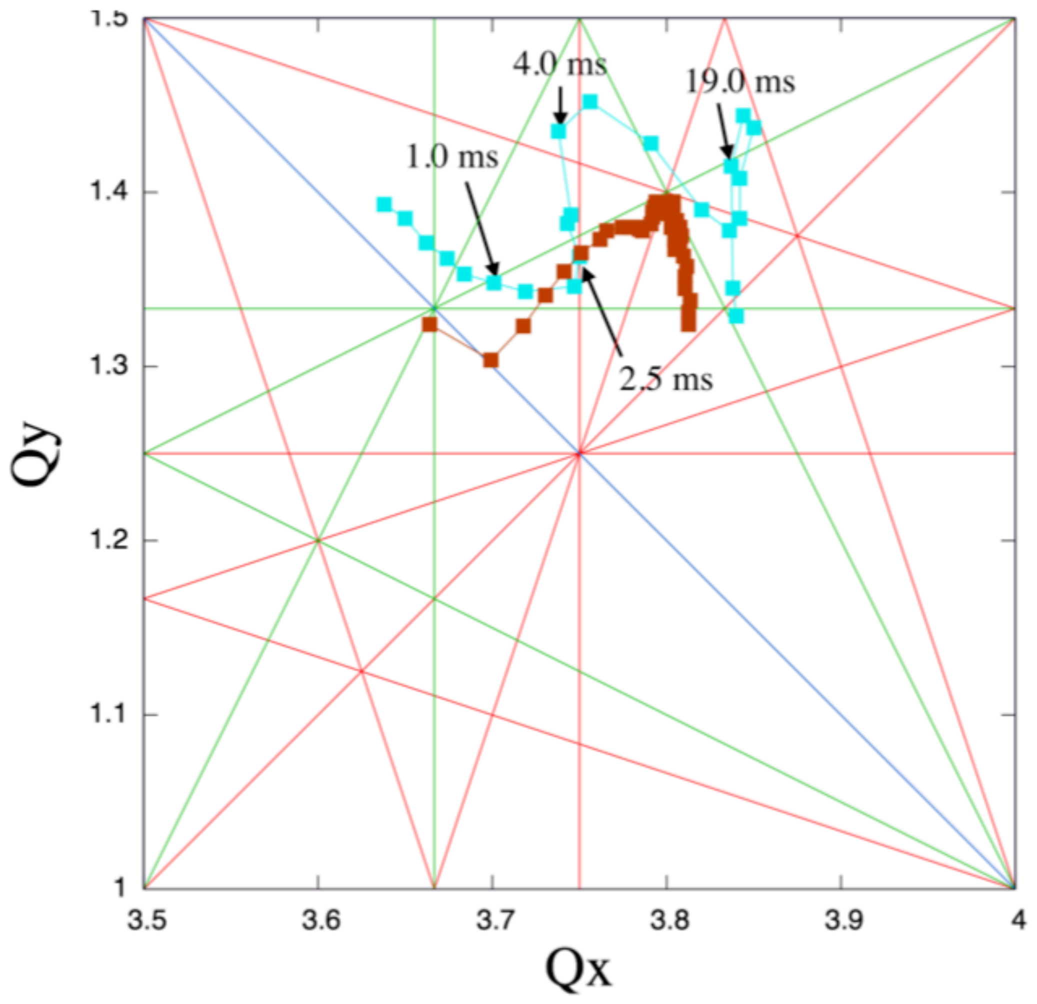


Figure 5: MAIN RING betatron tune footprints. Blue and brown squares indicate measurements and simulations, respectively.

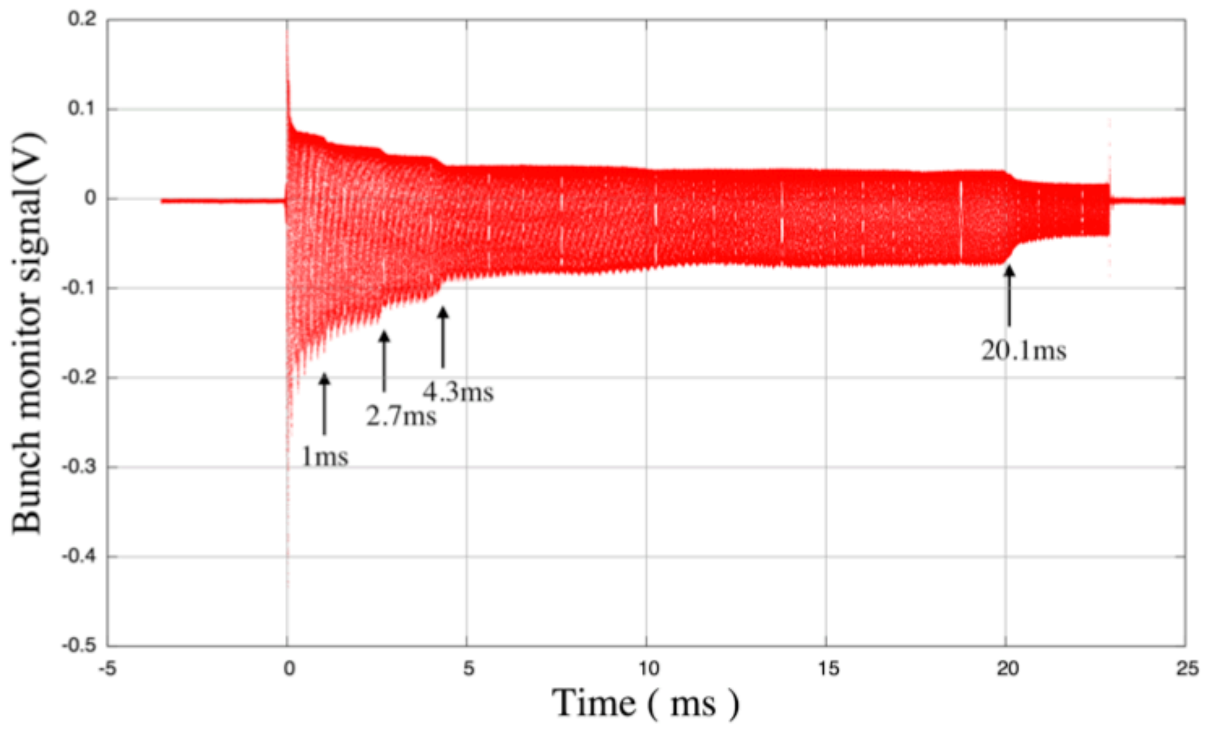


Figure 6: The output signal from the bunch monitor. There are some remarkable beam losses during acceleration.

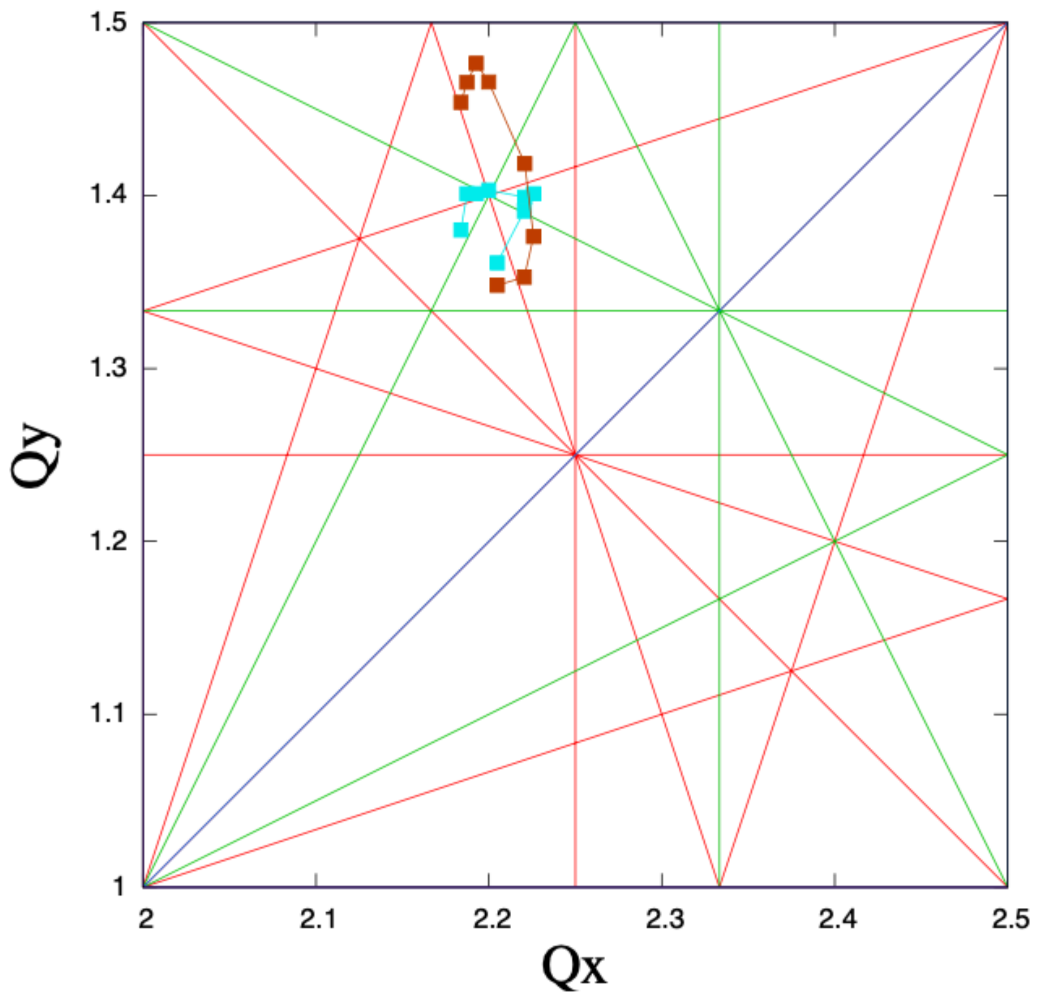


Figure 7: BOOSTER betatron tune footprints. Blue and brown squares indicate measurements and simulations, respectively.

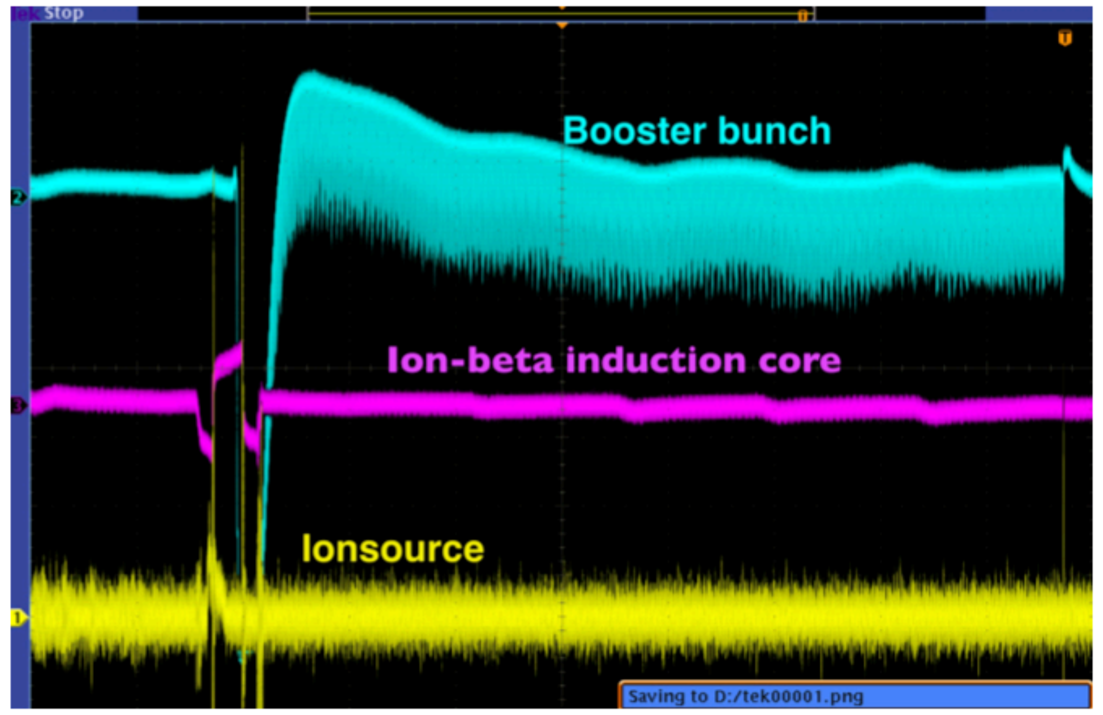
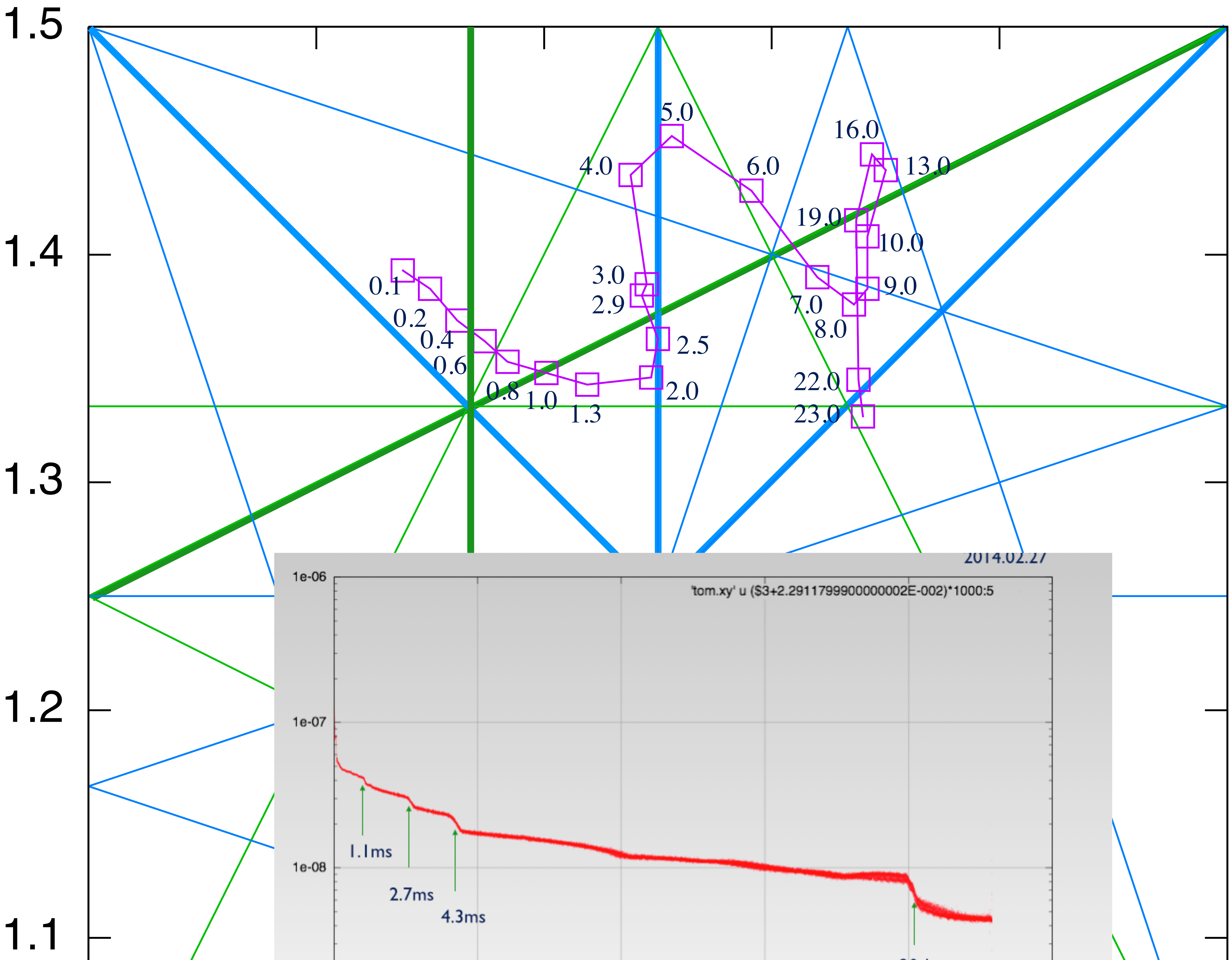
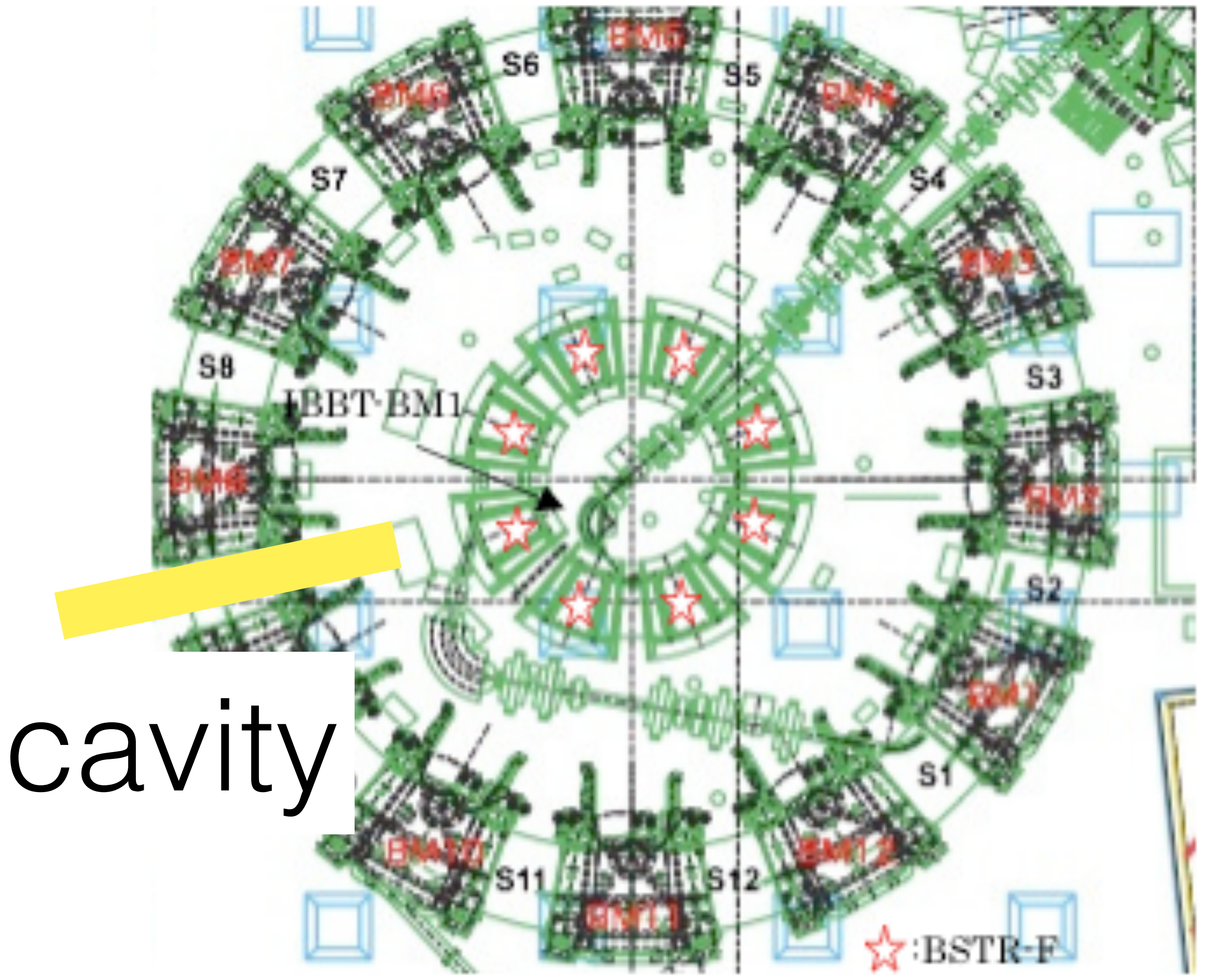
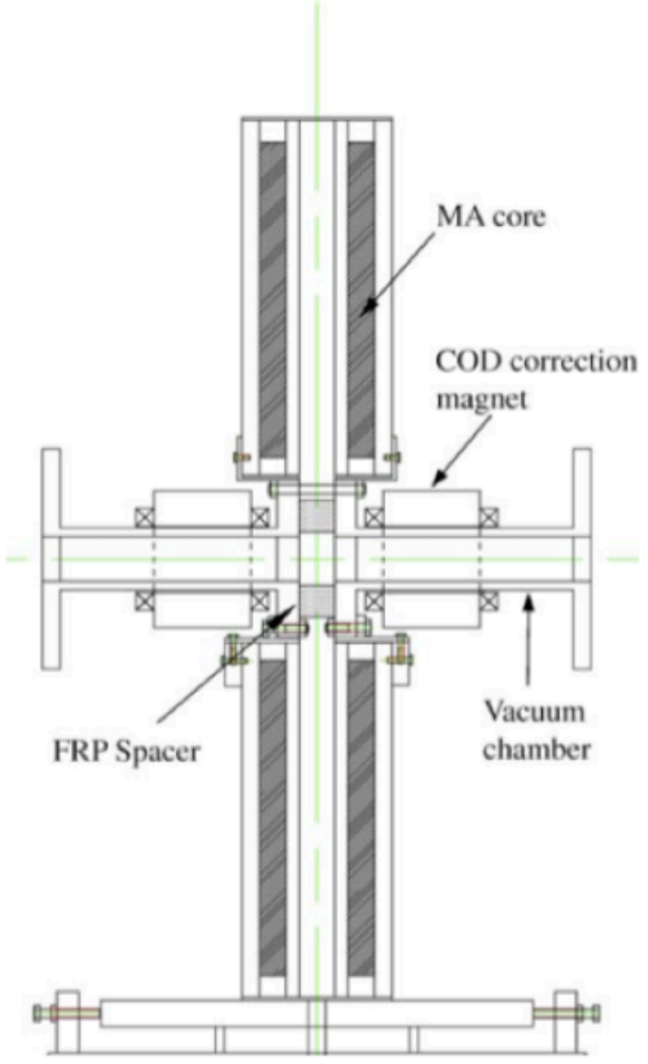


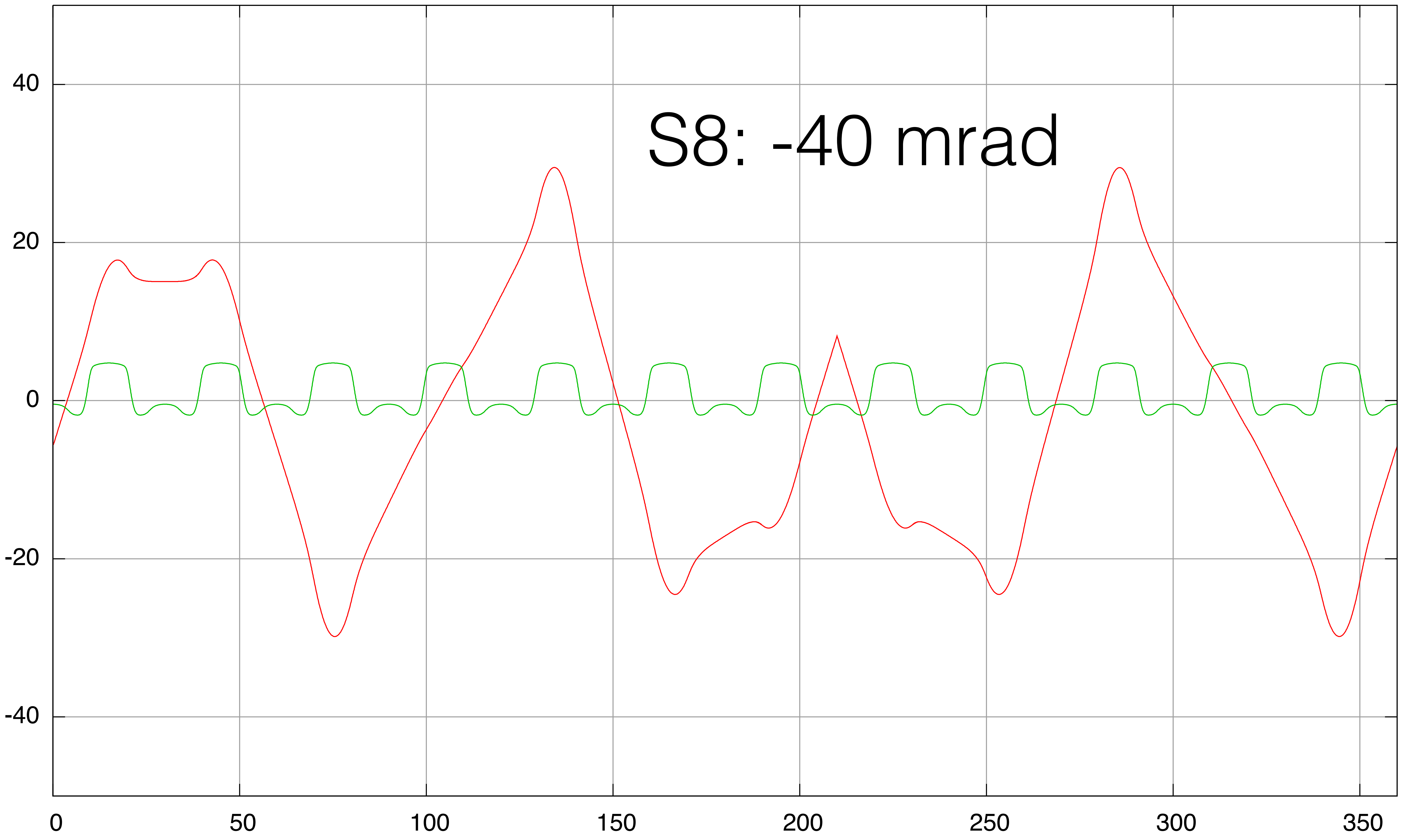
Figure 8: The output signal from the bunch monitor indicated by a blue line. There is no remarkable beam loss during acceleration.

Beam loss caused by the betatron resonances in the main ring of KURNS FFA





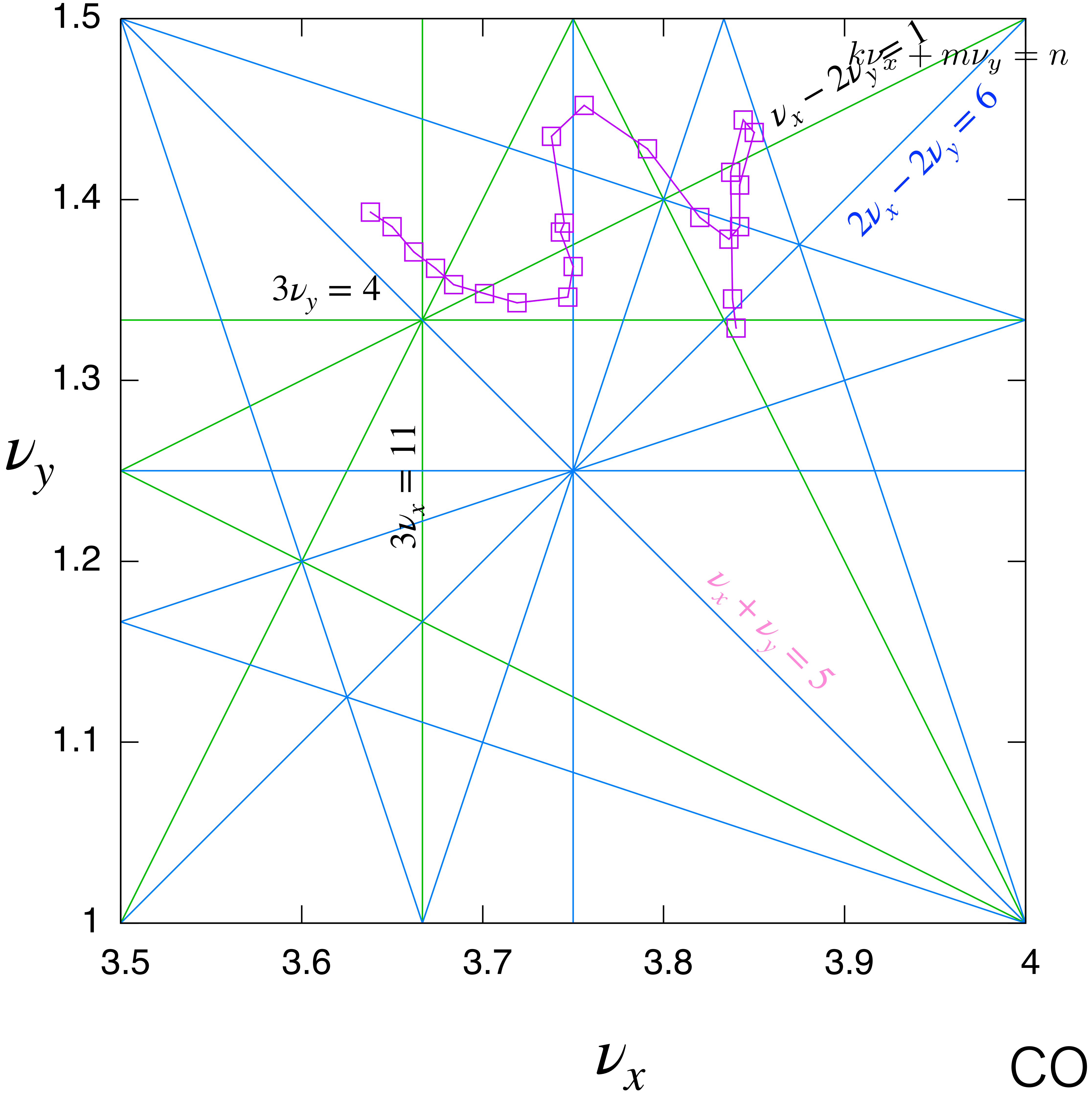




Leakage field in the straight section is absorbed by the cavity. Therefore, an apparent kick appears in the straight section.

$$A_{3m}e^{ia_{3m}} = \frac{1}{48\pi B\rho}\int_0^C \frac{\partial^2 B_y}{\partial x^2}\beta_x^{3/2}e^{i[3(\mu_x-\nu_x s/R)+ms/R]}ds$$

$|k| + |m| = \mathrm{order}$



order =1 ：integer resonance

caused by dipole

$\nu_x = n \qquad \nu_y = n$

order = 2 ：half integer resonance

caused by normal quadrupole

$2\nu_x = n \qquad 2\nu_y = n$

caused by skew quadrupole

$\nu_x + \nu_y = n$	$\nu_x - \nu_y = n$
sum resonance	difference resonance
$\epsilon_x - \epsilon_y = C$	$\epsilon_x + \epsilon_y = C$

C: constant

order = 3 : third integer resonance

caused by normal sextupole

$3\nu_x = n, \nu_x \pm 2\nu_y = n$

caused by skew sextupole

$3\nu_y = n, 2\nu_x \pm \nu_y = n$

COD makes driving terms large

	main ring	booster
pole shape optimization was done properly＊	no	no
return yoke	no	yes
field clamp	no(doesn’t work)	yes
tune excursion	yes	yes(bit smaller than MR)
resonance crossing	yes	yes(bit less than MR)
leakage field at the straight section	yes(>100 G)	no(< 10 G)
magnetic material at the straight section	yes	yes(more than MR)
apparent kick at the straight section	yes	no (if yes, very small)
large cod	yes	no
large resonance driving term	yes (probably)	no
large beam loss	yes	no

Then what should we have done for the main ring?

speculations

dribble of thoughts

Should we have put the return yoke?   That might be one thing.

But, if we did so, we would discard the advantages of yoke-free magnets.

We should have put the system which can measure COD very easily.

Put non distractive BPMs at every cell.

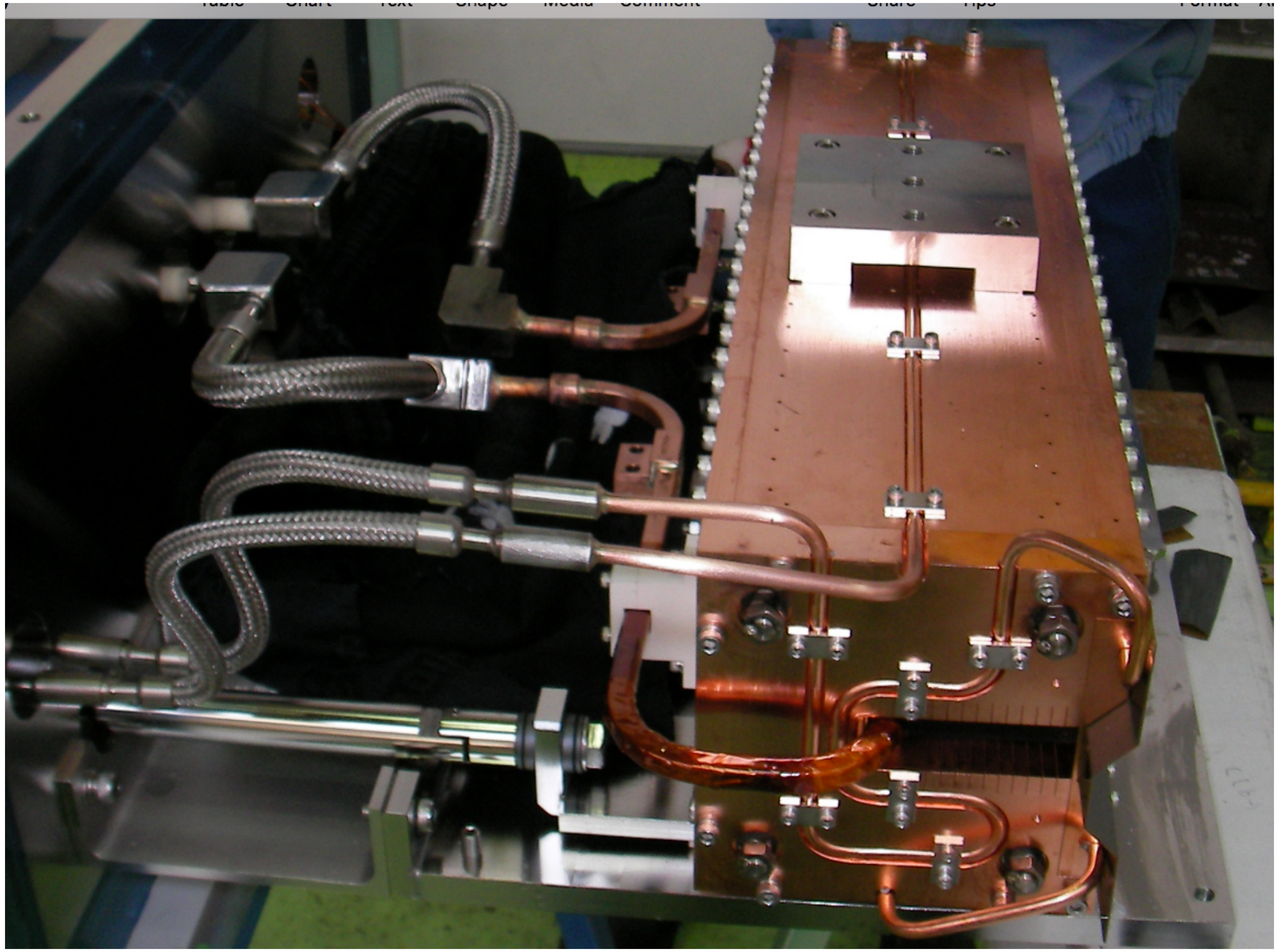
Install COD correction system.

It is based on independent power supply for the magnet.

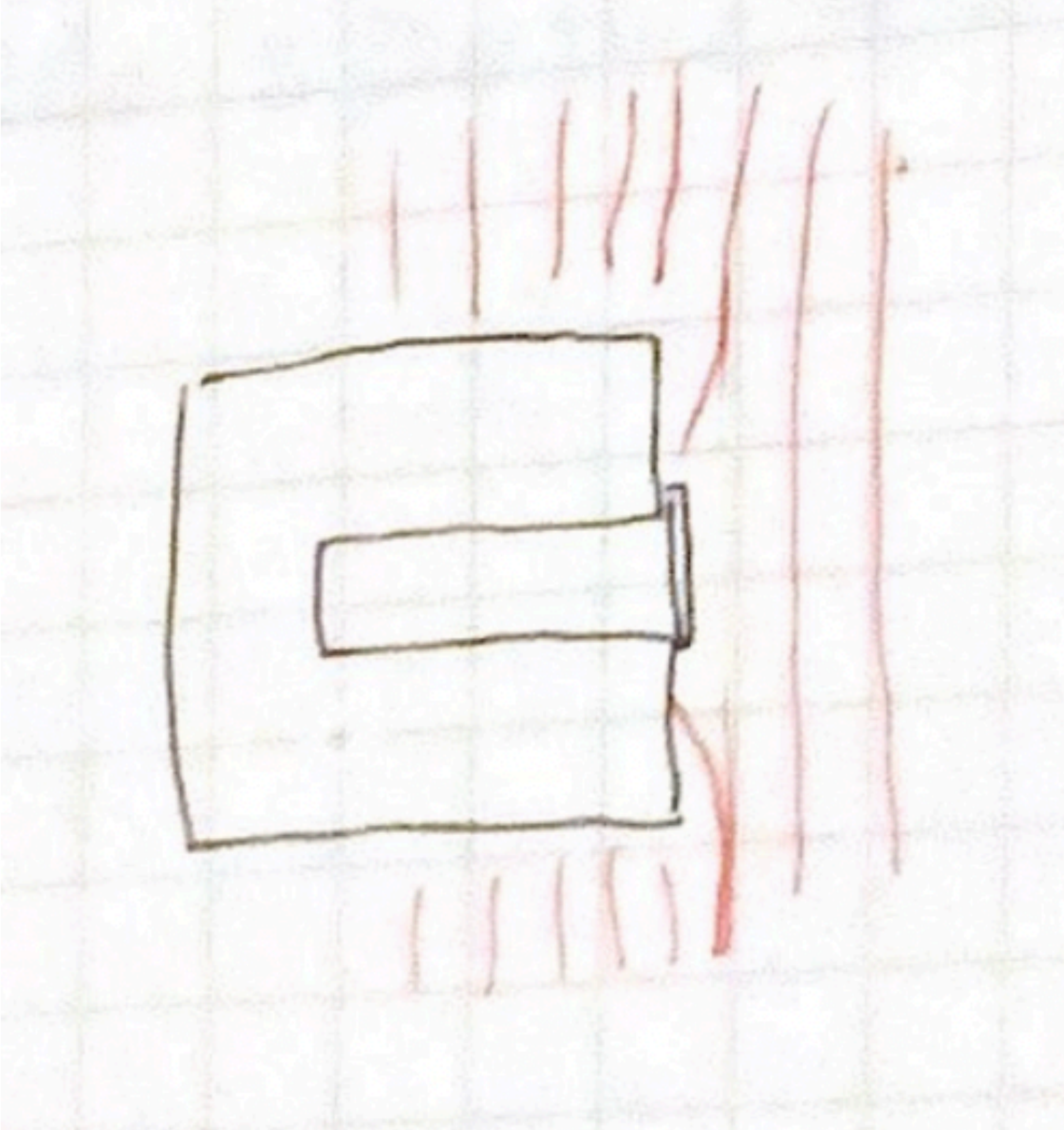
Every magnet is excited by its own power supply.
(One-by-one excitation can be done for FFA)

That’s it? All evil is from only COD?

not only dipole but quad

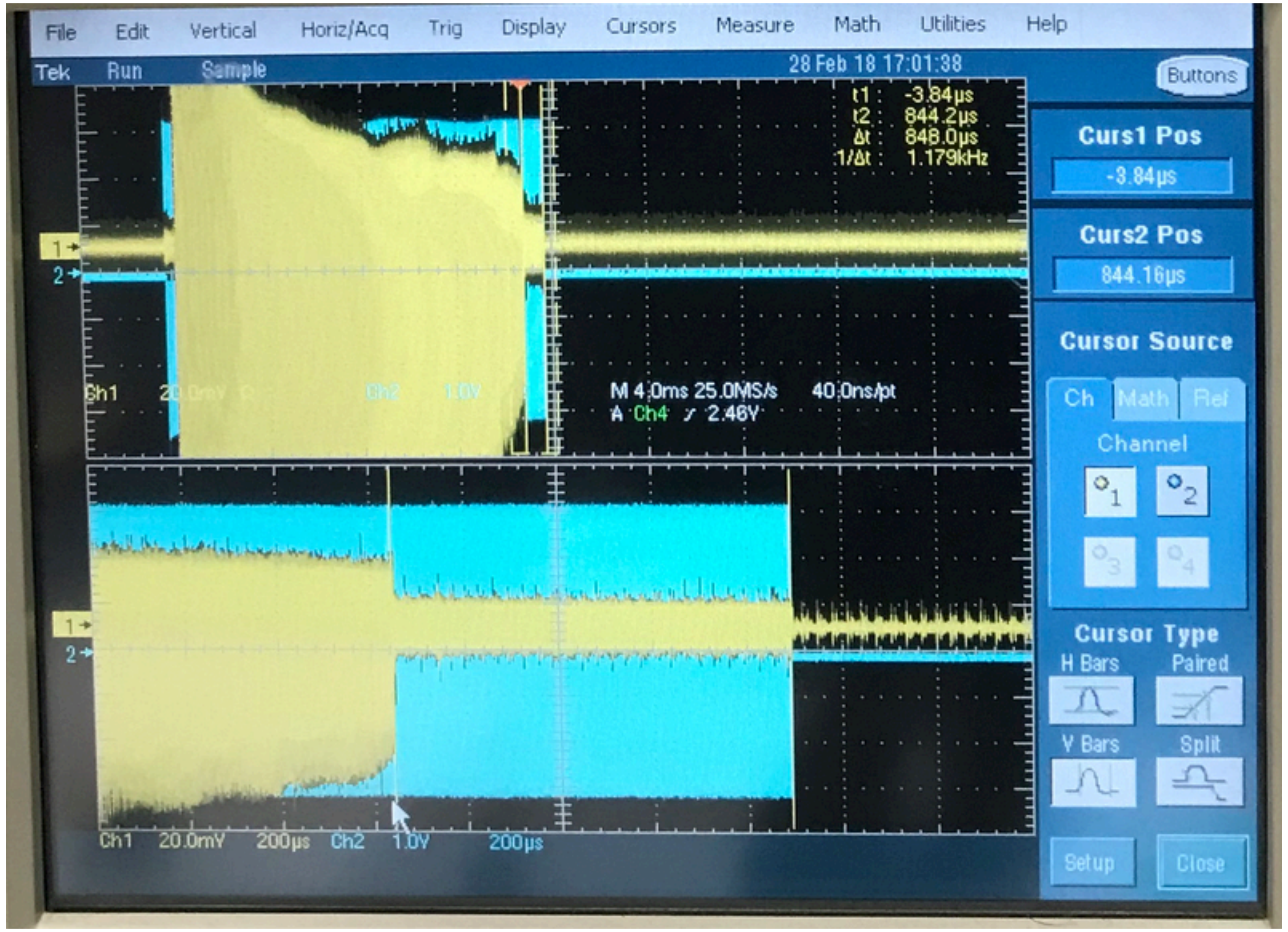


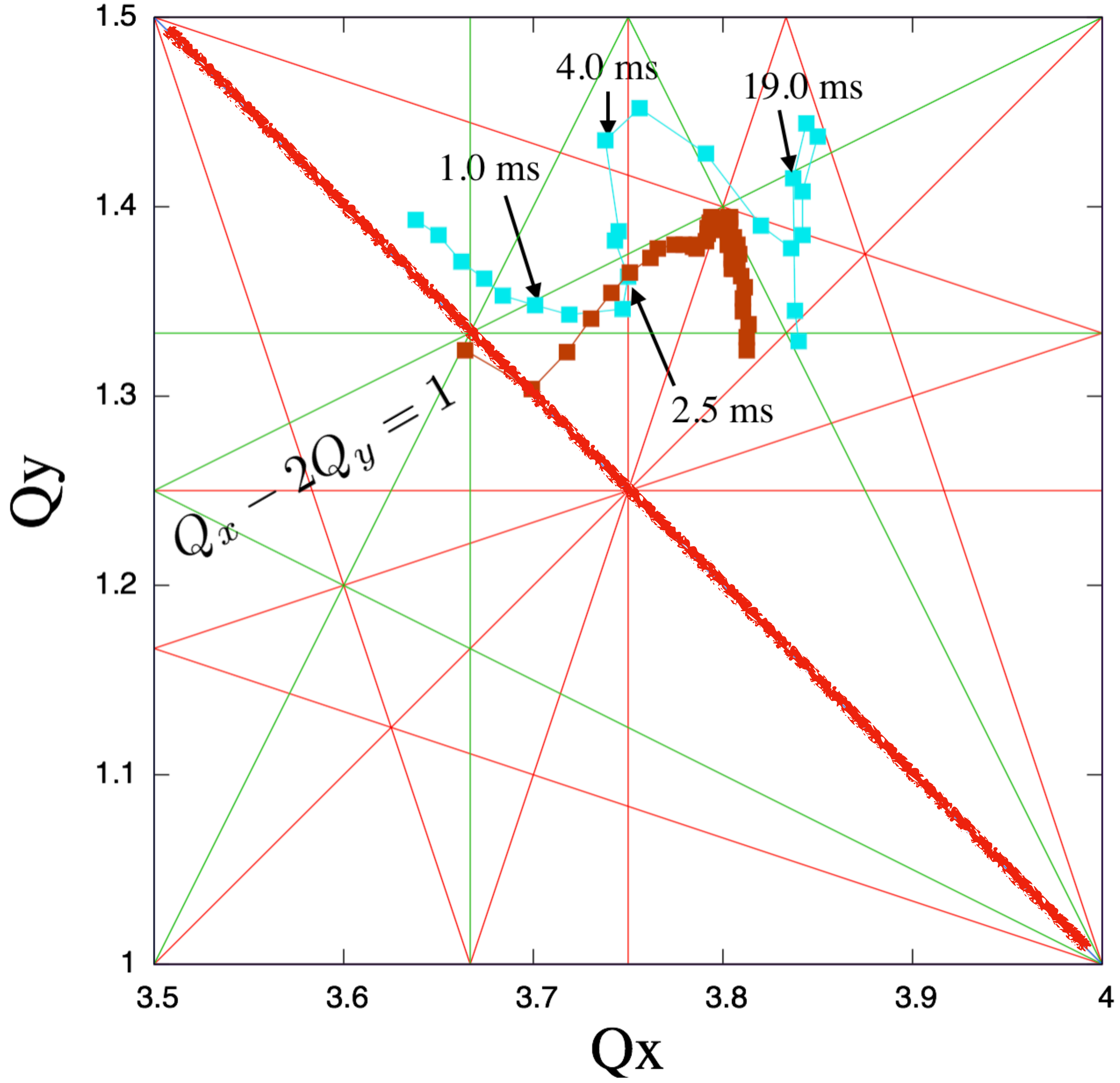
Beam extraction septum



Leakage field absorption generates extra quad field.

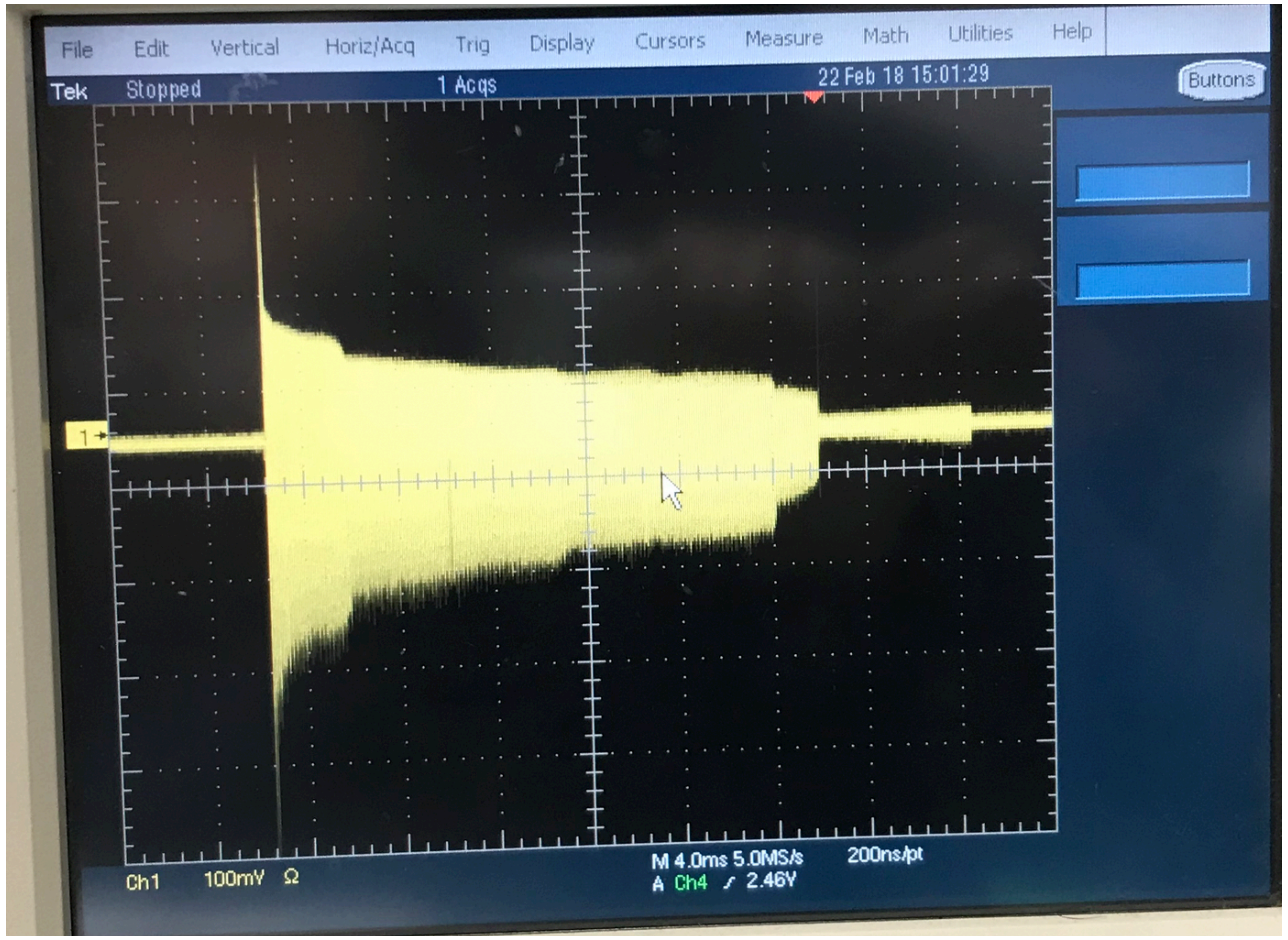
things happen once in a while





At the edge of patch, quadrupole component of D field is enhanced. That makes Qy higher. By some reason, the position of the patch had been moved.Dispatch Uesugi-san to reposition the patches.

fixed!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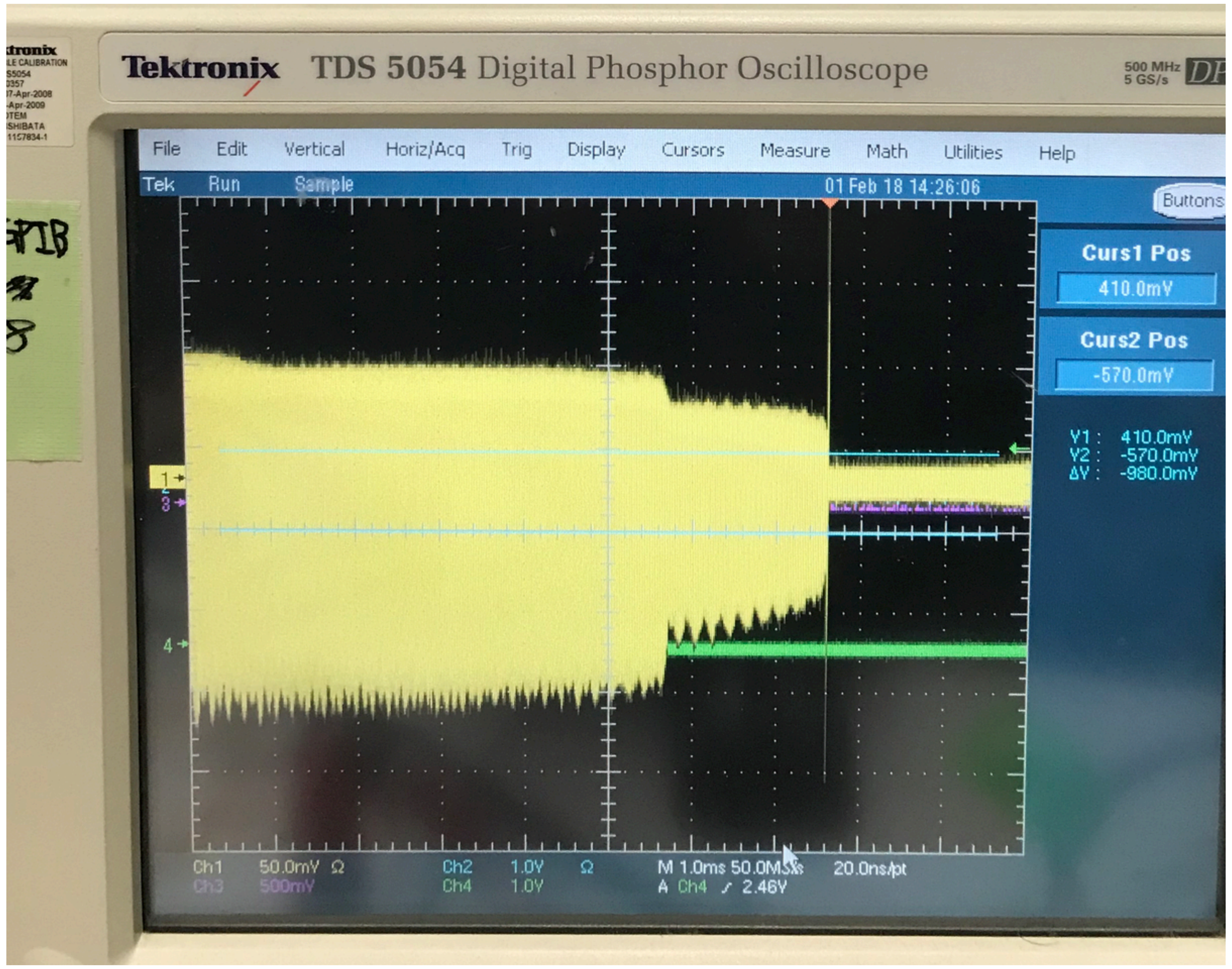
Buttons
Ch1
100mV Ω
M 4.0ms 5.0MS/s
200ns/pt
A Ch4 ⟋ 2.46V


Tektronix
TDS 5054 Digital Phosphor Oscilloscope
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Buttons
Curs1 Pos
410.0mV
Curs2 Pos
-570.0mV
V1 : 410.0mV
V2 : -570.0mV
ΔV : -980.0mV
Ch1 50.0mV Ω
Ch3 500mV
Ch2 1.0V Ω
Ch4 1.0V
M 1.0ms 50.0MS/s
20.0ns/pt
A Ch4 ⟋ 2.46V

What we learned

Easy handle COD measurement/correction system is essential.

Do not place magnetic material in the beam line without evaluating the effect of field disturbance.

Do not place iron where there is a leakage magnetic field without evaluating the effect of field disturbance. even if it is far from the beam line

At the designing stage, reduce the leakage field as small as possible.

Life is too short to fight with the leakage field.