Introduction to Accelerator Physics

Part 2

Pedro Castro / Accelerator Physics Group (MPY)
Hamburg, 1st February 2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Working with accelerators in the control room …

The job:

- switch on/start up accelerator systems
- apply procedures to
  - inject beam
  - reach required beam intensity, energy …
  - correct beam position, establish collisions
  - …
- use feedback systems to get stable beam position, intensity …
- perform measurements: beam emittance, energy spread …
- eventually, optimize parameters to improve overall performance

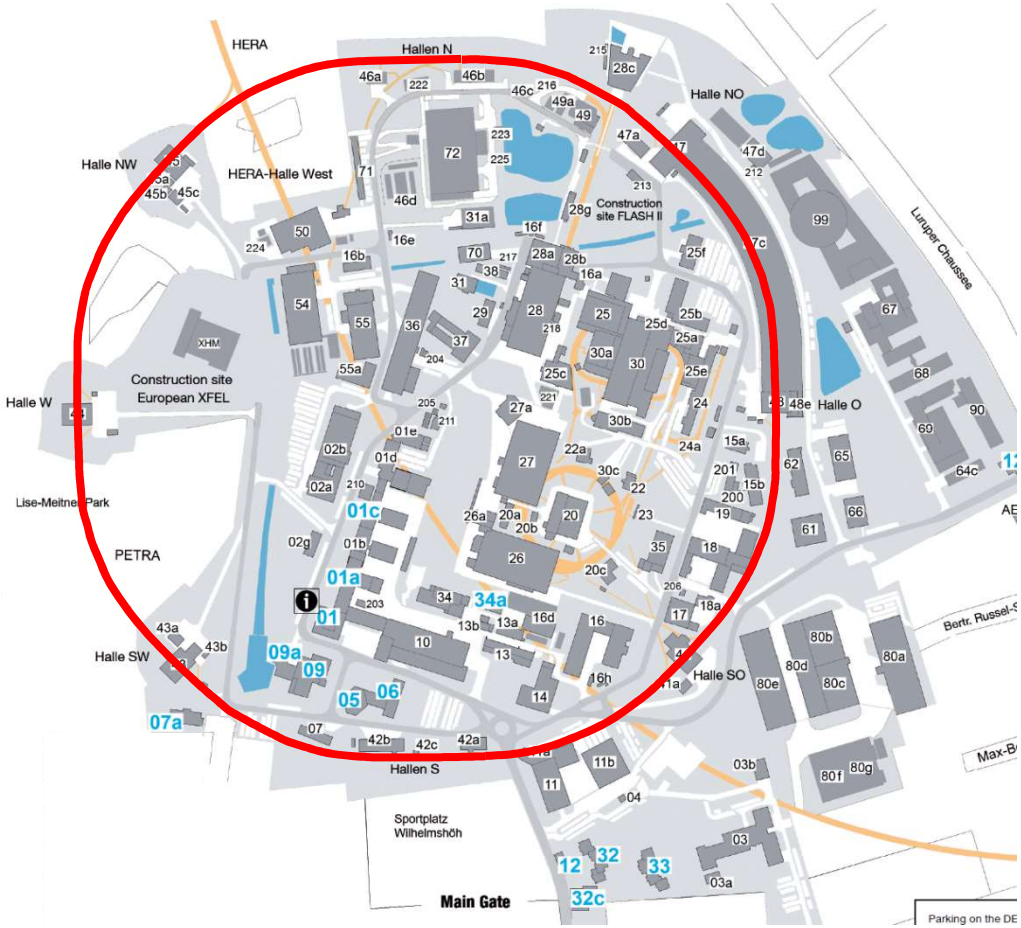
The job requires:

- a lot of (accelerator) physics knowledge
- a lot of (accelerator) engineering knowledge

(in case of problems)

- some Sherlock Holmes' skills

The case begins…



Accelerator Control Room
Hamburg, DESY
Sat. 12th June 2010
2 o'clock a.m.
PETRA runs with a beam current of 75 mA

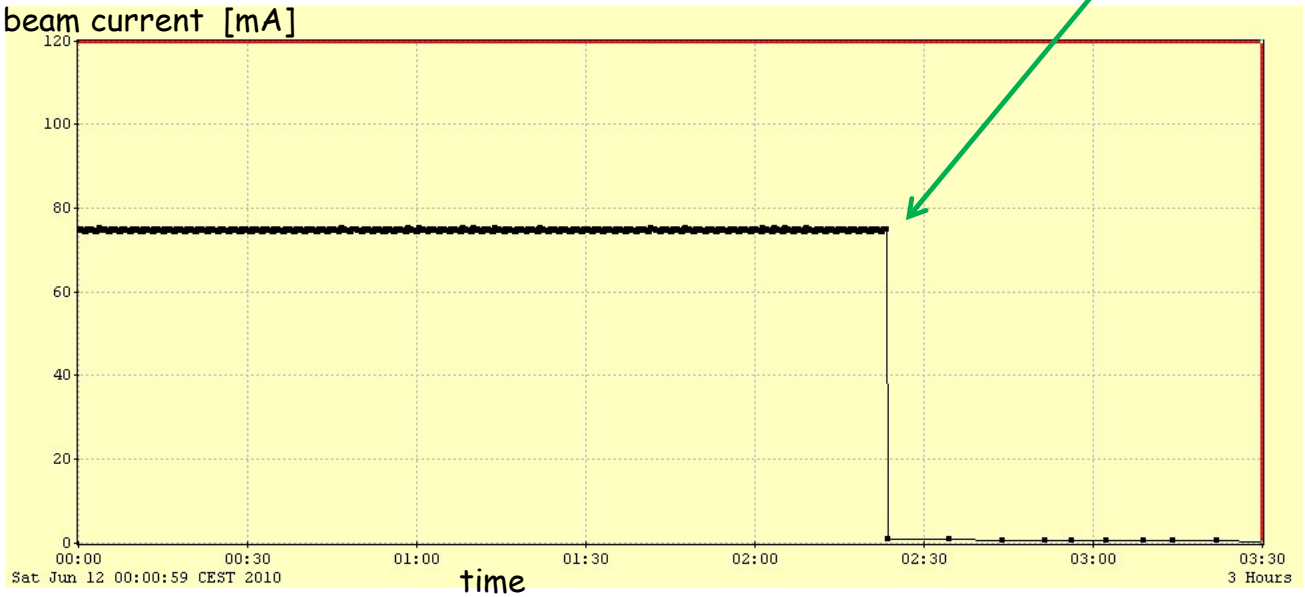
02:24 a.m.: beam lost

02:24 a.m.: beam lost

The Main Accelerator Control Room

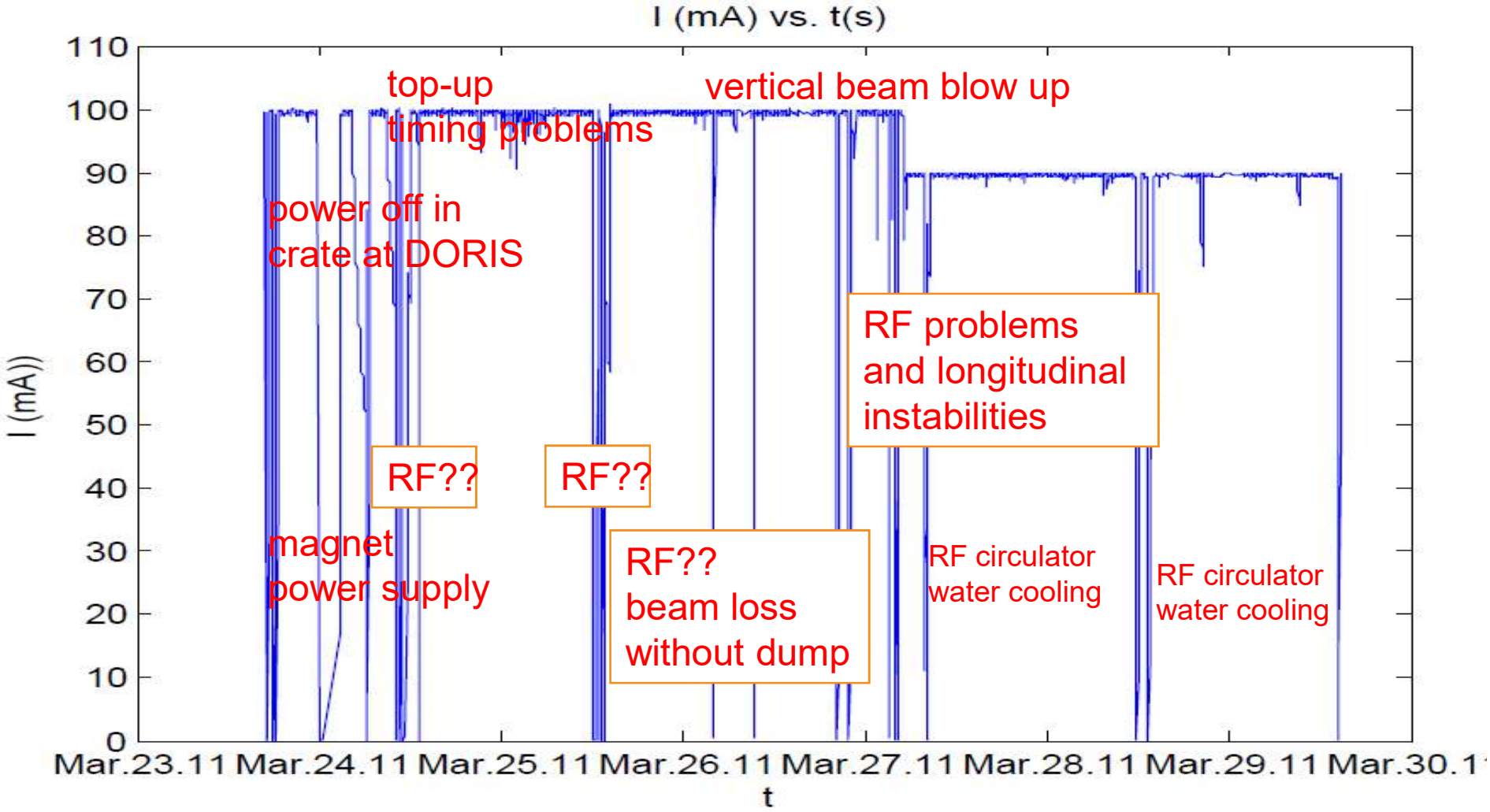
Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost



One example of PETRA run over 7 days

Run number 4: 60 Bunches; 23rd – 30th March, 2011



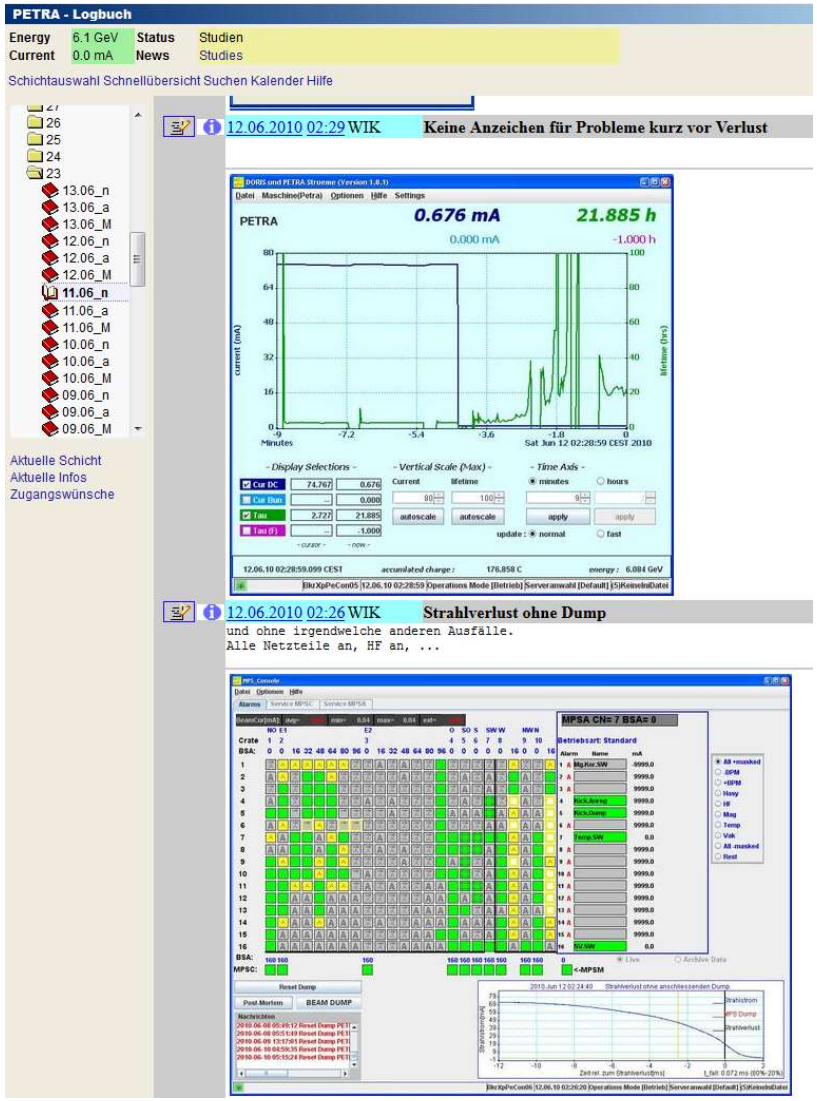
Source: K. Balewski (MAC report 2011)

Beam lost at 02:24 a.m.

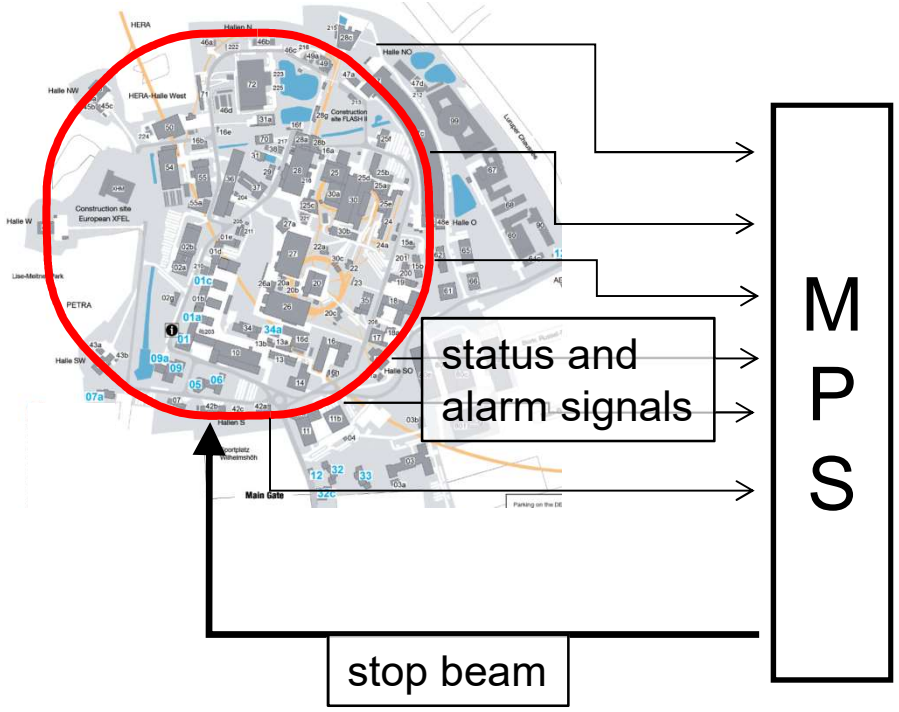
The link to the electronic logbook:

http://ttfinfo.desy.de/petra/show.jsp?dir=/2010/23/11.06_n&pos=2010-06-12T02:26:3

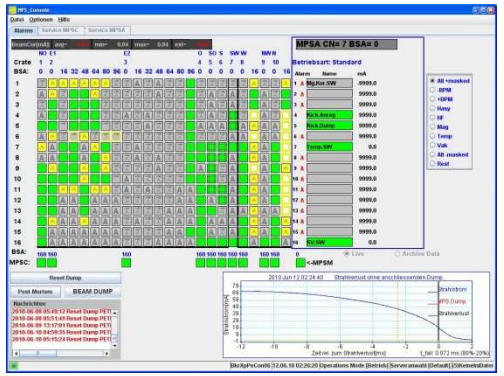
What to do?



Alarm overview: the Machine Protection System

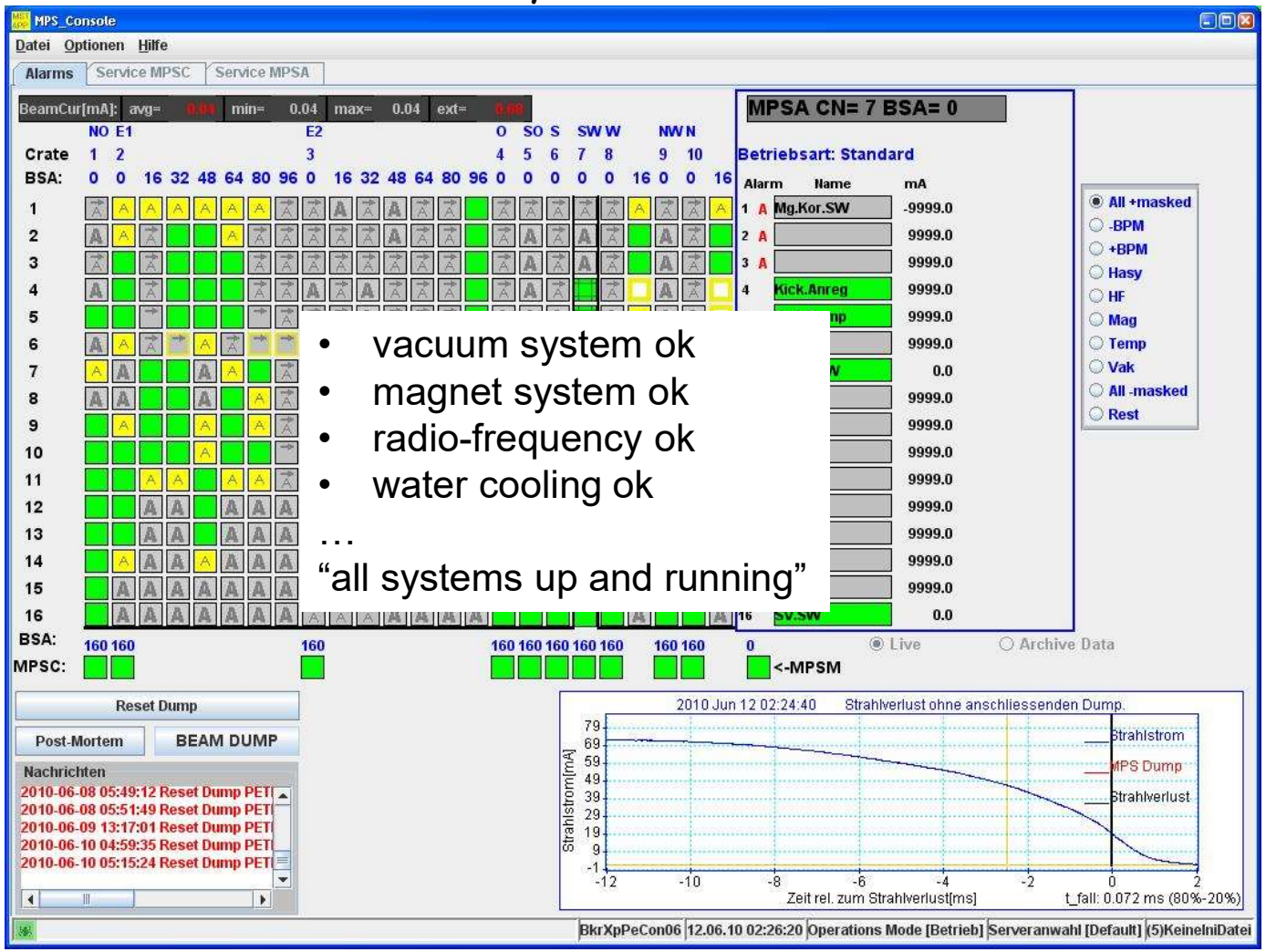


control system



Alarm overview: the Machine Protection System

The Machine Protection System status from 12th June 2010 at 02:26



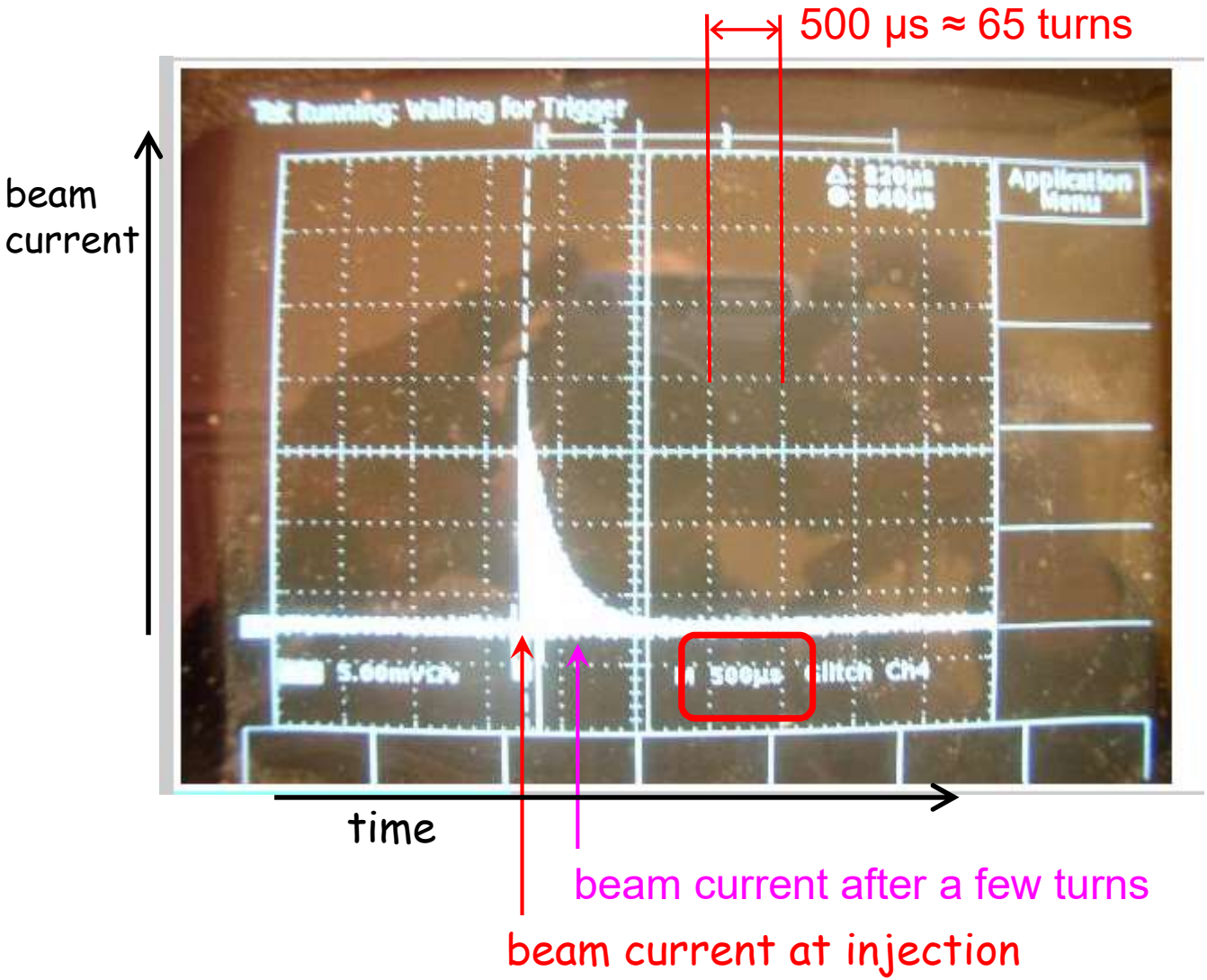
- vacuum system ok
- magnet system ok
- radio-frequency ok
- water cooling ok

…

“all systems up and running”

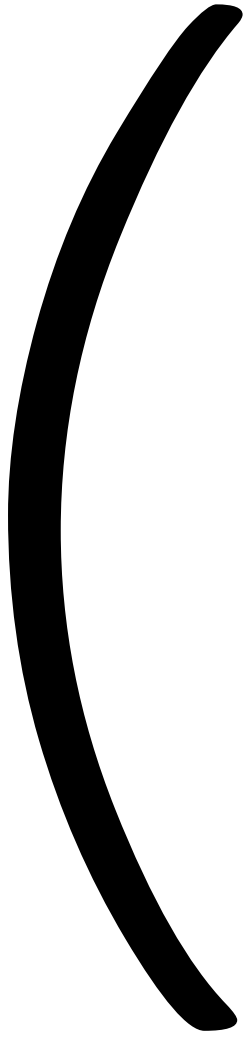
12th June 2010 02:26

Electrons can be injected but cannot be stored !

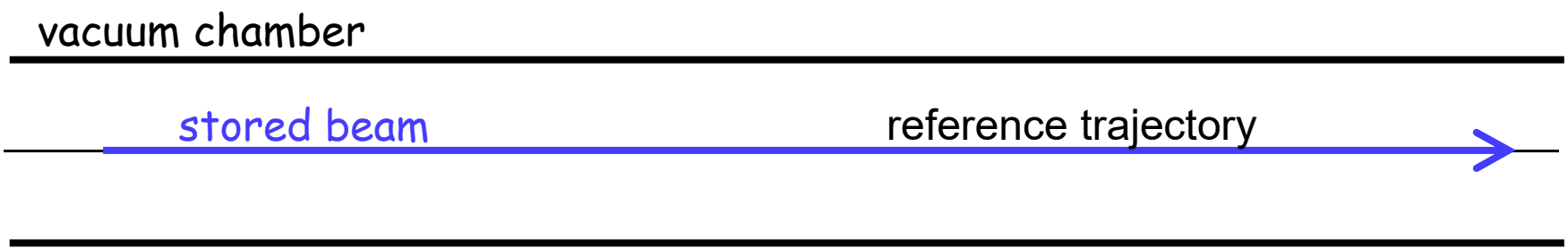


injection problem?

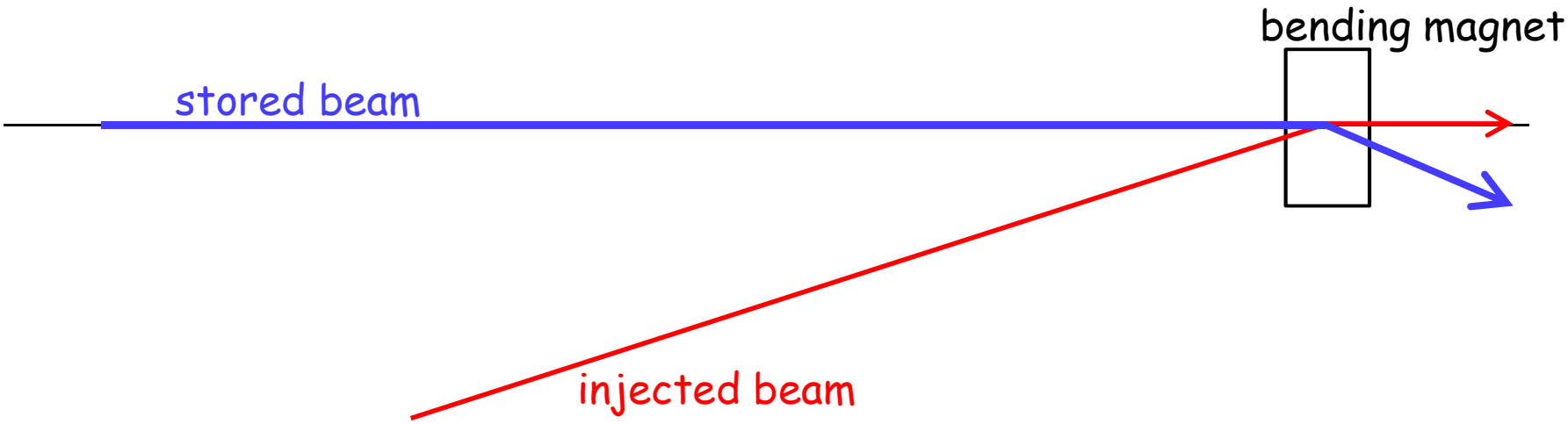
Circular accelerators: injection system



Next suspect: injection



Next suspect: injection



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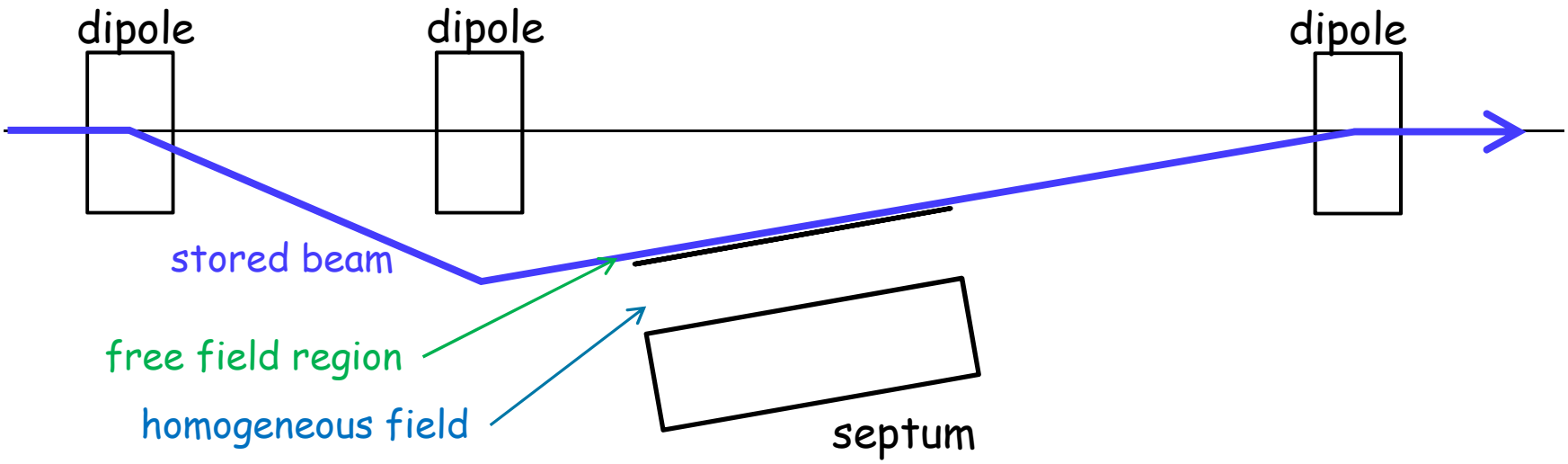
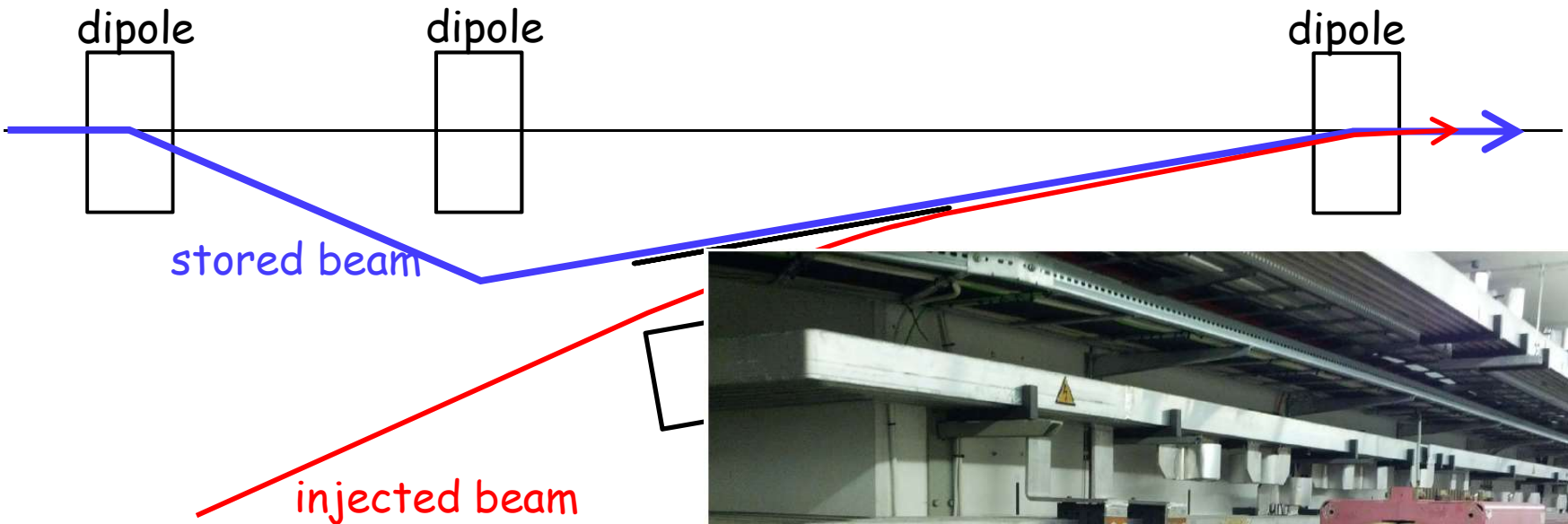
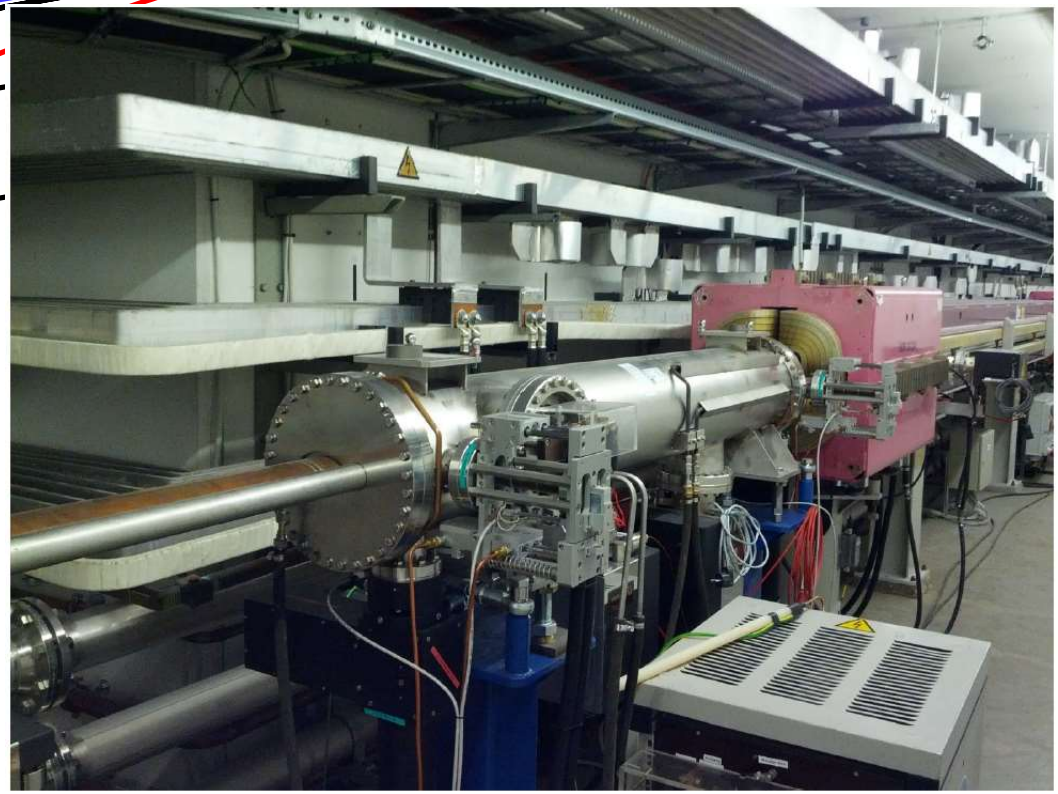


Next suspect: injection + accumulation

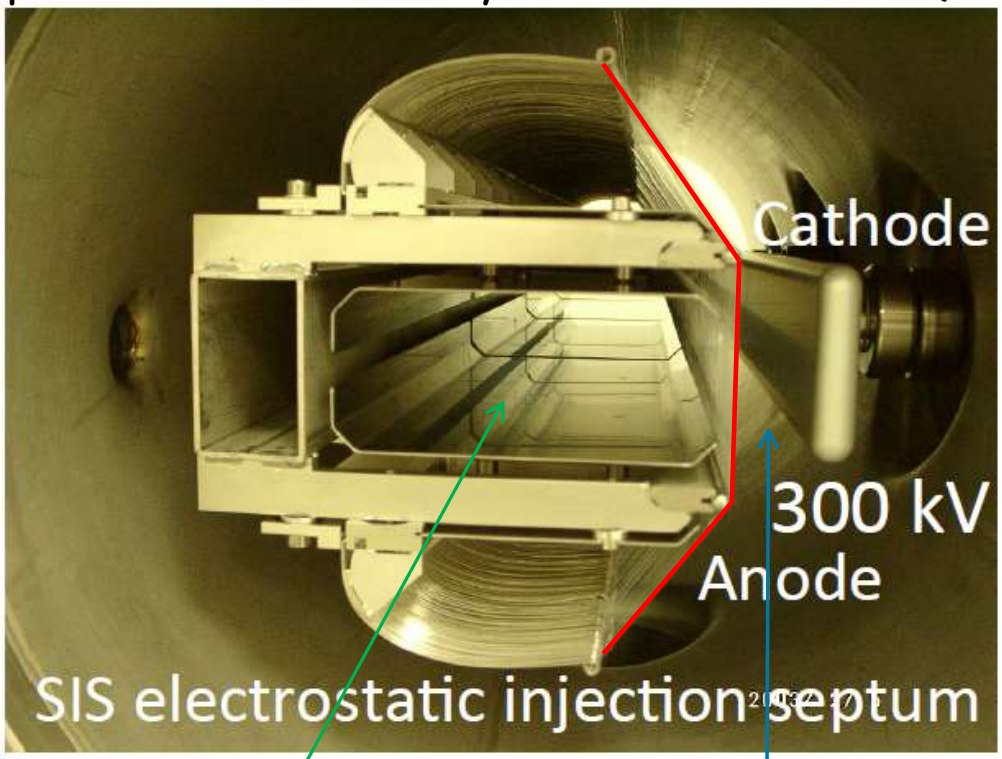


PETRA
septum



Next suspect: injection + accumulation

septum at the Proton Synchrotron Booster (PSB) at CERN

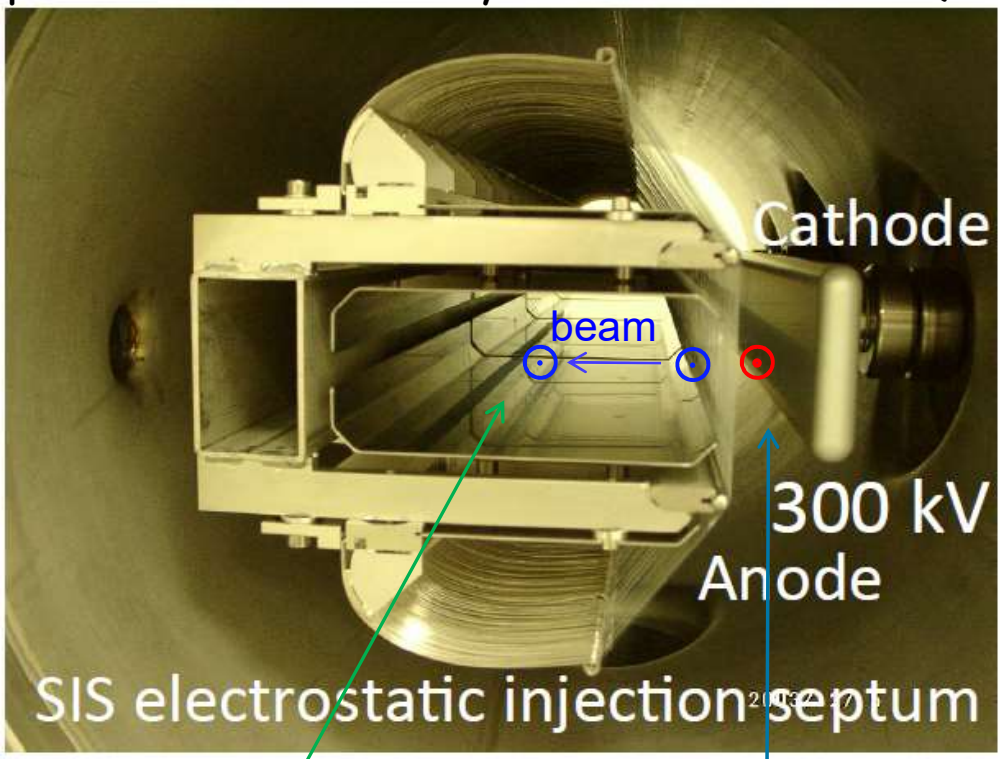


free field region

homogeneous field

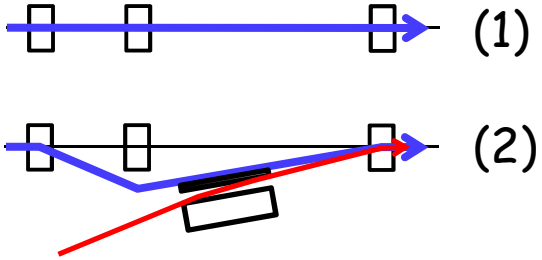
Next suspect: injection + accumulation

septum at the Proton Synchrotron Booster (PSB) at CERN



stored beam

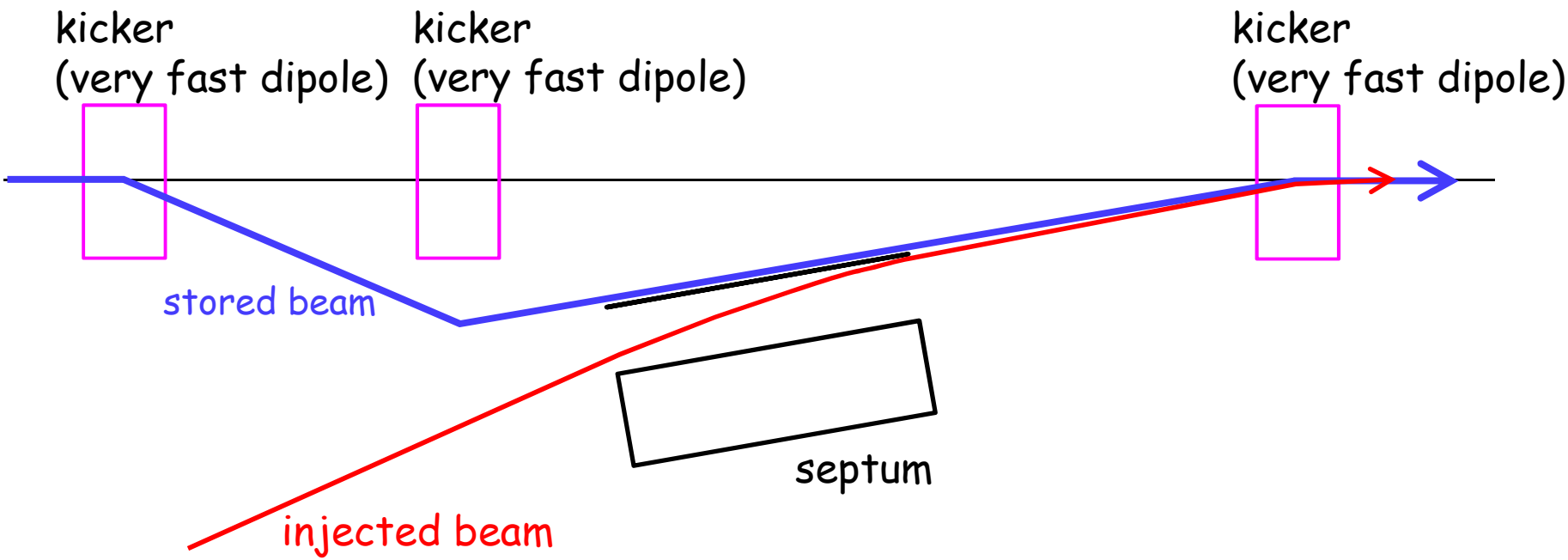
injected beam

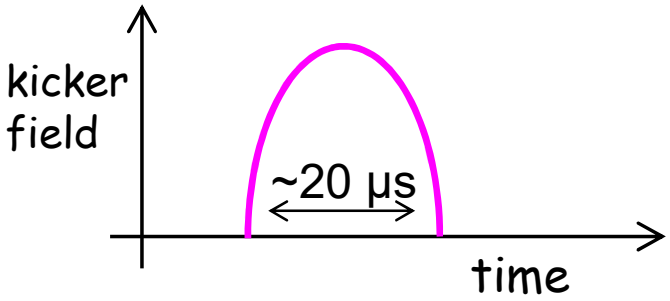


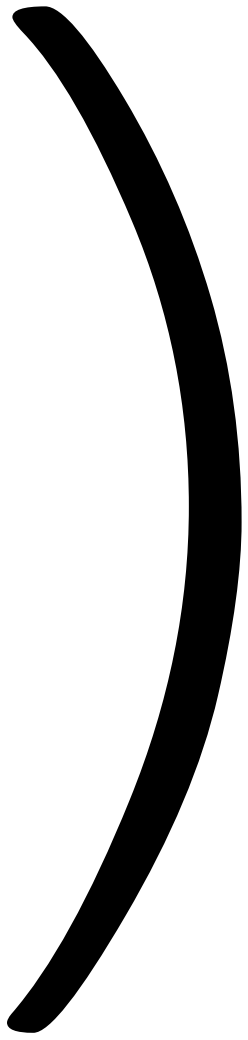
free field region

homogeneous field

Next suspect: injection + accumulation

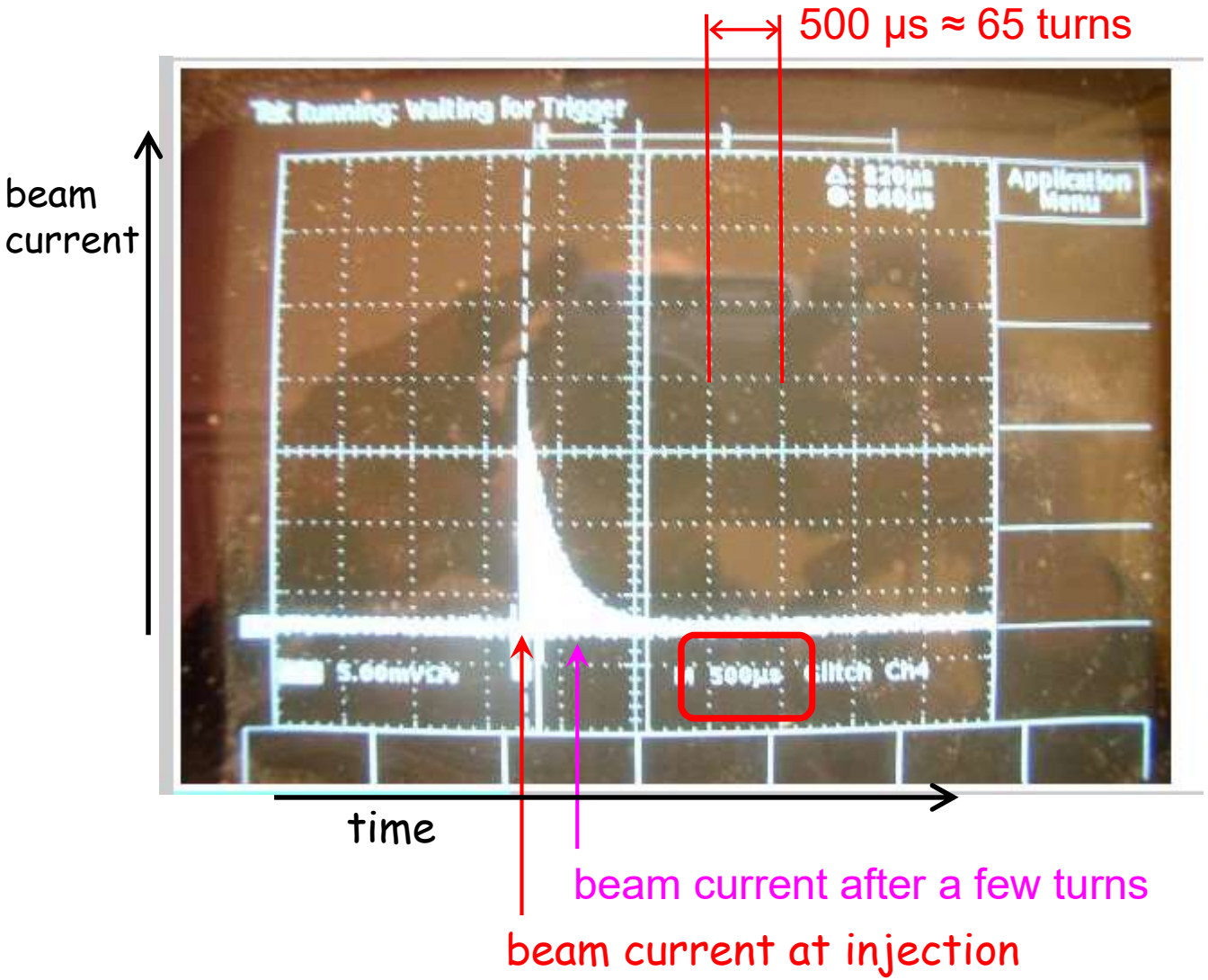






Circular accelerators: injection system

Electrons can be injected but cannot be stored !



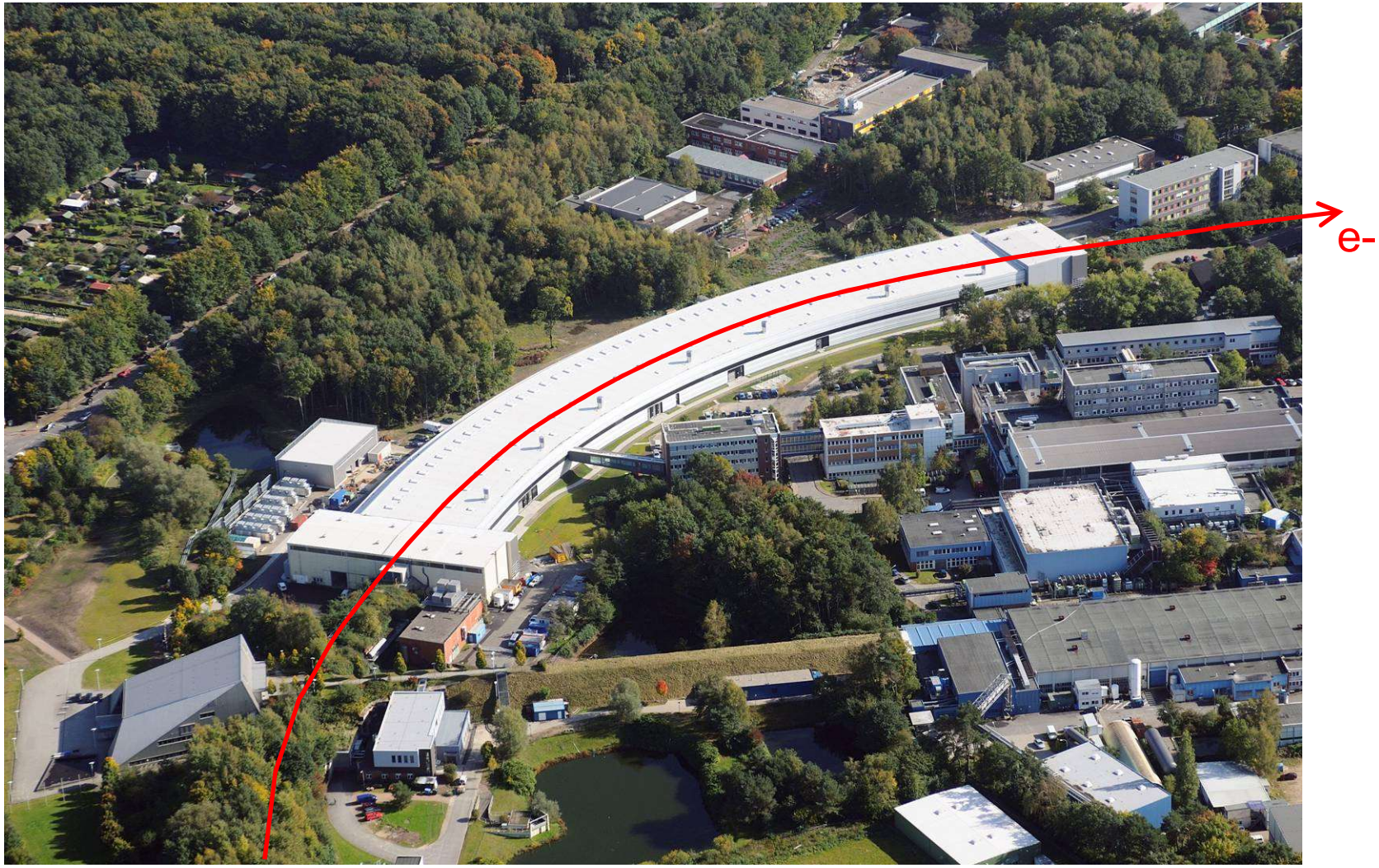
~~injection problem?~~

Next suspect: a problem with vacuum chamber

Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost
07:00 a.m.: visual inspection
in accelerator

Next suspect: the new octant in 'Max von Laue hall'



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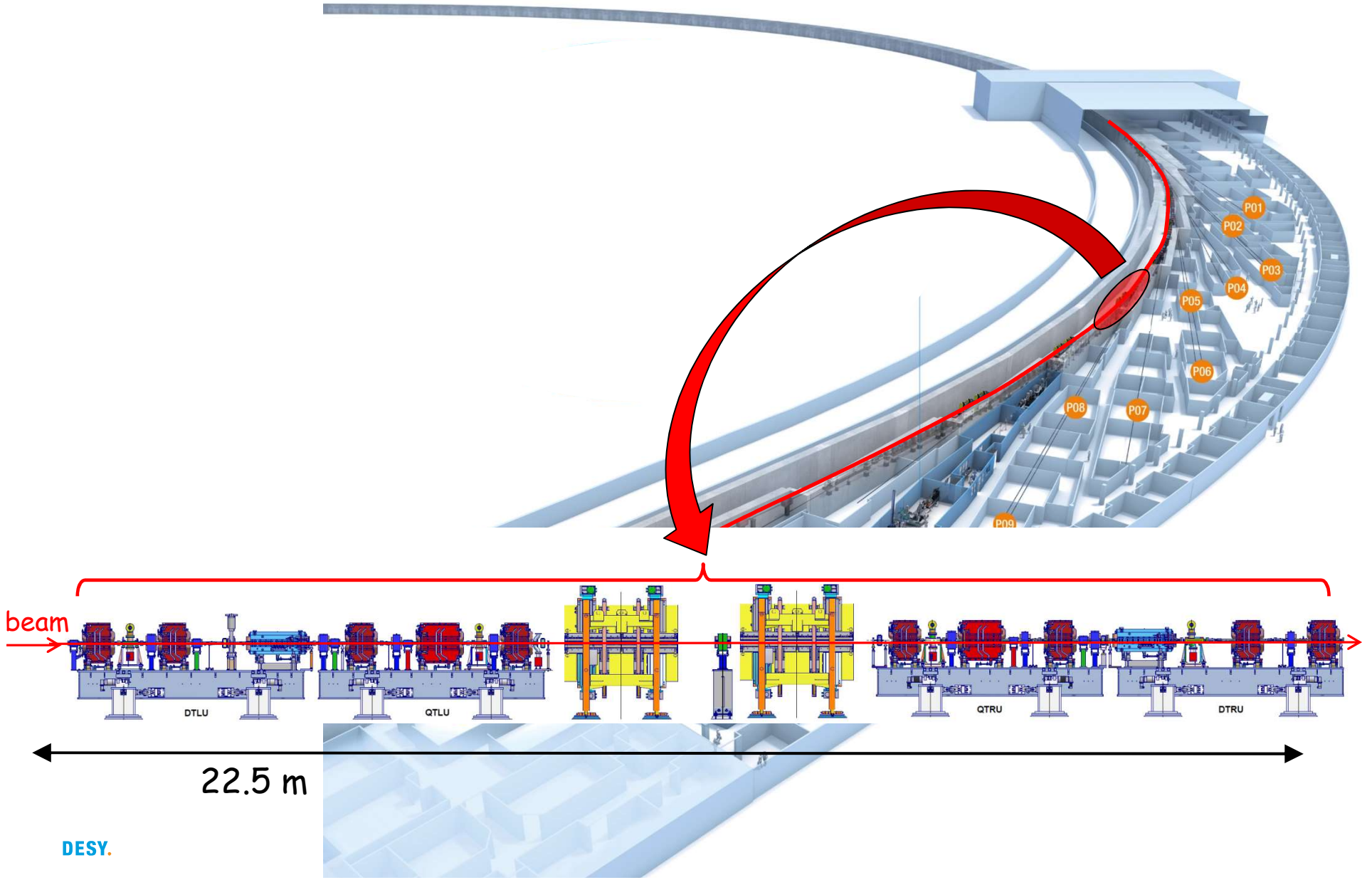

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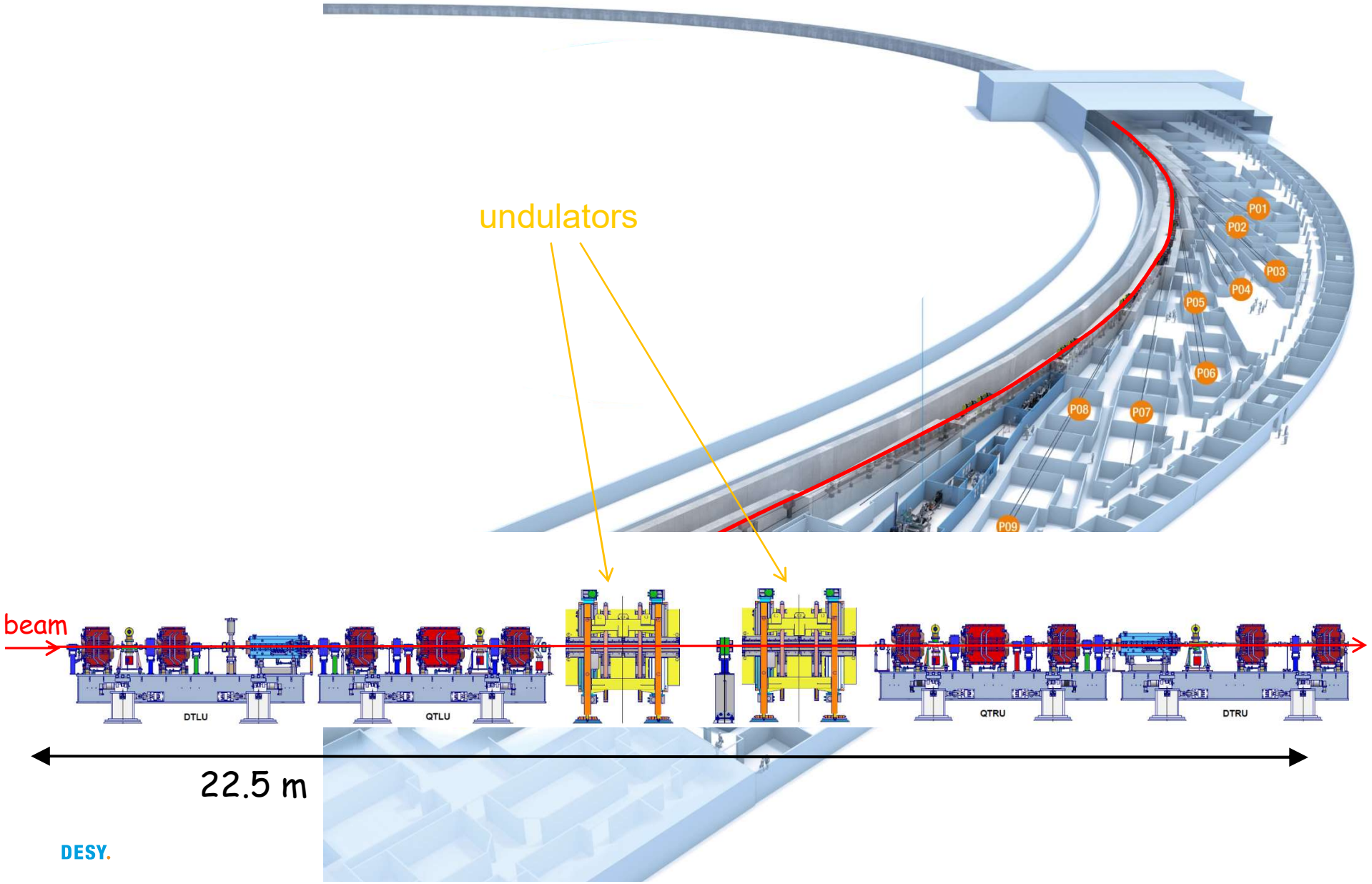
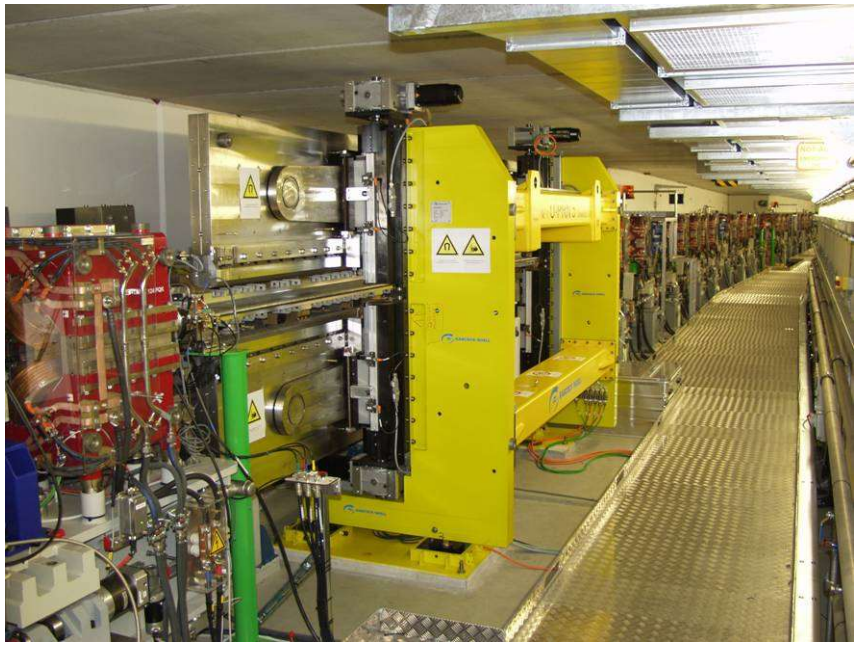


Next suspect: the new octant in 'Max von Laue hall'

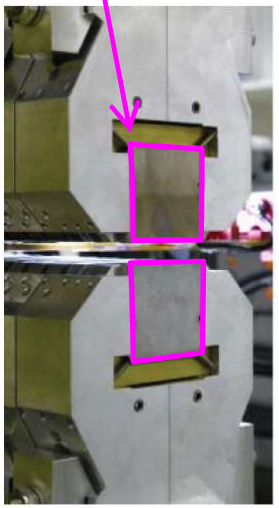
Undulator PU 10



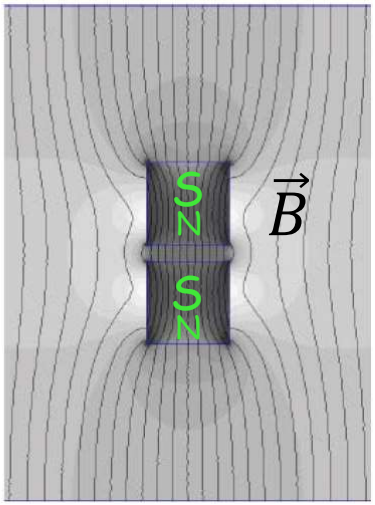
Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost
07:00 a.m.: visual inspection
in new octant

permanent magnets



undulator field lines



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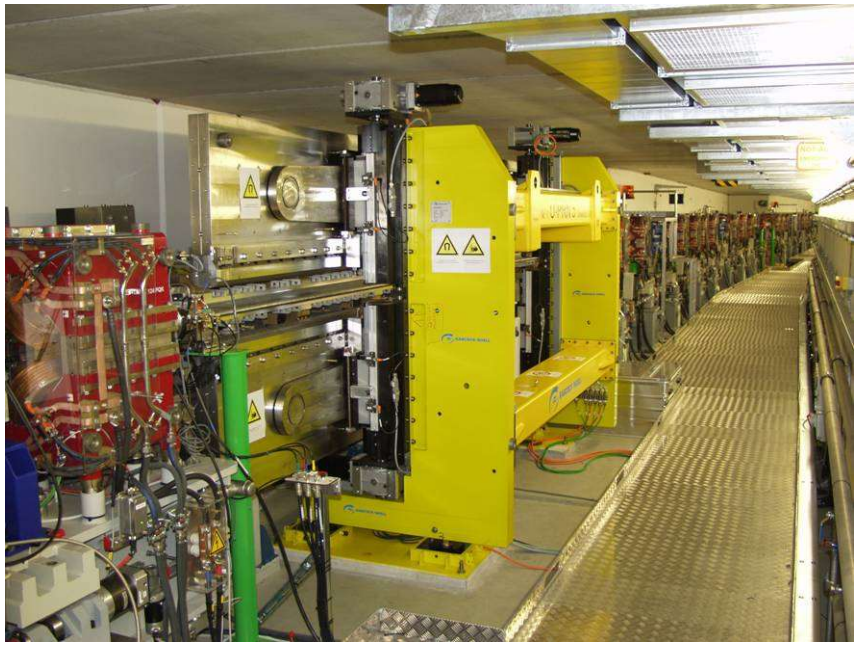

Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost
07:00 a.m.: visual inspection
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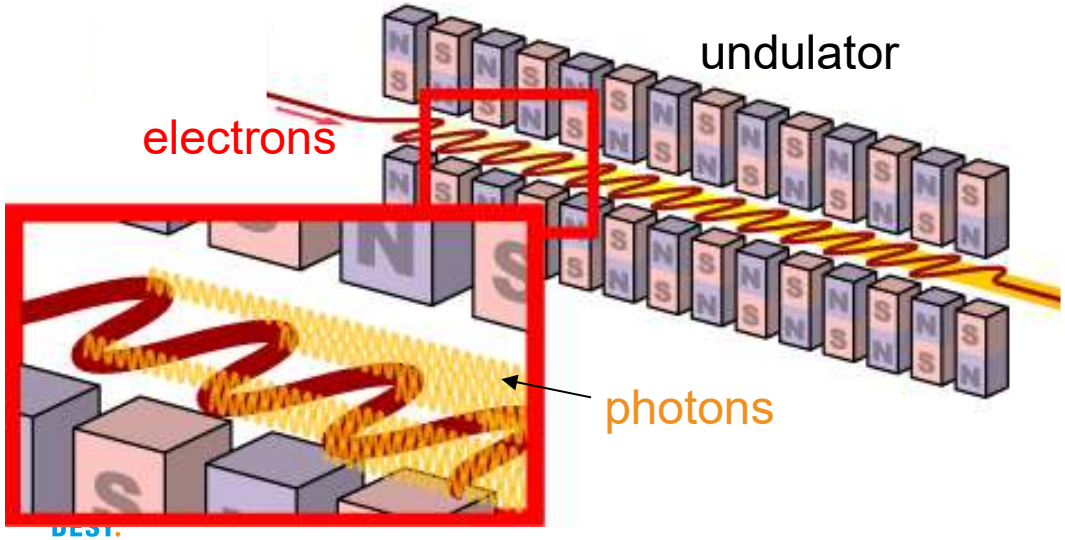
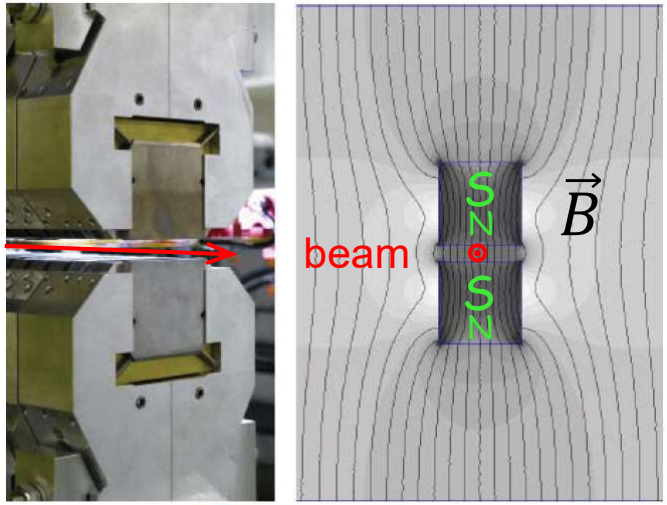


undulator field lines



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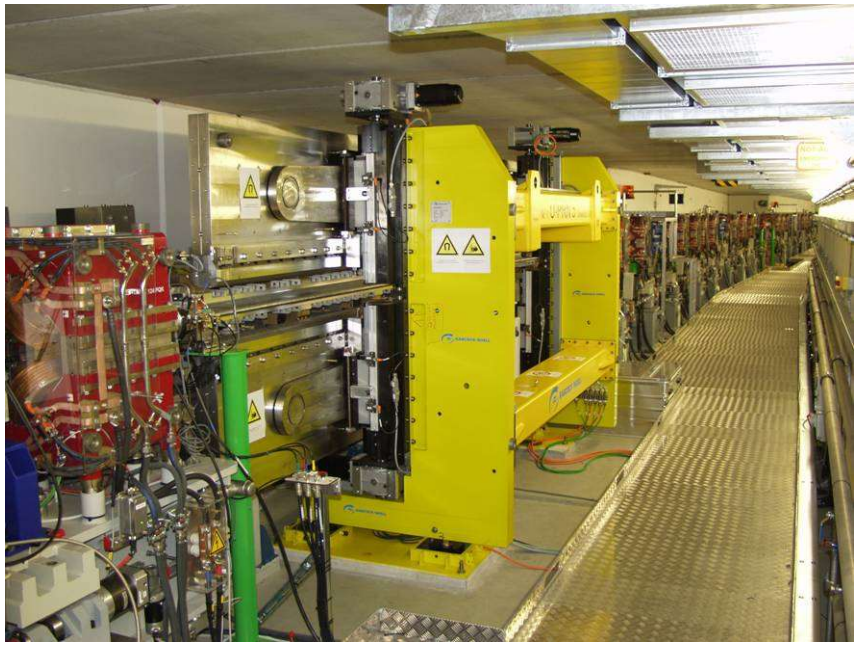
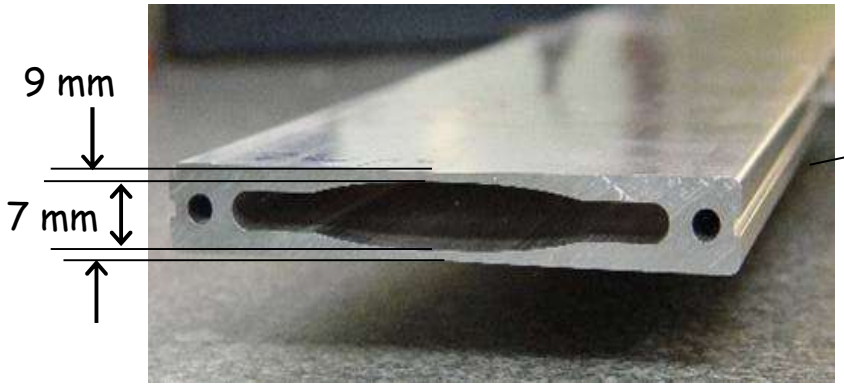
Undulator PU 10



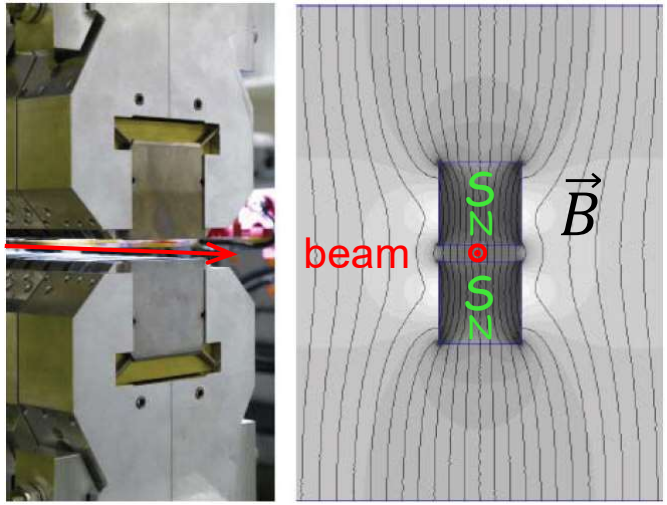
Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost
07:00 a.m.: visual inspection
in new octant

very flat undulator vacuum chambers

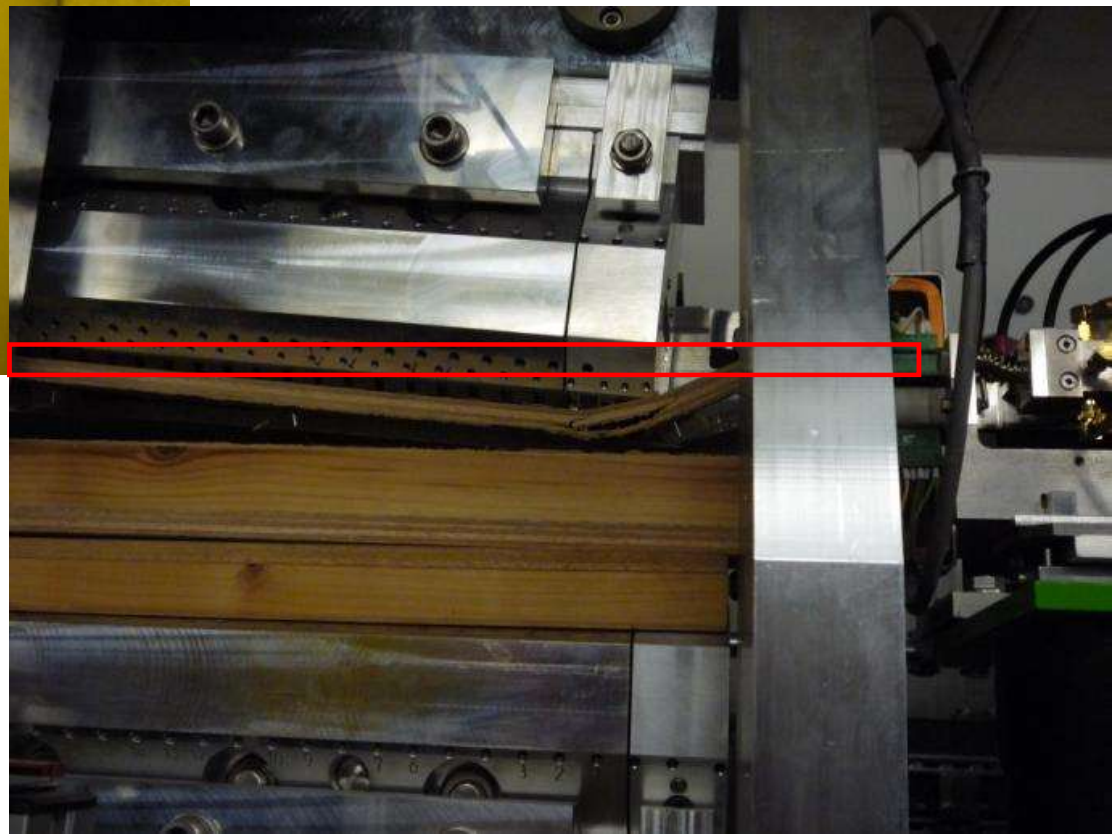


undulator field lines



Next suspect: the new octant in 'Max von Laue hall'

a couple of months earlier…



vacuum chamber

No findings in visual inspection

The electronic logbook:

citation from the logbook: "Visual inspection of new octant: no findings"

citation from the logbook: "What we have tried so far: …"

time of entries

12.06.2010 10:34 **Sonstiges** Kuehl, Vogt, Keil **Was haben wir alles versucht:**

- Optische Inspektion des neuen Achtels (nichts gefunden). Nur BPM nach Undulator PU03 zeigt 6 µSv/h während im Rest immer Werte unter 1 µSv/h gemessen werden.
- Sender-Untersuchungen:
  - Sender beide aus = 100 µs Strahl
  - Sender SL aus SR ein (9 MV) = 700 µs Strahl
  - Sender SR aus SL ein (9 MV) = 700 µs Strahl
  - Beide Sender ein = 700 µs Strahl
  - Sender SR um 180 Grad verstellt (Gegenphase) = ca. 100 µs Strahl
- 500 MHz-Frequenz kontrolliert; Synchronisation kontrolliert; Orbit liegt auf dem ersten Turn mittig (damit sollte Energie stimmen). Turn-By-Turn Daten zeigen, daß Energieanpassung stimmt
- First-Turn hat nicht unübliche Amplituden (H: 5 mm, V: 2mm); horizontale Tune stimmt; vertikaler Tune ist nicht zu messen
- Einzelne Spulen vertikal und horizontal mit Phasenvorschub gedreht und die Apertur ausgeleuchtet. Es ist damit keine Vermessung zu erreichen; nach beiden Richtungen wir die Injektion schlechter (d.h. noch weniger Turns).
- 3er Beule im Norden und Westen über die Wigglerstrecken (H + V), jeweils mit Phasenverschiebung. Keine Verbesserung.
- 3er Beulen über jeweils einen halben Ring (H + V), jeweils mit Phasenverschiebung. Keine Verbesserung.
- Alle Ventile geschlossen und wieder geöffnet. Hilft nichts.
- Schirm hinter Septum rein und raus gefahren.
- Mit den letzten Spulen im Transportweg (V) sowie IME und Septum gewedelt: man kann damit die Injektion nur noch schlechter machen
- On Axis Injektion aufgesetzt (Kicker 3/Septum durchgefahren)
- Kollimatoren/Scraper rausgefahren: Keine Verbesserung
- Tunekreise gedreht: Keine Verbesserung
- Trans. Feedbacks und long. Feedback ein/aus: Keine Verbesserung

12.06.2010 07:52 **Sonstiges** Kuehl, Vogt, Keil **Optische Inspektion des neuen Achtels, keine Auffälligkeiten**

Naja, bis auf den BPM nach Undulator PU03 dort haben wir 6 µSv/h gemessen, alle anderen < 1 µSv/h.

12.06.2010 07:02 **Sonstiges** has **Frühschicht: Kühl, Schulz, Hansen, Wierzcholek**

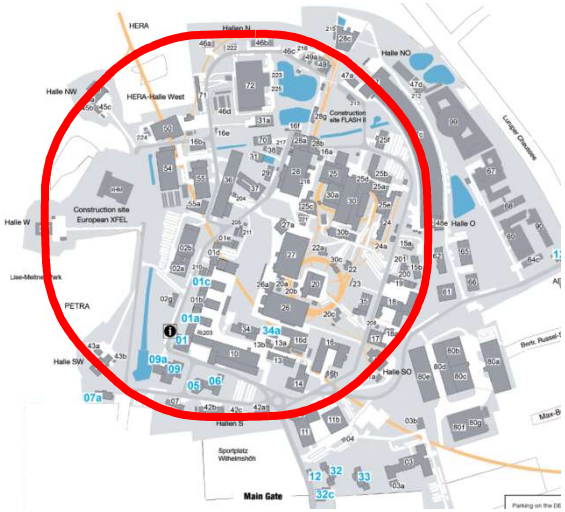
Schichtbeginn kein gespeicherter Strahl. Nur ca. 1000 Umläufe, keine Ausfälle

citation from the logbook: "Visual inspection of new octant: no findings"

…when you have eliminated the impossible,
whatever remains, *however improbable*, must be the truth

Sherlock Holmes, The Sign of the Four
Sir Arthur Conan Doyle

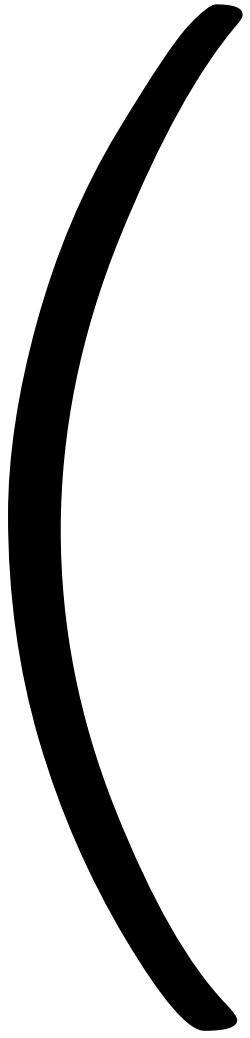
Next suspect: an aperture problem



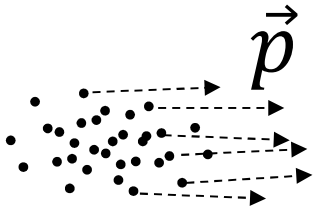
Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost
07:00 a.m.: visual inspection in new octant
11:52 a.m.: start aperture scan

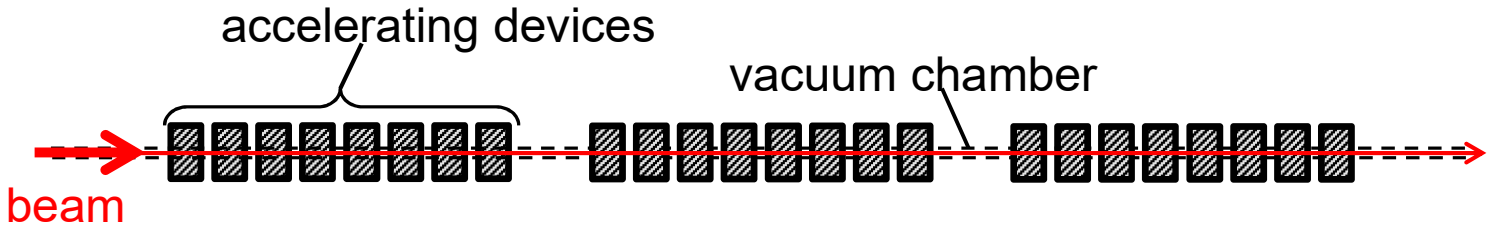
we need a
beam focusing
system



Need of focusing

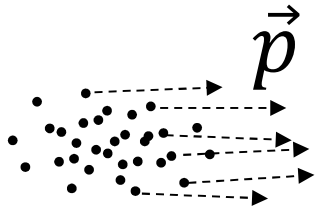


beam / bunch



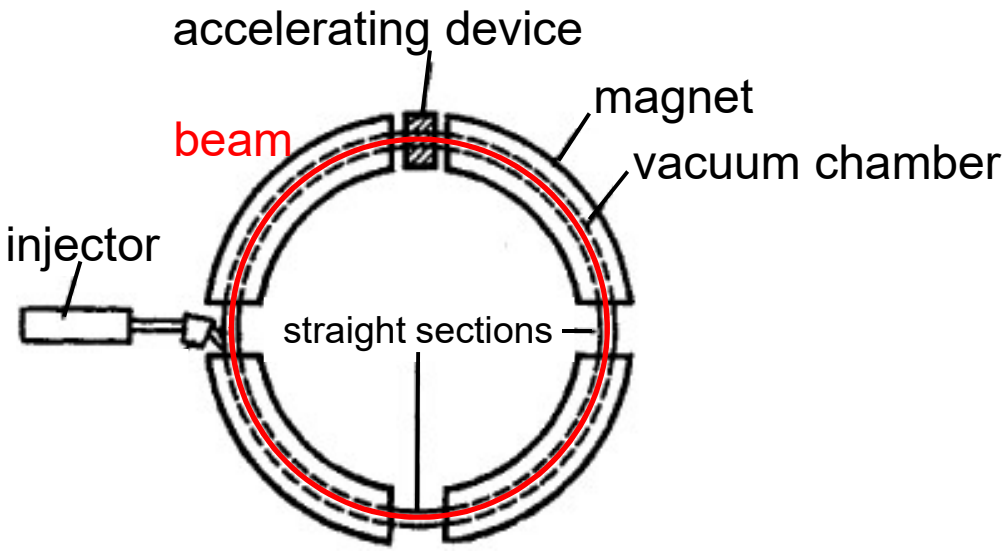
linear accelerator (linac)

Need of focusing



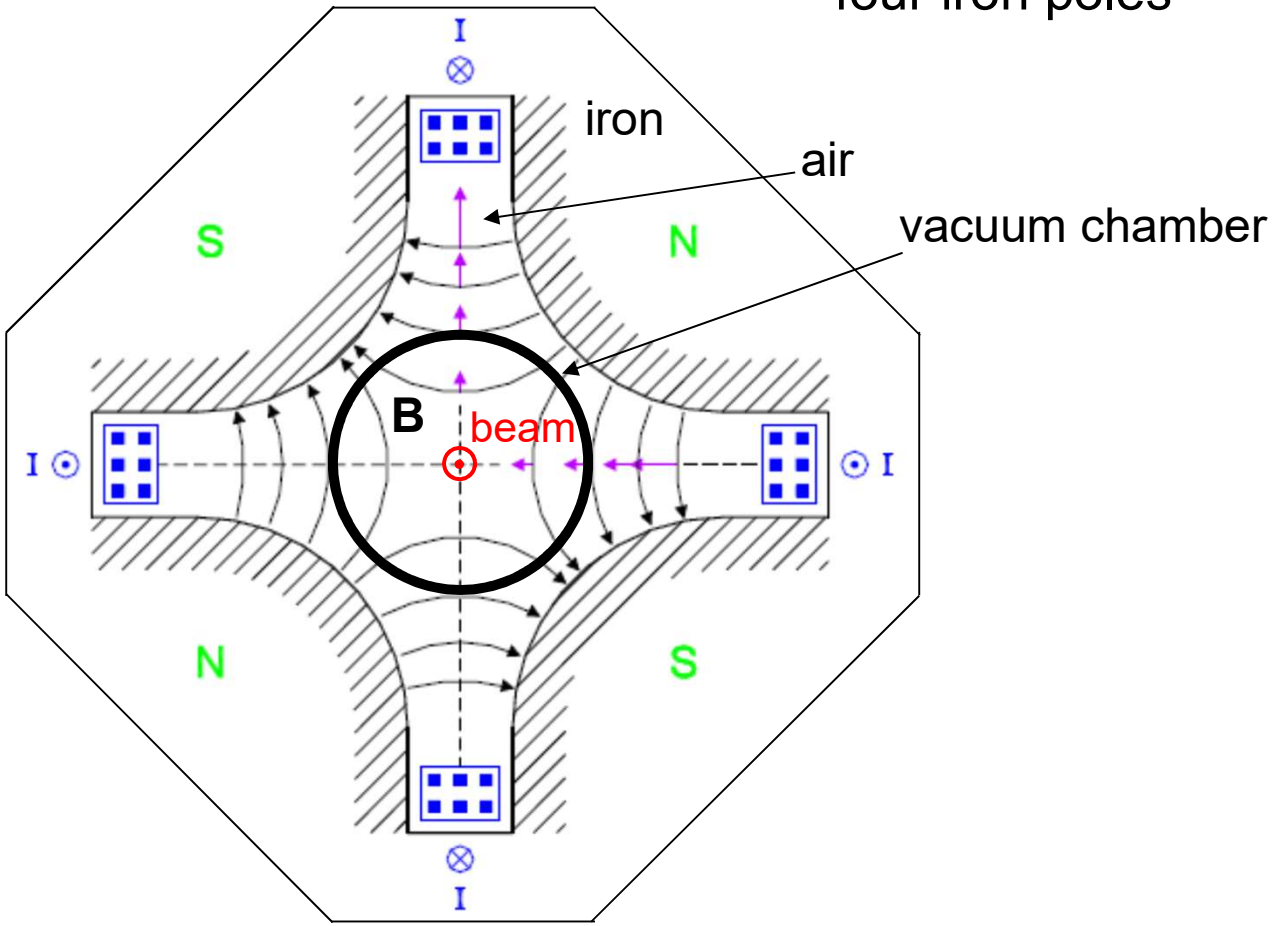
beam / bunch

we need to focus the beam !

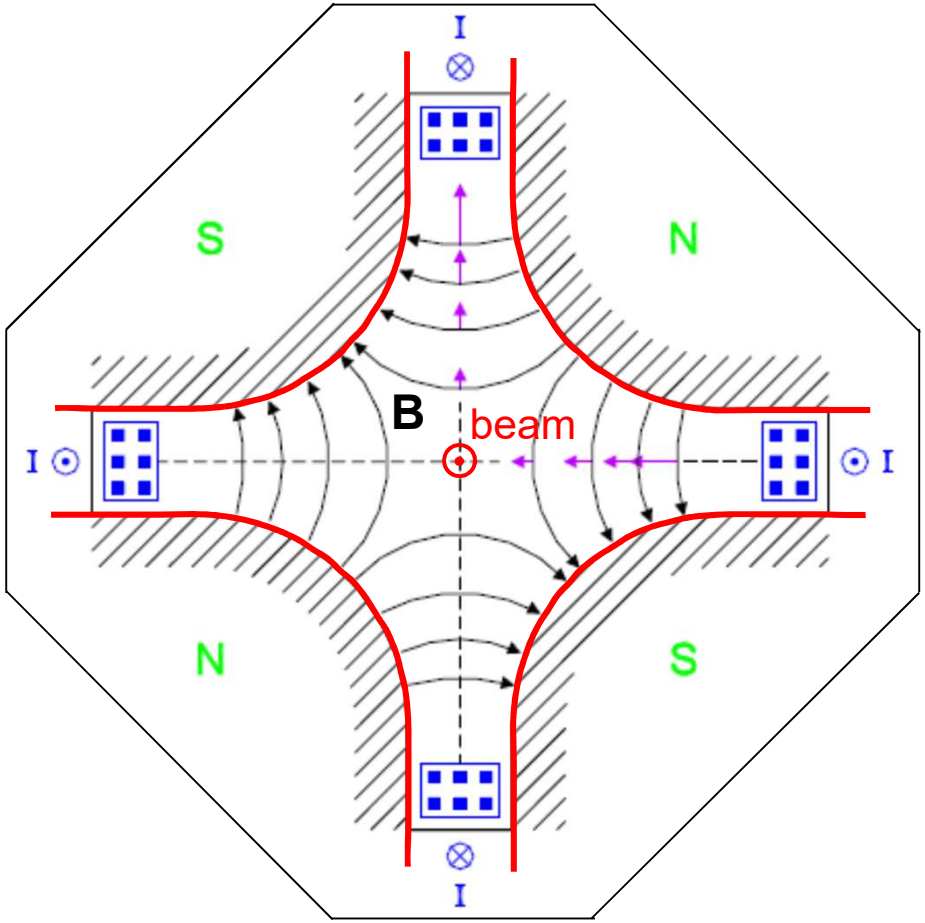


Need of focusing

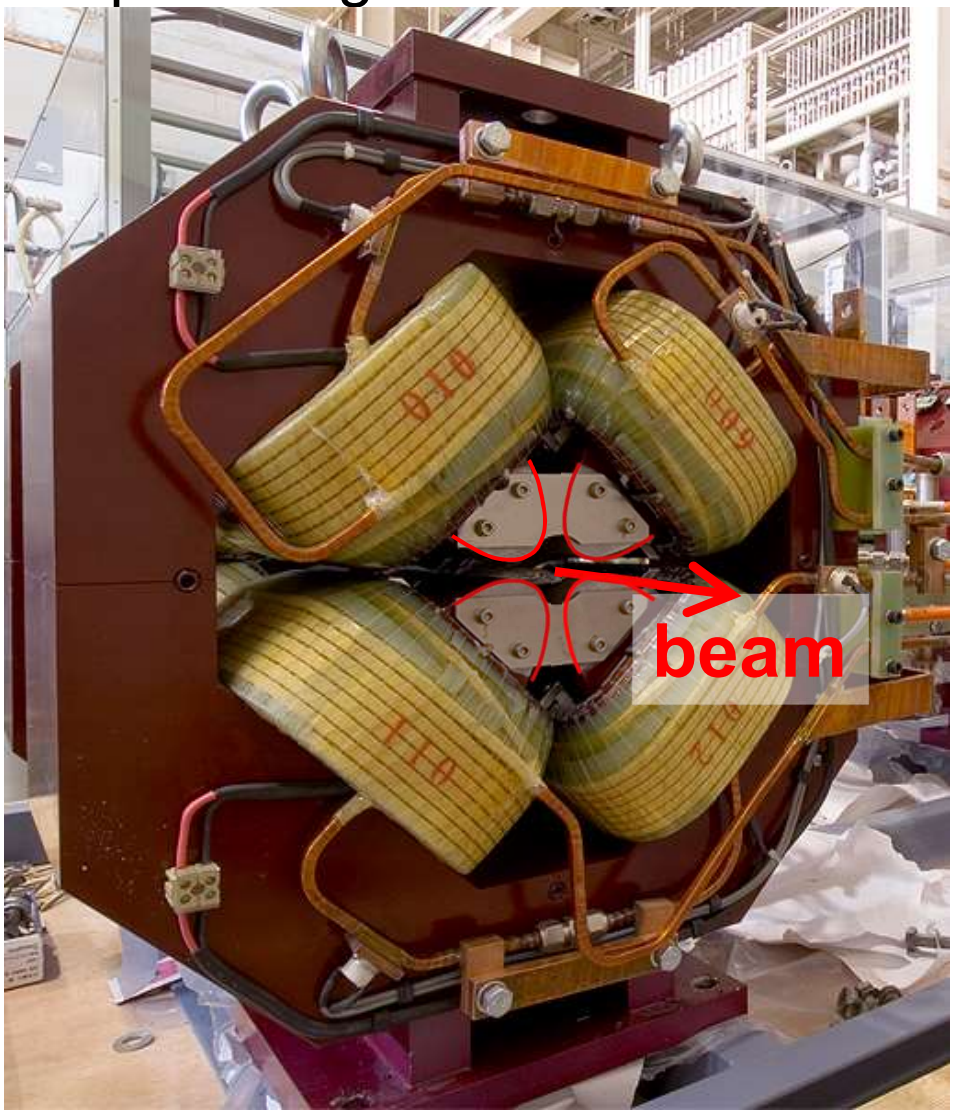
quadrupole magnet:
four iron poles



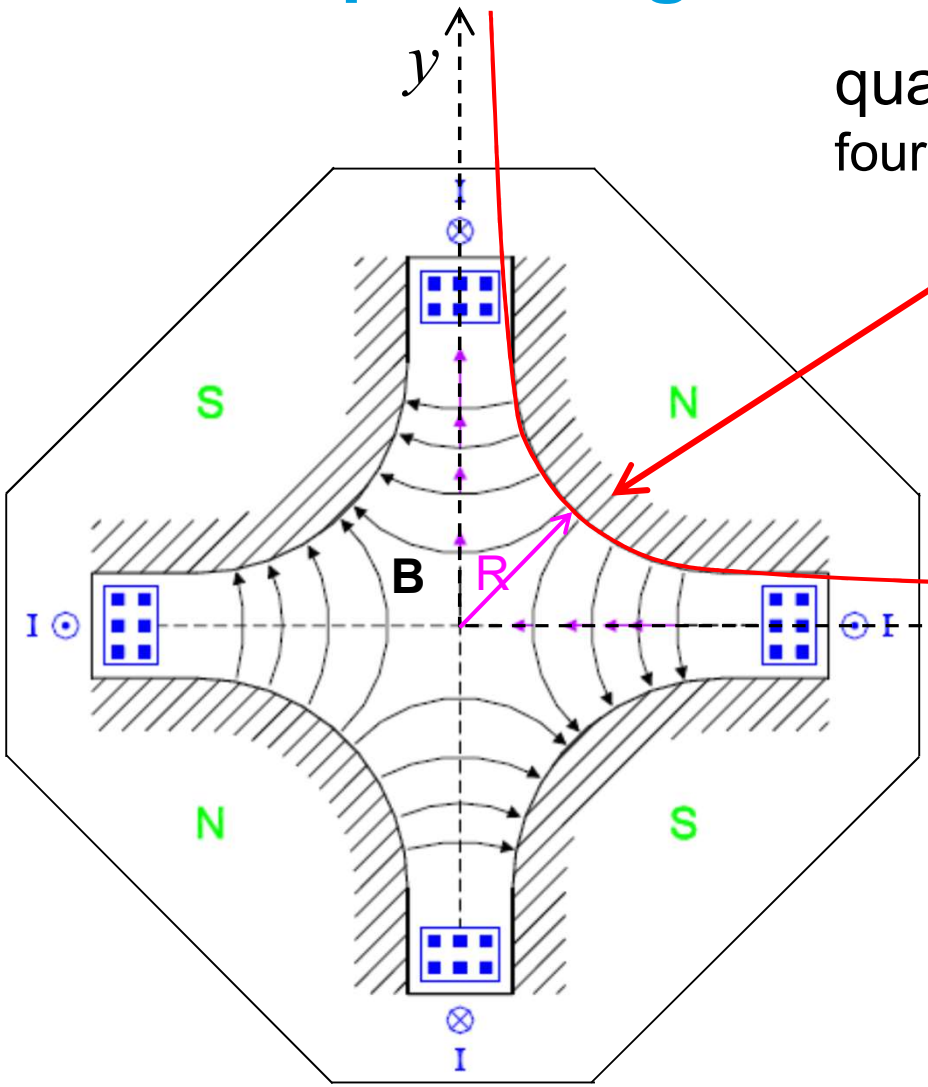
Quadrupole magnets



quadrupole magnet:



Quadrupole magnets



quadrupole magnet:
four iron pole shoes of hyperbolic contour

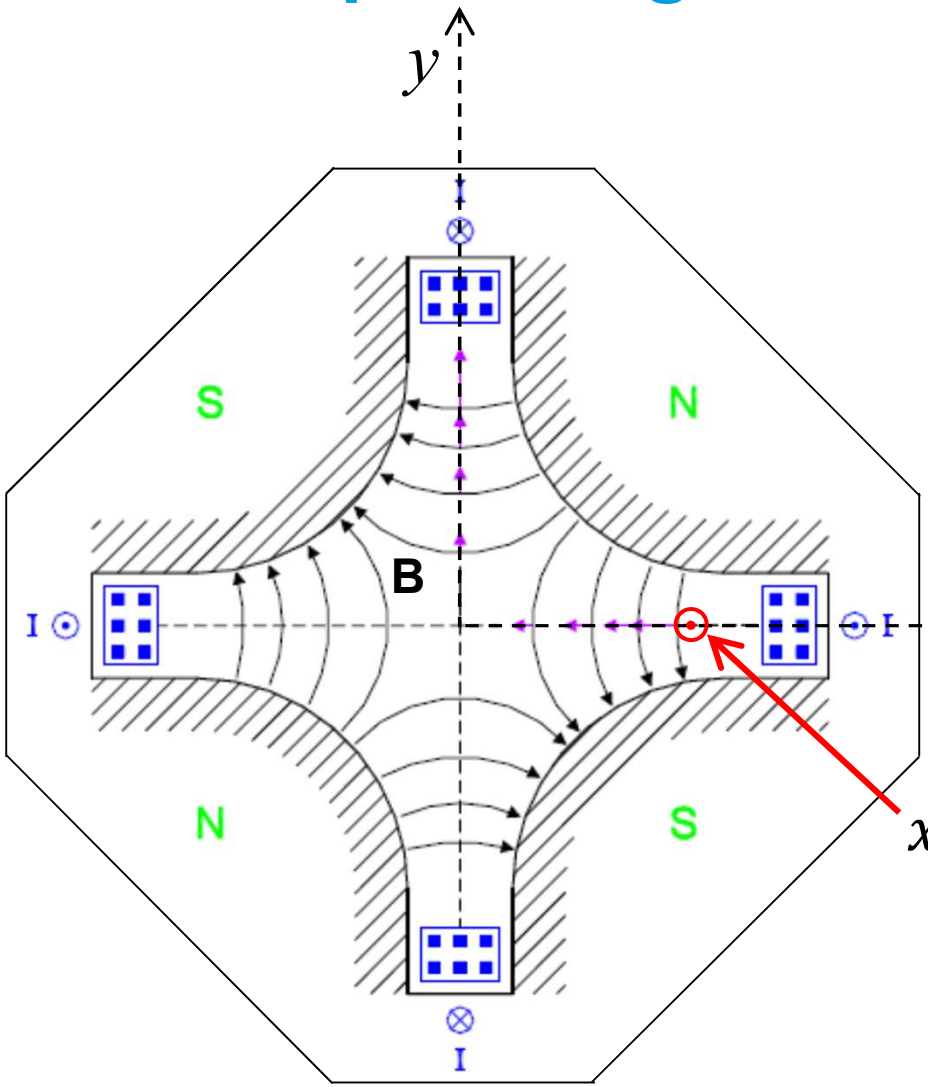
hyperbola $x \cdot y = const.$

x

$$B_x = -g \cdot y$$
$$B_y = -g \cdot x$$

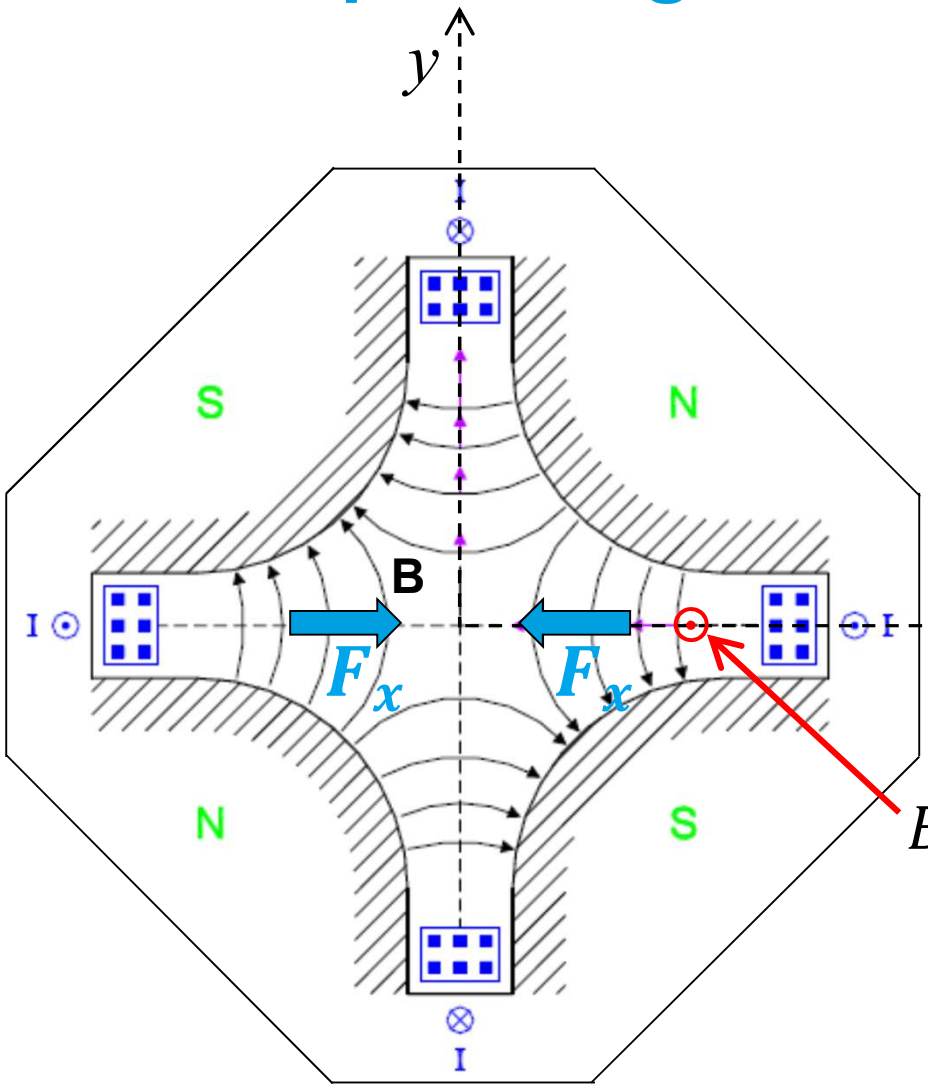
$$g = \frac{\mu_0 I}{R^2} \text{ (quadrupole gradient)}$$

Quadrupole magnets



$x \neq 0$ and $y = 0$

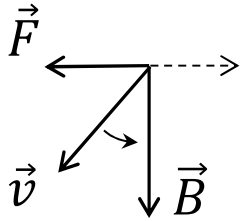
Quadrupole magnets



x

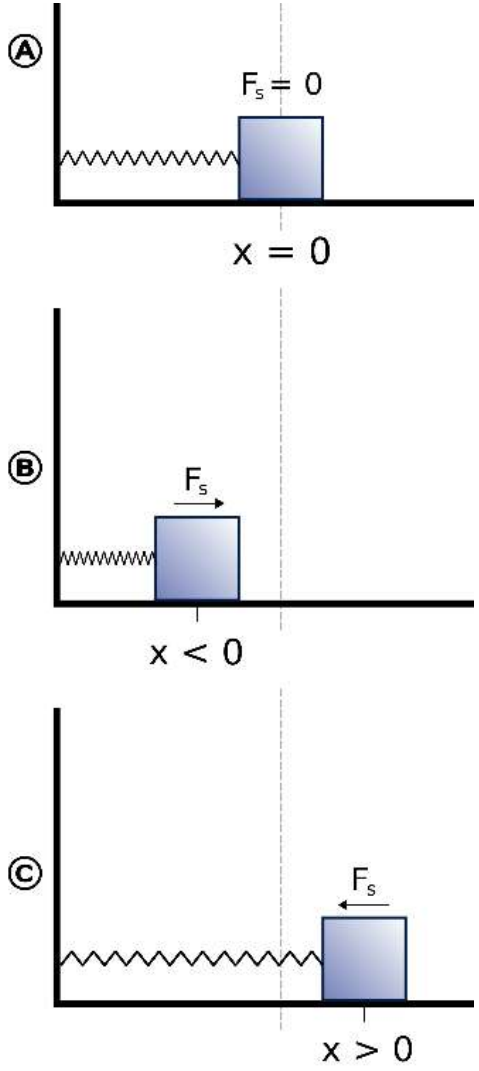
$B_x = 0$

$B_y = -g \cdot x \quad \rightarrow \quad F_x = -g \cdot x$



$\vec{F} = q\vec{v} \times \vec{B}$ (Lorentz force)

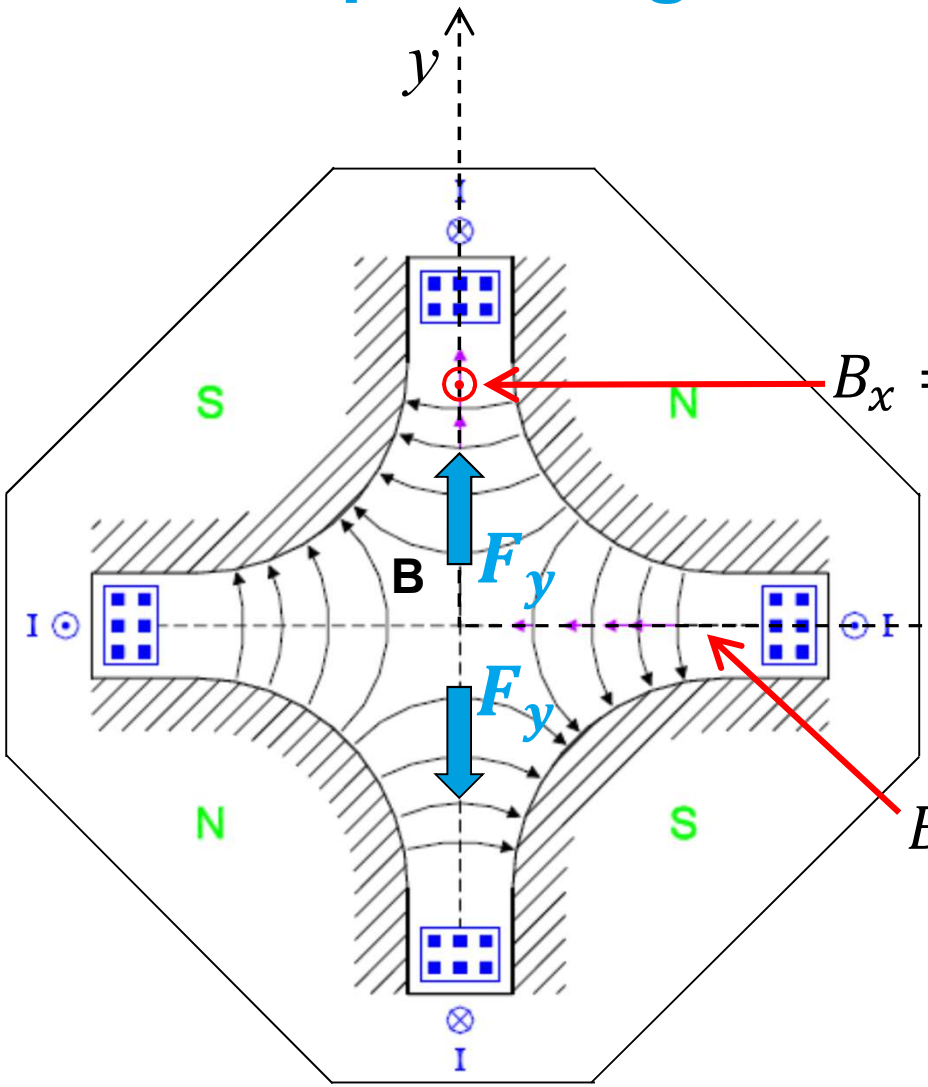
Classical mechanics: harmonic oscillator

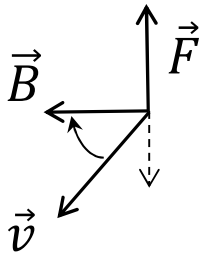


restoring force:

$$F = -kx$$

Quadrupole magnets





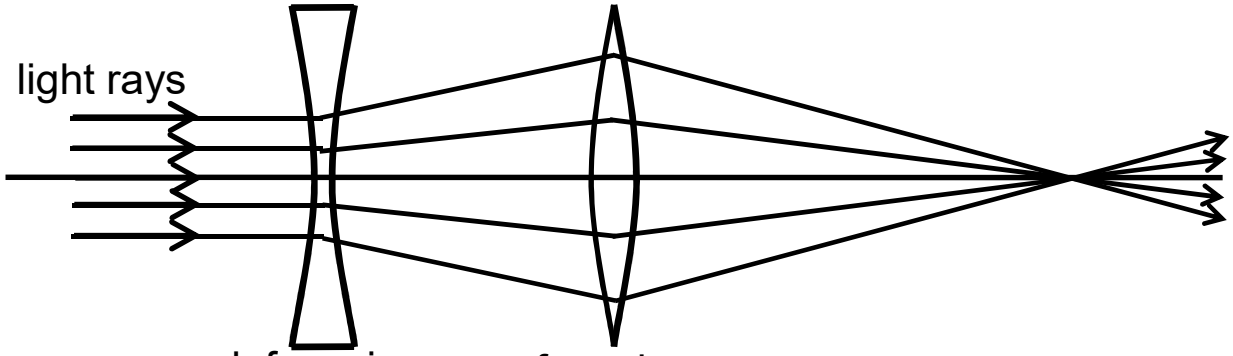
$$B_x = -g \cdot y \quad \rightarrow \quad F_y = g \cdot y$$

defocusing

$$B_y = -g \cdot x \quad \rightarrow \quad F_x = -g \cdot x$$

focusing !

In light optics…



f: focal length

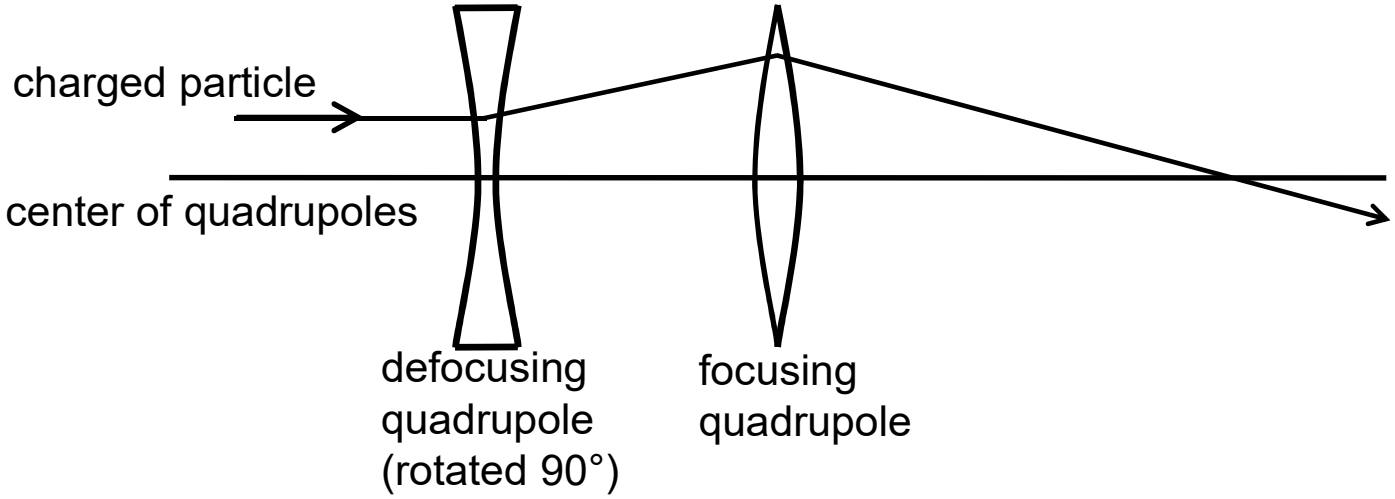
f^*: system focal length

$$\frac{1}{f^*} = \frac{1}{f_D} + \frac{1}{f_F} - \frac{d}{f_D f_F}$$ (light optics)

if $f_D = -f_F = f$ $\quad \frac{1}{f^*} = \frac{d}{f^2} > 0$

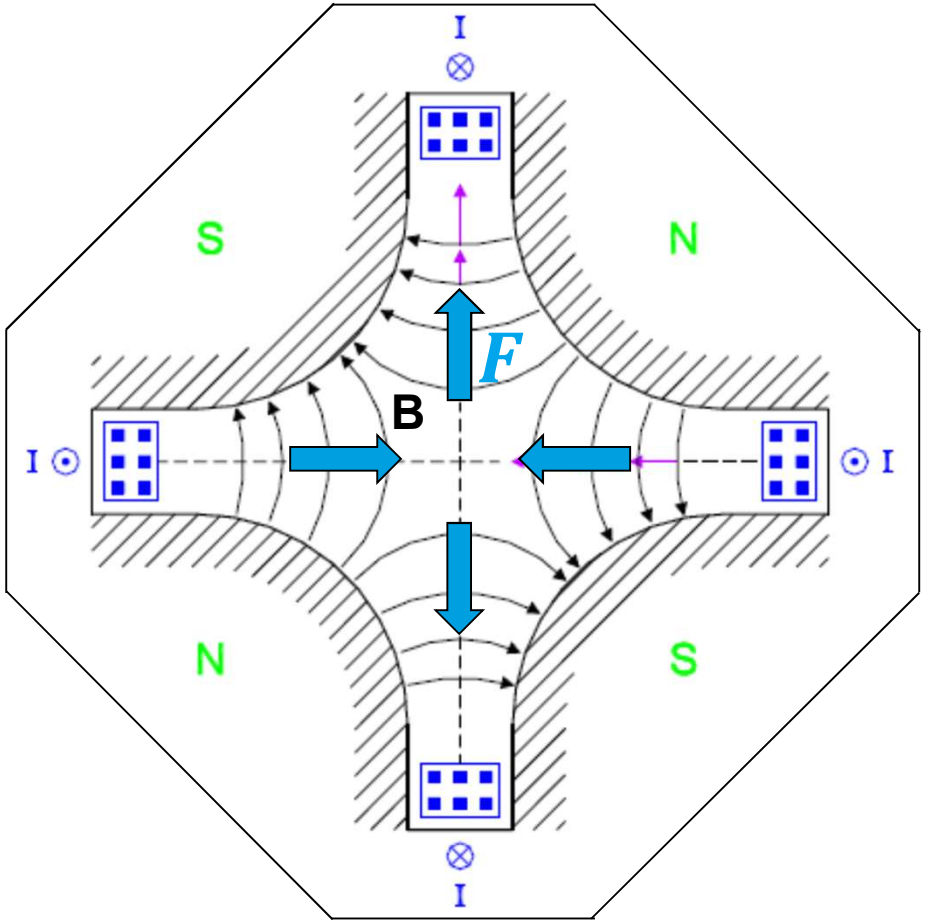
Quadrupole magnets

QD + QF = net focusing effect:

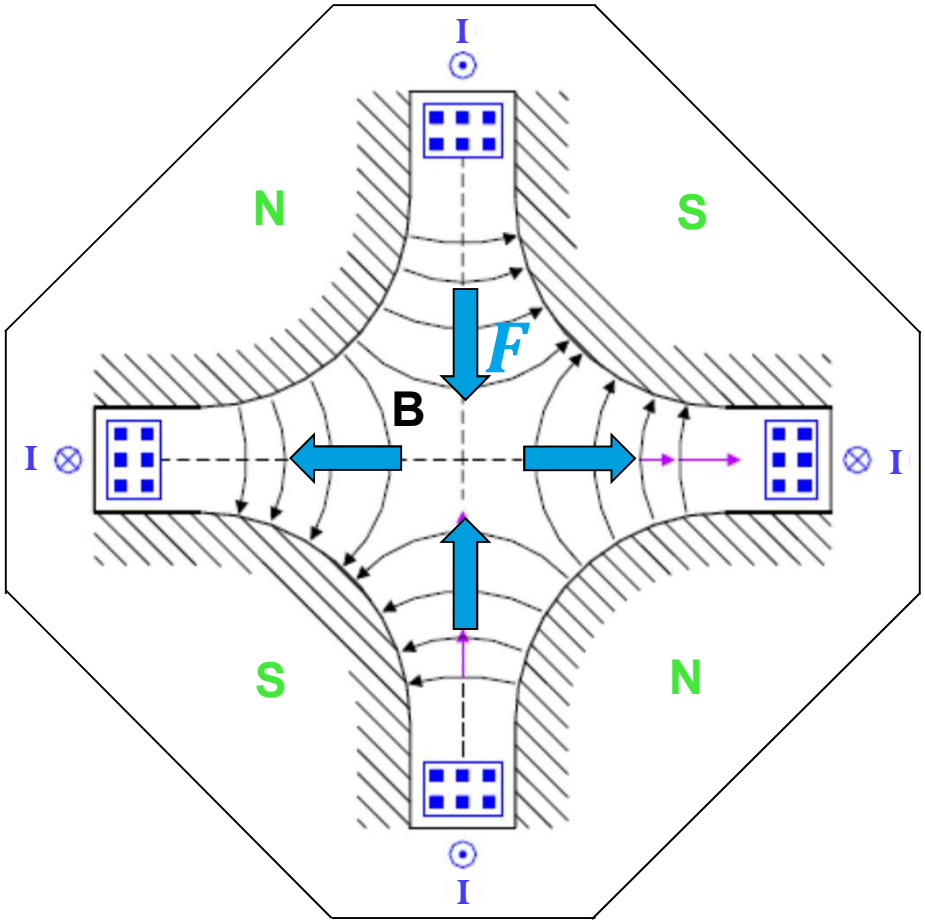


Quadrupole magnets

vertical defocusing
horizontal focusing



vertical focusing
horizontal defocusing

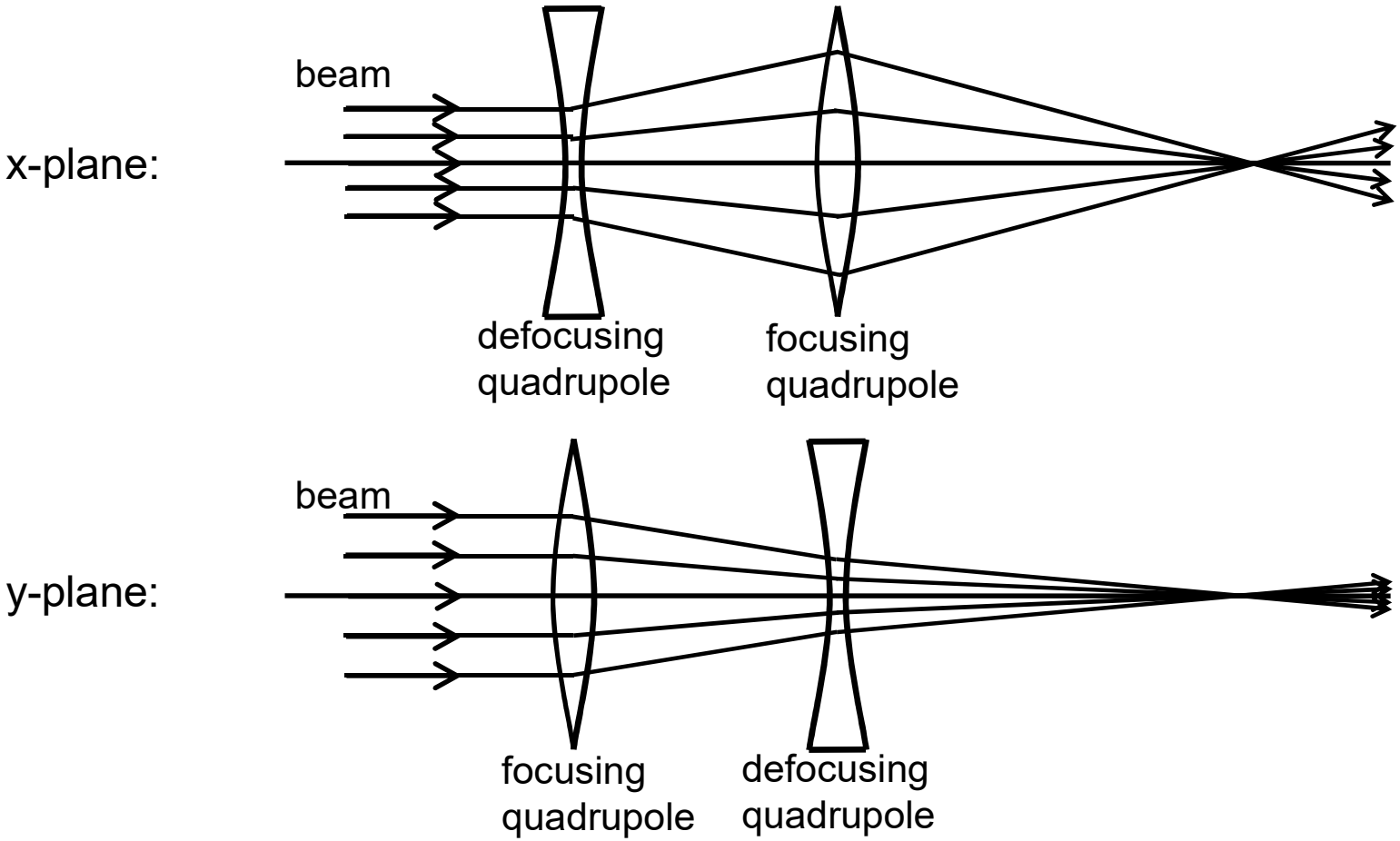


rotated 90°

I = -I

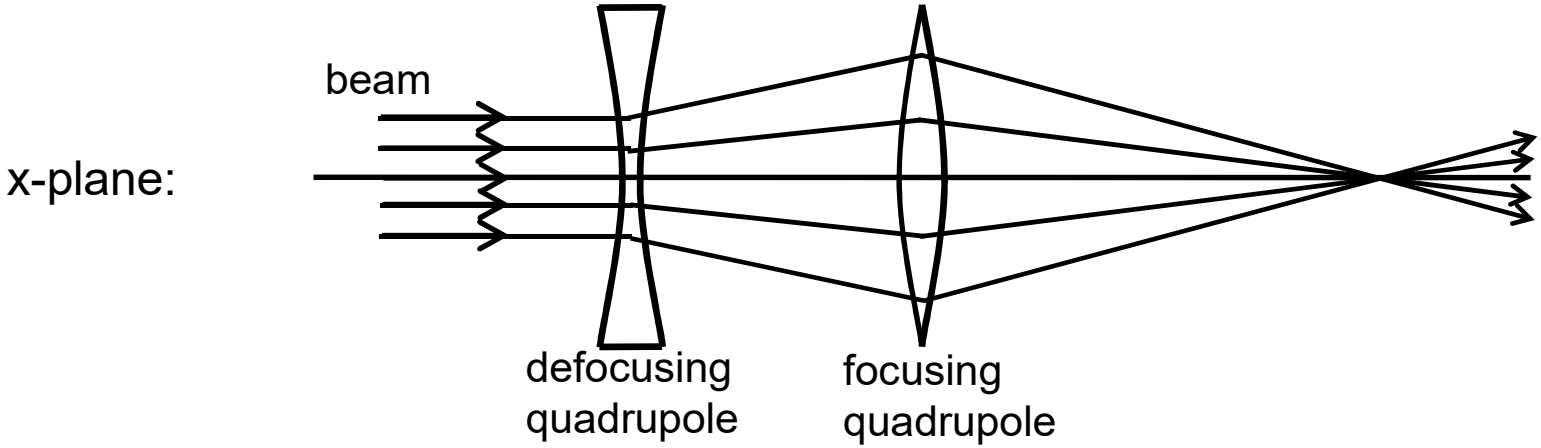
Quadrupole magnets

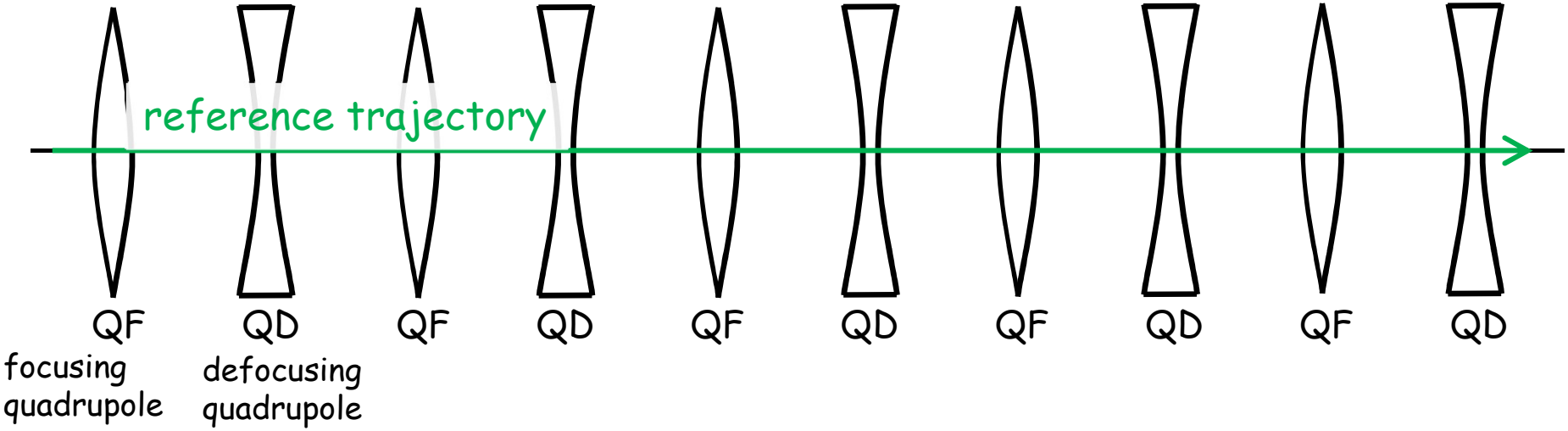
QD + QF = net focusing effect:



Quadrupole magnets

QD + QF = net focusing effect:

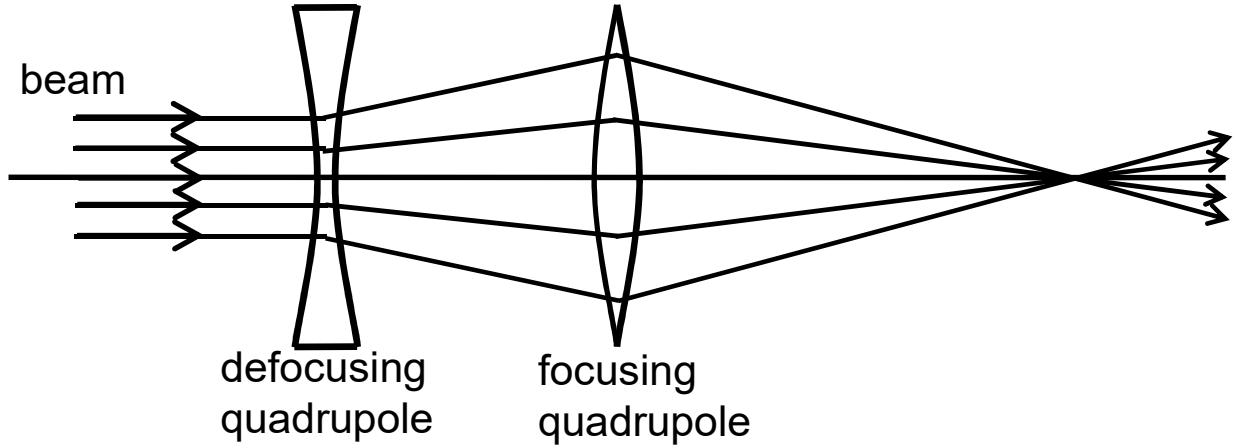


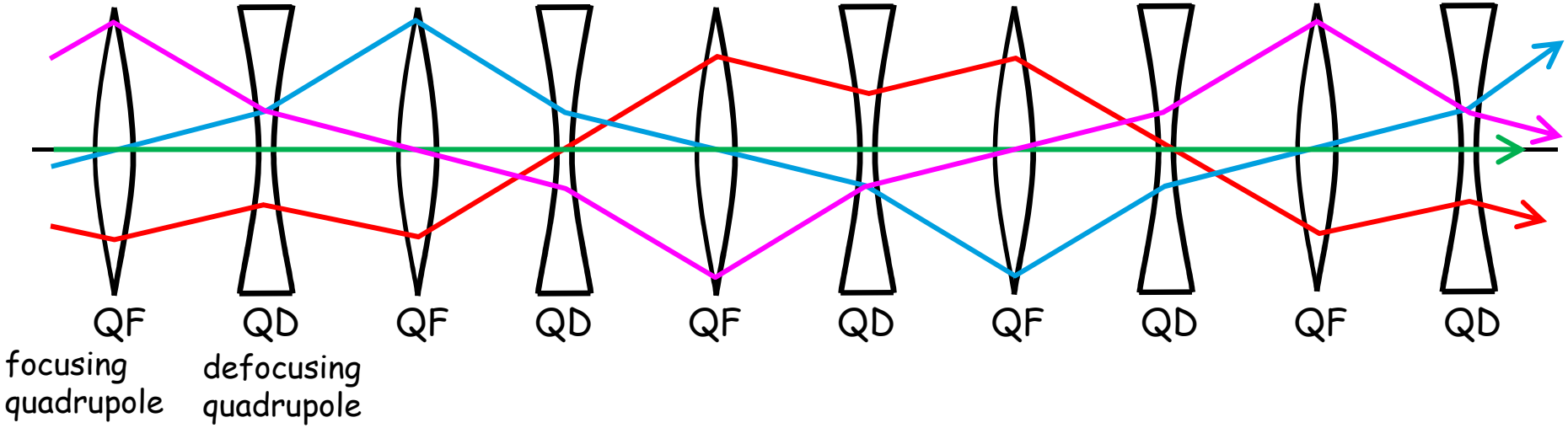


Quadrupole magnets

QD + QF = net focusing effect:

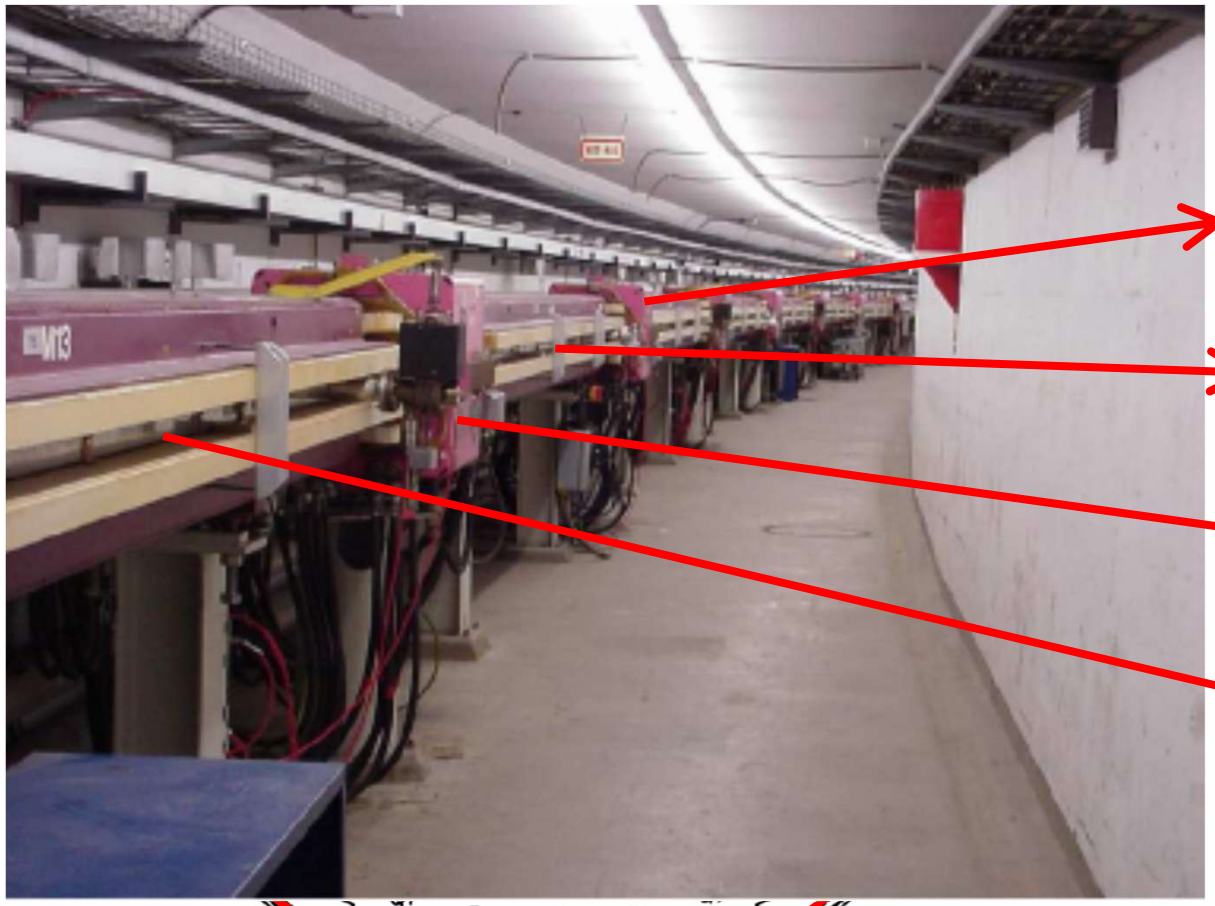
x-plane:

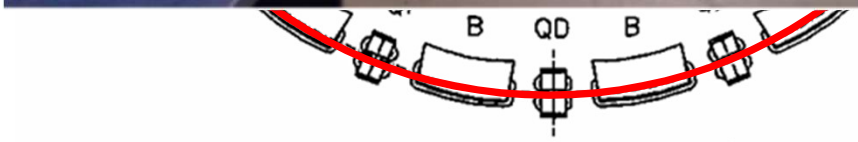


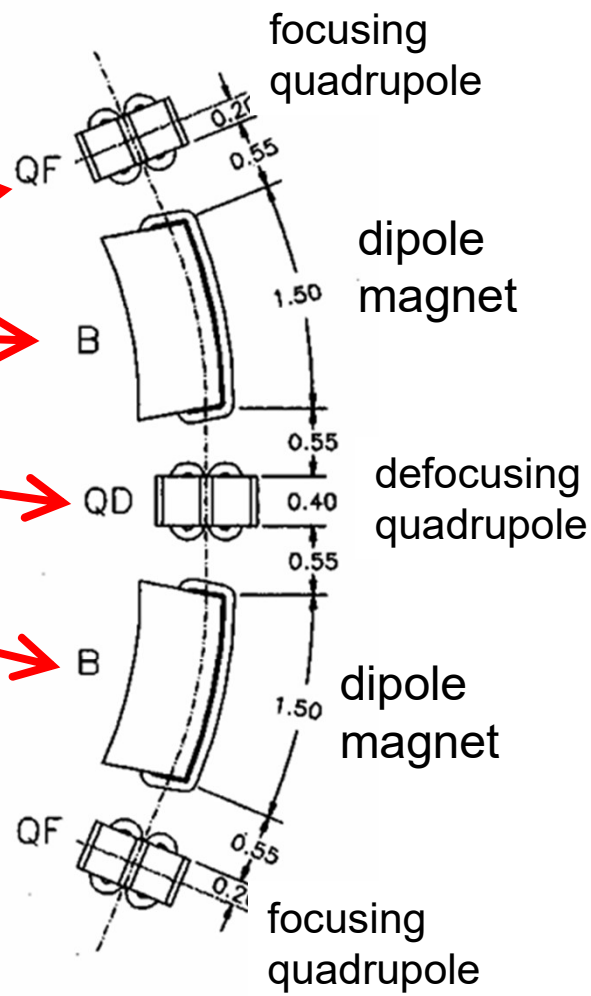


Circular accelerator

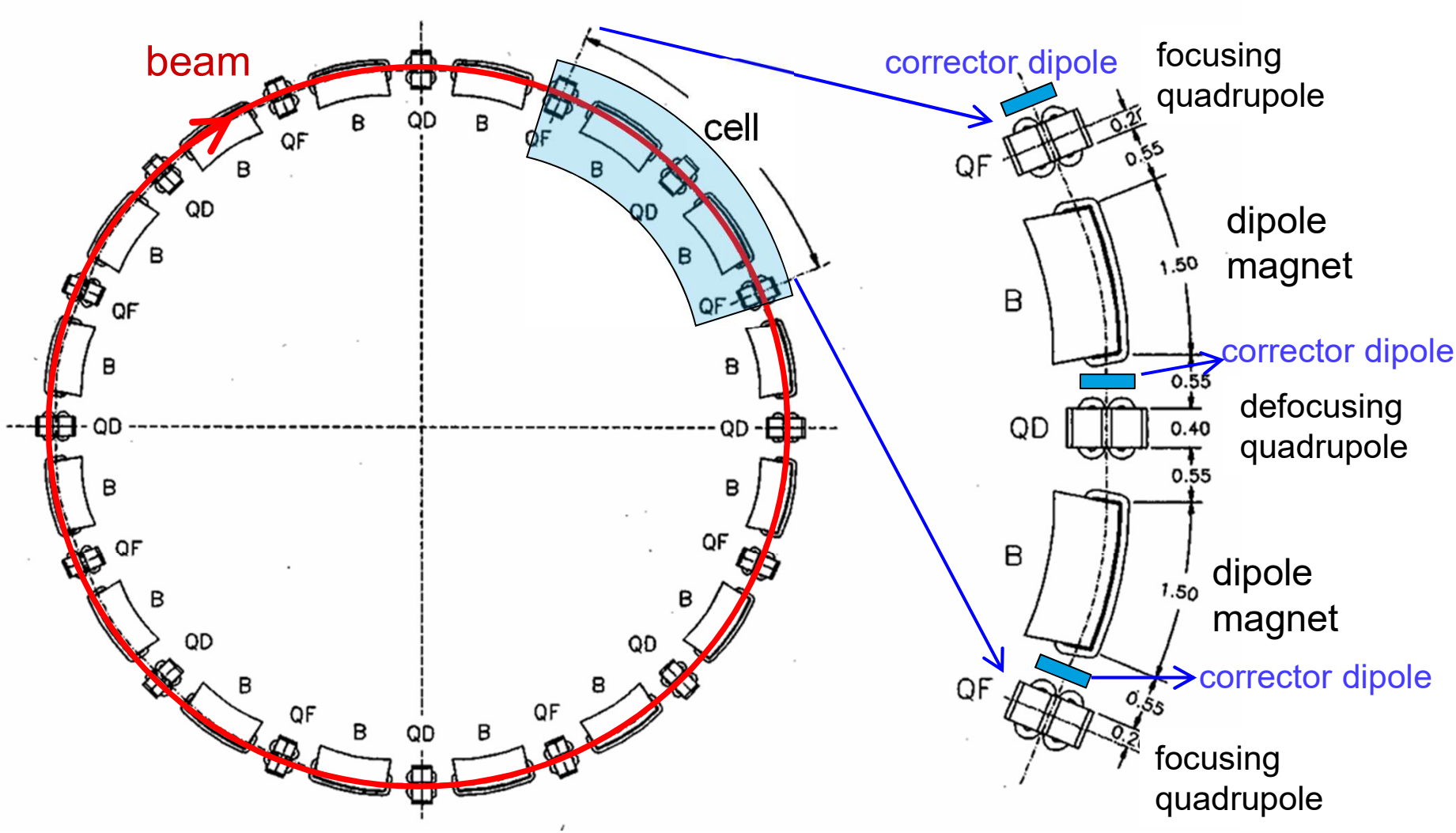
PETRA

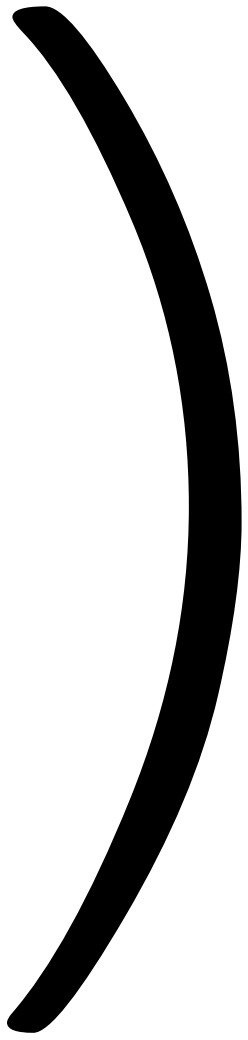






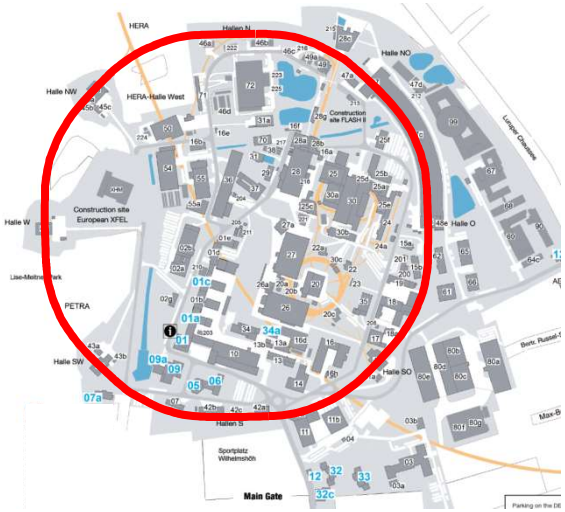
Circular accelerator





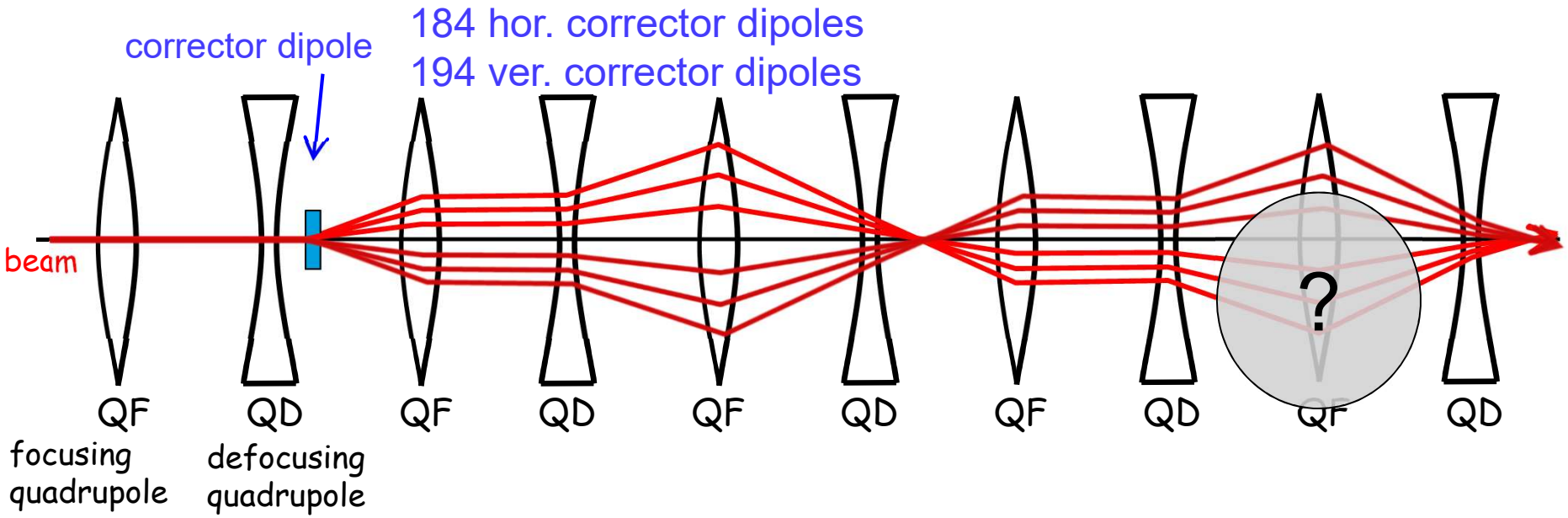
we have a
beam focusing
system

Next suspect: an aperture problem

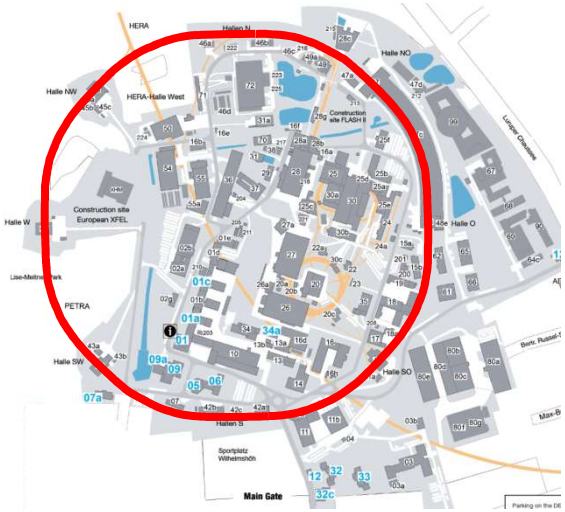


Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost
07:00 a.m.: visual inspection in new octant
11:52 a.m.: start aperture scan



First useful hint: aperture problem



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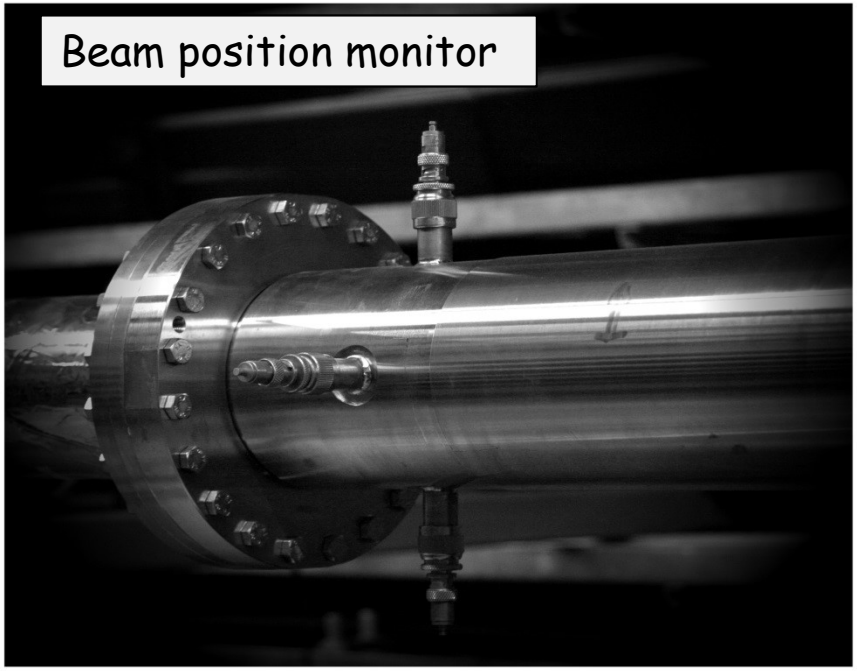
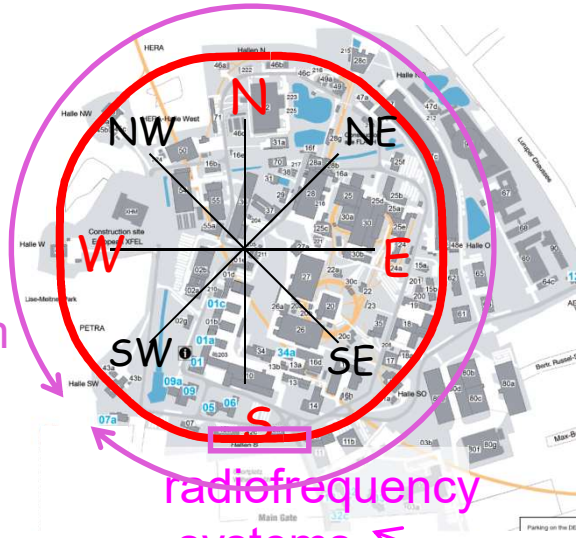


244 beam position monitors

First useful hint: horizontal aperture problem



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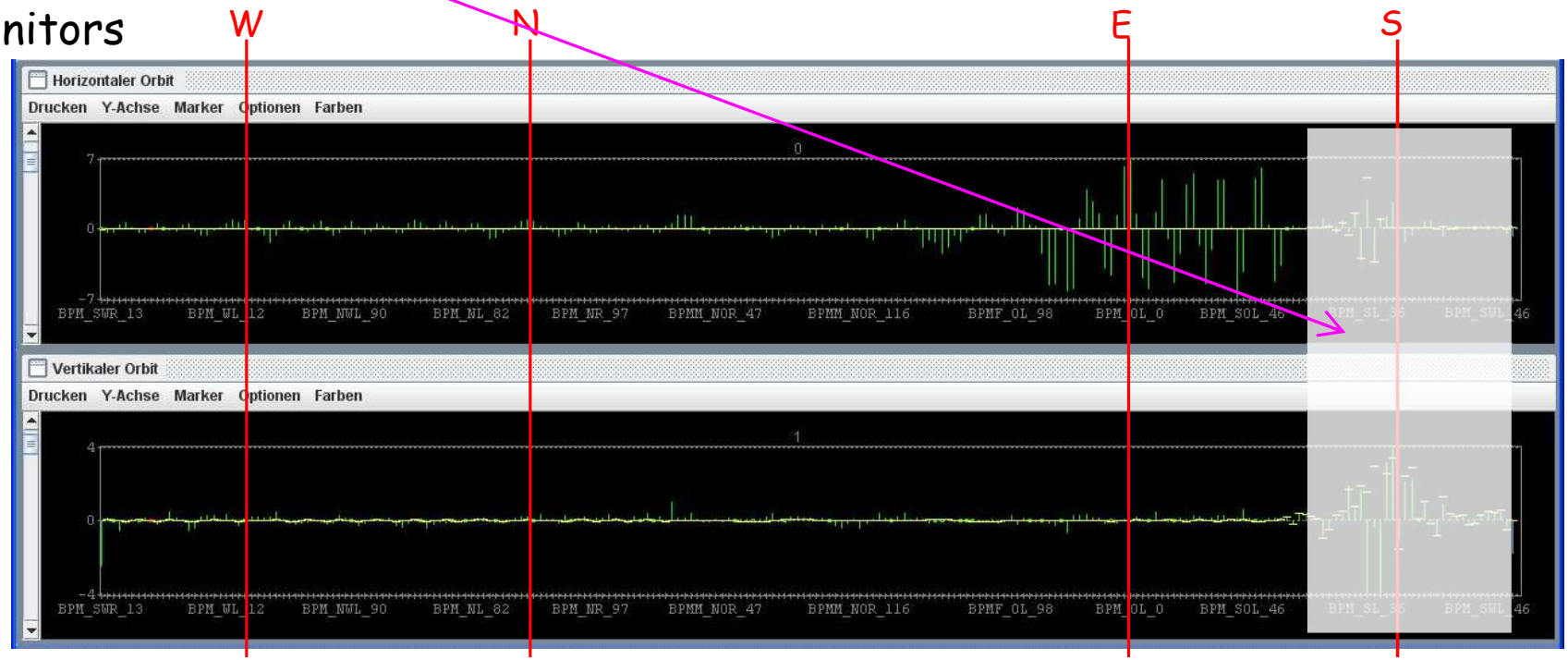
244 monitors

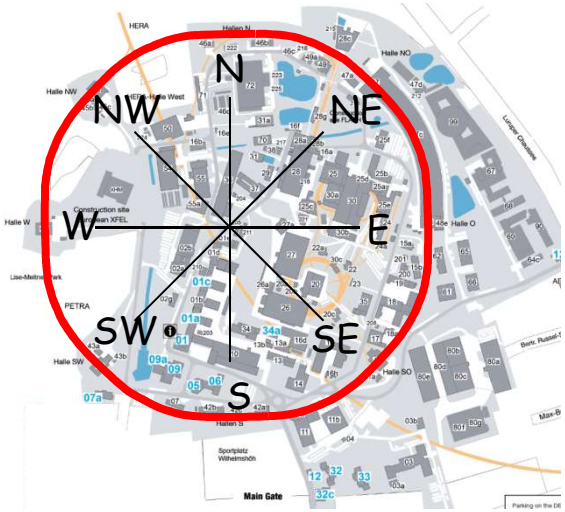


horizontal beam pos. [mm]

vertical beam pos. [mm]

DESY.

First useful hint: horizontal aperture problem



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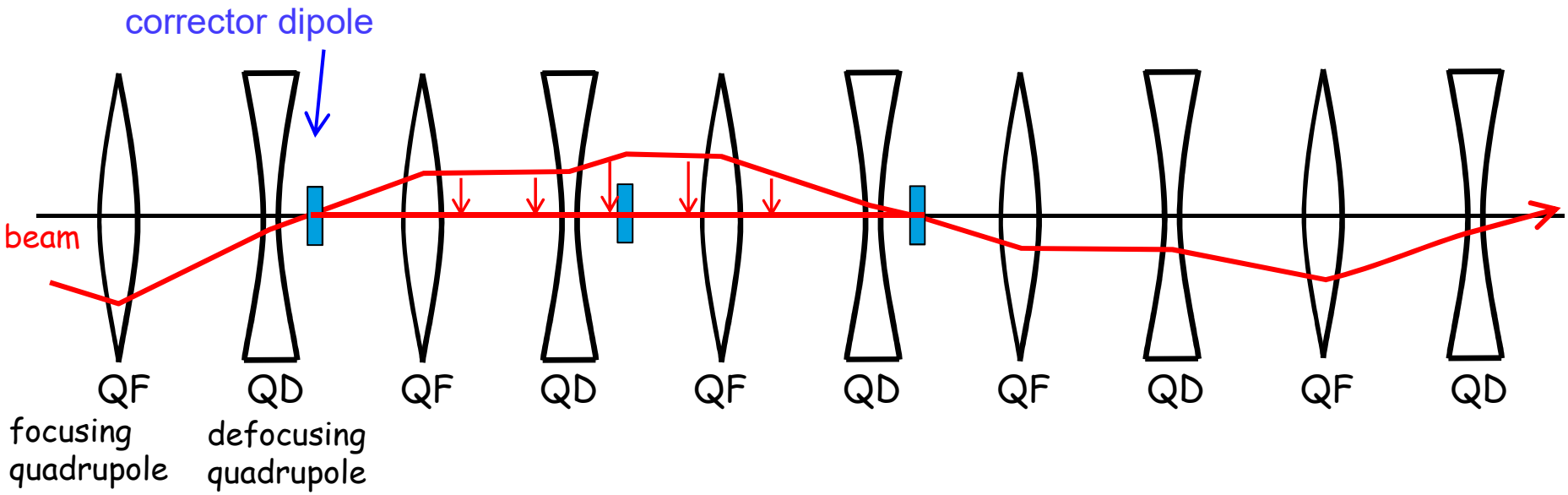
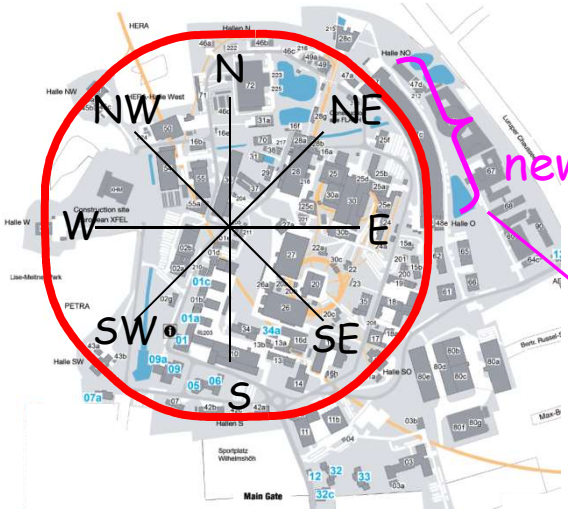


First useful hint: horizontal aperture problem



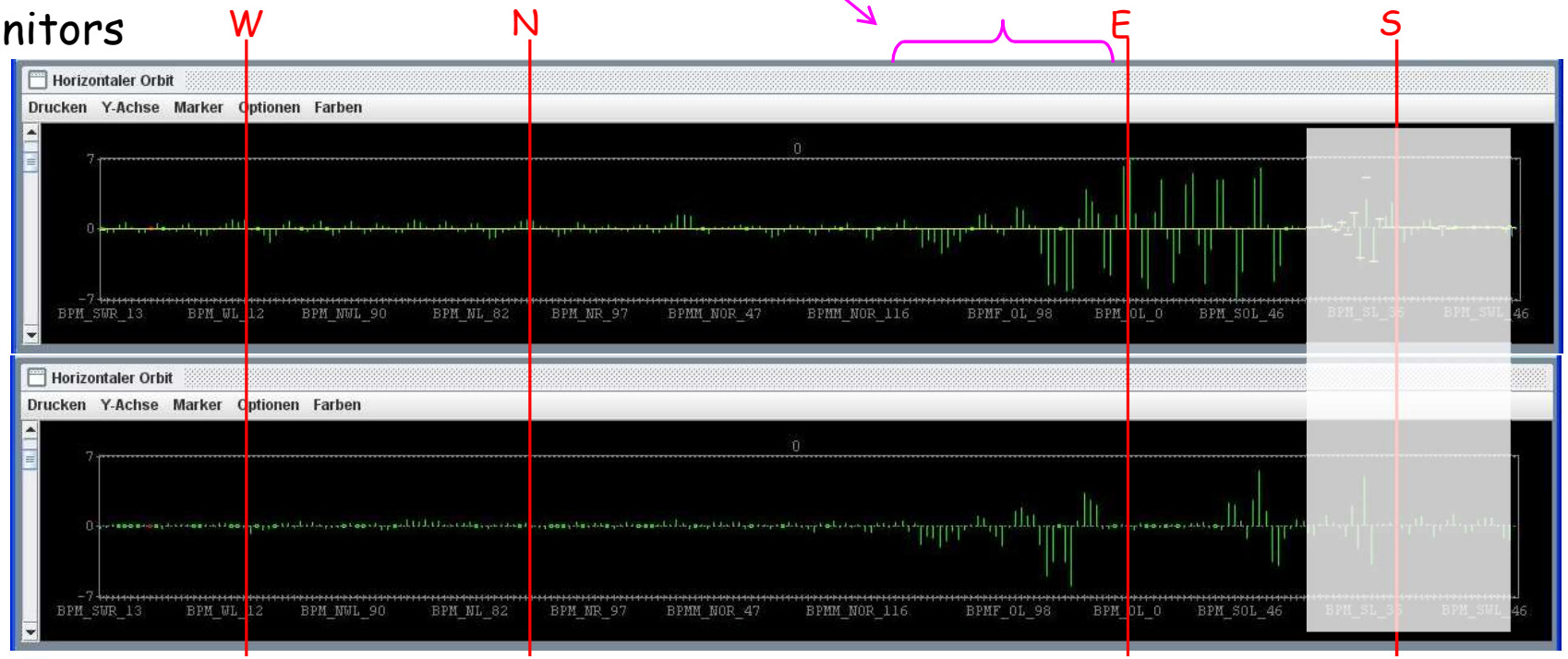
Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost
07:00 a.m.: visual inspection
in new octant
11:52 a.m.: start aperture scan
13:20 a.m.: beam stored

244 monitors

horizontal beam pos. [mm]

after 'flattening' the orbit



DESY.

horizontal aperture problem in the new octant

citation from the logbook: "the problem is at the end of the new octant"

PETRA **Samstag 12. Juni 2010 Morgen**

new

12.06.2010 13:56 KB, JK **Das Problem ist am Ende des neuen Achtels**

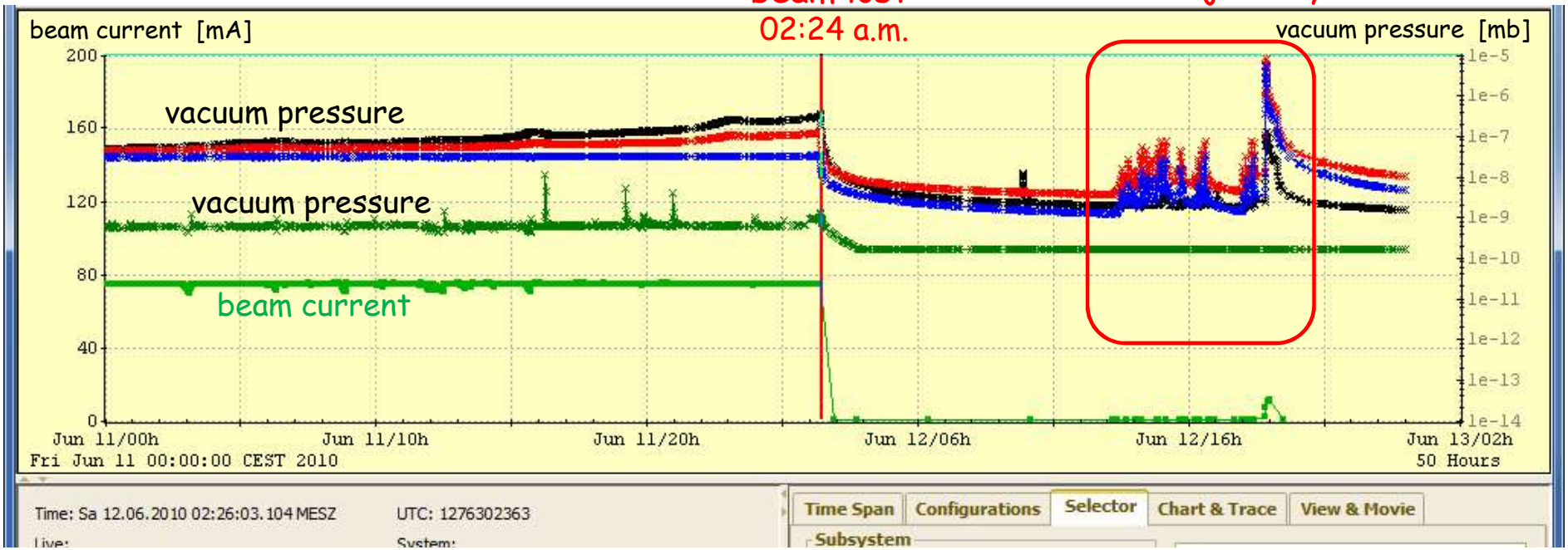
Wir korrigieren abschnittsweise den horizontalen Orbit auf den goldenen Orbit und überprüfen nach jeder Korrektur, ob sich noch Strahl injizieren läßt. Der Injektionsbereich SOR wird dabei ausgelassen.

Es bleibt eine symmetrische horizontale Beule in Zelle Nr. 8. Wird diese Beule herauskorrigiert, ist der Strahl weg und das bekannte Muster des exponentiellen Strahlverlusts ist wieder da. Das Problem leigt daher horizontal in Zelle 8.

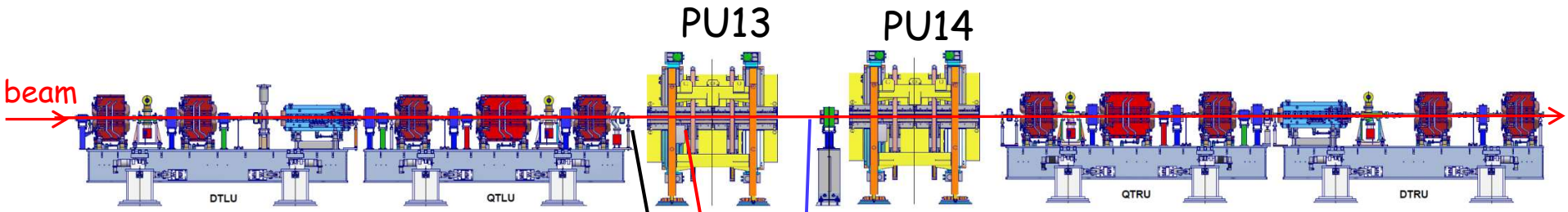
second hint: vacuum pressure raise in the new octant

beam lost
02:24 a.m.

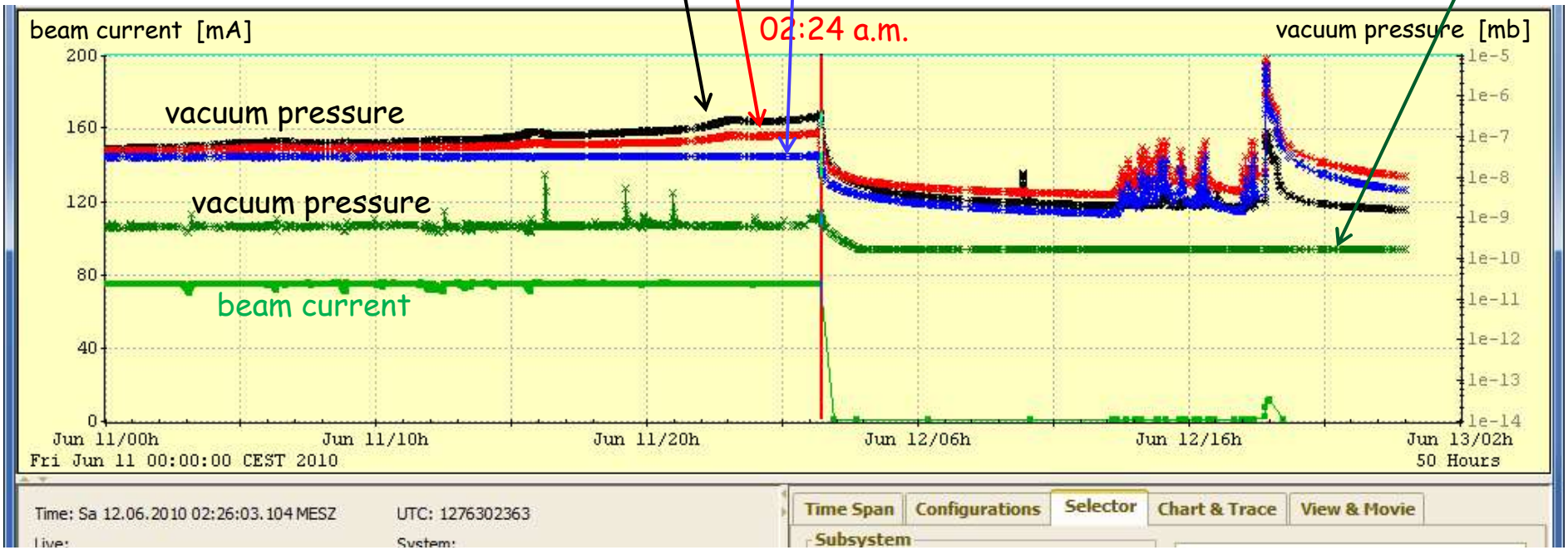
aperture scan
+ trajectory corrections



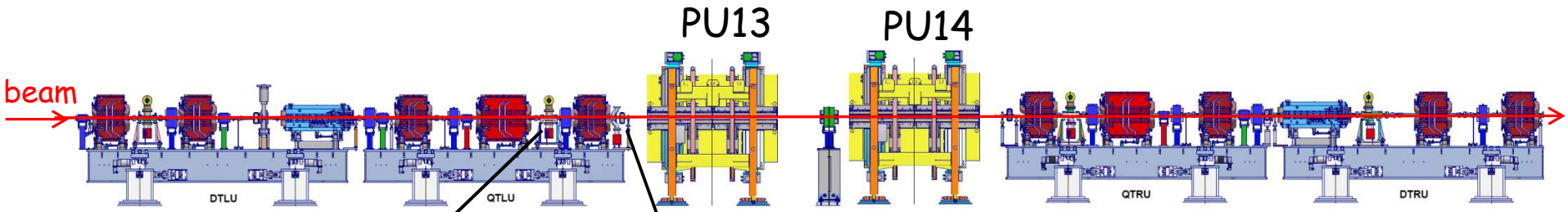
horizontal aperture problem in the new octant

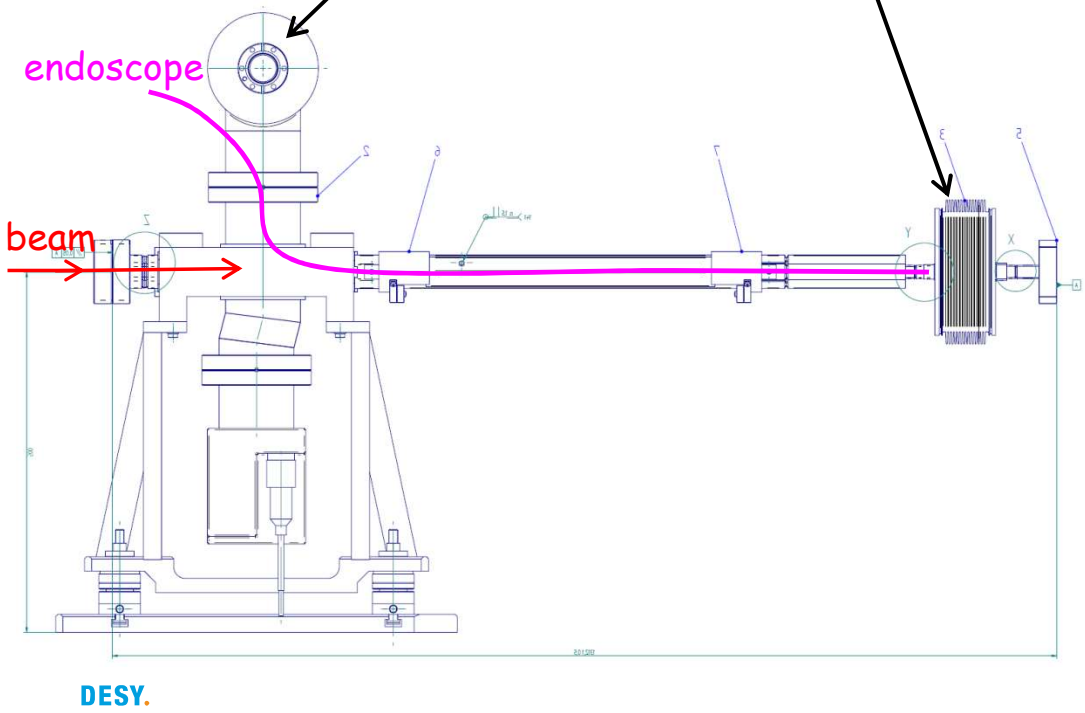


second hint: vacuum pressure raise in the new octant

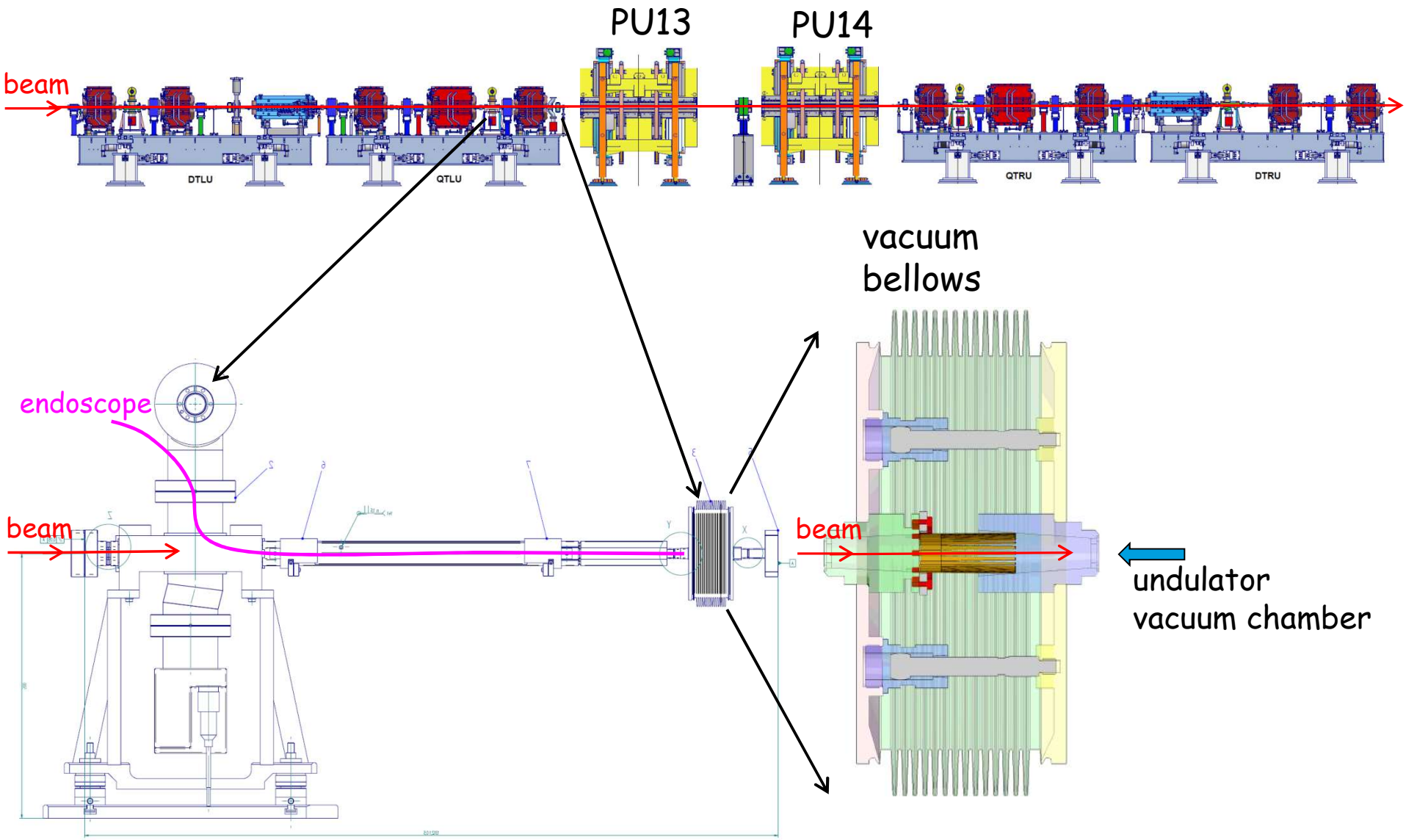


visual inspection inside the vacuum chamber…



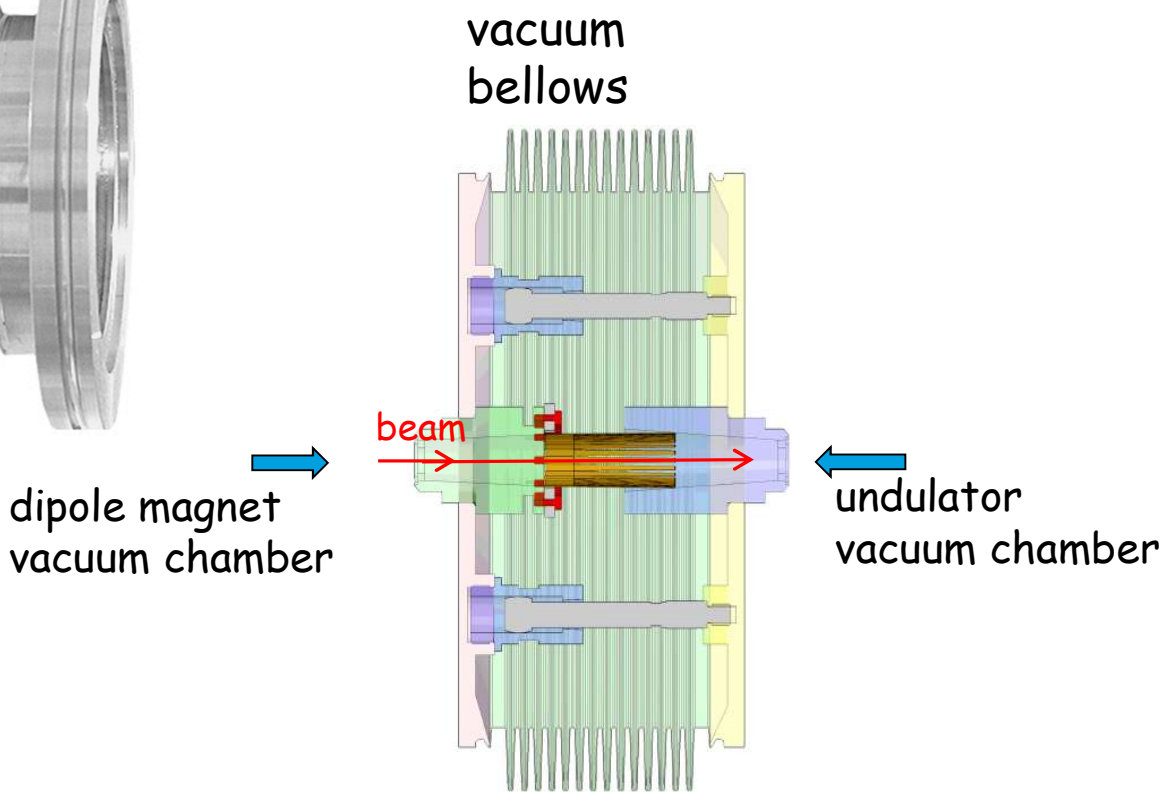


visual inspection inside the vacuum chamber…



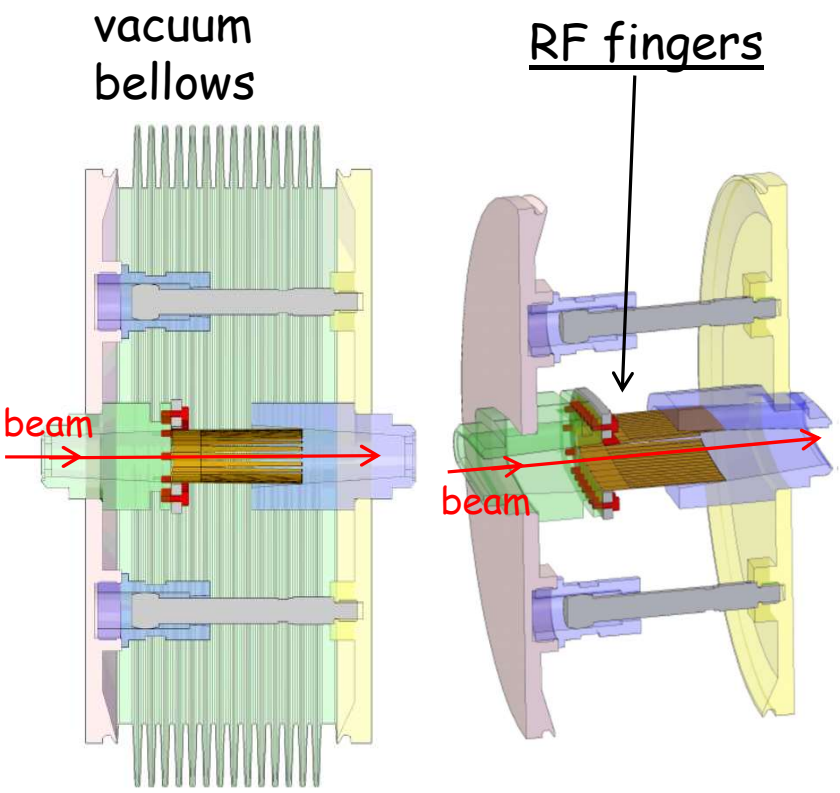
visual inspection inside the vacuum chamber…

an example of vacuum bellows

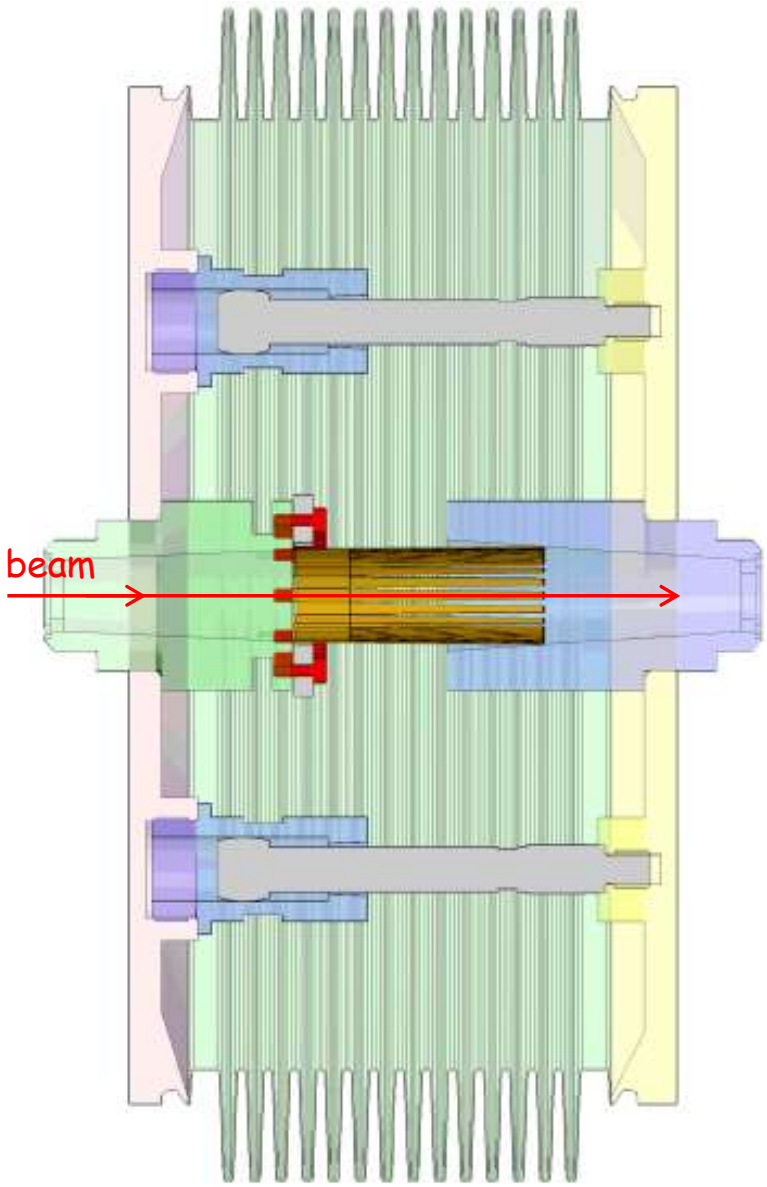


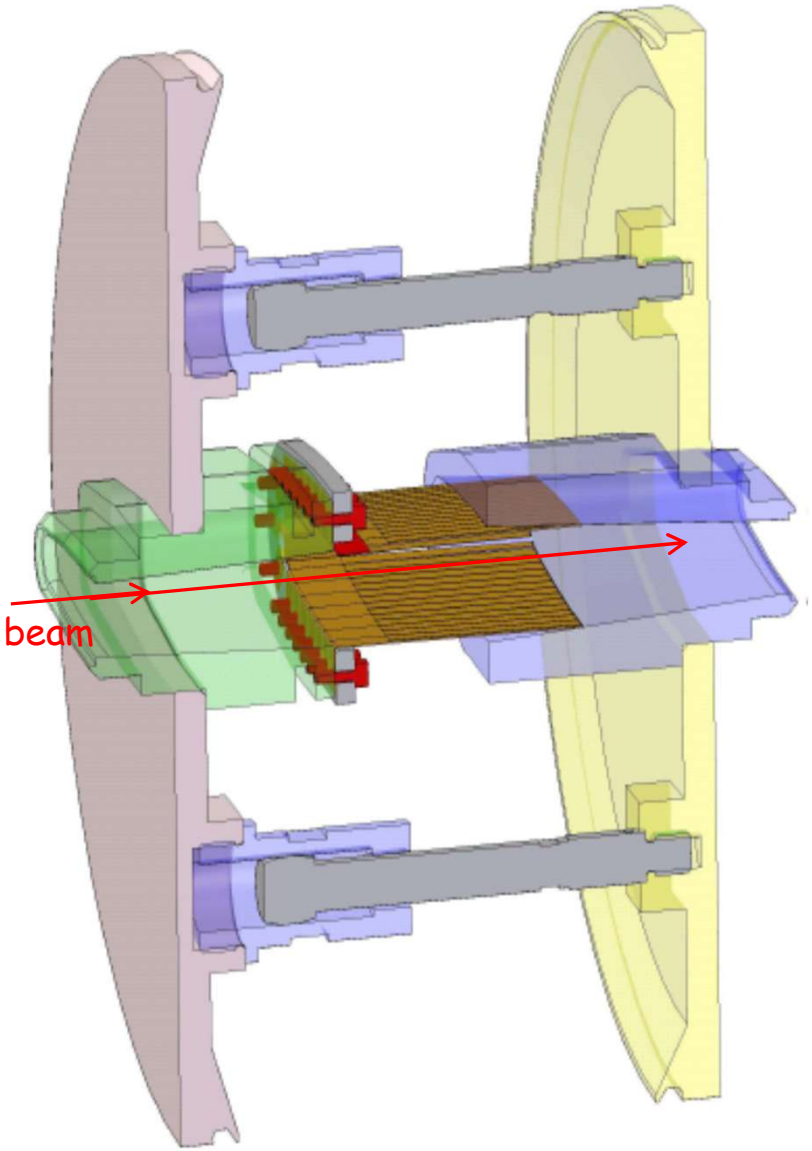
visual inspection inside the vacuum chamber…

an example of vacuum bellows

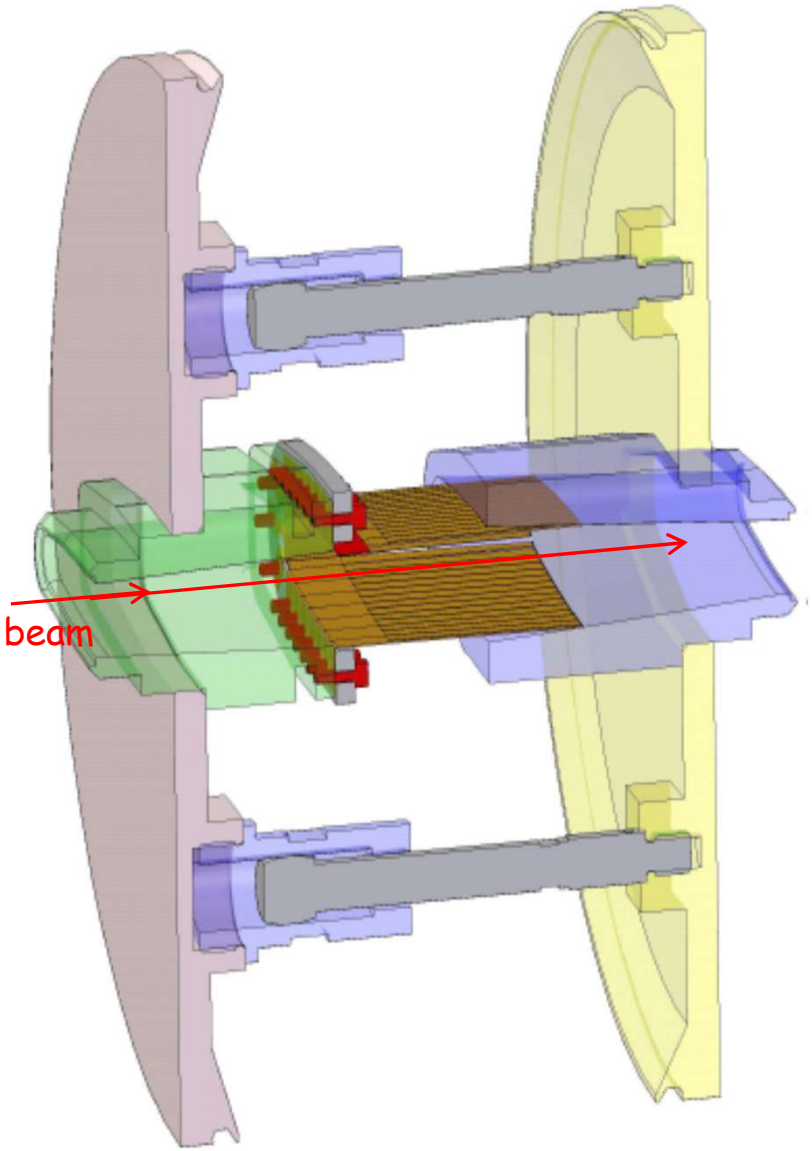


the problem was found: RF fingers

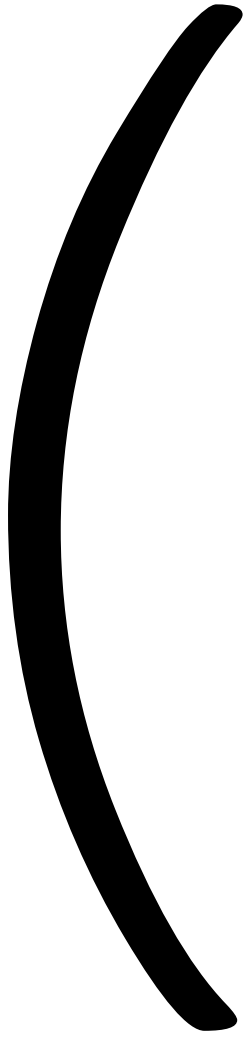




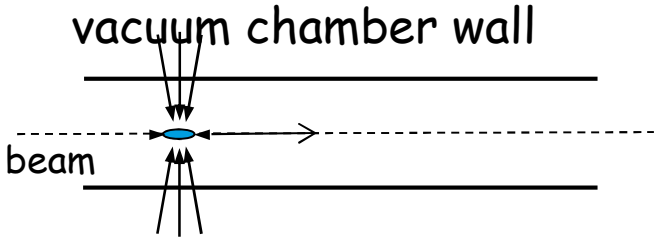
the problem was found: RF fingers



why do we need RF fingers ?

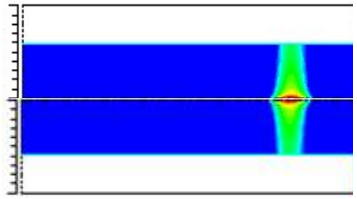


RF fingers and wakefields

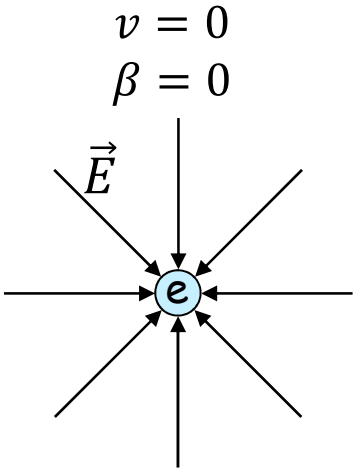


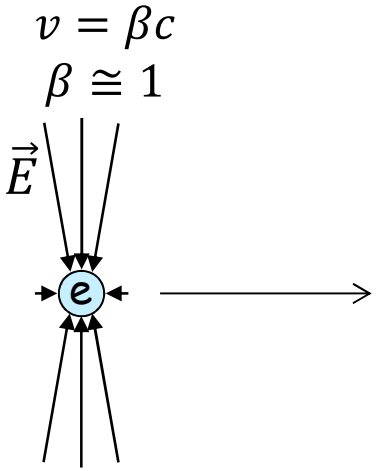
$\vec{E}$: electric field ?

simulation

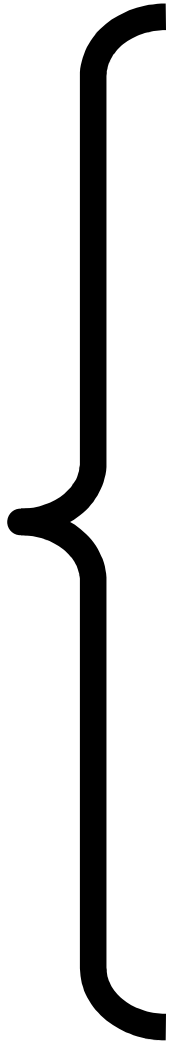


electric field of a relativistic particle



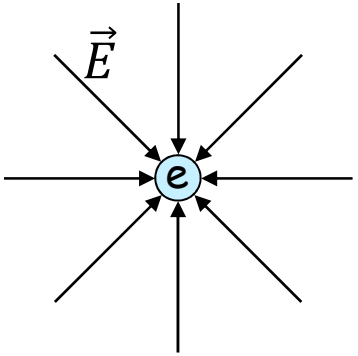


relativistic
expression



electric field of a relativistic particle

$v = 0$
$\beta = 0$



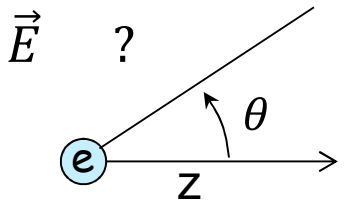
$$\vec{E} = \frac{q}{4\pi\varepsilon_0}\frac{1}{r^2}\frac{\vec{r}}{r}$$

$\gamma = 1$
$\beta = 0$

$$\vec{E} = \frac{q}{4\pi\varepsilon_0}\frac{(1-\beta^2)}{(1-\beta^2\sin^2\theta)^{3/2}r^2}\frac{\vec{r}}{r}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$v = \beta c$

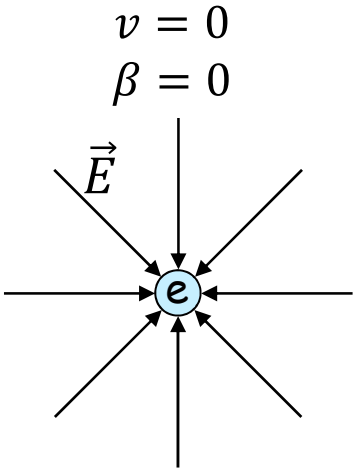


cylindrical coordinates

$$E_z(\theta = 0) = \frac{q}{4\pi\varepsilon_0}\frac{1}{\gamma^2 r^2}\frac{\vec{r}}{r}$$

$$E_r\left(\theta = \frac{\pi}{2}\right) = \frac{q}{4\pi\varepsilon_0}\frac{\gamma}{r^2}\frac{\vec{r}}{r}$$

electric field of a relativistic particle

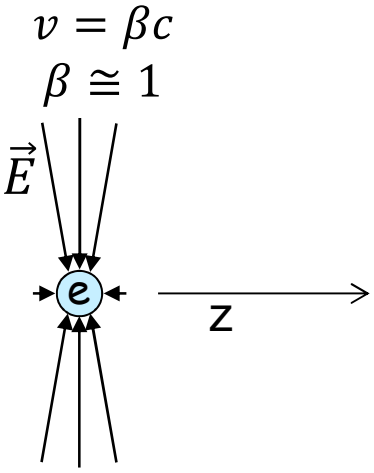


$$\vec{E} = \frac{q}{4\pi\varepsilon_0}\frac{1}{r^2}\frac{\vec{r}}{r}$$

$\gamma = 1$
$\beta = 0$

$$\vec{E} = \frac{q}{4\pi\varepsilon_0}\frac{(1-\beta^2)}{(1-\beta^2\sin^2\theta)^{3/2}r^2}\frac{\vec{r}}{r}$$

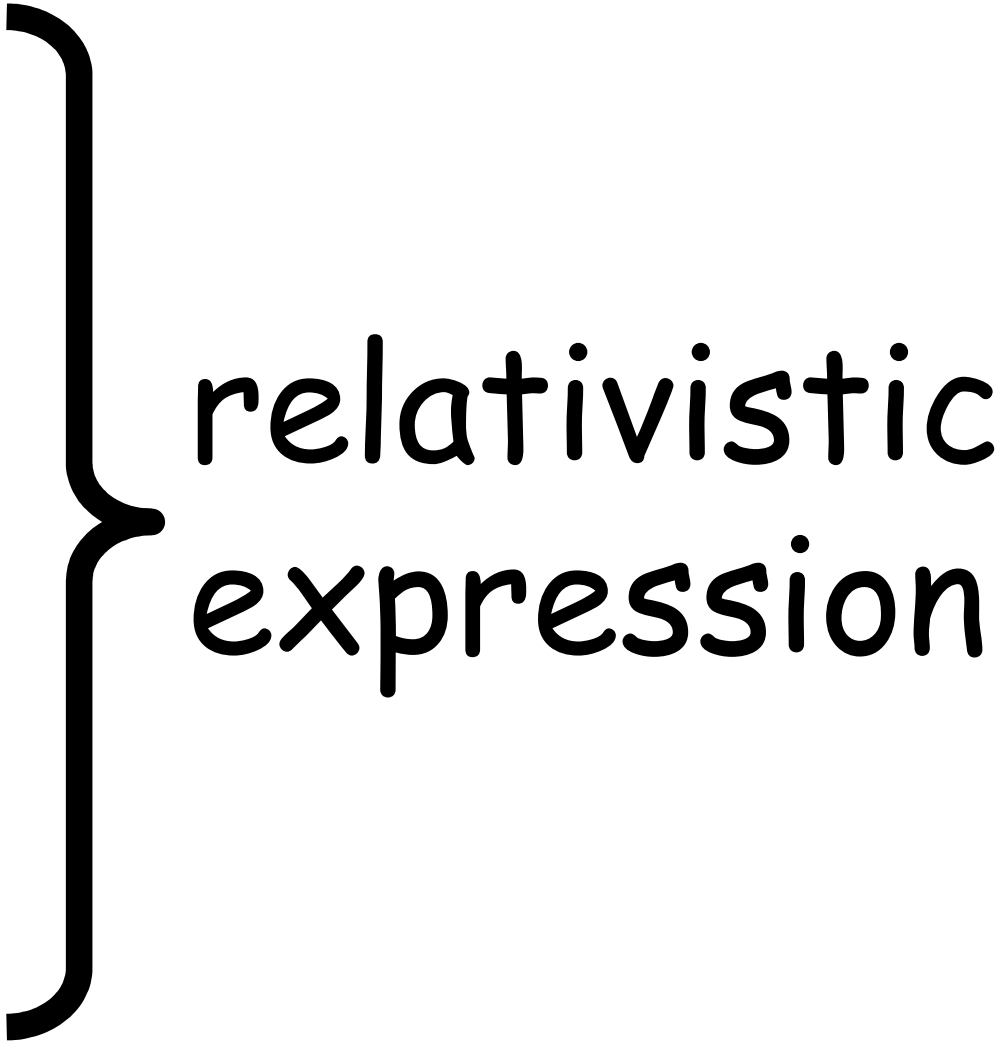
$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$



$\gamma \gg 1$
$\beta \cong 1$

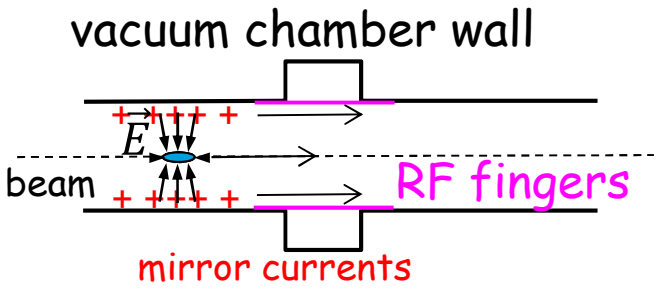
$$E_z(\theta = 0) = \frac{q}{4\pi\varepsilon_0}\frac{1}{\gamma^2 r^2}\frac{\vec{r}}{r} \xrightarrow{\gamma \to \infty} 0$$

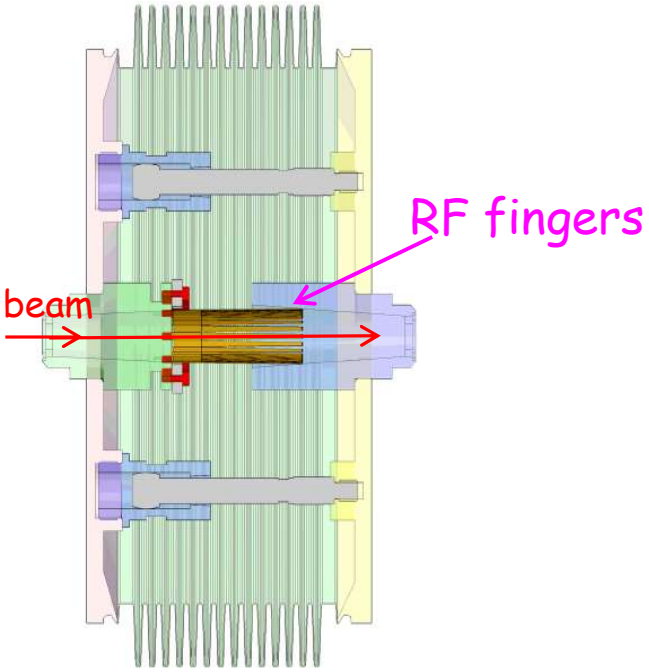
$$E_r\left(\theta = \frac{\pi}{2}\right) = \frac{q}{4\pi\varepsilon_0}\frac{\gamma}{r^2}\frac{\vec{r}}{r} \xrightarrow{\gamma \to \infty} \infty$$

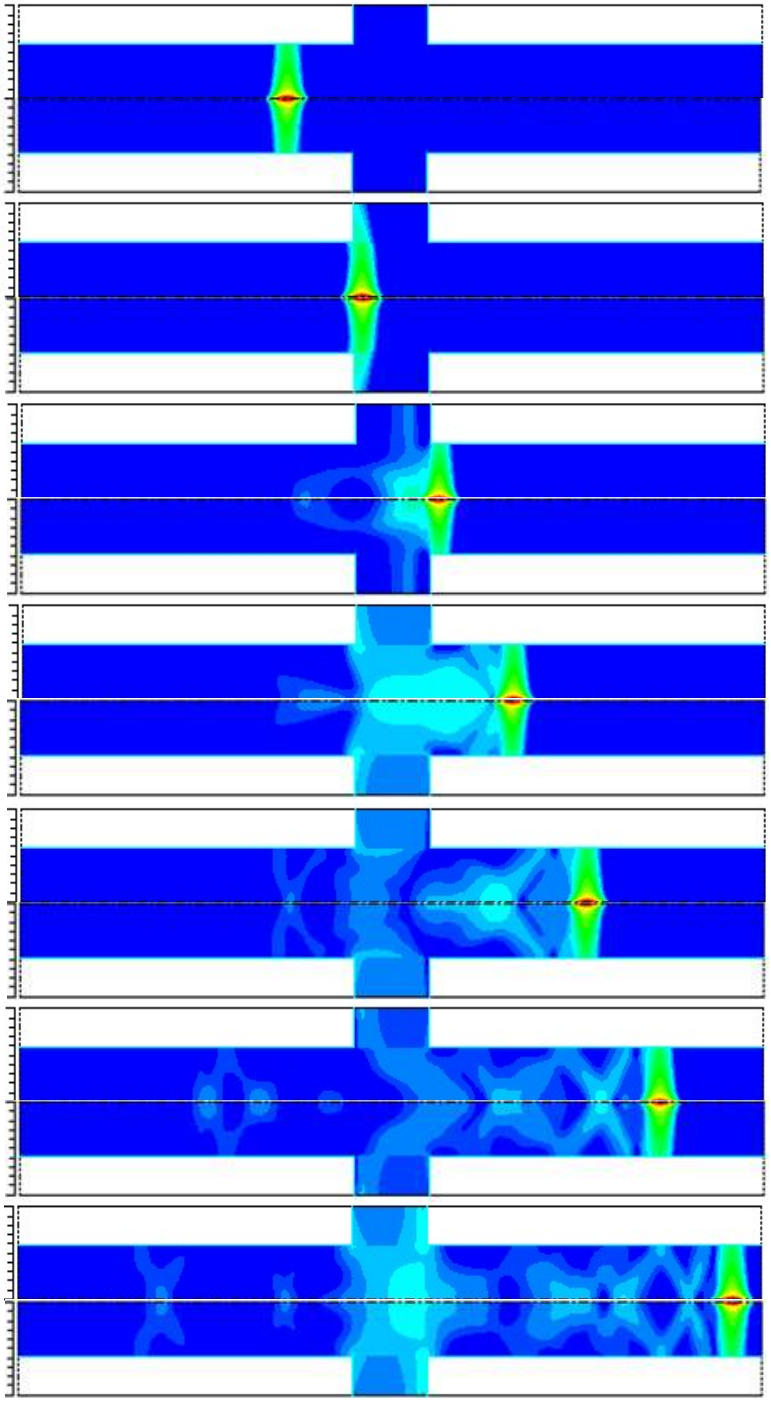

relativistic
expression

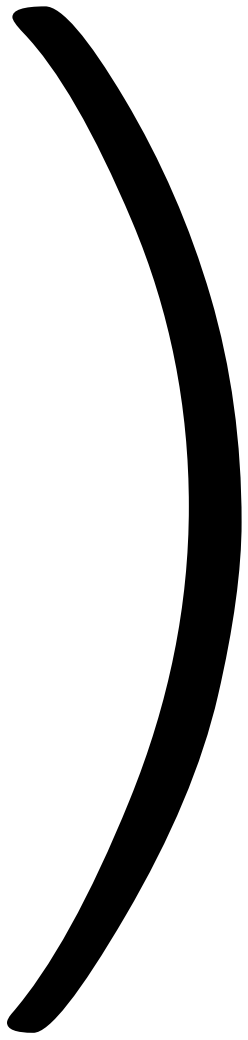
RF fingers and wakefields

simulation



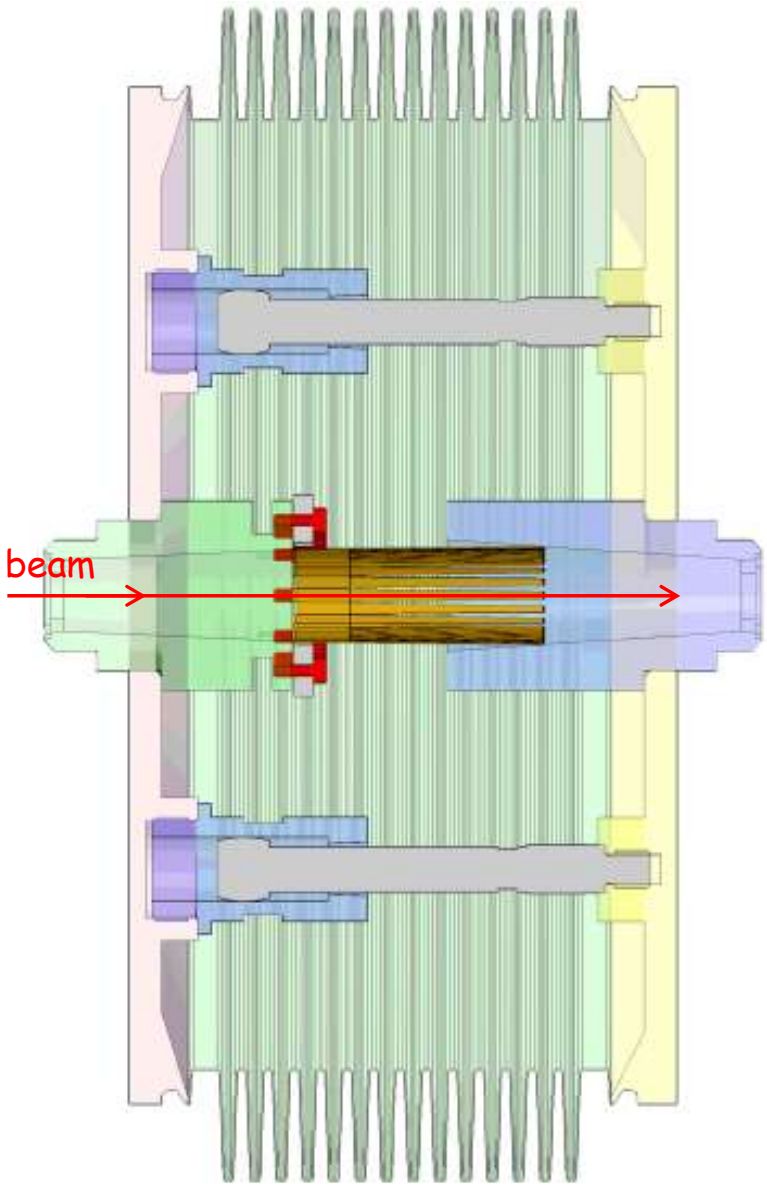






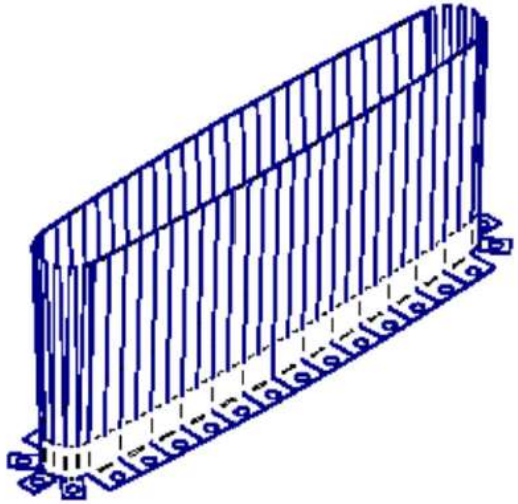
we need RF fingers

RF fingers and wakefields



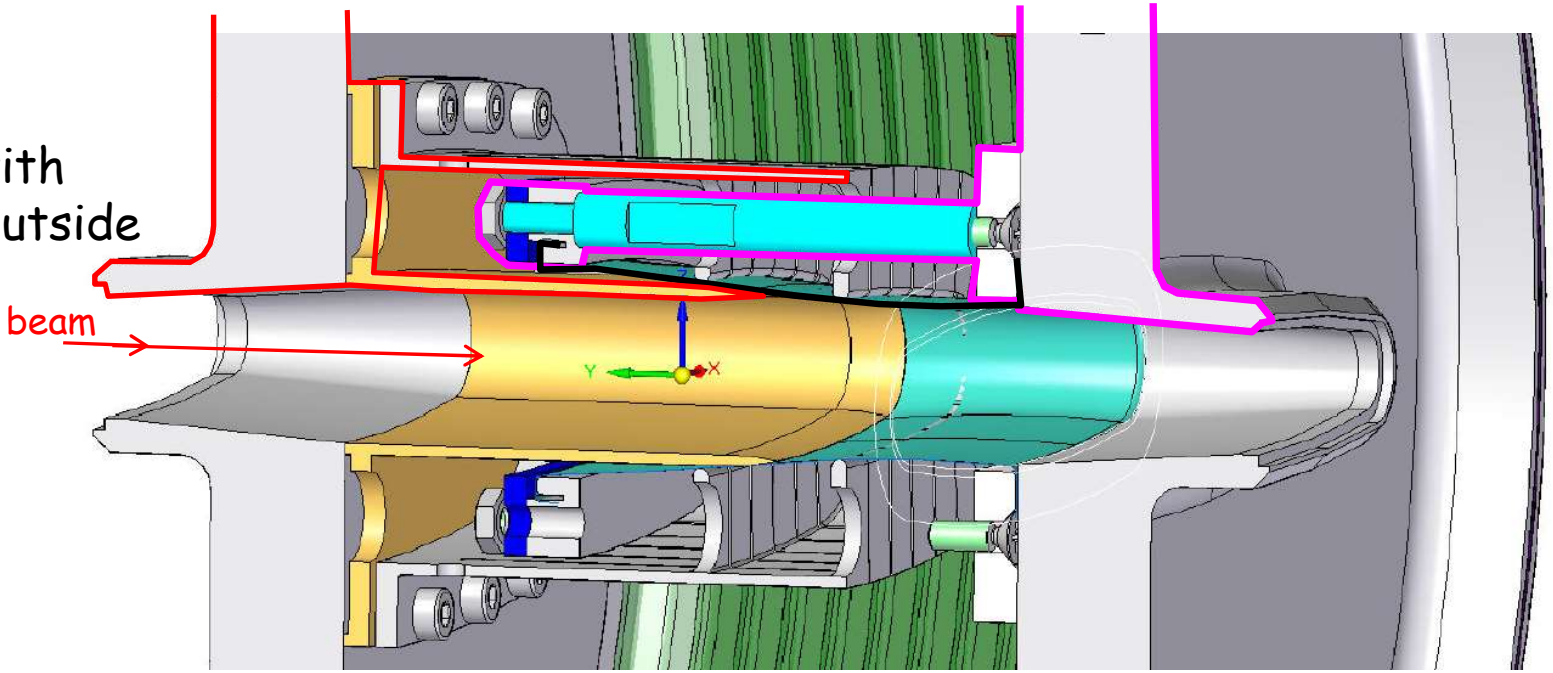
RF fingers: improvements done

old RF fingers were tilted outwards by 2 degrees



new RF fingers have stronger tilt, more tension

new design with
RF fingers outside



Summing-up of this part

Circular accelerators: the synchrotron

- basic components
  - dipole, quadrupole, undulator magnets, corrector dipoles
  - injection system (kickers and septum)
  - beam position monitors
  - vacuum pumps, vacuum pressure monitors
  - vacuum chambers, bellows
- advanced accelerator physics
  - electric field of a relativistic particle
  - mirror currents and wakefields
  - RF shielding (RF fingers)
- basic concepts in operation
  - e-logbook, Machine Protection System MPS
  - trajectory (orbit) corrections
  - aperture scans

Contact

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