Introduction to Accelerator Physics

Part 1

Pedro Castro / Accelerator Physics Group (MPY)
Hamburg, 23rd July 2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

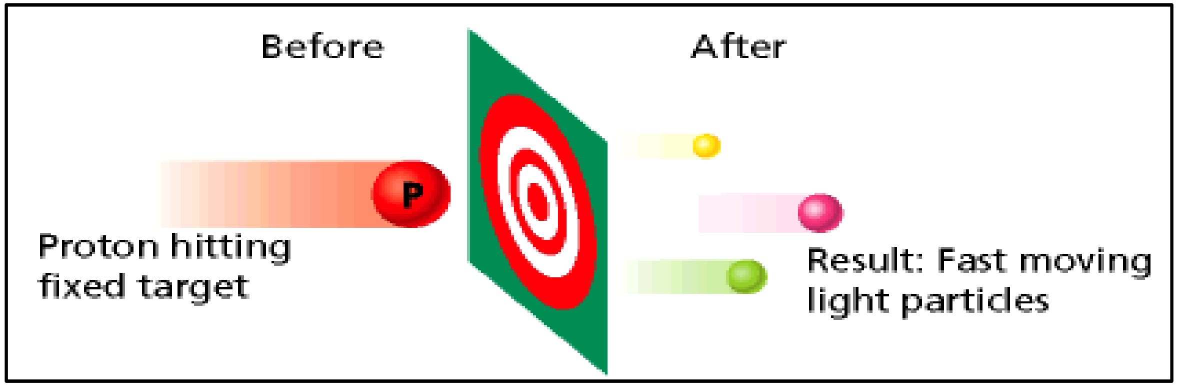
	length	lab	run	particles	energy	dipole field
PETRA	2.3 km	DESY	1978-1986	e-/e+	2x19 GeV	0.33 T
PETRA II	2.3 km	DESY	1987-2007	e- or e+ p	12 GeV 40 GeV	0.21 T 0.7 T
PETRA III	2.3 km	DESY	2009- ?	e-	6 GeV	0.10 T
HERA	6.3 km	DESY	1992-2007	e- or e+ p	27.5 GeV 920 GeV	0.274 T 5 T
LEP	27 km	CERN	1989-2000	e-/e+	2x105 GeV	0.135 T
LHC	27 km	CERN	2010- ?	p/p	2x7000 GeV	8.3 T
FLASH	0.3 km	DESY	2004- ?	e-	1.2 GeV	
XFEL	3 km	DESY	2016- ?	e-	17.5 GeV	
ILC	30 km	?	?	e-/e+	2x250 GeV	

DESY CERN

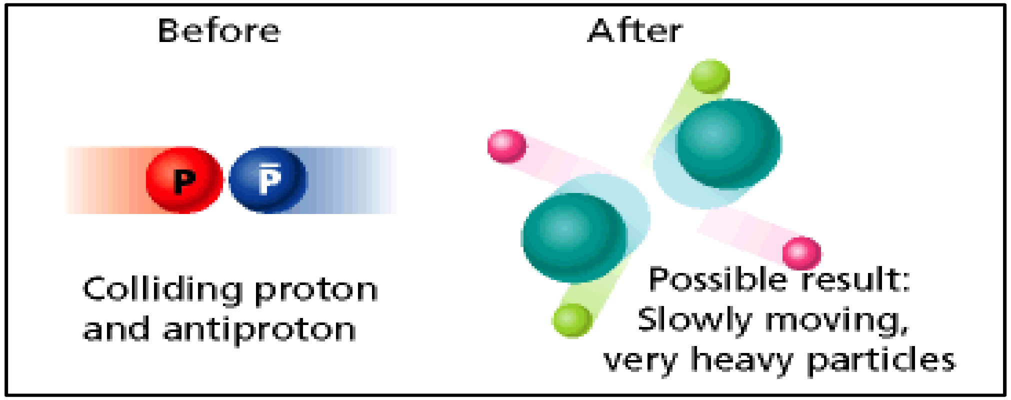
Applications of Accelerators (1)

Particle colliders for High Energy Physics (HEP) experiments

Fixed target experiments



Two beams collider experiments

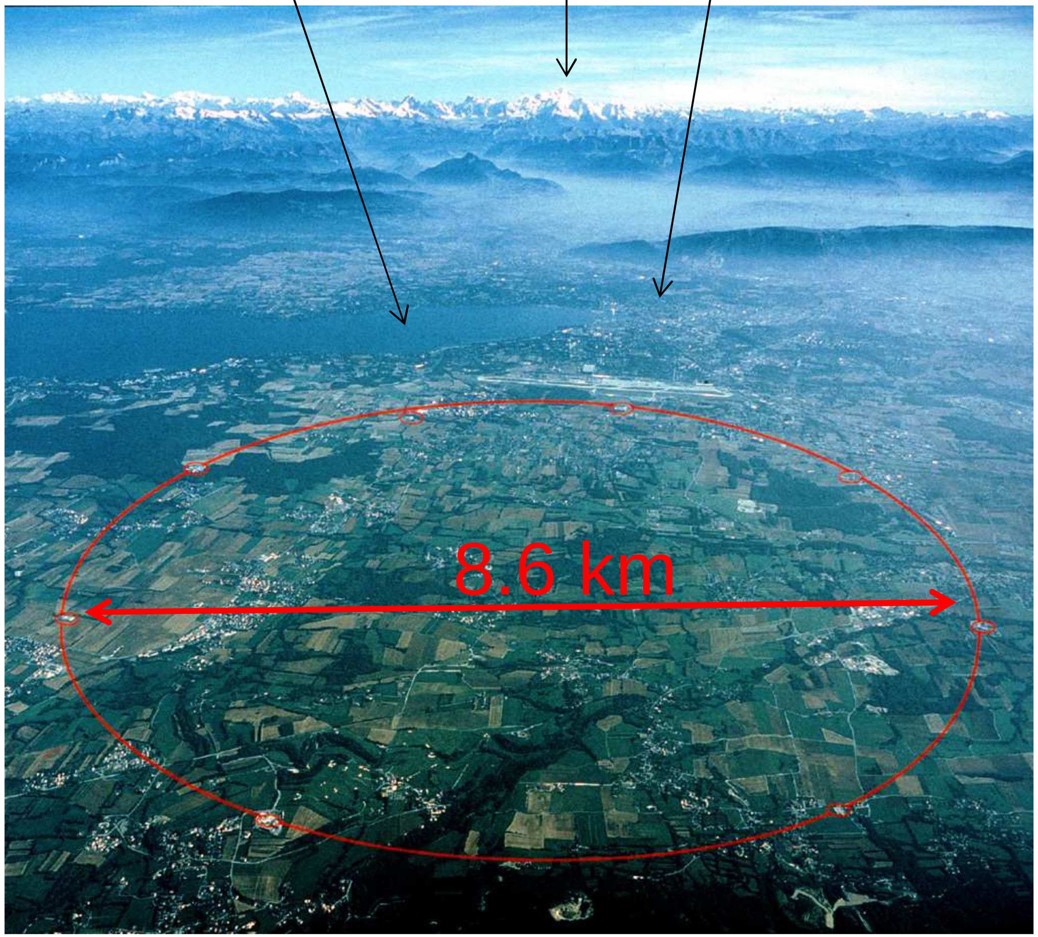


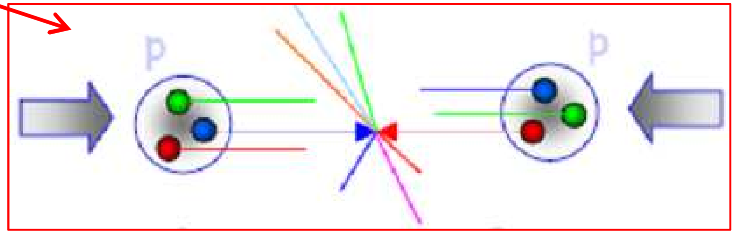
Applications of Accelerators (1)

Particle colliders for High Energy Physics experiments

Example: the Large Hadron Collider (LHC) at CERN

Lake Geneva Mont Blanc Geneva

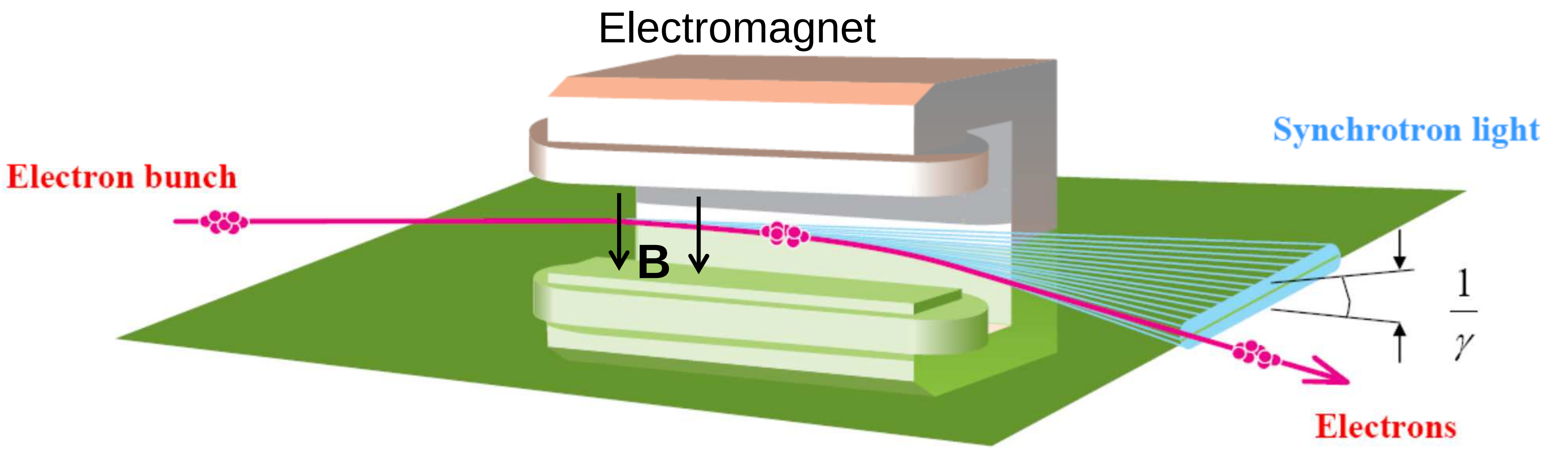




superconducting magnets
(inside a cryostat)

Applications of Accelerators (2)

Light sources for biology, physics, chemistry… experiments

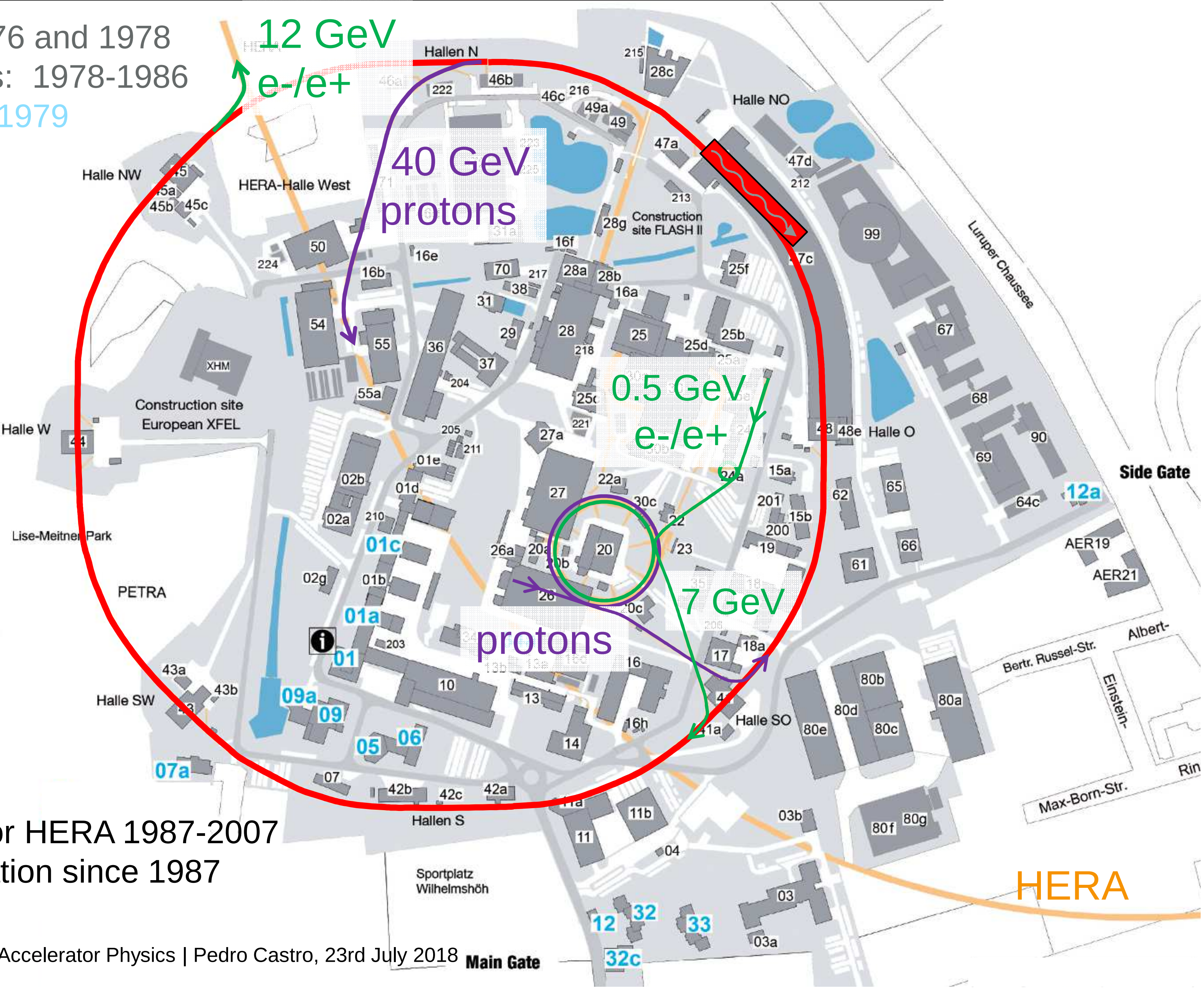


- structural analysis of crystalline materials
- X-ray crystallography (of proteins)
- X-ray microscopy
- X-ray absorption (or emission) spectroscopy
- …

Example: Positron-Elektron-Tandem-Ring-Anlage (PETRA)
'positron-electron tandem ring accelerator' at DESY

built between 1976 and 1978
HEP experiments: 1978-1986
gluon discovery: 1979

2.3 km long



pre-accelerator for HERA 1987-2007
synchrotron radiation since 1987

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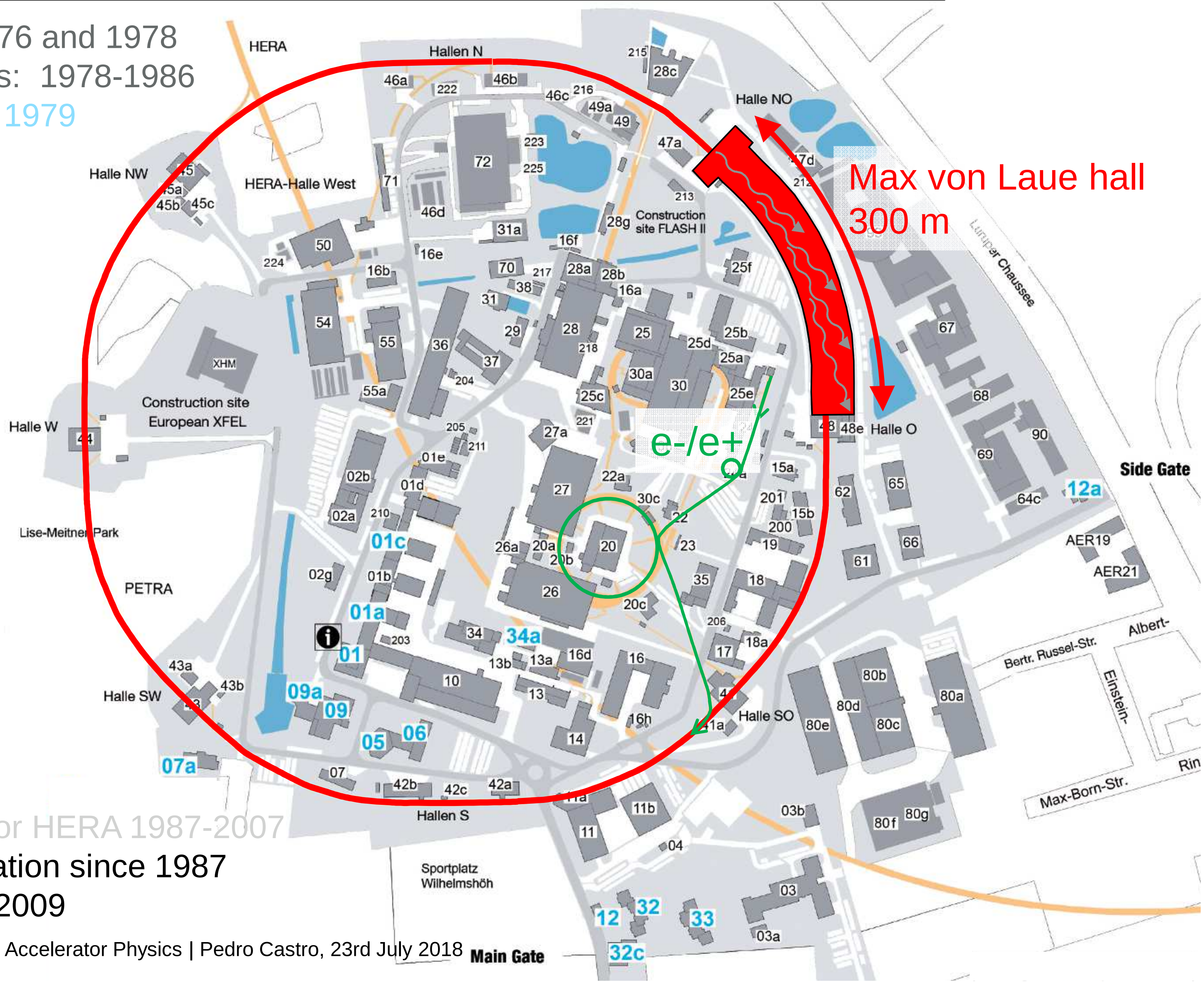
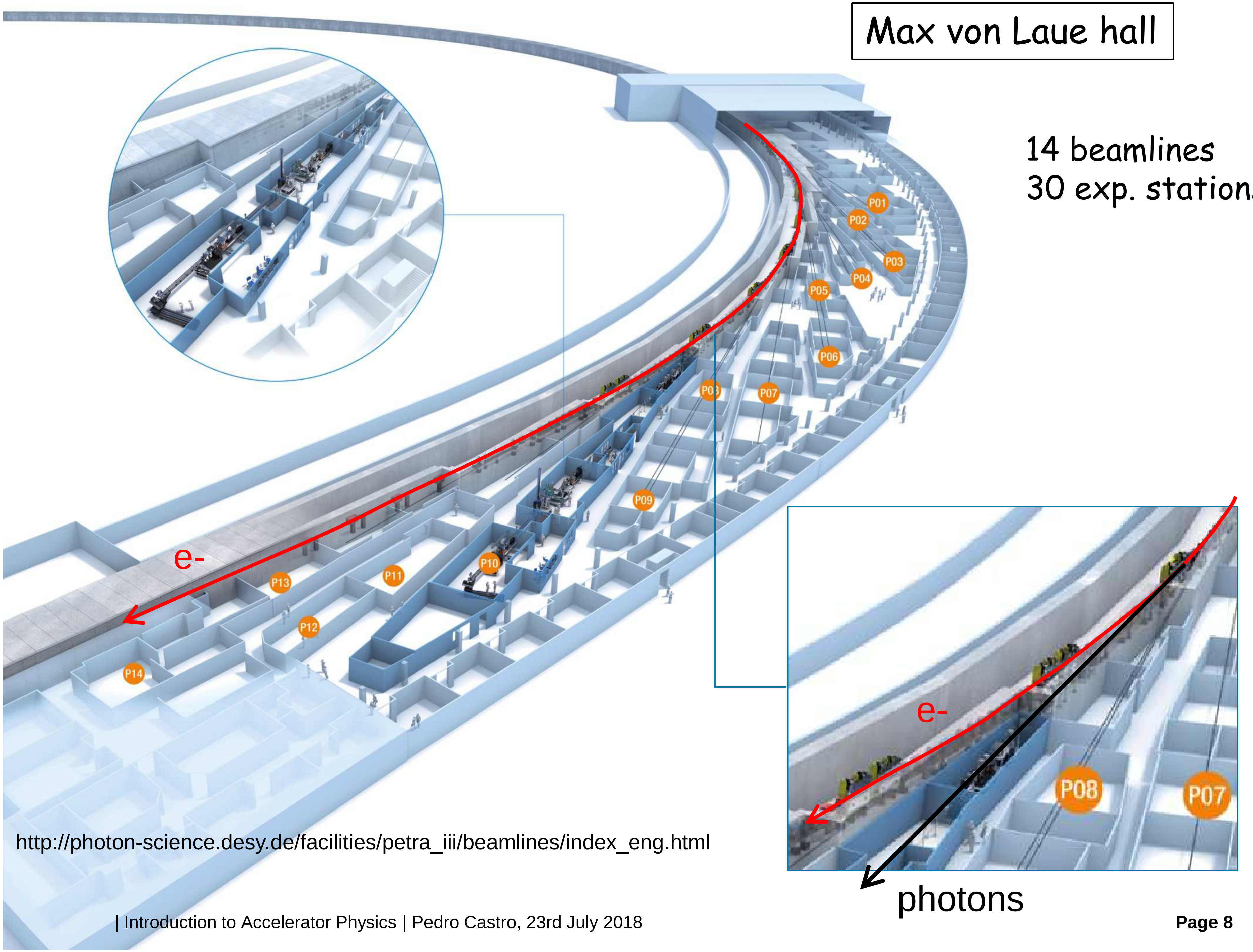


pre-accelerator for HERA 1987-2007
synchrotron radiation since 1987
PETRA III since 2009

Max von Laue hall

14 beamlines
30 exp. stations



http://photon-science.desy.de/facilities/petra_iii/beamlines/index_eng.html

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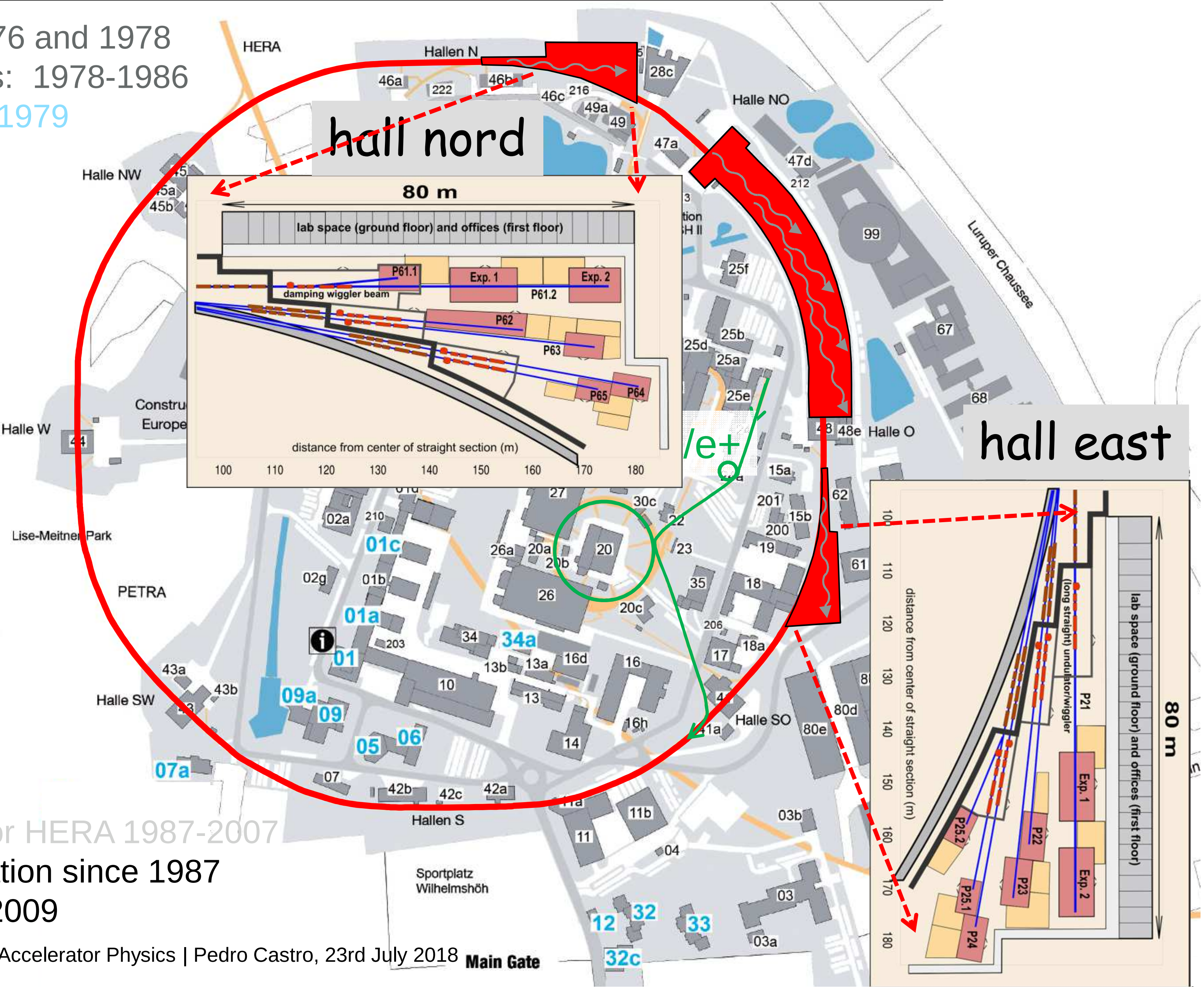


pre-accelerator for HERA 1987-2007
synchrotron radiation since 1987
PETRA III since 2009

Applications of Accelerators (3)

Accelerators in medicine

For radioisotope production

$$\text{proton beam} + \text{stable isotope} \xrightarrow{\text{transmutation}} \text{radioactive isotope}$$

For radiotherapy and radiosurgery:

- x-rays and gamma-rays
- ions (from protons to atoms with atomic number up to 18, Argon)
- neutrons

Applications of Accelerators (3)

Accelerators in medicine

For radioisotope production

For example:

18 MeV proton accelerator $\xrightarrow{p}$ Oxygen-18 (stable) — target

(transmutation)

Fluorine-18 (half-life time = 110 min.)

97% of decays

Oxygen-18 + positron

Applications of Accelerators (3)

Accelerators in medicine

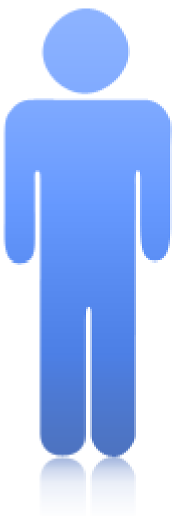
For radioisotope production

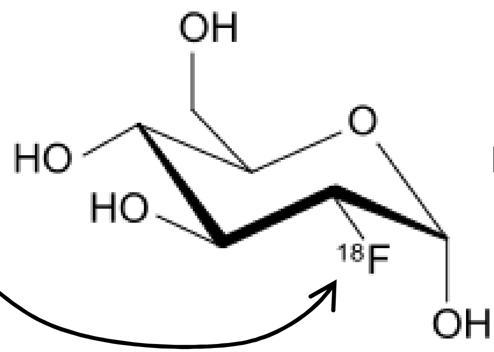
For example:

18 MeV proton accelerator $\xrightarrow{p}$ $\frac{\text{target}}{\text{Oxygen-18}}$

$\underbrace{\xrightarrow{p} \text{Oxygen-18}}$ (transmutation)

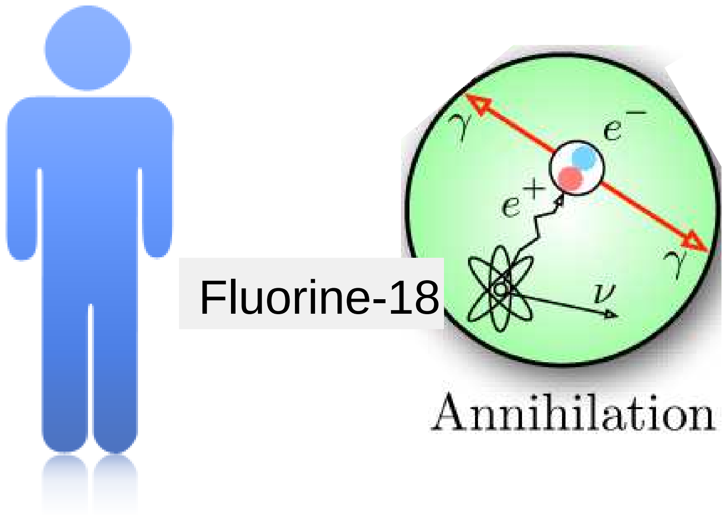
Fluorine-18 (half-life time = 110 min.)

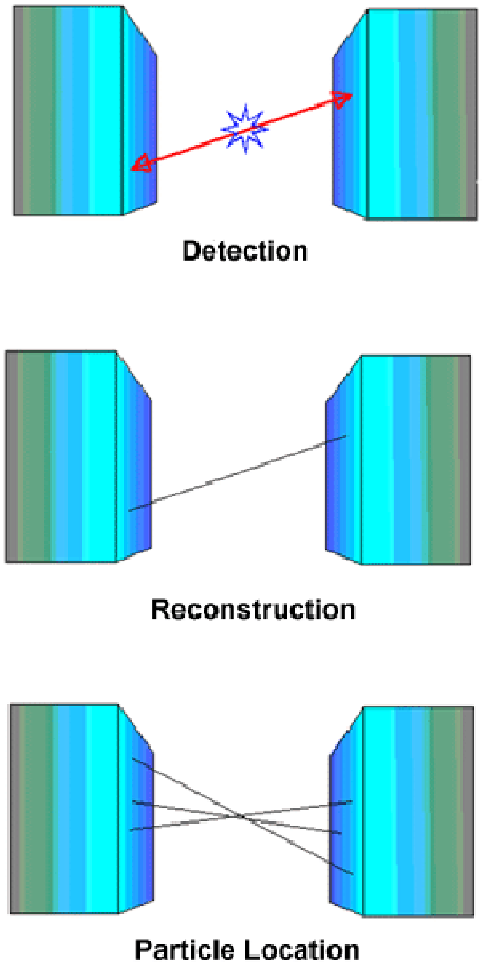




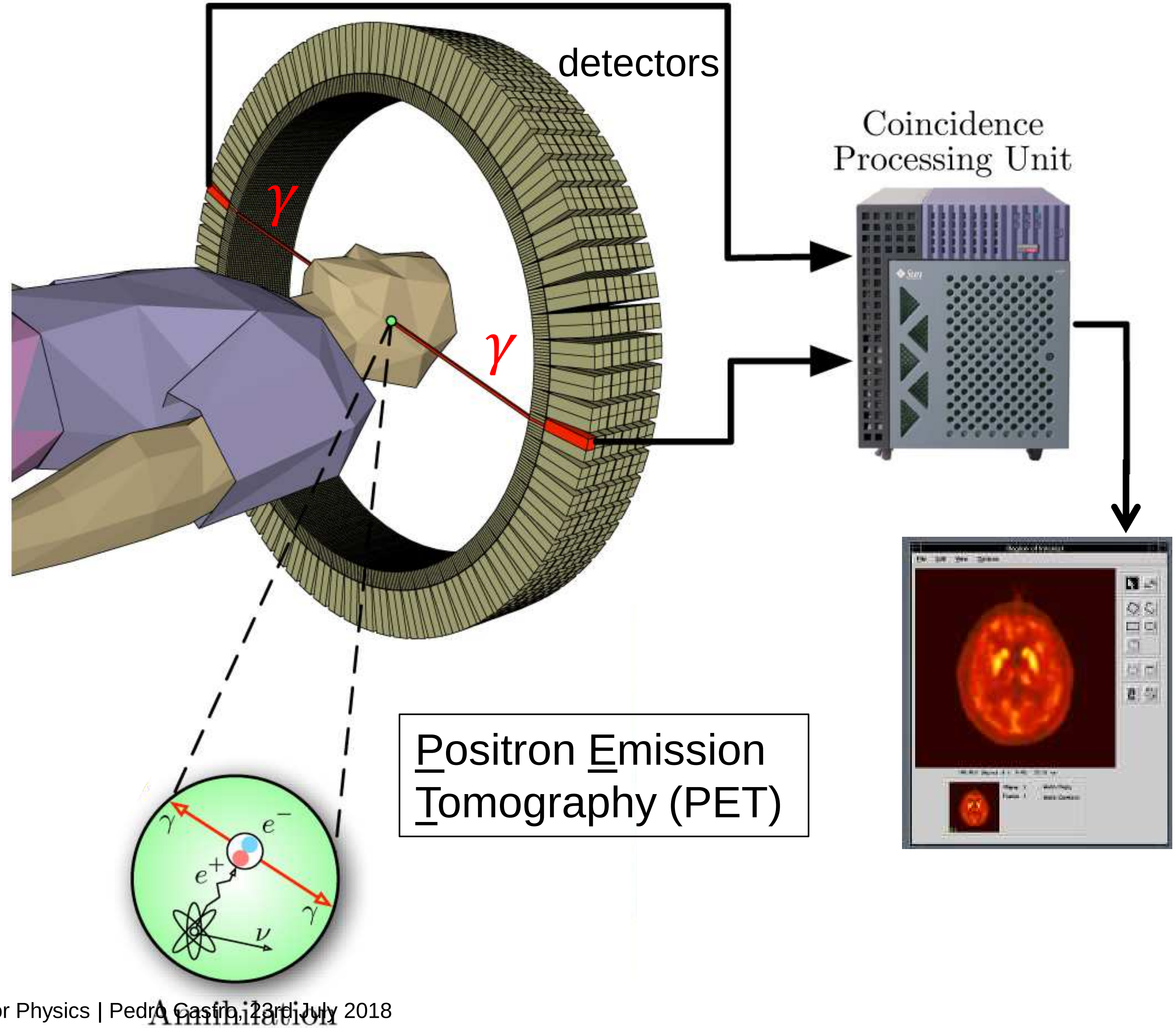
Fludeoxyglucose (^{18}F)

Applications of Accelerators (3)

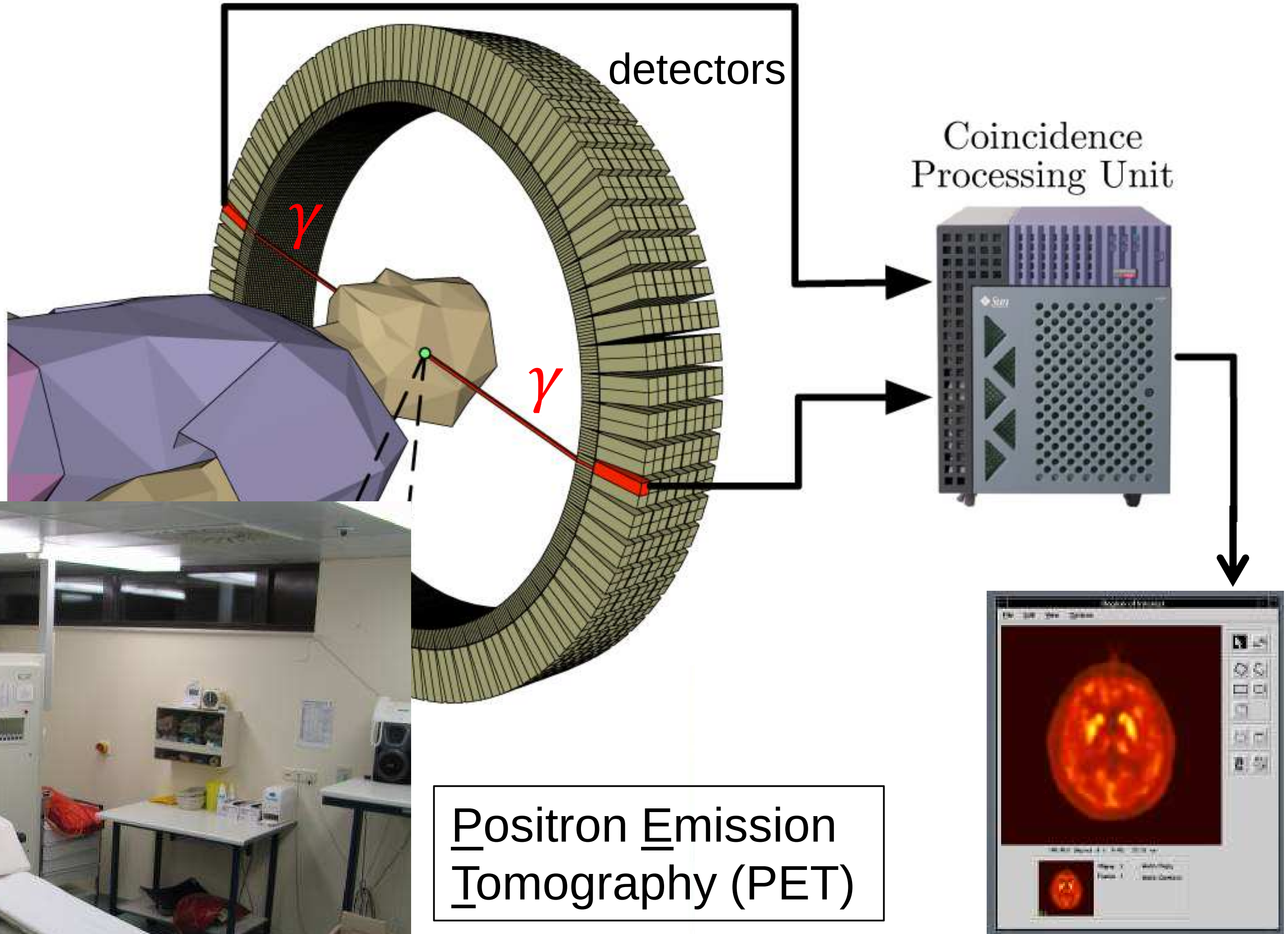




Applications of Accelerators (3)



Applications of Accelerators (3)



Positron Emission
Tomography (PET)

Applications of Accelerators (4)

For industrial applications:

Application	
Ion implantation	~ 9500
Electron cutting and welding	~ 4500
Electron beam and x-ray irradiators	~ 2000
Ion beam analysis (including AMS)	~ 200
Radioisotope production (including PET)	~ 900
Nondestructive testing (including security)	~ 650
Neutron generators (including sealed tubes)	~ 1000

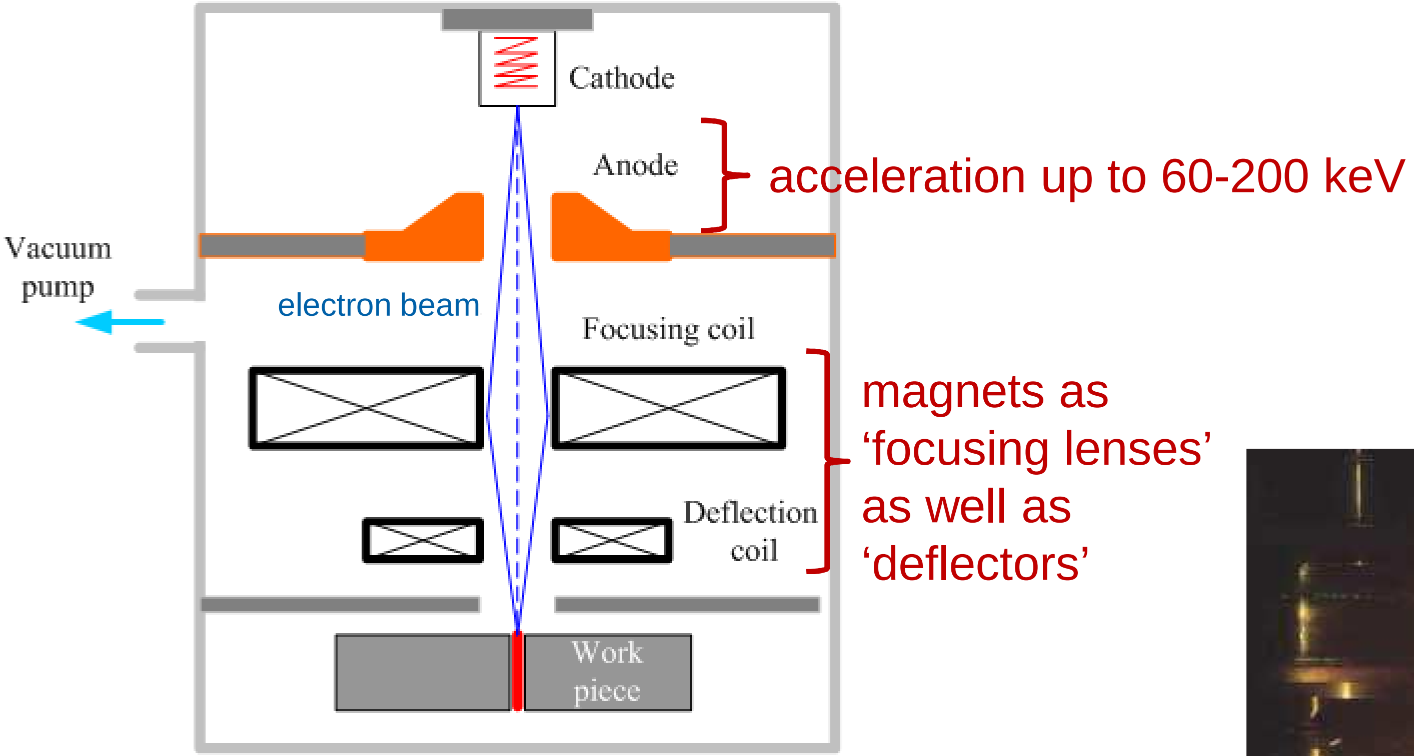
approx. numbers from 2007 (worldwide)

with energies up to 15 MeV

Applications of Accelerators (4)

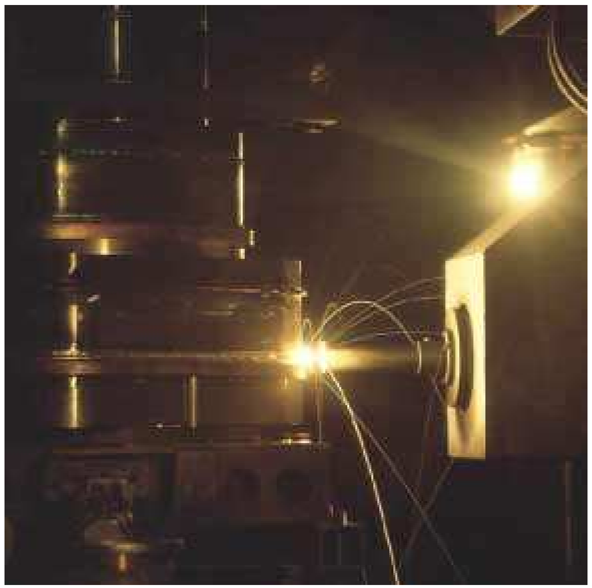
For industrial applications:

an example: electron beam welding



up to 15 cm

'deep welding effect'



Worldwide …

- About 120 accelerators for research in "nuclear and particle physics"
- About 70 electron storage rings and electron linear accelerators used as light sources (so-called 'synchrotron radiation sources')

- More than 7,000 accelerators for medicine

  radiotherapy (>7,500), radioisotope production (200)

- More than 18,000 industrial accelerators

  ion implantation (>9,000) , electron cutting and welding (>4,000) …

Worldwide …

> About 120 accelerators for research in "nuclear and particle phy

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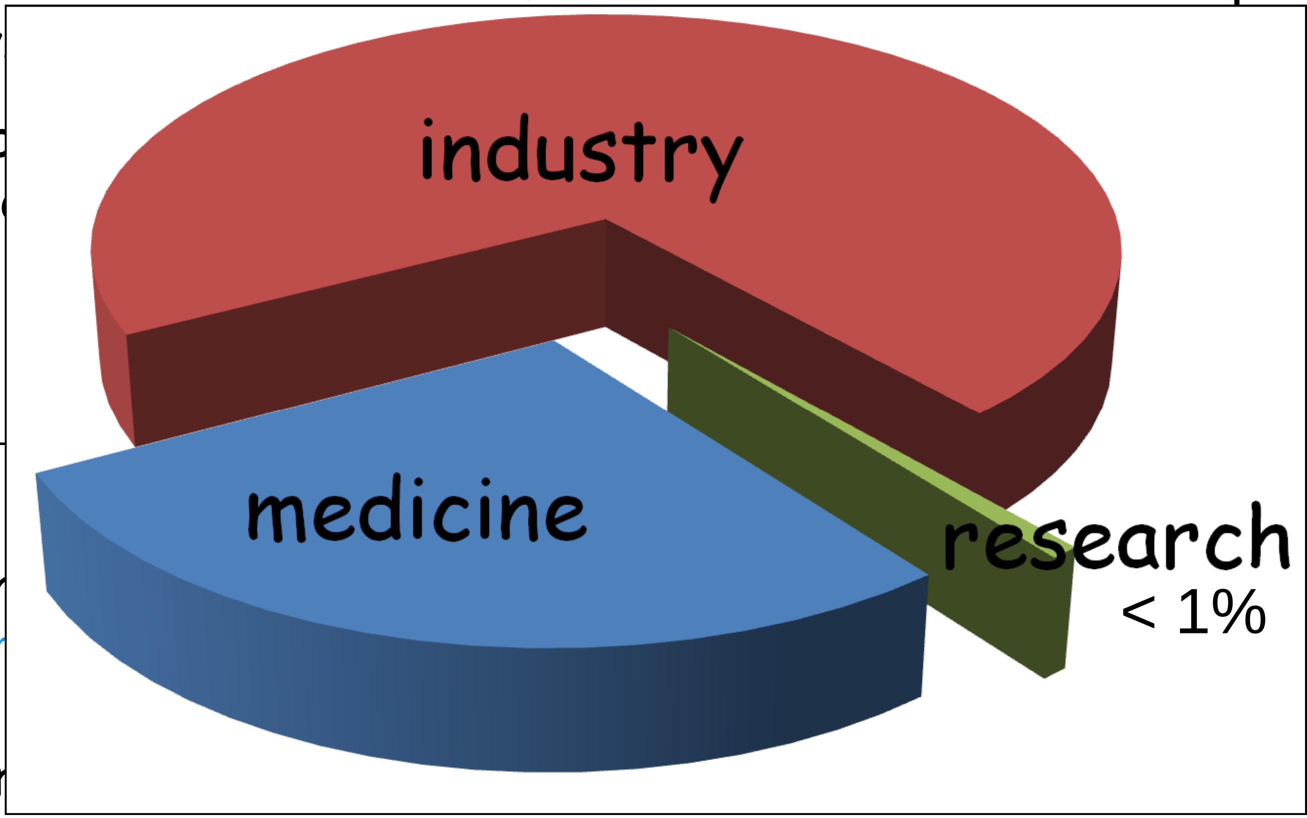

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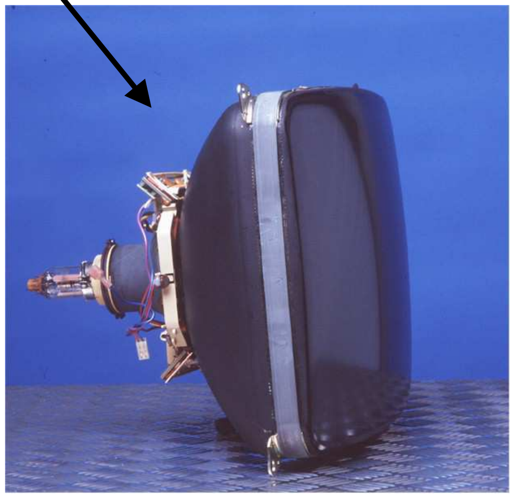
ion implantation (>9,000) , electron cutting and welding (>4,000) …

Applications of Accelerators (5)

Many millions of television sets, oscilloscopes using CRTs (Cathode Ray Tube)

TV

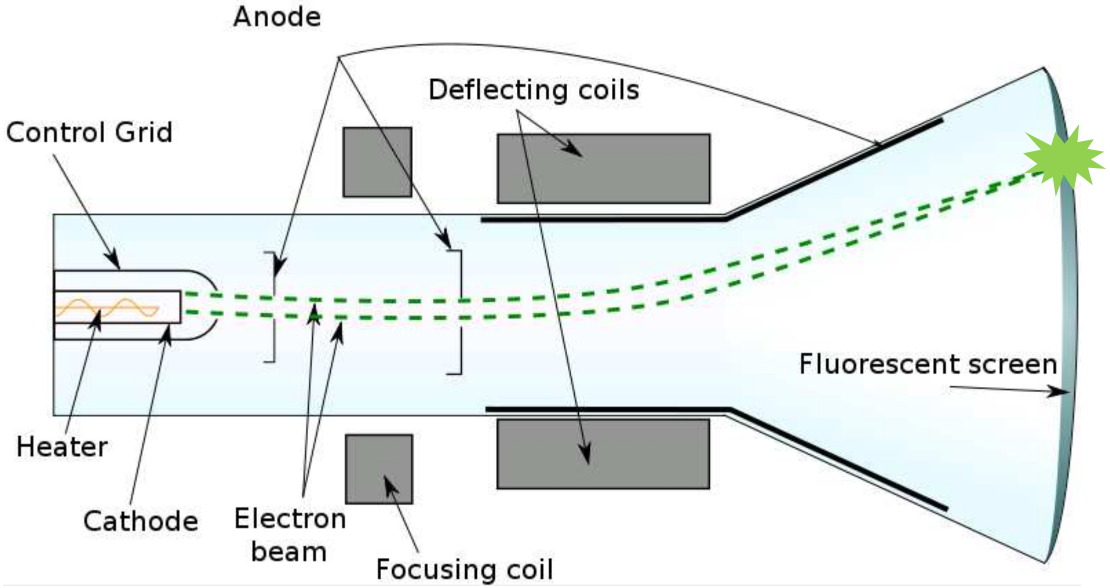


oscilloscope

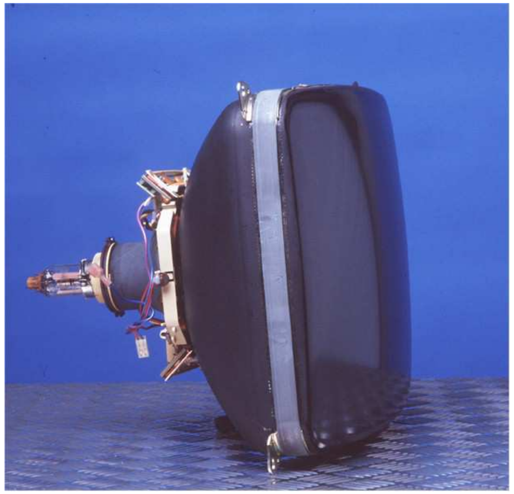
Applications of Accelerators (5)

Many millions of television sets, oscilloscopes using CRTs (Cathode Ray Tube)

acceleration

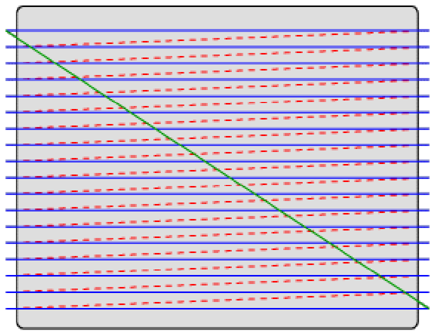


magnets as ‘focusing lenses’
as well as ‘deflectors’



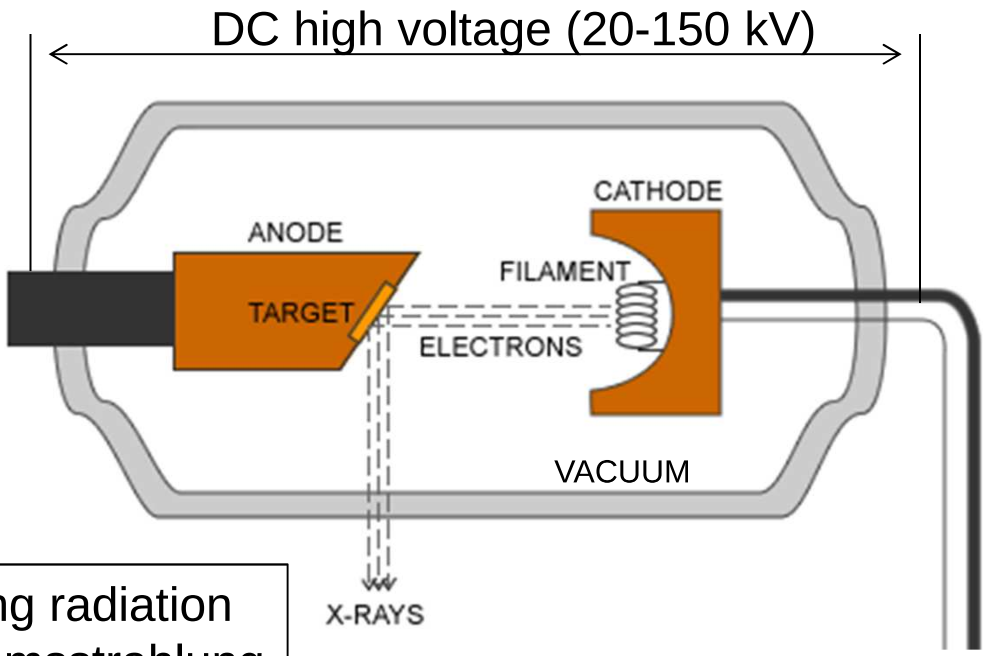
25 frames / s

625
lines



Applications of Accelerators (6)

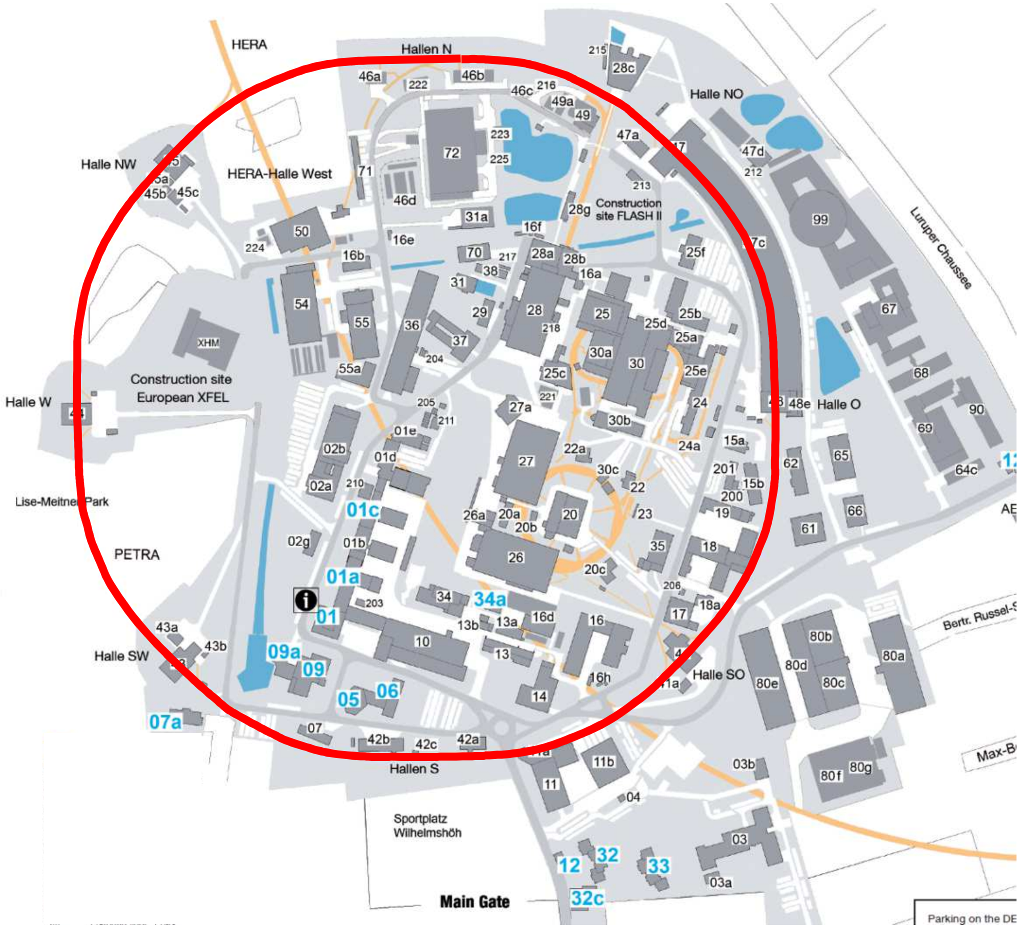
X-ray tubes



braking radiation
or bremsstrahlung

Working with accelerators in the control room …

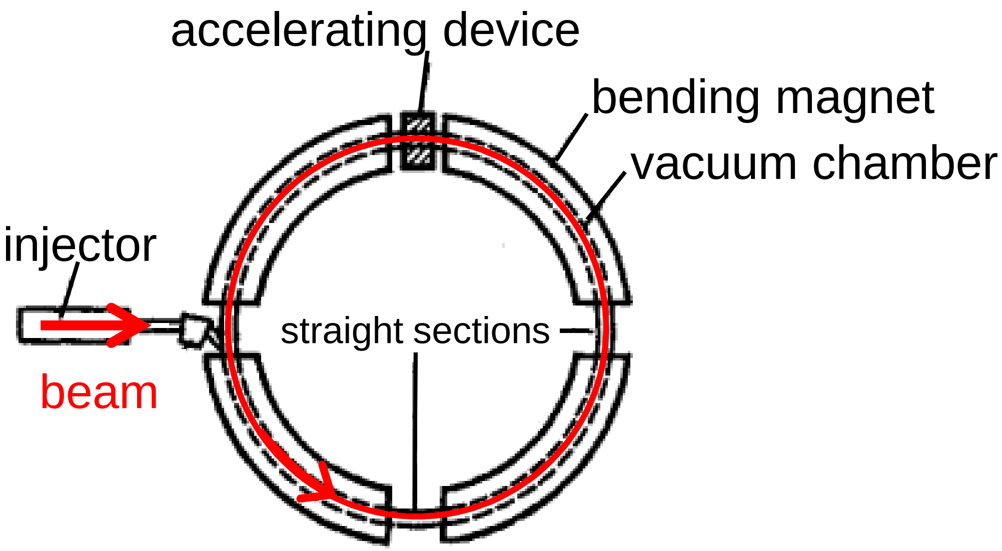
The case begins…



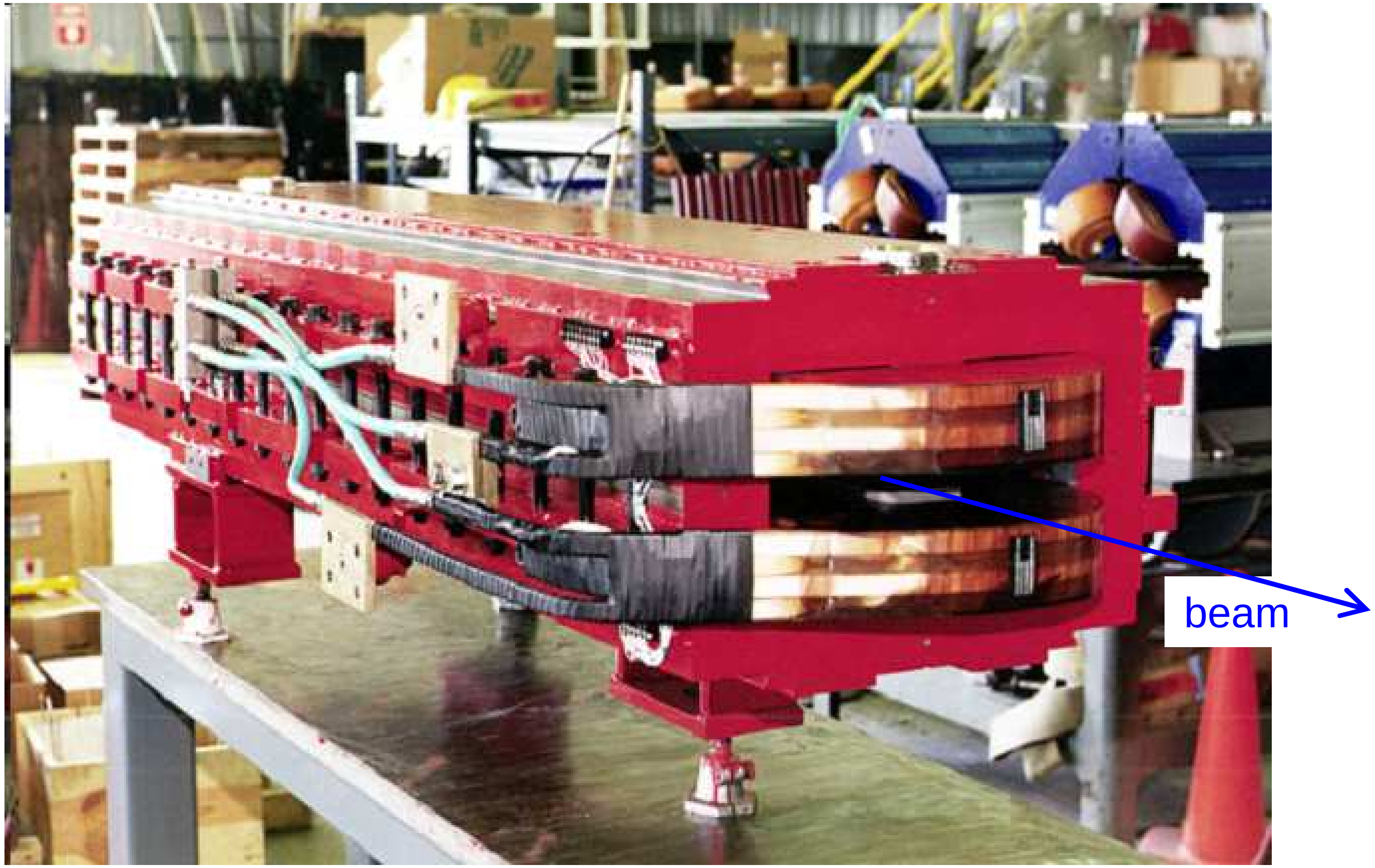
Accelerator Control Room
Hamburg, DESY
Sat. 12th June 2010
2 o'clock a.m.
PETRA runs with a beam current of 75 mA

02:24 a.m.: beam lost

Circular accelerators: the synchrotron



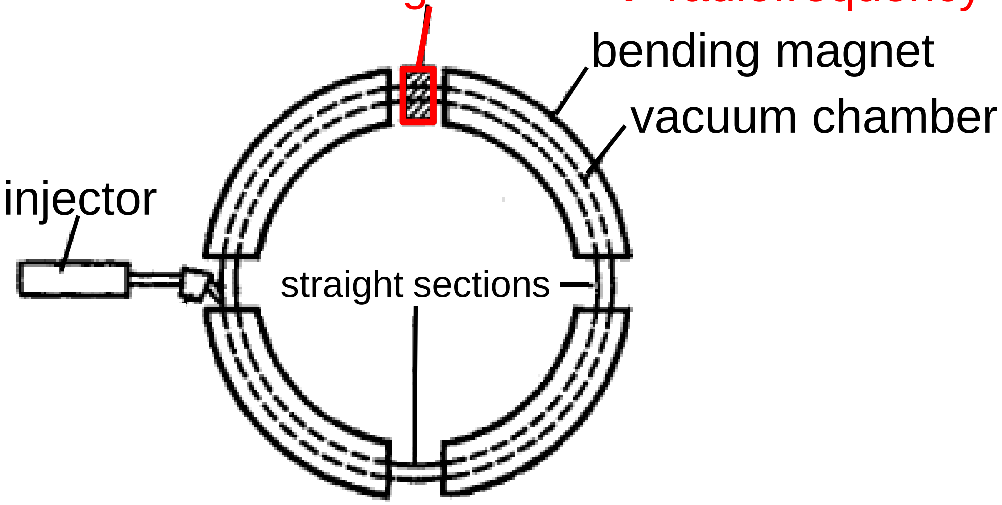
Dipole magnet



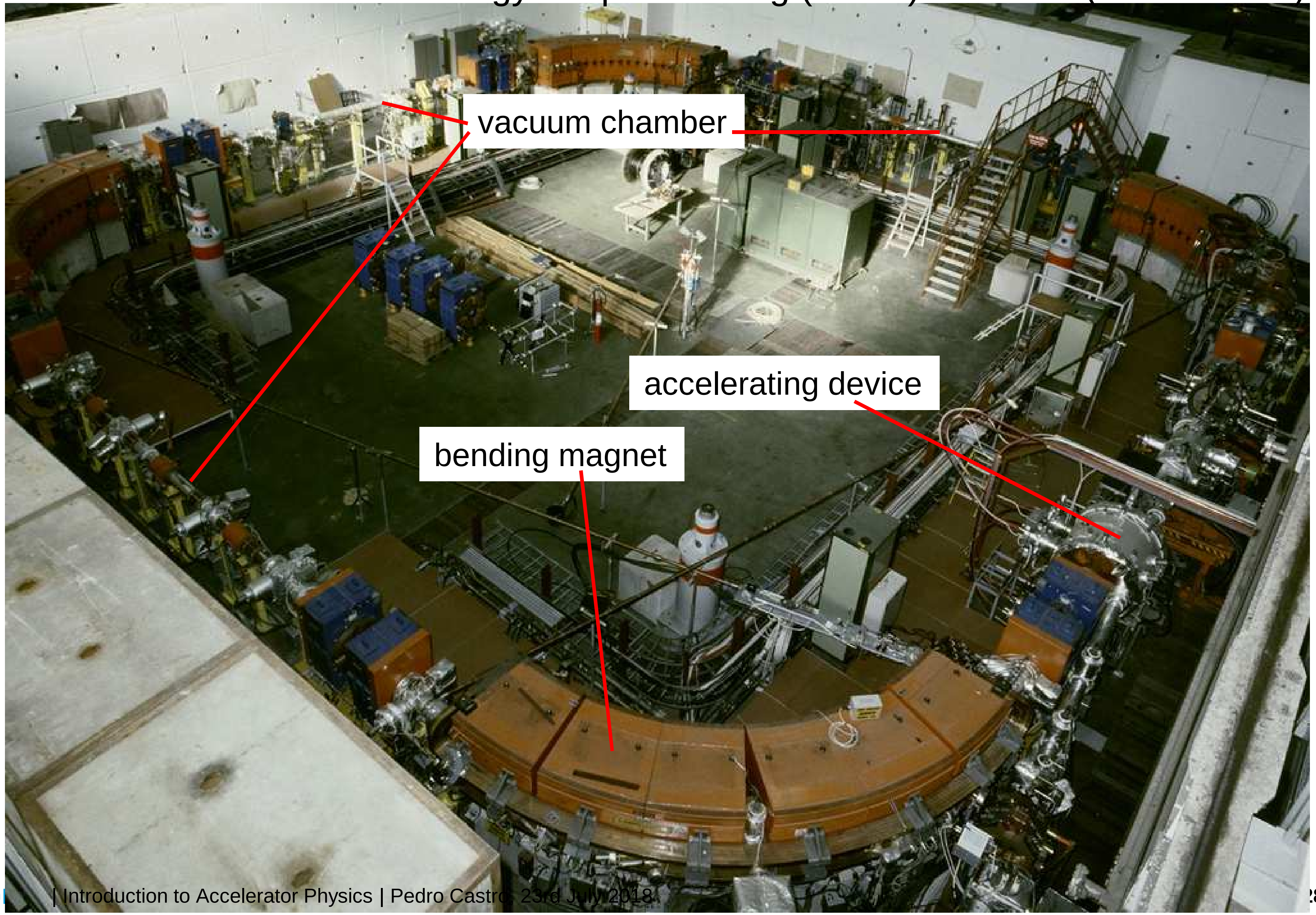
→ dipole magnets: tomorrow

Circular accelerators: the synchrotron

accelerating device → radiofrequency acceleration: tomorrow

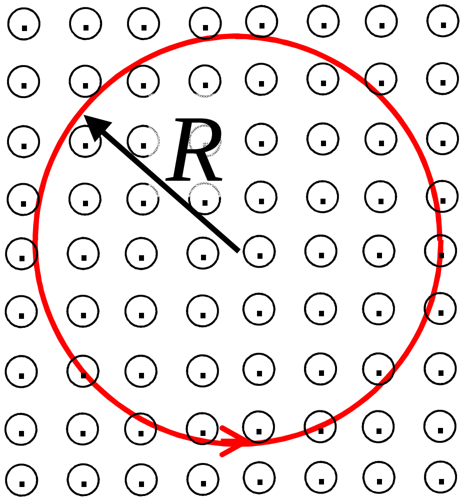


Low Energy Antiproton Ring (LEAR) at CERN (built in 1982)



Circular accelerators: the synchrotron

B (perpendicular)



$$\vec{F} = \frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B}$$

magnetic field

momentum charge velocity

of the particle

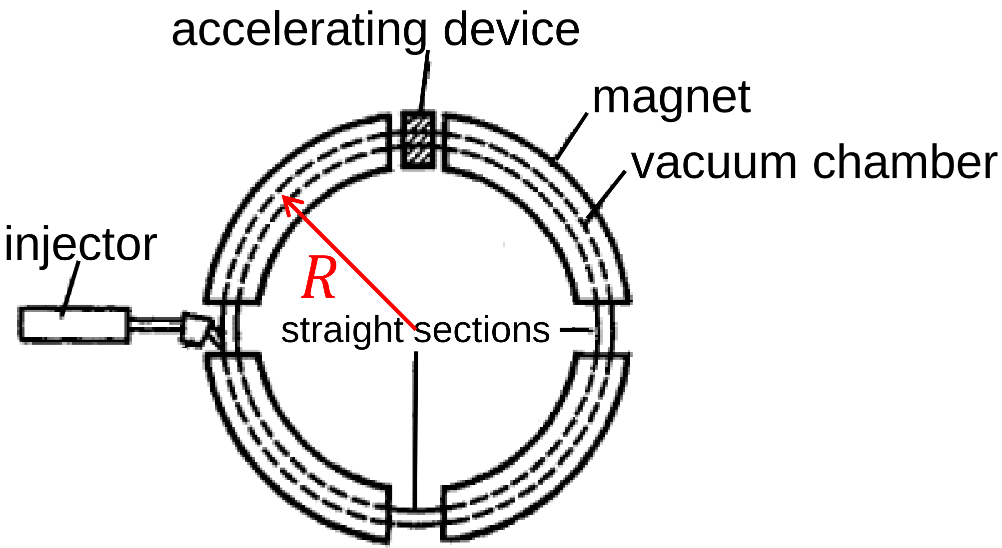
$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = qvB$$

$$\vec{F} \perp \vec{v} \quad \rightarrow \quad F = m\frac{v^2}{R}$$

(circular motion)

$$qB = \frac{mv}{R} \quad \rightarrow \quad R = \frac{mv}{qB}$$

Circular accelerators: the synchrotron



$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = qvB$$

$$\vec{F} \perp \vec{v} \quad \rightarrow \quad F = m\frac{v^2}{R}$$

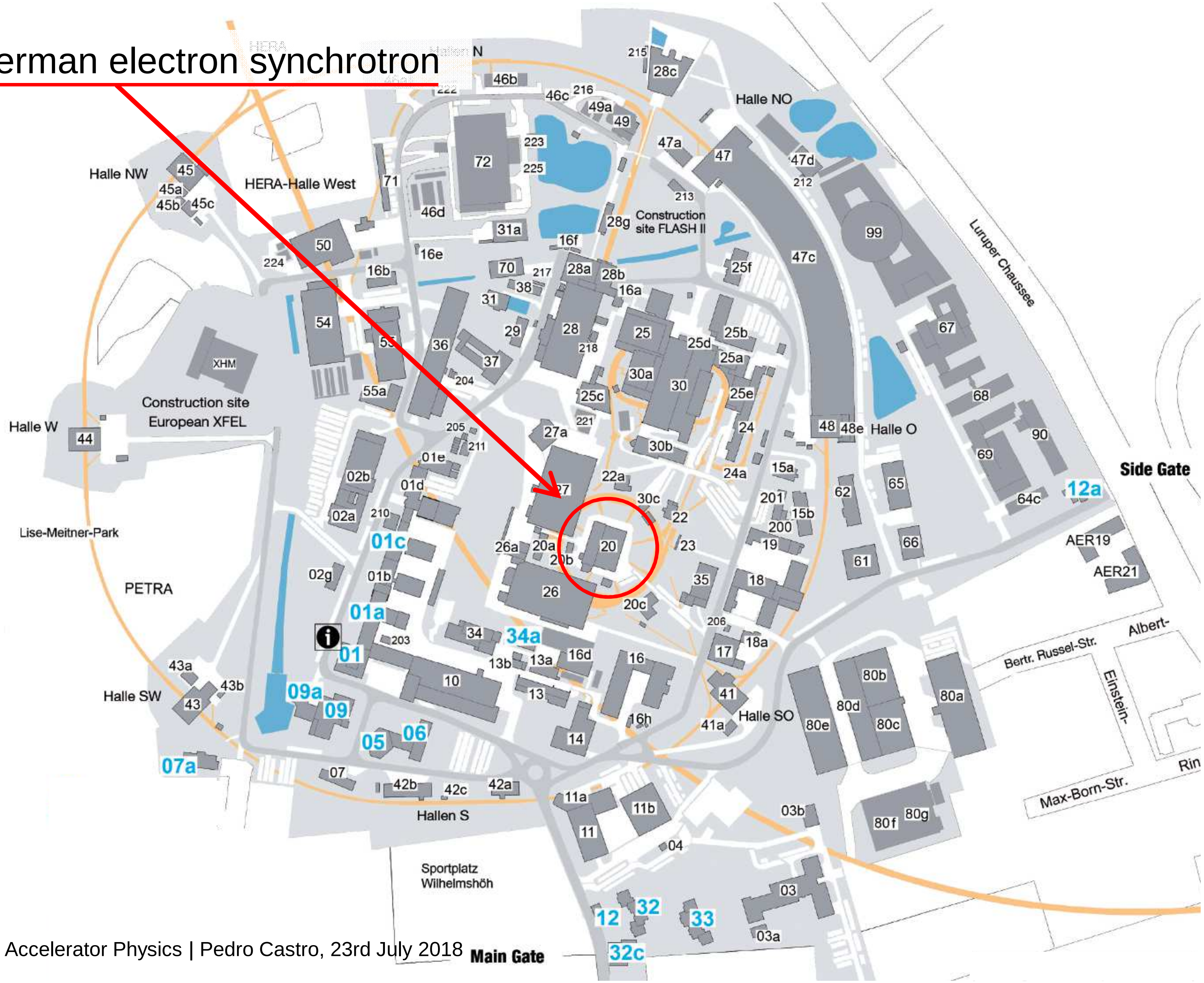
(circular motion)

$$qB = \frac{mv}{R} \quad \rightarrow \quad R = \frac{mv}{qB} = constant$$

→ increase B synchronously with $p = mv$ of particle

DESY (Deutsches Elektronen Synchrotron)

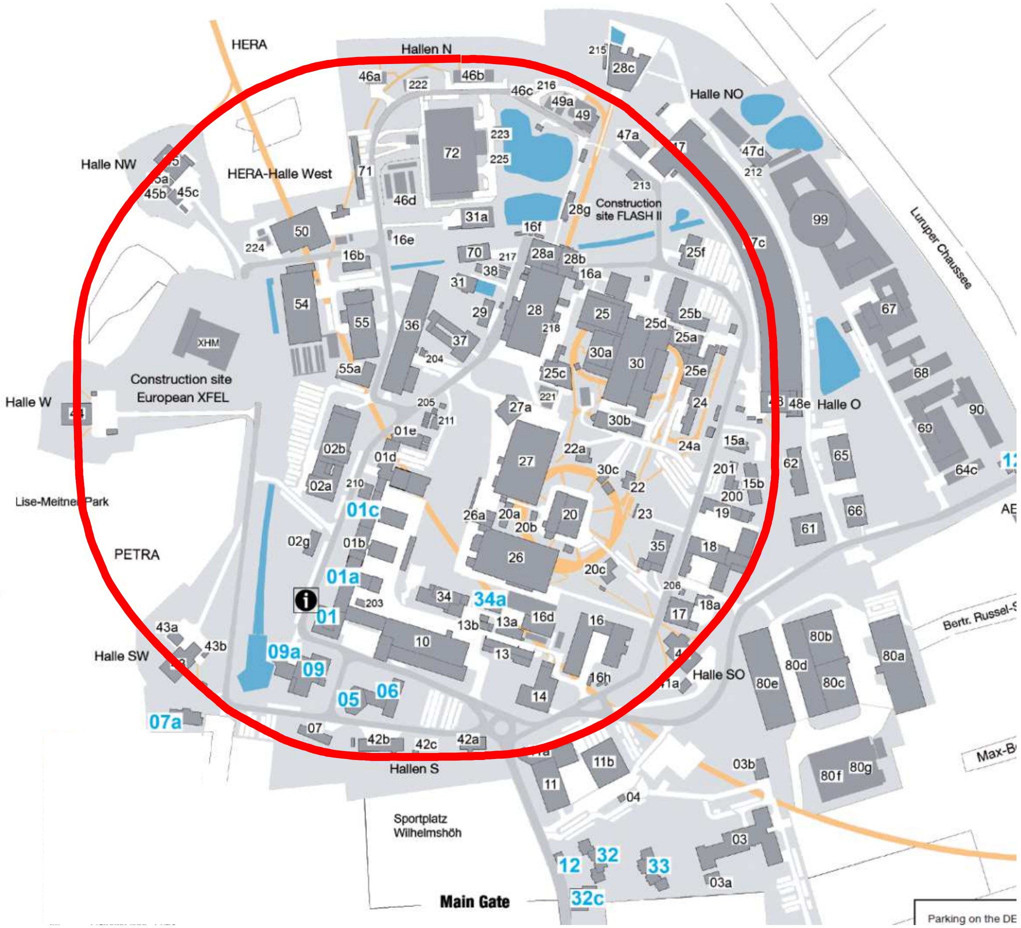
DESY: German electron synchrotron



DESY (Deutsches Elektronen Synchrotron)

DESY: German electron synchrotron, 1964, 7.4 GeV

back to the case...



Hamburg, DESY
Sat. 12th June 2010
2 o'clock a.m.
PETRA runs with 75 mA

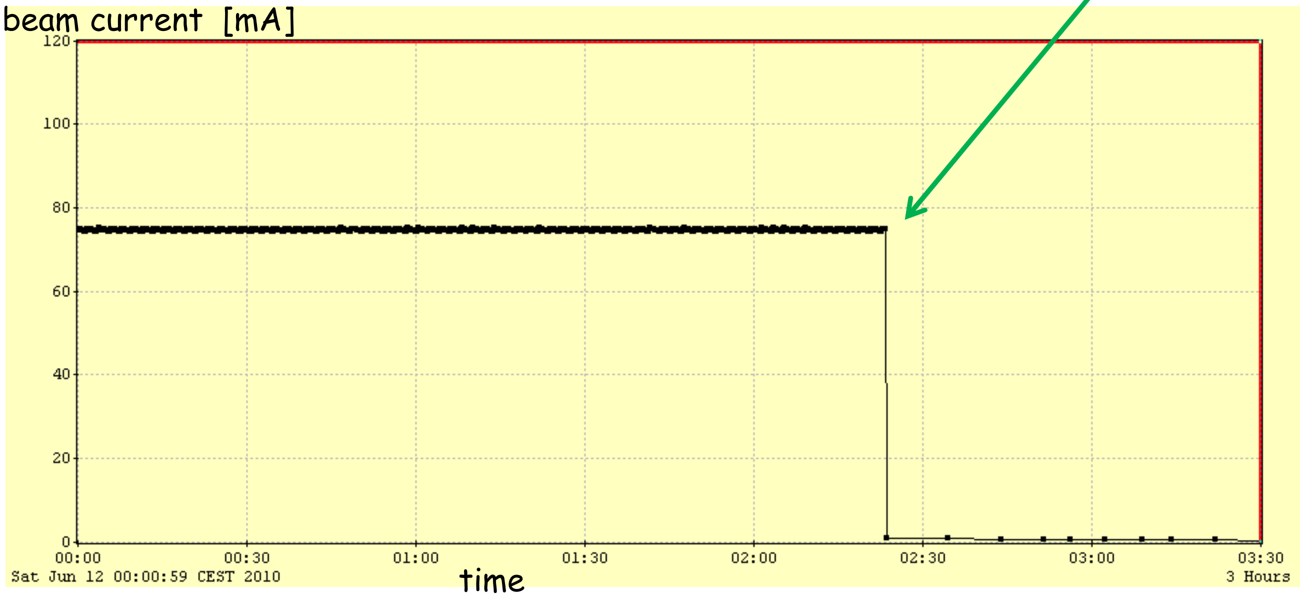
02:24 a.m.: beam lost

02:24 a.m.: beam lost

The Main Accelerator Control Room

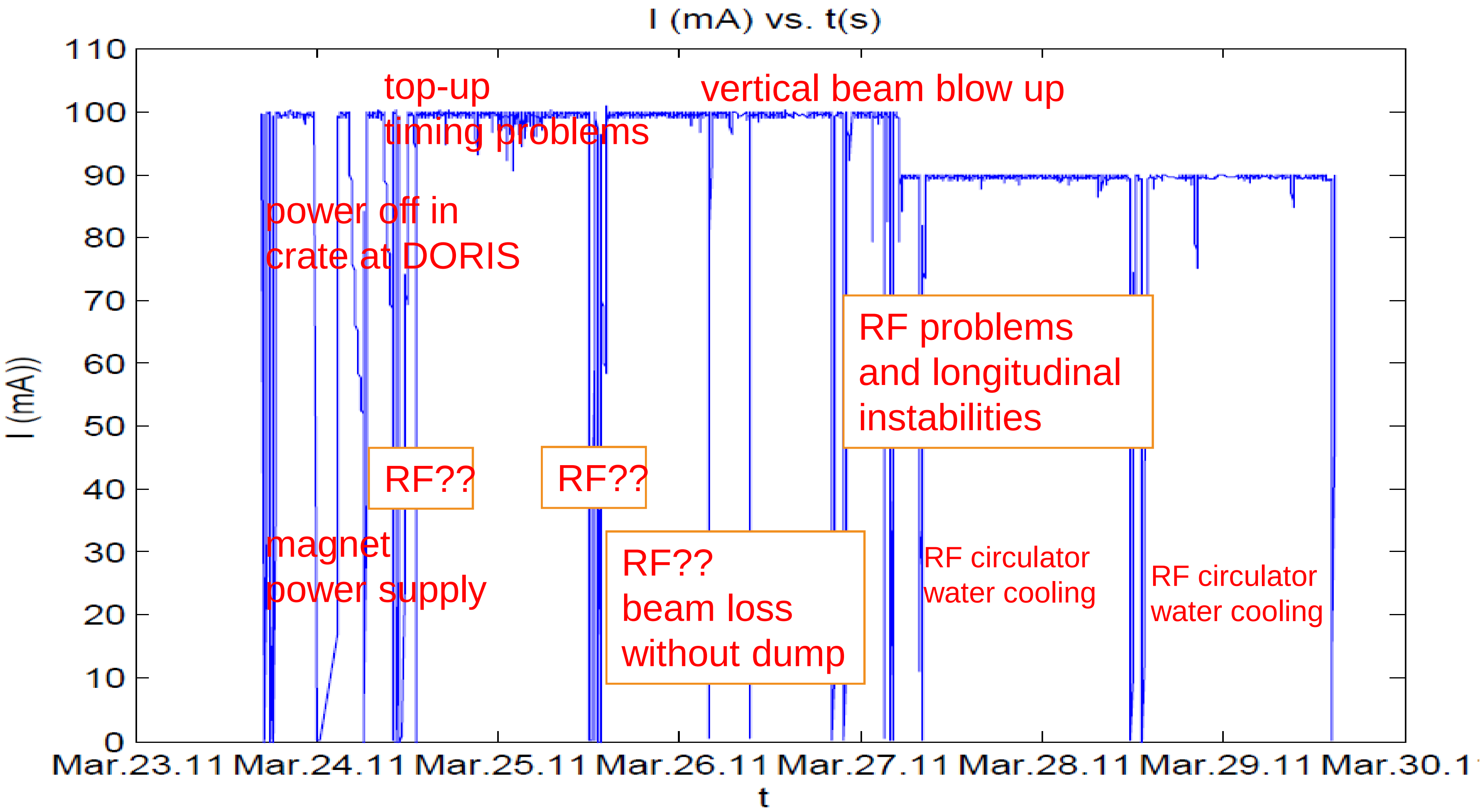
Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost



One example of PETRA run over 7 days

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



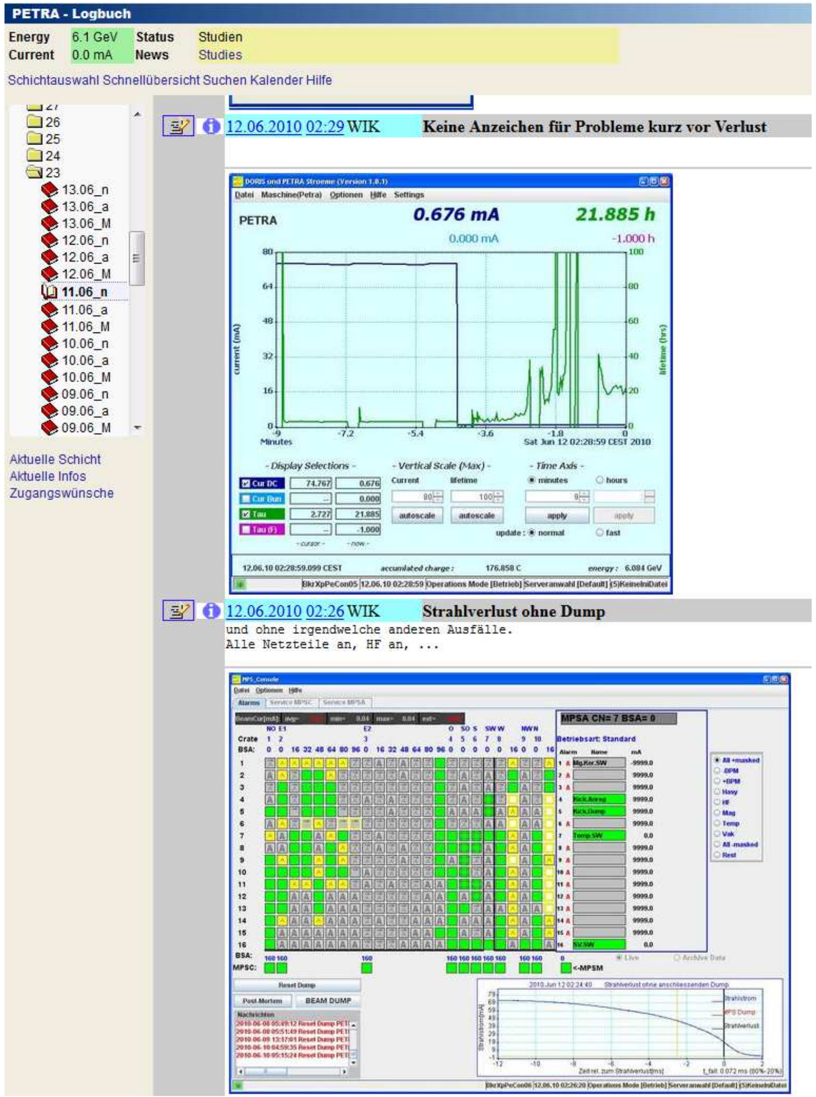
Source: K. Balewski (MAC report 2011)

Beam lost at 02:24 a.m.

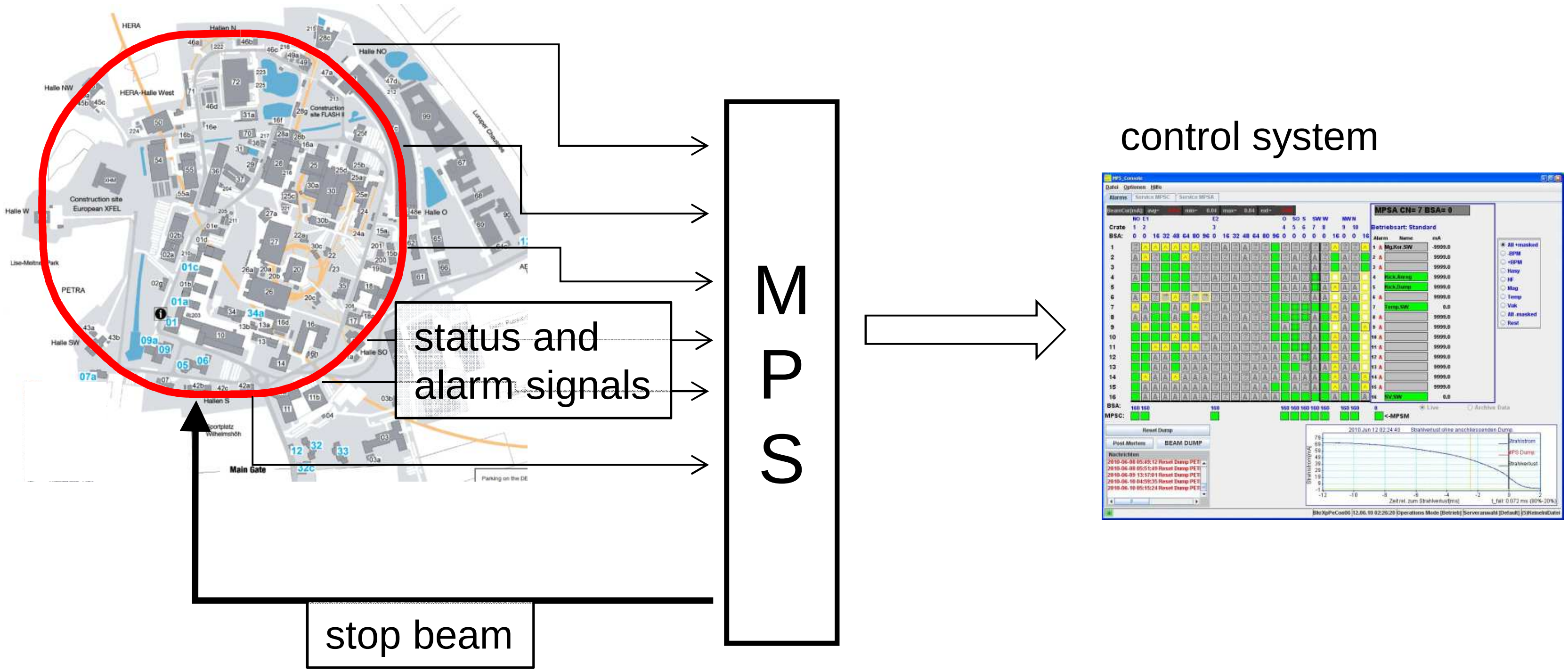
The link to the electronic logbook:

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

What to do?

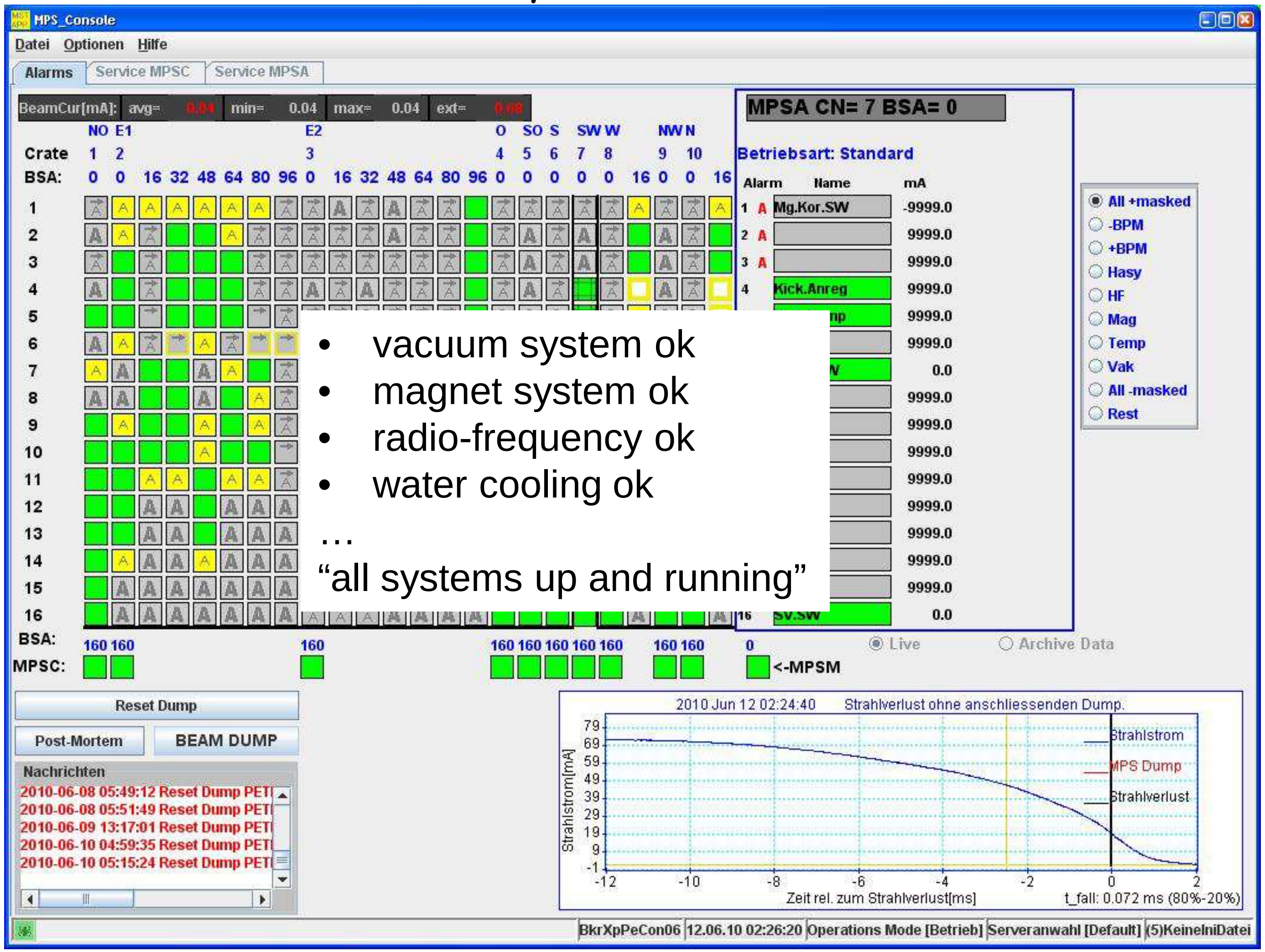


Alarm overview: the Machine Protection System



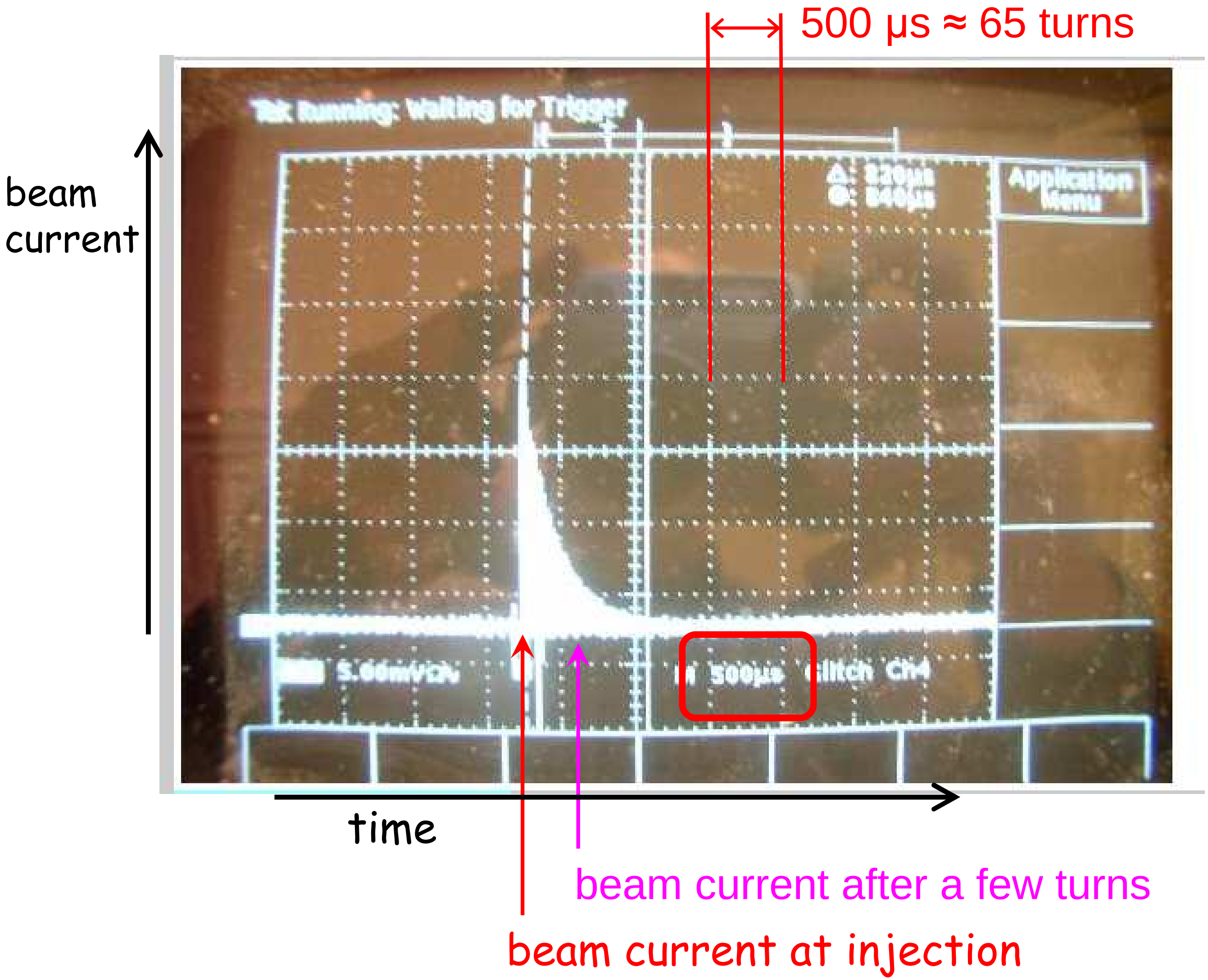
Alarm overview: the Machine Protection System

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



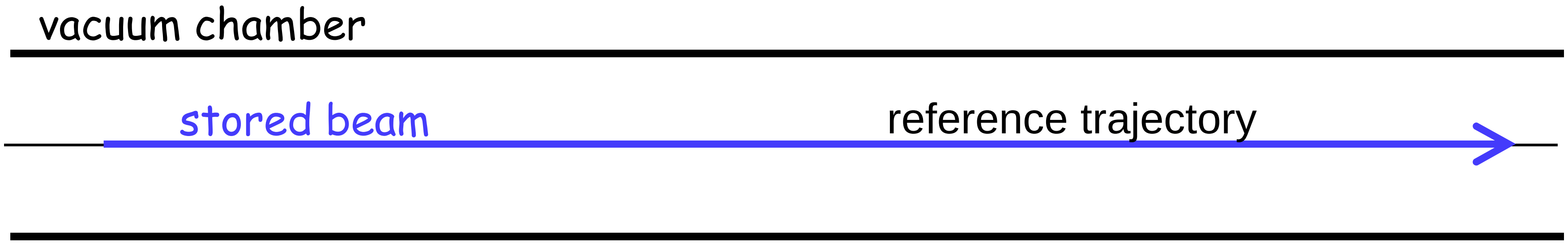
12th June 2010 02:26

Electrons can be injected but cannot be stored !



injection problem?

Next suspect: injection



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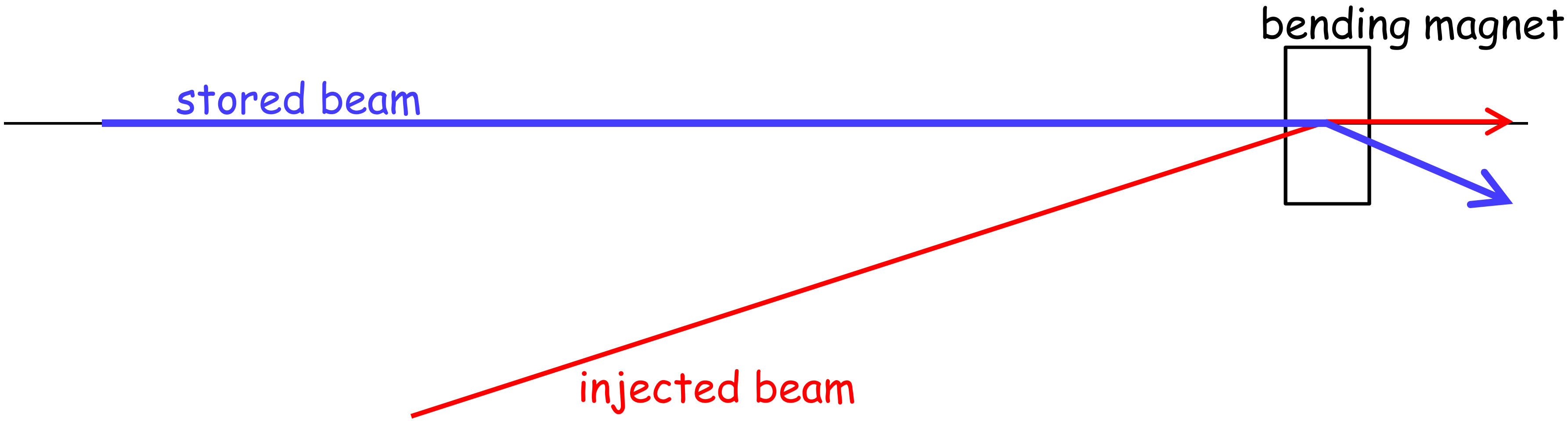

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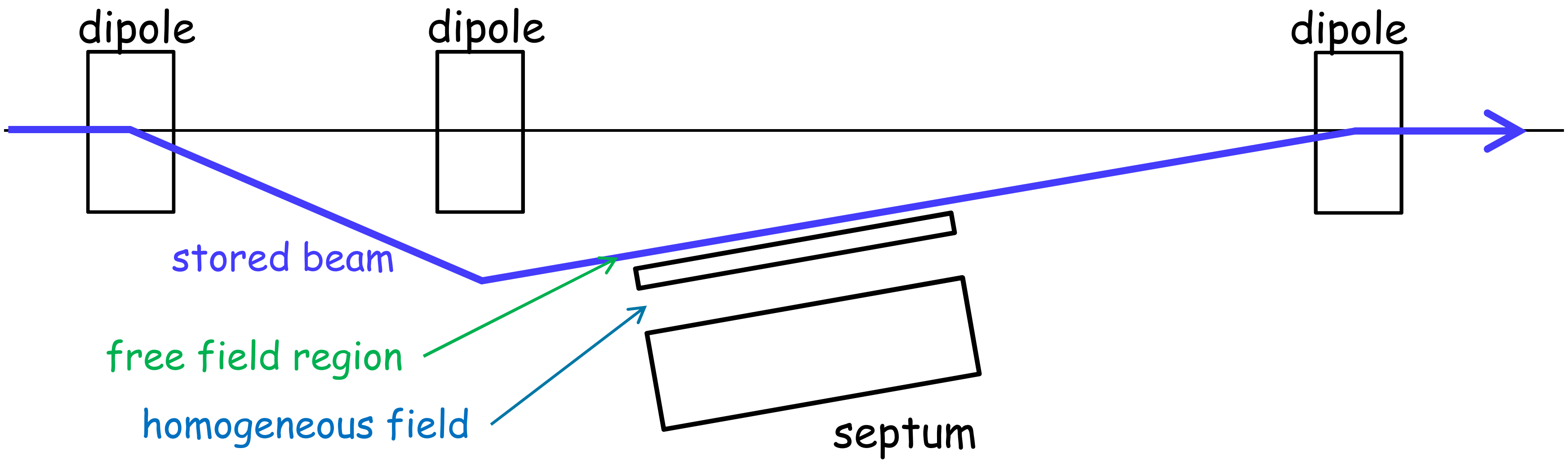

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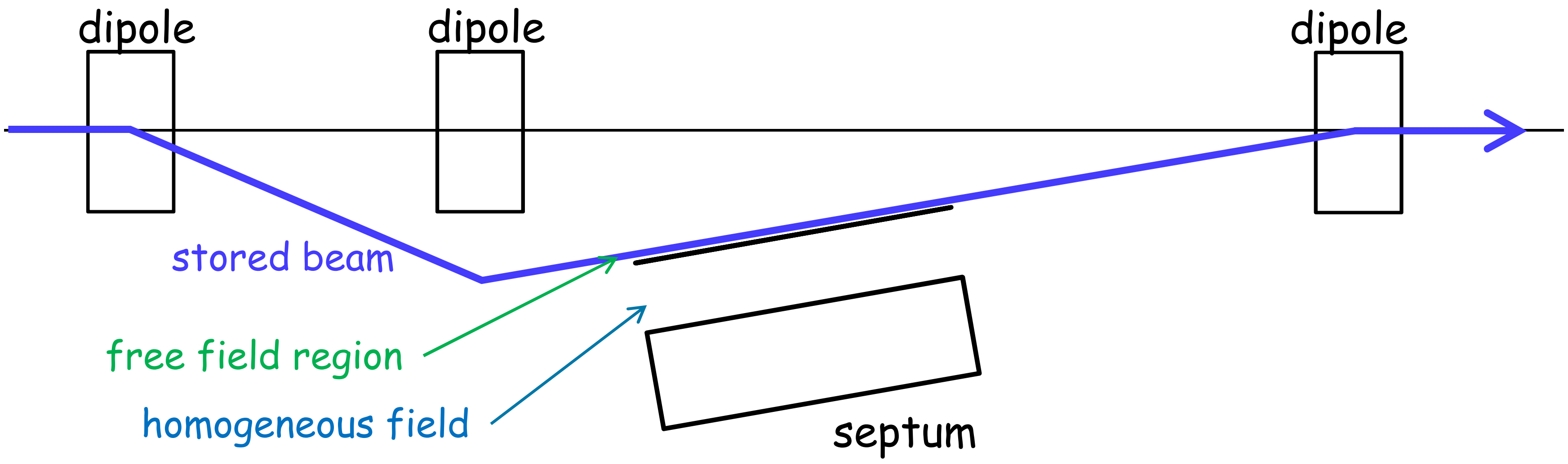
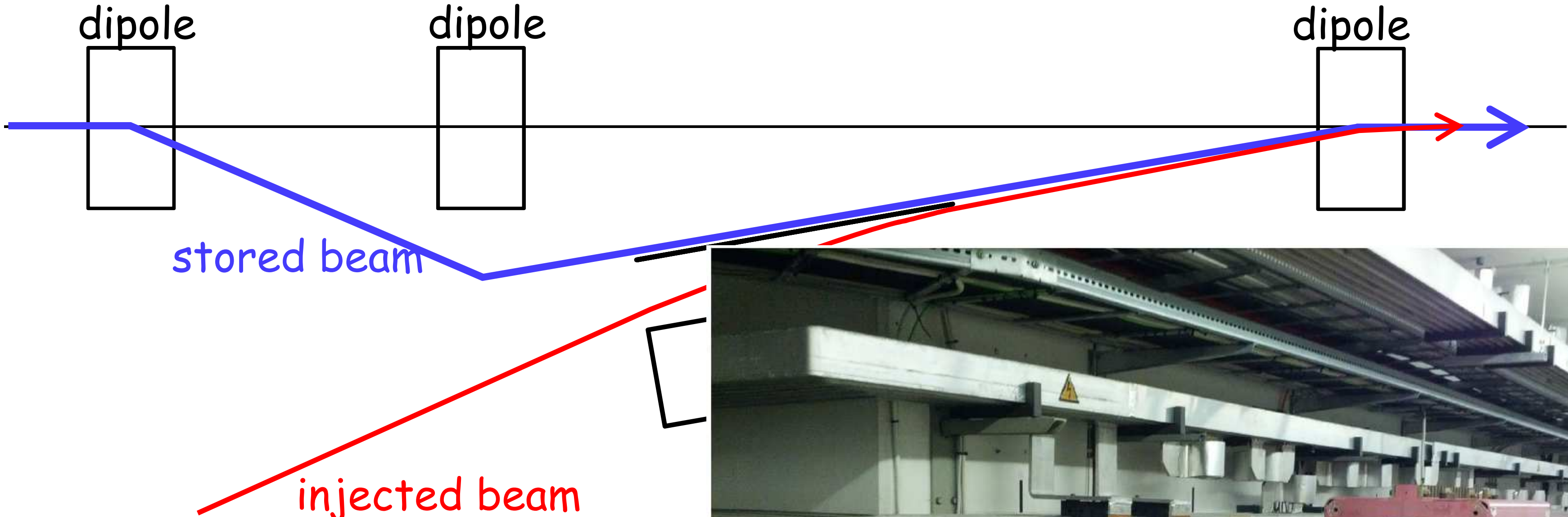
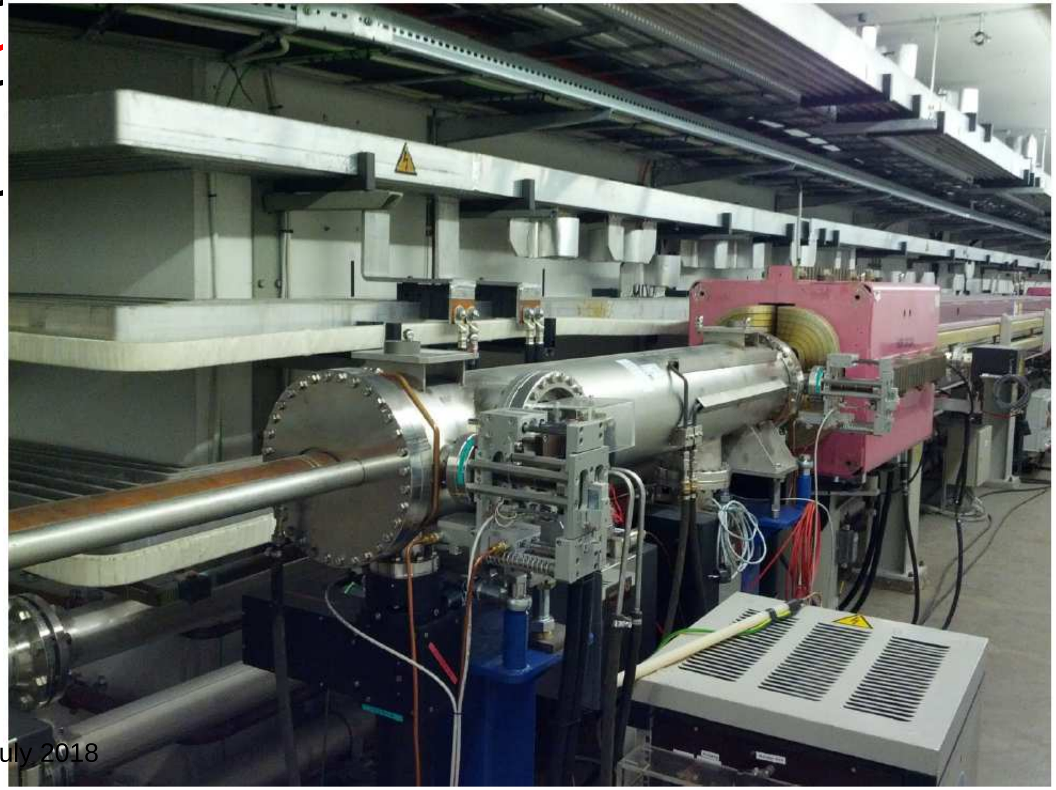


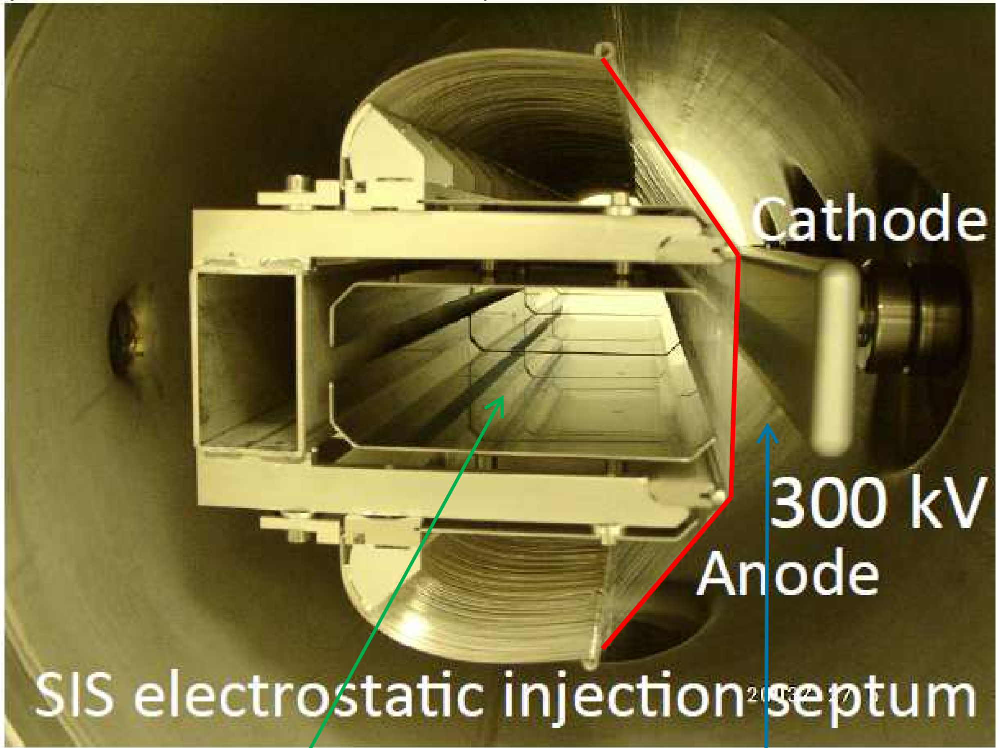
Next suspect: injection + accumulation





Next suspect: injection + accumulation

septum at the Proton Synchrotron Booster (PSB) at CERN



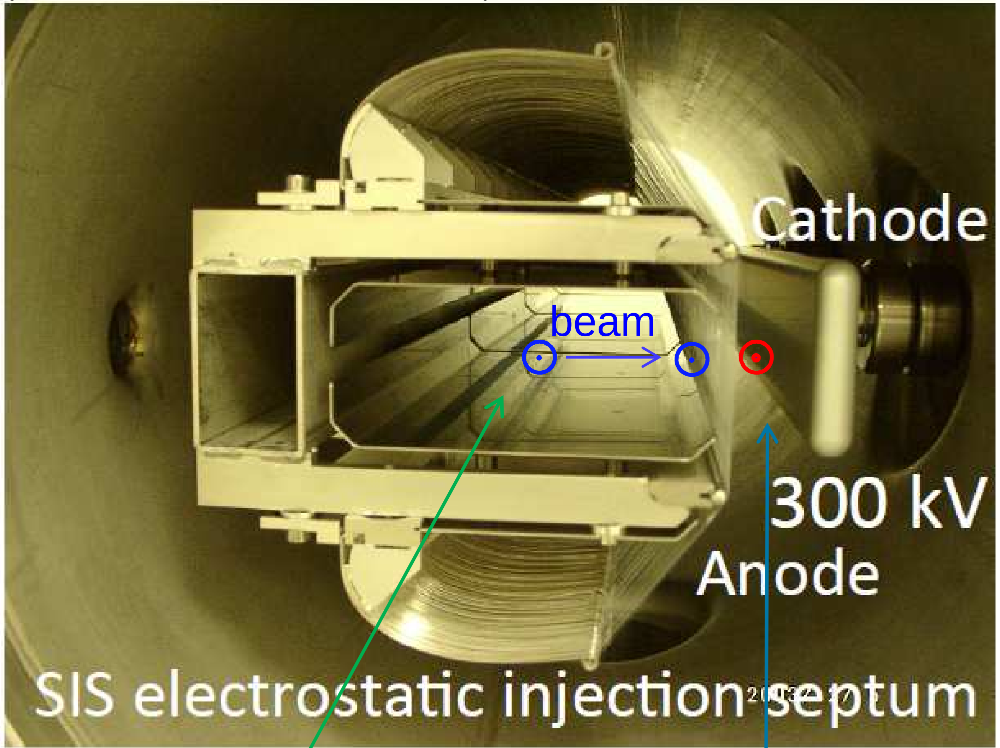
free field region

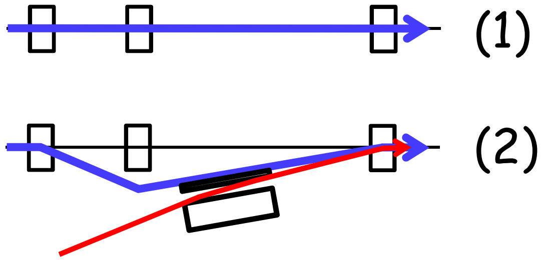
homogeneous field

Next suspect: injection + accumulation

septum at the Proton Synchrotron Booster (PSB) at CERN

stored beam





injected beam

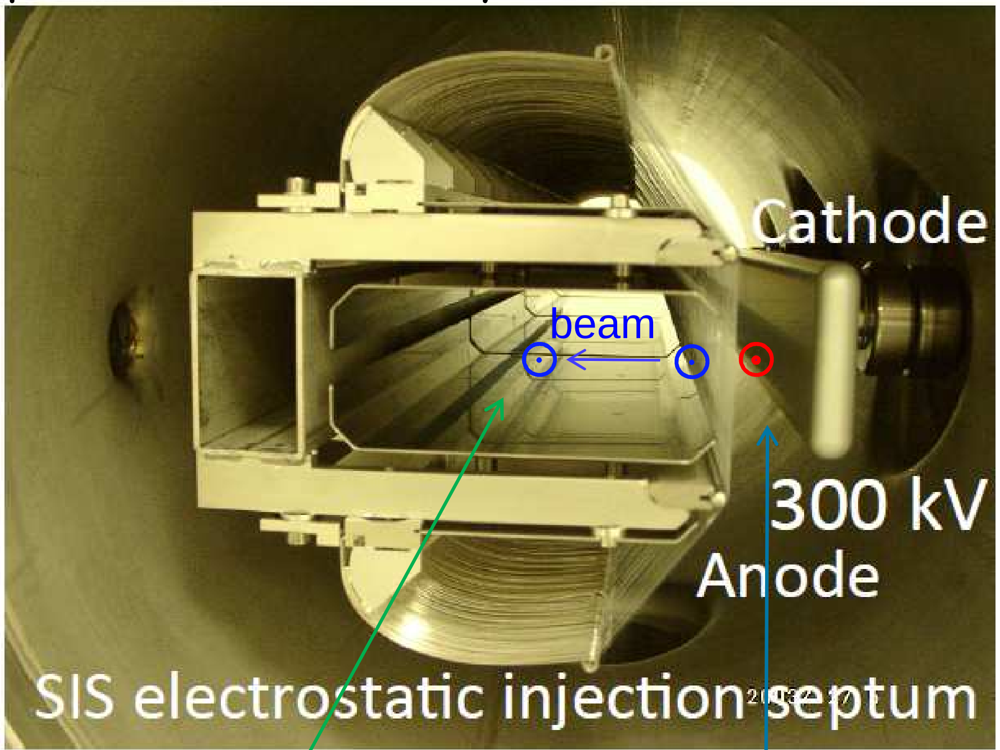
free field region

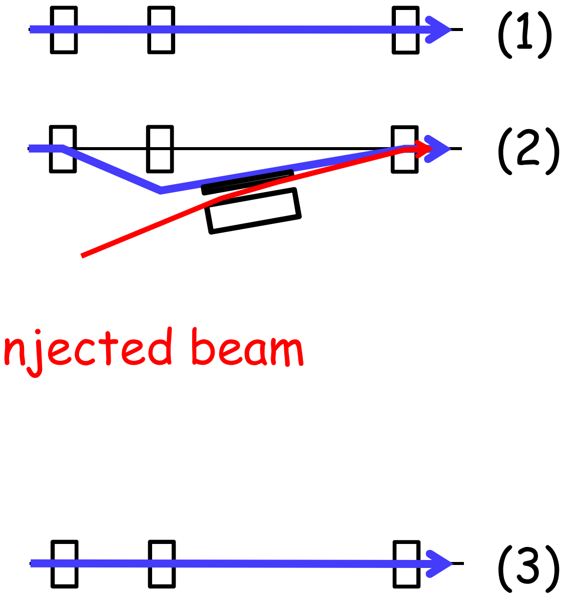
homogeneous field

Next suspect: injection + accumulation

septum at the Proton Synchrotron Booster (PSB) at CERN

stored beam





injected beam

free field region

homogeneous field

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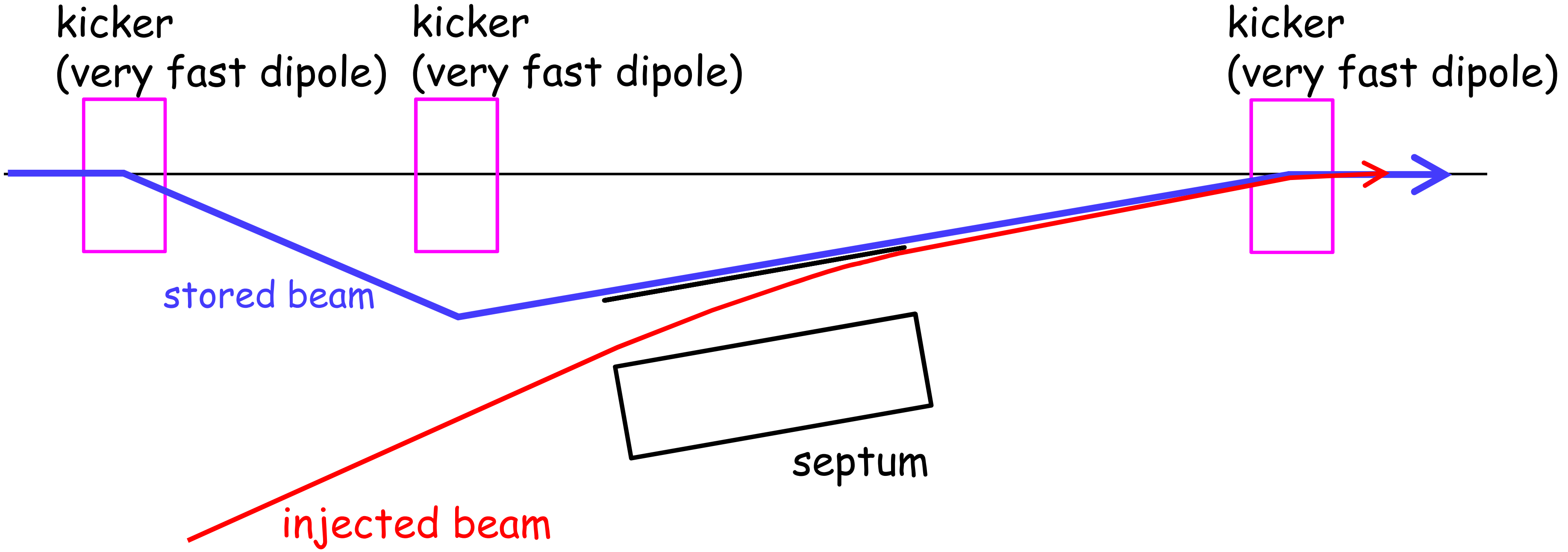

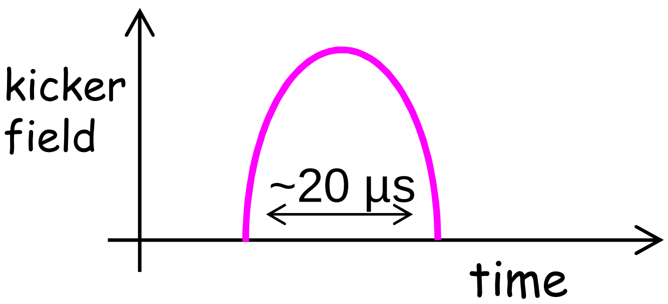

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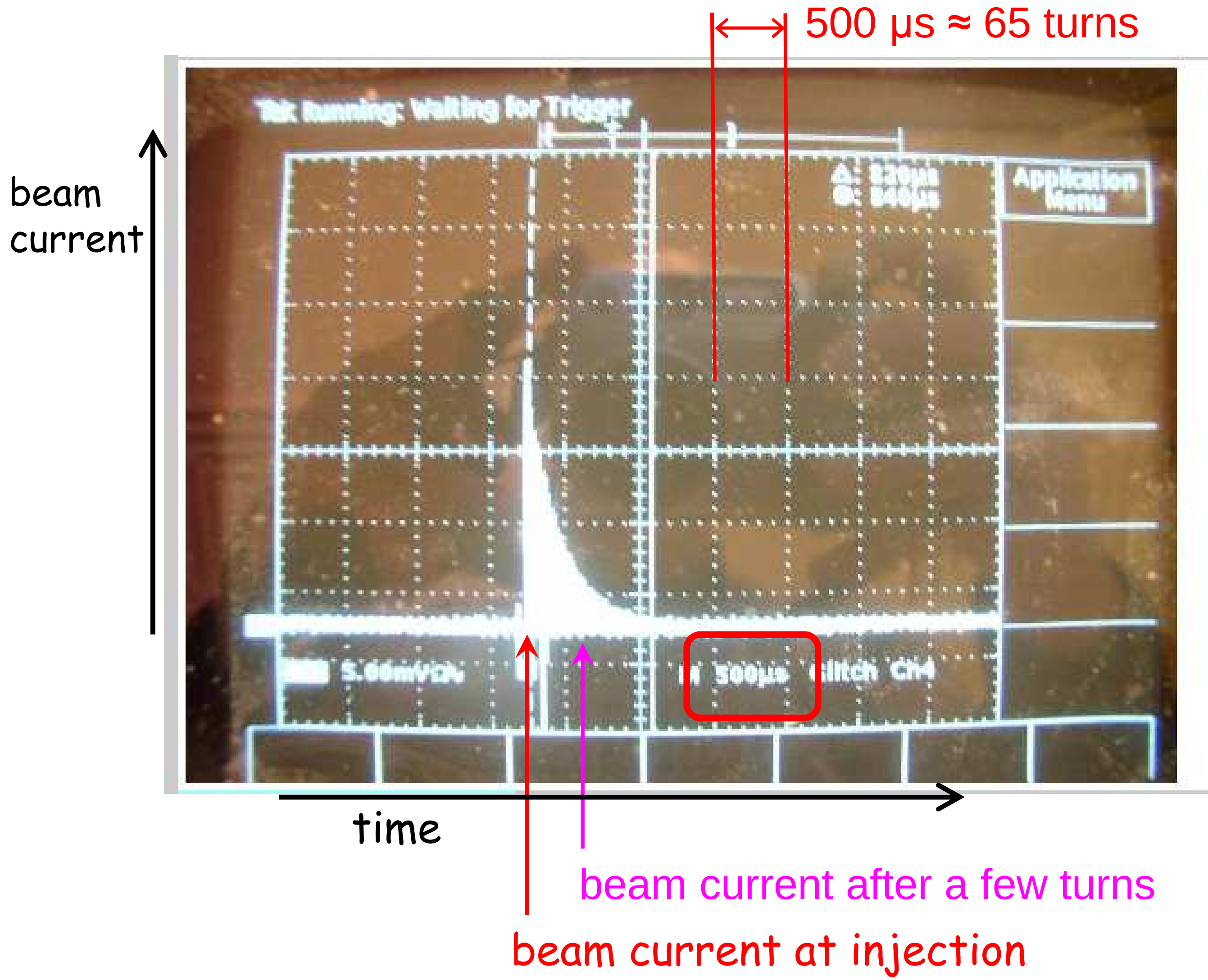


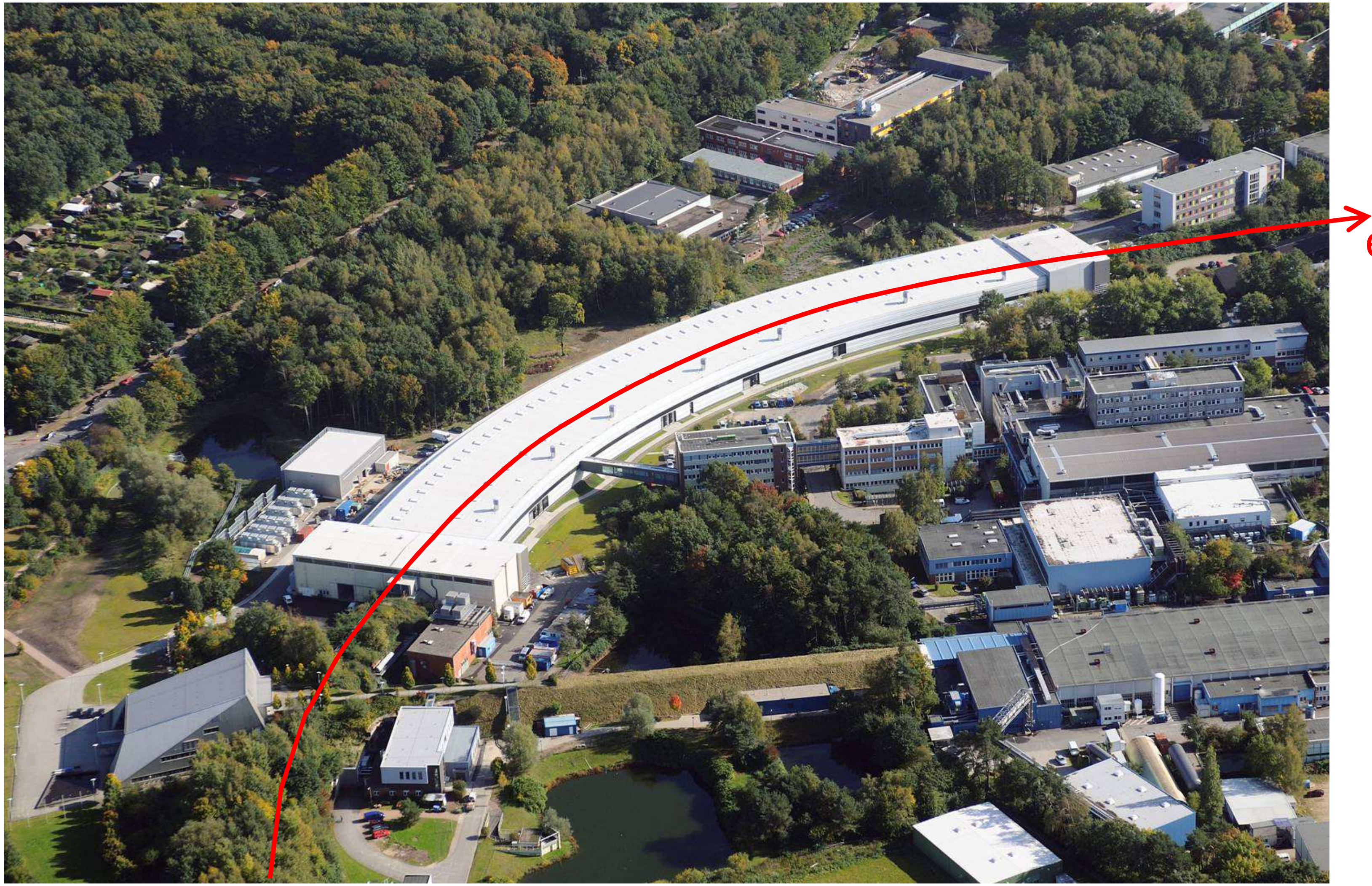
~~injection problem?~~

Next suspect: a problem with vacuum chamber

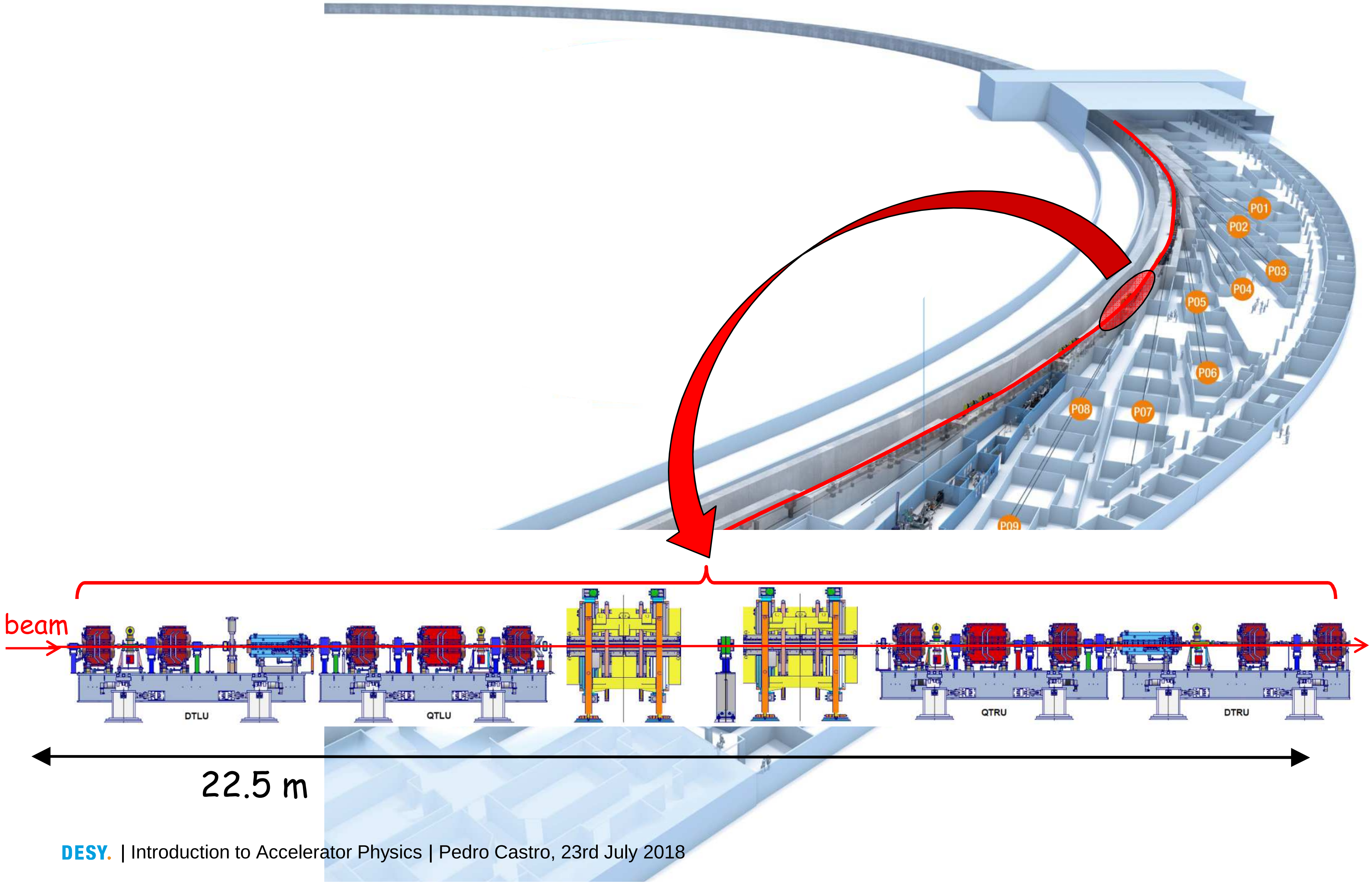
Hamburg, DESY
Sat. 12th June 2010

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

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



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



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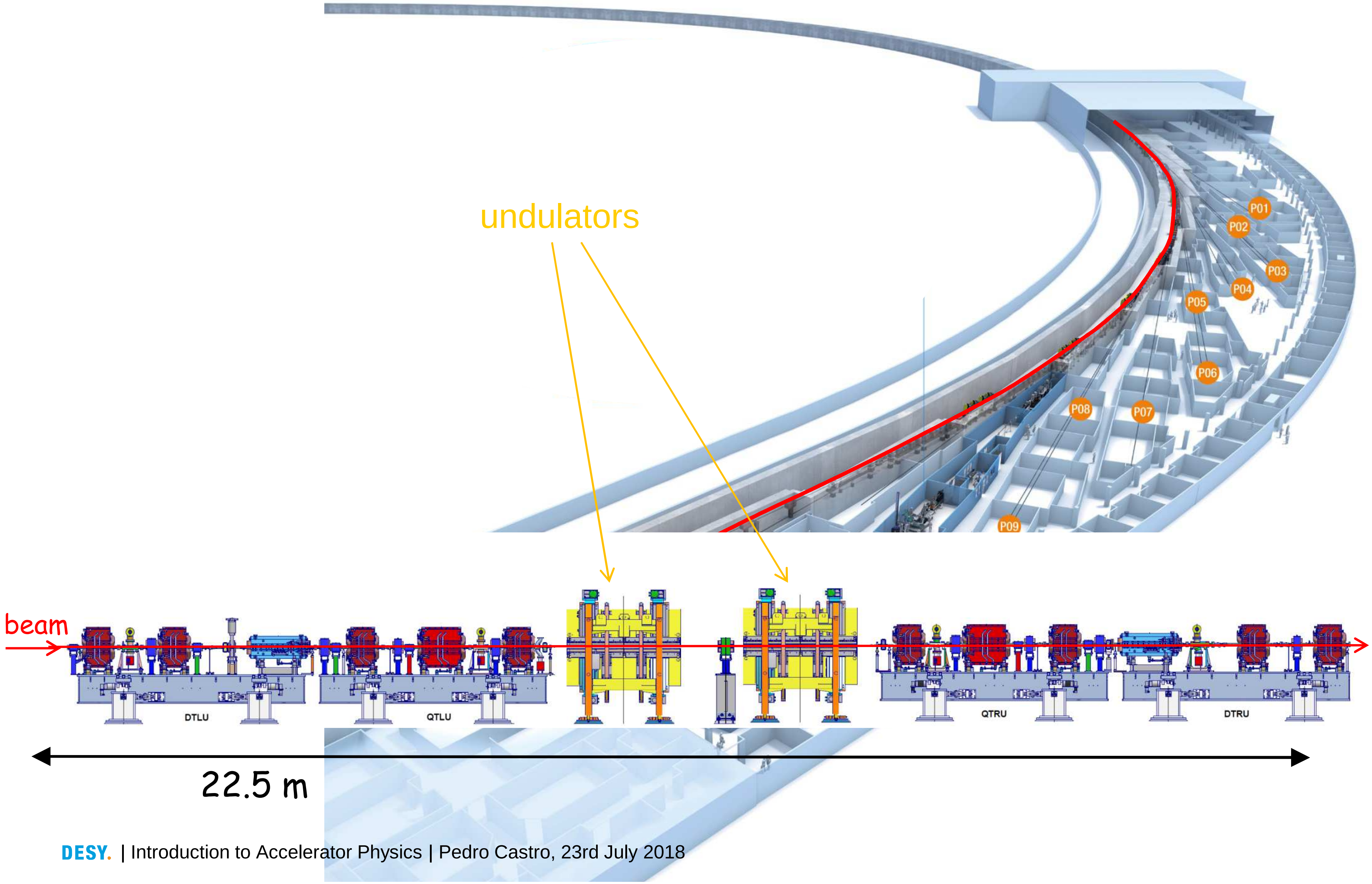
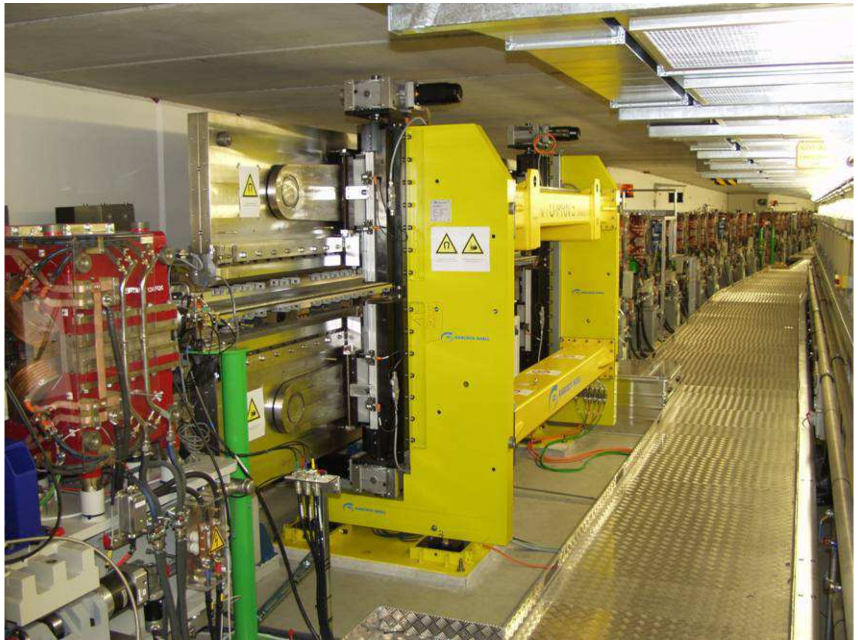


Next suspect: the new octant in 'Max von Laue hall'

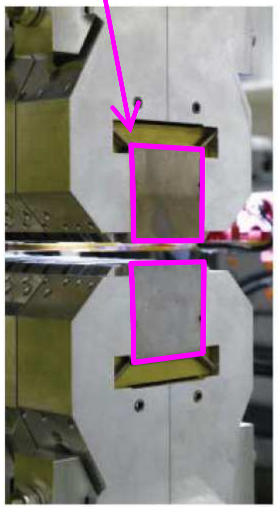
Undulator PU 10



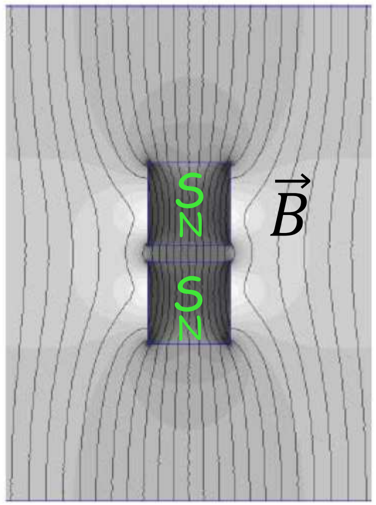
Hamburg, DESY
Sat. 12th June 2010

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

permanent magnets



undulator field lines



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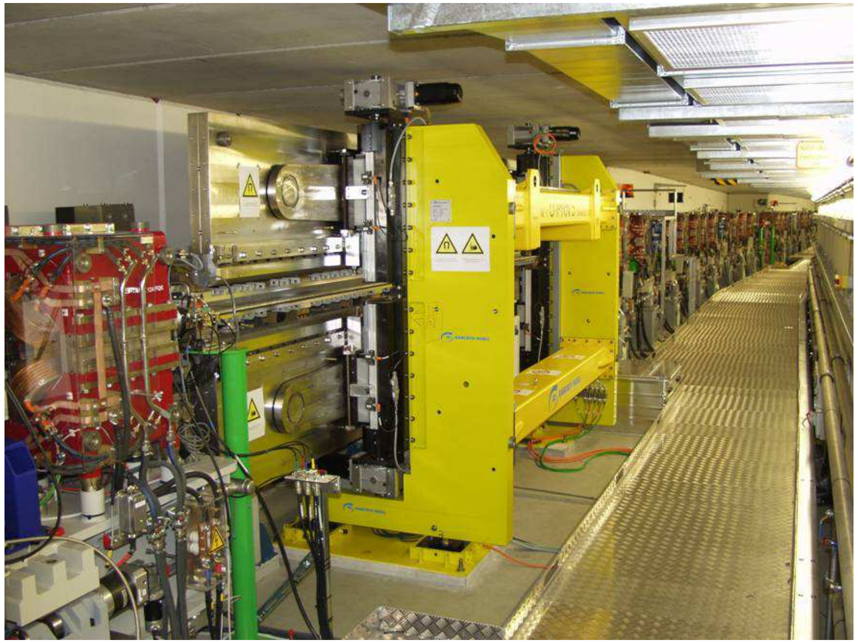
Undulator PU 10



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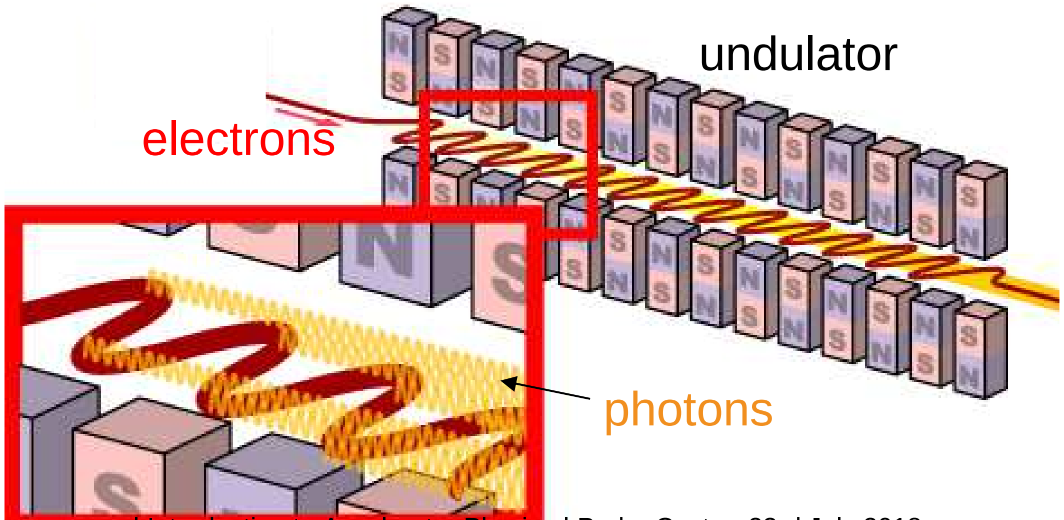
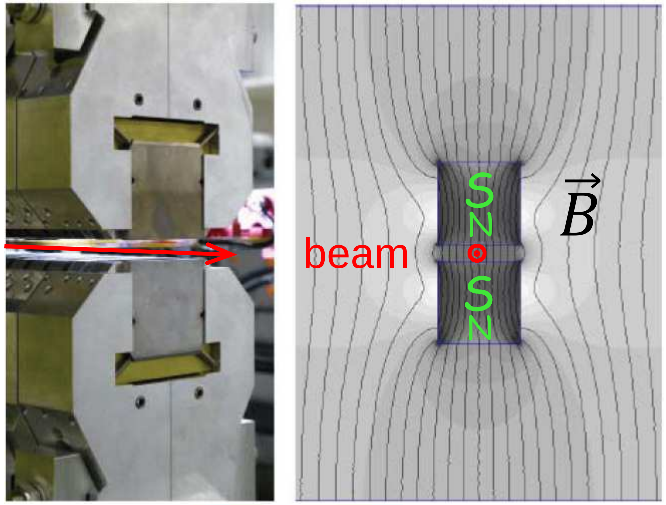


undulator field lines



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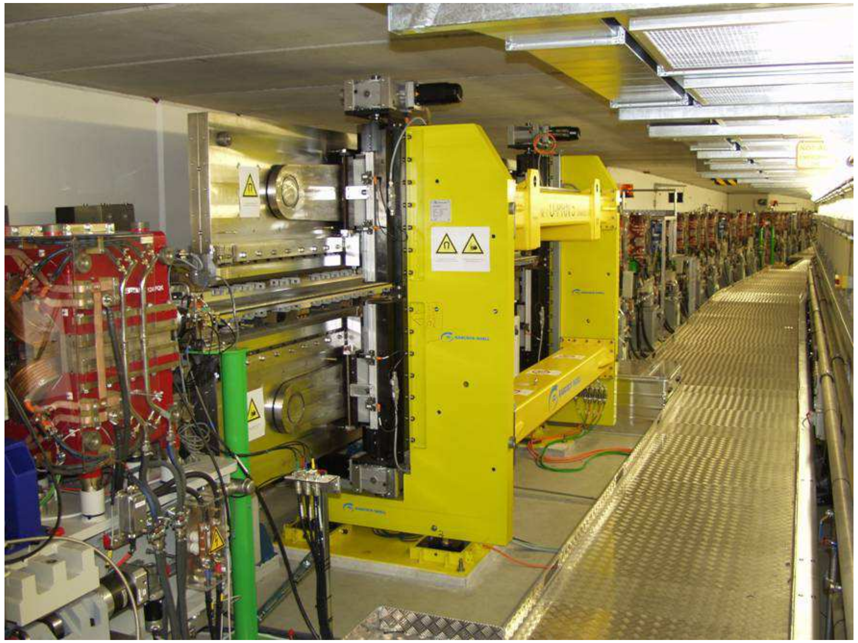
Undulator PU 10



Hamburg, DESY
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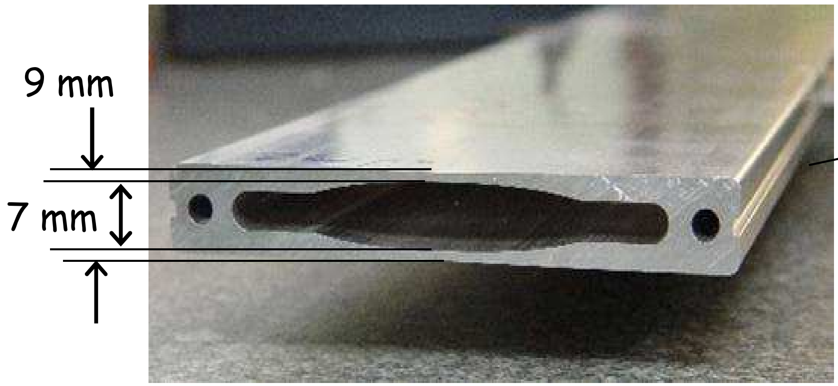
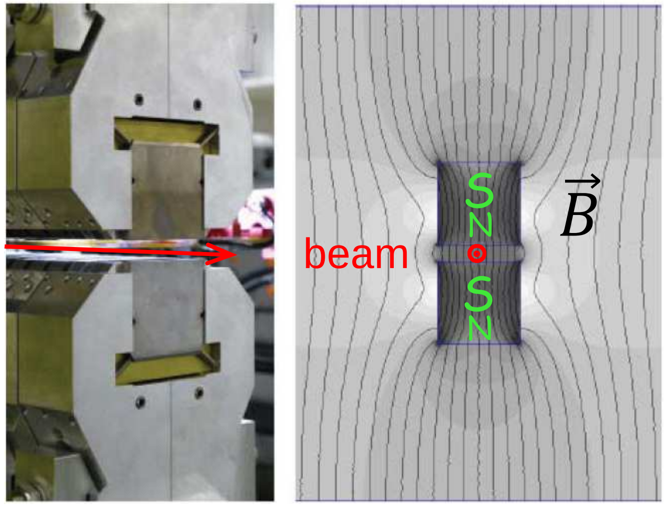
very flat undulator vacuum chambers

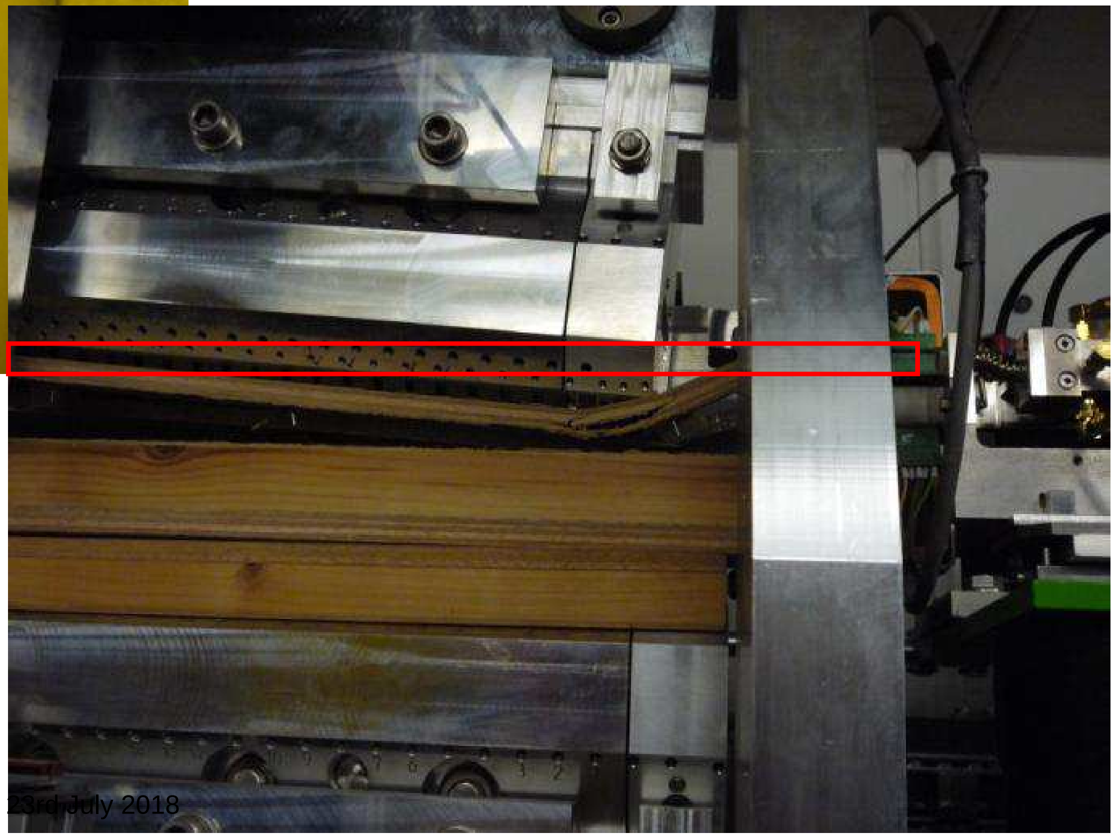


undulator field lines



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:

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" 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**

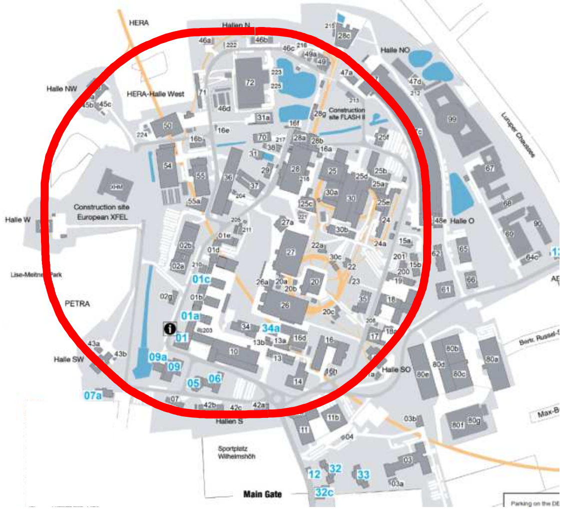
Schichtbeginn kein gespeicherter Strahl. Nur ca. 1000 Umläufe, keine Ausfälle

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

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in new octant
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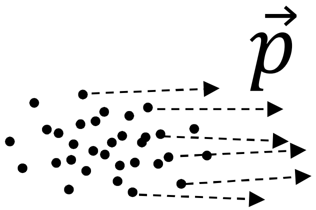
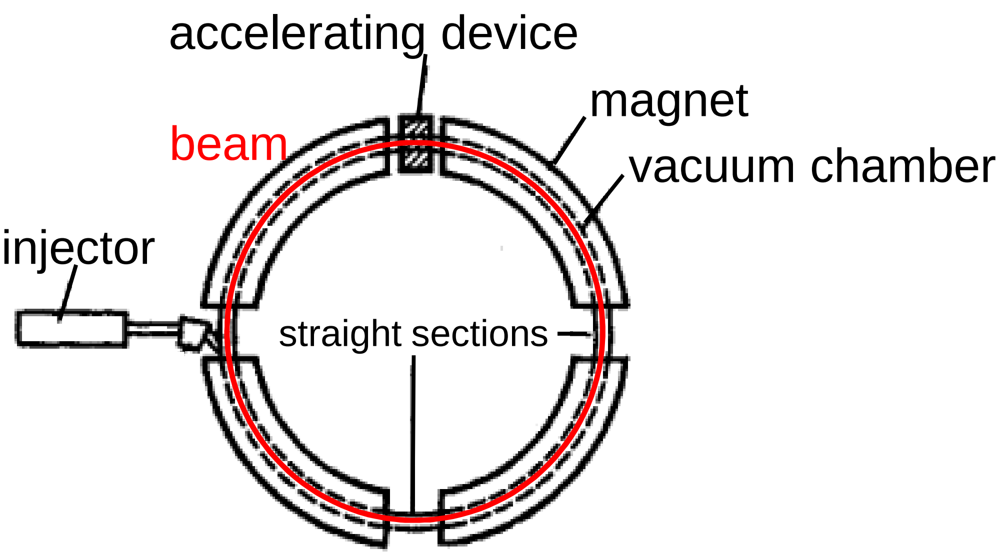
Need of focusing

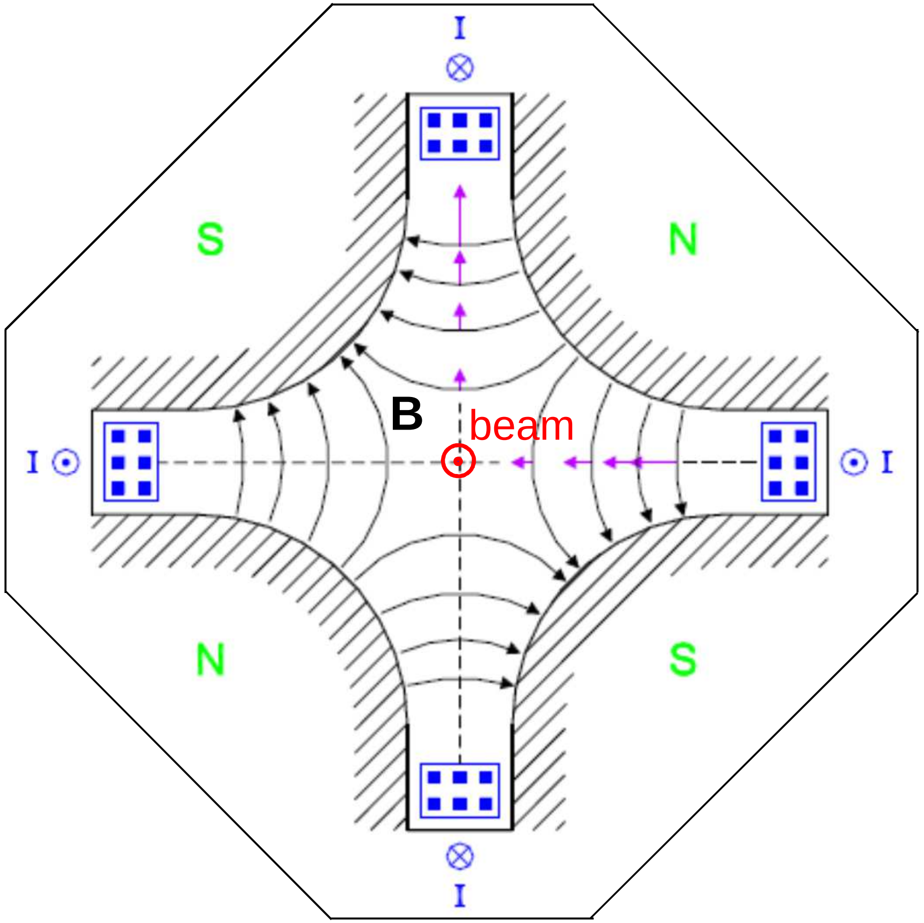


beam / bunch

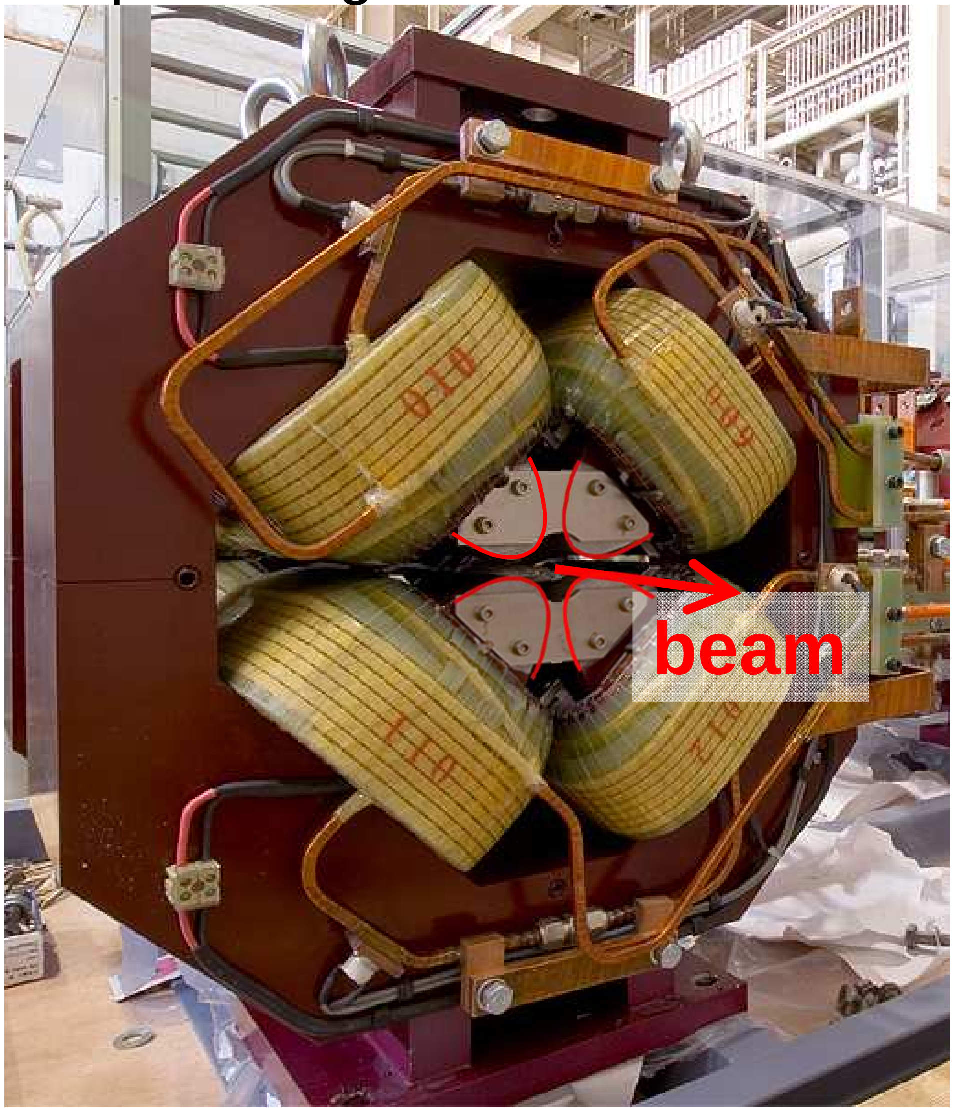
we need to focus the beam !



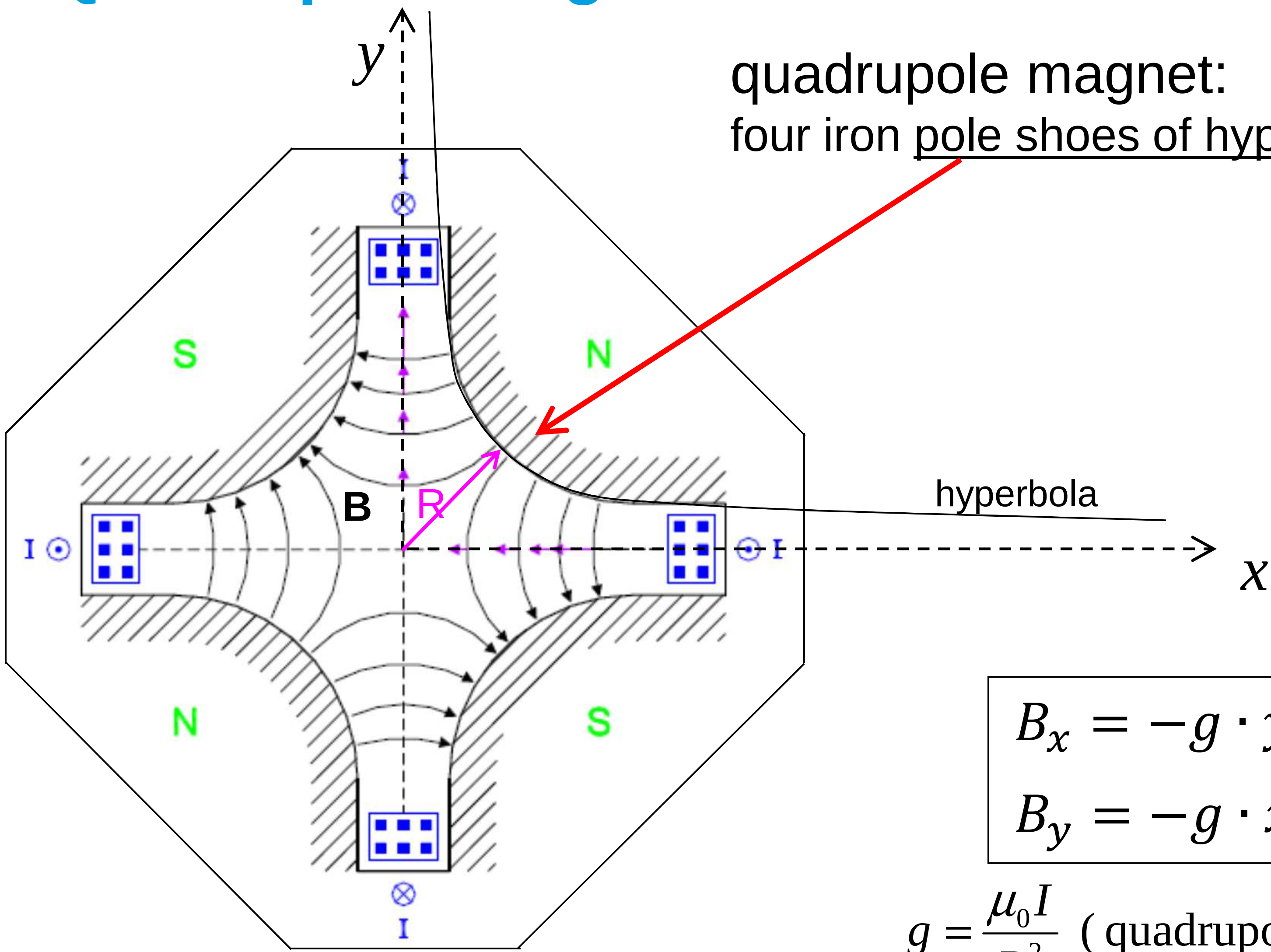
Quadrupole magnets



quadrupole magnet:



Quadrupole magnets



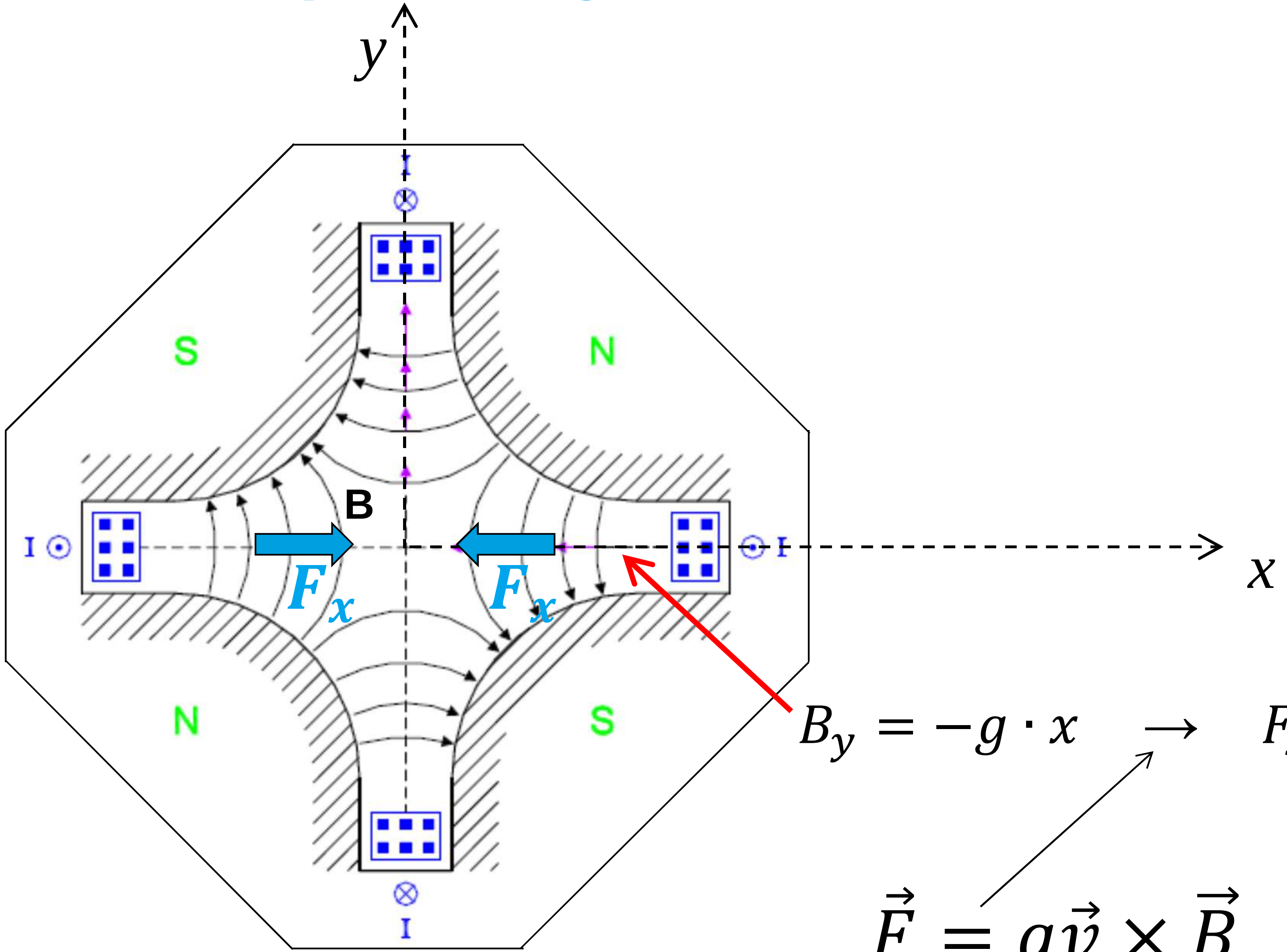
quadrupole magnet:

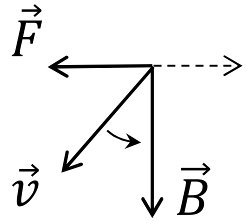
four iron pole shoes of hyperbolic contour

$$\boxed{\begin{aligned} B_x &= -g \cdot y \\ B_y &= -g \cdot x \end{aligned}}$$

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

Quadrupole magnets

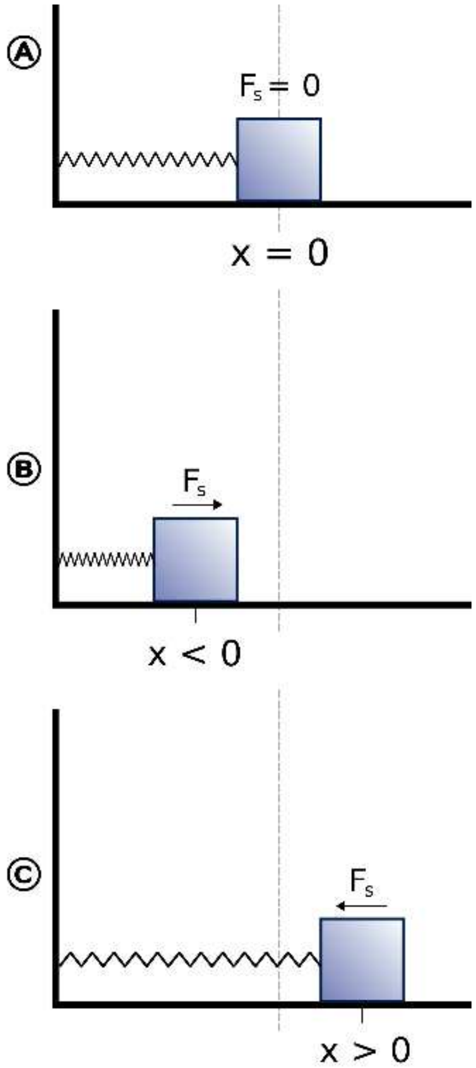




$$B_y = -g \cdot x \quad \longrightarrow \quad F_x = -g \cdot x$$

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

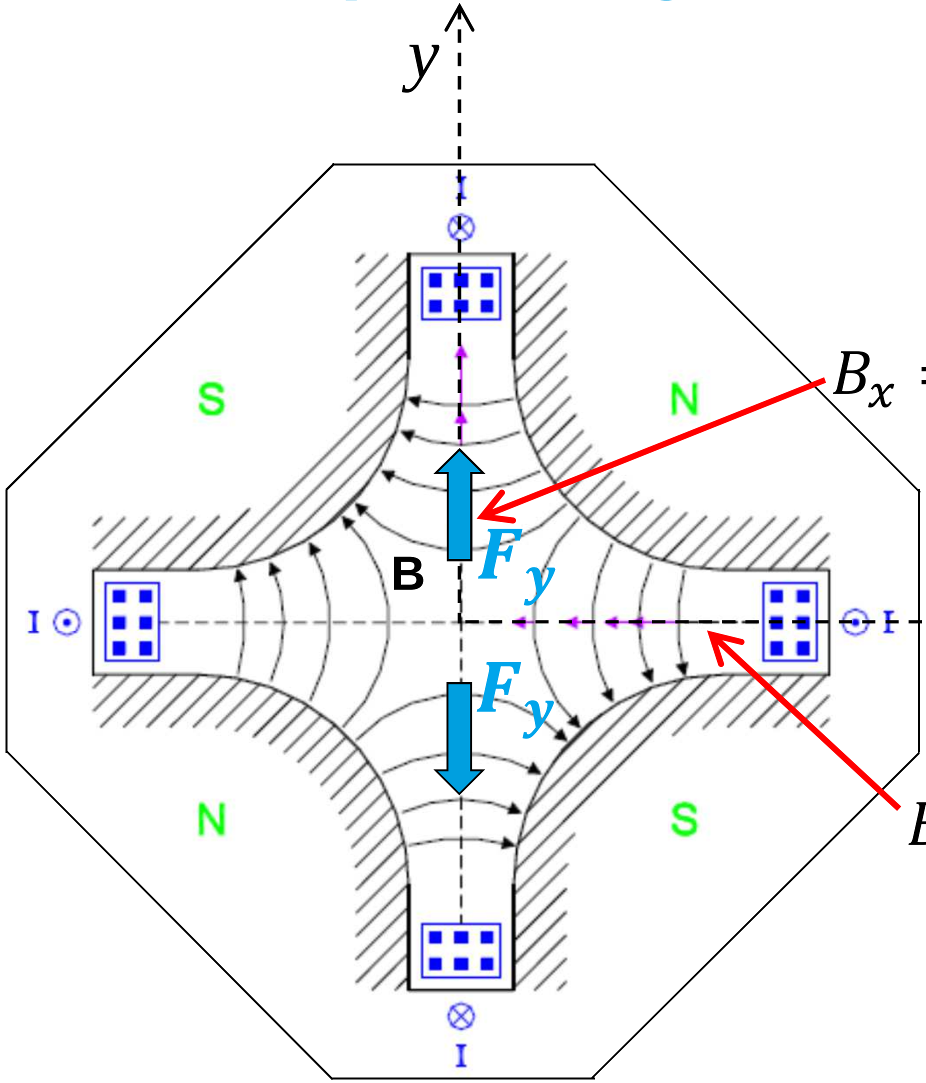
Classical mechanics: harmonic oscillator

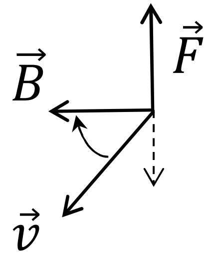


restoring force:

$$F = -kx$$

Quadrupole magnets





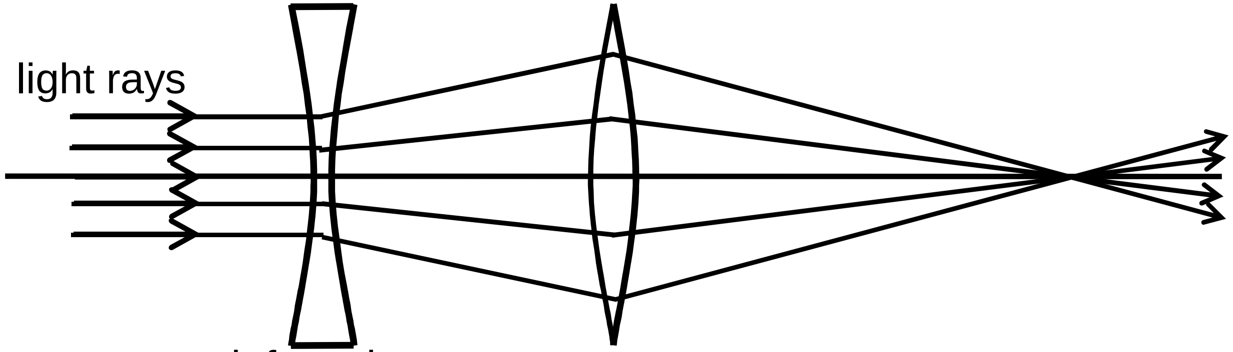
$$B_x = -g \cdot y \quad \rightarrow \quad F_y = g \cdot y$$

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

$$\frac{1}{f^*} = \frac{1}{f_D} + \frac{1}{f_F} - \frac{d}{f_D f_F}$$

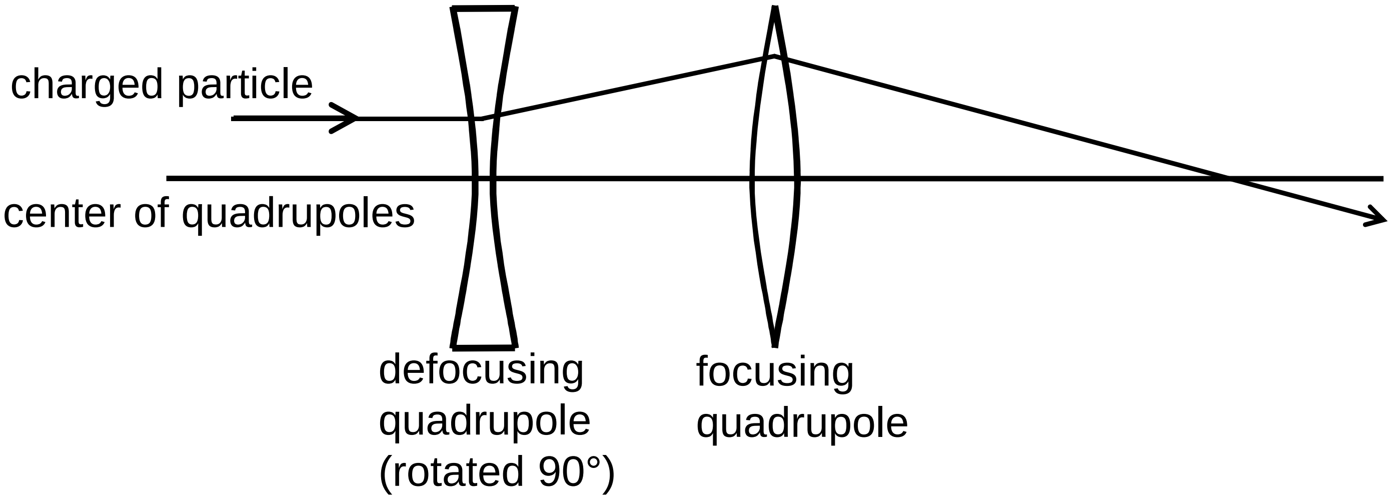
(light optics)

if $f_D = -f_F = f$

$$\frac{1}{f^*} = \frac{d}{f^2} > 0$$

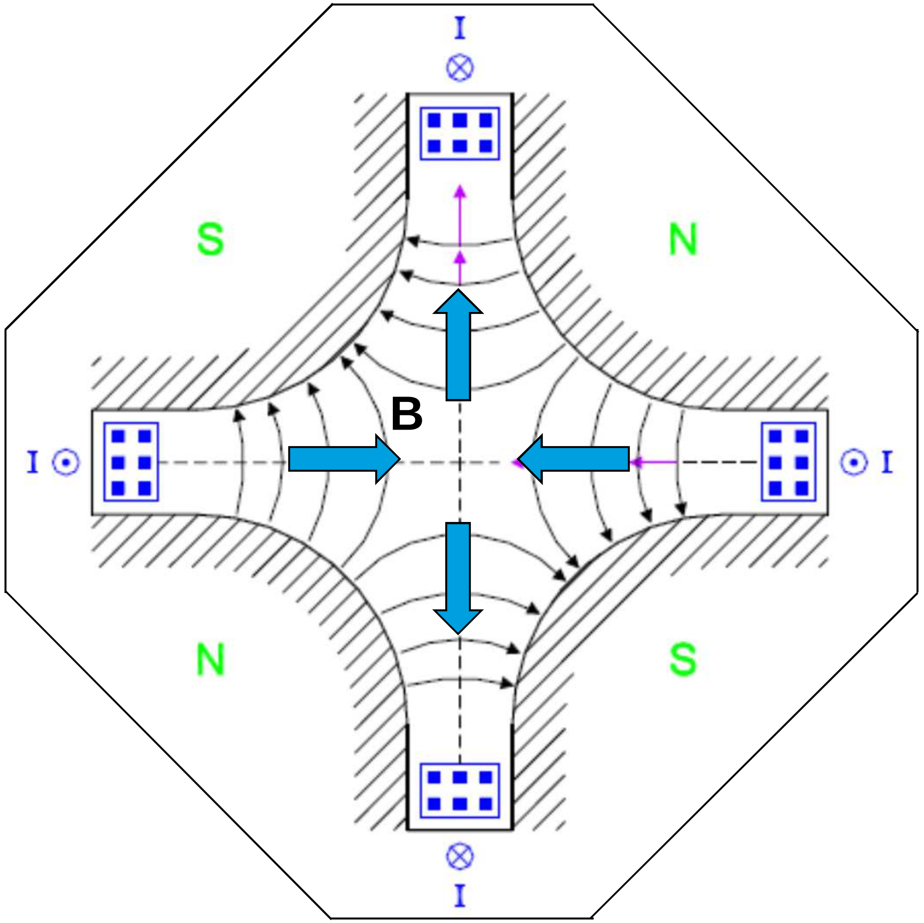
Quadrupole magnets

QD + QF = net focusing effect:

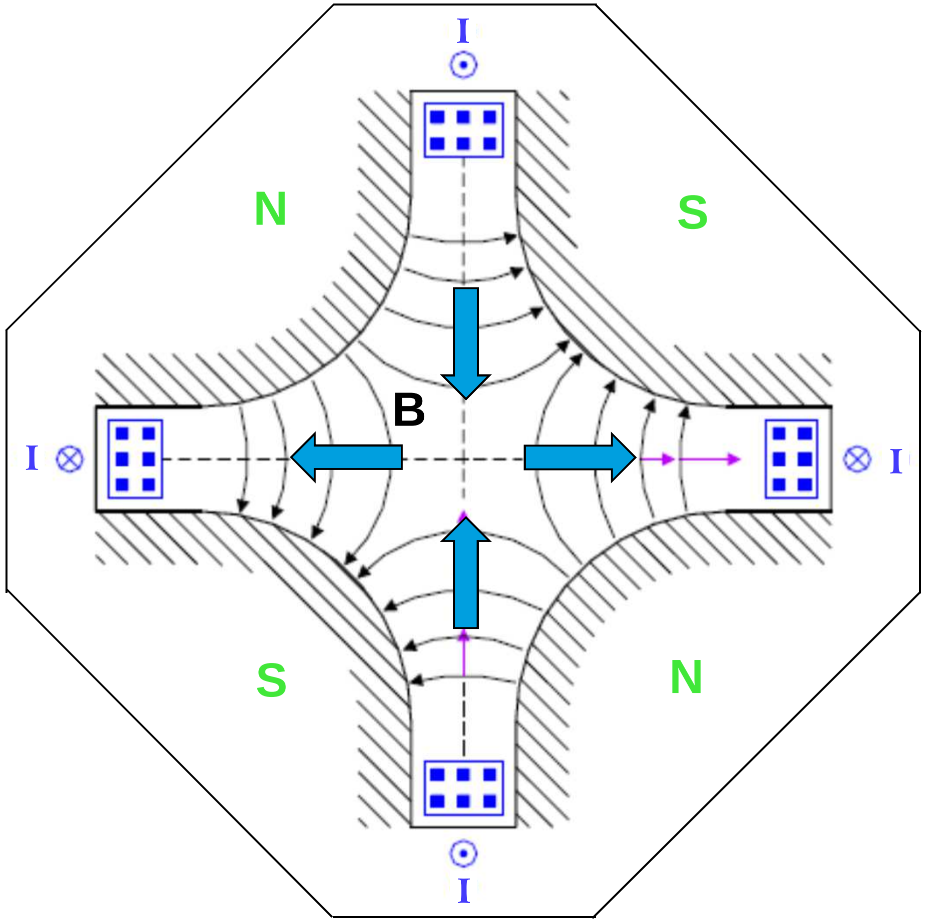


Quadrupole magnets

vertical defocusing
horizontal focusing



vertical focusing
horizontal defocusing

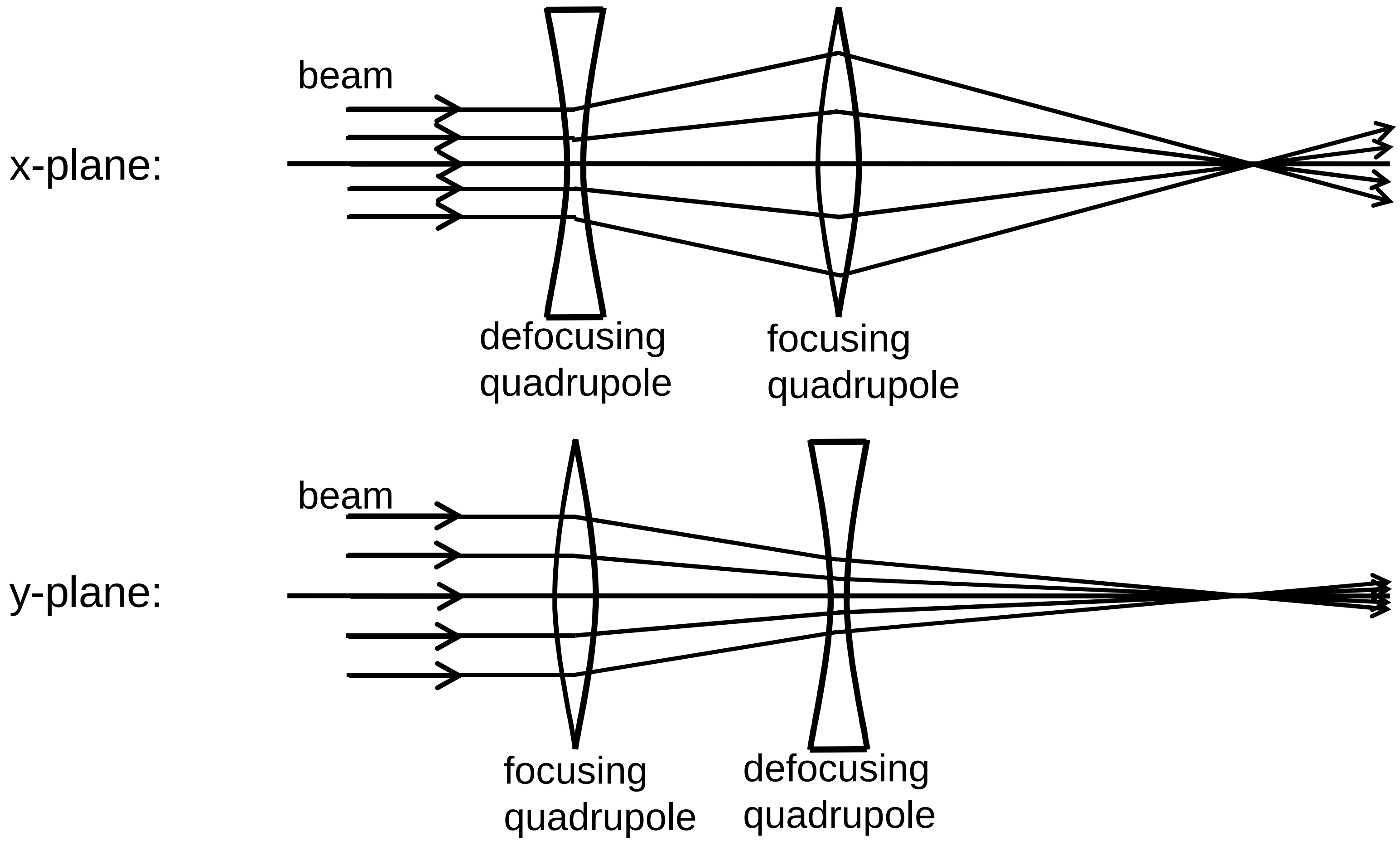


rotated 90°

I = -I

Quadrupole magnets

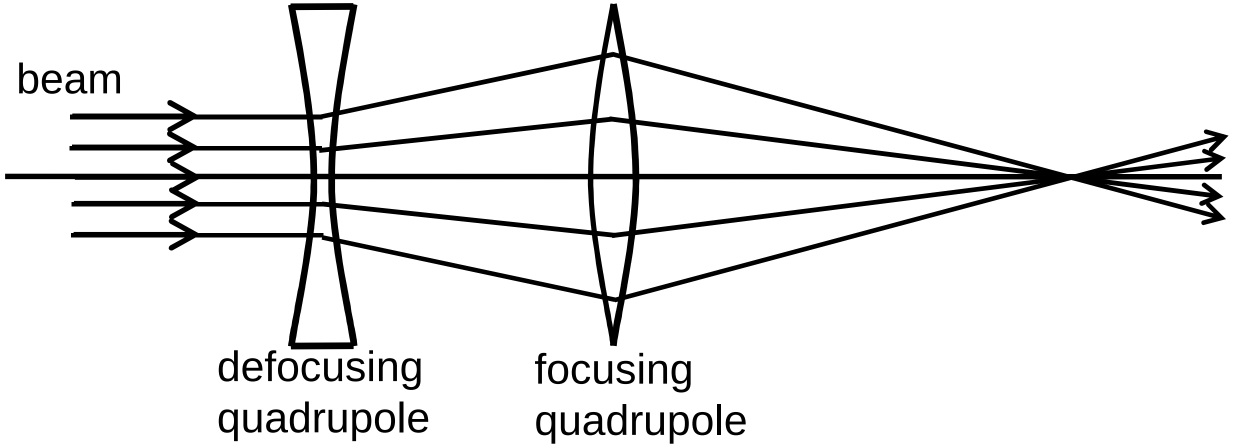
QD + QF = net focusing effect:

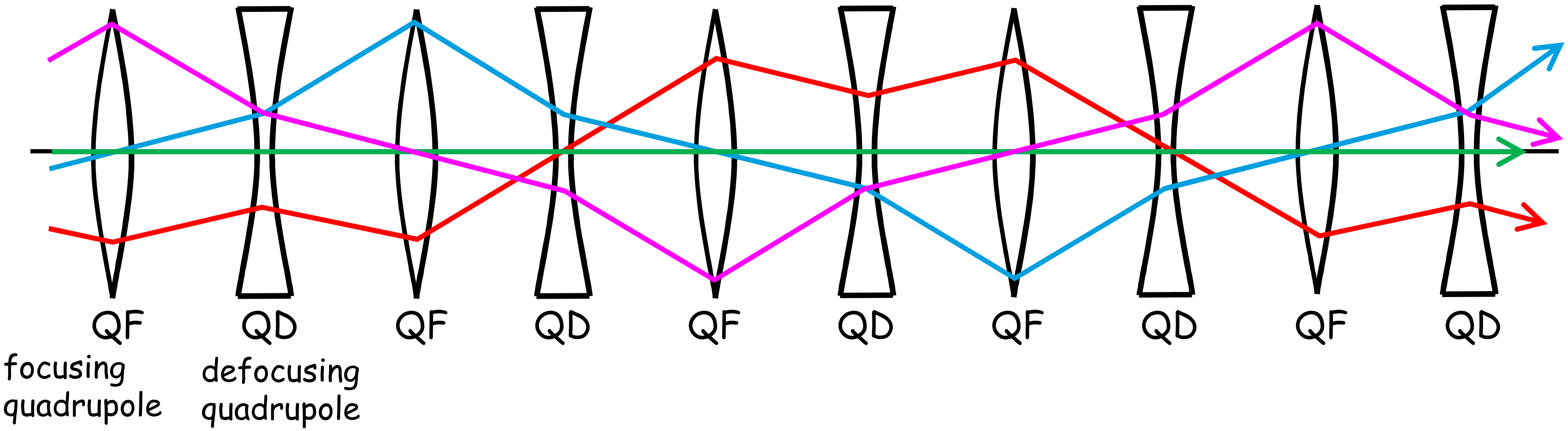


Quadrupole magnets

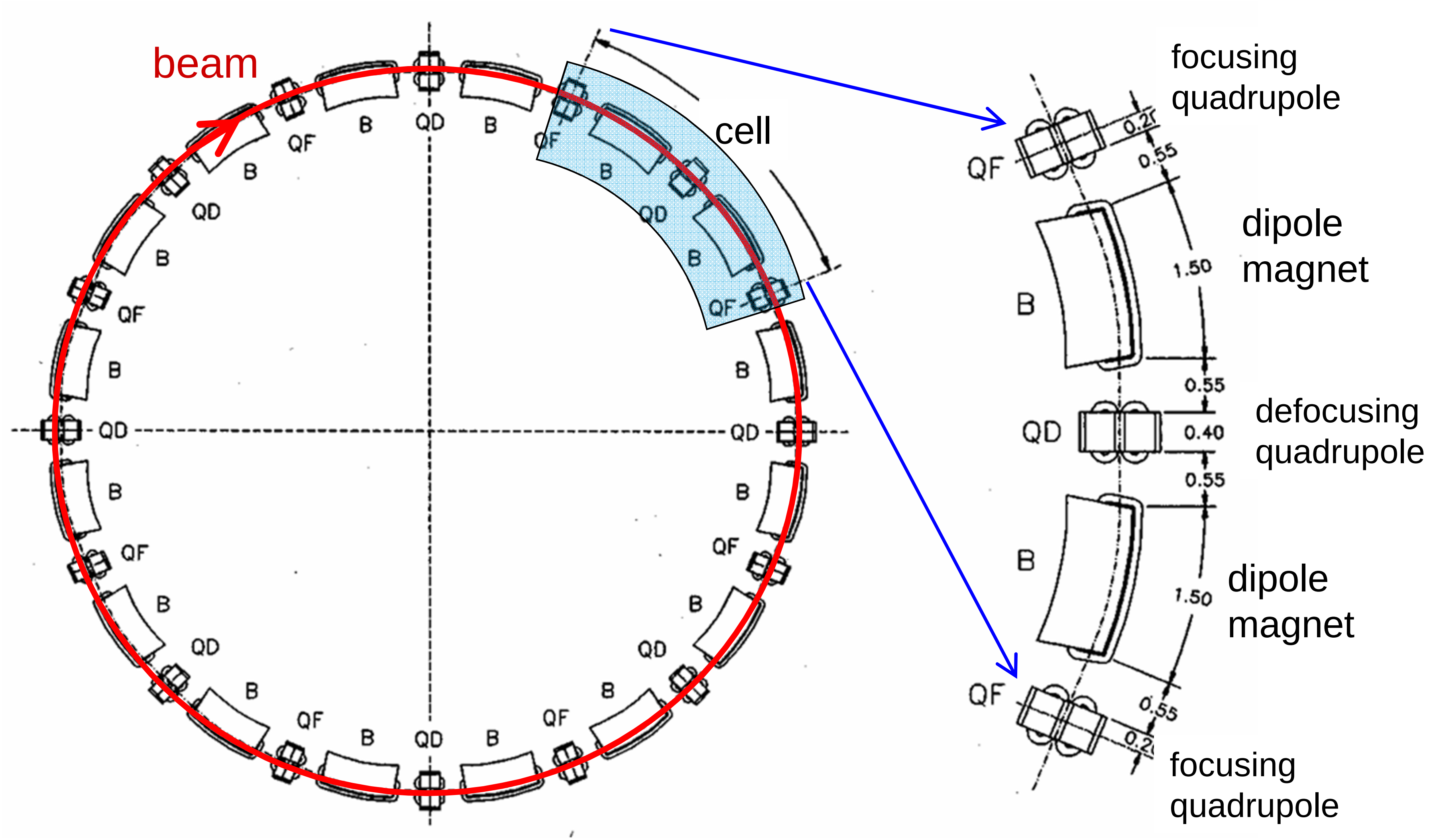
QD + QF = net focusing effect:

x-plane:



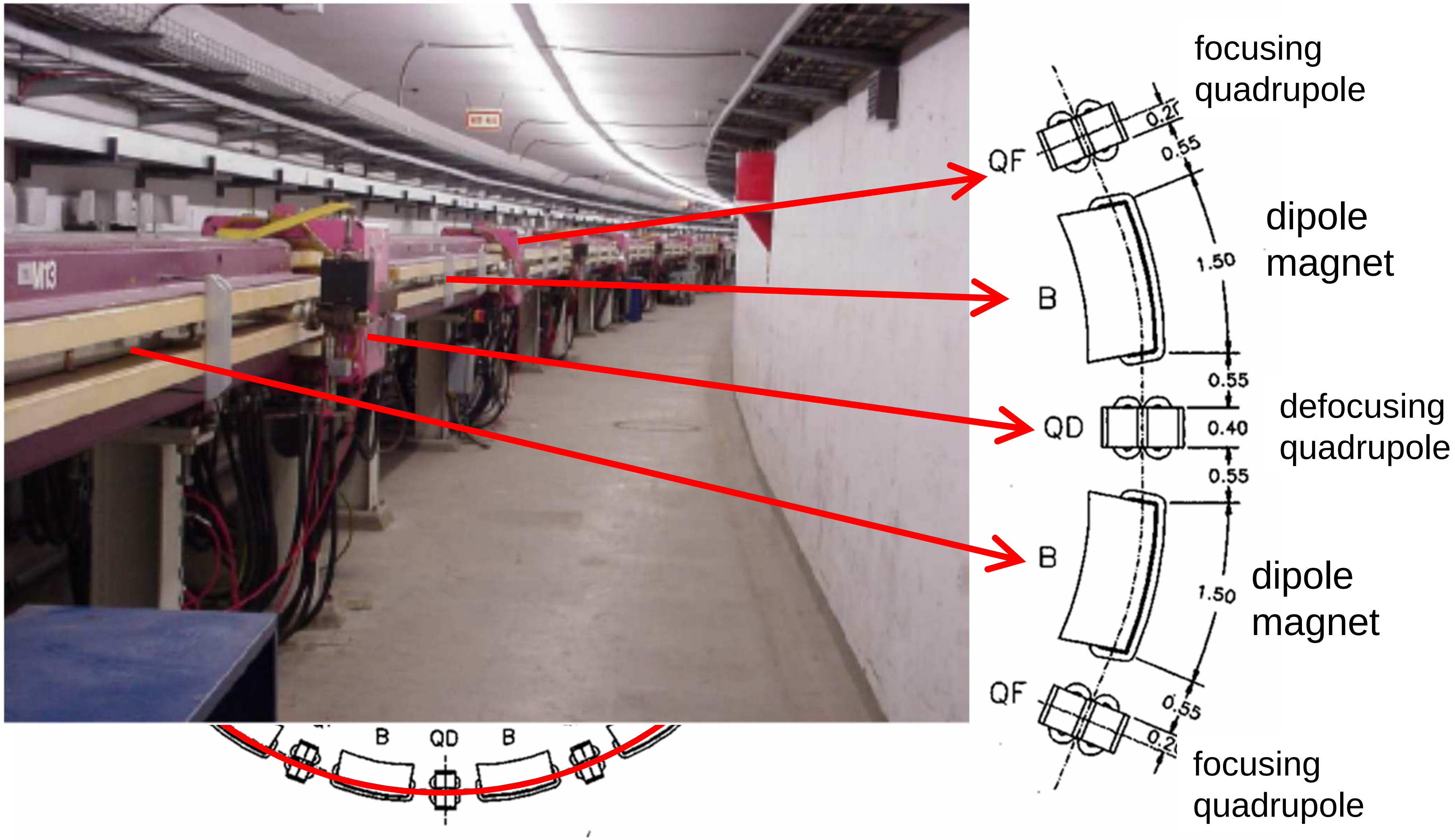


Circular accelerator

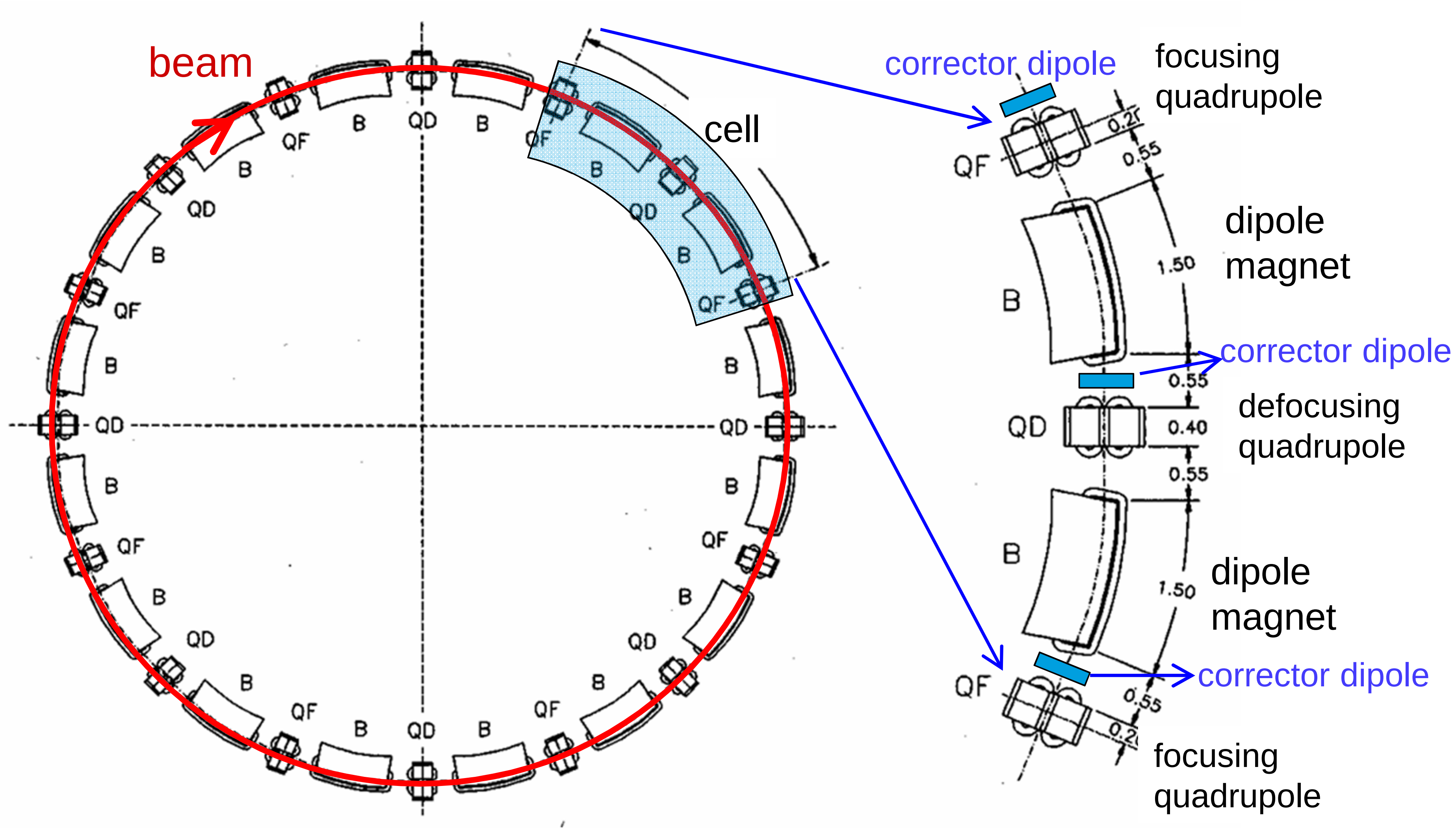


Circular accelerator

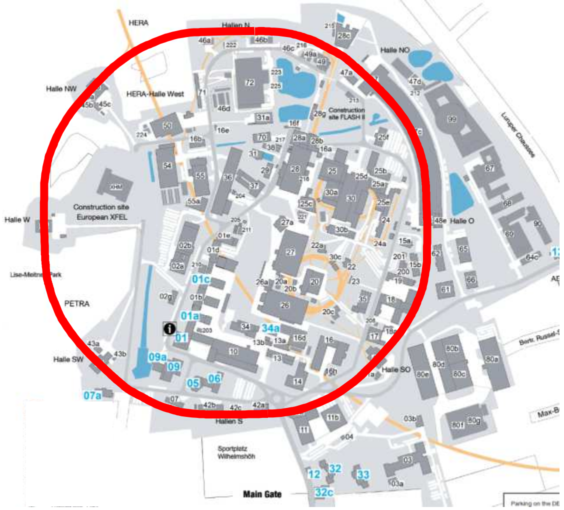
PETRA



Circular accelerator



Next suspect: an aperture problem



Hamburg, DESY
Sat. 12th June 2010

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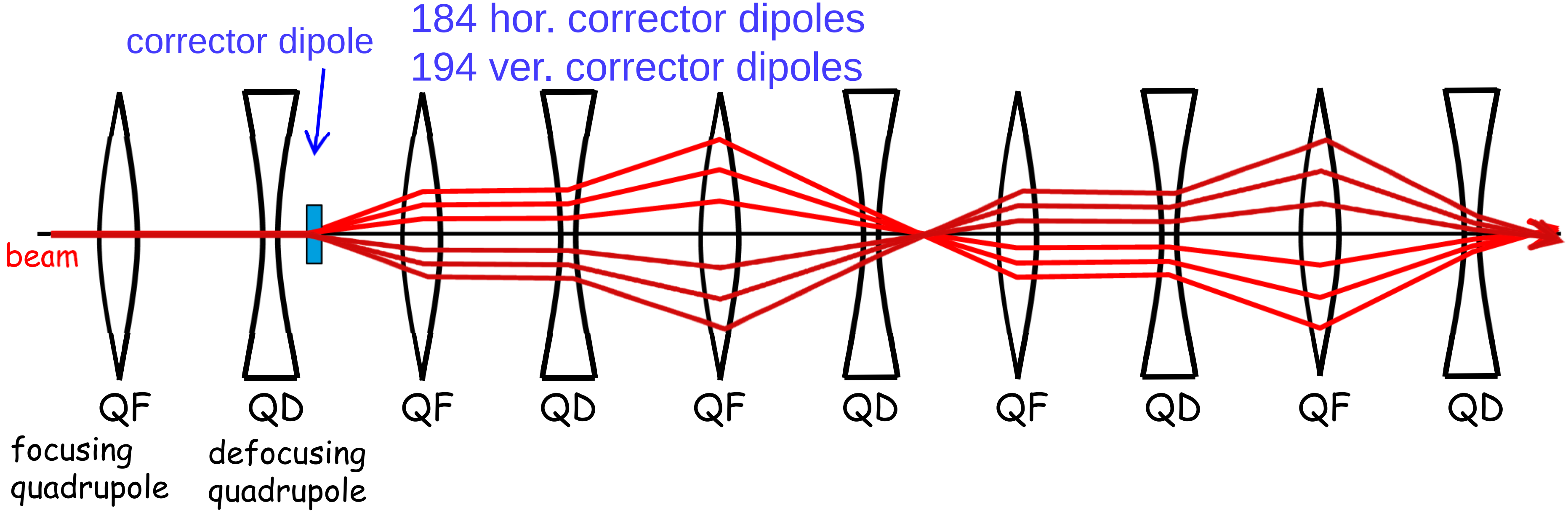
184 hor. corrector dipoles
194 ver. corrector dipoles



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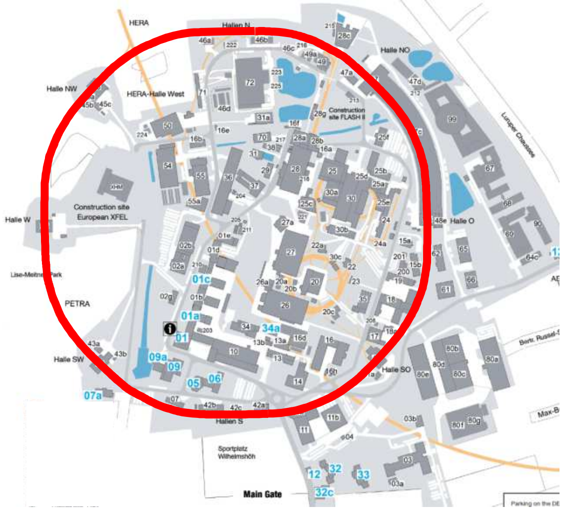

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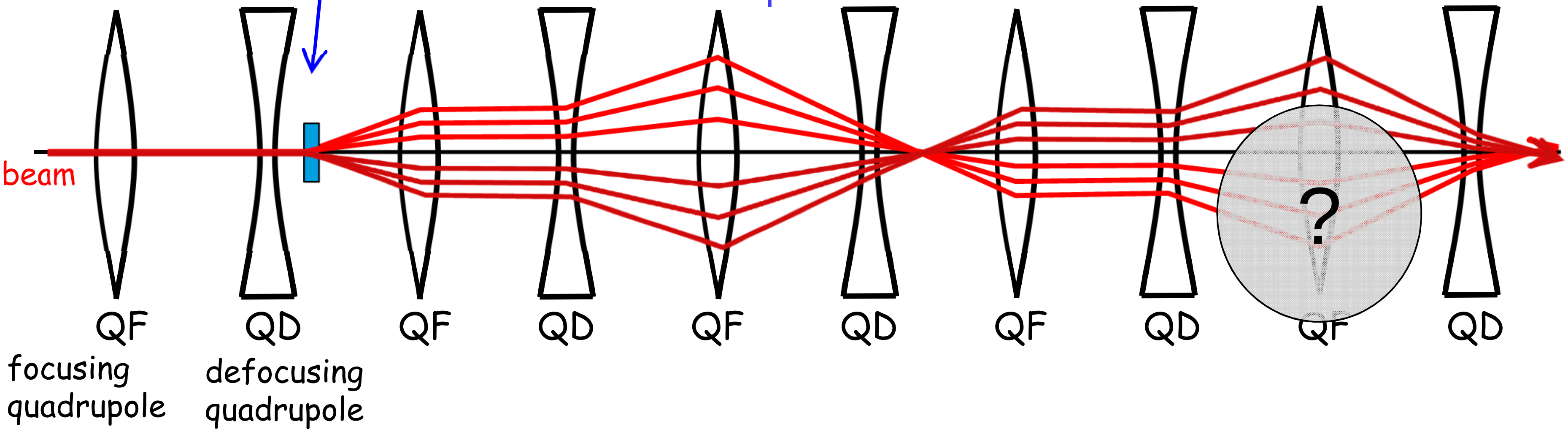
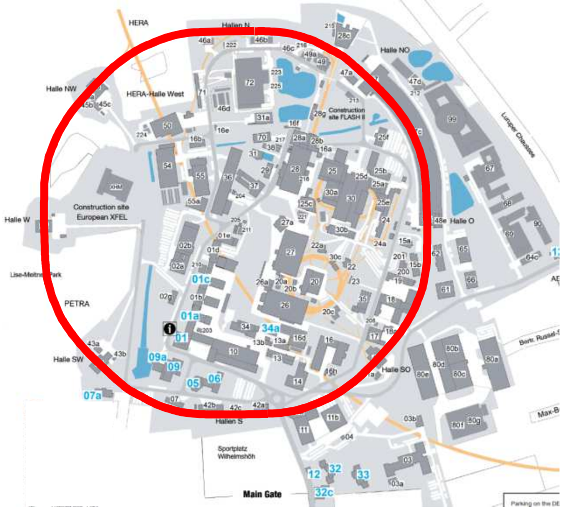
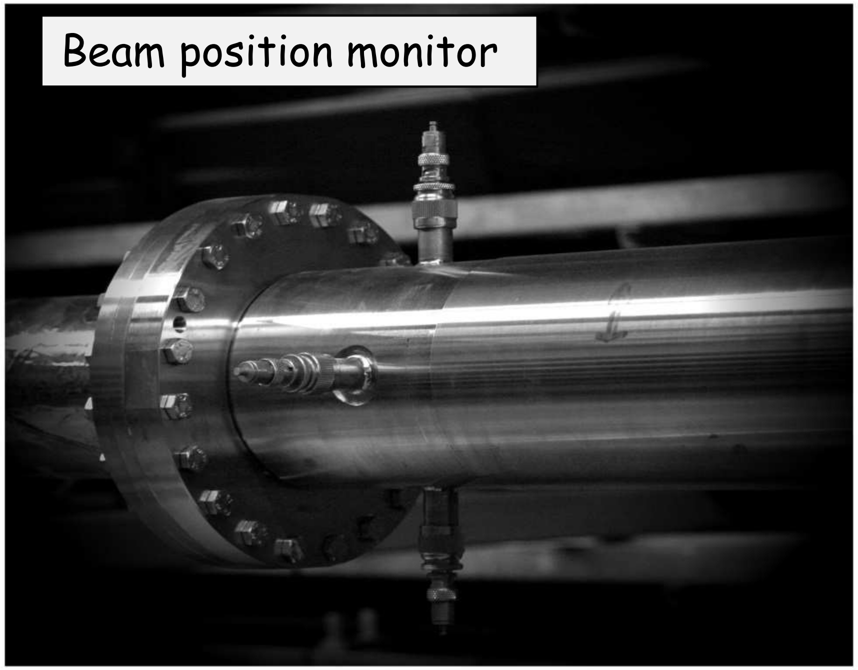


First useful hint: aperture problem





Hamburg, DESY
Sat. 12th June 2010

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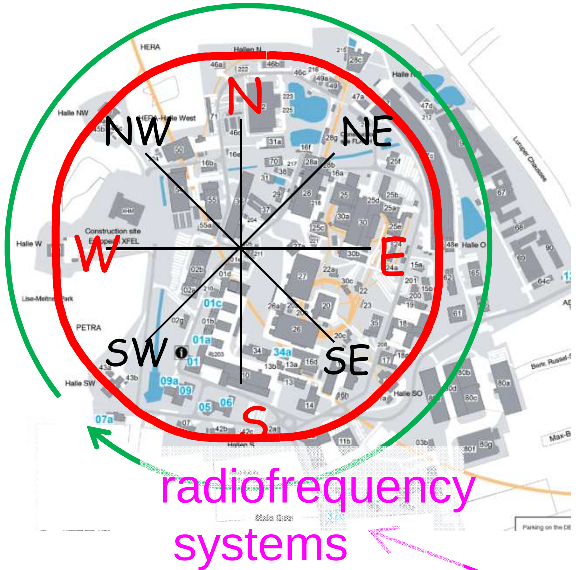
13:20 a.m.: beam stored

244 beam position monitors

First useful hint: horizontal aperture problem



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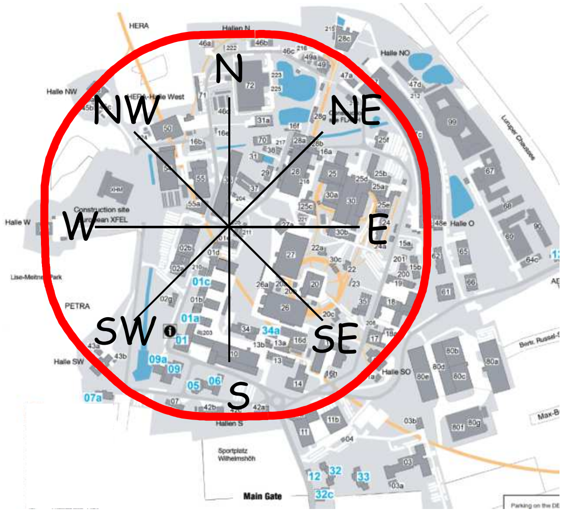
244 monitors

horizontal beam pos. [mm]

vertical beam pos. [mm]

First useful hint: horizontal aperture problem



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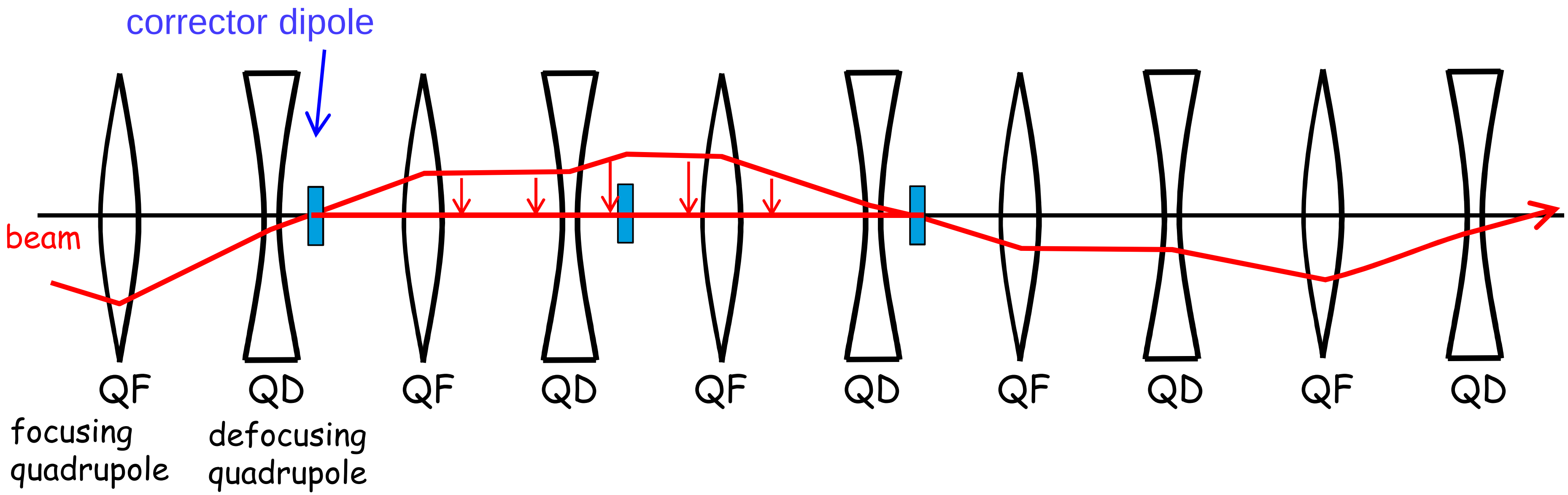
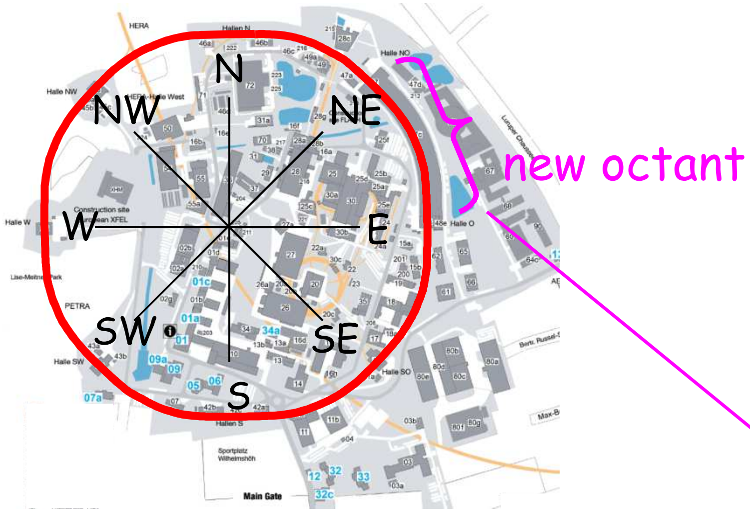


First useful hint: horizontal aperture problem



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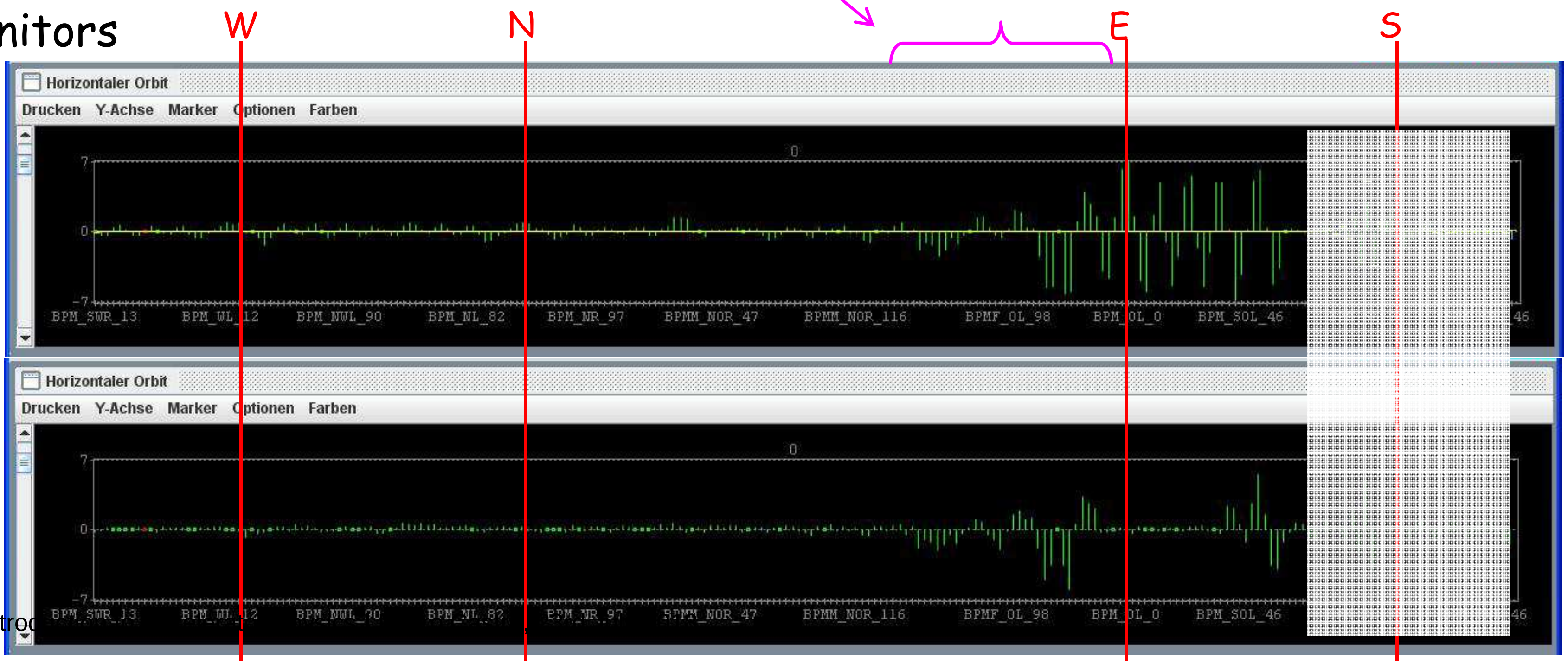
244 monitors

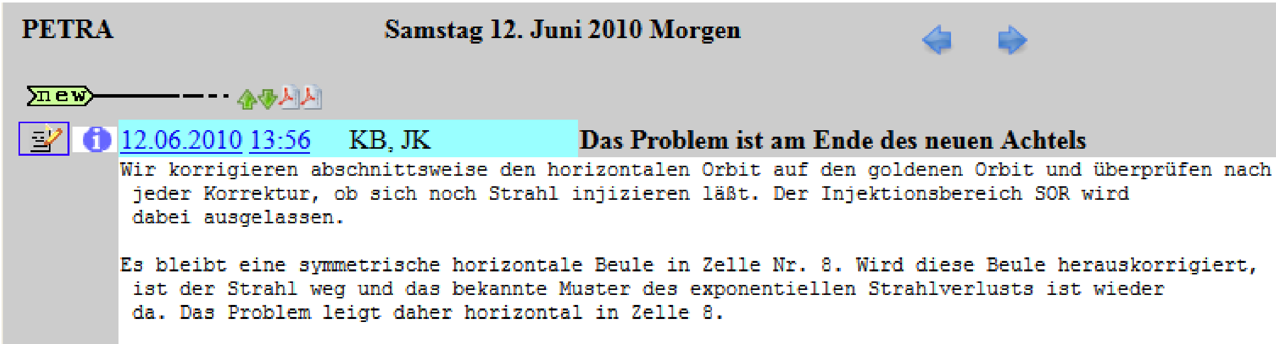
horizontal beam pos. [mm]



after 'flattening' the orbit

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

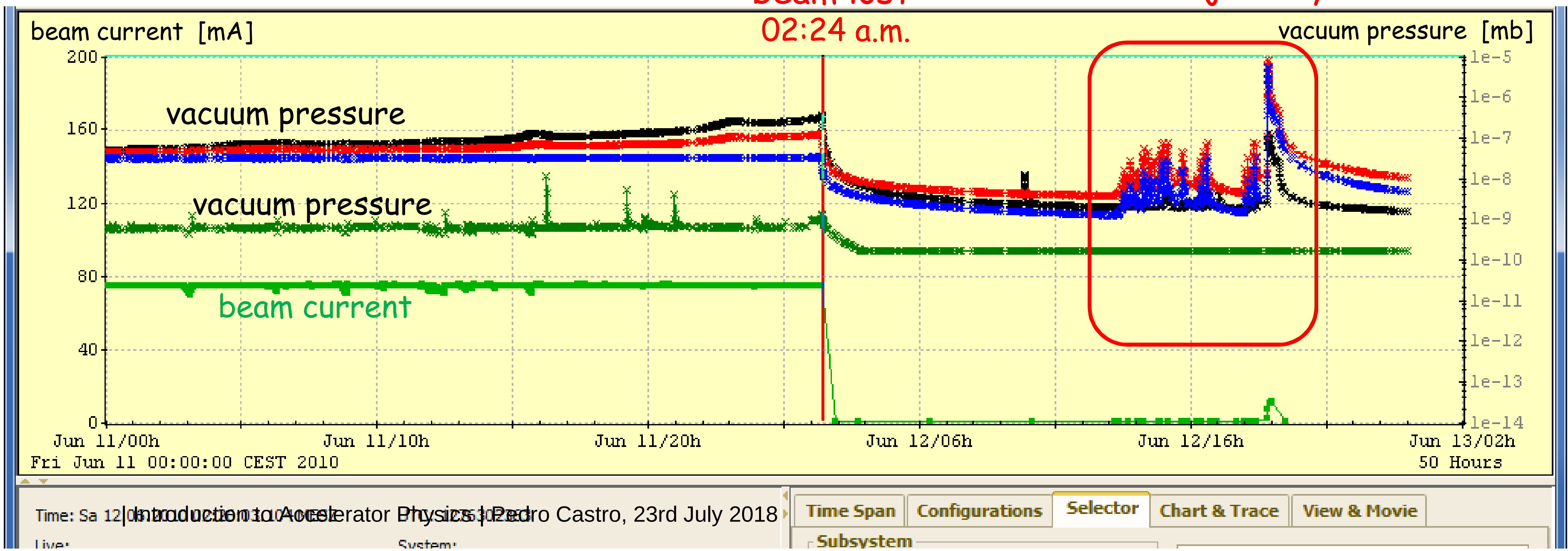
new

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

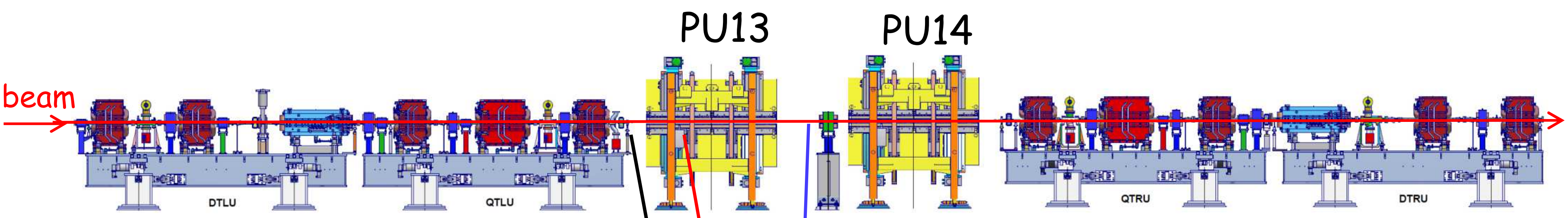
Wir korrigieren abschnittsweise den horizontalen Orbit auf den goldenen Orbit und überprüfen nach jeder Korrektur, ob sich noch Strahl injizieren läßt. Der Injektionsbereich SOR wird dabei ausgelassen.

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.

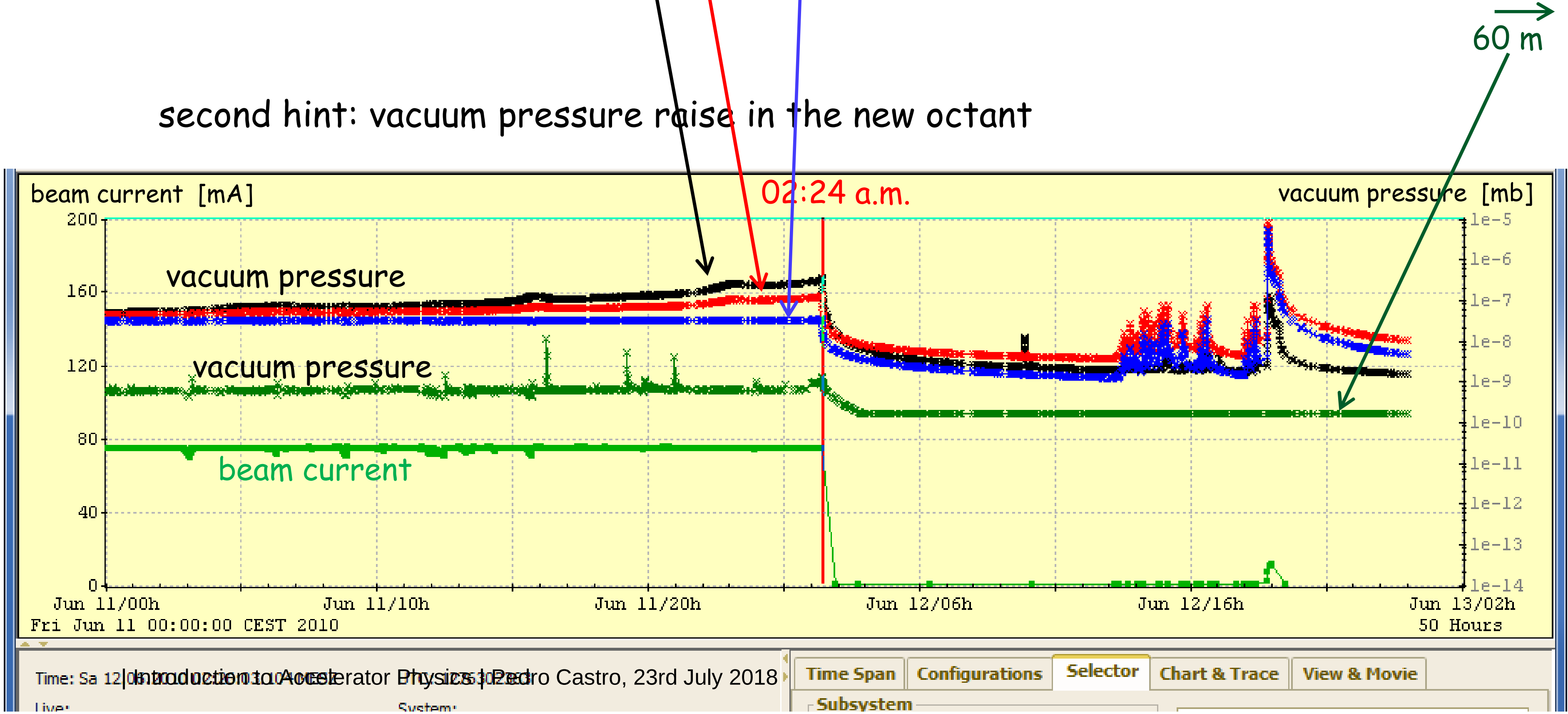
second hint: vacuum pressure raise in the new octant



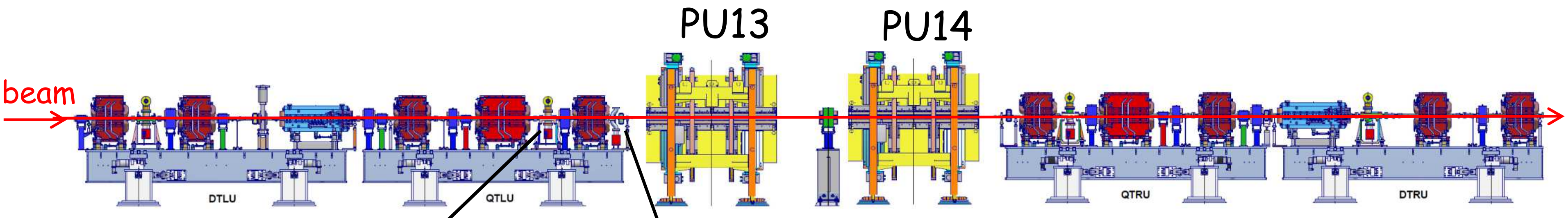
horizontal aperture problem in the new octant

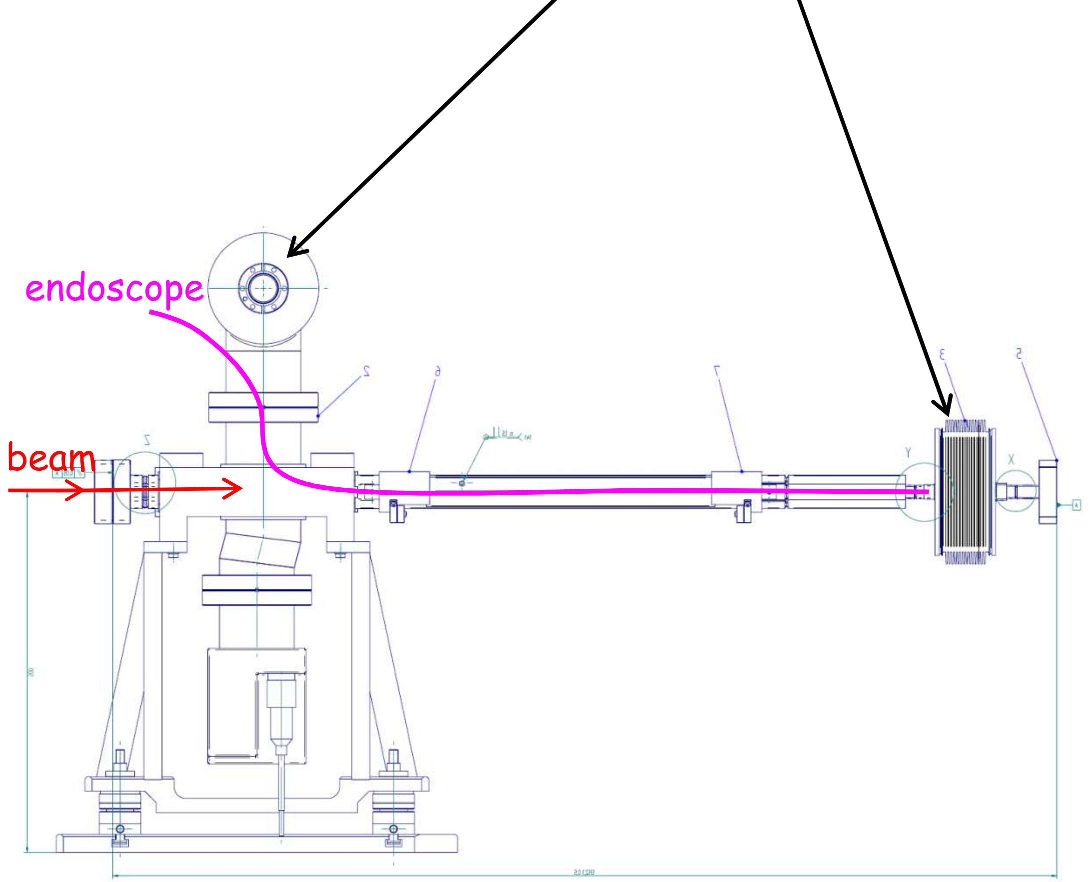


second hint: vacuum pressure raise in the new octant

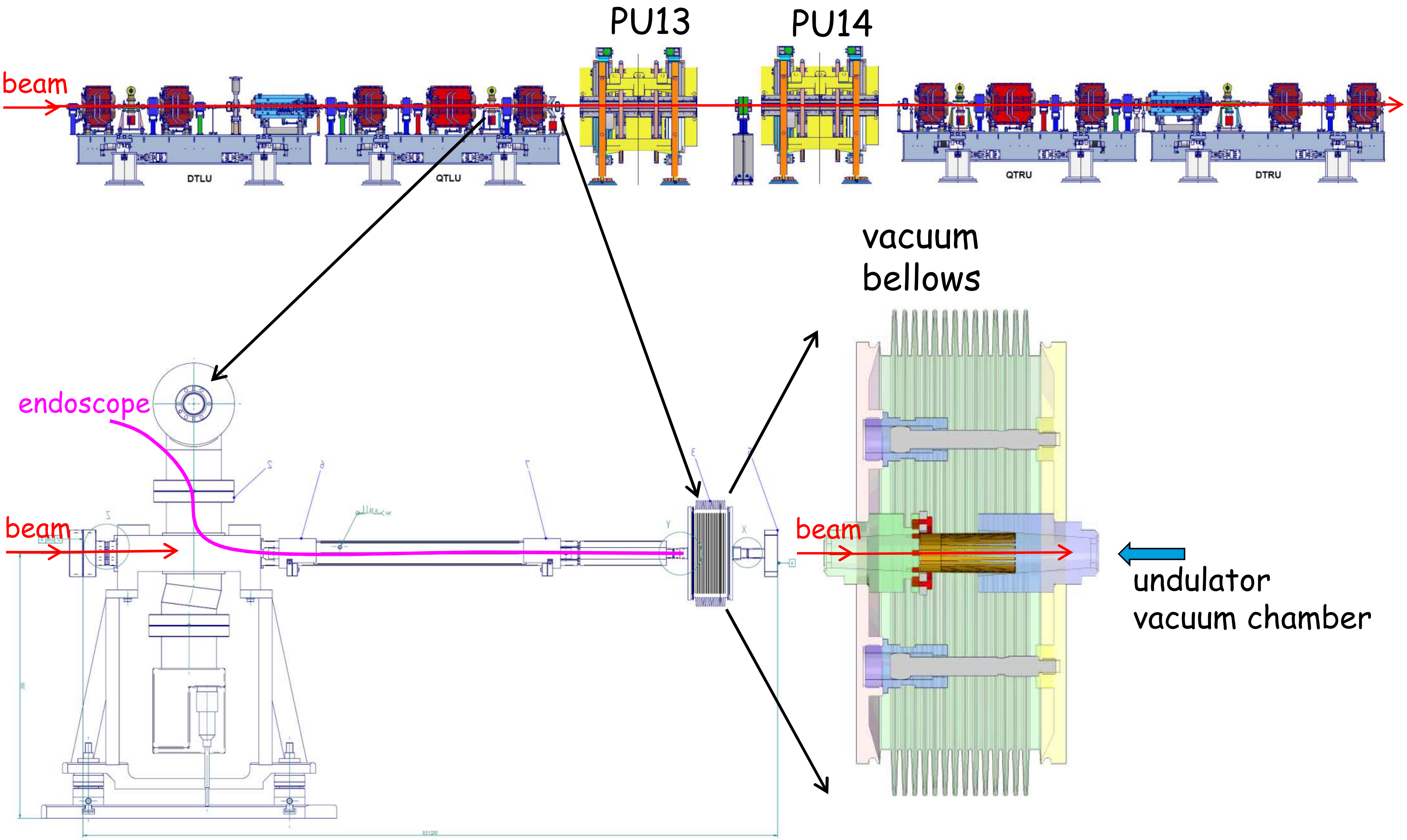


visual inspection inside the vacuum chamber…



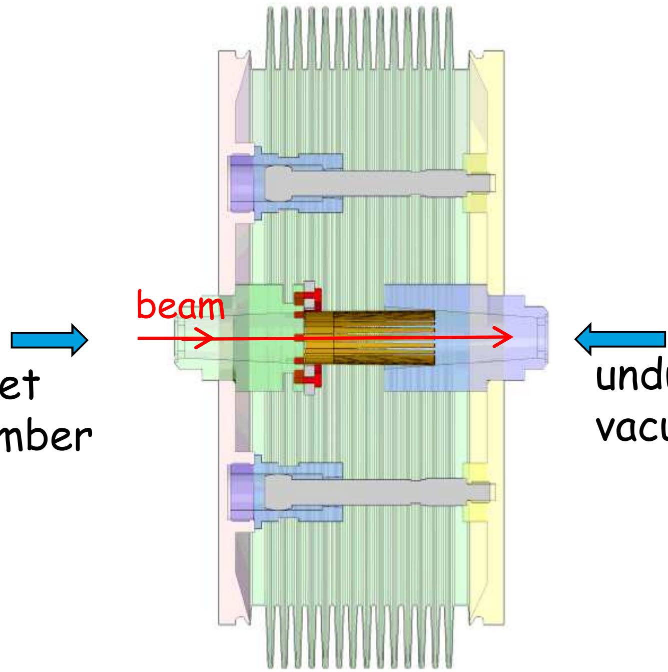


visual inspection inside the vacuum chamber…

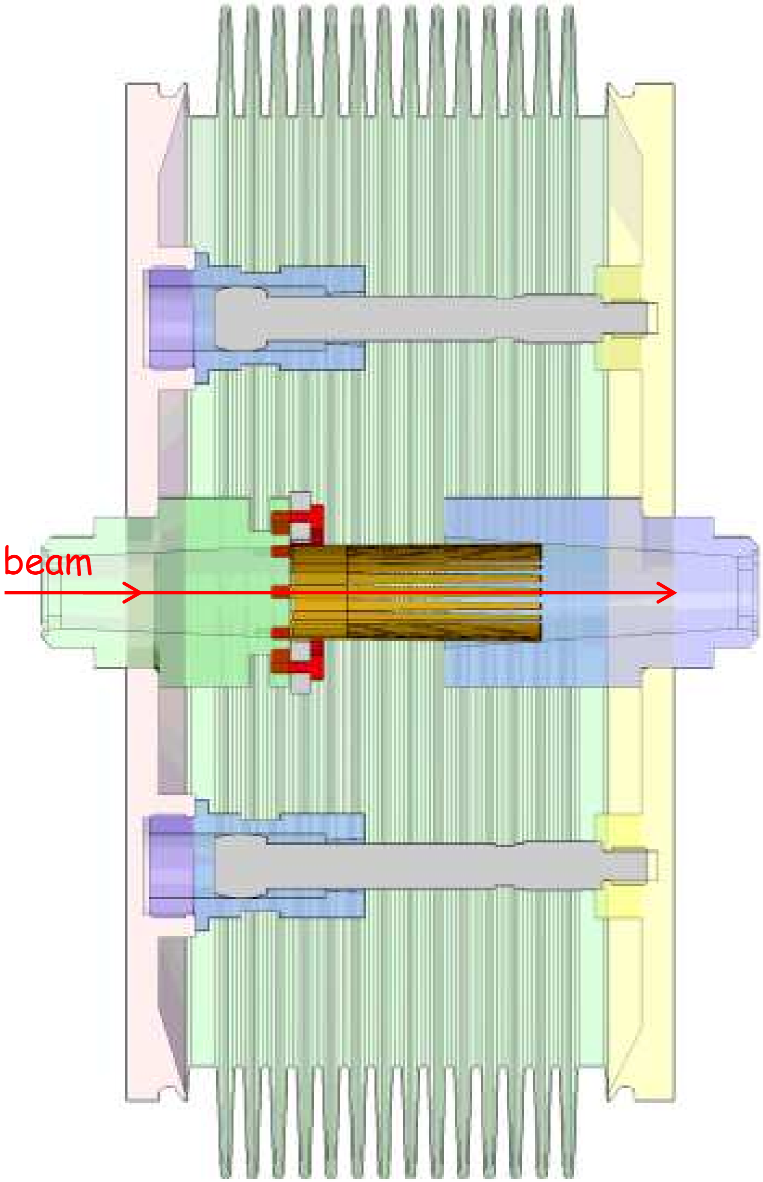


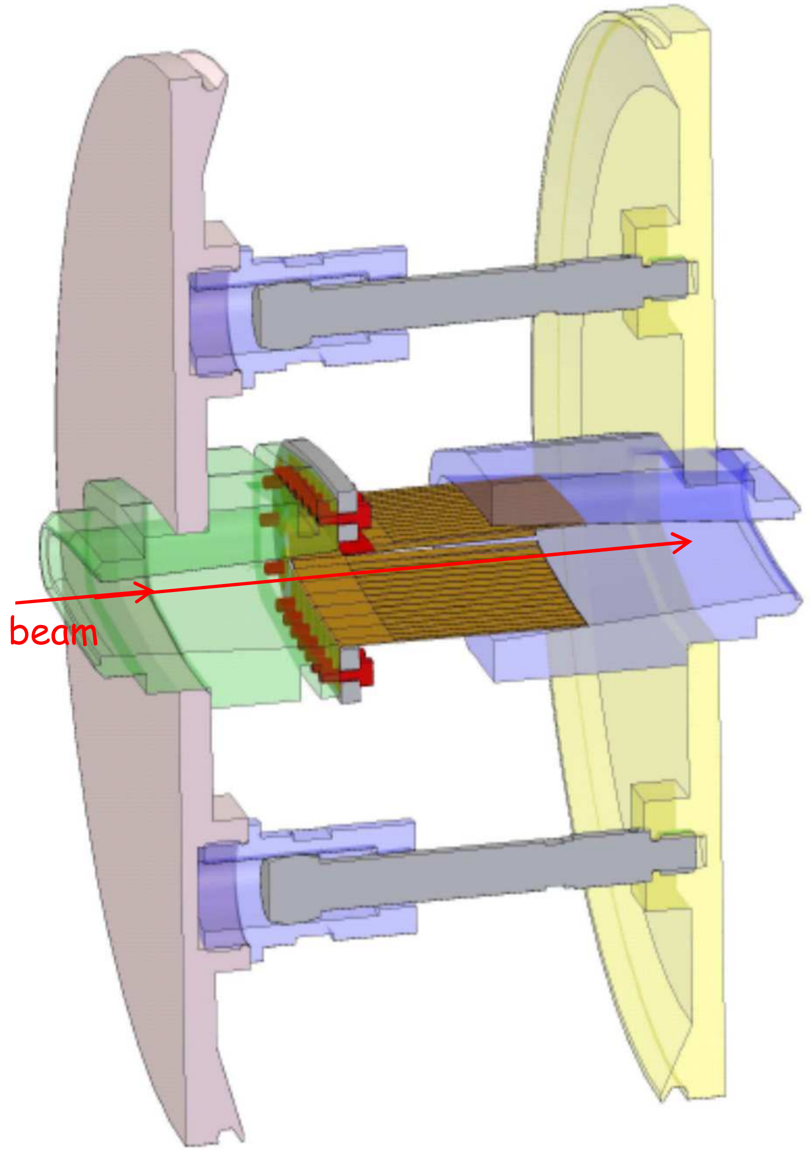
visual inspection inside the vacuum chamber…

an example of vacuum bellows



the problem was found: RF fingers





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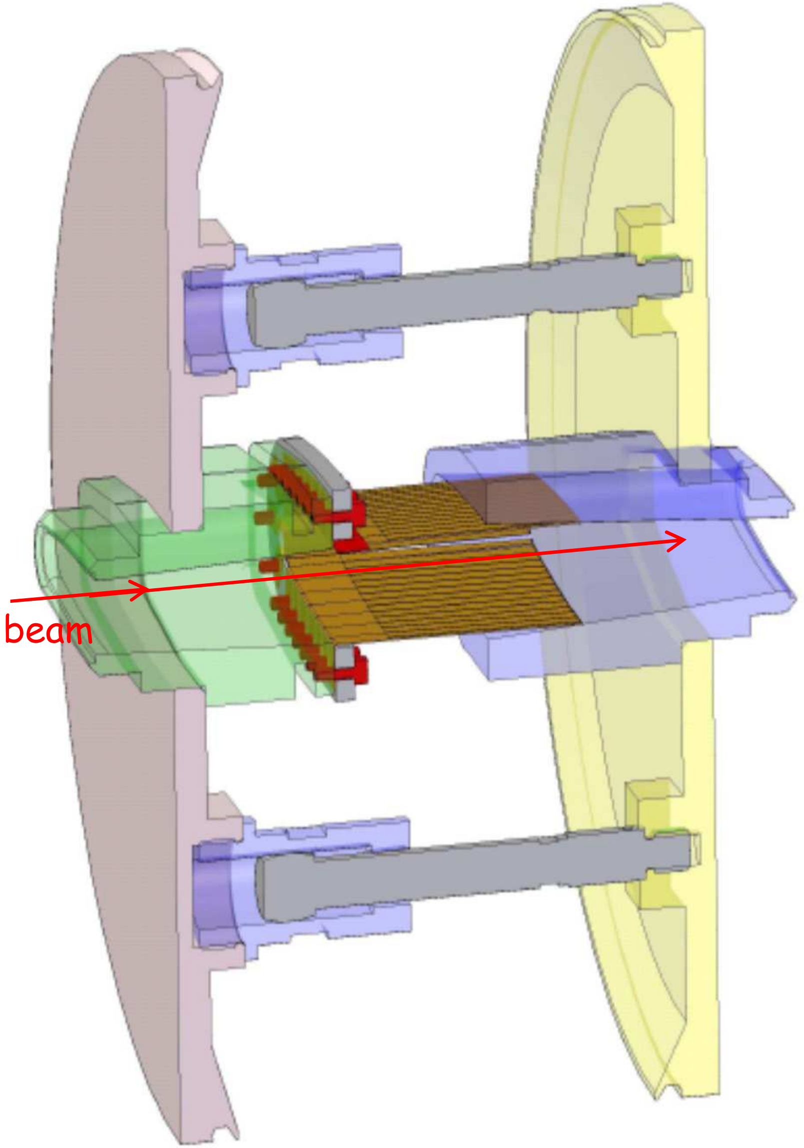
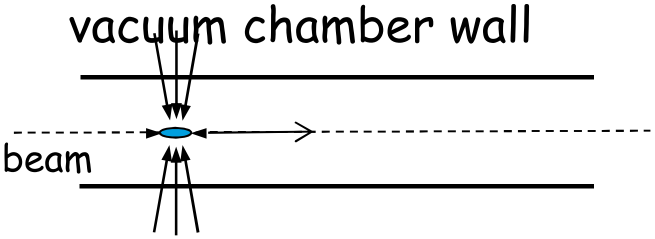


RF fingers and wakefields

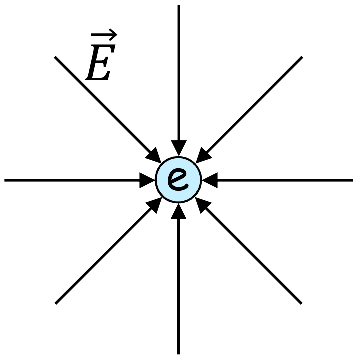


$\vec{E}$: electric field ?

electric field of a charged particle

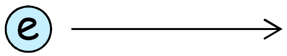
$v = 0$

$\vec{E}$



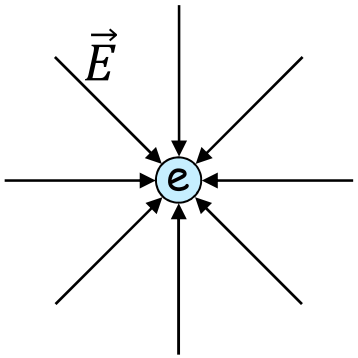
$v = \beta c$

$\vec{E}$?



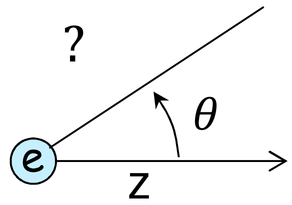
electric field of a relativistic particle

$$v = 0$$
$$\beta = 0$$



$$v = \beta c$$

$\vec{E}$?



cylindrical coordinates

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

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

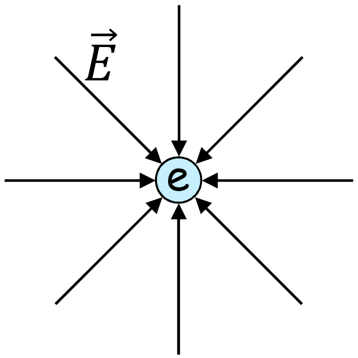
$$\boxed{\vec{E} = \frac{q}{4\pi\varepsilon_0}\frac{(1-\beta^2)}{(1-\beta^2\sin^2\theta)^{3/2}r^2}\frac{\vec{r}}{r}}$$

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

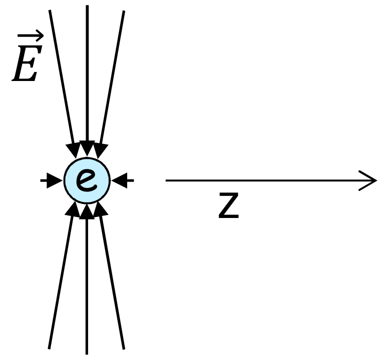
$$\left\{\begin{array}{l} \boxed{E_z(\theta = 0) = \frac{q}{4\pi\varepsilon_0}\frac{1}{\gamma^2 r^2}\frac{\vec{r}}{r}} \\ \boxed{E_r\left(\theta = \frac{\pi}{2}\right) = \frac{q}{4\pi\varepsilon_0}\frac{\gamma}{r^2}\frac{\vec{r}}{r}} \end{array}\right.$$

electric field of a relativistic particle

$v = 0$
$\beta = 0$



$v = \beta c$
$\beta \cong 1$



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

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

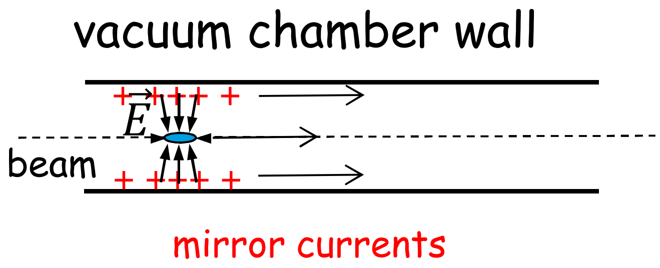
$\gamma \gg 1$
$\beta \cong 1$

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

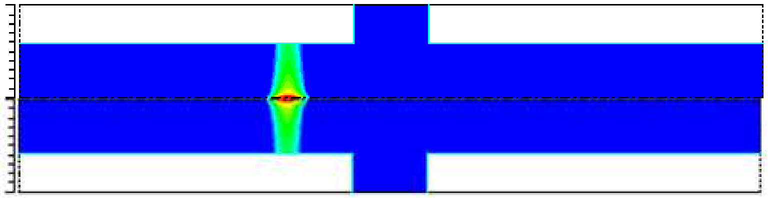
$$\begin{cases} \boxed{E_z(\theta = 0) = \dfrac{q}{4\pi\varepsilon_0}\dfrac{1}{\gamma^2 r^2}\dfrac{\vec{r}}{r}} \xrightarrow{\gamma\to\infty} 0 \\ \boxed{E_r\left(\theta = \dfrac{\pi}{2}\right) = \dfrac{q}{4\pi\varepsilon_0}\dfrac{\gamma}{r^2}\dfrac{\vec{r}}{r}} \xrightarrow{\gamma\to\infty} \infty \end{cases}$$

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

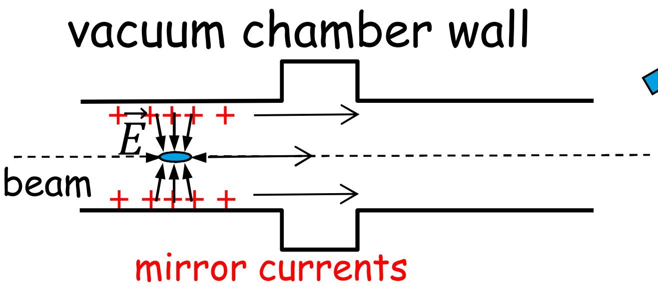
RF fingers and wakefields



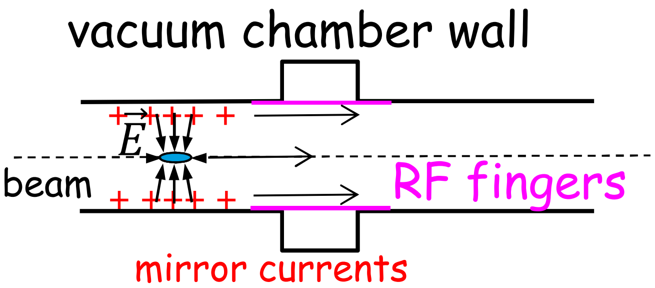
RF fingers and wakefields

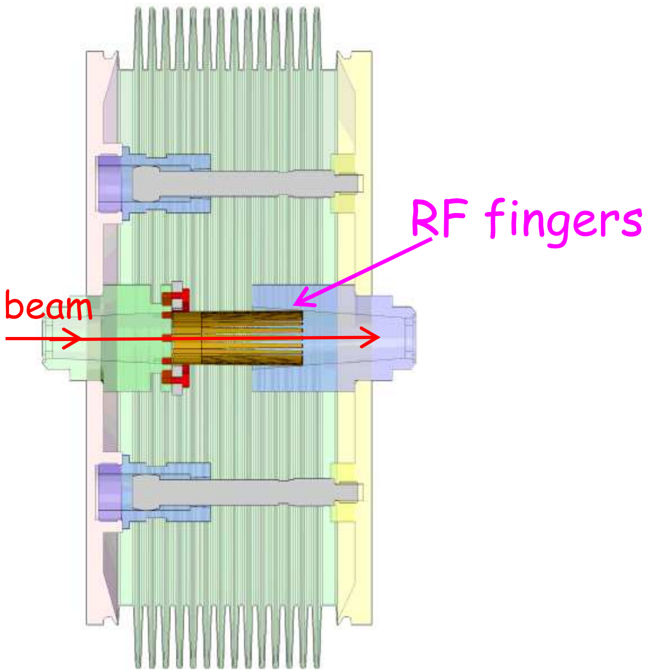


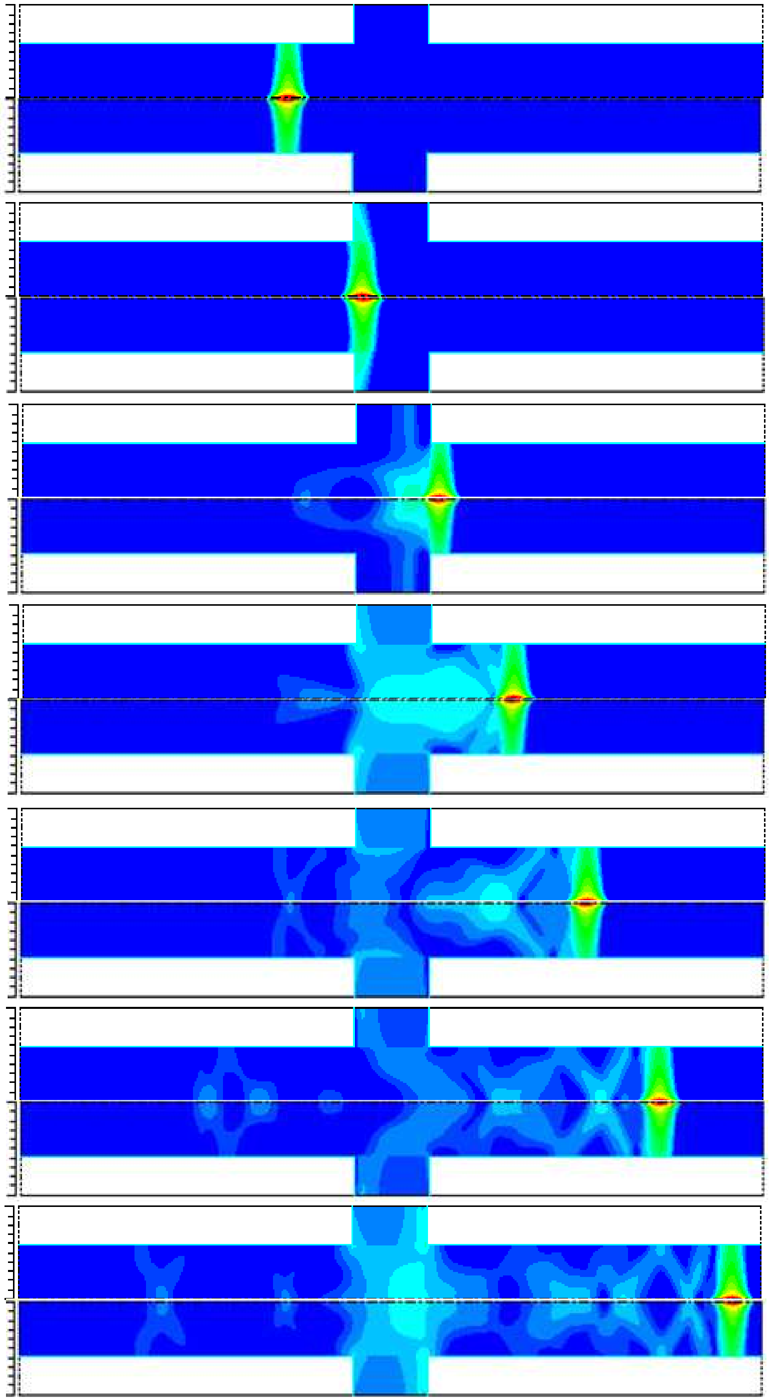
simulation



RF fingers and wakefields

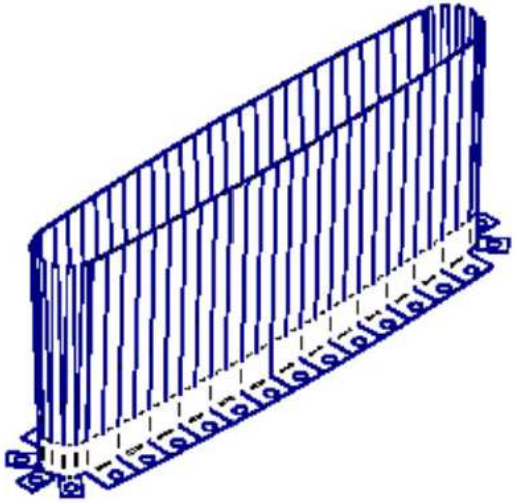






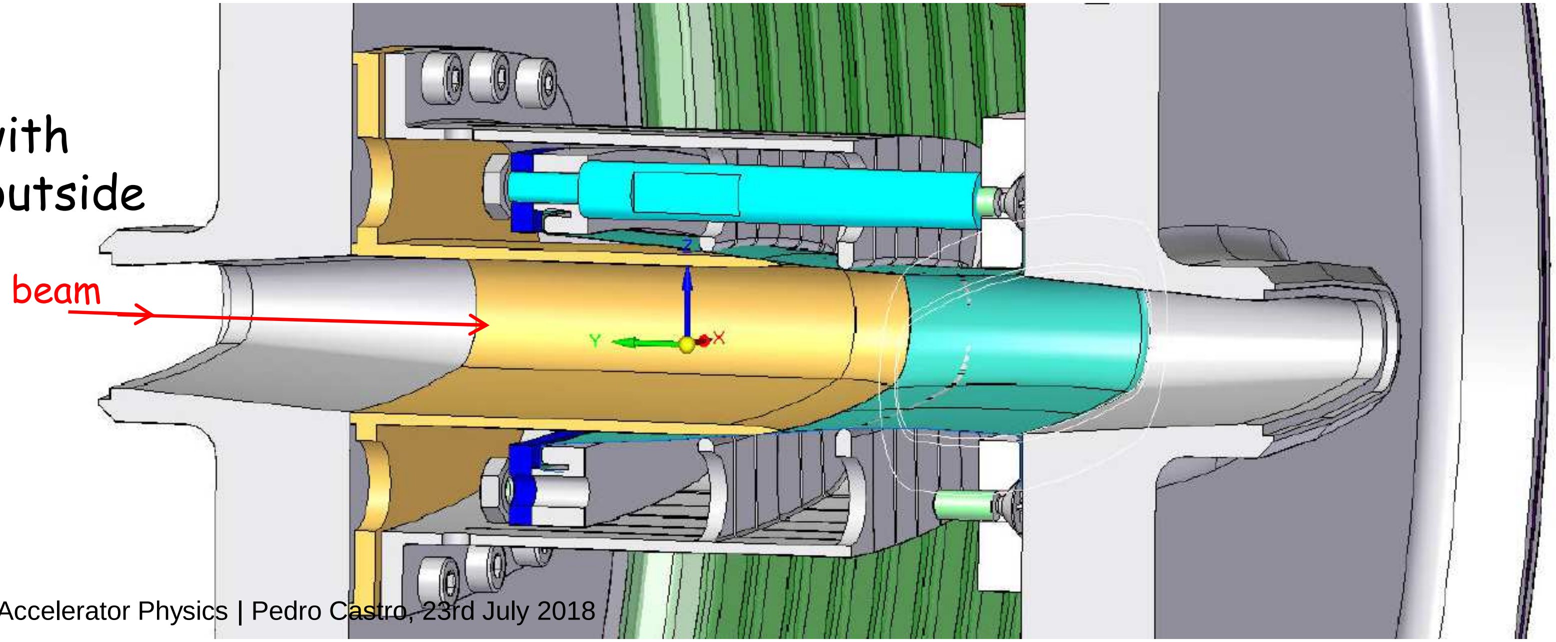
RF fingers: improvements done

old RF fingers were tilted outwards by 2 degrees



new RF fingers have stronger tilt, more tension

new design with
RF fingers outside



RF fingers: improvements done

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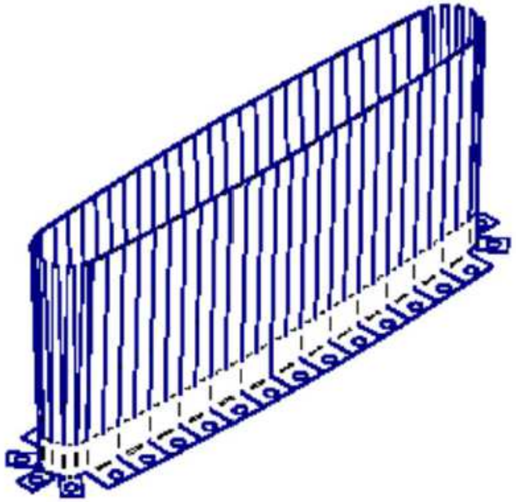

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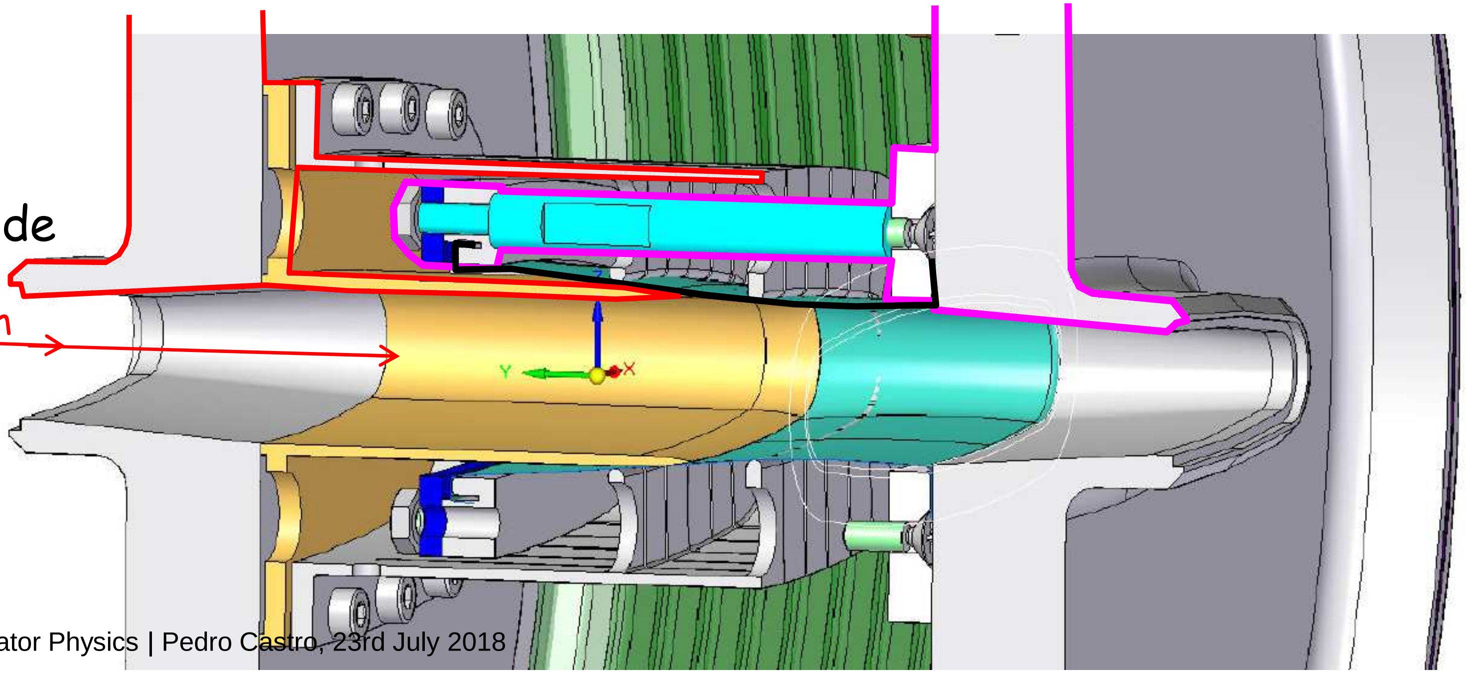


Summing-up of this part

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
- trajectory (orbit) corrections
- aperture scans

Contact

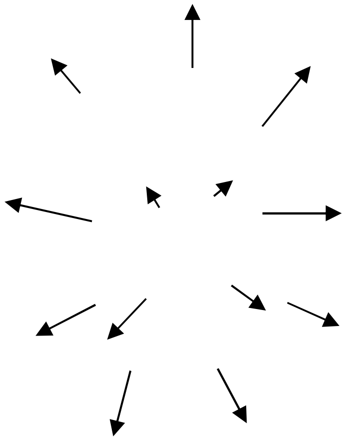
DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

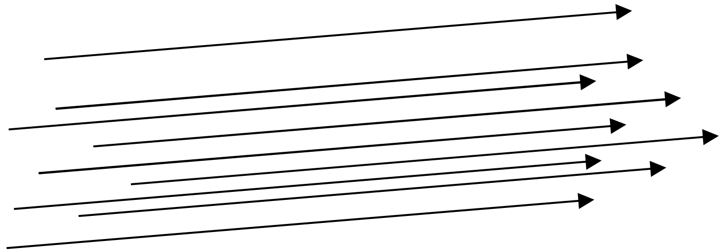
Pedro Castro
MPY
pedro.castro@desy.de

Relativity helps against Coulomb repulsion

a bunch of electrons at rest



a high-relativistic bunch of electrons



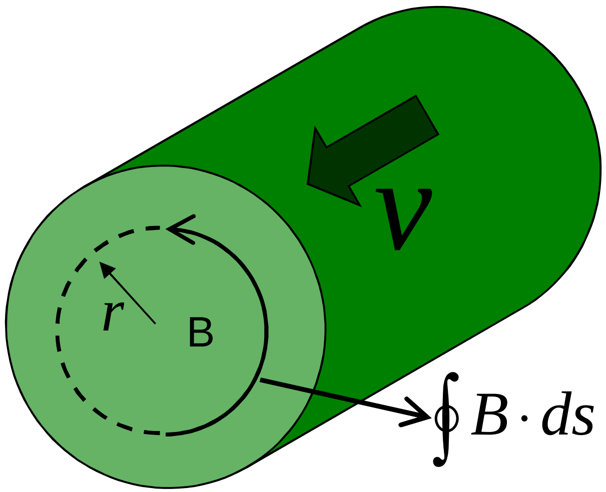
Magnetic field of a charged-particle beam

$\rho =$ uniform charge density

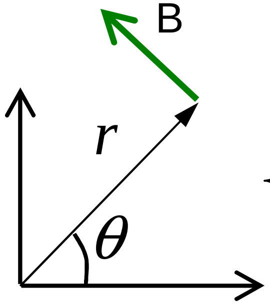
Ampere's law:

$$\oint \vec{B} \cdot ds = \mu_0 I$$

current through the circle



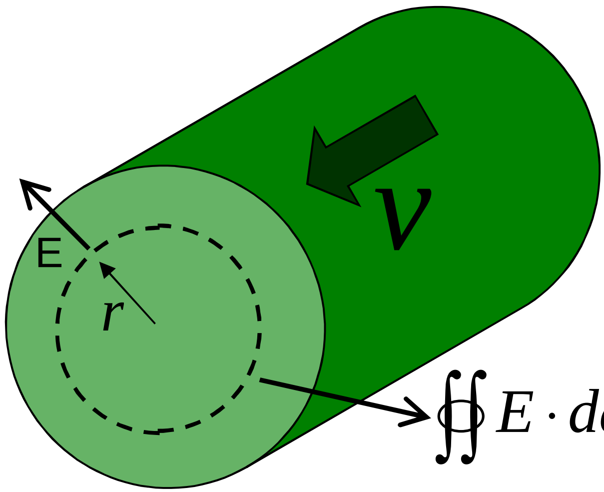
$$\oint B \cdot ds = 2\pi r B = \mu_0 \pi r^2 v \rho \quad \rightarrow \quad B = \frac{\mu_0 v \rho}{2} r$$



$$\begin{cases} B_x = -\dfrac{\mu_0 v \rho}{2} r \sin\theta \\ B_y = \dfrac{\mu_0 v \rho}{2} r \cos\theta \end{cases}$$

Electric field of a charged-particle beam

$$\rho = \text{uniform charge density}$$

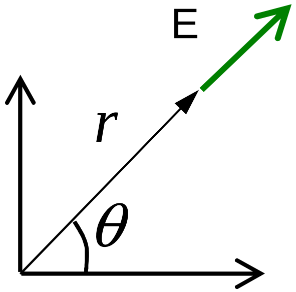


Gauss's law:

$$\oiint \vec{E} \cdot d\vec{a} = \frac{Q}{\varepsilon_0}$$

charge inside the volume

$$\oiint E \cdot da = E\, 2\pi\, r\, l = \frac{\pi r^2 l\, \rho}{\varepsilon_0} \quad \rightarrow \quad E = \frac{\rho}{2\varepsilon_0} r$$

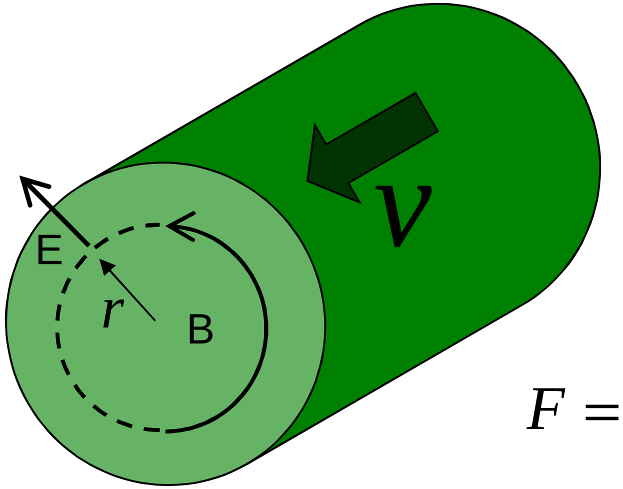


$$\begin{cases} E_x = \dfrac{\rho}{2\varepsilon_0} r \cos\theta \\[2ex] E_y = \dfrac{\rho}{2\varepsilon_0} r \sin\theta \end{cases}$$

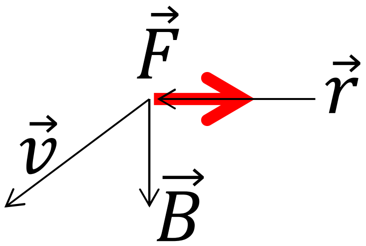
Electric and magnetic forces

$\rho =$ uniform charge density

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



$$F = q(E - vB) = q\left(\frac{\rho}{2\varepsilon_0}r - v\frac{\mu_0 v\rho}{2}r\right)$$



$$F = \frac{q\rho r}{2\varepsilon_0}\left(1 - \varepsilon_0\mu_0 v^2\right) = \frac{q\rho r}{2\varepsilon_0}\left(1 - \frac{v^2}{c^2}\right)$$

$$\boxed{F = \frac{q\rho r}{2\varepsilon_0\,\gamma^2}}$$