Introduction to Accelerator Physics

Part 1

Pedro Castro / Accelerator Physics Group (MPY)
Introduction to Accelerator Physics
DESY, 24th July 2017

HELMHOLTZ ASSOCIATION

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

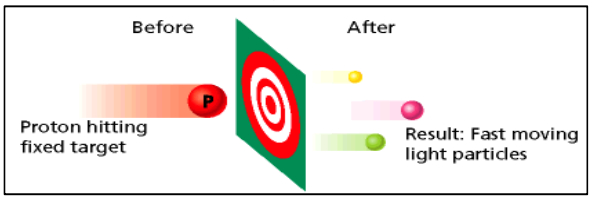
DESY

Applications of accelerators

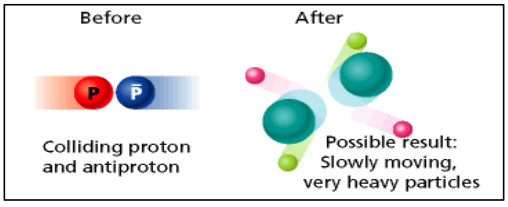
Applications of Accelerators (1)

Particle colliders for High Energy Physics (HEP) experiments

Fixed target experiments



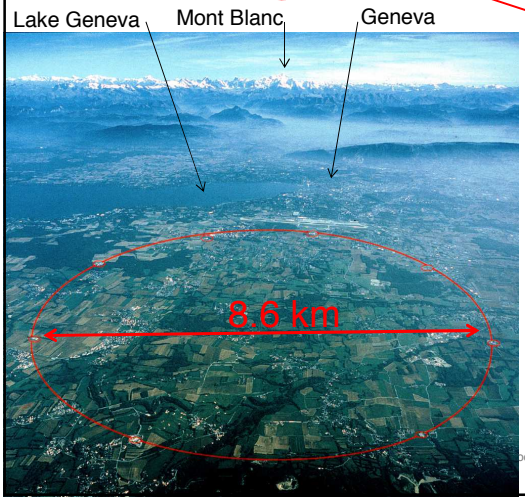
Two beams collider experiments

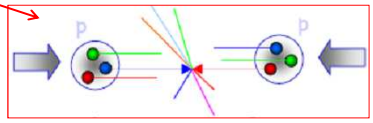


Applications of Accelerators (1)

Particle colliders for High Energy Physics experiments

Example: the Large Hadron Collider (LHC) at CERN





built between 2001 and 2009
Higgs discovery: July 2012

superconducting magnets
(inside a cryostat)

Worldwide …

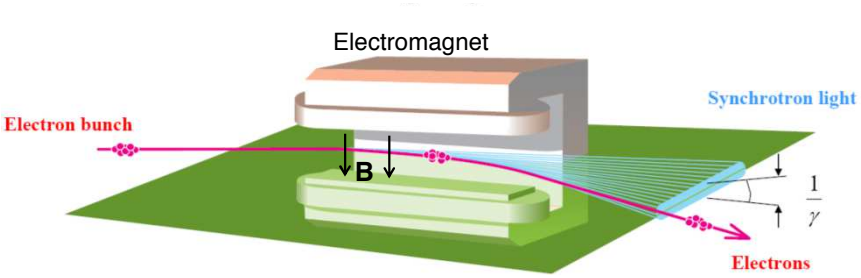
- About 120 accelerators for research in "nuclear and particle physics" http://en.wikipedia.org/wiki/List_of_accelerators_in_particle_physics

Applications of Accelerators (2)

Light sources for biology, physics, chemistry… experiments

Applications of Accelerators (2)

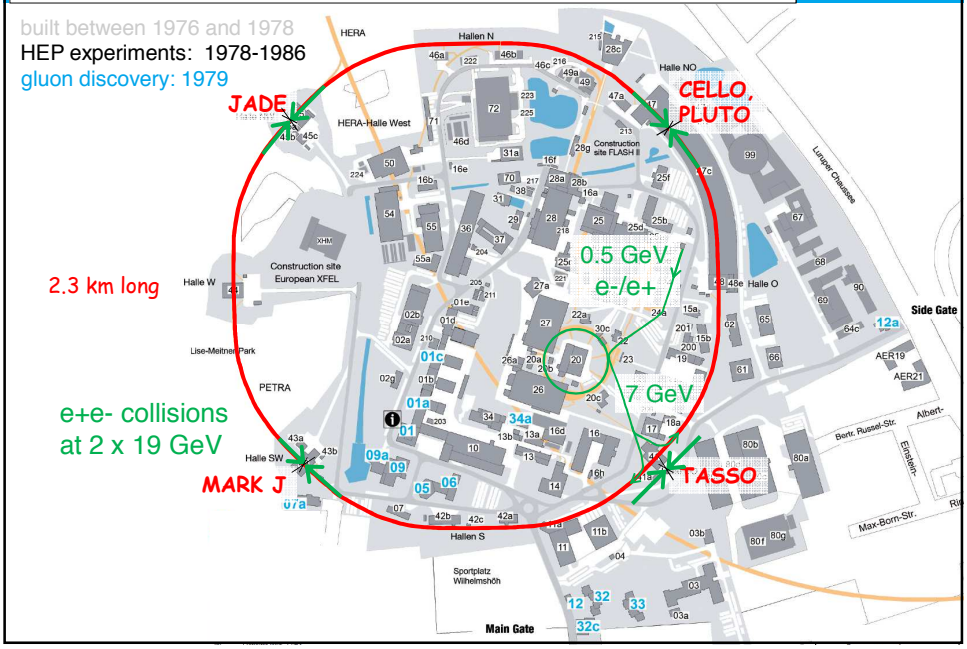
Light sources for biology, physics, chemistry… experiments



- 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



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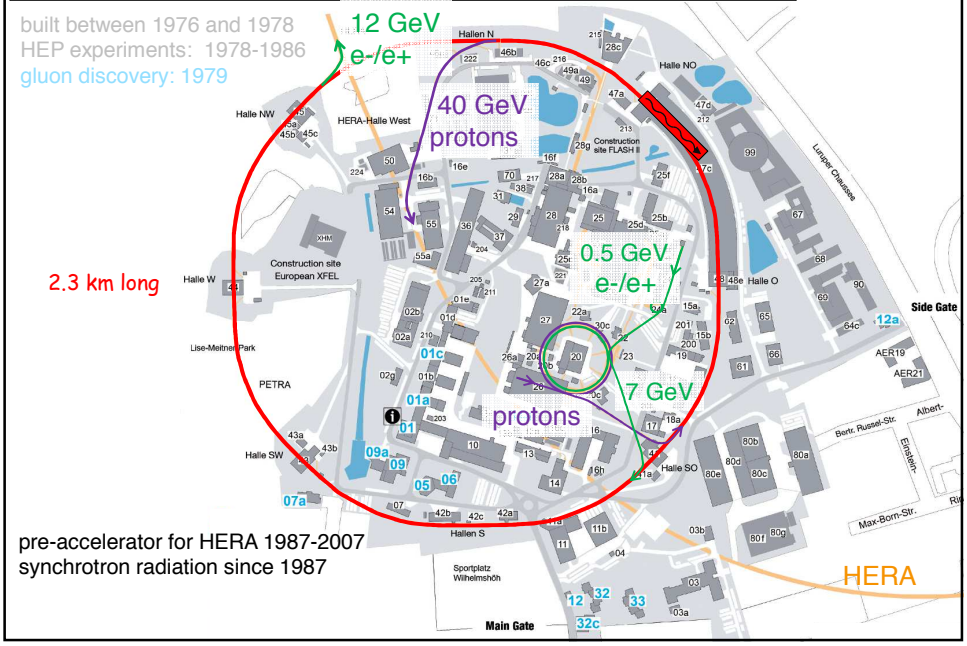

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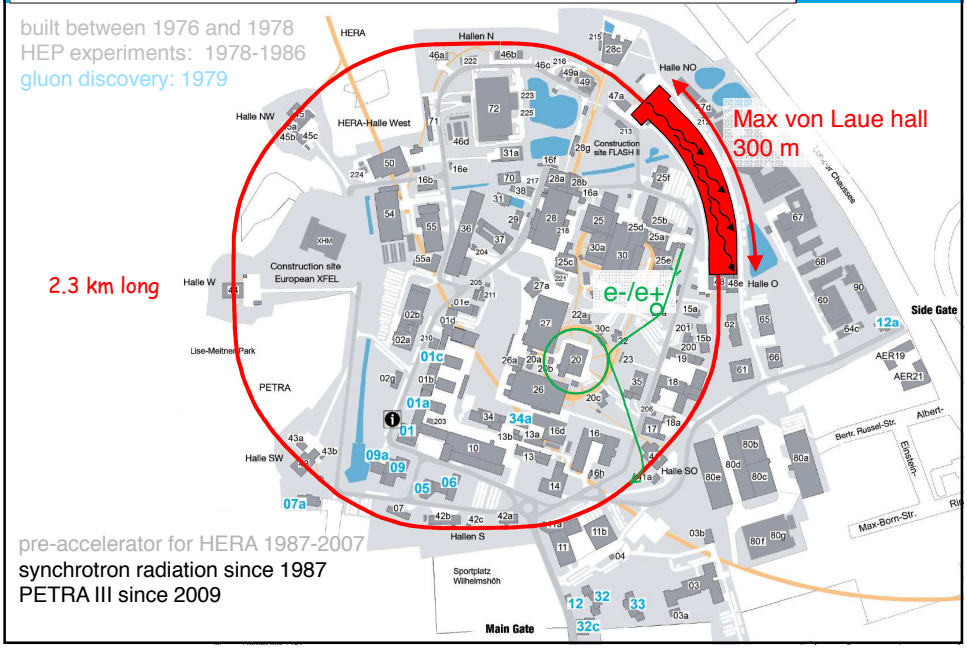
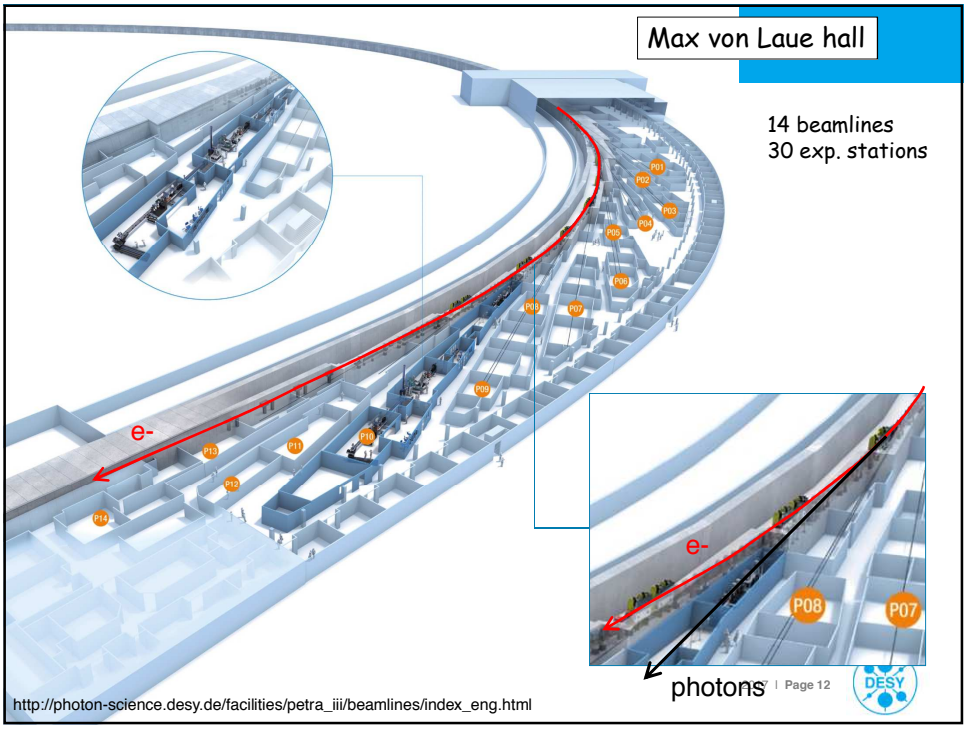


pre-accelerator for HERA 1987-2007
synchrotron radiation since 1987
PETRA III since 2009

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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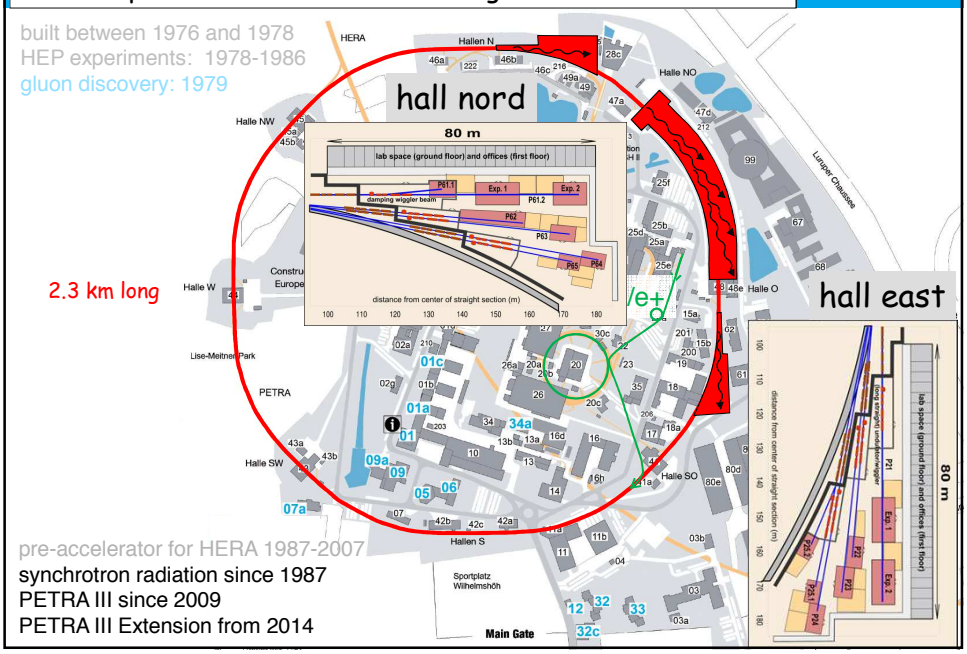


2.3 km long

pre-accelerator for HERA 1987-2007
synchrotron radiation since 1987
PETRA III since 2009
PETRA III Extension from 2014

Worldwide ...

- About 120 accelerators for research in "nuclear and particle physics" http://en.wikipedia.org/wiki/List_of_accelerators_in_particle_physics
- About 70 electron storage rings and electron linear accelerators used as light sources (so-called 'synchrotron radiation sources')
  http://en.wikipedia.org/wiki/List_of_synchrotron_radiation_facilities

Applications of Accelerators (3)

Accelerators in medicine

For radioisotope production

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

cyclotron | 18 MeV proton accelerator

Applications of Accelerators (3)

Accelerators in medicine

For radioisotope production

For example:

18 MeV proton accelerator —p→ target: Oxygen-18 (stable) —(transmutation)→ Fluorine-18 (half-life time = 110 min.)

97% of decays

Oxygen-18 + positron

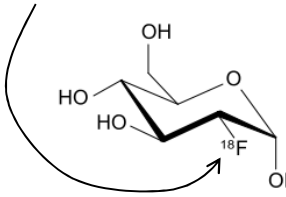
Applications of Accelerators (3)

Accelerators in medicine

For radioisotope production

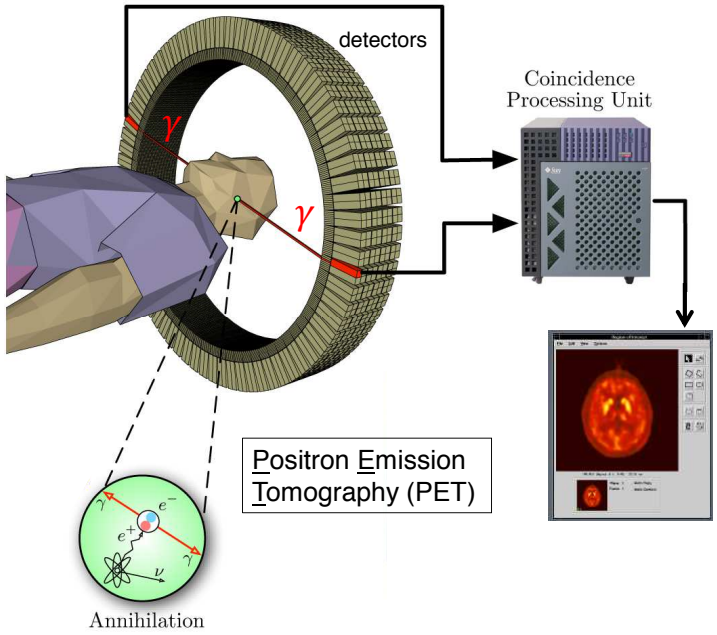
For example:

18 MeV proton accelerator —p→ target: Oxygen-18 —(transmutation)→ Fluorine-18 (half-life time = 110 min.)

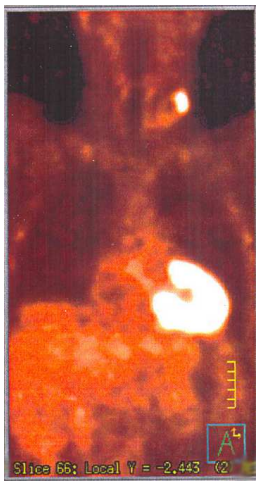


Fludeoxyglucose (^{18}F)

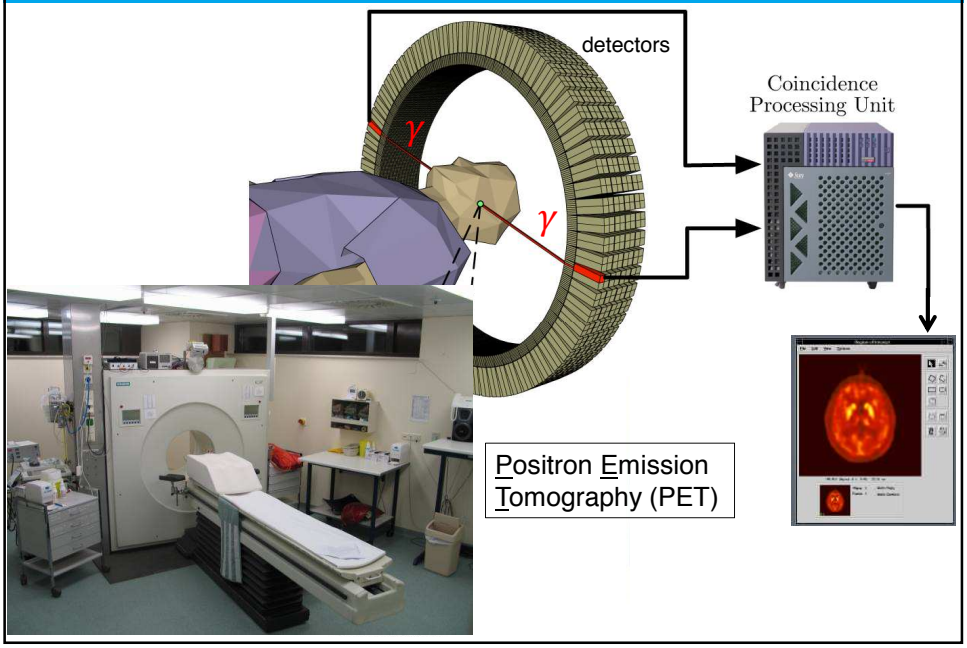
Applications of Accelerators (3)



PET



Applications of Accelerators (3)



Positron Emission Tomography (PET)

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)

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

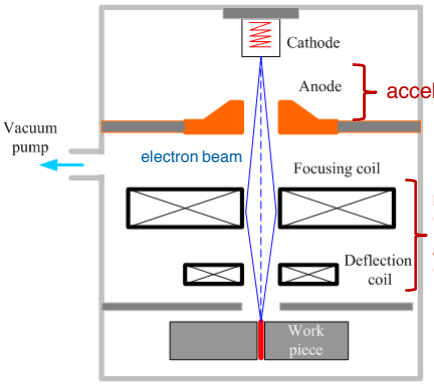
approx. numbers from 2007 (worldwide)

with energies up to 15 MeV

Applications of Accelerators (4)

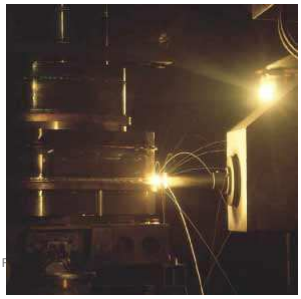
For industrial applications:

an example: electron beam welding



acceleration up to 60-200 keV

magnets as 'focusing lenses' as well as 'deflectors'



up to 15 cm

'deep welding effect'

Worldwide …

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- 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) …

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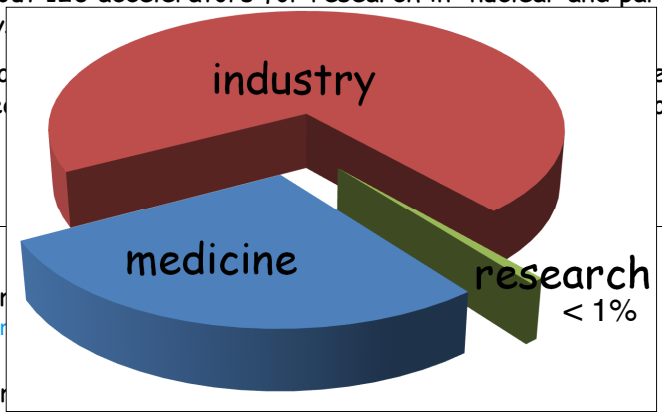

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- Mor
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Worldwide …

- 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')

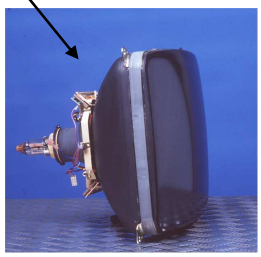
…and there is more !!!

- 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) …

Applications of Accelerators (5)

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

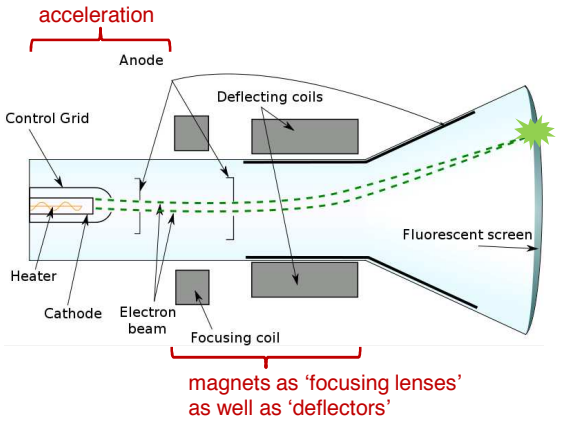
TV

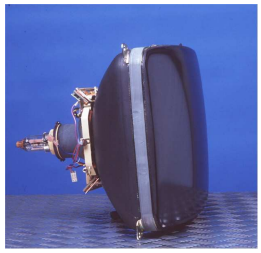


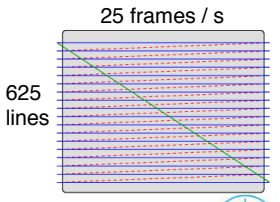
oscilloscope

Applications of Accelerators (5)

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

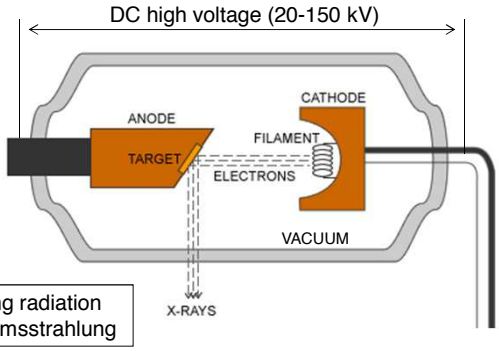






Applications of Accelerators (6)

X-ray tubes



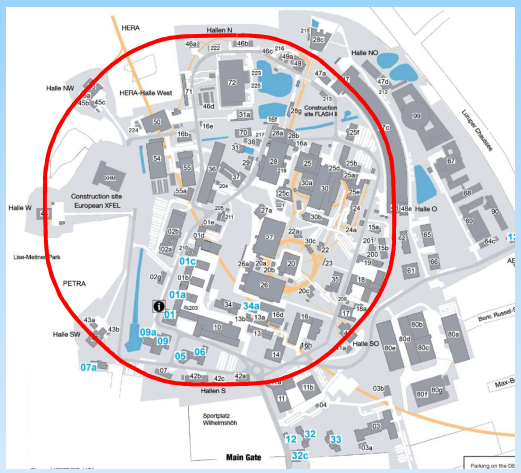
braking radiation or bremsstrahlung

Working with accelerators in the control room …

…requires:

- a lot of (accelerator) physics knowledge
- a lot of (accelerator) engineering knowledge
- some Sherlock Holmes' skills

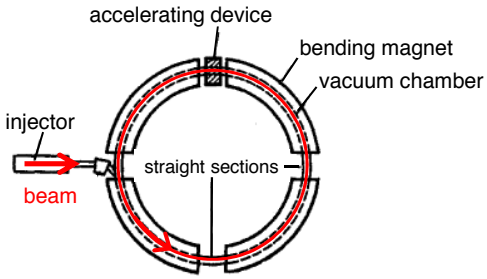
The case begins…



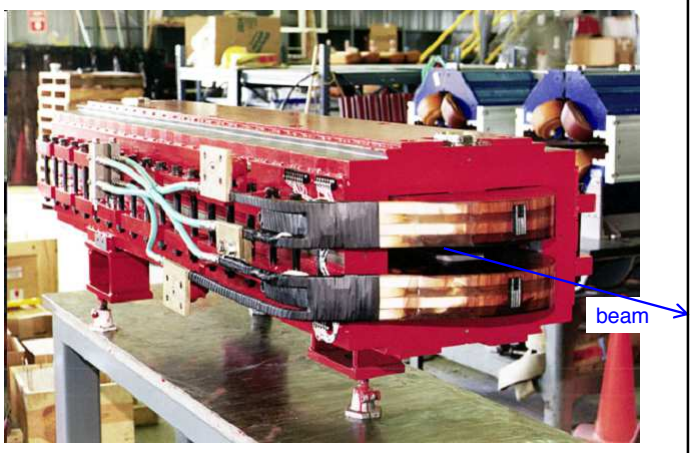
Accelerator Control Room
Hamburg, DESY
Sat. 12th June 2010
2 o'clock a.m.
PETRA runs with a beam current of 75 mA

02:24 a.m.: beam lost

Circular accelerators: the synchrotron

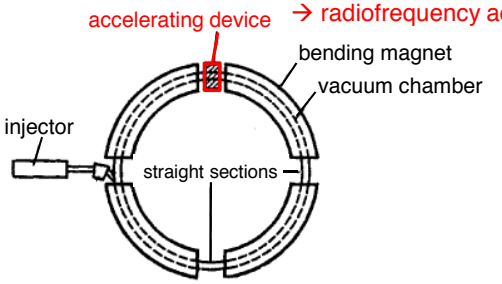


Dipole magnet



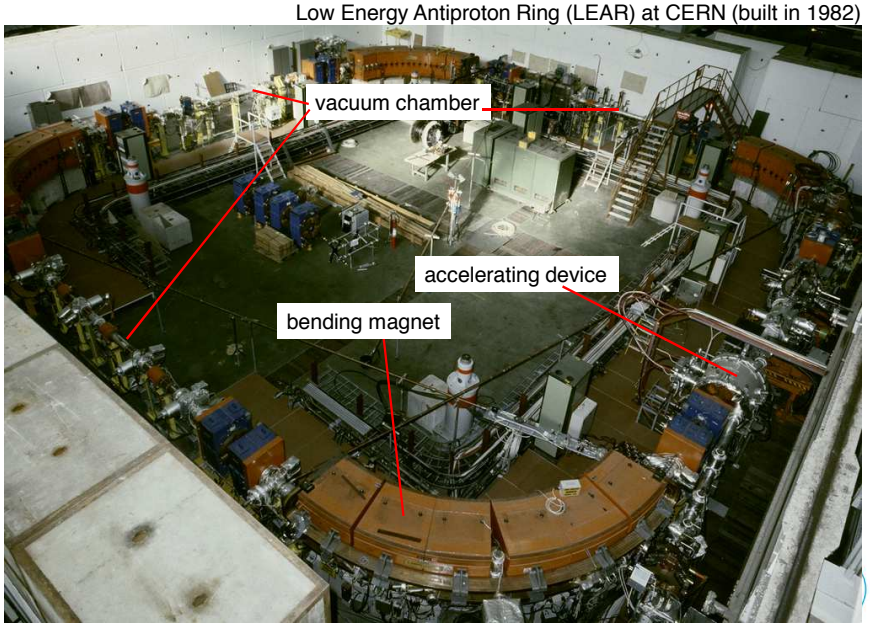
→ dipole magnets: tomorrow

Circular accelerators: the synchrotron

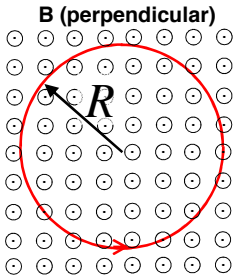


Circular accelerators: the synchrotron

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



Circular accelerators: the synchrotron



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

momentum, charge, velocity: of the particle; magnetic field

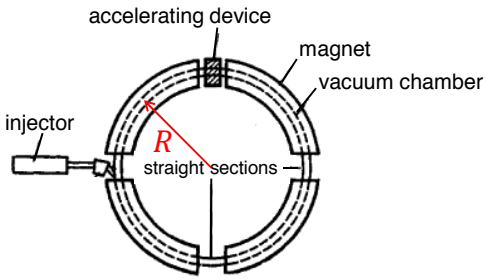
$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = qvB$$

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

(circular motion)

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

Circular accelerators: the synchrotron



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

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

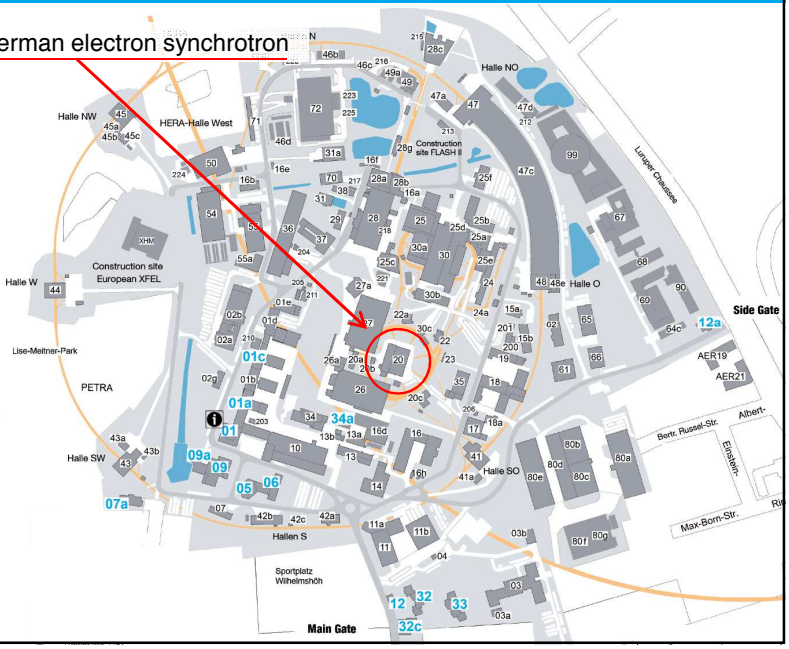
(circular motion)

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

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

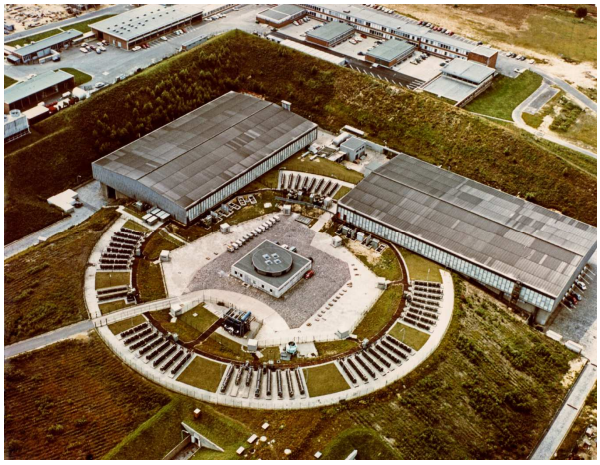
DESY (Deutsches Elektronen Synchrotron)

DESY: German electron synchrotron



DESY (Deutsches Elektronen Synchrotron)

DESY: German electron synchrotron, 1964, 7.4 GeV

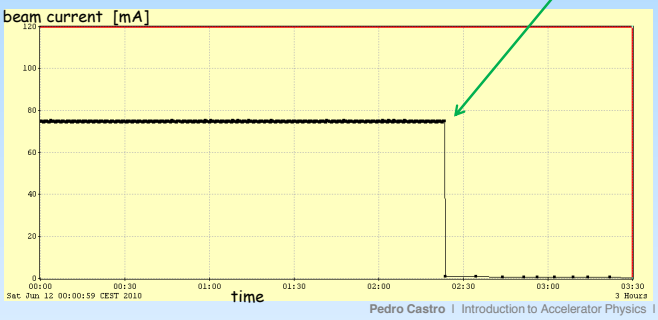


02:24 a.m.: beam lost

The Main Accelerator Control Room

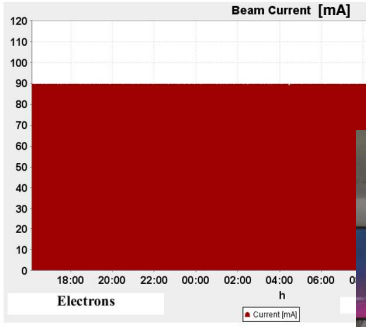
Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost



PETRA runs with beam around the clock

PETRA Energy: 6.083 GeV Lifetime: 1.36 h Current: 89.55 mA



Und.	Gap	Status
PU01a	17.91	
PU01b	18.13	
PU02	10.51	
PU03	11.04	
PU04	23.46	
PU05	10.56	

Number of Bunches: 40 Mea

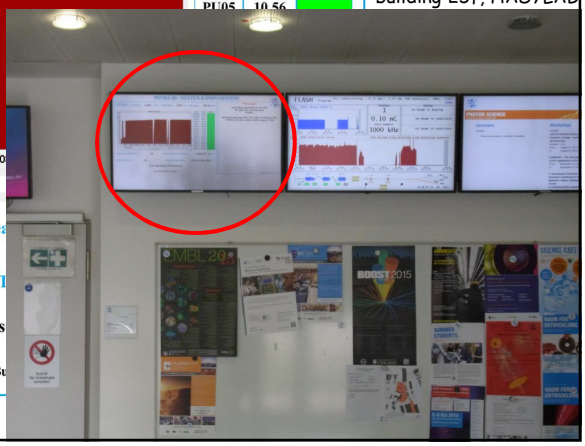
Orbit Control: On T

User Operations

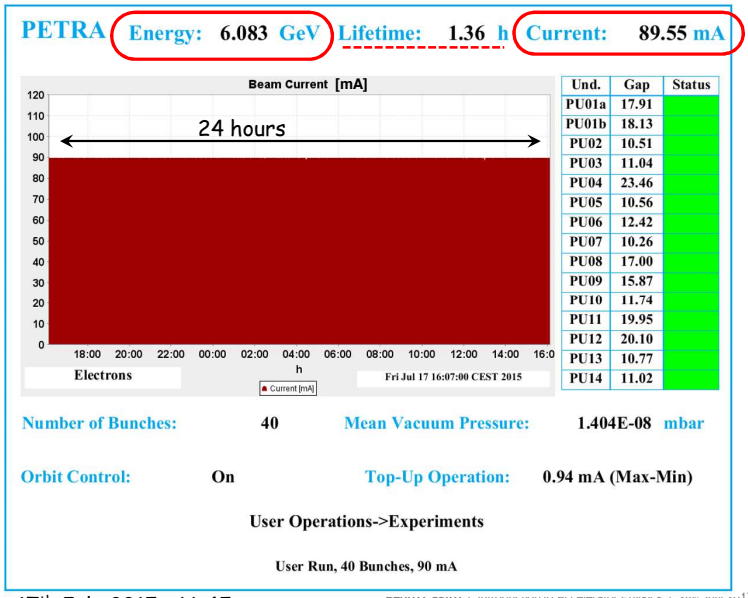
User Run, 40 Bu

17th July 2015 16:45

building 25f, HASYLAB



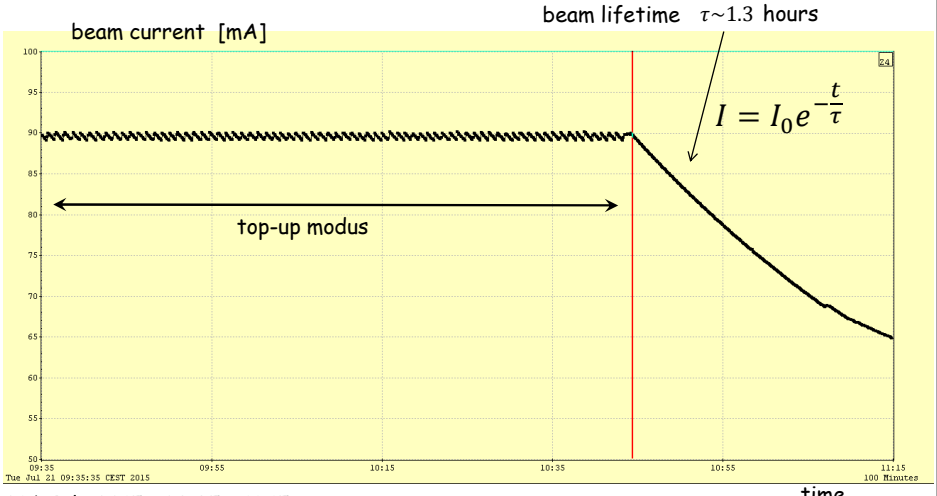
PETRA runs with beam around the clock



Und.	Gap	Status
PU01a	17.91	
PU01b	18.13	
PU02	10.51	
PU03	11.04	
PU04	23.46	
PU05	10.56	
PU06	12.42	
PU07	10.26	
PU08	17.00	
PU09	15.87	
PU10	11.74	
PU11	19.95	
PU12	20.10	
PU13	10.77	
PU14	11.02	

17th July 2015 16:45

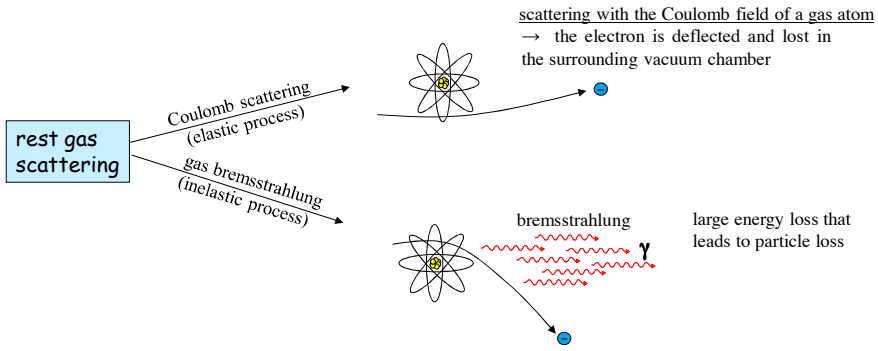
An example of PETRA running with 'top-up' modus on/off



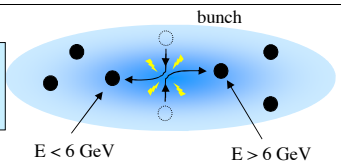
21st July 2015 09:35 - 11:15

Beam lifetime

The lifetime of an electron beam is mainly limited by two effects:

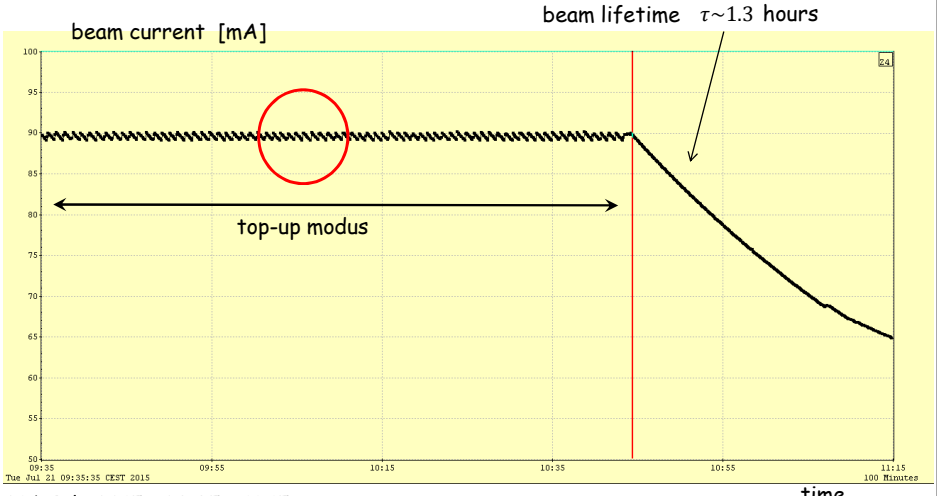


Coulomb scattering between two electrons from the same bunch



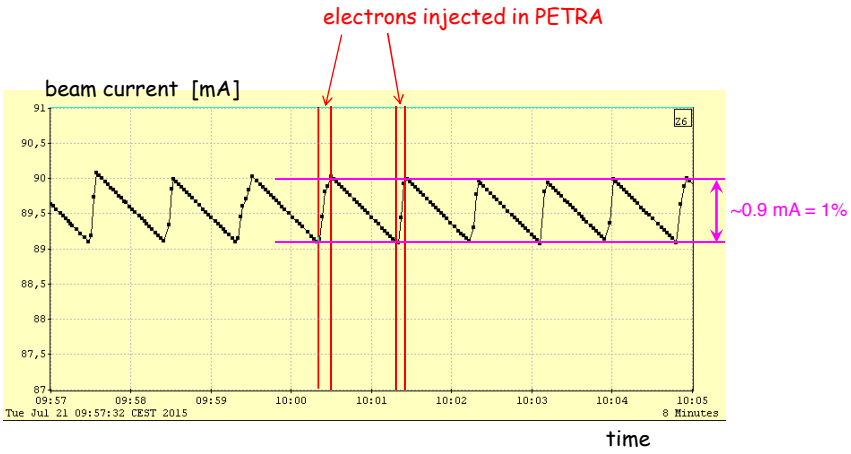
electrons can gain or loose energy
→ called Touchek effect
→ depends on the density of the electron bunch

An example of PETRA running with 'top-up' modus on/off



21st July 2015 09:35 - 11:15

'top-up' modus



'top-up' modus

What are the advantages of running in 'top-up' modus?

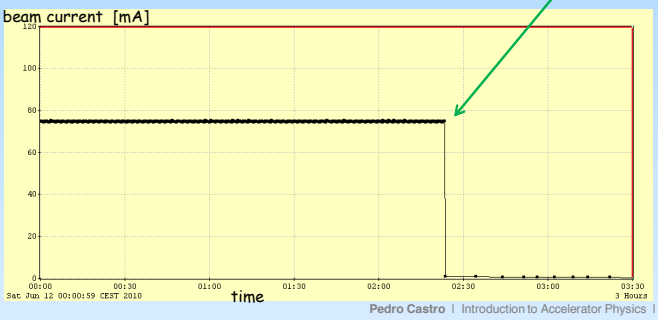
- stable intensity conditions for measurements
- constant heat load on optical components (mirrors, filters, crystals…)
  - stable photon beam angle and position ('pointing stability')
  - stable wavelength
- constant heat load on accelerator vacuum chamber
- increased stability of all systems
- diagnostics: small dynamic range

02:24 a.m.: beam lost

The Main Accelerator Control Room

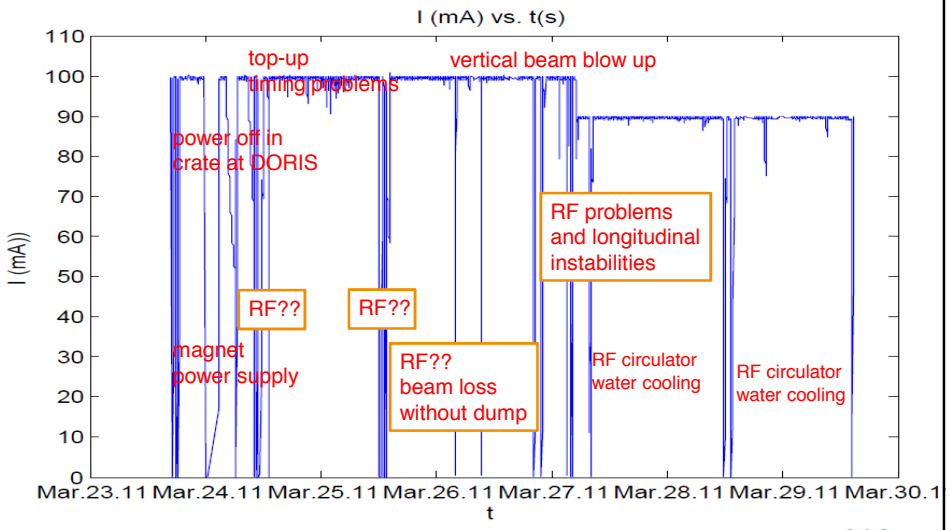
Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost



One example of PETRA run over 7 days

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



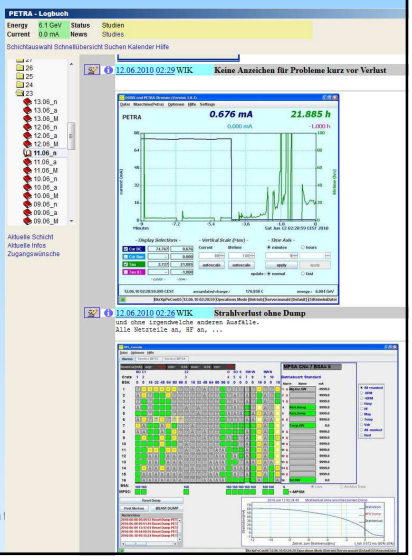
Source: K. Balewski (MAC report 2011)

Beam lost at 02:24 a.m.

The link to the electronic logbook:

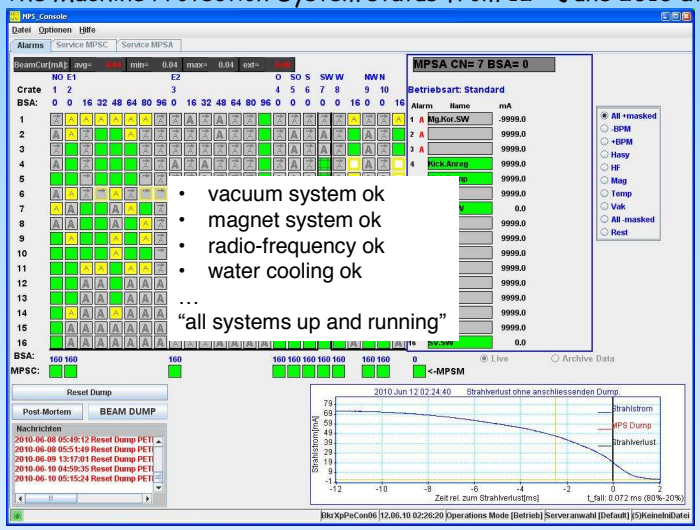
http://ttfinfo.desy.de/petra/show.jsp?dir=/2010/23/11.06_n&pos=2010-06-12T02:26:30

What to do?



The first suspect released: MPS is not guilty

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



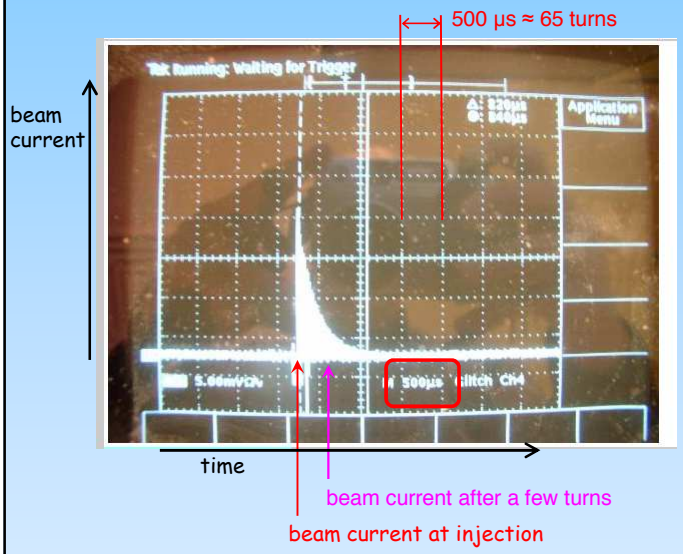
- vacuum system ok
- magnet system ok
- radio-frequency ok
- water cooling ok

…

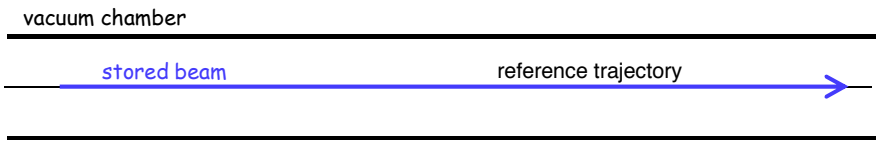
"all systems up and running"

12th June 2010 02:26

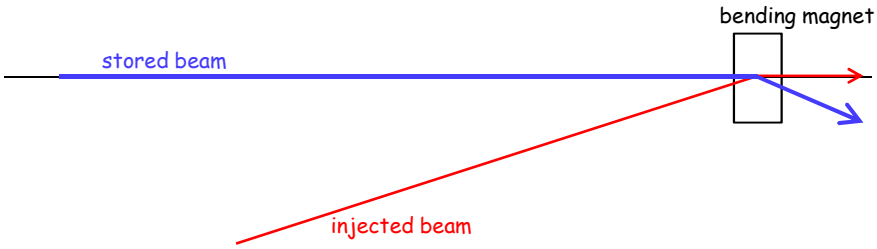
Electrons can be injected but cannot be stored !



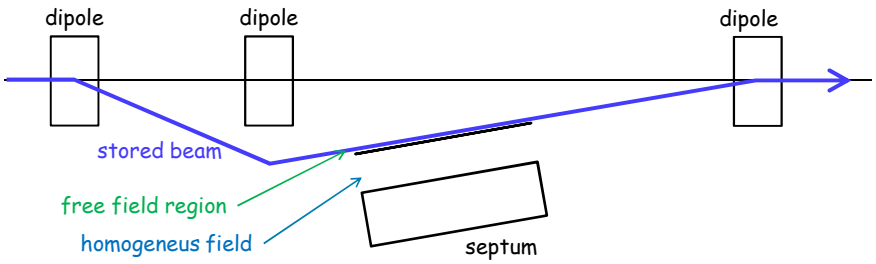
Next suspect: injection



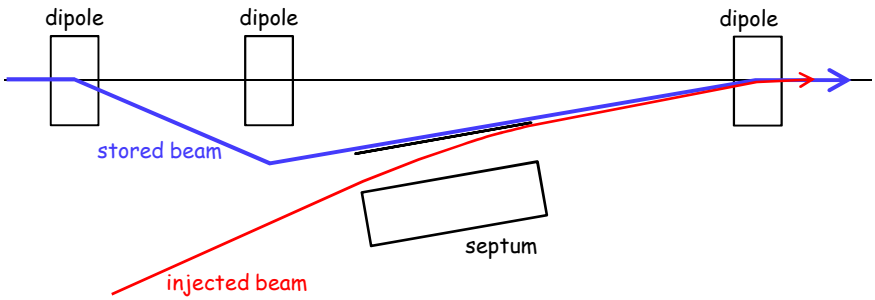
Next suspect: injection



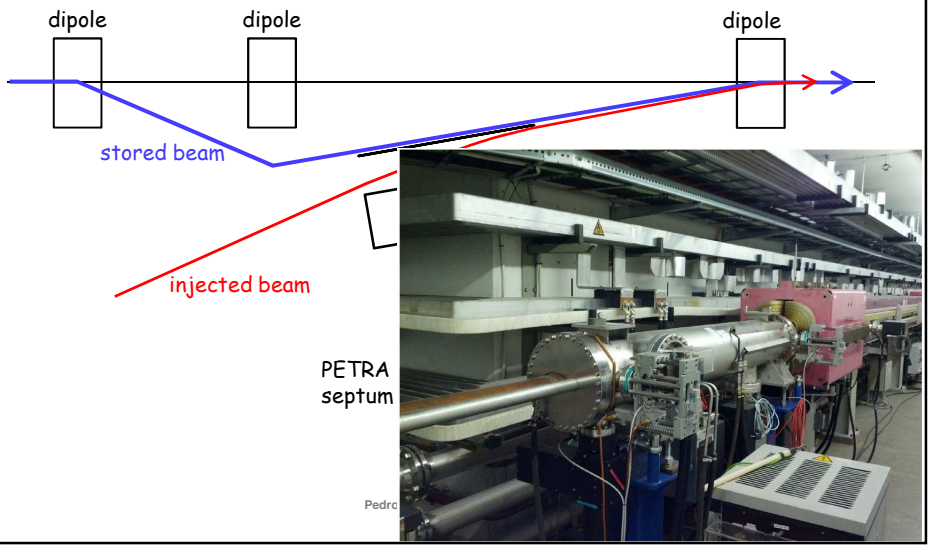
Next suspect: injection



Next suspect: injection + accumulation

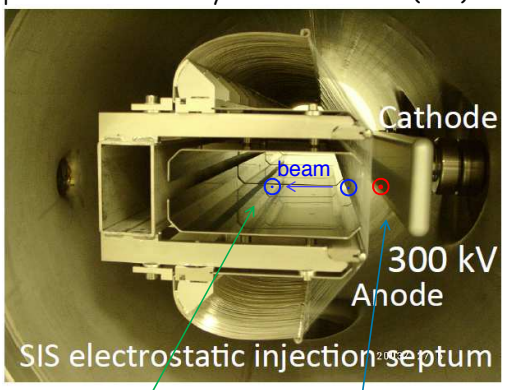


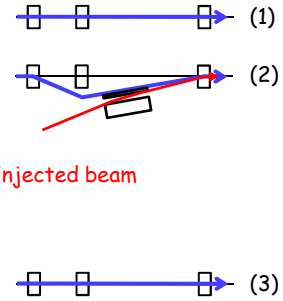
Next suspect: injection + accumulation



Next suspect: injection + accumulation

septum at the Proton Synchrotron Booster (PSB) at CERN





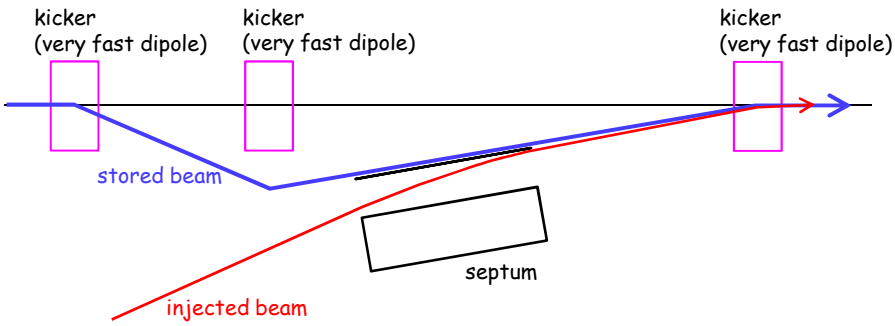
stored beam

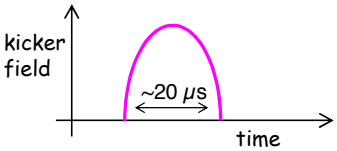
injected beam

free field region

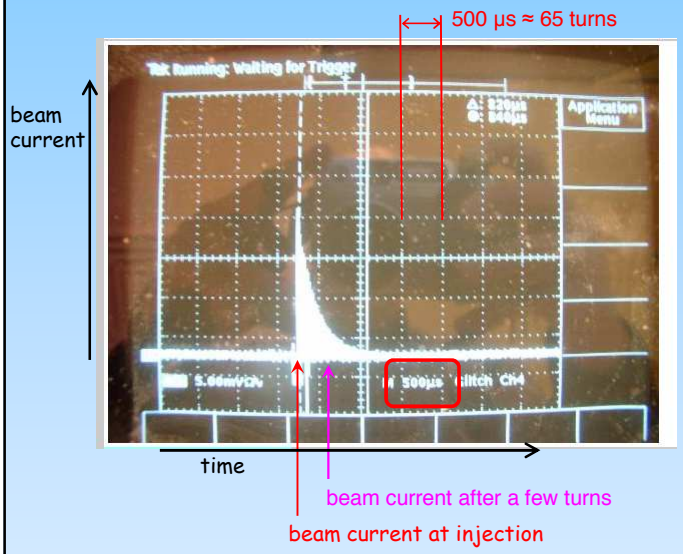
homogeneus field

Next suspect: injection + accumulation





Electrons can be injected but cannot be stored !



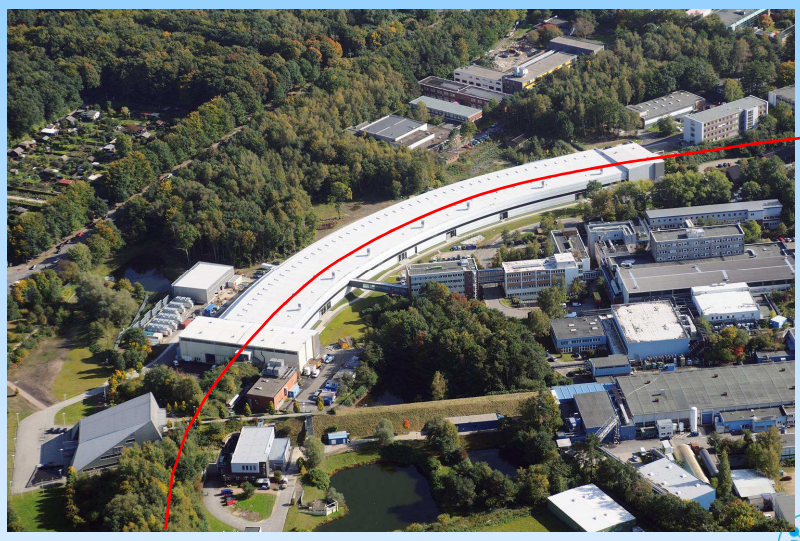
~~injection problem~~
or
aperture problem?

Next suspect: an aperture problem

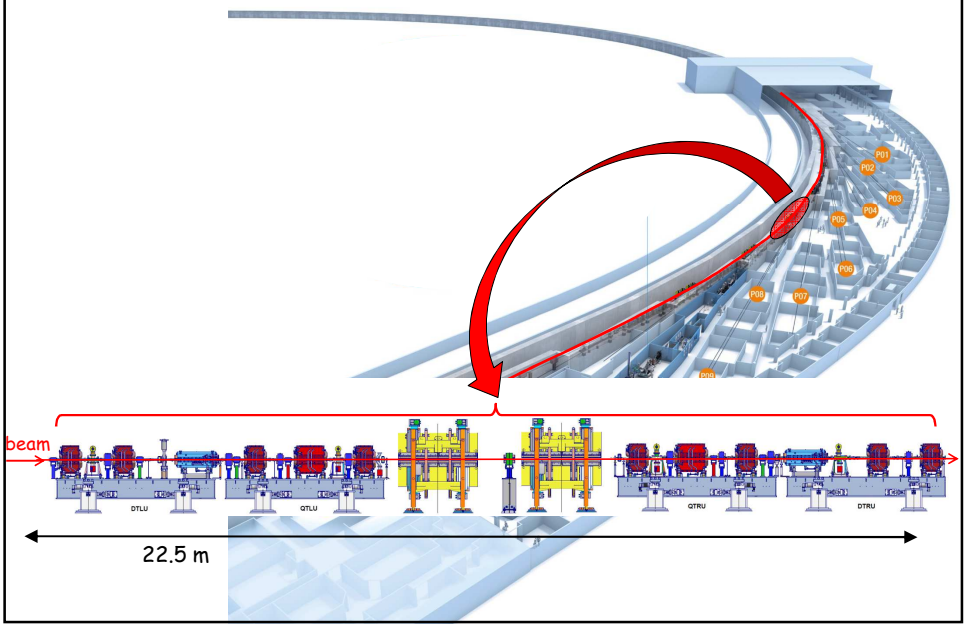
Hamburg, DESY
Sat. 12th June 2010

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'

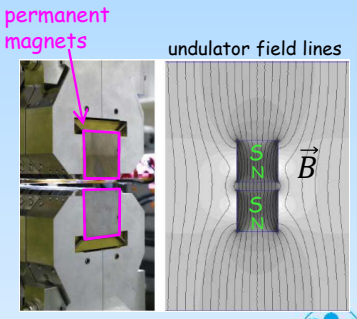


Next suspect: the new octant in 'Max von Laue hall'

Undulator PU 10

Hamburg, DESY
Sat. 12th June 2010

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

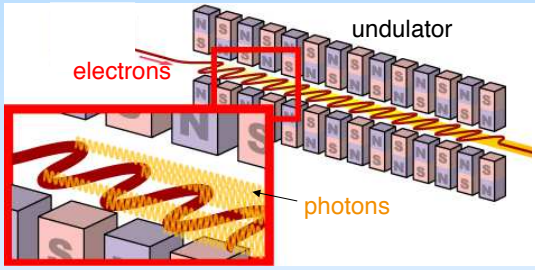


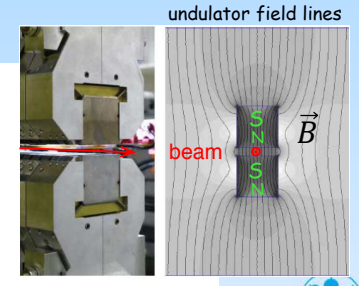
Next suspect: the new octant in 'Max von Laue hall'

Undulator PU 10

Hamburg, DESY
Sat. 12th June 2010

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





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
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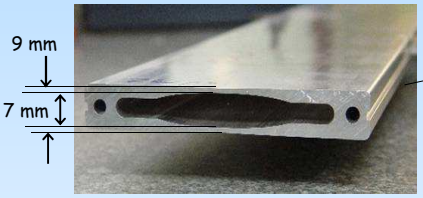
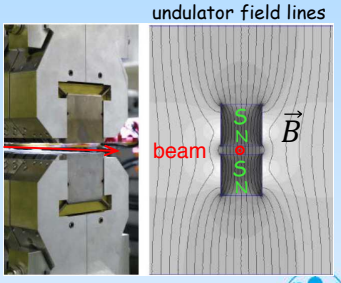
very flat undulator vacuum chambers

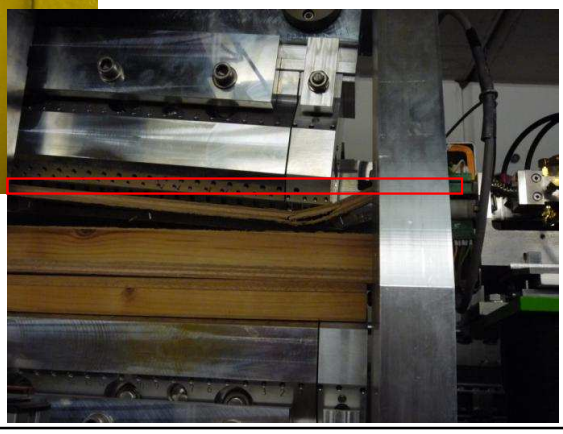


undulator field lines



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

a couple of months earlier…



vacuum chamber

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**

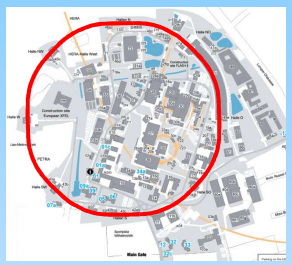
Naja, bis auf den BPM nach Undulator PU03 dort haben wir 6 µSv/h gemessen, alle anderen < 1 µSv/h.

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"

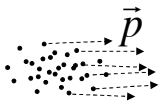
Next suspect: an aperture problem



Hamburg, DESY
Sat. 12th June 2010

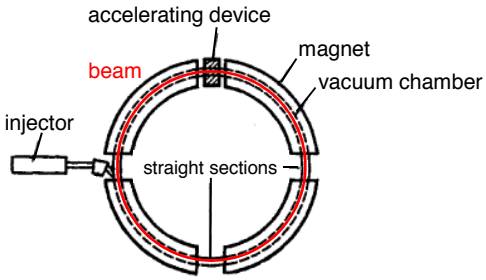
02:24 a.m.: beam lost
07:00 a.m.: visual inspection in new octant
11:52 a.m.: start aperture scan

Need of focusing



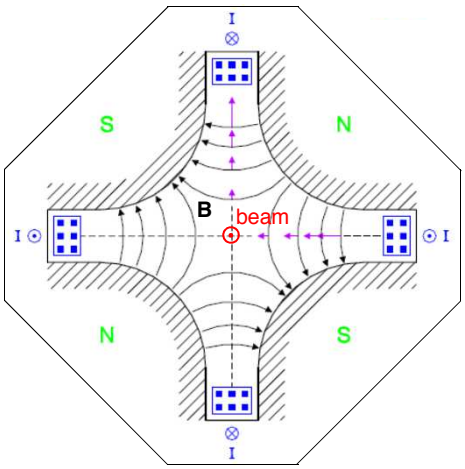
beam / bunch

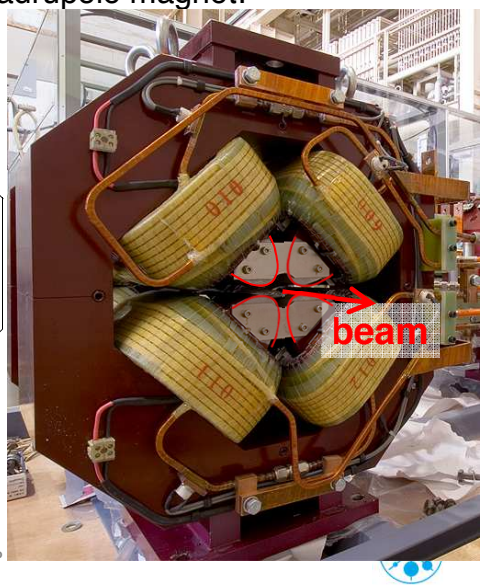
we need to focus the beam !



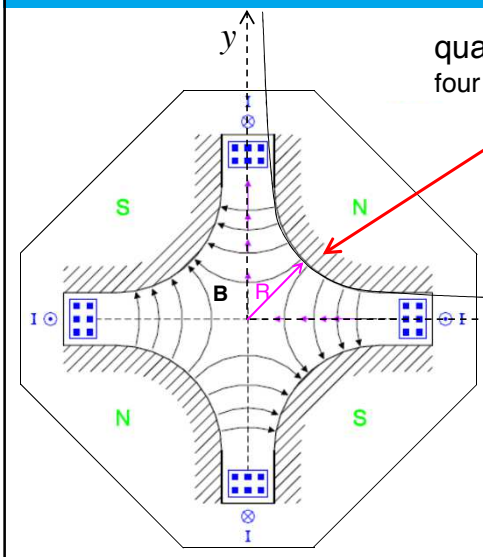
Quadrupole magnets

quadrupole magnet:





Quadrupole magnets

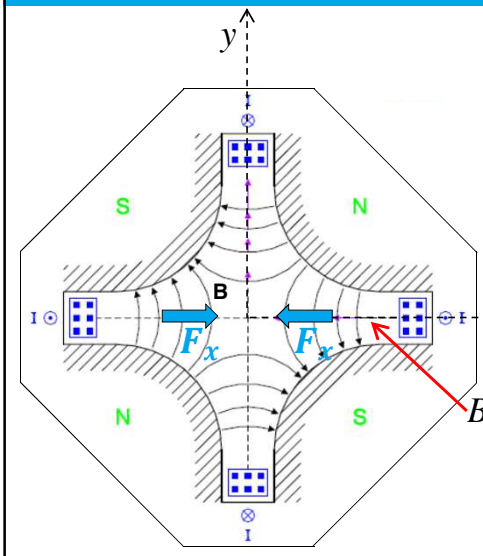


quadrupole magnet:
four iron pole shoes of hyperbolic contour

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

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

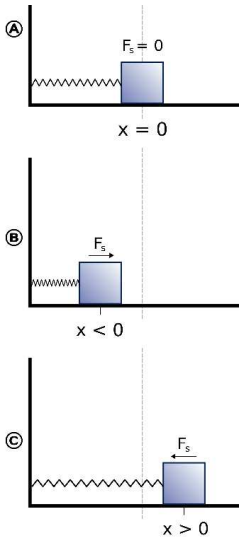
Quadrupole magnets



$$B_y = -g \cdot x \Rightarrow F_x = -g \cdot x$$

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

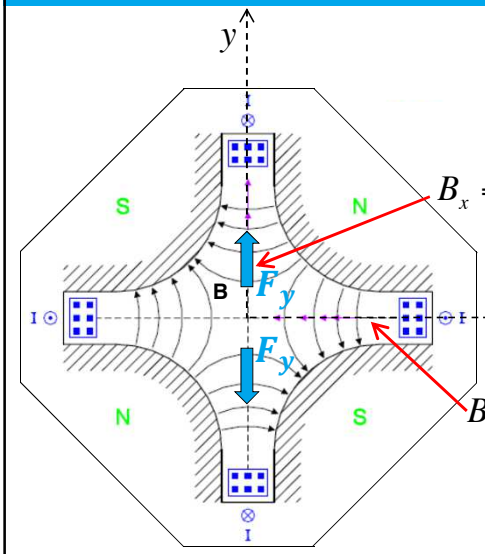
Classical mechanics: harmonic oscillator



restoring force:

$$F = -kx$$

Quadrupole magnets



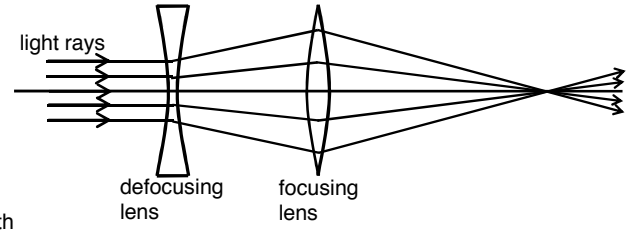
$$B_x = g \cdot y \quad \Rightarrow \quad F_y = g \cdot y$$

defocusing

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

focusing !

In light optics…



f: focal length

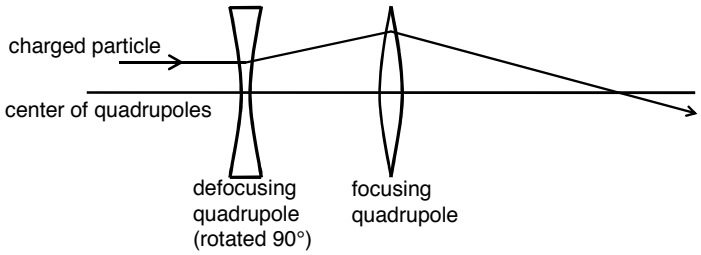
f^*: system focal length

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

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

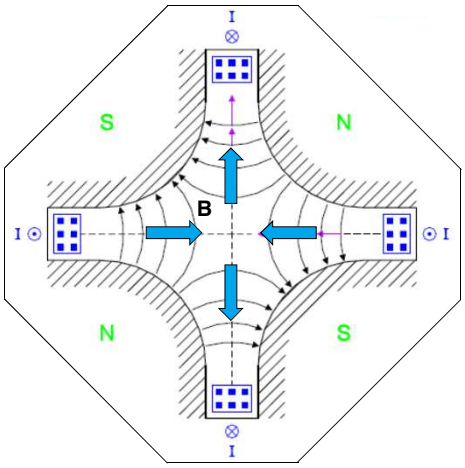
Quadrupole magnets

QD + QF = net focusing effect:

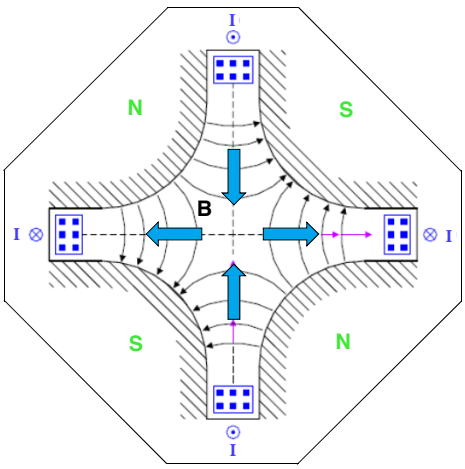


Quadrupole magnets

vertical defocusing
horizontal focusing



vertical focusing
horizontal defocusing



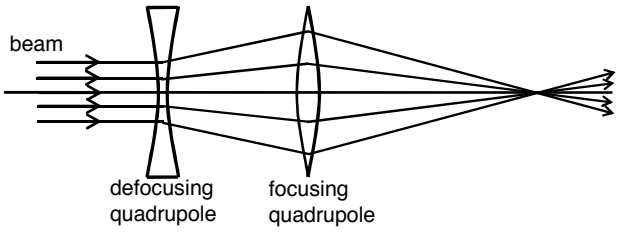
rotated 90°

$\bar{I} = -\bar{I}$

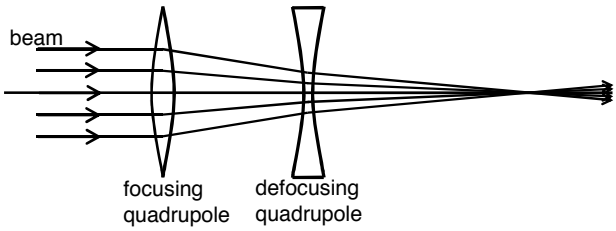
Quadrupole magnets

QD + QF = net focusing effect:

x-plane:

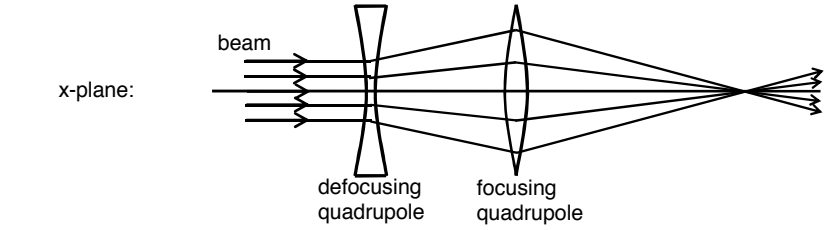


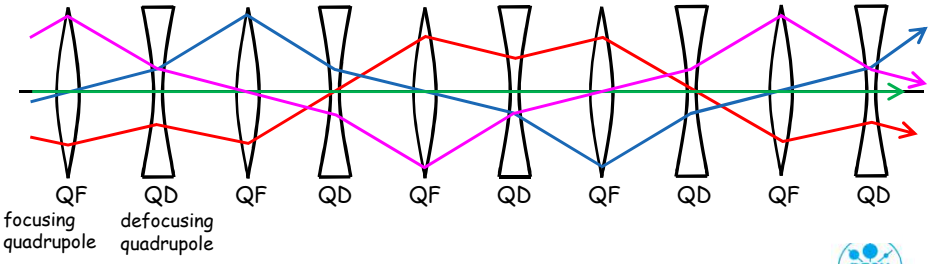
y-plane:



Quadrupole magnets

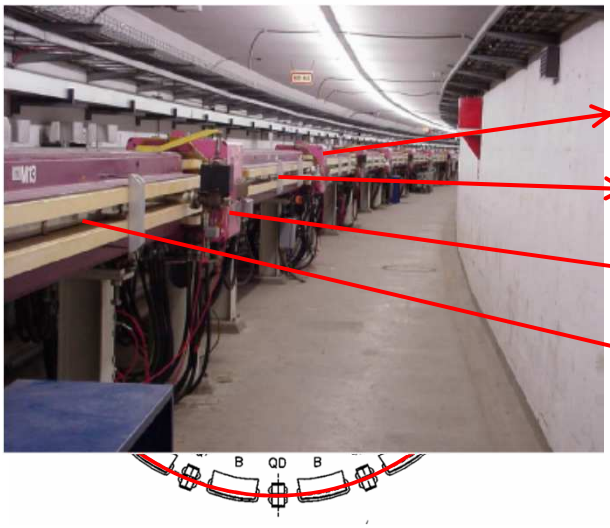
QD + QF = net focusing effect:

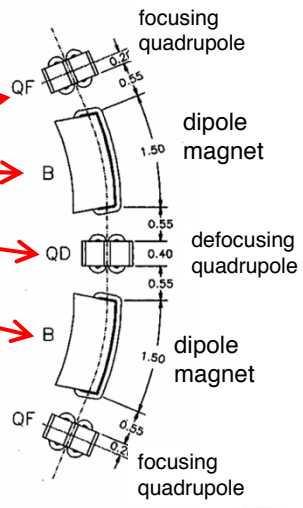




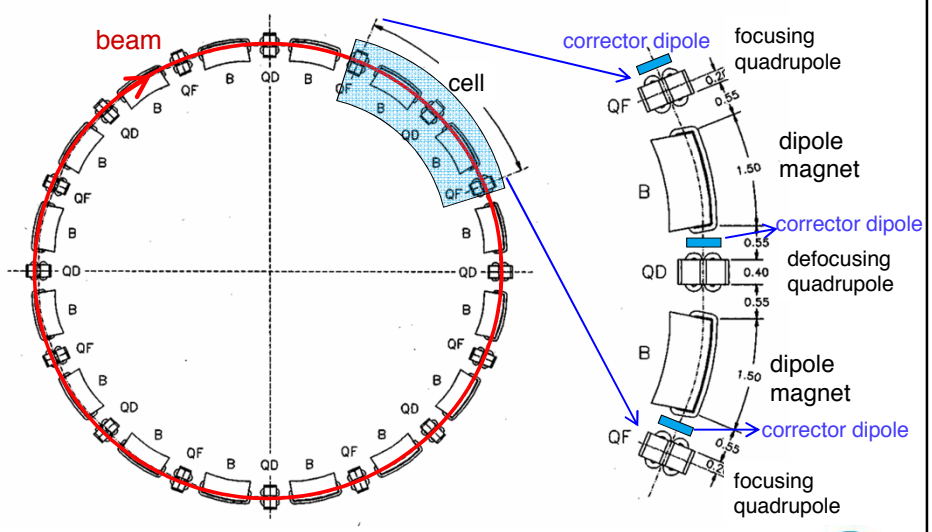
Circular accelerator

PETRA

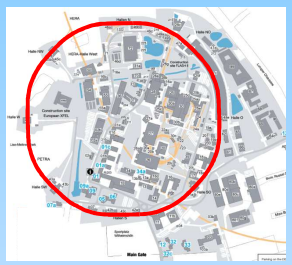




Circular accelerator



Next suspect: an aperture problem



Hamburg, DESY
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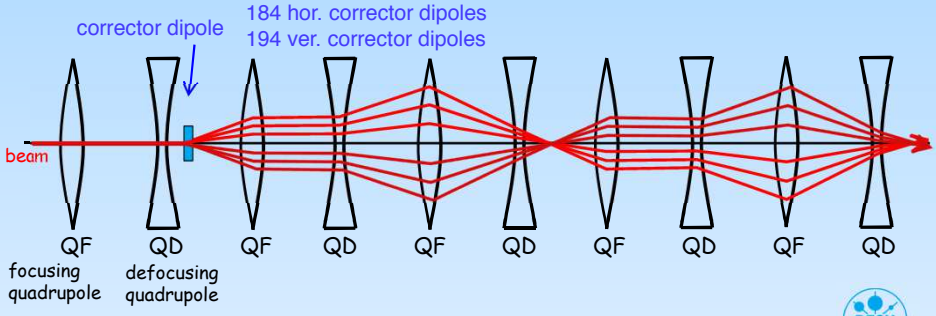
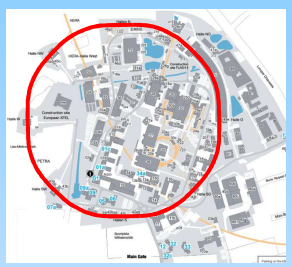
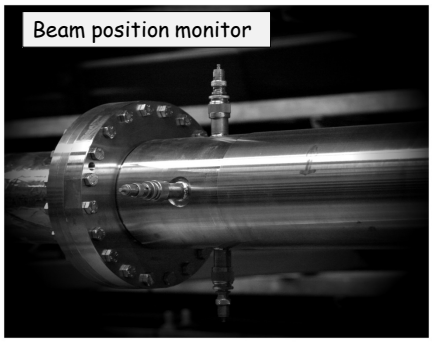


First useful hint: aperture problem



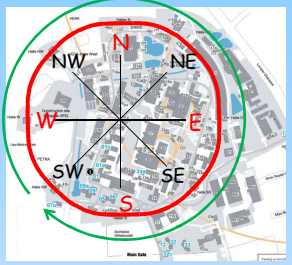
Hamburg, DESY
Sat. 12th June 2010

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 beam position monitors

First useful hint: aperture problem



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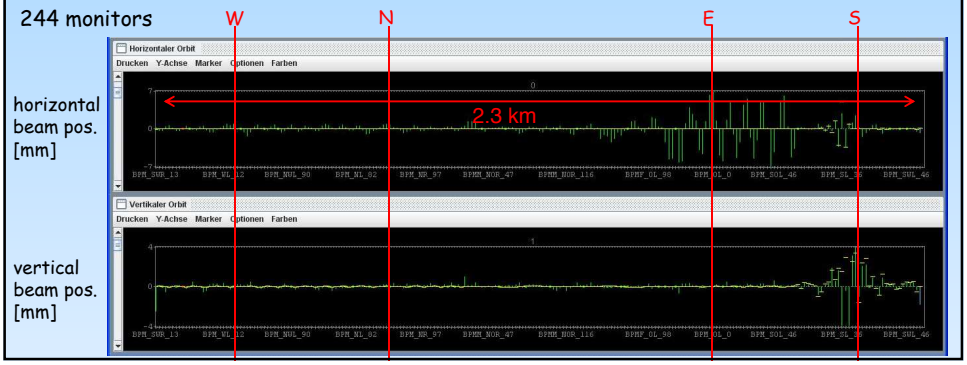
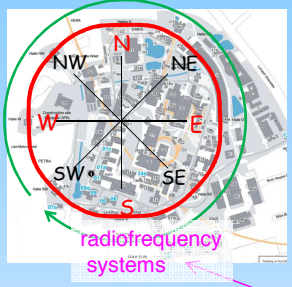
244 monitors



horizontal beam pos. [mm]

vertical beam pos. [mm]

First useful hint: horizontal aperture problem



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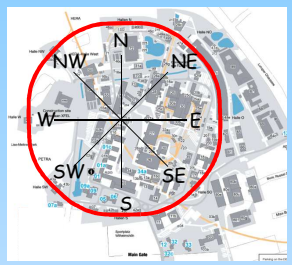
244 monitors

horizontal beam pos. [mm]

vertical beam pos. [mm]

First useful hint: horizontal aperture problem



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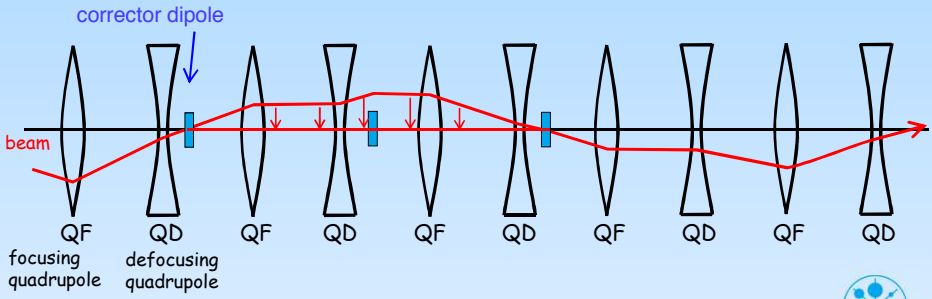
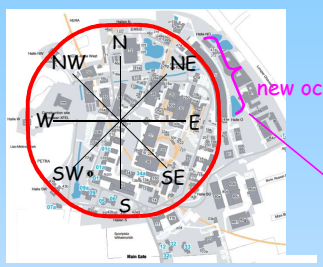


First useful hint: horizontal aperture problem



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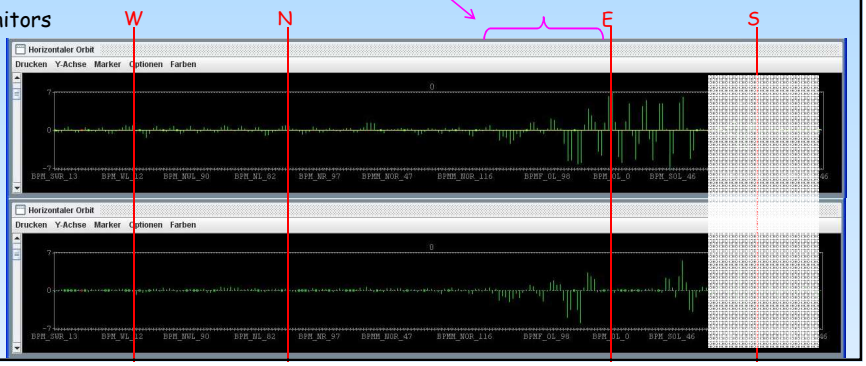
244 monitors

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**

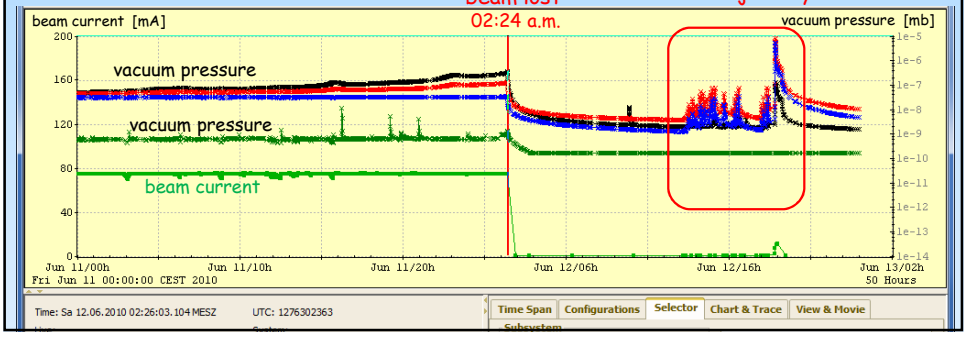
Wir korrigieren abschnittsweise den horizontalen Orbit auf den goldenen Orbit und überprüfen nach jeder Korrektur, ob sich noch Strahl injizieren läßt. Der Injektionsbereich SOR wird dabei ausgelassen.

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.

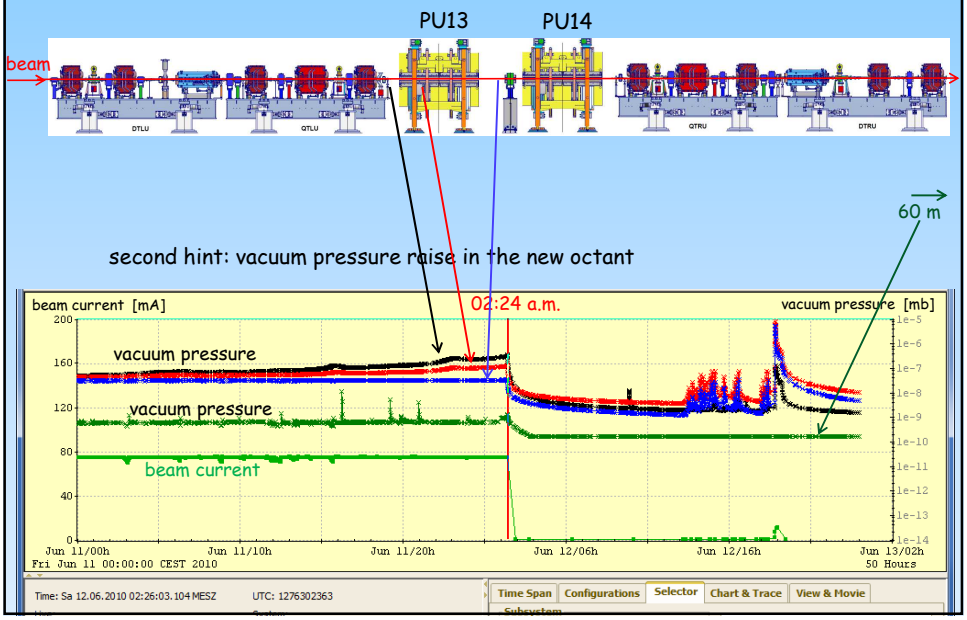
second hint: vacuum pressure raise in the new octant

beam lost

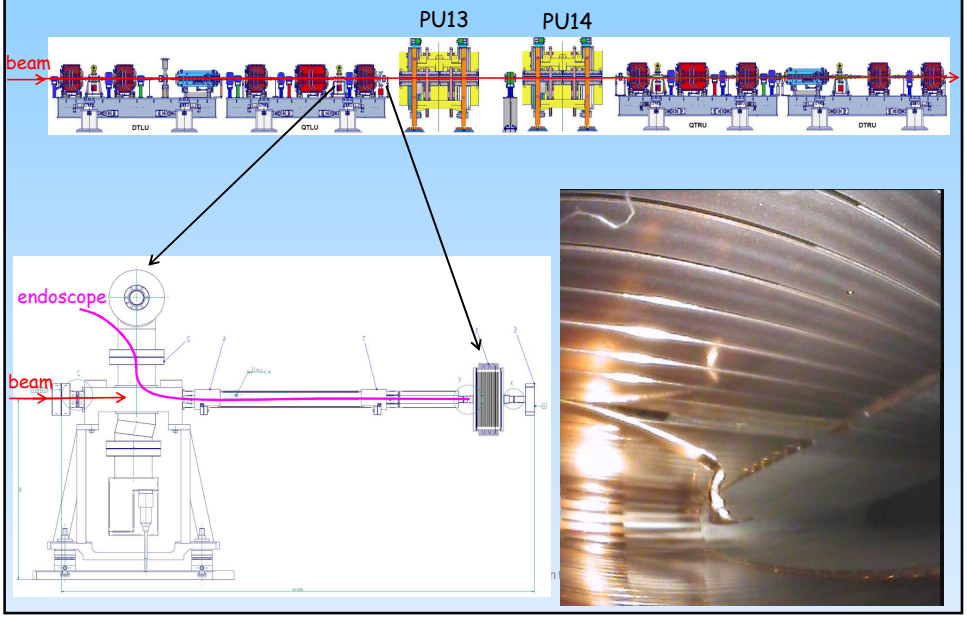
aperture scan
+ trajectory corrections



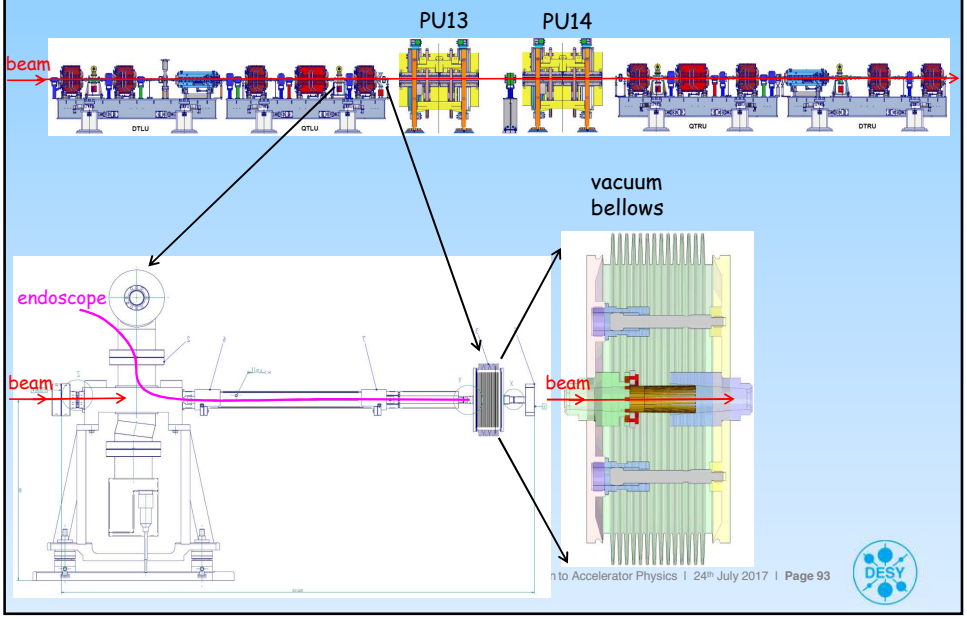
horizontal aperture problem in the new octant



visual inspection inside the vacuum chamber…

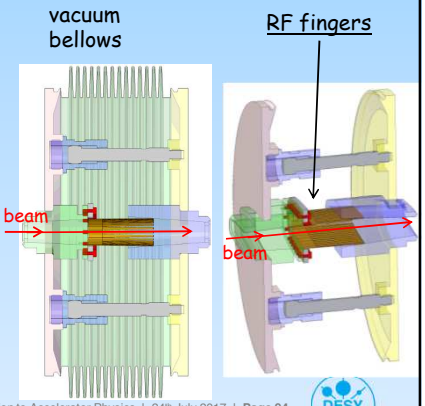


visual inspection inside the vacuum chamber…

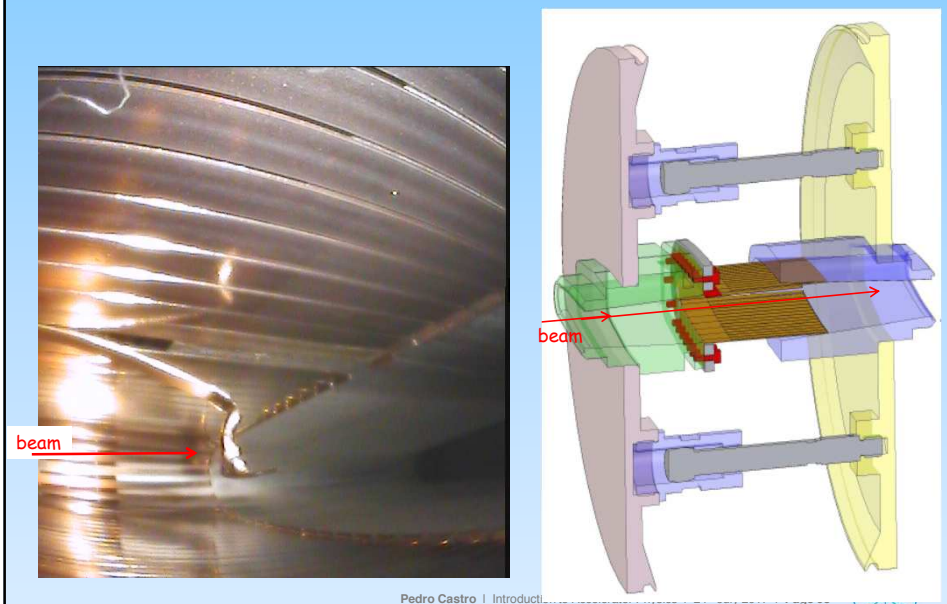


visual inspection inside the vacuum chamber…

an example of vaccum bellows

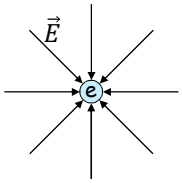


the problem was found: RF fingers

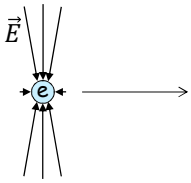


electric field of a relativistic particle

$v = 0$
$\beta = 0$



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



electric field of a relativistic particle

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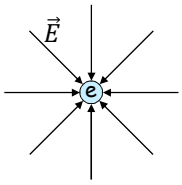
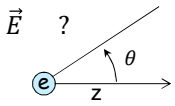


$v = \beta c$

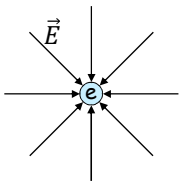


$$\vec{E} = \frac{q}{4\pi\varepsilon_0}\frac{(1-\beta^2)}{(1-\beta^2\sin^2\theta)^{3/2}r^2}\frac{\vec{r}}{r}$$

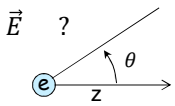
$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

electric field of a relativistic particle

$v = 0$
$\beta = 0$



$v = \beta c$



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

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

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

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electric field of a relativistic particle

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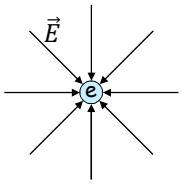
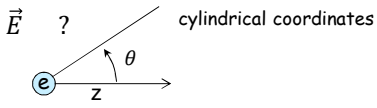


$$\vec{E} = \frac{q}{4\pi\varepsilon_0}\frac{1}{r^2}\frac{\vec{r}}{r}$$

$v = \beta c$



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

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

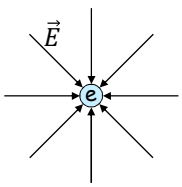
$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

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

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

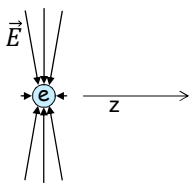
electric field of a relativistic particle

$v = 0$
$\beta = 0$



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

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



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

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

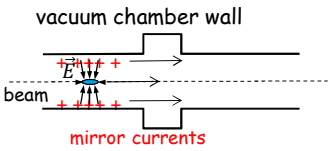
$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

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

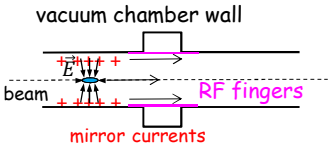
$$E_z(\theta = 0) = \frac{q}{4\pi\varepsilon_0}\frac{1}{\gamma^2 r^2}\frac{\vec{r}}{r} \xrightarrow{\gamma \to \infty} 0$$

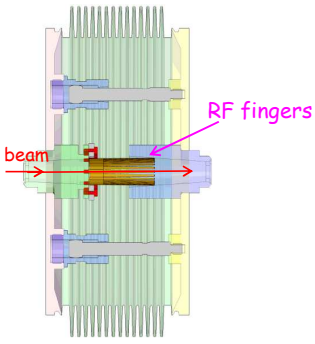
$$E_r\left(\theta = \frac{\pi}{2}\right) = \frac{q}{4\pi\varepsilon_0}\frac{\gamma}{r^2}\frac{\vec{r}}{r} \xrightarrow{\gamma \to \infty} \infty$$

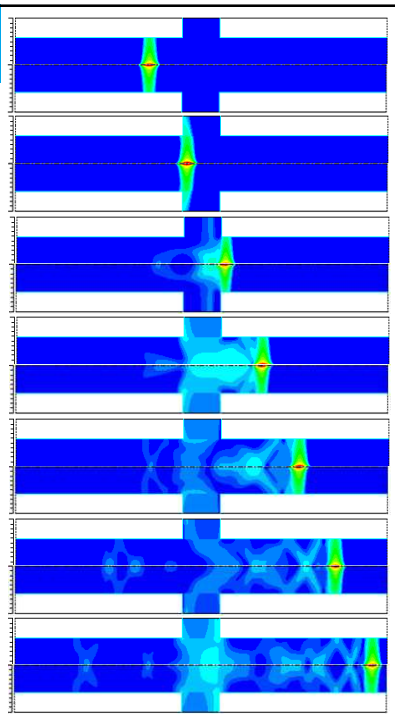
RF fingers and wakefields



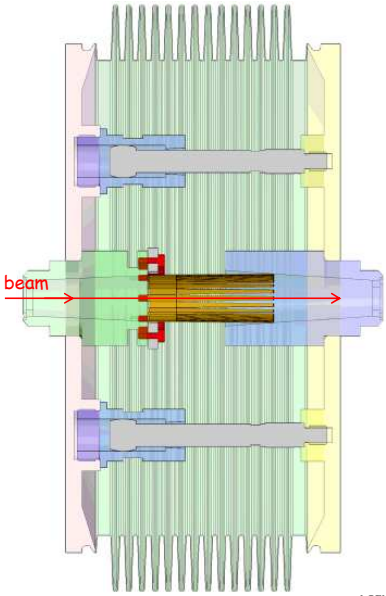
RF fingers and wakefields





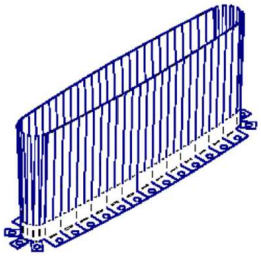


RF fingers and wakefields



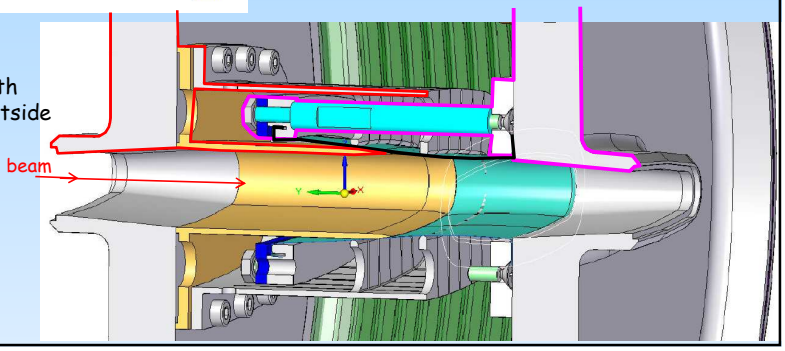
RF fingers: improvements done

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
- **accelerator physics**
  - rest gas scattering (limiting beam lifetime)
  - Touchek effect (limiting beam lifetime)
  - wakefields, RF shielding (RF fingers)

  → ‘collective effects’
- **basic concepts in operation**
  - top-up modus
  - aperture scans
  - trajectory (orbit) corrections

Thank you for your attention

pedro.castro@desy.de