Introduction to Accelerator Physics

Part 1

Pedro Castro / Accelerator Physics Group (MPY)
Zeuthen, 2nd August 2022
<table>
<thead>
<tr>
<th>length</th>
<th>lab</th>
<th>run</th>
<th>particles</th>
<th>energy</th>
<th>dipole field</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETRA</td>
<td>2.3 km</td>
<td>DESY</td>
<td>1978-1986</td>
<td>e-/e+</td>
<td>2x19 GeV</td>
</tr>
<tr>
<td>PETRA II</td>
<td>2.3 km</td>
<td>DESY</td>
<td>1987-2007</td>
<td>e- or e+ p</td>
<td>12 GeV 40 GeV</td>
</tr>
<tr>
<td>PETRA III</td>
<td>2.3 km</td>
<td>DESY</td>
<td>2009-?</td>
<td>e-</td>
<td>6 GeV</td>
</tr>
<tr>
<td>HERA</td>
<td>6.3 km</td>
<td>DESY</td>
<td>1992-2007</td>
<td>e- or e+ p</td>
<td>27.5 GeV 920 GeV</td>
</tr>
<tr>
<td>LEP</td>
<td>27 km</td>
<td>CERN</td>
<td>1989-2000</td>
<td>e-/e+</td>
<td>2x105 GeV</td>
</tr>
<tr>
<td>LHC</td>
<td>27 km</td>
<td>CERN</td>
<td>2010-?</td>
<td>p/p</td>
<td>2x7000 GeV</td>
</tr>
<tr>
<td>FLASH</td>
<td>0.3 km</td>
<td>DESY</td>
<td>2004-?</td>
<td>e-</td>
<td>1.2 GeV</td>
</tr>
<tr>
<td>XFEL</td>
<td>3 km</td>
<td>DESY</td>
<td>2016-?</td>
<td>e-</td>
<td>17.5 GeV</td>
</tr>
<tr>
<td>ILC</td>
<td>30 km</td>
<td>?</td>
<td>?</td>
<td>e-/e+</td>
<td>2x250 GeV</td>
</tr>
</tbody>
</table>
Scope of this lecture:

1. The four most important applications of accelerators
2. Main accelerators at DESY
3. Working with accelerators in the control room

The Main Accelerator Control Room
Scope of this lecture:

1. **Synchrotrons**: key components and their challenges to reach high energies:
   - Dipole magnetic fields
   - Superconducting dipoles
   - Quadrupole magnets to focus beams

2. **Synchrotrons and Linear Accelerators**:
   - Acceleration using radio-frequency electromagnetic fields

Part 4, tomorrow

Part 2

Part 3, tomorrow
1. Overview of charged particle accelerators

A historical overview of particle accelerators?

CERN summer student lecture: Particle Accelerators, M. Schaumann
https://indico.cern.ch/event/1132543
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

built between 2001 and 2009
Higgs discovery: July 2012

8.6 km

superconducting magnets (inside a cryostat)
 Worldwide ...

> About 120 accelerators for research in “nuclear and particle physics”

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
-...

Electromagnet

Electron bunch

Synchrotron light

Electrons
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

0.5 GeV \(e^-/e^+\) collisions at 2 \(\times\) 19 GeV

2.3 km long
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

**12 GeV**
- e-/e+

**40 GeV**
- protons

**0.5 GeV**
- e-/e+

**7 GeV**
- protons

**2.3 km long**

pre-accelerator for HERA 1987-2007

synchrotron radiation since 1987
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
- Max von Laue hall 300 m
- 2.3 km long
- Pre-accelerator for HERA 1987-2007
- Synchrotron radiation since 1987
- PETRA III since 2009
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
- PETRA III since 2009, PETRA IV 2029?

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:

- \( x\text{-rays and gamma-rays} \)
- \( \text{ions (from protons to atoms with atomic number up to 18, Argon)} \)
- \( \text{neutrons} \)
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 → 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 → Oxygen-18 → Fluorine-18 (half-life time = 110 min.)

Fludeoxyglucose ($^{18}$F)
Applications of Accelerators (3)

Positron Emission Tomography (PET)

Annihilation
Applications of Accelerators (3)

Positron Emission Tomography (PET)
> 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:

<table>
<thead>
<tr>
<th>Application</th>
<th>~ numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion implantation</td>
<td>9500</td>
</tr>
<tr>
<td>Electron cutting and welding</td>
<td>4500</td>
</tr>
<tr>
<td>Electron beam and x-ray irradiators</td>
<td>2000</td>
</tr>
<tr>
<td>Ion beam analysis (including AMS)</td>
<td>200</td>
</tr>
<tr>
<td>Radioisotope production (including PET)</td>
<td>900</td>
</tr>
<tr>
<td>Nondestructive testing (including security)</td>
<td>650</td>
</tr>
<tr>
<td>Neutron generators (including sealed tubes)</td>
<td>1000</td>
</tr>
</tbody>
</table>

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 ...

> 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) …
Many millions of television sets, oscilloscopes using CRTs (Cathode Ray Tube)
Applications of Accelerators (5)

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

acceleration

Anode

Control Grid

Deflecting coils

Fluorescent screen

Heater

Cathode

Electron beam

Focusing coil

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

25 frames / s

625 lines
Applications of Accelerators (6)

X-ray tubes

DC high voltage (20-150 kV)

braking radiation or bremsstrahlung
Main accelerators at DESY

- PETRA EXP 2010
- FLASH II 2015
- PETRA 3 6 GeV
- P3X Nord 2015
- P3X Ost 2015/16
- DESY 1964
- XFEL 17.5 GeV
- XFEL.EU 2016/17
- FLASH 1.25 GeV
- FLASH 2005
- XFEL.EU 2016/17
- P3X Nord 2015
DESY (Deutsches Elektronen Synchrotron)
German electron synchrotron

1964, 7.4 GeV
Positron-Elektron-Tandem-Ring-Anlage (PETRA)
‘positron-electron tandem ring accelerator’
Free-electron LASer in Hamburg (FLASH)
Free-electron LASer in Hamburg (FLASH)

Superconducting linear accelerator

12 undulator modules

6 undulator modules

photon exp. halls

300 long, 1.2 GeV
First beam 2004

λ = 4 - 45 nm
European X-ray Free-Electron Laser (XFEL)
European X-ray Free-Electron Laser (XFEL)

2 km superconducting linear accelerator

Undulators and experiments

European XFEL
3 km long 17.5 GeV
First beam 2016

\[ \lambda = 0.05 - 6 \text{ nm} \]
HERA (Hadronen-Elektronen-Ring-Anlage)
Hadron-electron ring accelerator

27.5 GeV (electrons) / 920 GeV (protons) / 6.3 km / 1992 - 2007

- Superconducting magnets for 920 GeV protons
- Normal conducting magnets for 27.5 GeV electrons
Working with accelerators in the control room ...

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

The job requires:
- a lot of (accelerator) physics knowledge
- a lot of (accelerator) engineering knowledge
The case begins...

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

02:24 a.m.: beam lost
02:24 a.m.: beam lost

The Main Accelerator Control Room

Hamburg, DESY
Sat. 12\textsuperscript{th} June 2010

02:24 a.m.: beam lost
02:24 a.m.: beam lost

What to do?

DON'T PANIC
Run number 4: 60 Bunches; 23rd – 30th March, 2011

- Top-up timing problems
- Power off in crate at DORIS
- Vertical beam blow up
- RF problems and longitudinal instabilities
- Beam loss without dump
- RF circulator water cooling
- RF circulator water cooling

Source: K. Balewski (MAC report 2011)
Beam lost at 02:24 a.m.

The link to the electronic logbook:


What to do?

DON'T PANIC
Alarm overview: the Machine Protection System

[Diagram showing the connection between the Machine Protection System (MPS) and the control system, with status and alarm signals flowing through to stop beam.]
Alarm overview: the Machine Protection System

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

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

“all systems up and running”
Electrons can be injected but cannot be stored!

beam current after a few turns
beam current at injection

500 μs ≈ 65 turns

injection problem?
Circular accelerators: injection system
Next suspect: injection

vacuum chamber

stored beam reference trajectory
Next suspect: injection

stored beam

bending magnet

injected beam
Next suspect: injection

stored beam
free field region
homogeneous field

septum
Next suspect: injection + accumulation

- Dipole
- Stored beam
- Injected beam
- PETRA septum
Next suspect: injection + accumulation

septum at the Proton Synchrotron Booster (PSB) at CERN
Next suspect: injection + accumulation

septum at the Proton Synchrotron Booster (PSB) at CERN

stored beam

injected beam

Cathode

300 kV
Anode

SIS electrostatic injection septum

free field region

homogeneous field
Next suspect: injection + accumulation

septum at the Proton Synchrotron Booster (PSB) at CERN

stored beam

beam

Cathode

Anode

300 kV

SIS electrostatic injection septum

injected beam

free field region

homogeneous field

(1)

(2)

(3)
Next suspect: injection + accumulation

- kicker (very fast dipole)
- stored beam
- injected beam
- septum
- kicker (very fast dipole)

kicker field

\[ \sim 20 \mu s \]
Circular accelerators: injection system
Electrons can be injected but cannot be stored!

beam current after a few turns

beam current at injection

500 μs ≈ 65 turns

injection problem?
Next suspect: a problem with vacuum chamber

Hamburg, DESY
Sat. 12\textsuperscript{th} 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'

beam

22.5 m

undulators
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
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

very flat undulator vacuum chambers

undulator field lines

beam

\( \vec{B} \)
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 EUOS dort haben wir 6 μSv/h gemessen, alle anderen < 1 μSv/h.

12.06.2010 07:02 Sonstiges  has
Frühschicht: Kühl, Schulz, Hansen, Wierzchole
Schichtbeginn kein gepeicheter Strahl. Nur ca. 1000 Umläufe, keine Ausfälle

citation from the logbook: “Visual inspection of new octant: no findings”
citations from the logbook: “What we have tried so far: ...”

<table>
<thead>
<tr>
<th>Time</th>
<th>Entry</th>
</tr>
</thead>
</table>
| 12.06.2010 10:34 | **Sonstiges** Kuehl, Vogt, Keil | **Was haben wir alles versucht:**
| **Optische Inspektion des neuen Achtweltes (nichts gefunden).** Nur EBW nach Undulator FU03 zeigt 6 μSv/h während im Rest immer Werte unter 1 μSv/h gemessen werden.
| Sender-Untersuchungen:
| Sender beide aus = 100 μSv Strahl
| Sender SL aus SL ein (3 MV) = 700 μSv Strahl
| Sender SR aus SL ein (9 MV) = 700 μSv Strahl
| Beide Sender ein = 700 μSv Strahl
| Sender SR um 180 Grad vertauscht (Gegenphase) = ca. 100 μSv Strahl
| 500 MHz-Frequenz kontrolliert; Synchronisation kontrolliert; Orbit liegt auf dem ersten Turn mittig (damit sollte Energie stimmen). Turn-By-Turn Daten zeigen, daß Energieaufnahme 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 Wigglerstracken (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 IMB und Septum gewendet: man kann damit die Injektion nur noch schlechter machen
| On Axis Injektion aufgesetzt (Klicker 3/Septum durchgefahren)
| Kolimatore/Scrapers ausgefahren: Keine Verbesserung
| Tunkreise gedreht: Keine Verbesserung
| Trans, Feedbacks und long. Feedback ein/aus: Keine Verbesserung

**Optische Inspektion des neuen Achtweltes, keine Auffälligkeiten**

Naja, bis auf den EBW nach Undulator FU03 dort haben wir 6 μSv/h gemessen, alle anderen < 1 μSv/h.

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| 12.06.2010 07:02 | **Sonstiges** Kuehl, Schulz, Hansen, Wierchalek | **Frühschicht:** Kühl, Schulz, Hansen, Wierchalek
| Schichtbeginn kein gespeicherter Strahl. Nur ca. 1000 Umläufe, keine Auffällige

**citations from the logbook: “Visual inspection of new octant: no findings”**
...when you have eliminated the impossible, whatever remains, however improbable, must be the truth

Sherlock Holmes, *The Sign of the Four*
Sir Arthur Conan Doyle
Next suspect: an aperture problem

Hamburg, DESY
Sat. 12th June 2010

02:24 a.m.: beam lost
07:00 a.m.: visual inspection in new octant
11:52 a.m.: start aperture scan
we need a beam focusing system
Need of focusing

we need to focus the beam!
Need of focusing

quadrupole magnet:
four iron poles

iron

air

vacuum chamber

beam
Quadrupole magnets

quadrupole magnet:
Quadrupole magnets

quadrupole magnet:
four iron pole shoes of hyperbolic contour

\[ \text{gradient quadrupole} \]

\( x \cdot y = \text{const.} \)

\( B_x = -g \cdot y \)
\( B_y = -g \cdot x \)

\[ g = \frac{\mu_0 I}{R^2} \quad (\text{quadrupole gradient}) \]
Quadrupole magnets

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

\[ B_y = -g \cdot x \quad \rightarrow \quad F_x = -g \cdot x \]

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

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

\( f^* \): system focal length  

if \( f_D = -f_F = f \),  

\[ \frac{1}{f^*} = \frac{d}{f^2} > 0 \]
Quadrupole magnets

QD + QF = net focusing effect:

charged particle

center of quadrupoles
defocusing quadrupole (rotated 90°) focusing quadrupole
Quadrupole magnets

vertical defocusing
horizontal focusing

vertical focusing
horizontal defocusing

rotated 90°

\[ I = -I \]
Quadrupole magnets

QD + QF = net focusing effect:

x-plane:
beam

defocusing quadrupole  focusing quadrupole

y-plane:
beam

focusing quadrupole  defocusing quadrupole
Quadrupole magnets

\[ \text{QD} + \text{QF} = \text{net focusing effect:} \]

x-plane:

Beam

reference trajectory

focusing quadrupole
defocusing quadrupole
defocusing quadrupole
focusing quadrupole
Quadrupole magnets

\[ QD + QF = \text{net focusing effect} : \]

x-plane:

beam
defocusing quadrupole focusing quadrupole

focusing quadrupole defocusing quadrupole
Circular accelerator
Circular accelerator

PETRA
Circular accelerator

beam
cell
corrector dipole
focusing quadrupole
dipole magnet
defocusing quadrupole
dipole magnet
corrector dipole
focusing quadrupole
we have a beam focusing system
Next suspect: an aperture problem

Hamburg, DESY
Sat. 12th June 2010

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

Next suspect: an aperture problem
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
First useful hint: aperture problem

Hamburg, DESY
Sat. 12\textsuperscript{th} 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

Hamburg, DESY
Sat. 12th June 2010

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

244 monitors

2.3 km
First useful hint: horizontal aperture problem

Hamburg, DESY
Sat. 12th June 2010

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

244 monitors

radiofrequency systems

horizontal beam pos. [mm]

vertical beam pos. [mm]
First useful hint: horizontal aperture problem

Hamburg, DESY
Sat. 12th June 2010

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

Hamburg, DESY
Sat. 12th June 2010

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

244 monitors

horizontal beam pos. [mm]
after 'flattening' the orbit
horizontal aperture problem in the new octant

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

second hint: vacuum pressure raise in the new octant
beam lost
aperture scan + trajectory corrections
horizontal aperture problem in the new octant

second hint: vacuum pressure raise in the new octant

beam current [mA]

vacuum pressure [mb]

60 m
visual inspection inside the vacuum chamber...
visual inspection inside the vacuum chamber...
visual inspection inside the vacuum chamber...

an example of vacuum bellows

dipole magnet
vacuum chamber

vacuum bellows

beam

undulator vacuum chamber
visual inspection inside the vacuum chamber...

an example of vacuum bellows
the problem was found: RF fingers
the problem was found: RF fingers
why do we need RF fingers?
RF fingers and wakefields

\[ \vec{E} \text{ : electric field?} \]
electric field of a relativistic particle

\[
\begin{align*}
\nu &= 0 \\
\beta &= 0
\end{align*}
\]

\[
\begin{align*}
\nu &= \beta c \\
\beta &\approx 1
\end{align*}
\]
relativistic expression
electric field of a relativistic particle

\[ \nu = 0 \]
\[ \beta = 0 \]

\[ \mathbf{E} = \frac{q}{4\pi\varepsilon_0} \frac{1}{r^2} \frac{\mathbf{r}}{r} \]

\[ \gamma = 1 \]
\[ \beta = 0 \]

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

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

\[ \nu = \beta c \]

\[ \mathbf{E} \quad ? \]

\[ \begin{align*}
E_z(\theta = 0) &= \frac{q}{4\pi\varepsilon_0} \frac{1}{\gamma^2 r^2} \frac{\mathbf{r}}{r} \\
E_r(\theta = \frac{\pi}{2}) &= \frac{q}{4\pi\varepsilon_0} \frac{\gamma}{r^2} \frac{\mathbf{r}}{r}
\end{align*} \]
electric field of a relativistic particle

\[ \vec{E} = \frac{q}{4\pi\varepsilon_0} \left( \frac{1}{r^2} \right) \]

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

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

\[ \gamma = 1 \]
\[ \beta = 0 \]

\[ \vec{E} = \frac{q}{4\pi\varepsilon_0} \frac{1}{\gamma^2 r^2} \]

\[ \gamma \gg 1 \]
\[ \beta \approx 1 \]

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

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

\[ \gamma \to \infty \to 0 \]
\[ \gamma \to \infty \to \infty \]
}\text{relativistic expression}
RF fingers and wakefields
RF fingers and wakefields

vacuum chamber wall

beam

RF fingers

mirror currents

DESY. | Introduction to Accelerator Physics | Pedro Castro, 2nd August 2022
we need RF fingers
RF fingers and wakefields
RF fingers: improvements done

old RF fingers were tilted outwards by 2 degrees

new RF fingers have stronger tilt, more tension

new design with RF fingers outside
beam
Summing-up of this part

Circular accelerators: the synchrotron

- basic components
  - dipole, quadrupole, undulator magnets, corrector dipoles
  - injection system (kickers and septum)
  - beam position monitors
  - vacuum pumps, vacuum pressure monitors
  - vacuum chambers, bellows

- advanced accelerator physics
  - electric field of a relativistic particle
  - mirror currents and wakefields
  - RF shielding (RF fingers)

- basic concepts in operation
  - e-logbook, Machine Protection System MPS
  - trajectory (orbit) corrections
  - aperture scans
## Contact

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