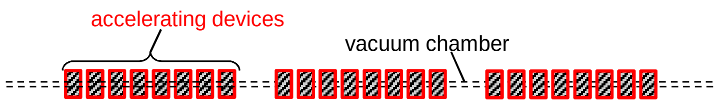
Introduction to Accelerator Physics

Part 3

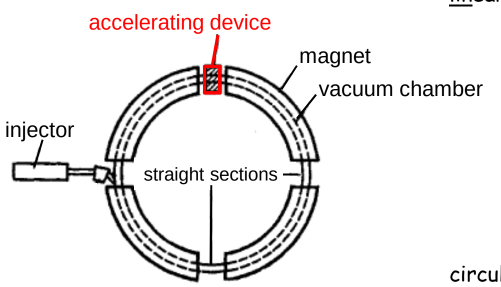
Pedro Castro / Accelerator Physics Group (MPY)
Introduction to Accelerator Physics
DESY, 25th July 2017

HELMHOLTZ | ASSOCIATION

DESY



linear accelerator (linac)



circular accelerator: synchrotron

Motion in electric and magnetic fields

Equation of motion under Lorentz Force

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

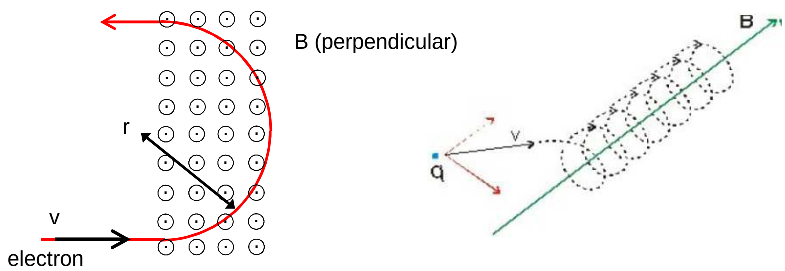
momentum charge velocity electric field magnetic field

of the particle

Motion in magnetic fields

if the electric field is zero (E=0), then

$$\vec{F} = \frac{d\vec{p}}{dt} = q \cdot \vec{v} \times \vec{B} \quad \rightarrow \quad \vec{F} \perp \vec{v}$$



Magnetic fields <u>do not change</u> the particles energy, only electric fields do !

Motion in magnetic fields

if the electric field is zero (E=0), then

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

$$E^2 = \vec{p}^2 c^2 + E_0^2$$

energy-momentum relation in special relativity

total energy

momentum

energy at rest

Motion in magnetic fields

if the electric field is zero (E=0), then

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

$$E^2 = \vec{p}^2 c^2 + E_0^2$$

$$E\frac{dE}{dt} = c^2 \vec{p}\frac{d\vec{p}}{dt} = c^2 q\, \vec{p}(\vec{v} \times \vec{B}) = c^2 q \left|\vec{p}\right| \left|\vec{v} \times \vec{B}\right| \cos\phi = 0$$

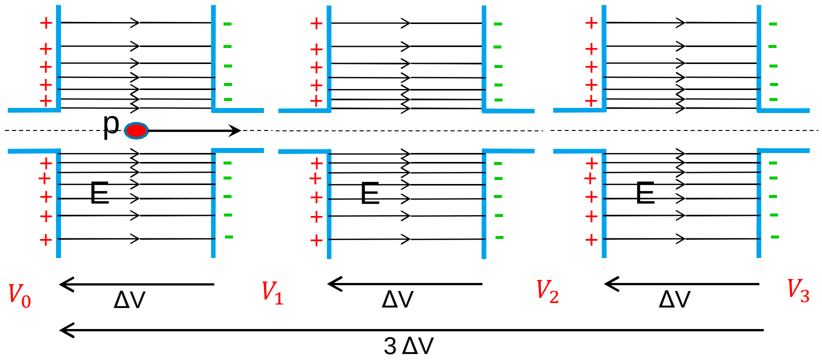
since $\vec{v} \times \vec{B} \perp \vec{v}$ ➔ $\phi = 90^\circ$

Magnetic fields <u>do not change</u> the particles energy, only electric fields do !

In general:

- Static magnetic fields → to guide (bend + focus) particle beams

acceleration with DC electric fields

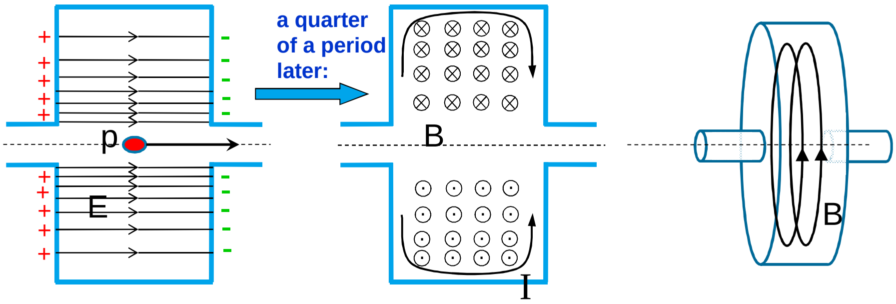


In general:

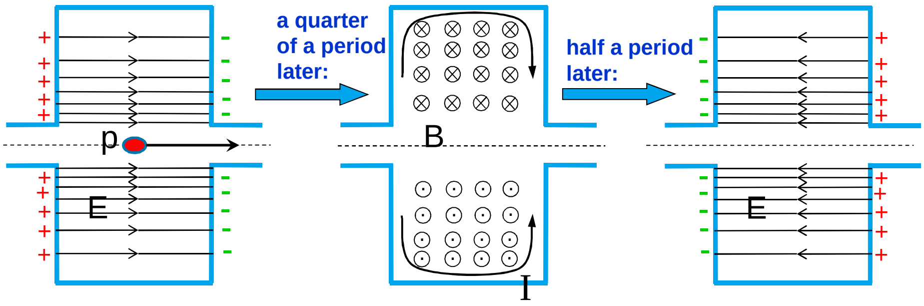
- Static magnetic fields → to guide (bend + focus) particle beams

- Static electric fields → accelerate particle beams (low energy)
- Radio-frequency EM fields → accelerate particle beams (high E)

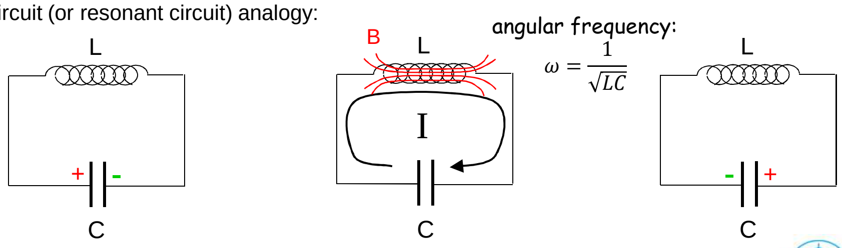
RF cavity basics: the pill box cavity



RF cavity basics: the pill box cavity



LC circuit (or resonant circuit) analogy:



angular frequency:

$$\omega = \frac{1}{\sqrt{LC}}$$

Maxwell's equations
(differential formulation in SI units)

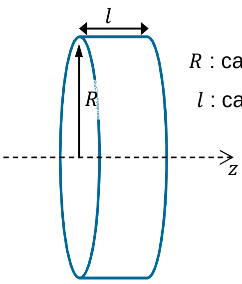
$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$

+ boundary conditions



R : cavity radius

l : cavity length

⇨

TM modes
(transverse magnetic modes)

set of solutions with $B_z = 0$ (that is, $\vec{B}$ is transverse)

~~set of solutions with $E_z = 0$ (that is, $\vec{E}$ is transverse)~~

~~TE modes~~
~~(transverse electric modes)~~

Maxwell's equations
(differential formulation in SI units)

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\times\vec{B} = \mu_0\vec{J} + \mu_0\varepsilon_0\frac{\partial\vec{E}}{\partial t}$$

+ boundary conditions

R : cavity radius

l : cavity length

set of solutions with $B_z = 0$ (that is, $\vec{B}$ is transverse)

$$\begin{cases} E_z = E_0 J_m\left(x_{mn}\frac{r}{R}\right)\cos m\theta\cos\left(\frac{p\pi}{l}z\right)e^{j\omega t} \\ E_r = -\frac{p\pi}{l}\frac{R}{x_{mn}}E_0 J'_m\left(x_{mn}\frac{r}{R}\right)\cos m\theta\sin\left(\frac{p\pi}{l}z\right)e^{j\omega t} \\ E_\theta = -\frac{p\pi}{l}\frac{mR^2}{x_{mn}{}^2 r}E_0 J_m\left(x_{mn}\frac{r}{R}\right)\sin m\theta\sin\left(\frac{p\pi}{l}z\right)e^{j\omega t} \\ B_z = 0 \\ B_r = -j\omega\frac{mR^2}{x_{mn}{}^2 r c^2}E_0 J_m\left(x_{mn}\frac{r}{R}\right)\sin m\theta\cos\left(\frac{p\pi}{l}z\right)e^{j\omega t} \\ B_\theta = -j\omega\frac{R}{x_{mn}c^2}E_0 J'_m\left(x_{mn}\frac{r}{R}\right)\cos m\theta\cos\left(\frac{p\pi}{l}z\right)e^{j\omega t} \end{cases}$$

indices:

$m = 0,1,2,\ldots$: number of full period variations in θ of the fields

$n = 1,2,\ldots$: number of zeros of the axial field component in $\vec{r}$

$p = 0,1,2,\ldots$: number of half period variations in z of the fields

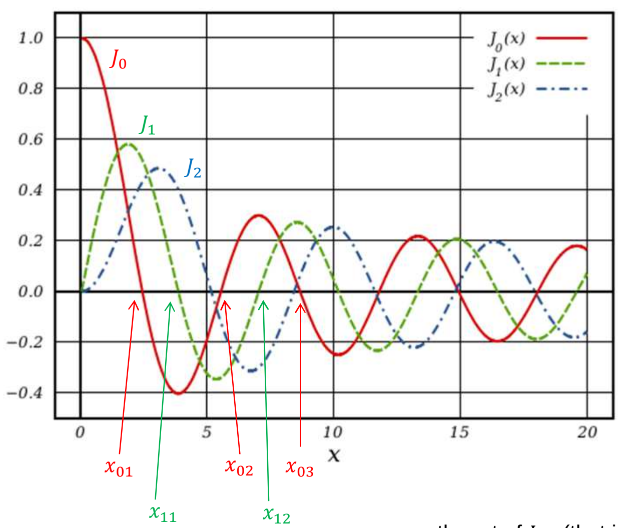
J_m : Bessel´s functions

x_{mn} : n-th root of J_m (that is, $J_m(x_{mn}) = 0$)

J'_m : derivative of the Bessel´s functions

angular frequency : $\omega = c\sqrt{\left(\frac{x_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$

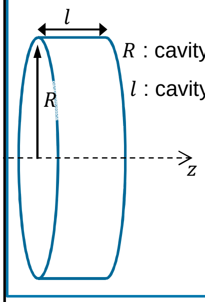
J_m : Bessel´s functions



m	x_{m1}	x_{m2}	x_{m3}
0	2.405	5.520	8.654
1	3.832	7.016	10.173
2	5.136	8.417	11.620

x_{mn} : n-th root of J_m (that is, $J_m(x_{mn}) = 0$)

boundary conditions



R : cavity radius

l : cavity length

fundamental solution with $B_z = 0$ (that is, $\vec{B}$ is transverse)

$$E_z = E_0 J_0\left(x_{01}\frac{r}{R}\right)e^{j\omega t}$$

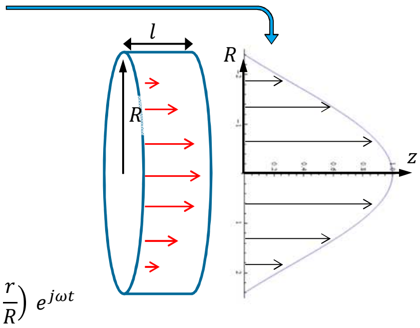
$$E_r = 0$$

$$E_\theta = 0$$

$$B_z = 0$$

$$B_r = 0$$

$$B_\theta = j\omega\frac{R}{x_{01}c^2}E_0 J_1\left(x_{01}\frac{r}{R}\right)e^{j\omega t}$$



$m = 0$: rotation symmetry of the fields

$n = 1$: no zeros of the axial field component in $\vec{r}$

$p = 0$: no variation in z of the fields

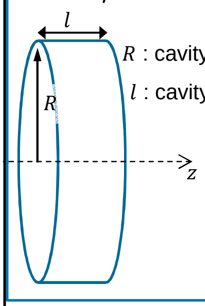
J_m : Bessel´s functions

J'_m : derivative of the Bessel´s functions

angular frequency : $\omega = c\frac{x_{01}}{R}$

$x_{01} = 2.405$

boundary conditions



R : cavity radius

l : cavity length

fundamental solution with $B_z = 0$ (that is, $\vec{B}$ is transverse)

$$E_z = E_0 J_0\left(x_{01}\frac{r}{R}\right)e^{j\omega t}$$

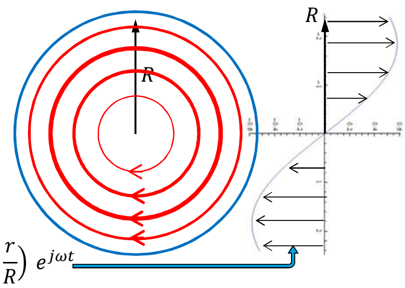
$$E_r = 0$$

$$E_\theta = 0$$

$$B_z = 0$$

$$B_r = 0$$

$$B_\theta = j\omega\frac{R}{x_{01}c^2}E_0 J_1\left(x_{01}\frac{r}{R}\right)e^{j\omega t}$$



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J_m : Bessel´s functions

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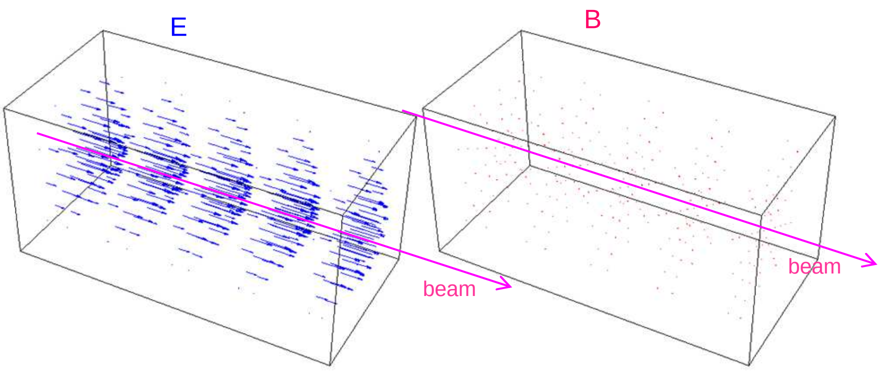
angular frequency : $\omega = c\frac{x_{01}}{R}$

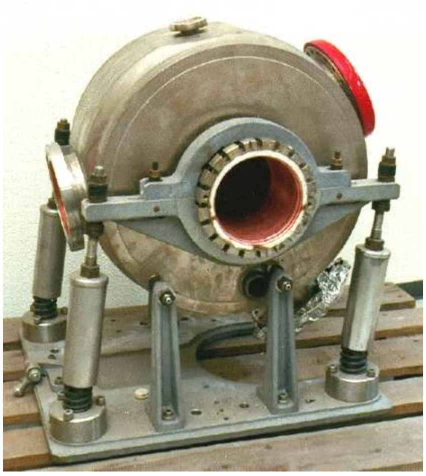
$x_{01} = 2.405$

Pill box cavity: 3D visualisation of E and B



Examples of pill box cavities

DESY cavity (pill box)

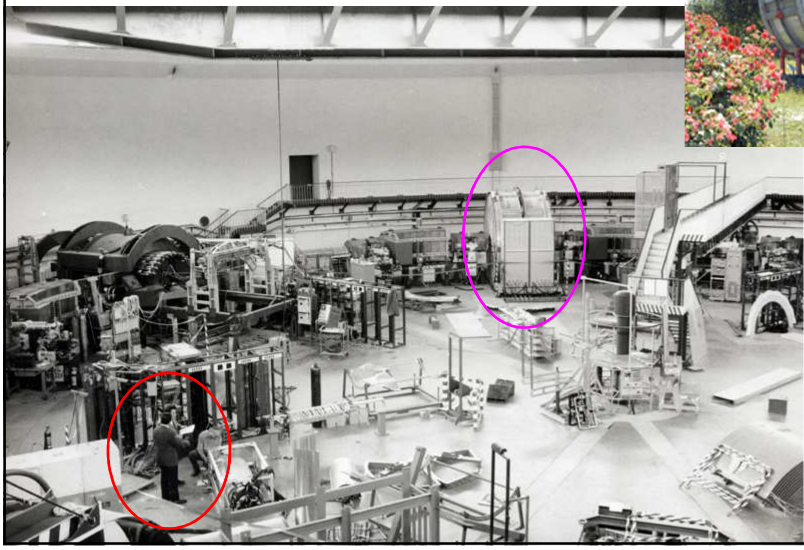


ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

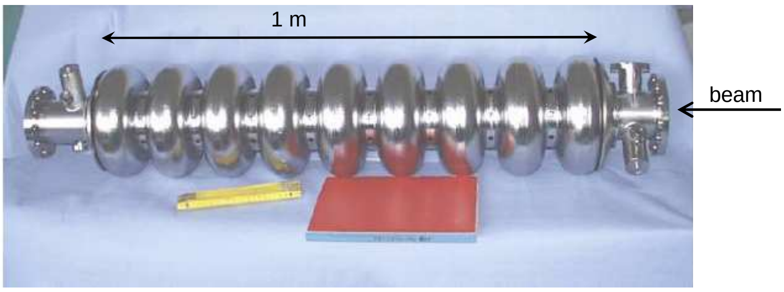
Examples of pill box cavities

ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

ADONE in 1963, Laboratori Nazionali di Frascati, Italy



Superconducting cavity used at DESY



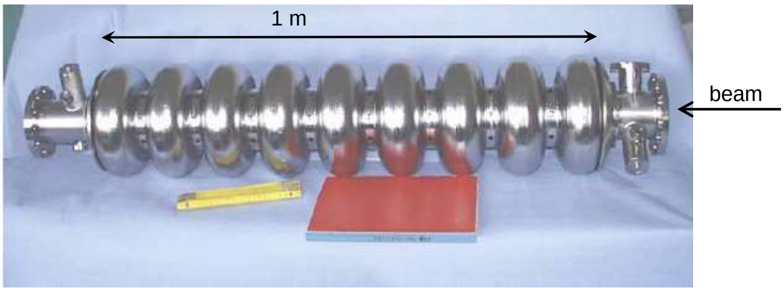
material: pure Niobium

operating temperature: 2 K

accelerating field gradient: up to 35 MV/m

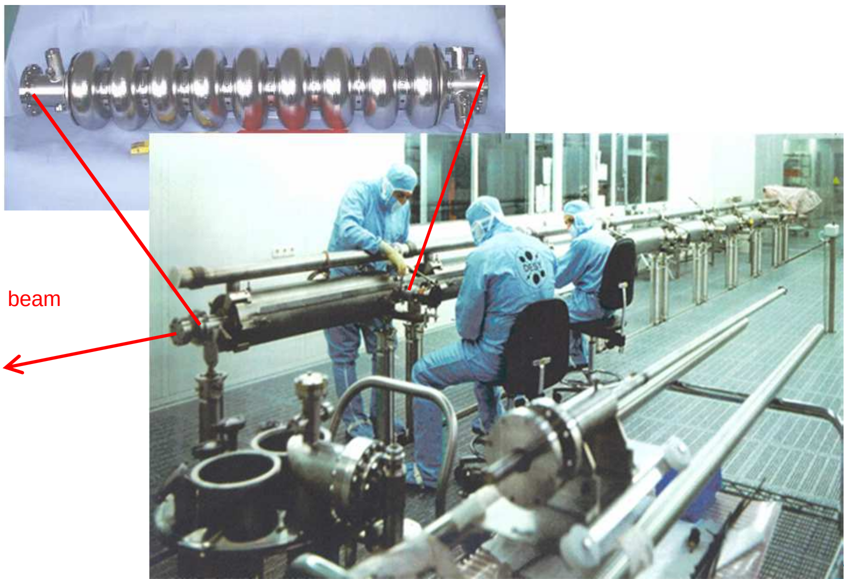
Superconducting cavity used at DESY

Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)

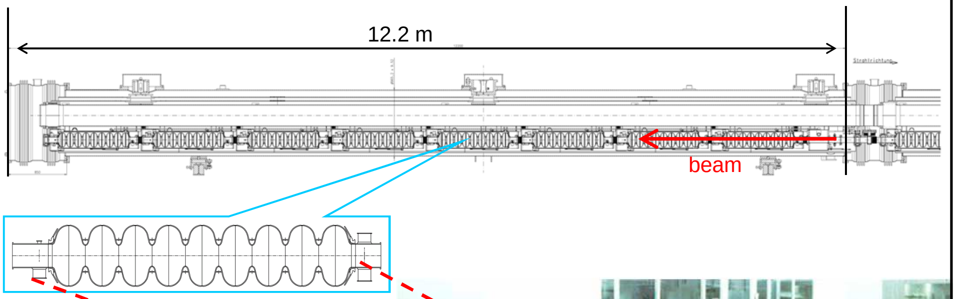


Free-electron LASer in Hamburg	0.3 km	DESY	2004- ?	e-	1.2 GeV
European X-ray Free-Electron Laser	3 km	DESY	2016- ?	e-	17.5 GeV
International Linear Collider	30 km	?	?	e-/e+	2x250 GeV

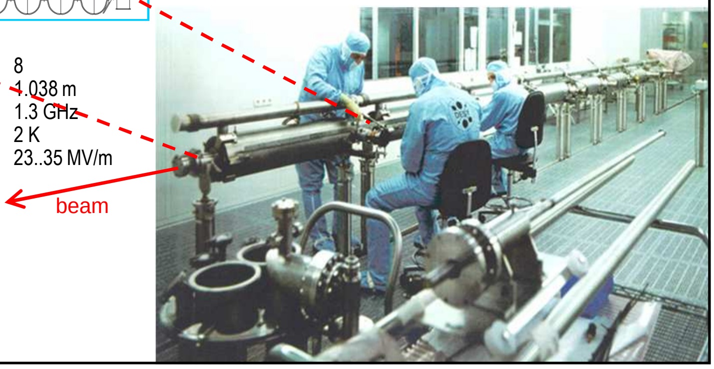
Cavities inside a cryostat



Cavities inside a cryostat

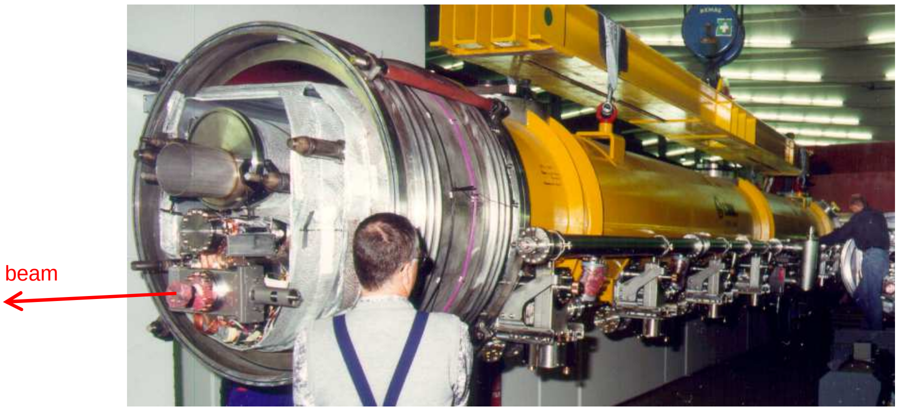


Number of cavities	8
Cavity length	1.038 m
Operating frequency	1.3 GHz
Operating temperature	2 K
Accelerating Gradient	23..35 MV/m



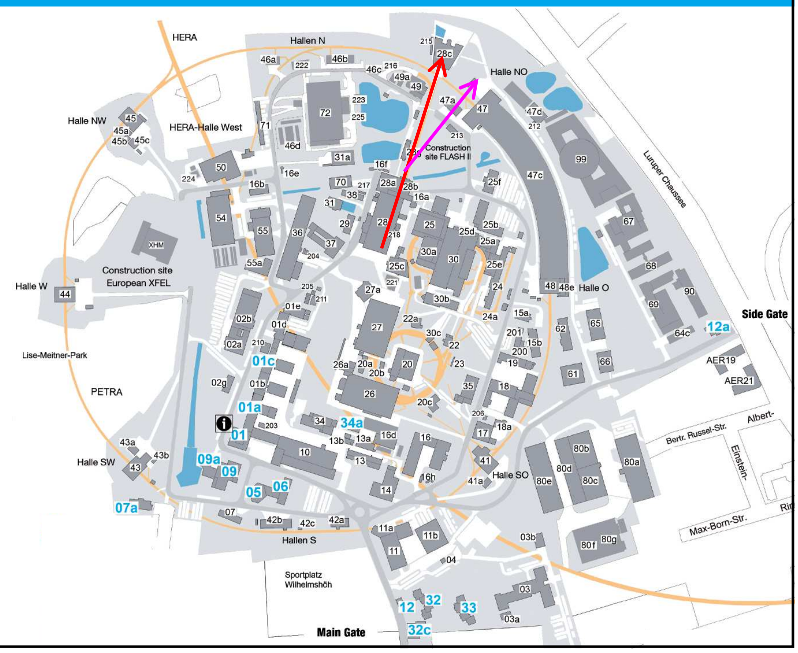
Cavities inside a cryostat

Cavities inside an accelerator module (cryostat)

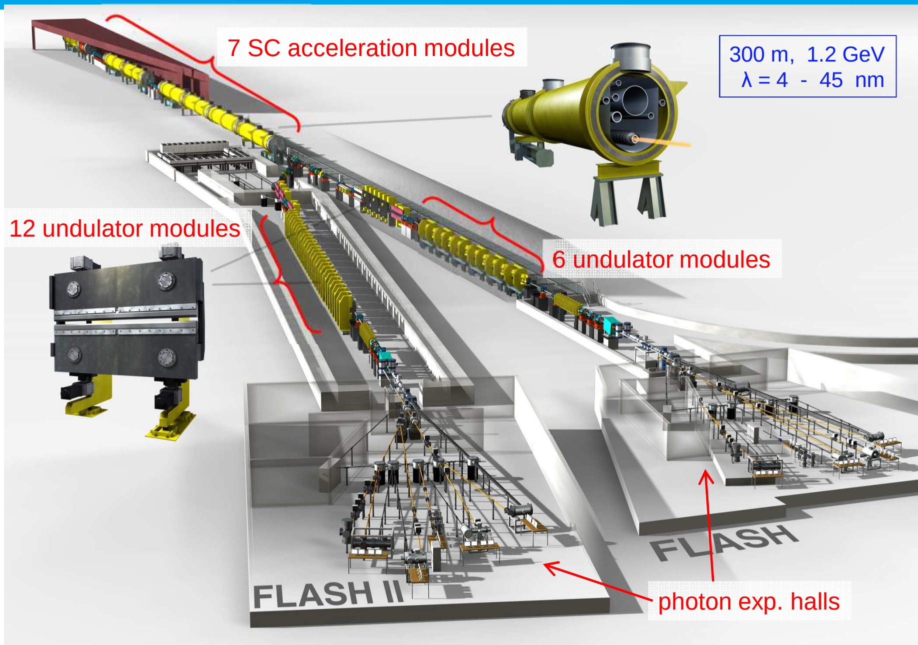


module installation in FLASH (2004)

Free-electron LASer in Hamburg (FLASH)



Free-electron LASer in Hamburg (FLASH)

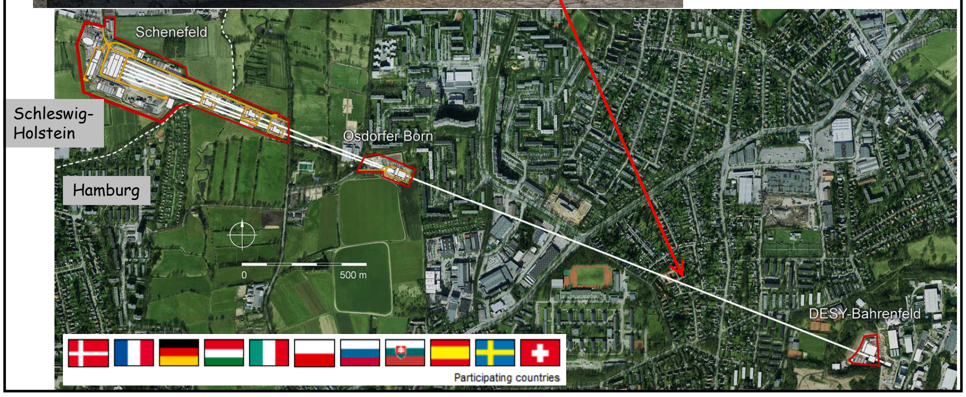


100 accelerator modules (cryostats) in XFEL

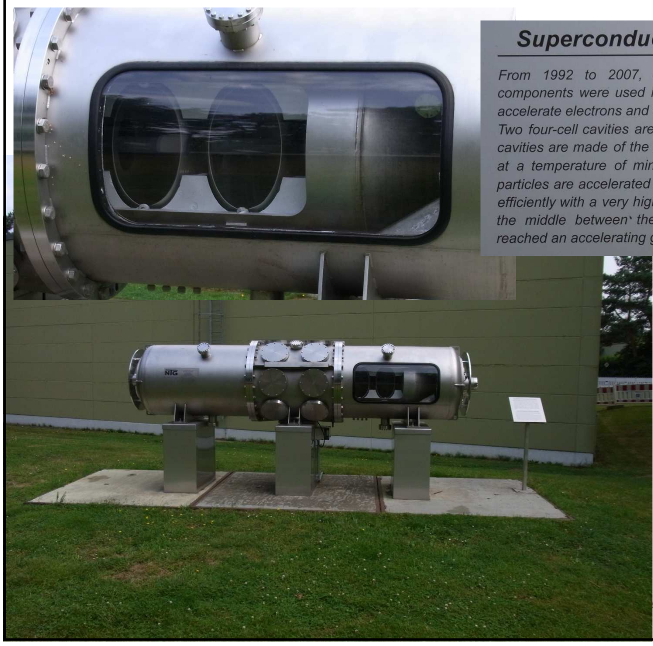
European X-ray Free-Electron Laser (XFEL)

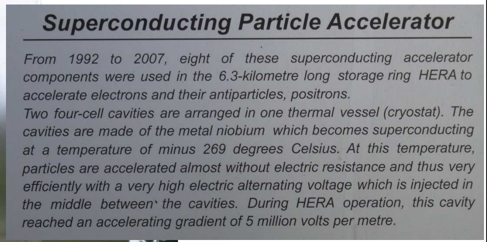
(3 km, 17.5 GeV)

λ = 0.05 - 6 nm



Superconducting cavities at HERA





Other accelerators using superconducting cavities

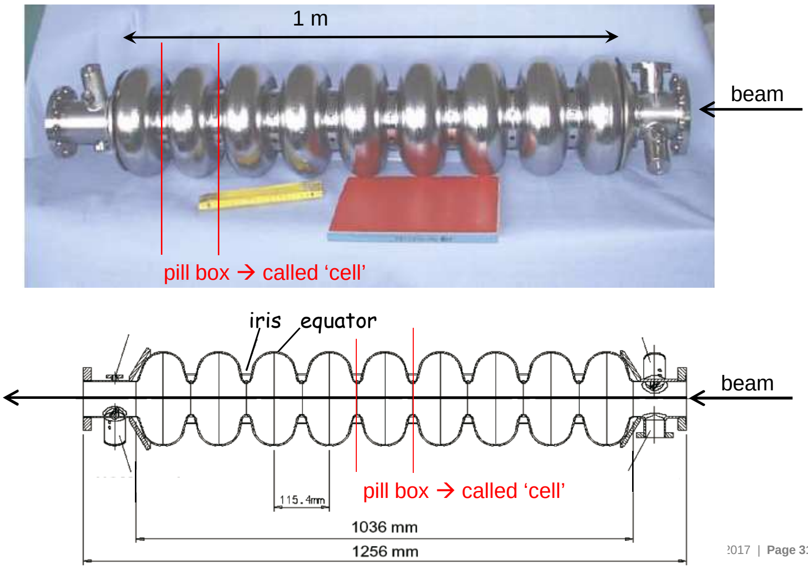
- 5 de-commissioned
- 11 in operation
- 4 in construction
- 9 in design phase

Total = 29

full list: http://tesla-new.desy.de/sites/site_tesla/content/e163749/e163751/infoboxContent163765/SRFAccelerators.pdf

Superconducting cavity used in FLASH and in XFEL

Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)

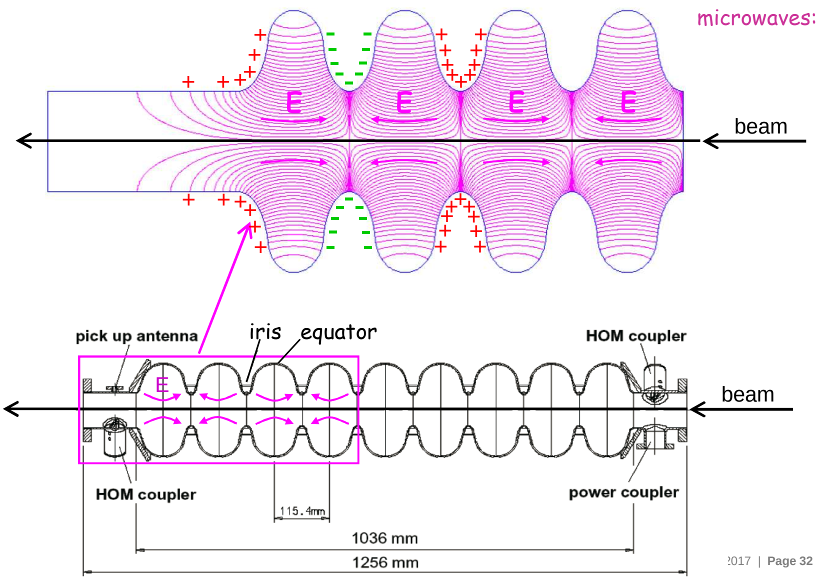


Accelerating field map

Simulation of the fundamental mode: electric field lines

$f_{RF} = 1.3$ GHz

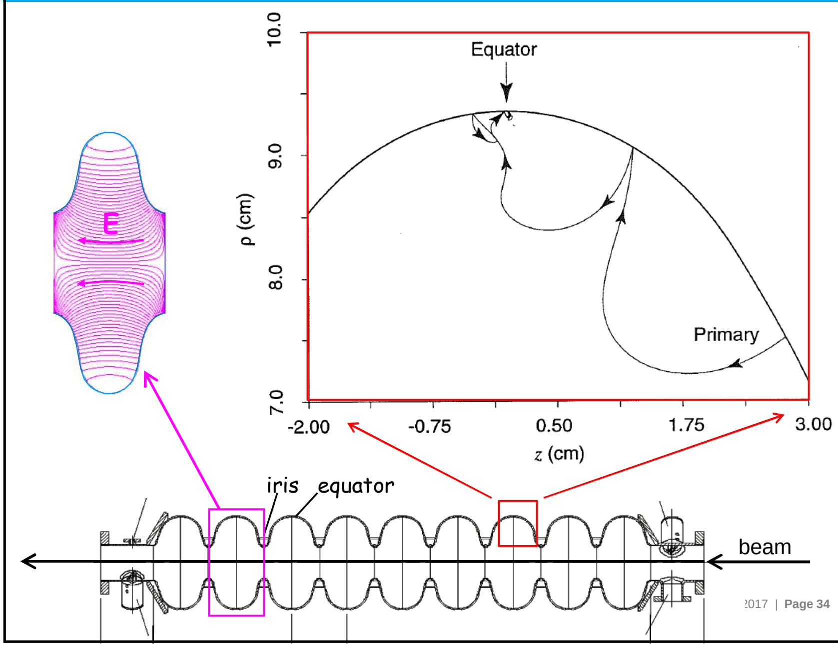
microwaves: (L-band)



Frequently Asked Questions

1) Why this shape?
2)
3)
4)
5)

Multipacting mitigation in superconducting cavities



1) Why this shape? ………………………………………………………… to reduce/avoid multipacting

2) How to feed $\vec{E}$ in?

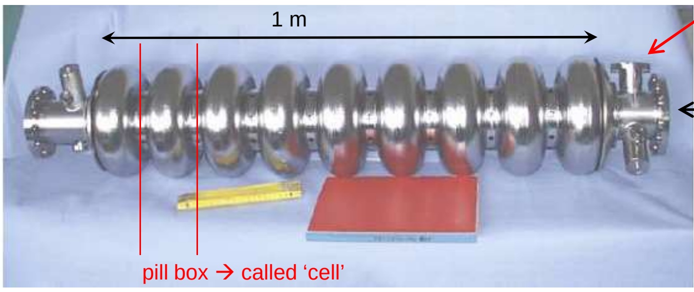
3)

4)

5)

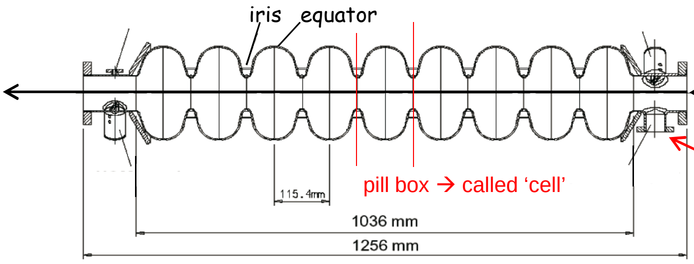
Superconducting cavity used in FLASH and in XFEL

Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)



RF input port
called 'input coupler'
or 'power coupler'

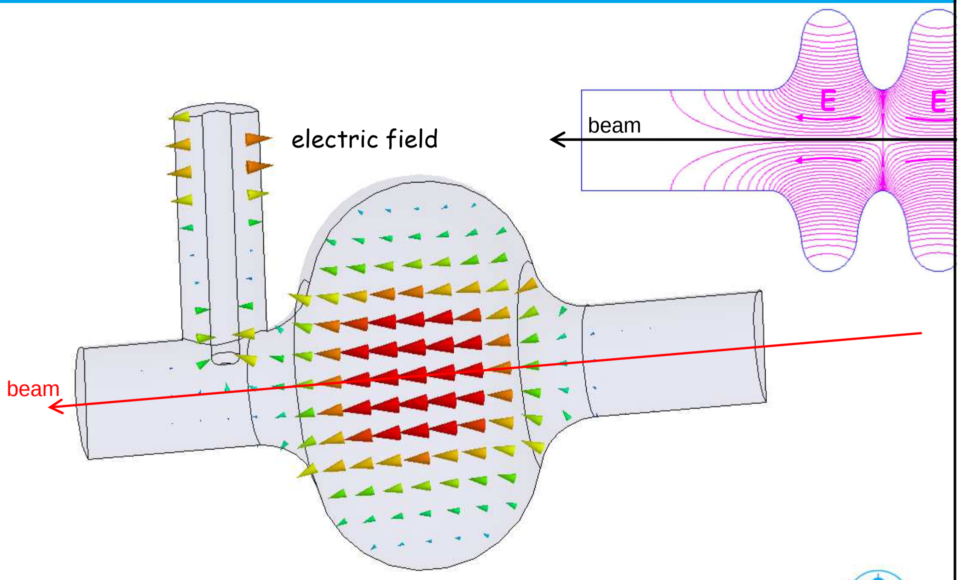
beam



beam

RF input port
called 'input coupler'

Fundamental mode coupler (input coupler)



1) Why this shape? .... to reduce/avoid multipacting

2) How to feed $\vec{E}$ in? .... with input couplers

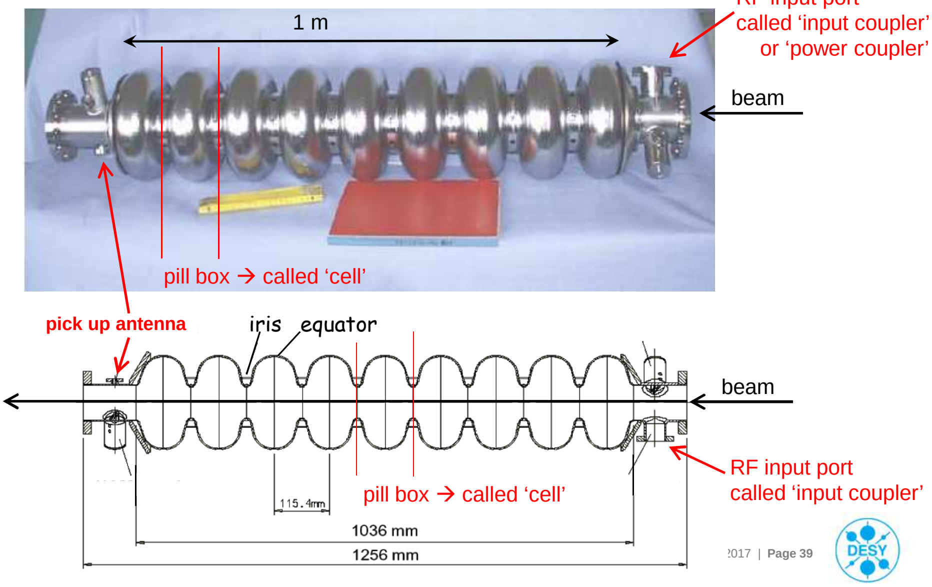
3) How to measure $\vec{E}$?

4)

5)

Superconducting cavity used in FLASH and in XFEL

Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)



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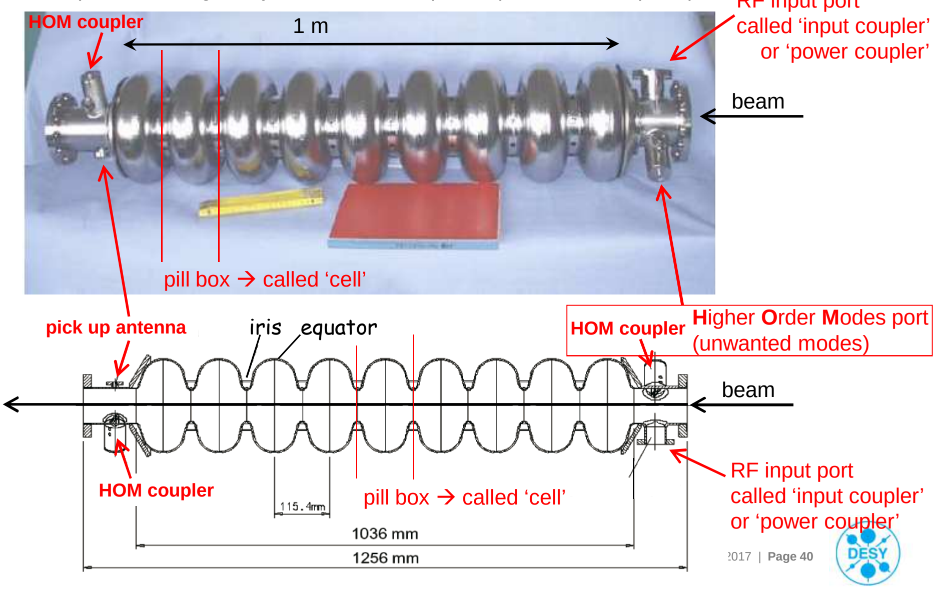


1) Why this shape? .... to reduce/avoid multipacting

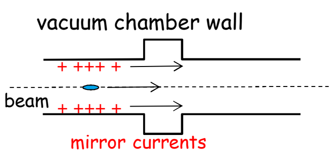
2) How to feed $\vec{E}$ in? .... with input couplers

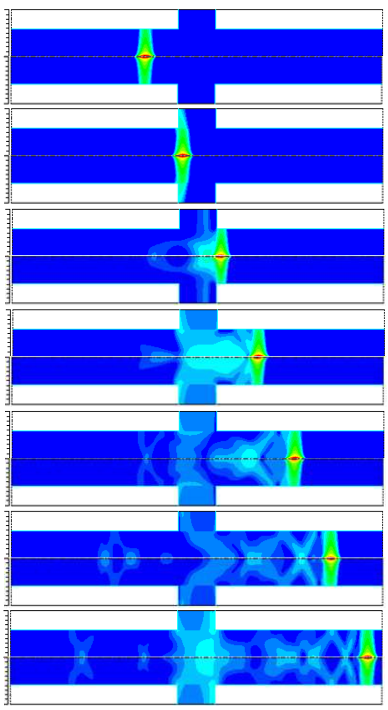
3) How to measure $\vec{E}$? .... with pick up antennas

4) What are HOM couplers for?

5)

Wakefields





1) Why this shape? .... to reduce/avoid multipacting

2) How to feed $\vec{E}$ in? .... with input couplers

3) How to measure $\vec{E}$? .... with pick up antennas

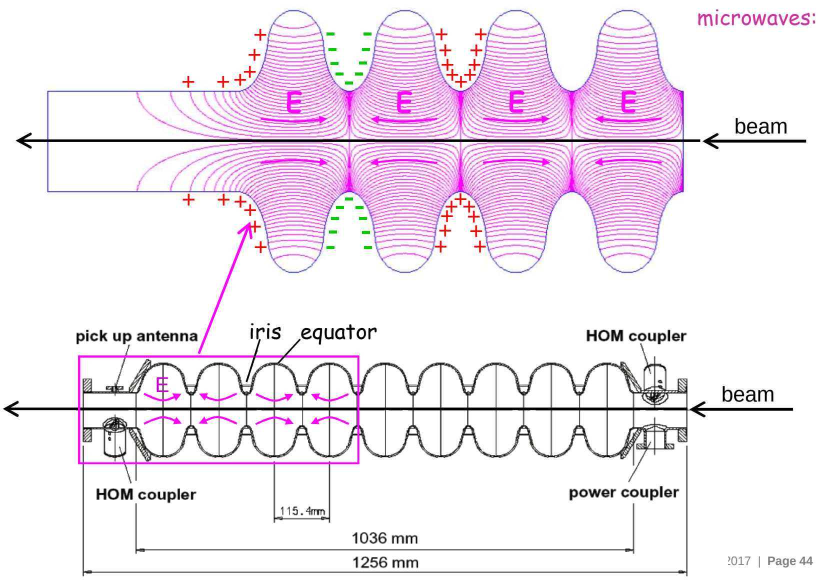
4) What are HOM couplers for? .... to reduce HOM (wakefields)

5) Is there a net acceleration?

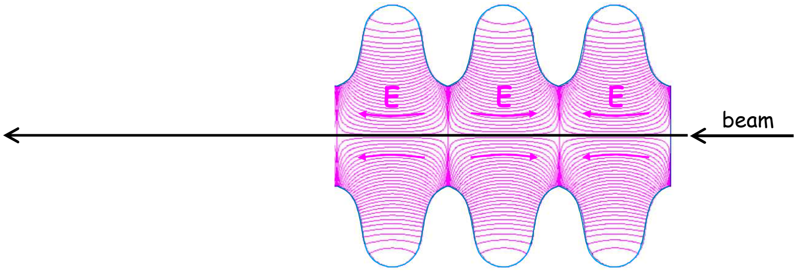
Accelerating field map

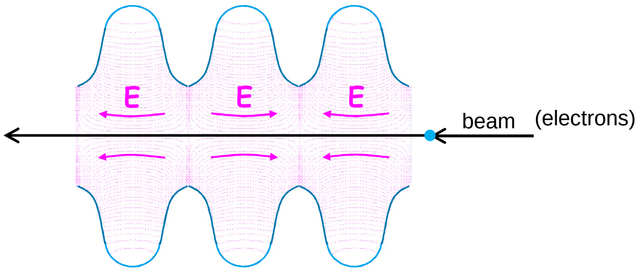
Simulation of the fundamental mode: electric field lines $f_{RF} = 1.3$ GHz

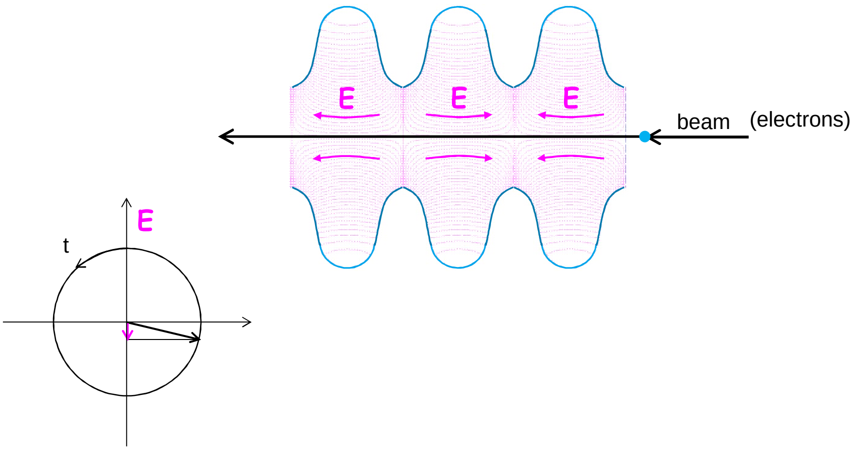
microwaves: (L-band)

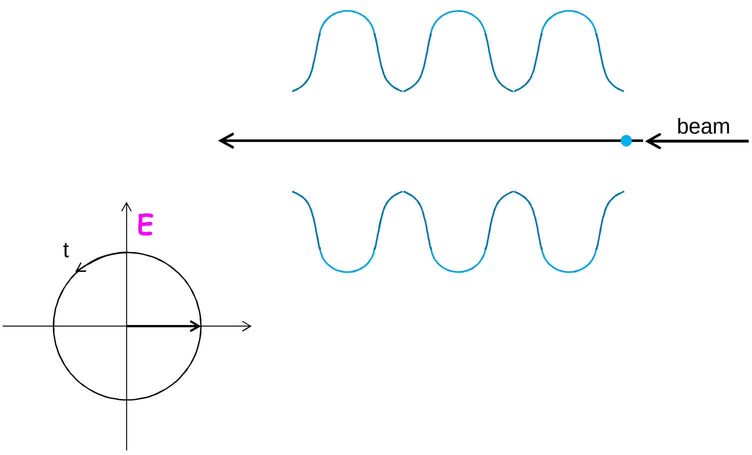


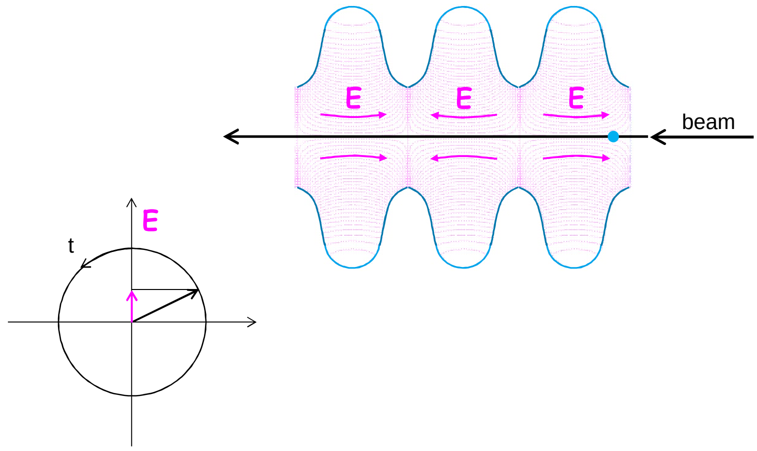
Simulation of the fundamental mode: electric field lines






E
E
E
beam
(electrons)
E
t


beam
E
t


E
E
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beam
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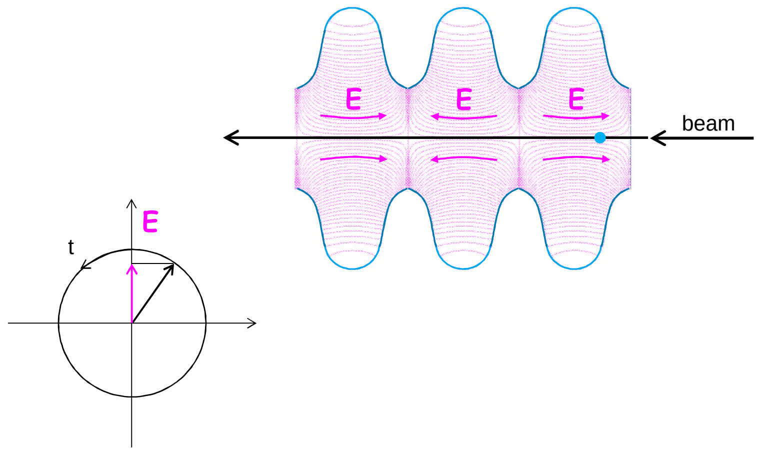
E
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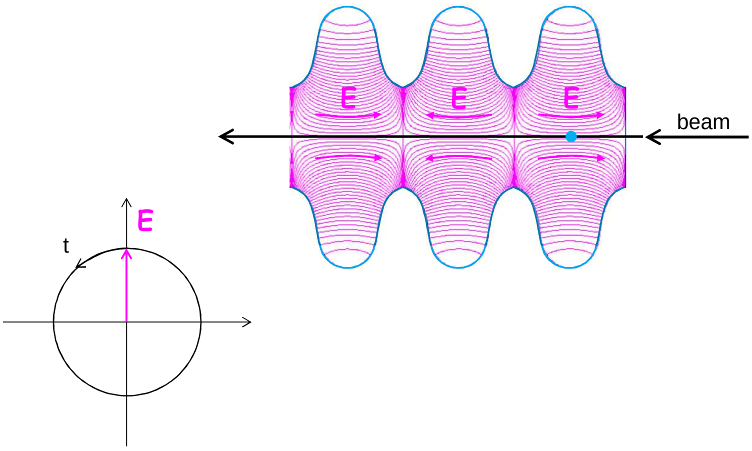
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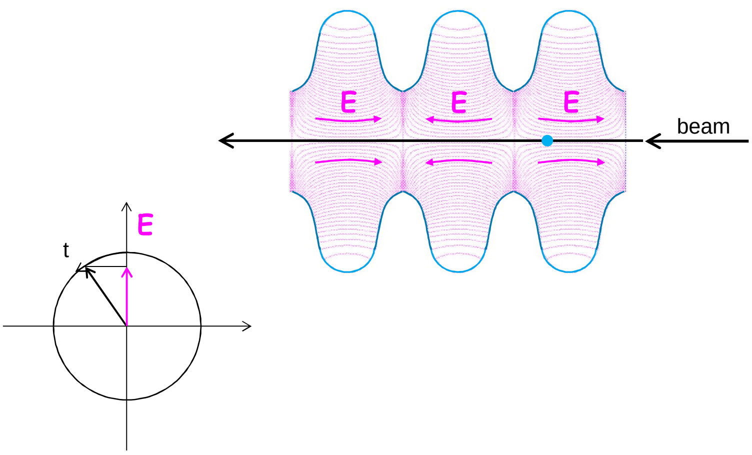
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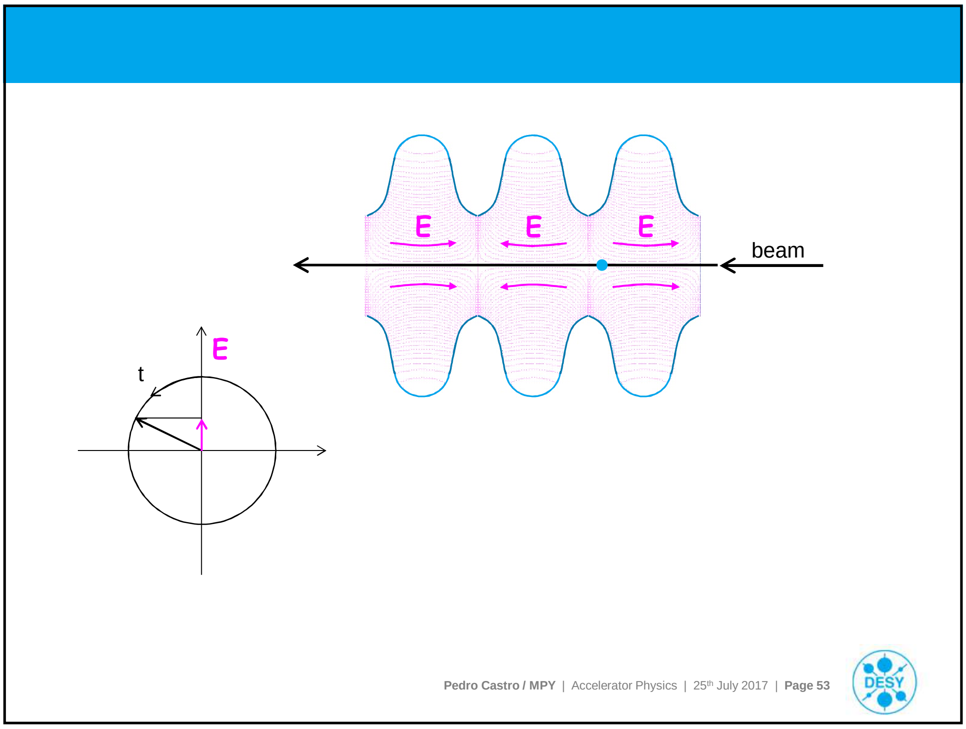
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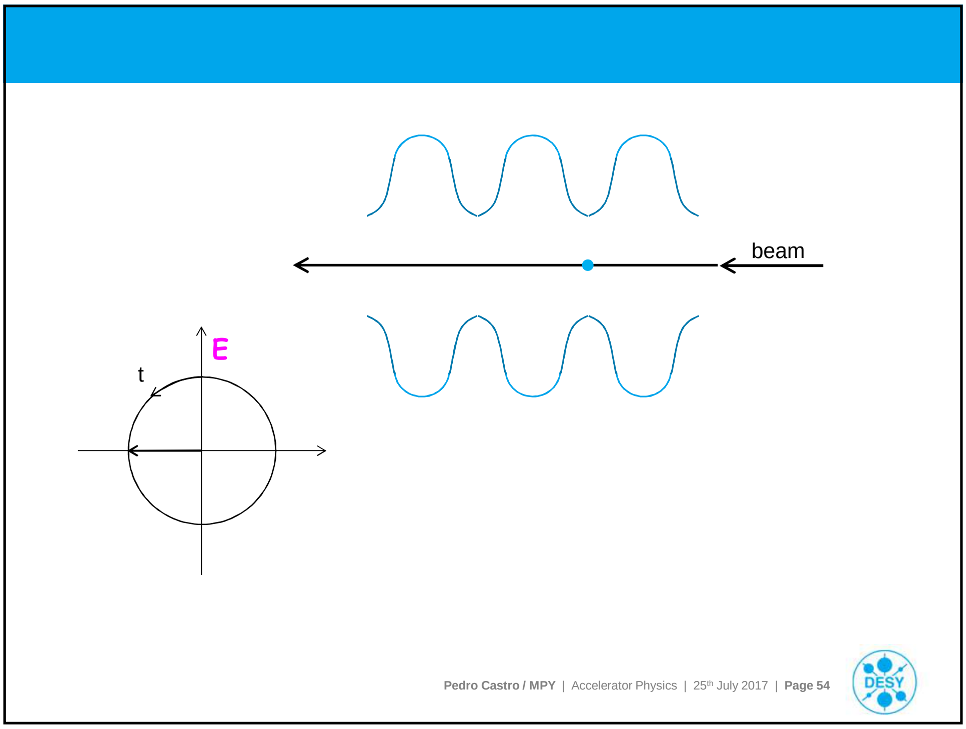
DESY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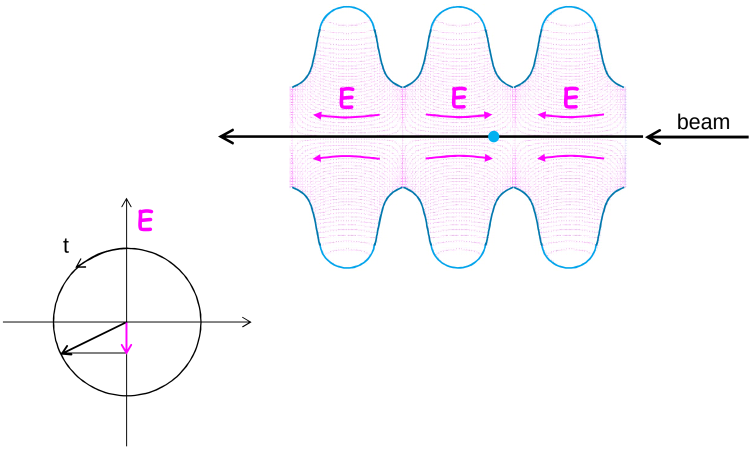
DESY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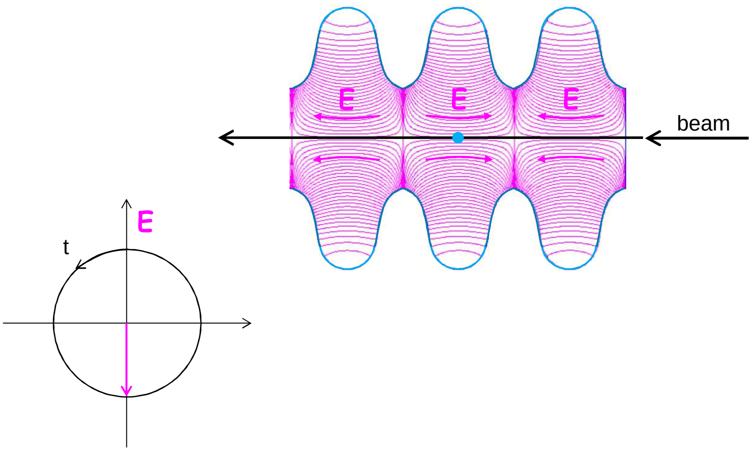
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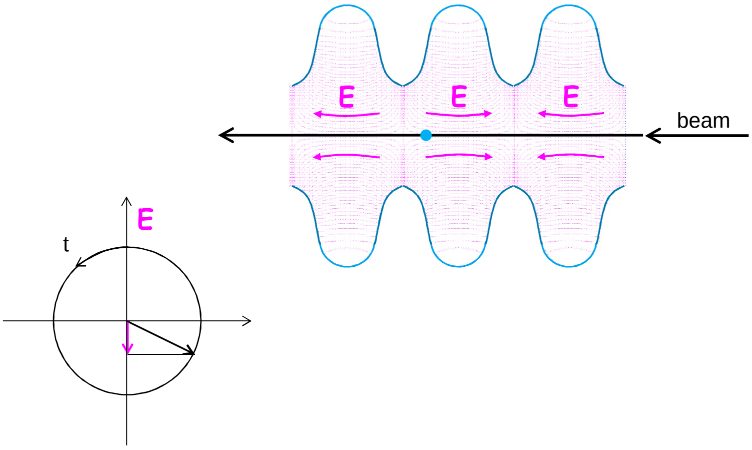
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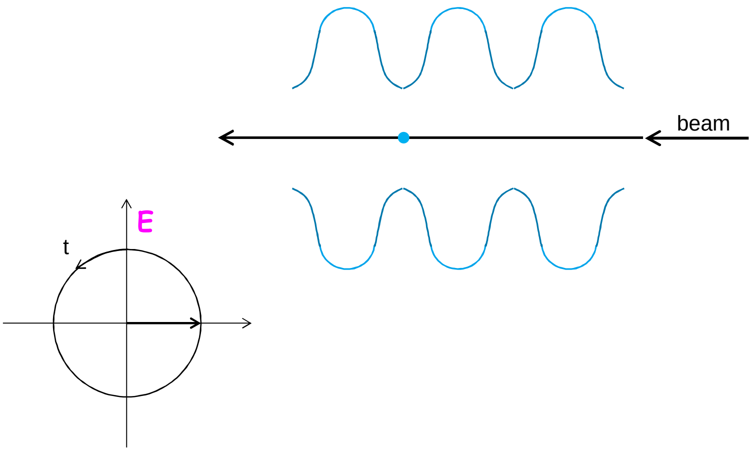
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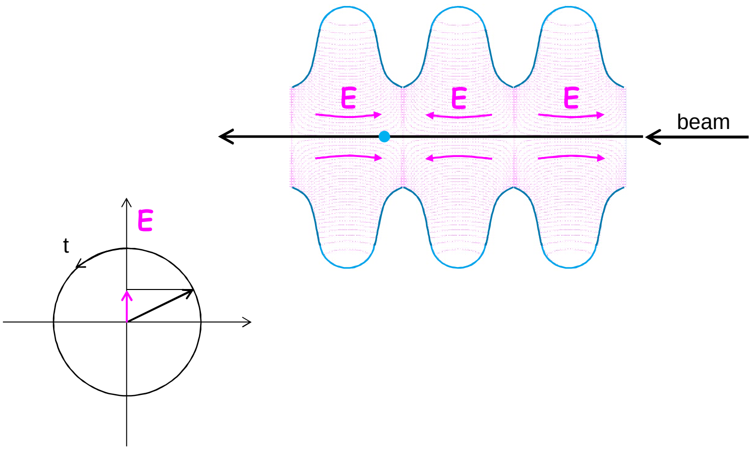
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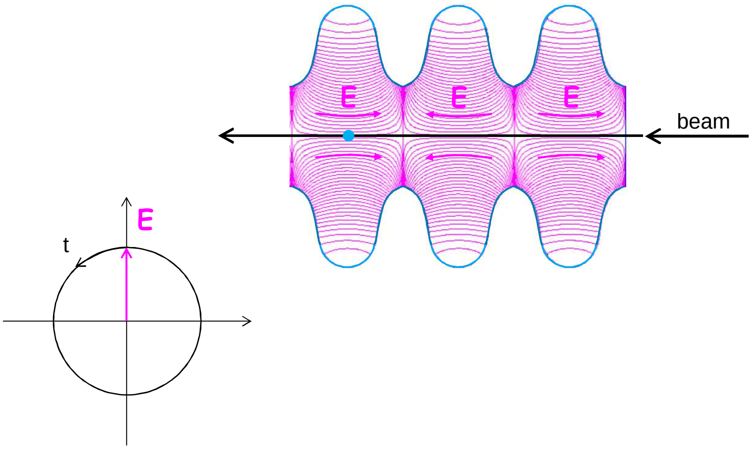
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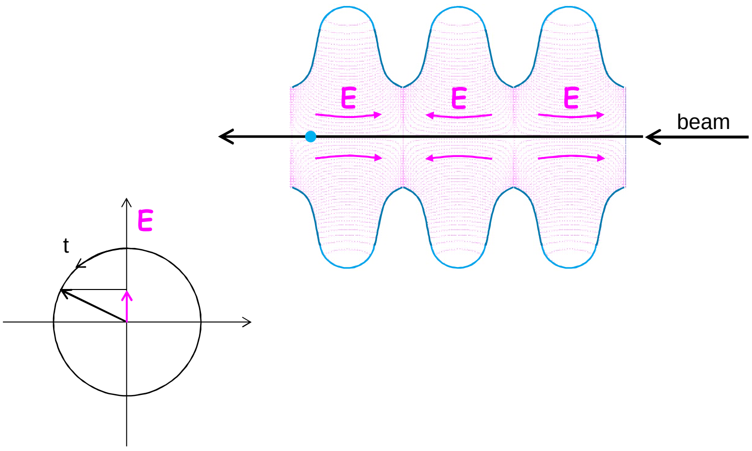
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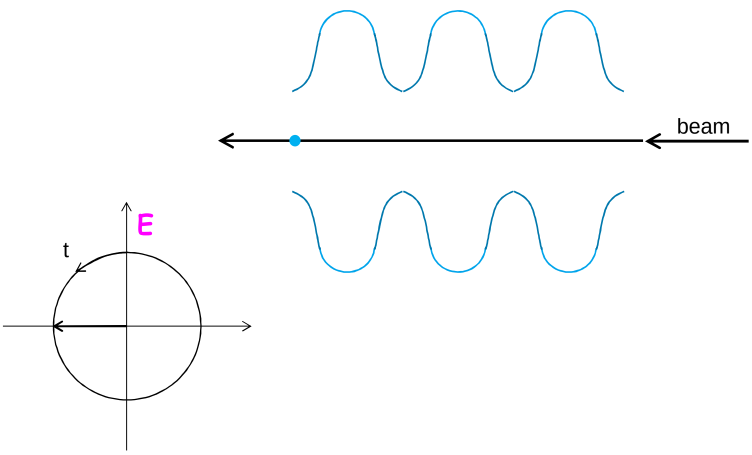
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1) Why this shape? .... to reduce/avoid multipacting

2) How to feed $\vec{E}$ in? .... with input couplers

3) How to measure $\vec{E}$? .... with pick up antennas

4) What are HOM couplers for? .... to reduce HOM (wakefields)

5) Is there a net acceleration? .... timing is the key

Summing-up of this part

Particle acceleration using radio-frequency fields:

basic cavity: pill box
- analogy to an LC circuit
- infinite number of solutions for $\vec{E}$ and $\vec{B}$
- eq. for the fundamental solution for $\vec{E}$ and $\vec{B}$

superconducting cavity
- multipacting mitigation
- RF couplers and antennas
- wakefields and HOMs
- FLASH and XFEL

Exercise

Calculate the resonant frequency of the fundamental mode in a 'coca-cola' tin

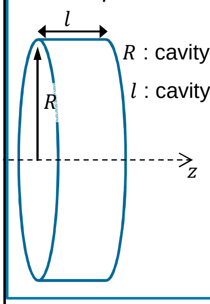
assume a cylindrical shape
with a diameter of 6.4 cm and a height of 12.1 cm

Exercise

Calculate the diameter of the ADONE pill box cavity for a fundamental frequency of 51 MHz

ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

boundary conditions



R : cavity radius

l : cavity length

fundamental solution with $B_z = 0$ (that is, $\vec{B}$ is transverse)

$$E_z = E_0 J_0\left(x_{01}\frac{r}{R}\right)e^{j\omega t}$$

$$E_r = 0$$

$$E_\theta = 0$$

$$B_z = 0$$

$$B_r = 0$$

$$B_\theta = j\omega \frac{R}{x_{01}c^2} E_0 J_1\left(x_{01}\frac{r}{R}\right) e^{j\omega t}$$

$m = 0$: rotation symmetry of the fields

$n = 1$: no zeros of the axial field component in $\vec{r}$

$p = 0$: no variation in z of the fields

J_m : Bessel´s functions

J'_m : derivative of the Bessel´s functions

angular frequency : $\omega = c\dfrac{x_{01}}{R}$ $\quad x_{01} = 2.405$

Exercise

Calculate the resonant frequency of the fundamental mode in a 'coca-cola' tin

assume a cylindrical shape
with a diameter of 6.4 cm and a height of 12.1 cm

$$\omega = c\frac{x_{01}}{R} = 3 \cdot 10^8 \frac{2.405}{0.032} = 2.25 \cdot 10^{10} \quad rad \cdot s^{-1}$$

$$f = \frac{\omega}{2\pi} = 3.6 \quad GHz$$

Microwave frequency bands

Letter Designation	Frequency range	Wavelength range	Typical uses
L band	1 to 2 GHz	15 cm to 30 cm	military telemetry, GPS, mobile phones (GSM), amateur radio
S band	2 to 4 GHz	7.5 cm to 15 cm	weather radar, surface ship radar, and some communications satellites (microwave ovens, microwave devices/communications, radio astronomy, mobile phones, wireless LAN, Bluetooth, ZigBee, GPS, amateur radio)
C band	4 to 8 GHz	3.75 cm to 7.5 cm	long-distance radio telecommunications
X band	8 to 12 GHz	25 mm to 37.5 mm	satellite communications, radar, terrestrial broadband, space communications, amateur radio
K_u band	12 to 18 GHz	16.7 mm to 25 mm	satellite communications

http://en.wikipedia.org/wiki/Microwave

Exercise

Calculate the diameter of the ADONE pill box cavity for a fundamental frequency of 51 MHz

ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

$$2\pi f = \omega = c\frac{x_{01}}{R}$$

$$R = c\frac{x_{01}}{2\pi f} = 3\cdot 10^8 \frac{2.405}{2\pi\, 51\cdot 10^6} = 2.25\, m$$

$$d = 2R = 4.5\, m$$

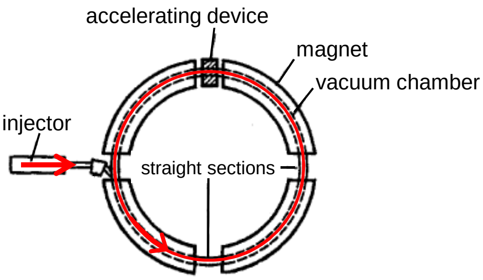
Introduction to Accelerator Physics

Part 4

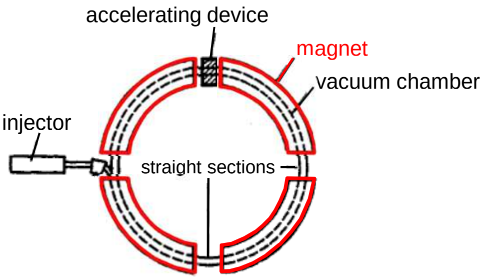
Pedro Castro / Accelerator Physics Group (MPY)
Introduction to Accelerator Physics
DESY, 25th July 2017

HELMHOLTZ
ASSOCIATION

Circular accelerators: the synchrotron

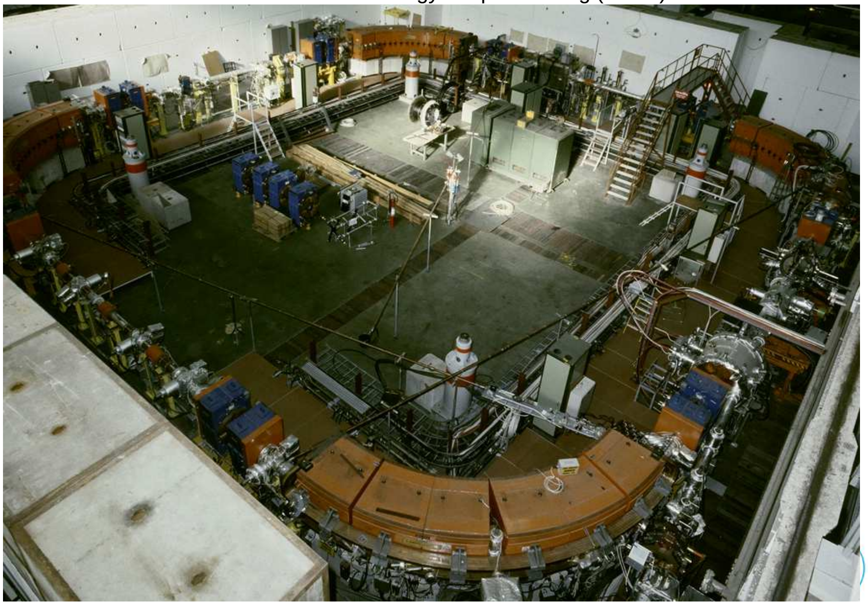


Circular accelerators: the synchrotron



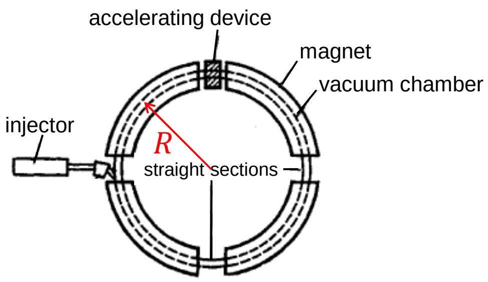
Circular accelerators: the synchrotron

Low Energy Antiproton Ring (LEAR) at CERN



Dipole magnet

Circular accelerators: the synchrotron



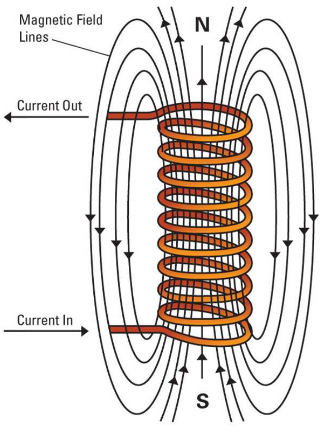
$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = qvB$$

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

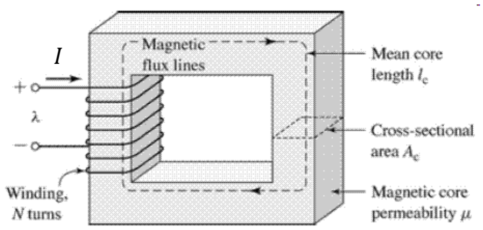
(circular motion)

$$qB = \frac{mv}{R} \rightarrow R = \frac{(mv)_{max}}{qB_{max}} = constant$$

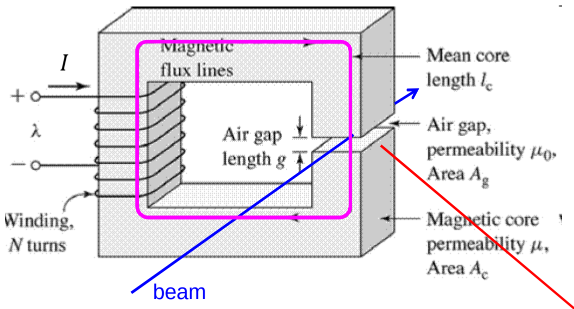
Electromagnet



permeability of iron = 300…10000 larger than air



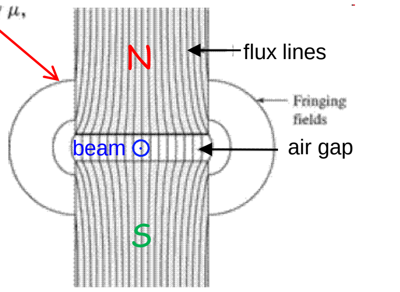
Dipole magnet



$$\int_{gap} \frac{\vec{B}}{\mu_0}\,\vec{ds} = \frac{B g}{\mu_0} = N\,I$$

$$\boxed{B = \frac{\mu_0 N\,I}{g}}$$

gap height



Ampere's law:

$$\oint \vec{H}\,\vec{ds} = I_{enclosed} = NI$$

$$\oint \vec{H}\,\vec{ds} = \int_{iron} \vec{H}\,\vec{ds} + \int_{gap} \vec{H}\,\vec{ds} = N\,I$$

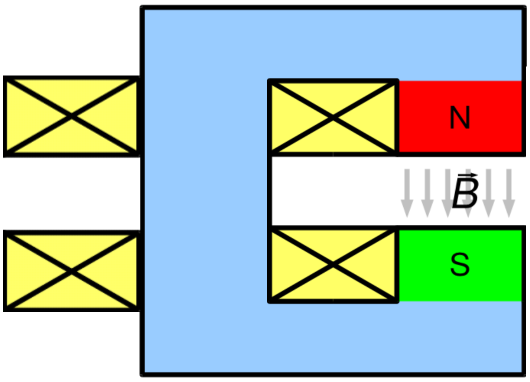
$$\cancel{\int_{iron} \frac{\vec{B}}{\mu_{iron}}}\,\vec{ds} + \int_{gap} \frac{\vec{B}}{\mu_0}\,\vec{ds} = N\,I$$

Dipole magnet cross section

increase B ➔ increase current, but power dissipated $P = R \cdot I^2$

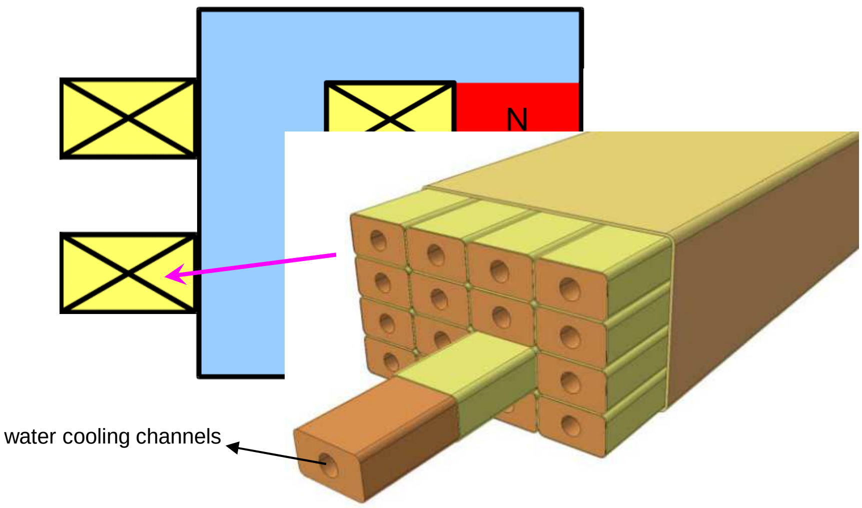
➔ large conductor cables

Dipole magnet cross section

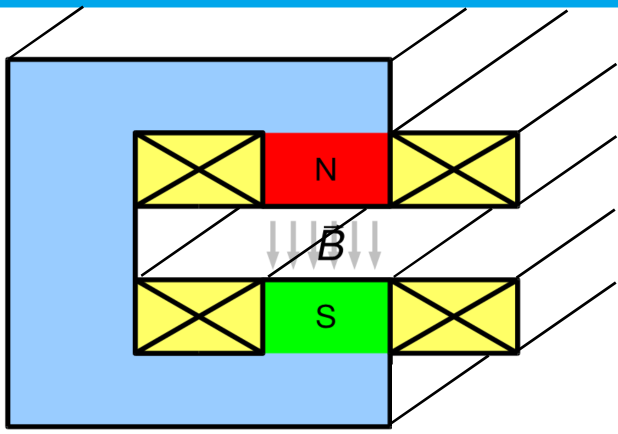


increase B ➔ increase current, but power dissipated $P = R \cdot I^2$
➔ large conductor cables

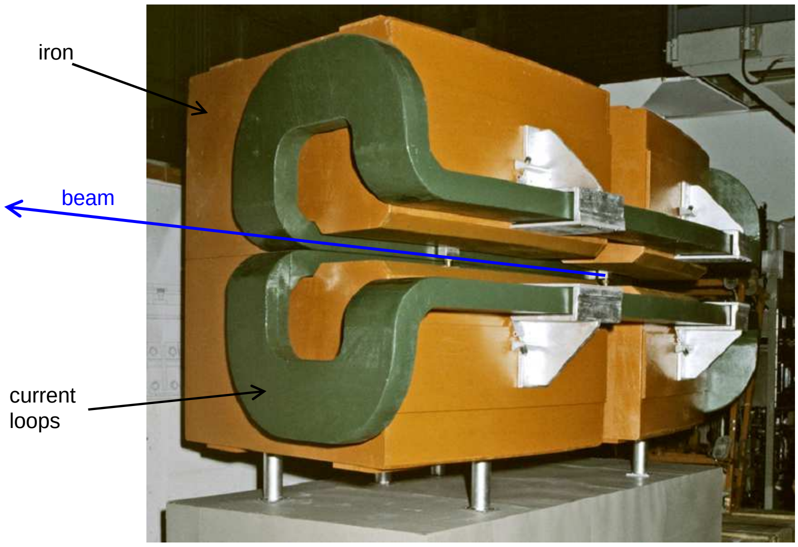
Dipole magnet cross section



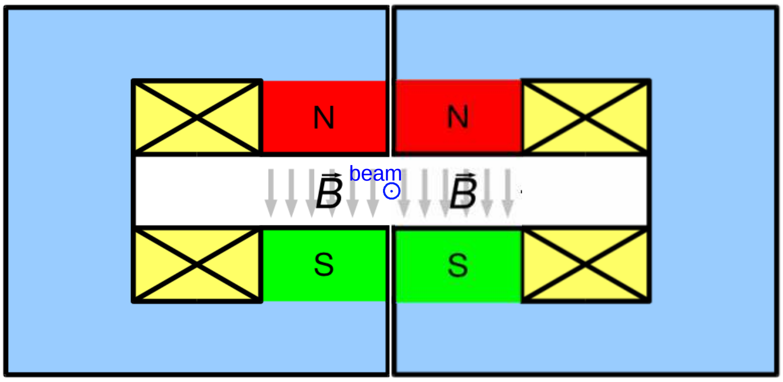
Dipole magnet cross section



Dipole magnet

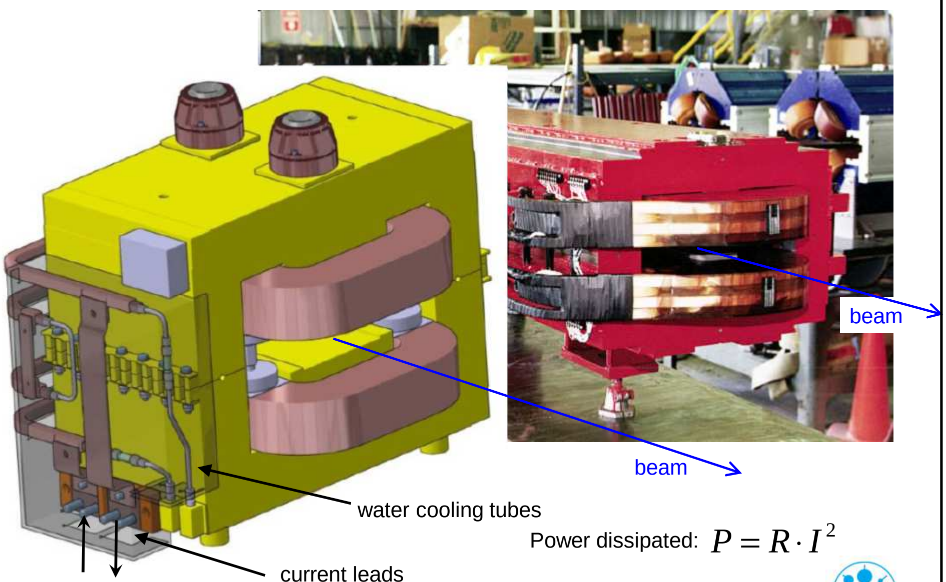


Dipole magnet cross section



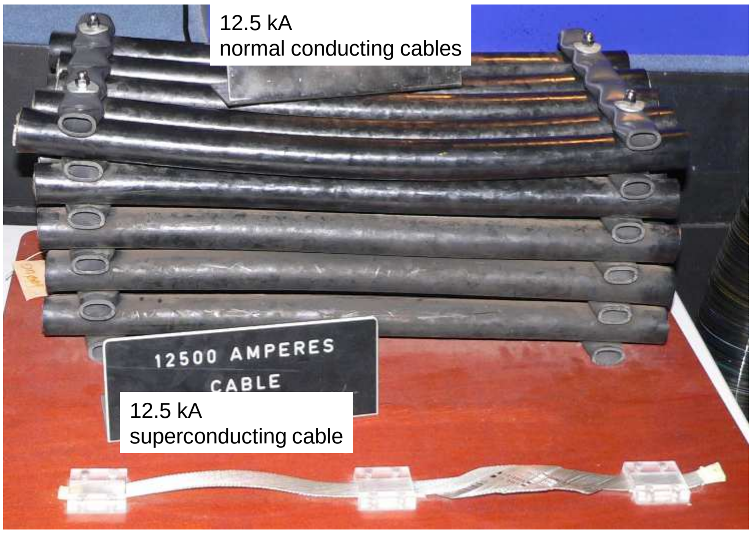
C magnet + C magnet = H magnet

Dipole magnet cross section (another design)



Power dissipated: $P = R \cdot I^2$

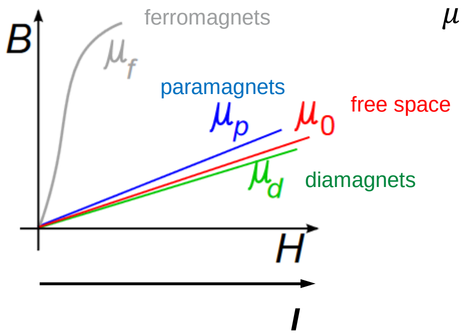
Superconductivity



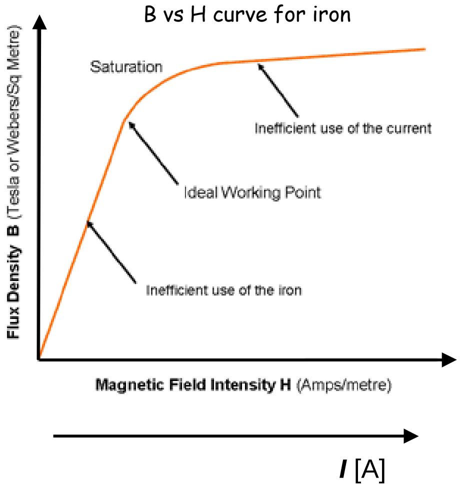
Saturation of iron: 1.6 – 2 T

increase B ➔ increase current, but power dissipated $\mathrm{P} = R \cdot I^2$
➔ large conductor cables
➔ saturation effects

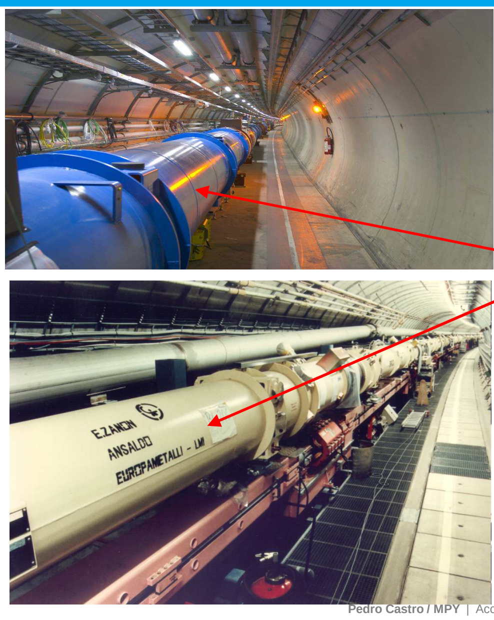
μ : permeability



Saturation of iron: 1.6 – 2 T



Superconducting dipole magnets

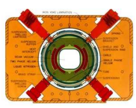
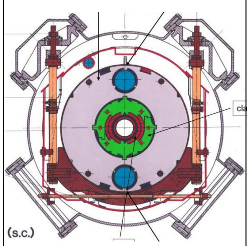
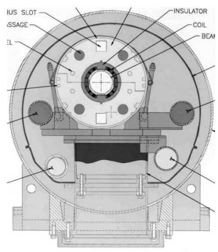
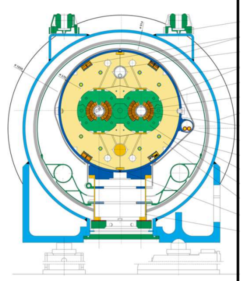


LHC

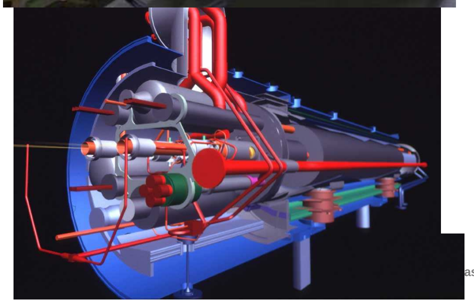
superconducting dipoles

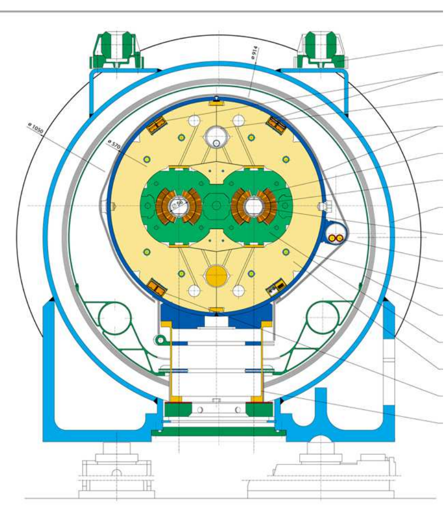
HERA

Superconducting dipole magnets: cross section

Tevatron	HERA	RHIC	LHC
Fermilab Chicago (USA)	DESY Hamburg (Germany)	Brookhaven Long Island (USA)	CERN Geneva (Switzerland)
4.5 T	5.3 T	3.5 T	8.3T
			

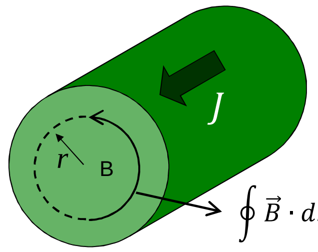
Superconducting dipole magnets





Dipole field inside 1 conductor

J: uniform current density

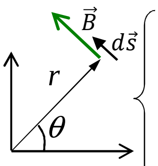


Ampere's law:

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I$$

$$\oint \vec{B} \cdot d\vec{s} = \oint B ds = 2\pi r B = \mu_0 \pi r^2 J$$

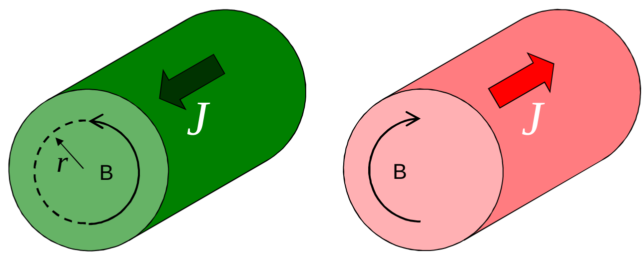
$$B = \frac{\mu_0 J}{2} r$$



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

Dipole field inside 2 conductors

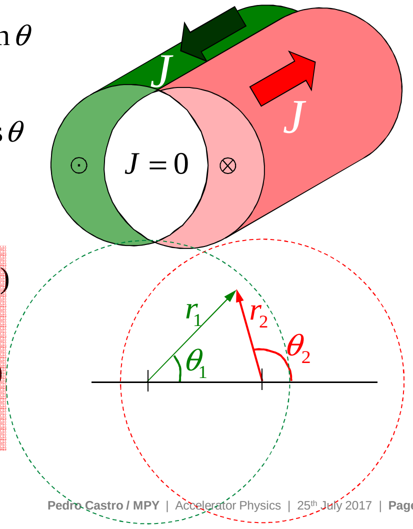
J = uniform current density



Dipole field inside 2 conductors

J = uniform current density

one conductor:
$$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\ B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$



superposition:

$$B_x = \frac{\mu_0 J}{2}(-r_1 \sin\theta_1 + r_2 \sin\theta_2)$$

$$B_y = \frac{\mu_0 J}{2}(r_1 \cos\theta_1 - r_2 \cos\theta_2)$$

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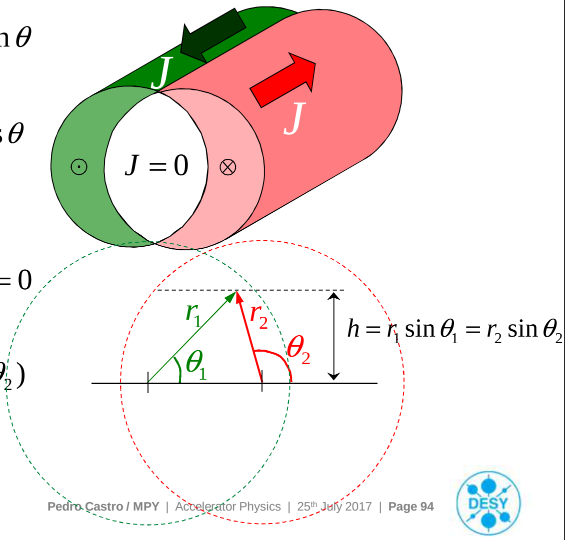
Dipole field inside 2 conductors

J = uniform current density

one conductor:
$$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\ B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$



$$B_x = \frac{\mu_0 J}{2}(-r_1 \sin\theta_1 + r_2 \sin\theta_2) = 0$$

$$B_y = \frac{\mu_0 J}{2}(r_1 \cos\theta_1 - r_2 \cos\theta_2)$$

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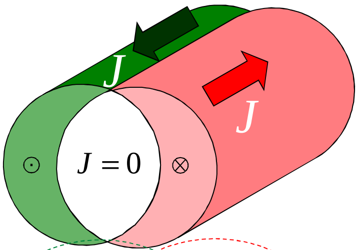
Dipole field inside 2 conductors

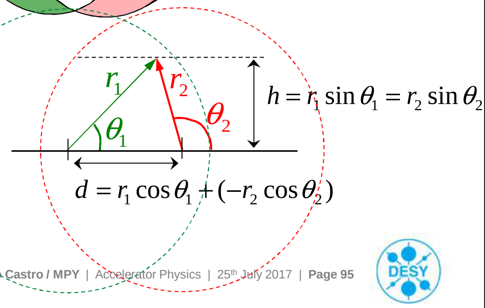
J = uniform current density

one conductor:
$$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\ B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$



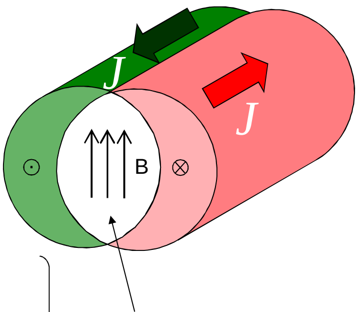
$$B_x = \frac{\mu_0 J}{2}(-r_1 \sin\theta_1 + r_2 \sin\theta_2) = 0$$

$$B_y = \frac{\mu_0 J}{2}(r_1 \cos\theta_1 - r_2 \cos\theta_2) = \frac{\mu_0 J}{2} d$$



Dipole field inside 2 conductors

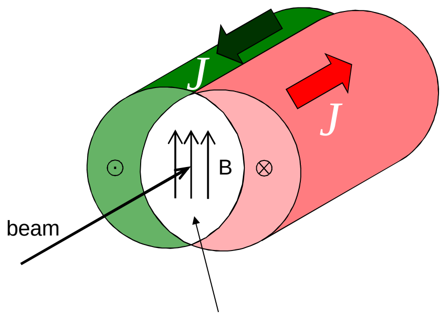
J = uniform current density



$$\left.\begin{aligned} B_x &= \frac{\mu_0 J}{2}(r_1 \sin\theta_1 - r_2 \sin\theta_2) = 0 \\ B_y &= \frac{\mu_0 J}{2}(r_1 \cos\theta_1 - r_2 \cos\theta_2) = \frac{\mu_0 J}{2} d \end{aligned}\right\}$$

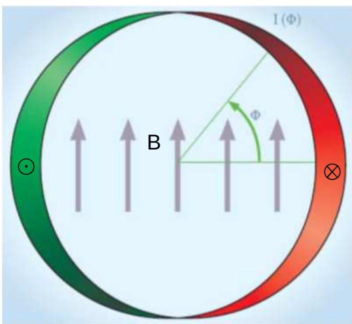
constant vertical field

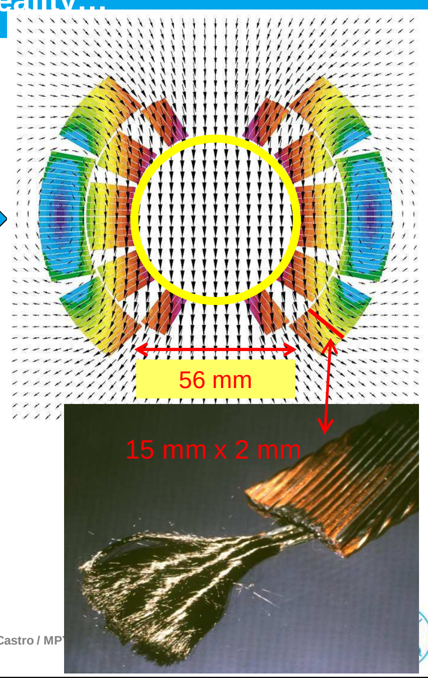
Dipole field inside 2 conductors



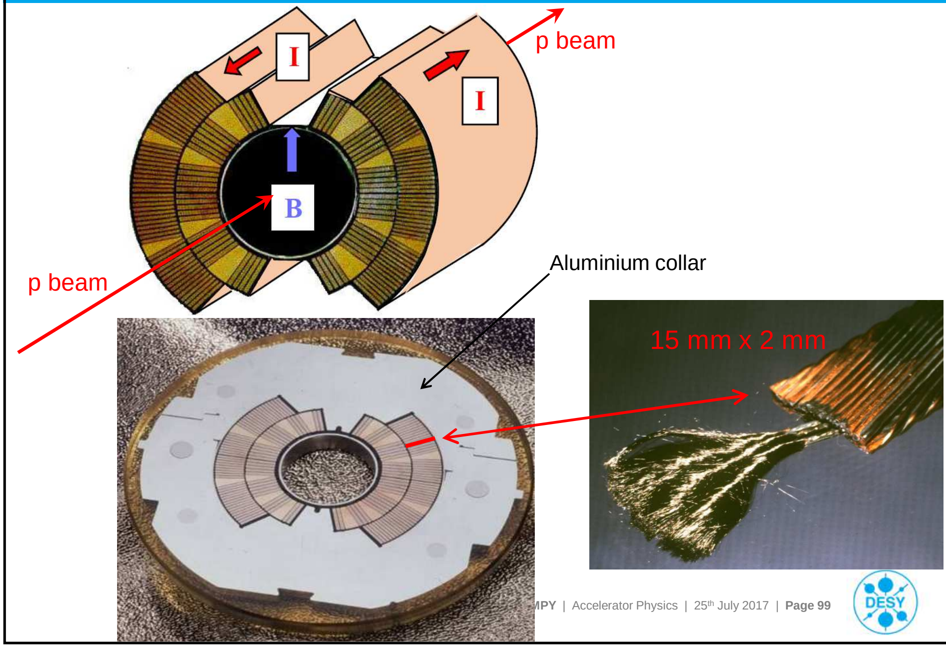
$$B_y = \frac{\mu_0 J}{2} d$$

From the principle … to the reality…

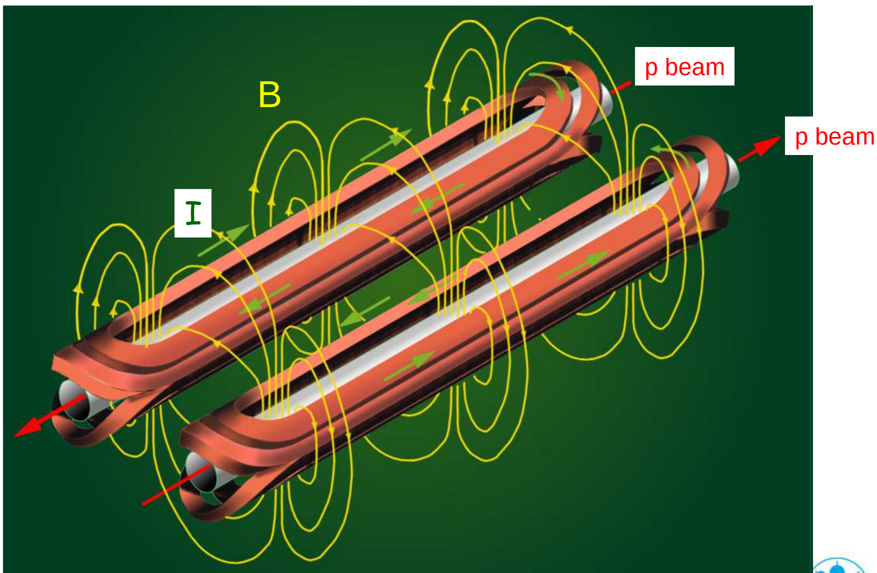


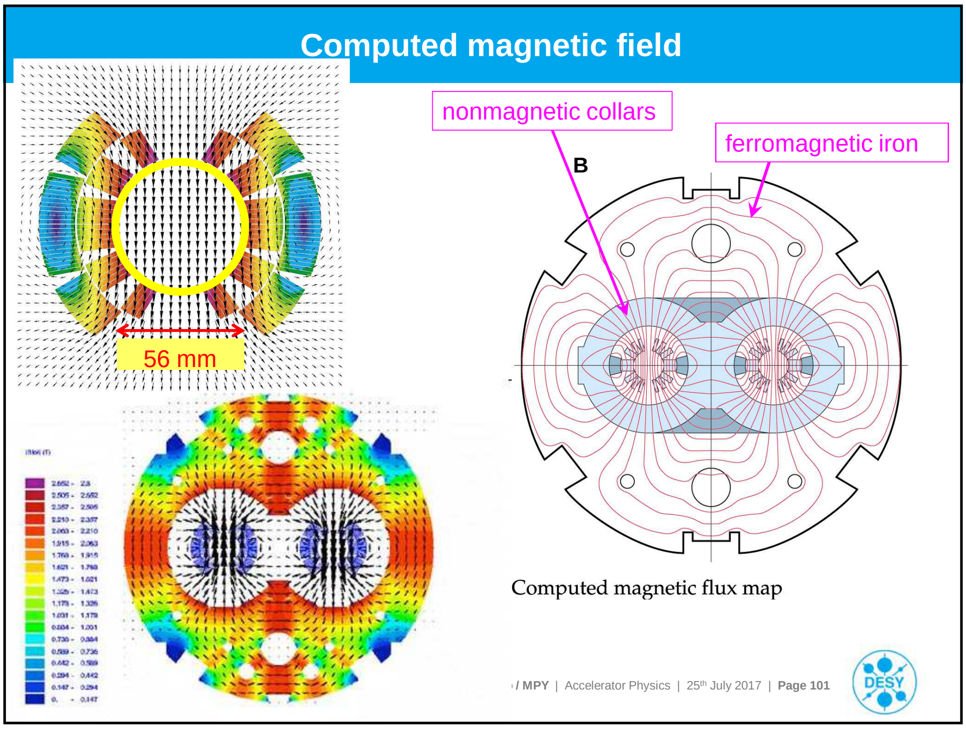


LHC dipole coils in 3D



LHC dipole coils in 3D




Computed magnetic field
nonmagnetic collars
ferromagnetic iron
B
56 mm
Computed magnetic flux map
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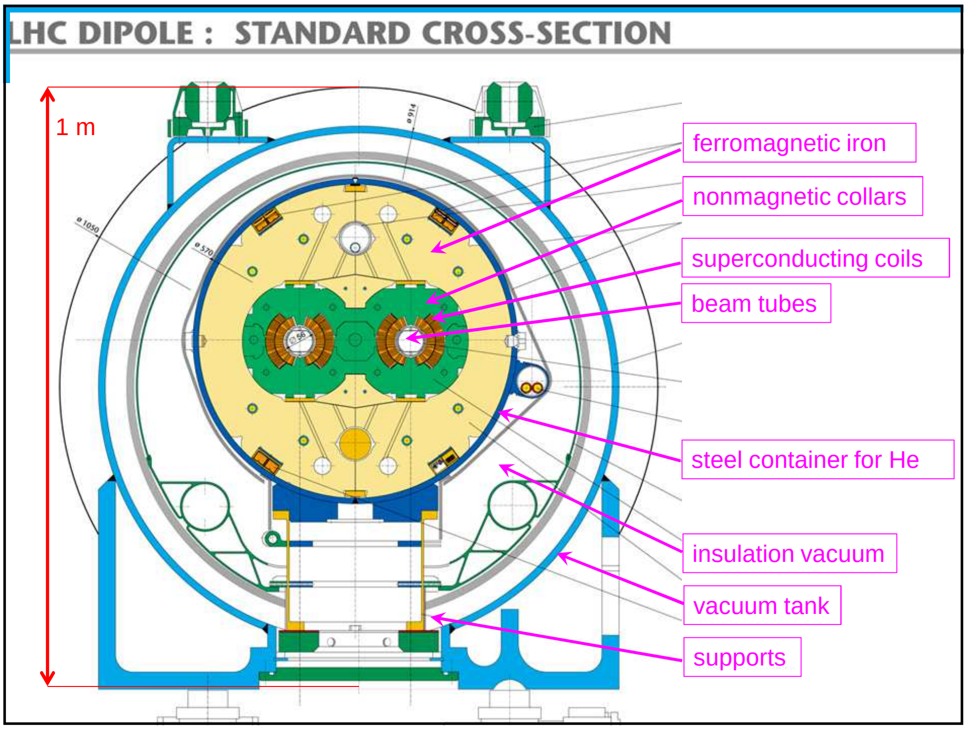
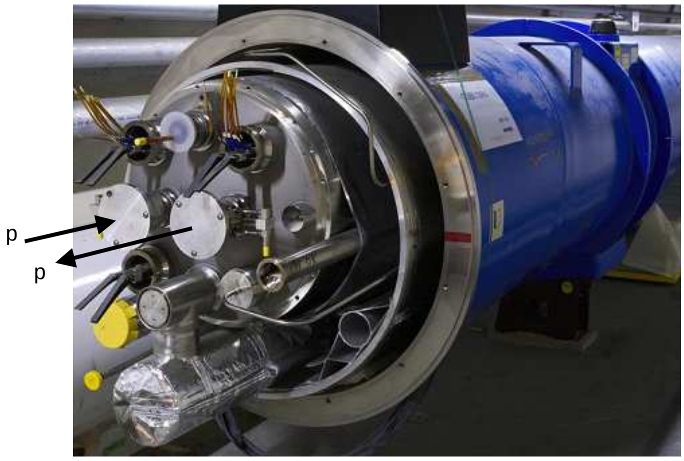
DESY


LHC DIPOLE : STANDARD CROSS-SECTION
1 m
ferromagnetic iron
nonmagnetic collars
superconducting coils
beam tubes
steel container for He
insulation vacuum
vacuum tank
supports

Superconducting dipole magnets

LHC dipole magnet interconnection:



Summing-up of this part

Circular accelerators: the synchrotron

RF cavities:
- pill-box cavity
- superconducting cavities

Dipole magnets:
- normal conducting dipoles
- superconducting dipoles

Thank you for your attention

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