Introduction to Accelerator Physics

Part 3

Pedro Castro / Accelerator Physics Group (MPY)
Hamburg, 26th July 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Accelerator lectures framework in Summer Student Prog.

<u>18th and 19th Aug.</u>: Future accelerators:

- Future colliders for the energy frontier, K. Buesser
- Plasma accelerators, J. Osterhoff

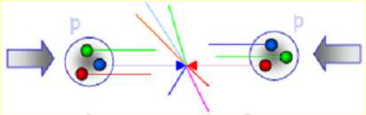
<u>Today:</u> focus on present day <u>and last 50 years</u> accelerator technology

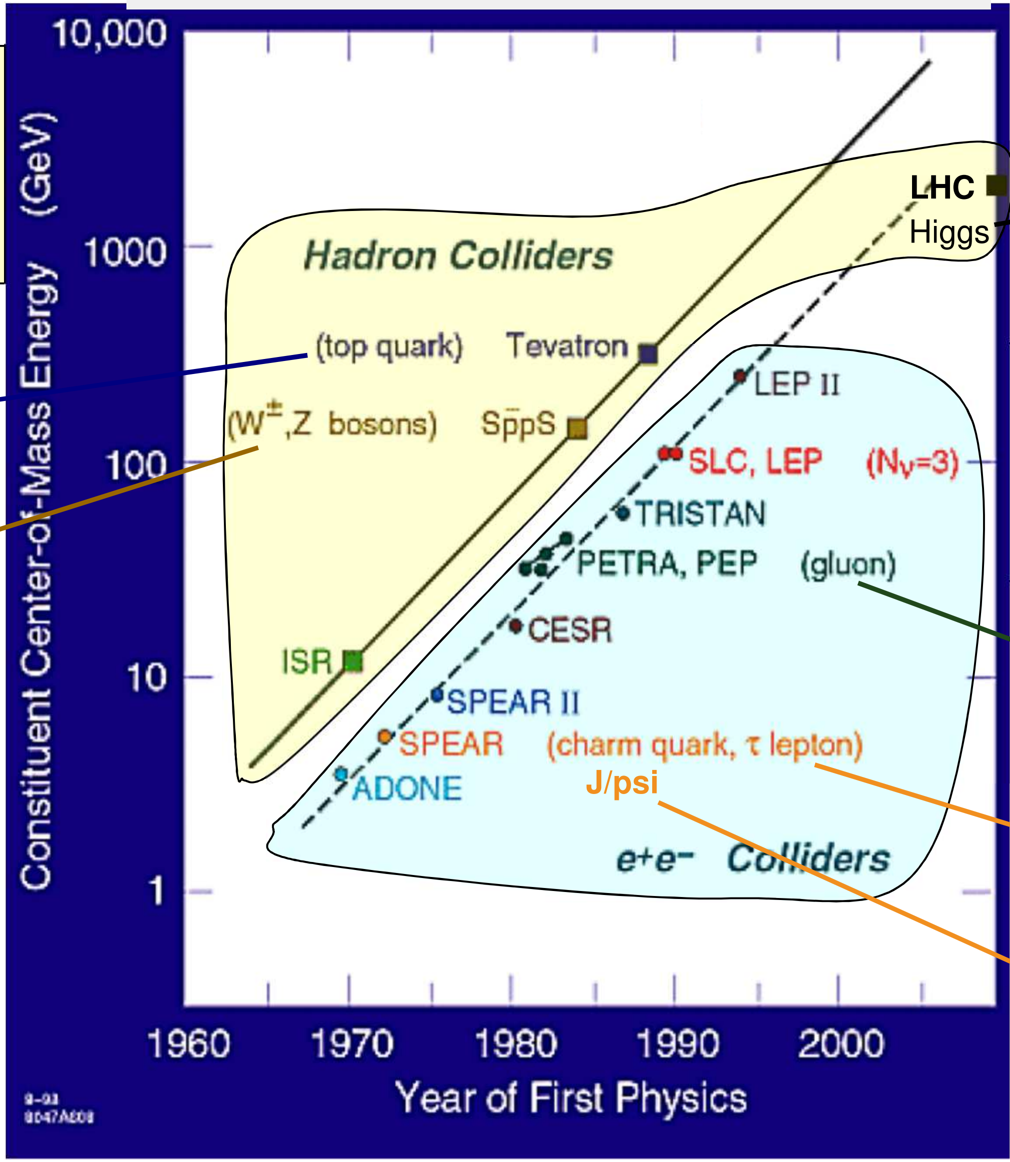
synchrotrons: machines for discoveries

Main HEP discoveries at synchrotrons in the last 50 years

Livingston plot (doubling E every 3.5 years)

hadron colliders:
$E_{cm} / 3$ quarks



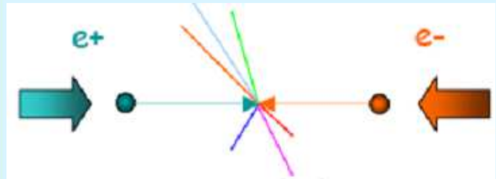


discovered 2012
NP 2013

discovered 1995

discovered 1983
NP 1984

e+e- colliders:



discovered 1979

discovered 1975
NP 1995

discovered 1974
NP 1976

Scope of this lecture:

1. Synchrotrons: key components and their challenges to reach high energies:

- Dipole magnetic fields
- Superconducting dipoles

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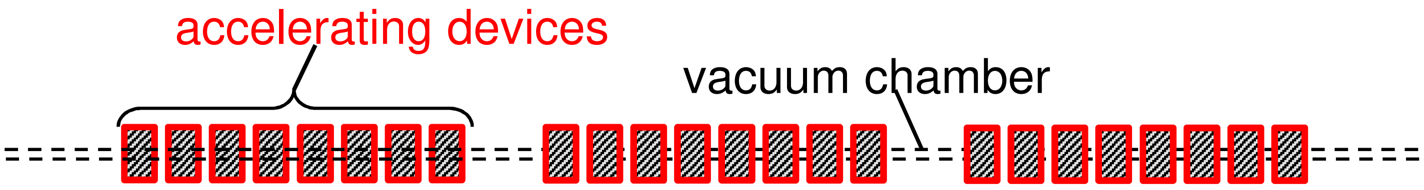
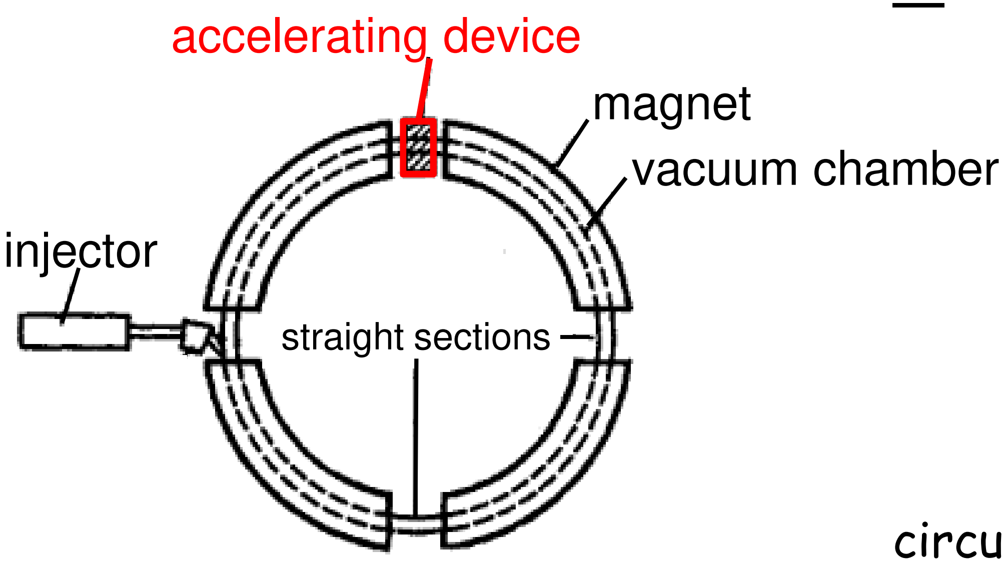
- Quadrupole magnets to focus beams Part 2, yesterday

2. Synchrotrons and Linear Accelerators:

- Acceleration using radio-frequency electomagnetic fields Part 3



linear accelerator (linac)



circular accelerator: synchrotron

Motion in electric and magnetic fields

Equation of motion under Lorentz Force

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

magnetic field

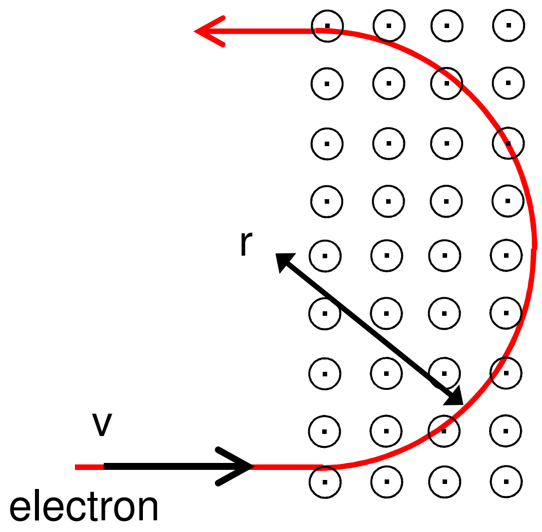
momentum charge velocity electric field

of the particle

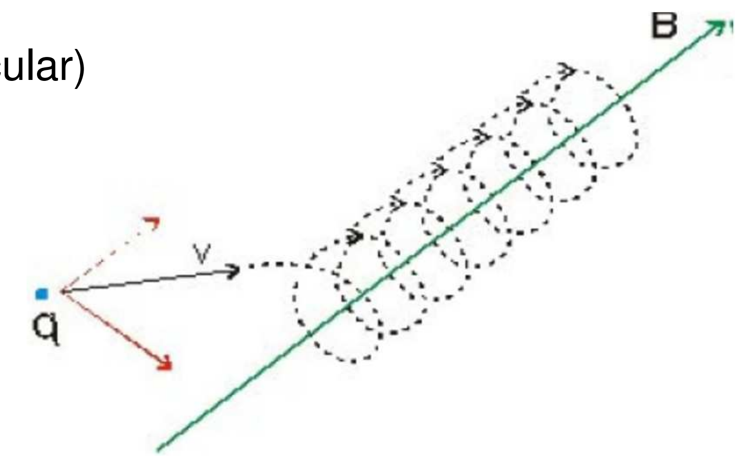
Motion in magnetic fields

if the electric field is zero ($\vec{E} = 0$), then

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



B (perpendicular)



Magnetic fields do not change the particles energy

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

E: total energy

$\vec{p}$: momentum

E_0: energy at rest

Motion in magnetic fields

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

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

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

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

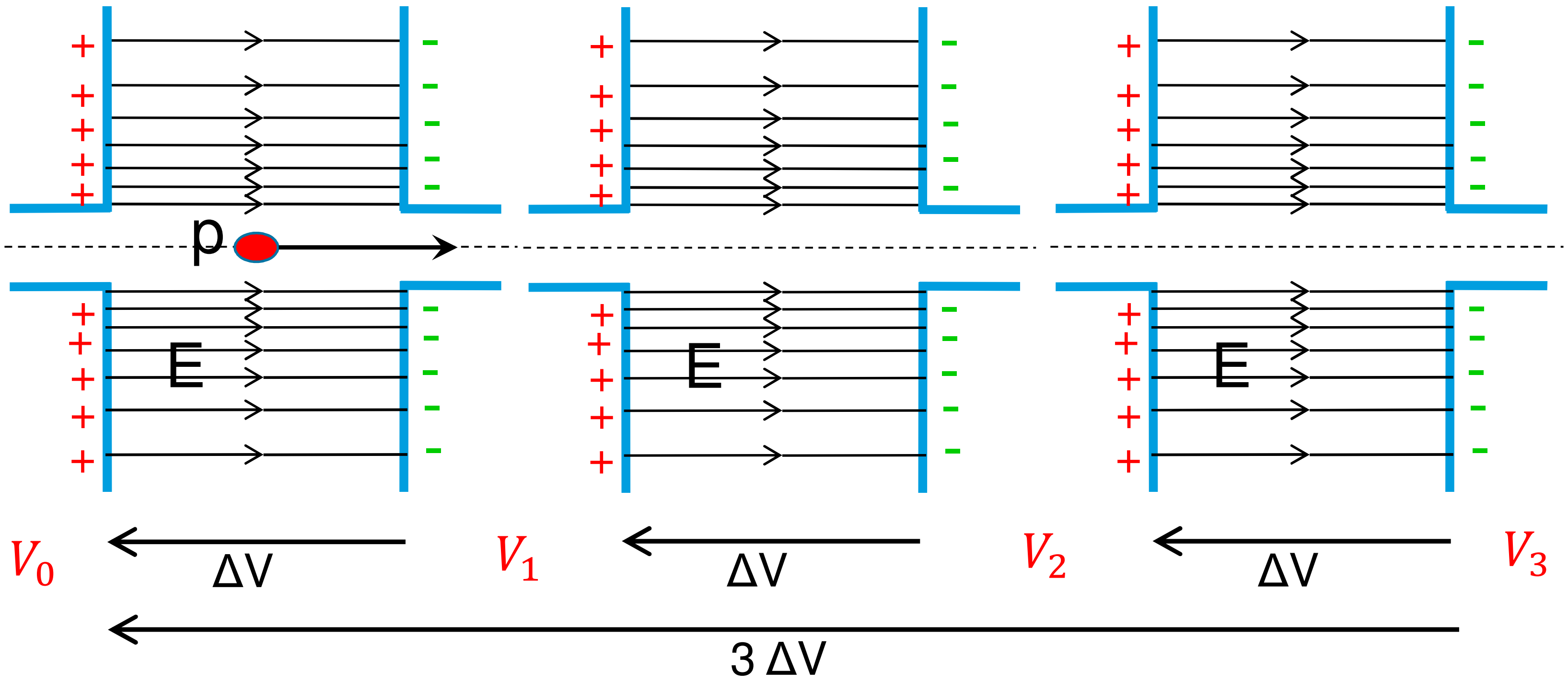
since $\vec{v} \times \vec{B} \perp \vec{v}$ ➔ $\emptyset = 90°$

Magnetic fields do not change the particles energy, only electric fields do !

In general:

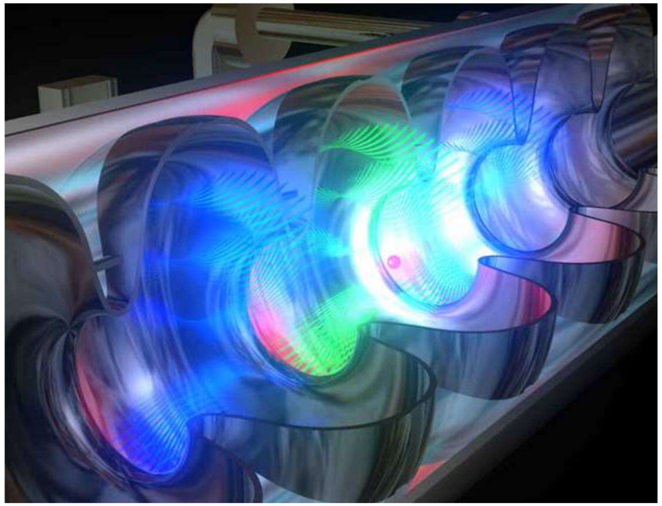
- Static magnetic fields → to guide (bend + focus) particle beams

acceleration with DC electric fields

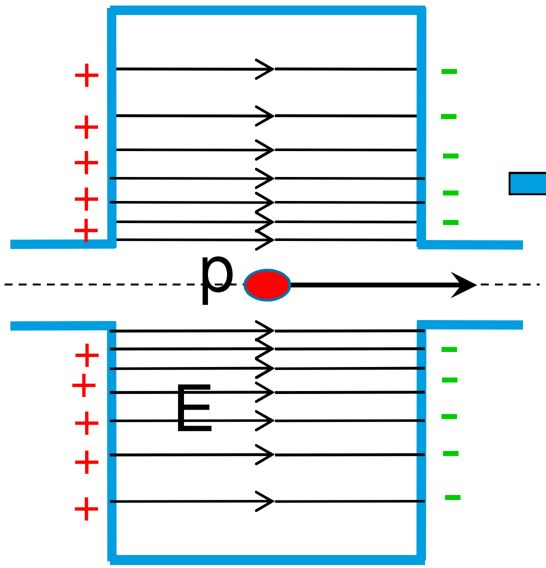


In general:

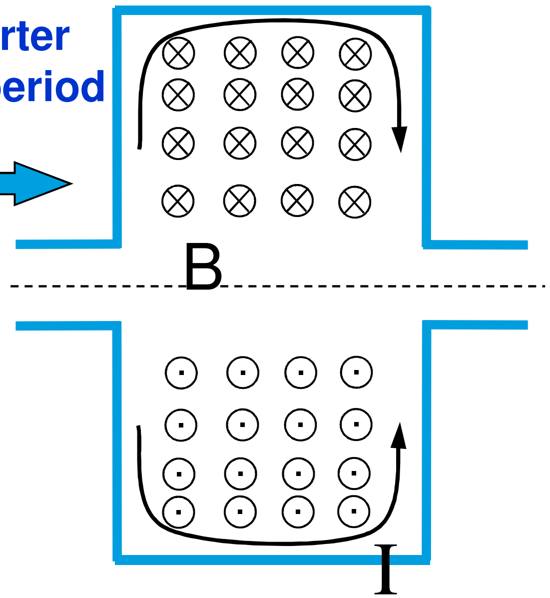
- Static magnetic fields → to guide (bend + focus) particle beams
- Static electric fields → accelerate particle beams (low energy)
- Radio-frequency EM fields → accelerate particle beams (high E)

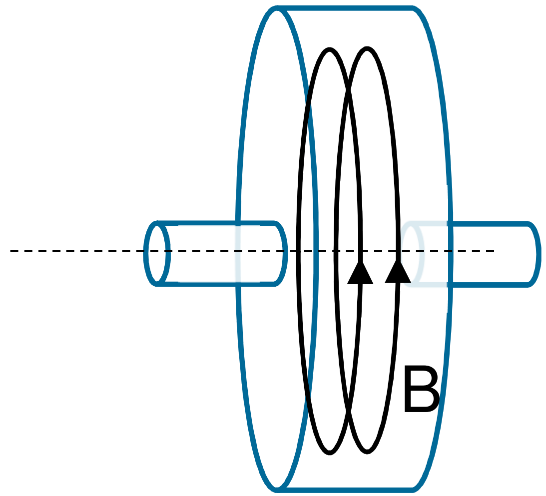


RF cavity basics: a cylindrical cavity



a quarter of a period later:





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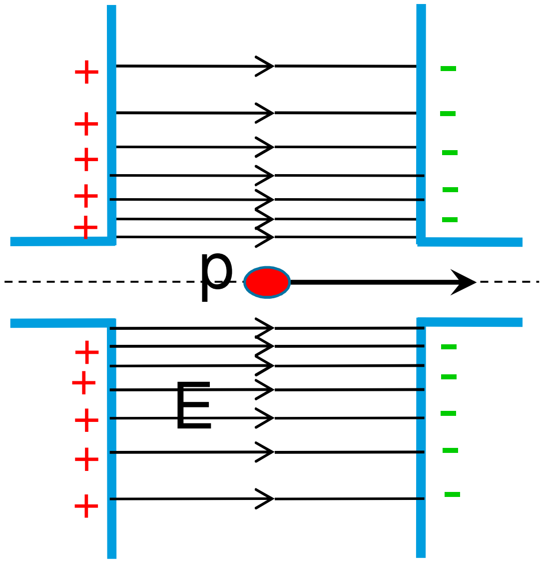
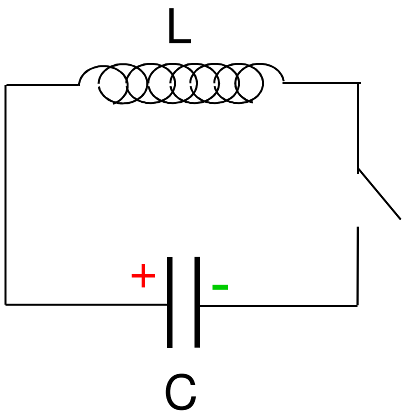


LC circuit (or resonant circuit) analogy:



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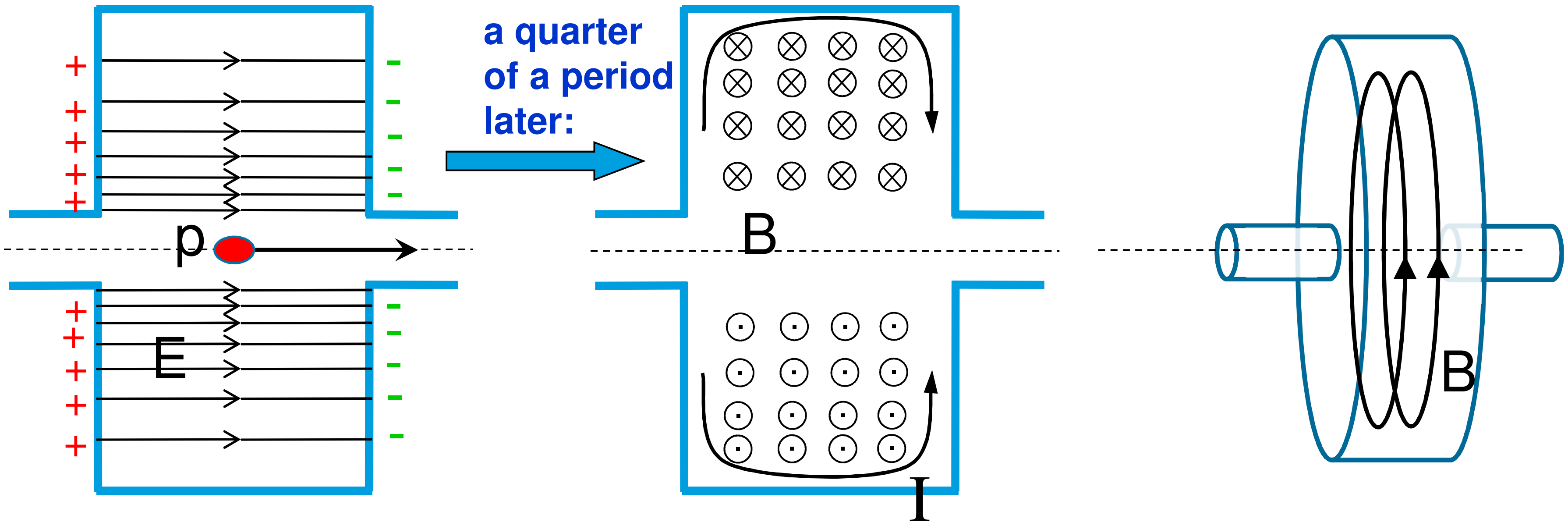

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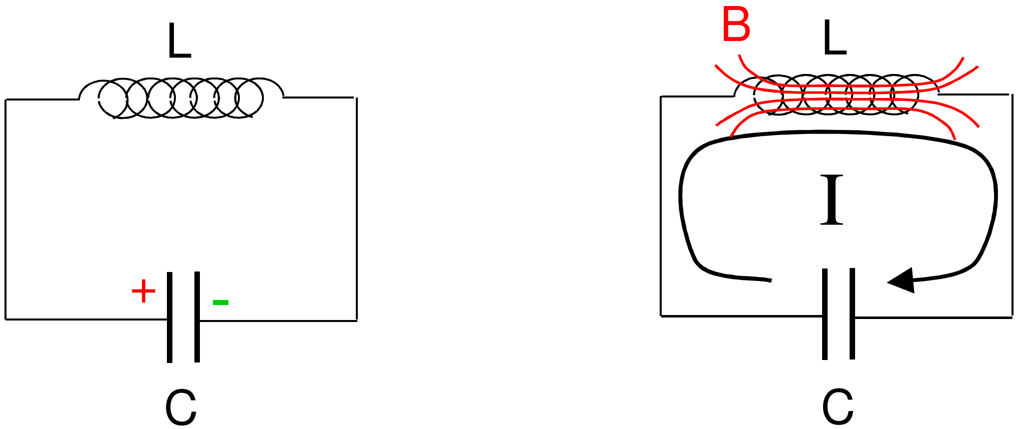

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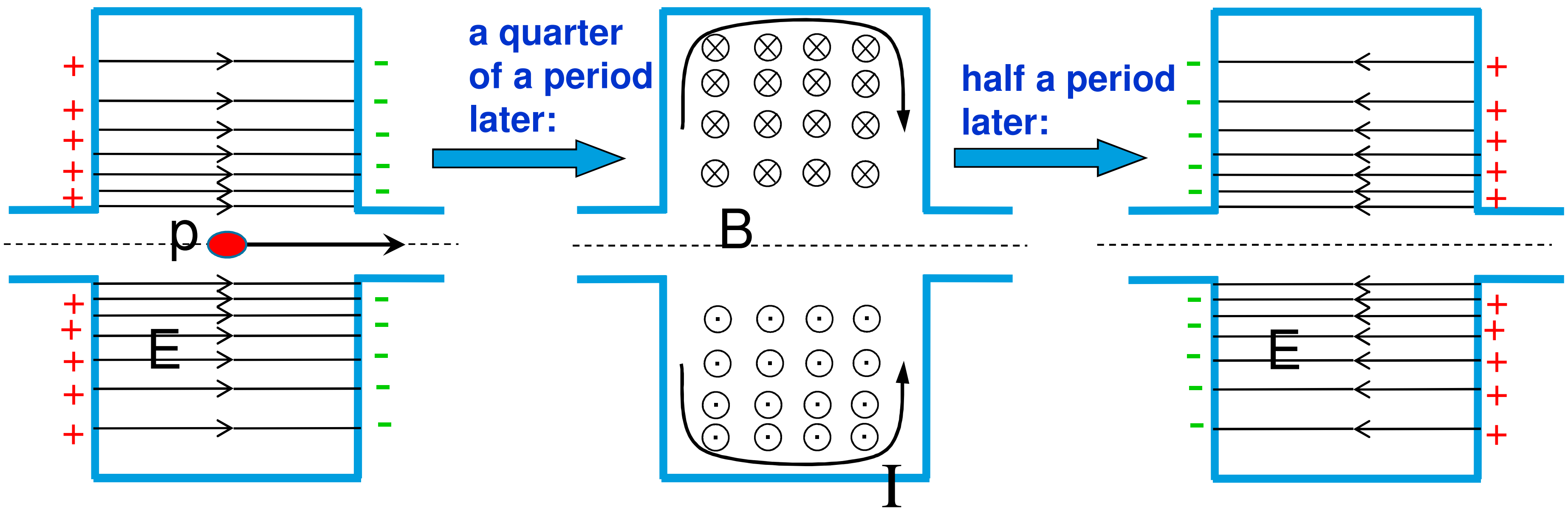

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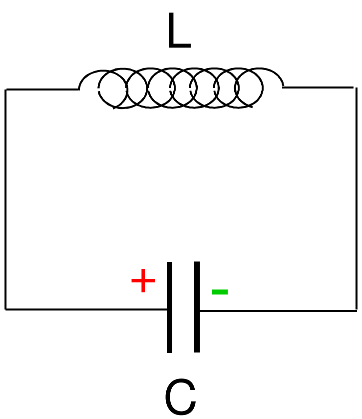
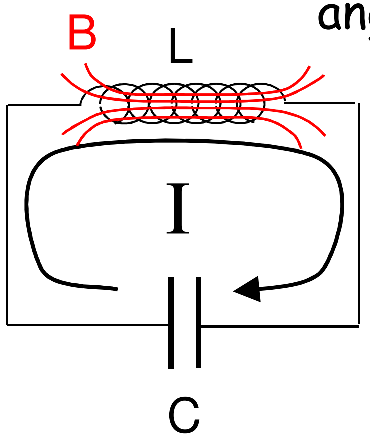
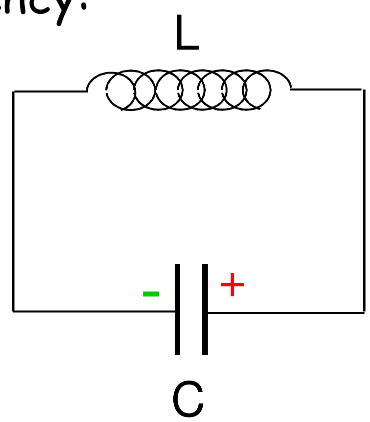




angular frequency:

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



Equations for the electric and magnetic fields in a pill box cavity

Maxwell's equations
(differential formulation in SI units)

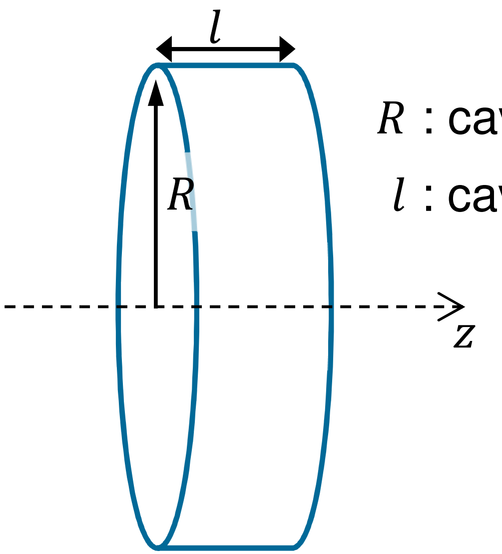
$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

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

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

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

+ 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

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

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

indices:

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

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

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B_z = 0 \\
B_r = -j\omega\frac{mR^2}{x_{mn}{}^2 rc^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} \\
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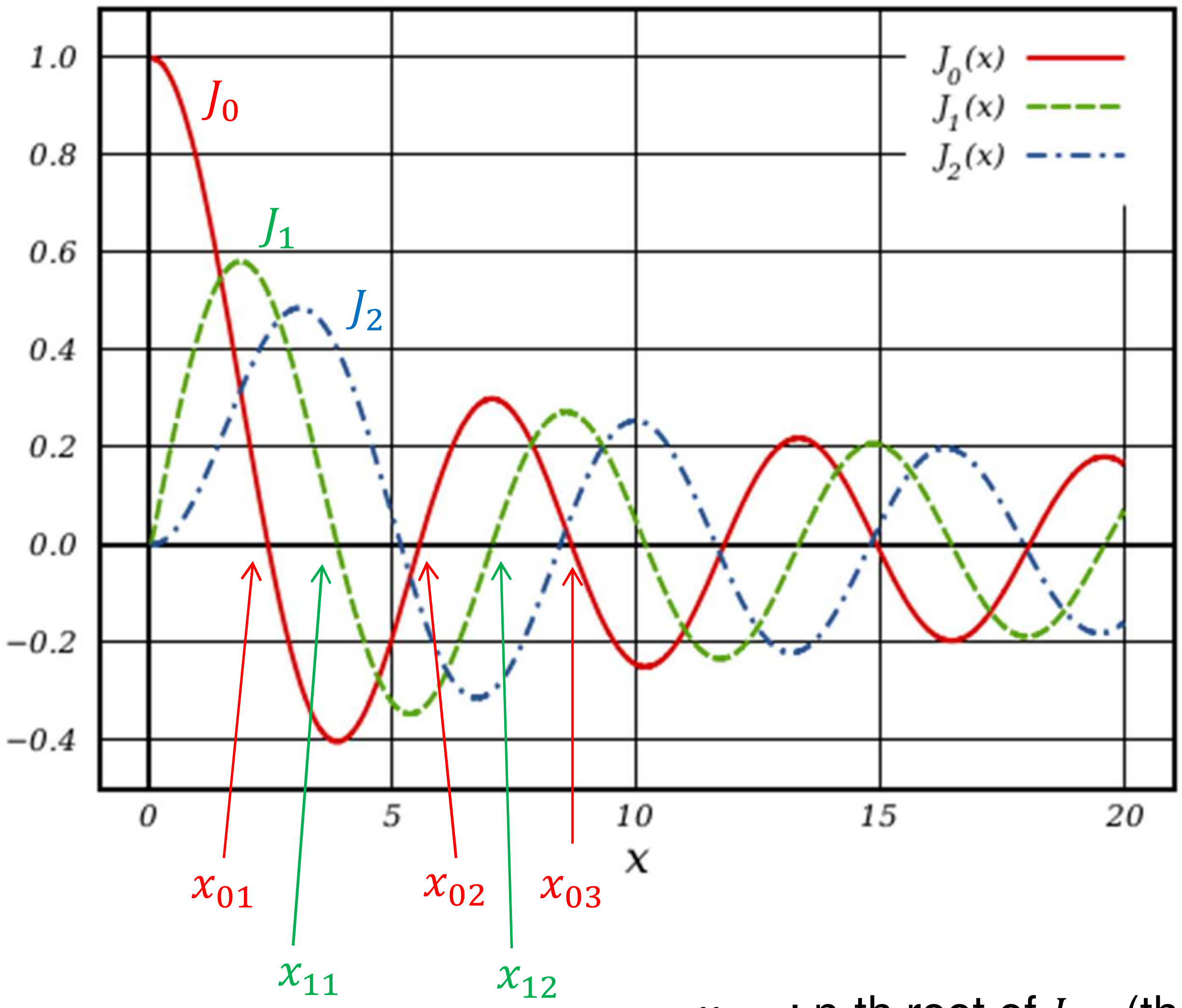

m	x_{m1}	x_{m2}	x_{m3}
0	2.405	5.520	8.654
1	3.832	7.016	10.173
2	5.136	8.417	11.620

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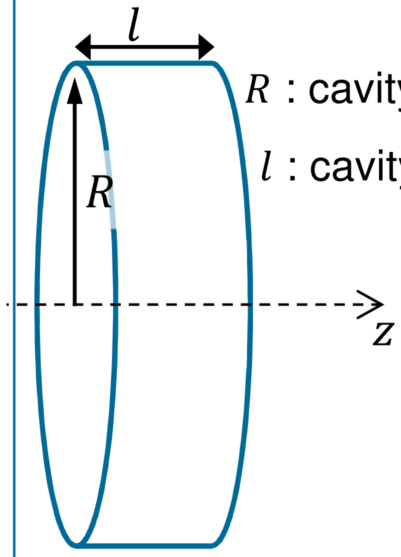
boundary conditions



R : cavity radius

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

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

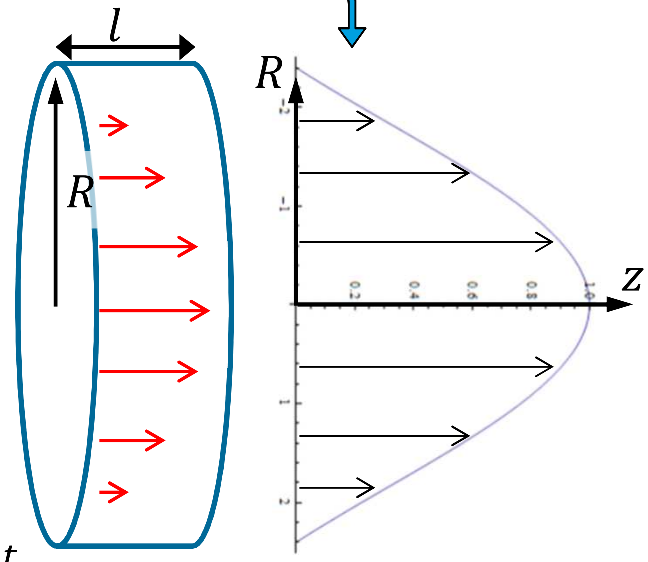
$$E_r = 0$$

$$E_\theta = 0$$

$$B_z = 0$$

$$B_r = 0$$

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



$m = 0$: 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

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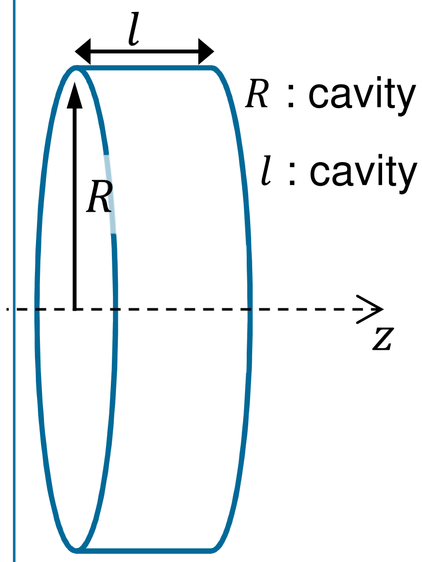
angular frequency : $\omega = c\frac{x_{01}}{R}$ $\quad x_{01} = 2.405$

boundary conditions



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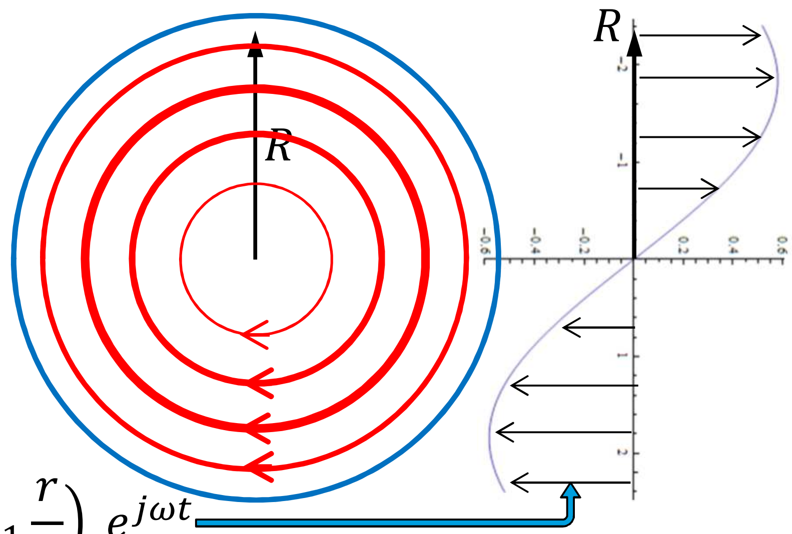
$$E_r = 0$$

$$E_\theta = 0$$

$$B_z = 0$$

$$B_r = 0$$

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



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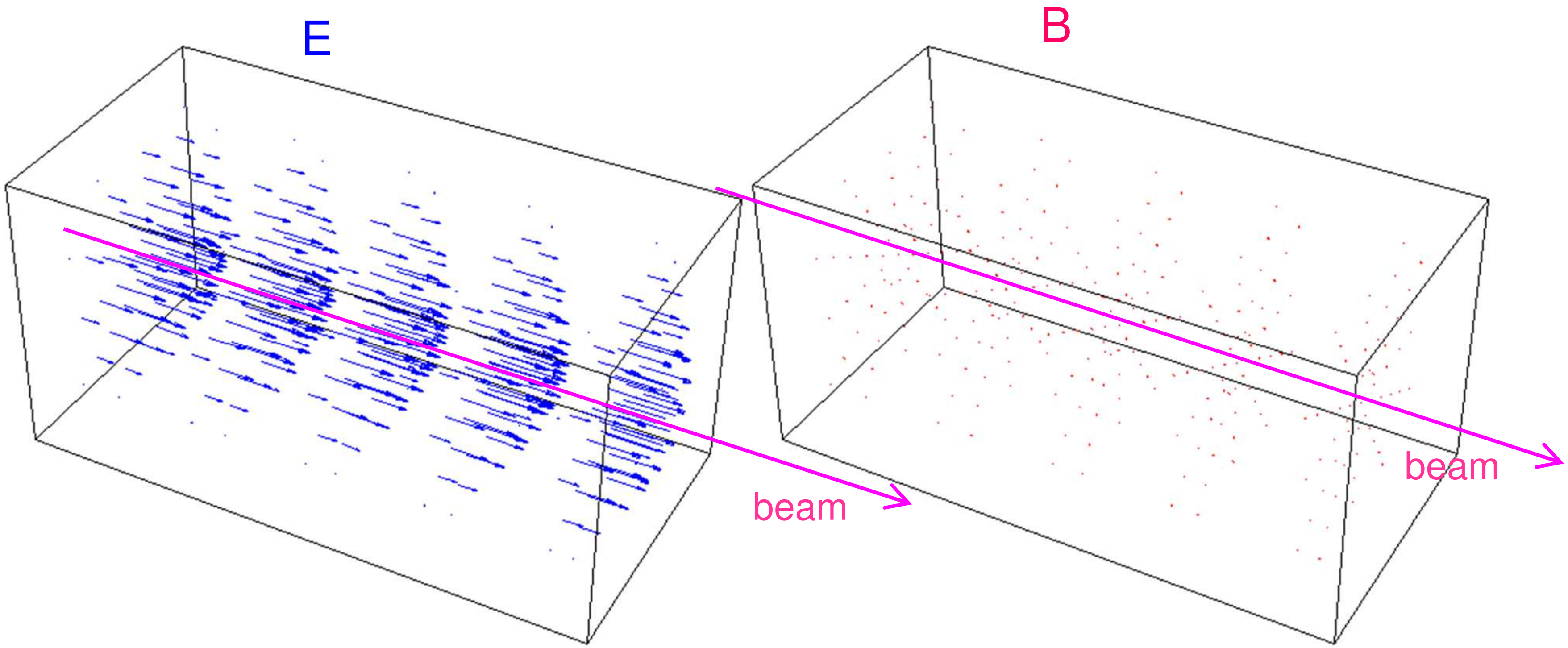
J'_m : derivative of the Bessel´s functions

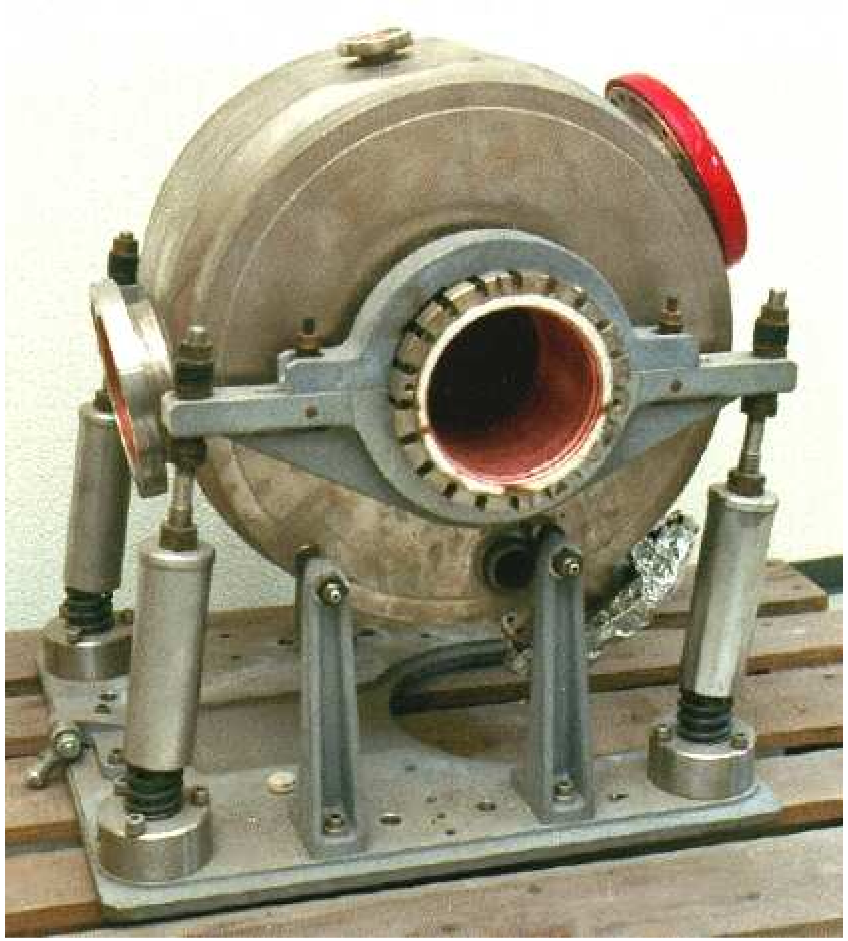
angular frequency : $\omega = c\dfrac{x_{01}}{R}$ $\qquad x_{01} = 2.405$

Pill box cavity: 3D visualisation of E and B



Examples of pill box cavities

DESY cavity (pill box)

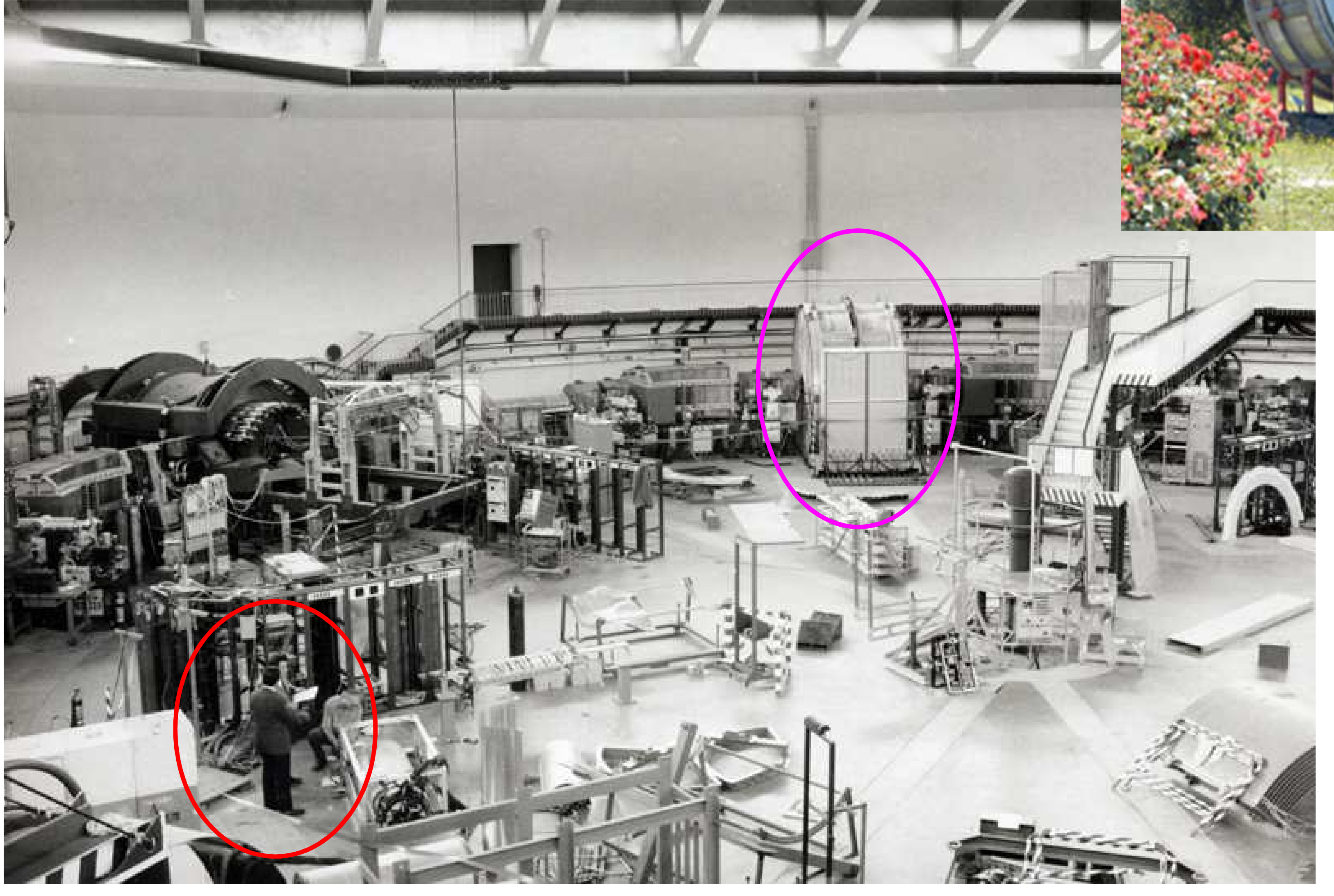


ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

Examples of pill box cavities

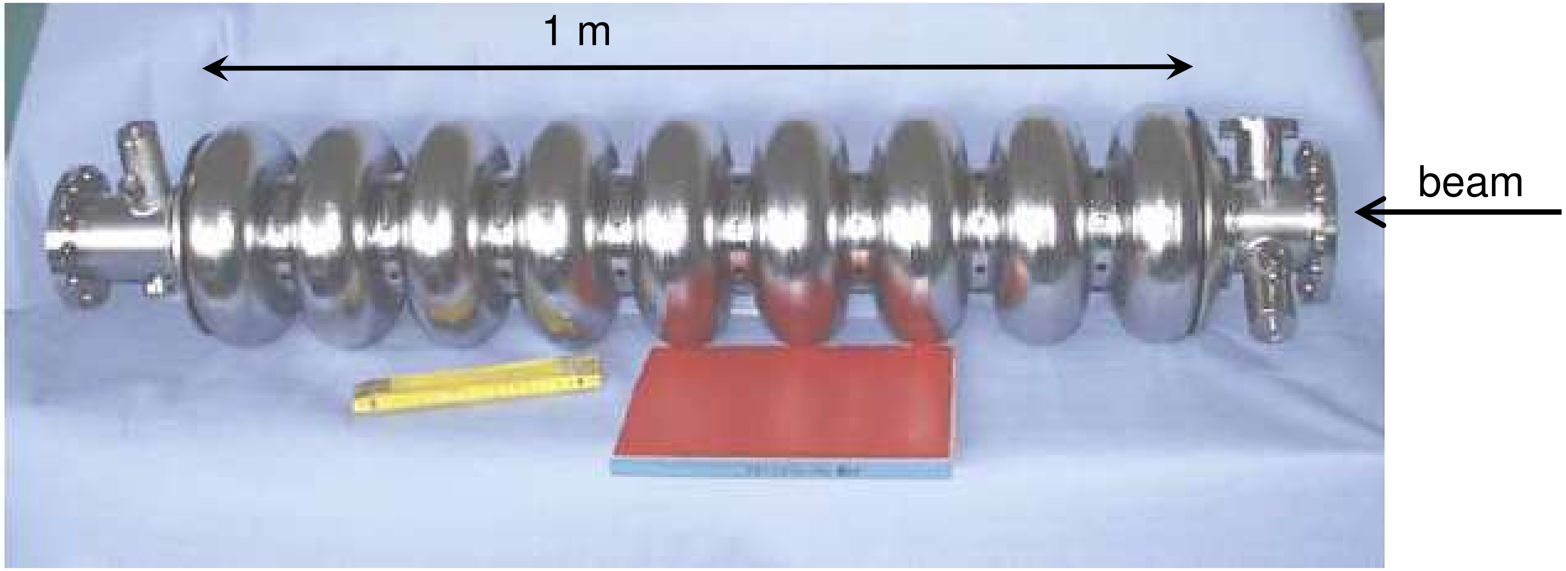
ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

ADONE in 1963, Laboratori Nazionali di Frascati, Italy



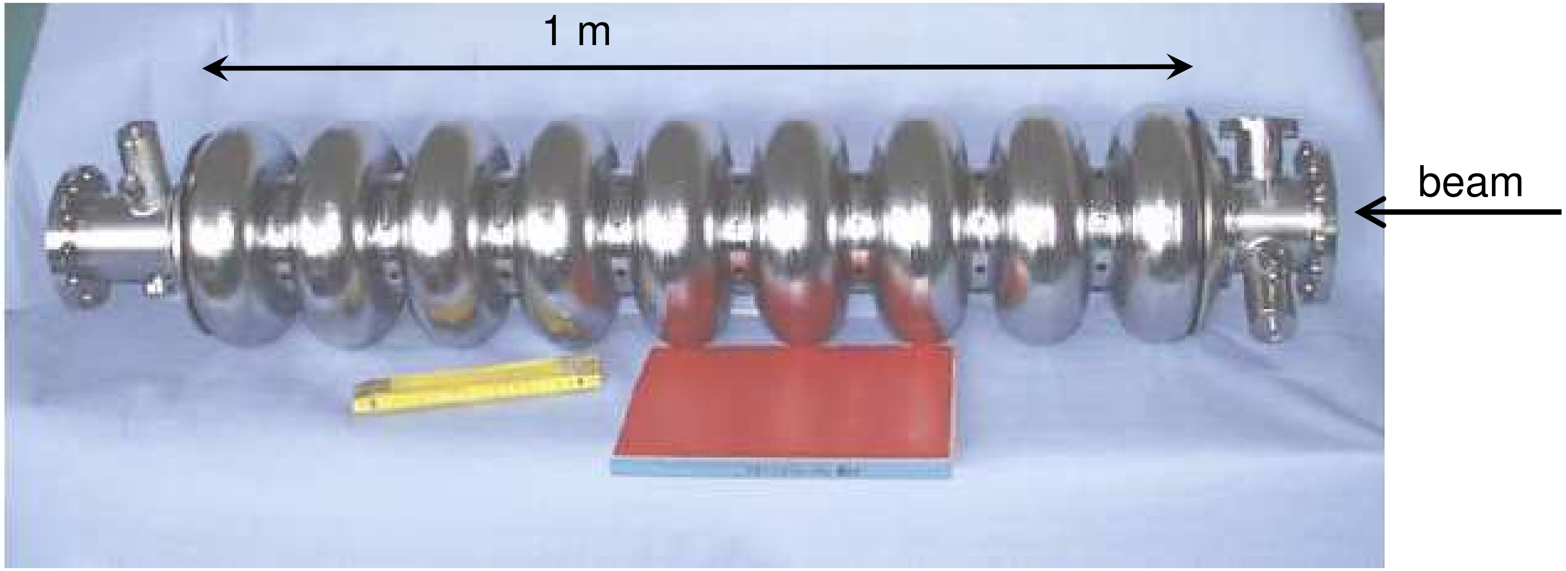
Superconducting cavity used at DESY

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

Superconducting cavity used at DESY

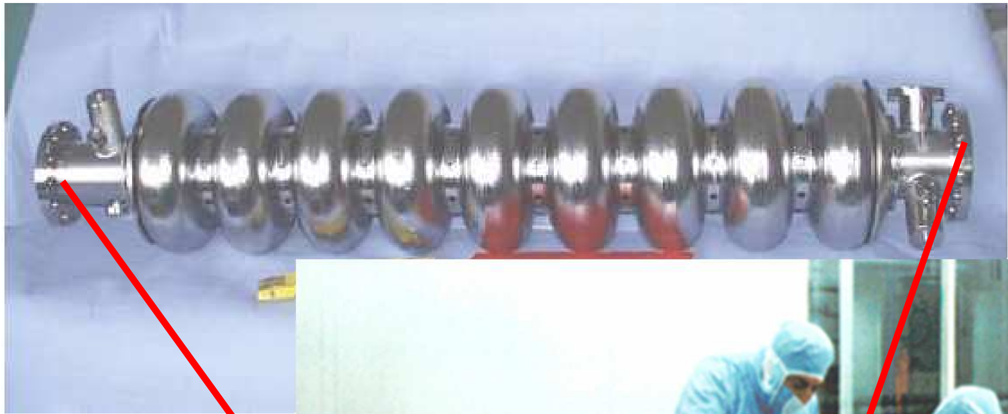


material: pure Niobium

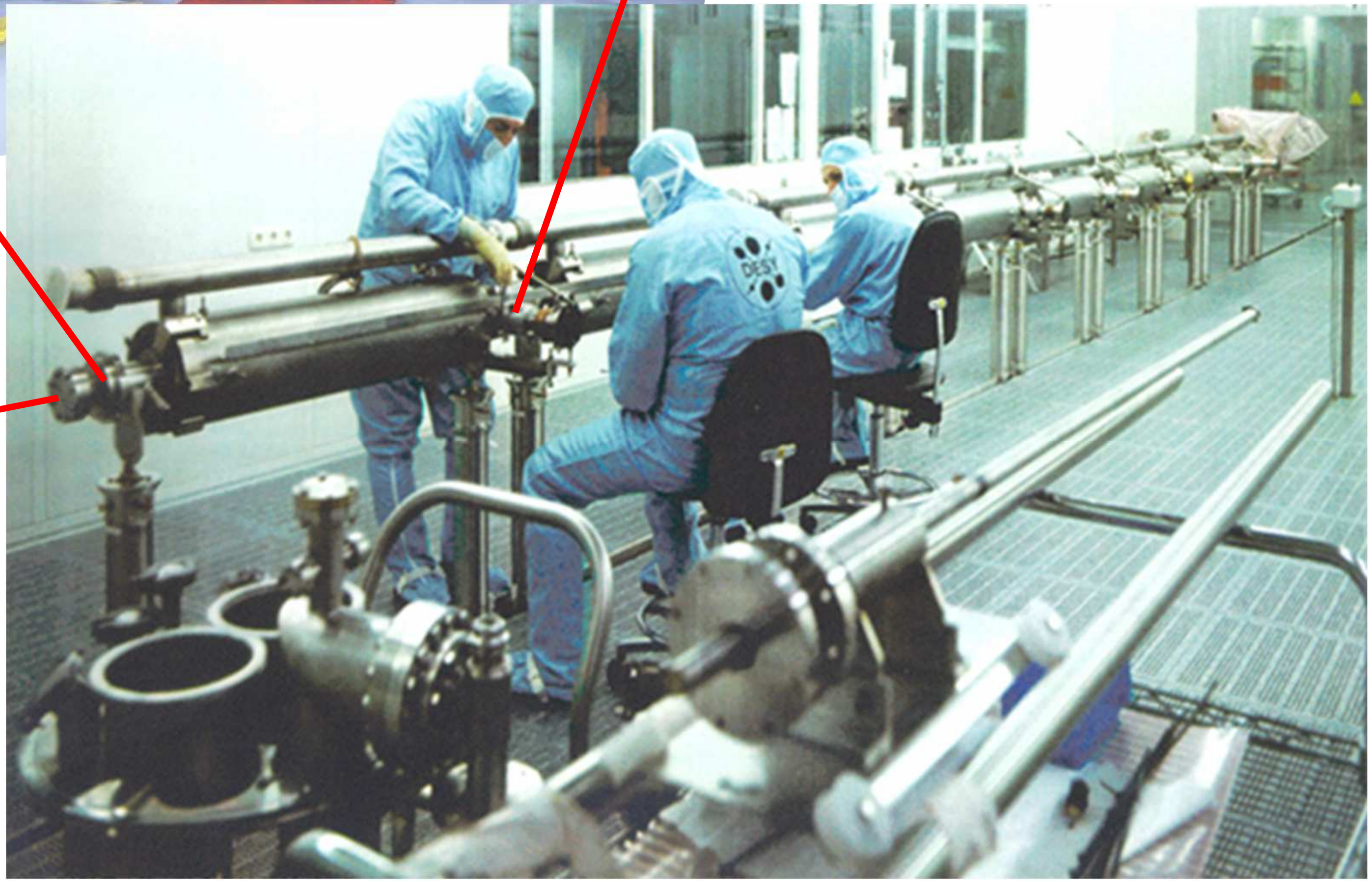
operating temperature: 2 K

accelerating field gradient: up to 35 MV/m

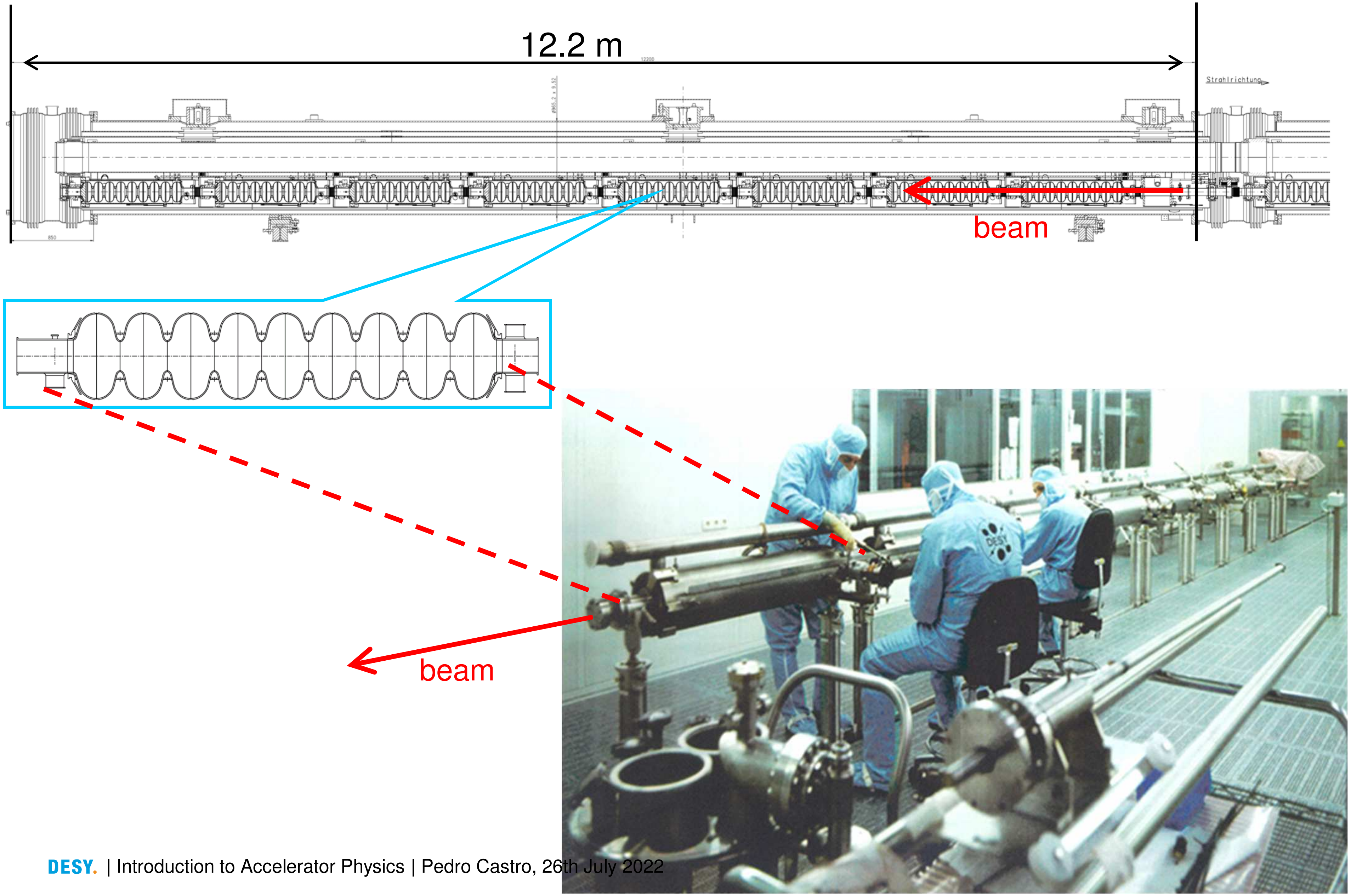
Cavities inside a cryostat



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



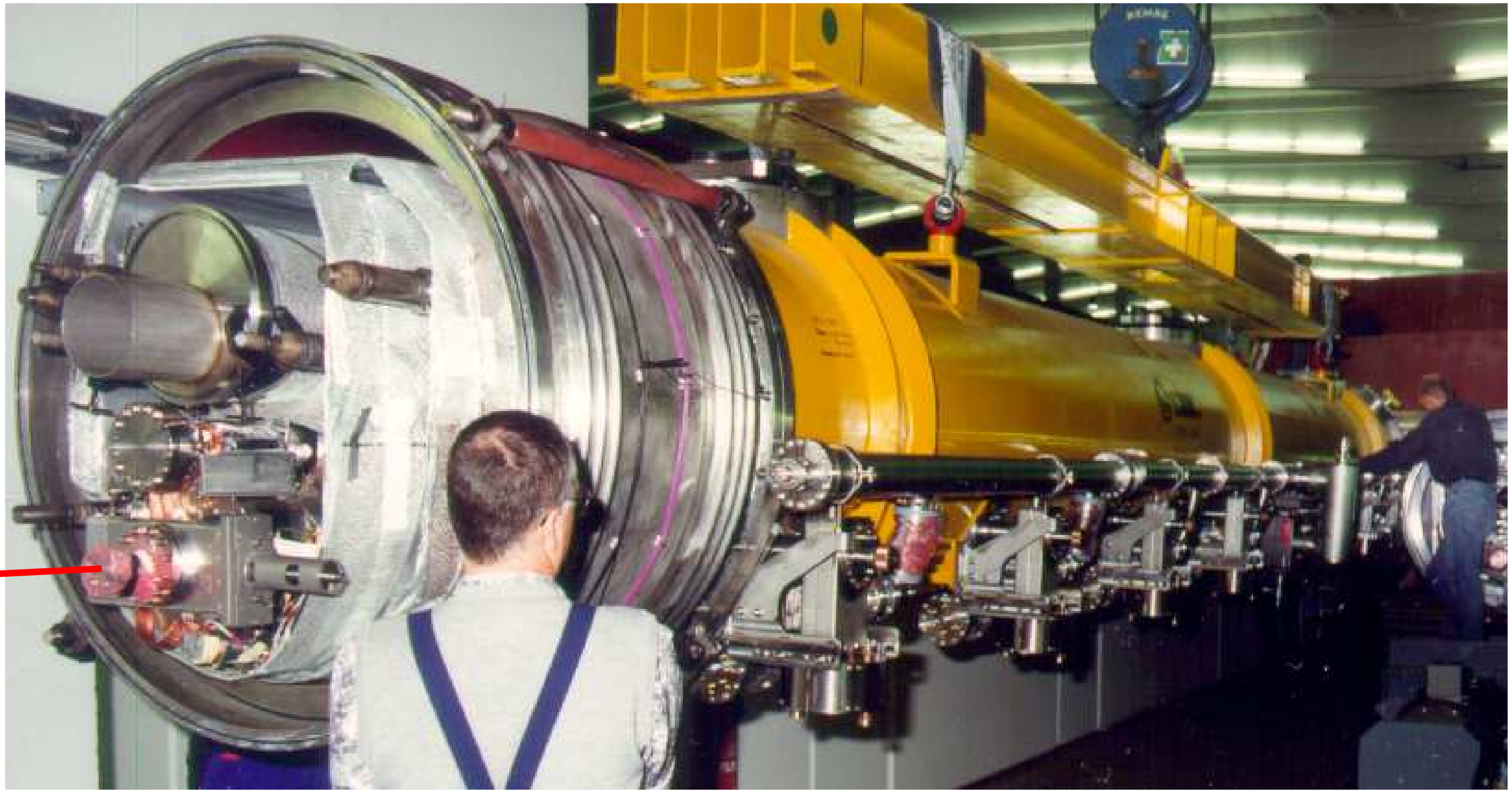
beam


12.2 m
Strahlrichtung
beam
beam

Cavities inside a cryostat

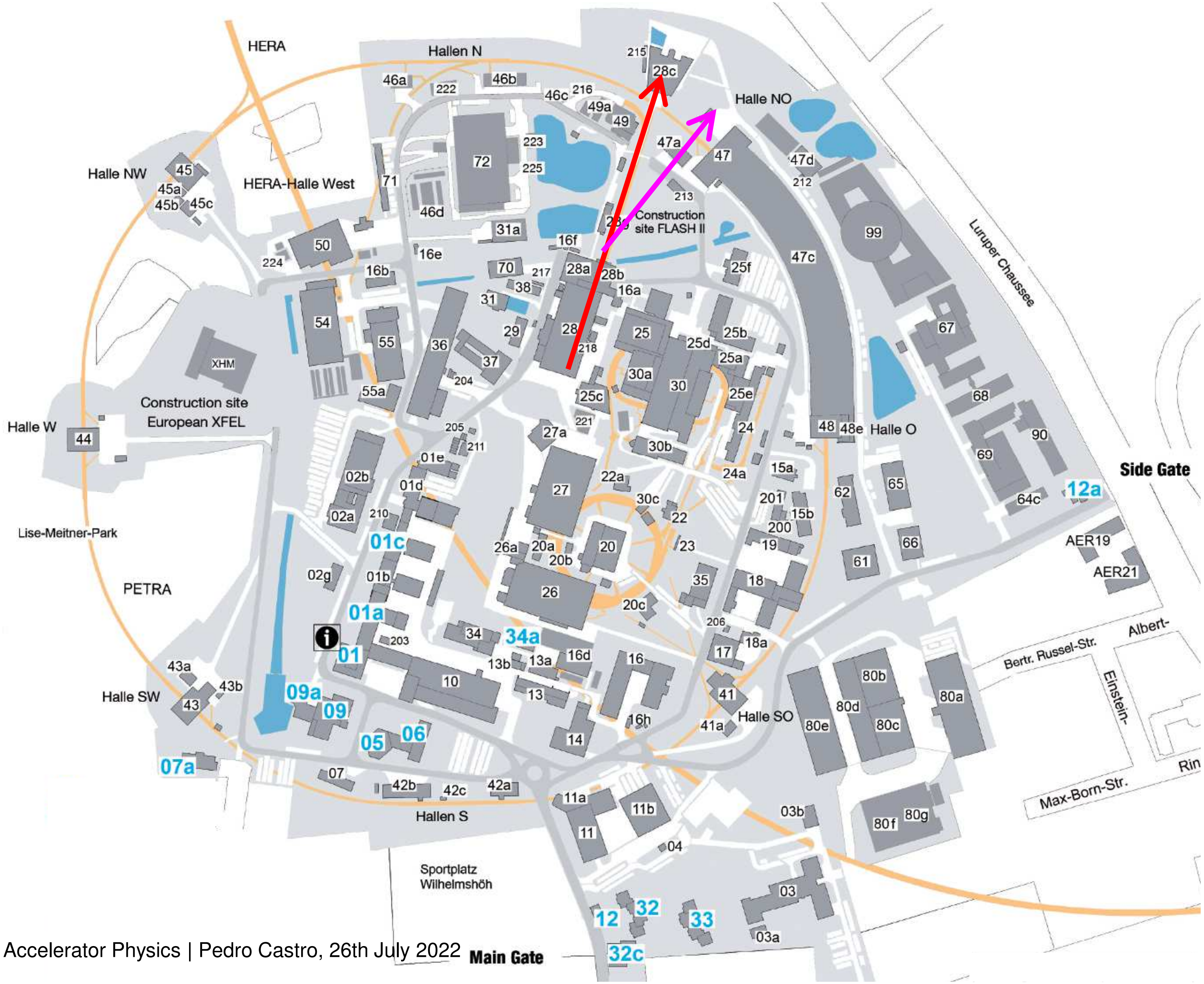
Cavities inside an accelerator module (cryostat)

beam

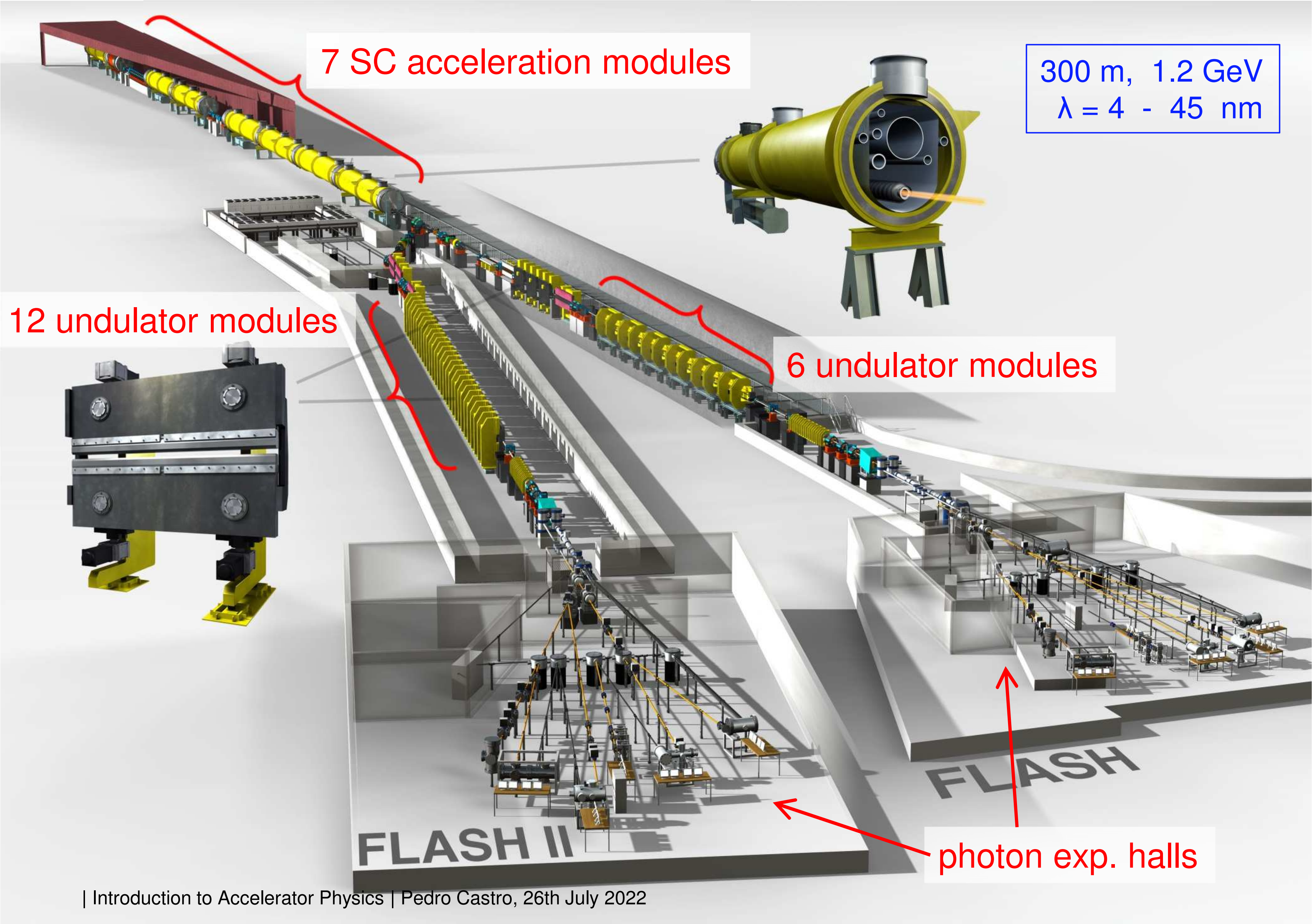


module installation in FLASH (2004)

Free-electron LASer in Hamburg (FLASH)



Free-electron LASer in Hamburg (FLASH)

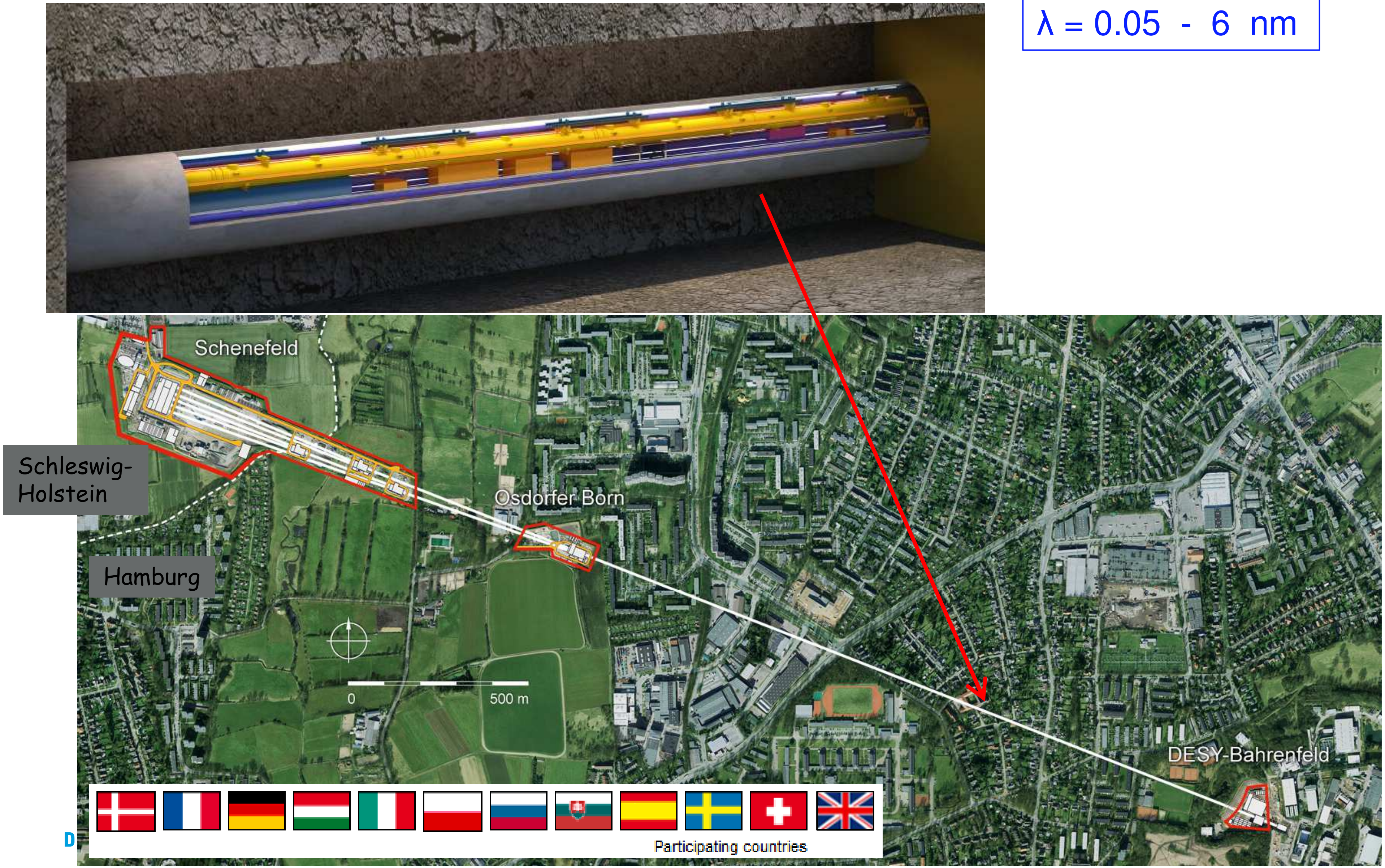


100 accelerator modules (cryostats) in XFEL

European X-ray Free-Electron Laser (XFEL)

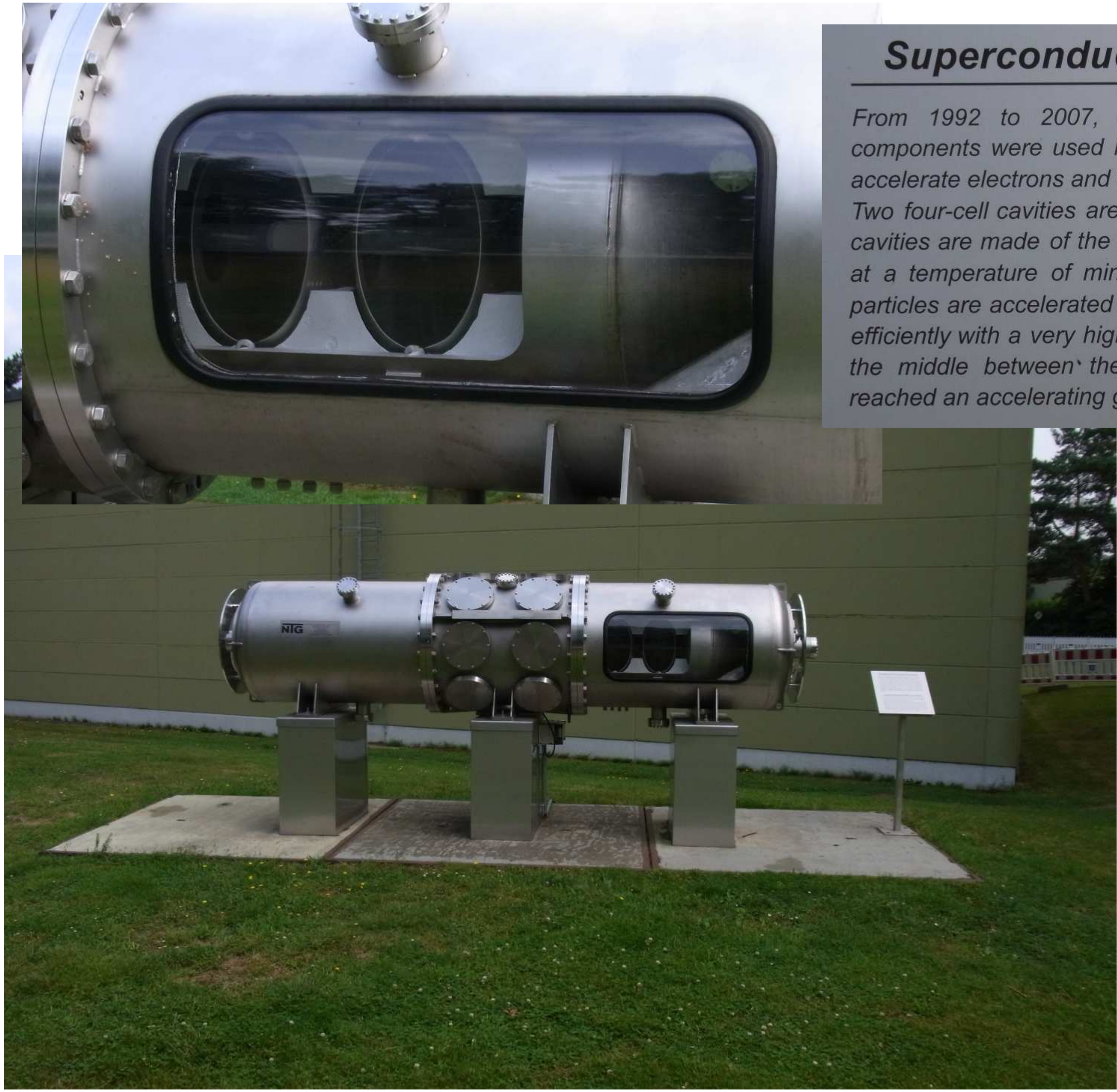
(3 km, 17.5 GeV)

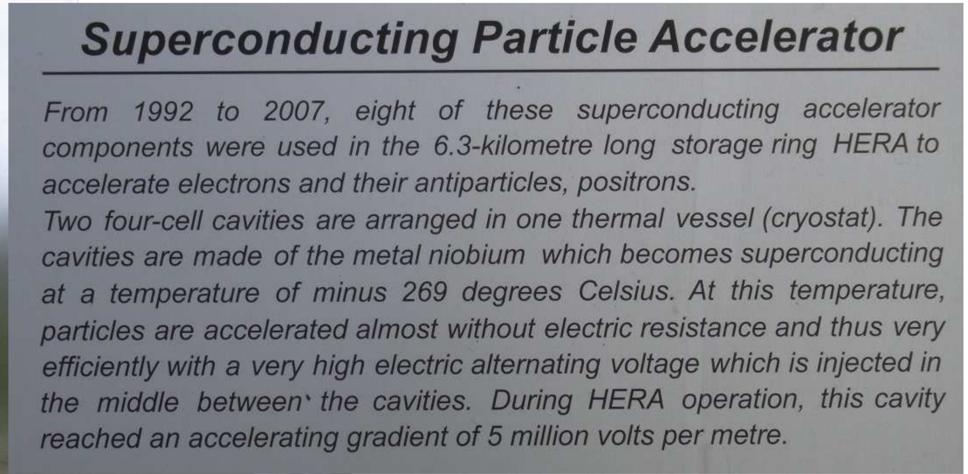
$\lambda = 0.05 - 6$ nm



Superconducting cavities at HERA

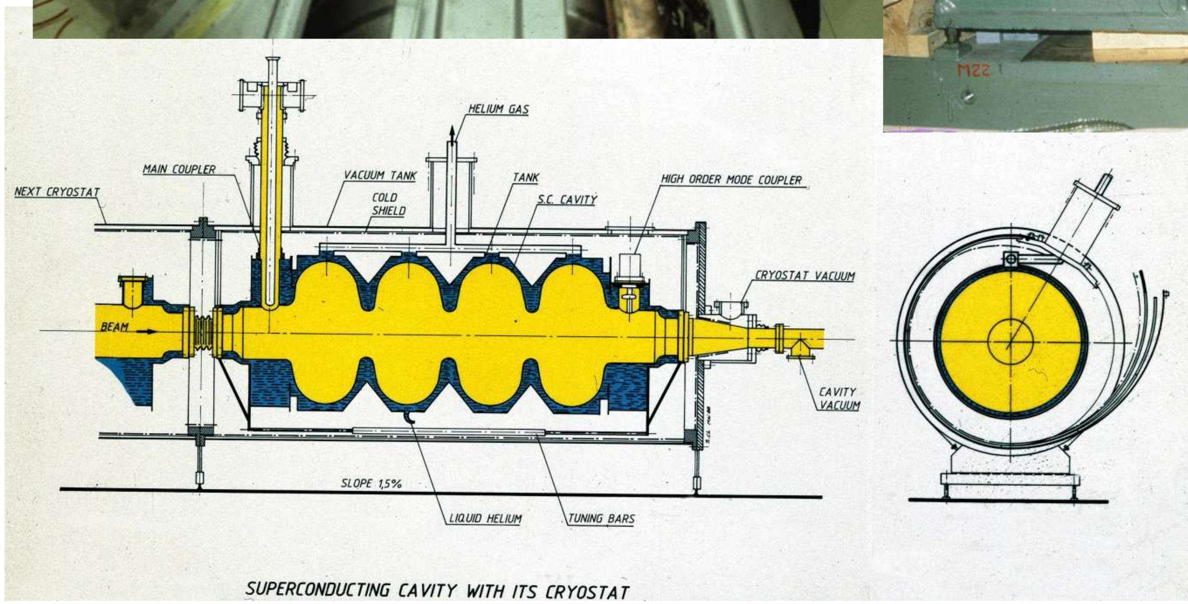
16 cavities
500 MHz





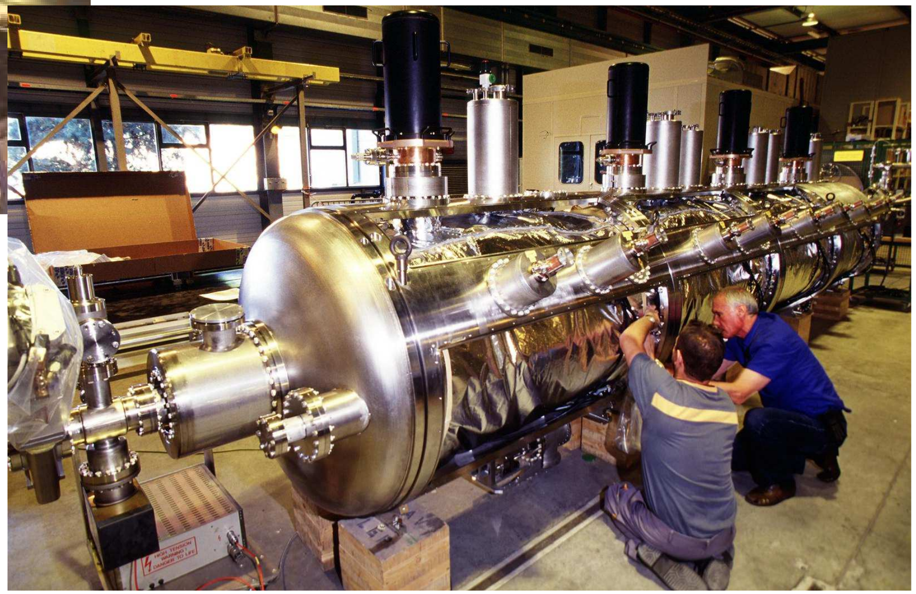
Superconducting cavities at LEP

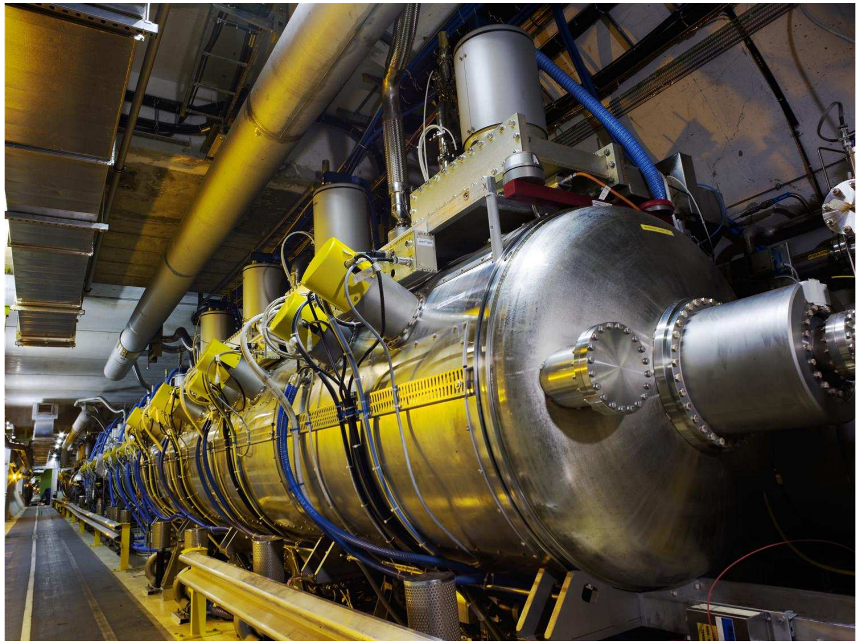
272 cavities
352 MHz



Superconducting cavities at LHC

16 cavities
400 MHz





Other accelerators using superconducting cavities

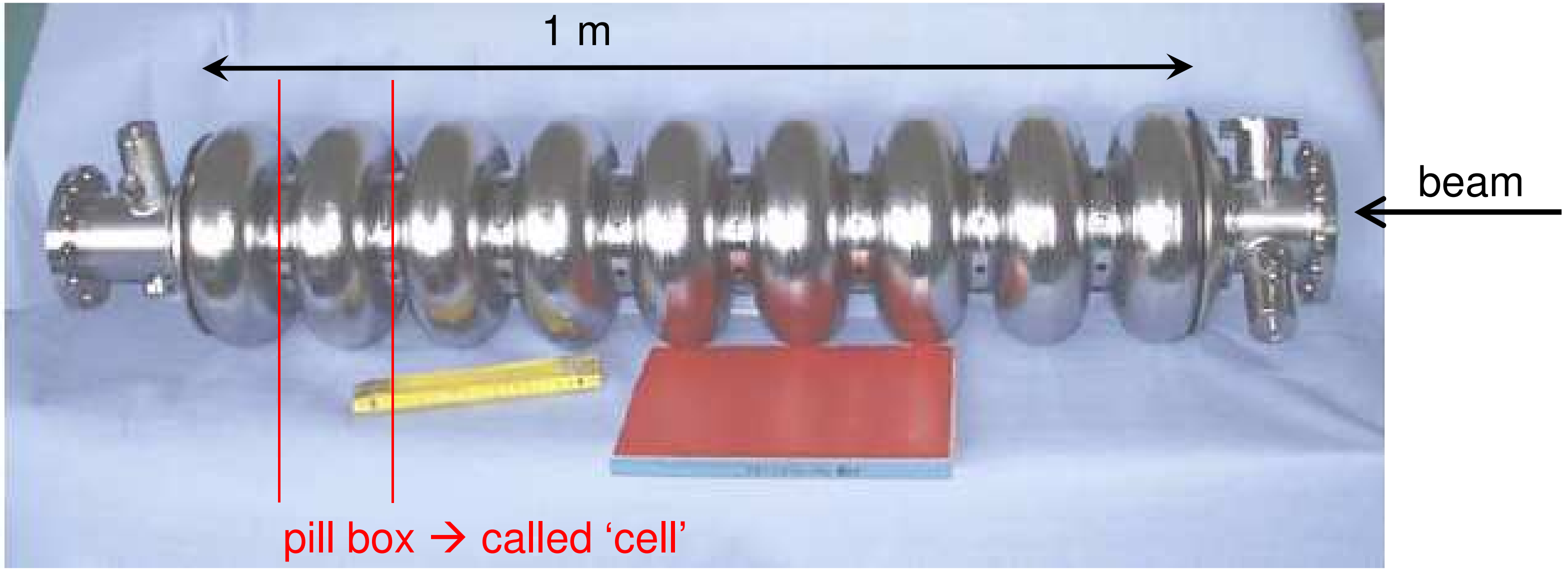
- 5 de-commissioned
- 11 in operation
- 4 in construction
- 9 in design phase

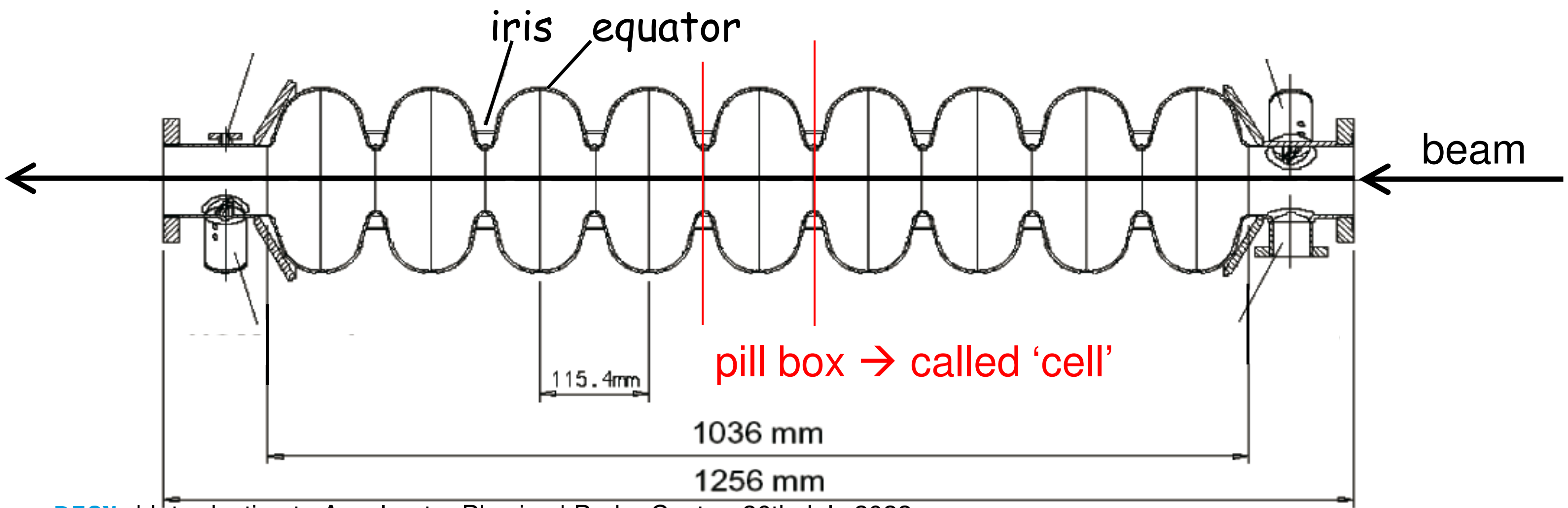
Total = 29

full list: http://tesla-new.desy.de/srf_accelerators

Superconducting cavity used in FLASH and in XFEL

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



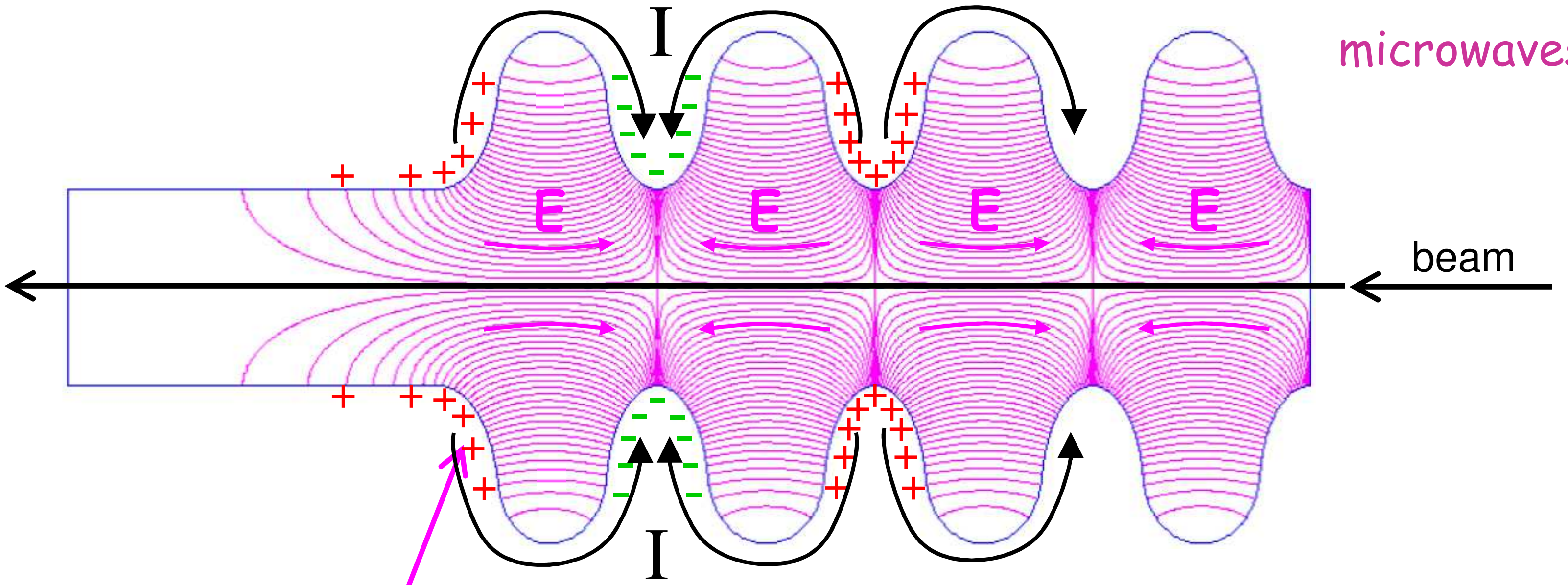


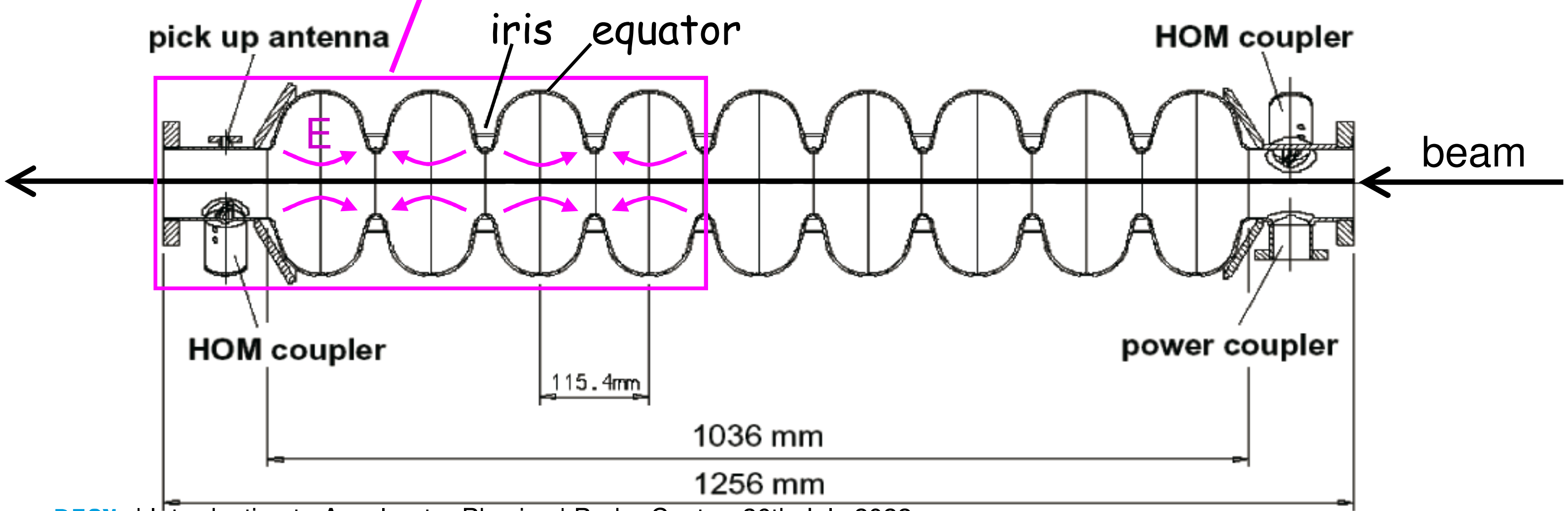
Accelerating field map

Simulation of the fundamental mode: electric field lines

$f_{RF} = 1.3\ \text{GHz}$

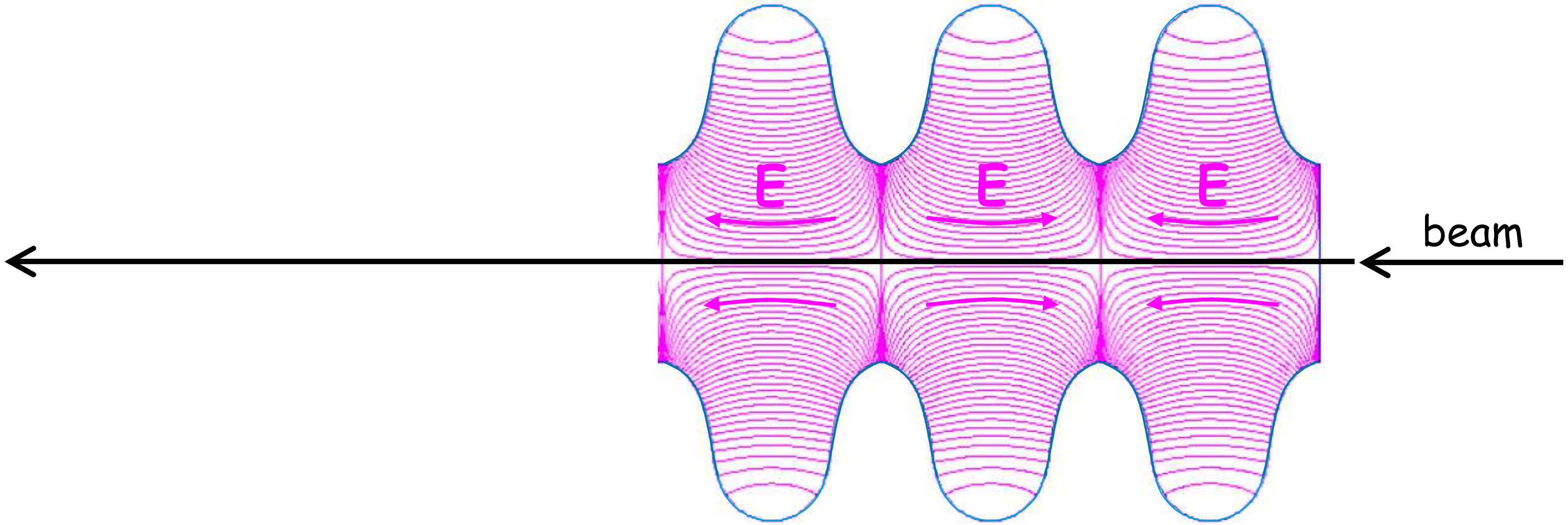
microwaves: (L-band)

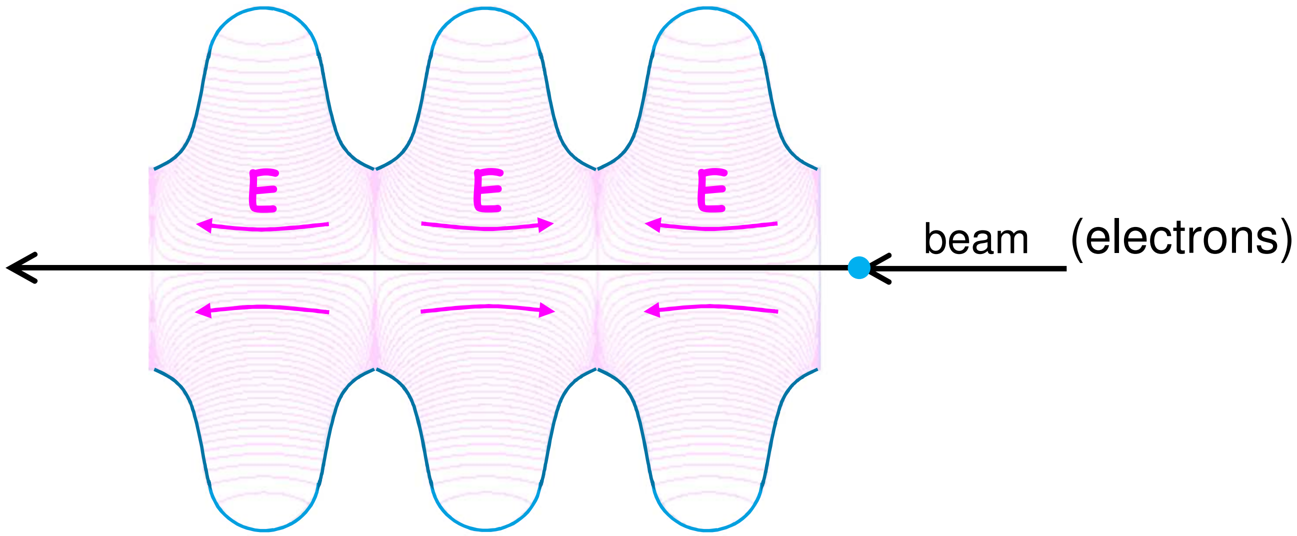


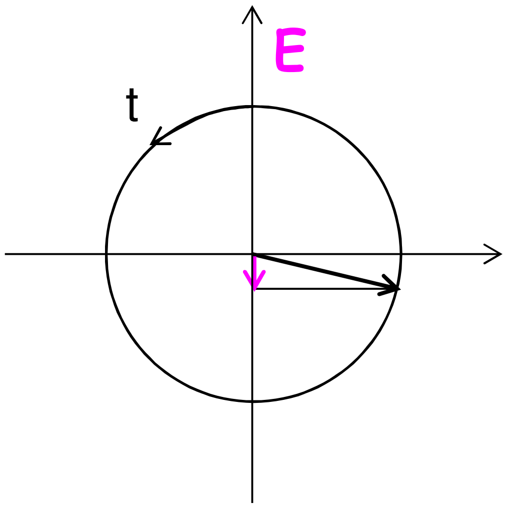


Is there a net acceleration?

Simulation of the fundamental mode: electric field lines




E
E
E
beam
(electrons)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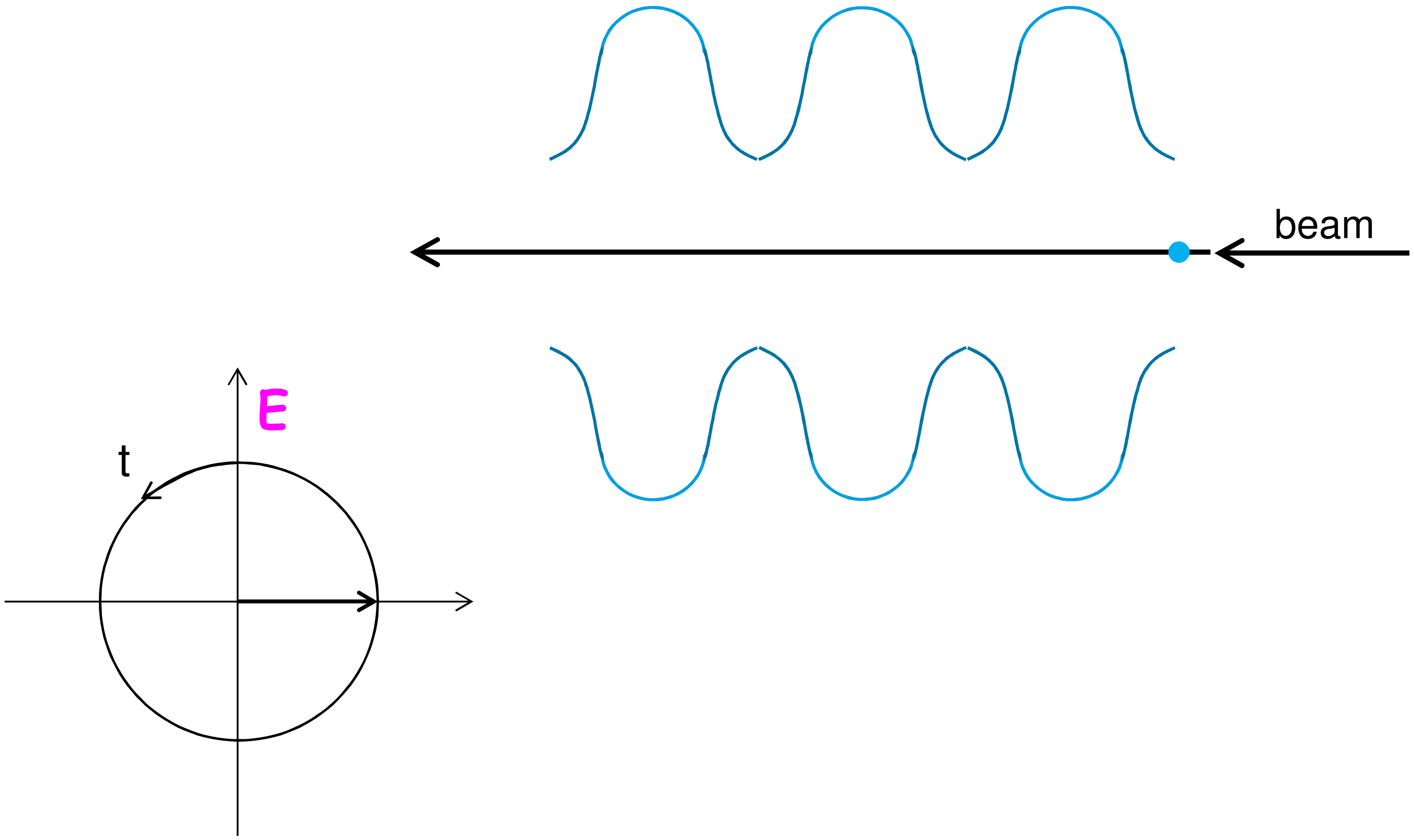
beam
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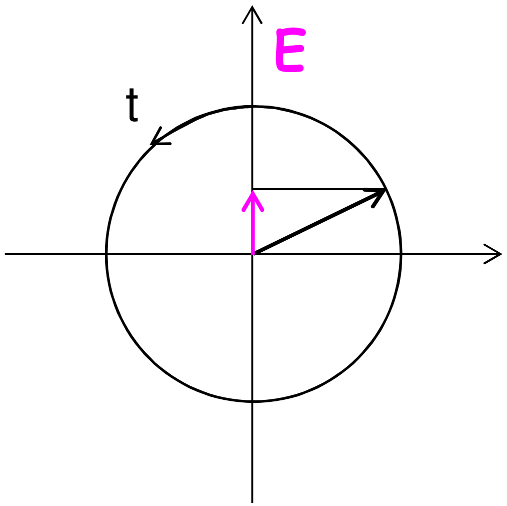
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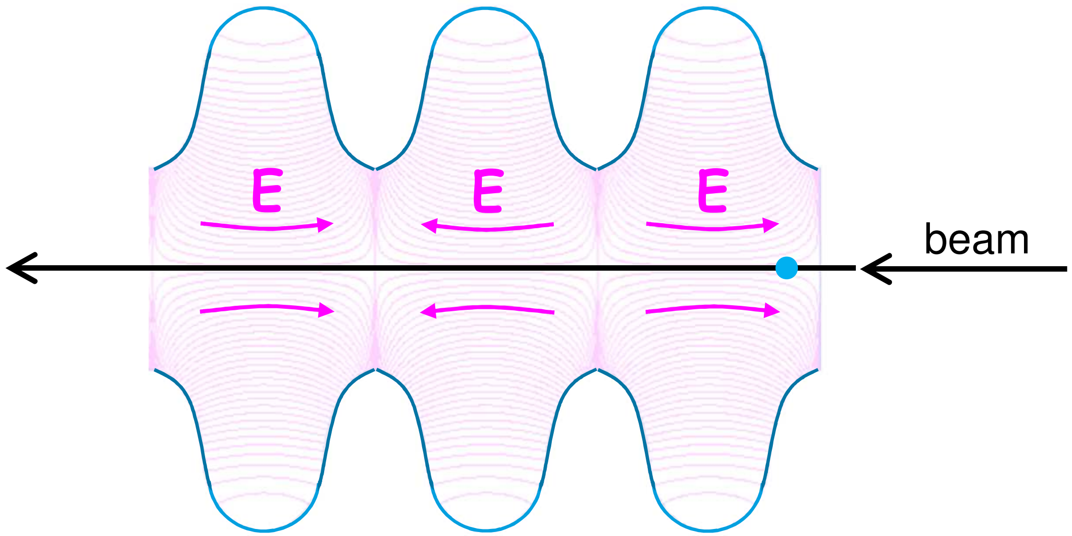
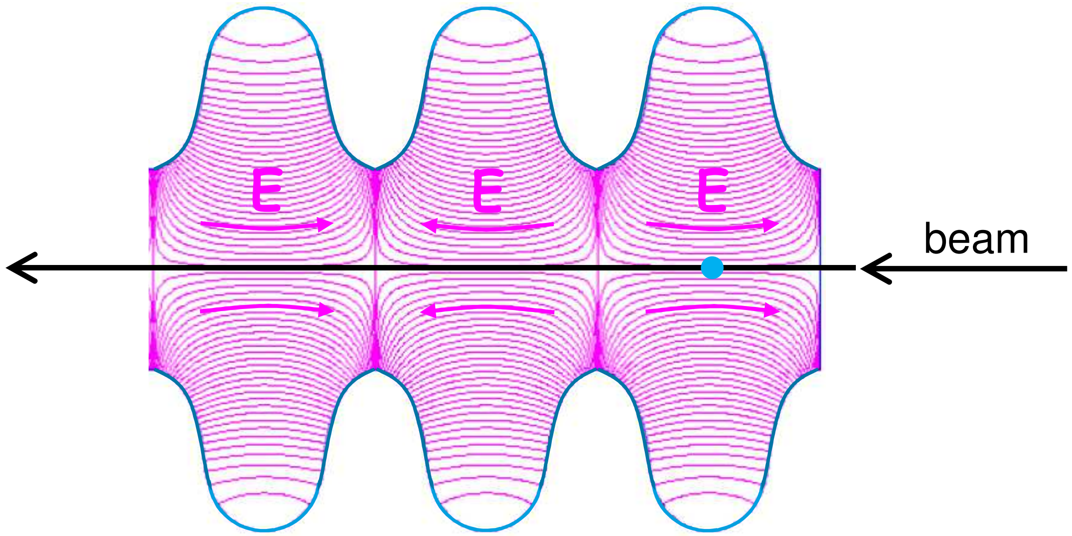
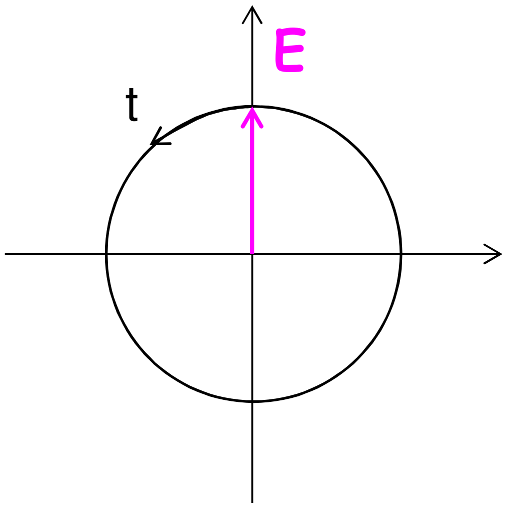

E
E
E
beam


E
E
E
beam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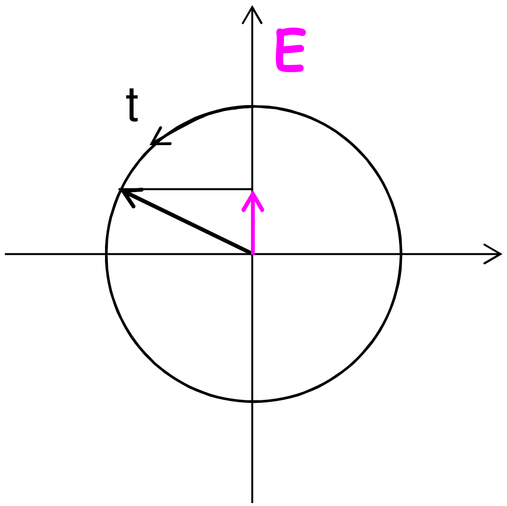
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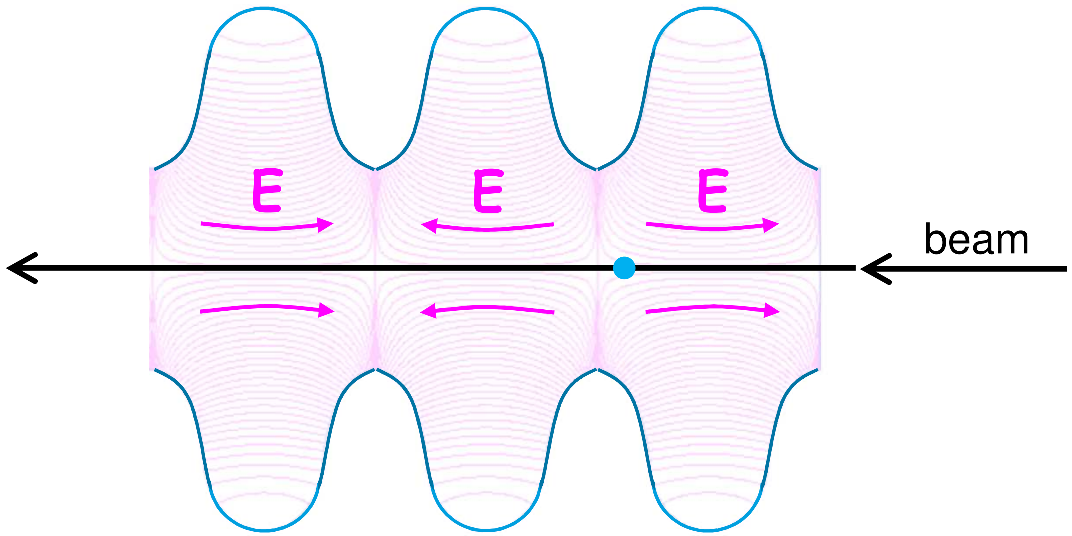
E
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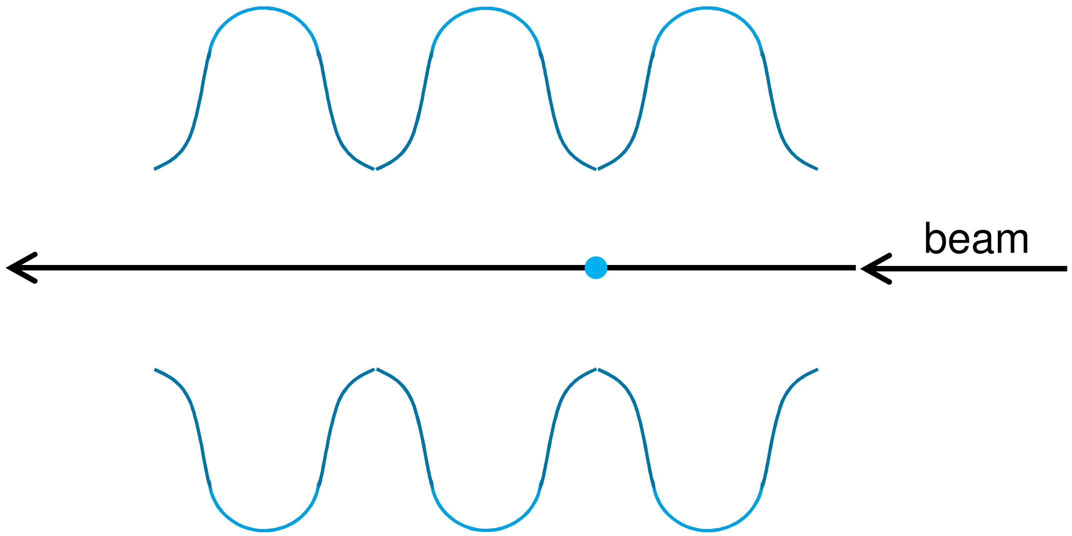
beam


beam
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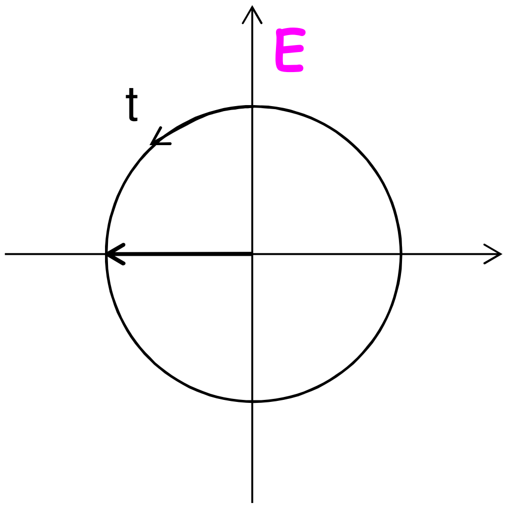

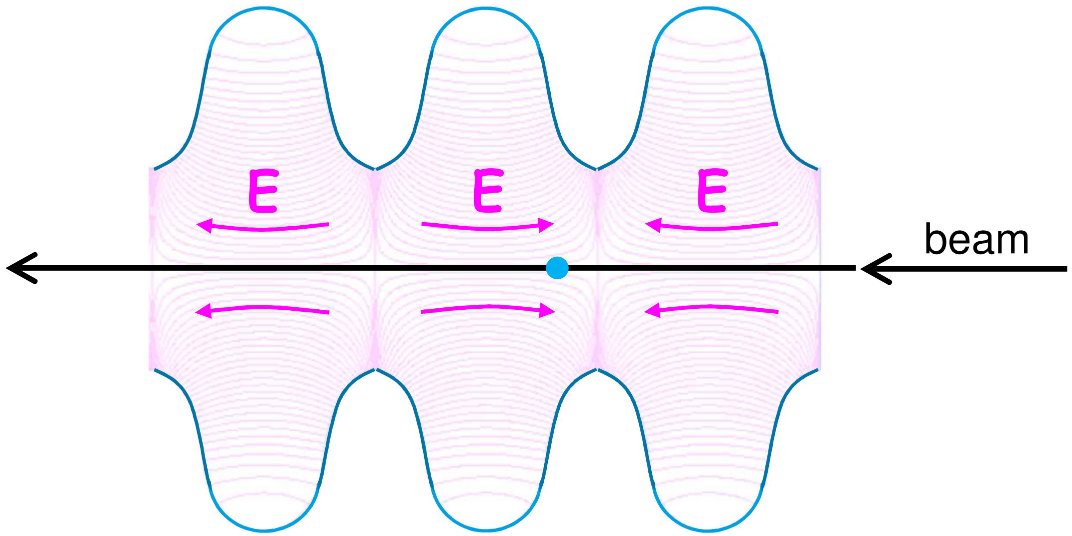
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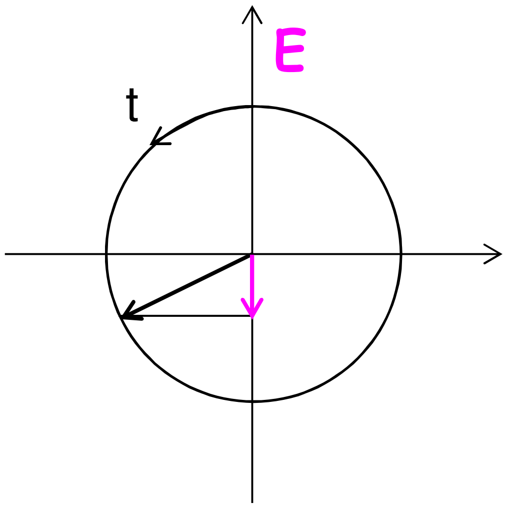
beam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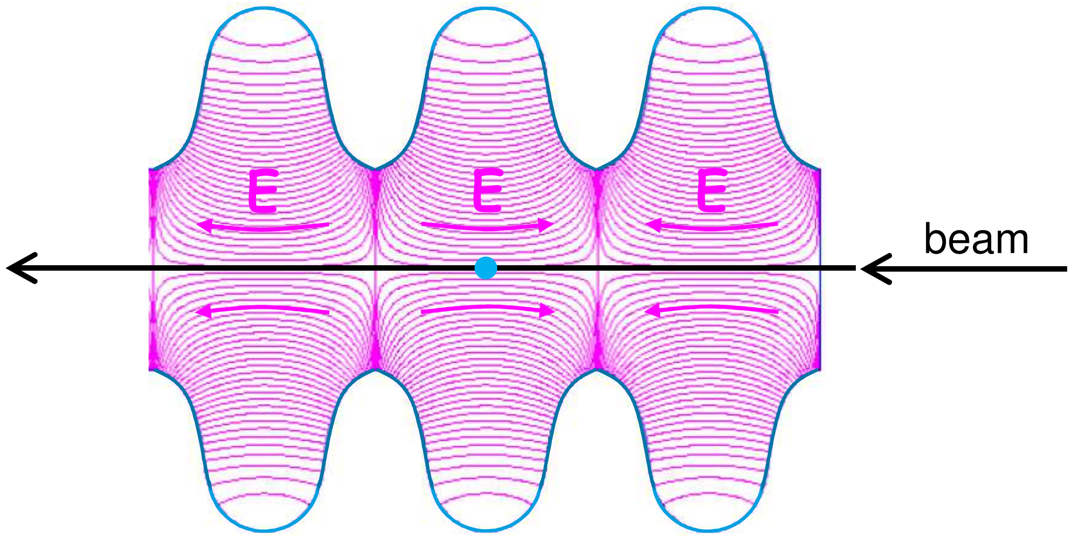
E
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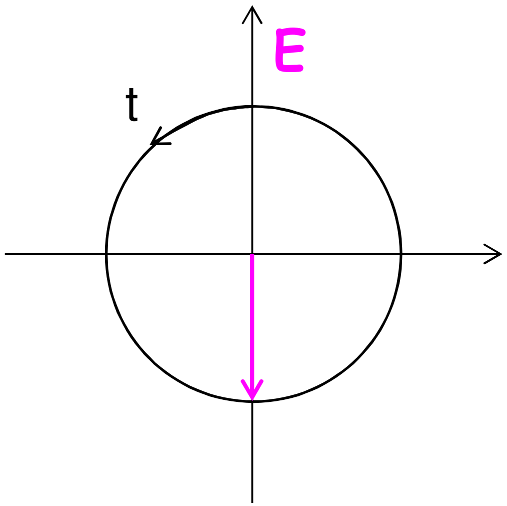
beam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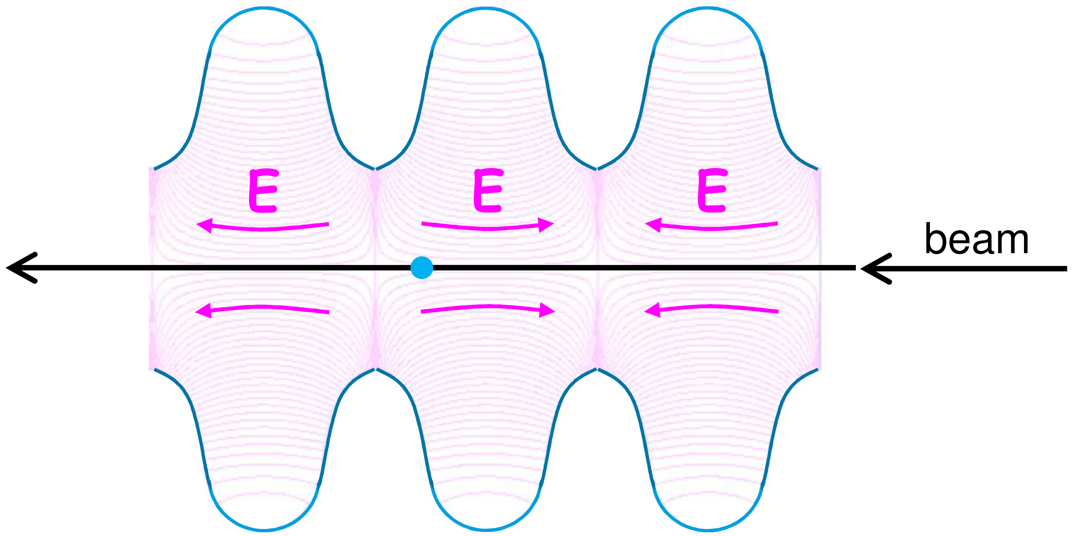
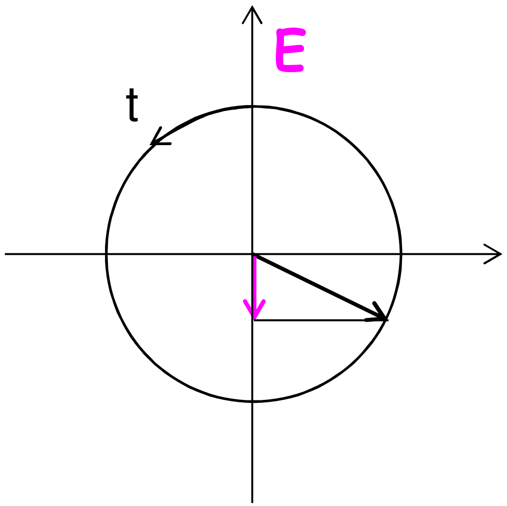

E
E
E
beam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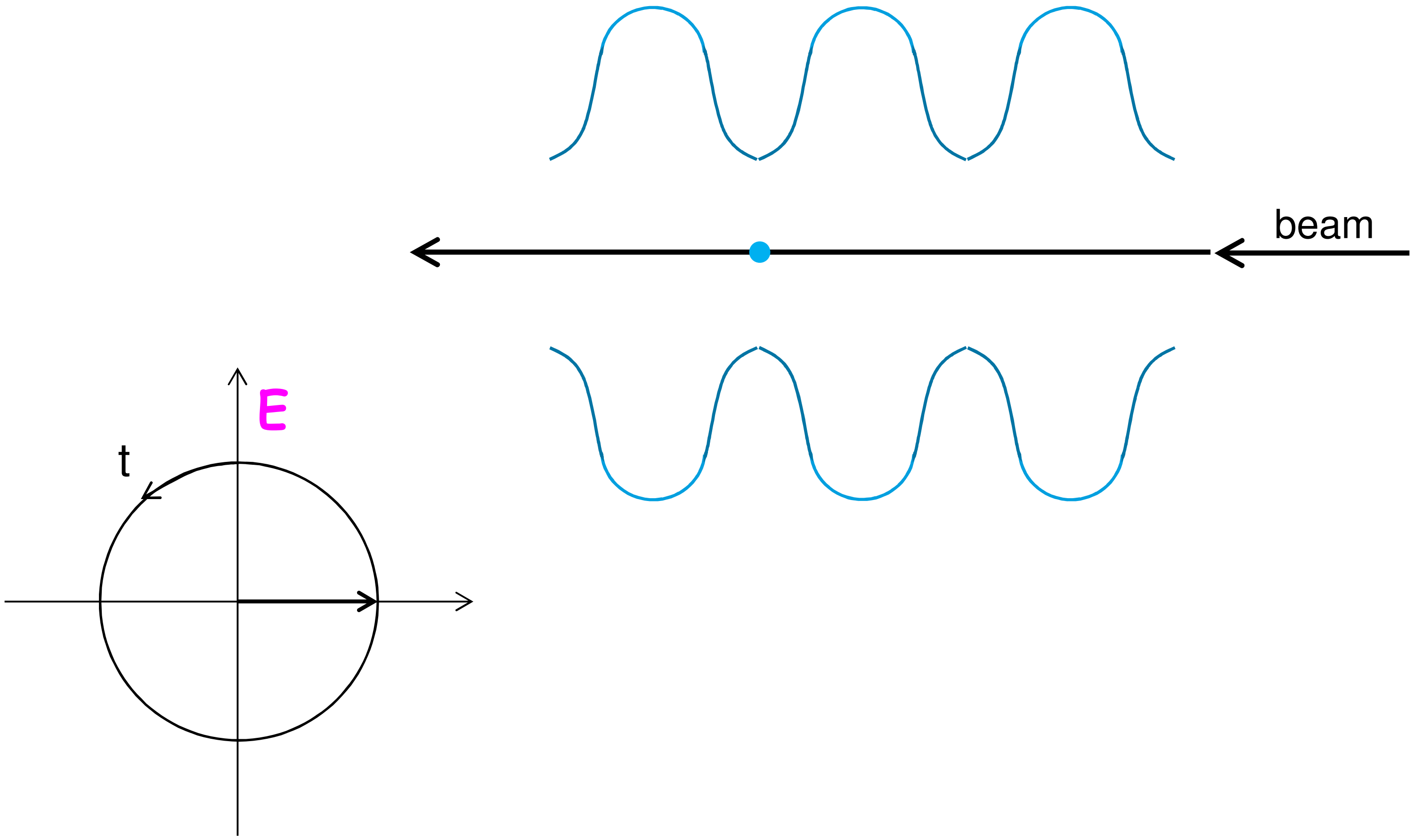
beam
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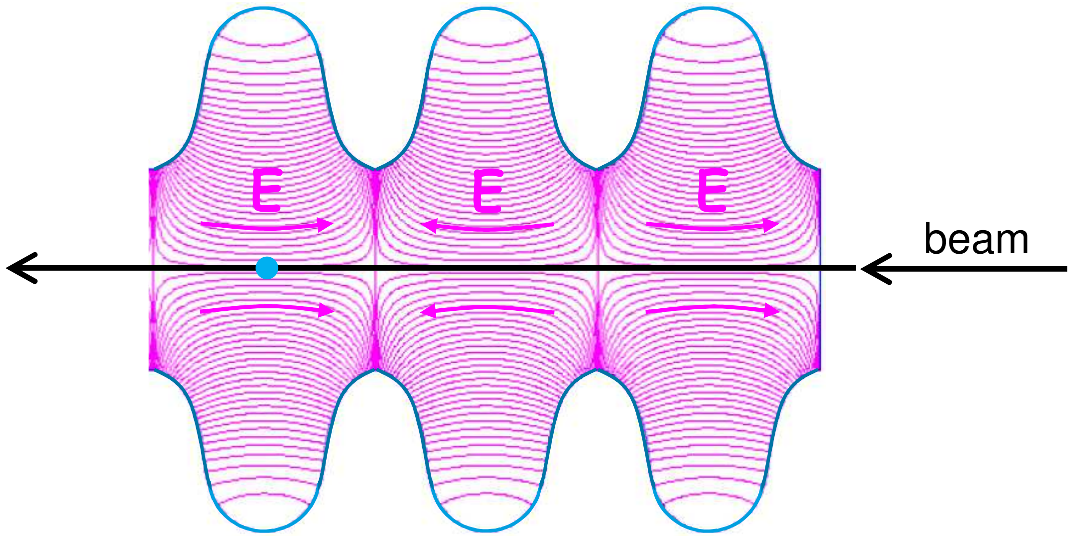
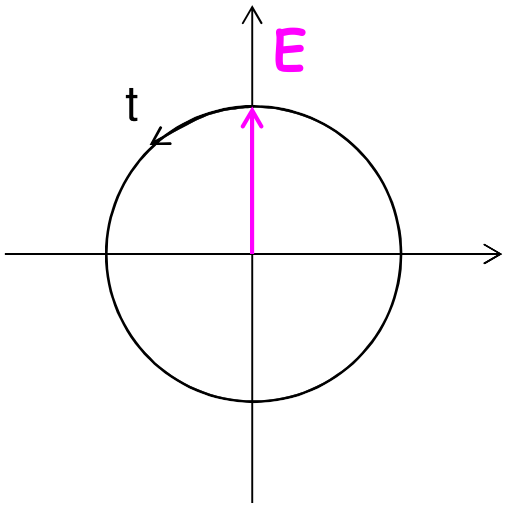

E
E
E
beam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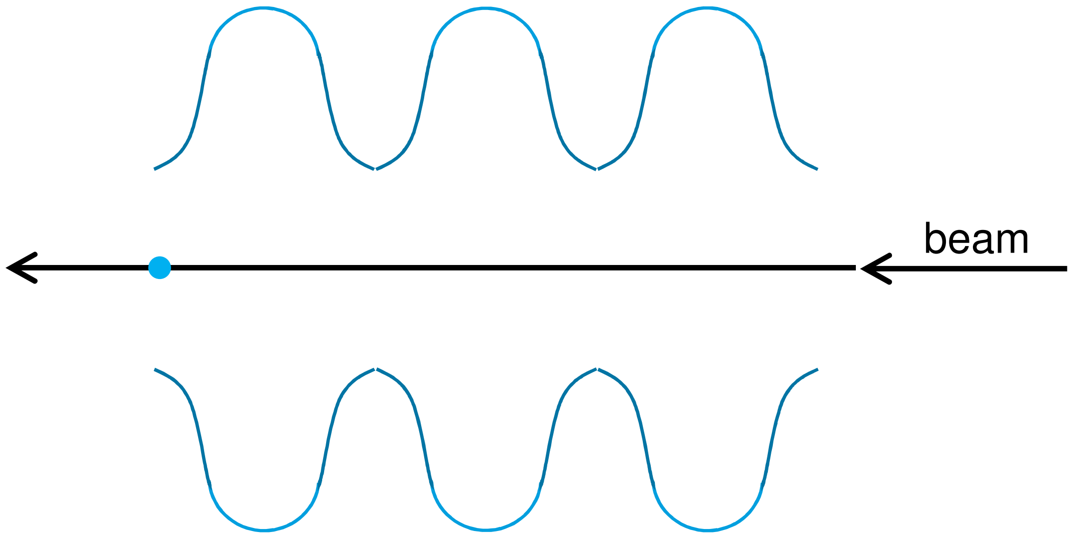
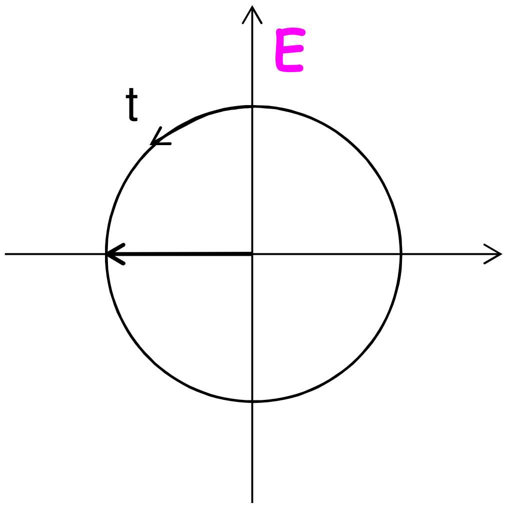

beam


E
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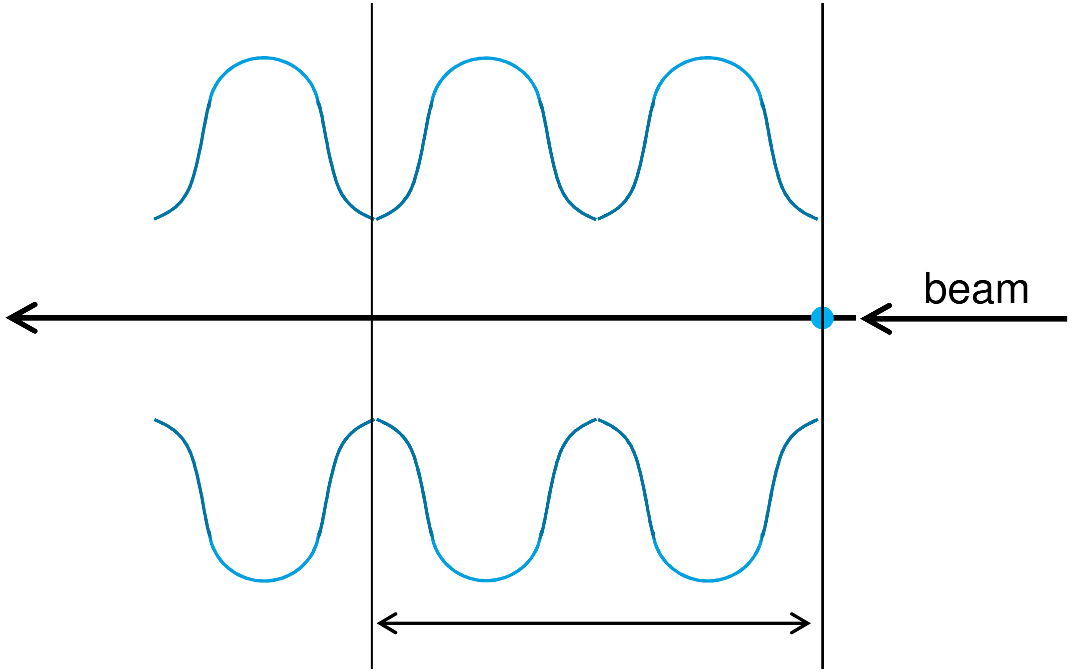
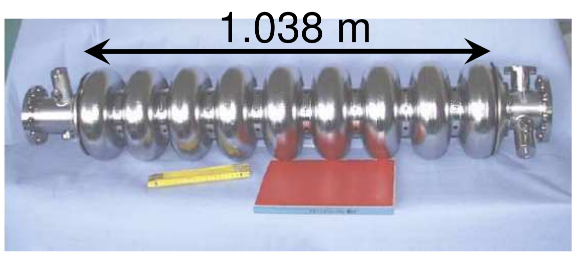
Is there a net acceleration? ……………………………… timing is the key

for electrons, $\beta \cong 1$





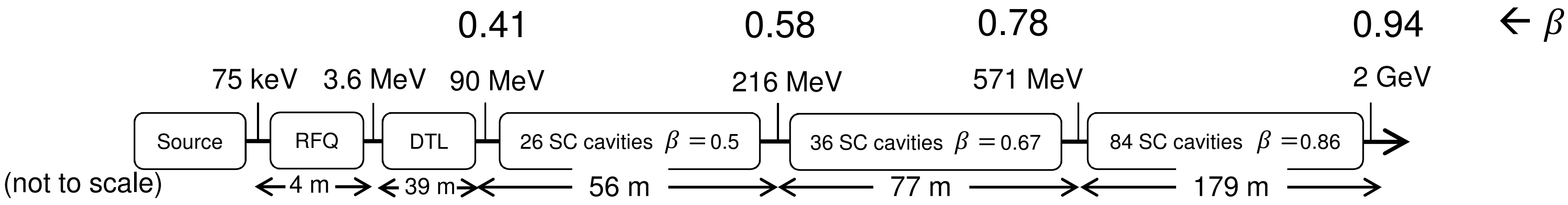
$$l = cT = \frac{c}{f} = \frac{3 \cdot 10^8}{1.3 \cdot 10^9} = 0.23\, m \quad \text{(2 cells)}$$

1 cavity (1.038 m) / 9 cells = 0.115 m

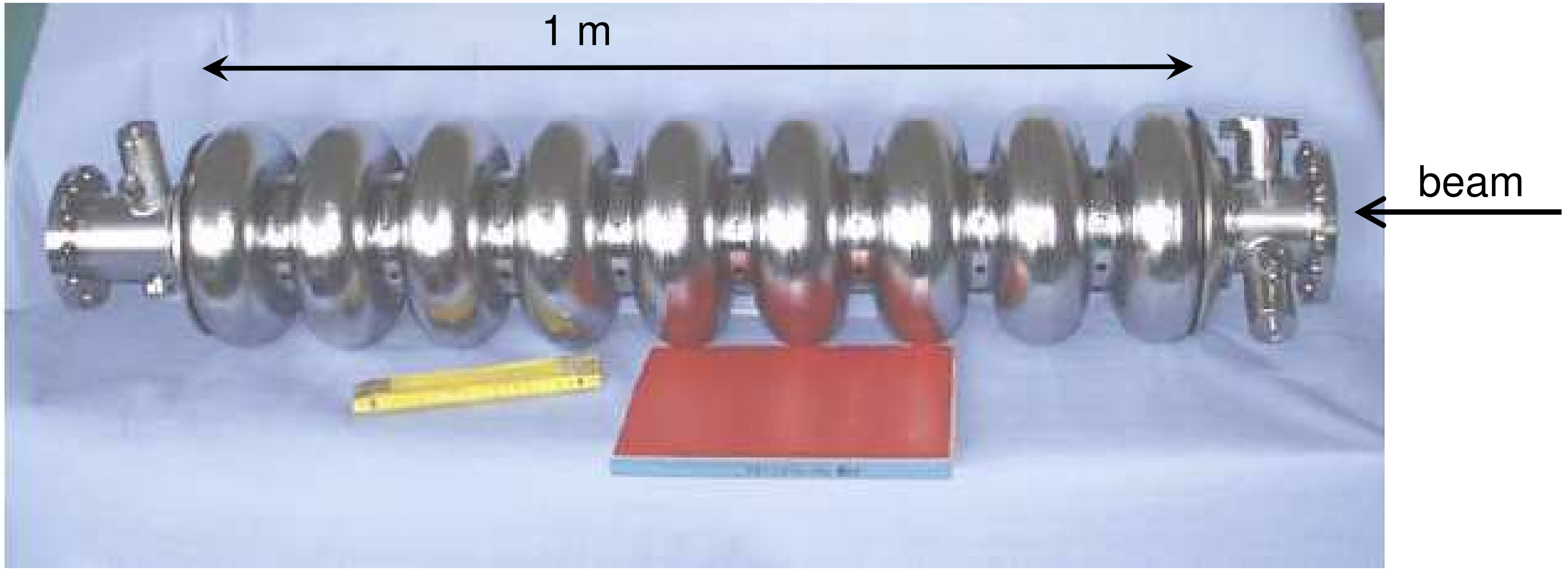
Is there a net acceleration? ……………………………… timing is the key

for protrons, $\beta < 1$

example: ESS (European Spallation Source), Lund, Sweden



Superconducting cavity used at DESY



Frequently Asked Questions

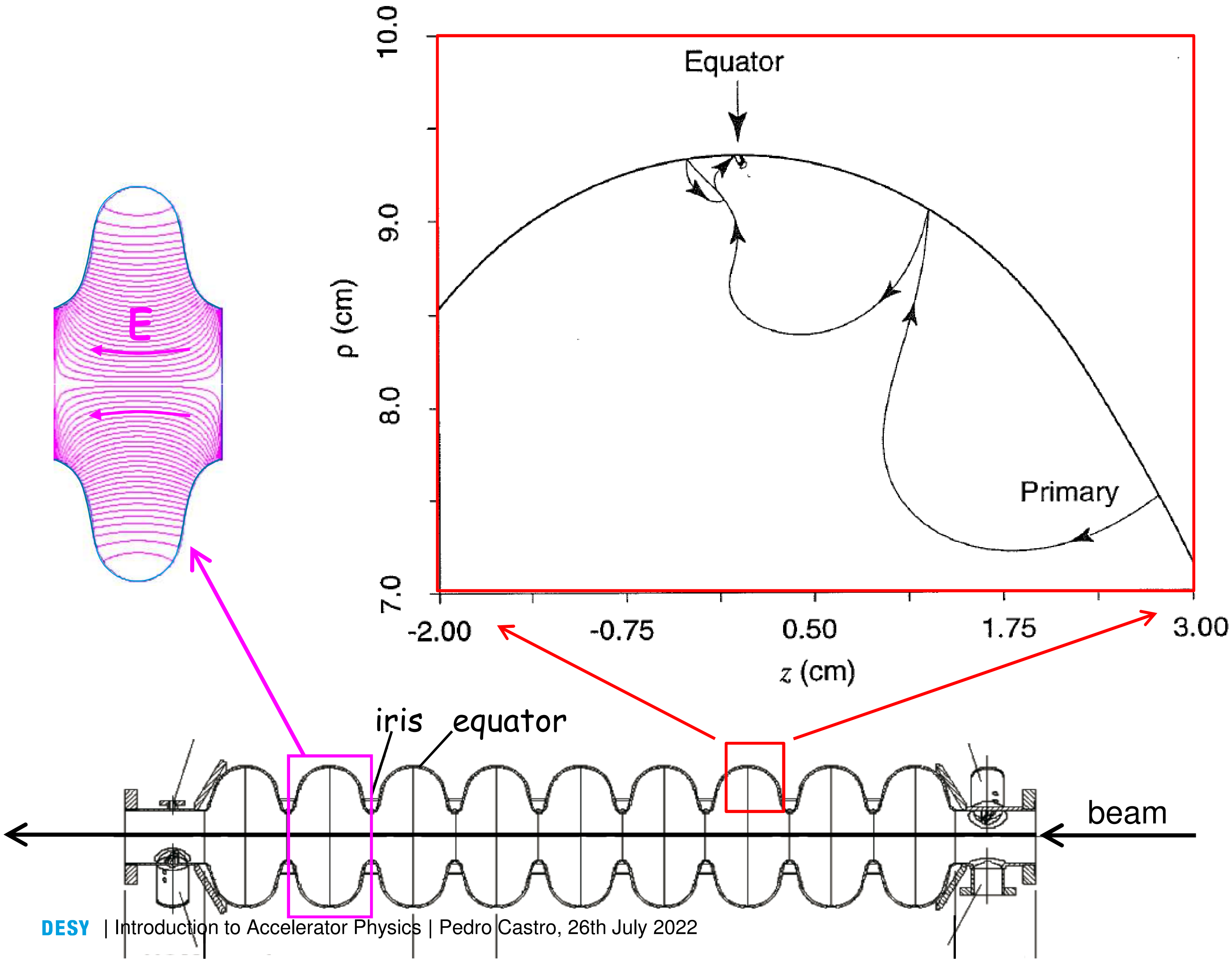
1) Why this shape?

2)

3)

4)

Multipacting mitigation in superconducting cavities



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

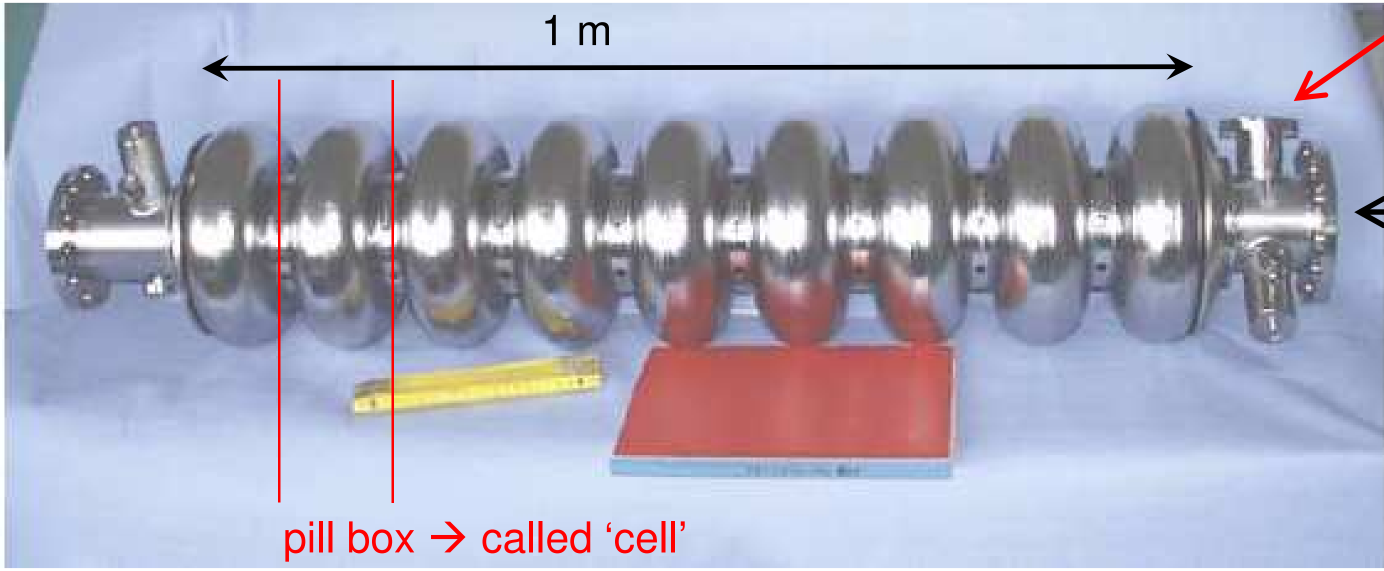
2) How to feed $\vec{E}$ in?

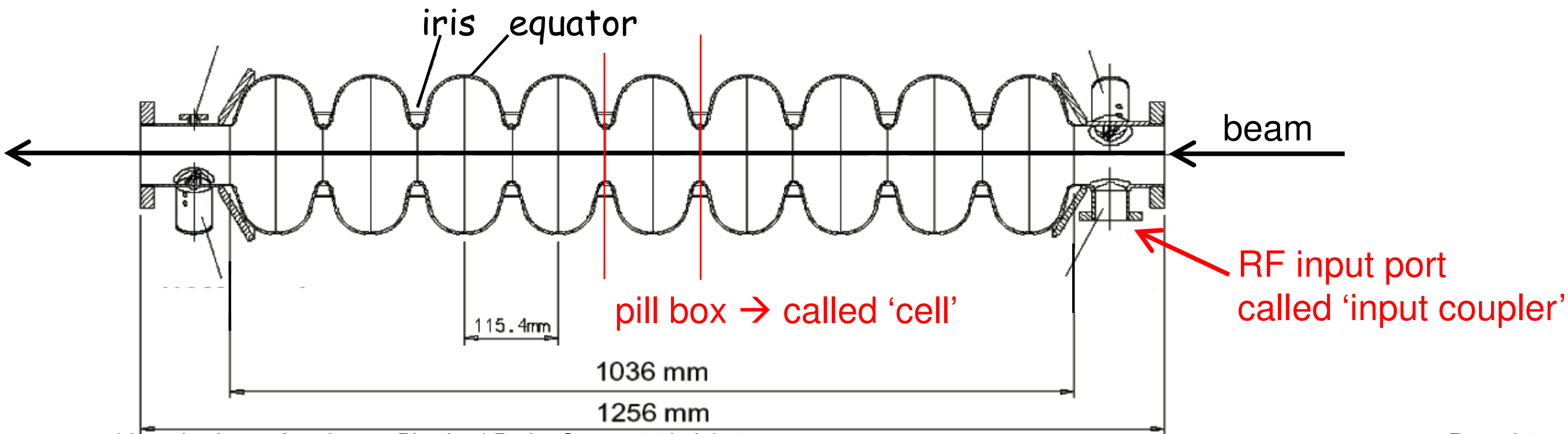
3)

4)

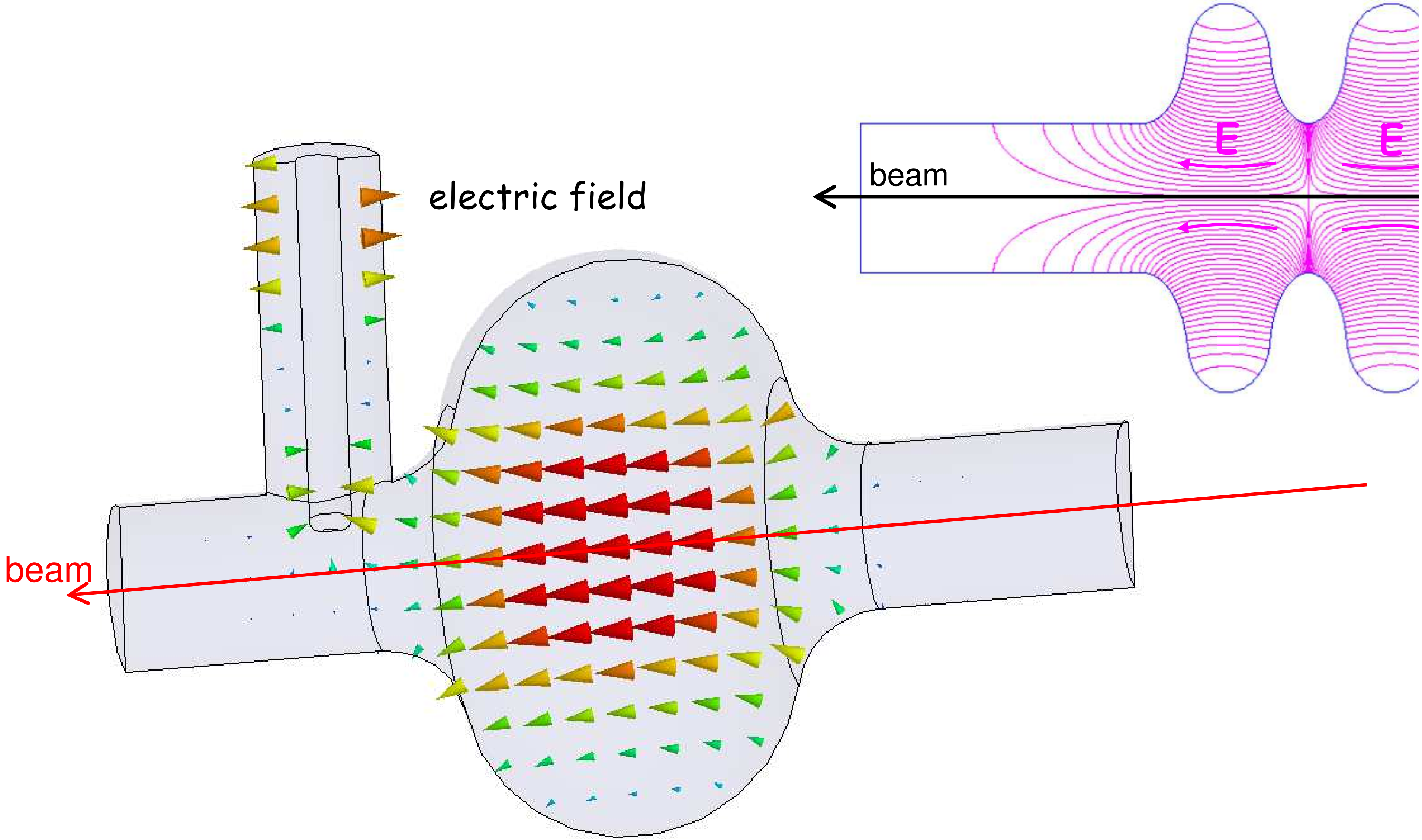
Superconducting cavity used in FLASH and in XFEL

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





Fundamental mode coupler (input coupler)



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

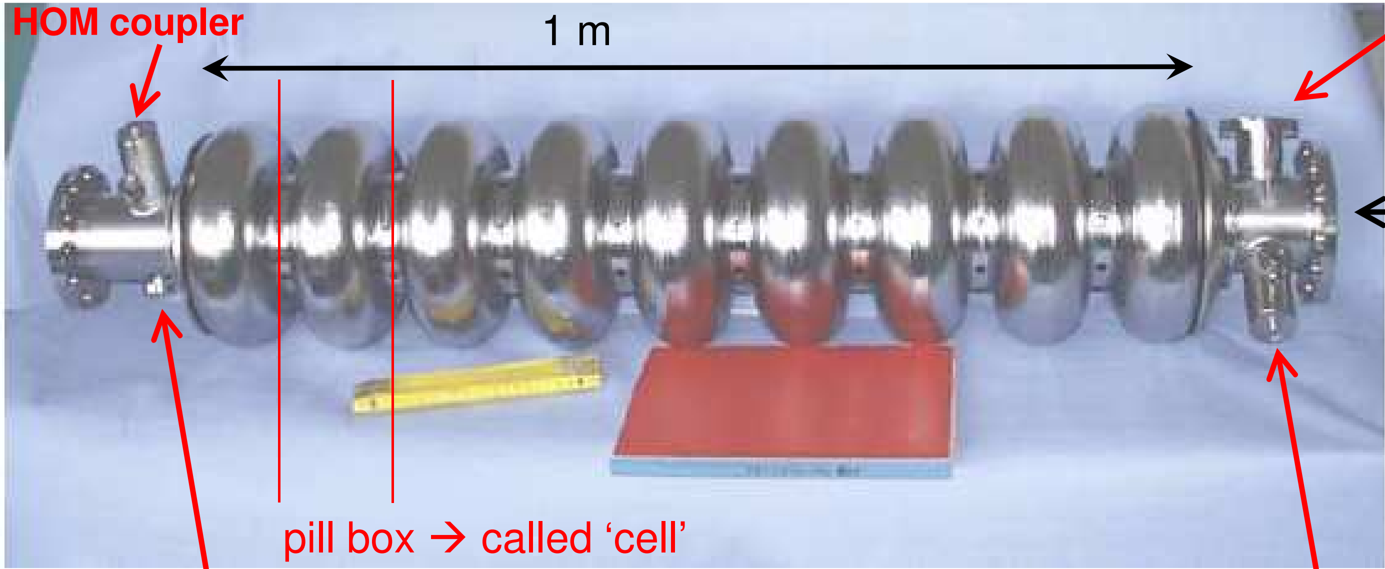
2) How to feed $\vec{E}$ in? .... with input couplers

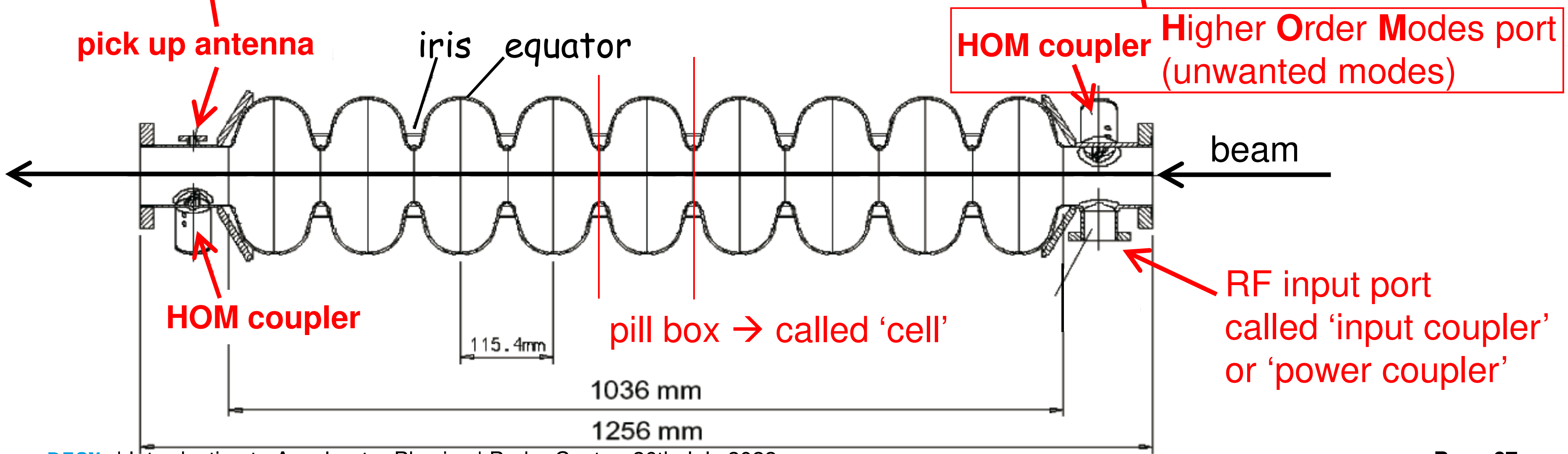
3) How to measure $\vec{E}$?

4)

Superconducting cavity used in FLASH and in XFEL

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





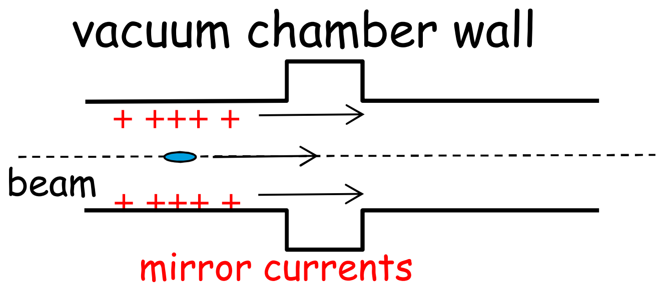
1) Why this shape? ……………………………………………… to reduce/avoid multipacting

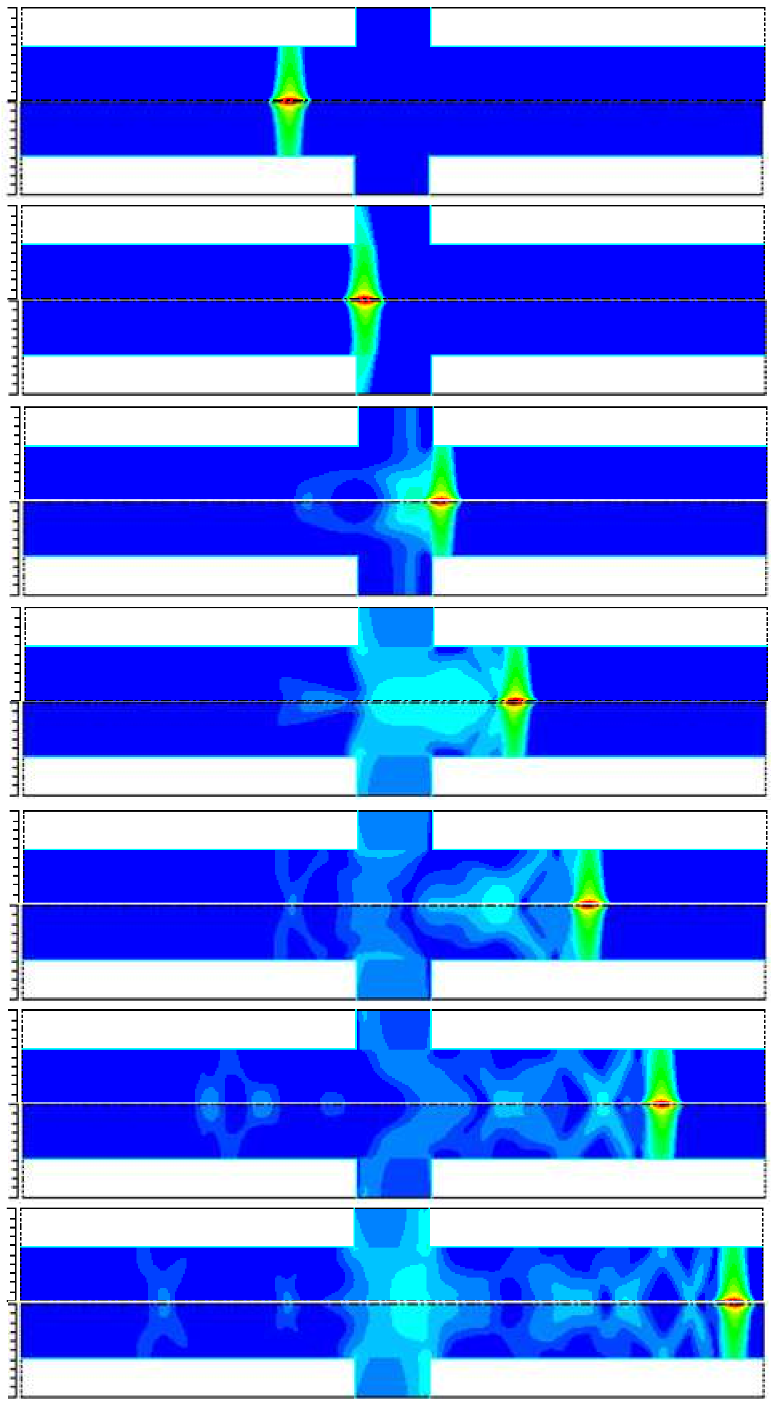
2) How to feed $\vec{E}$ in? …………………………………………… with input couplers

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

4) What are HOM couplers for?

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)

Summing-up of this part

Particle acceleration using radio-frequency fields:

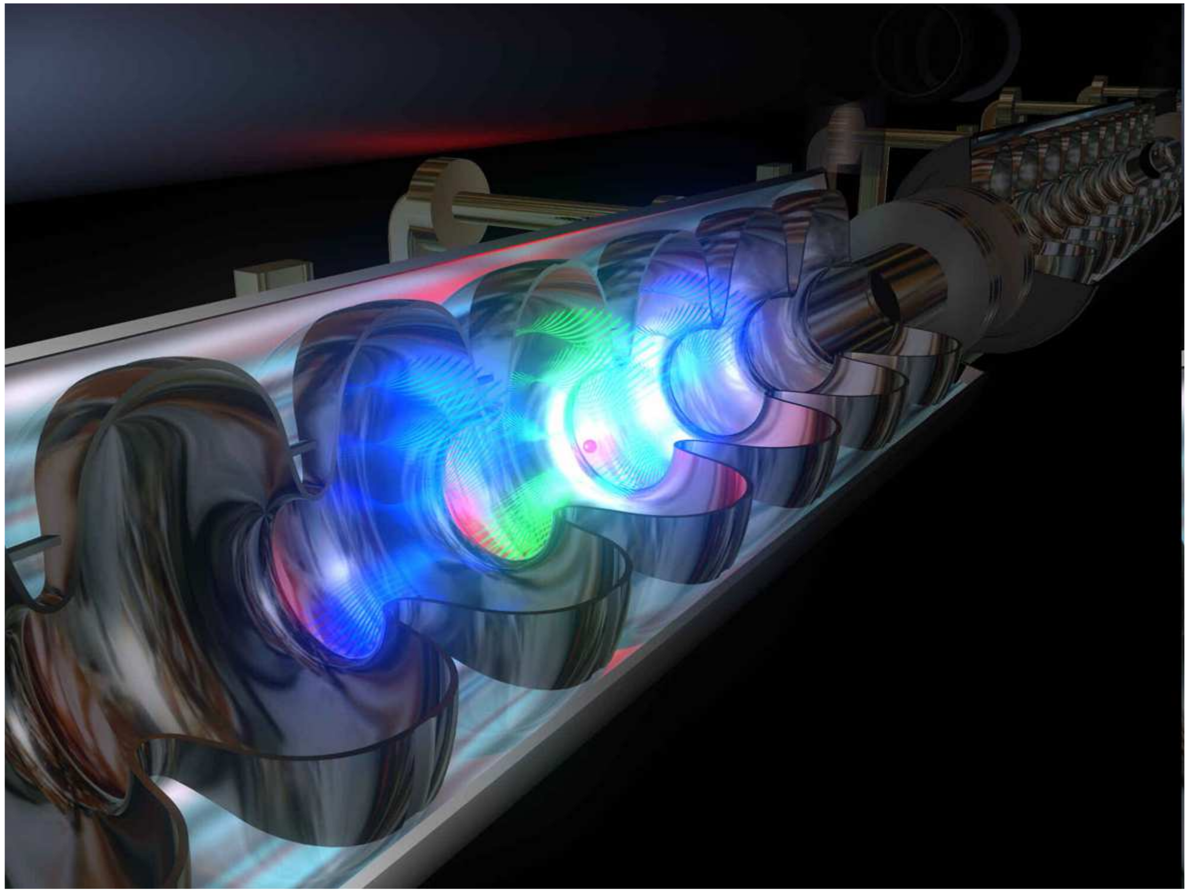
basic cavity:
pill box

- 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

MEDIA DATABASE. “Electron acceleration – a virtual simulation“



DESY→Press→Media database→European XFEL (with filter: media type=movies)

https://media.desy.de/DESYmediabank/?l=en#l=en&cid=3980&cname=European%20XFEL&f=2165&s=&p=&r=

YouTube: https://www.youtube.com/watch?v=FJO_DmM4q7M
search text: electron acceleration

Contact

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Elektronen-Synchrotron

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pedro.castro@desy.de