

Introduction to Accelerator Physics

Part 3

Pedro Castro / Accelerator Physics Group (MPY)
Hamburg, 3rd February 2023



Accelerator lectures framework in Summer Student Prog.

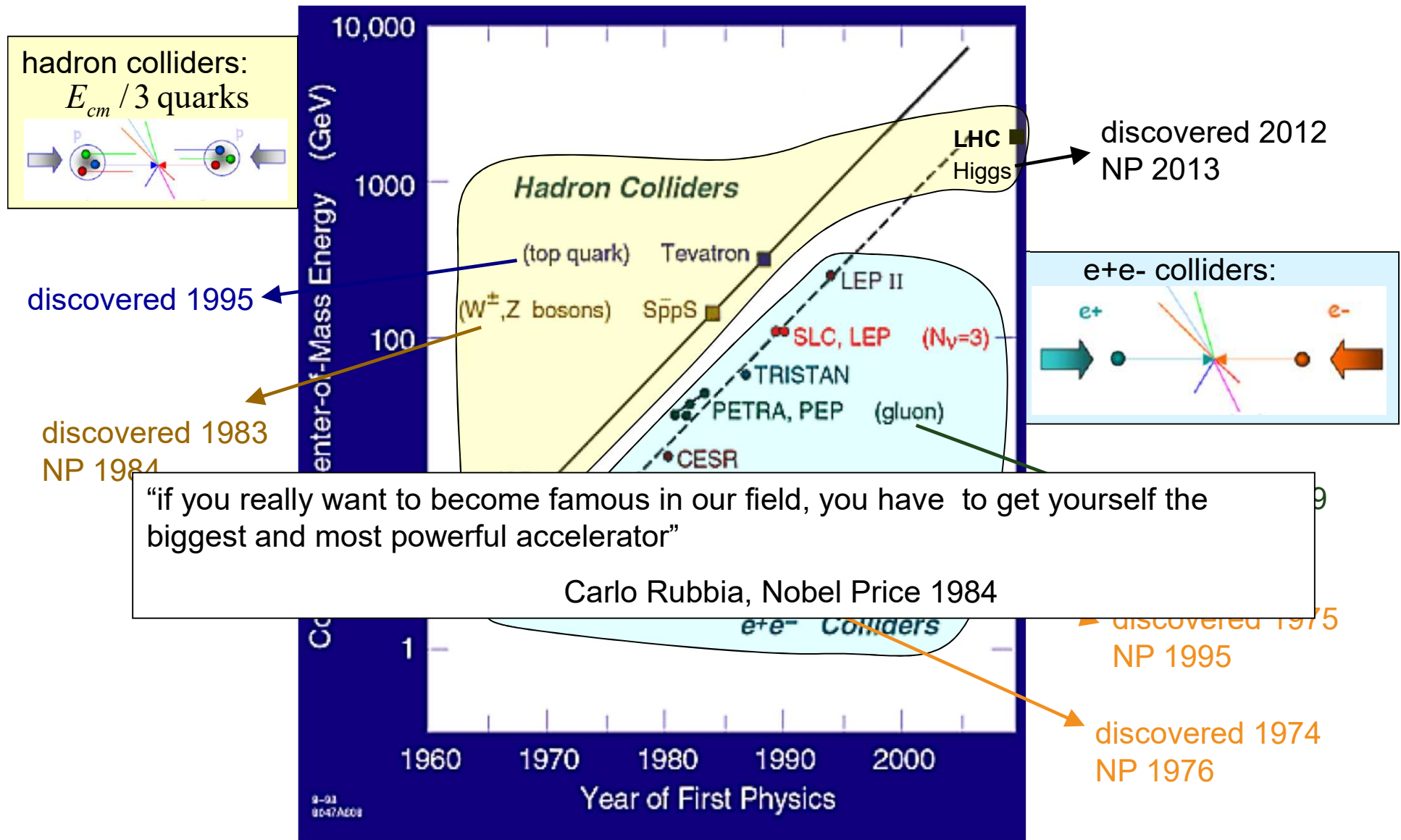
22nd Feb.: Plasma wakefield acceleration, J. Osterhoff

Today: focus on present day and last 50 years accelerator technology

synchrotrons: machines for discoveries

Facility	Particle(s) discovered	Year of discovery	Nobel Price
SPEAR	charm quark	1974	1976
SPEAR	tau lepton	1975	1995
PETRA	gluon	1979	
S \bar{p} pS	W^{\pm}, Z bosons	1983	1984
SLC, LEP	$N_{\nu} = 3$		
Tevatron	top quark	1995	
LHC	Higgs	2012	2013

Main HEP discoveries at synchrotrons in the last 50 years



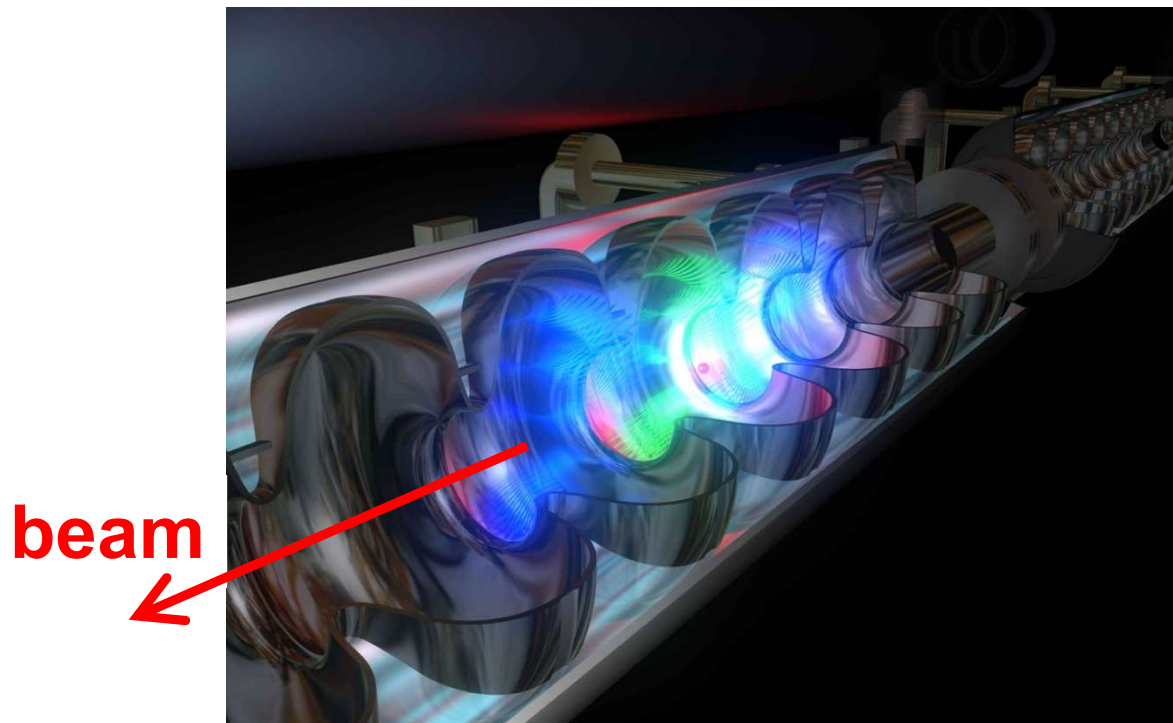
Scope of this lecture:

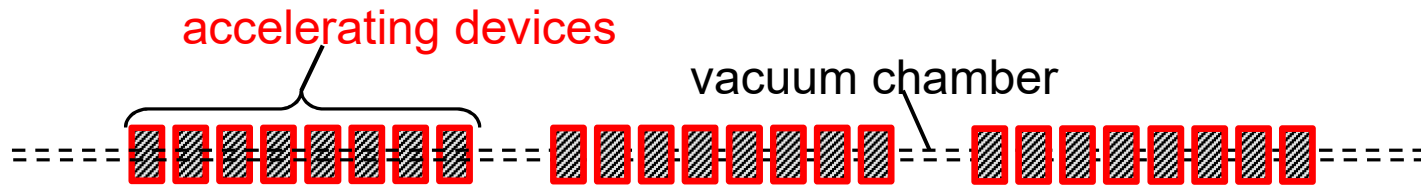
1. Synchrotrons: key components and their challenges to reach high energies:

- Dipole magnetic fields
- Superconducting dipoles
- Quadrupole magnets to focus beams

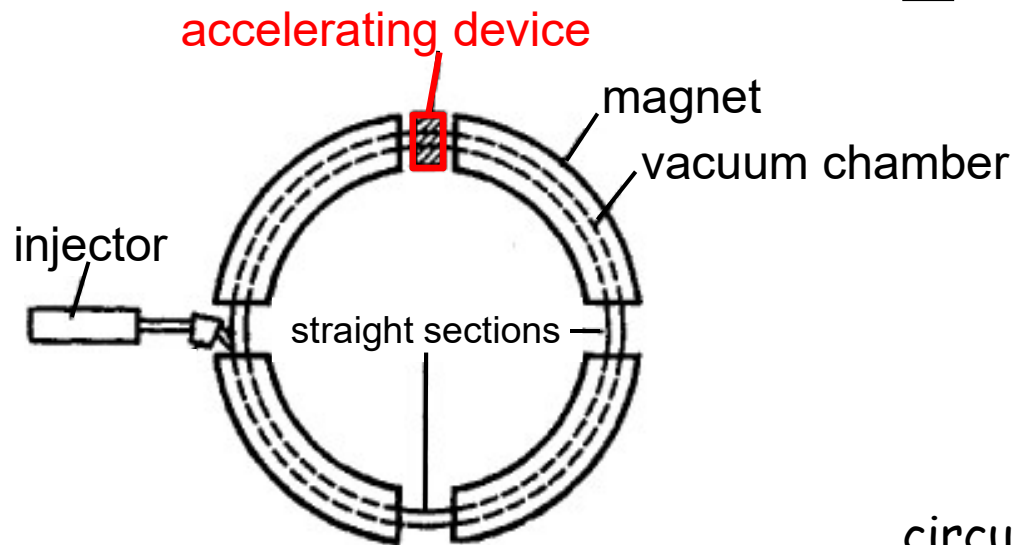
2. Synchrotrons and Linear Accelerators:

- Acceleration using radio-frequency electromagnetic fields





linear accelerator (linac)



circular accelerator: synchrotron

Motion in electric and magnetic fields

Equation of motion under Lorentz Force

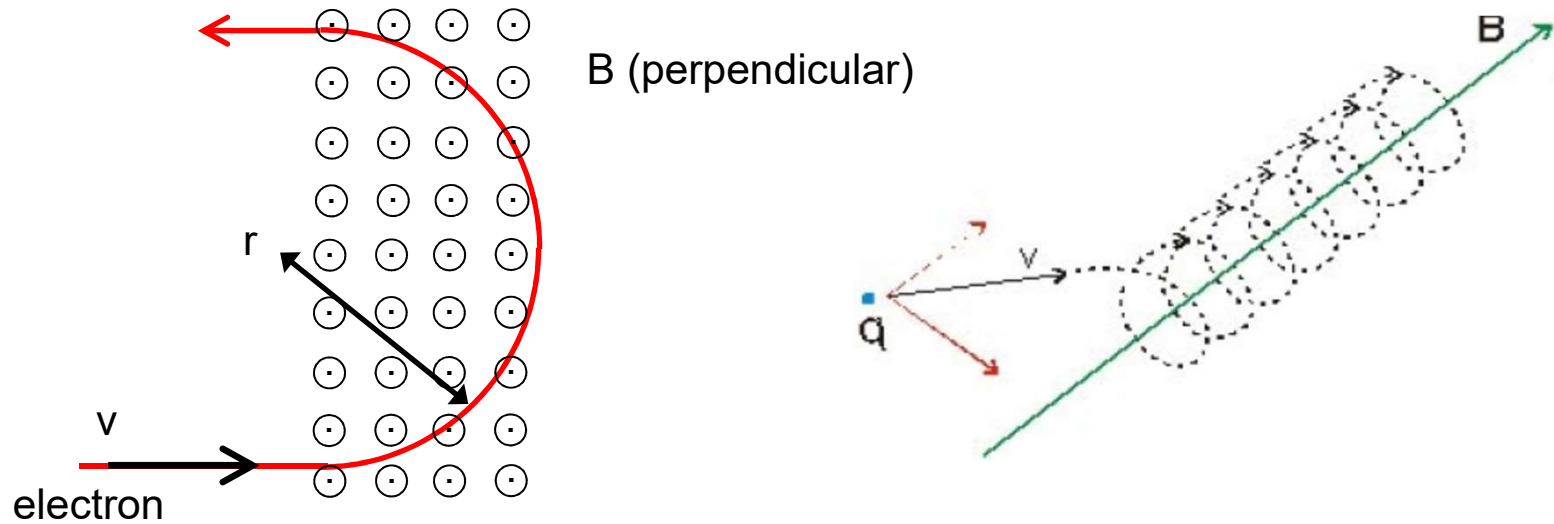
$$\frac{d\vec{p}}{dt} = \vec{F} = q (\vec{E} + \vec{v} \times \vec{B})$$

The diagram shows the Lorentz force equation with arrows pointing from labels to terms in the equation. A bracket under the first three terms is labeled 'of the particle'. The labels are: 'momentum' pointing to $\frac{d\vec{p}}{dt}$, 'charge' pointing to q , 'velocity' pointing to \vec{v} , 'electric field' pointing to \vec{E} , and 'magnetic field' pointing to \vec{B} .

Motion in magnetic fields

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

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



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

total energy

momentum

energy at rest

Motion in magnetic fields

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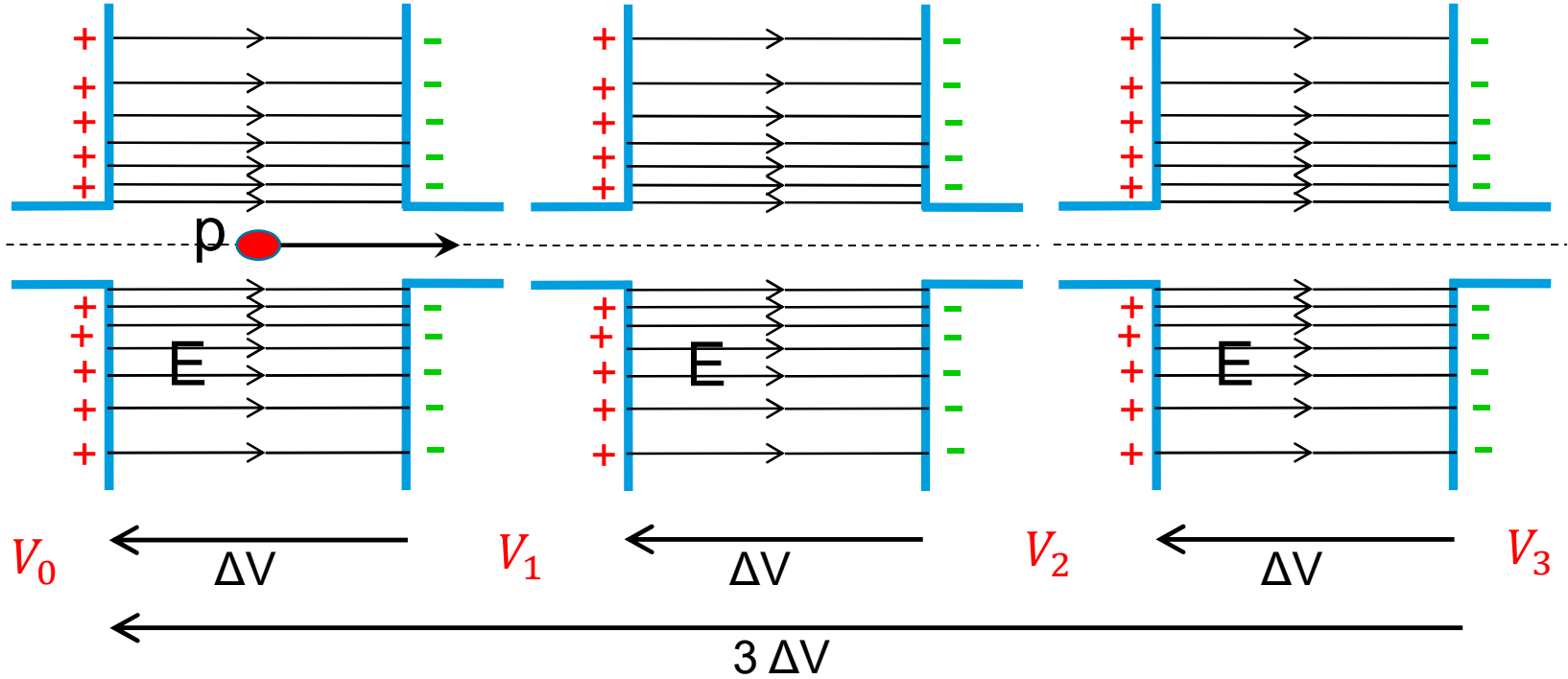
$$E^2 = \vec{p}^2 c^2 + E_0^2$$

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

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

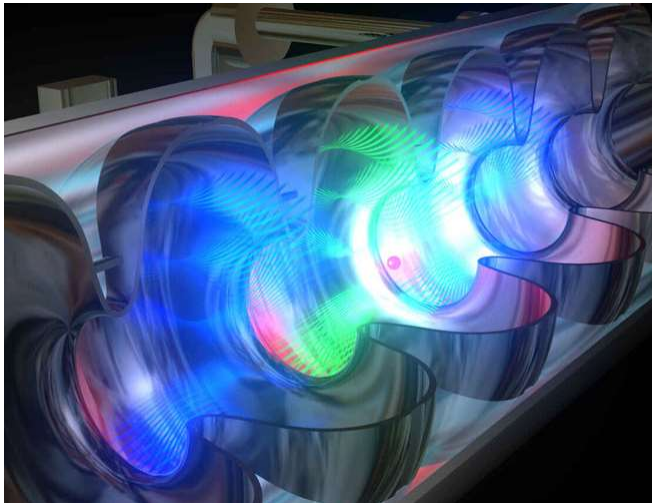
Magnetic fields do not change the particles energy, only electric fields do !

acceleration with DC electric fields

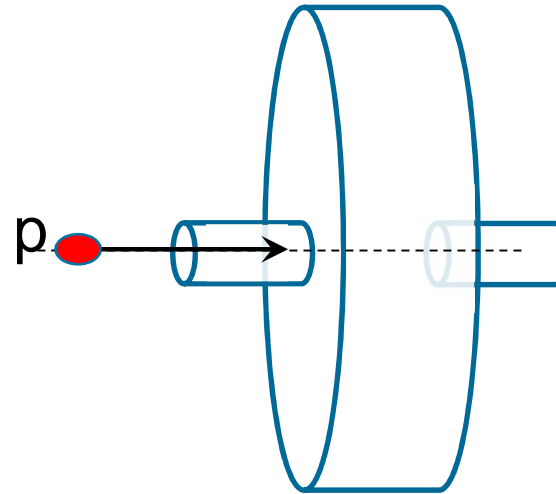
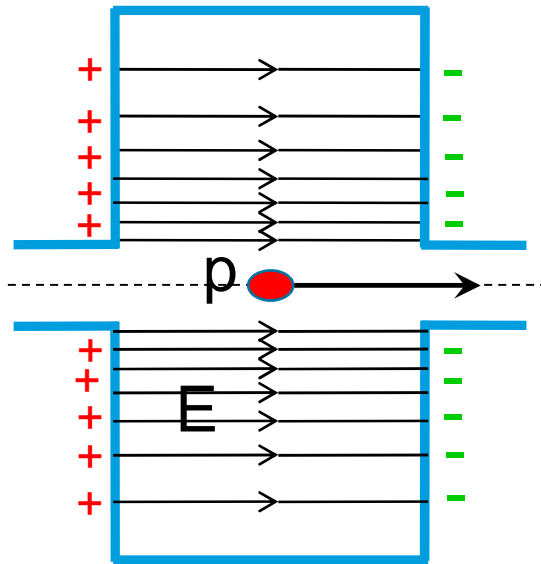


In general:

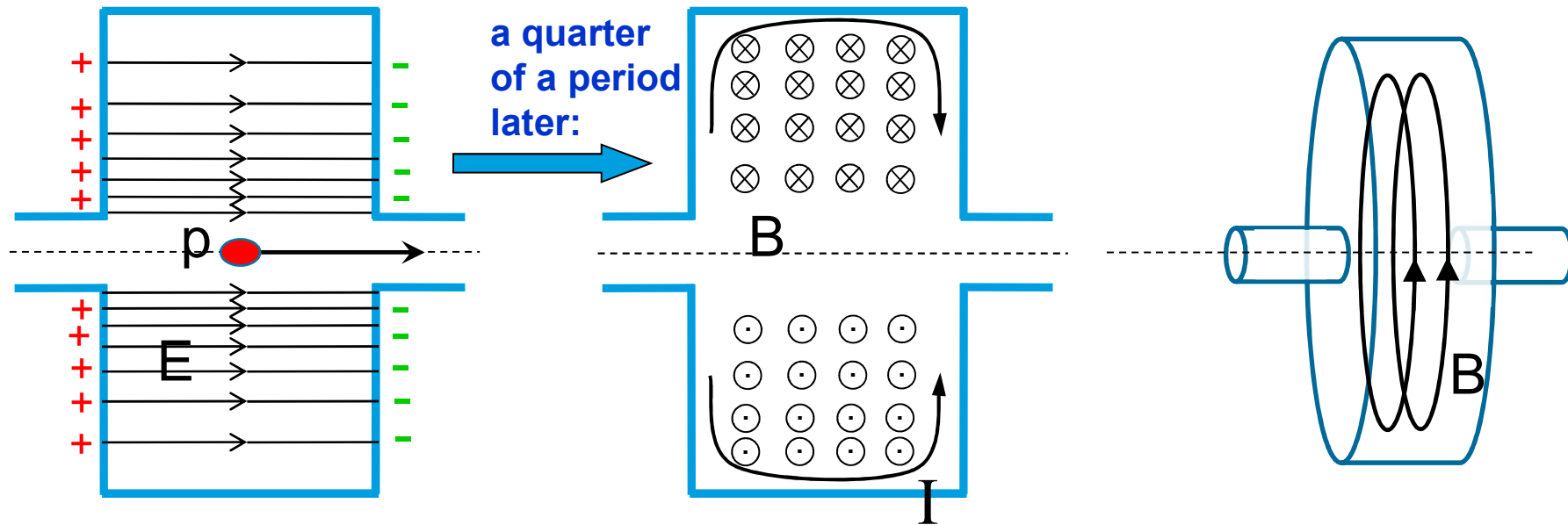
- Static magnetic fields \rightarrow to guide (bend + focus) particle beams
- Static electric fields \rightarrow accelerate particle beams (low energy)
- Radio-frequency EM fields \rightarrow accelerate particle beams (high E)



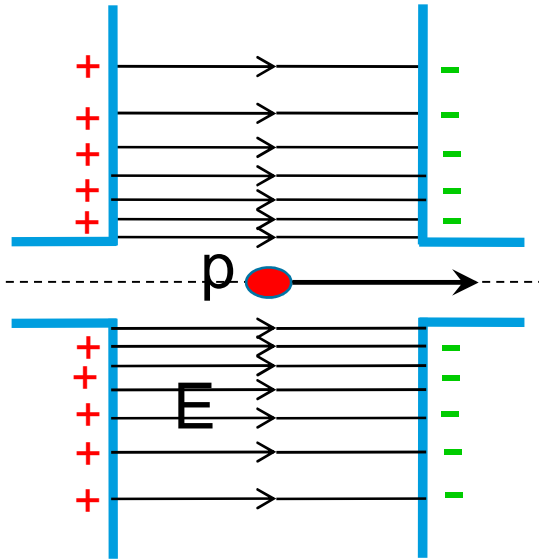
acceleration with RF (radio-frequency) electric fields



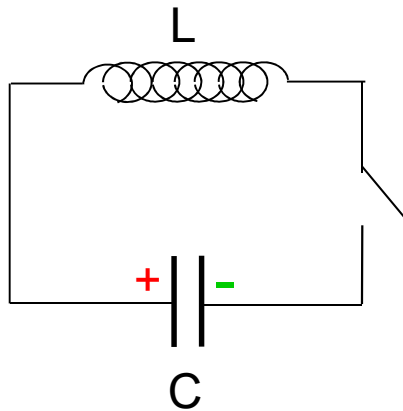
RF cavity basics: a cylindrical cavity



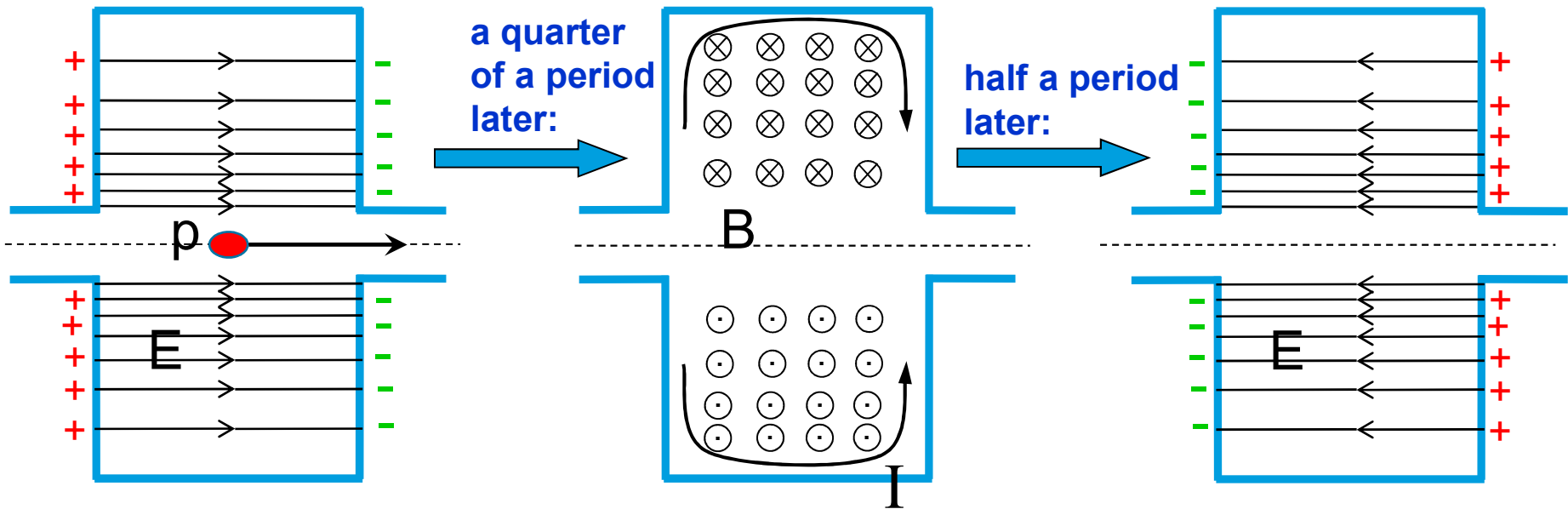
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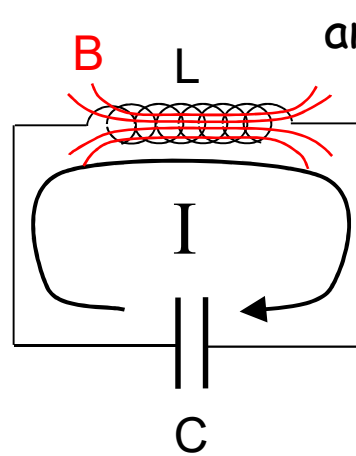
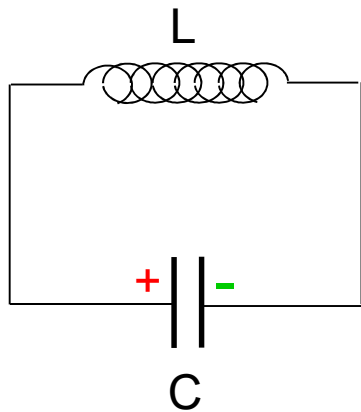
LC circuit (or resonant circuit) analogy:



RF cavity basics: a cylindrical cavity

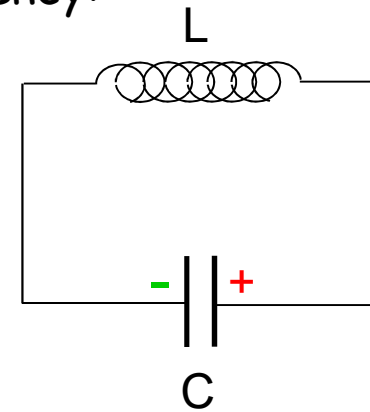


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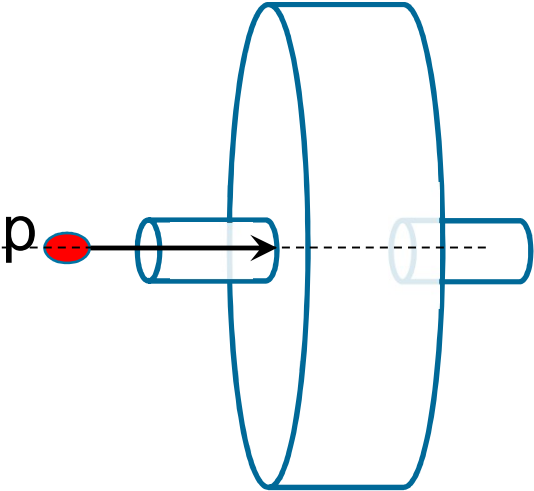
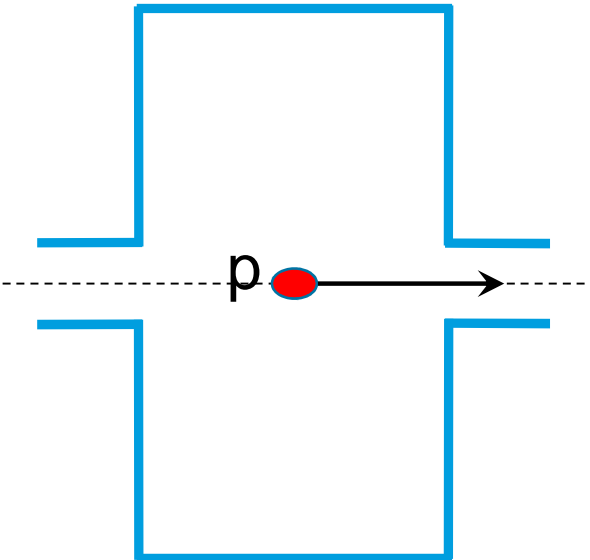


angular frequency:

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



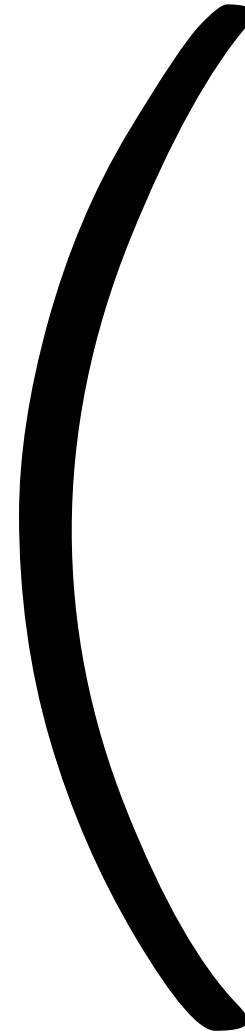
RF cavity basics: the pill box cavity



← pill boxes →



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



Maxwell's equations

(differential formulation in SI units)

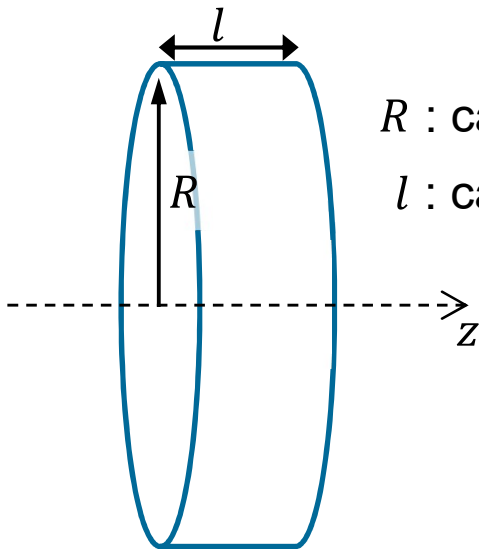
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$$\vec{\nabla} \cdot \vec{B} = 0$$

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

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

+ 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)~~

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

indices:

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

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

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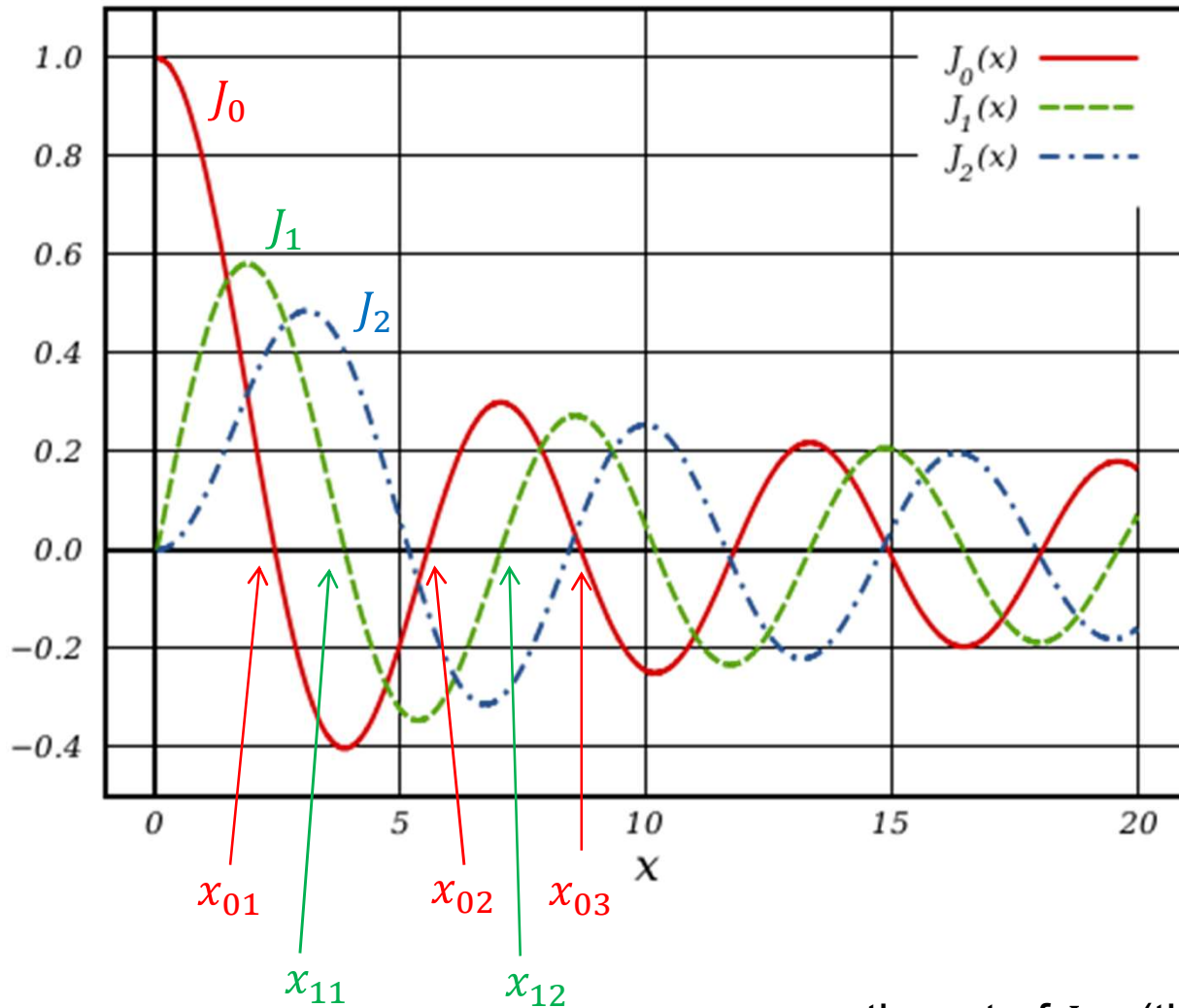
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m	x_{m1}	x_{m2}	x_{m3}
0	2.405	5.520	8.654
1	3.832	7.016	10.173
2	5.136	8.417	11.620

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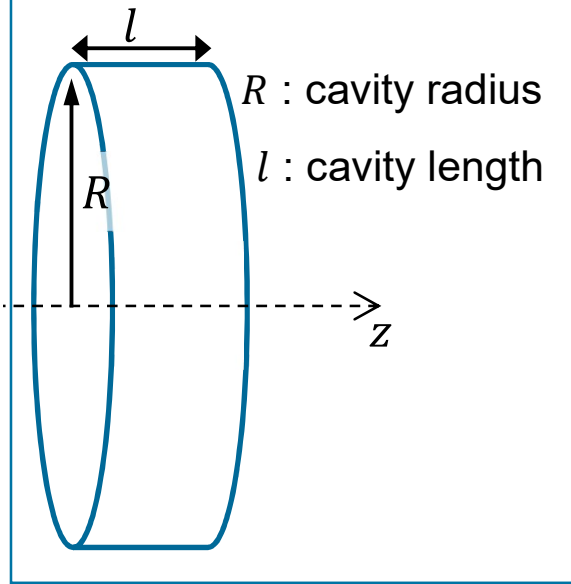
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boundary conditions



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

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

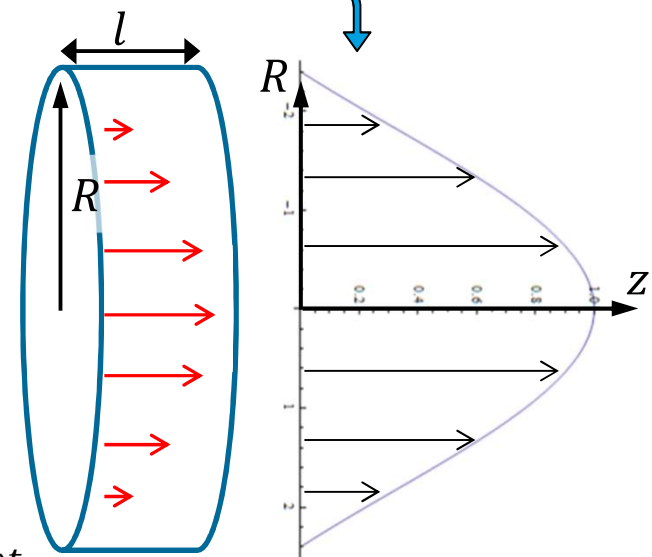
$$E_r = 0$$

$$E_\theta = 0$$

$$B_z = 0$$

$$B_r = 0$$

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



$m = 0$: rotation symmetry of the fields

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

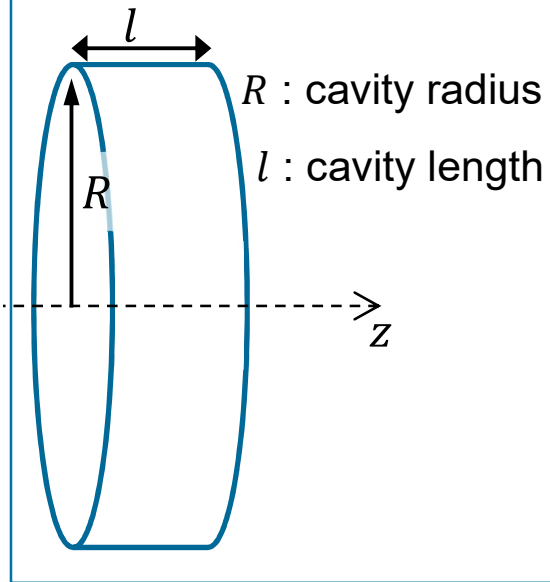
$p = 0$: no variation in z of the fields

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



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

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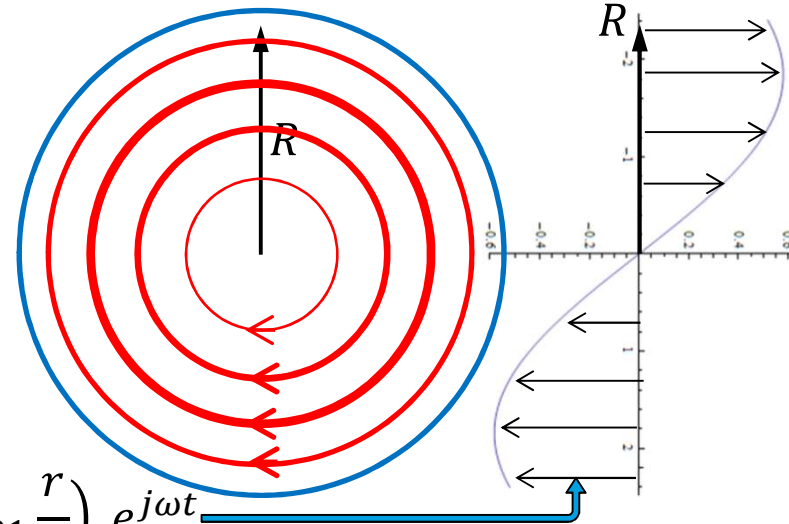
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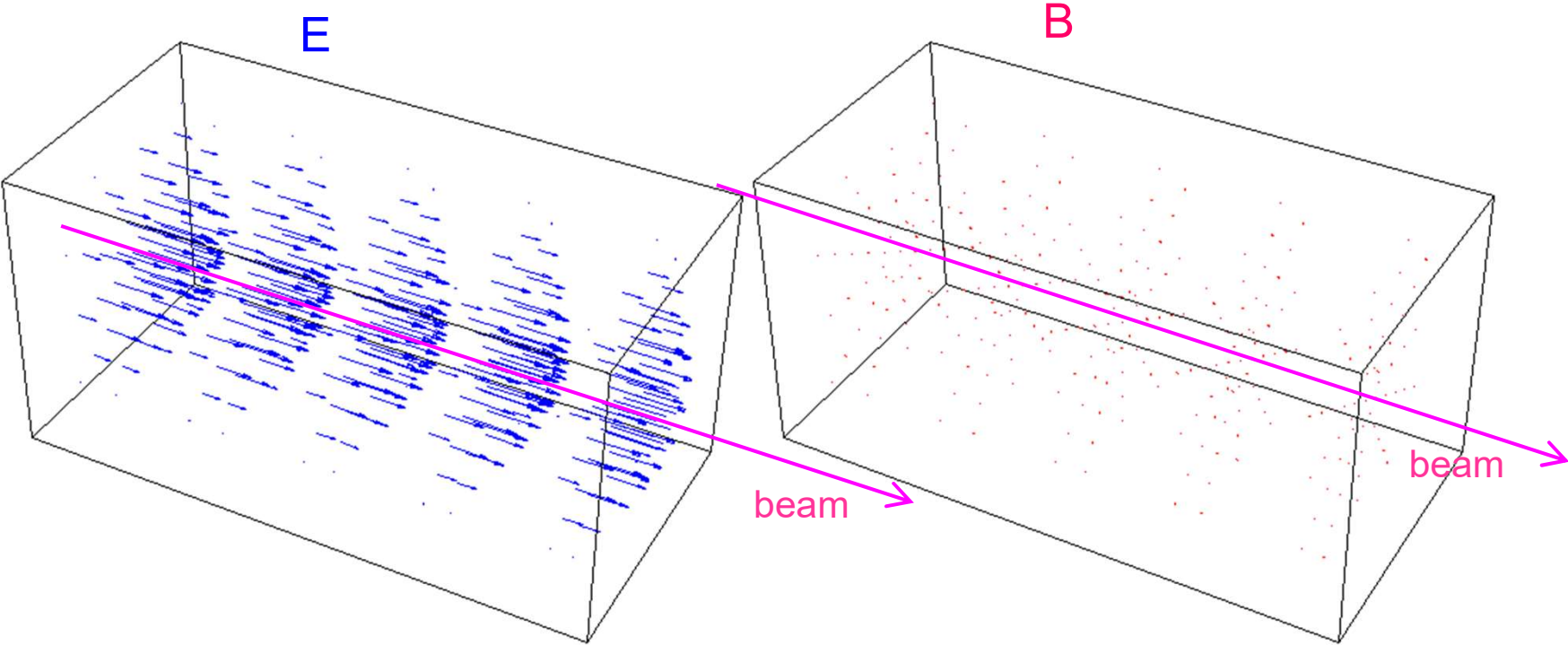
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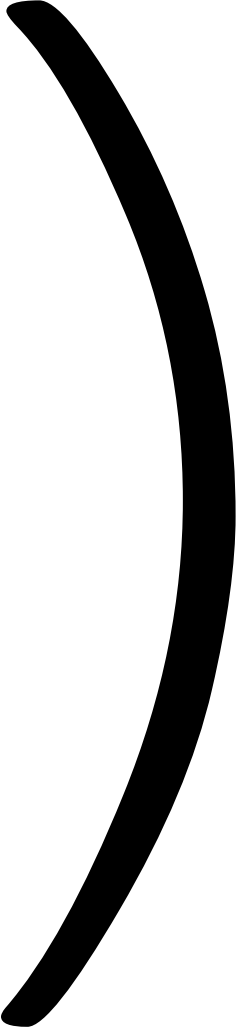
J_m : Bessel's functions

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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

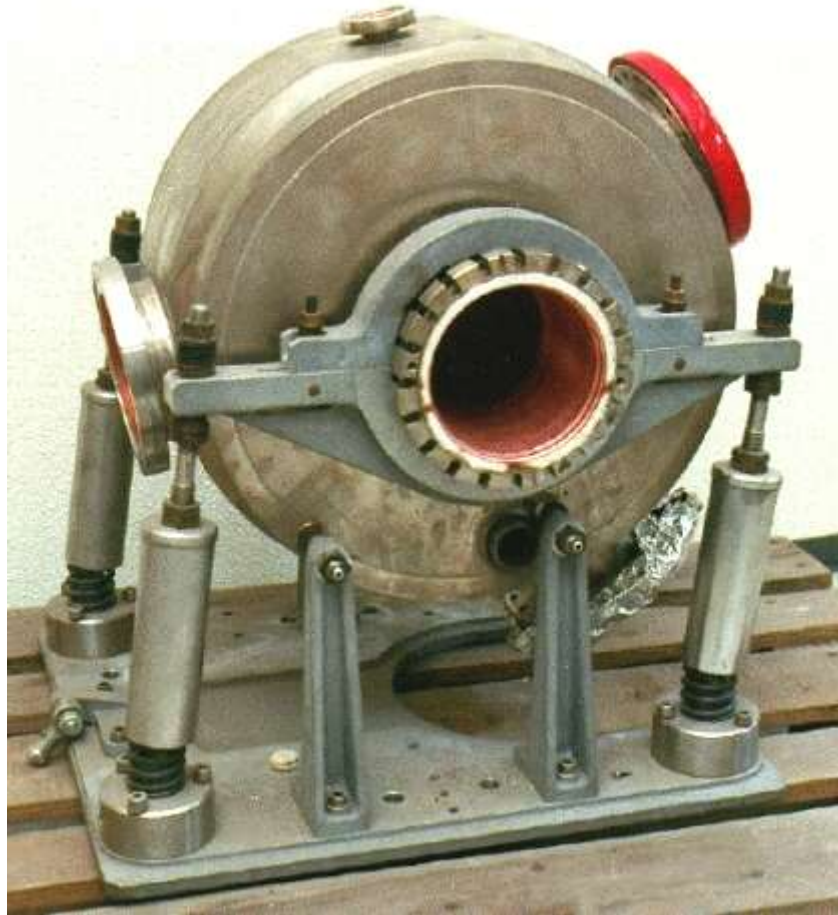




Equations for the electric
and magnetic fields
in a pill box cavity

Examples of pill box cavities

DESY cavity (pill box)



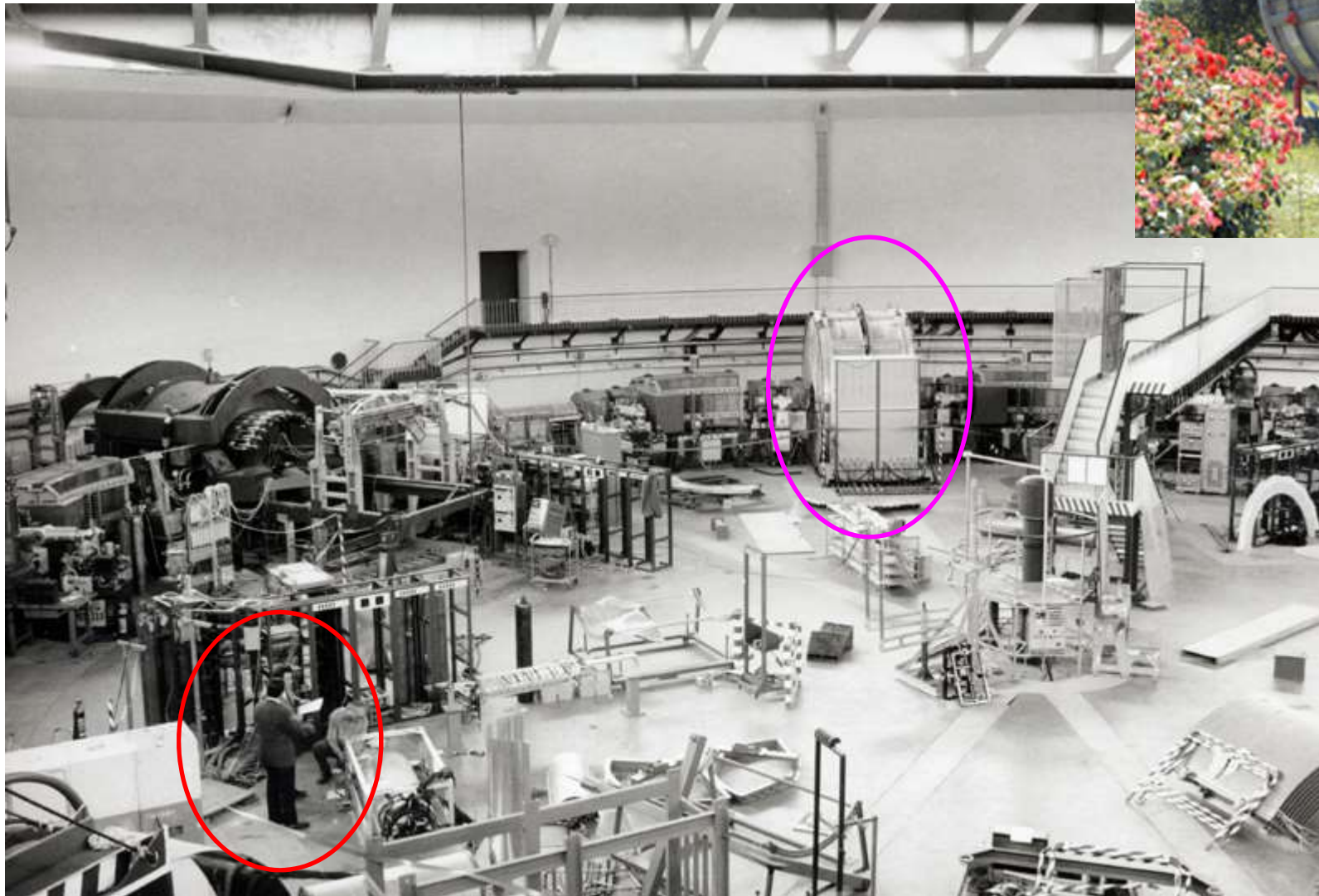
ADONE cavity 51 MHz (pill box)
Frascati lab, Italy



Examples of pill box cavities

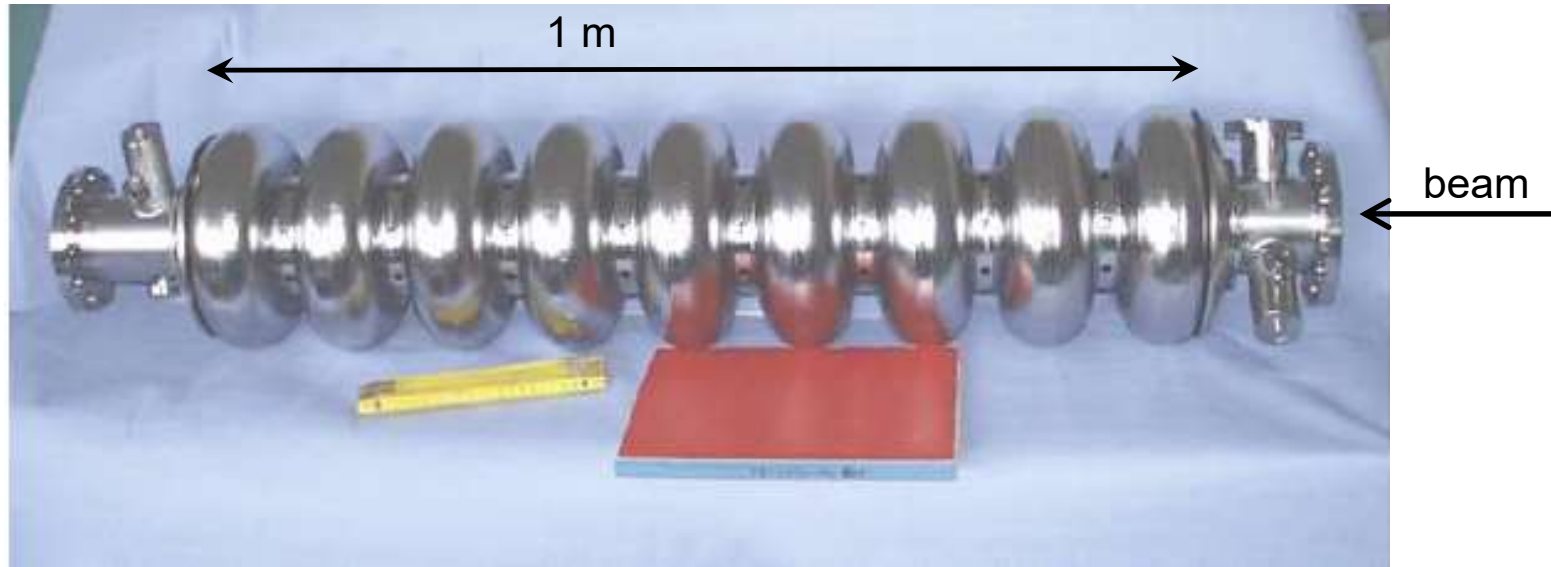
ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

ADONE in 1963, Laboratori Nazionali di Frascati, Italy



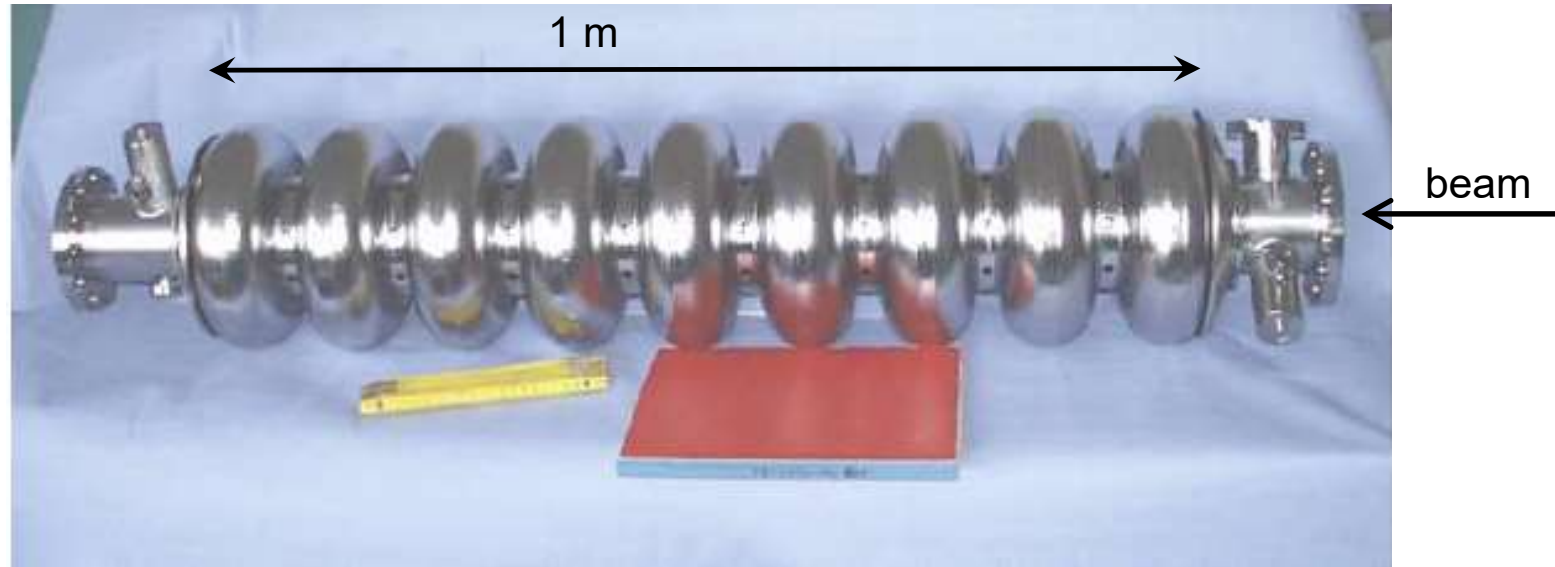
Superconducting cavity used at DESY

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



Free-electron <u>L</u> ASer in <u>H</u> amburg	0.3 km	DESY	2004-	?	e-	1.2 GeV
European <u>X</u> -ray <u>F</u> ree- <u>E</u> lectron <u>L</u> aser	3 km	DESY	2016-	?	e-	17.5 GeV
<u>I</u> nternational <u>L</u> inear <u>C</u> ollider	30 km	?	?		e-/e+	2x250 GeV

Superconducting cavity used at DESY

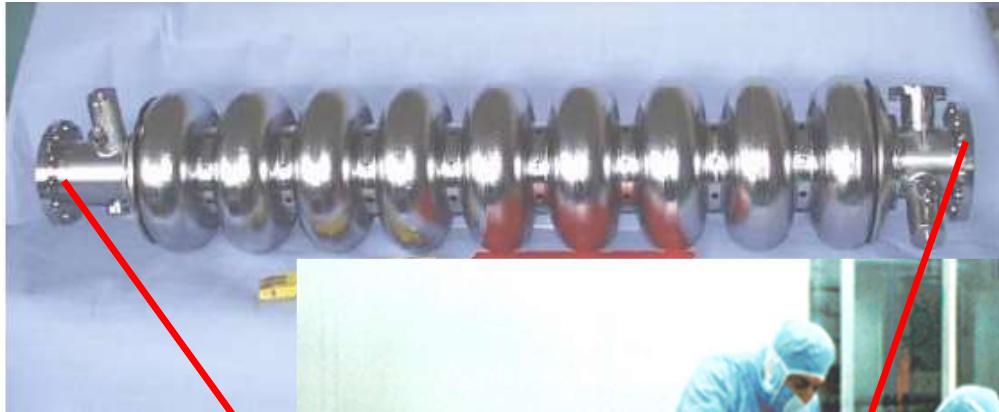


material: pure Niobium

operating temperature: 2 K

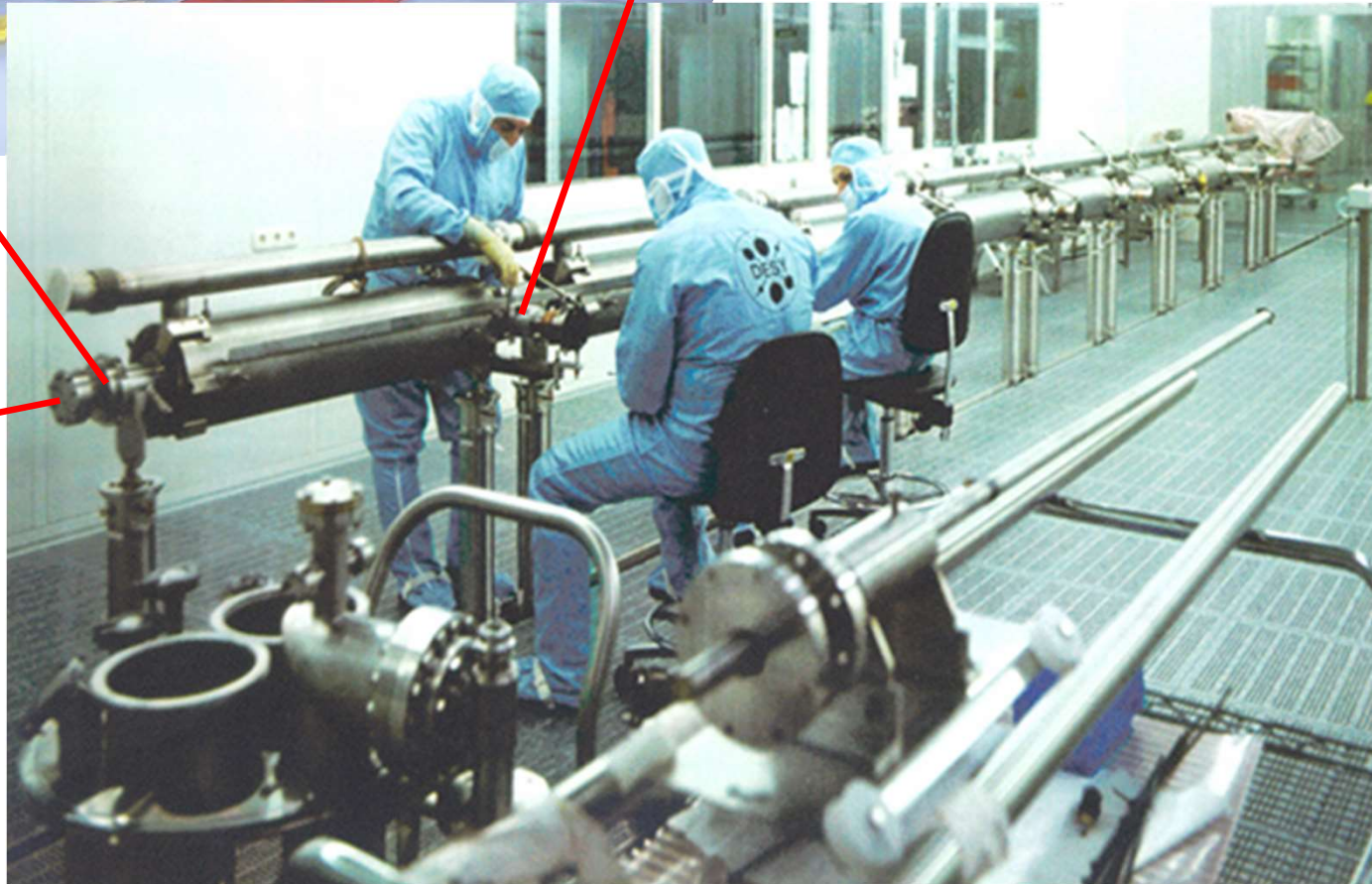
accelerating field gradient: up to 35 MV/m

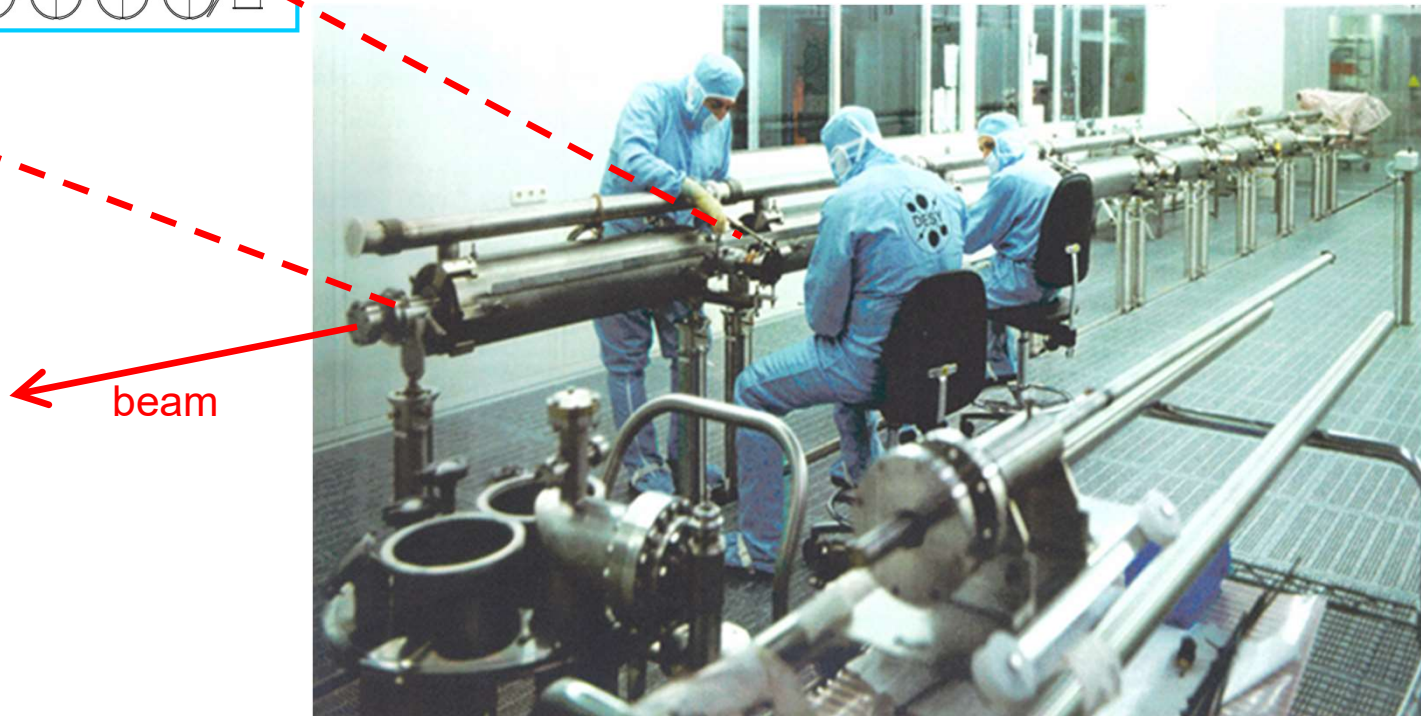
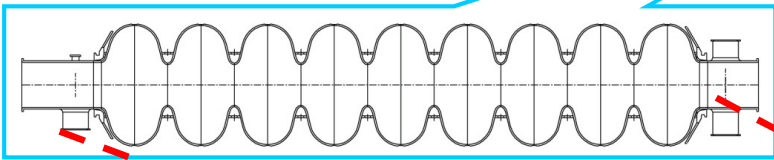
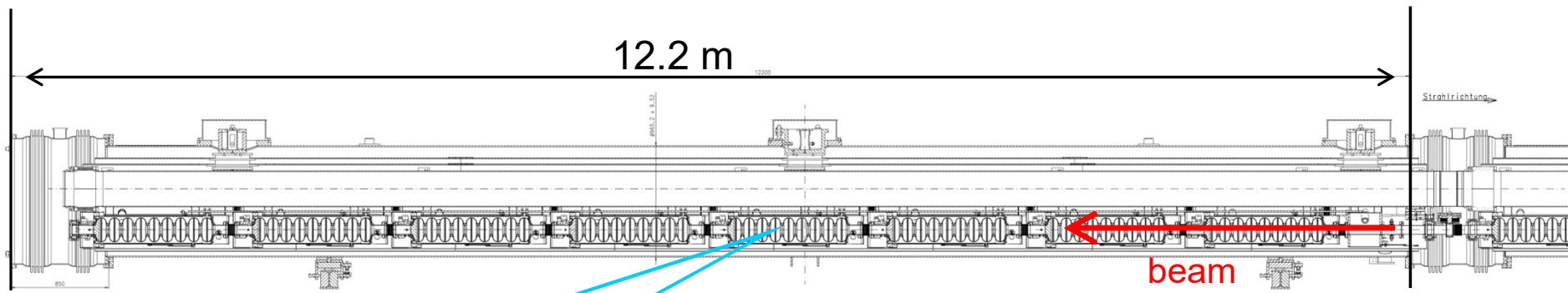
Cavities inside a cryostat



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

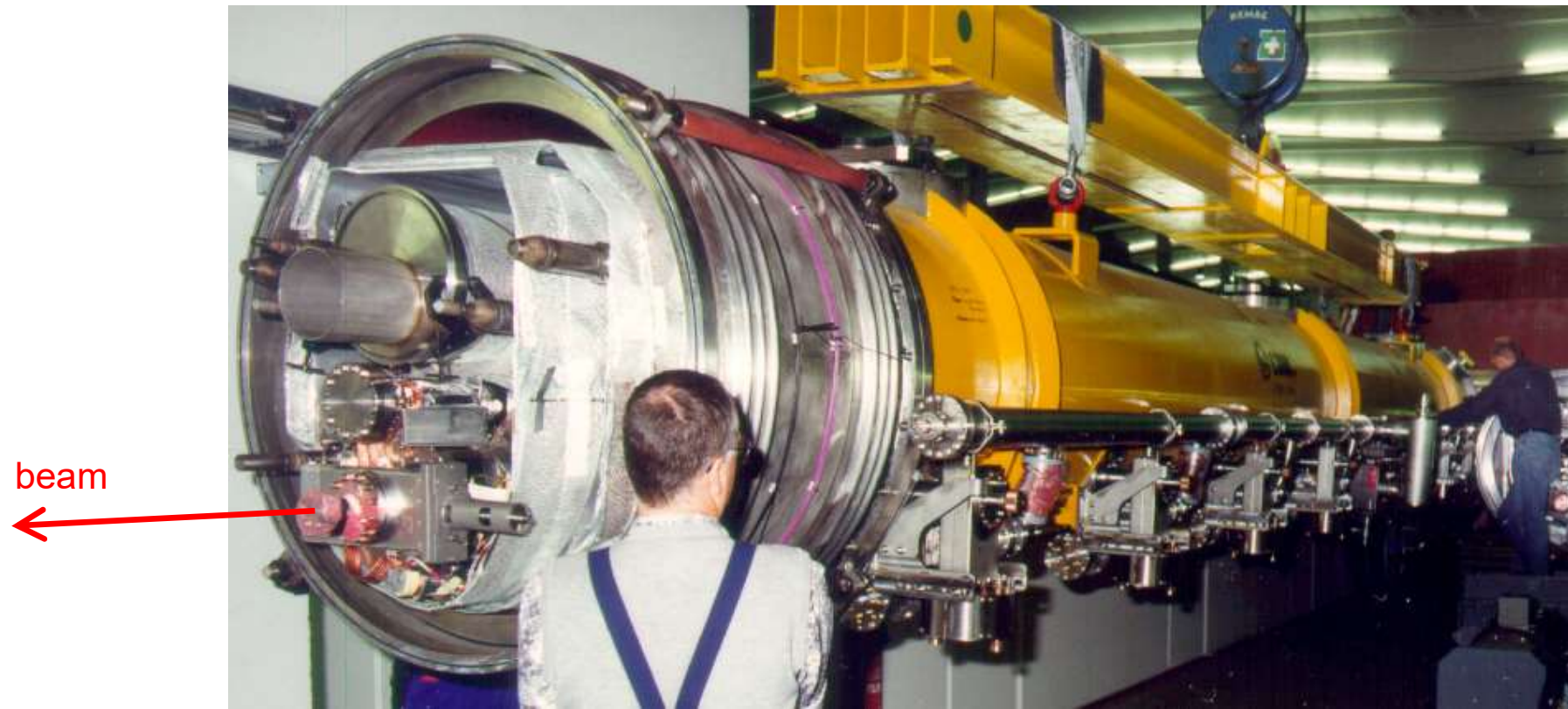




Cavities inside a cryostat

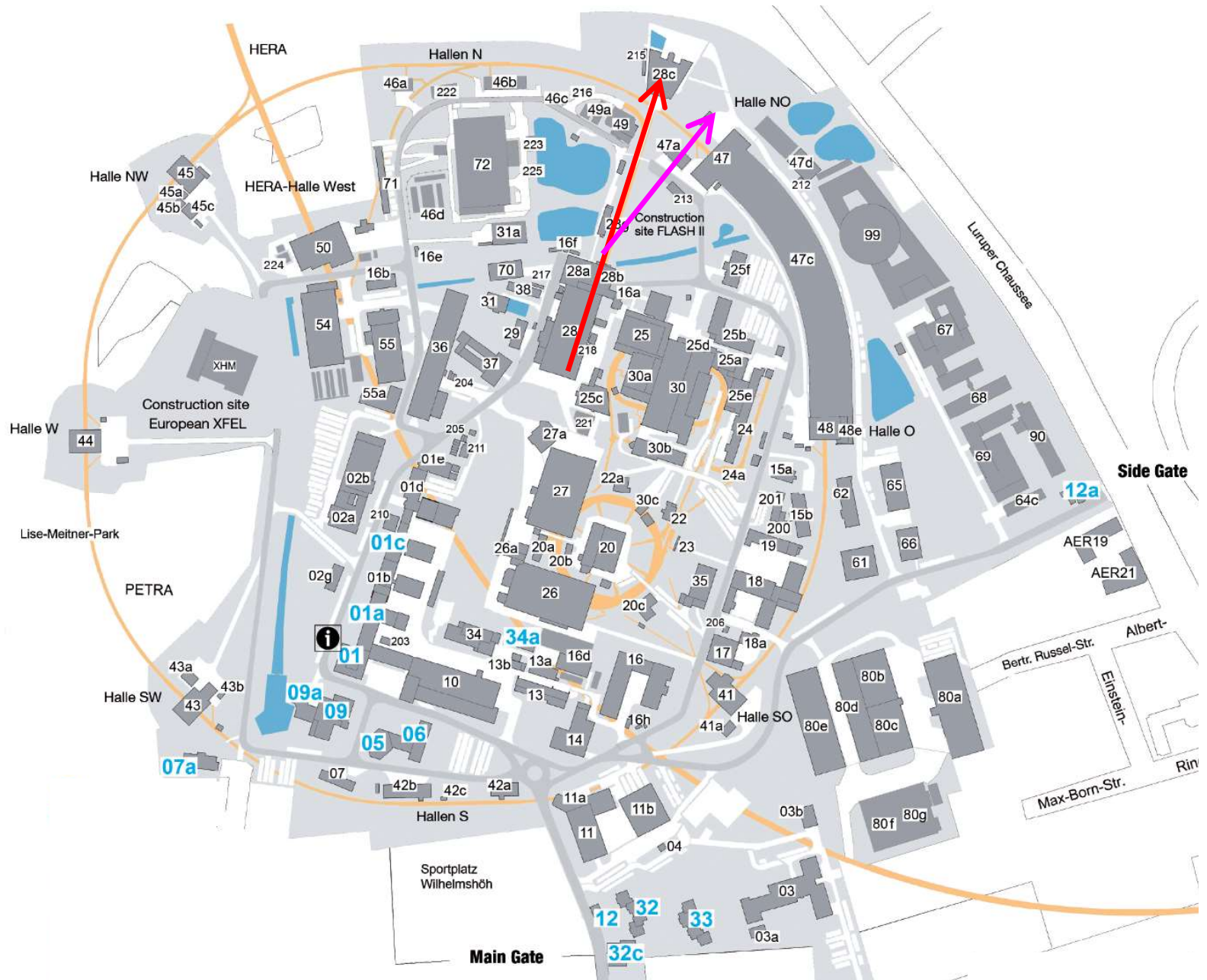


Cavities inside an accelerator module (cryostat)

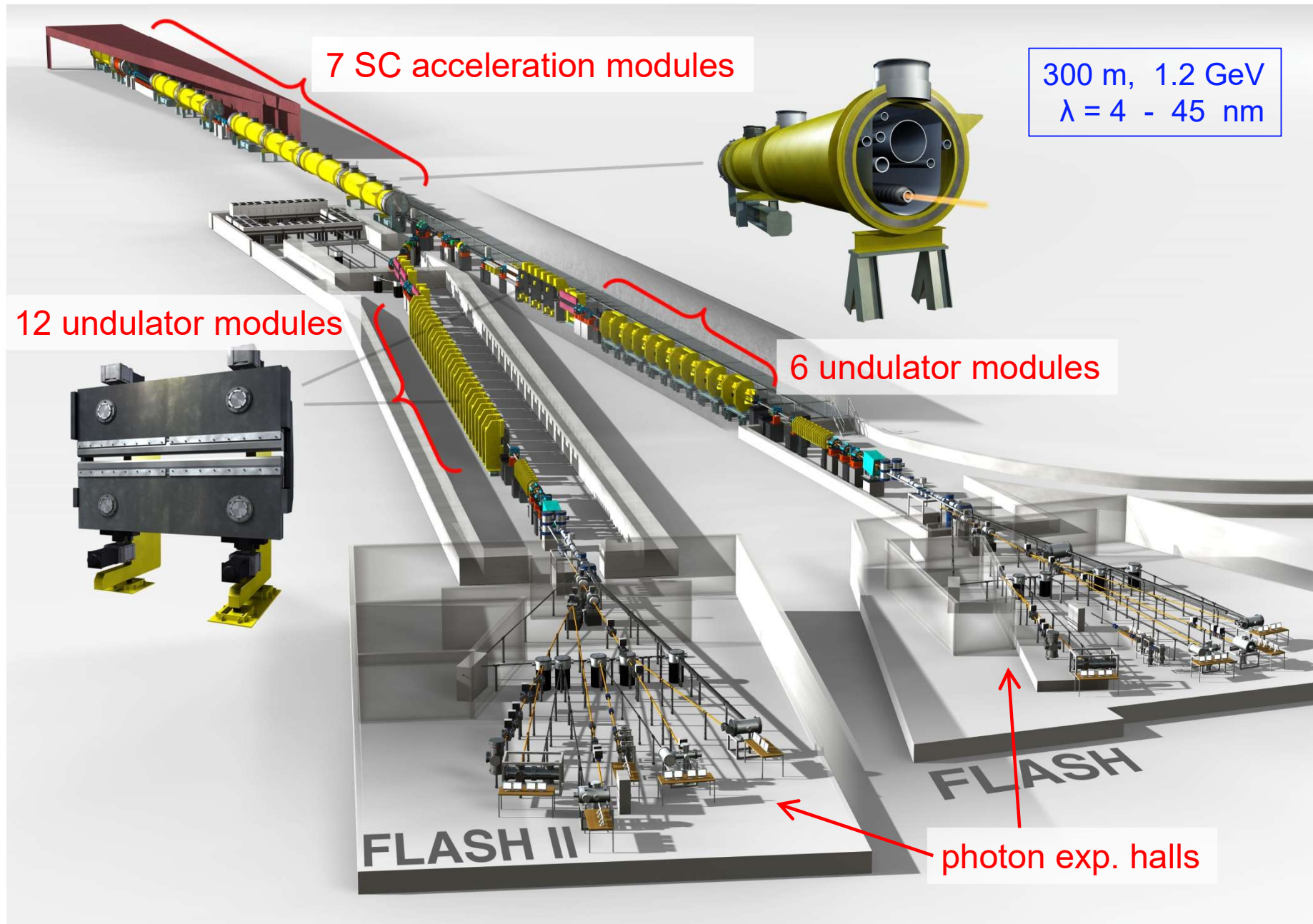


module installation in FLASH (2004)

Free-electron LASer in Hamburg (FLASH)



Free-electron LASer in Hamburg (FLASH)

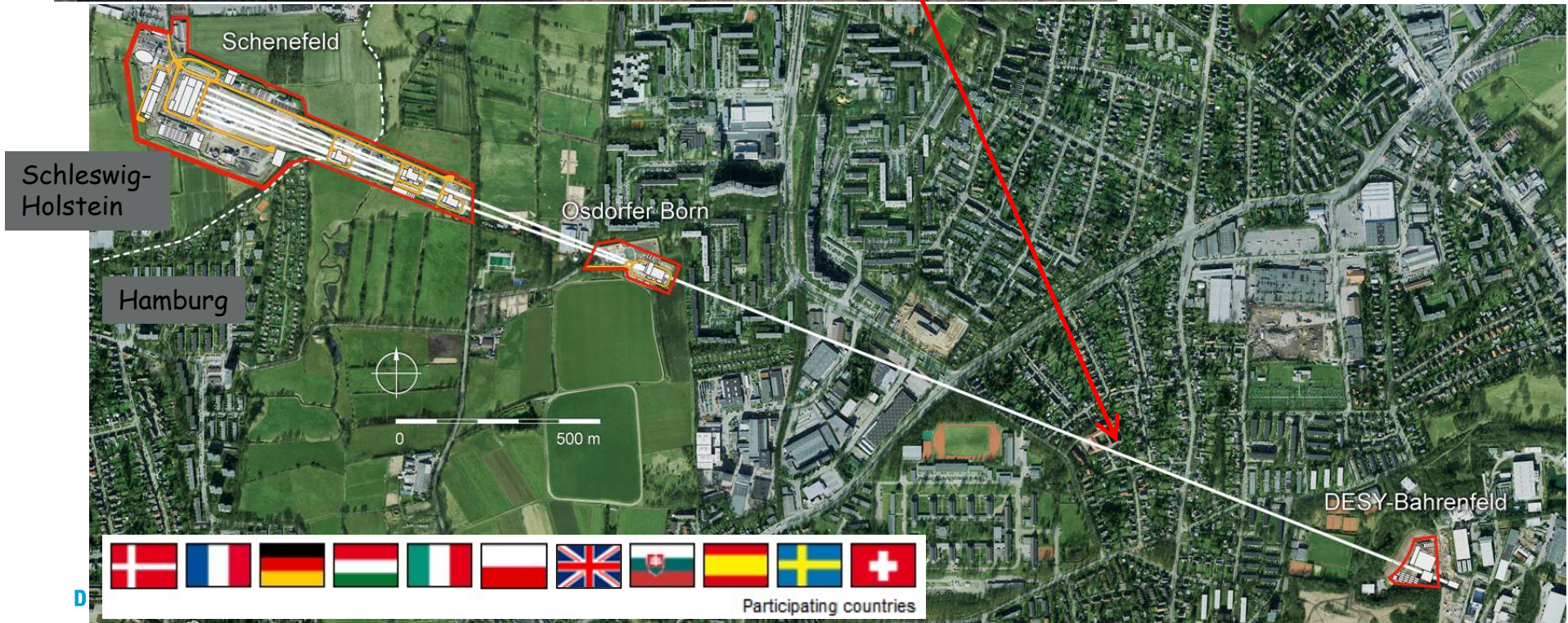
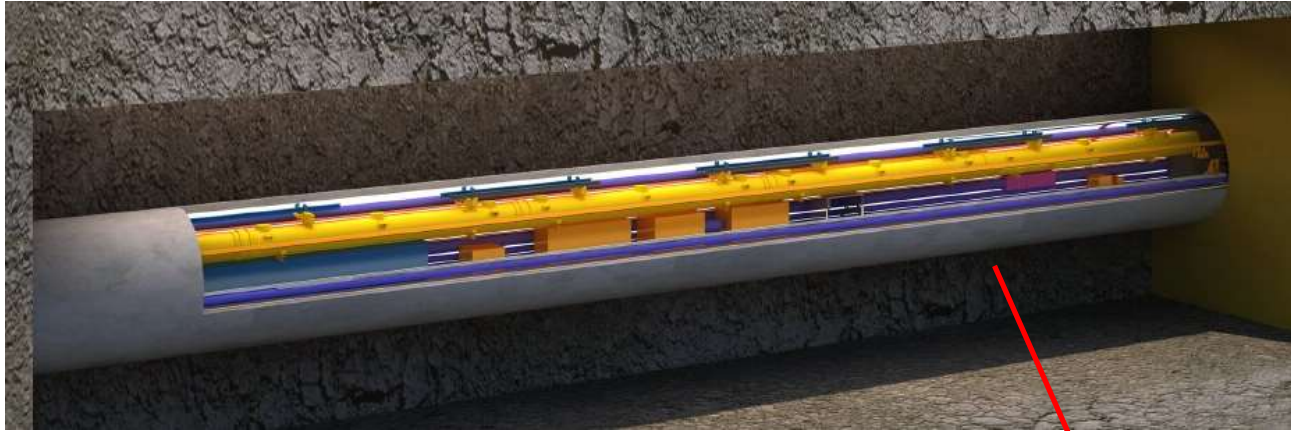


100 accelerator modules (cryostats) in XFEL

European X-ray Free-Electron Laser (XFEL)

(3 km, 17.5 GeV)

$\lambda = 0.05 - 6 \text{ nm}$



Superconducting cavities at HERA

16 cavities
500 MHz



Superconducting Particle Accelerator

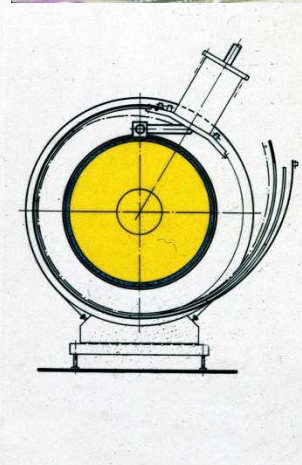
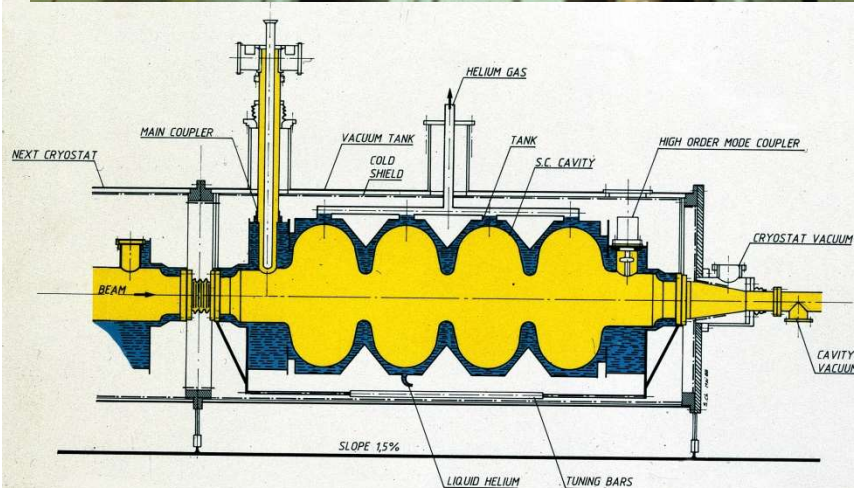
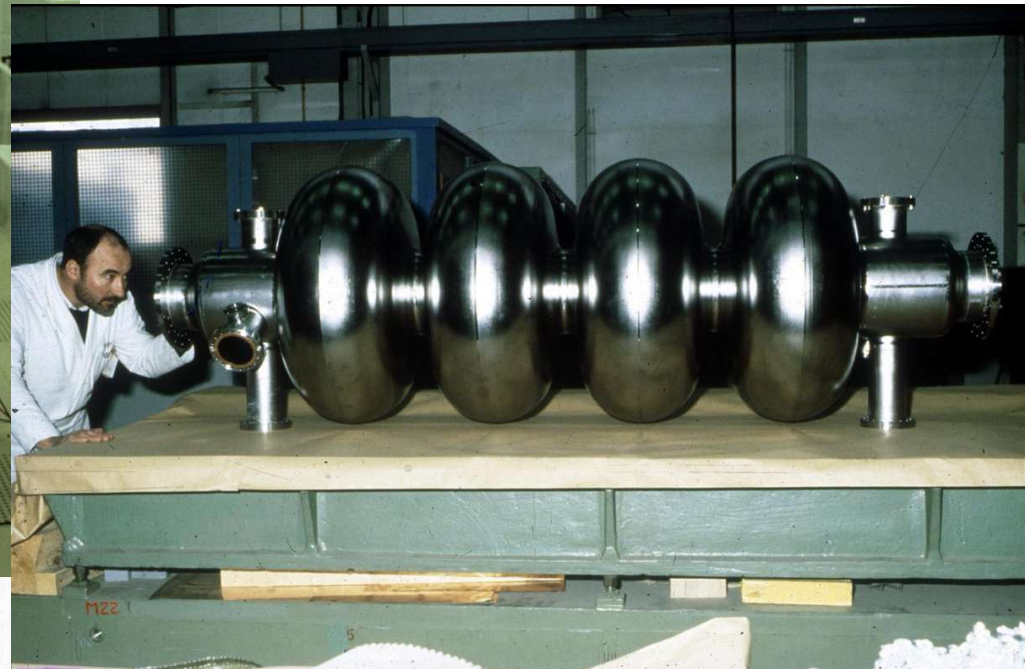
From 1992 to 2007, eight of these superconducting accelerator components were used in the 6.3-kilometre long storage ring HERA to accelerate electrons and their antiparticles, positrons.

Two four-cell cavities are arranged in one thermal vessel (cryostat). The cavities are made of the metal niobium which becomes superconducting at a temperature of minus 269 degrees Celsius. At this temperature, particles are accelerated almost without electric resistance and thus very efficiently with a very high electric alternating voltage which is injected in the middle between the cavities. During HERA operation, this cavity reached an accelerating gradient of 5 million volts per metre.



Superconducting cavities at LEP

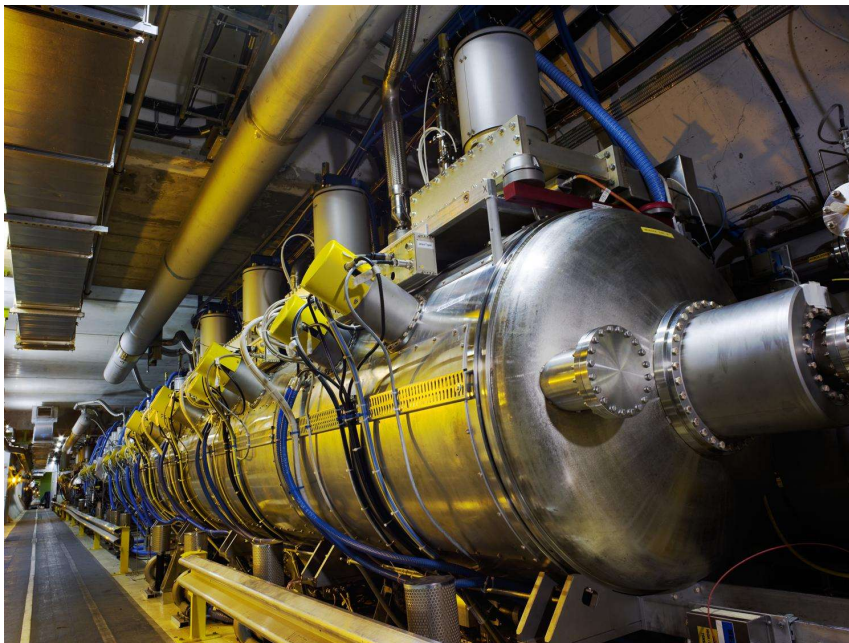
272 cavities
352 MHz



SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT

Superconducting cavities at LHC

16 cavities
400 MHz



Other accelerators using superconducting cavities

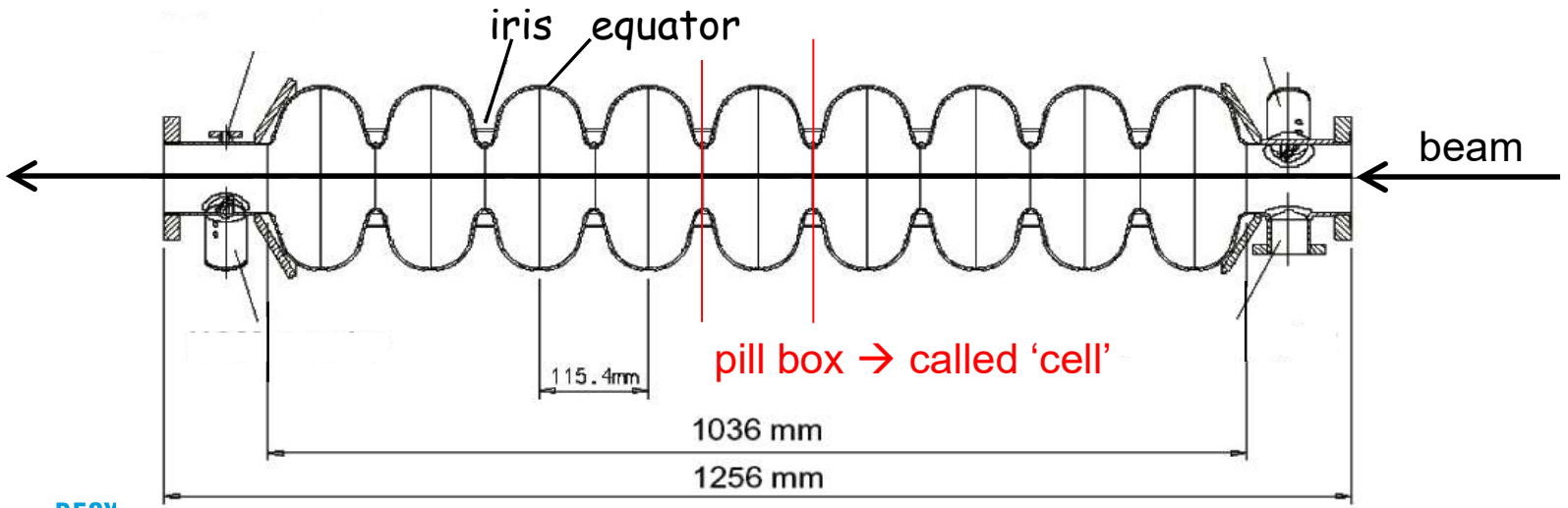
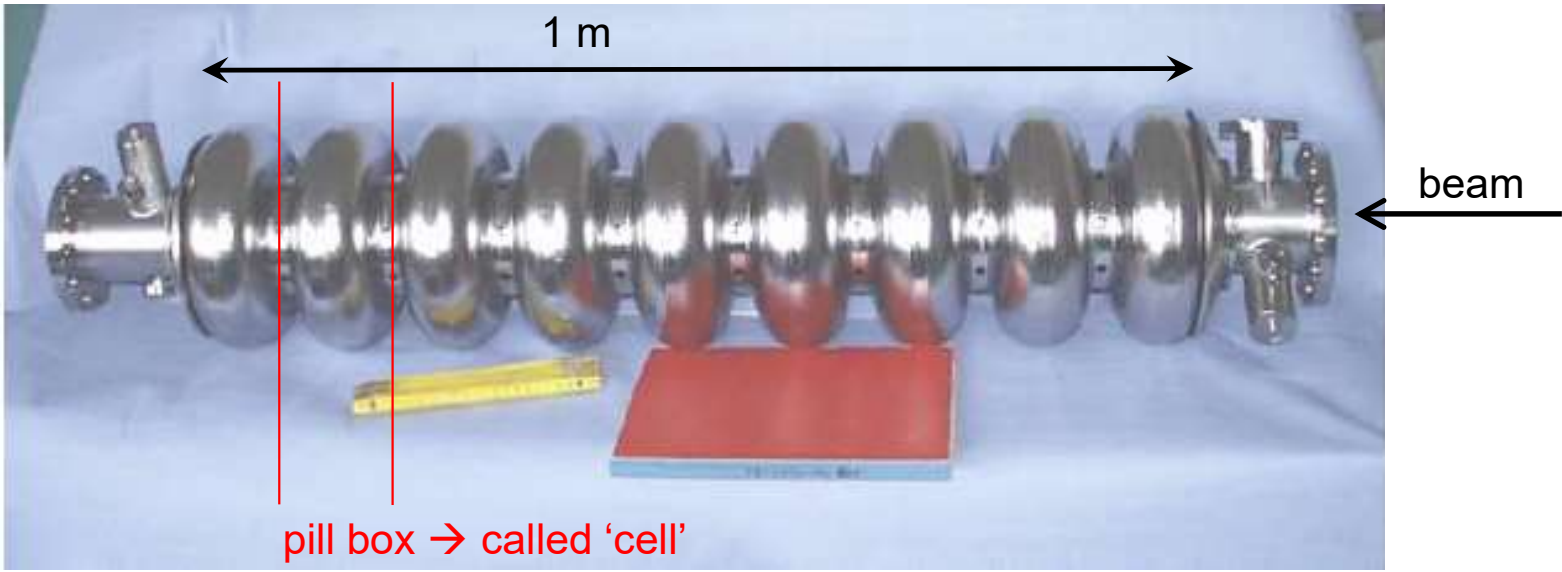
- 5 de-commissioned
- 11 in operation
- 4 in construction
- 10 in design phase

Total = 30

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)

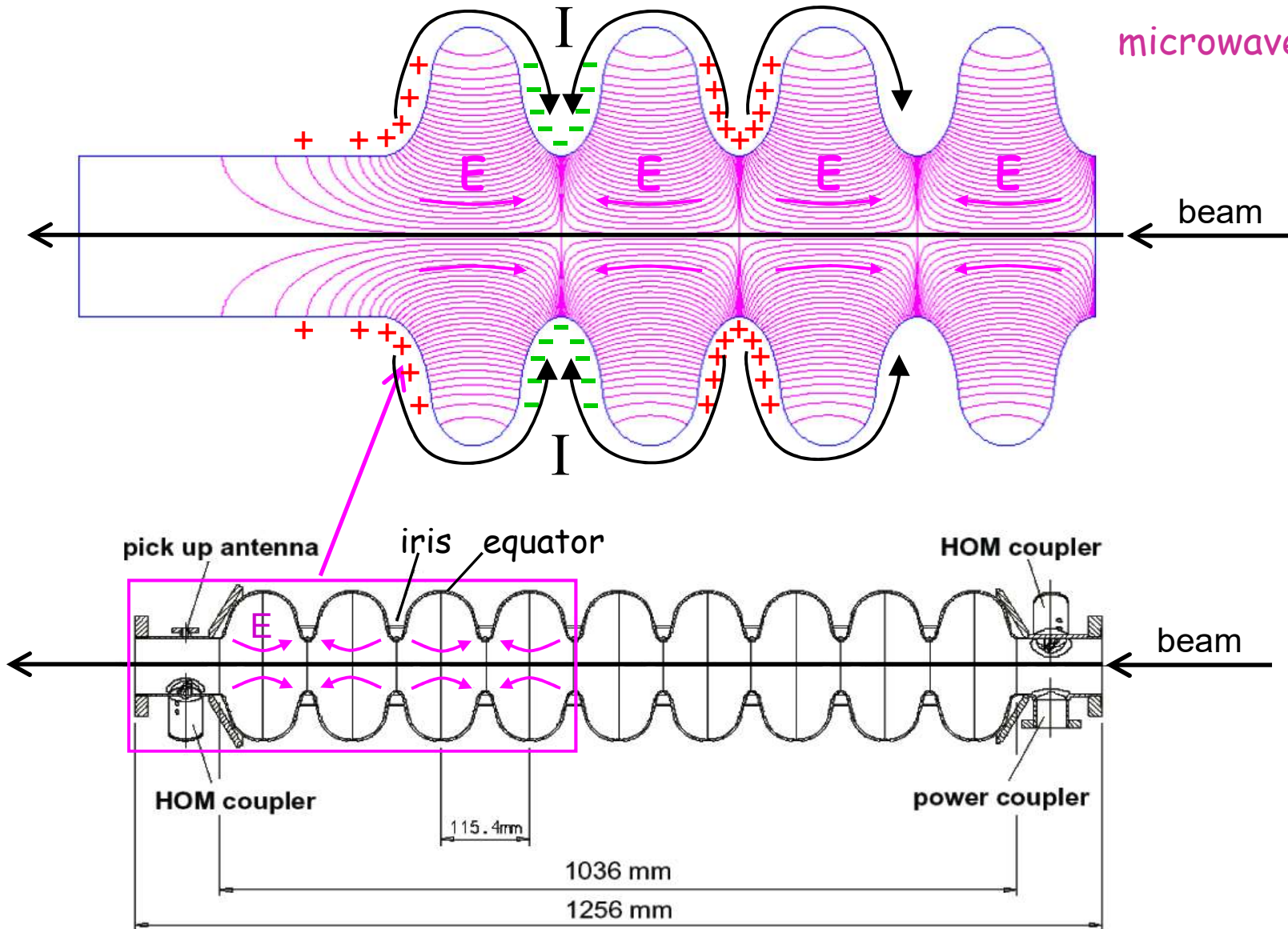


Accelerating field map

Simulation of the fundamental mode: electric field lines

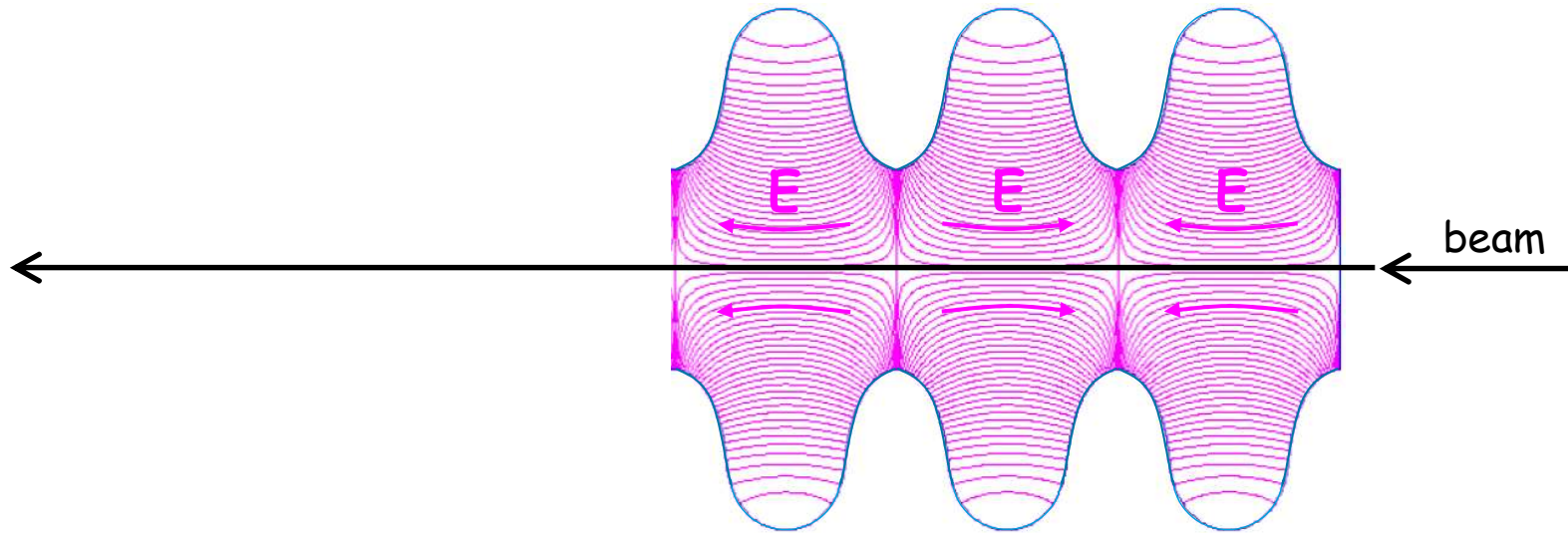
$f_{RF} = 1.3 \text{ GHz}$

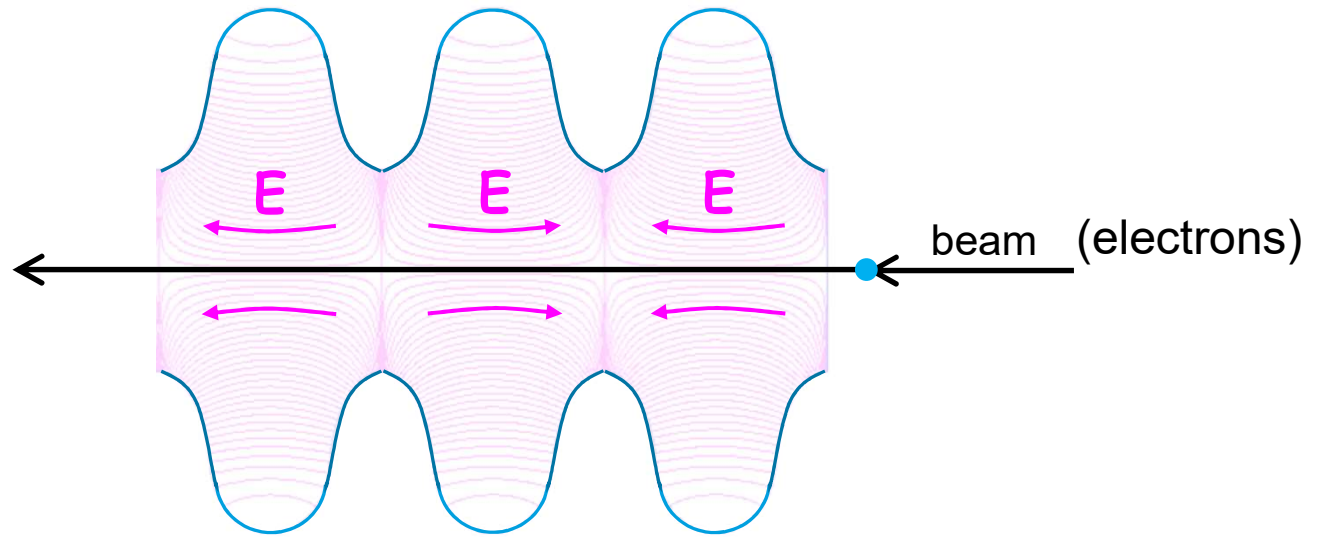
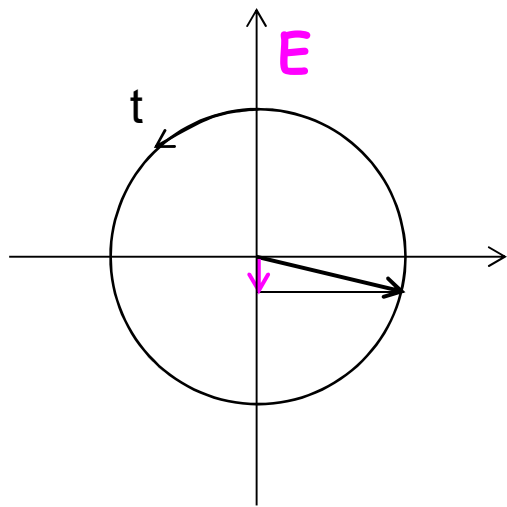
microwaves: (L-band)

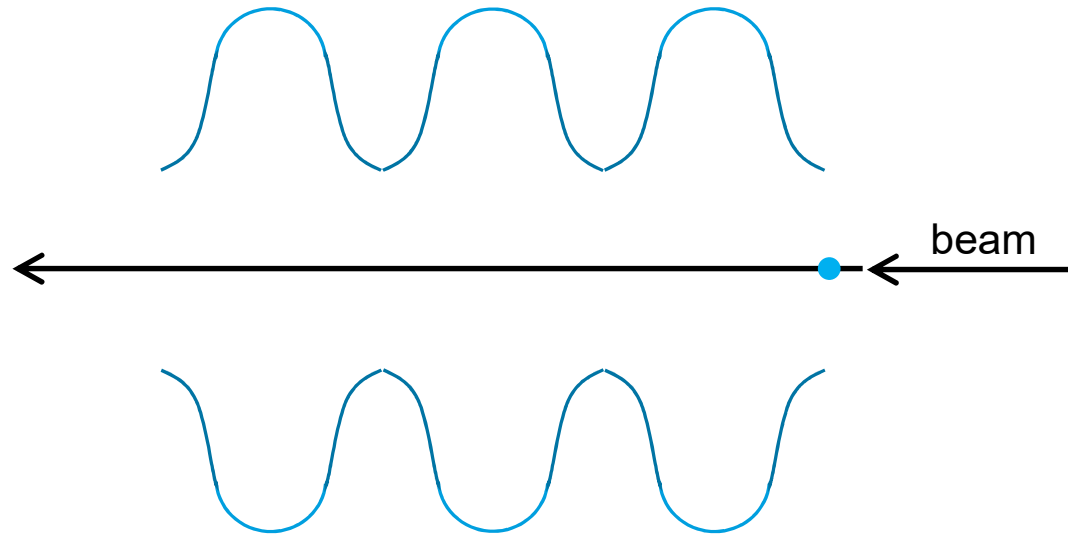
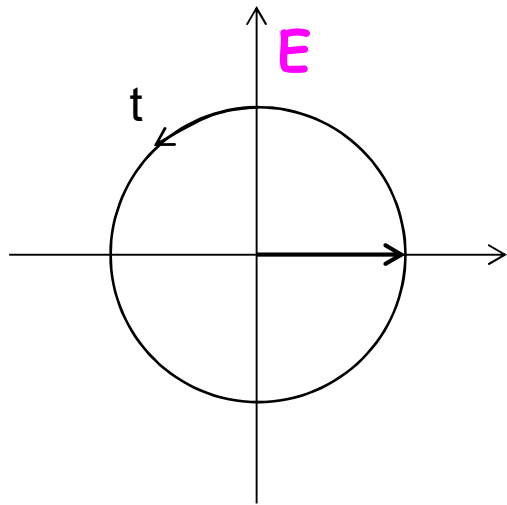


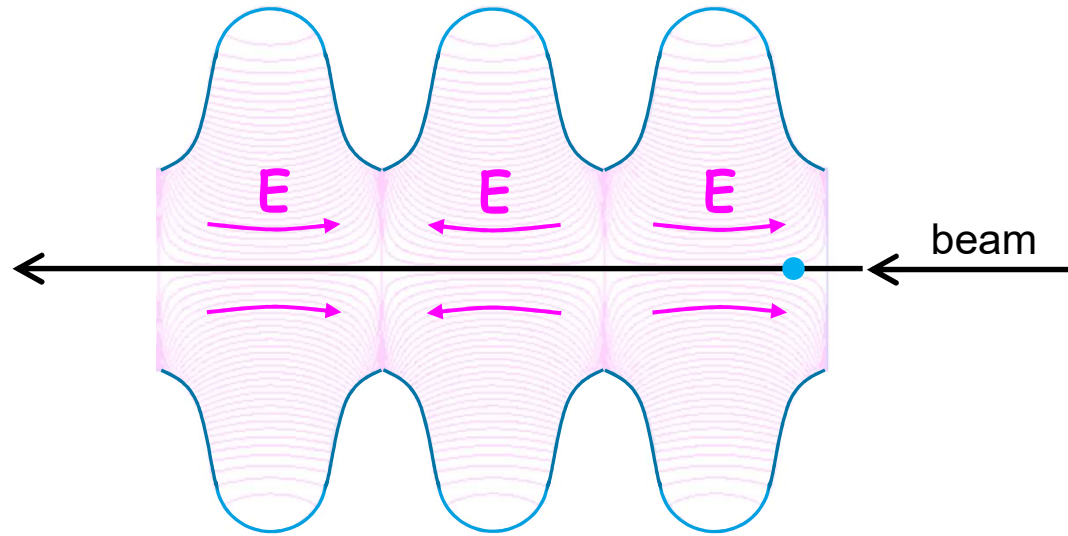
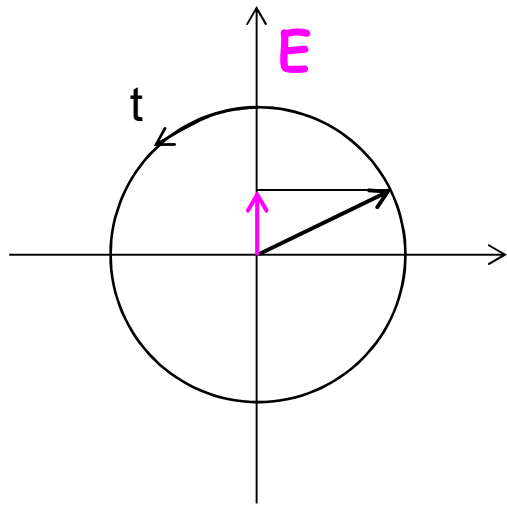
Is there a net acceleration?

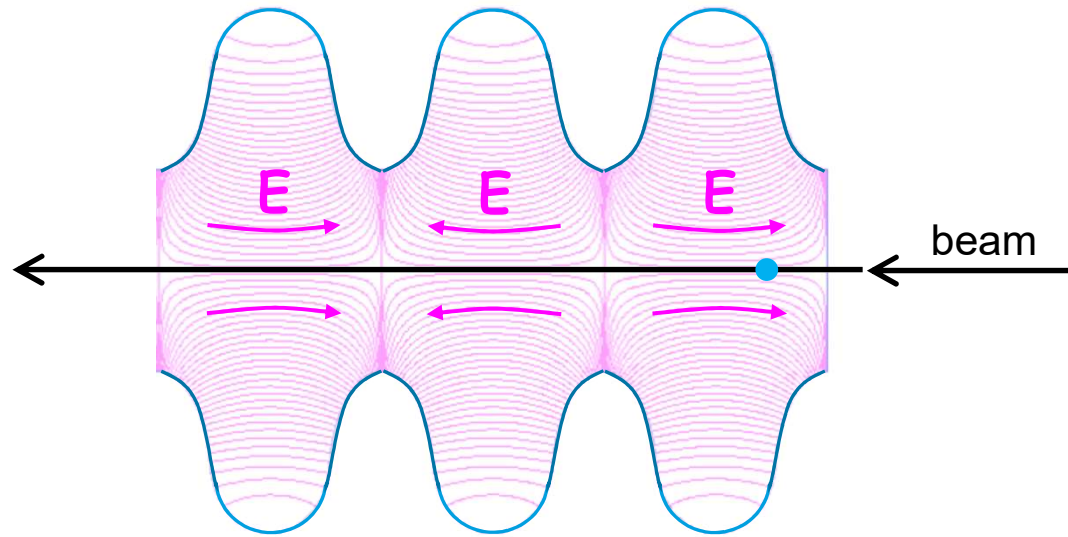
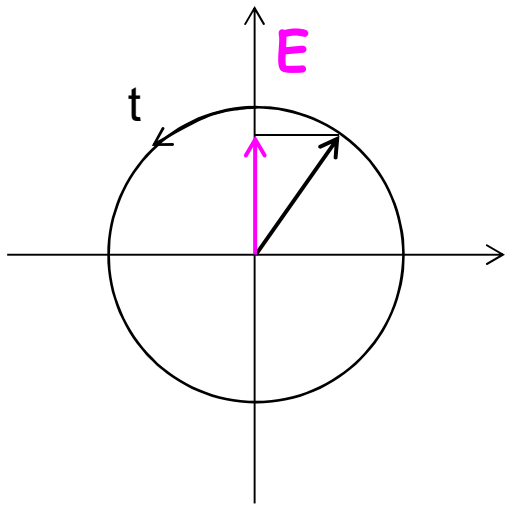
Simulation of the fundamental mode: electric field lines

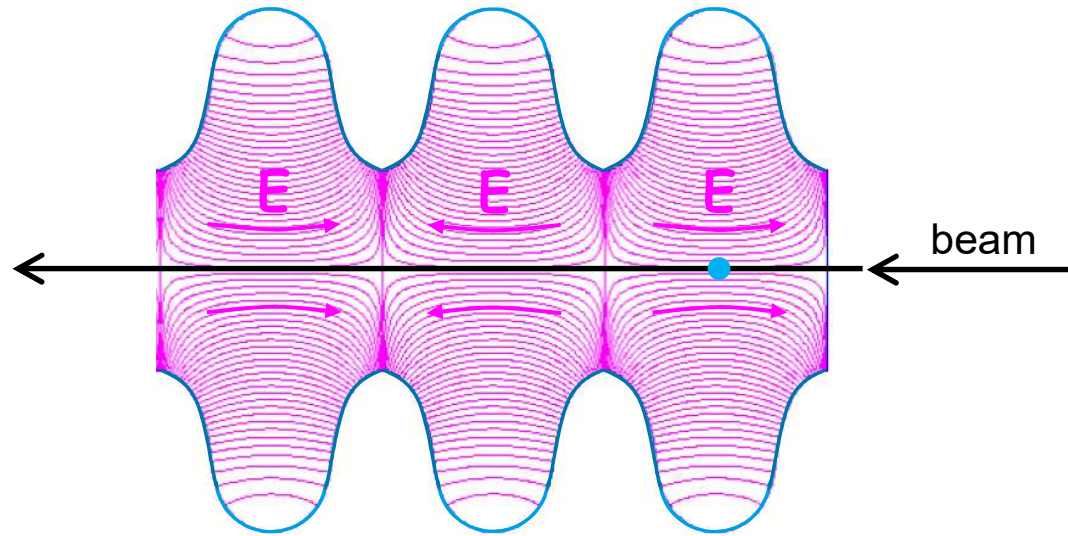
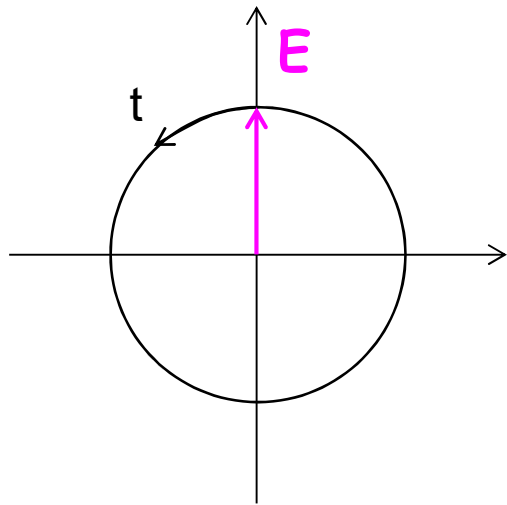


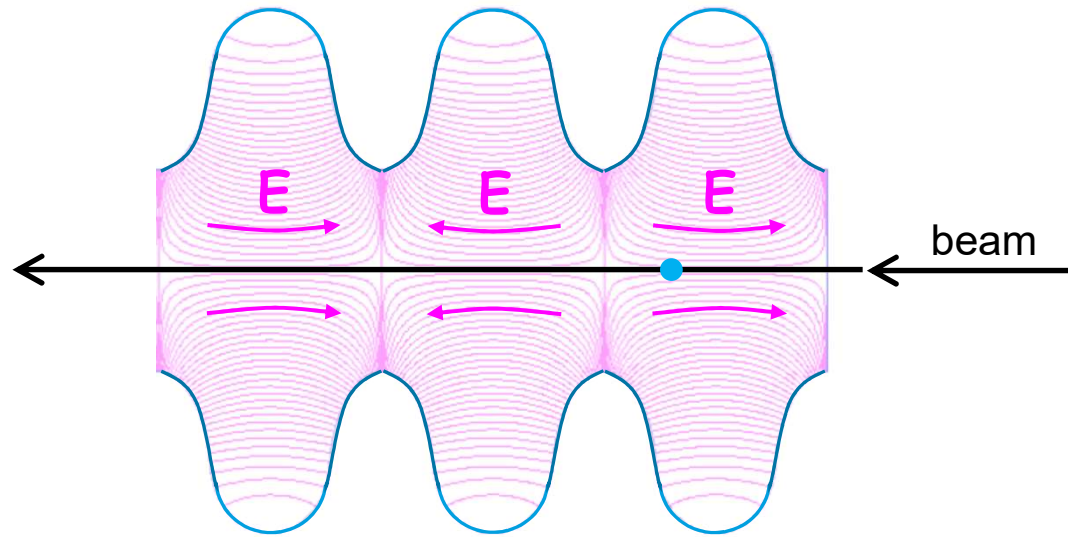
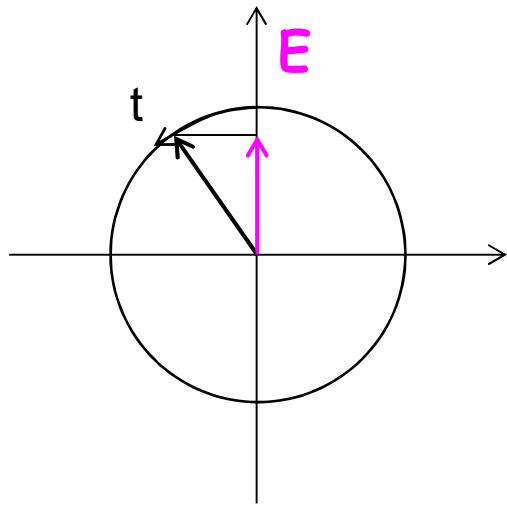


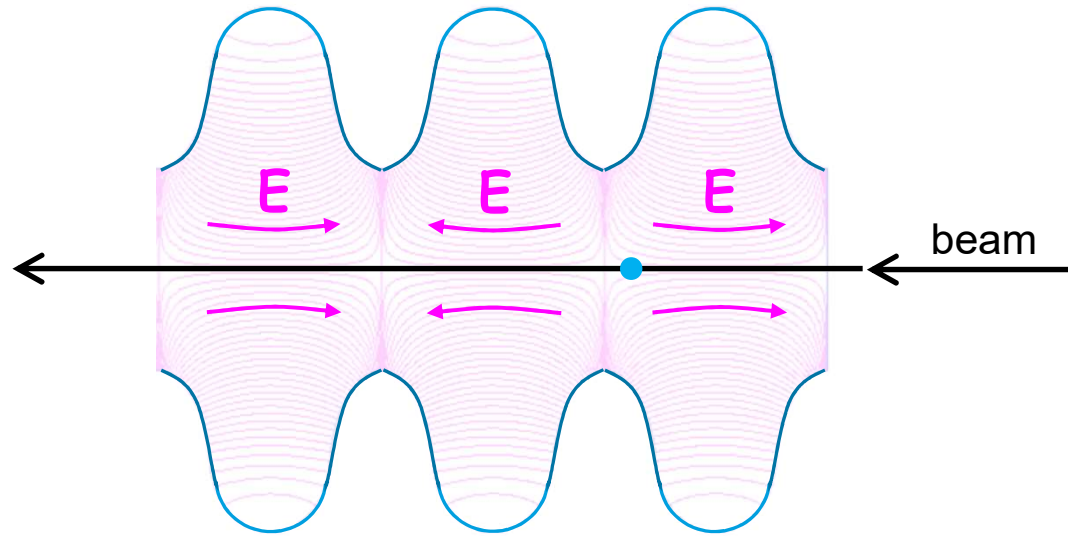
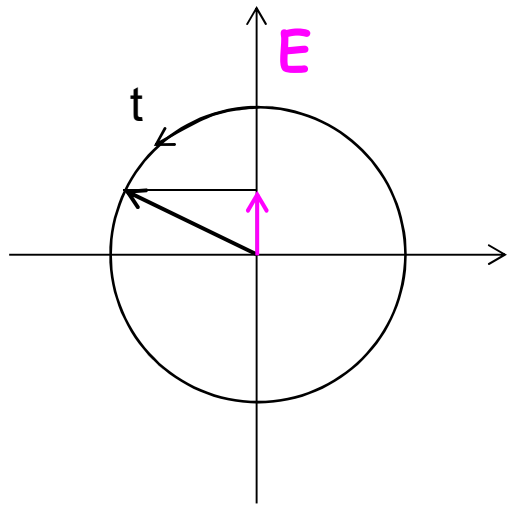


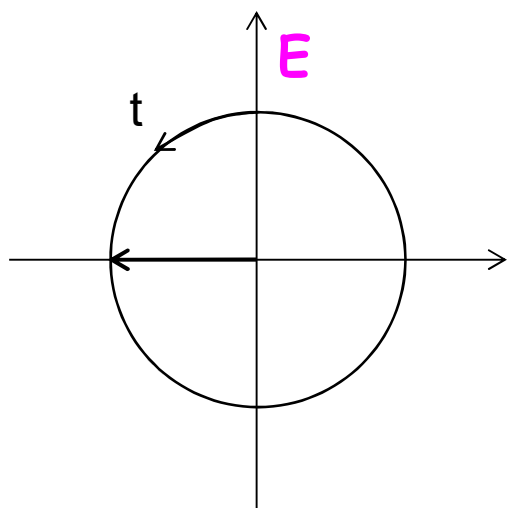
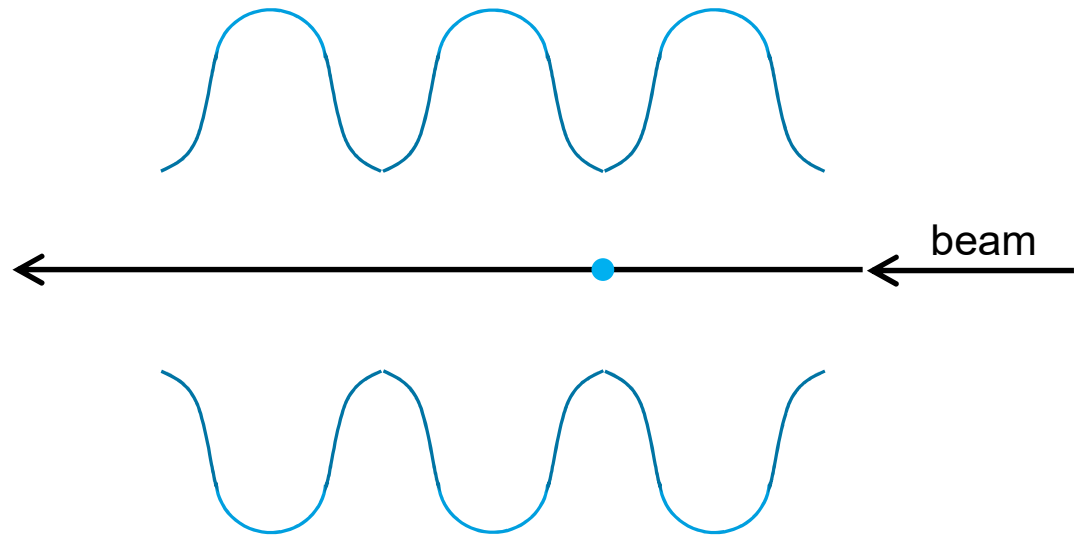


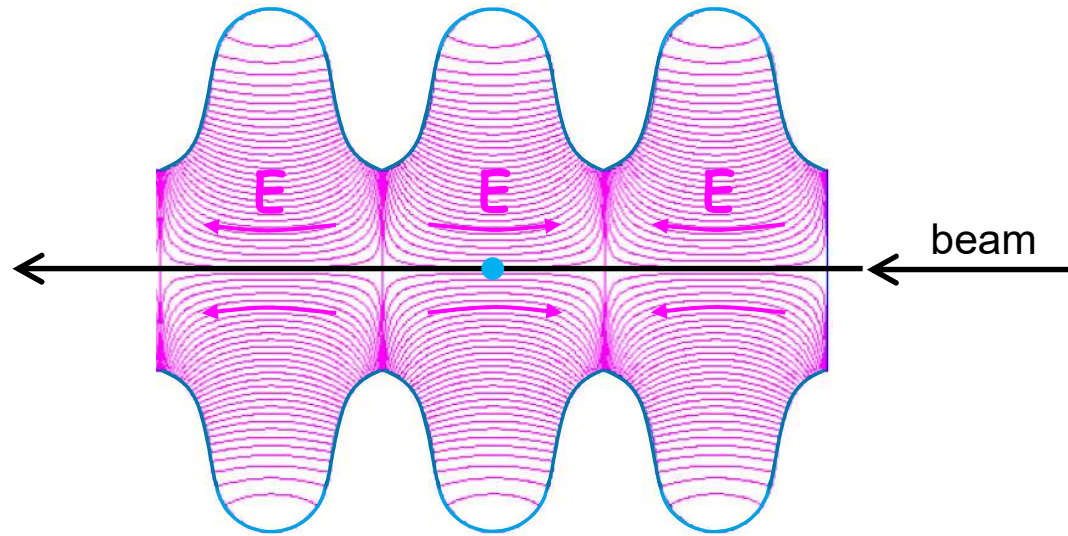
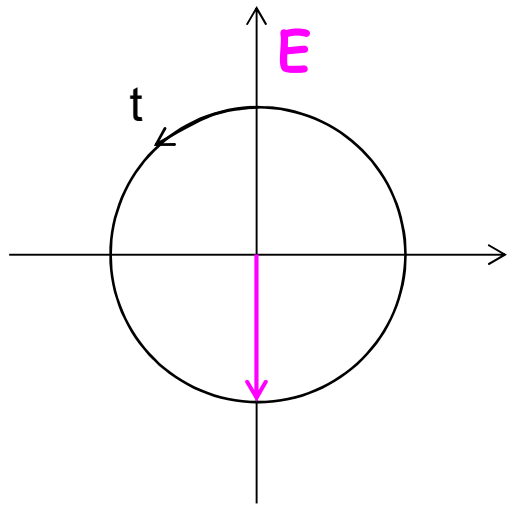


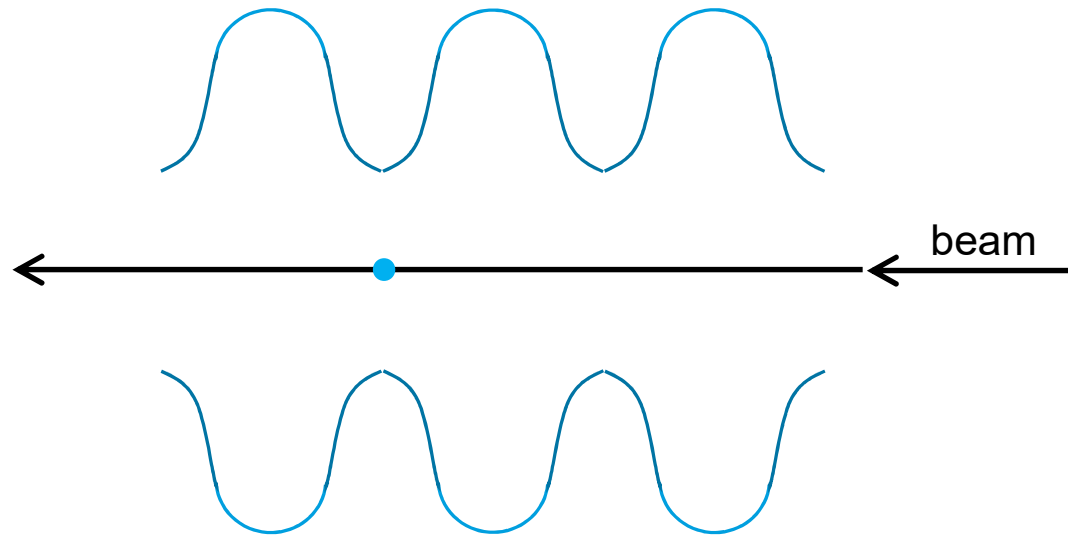
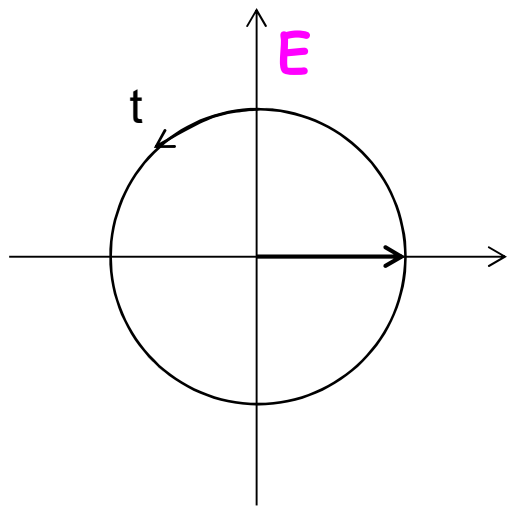


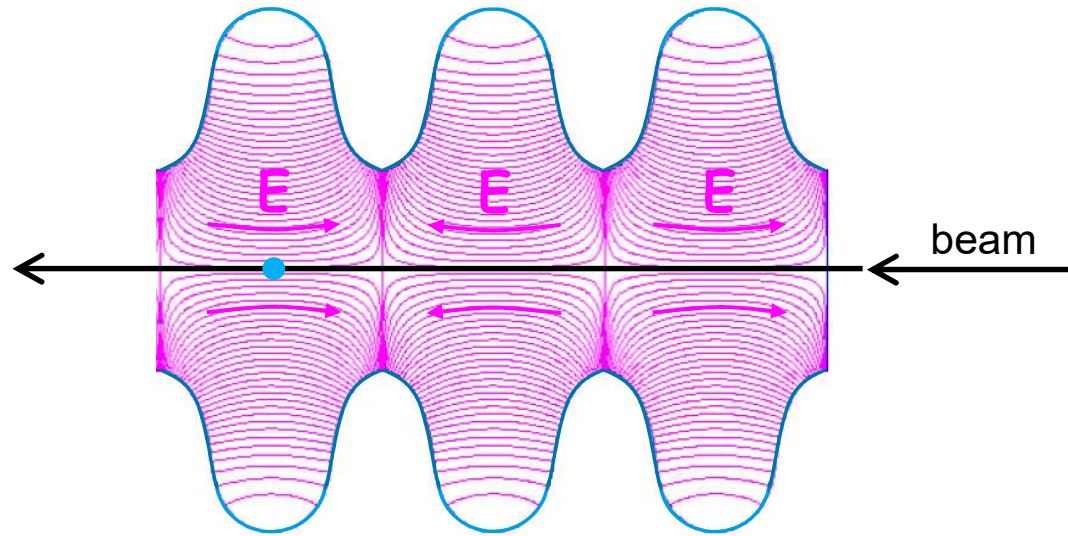
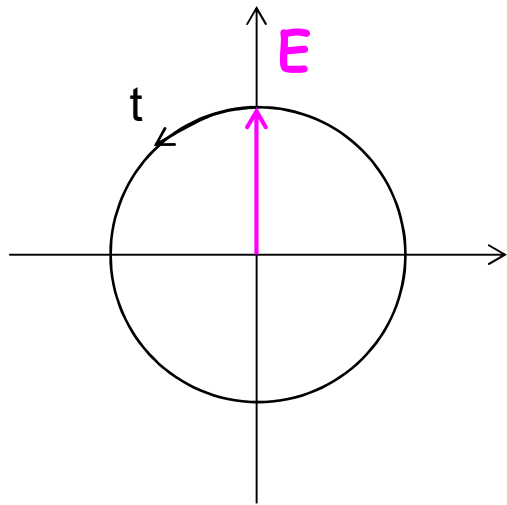


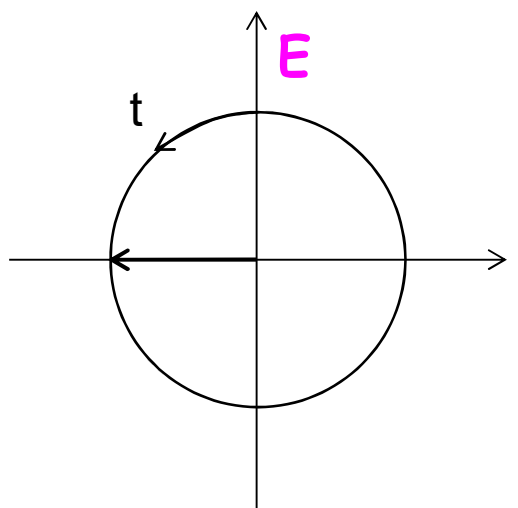
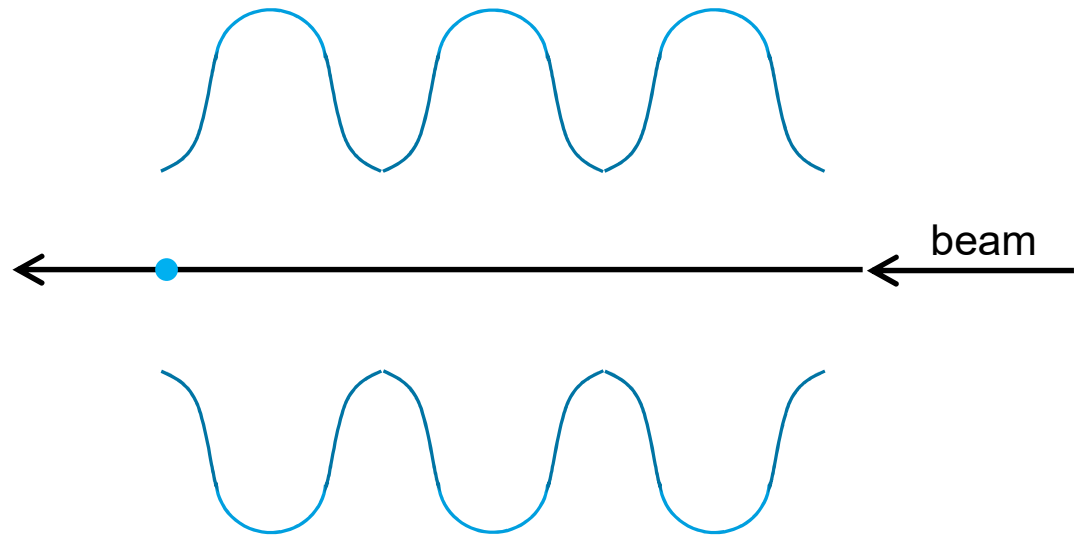








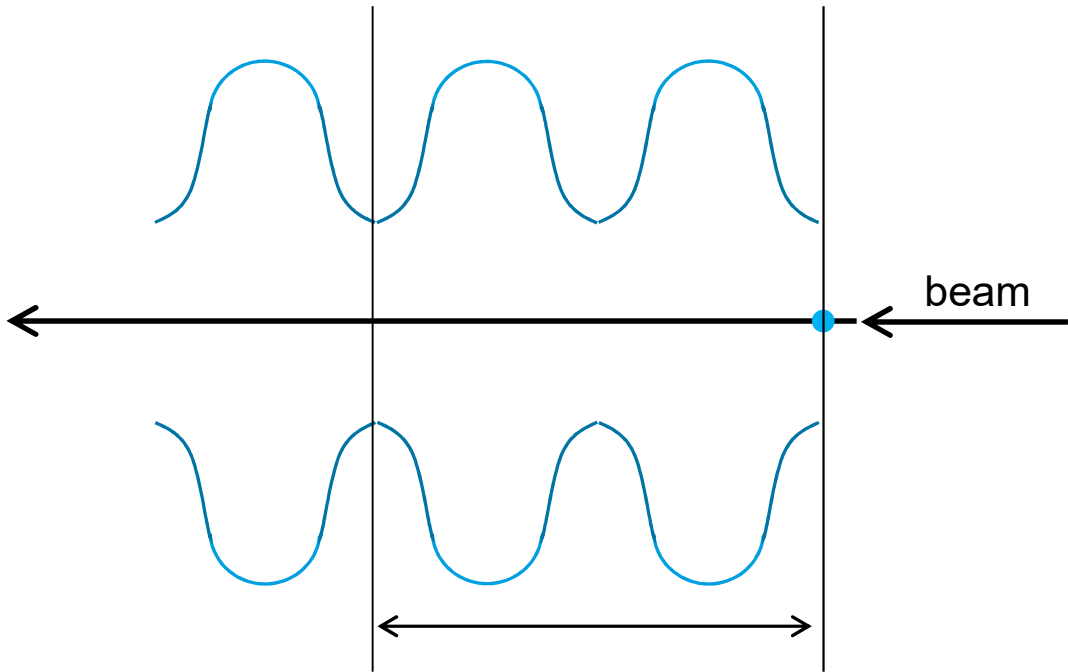




Is there a net acceleration? timing is the key

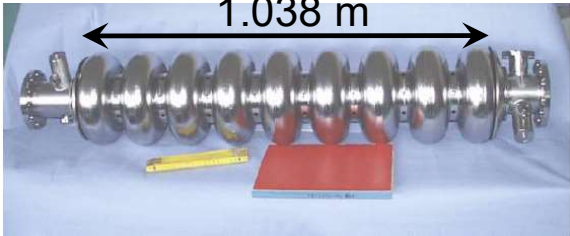
Is there a net acceleration? timing is the key

for electrons, $\beta \cong 1$



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

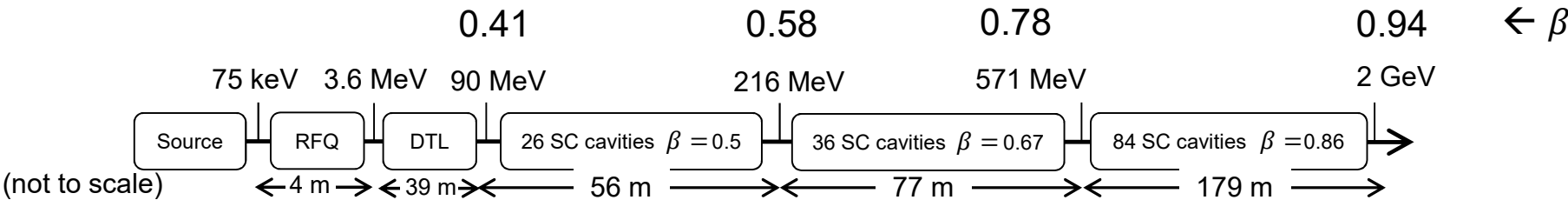
$$1 \text{ cavity } (1.038 \text{ m}) / 9 \text{ cells} = 0.115 \text{ m}$$



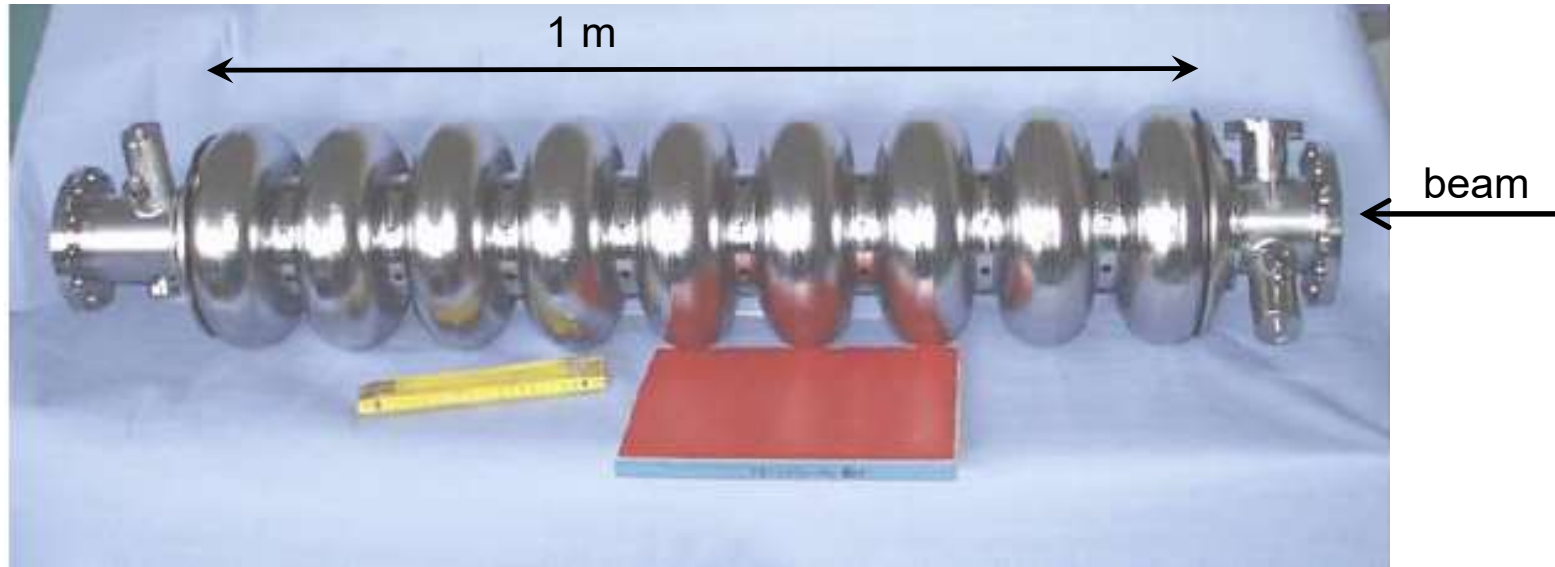
Is there a net acceleration? timing is the key

for protons, $\beta < 1$

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



Superconducting cavity used at DESY



Frequently Asked Questions

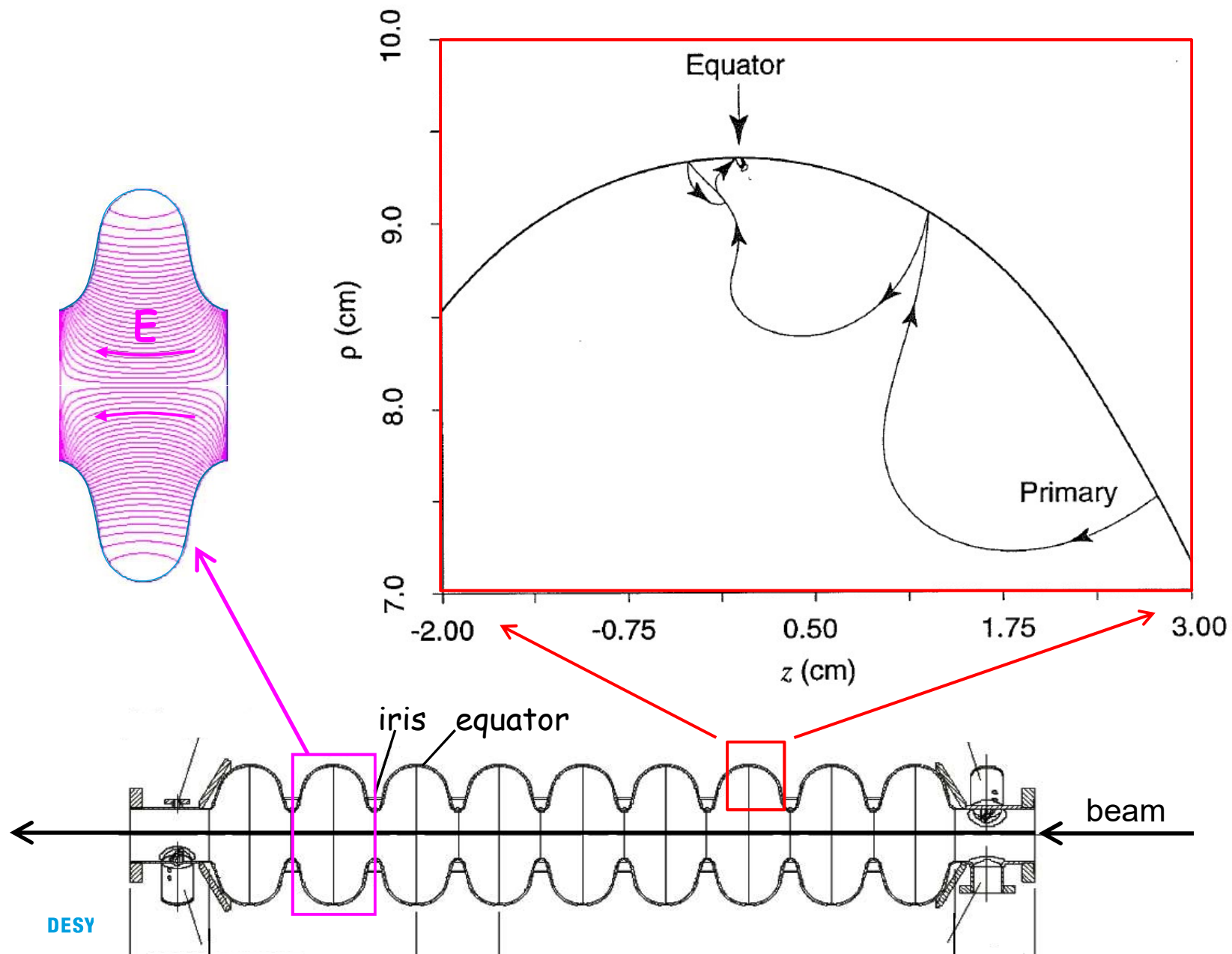
1) Why this shape?

2)

3)

4)

Multipacting mitigation in superconducting cavities



1) Why this shape? to reduce/avoid multipacting

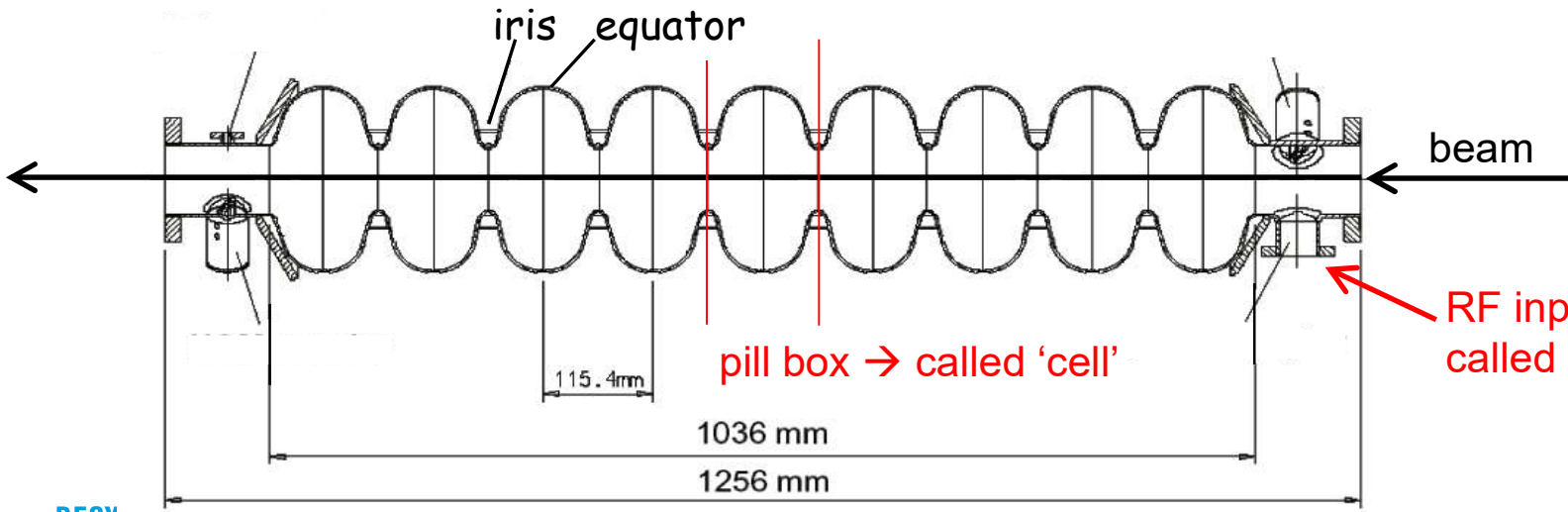
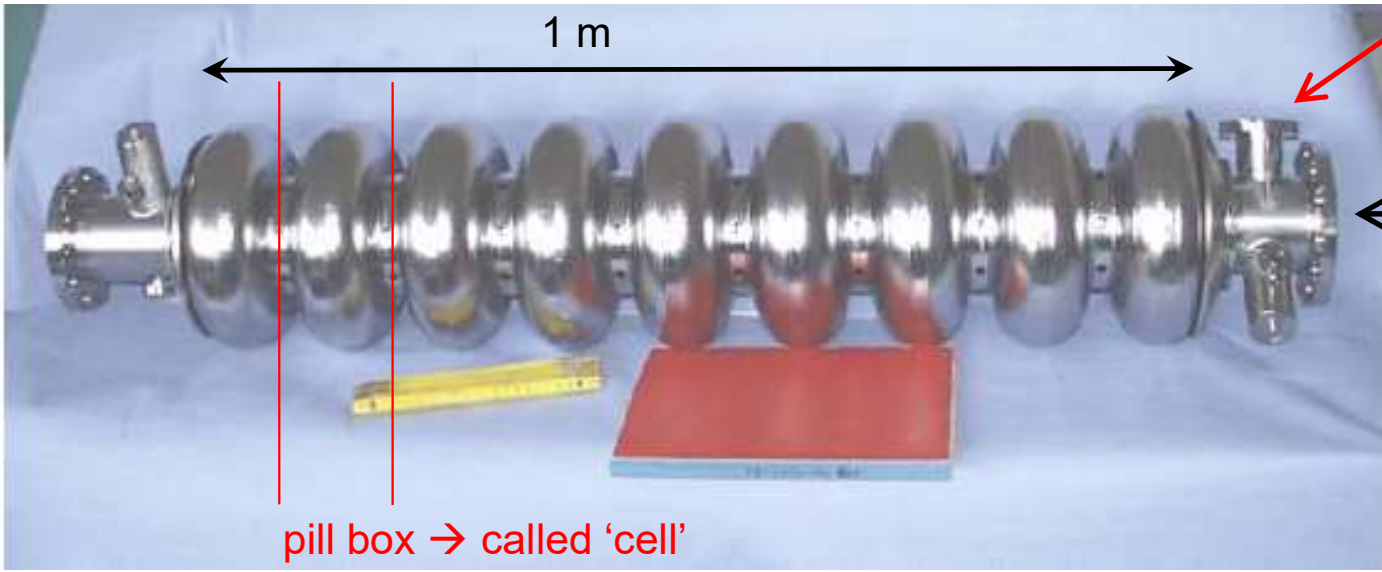
2) How to feed \vec{E} in?

3)

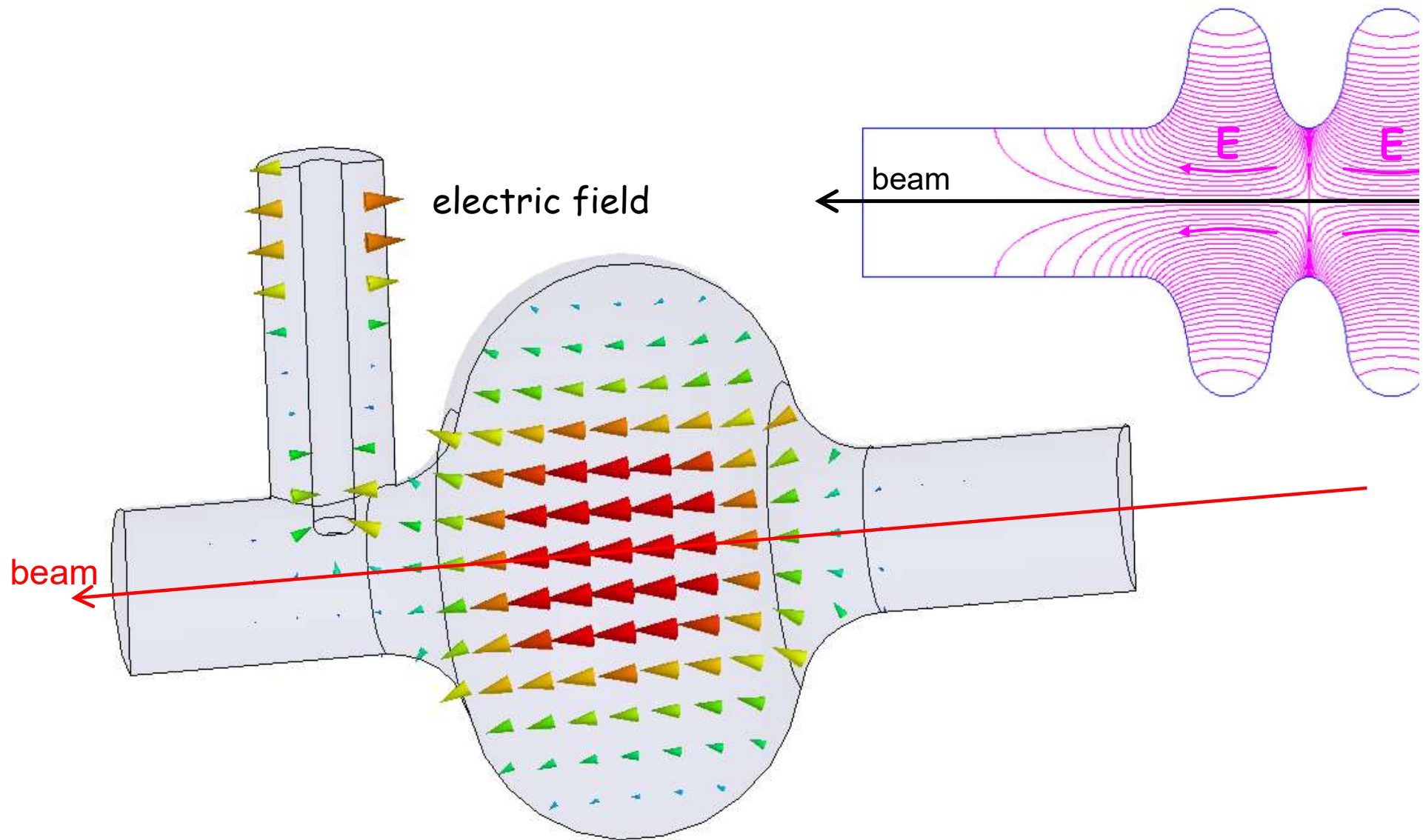
4)

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

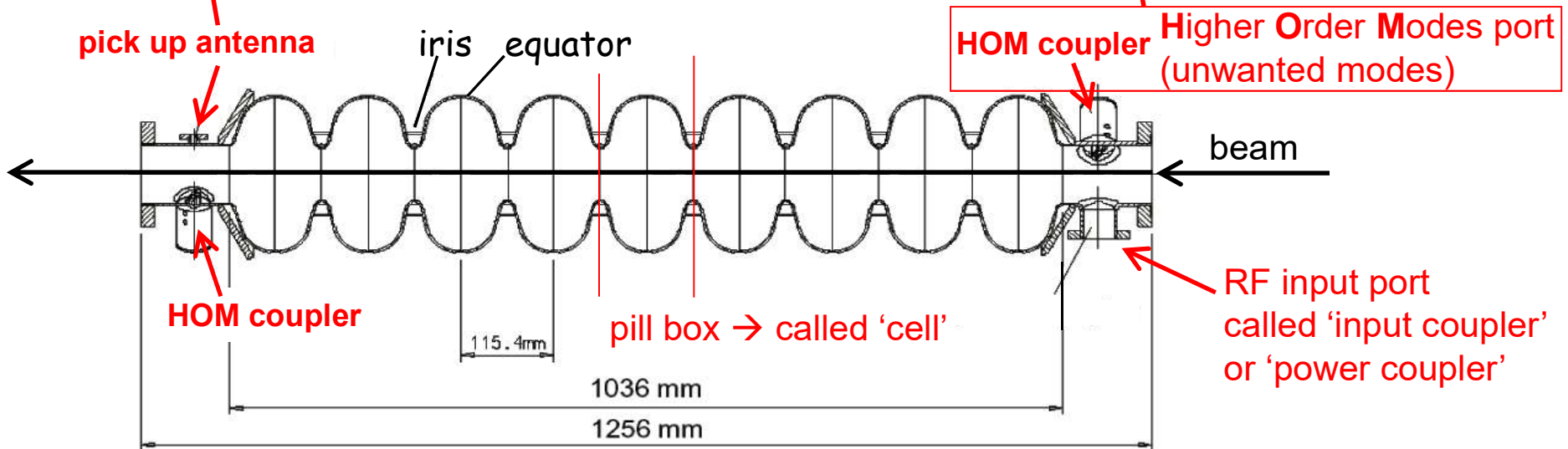
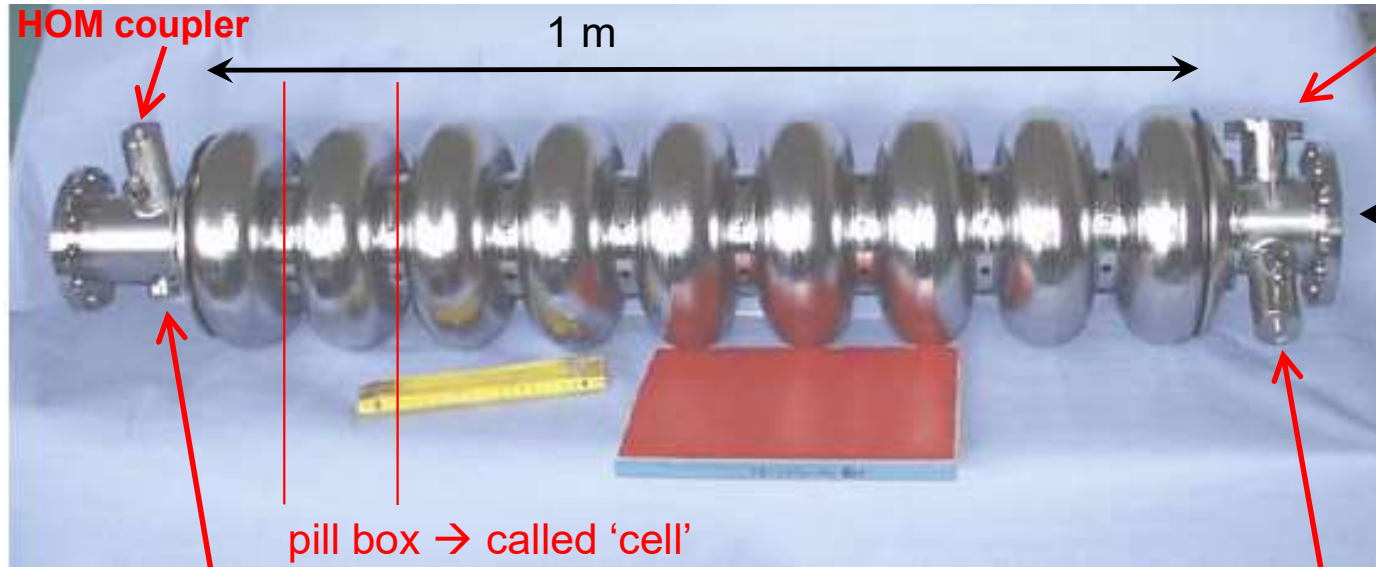
2) How to feed \vec{E} in? with input couplers

3) How to measure \vec{E} ?

4)

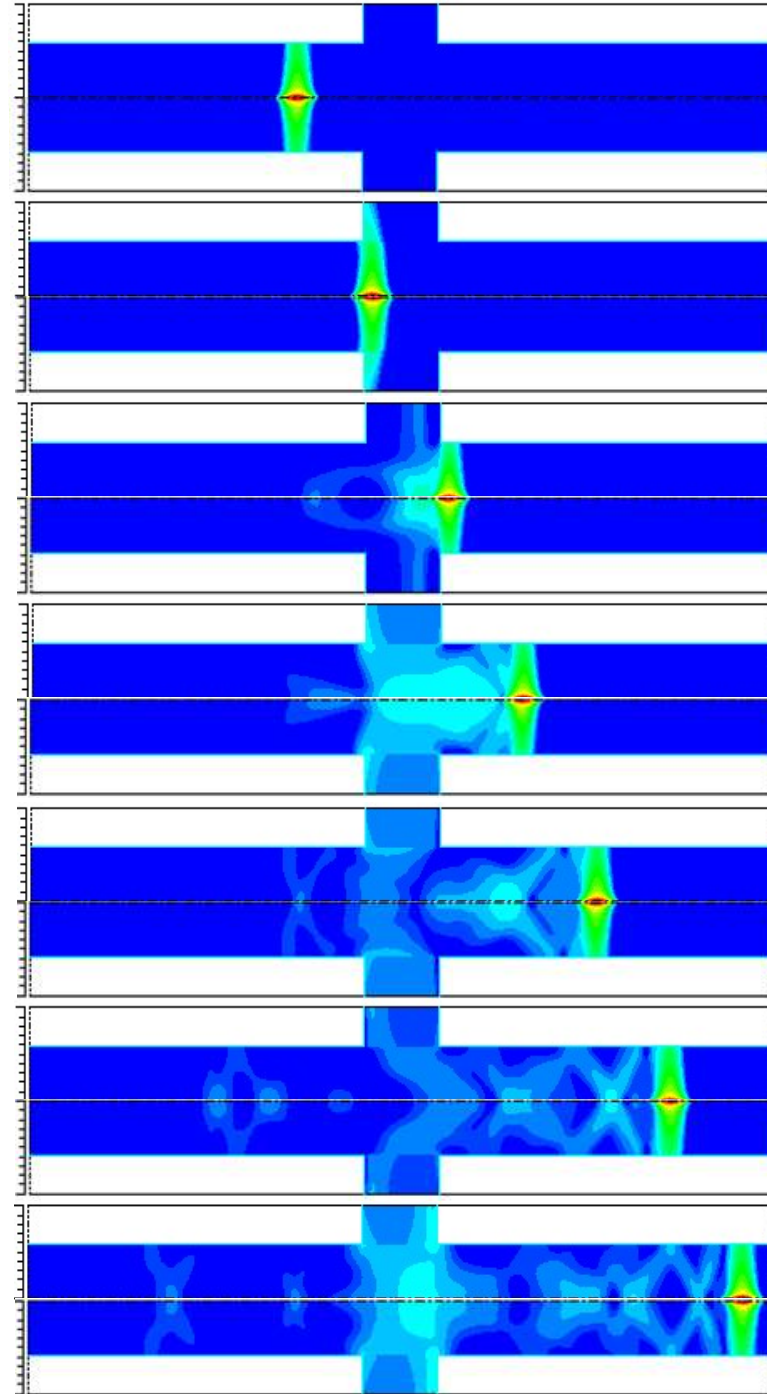
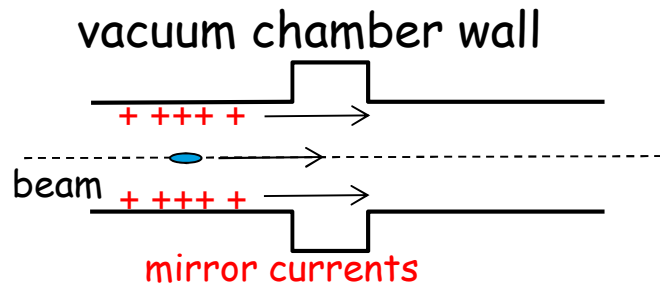
Superconducting cavity used in FLASH and in XFEL

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:

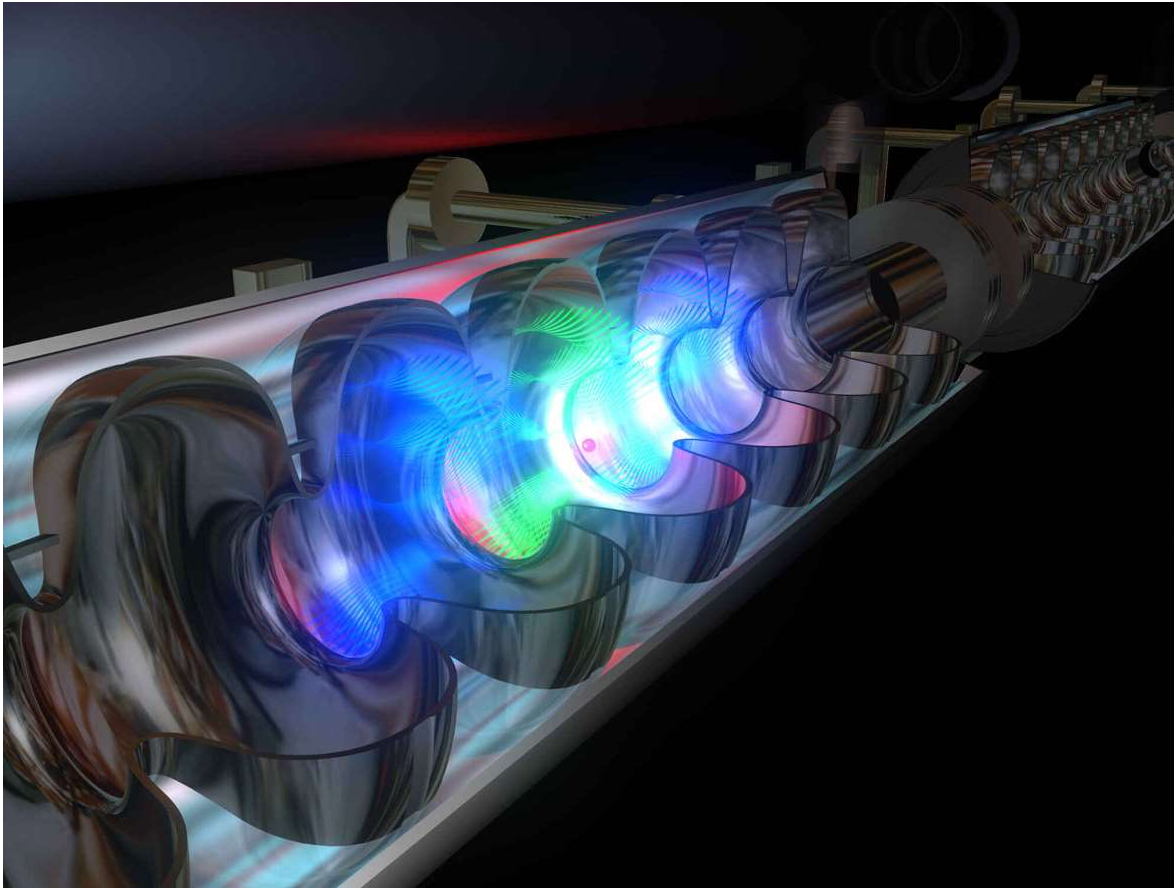
basic cavity:
pill box

{ 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

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MPY

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