RF Cavity Design

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Overview

- DC versus RF
  - Basic equations: Lorentz & Maxwell, RF breakdown
- Some theory: from waveguide to pillbox
  - rectangular waveguide, waveguide dispersion, standing waves … waveguide resonators, round waveguides, Pillbox cavity
- Accelerating gap
  - Induction cell, ferrite cavity, drift tube linac, transit time factor
- Characterizing a cavity
  - resonance frequency, shunt impedance,
  - beam loading, loss factor, RF to beam efficiency,
  - transverse effects, Panofsky-Wenzel, higher order modes, PS 80 MHz cavity (magnetic coupling)
- More examples of cavities
  - PEP II, LEP cavities, PS 40 MHz cavity (electric coupling),
- RF Power sources
- Many gaps
  - Why?
  - Example: side coupled linac, LIBO
- Travelling wave structures
  - Brillouin diagram, iris loaded structure, waveguide coupling
- Superconducting Accelerators
- RFQ's

DC versus RF

DC accelerator

RF accelerator

Lorentz force

A charged particle moving with velocity $\vec{v}$ through an electro-magnetic field experiences a force

$$\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) \qquad \vec{v} = \frac{\vec{p}}{m\gamma}$$

The energy of the particle is $W = \sqrt{\left(mc^2\right)^2 + \left(pc\right)^2} = \gamma mc^2$

$$W_{kin} = mc^2(\gamma - 1)$$

Change of W due to the this force (work done) ; differentiate:

$$W\mathrm{d}W = c^2\,\vec{p}\cdot\mathrm{d}\vec{p} = qc^2\,\vec{p}\cdot\left(\vec{E} + \vec{v}\times\vec{B}\right)\mathrm{d}t = qc^2\,\vec{p}\cdot\vec{E}\,\mathrm{d}t$$

$$\mathrm{d}W = q\vec{v}\cdot\vec{E}\,\mathrm{d}t$$

Note: no work is done by the magnetic field.

Maxwell's equations (in vacuum)

$$\nabla \times \vec{B} - \frac{1}{c^2}\frac{\partial}{\partial t}\vec{E} = 0 \qquad \nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} + \frac{\partial}{\partial t}\vec{B} = 0 \qquad \nabla \cdot \vec{E} = 0$$

(source-free)

<u>why not DC?</u>

1) DC ($\frac{\partial}{\partial t} \equiv 0$): $\nabla \times \vec{E} = 0$ which is solved by $\vec{E} = -\nabla \Phi$

Limit: If you want to gain 1 MeV, you need a potential of 1 MV!

2) Circular machine: DC acceleration impossible since $\oint \vec{E} \cdot \mathrm{d}\vec{s} = 0$

<u>With time-varying fields:</u>

$$\nabla \times \vec{E} = -\frac{\partial}{\partial t}\vec{B} \qquad \oint \vec{E} \cdot \mathrm{d}\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} \cdot \mathrm{d}\vec{A}$$

Maxwell's equation in vacuum (contd.)

$$\nabla\times\vec{B}-\frac{1}{c^2}\frac{\partial}{\partial t}\vec{E}=0 \qquad \nabla\cdot\vec{B}=0$$

$$\nabla\times\vec{E}+\frac{\partial}{\partial t}\vec{B}=0 \qquad \nabla\cdot\vec{E}=0$$

curl of 3rd and $\frac{\partial}{\partial t}$ of 1st equation:

$$\nabla\times\nabla\times\vec{E}+\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{E}=0$$

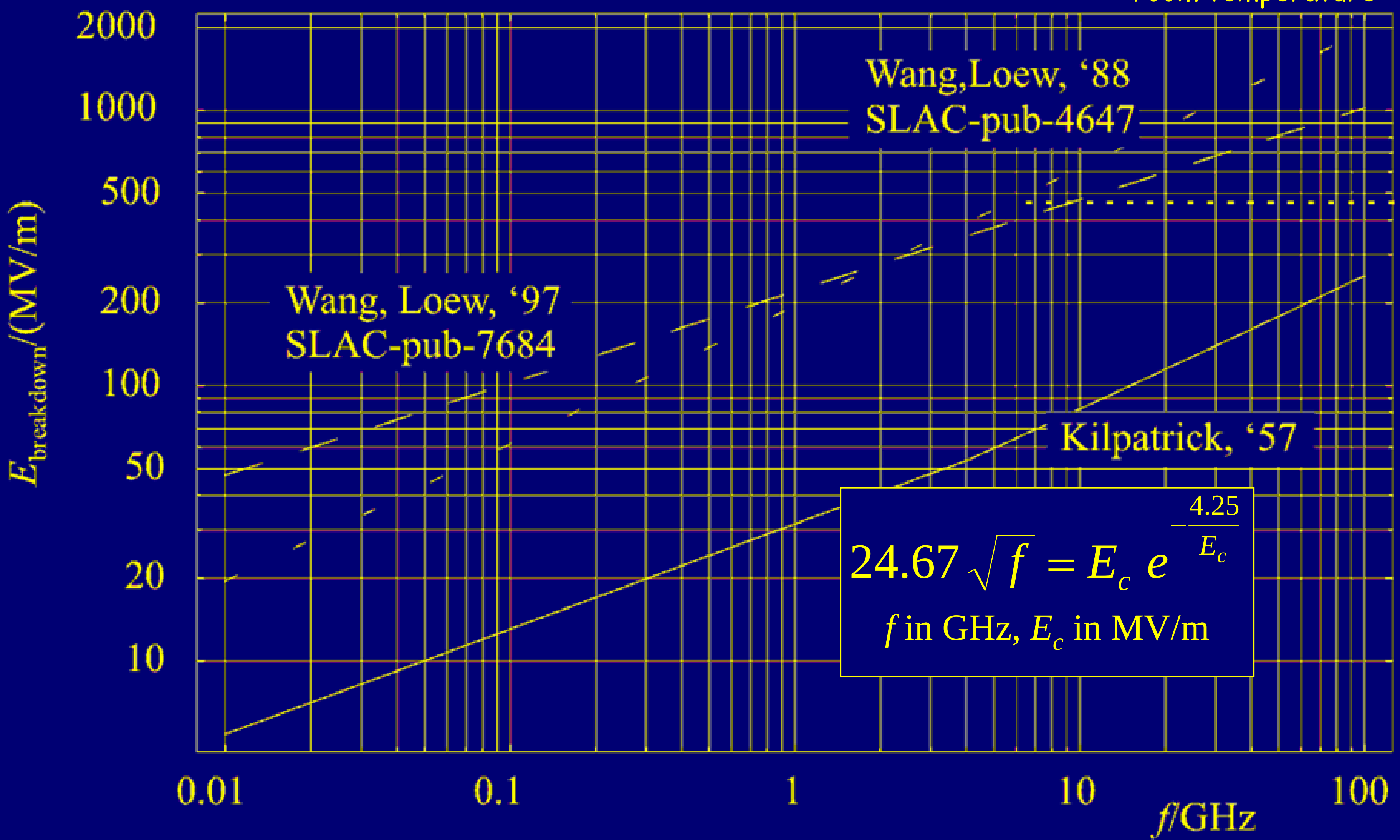
vector identity: $\nabla\times\nabla\times\vec{E}=\nabla\nabla\cdot\vec{E}-\Delta\vec{E}$

with 4th equation: $\Delta\vec{E}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{E}=0$

i.e. Laplace in 4 dimensions

Another reason for RF: breakdown limit

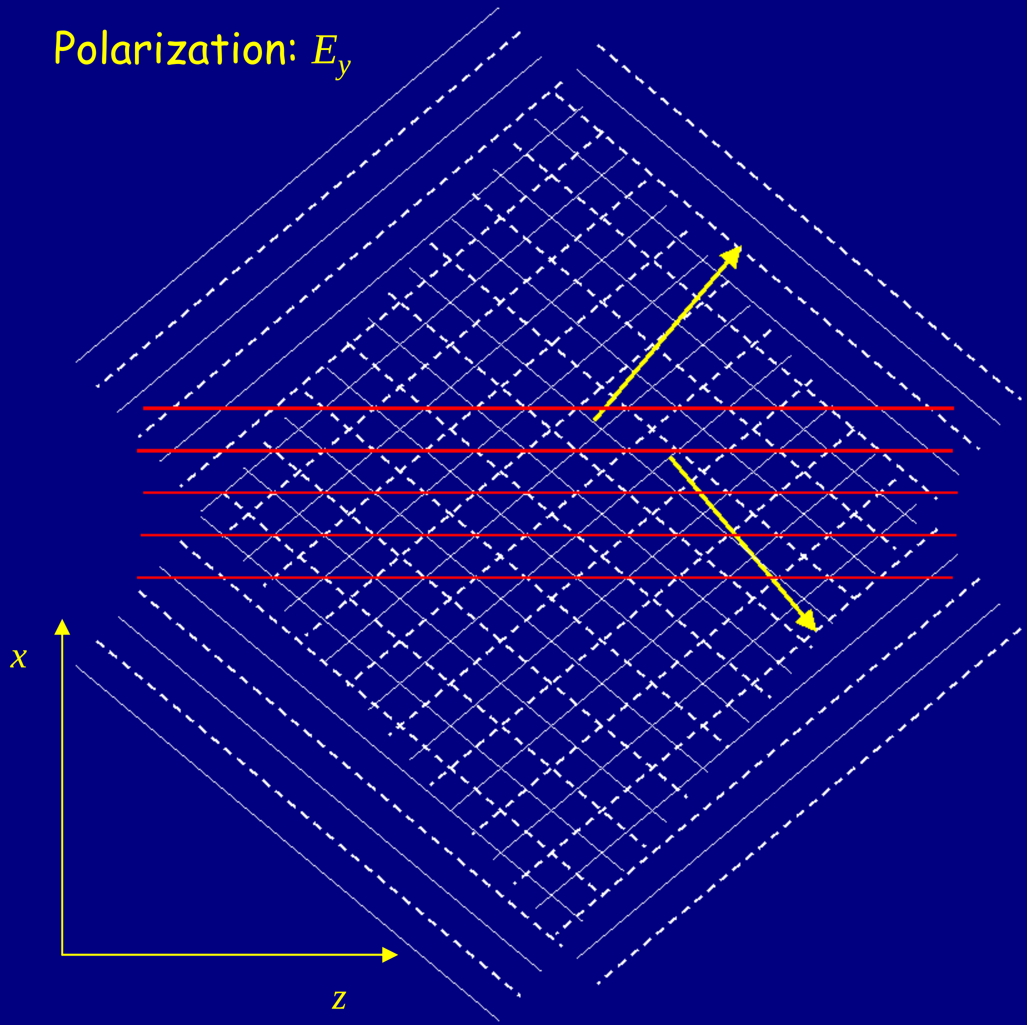
in vacuum,
Cu surface,
room temperature



Some theory: from waveguide to pillbox

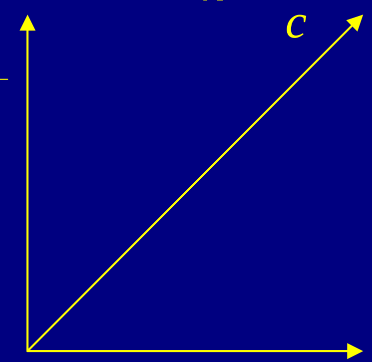
Polarization: E_y

frequency domain: $\frac{\partial}{\partial t} \equiv \mathrm{j}\omega$



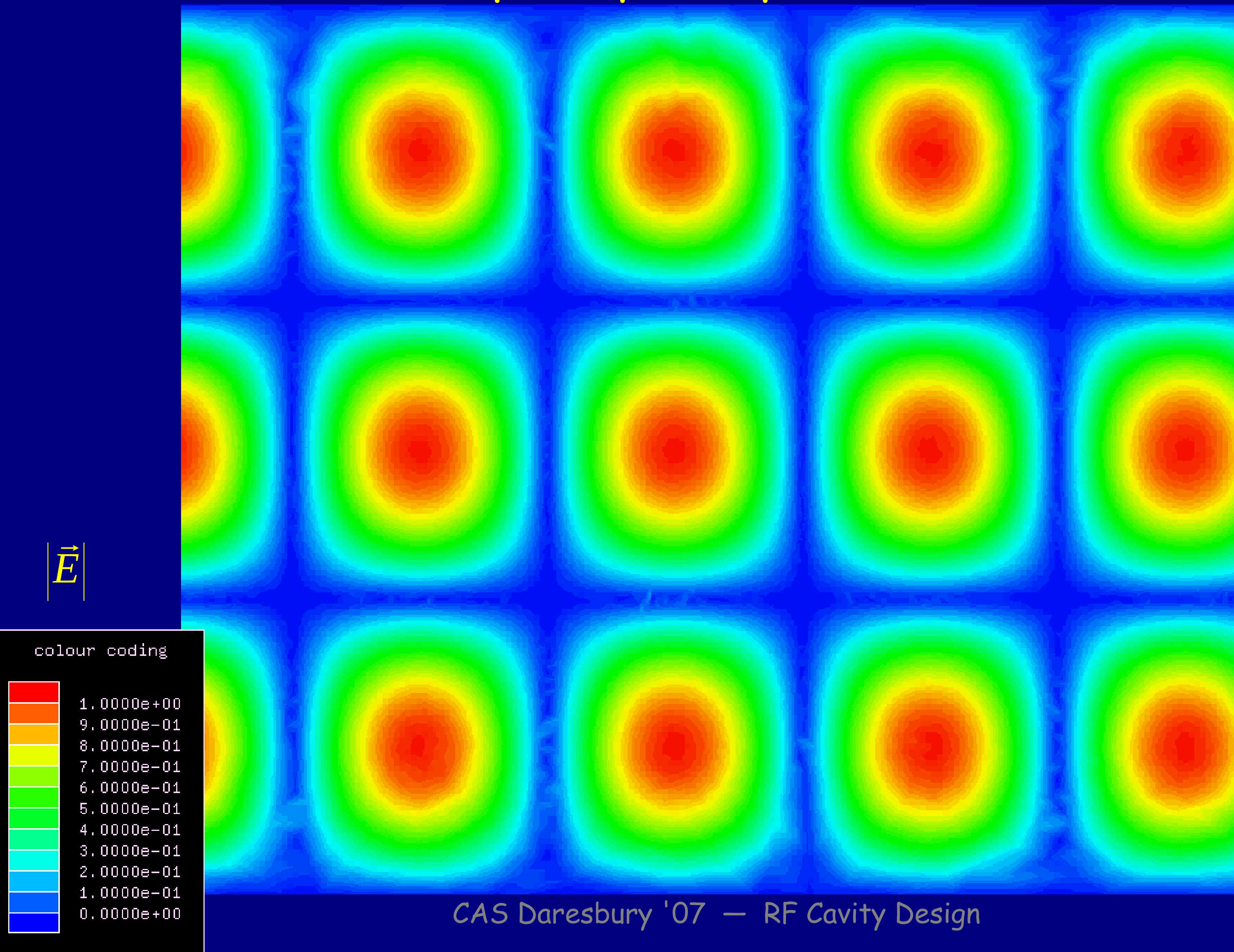
$$k = \frac{\omega}{c}$$

$$k_\perp = \frac{\omega_c}{c}$$



$$k_z = \frac{\omega}{c}\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}$$

2 superimposed plane waves



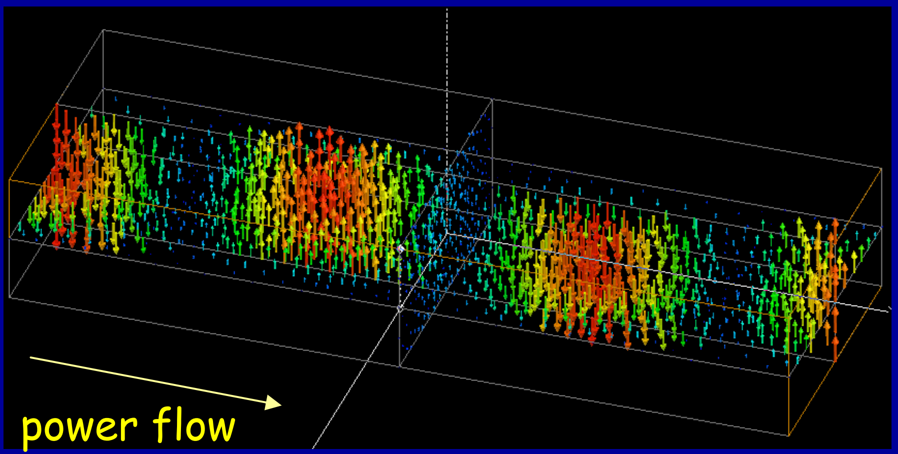
Waveguides

Fundamental (TE_{10} or H_{10}) mode
in a standard rectangular waveguide.

E.g. forward wave

electric field

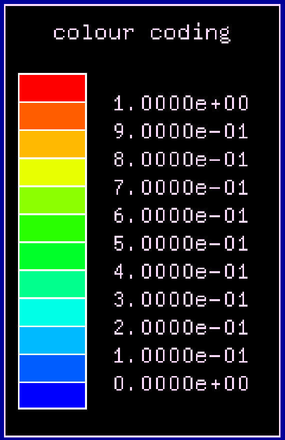
-y



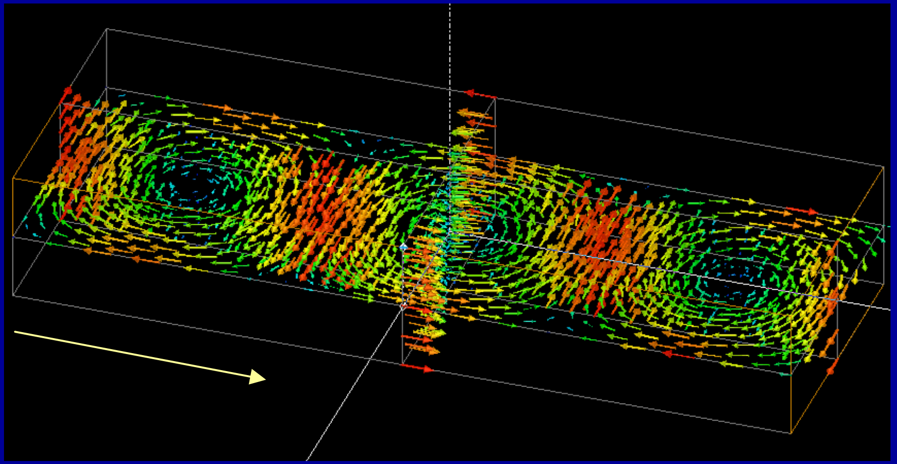
z

x

power flow: $\frac{1}{2}\mathrm{Re}\left\{ \iint\limits_{\substack{\text{cross}\\ \text{section}}} \vec{E} \times \vec{H}^* \cdot \mathrm{d}\vec{A} \right\}$



magnetic field

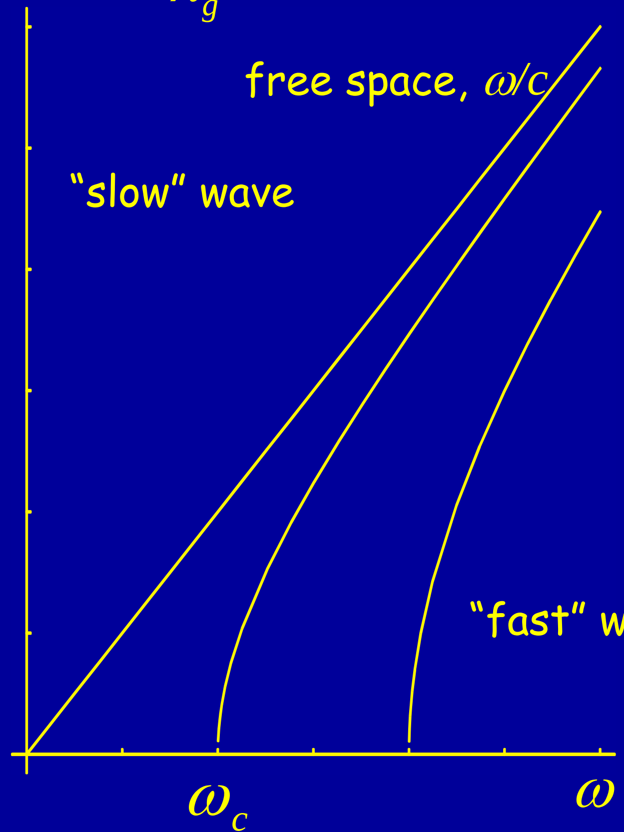


z

x

Waveguide dispersion

$$k_z = \mathrm{Im}\{\gamma\} = \frac{2\pi}{\lambda_g}$$



e.g.: TE_{10}-wave in rectangular waveguide:

$$\gamma = \mathrm{j}\sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{\pi}{a}\right)^2}$$

$$Z_0 = \frac{\mathrm{j}\omega\mu}{\gamma}$$

$$\lambda_{\mathrm{cutoff}} = 2a$$

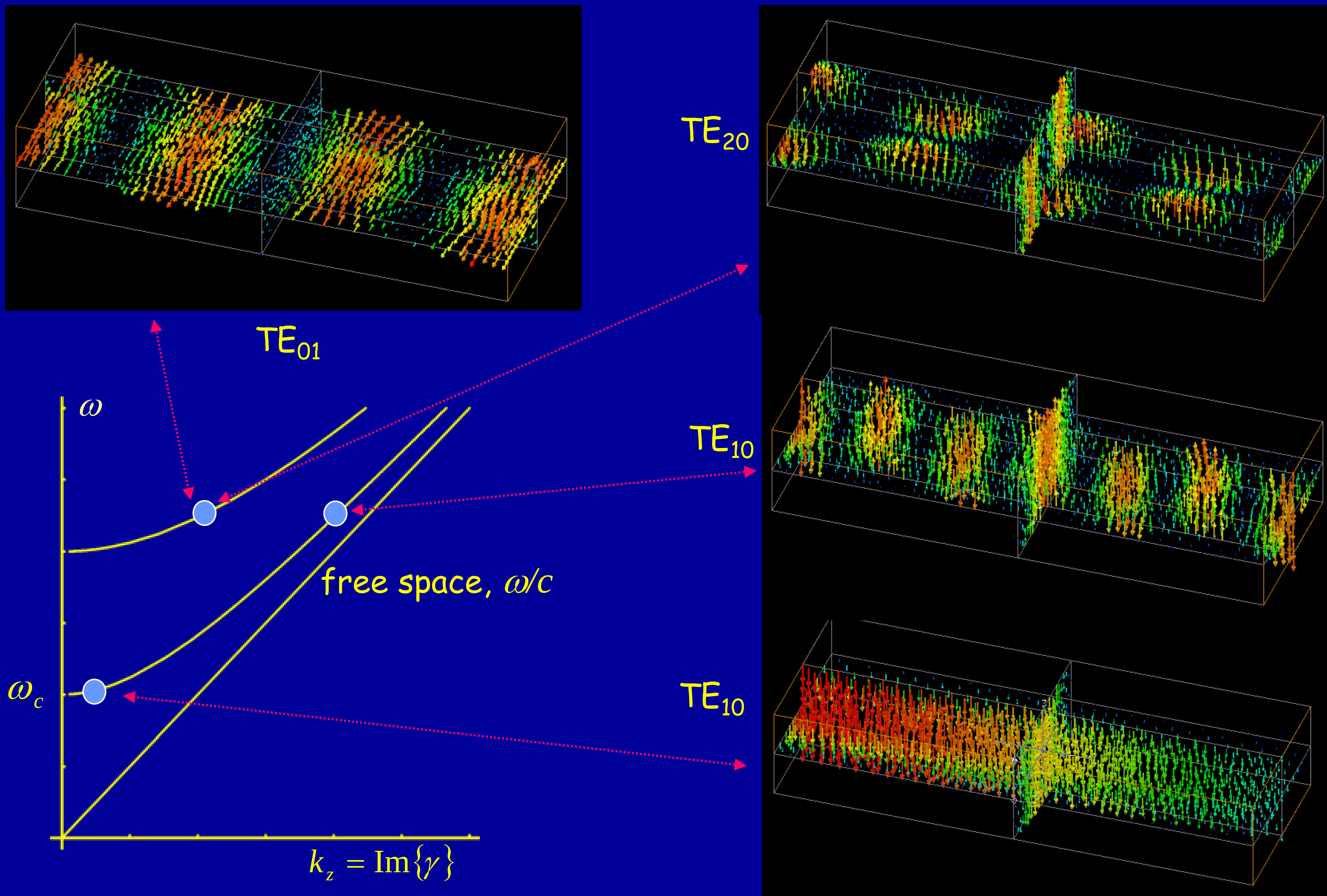
general cylindrical waveguide:

$$\gamma = \mathrm{j}\sqrt{\left(\frac{\omega}{c}\right)^2 - k_\perp^{\,2}}$$

$$Z_0 = \frac{\mathrm{j}\omega\mu}{\gamma} \text{ for TE,} \quad Z_0 = \frac{\gamma}{\mathrm{j}\omega\varepsilon} \text{ for TM}$$

In a hollow waveguide: phase velocity > c, group velocity < c

Waveguide dispersion (continued)



General waveguide equations:

Transverse wave equation (membrane equation): $$\Delta T + \left(\frac{\omega_c}{c}\right)^2 T = 0$$

	TE (or H) modes	TM (or E) modes
boundary condition:	$\vec{n} \cdot \nabla T = 0$	$T = 0$

longitudinal wave equations (transmission line equations):

$$\frac{\mathrm{d}U(z)}{\mathrm{d}z} + \gamma Z_0 I(z) = 0$$

$$\frac{\mathrm{d}I(z)}{\mathrm{d}z} + \frac{\gamma}{Z_0} U(z) = 0$$

propagation constant:

$$\gamma = \mathrm{j}\frac{\omega}{c}\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}$$

	TE (or H) modes	TM (or E) modes
characteristic impedance:	$Z_0 = \frac{\mathrm{j}\omega\mu}{\gamma}$	$Z_0 = \frac{\gamma}{\mathrm{j}\omega\varepsilon}$
ortho-normal eigenvectors:	$\vec{e} = \vec{u}_z \times \nabla T$	$\vec{e} = -\nabla T$

transverse fields:

$$\vec{E} = U(z)\vec{e}$$

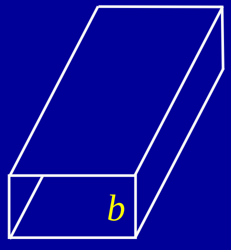
$$\vec{H} = I(z)\vec{u}_z \times \vec{e}$$

	TE (or H) modes	TM (or E) modes
longitudinal field:	$H_z = \left(\frac{\omega_c}{c}\right)^2 \frac{T\,U(z)}{\mathrm{j}\omega\mu}$	$E_z = \left(\frac{\omega_c}{c}\right)^2 \frac{T\,I(z)}{\mathrm{j}\omega\varepsilon}$

Rectangular waveguide : transverse eigenfunctions

TE (H) modes: $$T_{mn}^{(H)} = \frac{1}{\pi}\sqrt{\frac{ab\varepsilon_m\varepsilon_n}{(mb)^2+(na)^2}}\cos\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)$$

TM (E) modes: $$T_{mn}^{(E)} = \frac{2}{\pi}\sqrt{\frac{ab}{(mb)^2+(na)^2}}\sin\left(\frac{m\pi}{a}x\right)\sin\left(\frac{n\pi}{b}y\right)$$



$$\frac{\omega_c}{c} = \sqrt{\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2}$$

Round waveguide : transverse eigenfunctions

TE (H) modes: $$T_{mn}^{(H)} = \sqrt{\frac{\varepsilon_m}{\pi\left(\chi_{mn}'^2-m^2\right)}}\frac{\mathrm{J}_m\left(\chi_{mn}'\frac{\rho}{a}\right)}{\mathrm{J}_m\left(\chi_{mn}'\right)}\begin{Bmatrix}\cos(m\varphi)\\ \sin(m\varphi)\end{Bmatrix}$$

TM (E) modes: $$T_{mn}^{(E)} = \sqrt{\frac{\varepsilon_m}{\pi}}\frac{\mathrm{J}_m\left(\chi_{mn}\frac{\rho}{a}\right)}{\chi_{mn}\,\mathrm{J}_{m-1}\left(\chi_{mn}\right)}\begin{Bmatrix}\sin(m\varphi)\\ \cos(m\varphi)\end{Bmatrix}$$

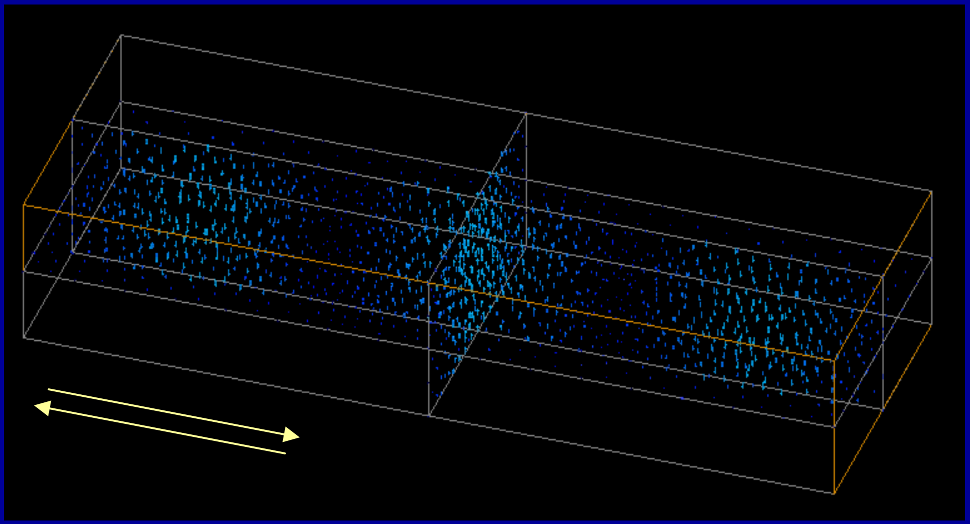
$$\frac{\omega_c}{c} = \frac{\chi_{mn}}{a}$$

where $$\varepsilon_i = \begin{cases}1 & for \quad i=0\\ 2 & for \quad i\neq 0\end{cases}$$

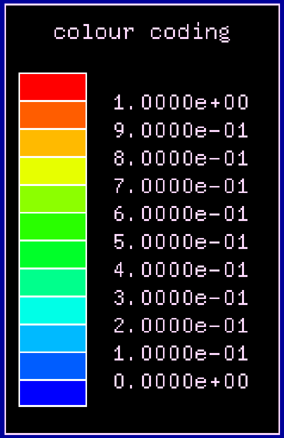
Standing wave – resonator

Same as above, but two counter-running waves of identical amplitude.

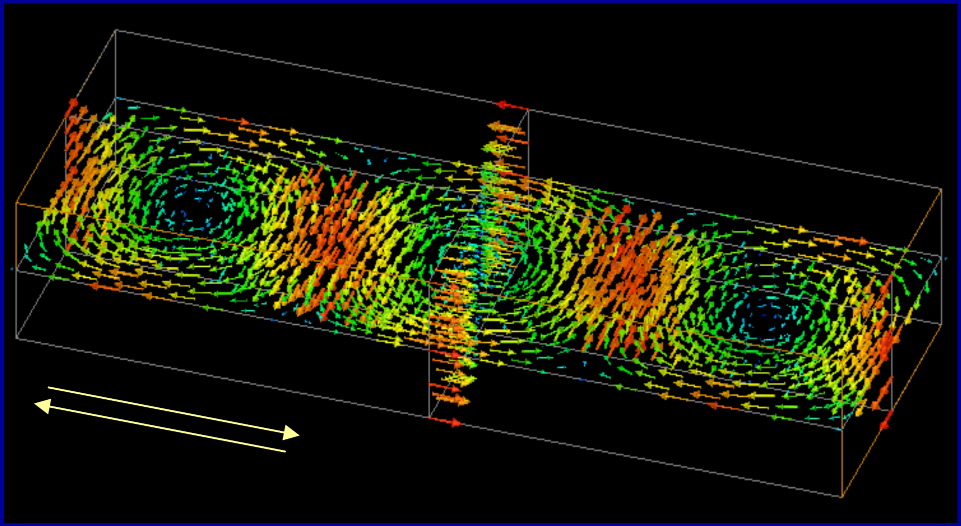
electric field



no net power flow: $\frac{1}{2}\mathrm{Re}\left\{ \iint\limits_{\substack{\text{cross}\\ \text{section}}} \vec{E} \times \vec{H}^* \cdot \mathrm{d}\vec{A} \right\} = 0$

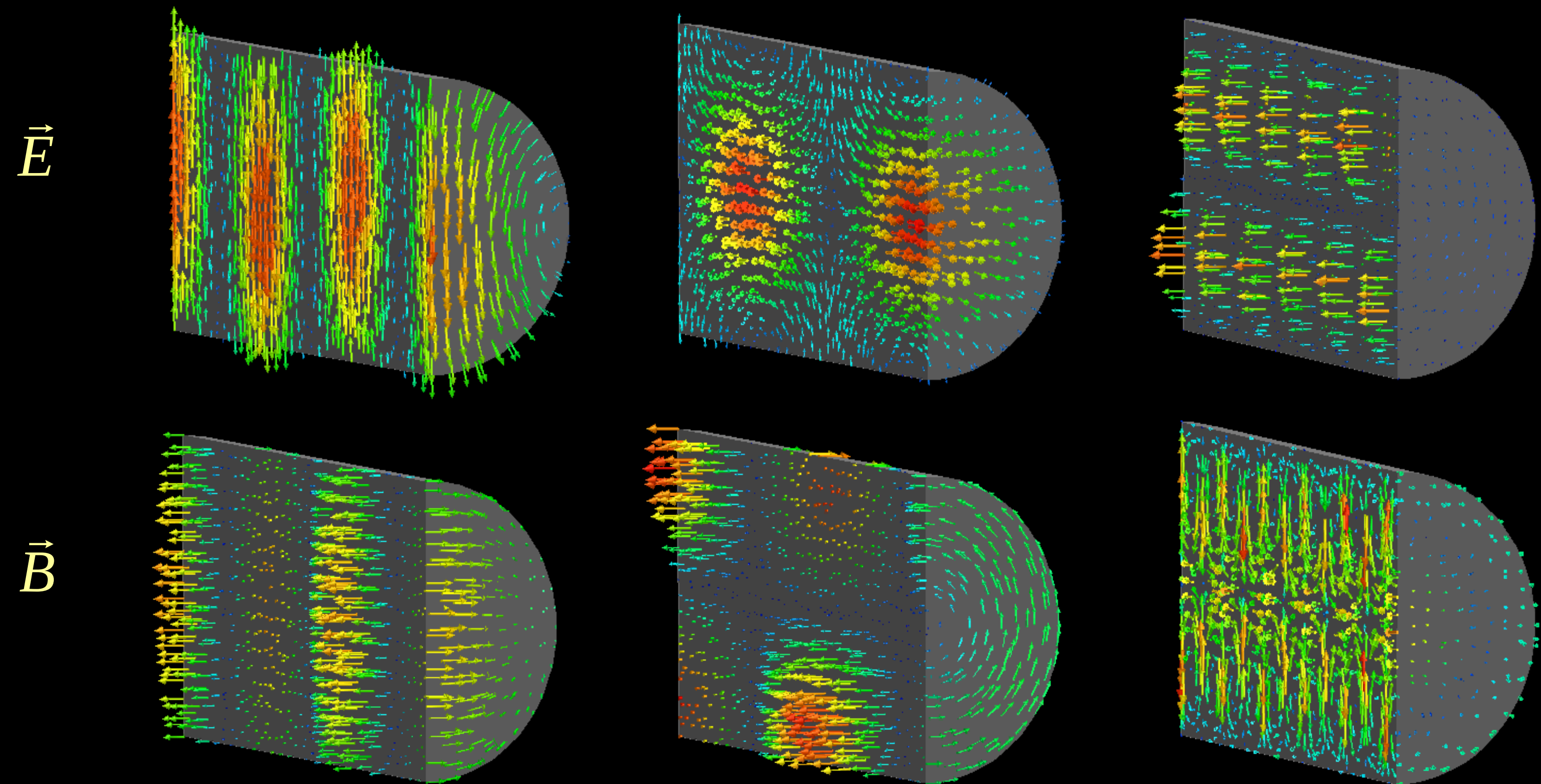


magnetic field (90° out of phase)



Round waveguide

parameters used in calculation:
f = 1.43, 1.09, 1.13 f_c, a: radius



TE_{11}: fundamental mode

$$\frac{f_c}{\text{GHz}} = \frac{87.85}{a\,/\,\text{mm}}$$

TM_{01}: axial electric field

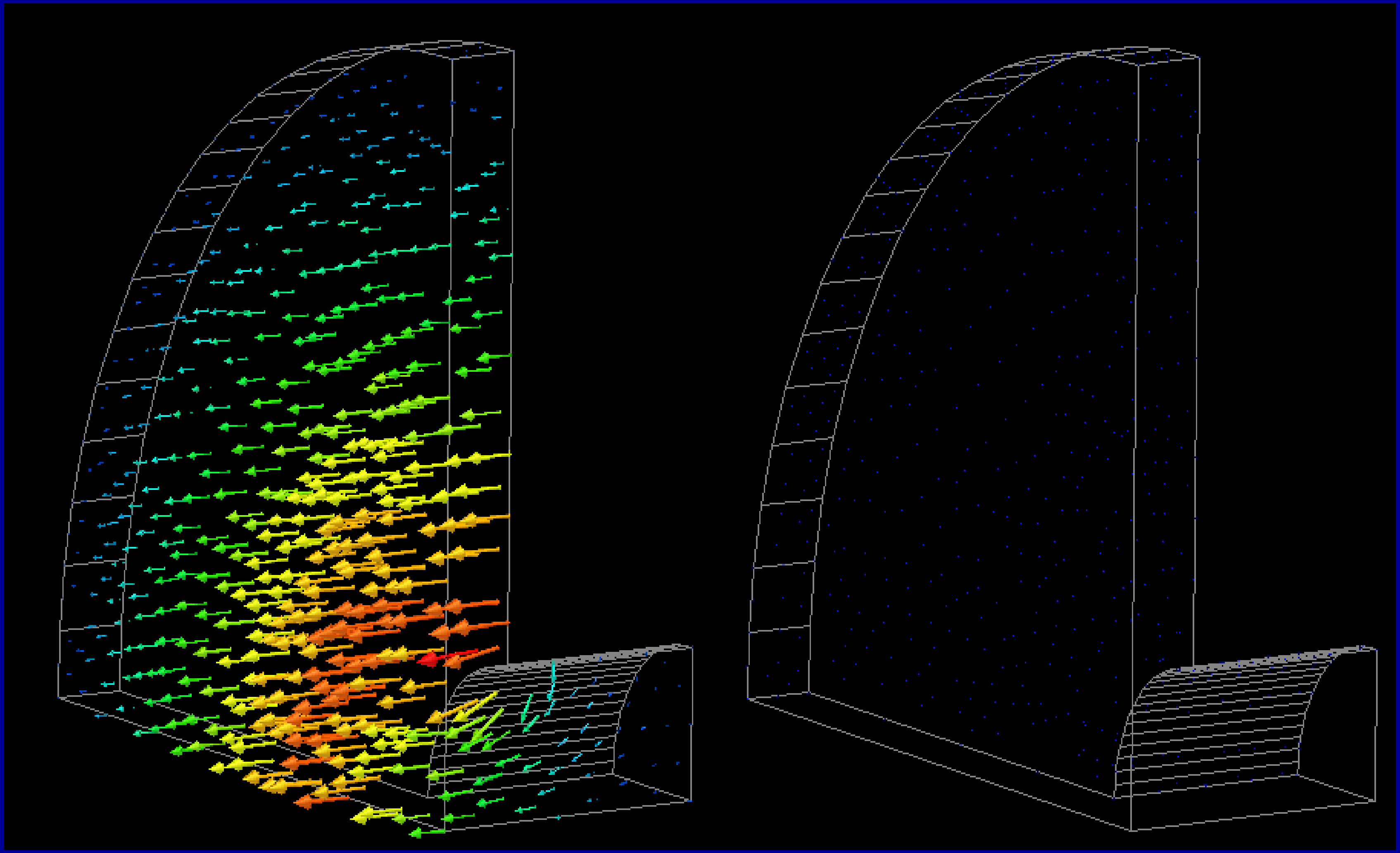
$$\frac{f_c}{\text{GHz}} = \frac{114.74}{a\,/\,\text{mm}}$$

TE_{01}: lowest losses!

$$\frac{f_c}{\text{GHz}} = \frac{334.74}{a\,/\,\text{mm}}$$

Pillbox cavity

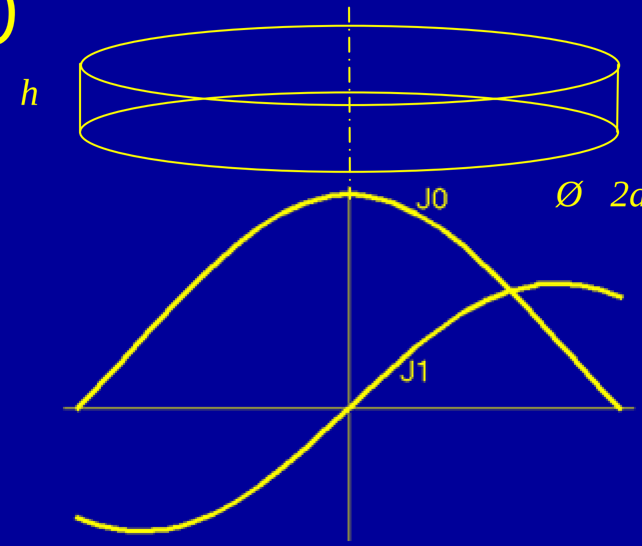
TM$_{010}$-mode (only 1/8 shown)



electric field magnetic field

Pillbox cavity field (w/o beam tube)

$$T(\rho,\varphi)=\sqrt{\frac{1}{\pi}}\frac{J_0\left(\frac{\chi_{01}\rho}{a}\right)}{\chi_{01}\,J_1\left(\frac{\chi_{01}}{a}\right)}\qquad \chi_{01}=2.40483...$$



The only non-vanishing field components :

$$E_z=\frac{1}{j\omega\varepsilon_0}\frac{\chi_{01}}{a}\sqrt{\frac{1}{\pi}}\frac{J_0\left(\frac{\chi_{01}\rho}{a}\right)}{a\,J_1\left(\frac{\chi_{01}}{a}\right)}$$

$$B_\varphi=\mu_0\sqrt{\frac{1}{\pi}}\frac{J_1\left(\frac{\chi_{01}\rho}{a}\right)}{a\,J_1\left(\frac{\chi_{01}}{a}\right)}$$

for later:

$$\omega_0\Big|_{pillbox}=\frac{\chi_{01}\,c}{a}\qquad \eta=\sqrt{\frac{\mu_0}{\varepsilon_0}}=377\,\Omega$$

$$Q\Big|_{pillbox}=\frac{\sqrt{2a\eta\sigma\chi_{01}}}{2\left(1+\frac{a}{h}\right)}$$

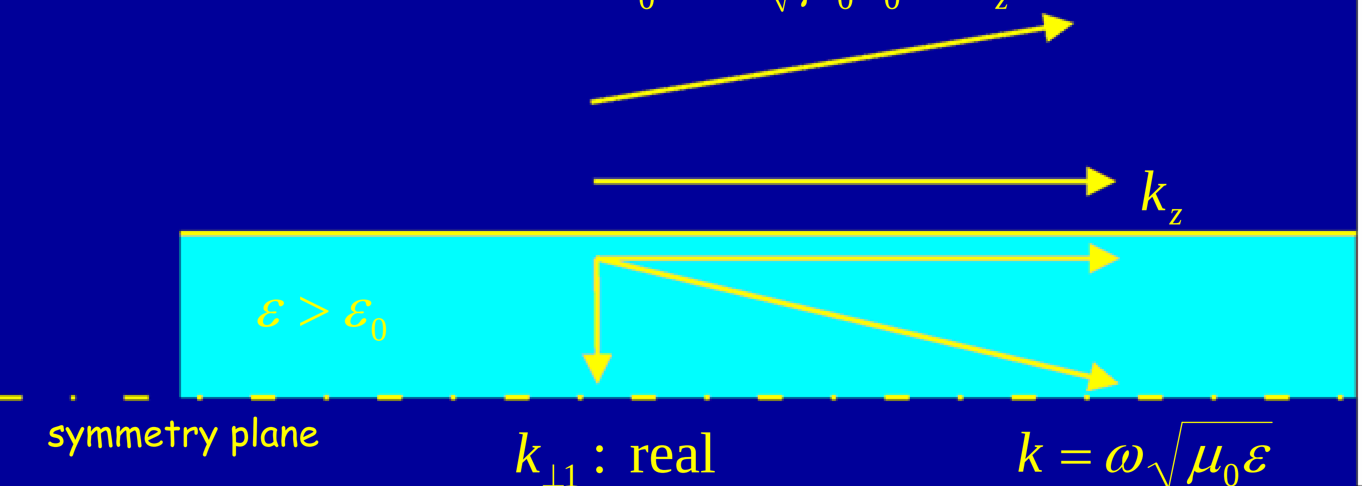
$$\frac{R}{Q}\Big|_{pillbox}=\frac{4\eta}{\chi_{01}^{\ 3}\pi\,J_1^2(\chi_{01})}\frac{\sin^2\left(\frac{\chi_{01}}{2}\frac{h}{a}\right)}{h/a}$$

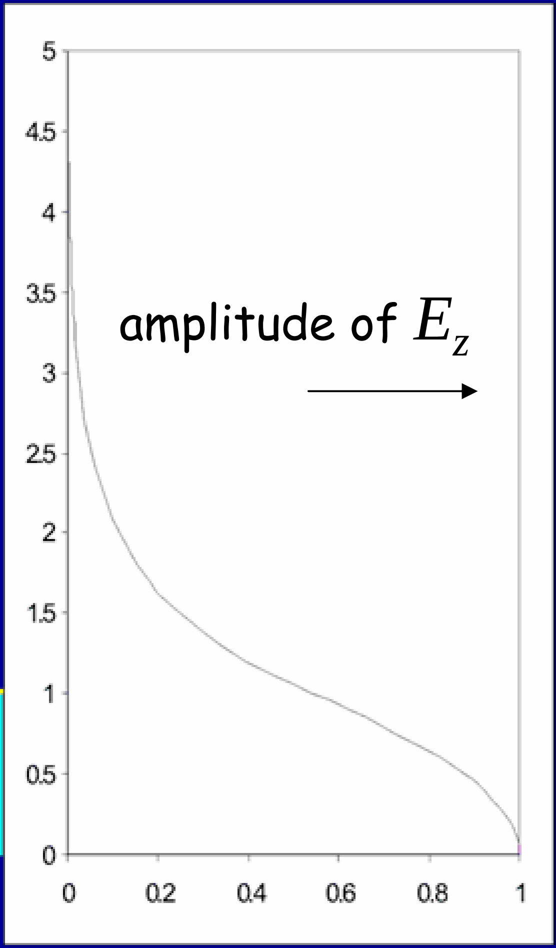
dielectric guide – transversely damped wave

There is another solution to $\left(\frac{\omega}{c}\right)^2 = k_0^2 = k_\perp^2 + k_z^2$:

$$k_\perp = \pm j\sqrt{k_z^2 - k_0^2}$$

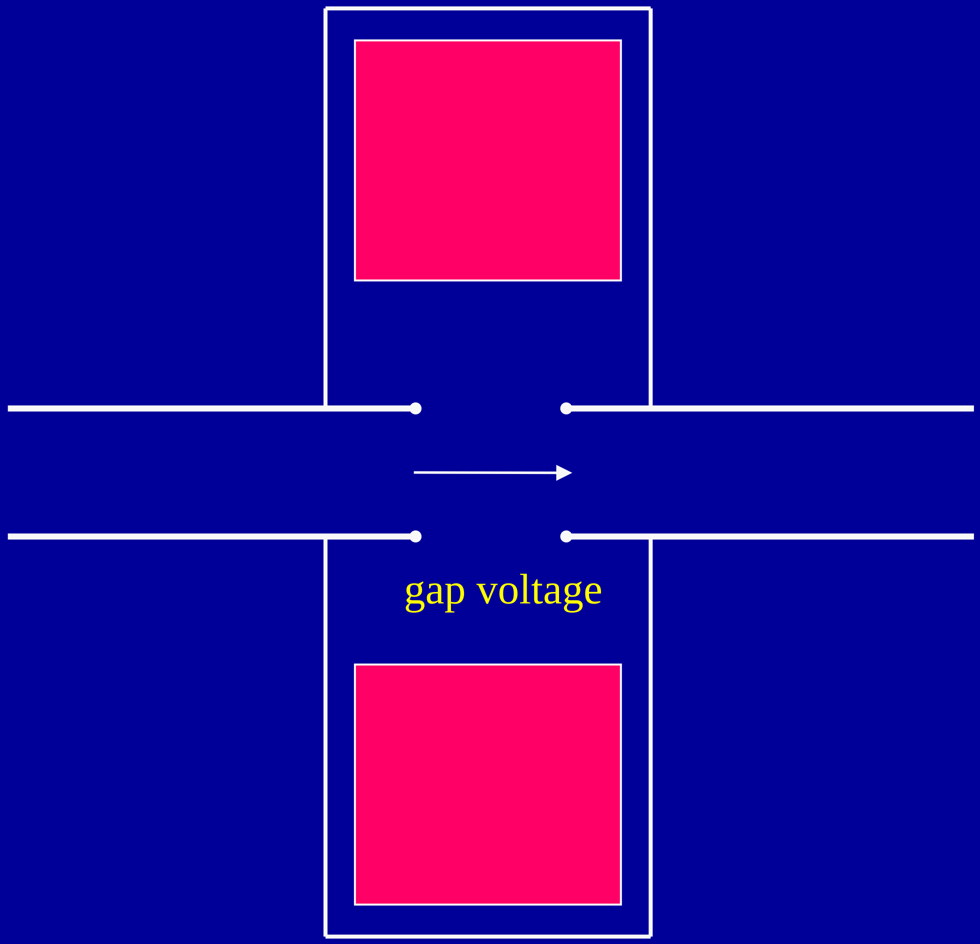
$$k_0 = \omega\sqrt{\mu_0\varepsilon_0} < k_z$$





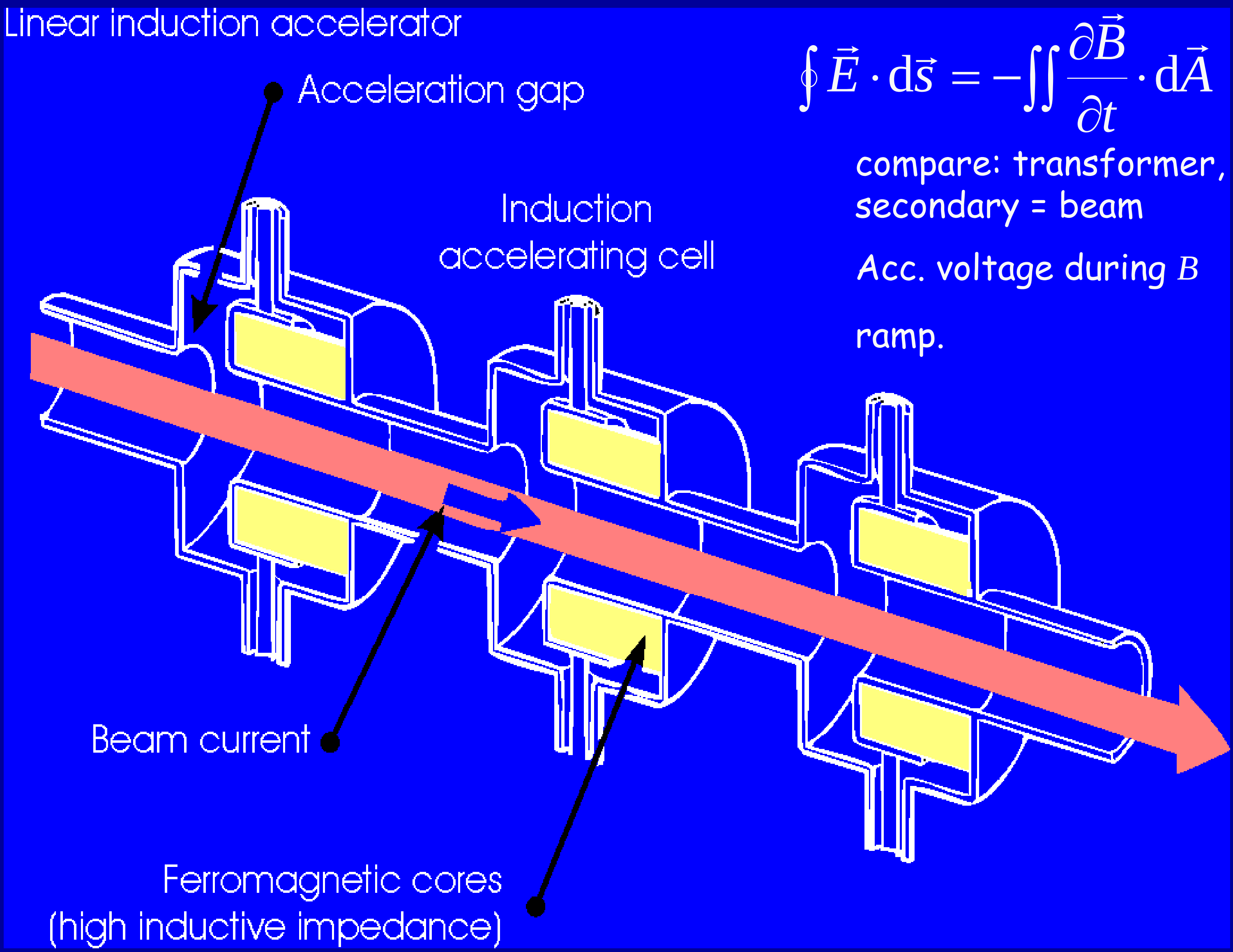
Accelerating gap

Accelerating gap



- We want a voltage across the gap!
- It cannot be DC, since we want the beam tube on ground potential.
- Use $$\oint \vec{E} \cdot \mathrm{d}\vec{s} = -\iint \frac{\mathrm{d}\vec{B}}{\mathrm{d}t} \cdot \mathrm{d}\vec{A}$$
- The "shield" imposes a
  - upper limit of the voltage pulse duration or – equivalently –
  - a lower limit to the usable frequency.
- The limit can be extended with a material which acts as "open circuit"!
- Materials typically used:
  - ferrites (depending on *f*-range)
  - magnetic alloys (MA) like Metglas®, Finemet®, Vitrovac®…
- resonantly driven with RF (ferrite loaded cavities) – or with pulses (induction cell)

Linear induction accelerator

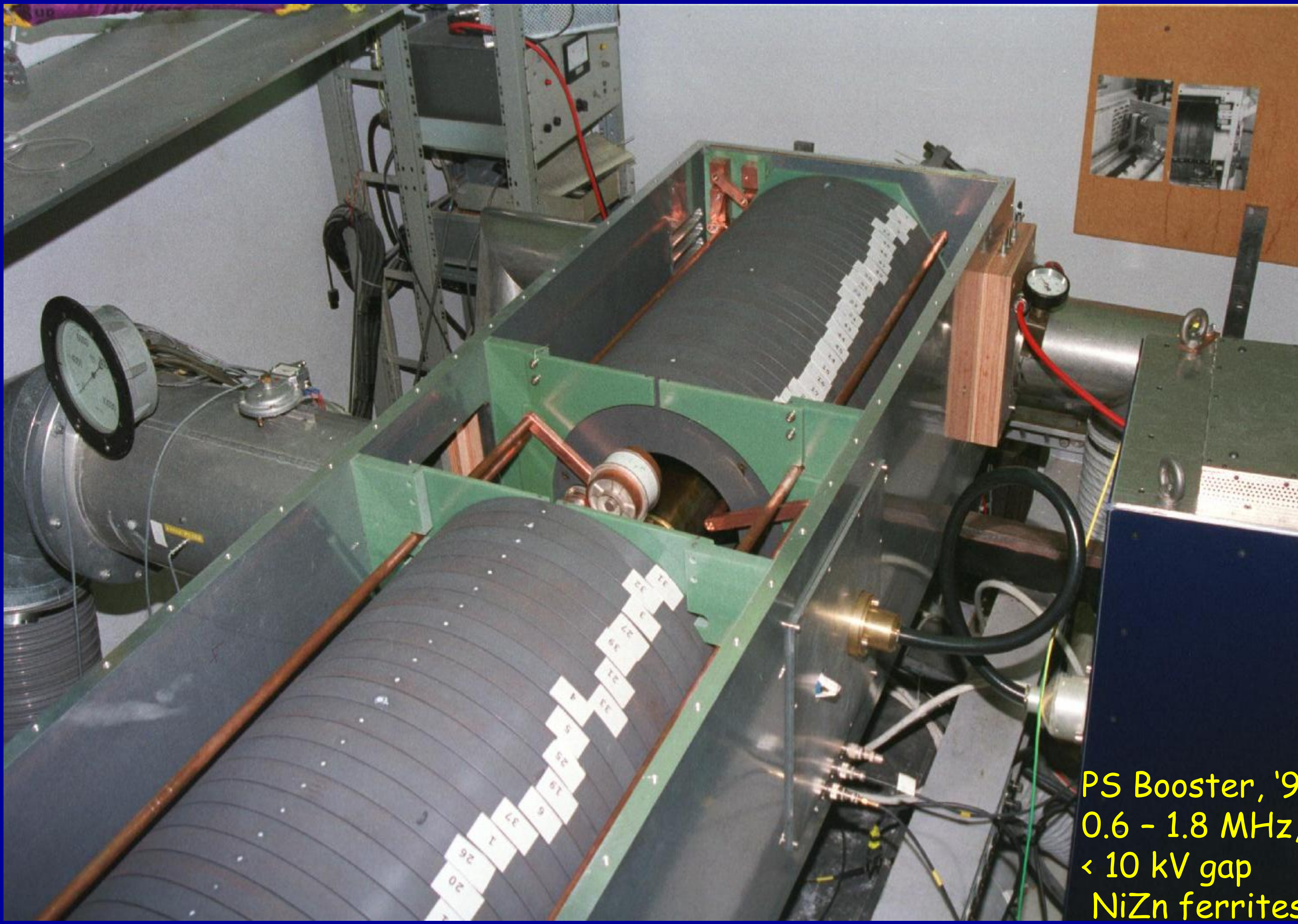


$$\oint \vec{E} \cdot \mathrm{d}\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} \cdot \mathrm{d}\vec{A}$$

compare: transformer, secondary = beam

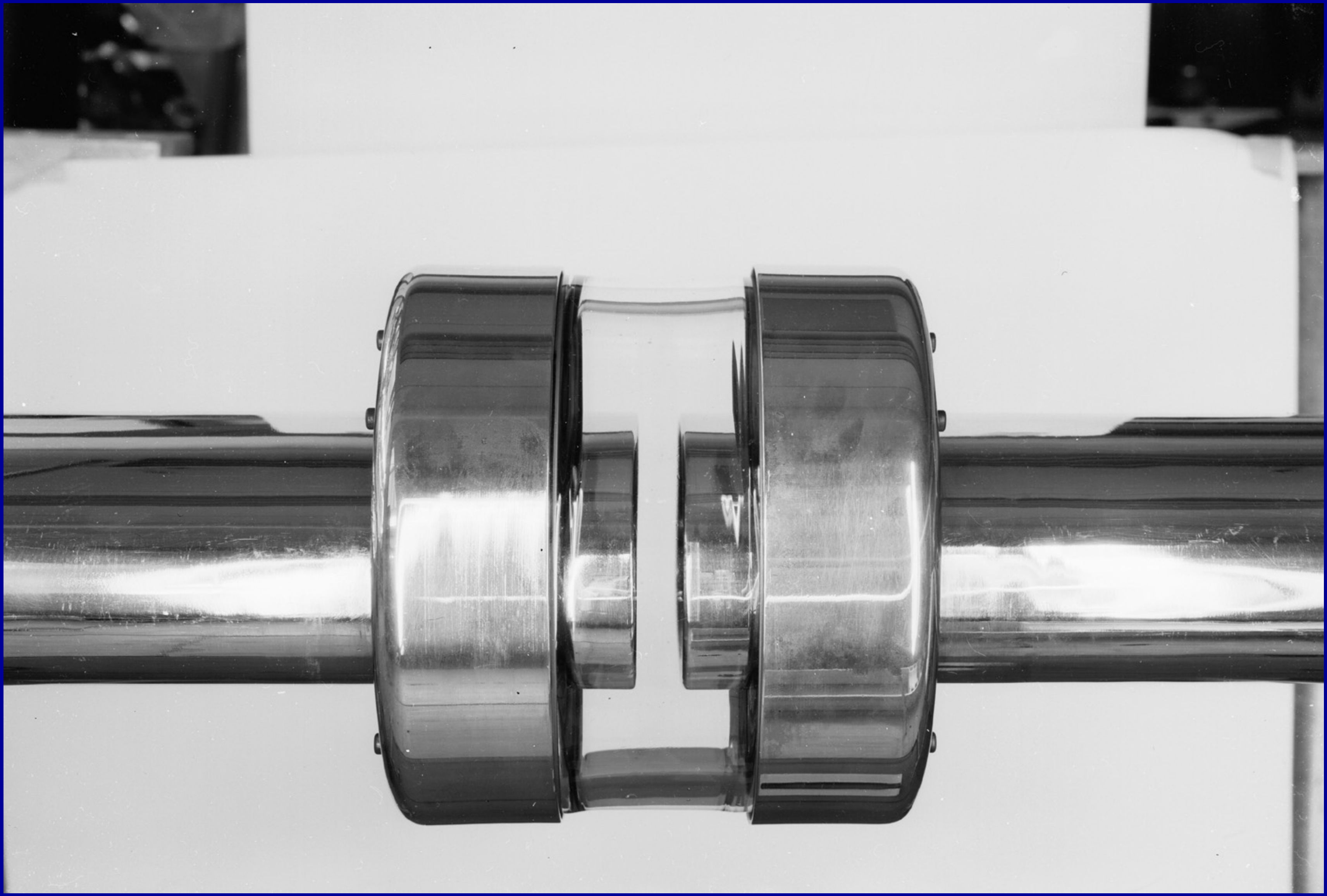
Acc. voltage during B ramp.

Ferrite cavity



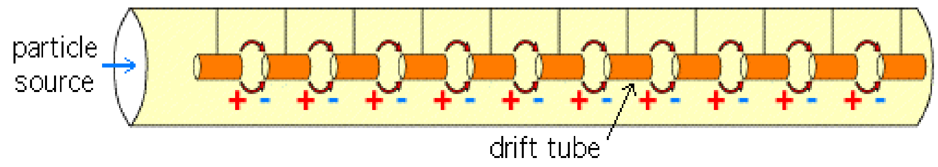
PS Booster, '98
0.6 – 1.8 MHz,
< 10 kV gap
NiZn ferrites

Gap of PS cavity (prototype)

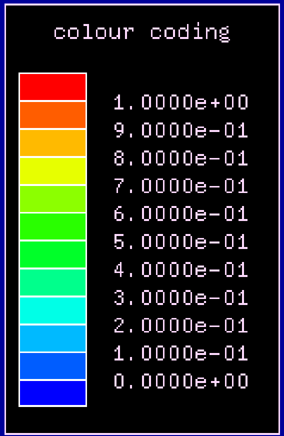


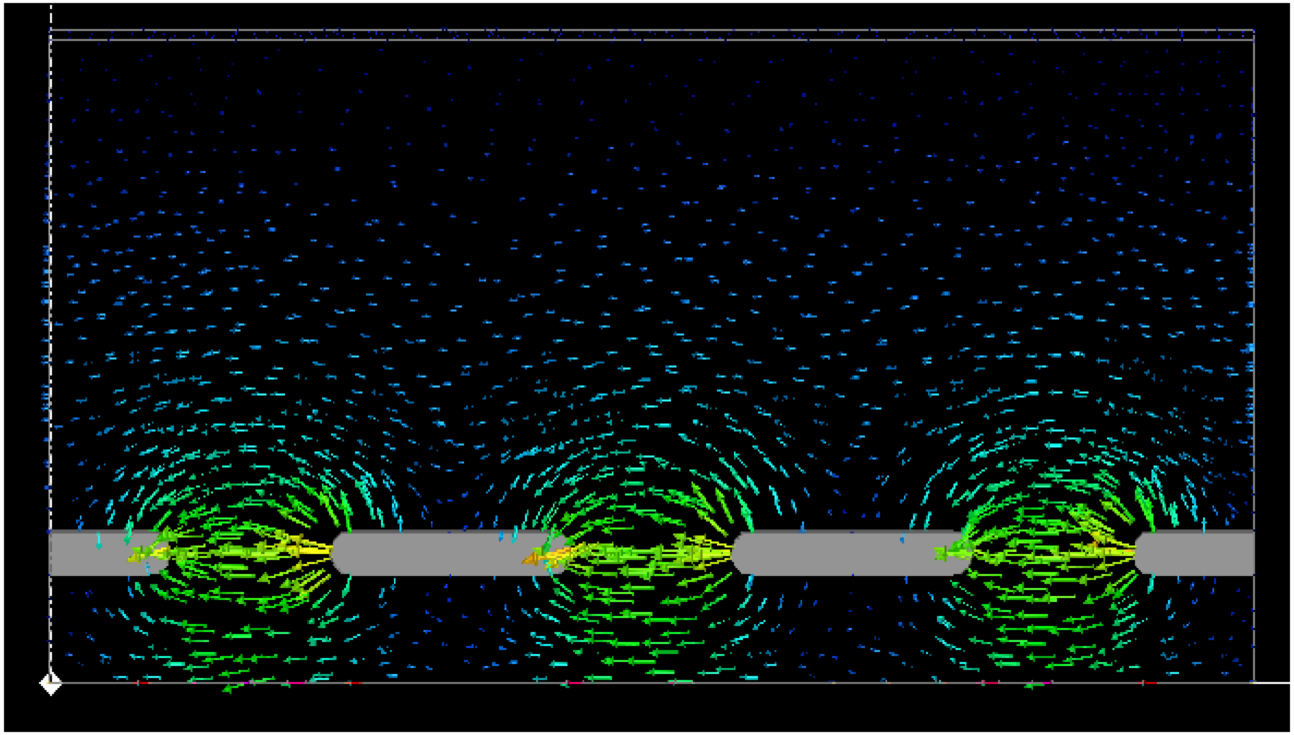
Drift Tube Linac (DTL) – how it works

For slow particles – protons @ few MeV e.g. – the drift tube lengths can easily be adapted.

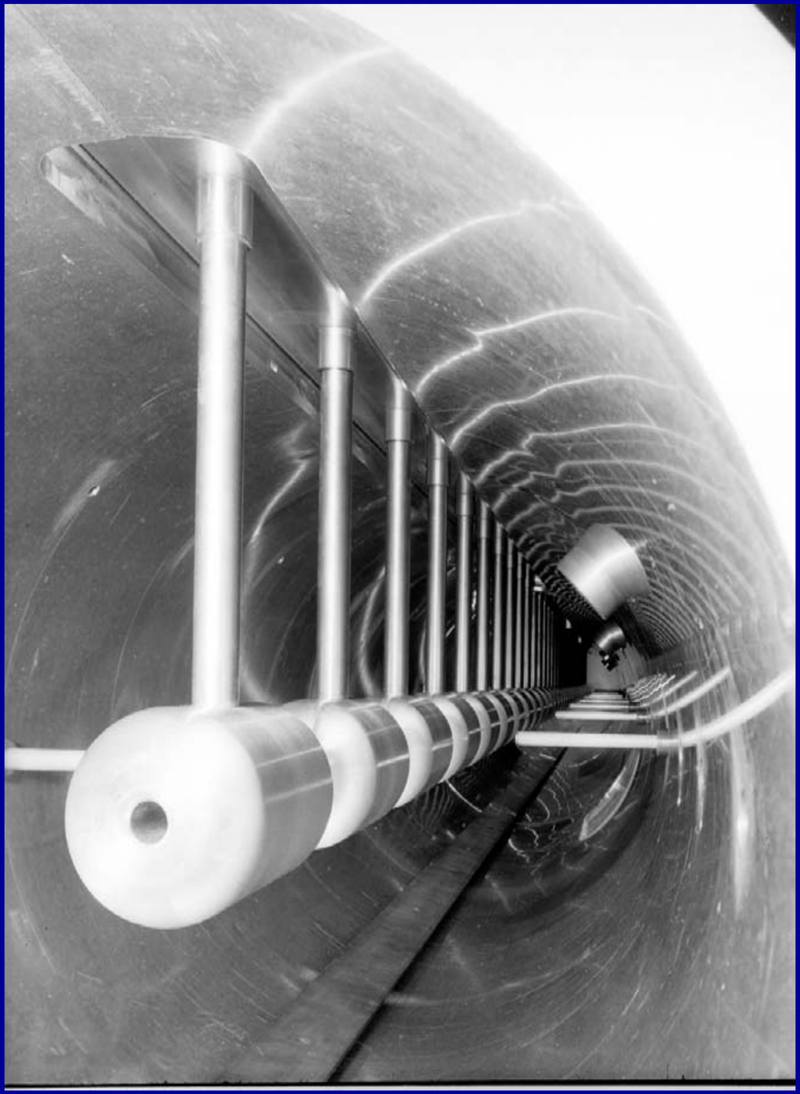


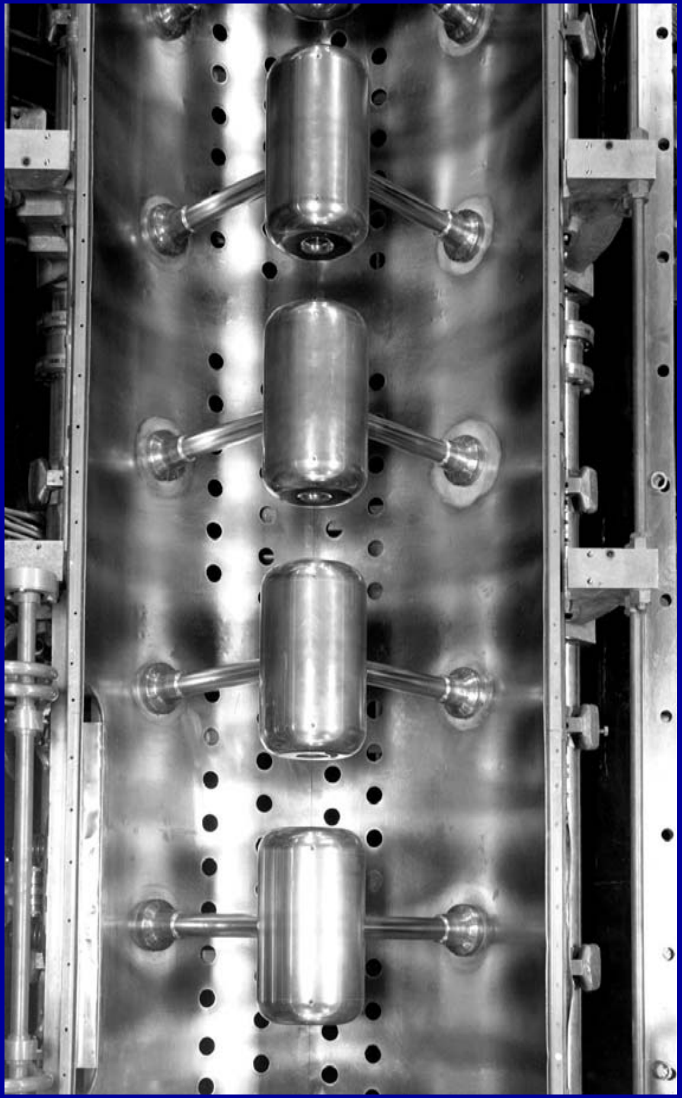
electric field





Drift tube linac – practical implementations





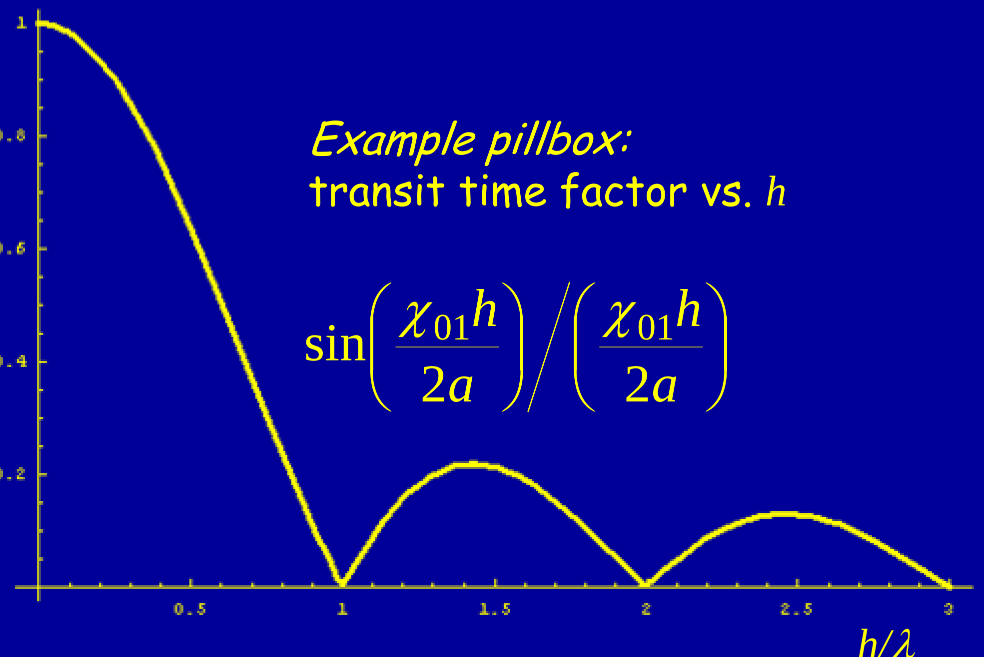
Transit time factor

If the gap is small, the voltage $\int E_z \mathrm{d}z$ is small.

If the gap large, the RF field varies notably while the particle passes.

Define the accelerating voltage $V_{gap} = \left| \int E_z e^{j\frac{\omega}{c}z} \mathrm{d}z \right|$

Transit time factor $\dfrac{\left| \int E_z e^{j\frac{\omega}{c}z} \mathrm{d}z \right|}{\left| \int E_z \mathrm{d}z \right|}$



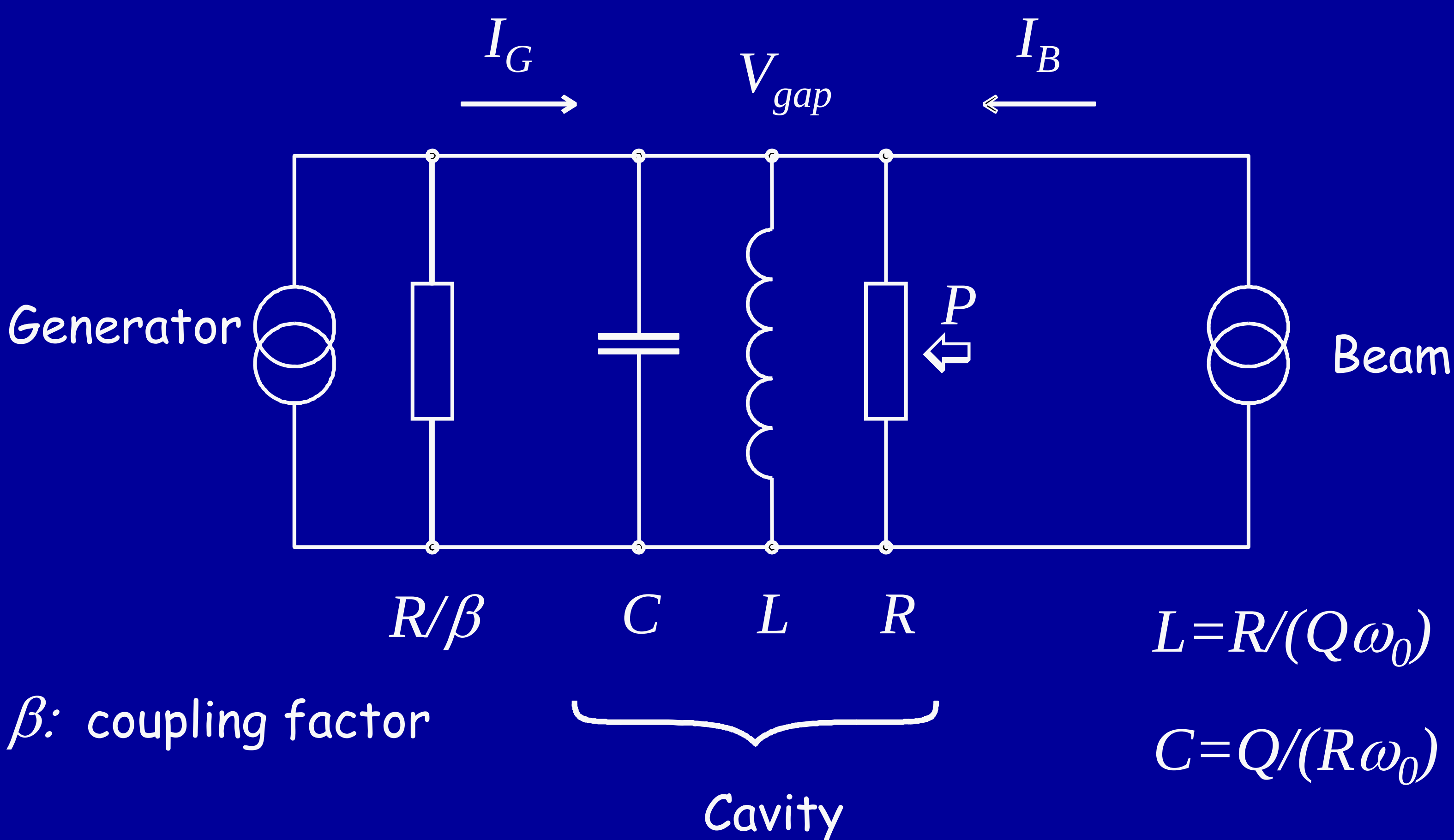
Example pillbox:
transit time factor vs. h

$$\sin\left(\frac{\chi_{01}h}{2a}\right) \Big/ \left(\frac{\chi_{01}h}{2a}\right)$$

Characterizing a cavity

Cavity resonator – equivalent circuit

Simplification: single mode



$L=R/(Q\omega_0)$

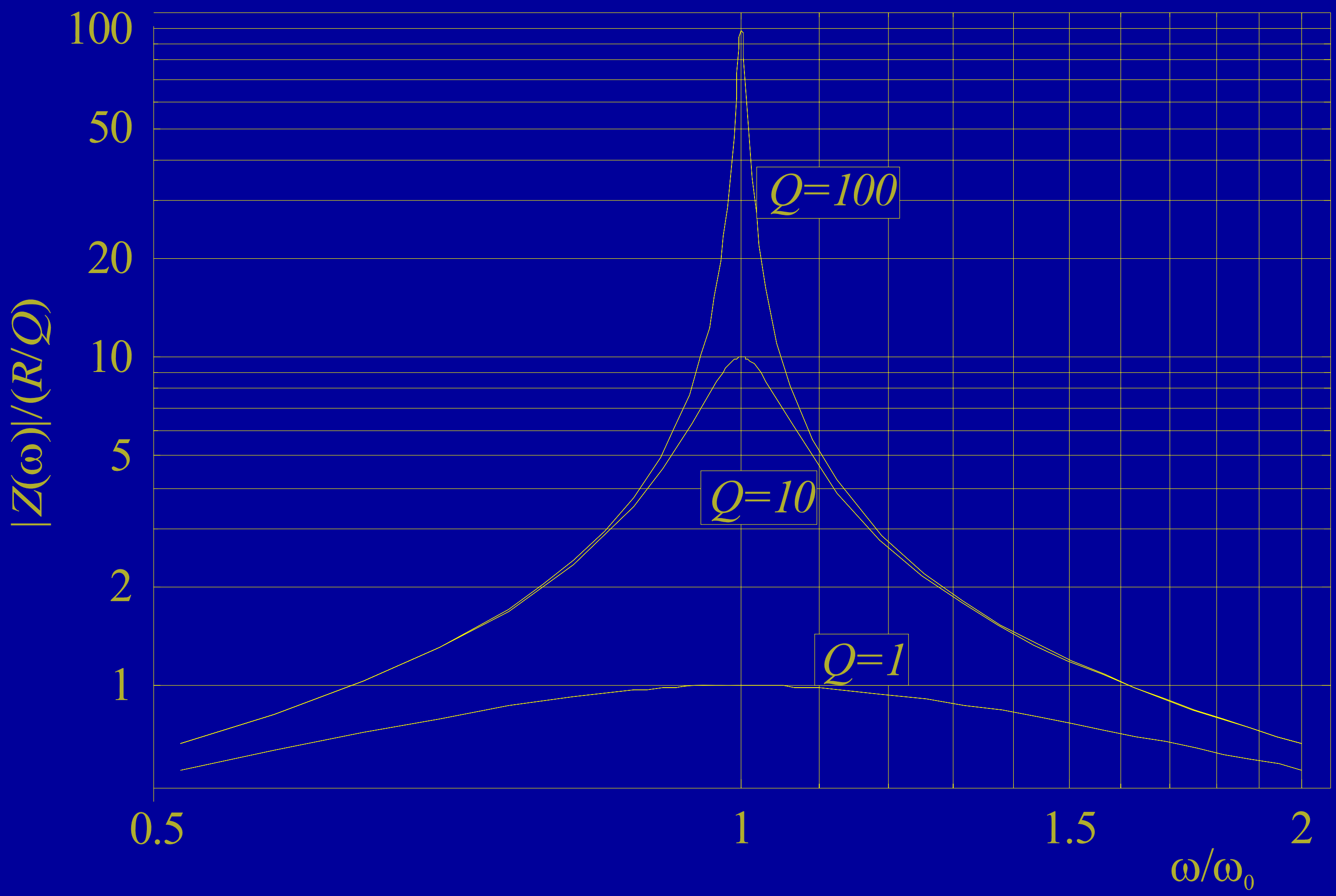
$C=Q/(R\omega_0)$

β: coupling factor

R: Shunt impedance

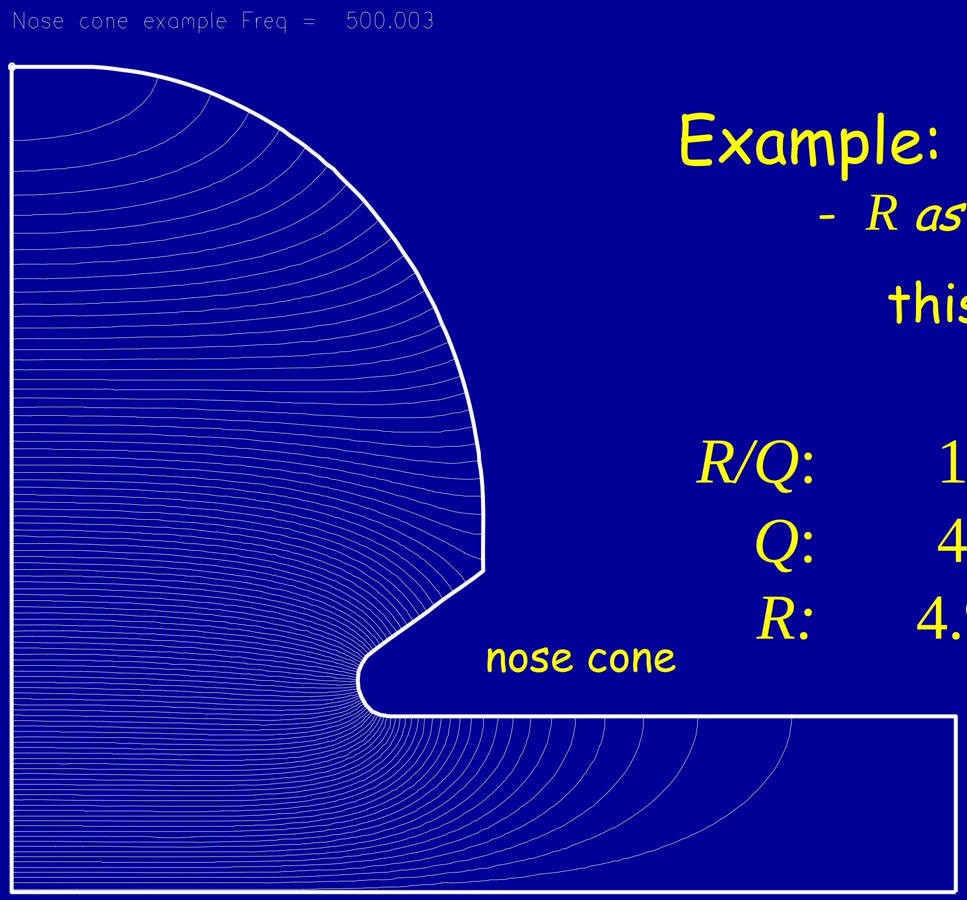
$\sqrt{L/C}$: R-upon-Q

Resonance



Reentrant cavity

Nose cones increase transit time factor, round outer shape minimizes losses.



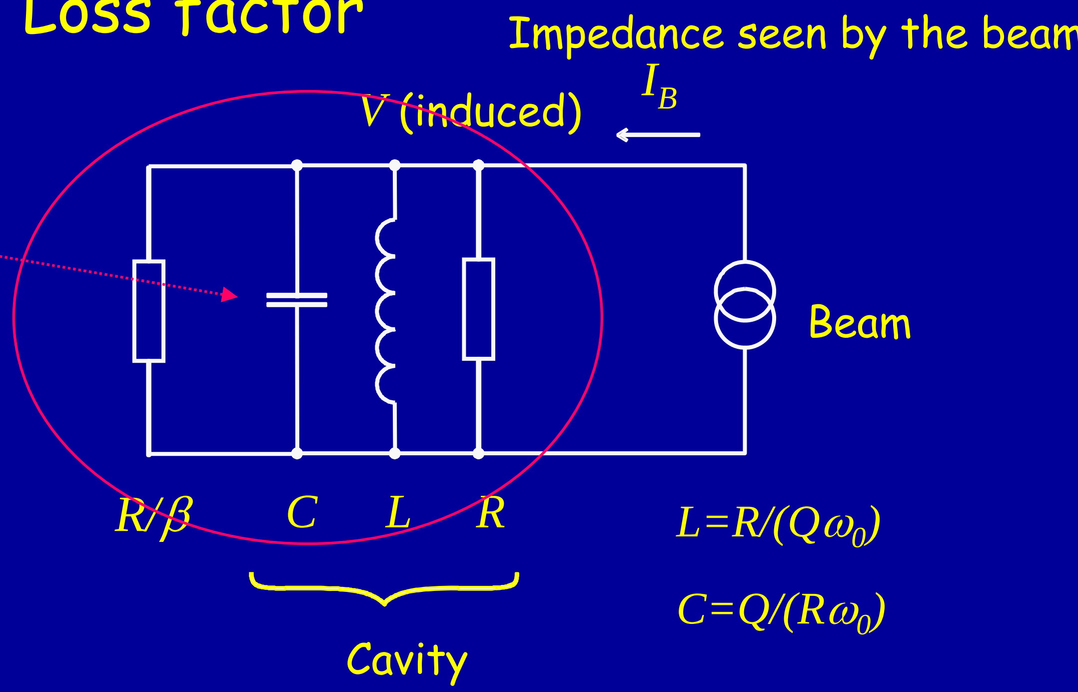
Example: KEK photon factory 500 MHz

- R as good as it gets -

	this cavity	optimized pillbox
R/Q:	111 Ω	107.5 Ω
Q:	44270	41630
R:	4.9 MΩ	4.47 MΩ

Loss factor

$$k_{loss} = \frac{\omega_0}{2}\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{4W} = \frac{1}{2C}$$

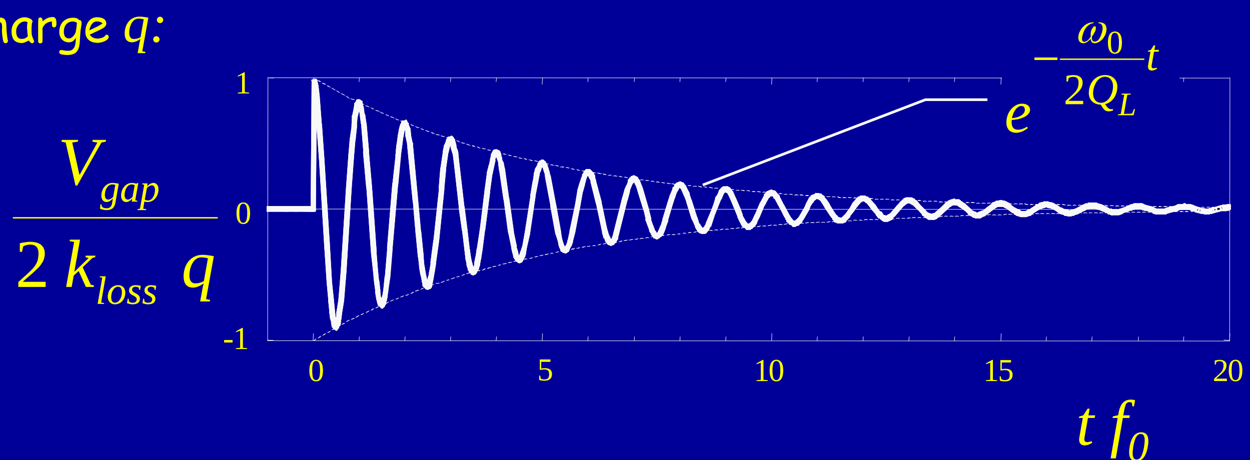


$L=R/(Q\omega_0)$

$C=Q/(R\omega_0)$

Energy deposited by a single charge q: $k_{loss}\, q^2$

Voltage induced by a single charge q:



Summary: relations V_{gap}, W, P_{loss}

gap voltage

$$\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{2\,\omega_0 W}$$

$$k_{loss} = \frac{\omega_0}{2}\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{4\,W}$$

$$R_{shunt} = \frac{\left|V_{gap}\right|^2}{2\,P_{loss}}$$

Energy stored inside the cavity

Power lost in the cavity walls

$$Q = \frac{\omega_0 W}{P_{loss}}$$

Beam loading – RF to beam efficiency

- The beam current "loads" the generator, in the equivalent circuit this appears as a resistance in parallel to the shunt impedance.
- If the generator is matched to the unloaded cavity, beam loading will cause the accelerating voltage to decrease.
- The power absorbed by the beam is $-\frac{1}{2}\mathrm{Re}\left\{V_{gap}\ I_B^*\right\}$, the power loss $P = \frac{\left|V_{gap}\right|^2}{2\,R}$.
- For high efficiency, beam loading shall be high.
- The RF to beam efficiency is $\eta = \frac{1}{1+\frac{V_{gap}}{R\left|I_B\right|}} = \frac{\left|I_B\right|}{\left|I_G\right|}$.

Characterizing cavities

- Resonance frequency

$$\omega_0 = \frac{1}{\sqrt{L \cdot C}}$$

- Transit time factor
  field varies while particle is traversing the gap

$$\frac{\left| \int E_z \, e^{\mathrm{j} \frac{\omega}{c} z} \mathrm{d}z \right|}{\left| \int E_z \mathrm{d}z \right|}$$

- Shunt impedance
  gap voltage – power relation

- Q factor

- R/Q
  independent of losses – only geometry!

- loss factor

Circuit definition

$$\left| V_{gap} \right|^2 = 2 \, R_{shunt} \, P_{loss}$$

$$\omega_0 W = Q P_{loss}$$

$$\frac{R}{Q} = \frac{\left| V_{gap} \right|^2}{2 \, \omega_0 \, W} = \sqrt{\frac{L}{C}}$$

$$k_{loss} = \frac{\omega_0}{2} \frac{R}{Q} = \frac{\left| V_{gap} \right|^2}{4 \, W}$$

Linac definition

$$\left| V_{gap} \right|^2 = R_{shunt} \, P_{loss}$$

$$\frac{R}{Q} = \frac{\left| V_{gap} \right|^2}{\omega_0 \, W}$$

$$k_{loss} = \frac{\omega_0}{4} \frac{R}{Q} = \frac{\left| V_{gap} \right|^2}{4 \, W}$$

Example Pillbox:

$$\omega_0\Big|_{pillbox} = \frac{\chi_{01}\,c}{a}$$

$$\chi_{01} = 2.4048$$

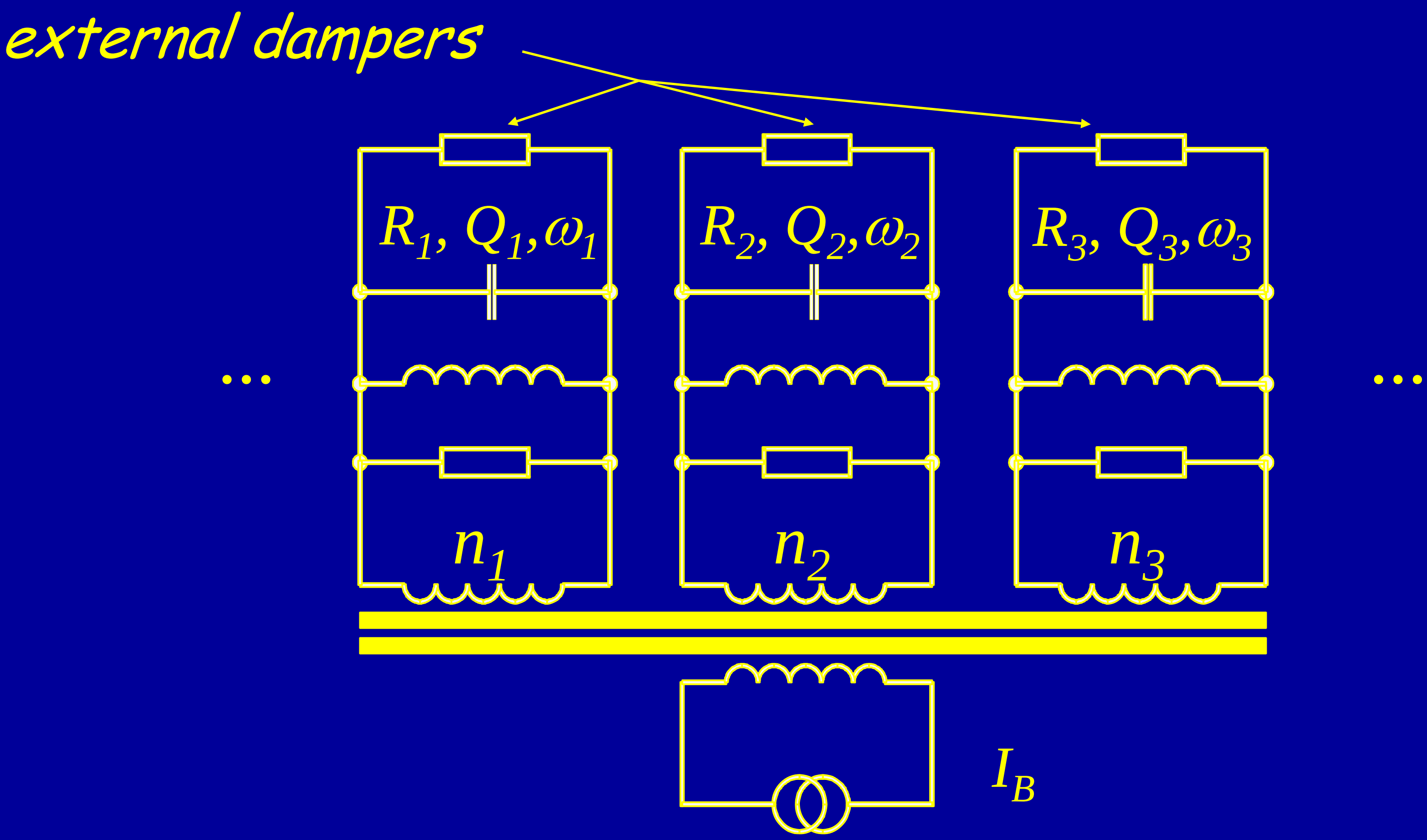
$$Q\Big|_{pillbox} = \frac{\sqrt{2a\eta\sigma\chi_{01}}}{2\left(1+\frac{a}{h}\right)}$$

$$\eta = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\,\Omega$$

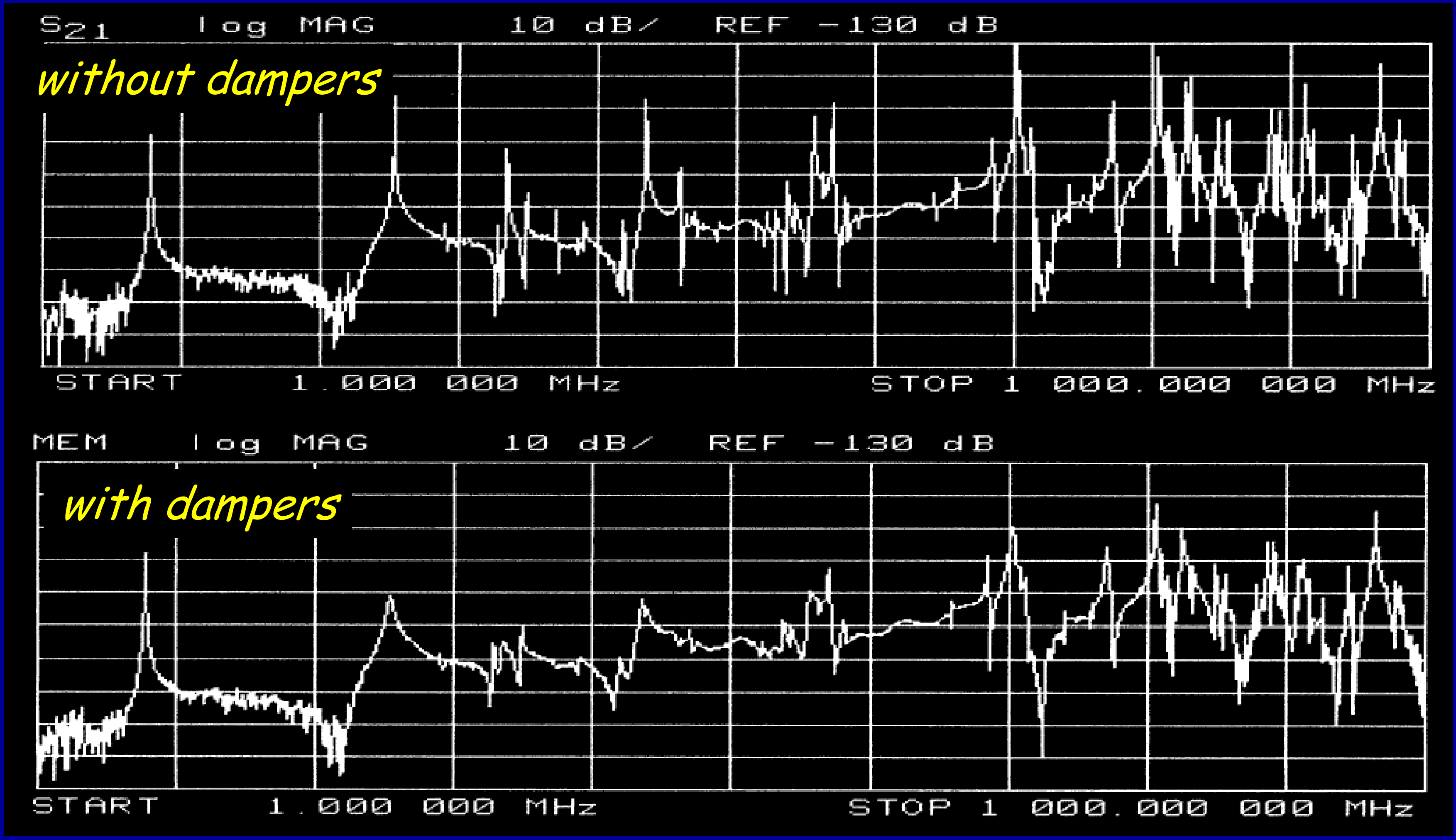
$$\sigma_{\mathrm{Cu}} = 5.8\cdot 10^7\,\mathrm{S/m}$$

$$\frac{R}{Q}\Big|_{pillbox} = \frac{4\eta}{\chi_{01}{}^3\pi\,\mathrm{J}_1^2\left(\chi_{01}\right)}\,\frac{\sin^2\left(\frac{\chi_{01}}{2}\frac{h}{a}\right)}{h/a}$$

Higher order modes

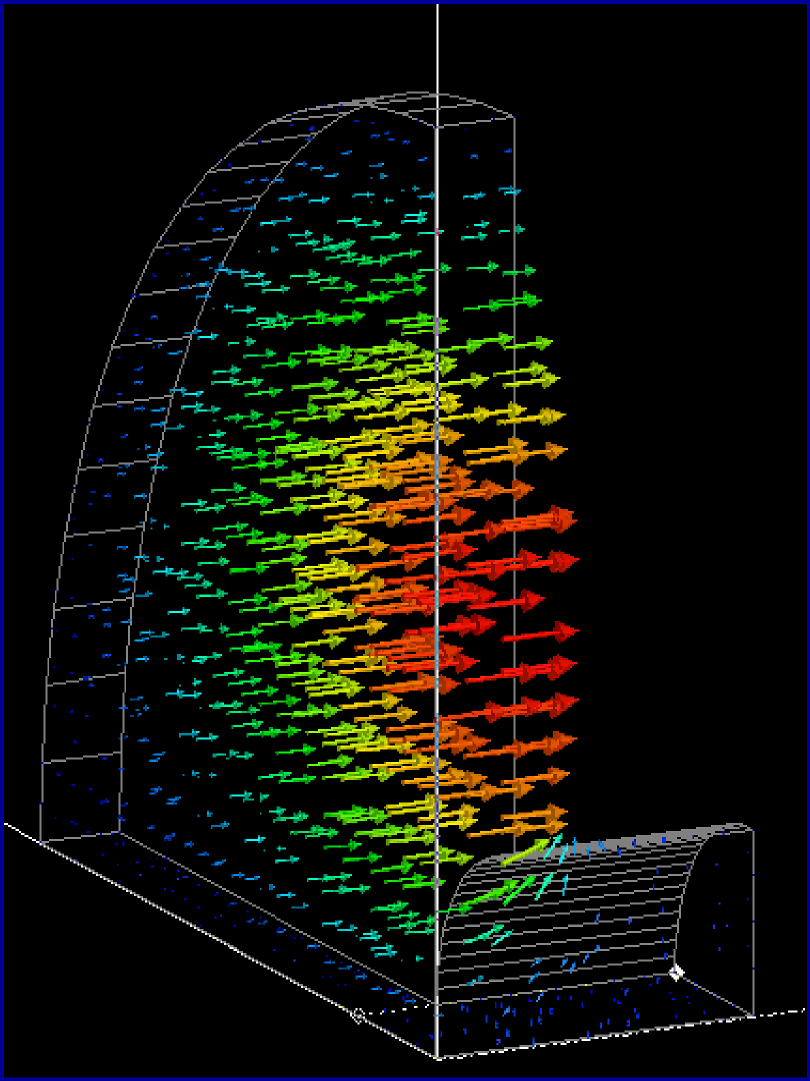


Higher order modes (measured spectrum)

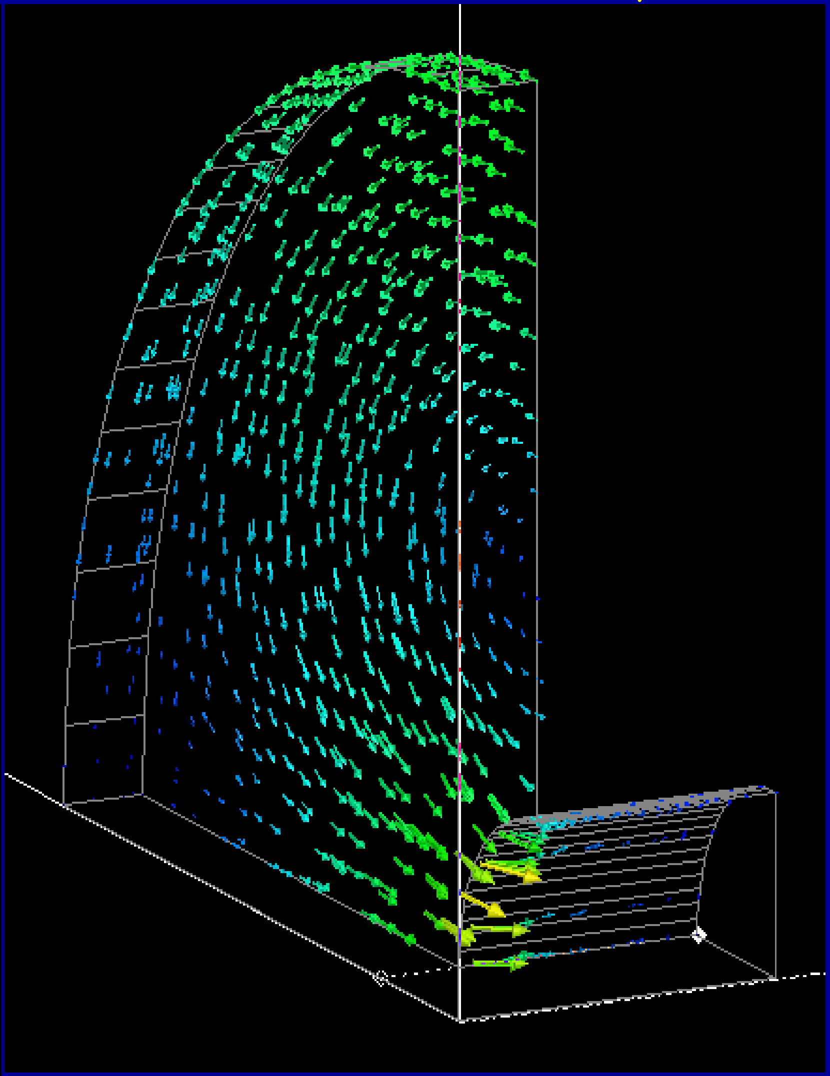


Pillbox: Dipole mode (TM_{110})

(only 1/8 shown)



electric field (@ 0°)



magnetic field (@ 90°)

Panofsky-Wenzel theorem

For particles moving virtually at $v=c$, the integrated transverse force (kick) can be determined from the transverse variation of the integrated longitudinal force!

$$\mathrm{j}\frac{\omega}{c}\vec{F}_{\perp} = \nabla_{\perp} F_{\parallel}$$

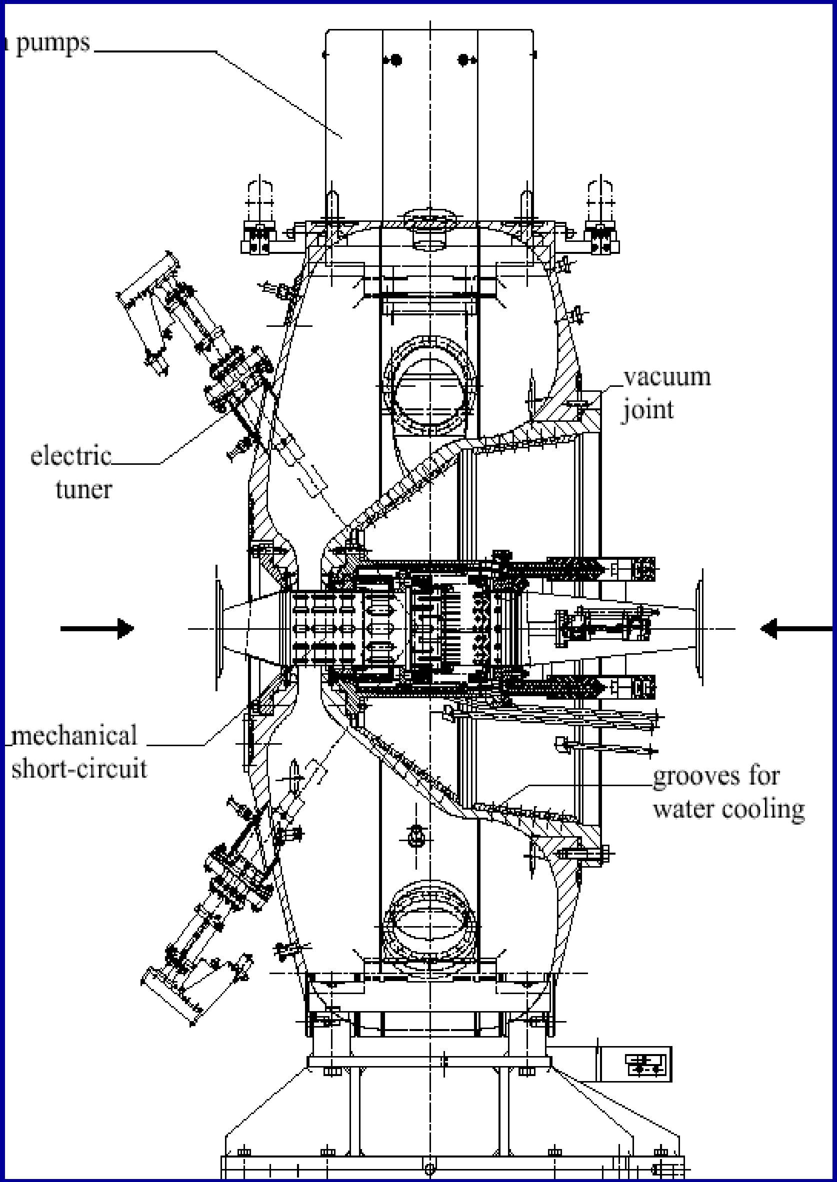
Pure TE modes: No net transverse force !

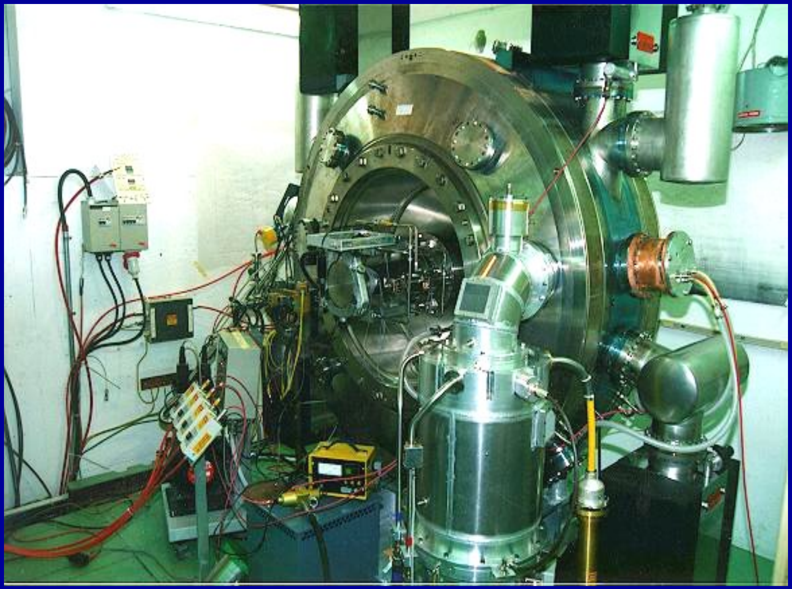
Transverse modes are characterized by

- the transverse impedance in ω-domain
- the transverse loss factor (kick factor) in t-domain !

W.K.H. Panofsky, W.A. Wenzel: "Some Considerations Concerning the Transverse Deflection of Charged Particles in Radio-Frequency Fields", RSI **27**, 1957]

CERN/PS 80 MHz cavity (for LHC)





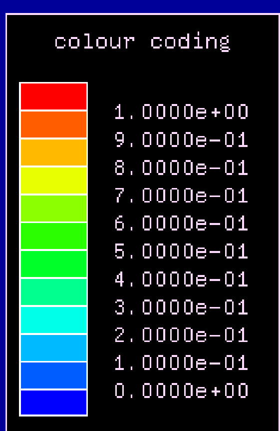
inductive (loop) coupling, low self-inductance

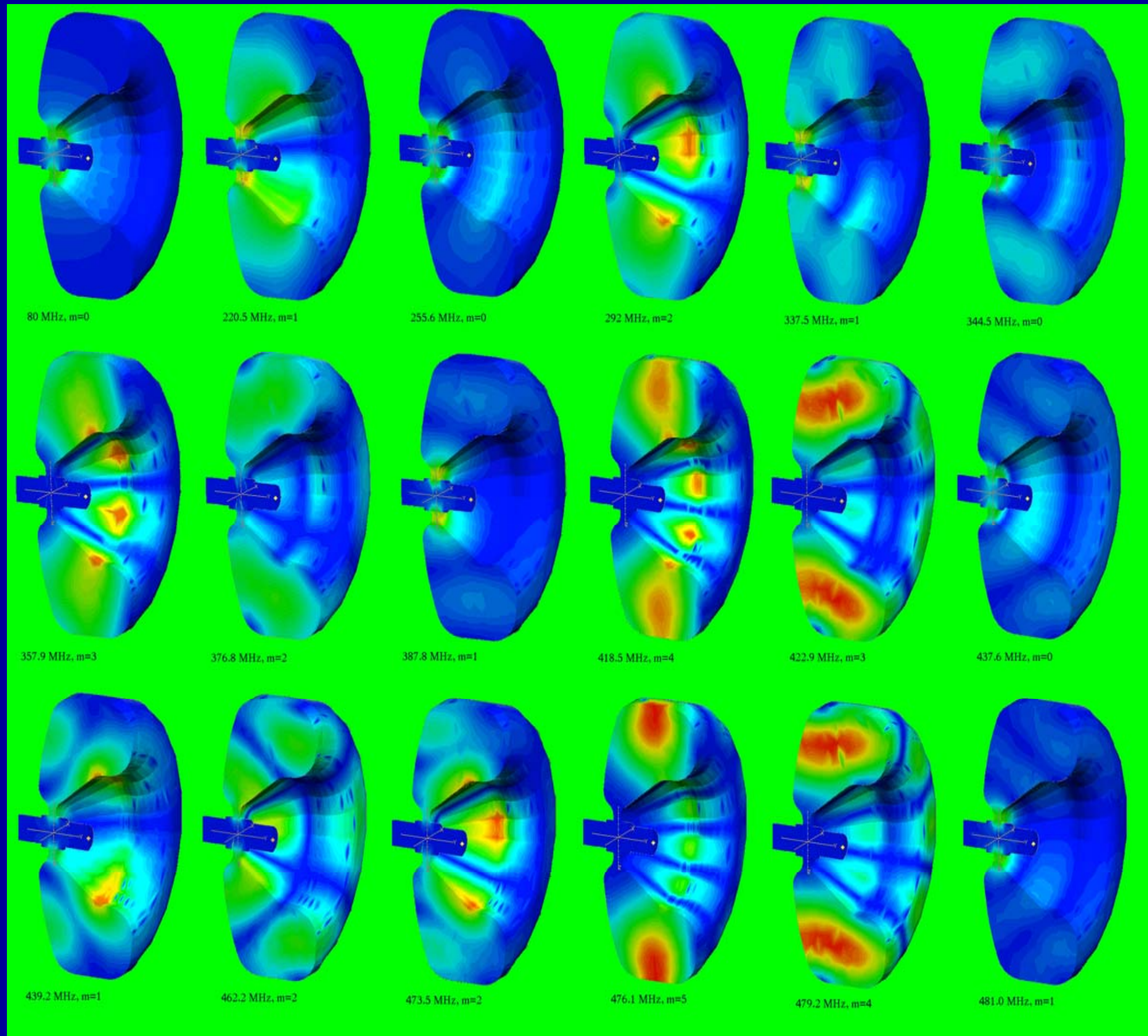
Higher order modes

Example shown: 80 MHz cavity PS for LHC.

Color-coded:

$$\left|\vec{E}\right|$$



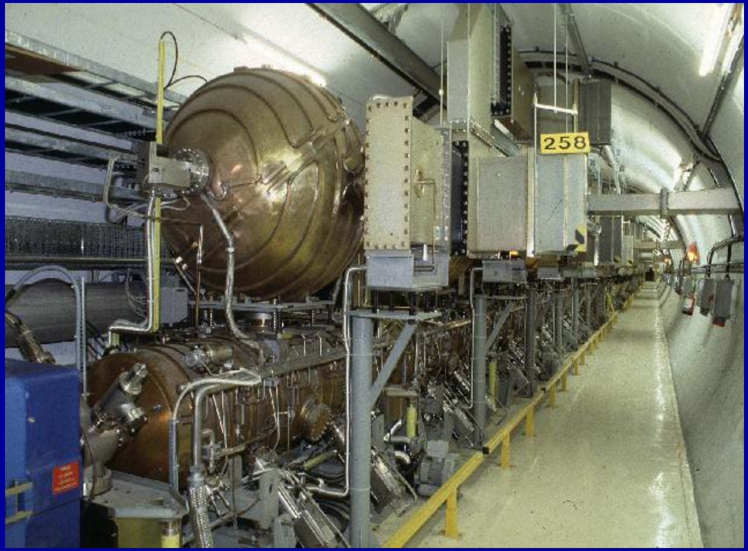


More examples of cavities

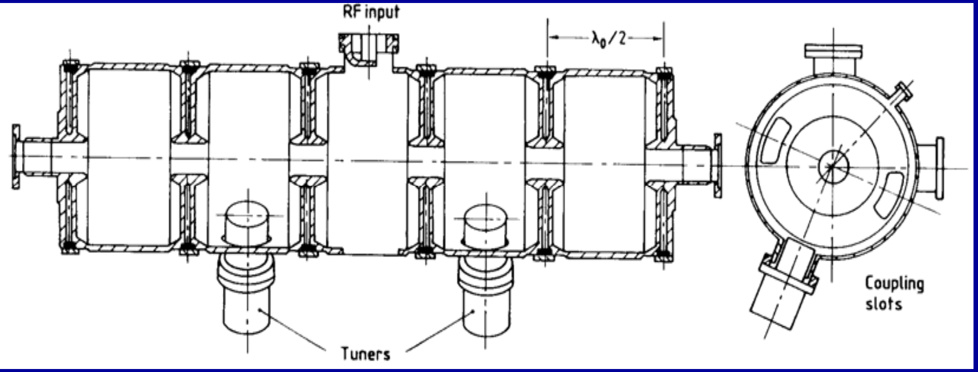
PS 19 MHz cavity (prototype, photo: 1966)

Examples of cavities

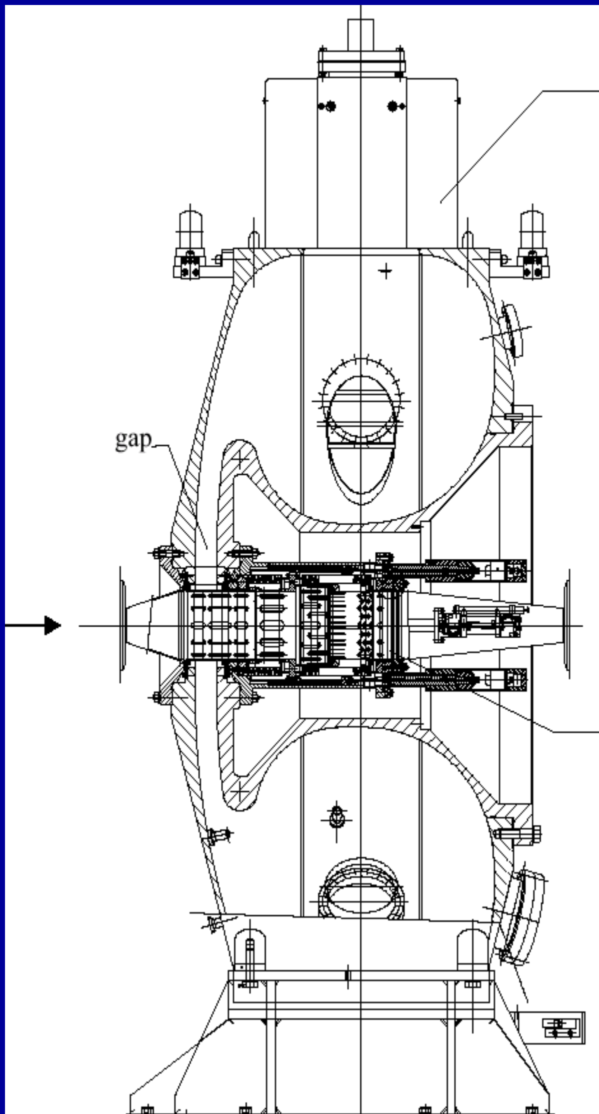
PEP II cavity
476 MHz, single cell,
1 MV gap with 150 kW,
strong HOM damping,

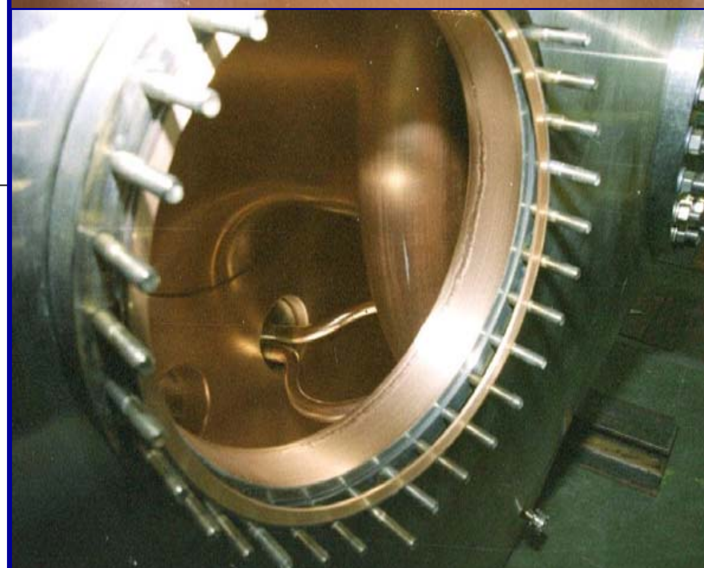


LEP normal-conducting Cu RF cavities,
350 MHz. 5 cell standing wave + spherical
cavity for energy storage, 3 MV



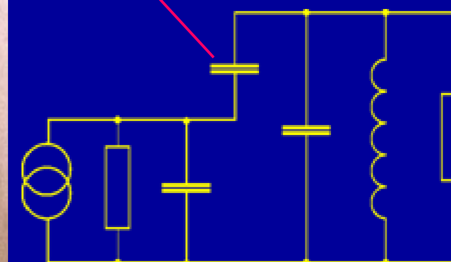
CERN/PS 40 MHz cavity (for LHC)





example for capacitive coupling

coupling C



cavity

RF power sources

RF Power sources

> 200 MHz: Klystrons

Thales TH1801, Multi-Beam Klystron (MBK), 1.3 GHz, 117 kV. Achieved:
48 dB gain, 10 MW peak, 150 kW average, η = 65 %

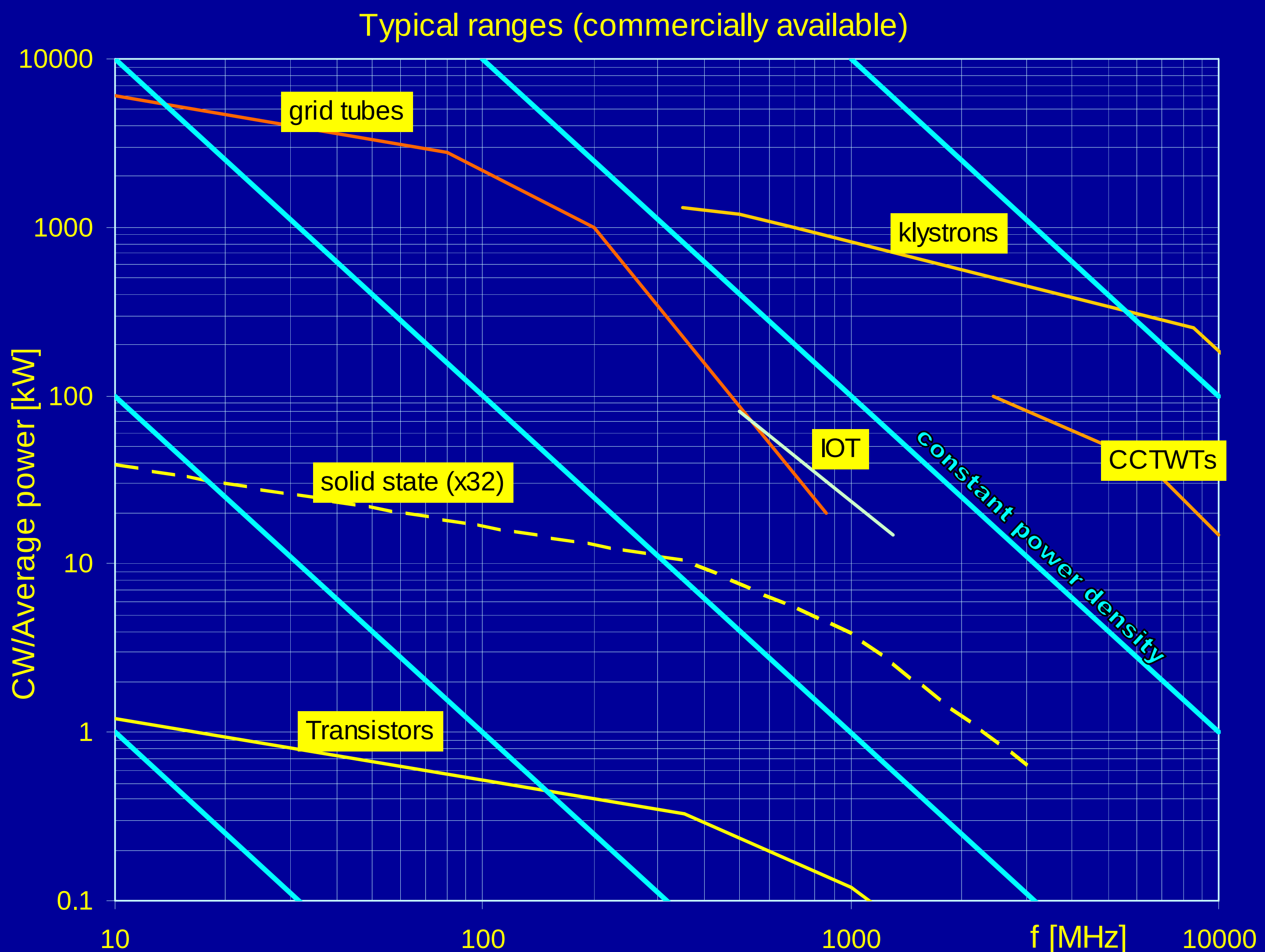
dB: $\frac{output\ power}{input\ power} = 10^{4.8}$

< 1000 MHz: grid tubes

Tetrode IOT UHF Diacrode

pictures from http://www.thales-electrondevices.com

RF power sources



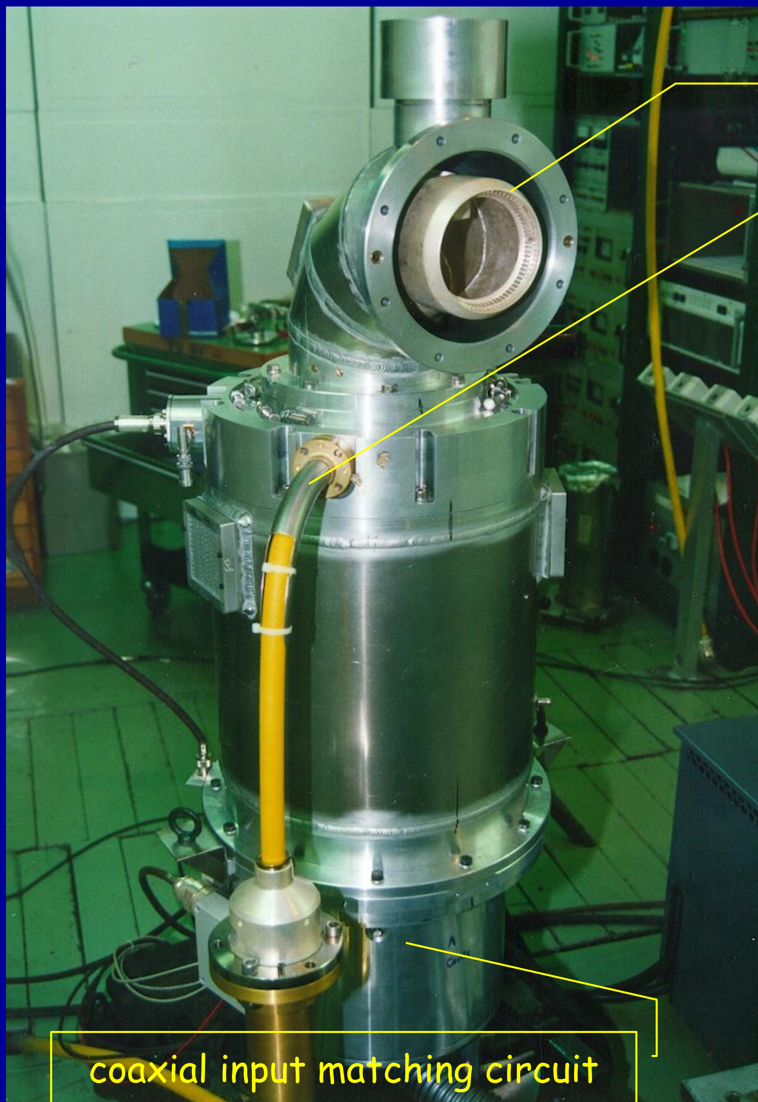
Example of a tetrode amplifier (80 MHz, CERN/PS)

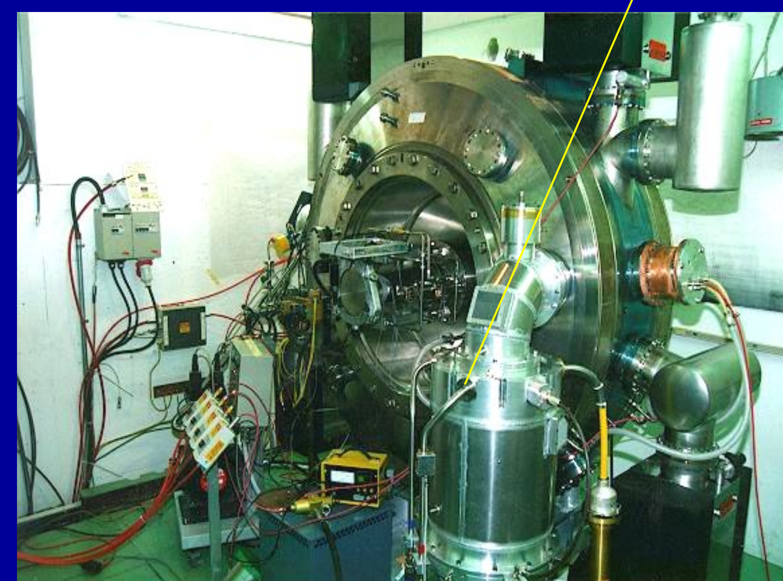
400 kW, with fast RF feedback

18 Ω coaxial output (towards cavity)

22 kV DC anode voltage feed-through with $\lambda/4$ stub

tetrode cooling water feed-throughs

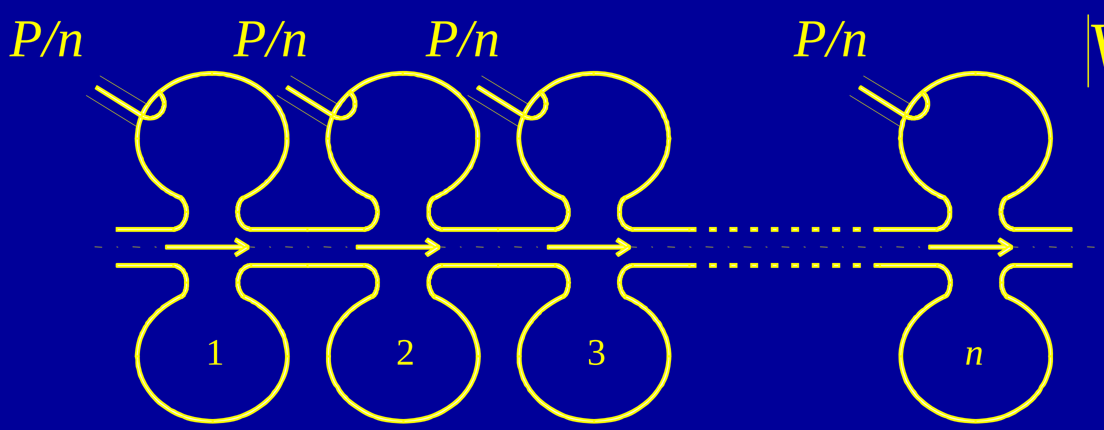




Many gaps

What do you gain with many gaps?

- The R/Q of a single gap cavity is limited to some 100 Ω. Now consider to distribute the available power to n identical cavities: each will receive P/n, thus produce an accelerating voltage of $\sqrt{2R\,P/n}$.
The total accelerating voltage thus increased, equivalent to a total equivalent shunt impedance of nR.

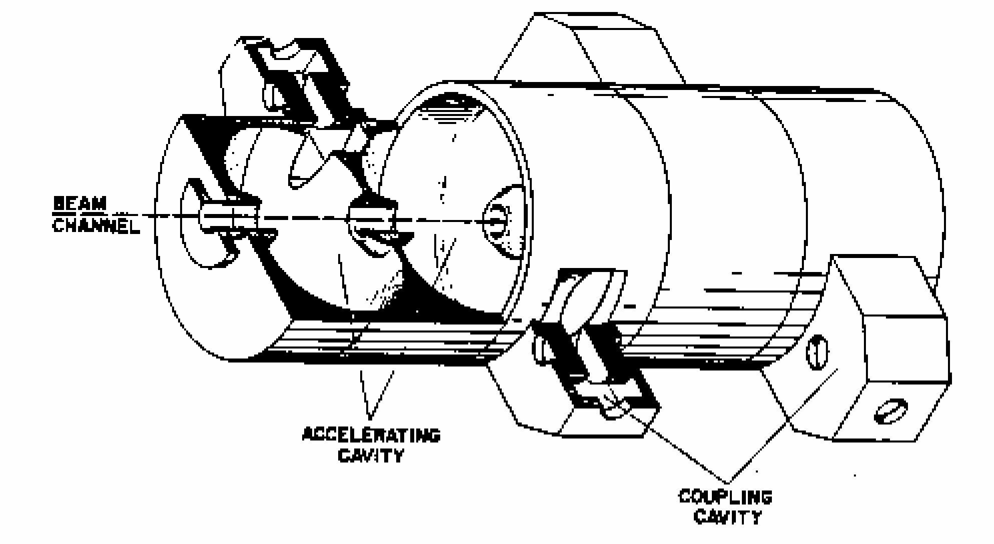


$$|V_{acc}| = n\sqrt{2R\frac{P}{n}} = \sqrt{2(nR)P}$$

Standing wave multicell cavity

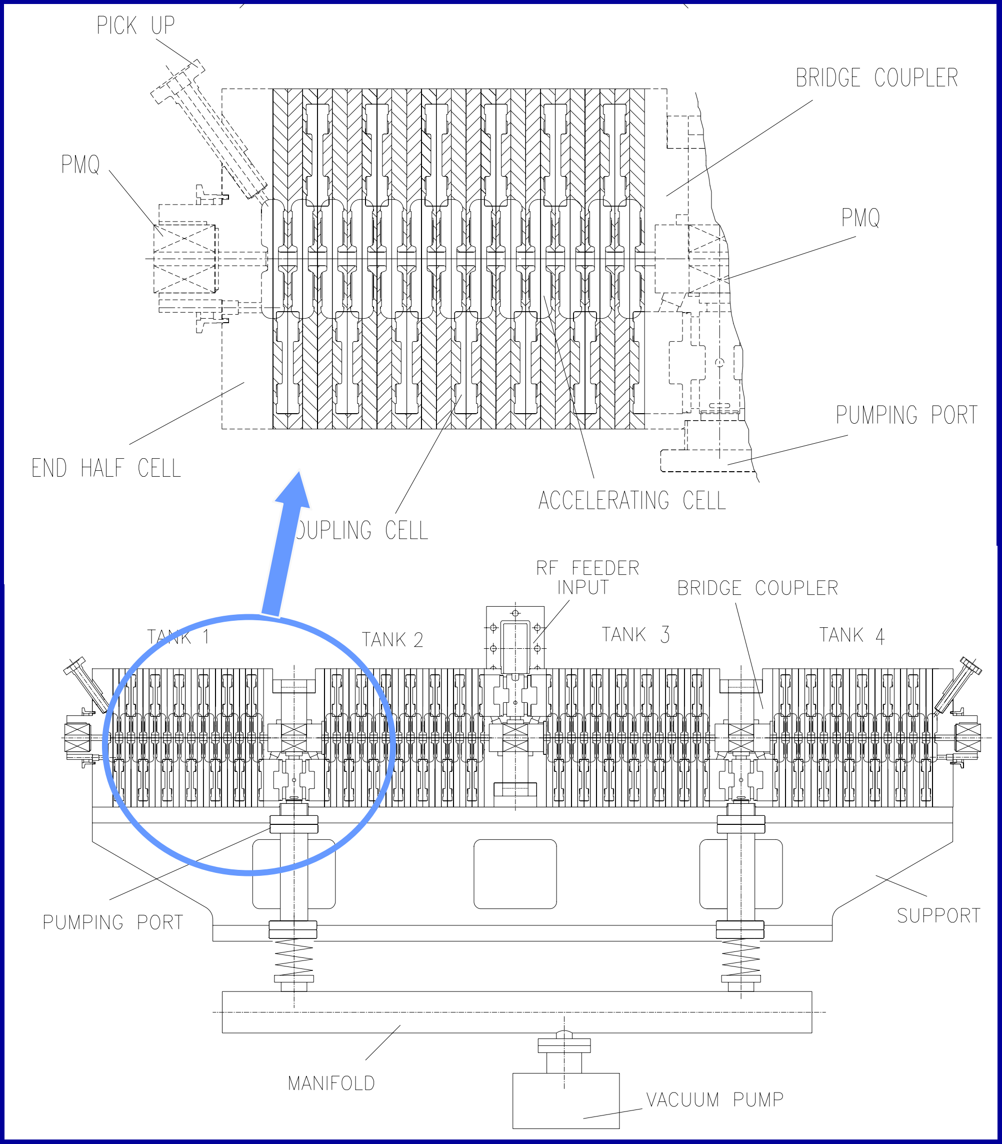
- Instead of distributing the power from the amplifier, one might as well couple the cavities, such that the power automatically distributes, or have a cavity with many gaps (e.g. drift tube linac).

- Coupled cavity accelerating structure (side coupled)



- The phase relation between gaps is important!

An example of Side Coupled Structure : LIBO (= Linac Booster)



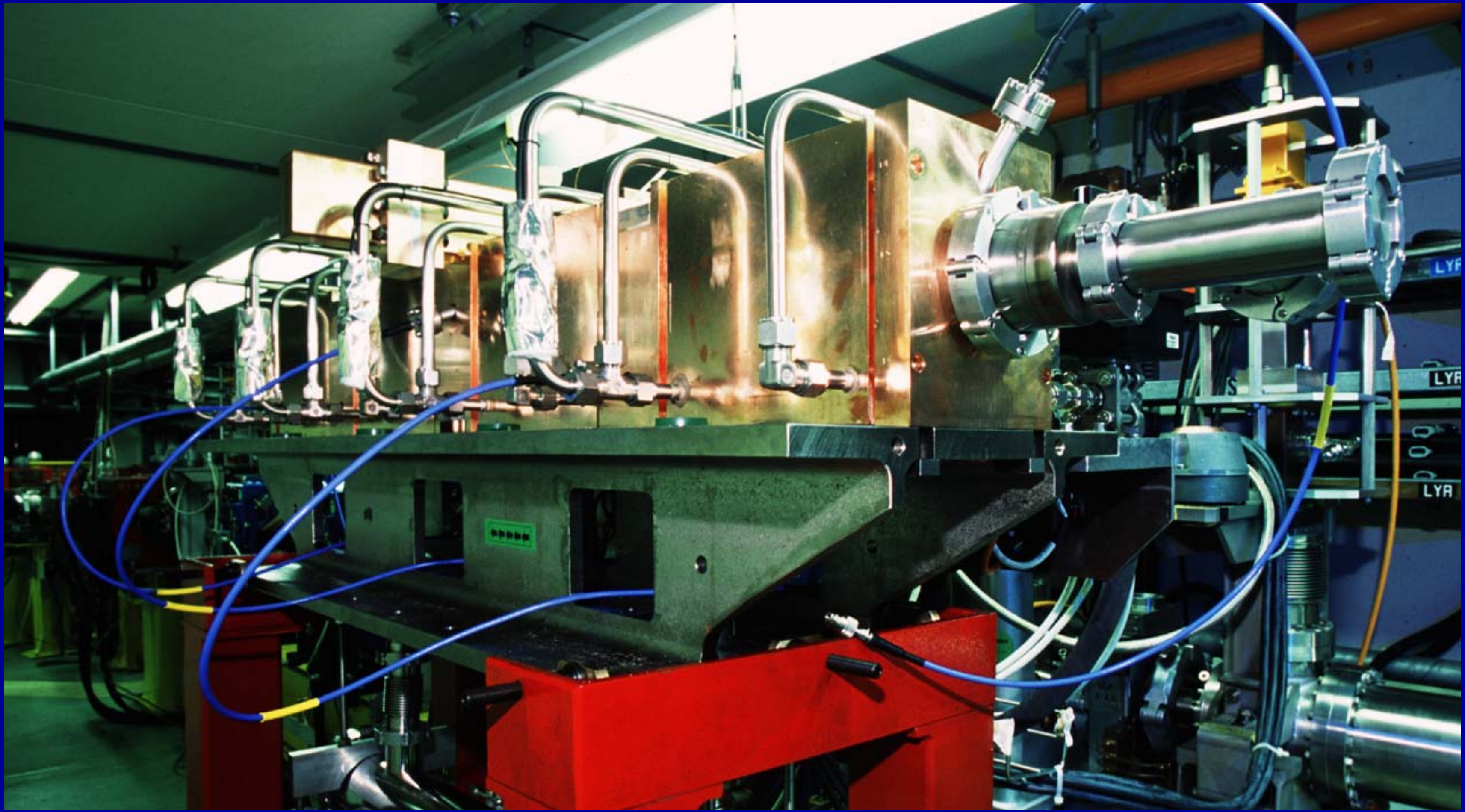
A 3 GHz Side Coupled Structure to accelerate protons out of cyclotrons from 62 MeV to 200 MeV

Medical application: treatment of tumours.

Prototype of Module 1 built at CERN (2000)

Collaboration CERN/INFN/ Tera Foundation

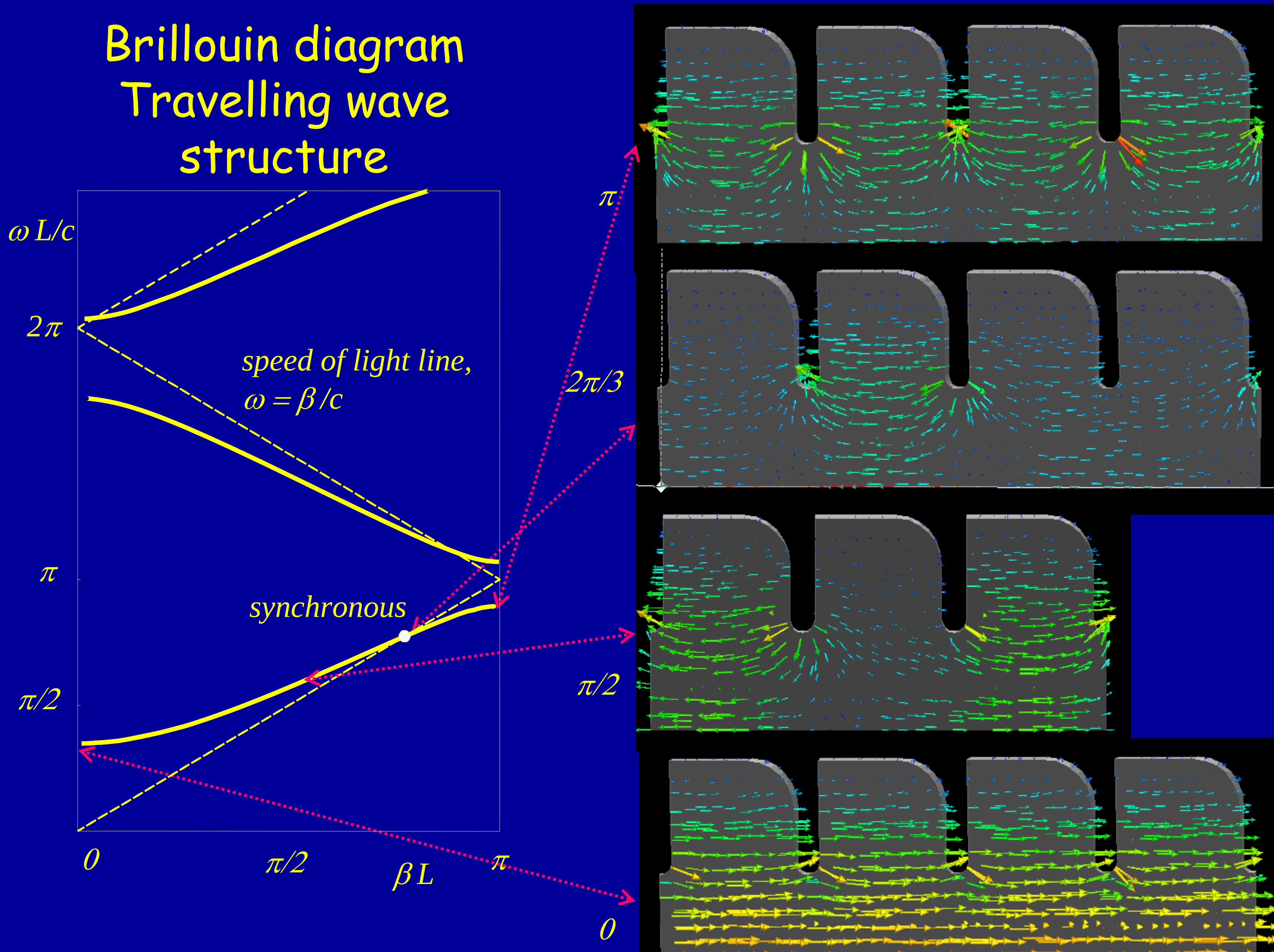
LIBO prototype



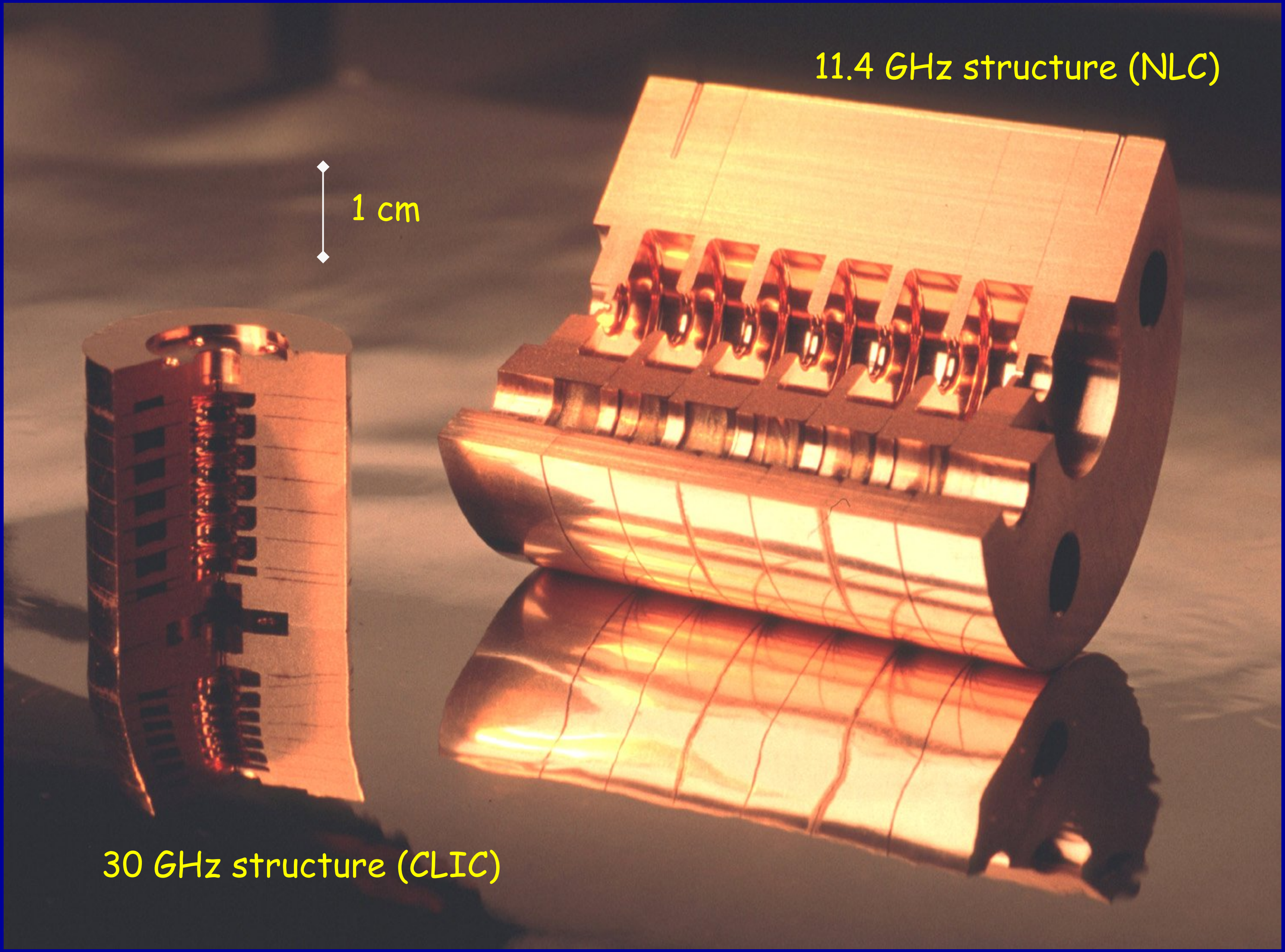
This Picture made it to the title page of CERN Courier vol. 41 No. 1 (Jan./Feb. 2001)

Travelling wave structures

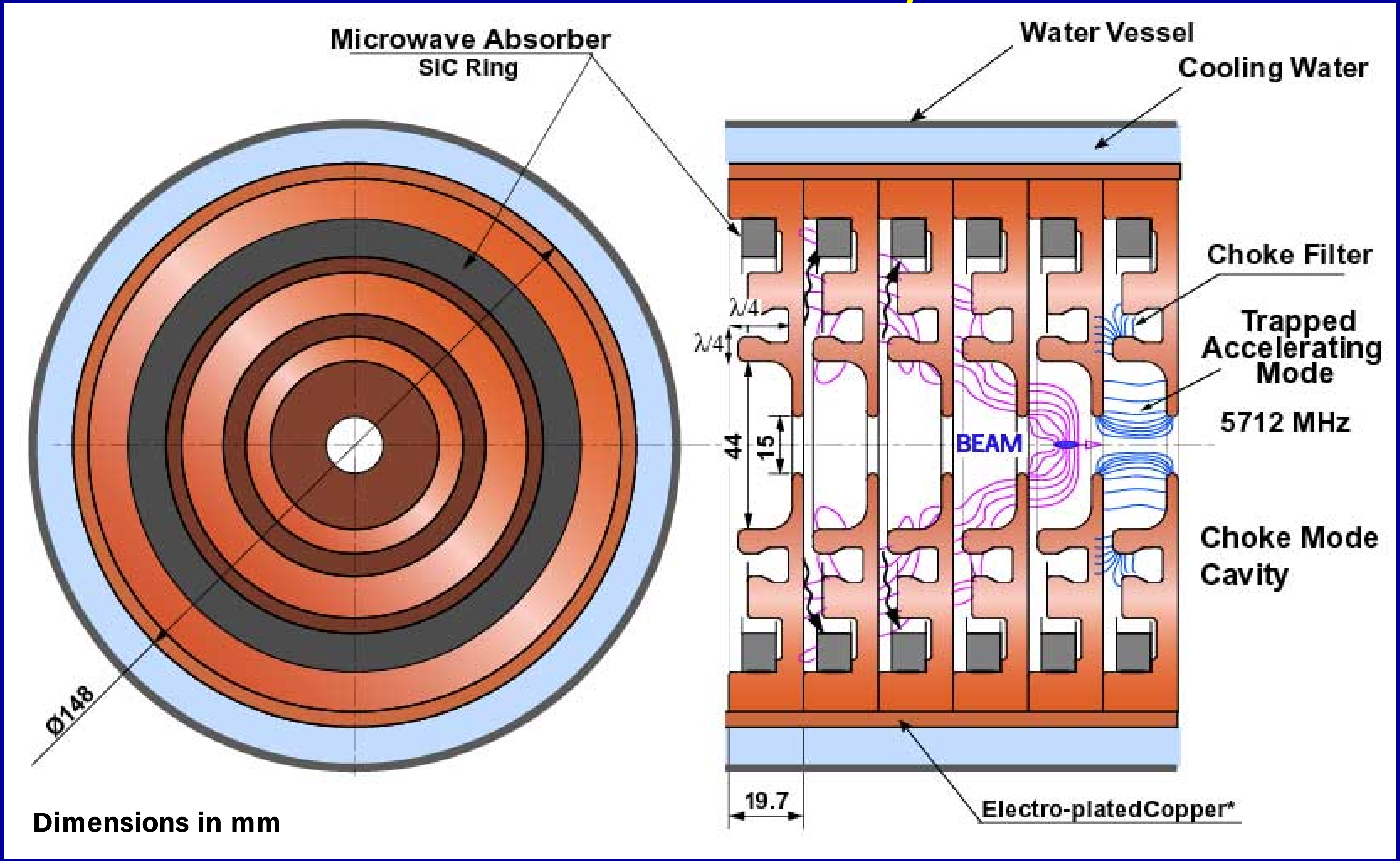
Brillouin diagram
Travelling wave structure



Iris loaded waveguide

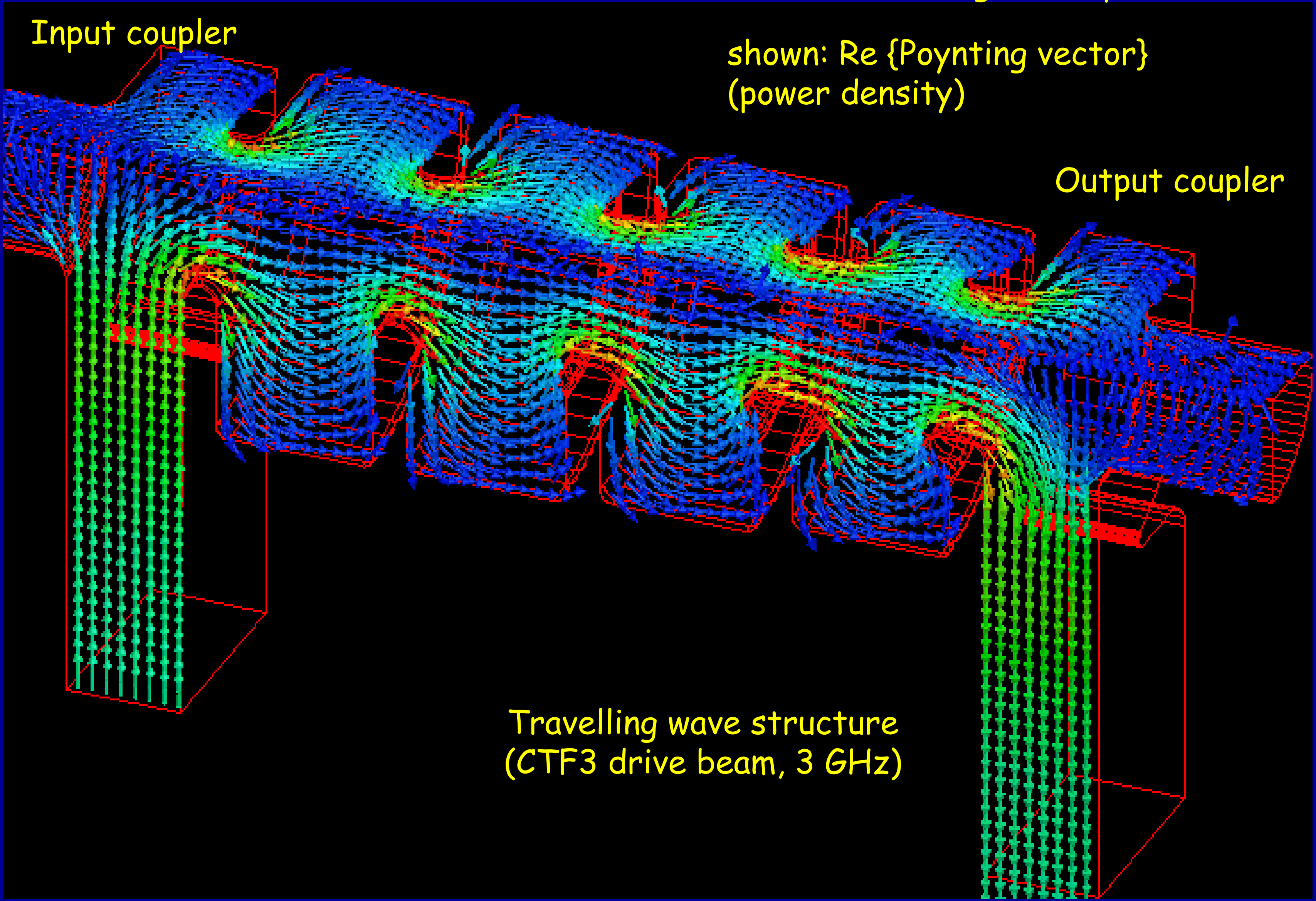


Disc loaded structure with strong HOM damping "choke mode cavity"

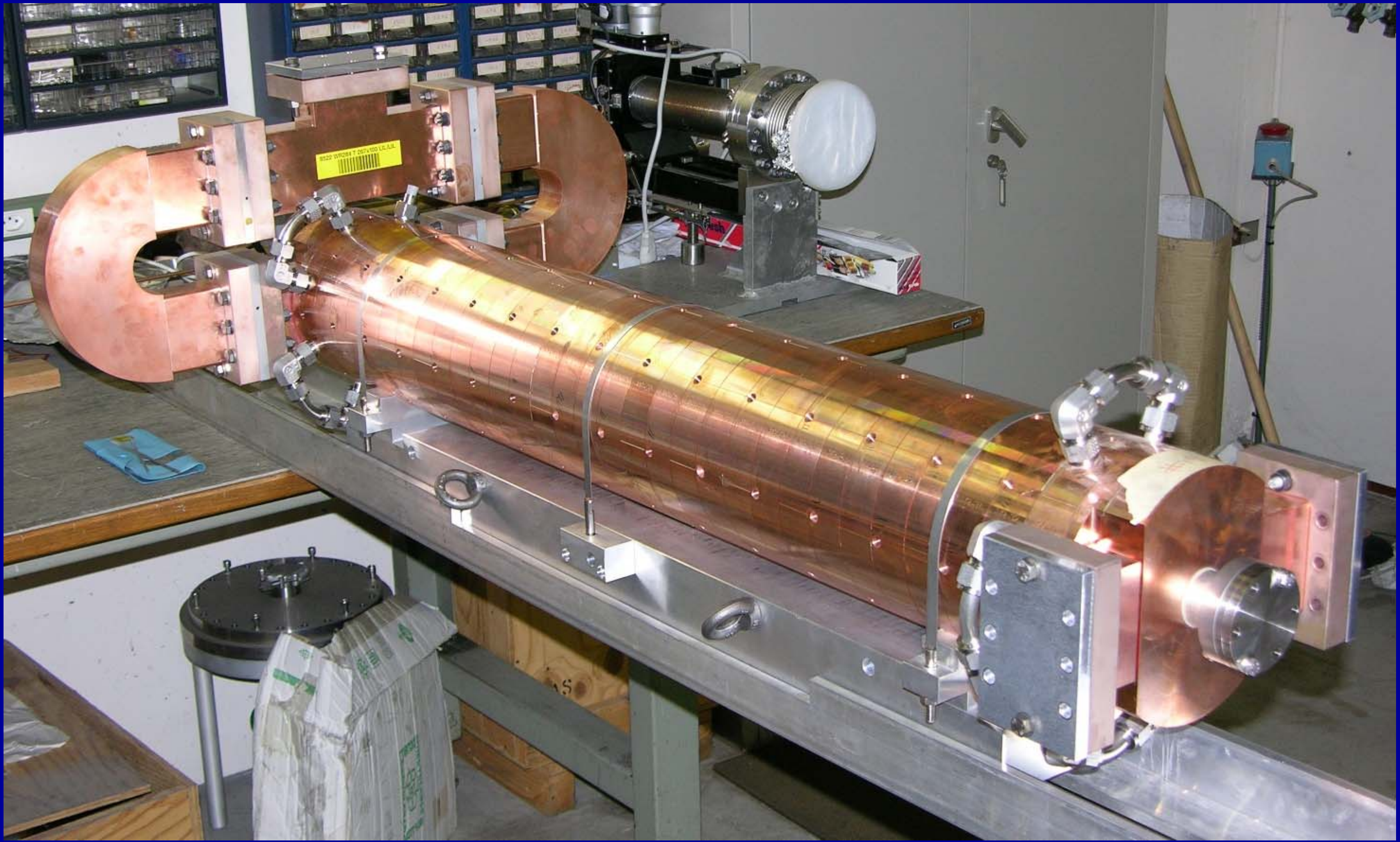


Waveguide coupling

$\frac{1}{4}$ geometry shown



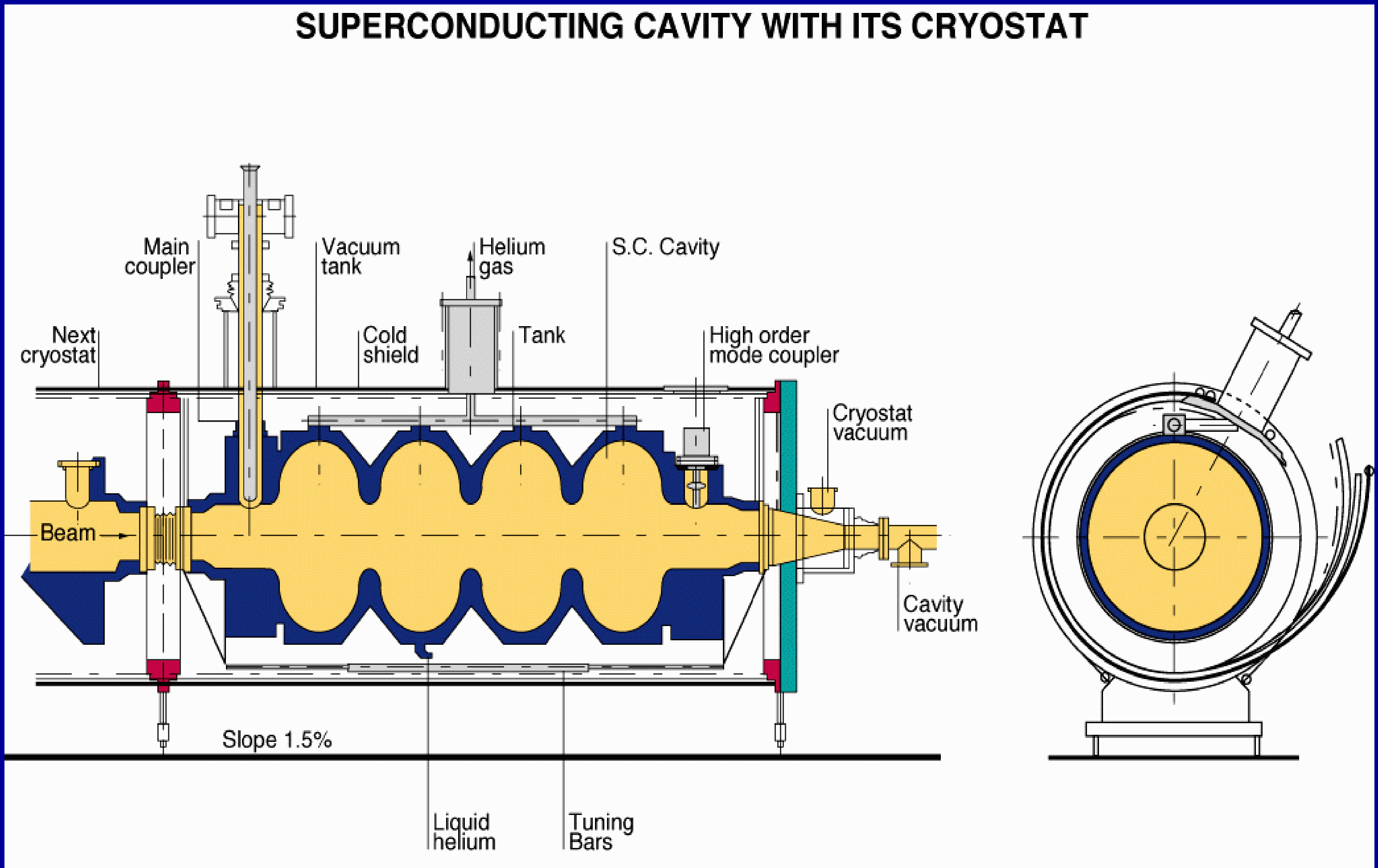
3 GHz Accelerating structure (CTF3)



Superconducting Linacs

LEP was not a linac, but still ...

LEP Superconducting cavities

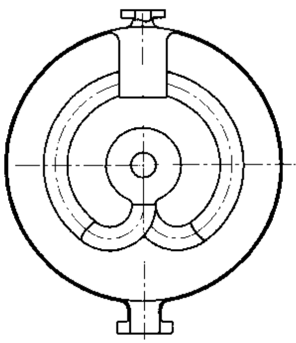


10.2 MV/ per cavity

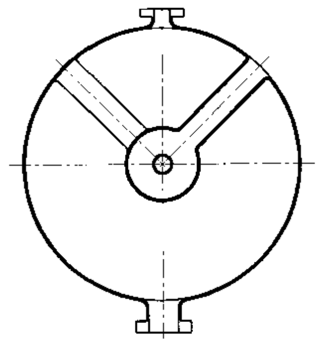
LHC SC RF, 4 cavity module, 400 MHz

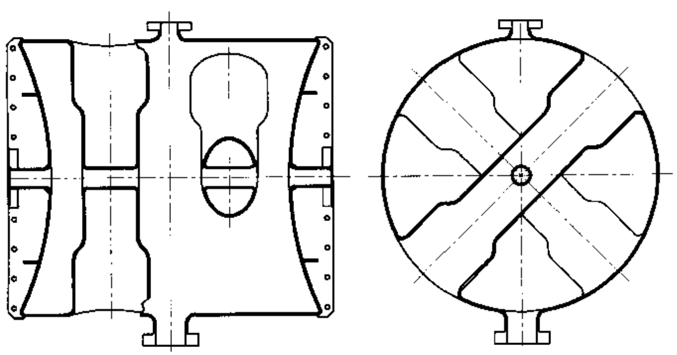
Small β superconducting cavities (example RIA, Argonne)

115 MHz split-ring cavity,



172.5 MHz $\beta = 0.19$ "lollipop" cavity





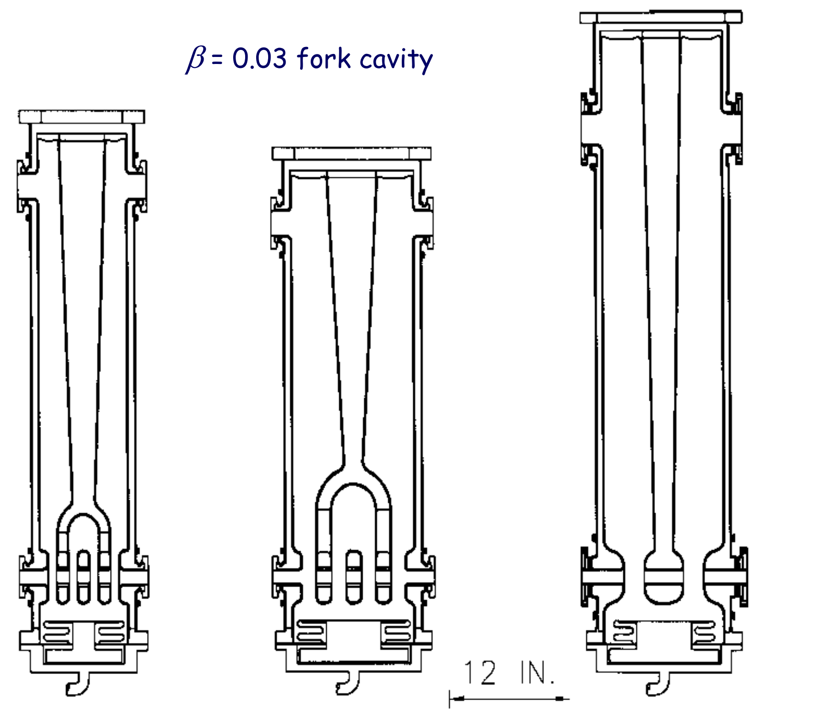
345 MHz $\beta = 0.4$ spoke cavity

57.5 MHz cavities:

$\beta = 0.06$ QWR (quarter wave resonator)

$\beta = 0.03$ fork cavity

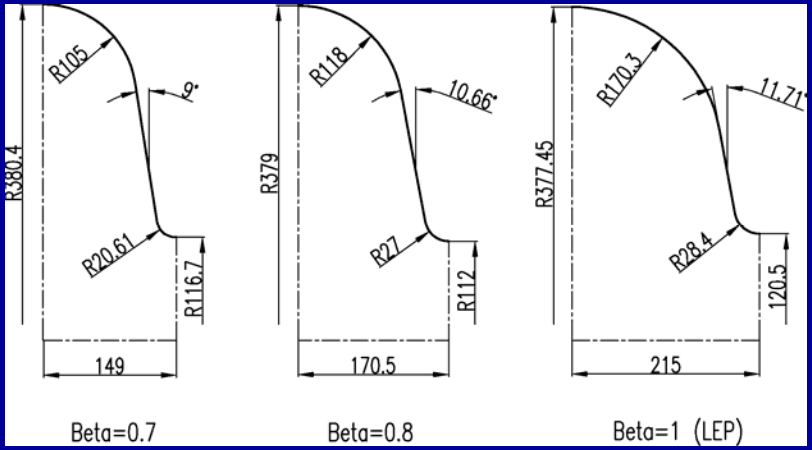
$\beta = 0.021$ fork cavity

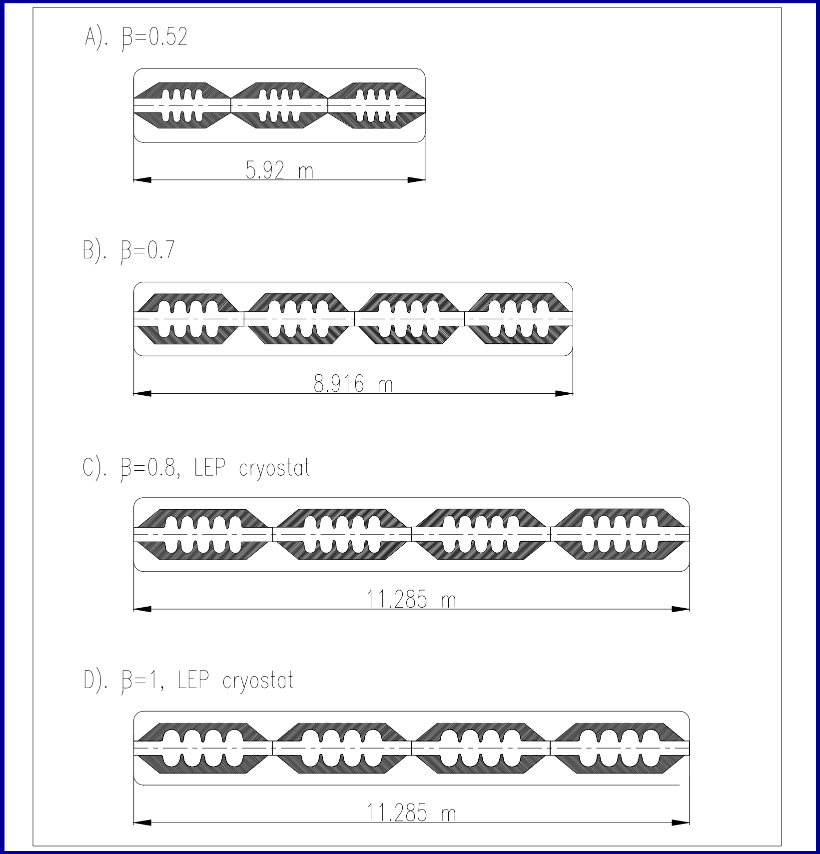


pictures from Shepard et al.: "Superconducting accelerating structures for a multi-beam driver linac for RIA", Linac 2000, Monterey

More superconducting cavities for linacs with $\beta < 1$ (proton driver - heavy ion)

Need to standardise construction of cavities:
only few different types of cavities are made for some β's
more cavities are grouped in cryostats



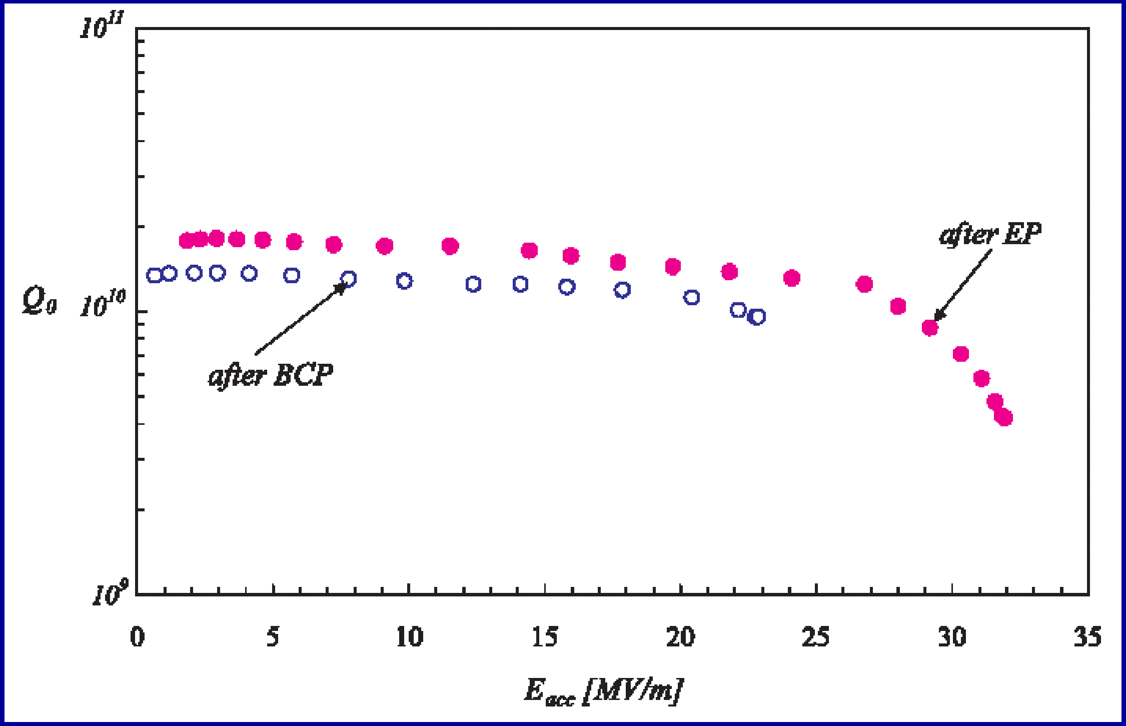


Example:
CERN design, SC linac 120 - 2200 MeV

ILC high gradient SC Linac at 1.3 GHz

Technology has made big progress, > 40 MV/m accelerating gradient have been obtained. The plot below illustrates the effect of "buffered chemical polishing" and "electro-polishing".

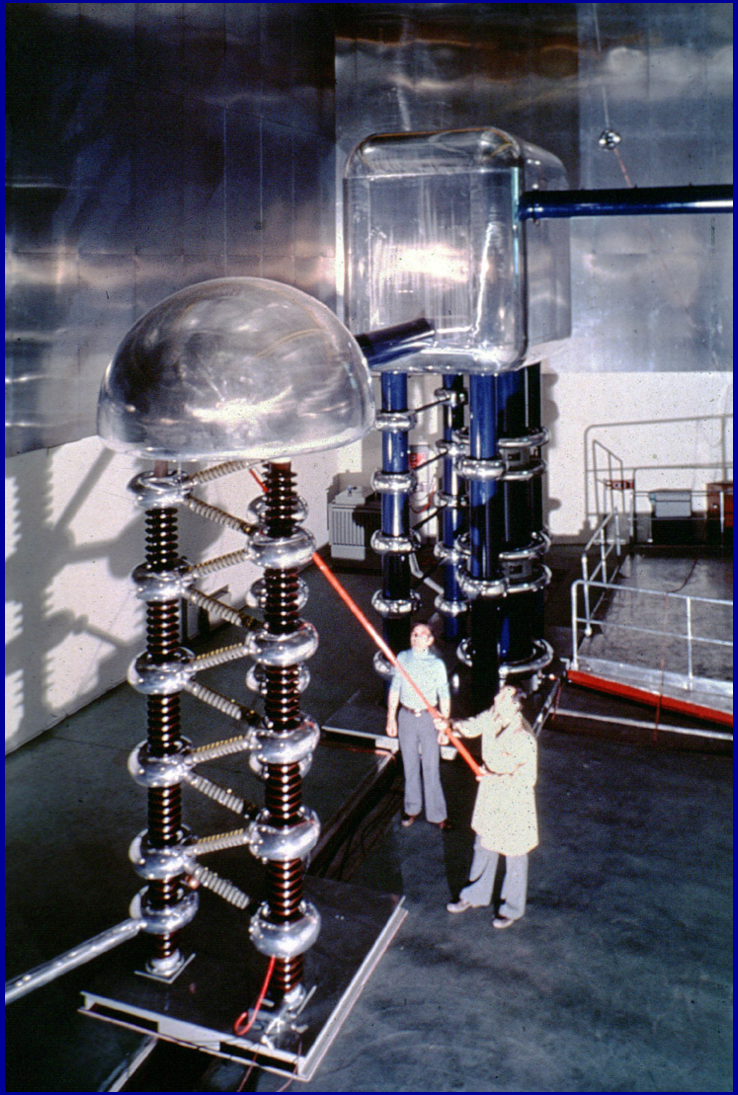
ILC 9-cell Niobium cavity



More on the ILC at http://www.linearcollider.org/cms/

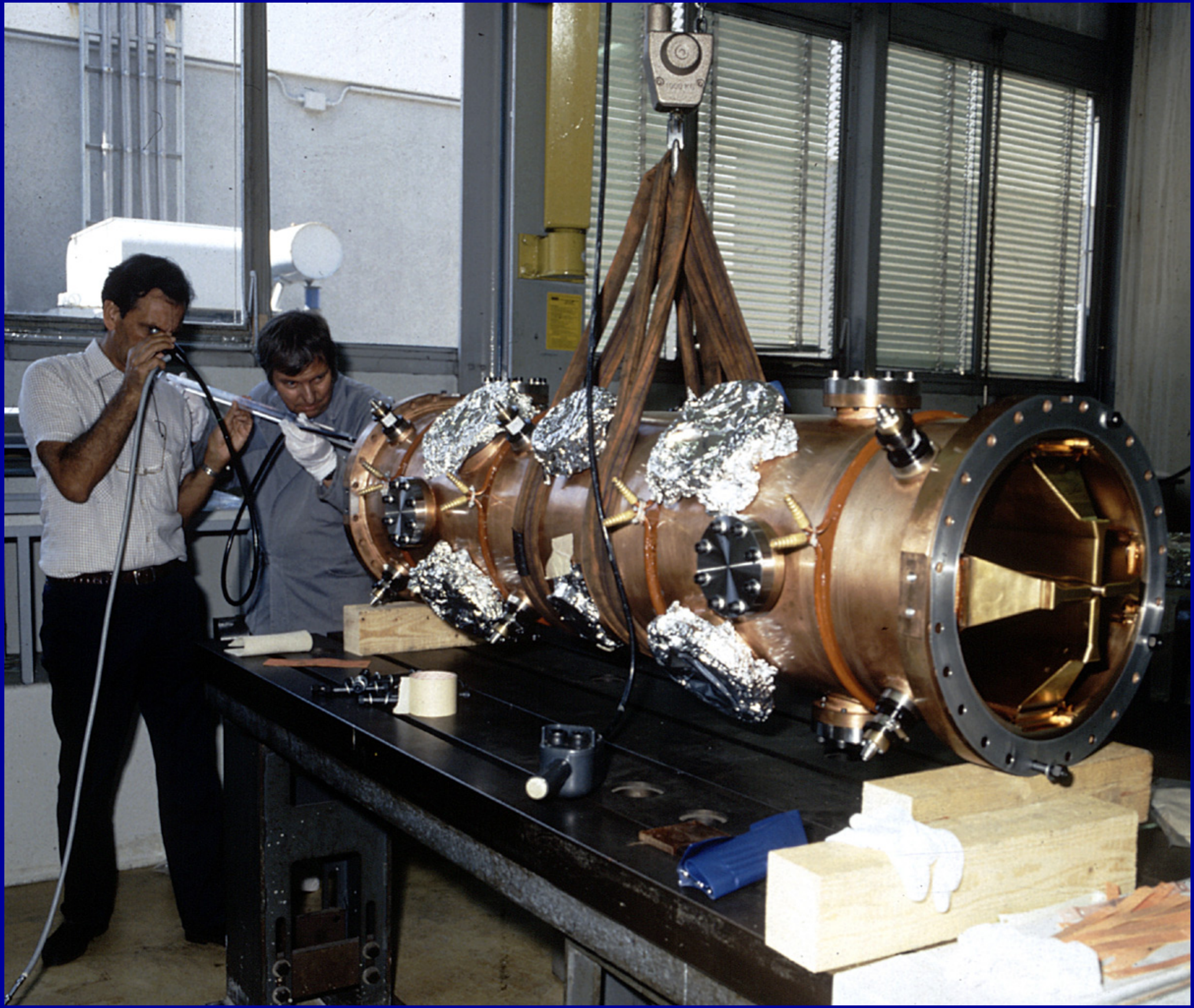
RFQ's

Old preinjector 750 kV DC , CERN Linac 2 before 1990



All this was replaced by the RFQ …

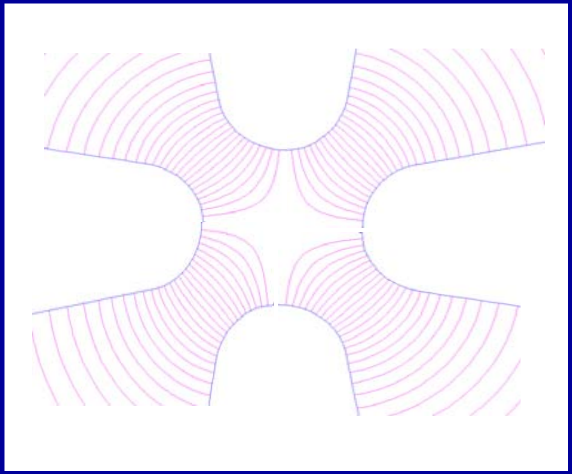
RFQ of CERN Linac 2

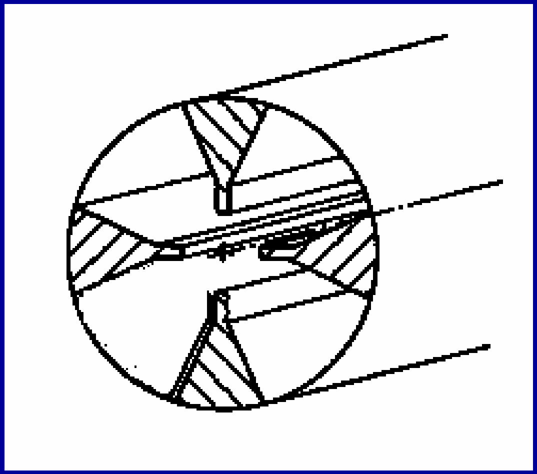


The Radio Frequency Quadrupole (RFQ)

Minimum Energy of a DTL: 500 keV (low duty) - 5 MeV (high duty)
At low energy / high current we need strong focalisation
Magnetic focusing (proportional to β) is inefficient at low energy.
Solution (Kapchinski, 70's, first realised at LANL):

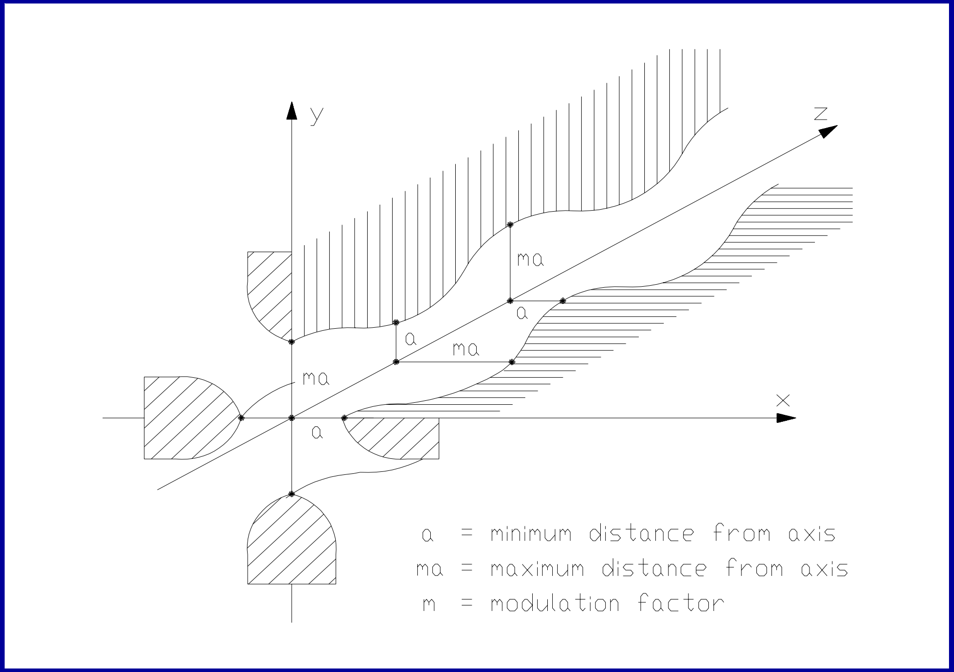
<u>Electric quadrupole focusing + bunching + acceleration</u>

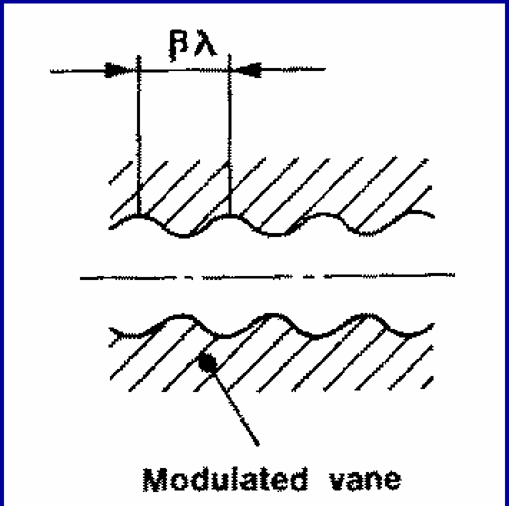




RFQ electrode modulation

The electrode modulation creates a longitudinal field component that creates the "bunches" and accelerates the beam.





A look inside CERN AD's "RFQD"