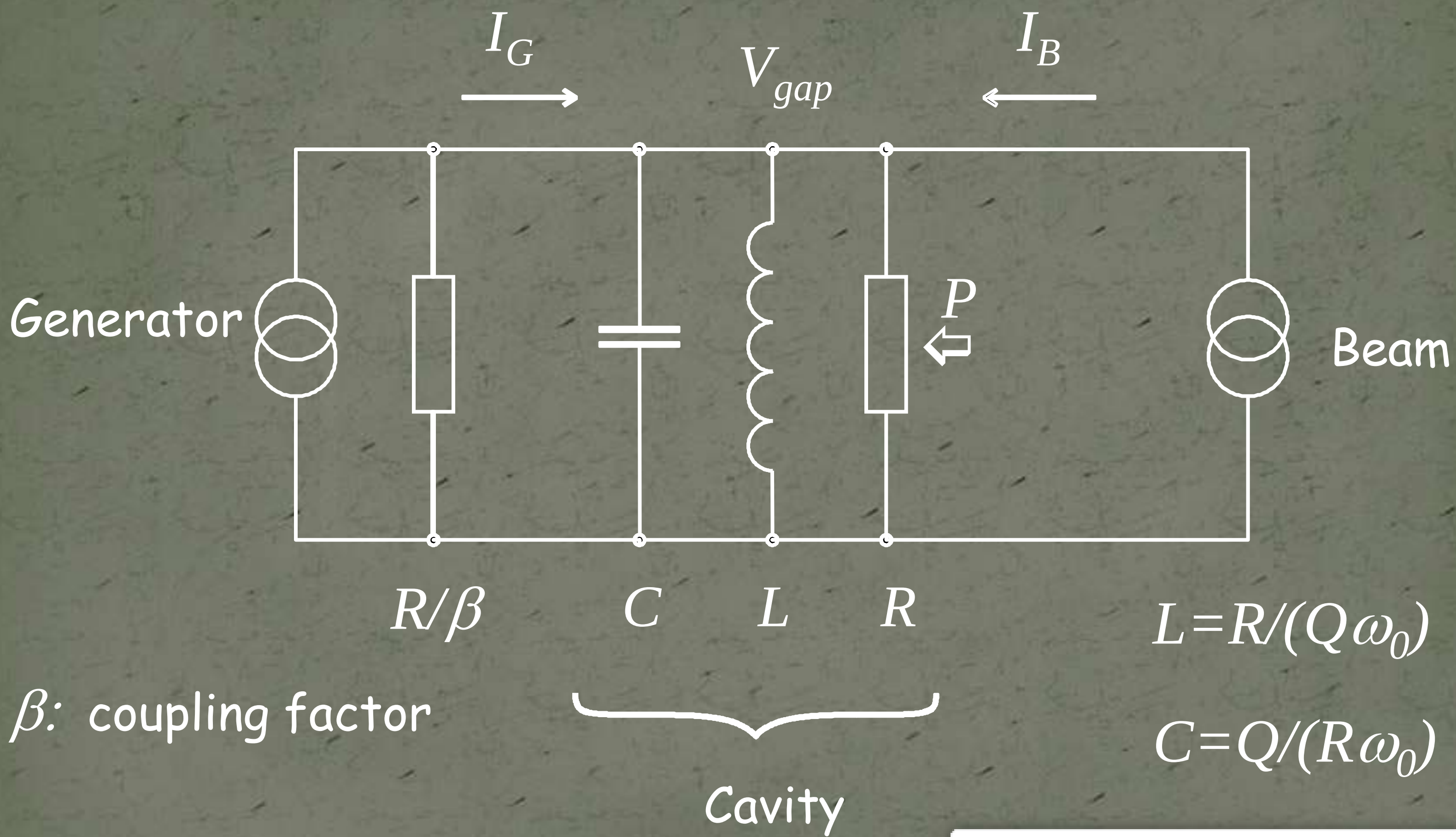
RF, part II

Erk Jensen, CERN BE-RF

Characterizing a cavity

Cavity resonator – equivalent circuit

Simplification: single mode



$L = R/(Q\omega_0)$

$C = Q/(R\omega_0)$

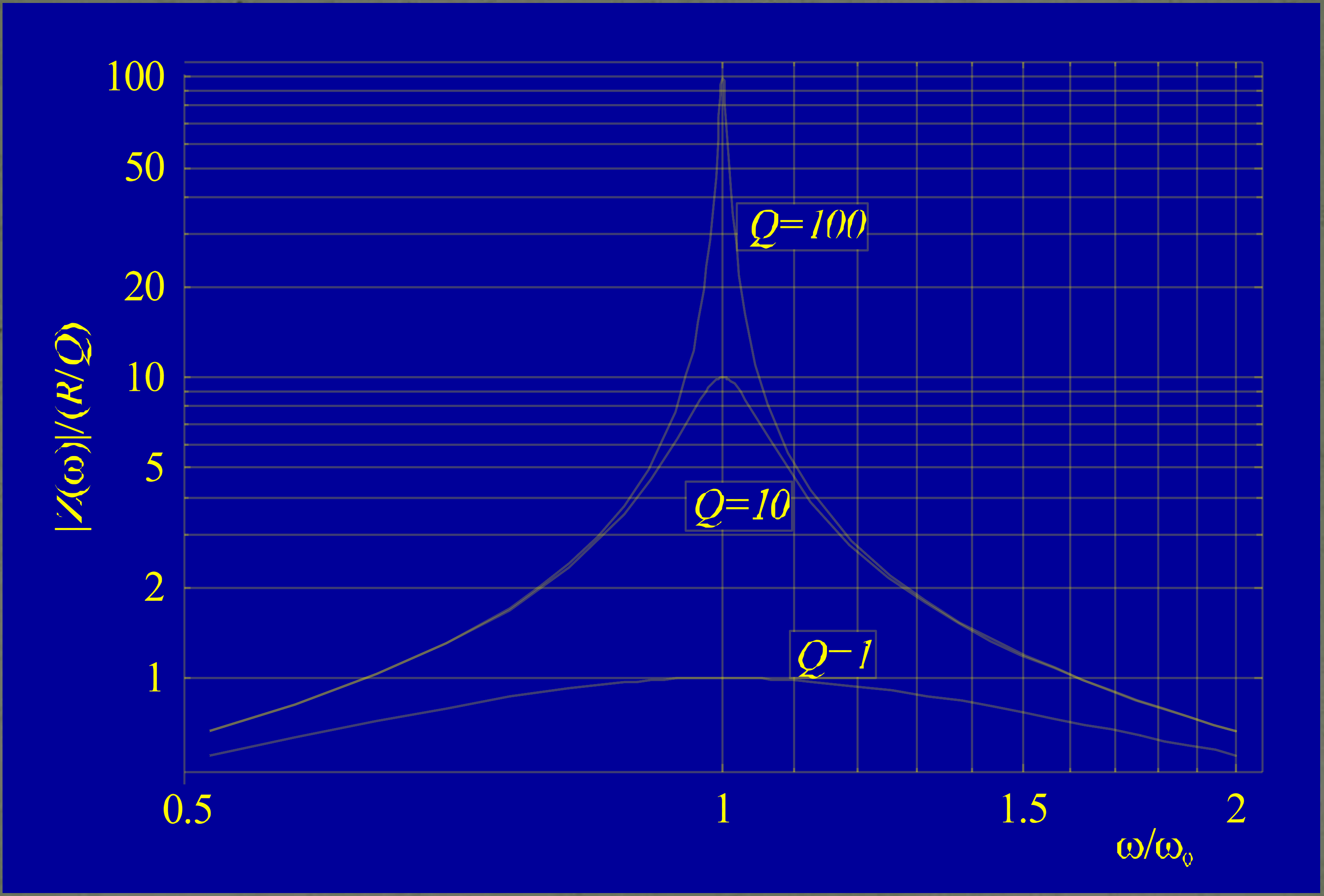
β: coupling factor

R: Shunt impedance

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

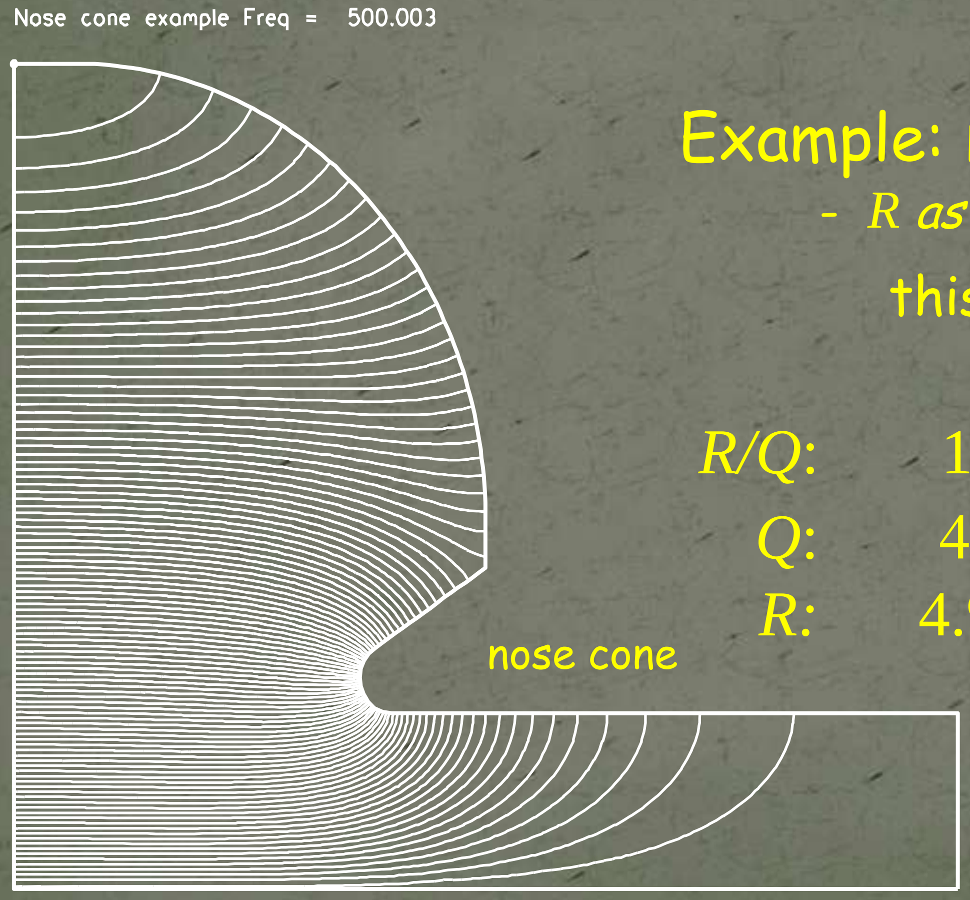
We have used this before when explaining the "fast feedback"

Resonance



Reentrant cavity

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



Example: KEK photon factory 500 MHz

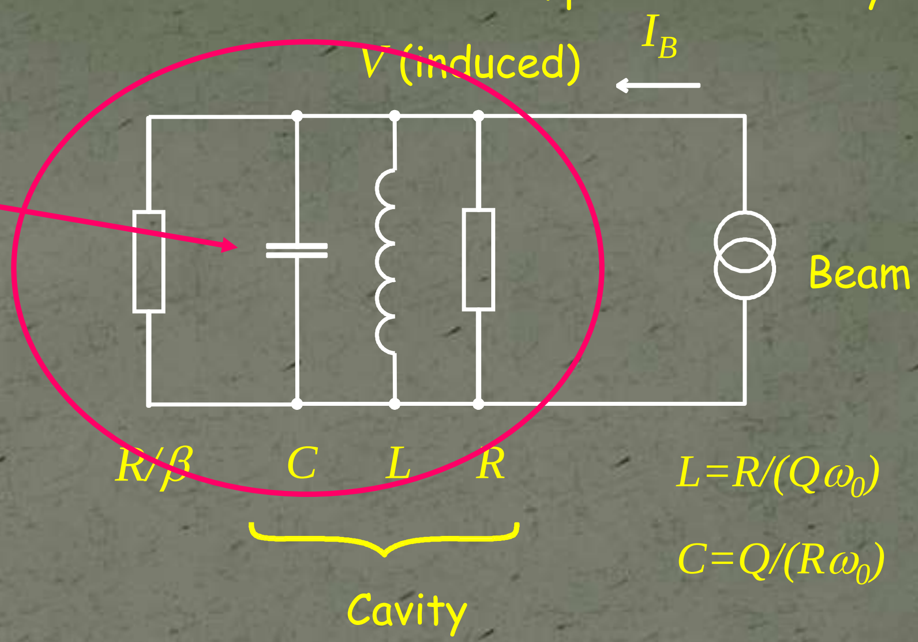
- *R as good as it gets* -

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

Loss factor

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

Impedance seen by the beam



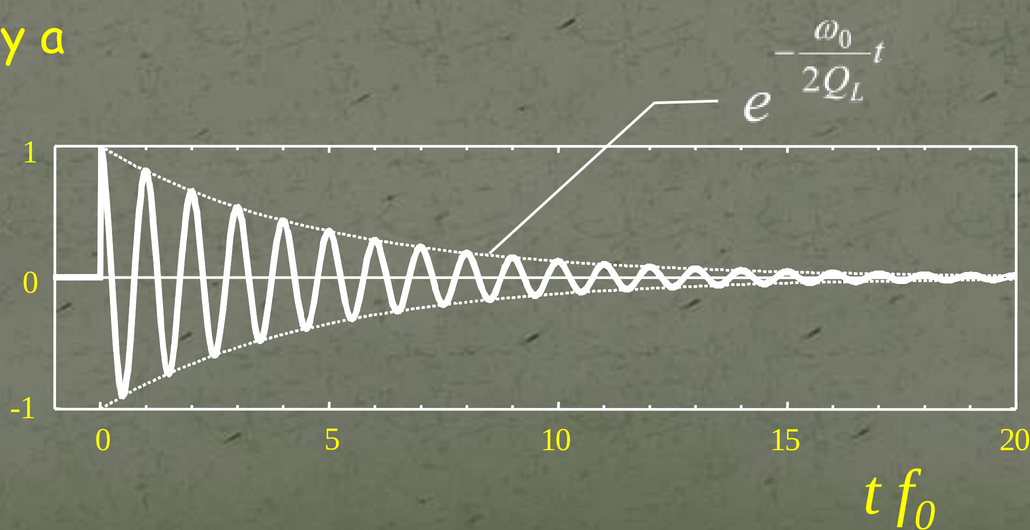
$L = R/(Q\omega_0)$

$C = Q/(R\omega_0)$

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

Voltage induced by a single charge q:

$$\frac{V_{gap}}{2\, k_{loss}\, q}$$



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

V_{gap}

gap voltage

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

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

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

W

Energy stored inside the cavity

P_{loss}

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 $-\frac{1}{2}\mathrm{Re}\{V_{gap}\ I_B^*\}$, the power loss $P = \frac{|V_{gap}|^2}{2R}$.
- For high efficiency, beam loading shall be high.
- The RF to beam efficiency is $\eta = \frac{1}{1 + \frac{V_{gap}}{R\,|I_B|}} = \frac{|I_B|}{|I_G|}$.

Cavity parameters

- Resonance frequency $\omega_0 = \frac{1}{\sqrt{L \cdot C}}$
- Transit time factor $\frac{\left|\int E_z e^{j\frac{\omega}{c}z} dz\right|}{\left|\int E_z dz\right|}$

  field varies while particle is traversing the gap

Circuit definition

- Shunt impedance $|V_{gap}|^2 = 2 R_{shunt} P_{loss}$

  gap voltage – power relation

- Q factor $\omega_0 W = Q P_{loss}$
- R/Q $\frac{R}{Q} = \frac{|V_{gap}|^2}{2 \omega_0 W} = \sqrt{\frac{L}{C}}$

  independent of losses – only geometry!

- loss factor $k_{loss} = \frac{\omega_0}{2} \frac{R}{Q} = \frac{|V_{gap}|^2}{4 W}$

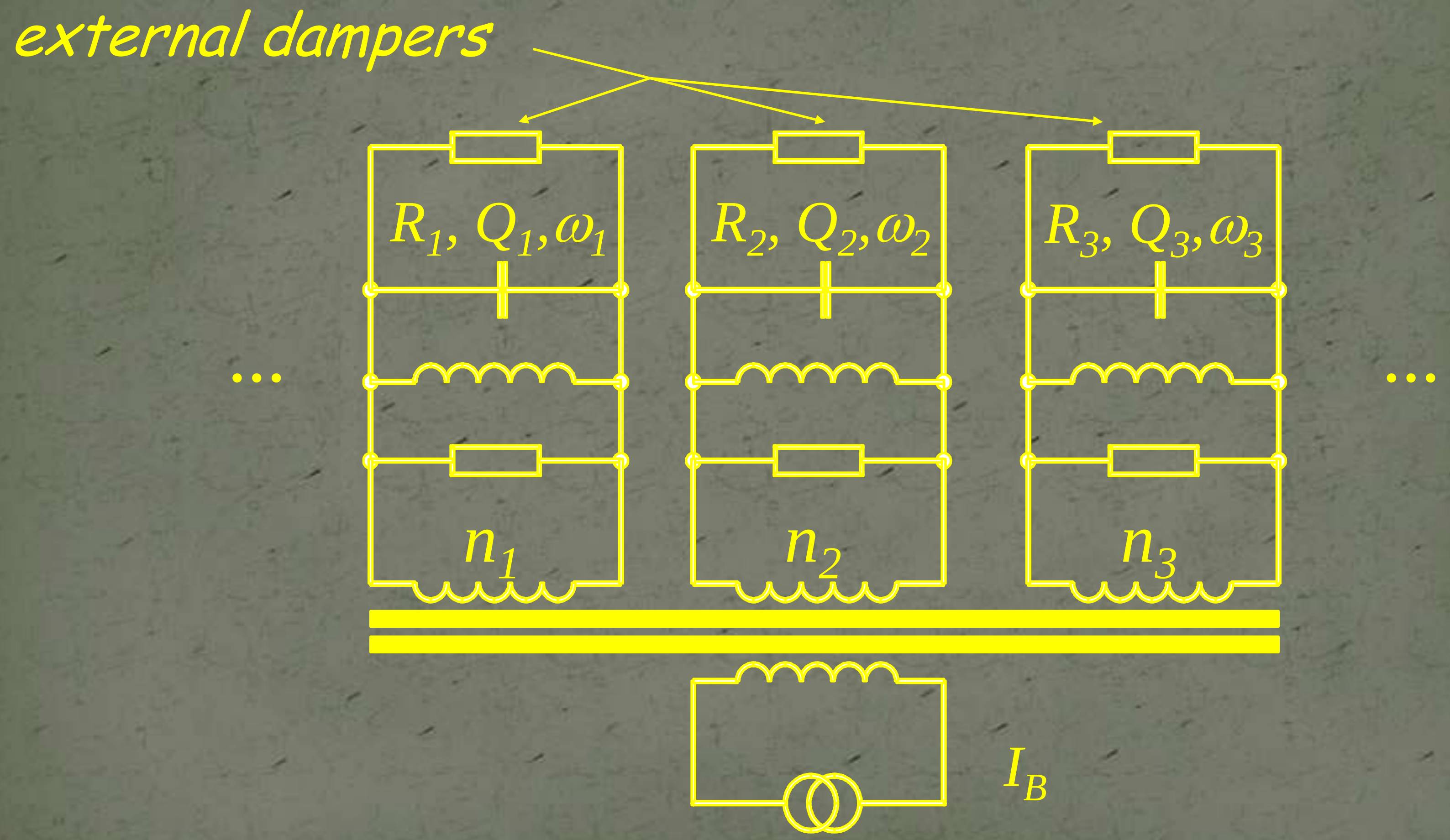
Linac definition

$$|V_{gap}|^2 = R_{shunt} P_{loss}$$

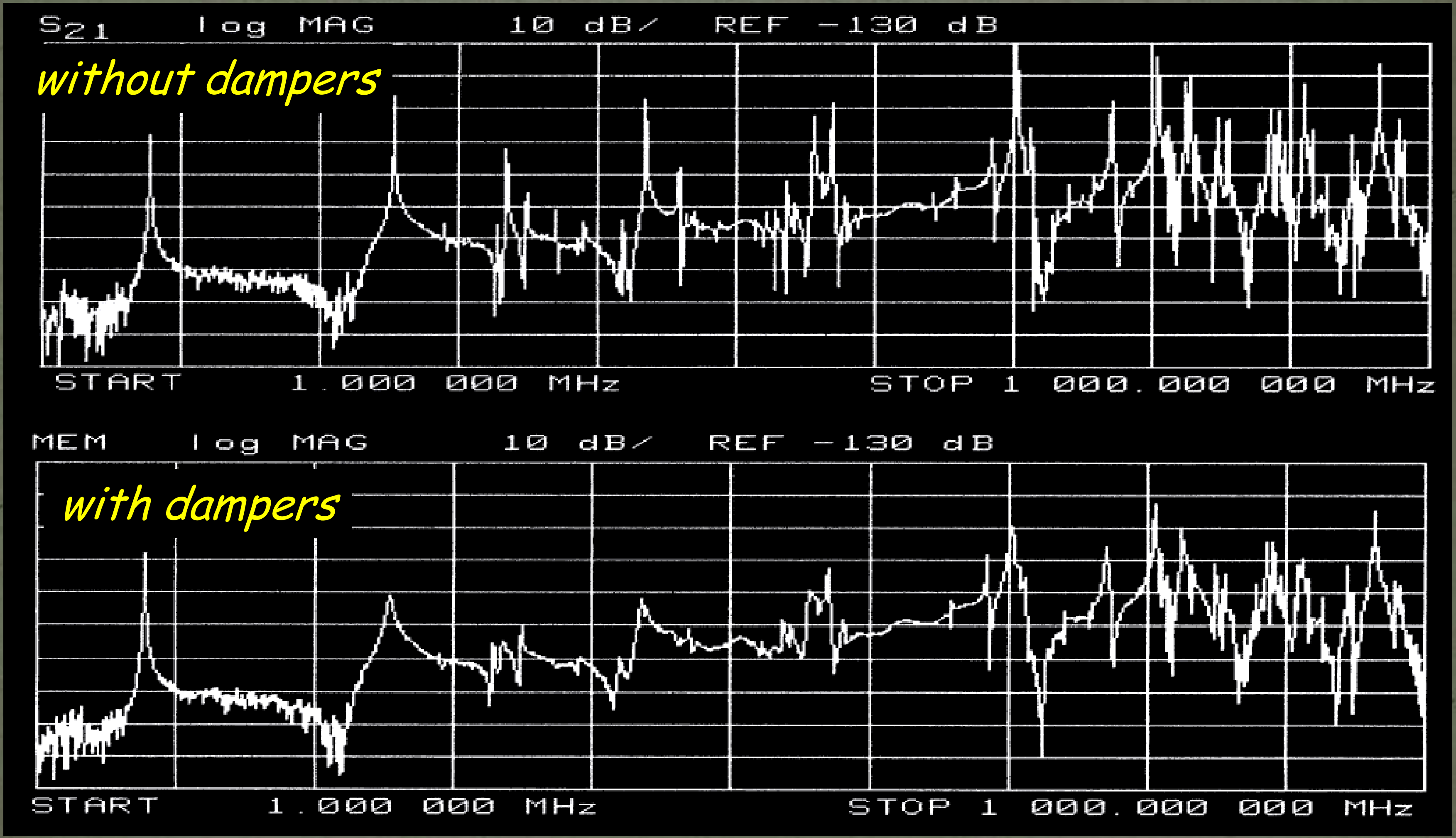
$$\frac{R}{Q} = \frac{|V_{gap}|^2}{\omega_0 W}$$

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

Higher order modes (HOM's)



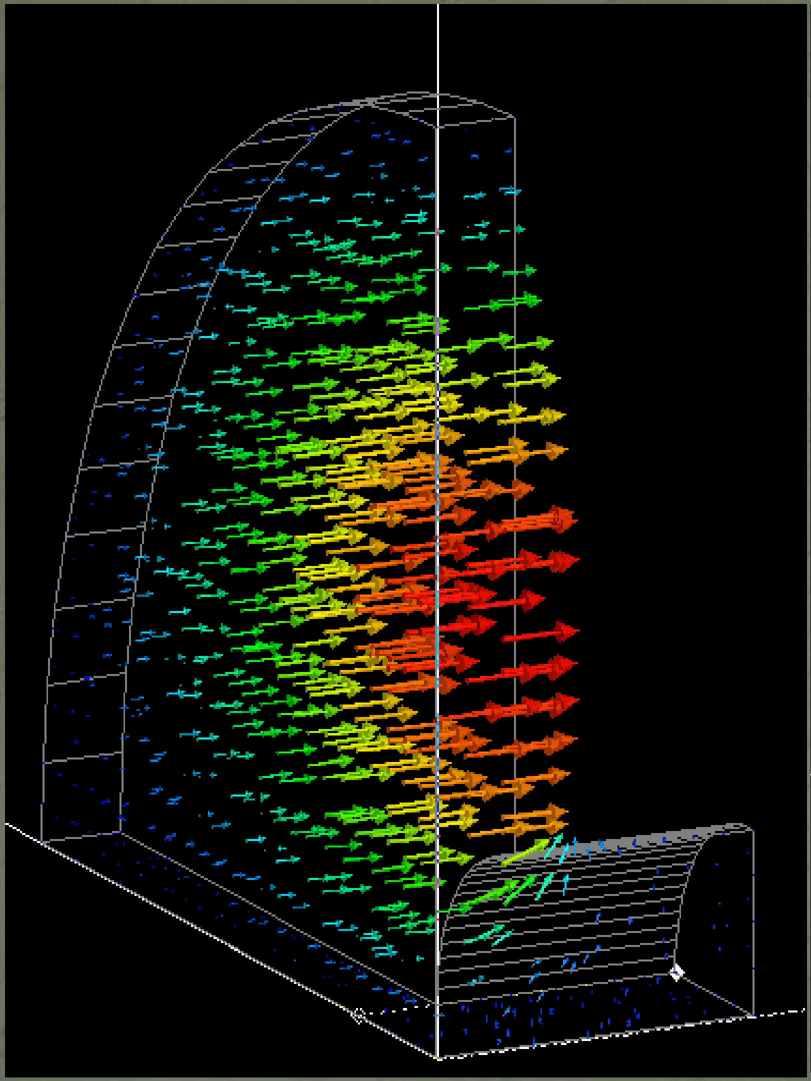
HOM (measured spectrum)



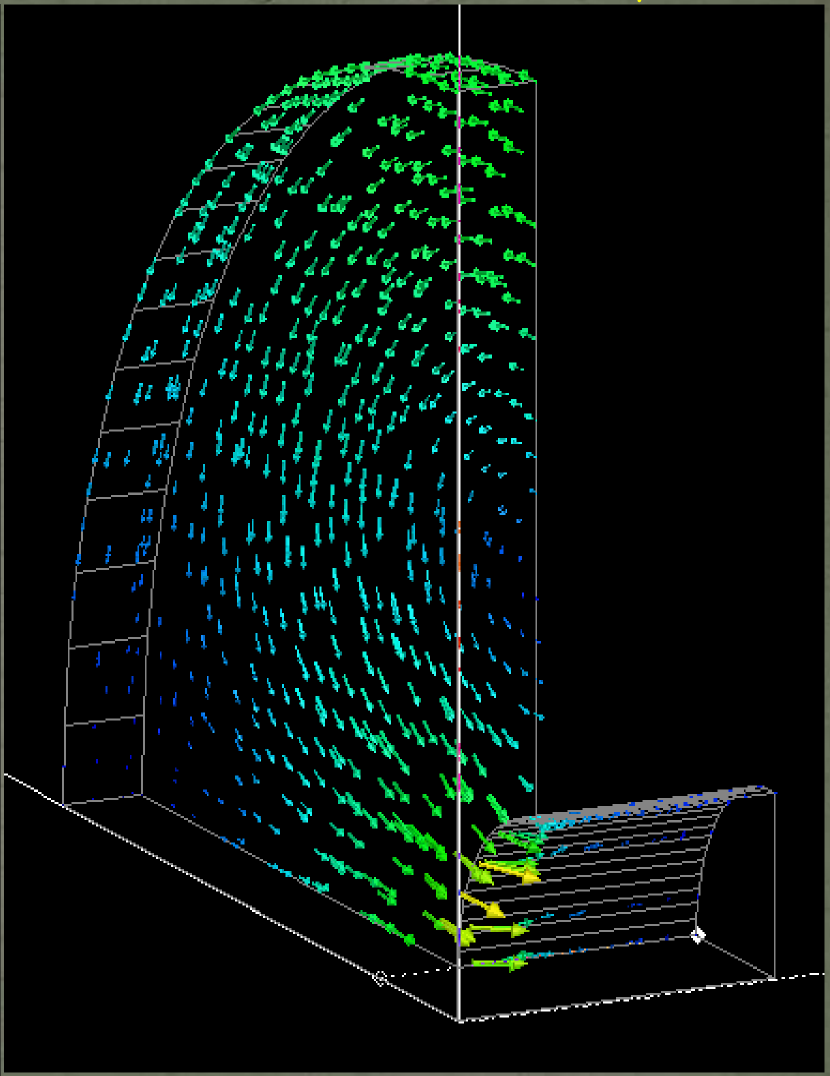
Pillbox: Dipole mode

(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!

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

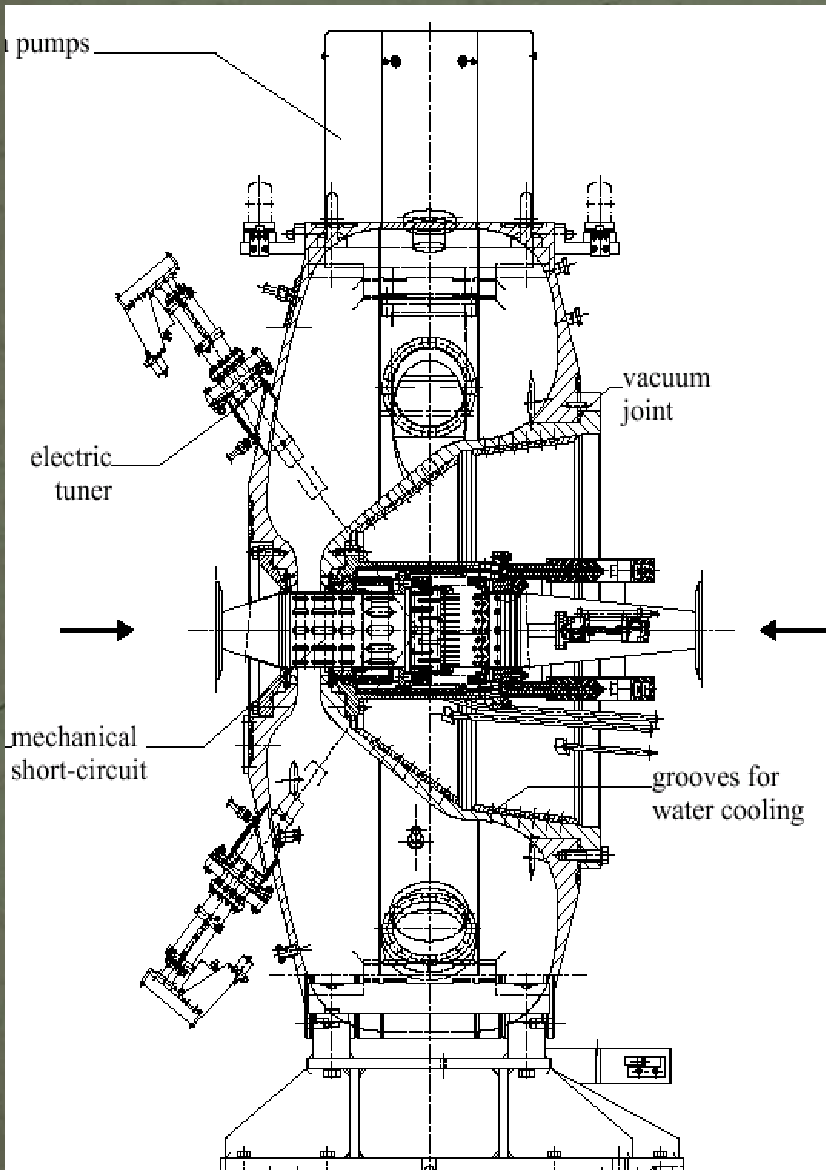
Pure TE modes: No net transverse force !

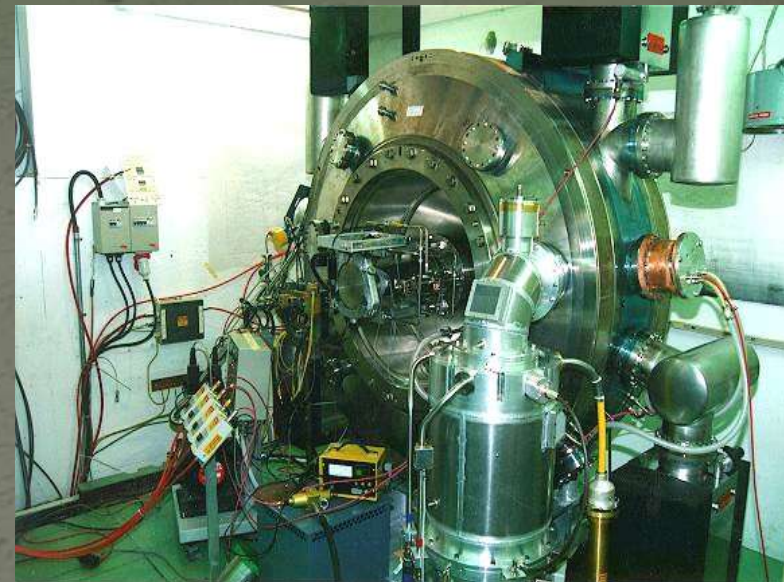
Transverse modes are characterized by

- 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)



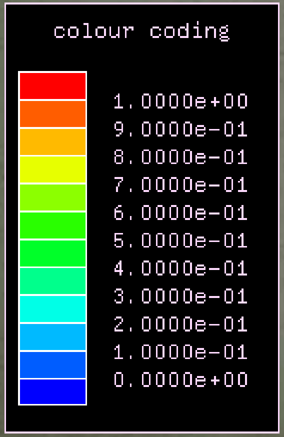


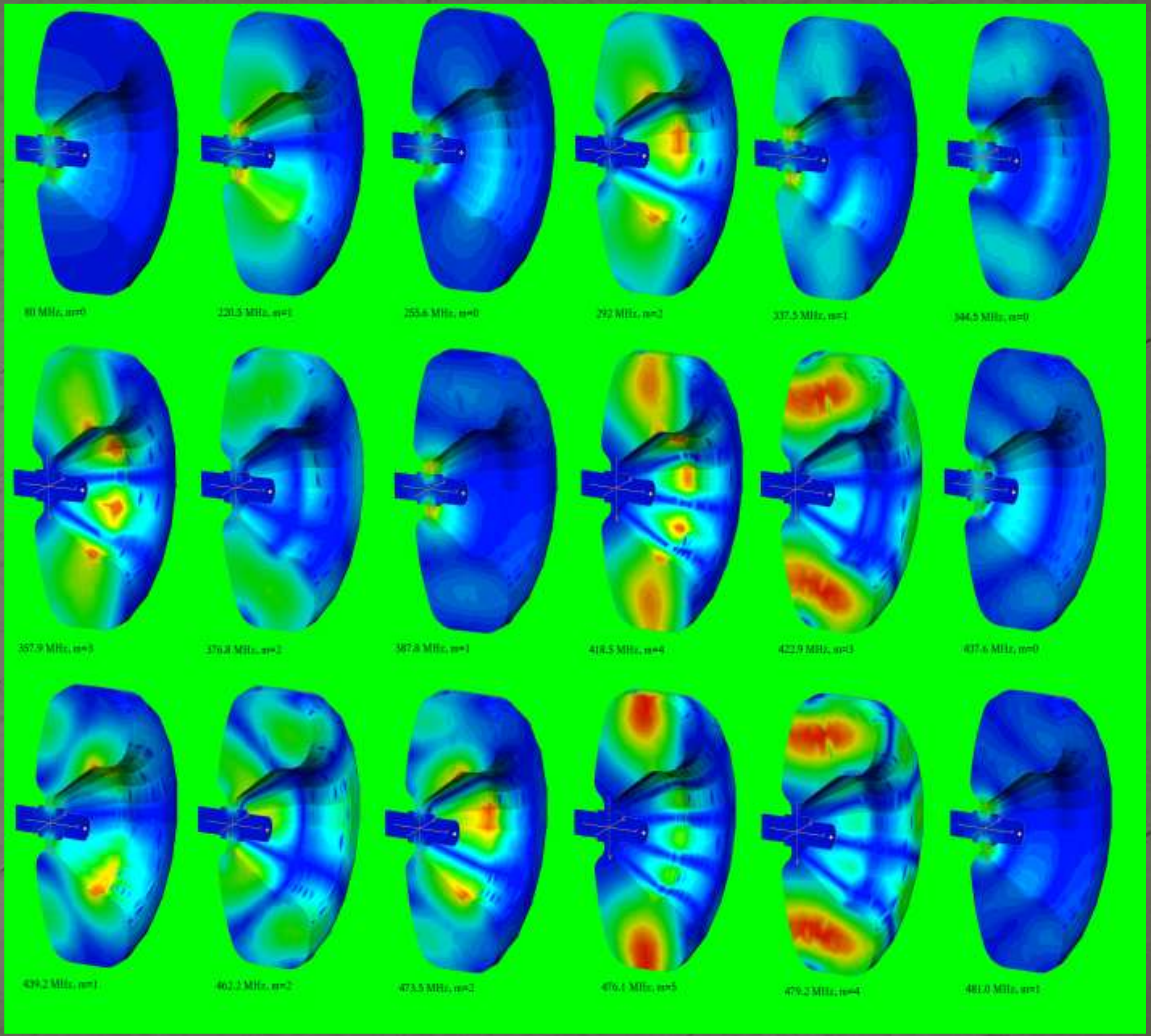
HOM's

Example shown: 80 MHz cavity PS for LHC.

Color-coded:

$|\vec{E}|$





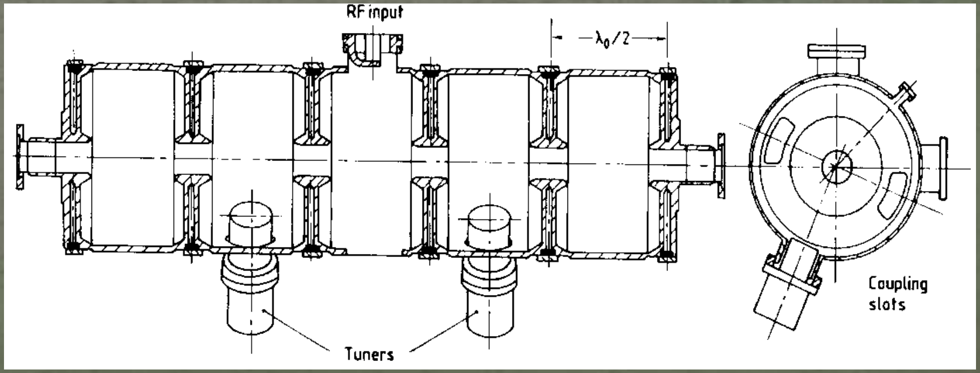
More examples of cavities

PS 19 MHz cavity (prototype, photo: 1966)

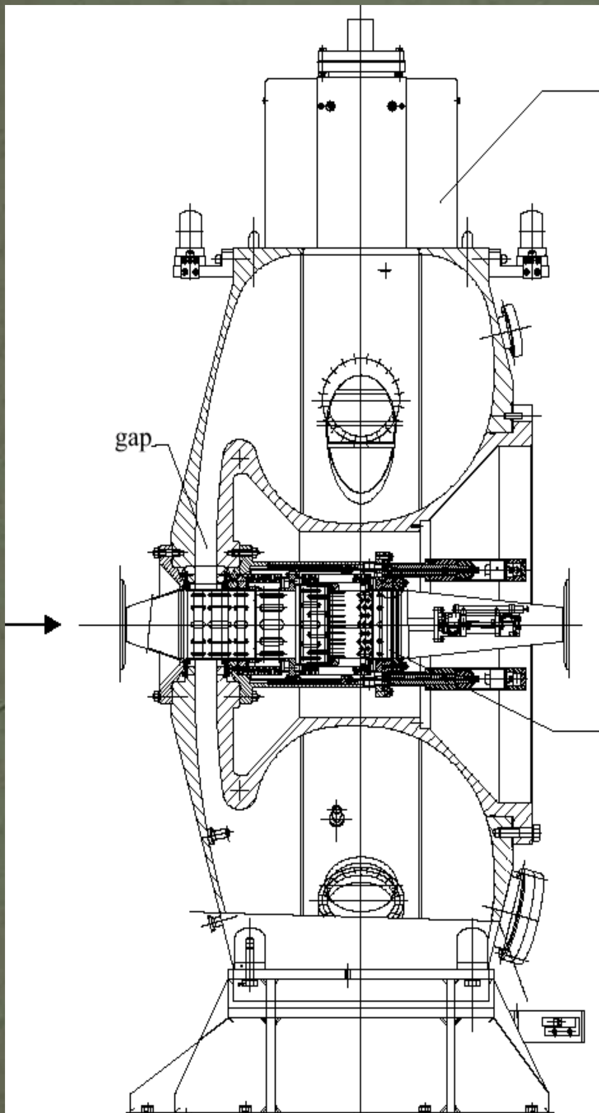
Examples of cavities

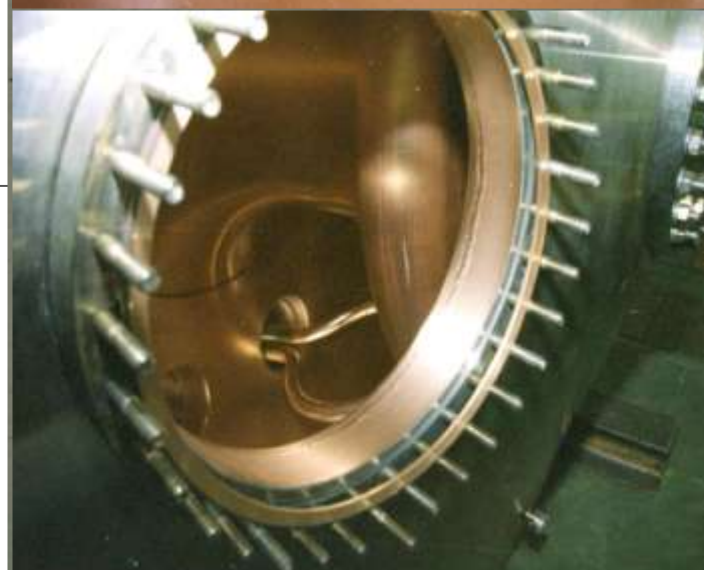
PEP II cavity
476 MHz, single cell,
1 MV gap with 150 kW,
strong HOM damping,

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



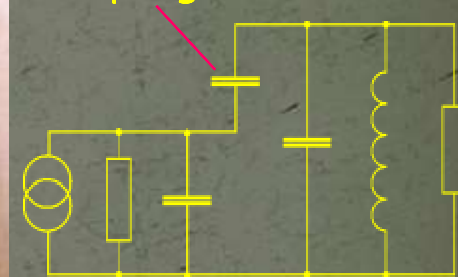
CERN/PS 40 MHz cavity (for LHC)





example for capacitive coupling

coupling C

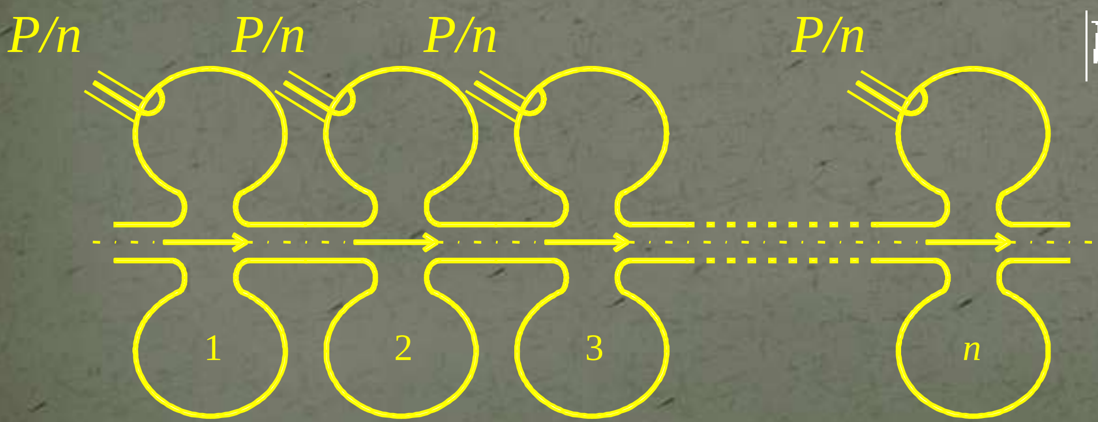


cavity

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 $\sqrt{2RP/n}$. The total accelerating voltage thus increased, equivalent to a total equivalent shunt impedance of nR .

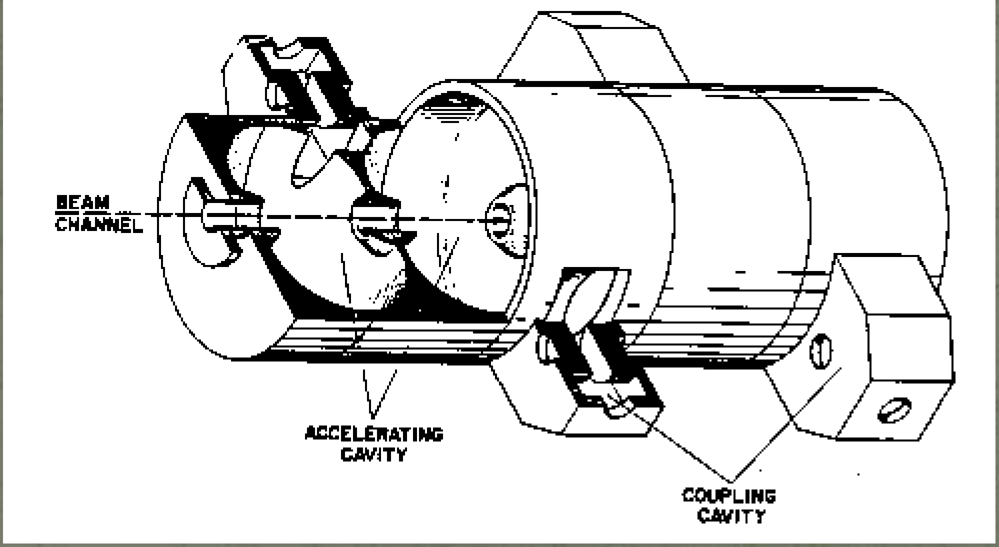


$$\left|V_{acc}\right| = n\sqrt{2R\frac{P}{n}} = \sqrt{2(nR)P}$$

Standing wave multicell cavity

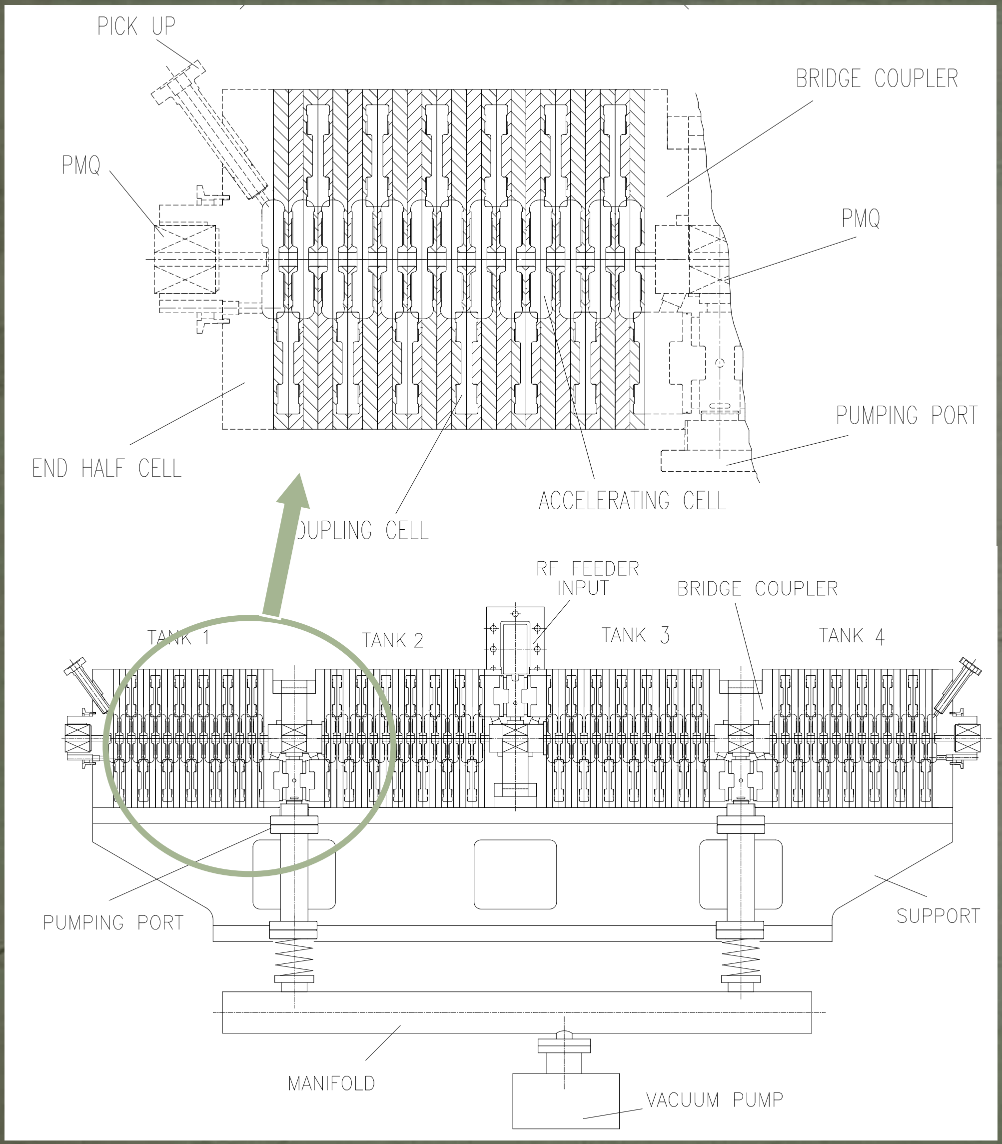
- Instead of distributing the power from the amplifier, one might as well couple the cavities, such that the power automatically distributes, or have a cavity with many gaps (e.g. drift tube linac).

- Coupled cavity accelerating structure (side coupled)



- The phase relation between gaps is important!

Side Coupled Structure : example LIBO



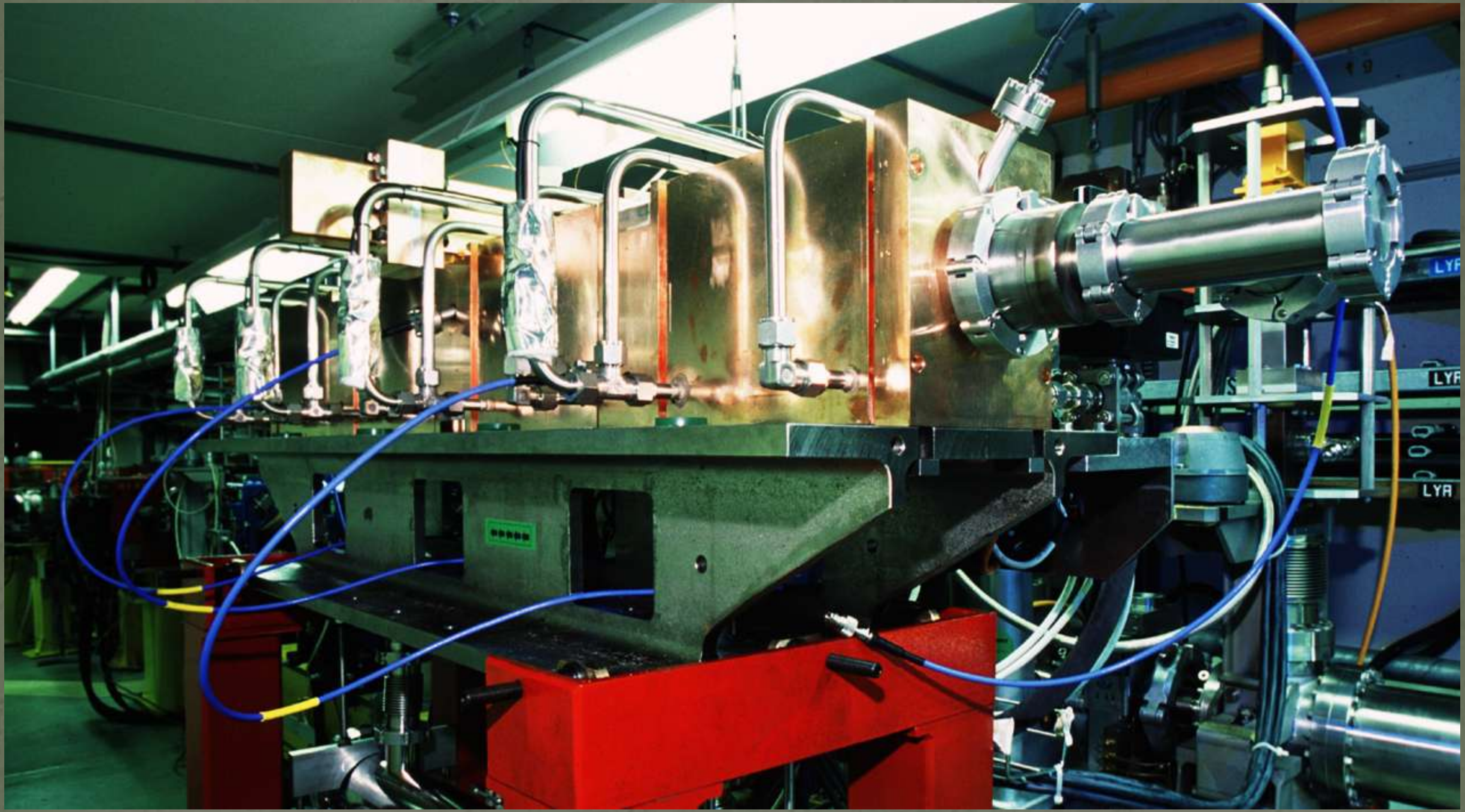
A 3 GHz Side Coupled Structure to accelerate protons out of cyclotrons from 62 MeV to 200 MeV

Medical application: treatment of tumours.

Prototype of Module 1 built at CERN (2000)

Collaboration CERN/INFN/ Tera Foundation

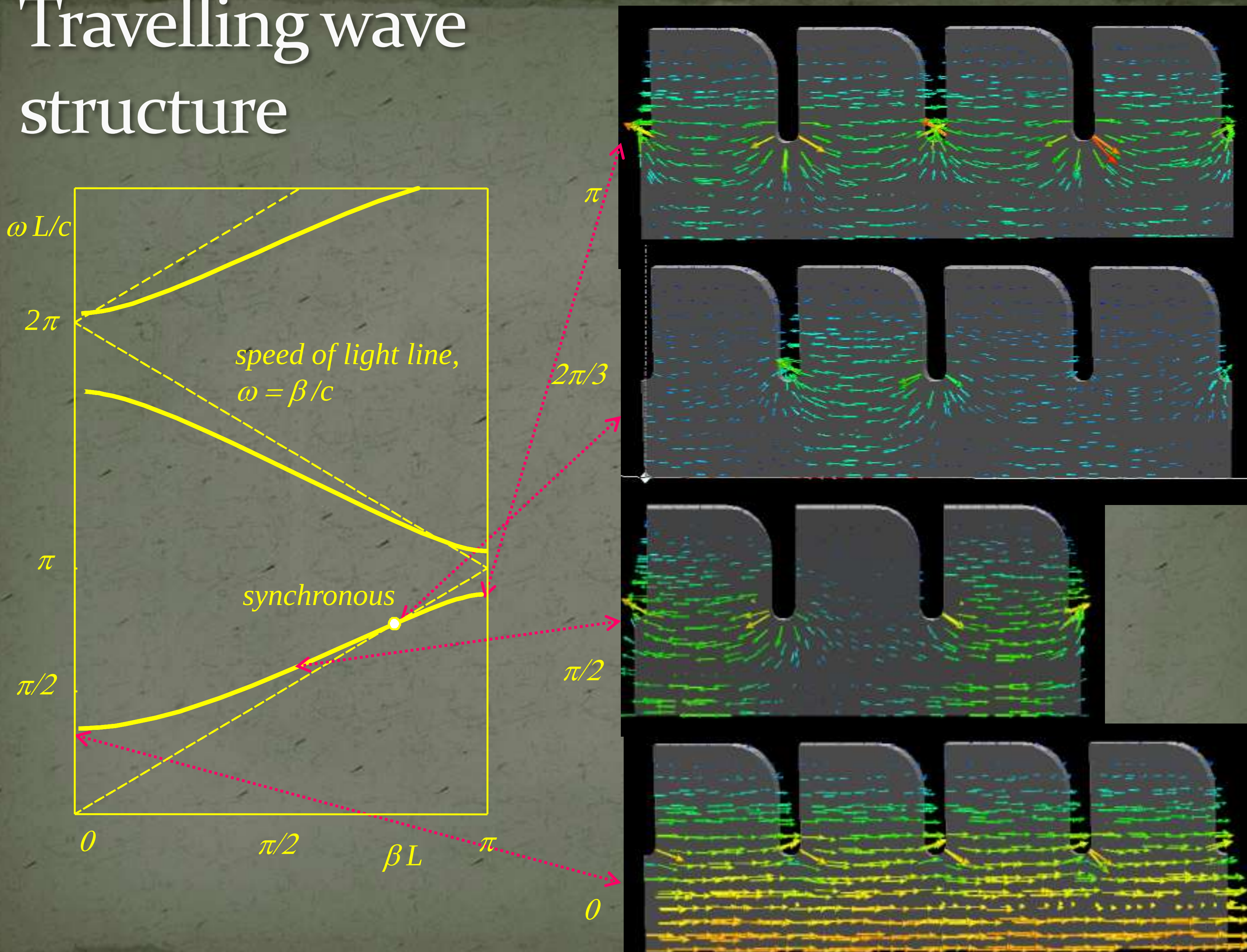
LIBO prototype



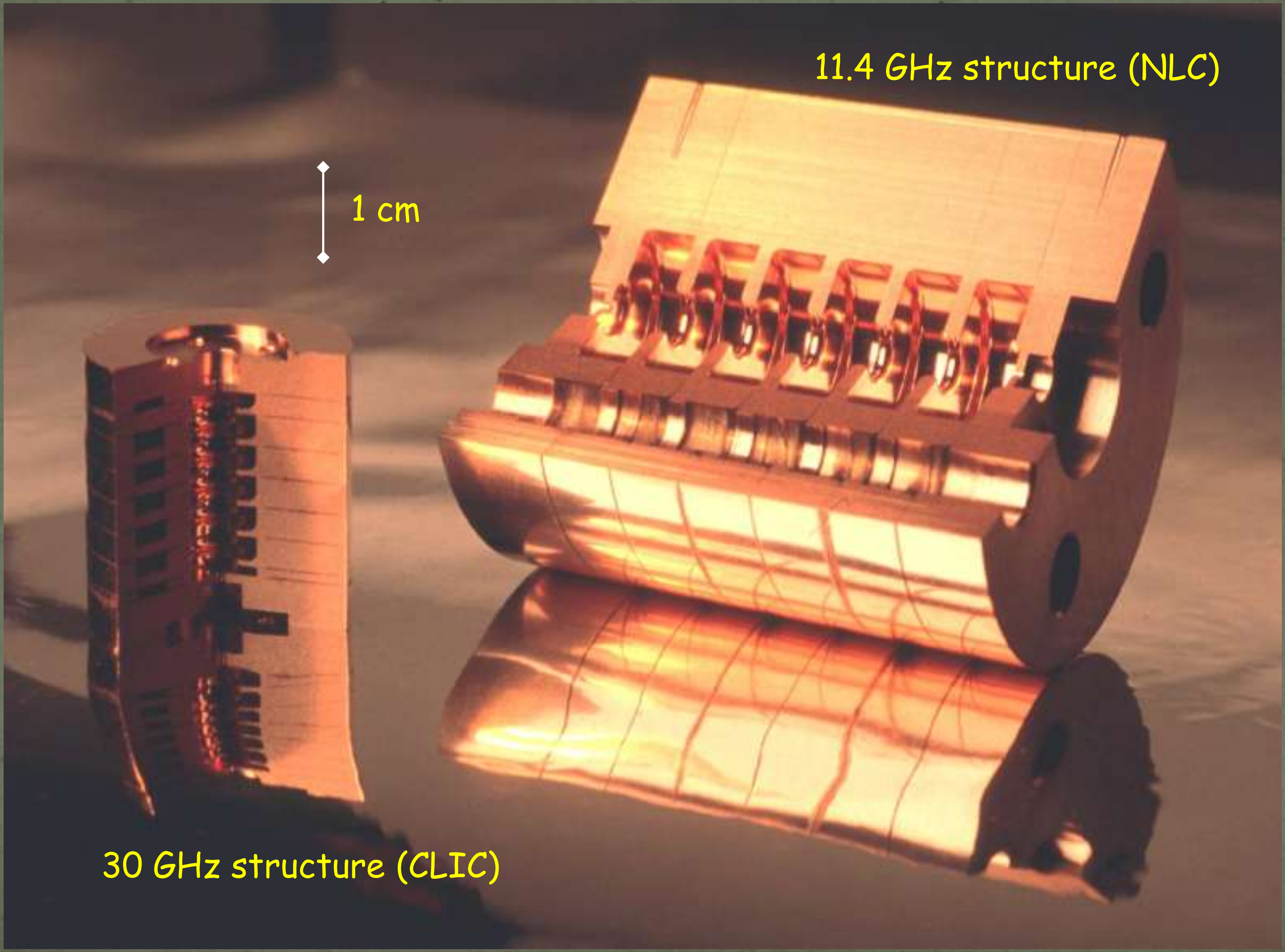
This Picture made it to the title page of CERN Courier vol. 41 No. 1 (Jan./Feb. 2001)

Travelling wave structures

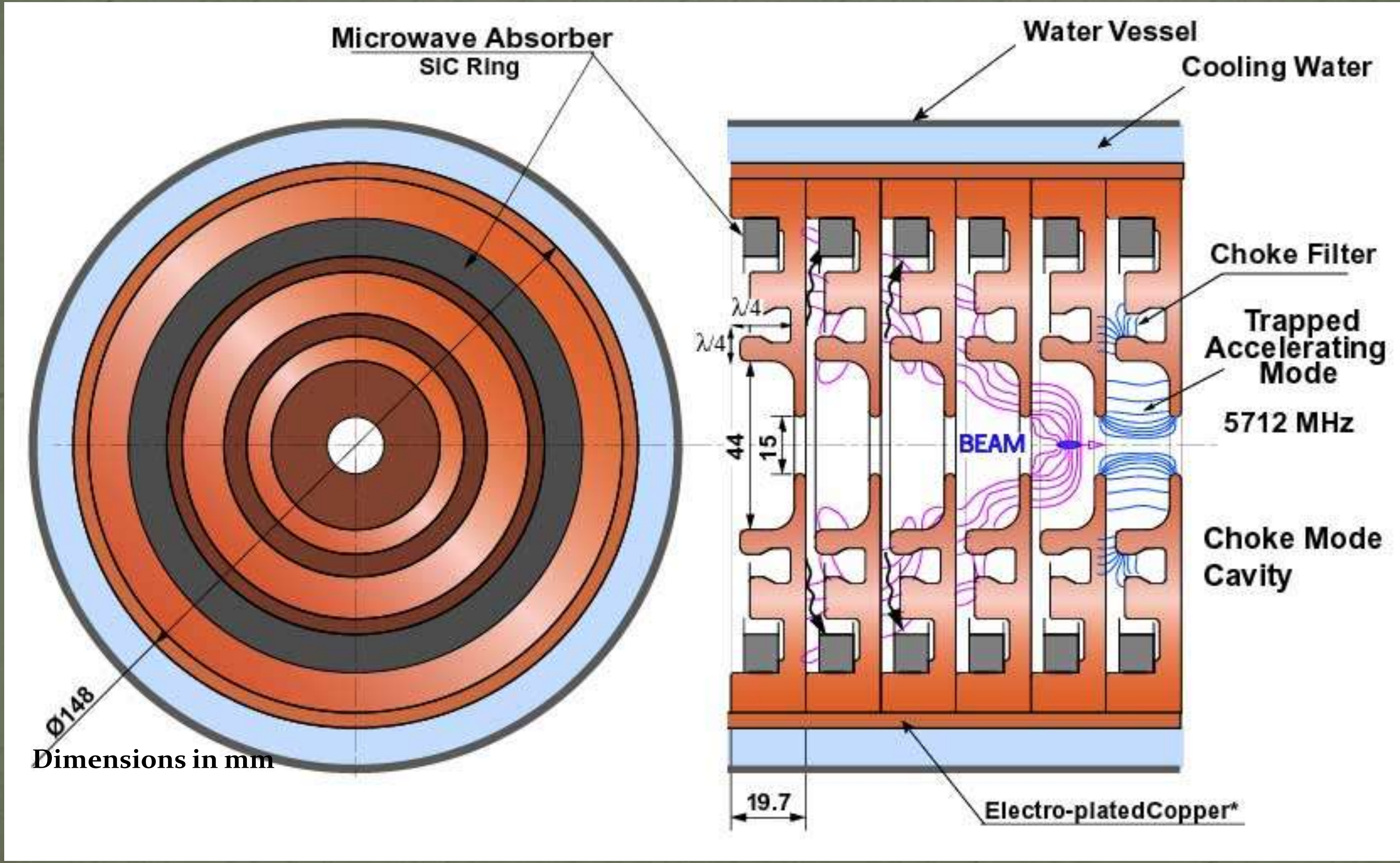
Travelling wave structure



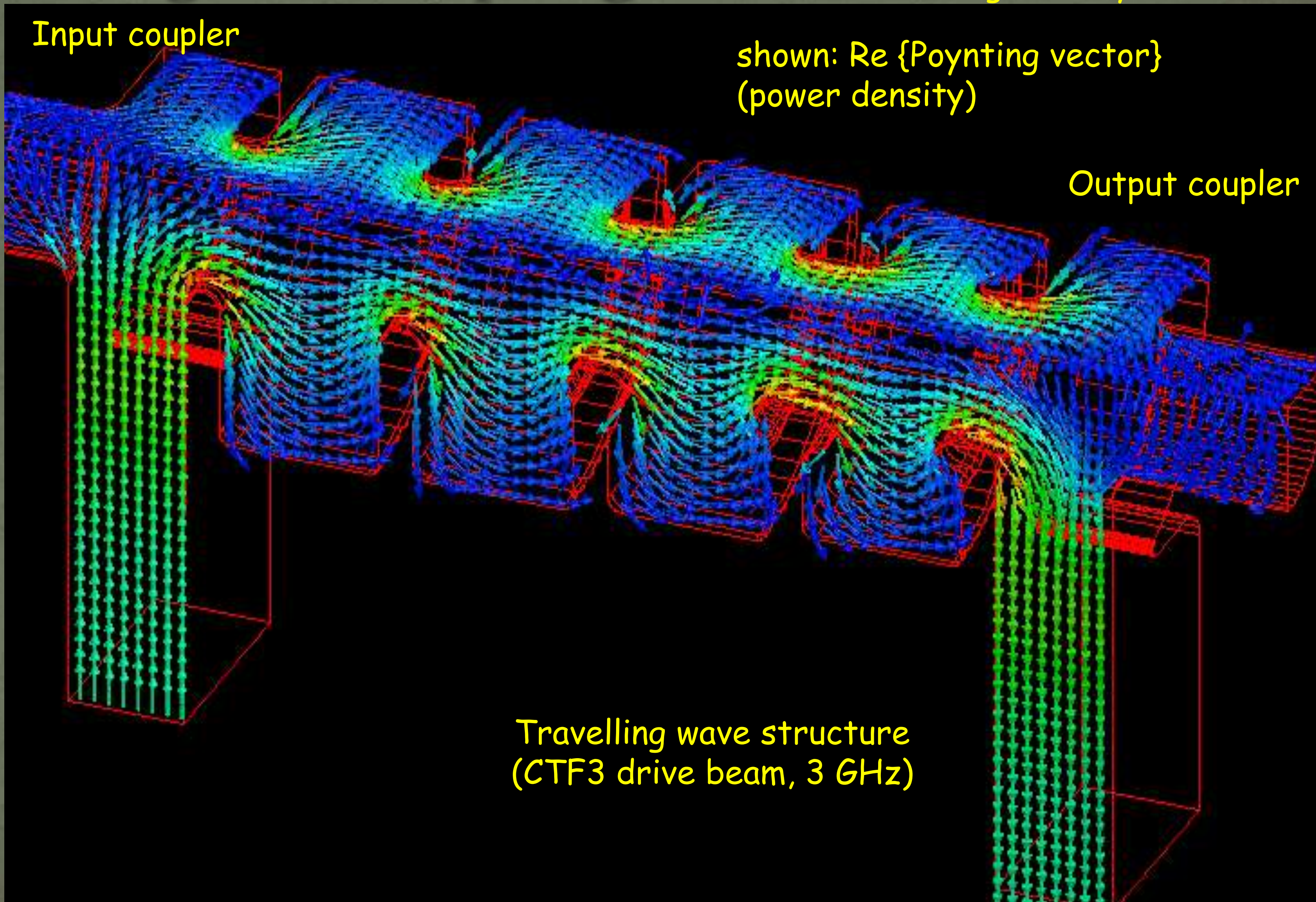
Iris loaded waveguide



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

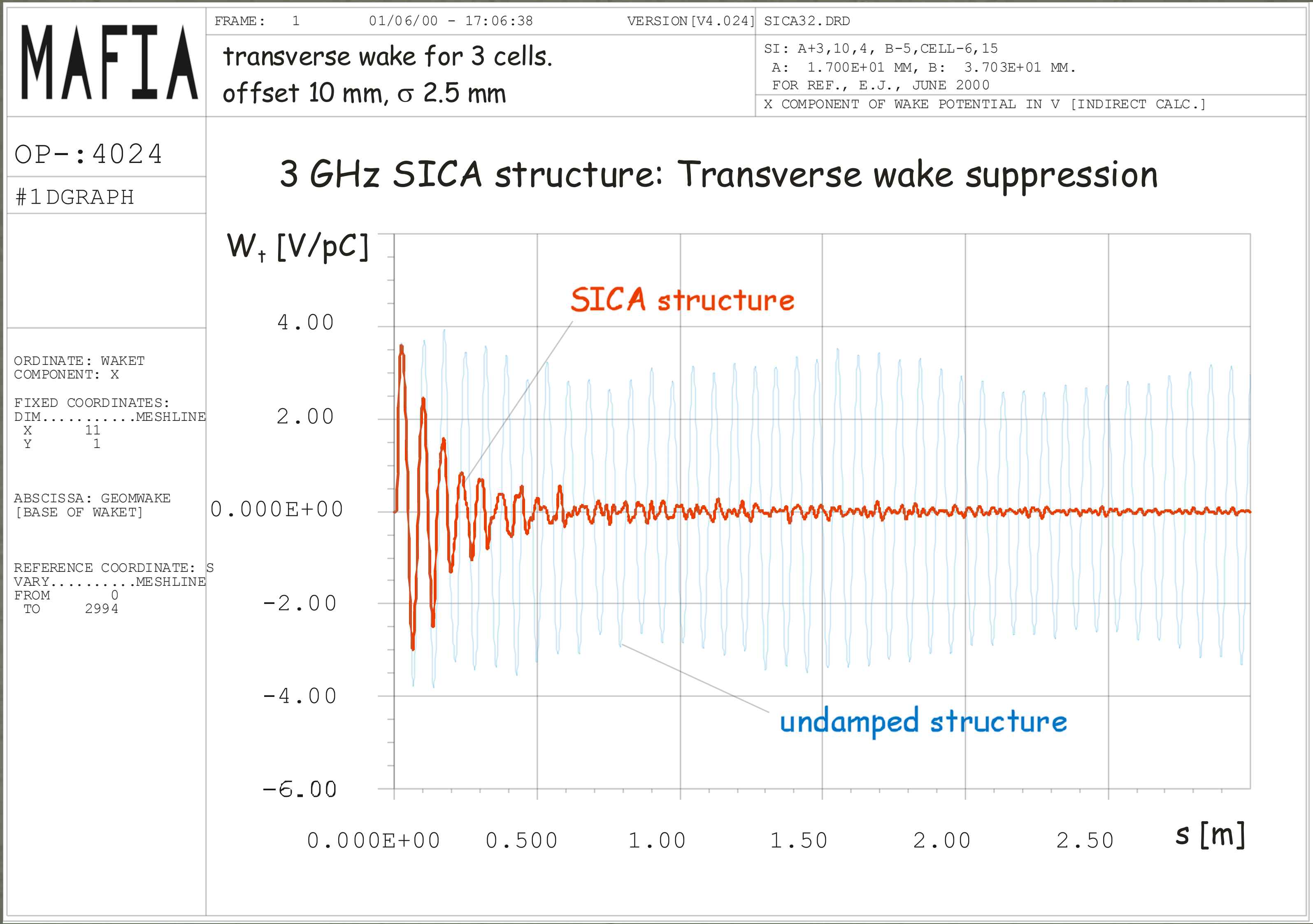


Waveguide coupling



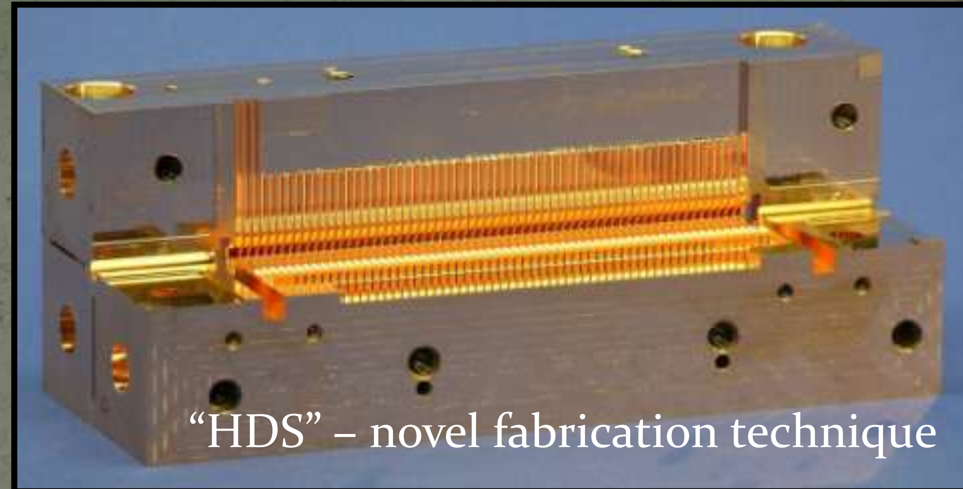
3 GHz Accelerating structure (CTF3)

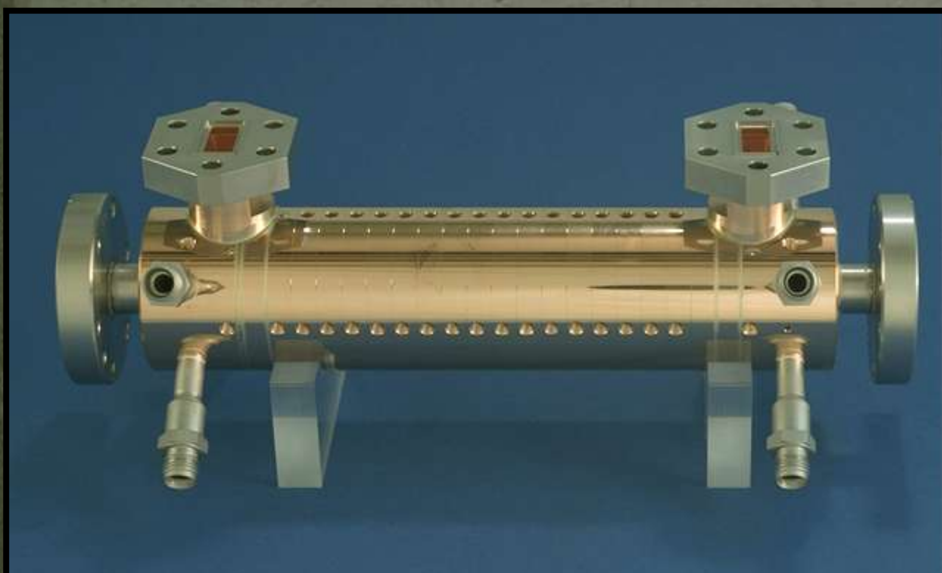
HOM damping at work

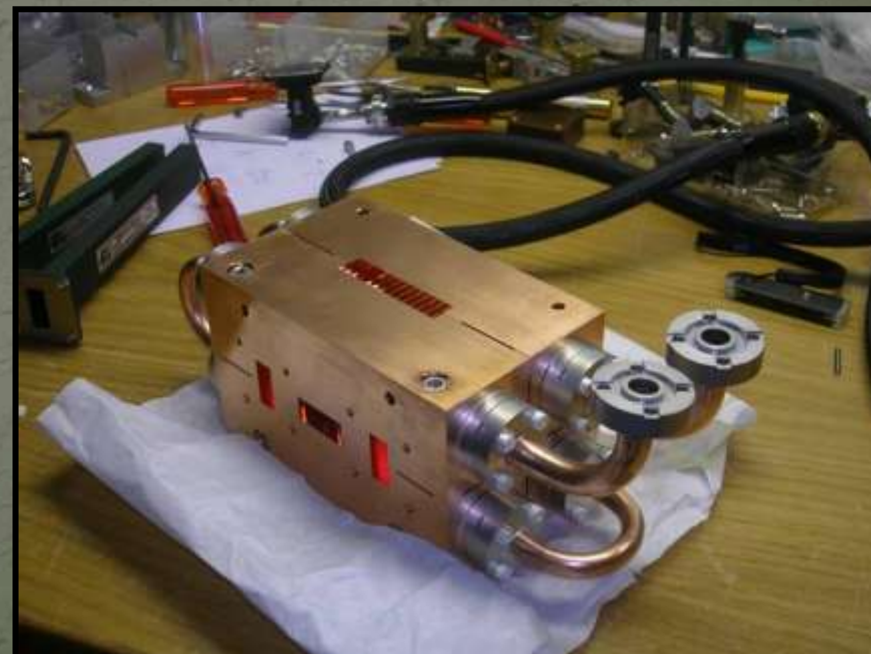


Recent CLIC structures (11.4, 12 and 30 GHz)


"T18" reached 105 MV/m!


"HDS" – novel fabrication technique





Superconducting Linacs

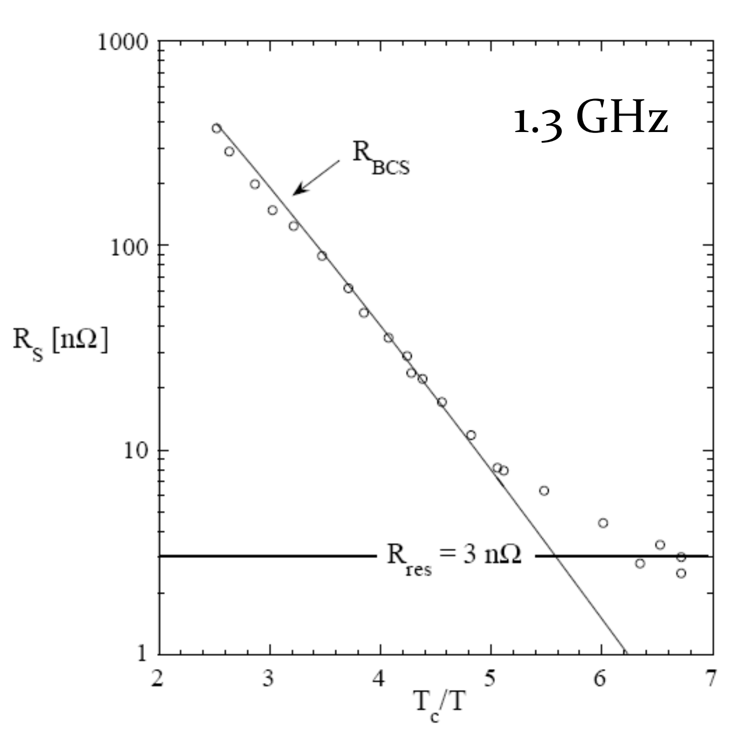
RF Superconductivity

- Different from DC, at RF the resistance is not exactly zero, but just very small. It is

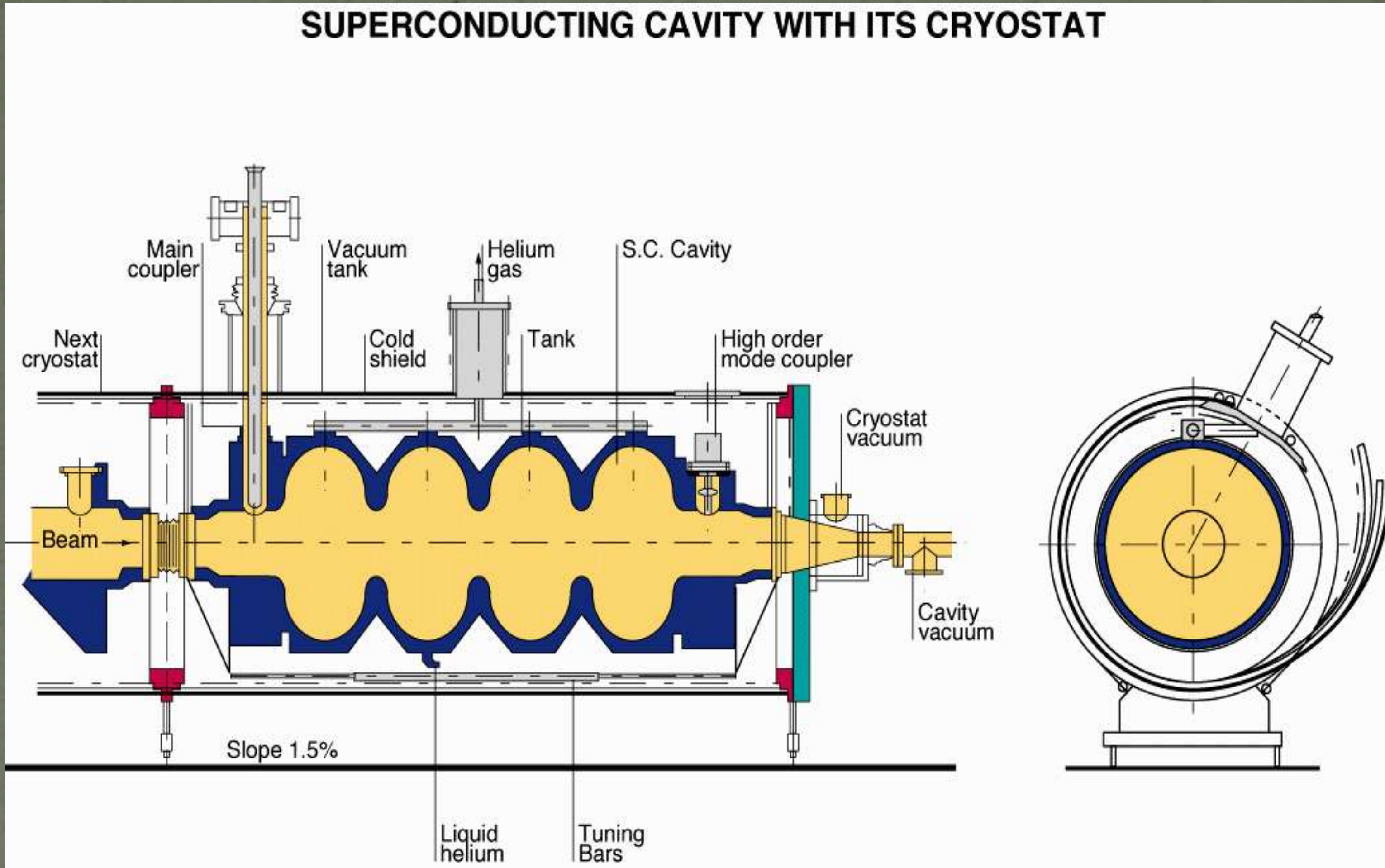
$$R_{surf} = R_{\mathrm{BCS}} + R_{res} \qquad R_{\mathrm{BCS}} \propto \omega^2 e^{-1.76 T_c/T}$$

- The maximum accelerating gradient is normally limited by the maximum possible surface magnetic field (the "superheating field", 180 mT for Nb, 400 mT for Nb_3Tn).

- Maximum acc. gradients are however obtained for Nb (ILC, ≈ 40 MV/m).

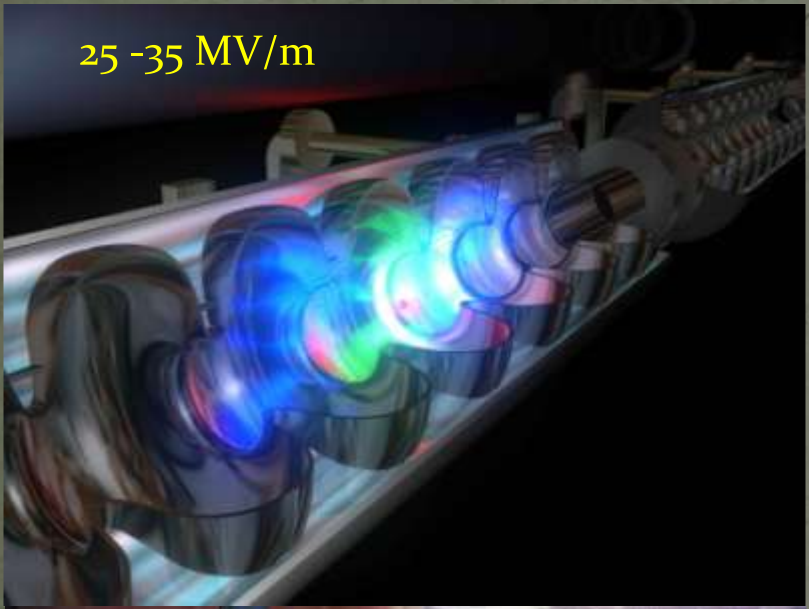


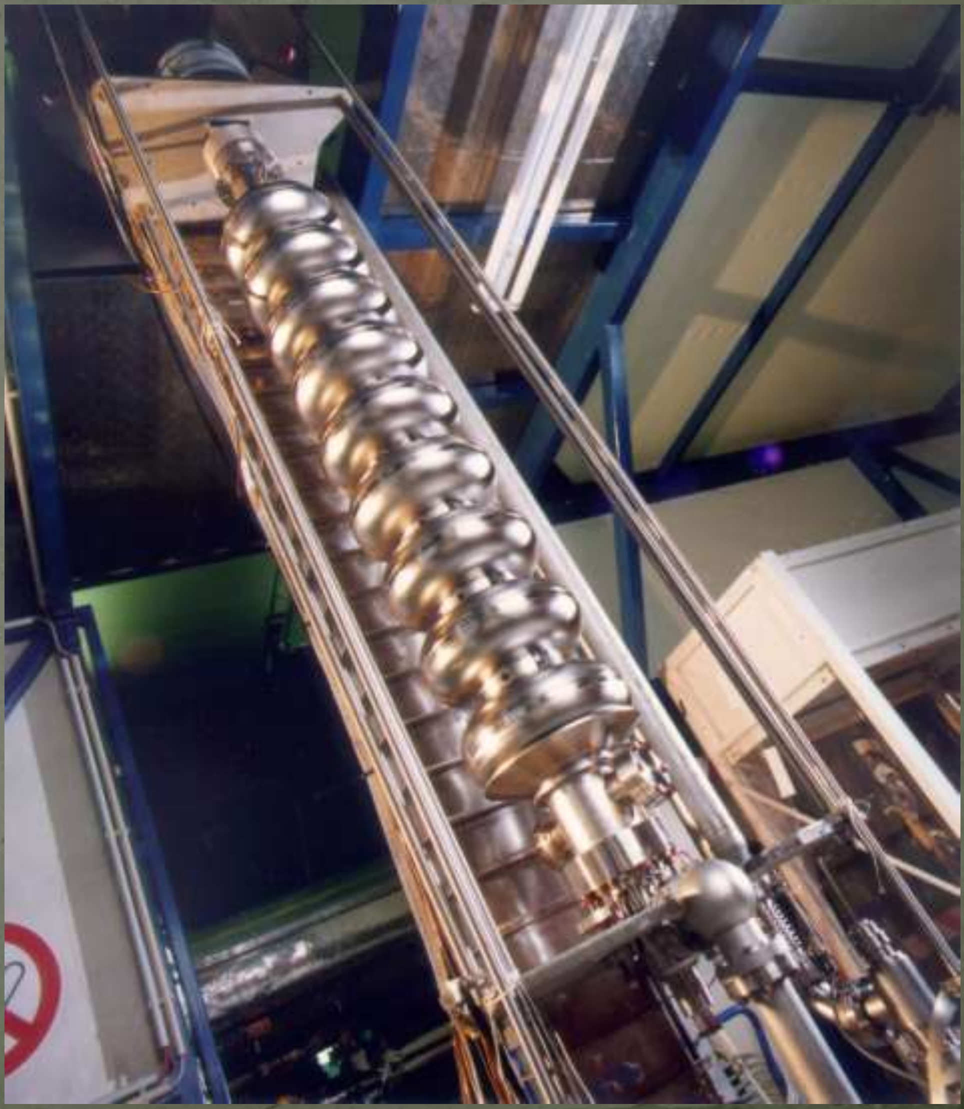
LEP Superconducting cavities



10.2 MV/ per cavity

TESLA/ILC SC cavities





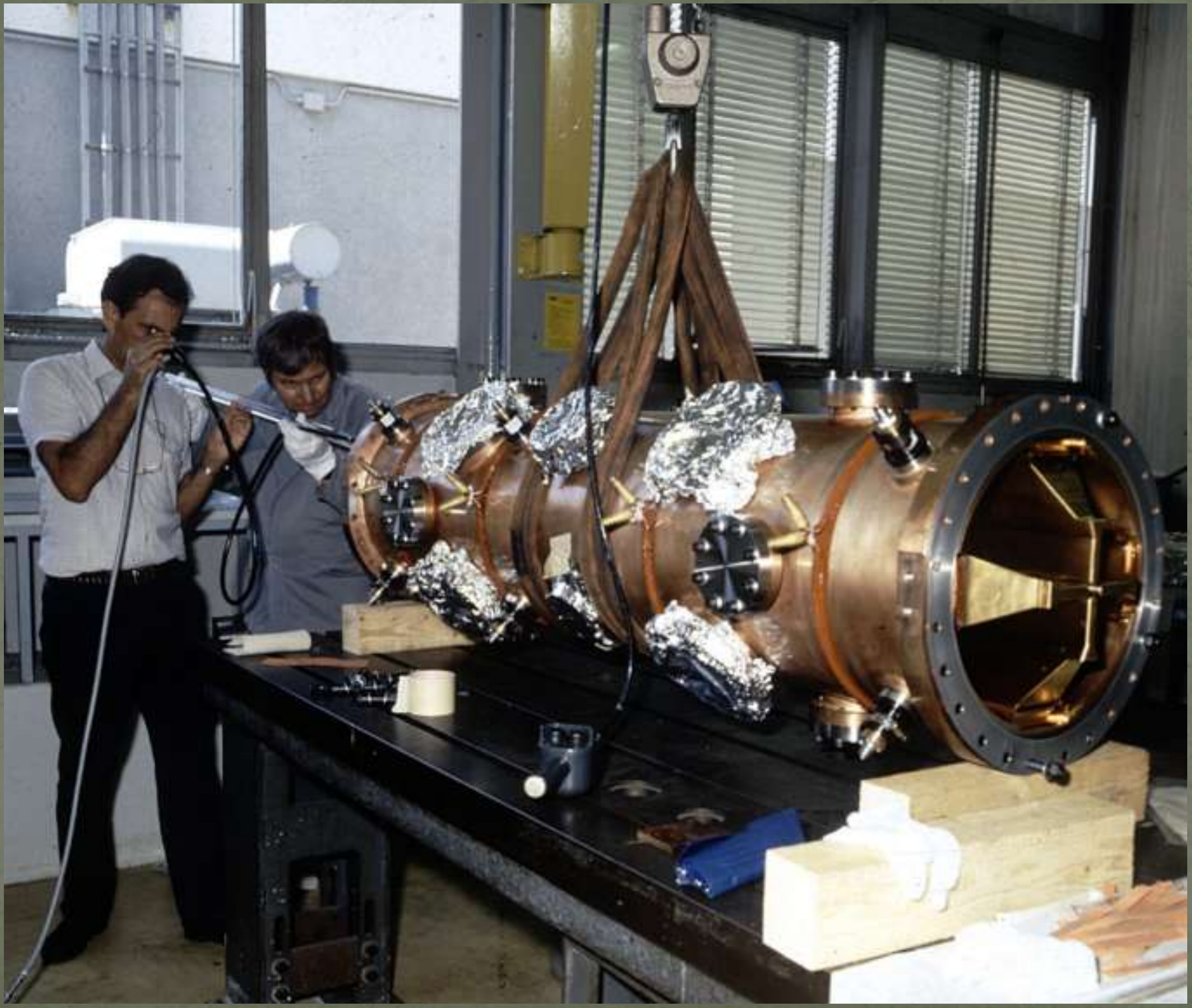
LHC SC RF, 4 cavity module, 400 MHz

RFQ's

Old pre-injector 750 kV DC , CERN Linac 2, before 1990

All this was replaced by the RFQ …

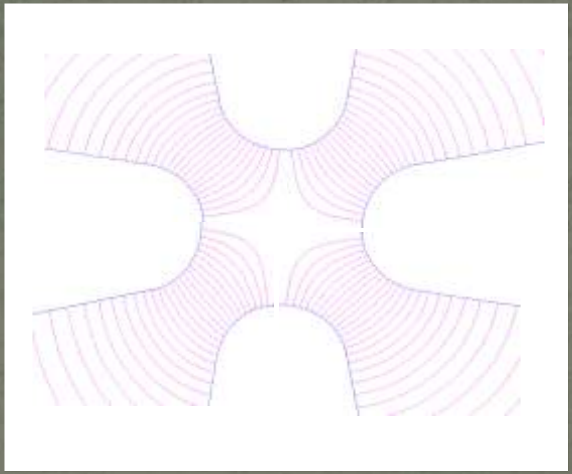
RFQ of CERN Linac 2

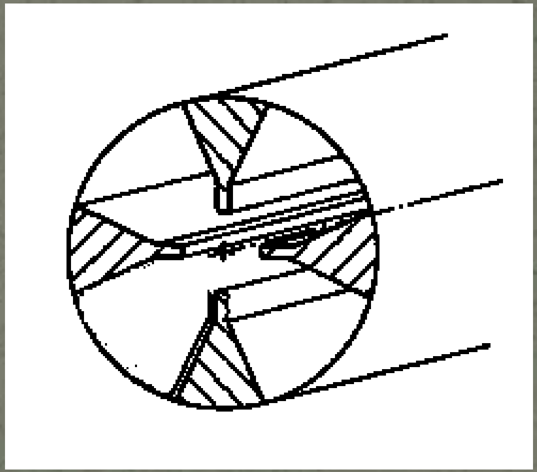


The Radio Frequency Quadrupole (RFQ)

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):

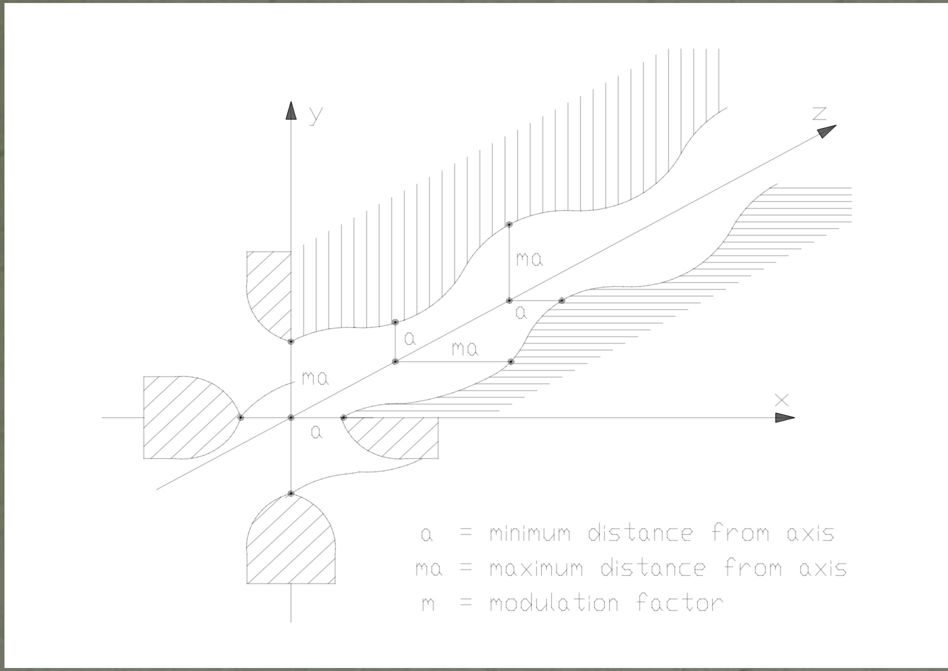
Electric quadrupole focusing + bunching + acceleration

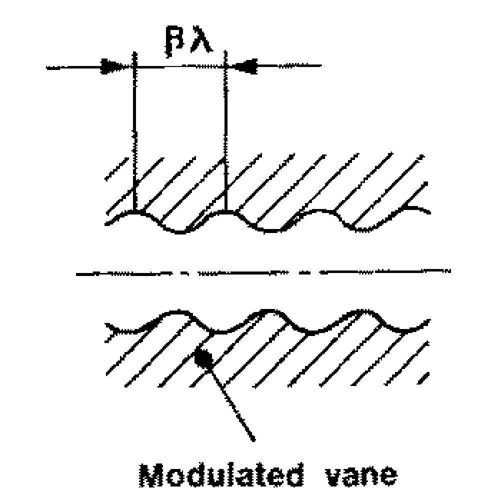




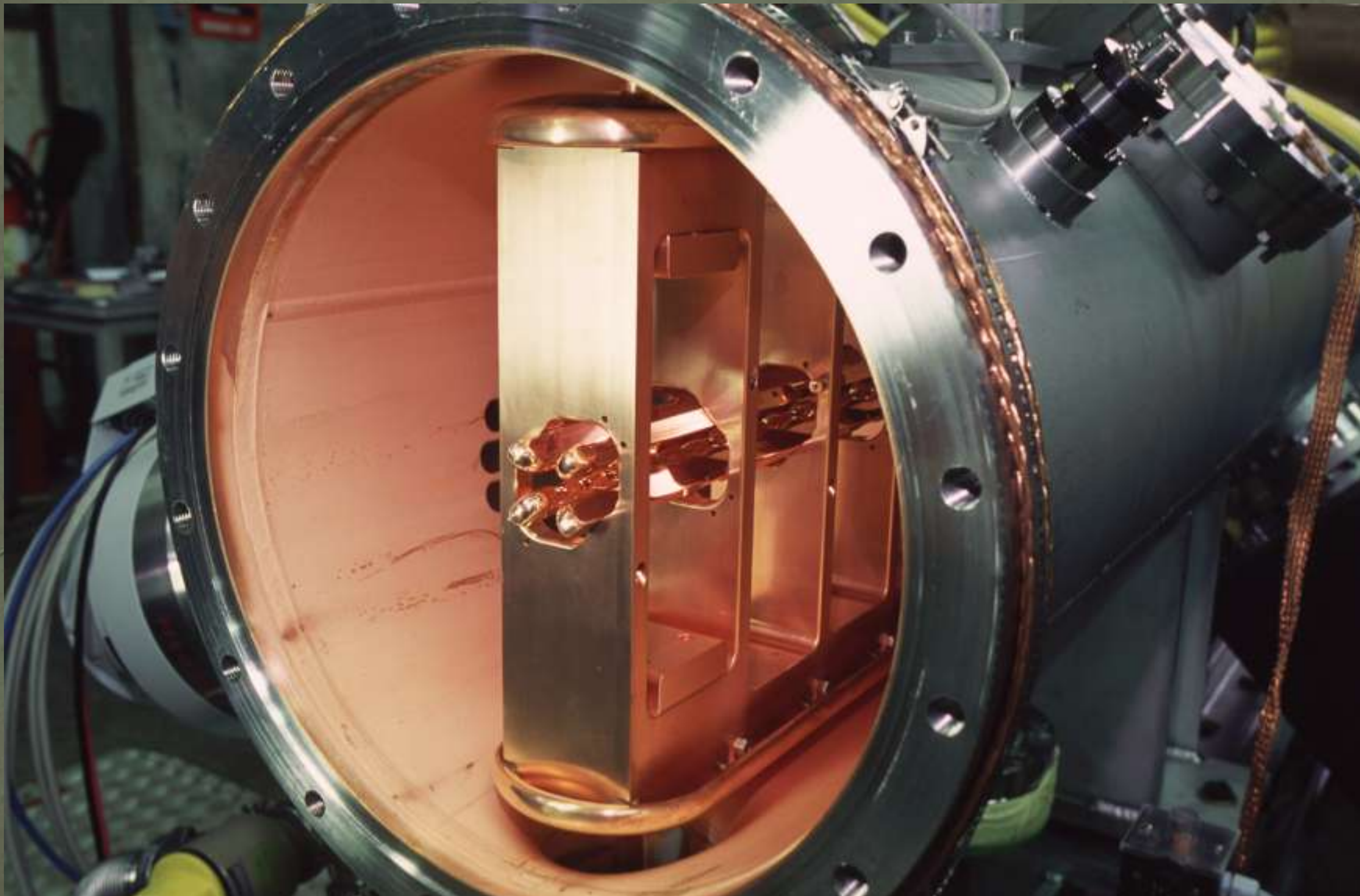
RFQ electrode modulation

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



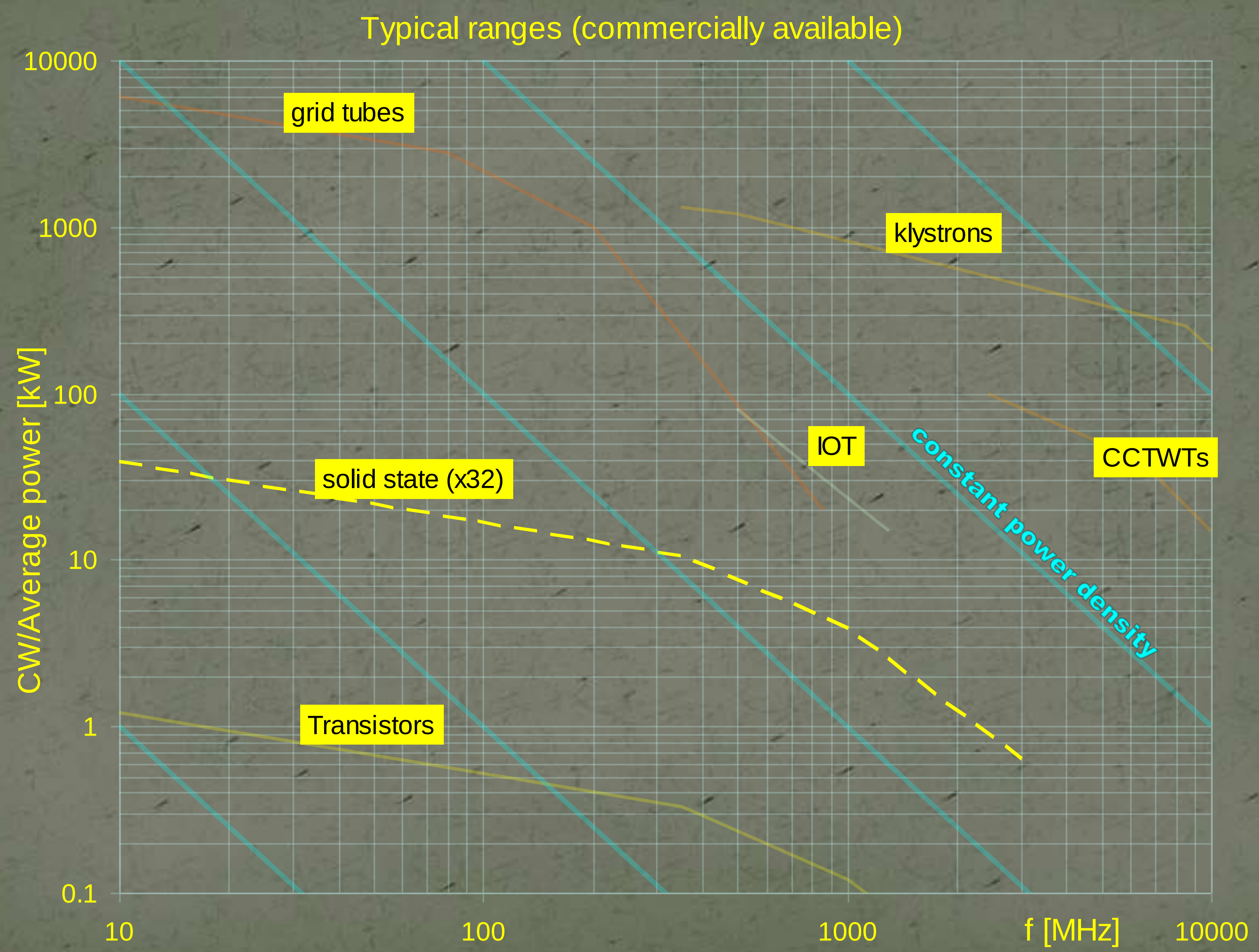


A look inside CERN AD's "RFQD"



RF power sources

RF power sources

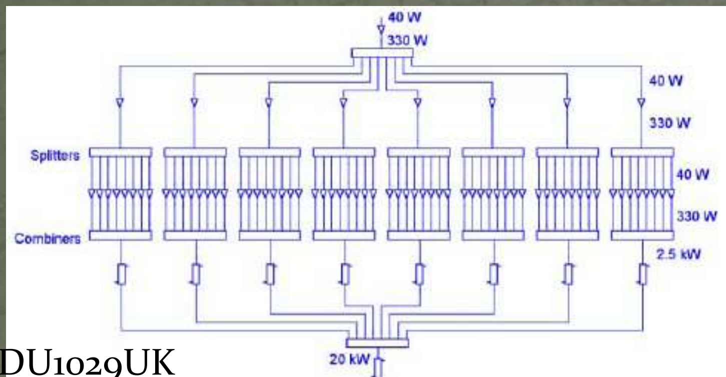


LEIR SSPA, 1 kW, 0.2 – 50 MHz

MRF151G

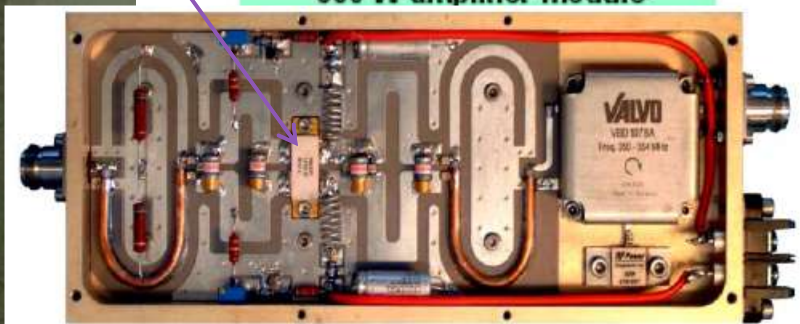
Soleil Booster SSPA, 40 kW, 352 MHz

147 modules

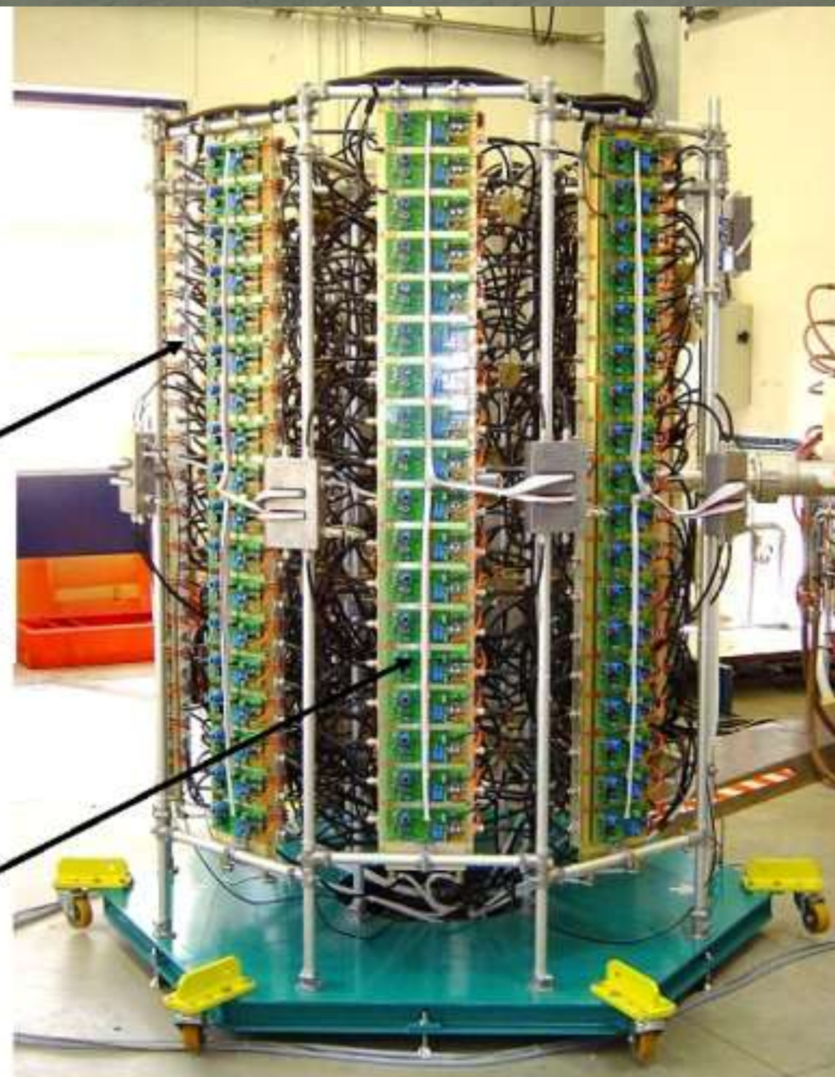


DU1029UK

330 W amplifier module

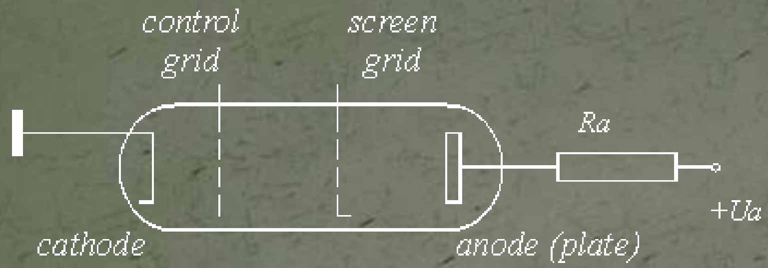


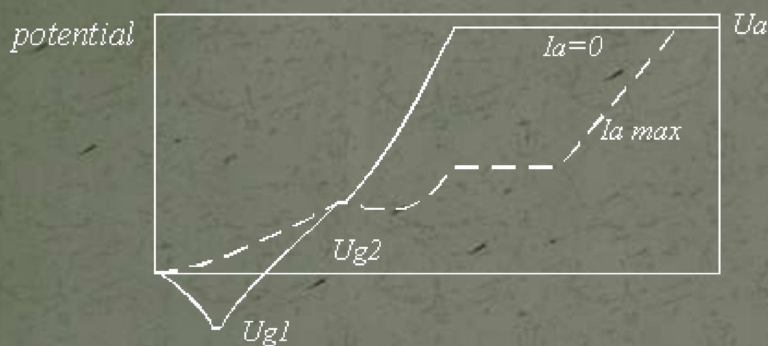
600 W, 300 Vdc / 30 Vdc converter



http://accelconf.web.cern.ch/AccelConf/e04/PAPERS/THPKF031.PDF

Tetrode





RS 1084 CJ (ex Siemens, now Thales), < 30 MHz, 75 kW

4CX250B (Eimac/CPI), < 500 MHz, 600 W (Anode removed)

YL1520 (ex Philips, now Richardson), < 260 MHz, 25 kW

High power tetrode amplifier

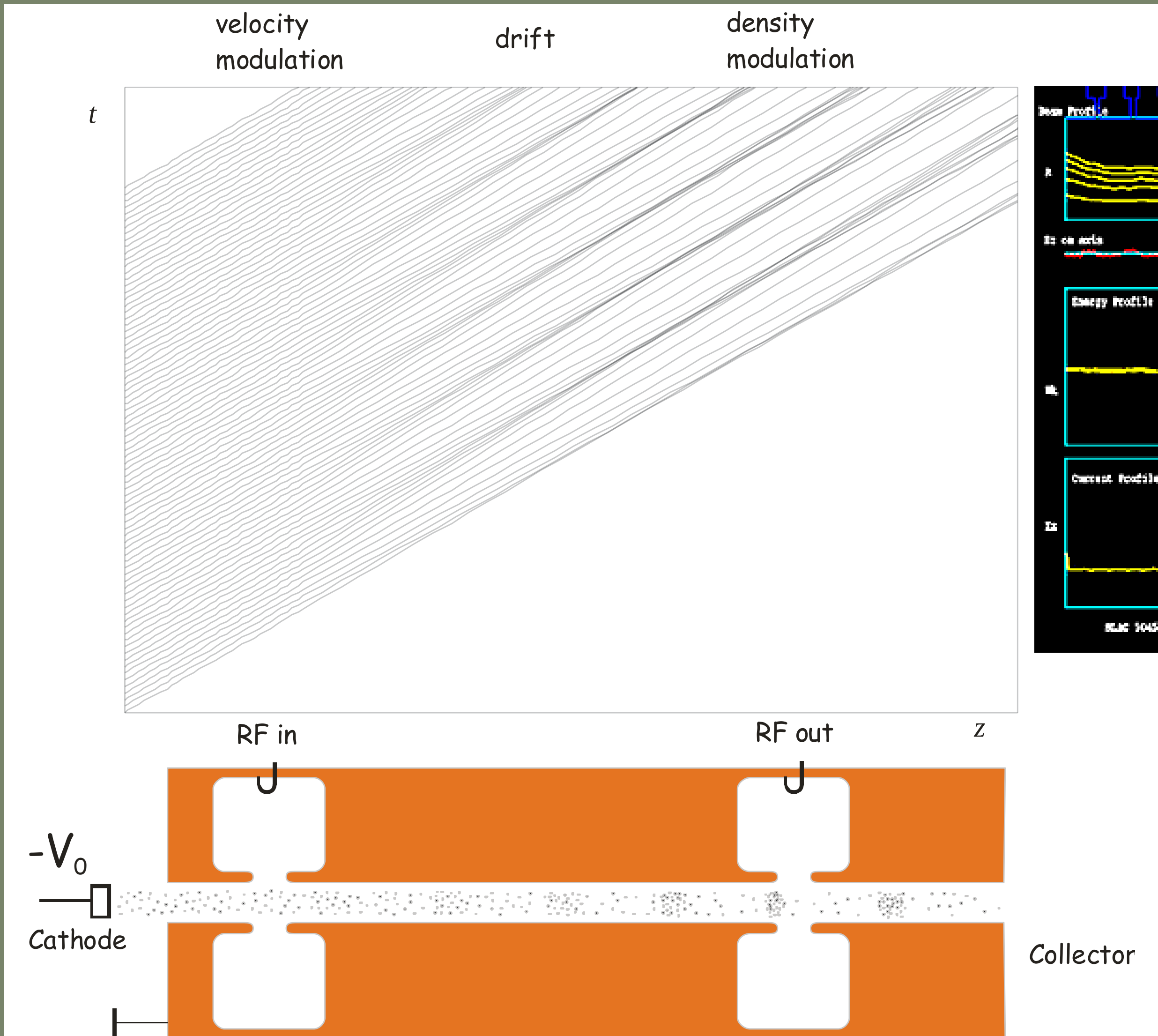
CERN Linac3: 100 MHz, 350 kW

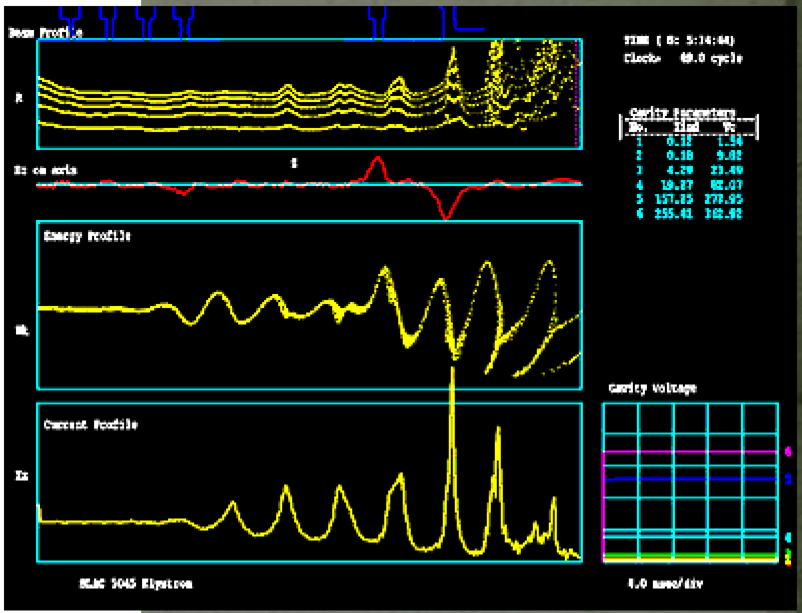
50 kW Driver: TH345, Final: RS 2054 SK

CERN PS: 13-20 MHz, 30 kW

Driver: solid state 400 W, Final: RS 1084 CJSC

Klystron principle





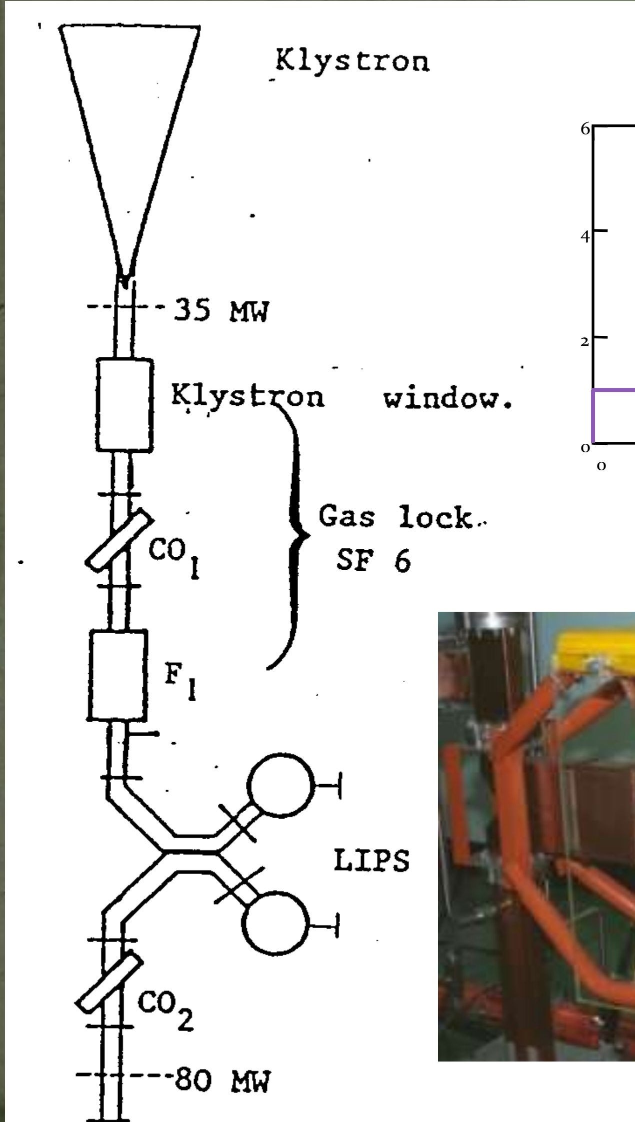
Klystrons

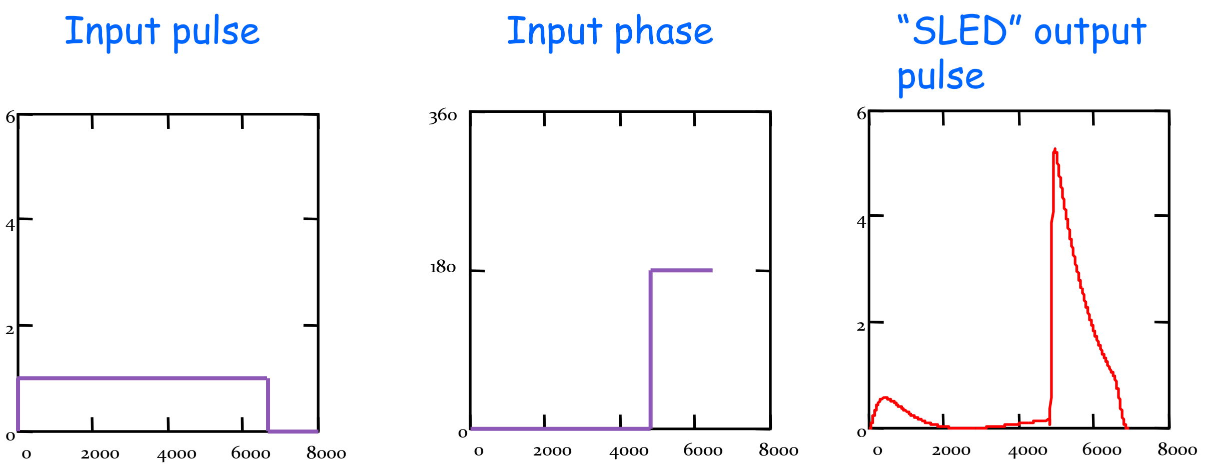
CERN CTF3 (LIL):
3 GHz, 45 MW,
4.5 μs, 50 Hz, η 45 %

CERN LHC:
400 MHz, 300 kW,
CW, η 62 %

RF pulse compression

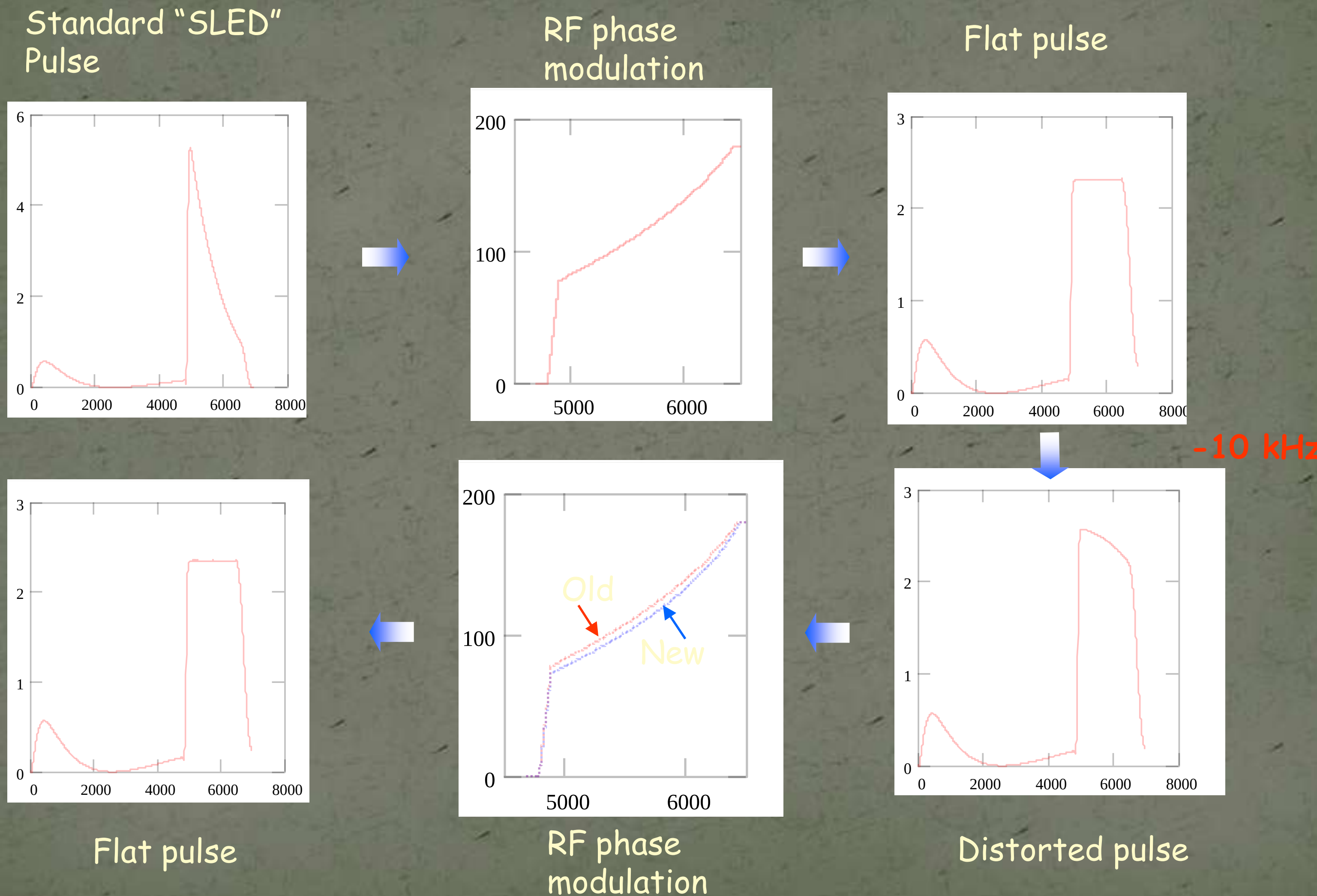
RF Pulse Compression





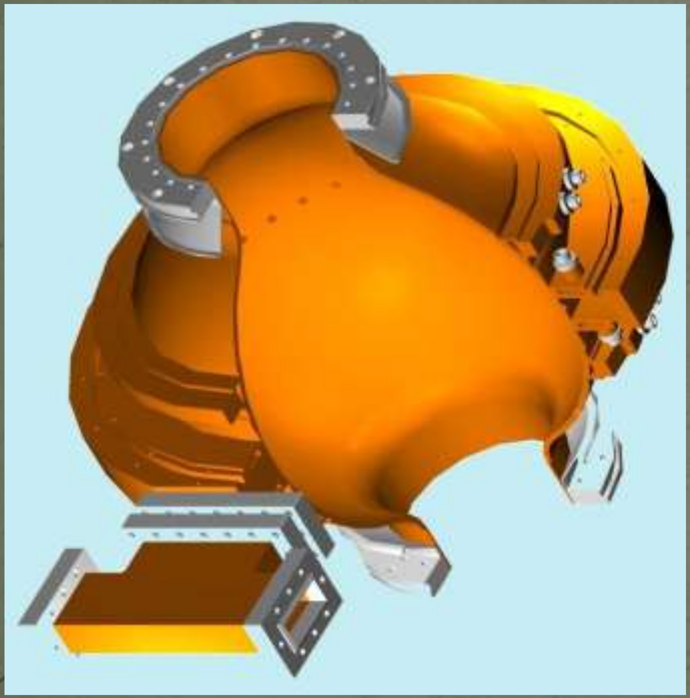
SLED: SLAC Energy Doubler   LIPS: LEP Injector Power Saver

Flat output pulses



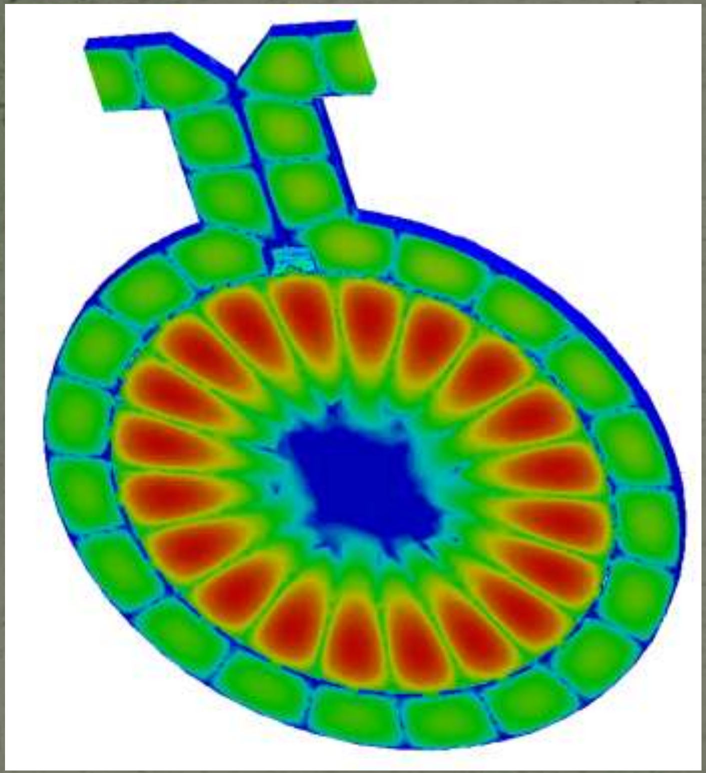
Pulse compressor

BOC „Barrel Open Cavity“

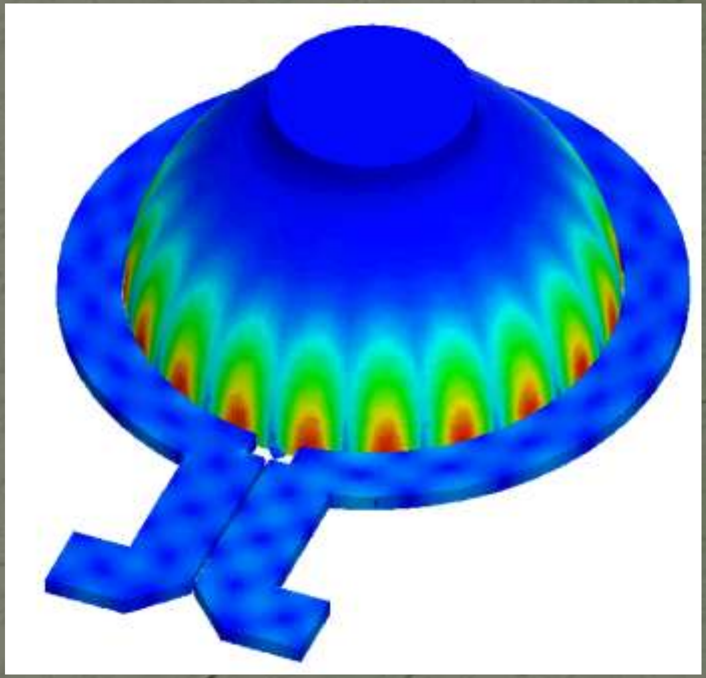


BOC

2.99848 GHz,
S11: -12.9 dB



Electric field, logarithmic scale



Magnetic field