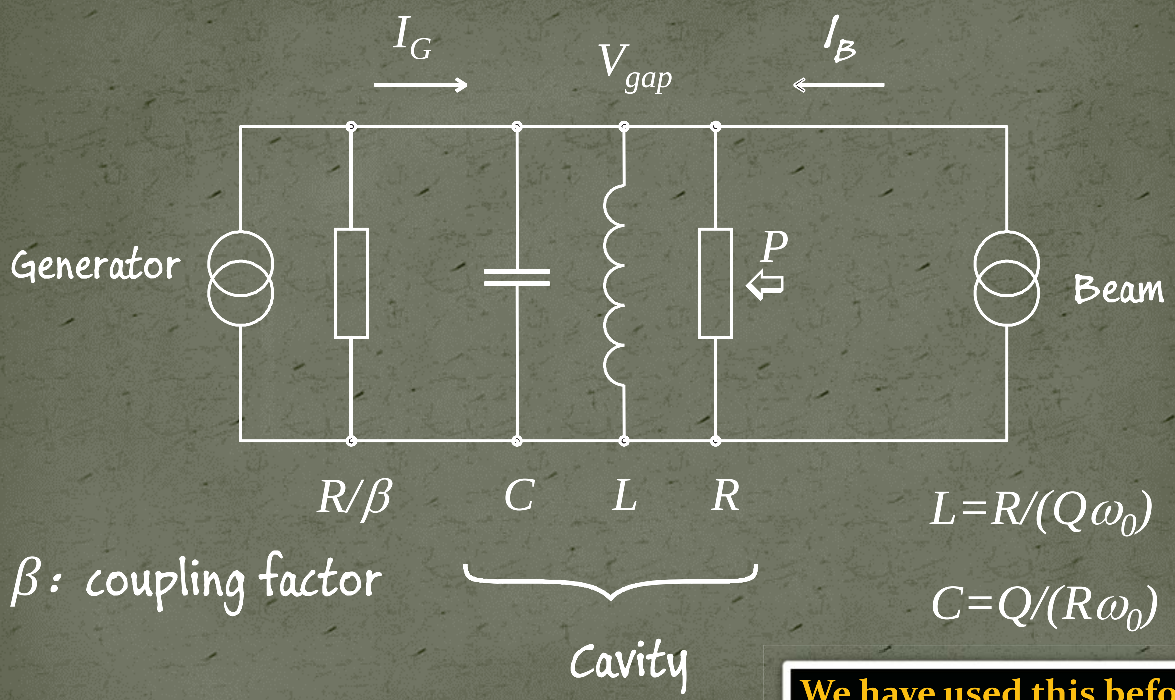
RF Systems II

Erk Jensen, CERN BE-RF

Characterizing a cavity

Cavity resonator – equivalent circuit

Simplification: single mode



$L=R/(Q\omega_0)$

$C=Q/(R\omega_0)$

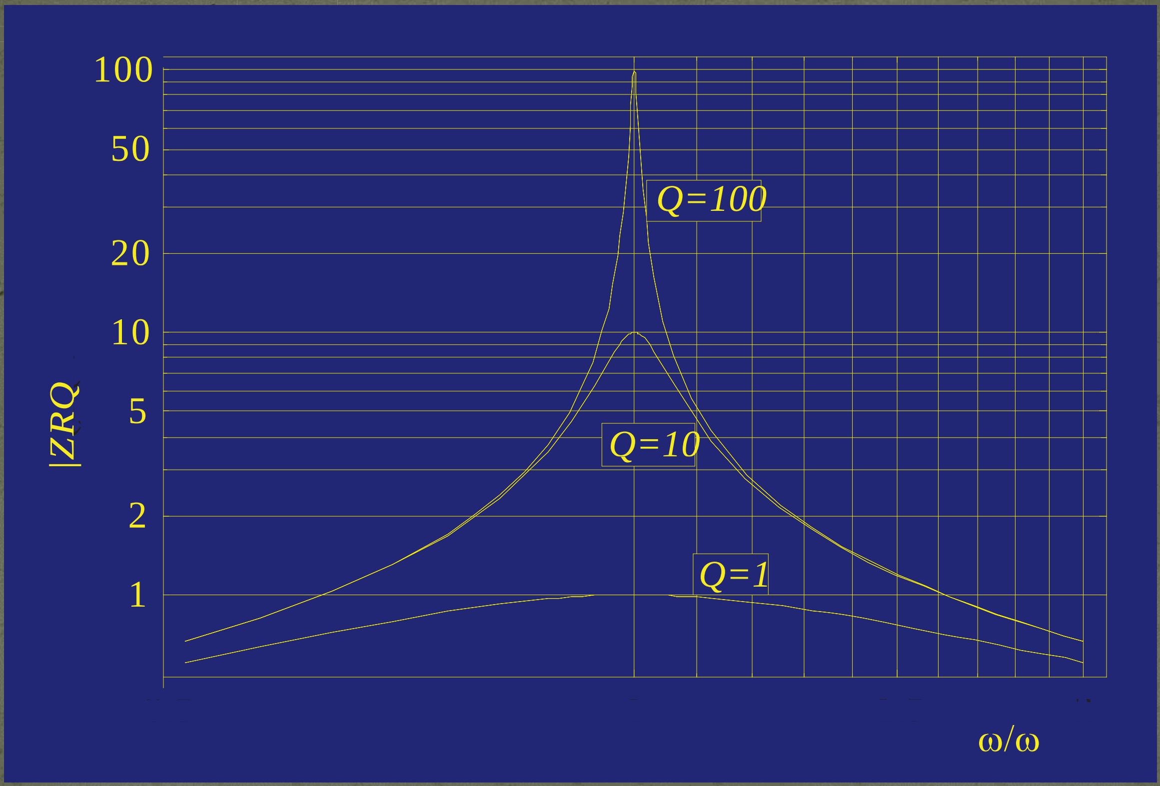
β: coupling factor

R: Shunt impedance

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

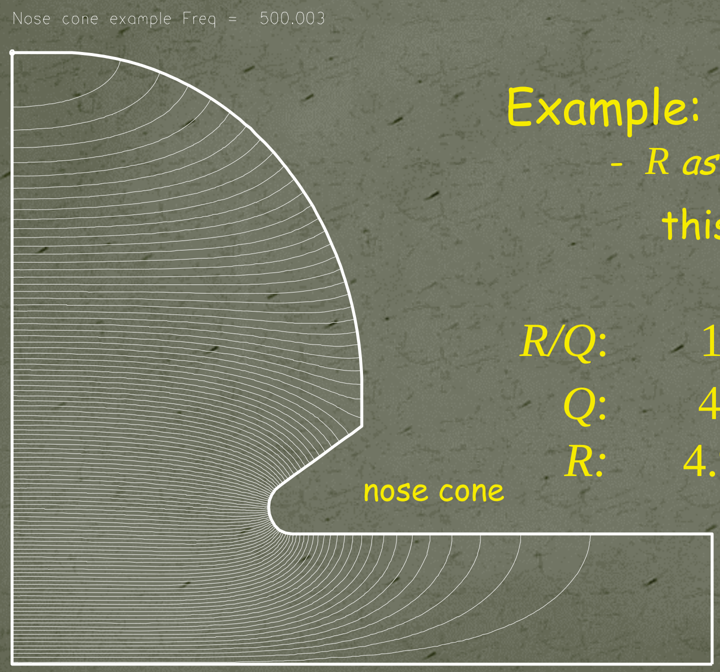
We have used this before when explaining the "fast feedback"

Resonance



Reentrant cavity

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



Example: KEK photon factory 500 MHz

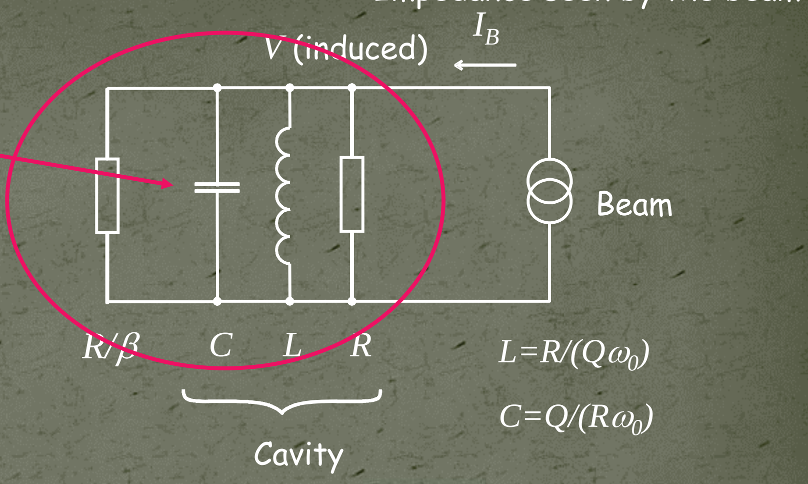
- R as good as it gets -

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

Loss factor

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

Impedance seen by the beam



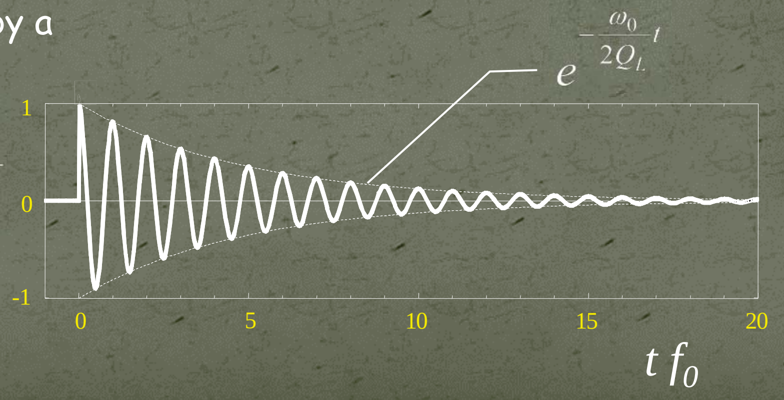
$L=R/(Q\omega_0)$

$C=Q/(R\omega_0)$

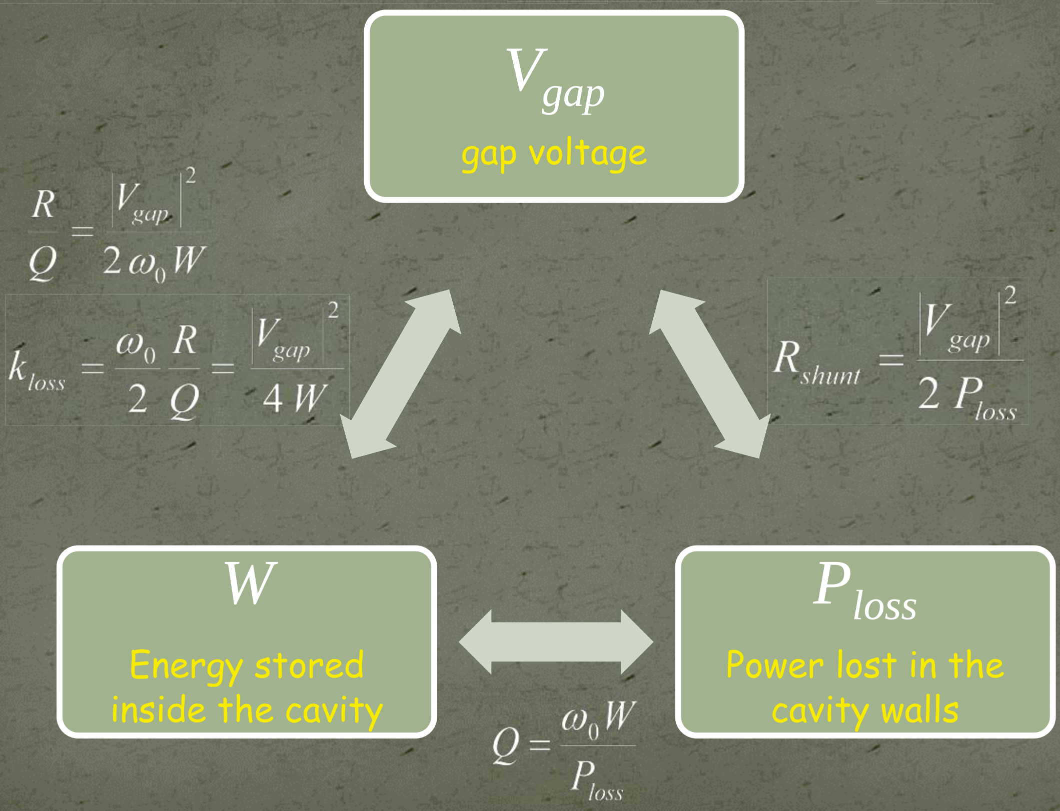
Energy deposited by a single charge q: $k_{loss}\, q^2$

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

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

Let’s talk about RF → beam efficiency!

- With zero beam current, RF power fed into the cavity excites a gap voltage, but it will be entirely lost in the cavity walls; this is characterized by the shunt impedance R:

$$|V_{acc}| = \frac{1}{2}\left(\sqrt{(4P)R}\right)$$

- A non-zero beam current induces a voltage reducing the gap voltage*); this is known as **beam loading** and normally considered a disadvantage.

$$|V_{acc}| = \frac{1}{2}\left(\sqrt{(4P + I_{beam}^2 R)R} - I_{beam}R\right)$$

- But: if we define the RF to beam efficiency as “increase of beam power” divided by “RF input power”, we find that large efficiency can be obtained only with large beam loading (at the expense of reduced accelerating voltage).
- Example: CLIC drive beam accelerated with 98% RF to beam efficiency.

---

*) for an accelerated beam! For a decelerated beam the voltage is increased

Cavity parameters

- Resonance frequency

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

- Transit time factor

  field varies while particle is traversing the gap

$$\frac{\int E_z e^{j\frac{\omega}{c}z} \mathrm{dz}}{\int E_z \mathrm{dz}}$$

Circuit definition

- Shunt impedance

  gap voltage – power relation

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

- Q factor

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

- R/Q

  independent of losses – only geometry!

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

- loss factor

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

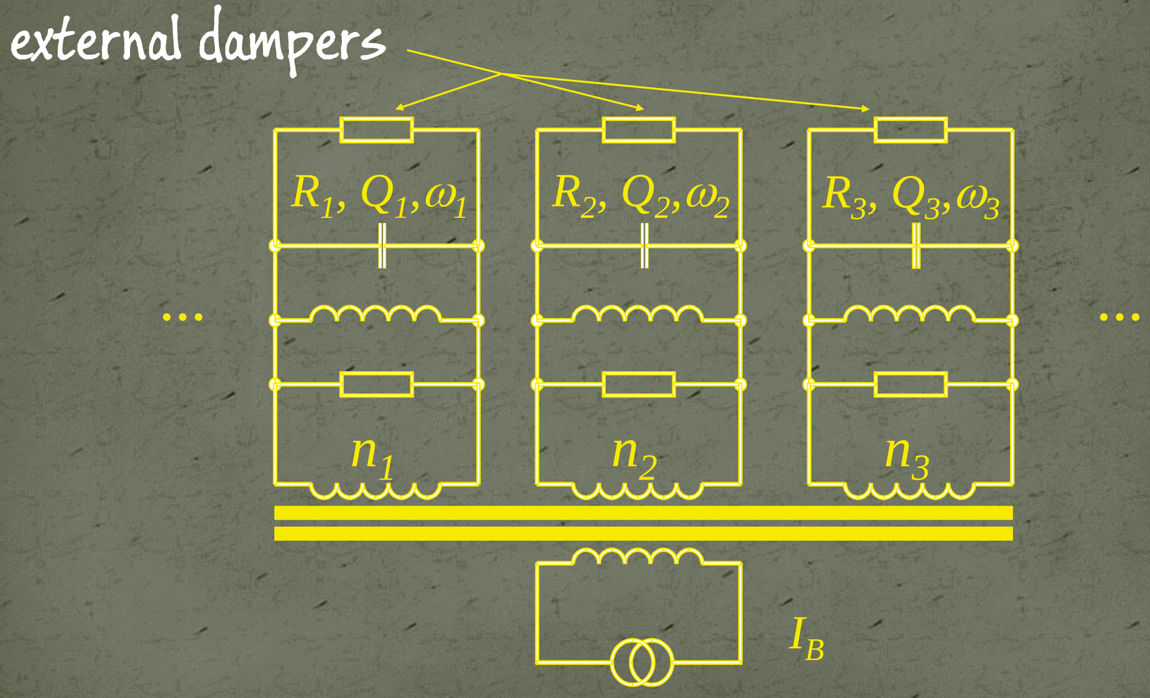
Linac definition

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

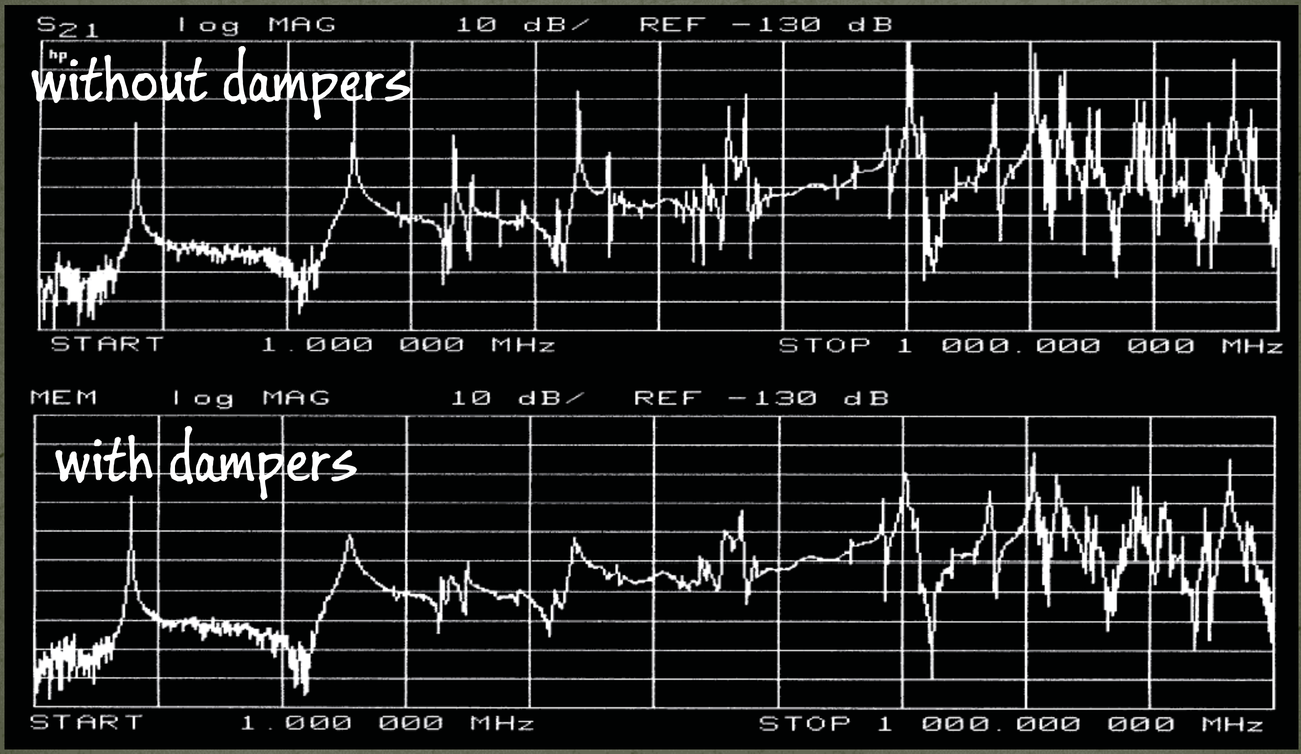
$$\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{\omega_0 W}$$

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

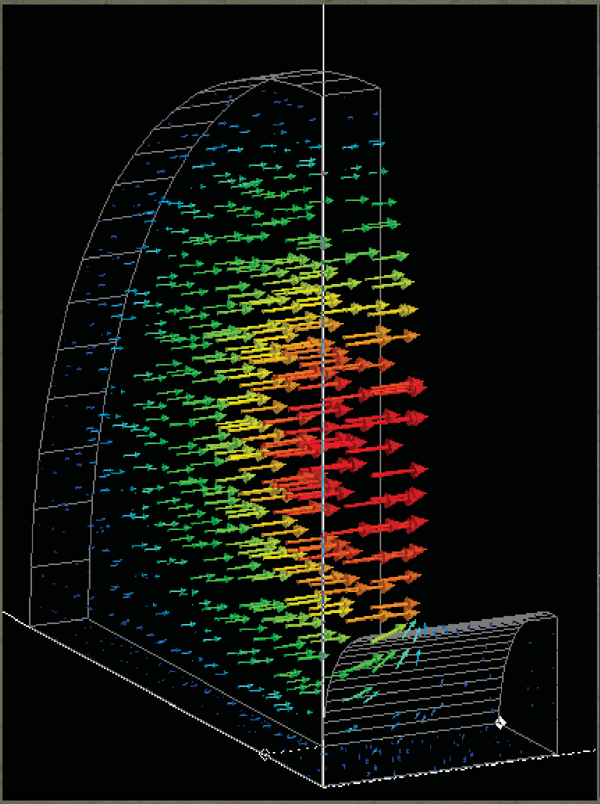
Higher order modes (HOM's)



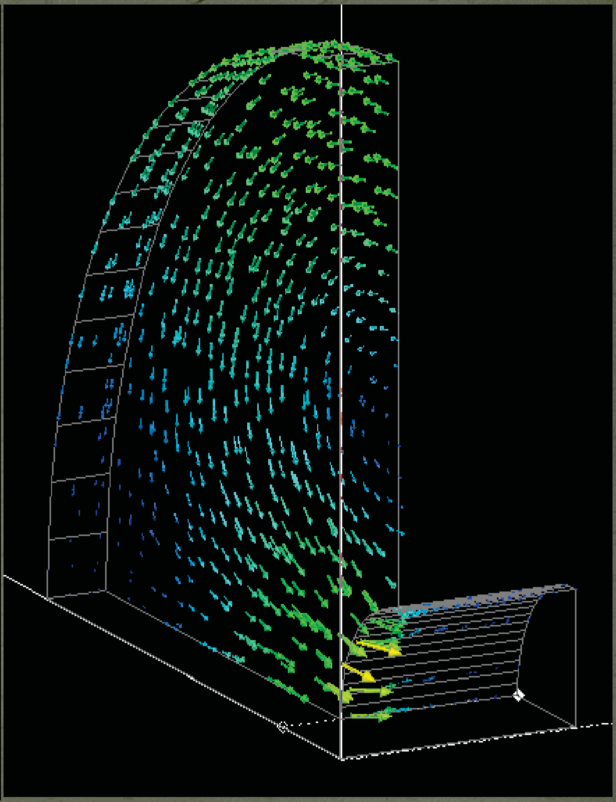
HOM (measured spectrum)



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!

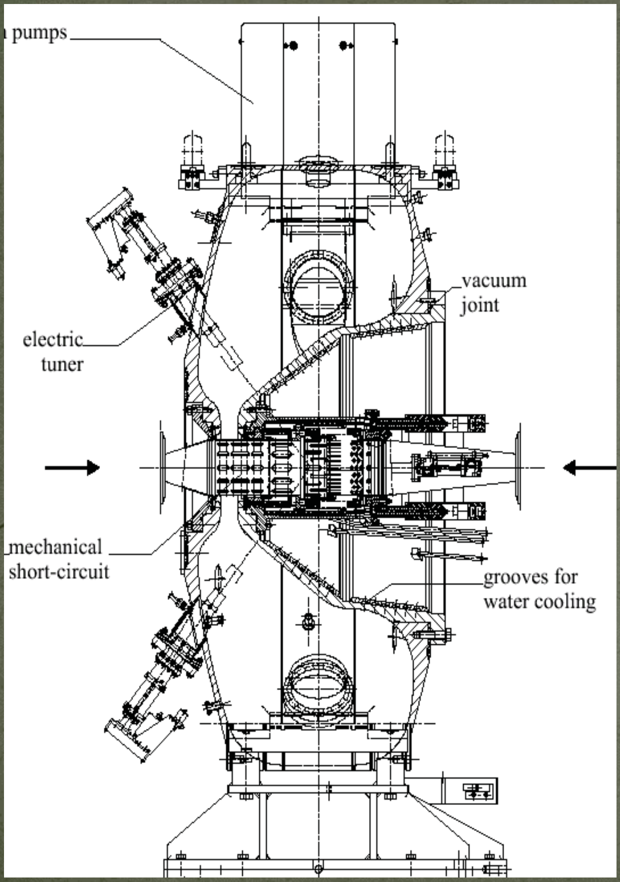
$$j\frac{\omega}{c}\vec{F}_{\perp} = \nabla_{\perp} F_{\parallel}$$

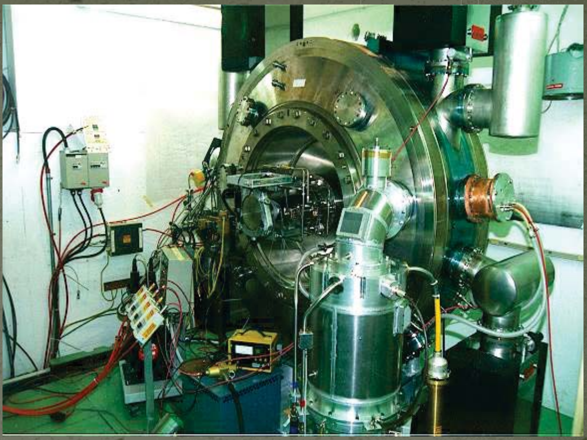
Pure TE modes: No net transverse force !

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)





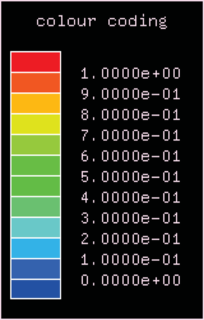
inductive (loop) coupling, low self-inductance

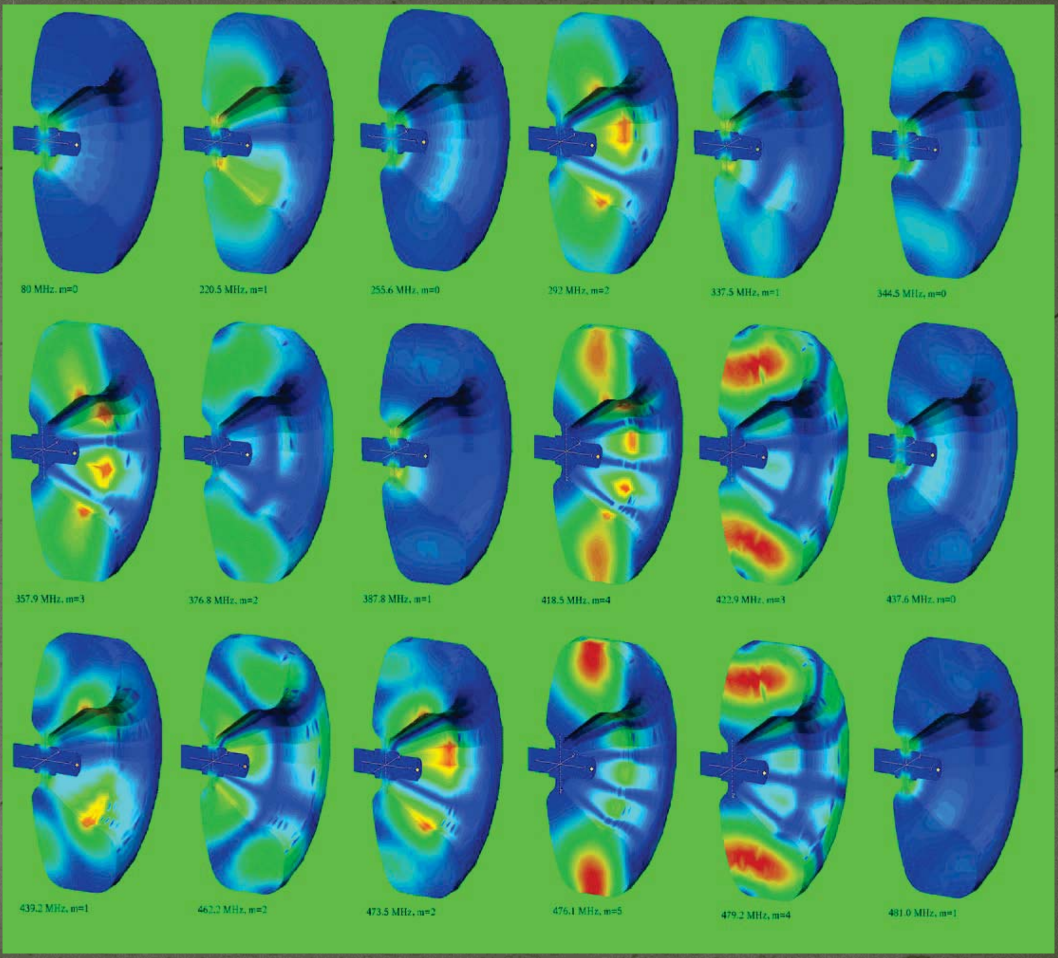
HOM's

Example shown:

80 MHz cavity PS for LHC.

Color-coded: $\vec{E}$



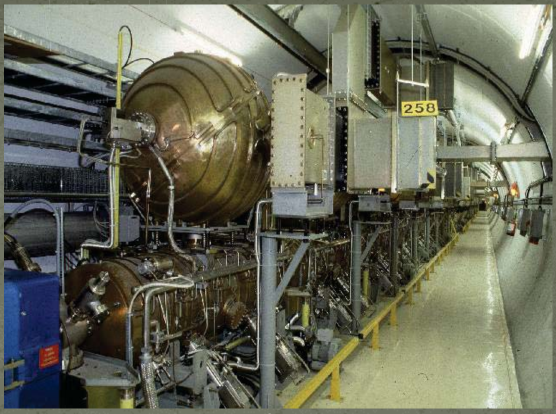


More examples of cavities

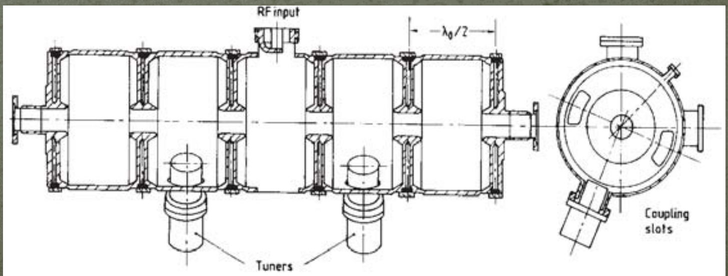
PS 19 MHz cavity (prototype, photo: 1966)

Examples of cavities

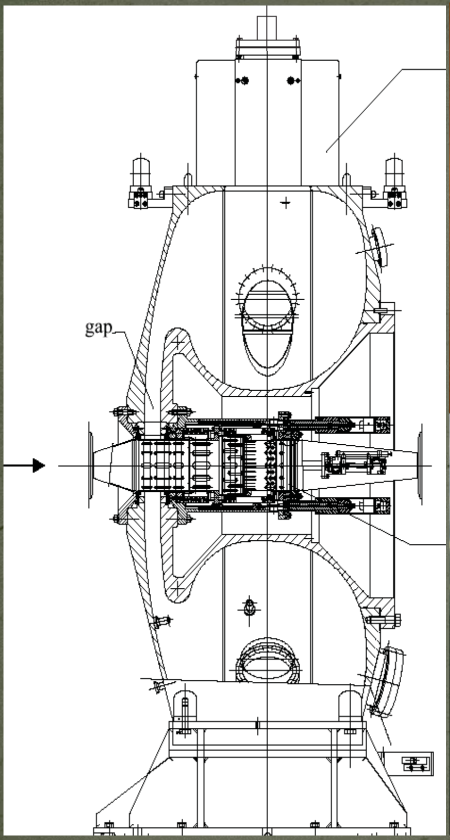
PEP II cavity
476 MHz, single cell,
1 MV gap with 150 kW,
strong HOM damping,

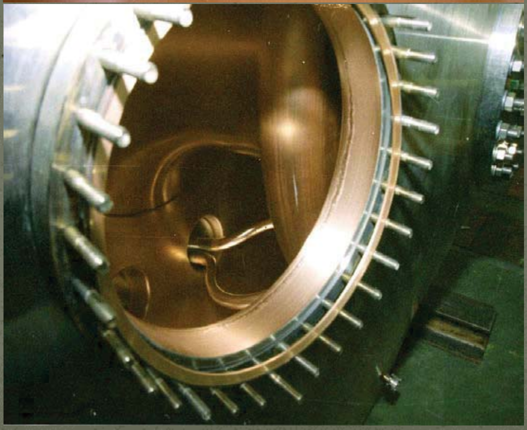


LEP normal-conducting Cu RF cavities,
352 MHz. 5 cell standing wave +
spherical cavity for energy storage, 3 MV

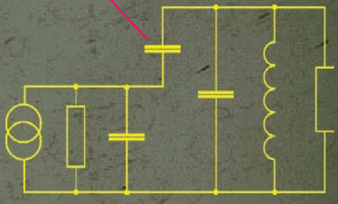


CERN/PS 40 MHz cavity (for LHC)





example for
capacitive coupling

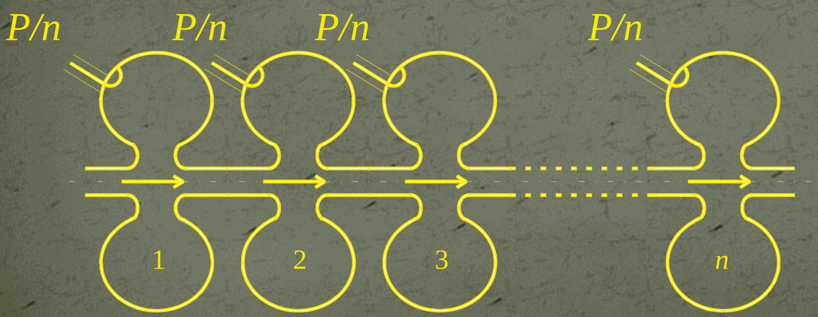

coupling C

cavity

Many gaps

What do you gain with many gaps?

- The R/Q of a single gap cavity is limited to some 100 **W**. 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.

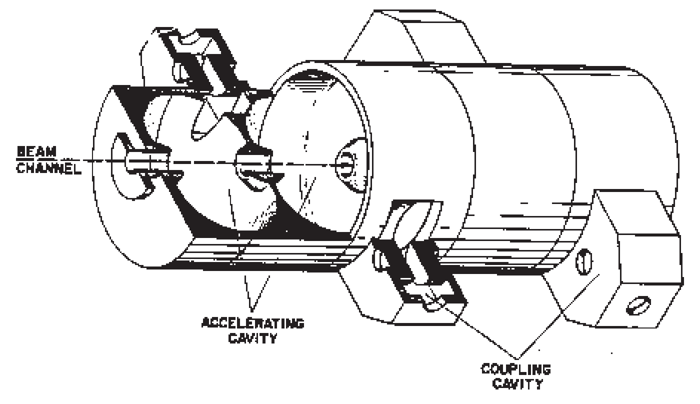


$$|V_{acc}| = n\sqrt{2\,R\frac{P}{n}} =$$
$$= \sqrt{2\,(nR)P}$$

Standing wave multicell cavity

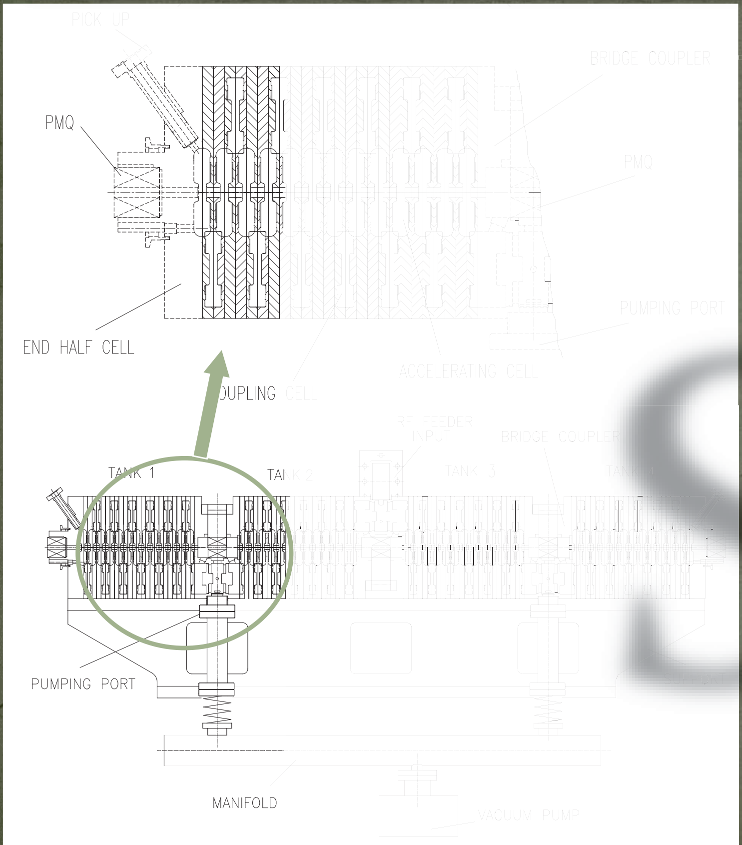
- Instead of distributing the power from the amplifier, one might as well couple the cavities, such that the power automatically distributes, or have a cavity with many gaps (e.g. drift tube linac).

- Coupled cavity accelerating structure (side coupled)



- The phase relation between gaps is important!

Side Coupled Structure : example LIBO



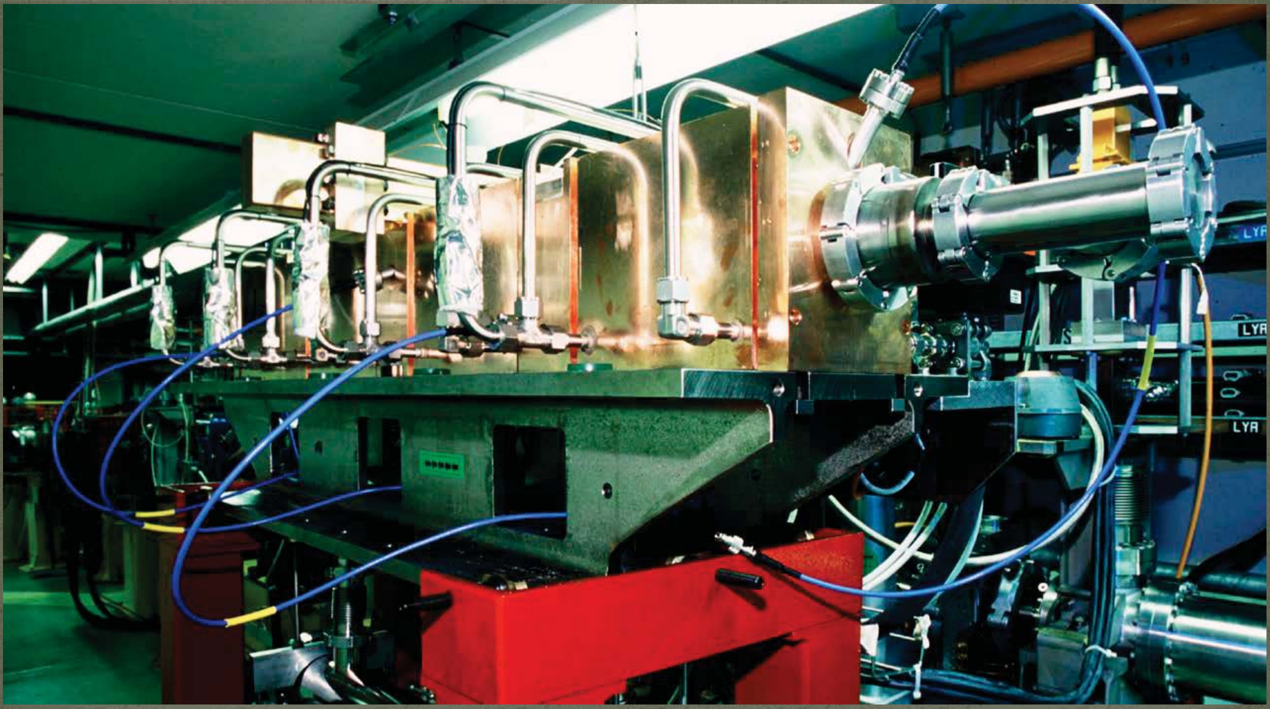
A 3 GHz Side Coupled Structure to accelerate protons out of cyclotrons from 62 MeV to 200 MeV

Medical application: treatment of tumours.

Prototype of Module 1 built at CERN (2000)

Collaboration CERN/INFN/ Tera Foundation

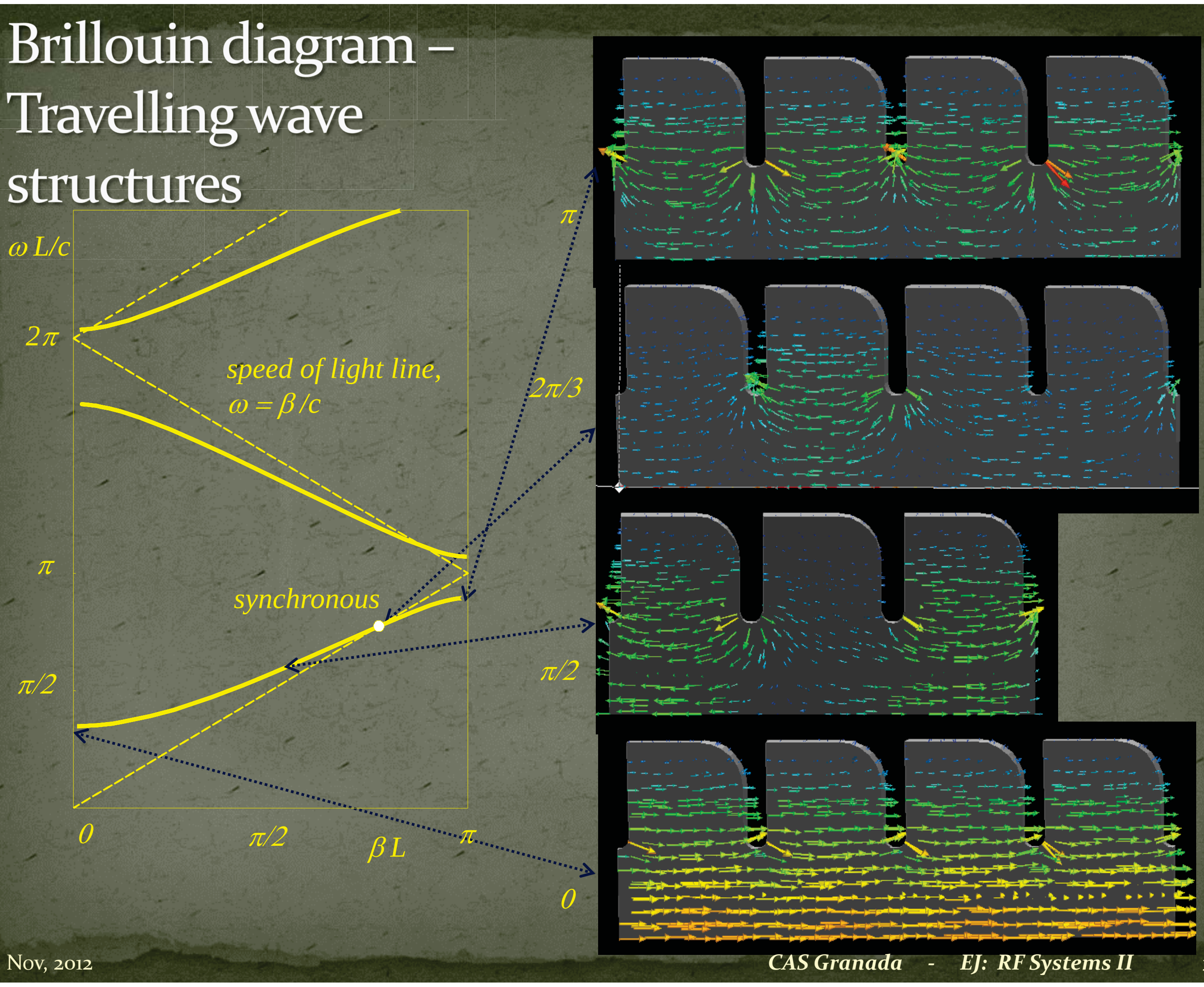
LIBO prototype



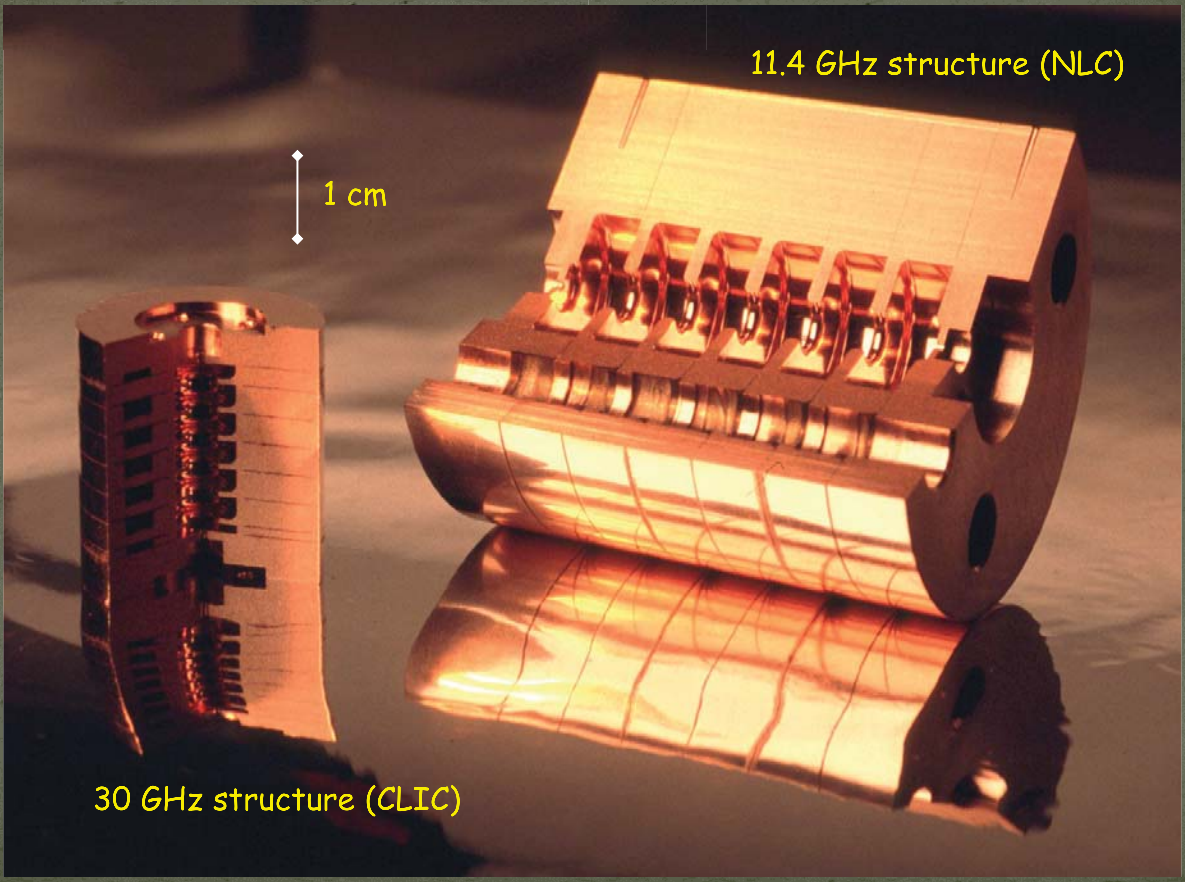
This Picture made it to the title page of CERN Courier vol. 41 No. 1 (Jan./Feb. 2001)

Travelling wave structures

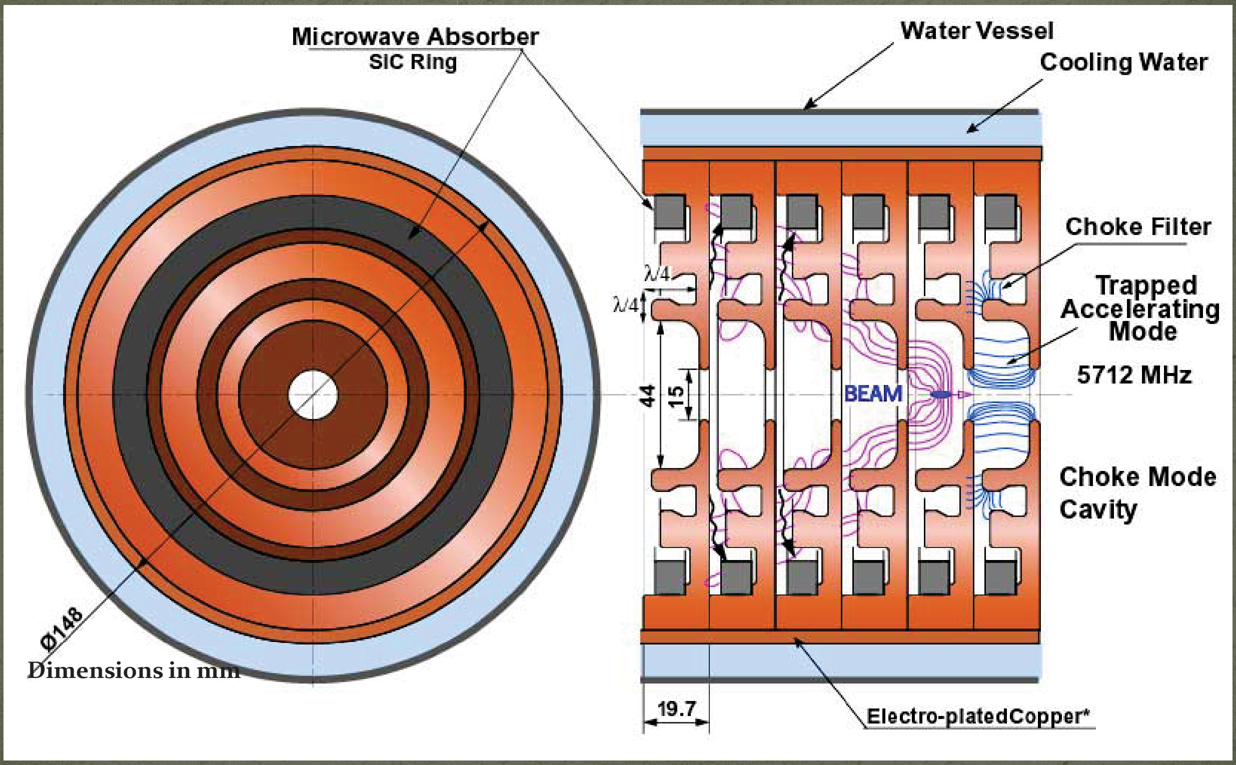
Brillouin diagram – Travelling wave structures



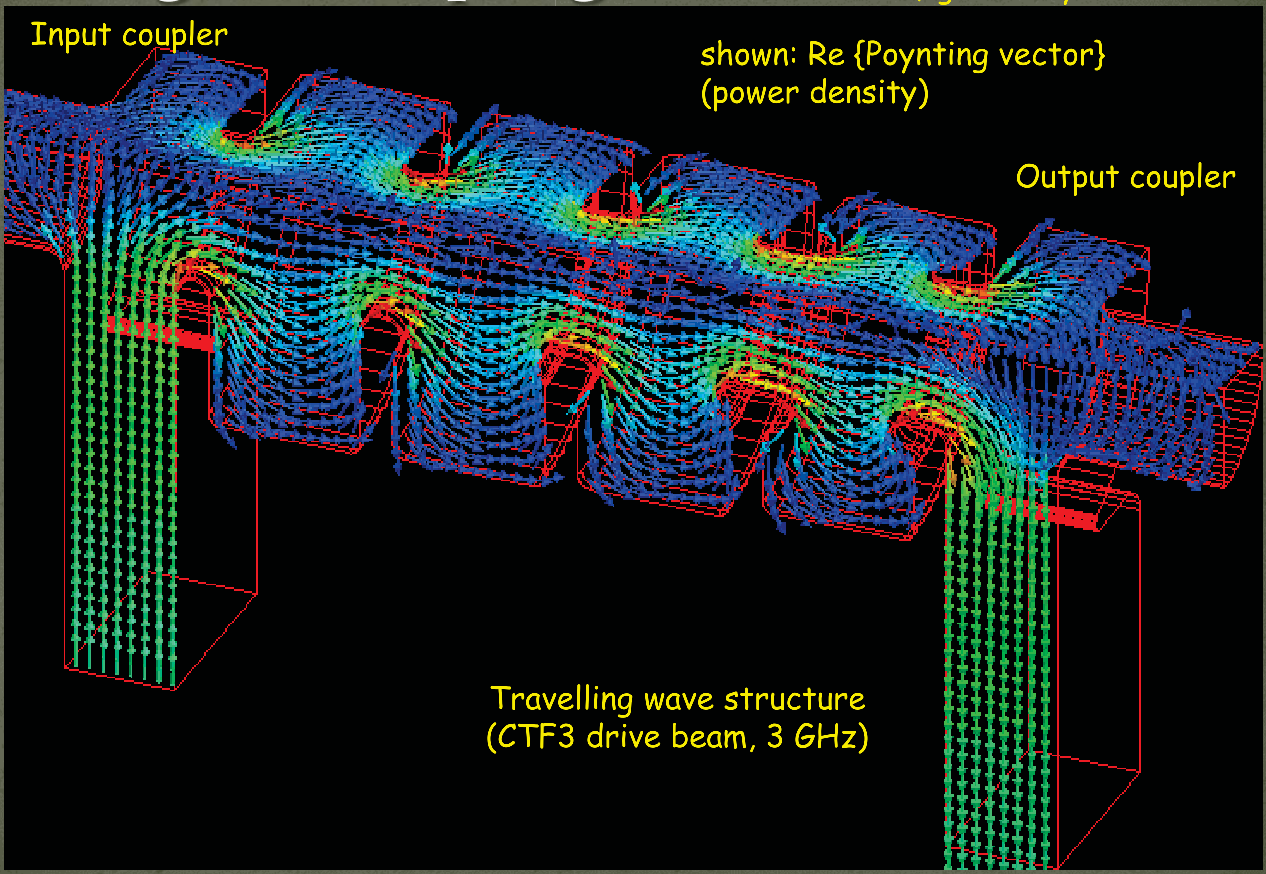
Iris loaded waveguide



Disc loaded structure with strong HOM damping “choke mode cavity”

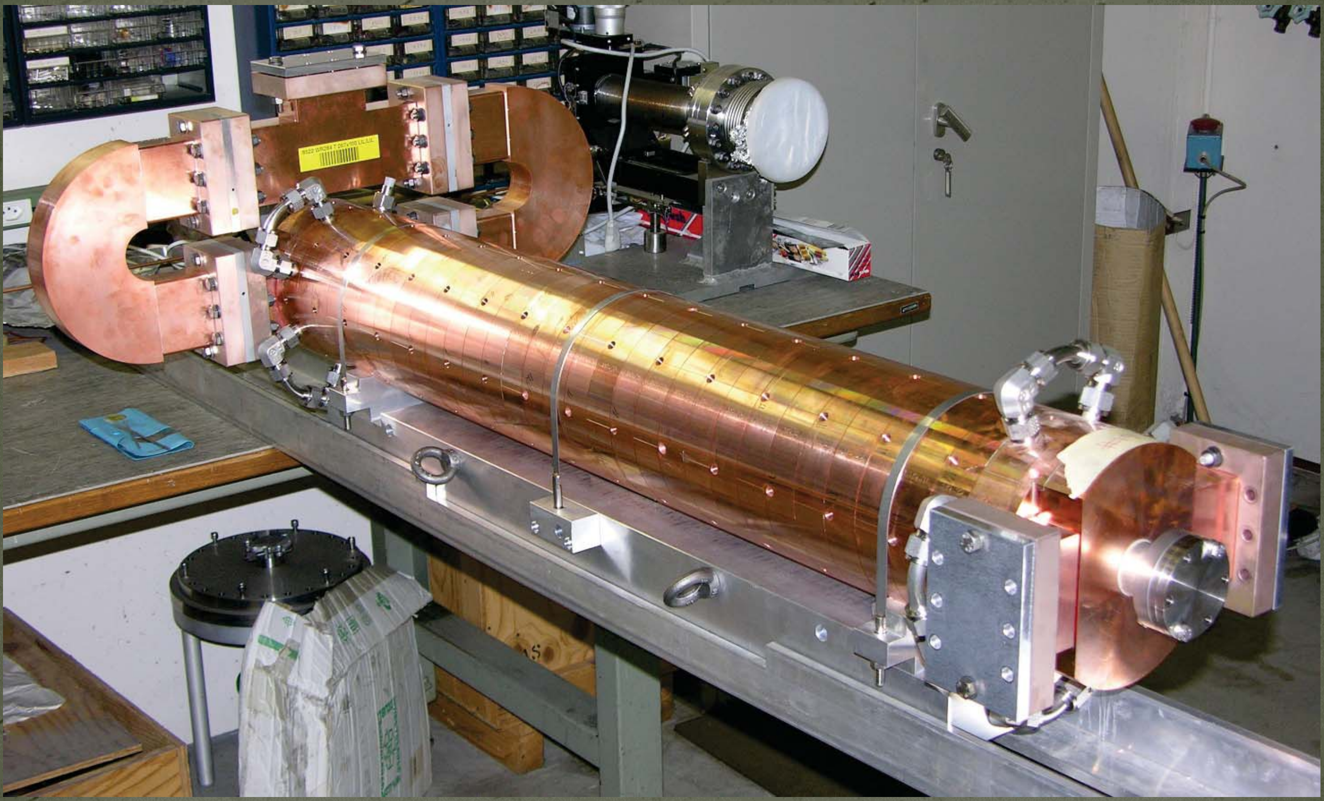


Waveguide coupling

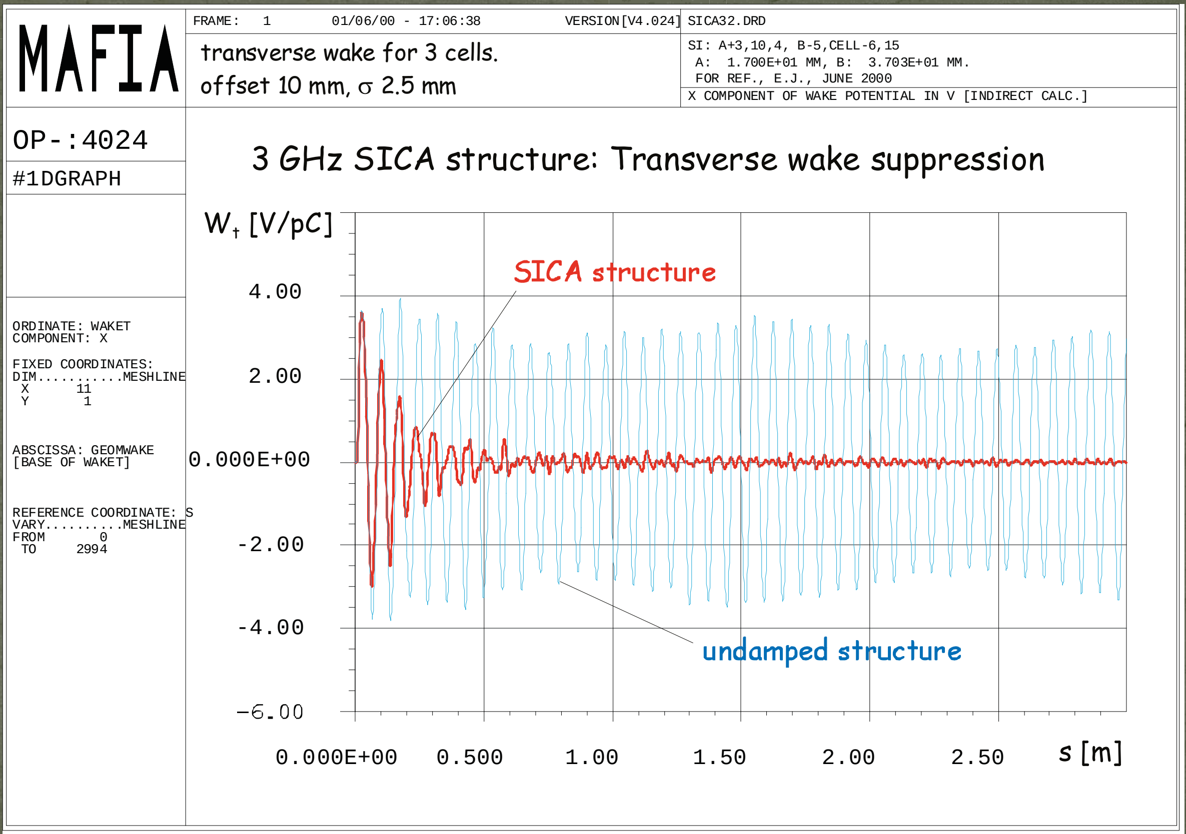


---

3 GHz Accelerating structure (CTF3)



HOM damping at work



MAFIA

FRAME: 1 01/06/00 - 17:06:38 VERSION[V4.024] SICA32.DRD

transverse wake for 3 cells.
offset 10 mm, σ 2.5 mm

```
SI: A+3,10,4, B-5,CELL-6,15
 A:  1.700E+01 MM, B:  3.703E+01 MM.
 FOR REF., E.J., JUNE 2000
X COMPONENT OF WAKE POTENTIAL IN V [INDIRECT CALC.]
```

OP-:4024

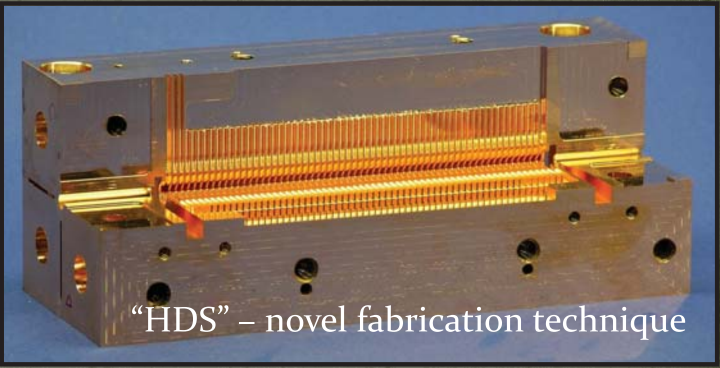
#1DGRAPH

```
ORDINATE: WAKET
COMPONENT: X

FIXED COORDINATES:
DIM............MESHLINE
 X      11
 Y       1

ABSCISSA: GEOMWAKE
[BASE OF WAKET]

REFERENCE COORDINATE: S
VARY..........MESHLINE
FROM       0
 TO     2994
```

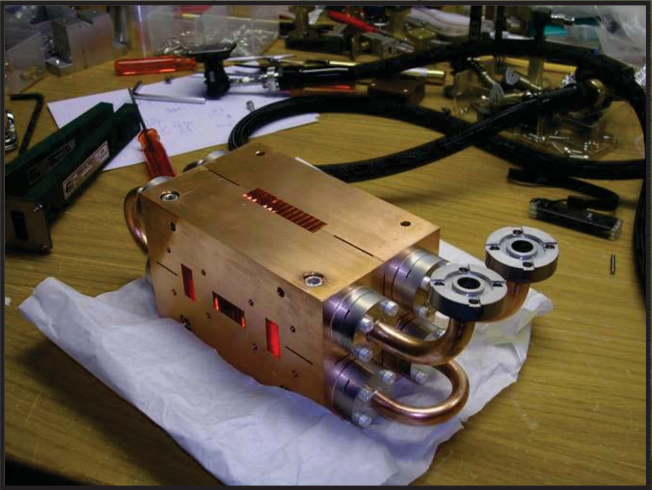
3 GHz SICA structure: Transverse wake suppression

Recent CLIC structures (11.4, 12 and 30 GHz)

"T18" reached 105 MV/m!



"HDS" – novel fabrication technique



Superconducting Linacs

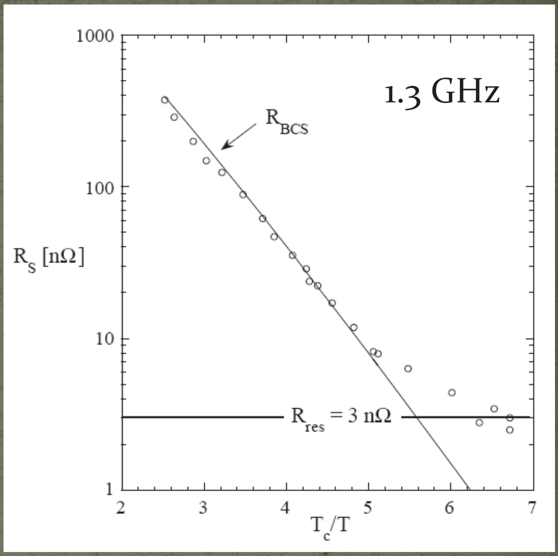
RF Superconductivity

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

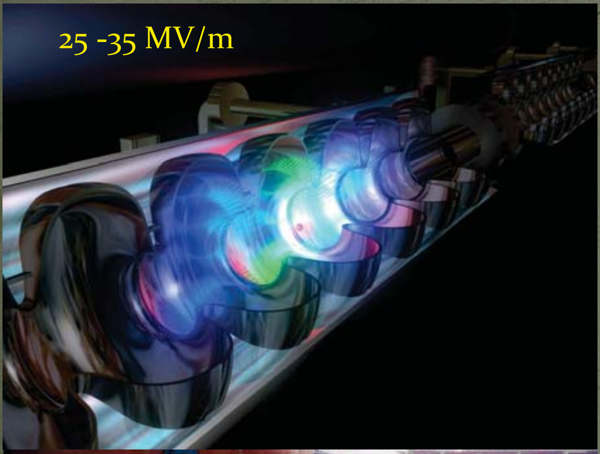
$$R_{surf} = R_{\mathrm{BCS}} + R_{res} \qquad R_{\mathrm{BCS}} \propto \omega^2 \, e^{-1.76 T_c/T}$$

- 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_3Sn).

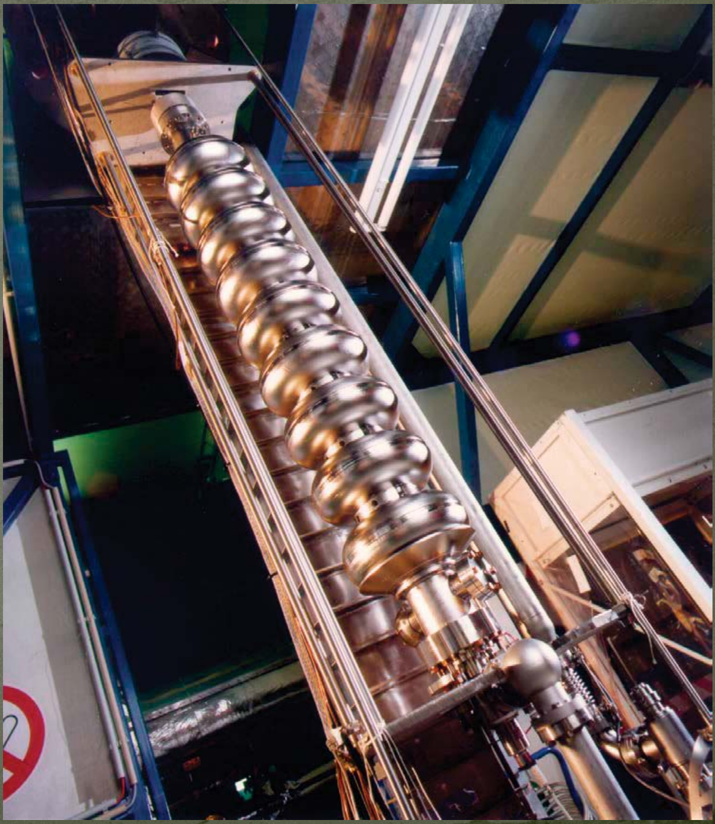
- Maximum acc. gradients are however obtained for Nb (ILC, ≈ 40 MV/m).



TESLA/ILC/X-FEL SC cavities, 1.3 GHz

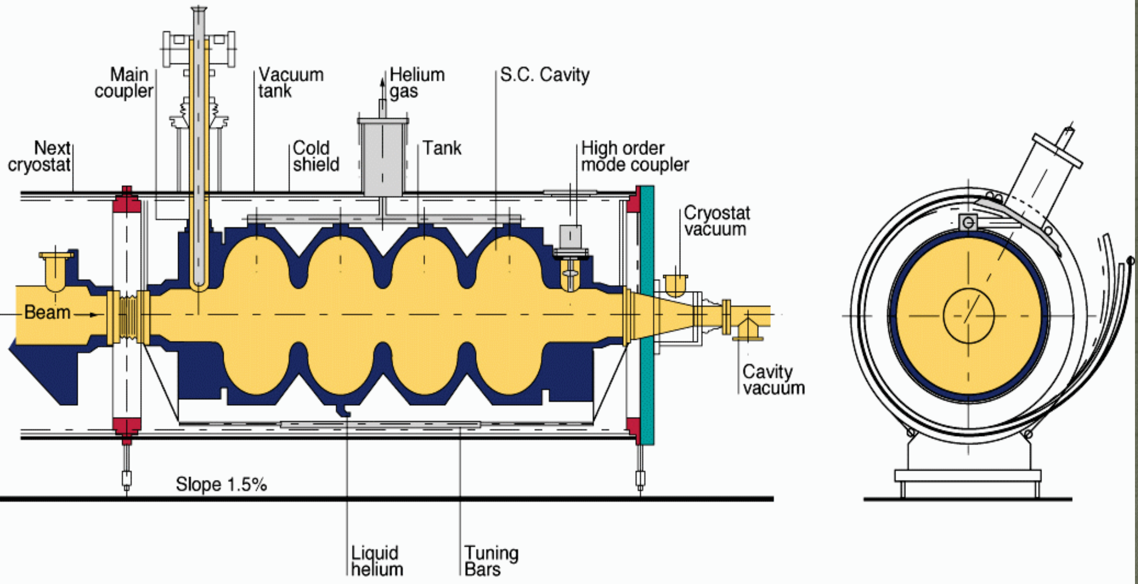


25 -35 MV/m



LEP Superconducting cavities

SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT



10.2 MV/ per cavity

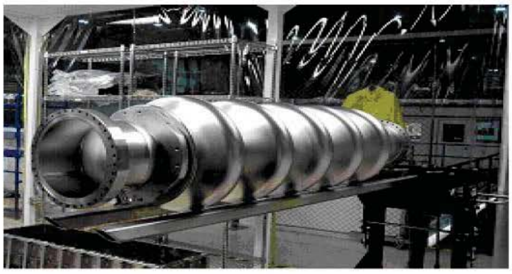
Nb coating techniques

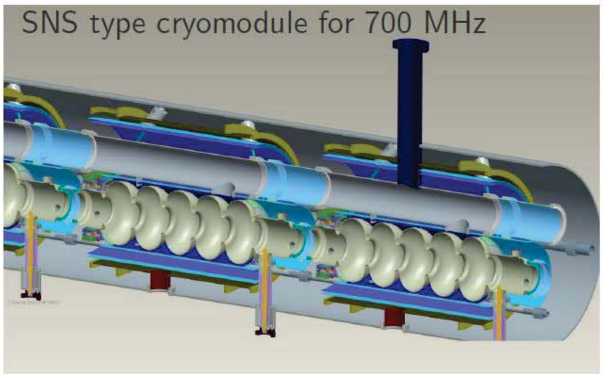
- Sputtering Nb on Cu
  - Advantages:
    - Due to the high cost of Nb, this can reduce cost!
    - The Cu substrate increases the mechanical & thermal stability (quench resistance).
  - Technology initially developed at CERN (Benvenuti, LEP, 1980); experts today at JLAB, Legnaro, Saclay, Sheffield & CERN
  - Technique used today for ALPI (LNL), Soleil, LHC & HIE-Isolde
  - Today, the max. fields are still smaller than for bulk Nb – is this an intrinsic limitation? An interesting field of R&D!
    - Can this technique be extended to new materials? (NbTiN, V_3Si, Nb_3Sn, HTS?)
- "Energetic Condensation"- HiPIMS
  - Gas phase deposition of Nb with additional kinetic energy to slow ions.
- Cathodic Arc Deposition
- …

---

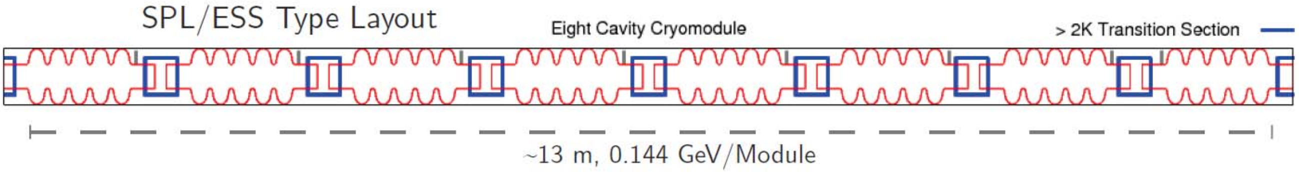
704 MHz cavities and cryomodule

ESS, eRHIC, SPL





5-cell cavities (1.6 m long), 8 per cryomodule

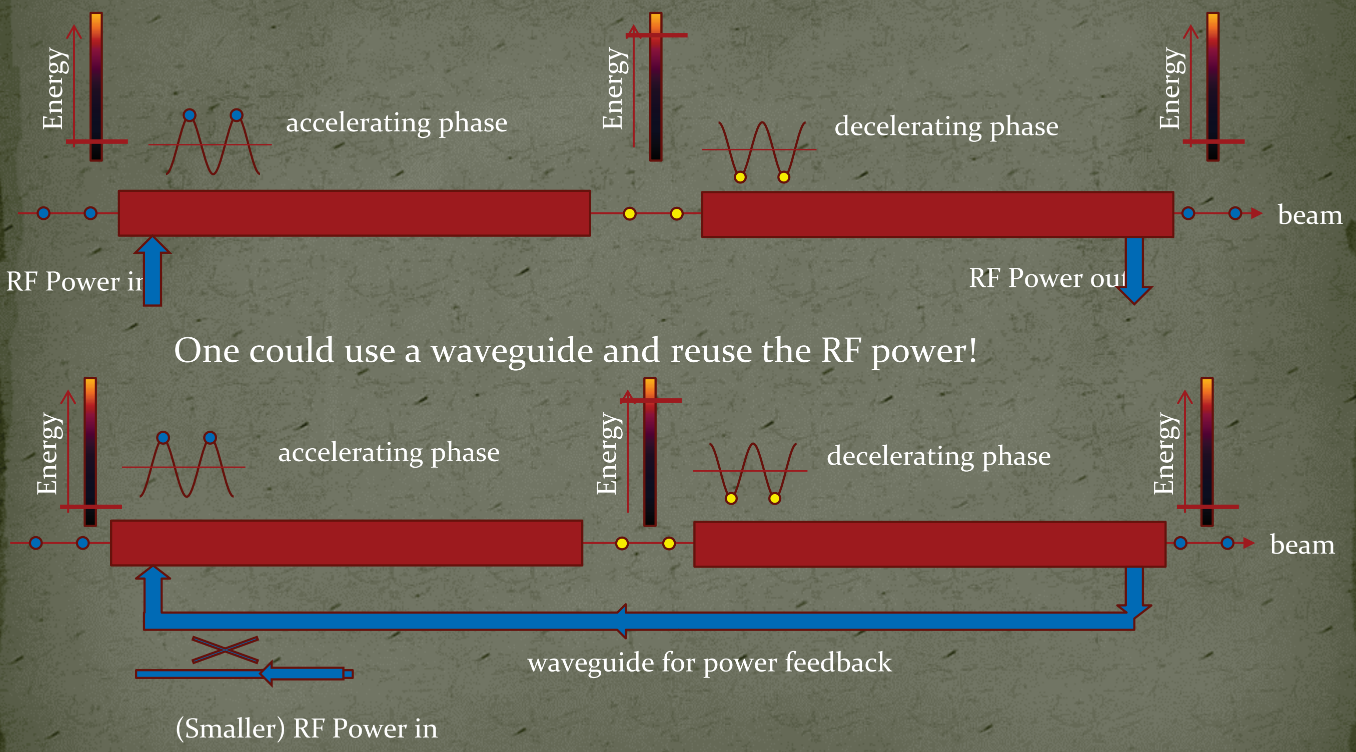


LHC SC RF, 4 cavity module, 400 MHz

Energy Recovery Linac

How to reach "power grid → beam" efficiencies above 100%

Recovering the energy from the beam – the concept



Energy

accelerating phase

Energy

decelerating phase

Energy

beam

RF Power in

RF Power out

One could use a waveguide and reuse the RF power!

Energy

accelerating phase

Energy

decelerating phase

Energy

beam

waveguide for power feedback

(Smaller) RF Power in

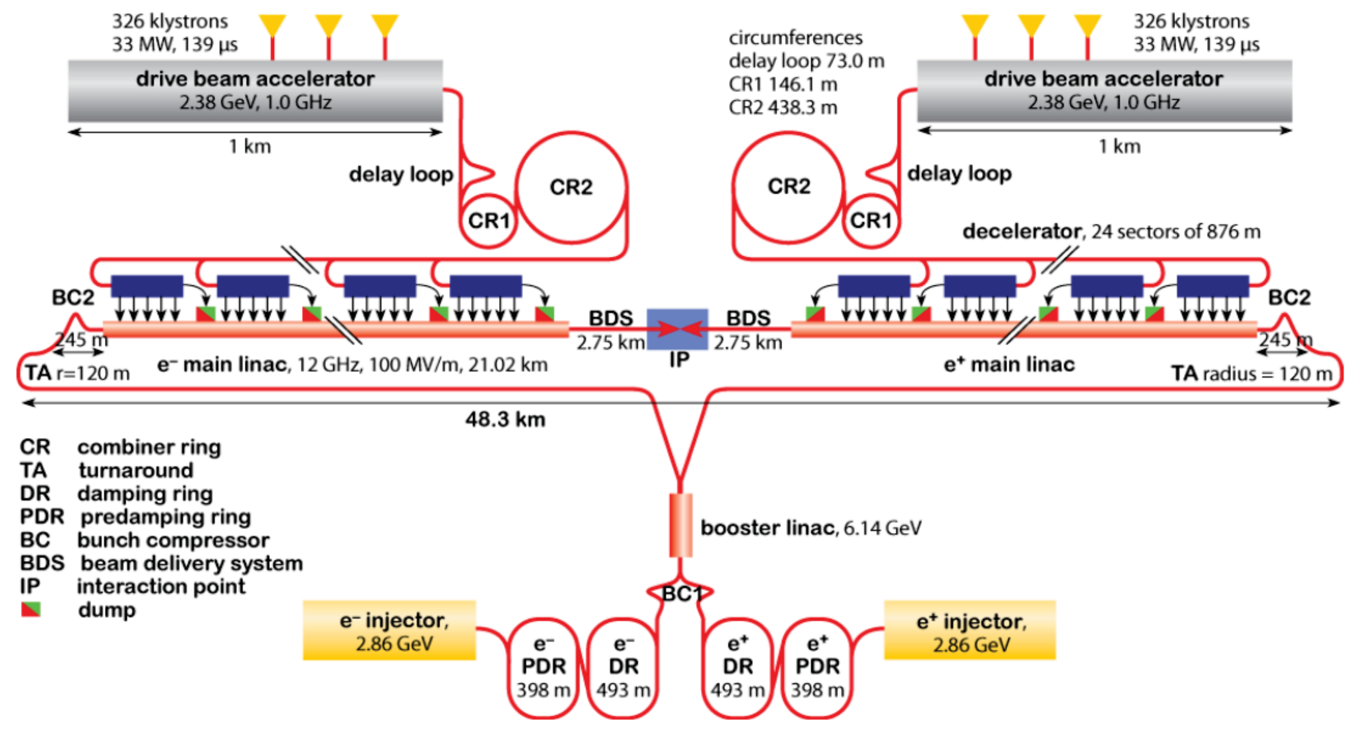
A word about CLIC

In the CLIC scheme, 90% of the drive beam power is recovered

(to produce the RF power for the main beam)

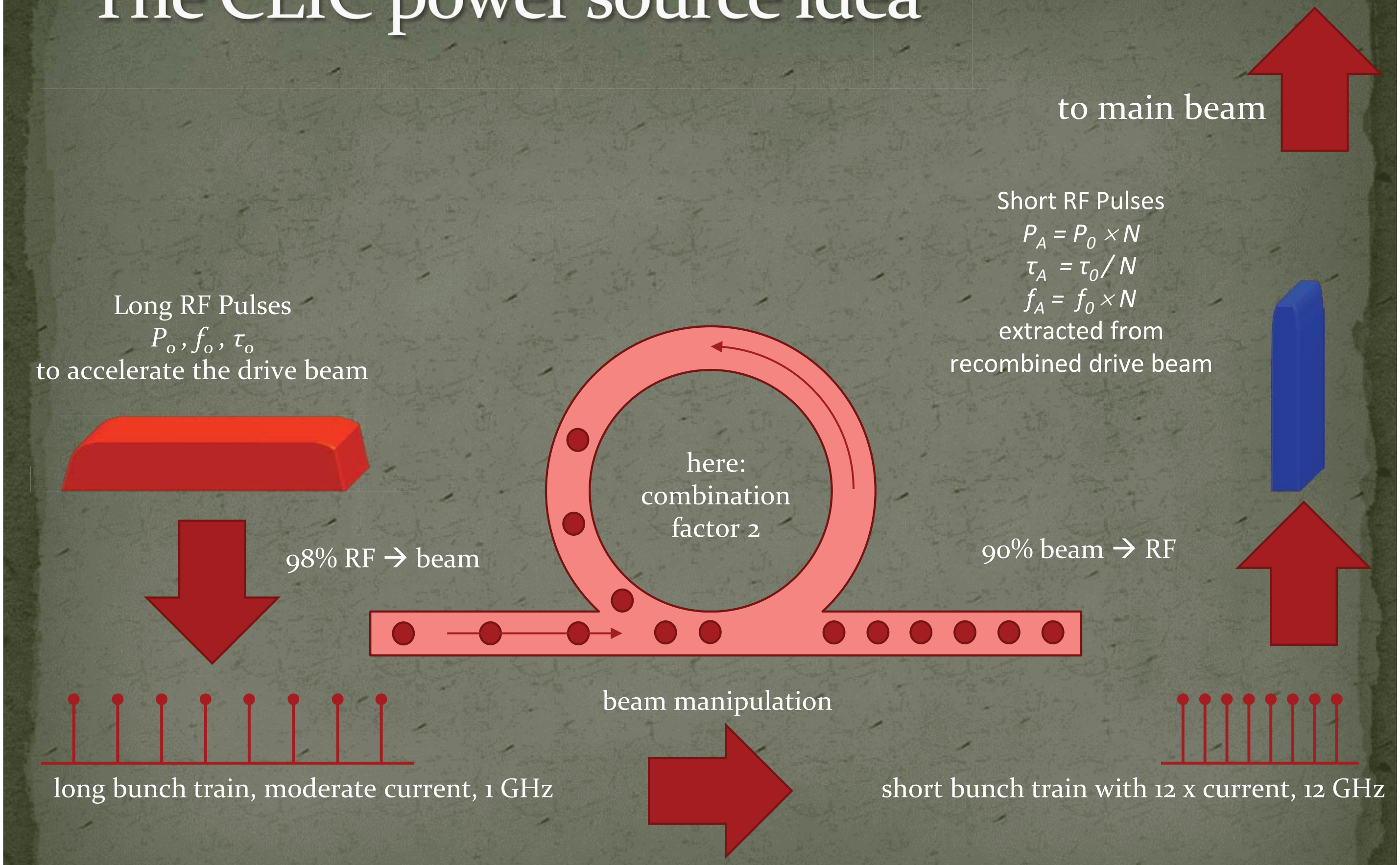
CLIC general layout

http://clic-study.org/accelerator/CLIC-inaNutshell.php



CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
◩	dump

The CLIC power source idea



to main beam

Short RF Pulses
$P_A = P_0 \times N$
$\tau_A = \tau_0 / N$
$f_A = f_0 \times N$
extracted from
recombined drive beam

Long RF Pulses
P_o, f_o, τ_o
to accelerate the drive beam

here:
combination
factor 2

98% RF → beam

90% beam → RF

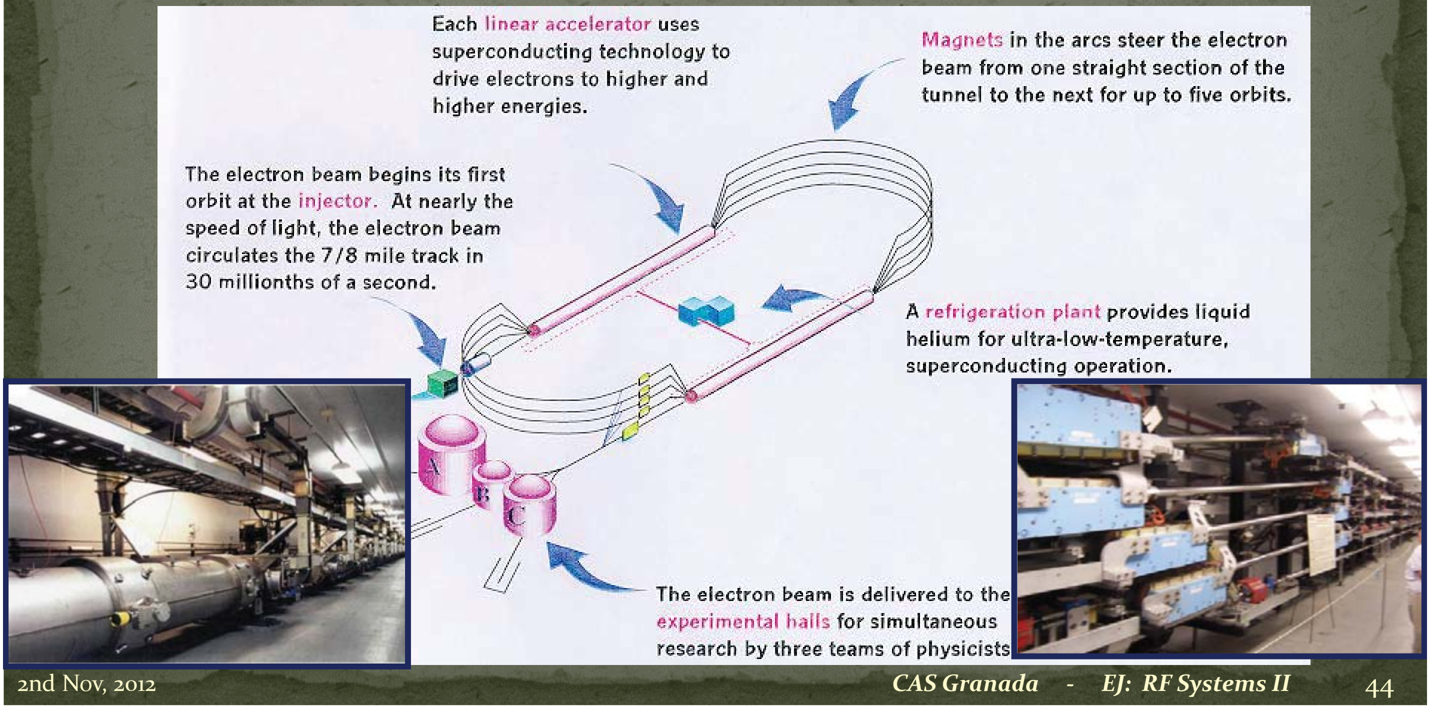
beam manipulation

long bunch train, moderate current, 1 GHz

short bunch train with 12 x current, 12 GHz

Recirculating Linac

- One could use the same accelerating structure more than once!
- CEBAF (Continuous Electron Beam Accelerator Facility) at JLAB, Newport News, VA, USA has been using this scheme successfully for many years.



Each linear accelerator uses superconducting technology to drive electrons to higher and higher energies.

Magnets in the arcs steer the electron beam from one straight section of the tunnel to the next for up to five orbits.

The electron beam begins its first orbit at the injector. At nearly the speed of light, the electron beam circulates the 7/8 mile track in 30 millionths of a second.

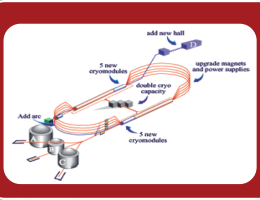
A refrigeration plant provides liquid helium for ultra-low-temperature, superconducting operation.

The electron beam is delivered to the experimental halls for simultaneous research by three teams of physicists

Recirculating Linac compared to linac and synchrotron

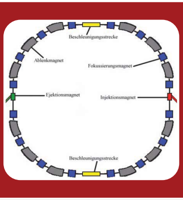
Linac

- Accelerating Structure used for 1 passage
- Less efficient
- Only single pass instabilities



Recirculating Linac

- Accelerating Structure used for some (2-10) passages
- Return arcs different for different energies
- Concerning instabilities, a good compromise



Synchrotron

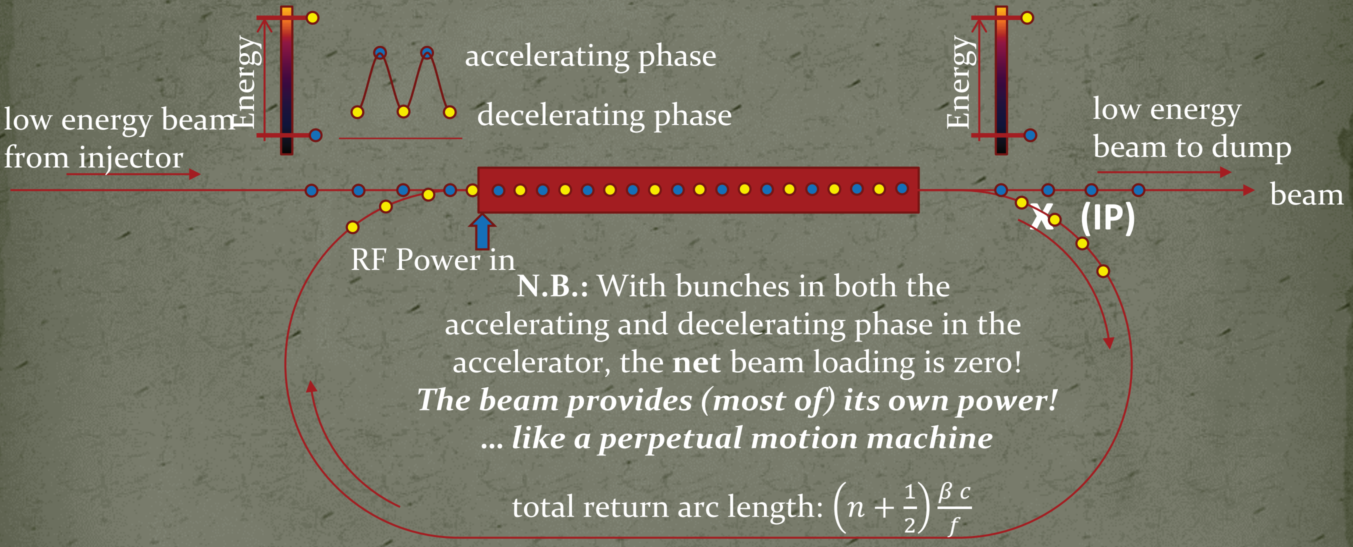
- Accelerator Structure used many times
- Periodic lattice
- Instabilities develop over many turns (coupled bunch, mode coupling

L. Merminga '07: *In a storage ring, electrons are stored for hours in an equilibrium state, whereas in an ERL it is the energy of the electrons that is stored. The electrons themselves spend little time in the accelerator (from ~1 to 10's of μs) thus never reach equilibrium. As a result, in common with linacs, the 6-dimensional phase space in ERLs is largely determined by the electron source properties by design. On the other hand, in common with storage rings, ERLs have high current carrying capability enabled by the energy recovery process, thus promising high efficiencies.*

http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/MOYKI03.PDF

Energy Recovery Linac:

Combine "Energy recovery" and "recirculating"

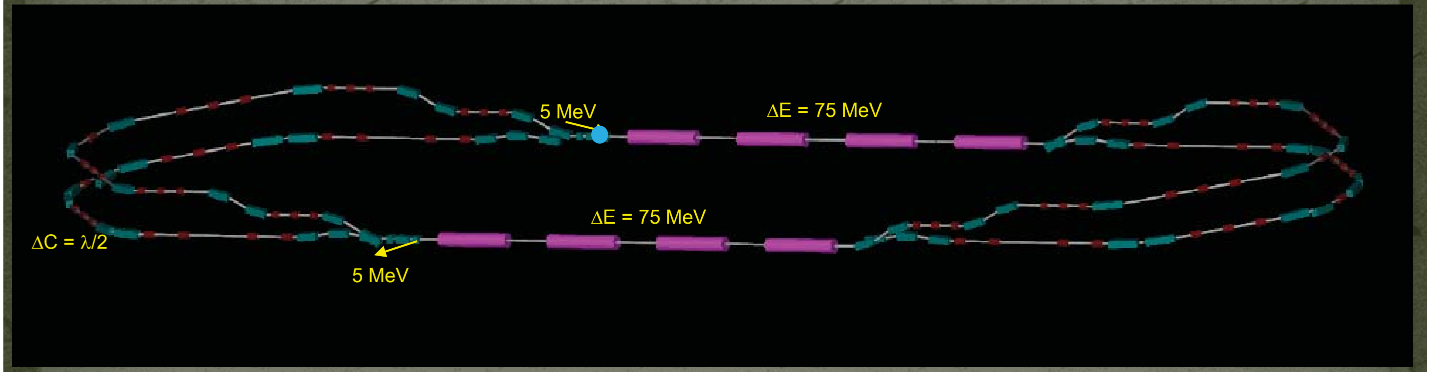


N.B.: With bunches in both the accelerating and decelerating phase in the accelerator, the **net** beam loading is zero!
The beam provides (most of) its own power!
… like a perpetual motion machine

total return arc length: $\left(n+\frac{1}{2}\right)\frac{\beta\, c}{f}$

LHeC ERL-TF (300 MeV) – Layout

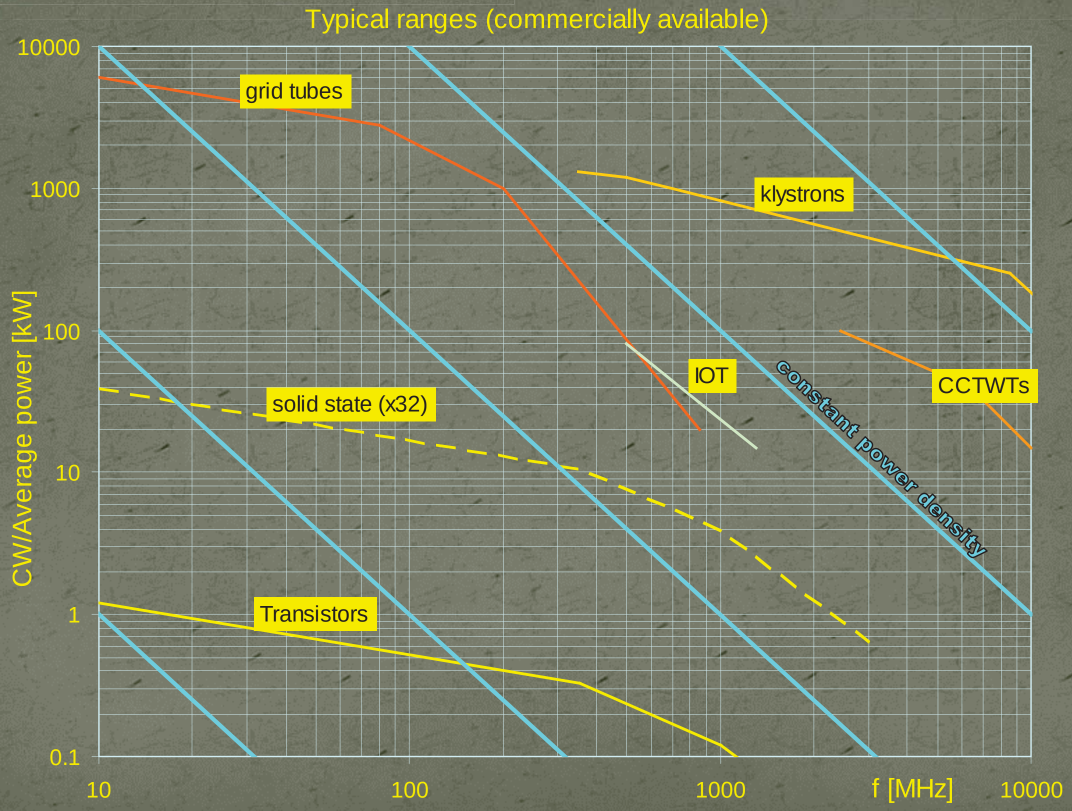
This model and animation by Alex Bogacz, Jefferson Lab



Two passes 'up' + Two passes 'down'

RF power sources

RF power sources



LEIR SSPA, 1 kW, 0.2 – 50 MHz

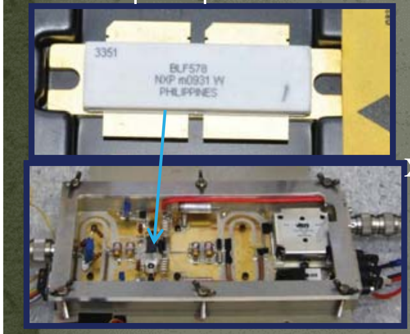
Taken from M. Paoluzzi, LEIR RF system

Soleil/ESRF Booster SSPA, 150 kW, 352 MHz

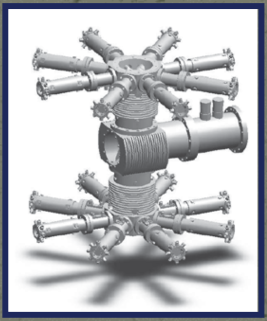
Taken from J. Jacob, CWRF 2012

- Initially developed by SOLEIL
- Transfer of technology to ELTA / AREVA

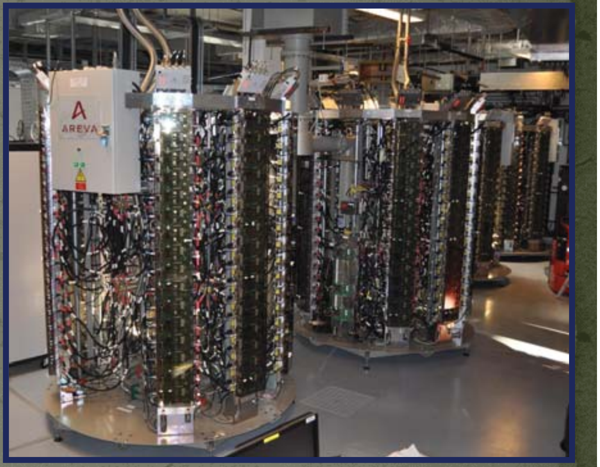
Pair of push-pull transistors



x 128



x 2



650 W RF module

- 6th generation LDMOSFET (BLF 578 / NXP), V_{ds} = 50 V
- Efficiency: 68 to 70 %

75 kW Coaxial combiner tree

with λ/4 transformers

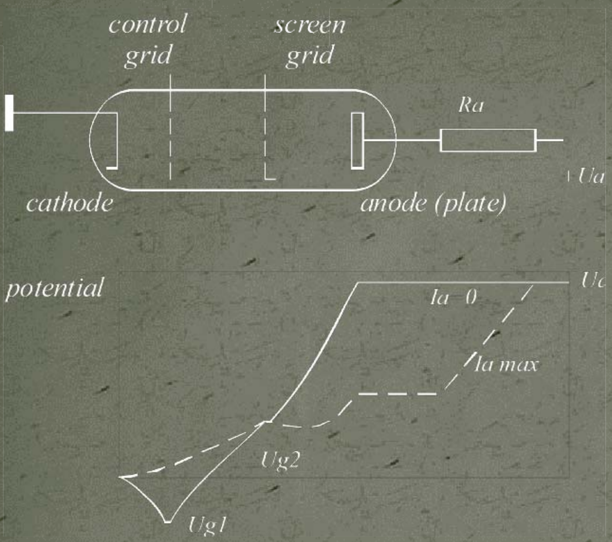
150 kW - 352.2 MHz Solid State Amplifiers for the ESRF booster

Efficiency: > 55 % at nominal power

- 1st batch of 4 x 150 kW SSAs from ELTA in operation on ESRF booster since March 2012
- 2nd batch of 3 x 150 kW SSAs in fabrication, will power 3 new cavities on ESRF storage ring

---

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

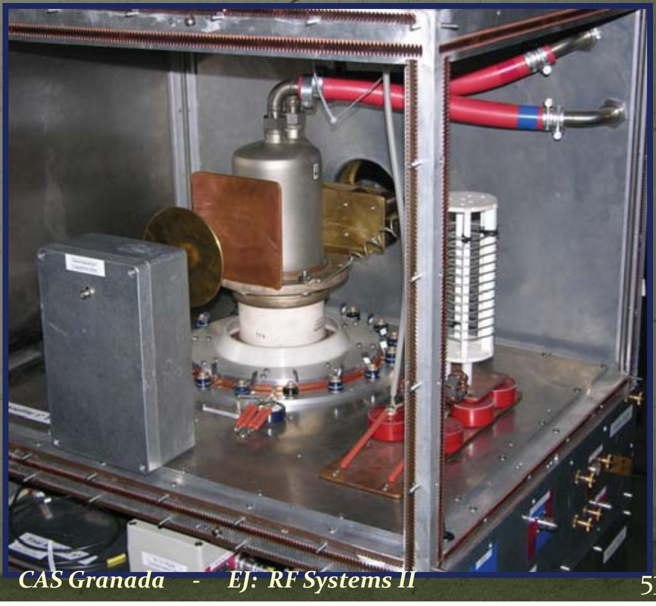
High power tetrode amplifier

CERN Linac3: 100 MHz, 350 kW

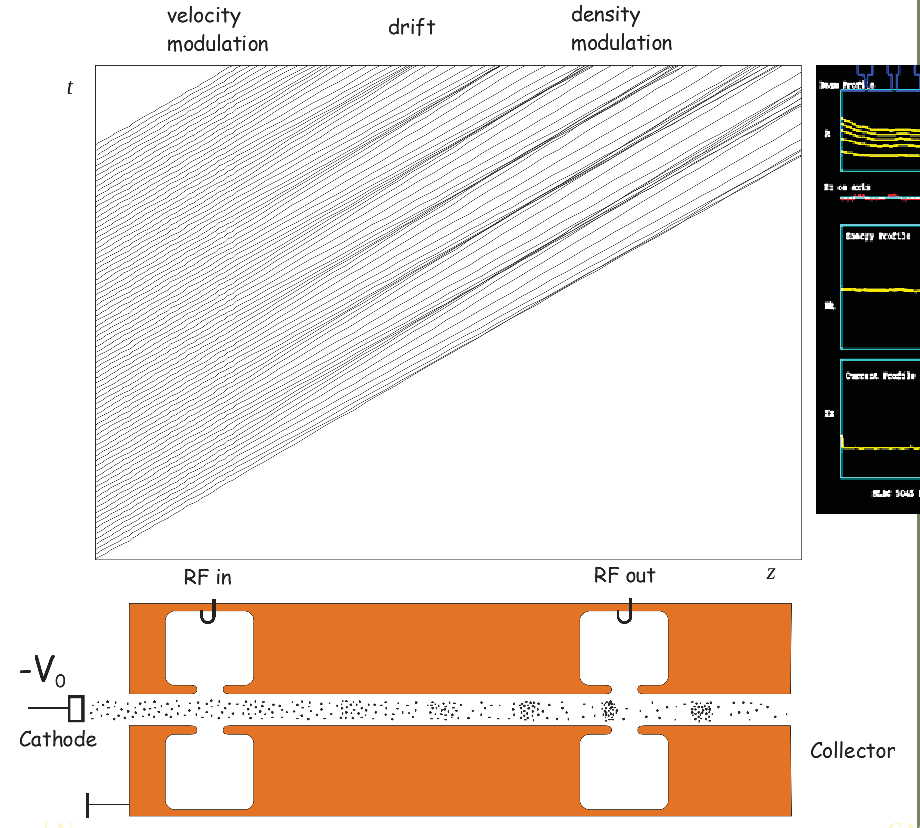
50 kW Driver: TH345, Final: RS 2054 SK

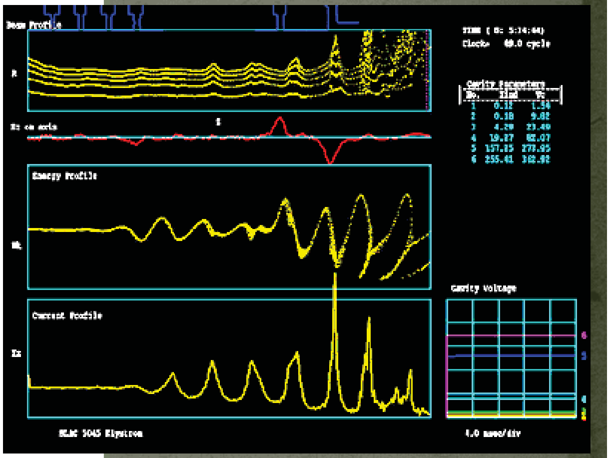
CERN PS: 13-20 MHz, 30 kW

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



Klystron principle





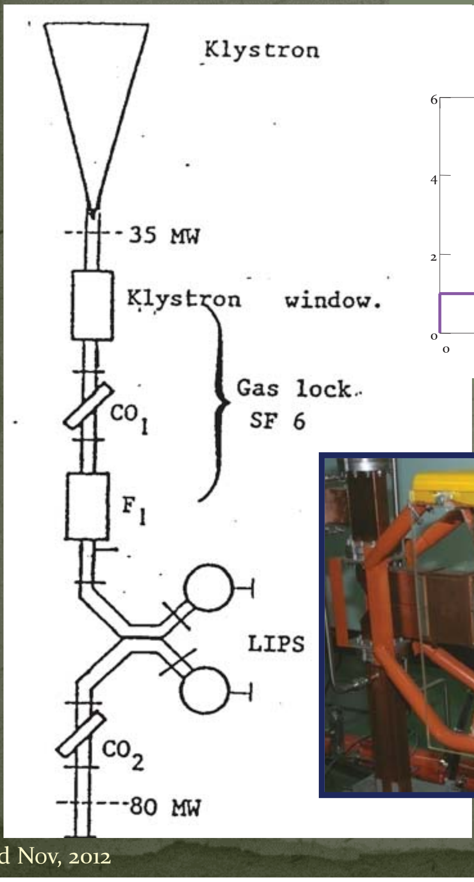
Klystrons

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

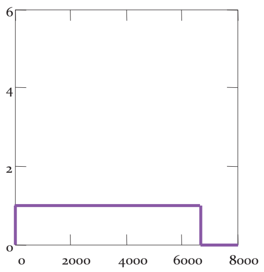
CERN LHC:
400 MHz, 300 kW,
CW, η 62 %

RF pulse compression

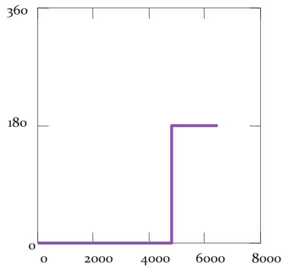
RF Pulse Compression



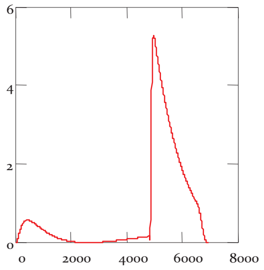
Input pulse



Input phase



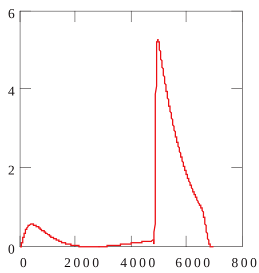
"SLED" output pulse



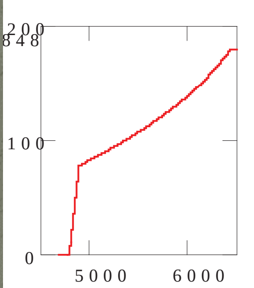
SLED: **S**LAC **E**nergy **D**oubler   **LIPS**: **L**EP **I**njector **P**ower **S**aver

Flat output pulses

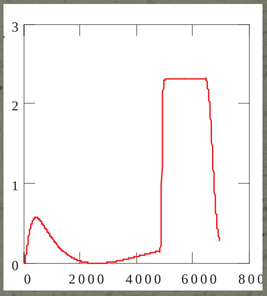
Standard "SLED" Pulse



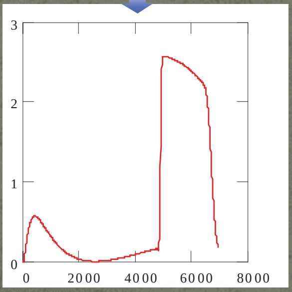
RF phase modulation



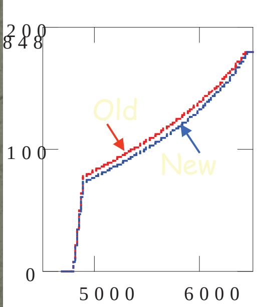
Flat pulse



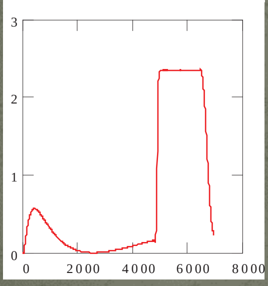
-10 kHz



Distorted pulse



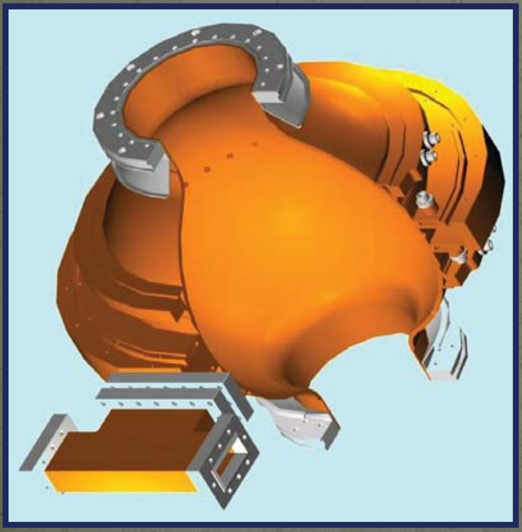
RF phase modulation



Flat pulse

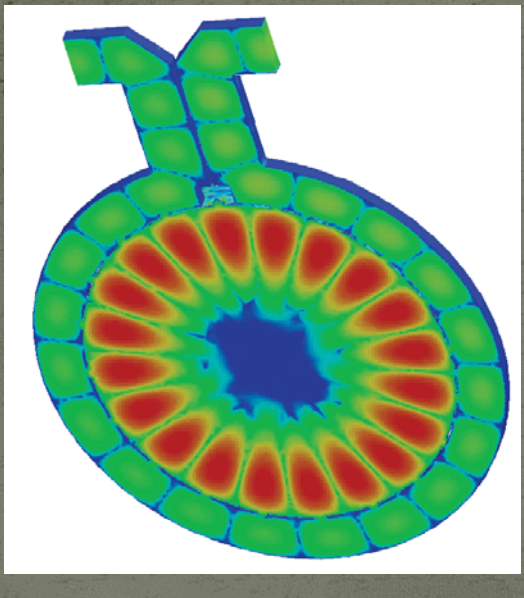
Pulse compressor

BOC „Barrel Open Cavity"

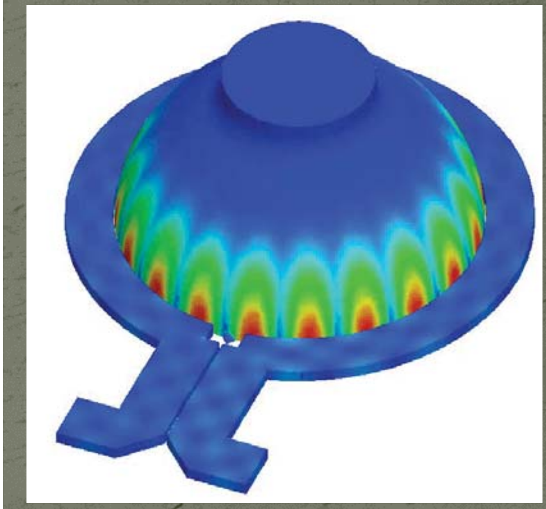


BOC

2.99848 GHz,
S11: -12.9 dB



Electric field, logarithmic scale



Magnetic field

Some examples

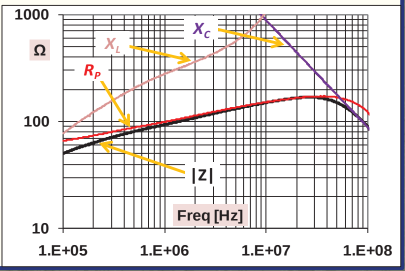
Some Power RF systems at CERN

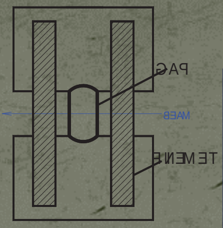
Finemet® based wide-band cavity

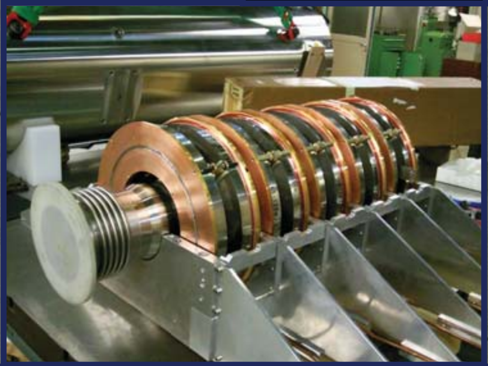
Finemet exhibits wideband response

C_P mostly depends on geometry and drives the high frequency response. The capacitive effect is enhanced by the final stage output capacitance.

R_P and L_P drive the low frequency response. They and are mostly dependent on Finemet® Characteristics.







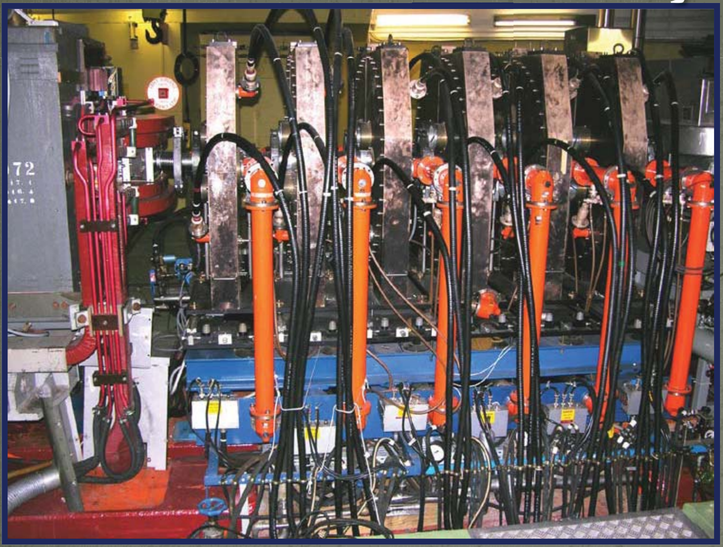

Mauro PAOLUZZI (CERN)

On-going project for CERN PSB upgrade

Instantaneous bandwidth:

0.6 MHz … 4 MHz, 0.7 kV per gap

CERN PS 200 MHz System



CERN PS 10 MHz cavity (1 of 10)

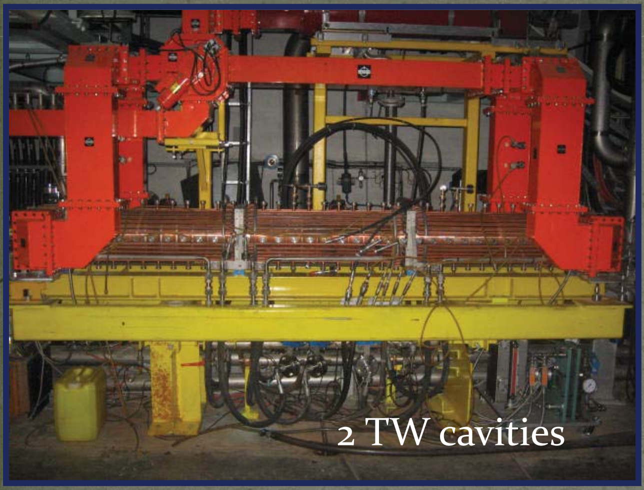
CERN PS 80 MHz Cavity (1997)

SPS 200 MHz RF system

Siemens:
4 x 550 kW (28 tetrode amplifiers)

Philips:
4 x 550 kW (72 tetrode amplifiers)

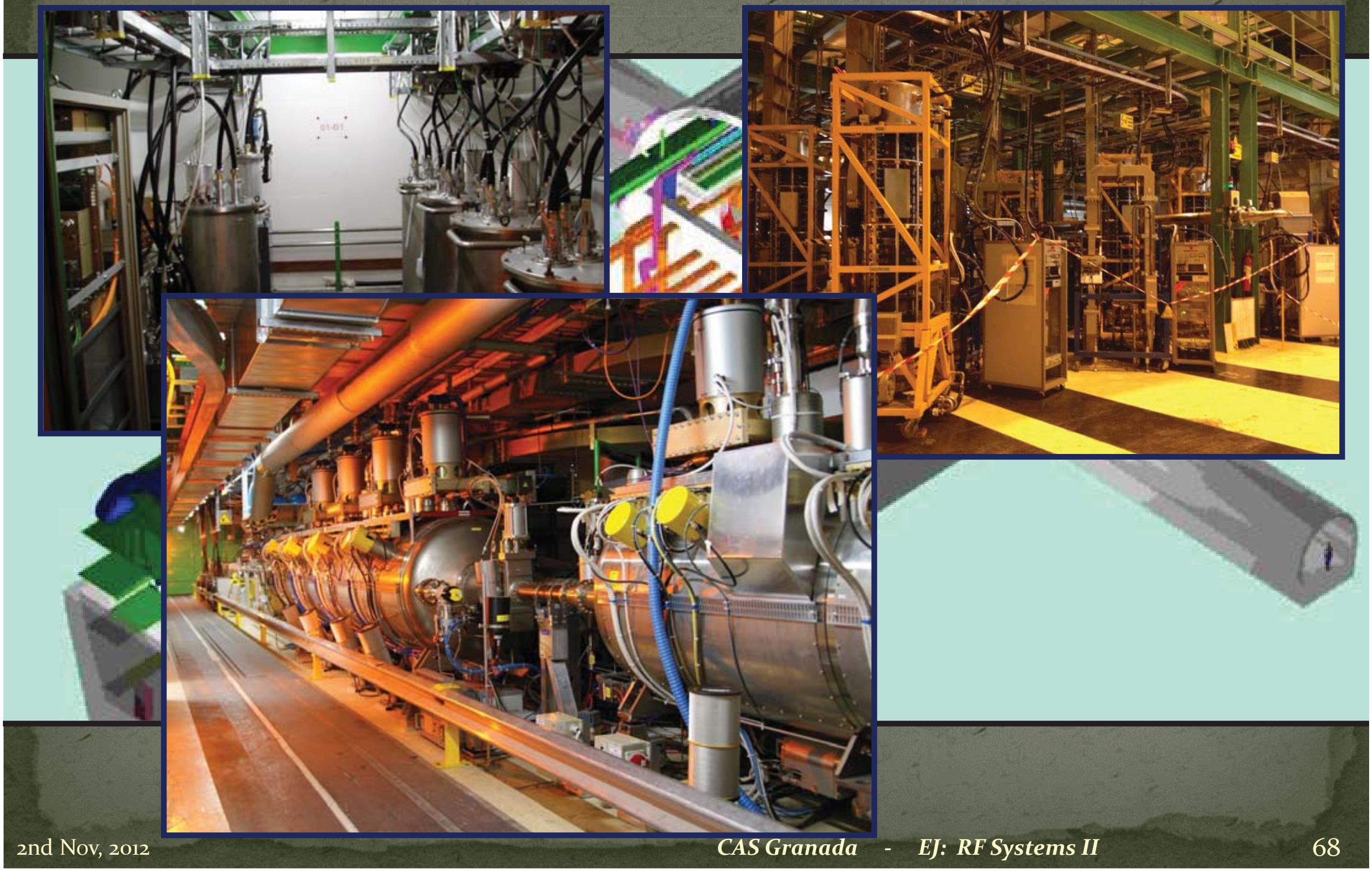
SPS 800 MHz RF System


2 TW cavities

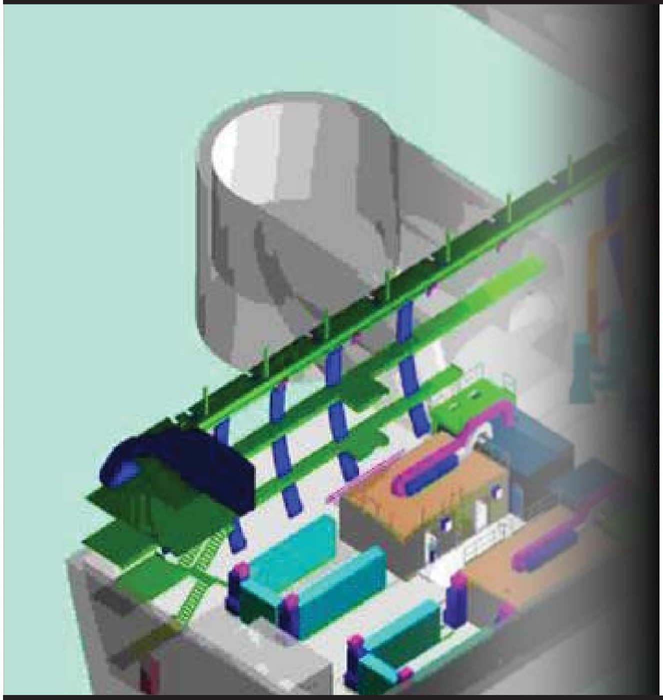

8 (old) klystrons

… soon to be replaced by an IOT based system

LHC High-Power RF System



LHC High-Power RF System



- 16 Klystrons
- 4 SC Cavity Modules
- 300 kW @ 400 MHz

- 1000 Interlocks
- … of which each could dump the beam

End of RF Systems II

Thank you for your attention!