RF Systems II

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The CERN Accelerator School

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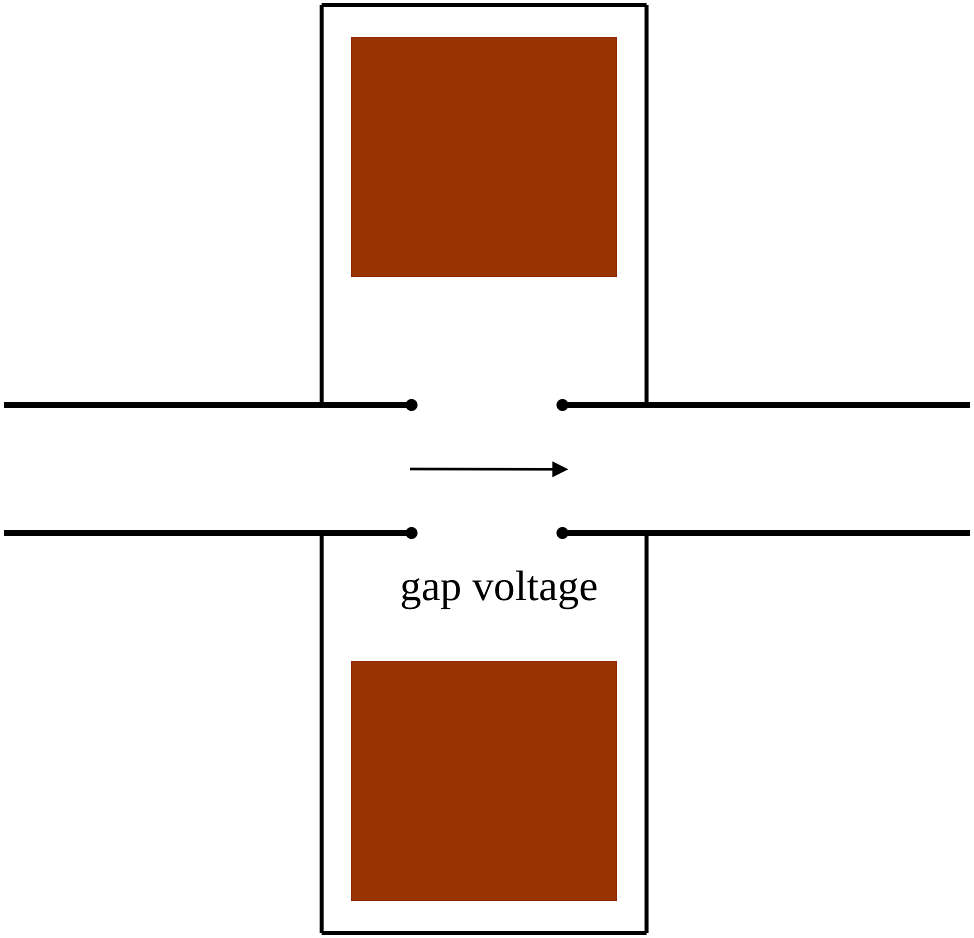
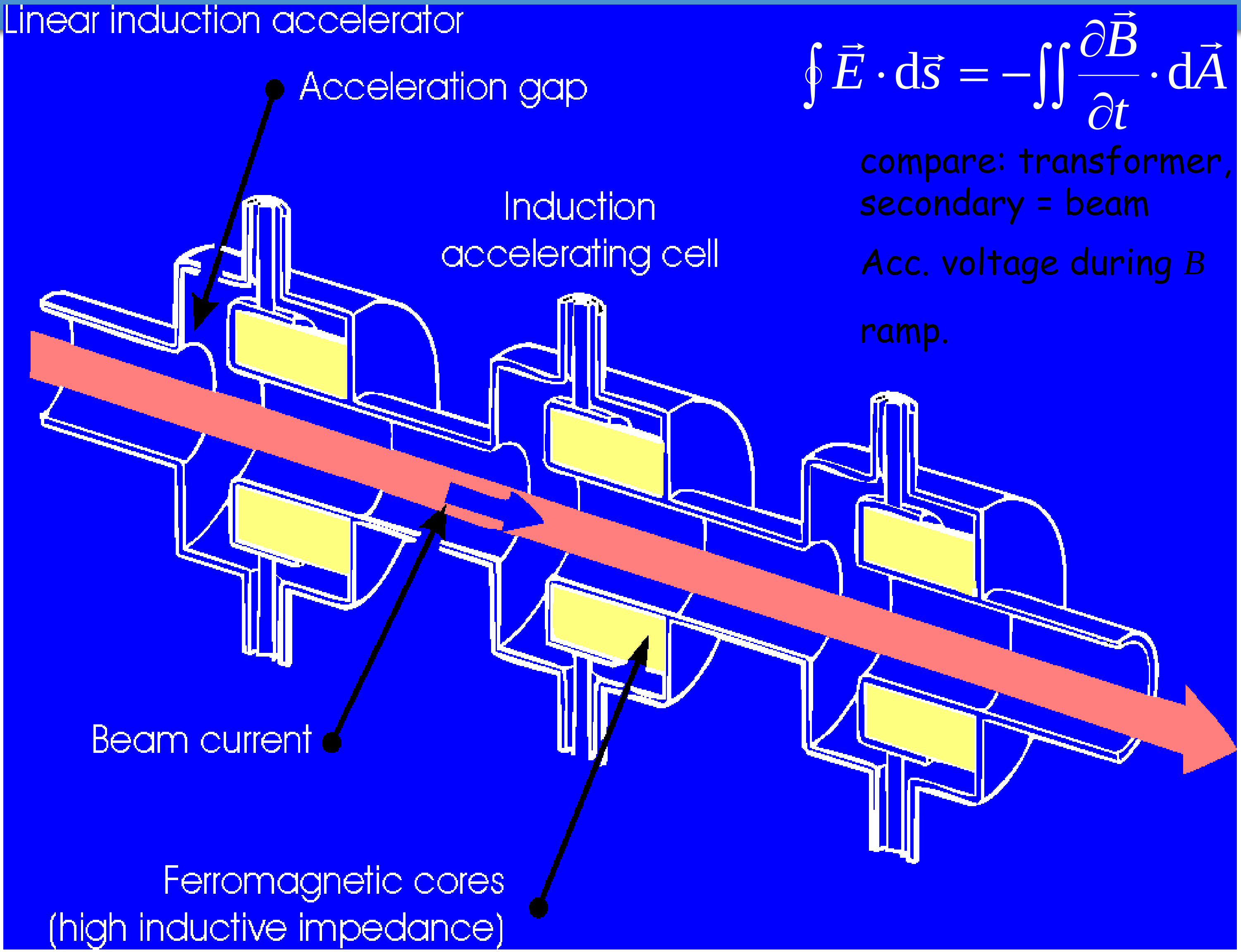
Accelerating gap

Accelerating Gap



- We want a voltage across the gap!
- It cannot be DC, since we want the beam tube on ground potential.
- Use $\oint \vec{E}\, d\vec{s} = -\iint \frac{d\vec{B}}{dt}\, d\vec{A}$
- 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

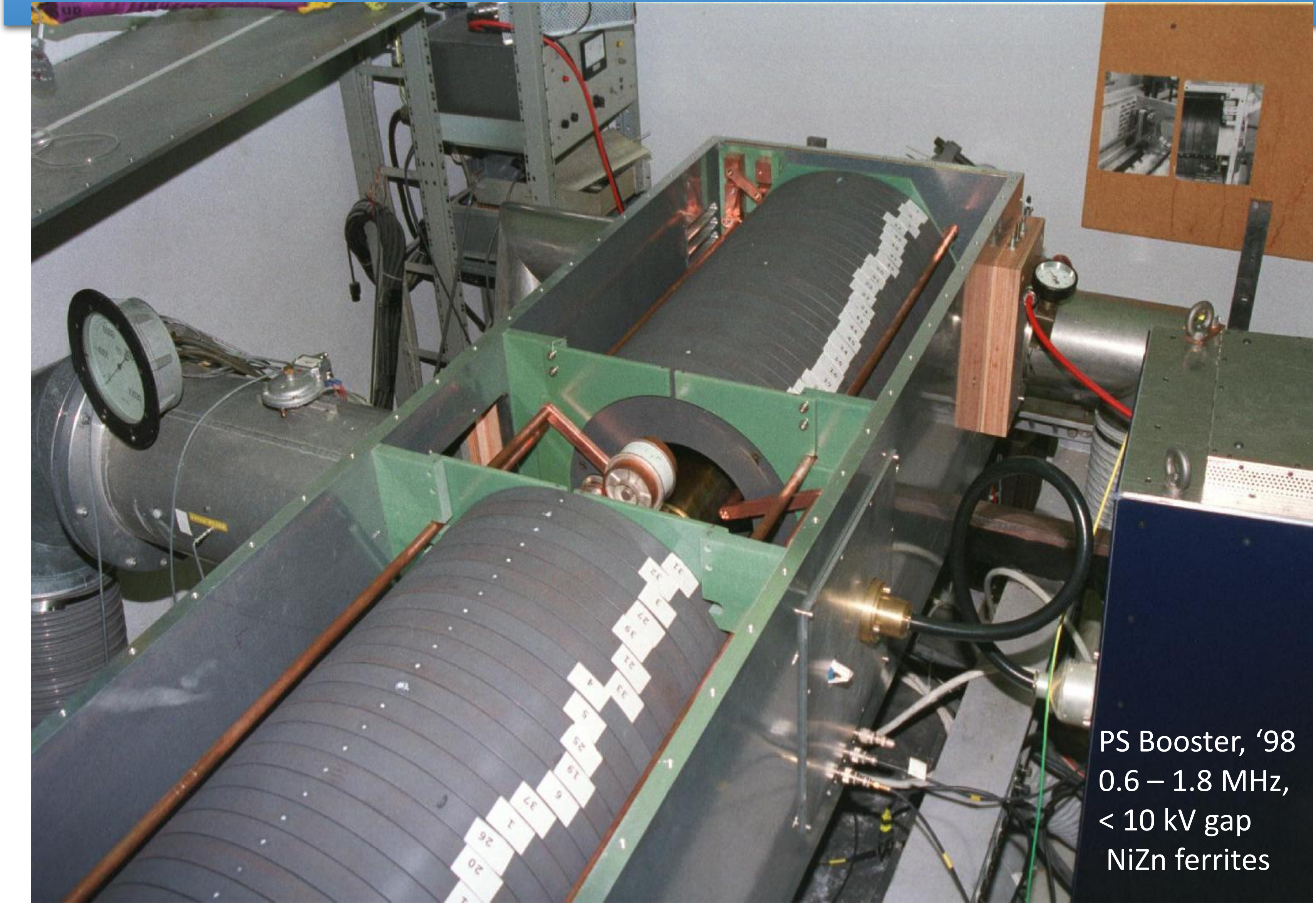


$$\oint \vec{E} \cdot \mathrm{d}\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} \cdot \mathrm{d}\vec{A}$$

compare: transformer, secondary = beam

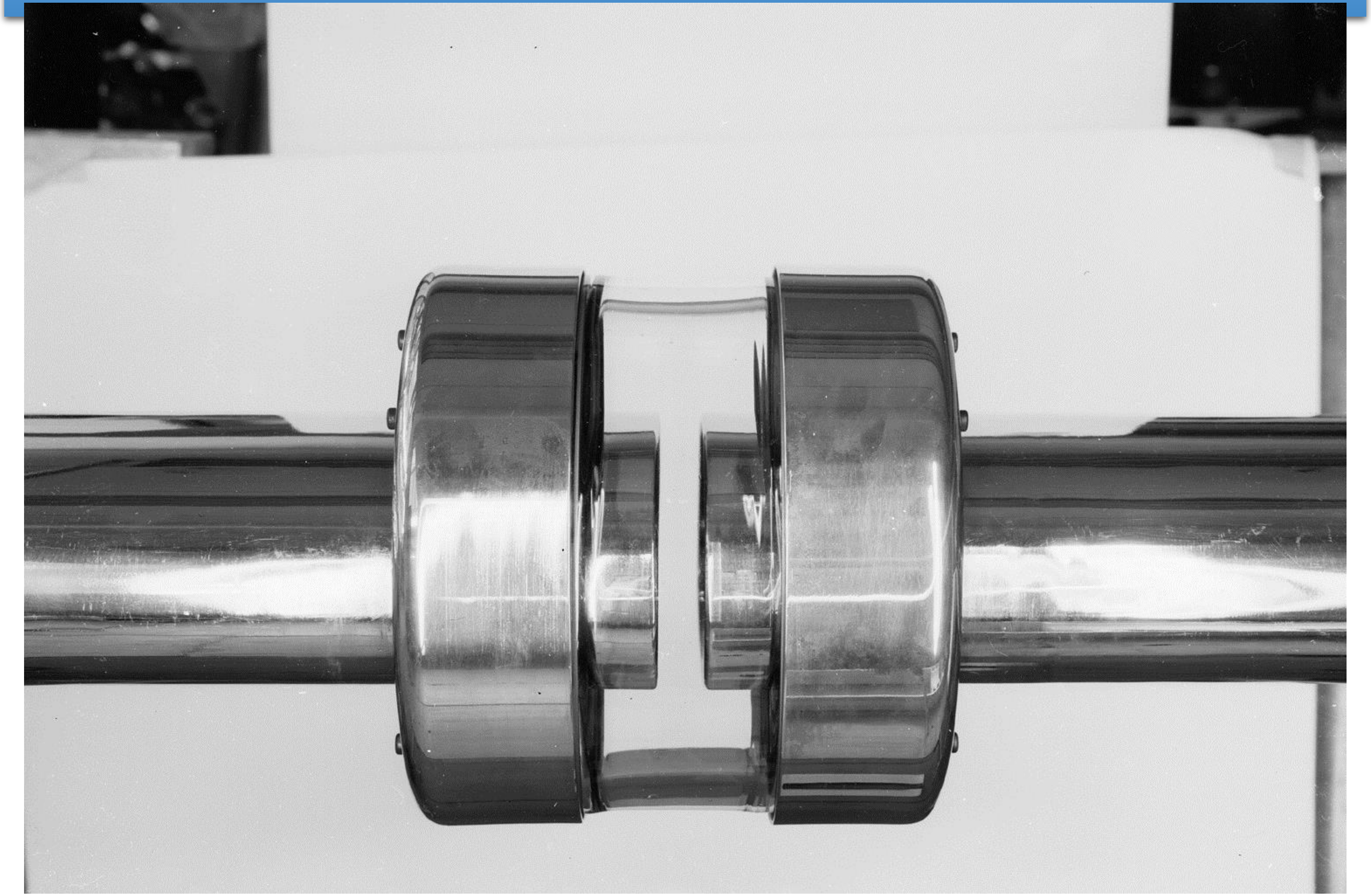
Acc. voltage during B ramp.

Ferrite cavity



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

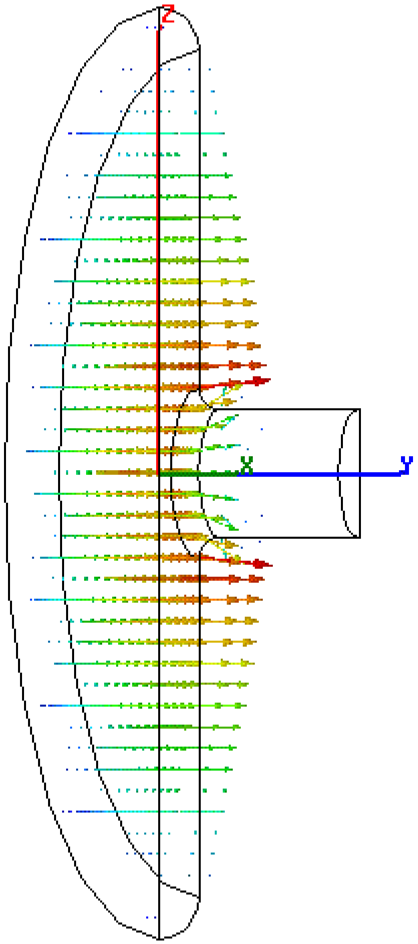
Gap of PS cavity (prototype)



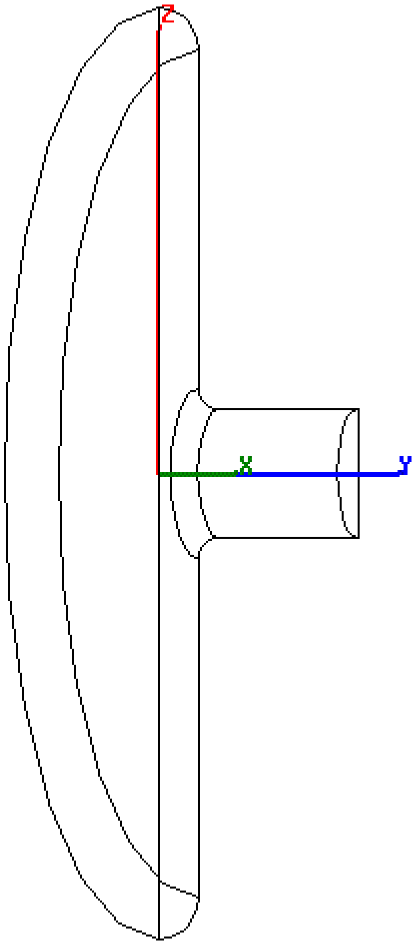
Characterizing a cavity

Reminder: The pillbox cavity

TM_{010}-mode (only 1/4 shown)



electric field



magnetic field

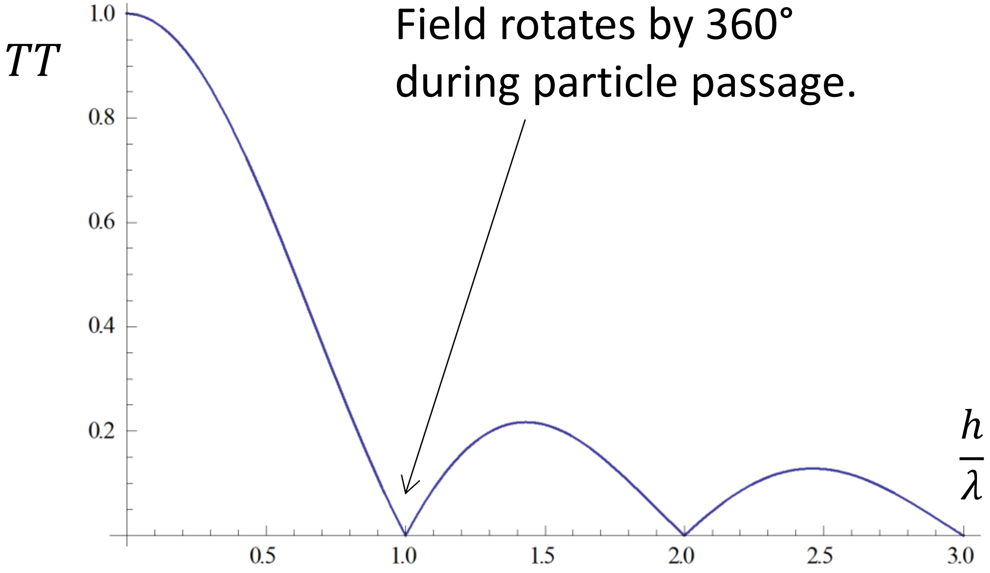
Transit time factor

The transit time factor is the ratio of the acceleration voltage to the (non-physical) voltage a particle with infinite velocity would see.

$$TT = \frac{|V_{acc}|}{\left|\int E_z \, dz\right|} = \frac{\left|\int E_z e^{j\frac{\omega}{\beta c}z} \, dz\right|}{\left|\int E_z \, dz\right|}$$

The transit time factor of an ideal pillbox cavity (no axial field dependence) of height (gap length) h is:

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



Field rotates by 360° during particle passage.

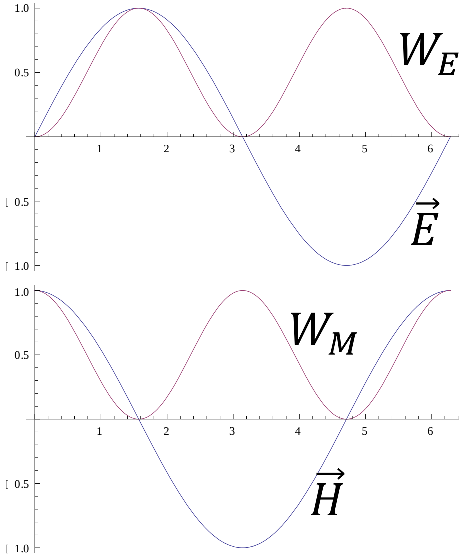
Stored energy

- The energy stored in the electric field is

$$W_E = \iiint\limits_{cavity} \frac{\varepsilon}{2} \left|\vec{E}\right|^2 dV.$$

- The energy stored in the magnetic field is

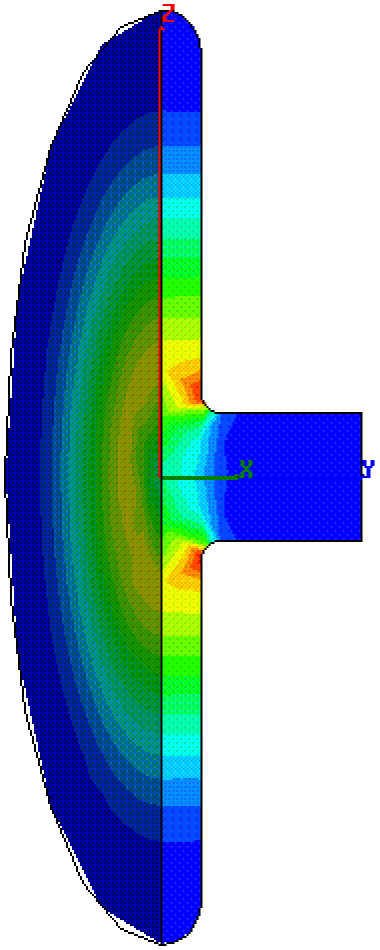
$$W_M = \iiint\limits_{cavity} \frac{\mu}{2} \left|\vec{H}\right|^2 dV.$$



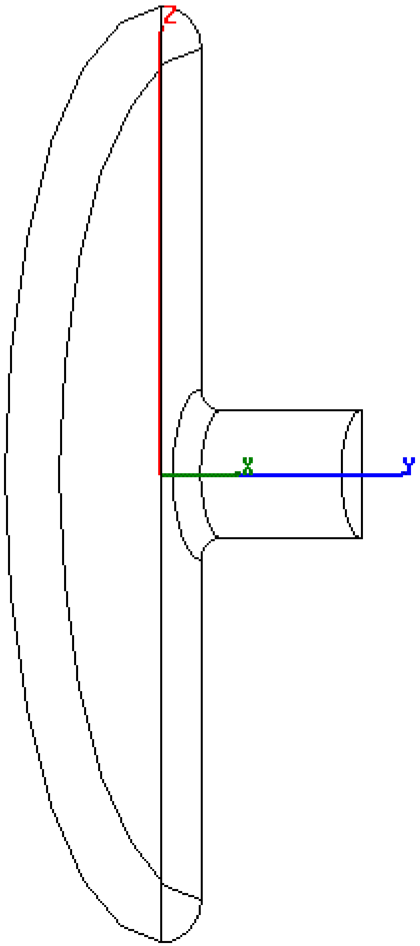
- Since $\vec{E}$ and $\vec{H}$ are 90 ° out of phase, the stored energy continuously swaps from electric energy to magnetic energy. On average, electric and magnetic energy must be equal.
- In steady state, the Poynting vector describes this energy flux.
- In steady state, the total energy stored (constant) is

$$W = \iiint\limits_{cavity} \left(\frac{\varepsilon}{2}\left|\vec{E}\right|^2 + \frac{\mu}{2}\left|\vec{H}\right|^2\right) dV.$$

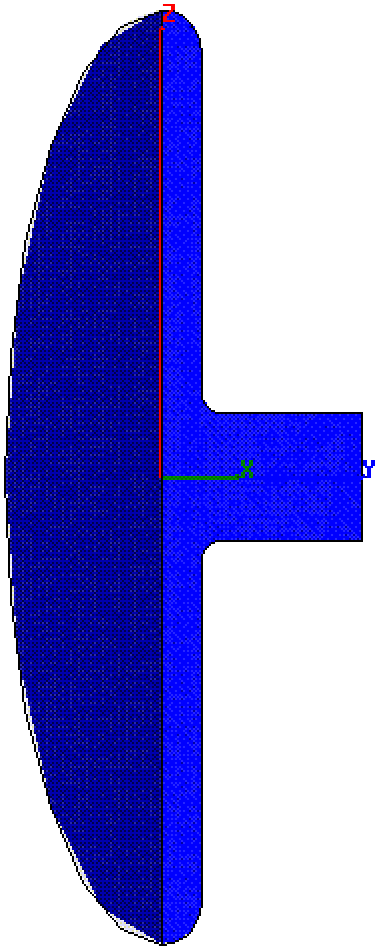
Stored energy and Poynting vector



electric field energy



Poynting vector



magnetic field energy

Wall losses (valid for good conductor)

- The losses P_{loss} are proportional to the stored energy W.
- The tangential magnetic field on the metallic surface is linked to a surface current $\vec{J}_A = \vec{n} \times \vec{H}$ (flowing in the skin depth).
- This surface current $\vec{J}_A$ sees a surface resistance $R_A = \sqrt{\frac{\omega\mu}{2\sigma}}$, resulting in a local power density flowing into the wall of $R_A|H_t|^2$.
- R_A is related to skin depth δ as $\delta\sigma R_A = 1$.
- The total wall losses result from

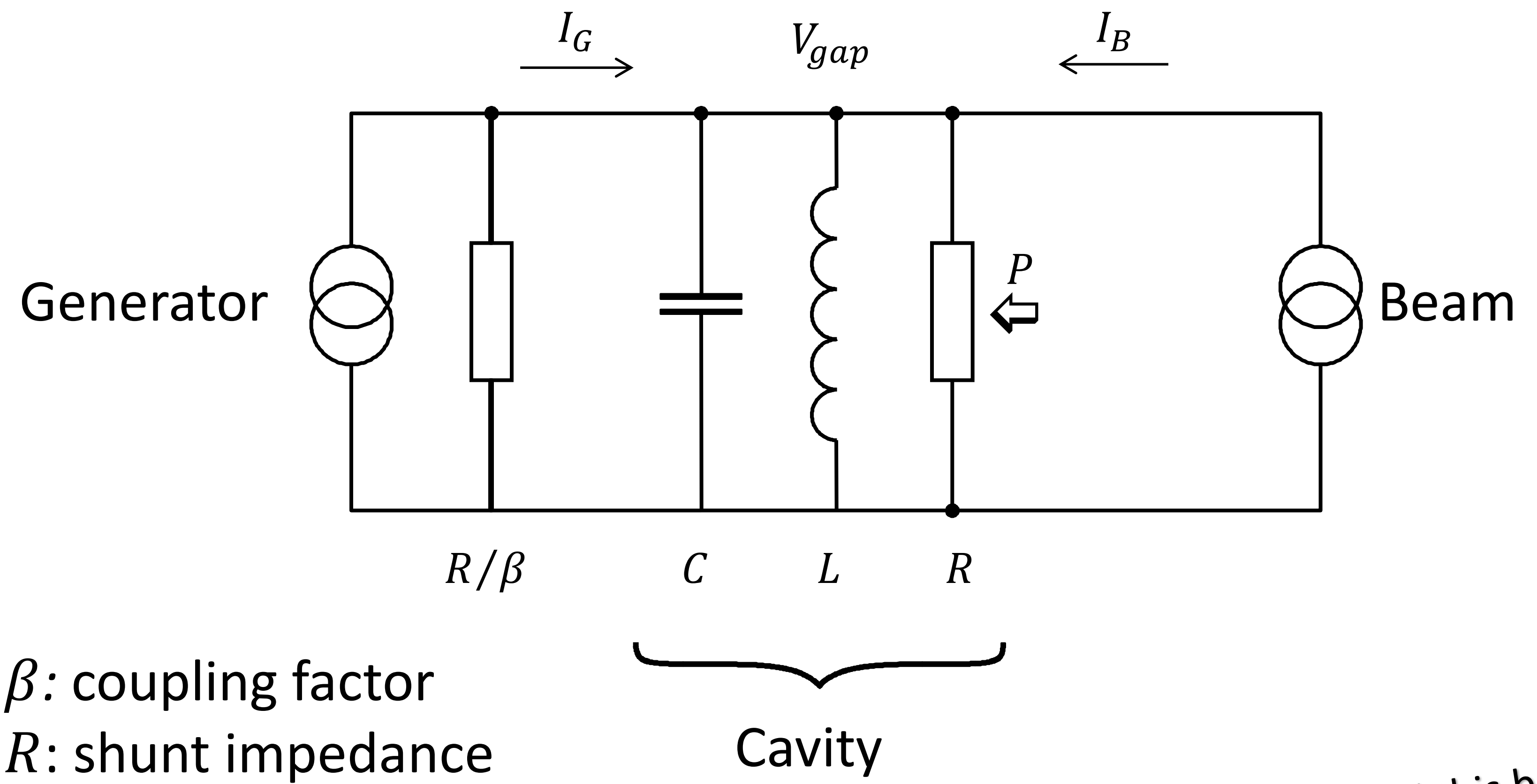
$$P_{loss} = \iint\limits_{wall} R_A |H_t|^2 \, dA$$

- The cavity Q (caused by wall losses) is defined as

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

Cavity resonator – equivalent circuit

Simplification: single mode



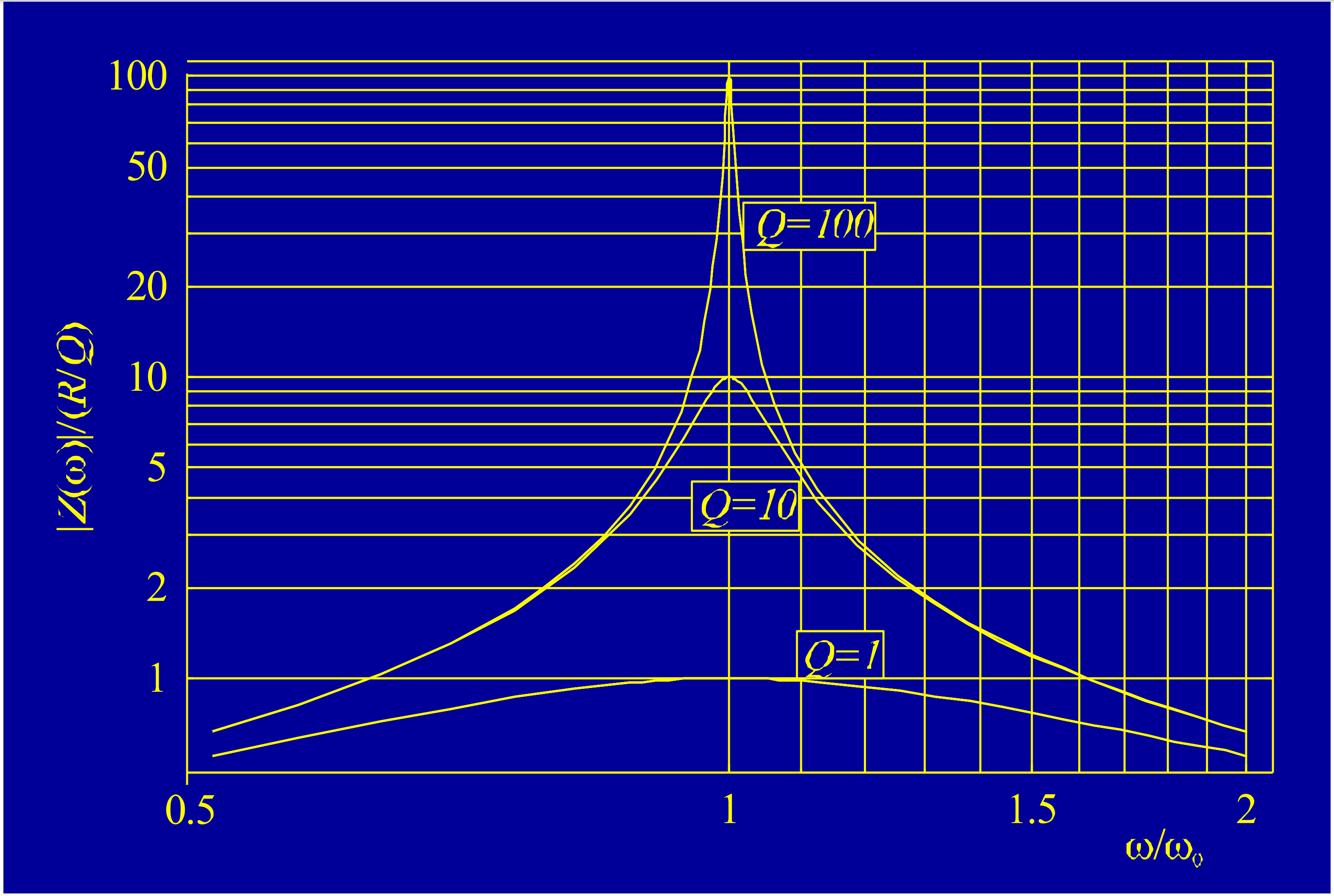
β: coupling factor

R: shunt impedance

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

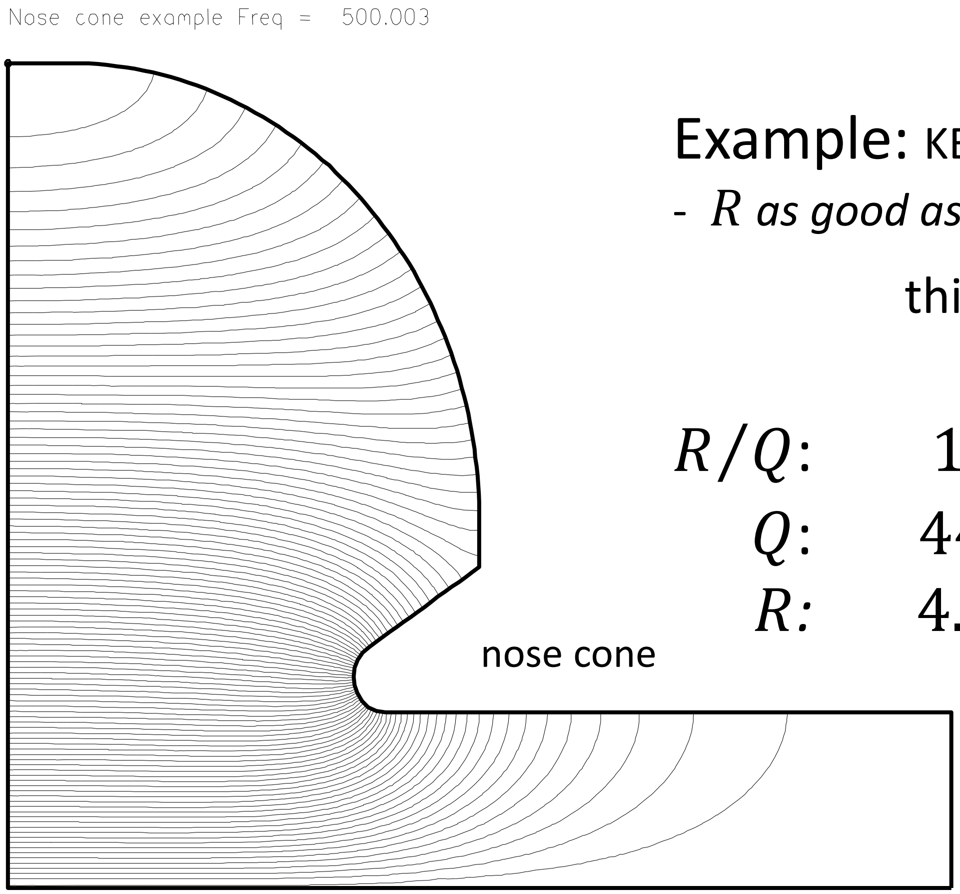
We have used this before when explaining the "fast feedback"

Resonance



Reentrant cavity

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



Example: KEK photon factory 500 MHz

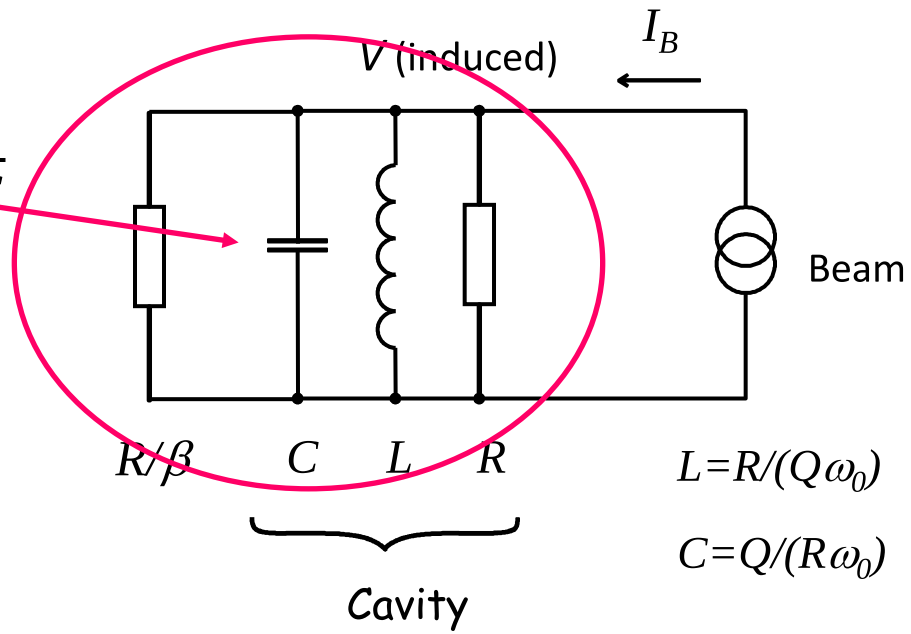
- *R as good as it gets* -

	this cavity	optimized pillbox
R/Q:	$111\ \Omega$	$107.5\ \Omega$
Q:	44,270	41,630
R:	$4.9\ \mathrm{M}\Omega$	$4.47\ \mathrm{M}\Omega$

Loss factor

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

Impedance seen by the beam

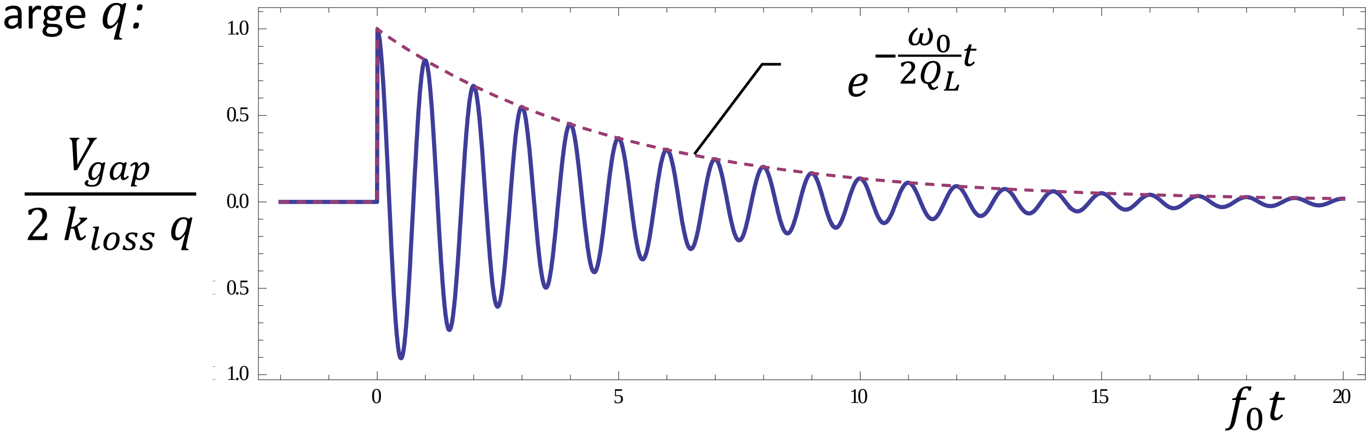


$L=R/(Q\omega_0)$

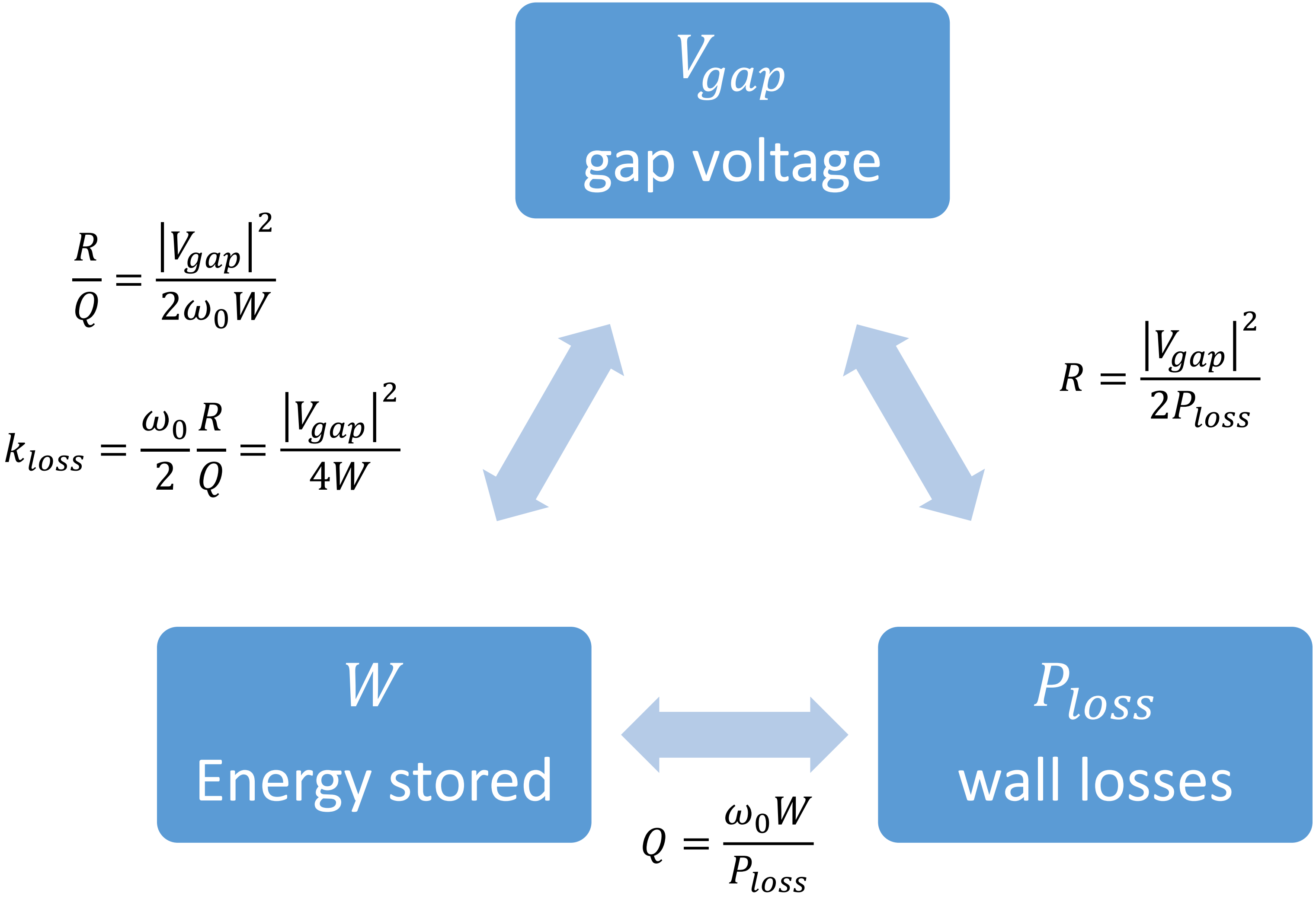
$C=Q/(R\omega_0)$

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

Voltage induced by a single charge q:



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



V_{gap}

gap voltage

W

Energy stored

P_{loss}

wall losses

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

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

$$R = \frac{\left|V_{gap}\right|^2}{2P_{loss}}$$

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

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.

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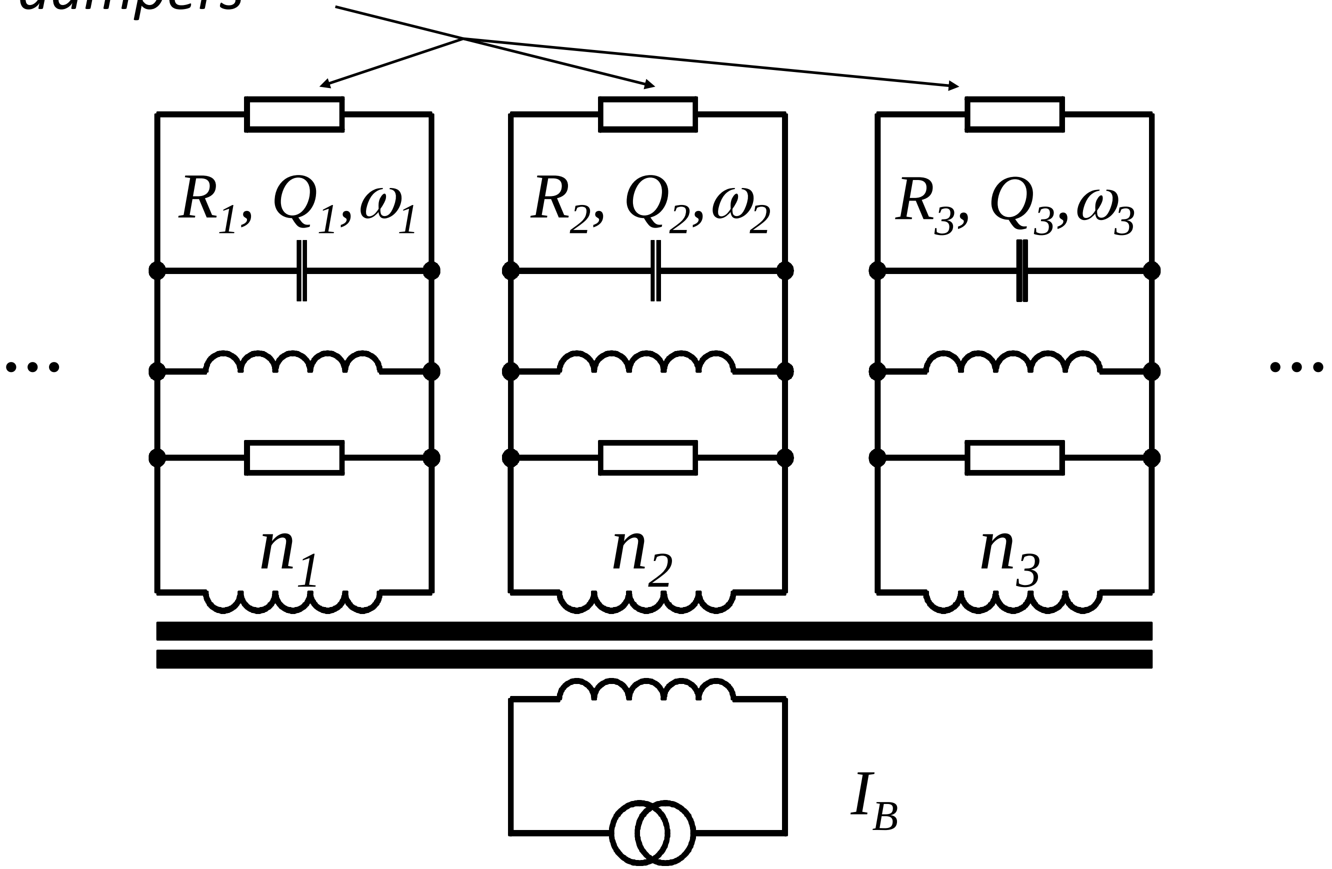
*) for an accelerated beam! For a decelerated beam the voltage is increased

Cavity parameters

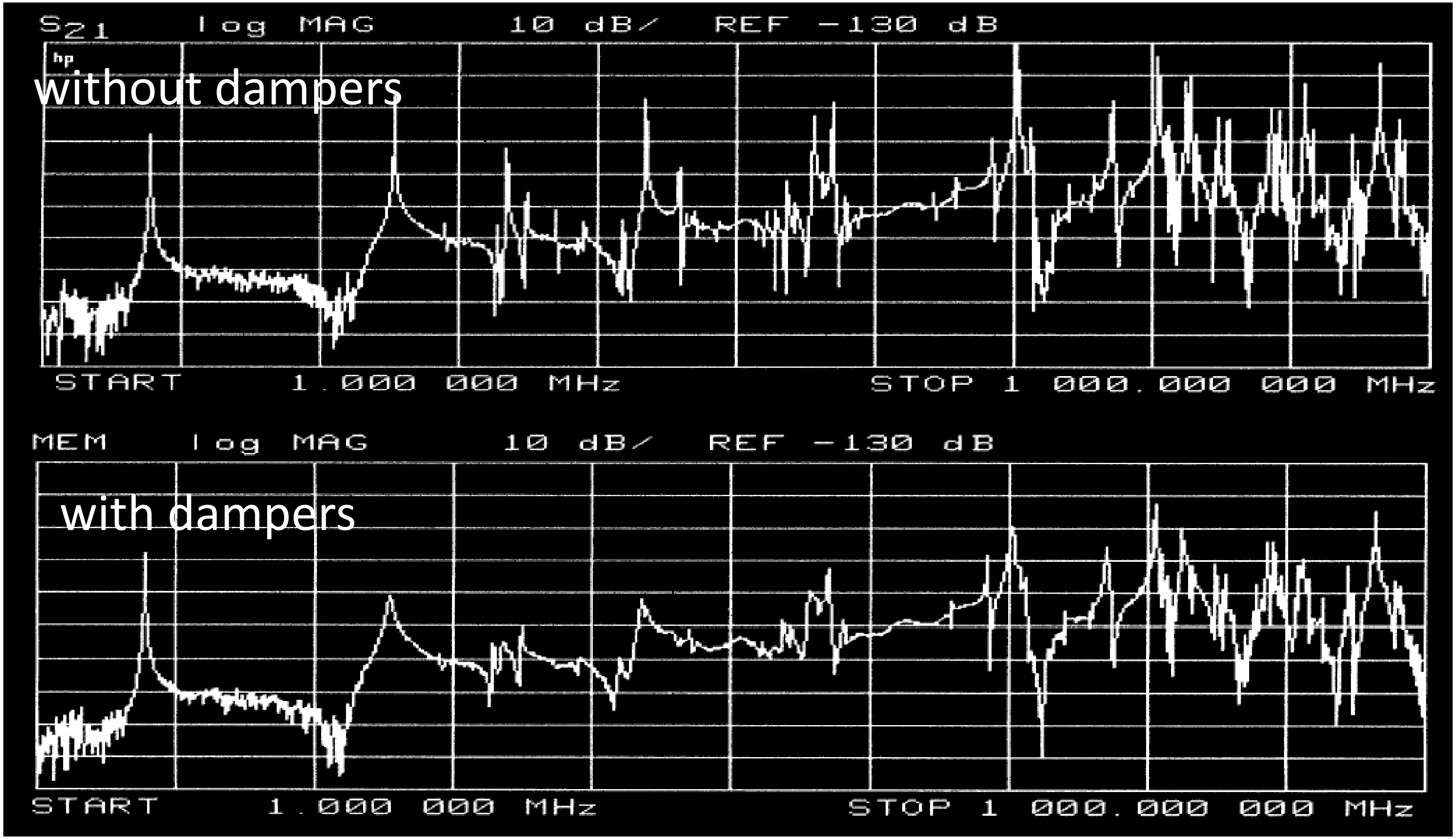
Resonance frequency	$\omega_0 = \frac{1}{\sqrt{L \cdot C}}$	
Transit time factor	$TT = \frac{\left\lvert \int E_z e^{j\frac{\omega}{\beta c}z}\, dz \right\rvert}{\left\lvert \int E_z\, dz \right\rvert}$	
Q factor	$\omega_0 W = Q\, P_{loss}$	
	Circuit definition	***Linac definition***
Shunt impedance	$\lvert V_{gap} \rvert^2 = 2\, R\, P_{loss}$	$\lvert V_{gap} \rvert^2 = R\, P_{loss}$
R/Q (R-upon-Q)	$\frac{R}{Q} = \frac{\lvert V_{gap} \rvert^2}{2\, \omega_0 W} = \sqrt{L/C}$	$\frac{R}{Q} = \frac{\lvert V_{gap} \rvert^2}{\omega_0 W}$
Loss factor	$k_{loss} = \frac{\omega_0}{2} \frac{R}{Q} = \frac{\lvert V_{gap} \rvert^2}{4W} = \frac{1}{2C}$	$k_{loss} = \frac{\omega_0}{4} \frac{R}{Q} = \frac{\lvert V_{gap} \rvert^2}{4W}$

Higher order modes (HOM's)

external dampers

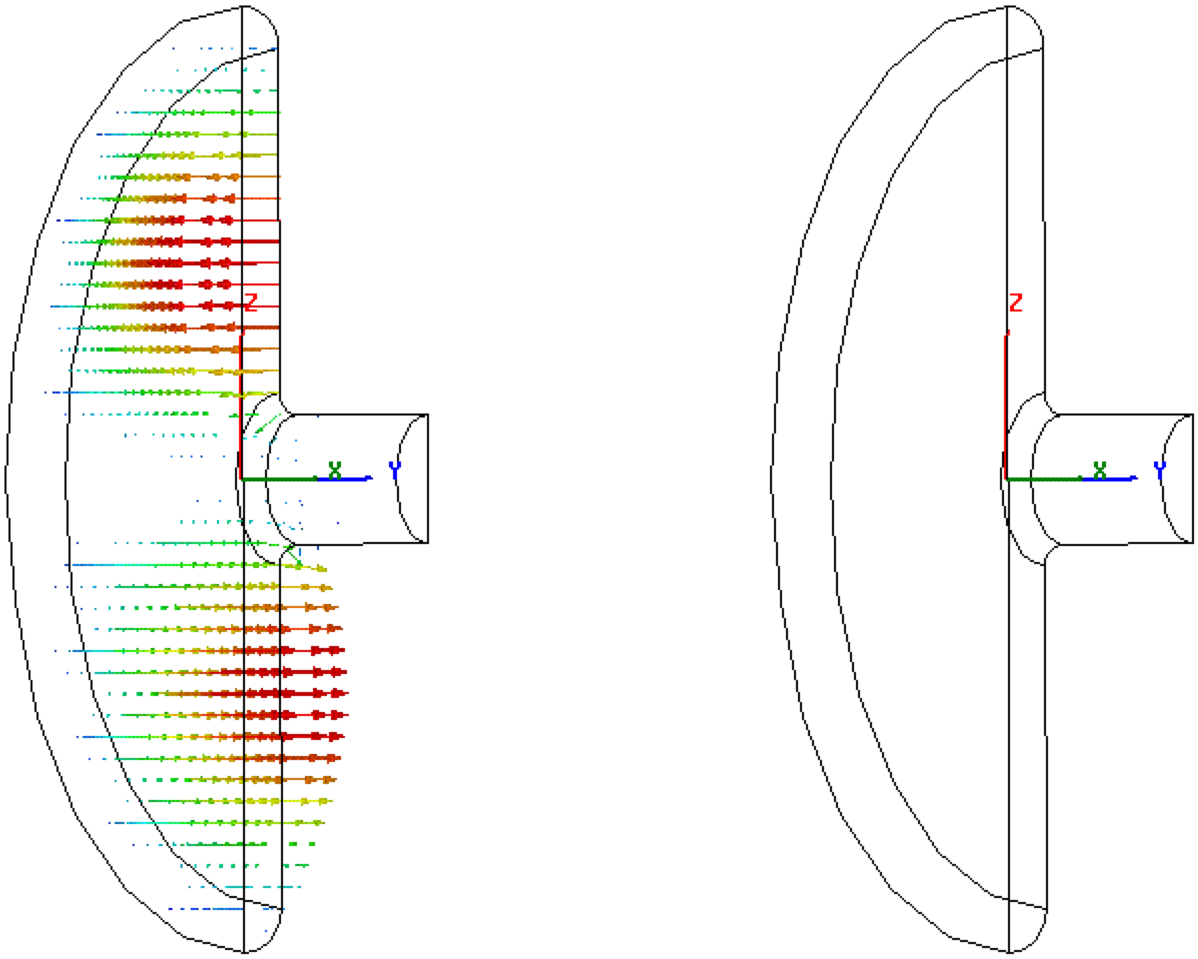


HOM (measured spectrum)



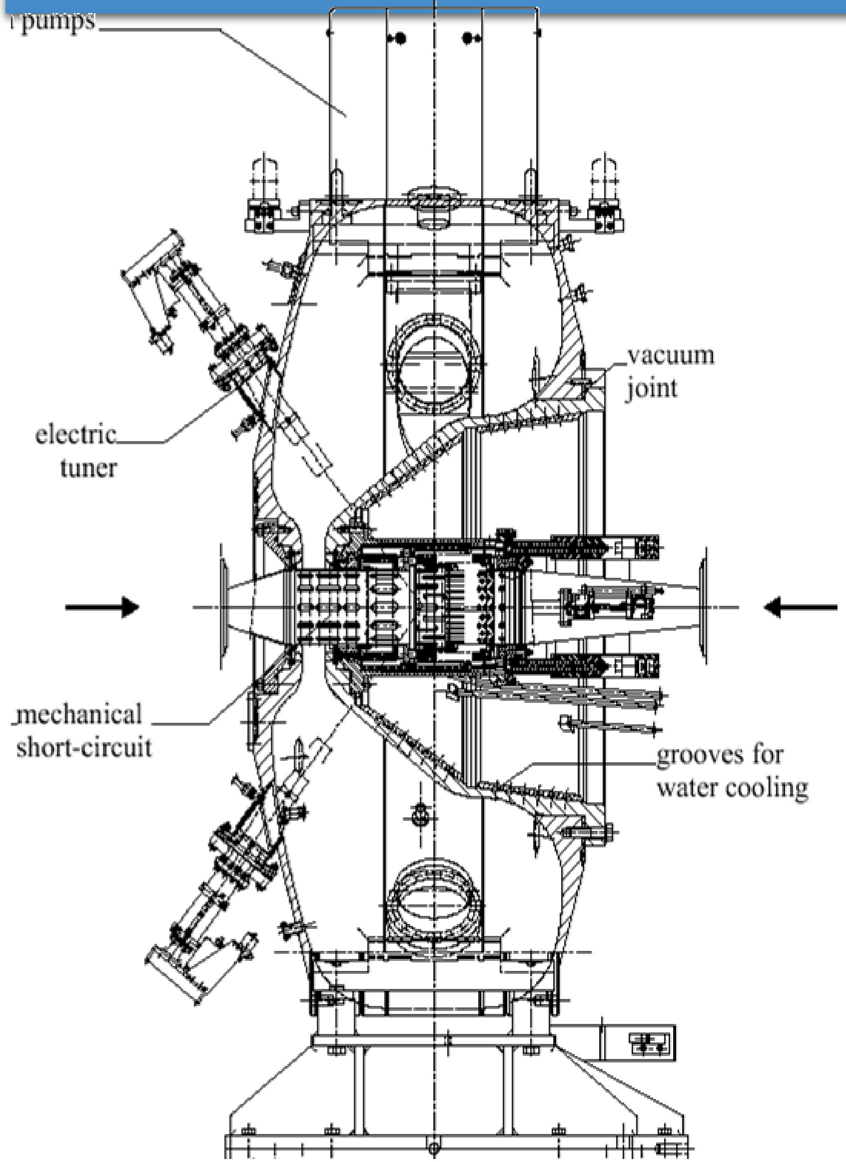
Dipole mode in a pillbox

TM_{110}-mode (only 1/4 shown)



electric field magnetic field

CERN/PS 80 MHz cavity (for LHC)



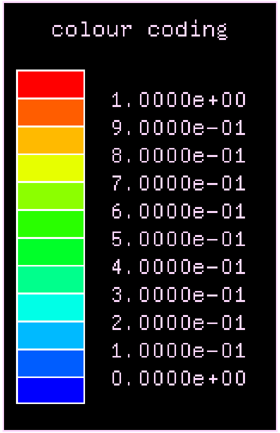
inductive (loop) coupling,
low self-inductance

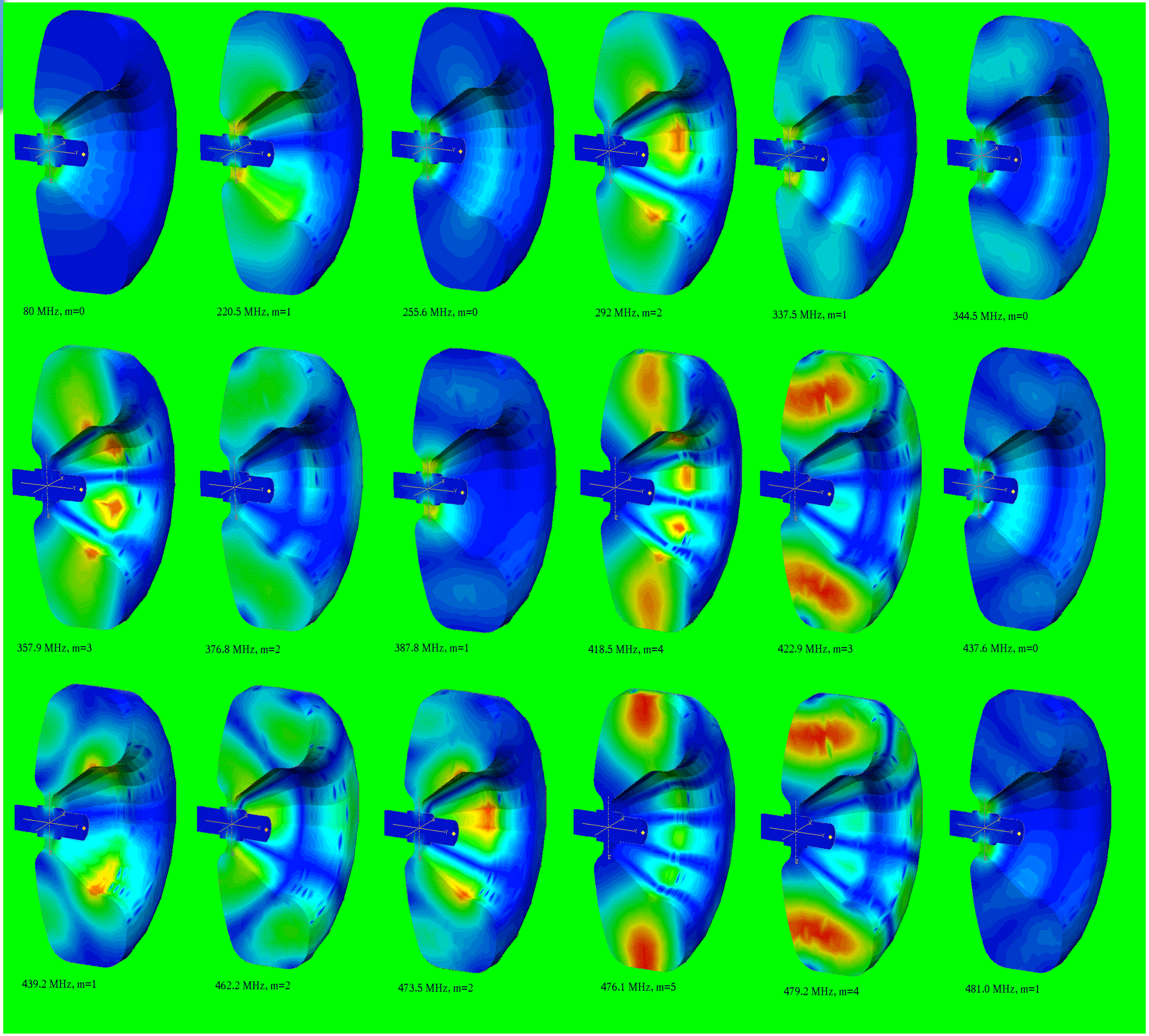
HOM's

Example shown:

CERN/PS 80 MHz cavity

Colour coding: $|\vec{E}|$

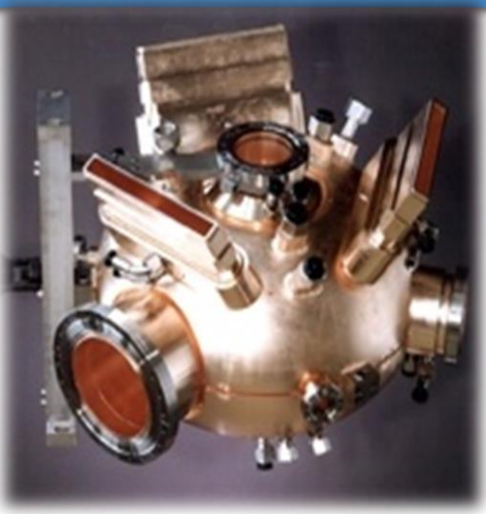




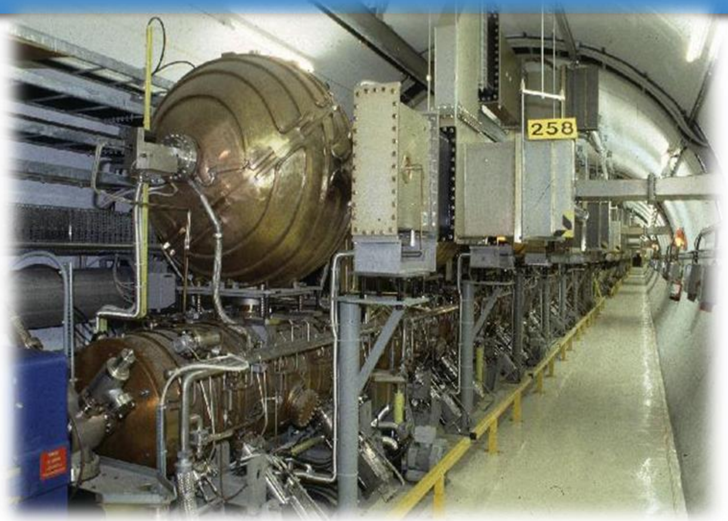
More examples of cavities

PS 19 MHz cavity (prototype, photo: 1966)

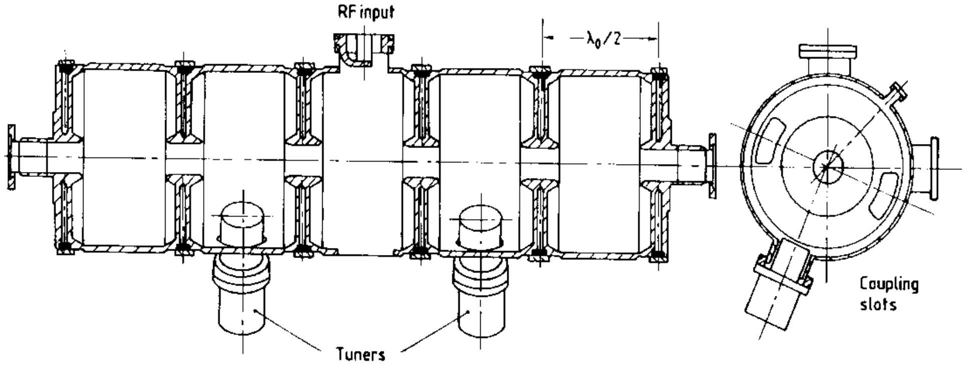
Examples of cavities



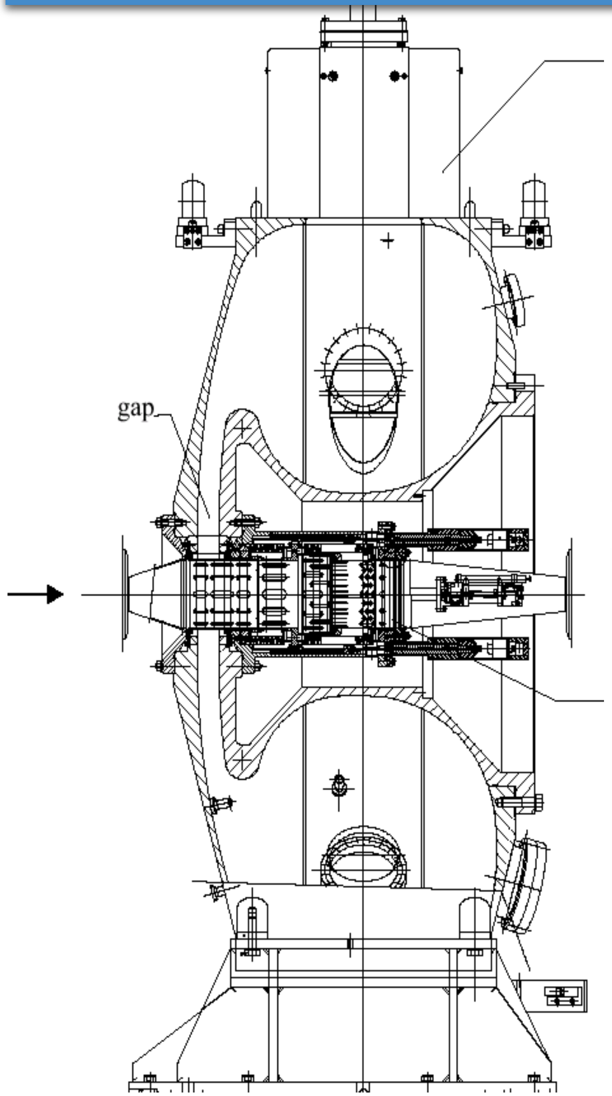
PEP II cavity
476 MHz, single cell,
1 MV gap with 150 kW,
strong HOM damping,

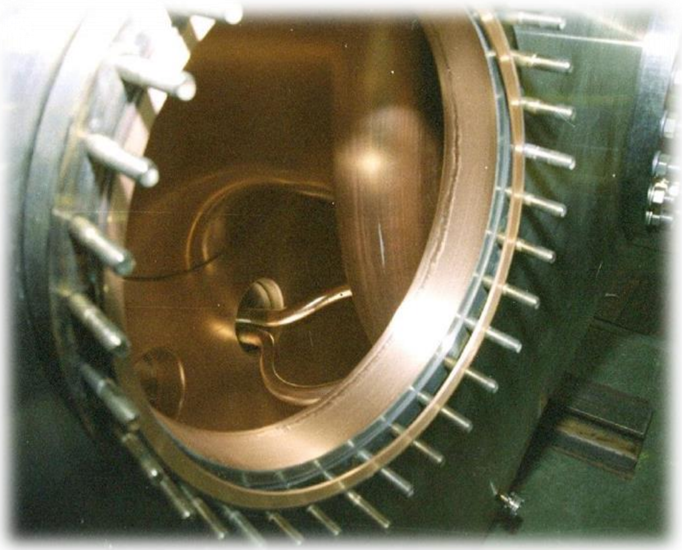


LEP normal-conducting Cu RF cavities,
352 MHz. 5 cell standing wave +
spherical cavity for energy storage, 3 MV



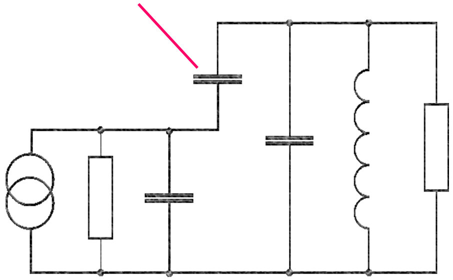
CERN/PS 40 MHz cavity (for LHC)





Example for capacitive coupling

Coupling C

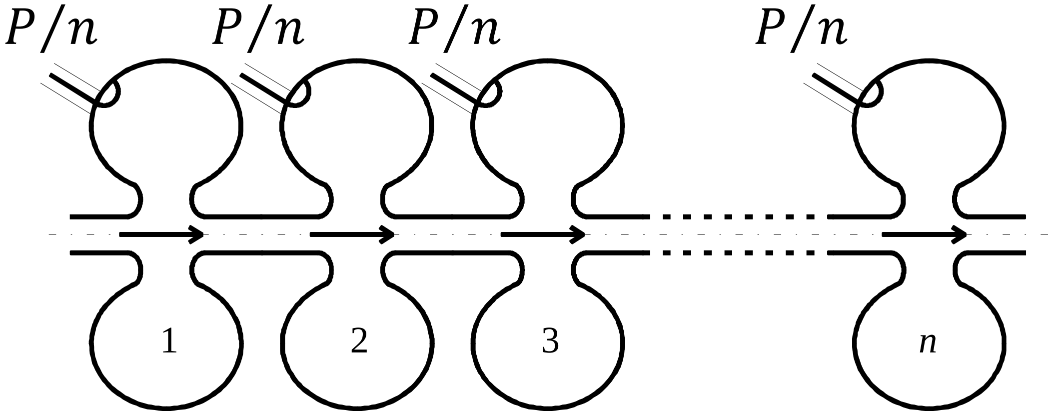


cavity

Many gaps

What do you gain with many gaps?

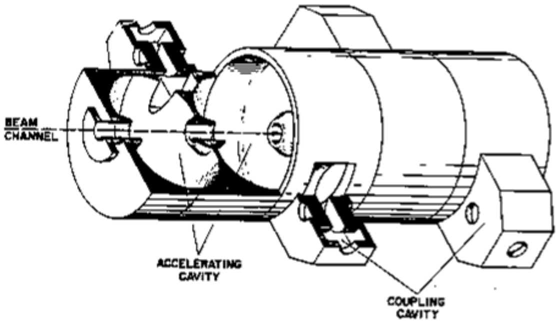
- The R/Q of a single gap cavity is limited to some $100\ \Omega$.
  Now consider to distribute the available power to n identical cavities: each will receive P/n, thus produce an accelerating voltage of $\sqrt{2RP/n}$.
- The total accelerating voltage thus increased, equivalent to a total equivalent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



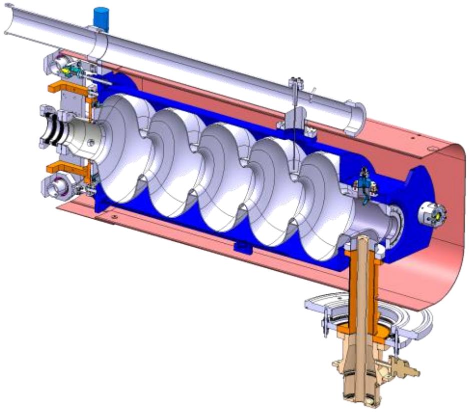
$$|V_{acc}| = n\sqrt{2R\frac{P}{n}} = \sqrt{2(nR)P}$$

Standing wave multi-cell 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 (example: side coupled)

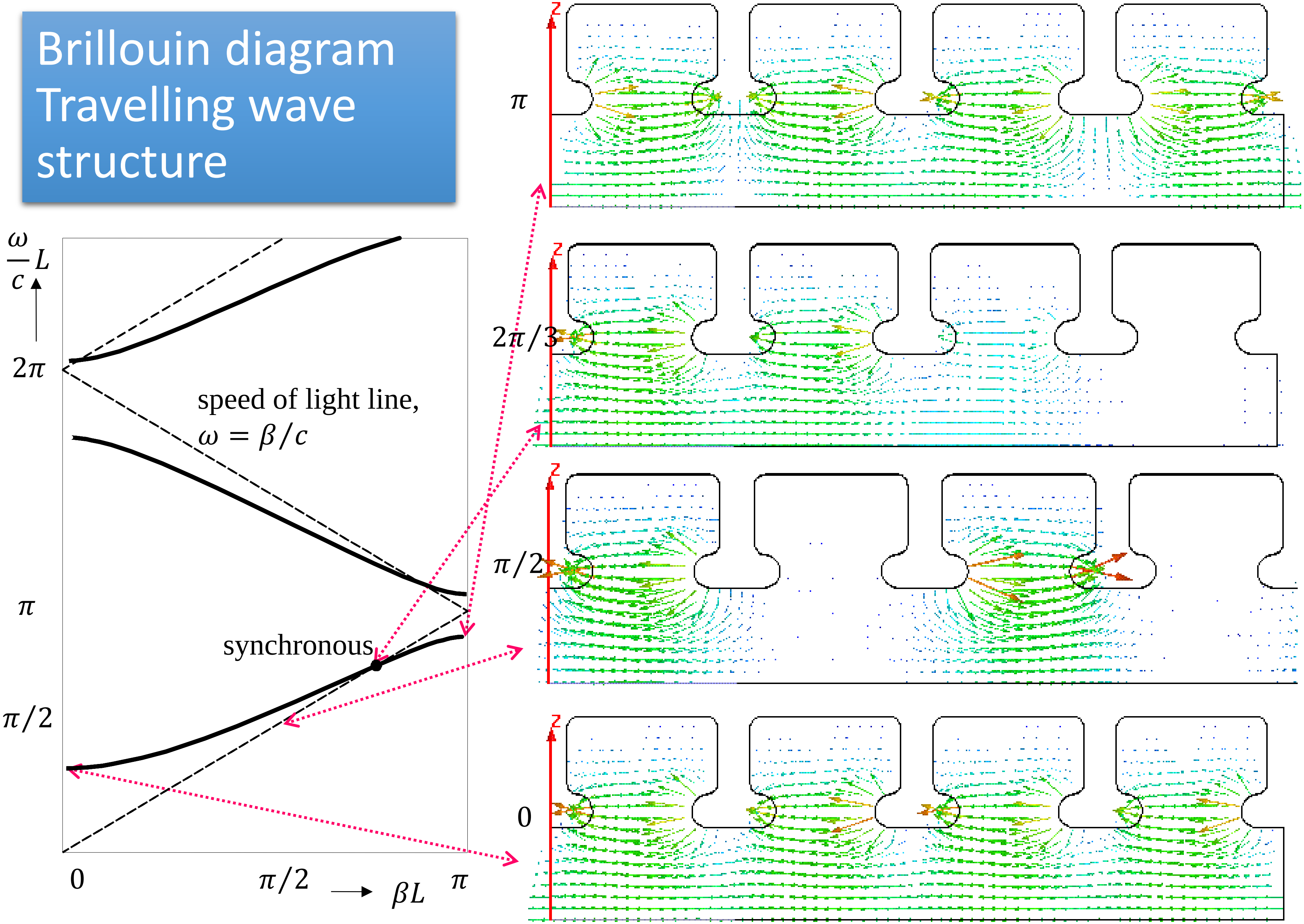


- “Standard” superconducting cavities are standing-wave, multi-cell cavities with a phase shift of π between cells (cell length $\lambda/2$)

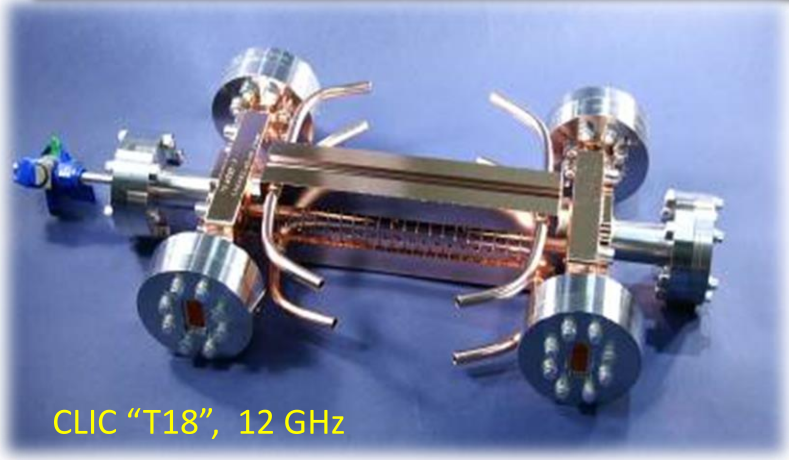


Travelling wave structures

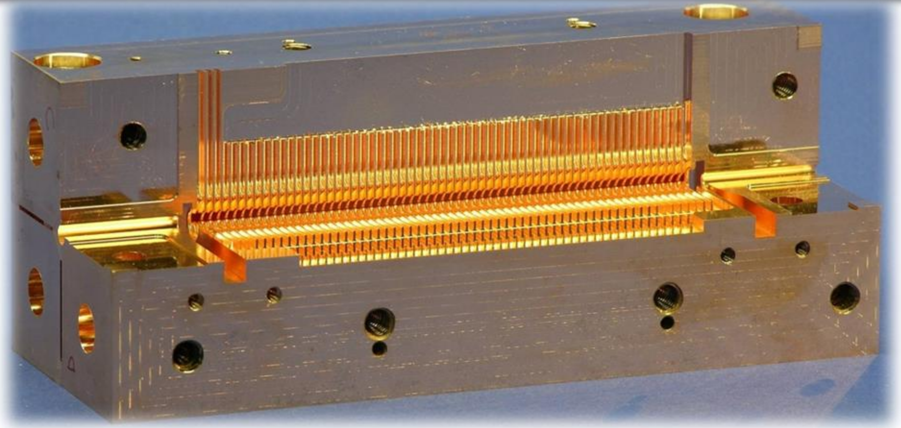
Brillouin diagram Travelling wave structure



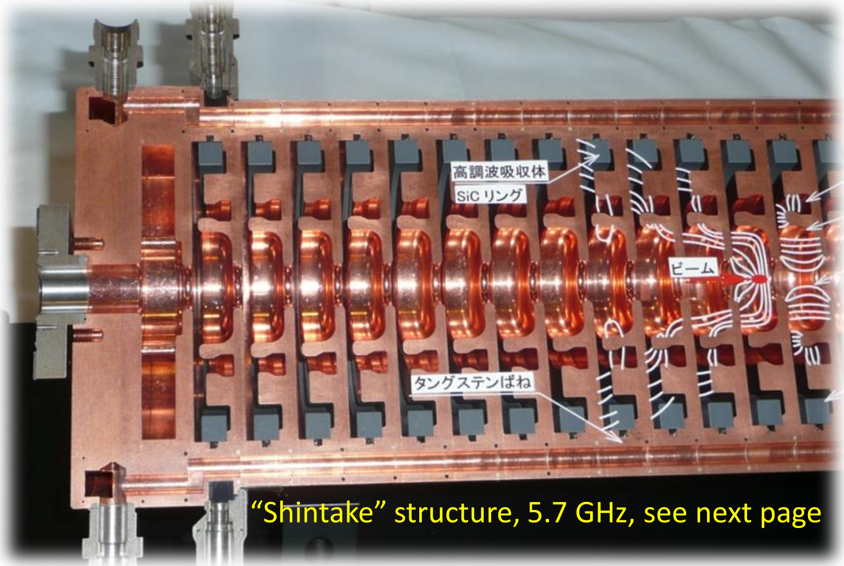
Travelling wave cavities



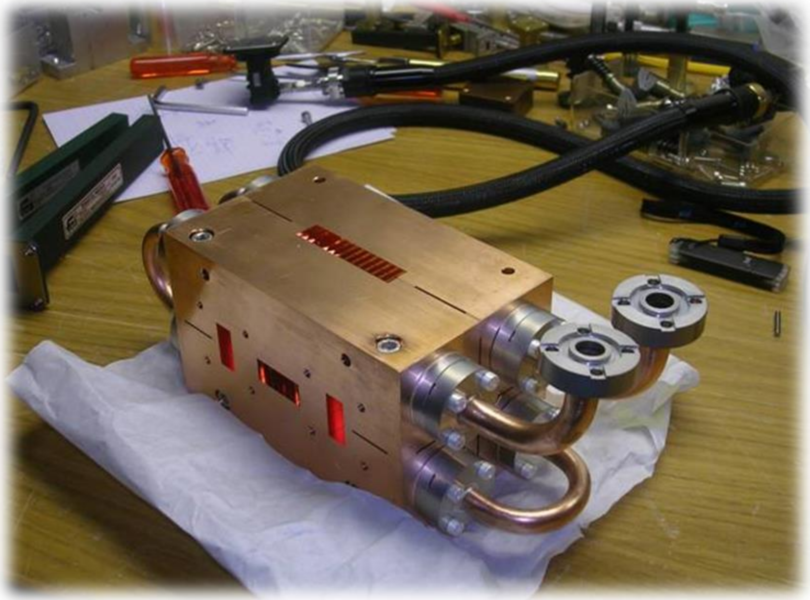
CLIC “T18”, 12 GHz



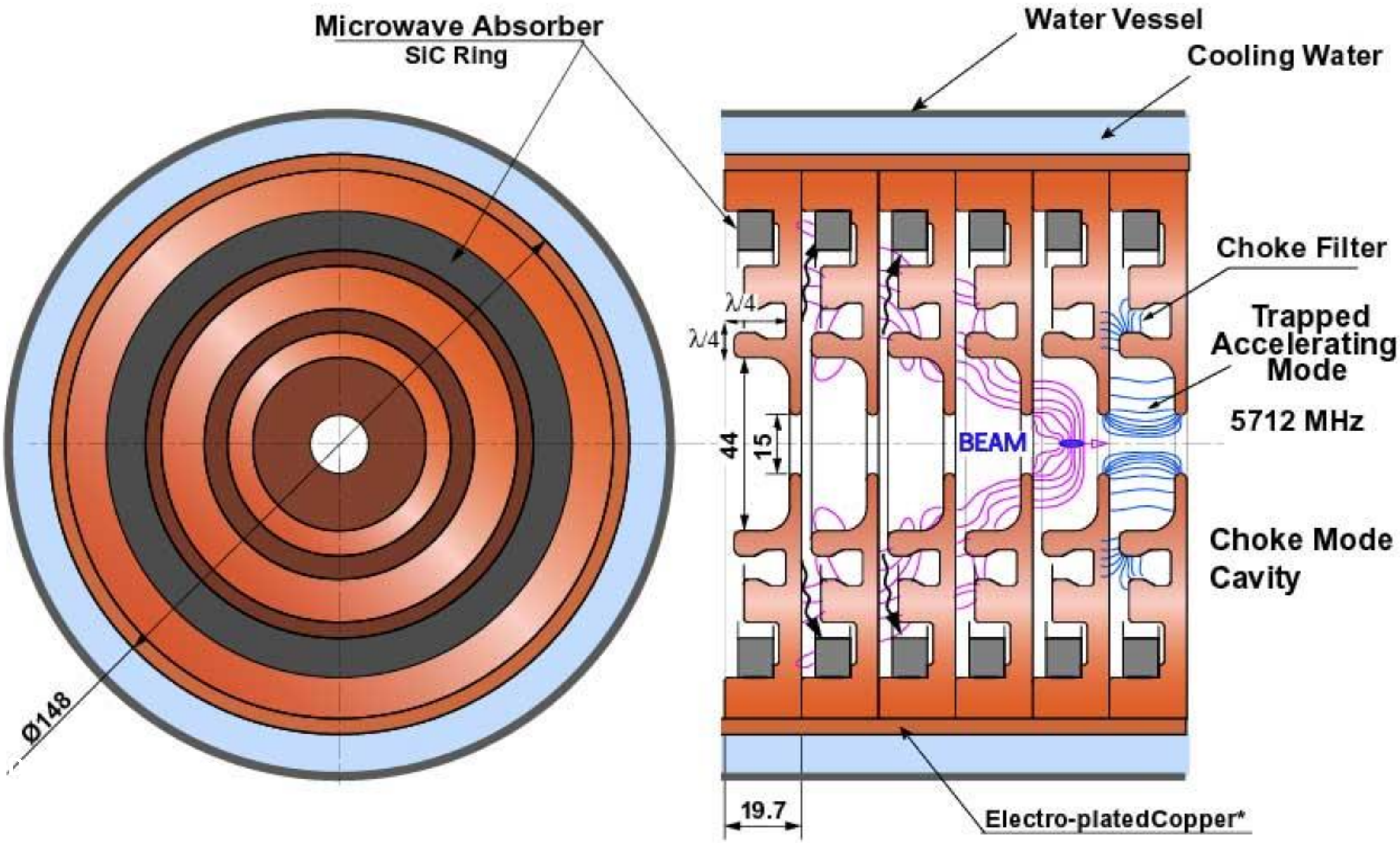
CLIC “HDS”, 12 GHz



“Shintake” structure, 5.7 GHz, see next page



Disc loaded structure with strong HOM damping "choke mode cavity" ("Shintake" structure)



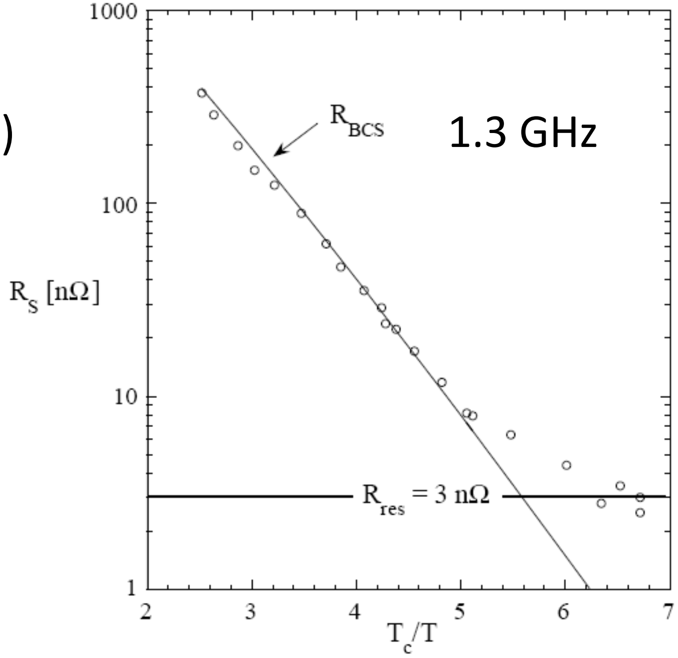
CERN SPS 200 MHz TW cavity

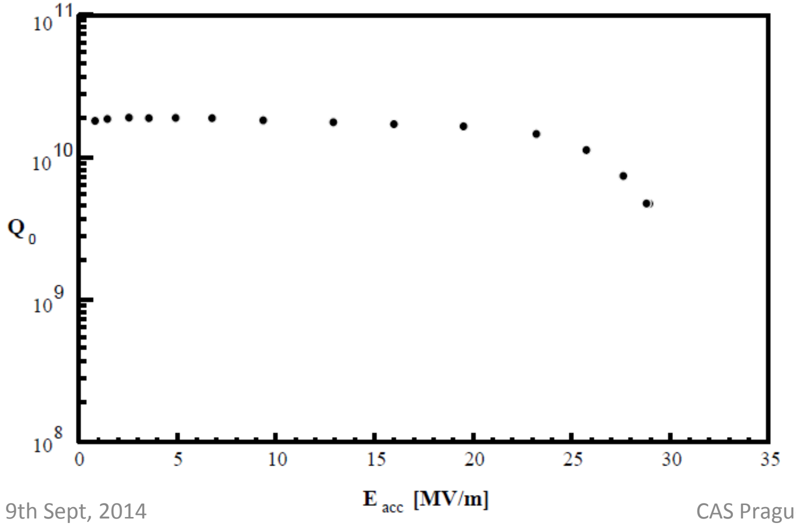
Superconducting RF

RF Superconductivity

- Different from DC, at RF the resistance R is not exactly zero, but just very small – the resulting Q_0 thus is not infinite, but very large.
- It is well described by BCS (Bardeen-Cooper-Schrieffer)

  Theory: $R_{BCS} \propto \frac{\omega^2}{T} \exp\left(-1.76\, \frac{T_c}{T}\right)$
- Surface resistance $R = R_{BCS} + R_{res}$.
- Good values for Q_0 are some 10^{10}.
- Typical performance plot of a SC cavity:

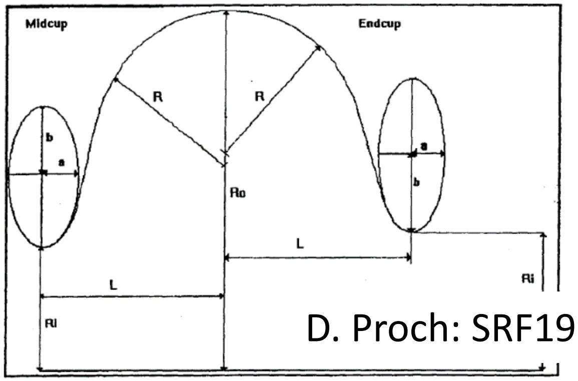




- The wall losses are small, but since they occur at low temperature, they are “expensive” to cool! (1000 W/W at 1.8 K!)
- Most used superconductor for RF applications is Nb.

“Elliptical” multi-cell cavities

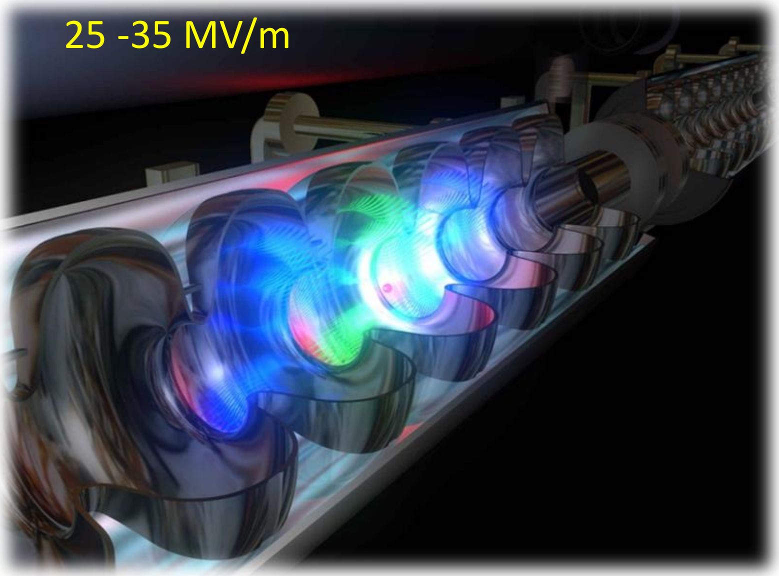
- The elliptical shape was found as optimum compromise between
    - maximum gradient (E_{acc}/E_{surf})
    - suppression of multipactor
    - mode purity
    - machinability
- Operated in π-mode, i.e. cell length is exactly $\beta\lambda/2$.
- It has become de facto standard, used for ions and leptons! E.g.:
    - ILC/X-FEL: 1.3 GHz, 9-cell cavity
    - SNS (805 MHz)
    - SPL/ESS (704 MHz)
    - LHC (400 MHz, single cell)

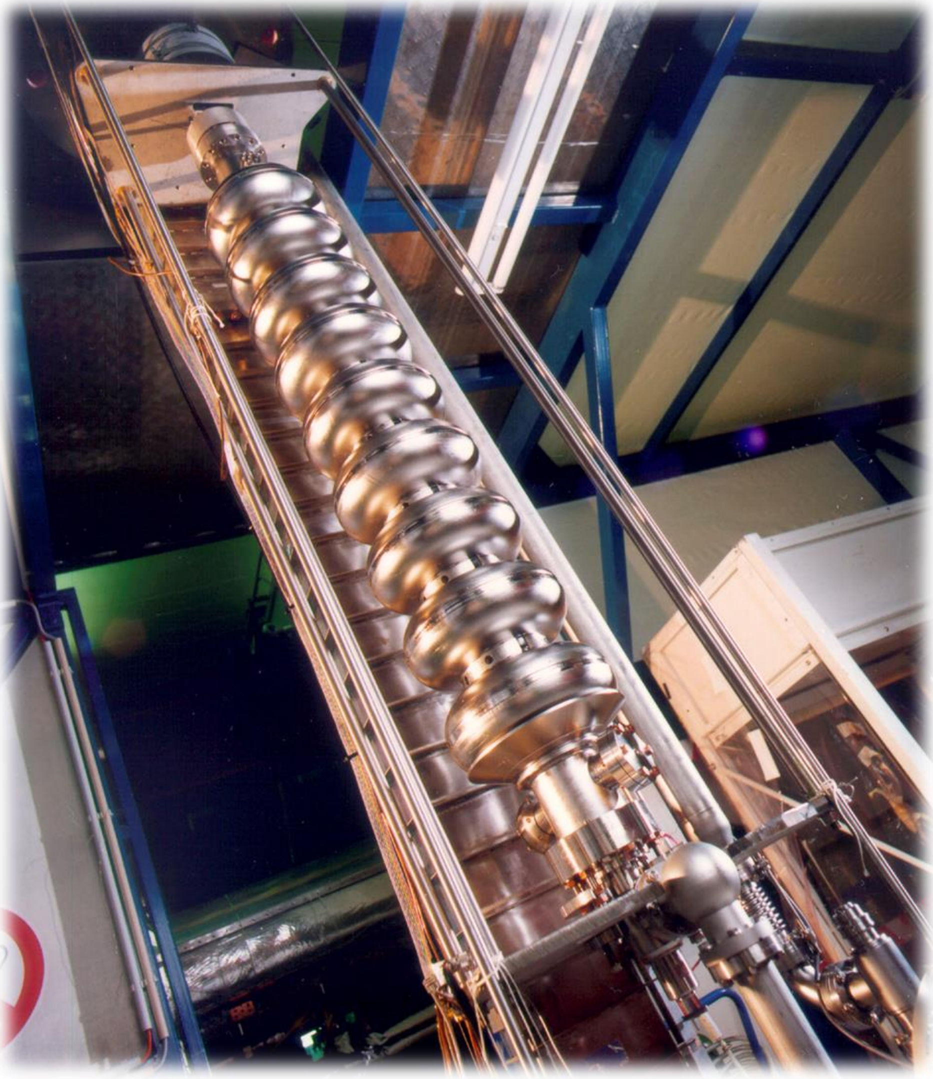


D. Proch: SRF1993 *)

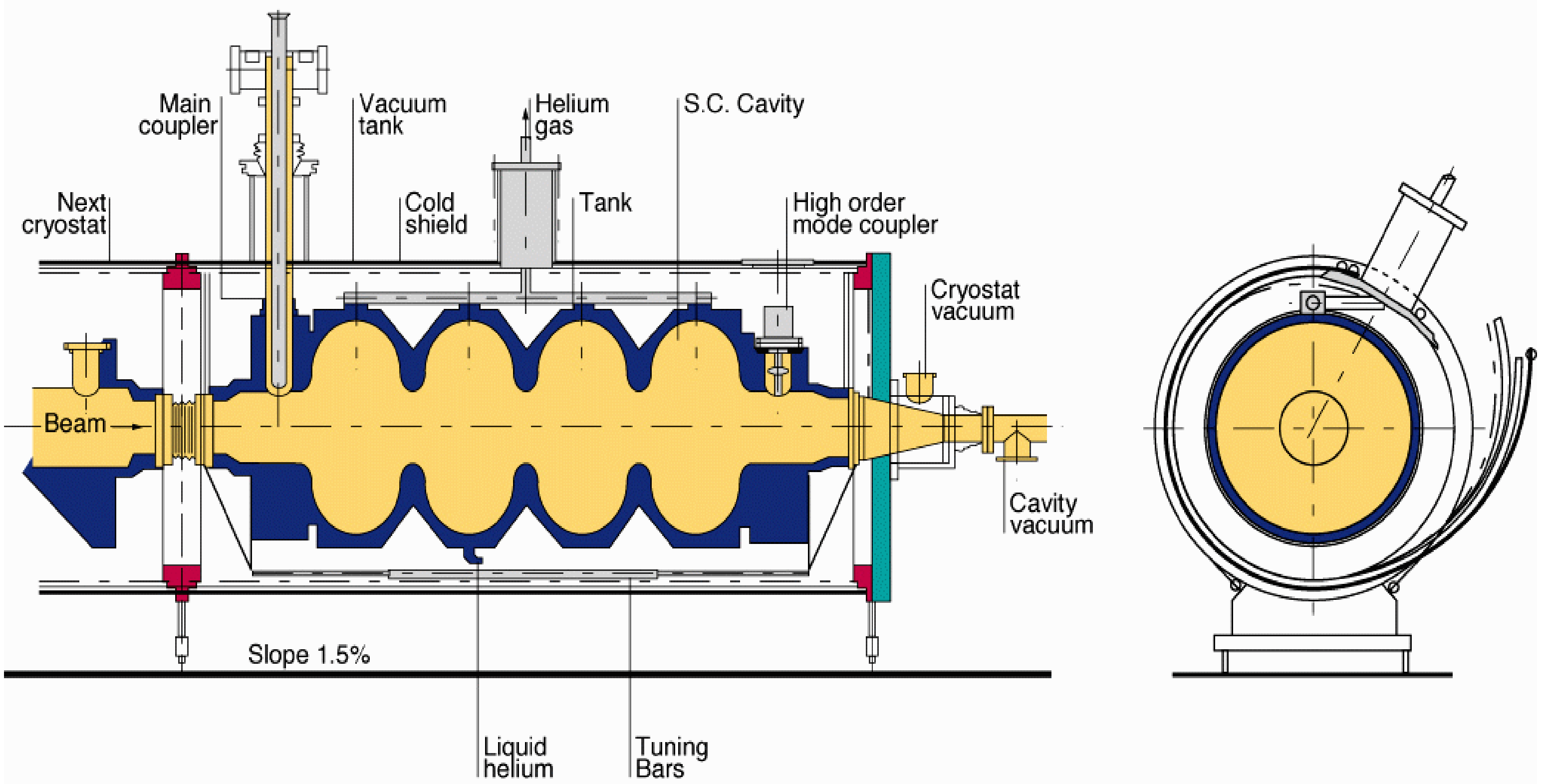
*): accelconf.web.cern.ch/accelconf/SRF93/papers/srf93g01.pdf

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





LEP Superconducting cavities

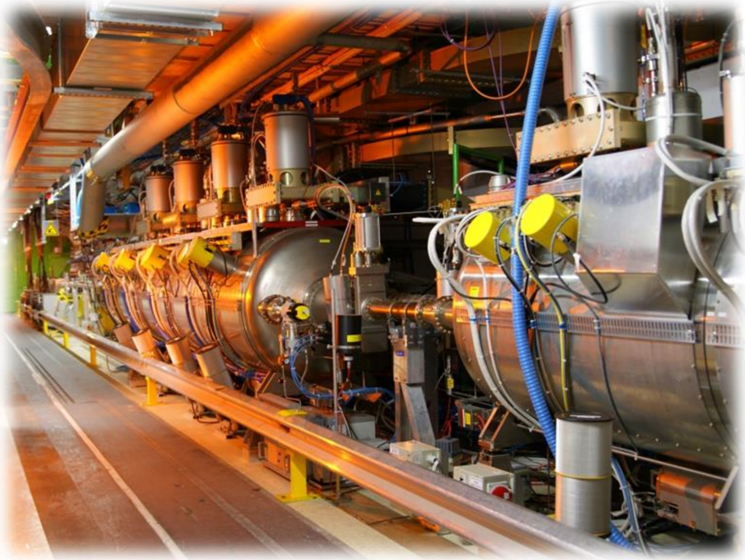


10.2 MV/ per cavity

Nb coating techniques

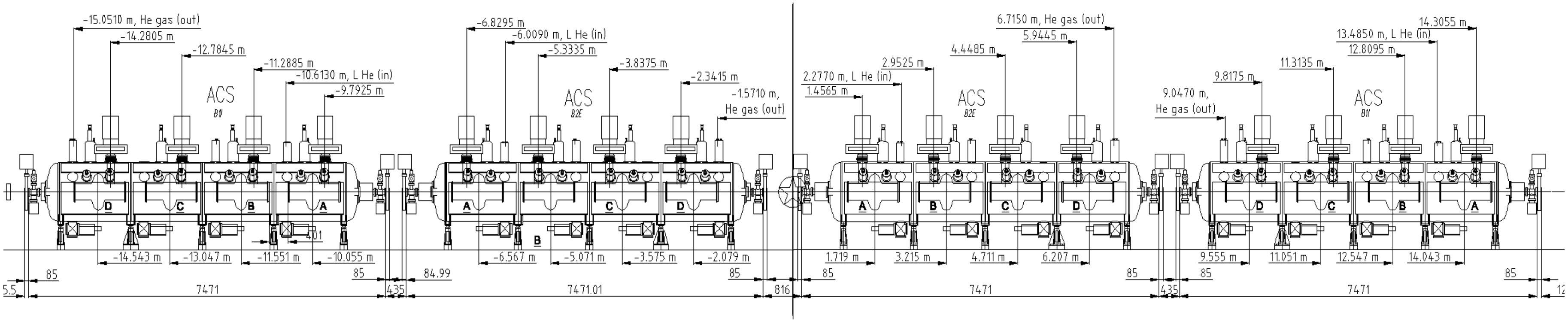
- Sputtering Nb on Cu
  - Advantages:
    - Due to the high cost of Nb, this can reduce cost!
    - The Cu substrate increases the mechanical & thermal stability (quench resistance).
  - Technology initially developed at CERN (Benvenuti, LEP, 1980); experts today at JLAB, Legnaro, Saclay, Sheffield & 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
- …

LHC SC RF, 4 cavity module, 400 MHz



installed in LHC IP4, 2 MV/cavity

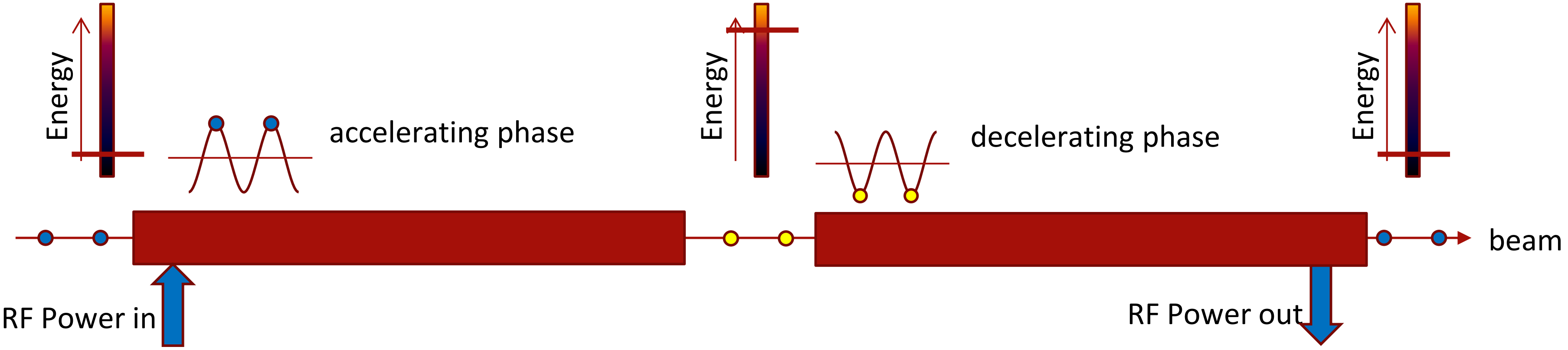
LHC spare module stored in CERN’s SM18



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

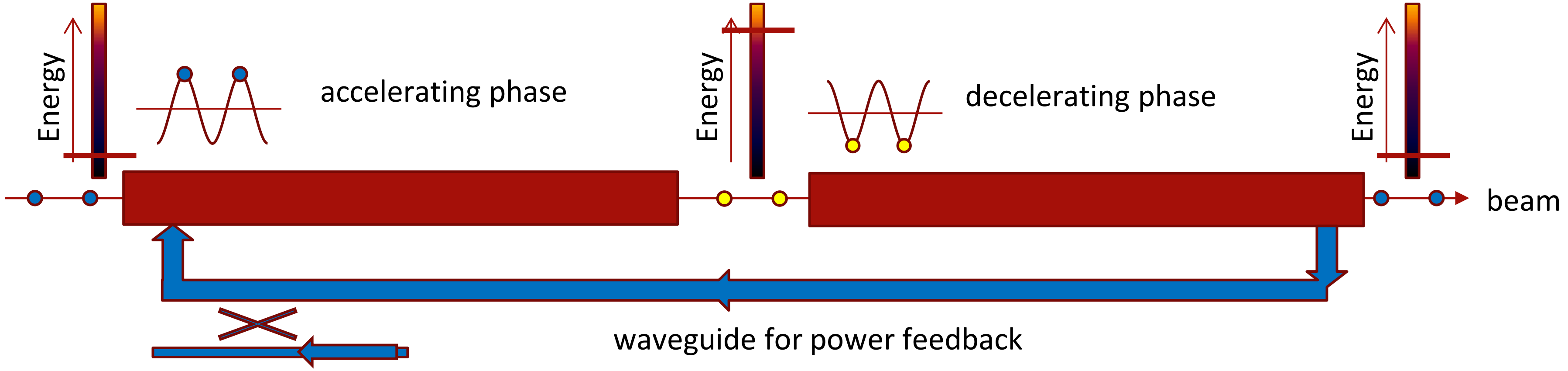
Energy

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

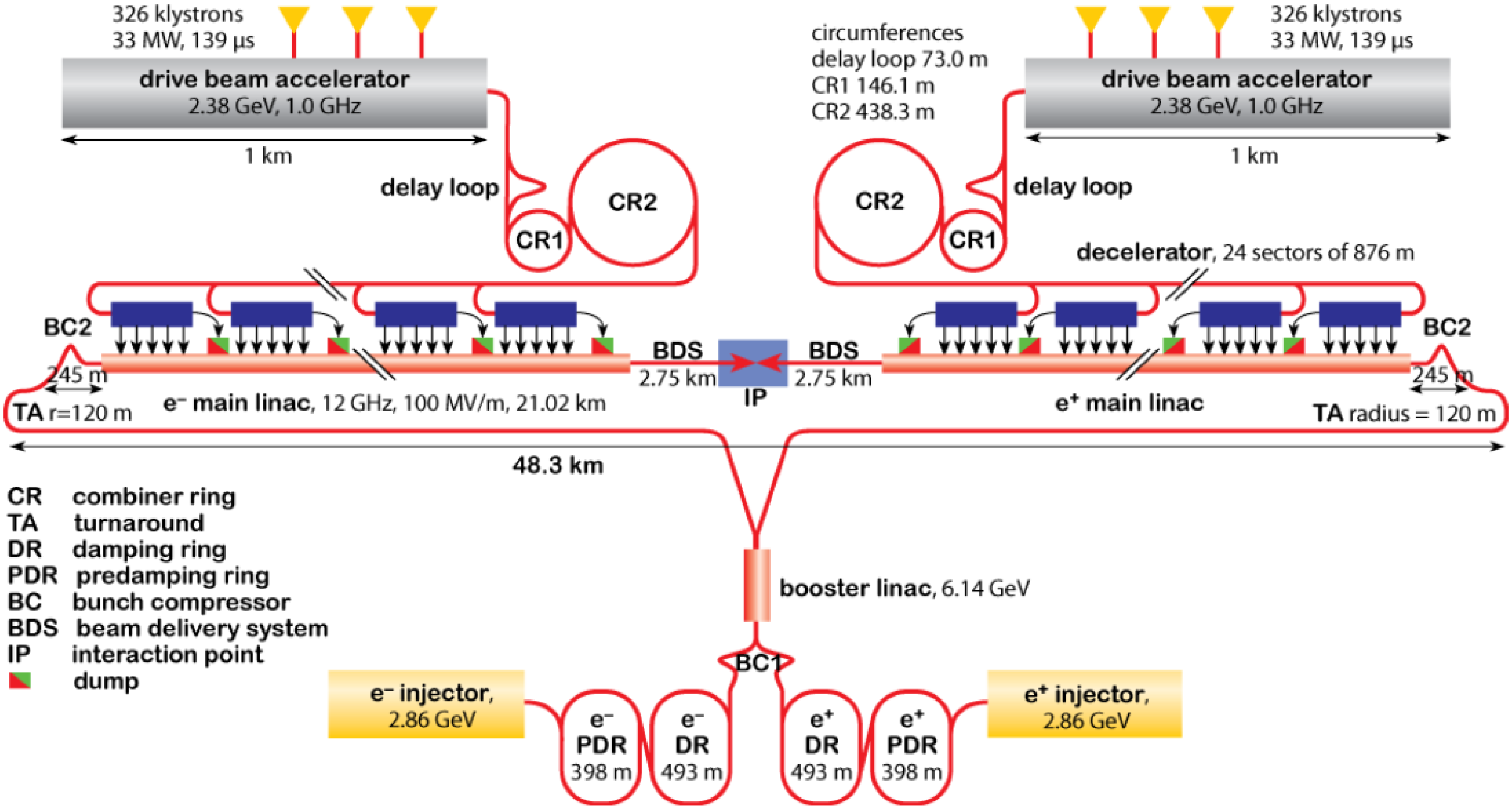
waveguide for power feedback

(Smaller) RF Power in

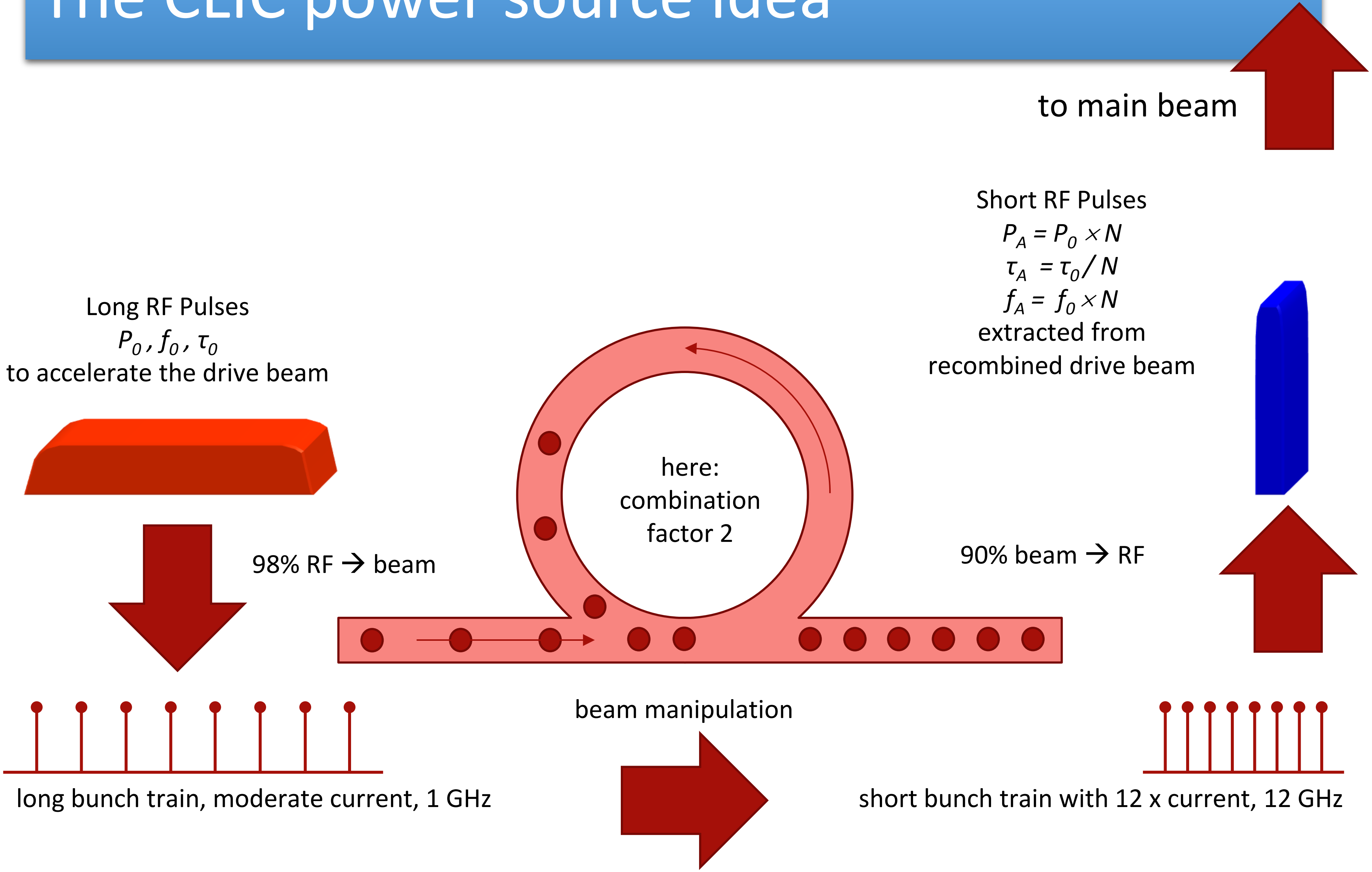
A word about CLIC

In the CLIC scheme, 90% of the drive beam power is recovered
(to produce the RF power for the main beam)

CLIC general layout



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_0 , f_0 , τ_0
to accelerate the drive beam

here:
combination
factor 2

98% RF → beam

90% beam → RF

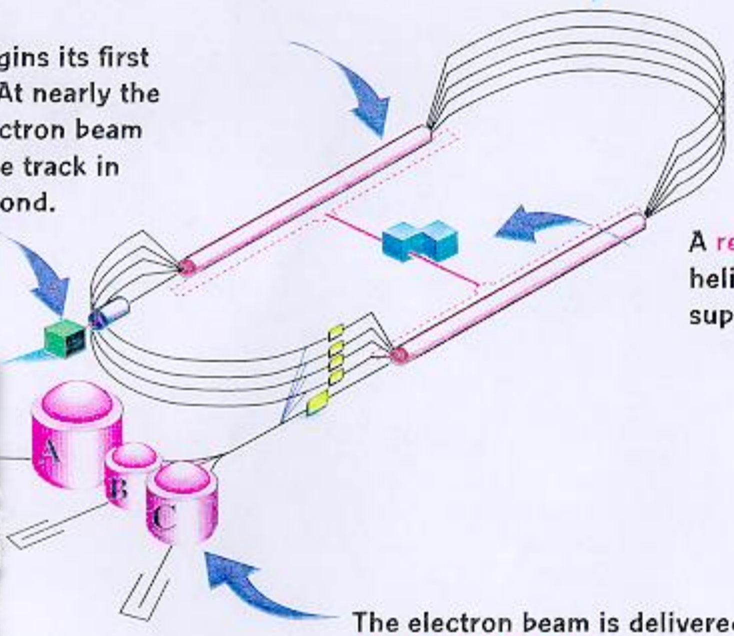
beam manipulation

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.



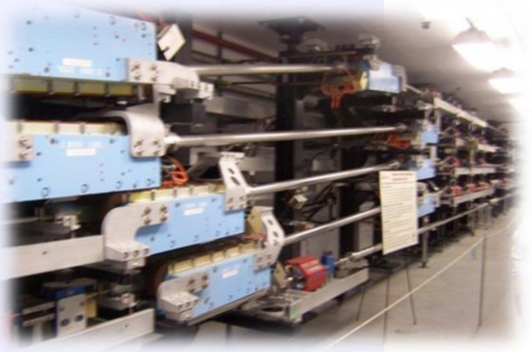
Each linear accelerator uses superconducting technology to drive electrons to higher and higher energies.

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.

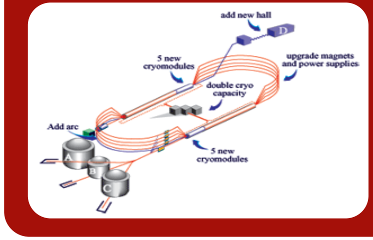
The electron beam is delivered to the experimental halls for simultaneous research by three teams of physicists.



Recirculating Linac compared to linac and synchrotron

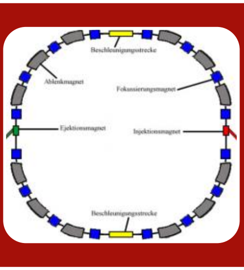
Linac

- 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

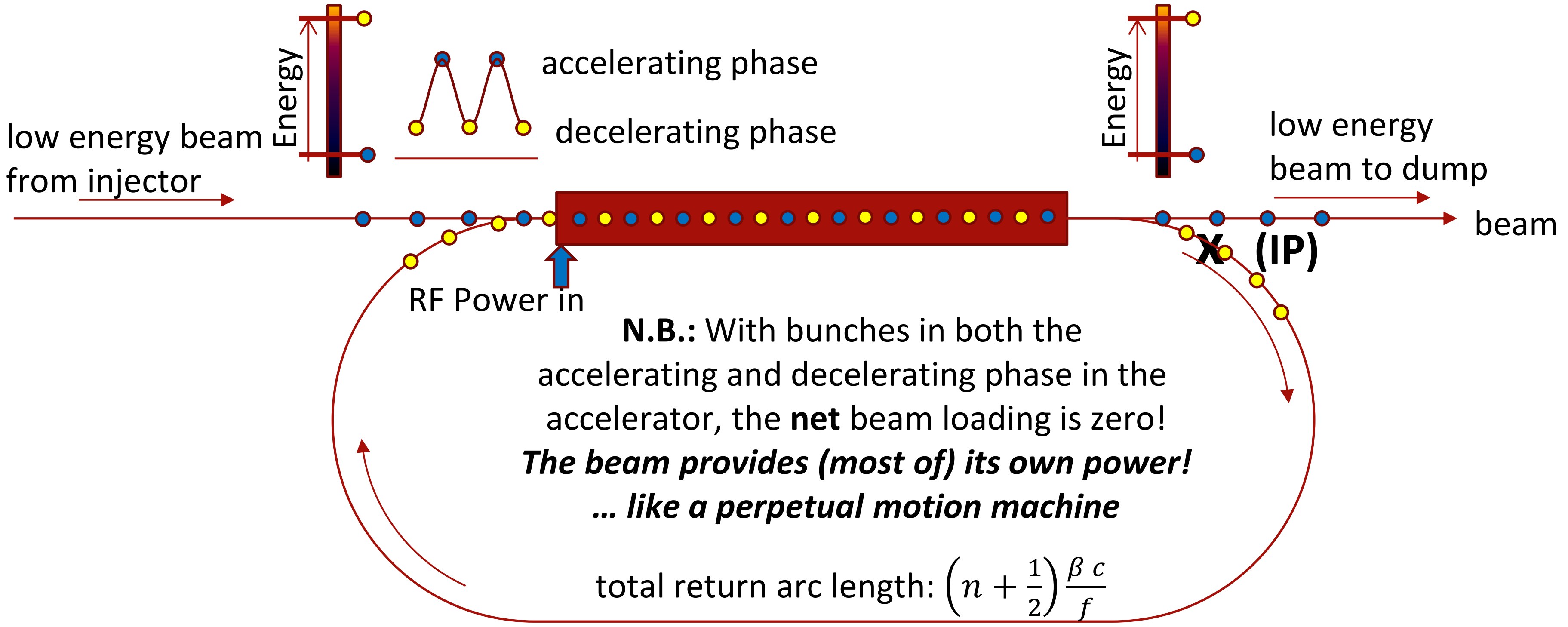
- Accelerator Structure used many times
- Periodic lattice
- Instabilities develop over many turns (coupled bunch, mode coupling)

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!

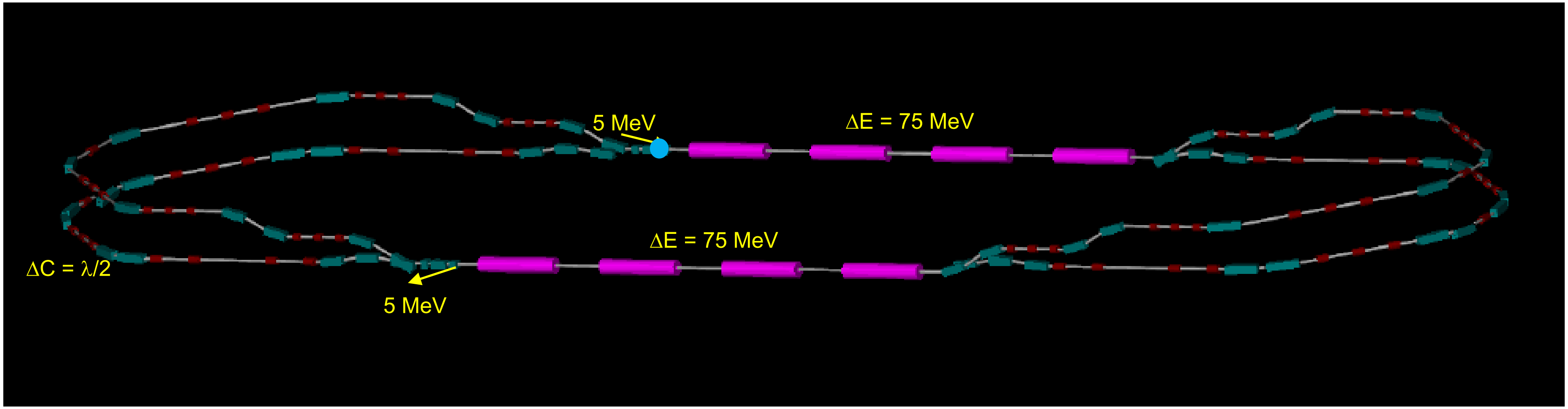
The beam provides (most of) its own power!

… 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

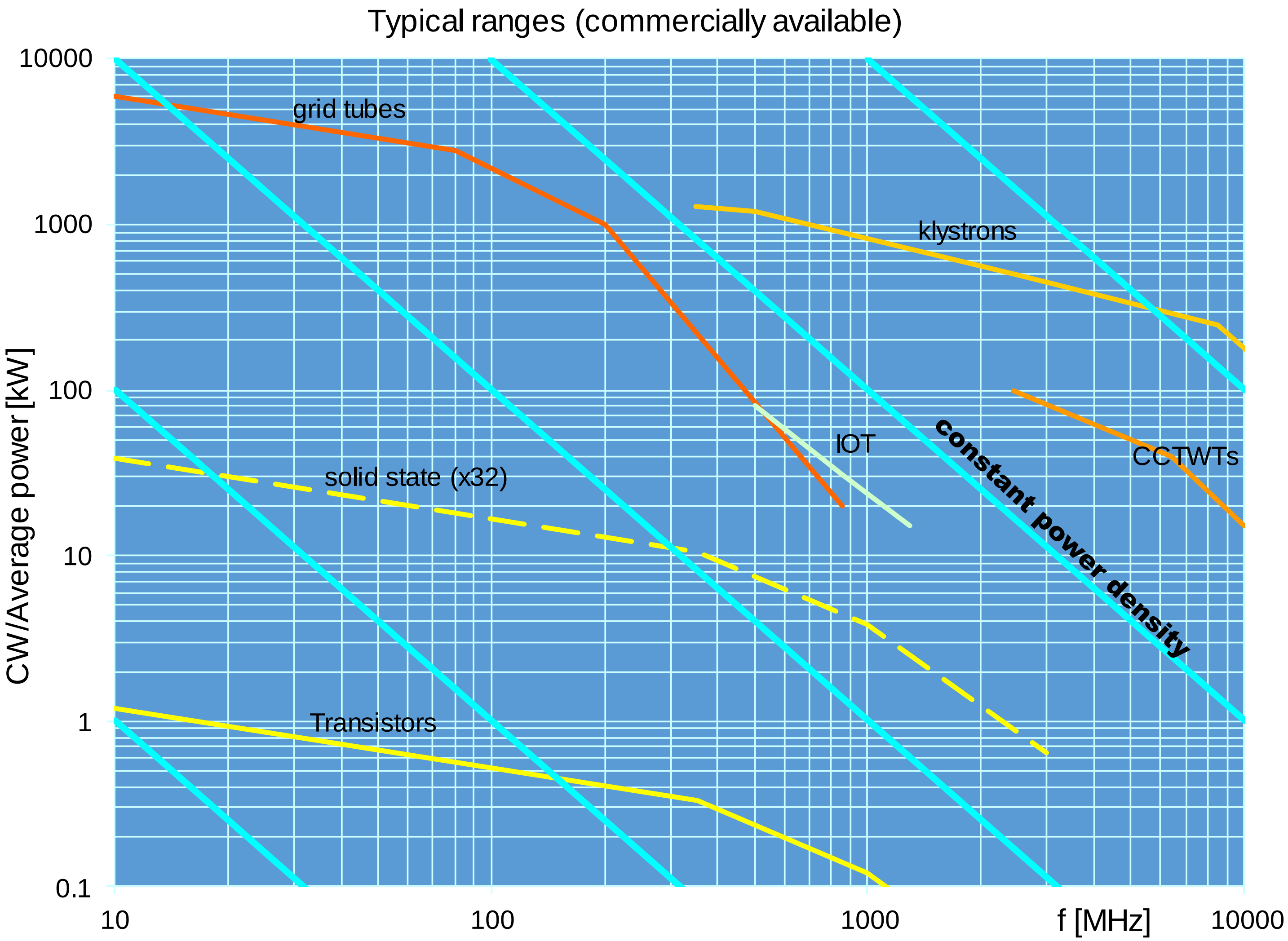
This model and animation by Alex Bogacz, Jefferson Lab



Two passes ‘up’ + Two passes ‘down’

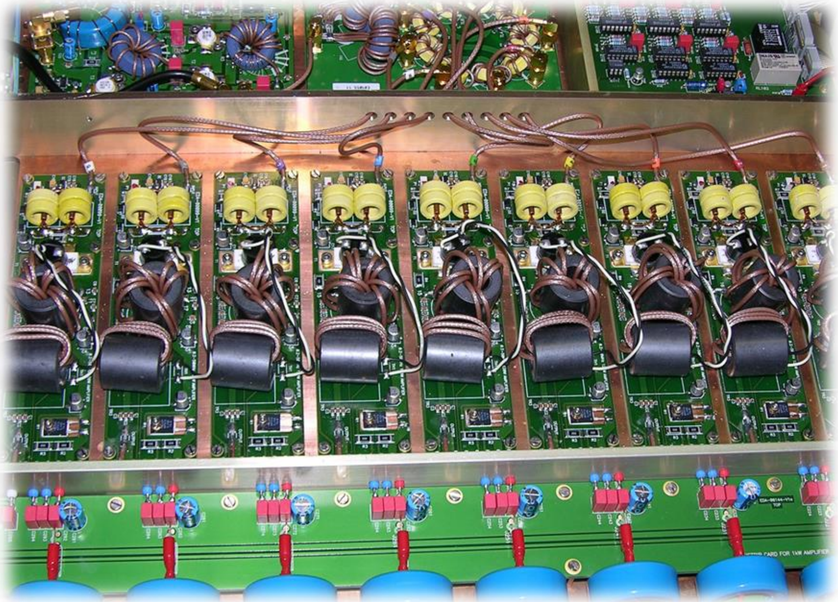
RF power sources

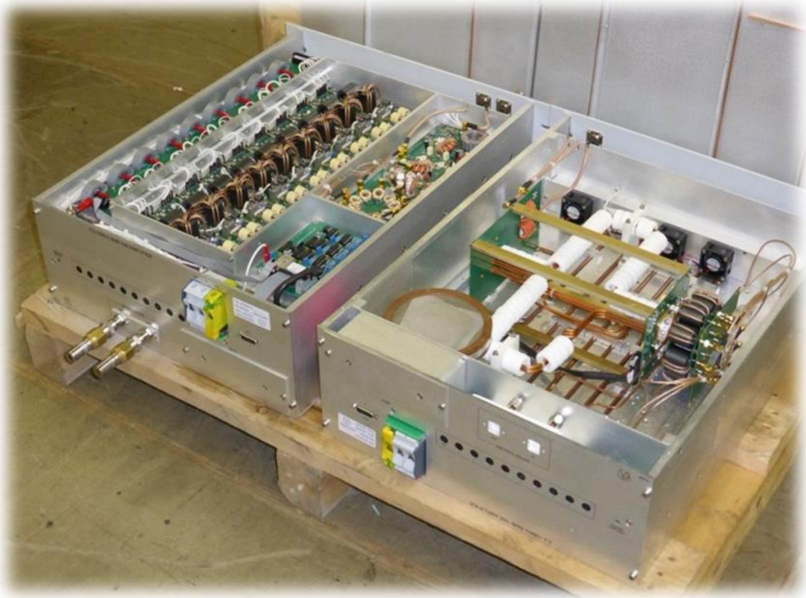
RF power sources



Example SSPA, 1 kW

$(0.2 \div 50)$ MHz, 1 kW solid state amplifier for LEIR





$(0.2 \div 10)$ MHz, 1 kW SSPA for MedAustron

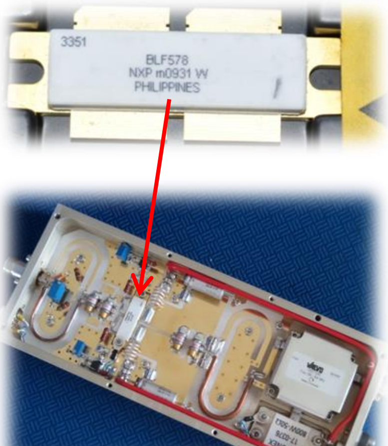
M. Paoluzzi

Soleil/ESRF Booster SSPA, 150 kW, 352 MHz

Taken from J. Jacob, CWRF 2014

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

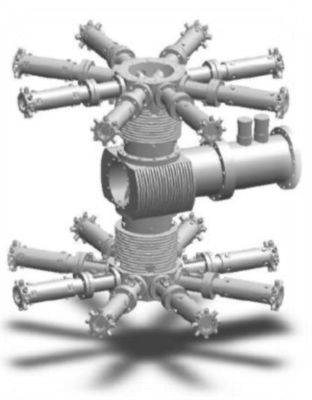
Pair of push-pull transistors



650 W RF module

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

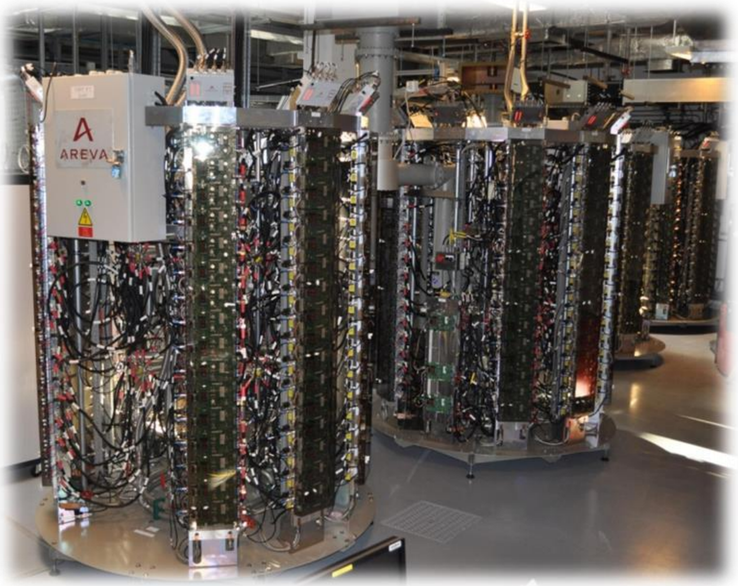
x 128



75 kW Coaxial combiner tree

with $\lambda/4$ transformers

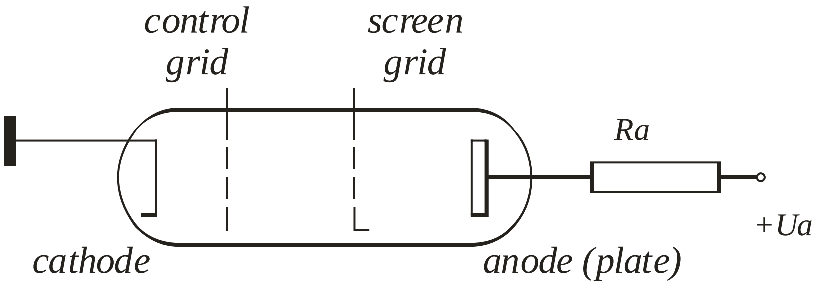
x 2

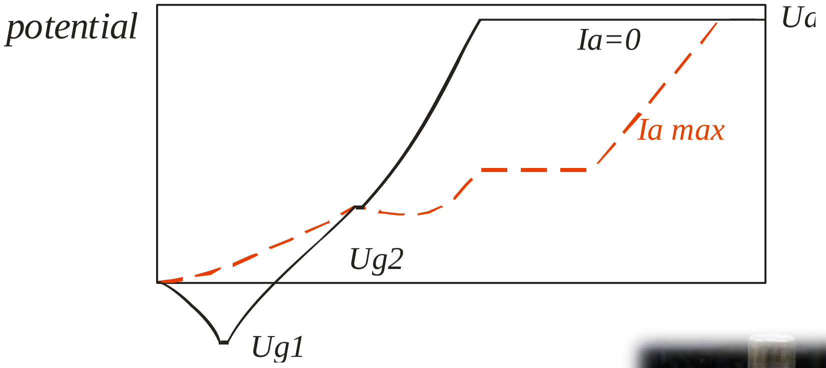


150 kW, 352.2 MHz Solid State Amplifiers for the ESRF booster (7 in operation)

Efficiency: > 57 % at nominal power

Tetrodes





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

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

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

High power tetrode amplifier

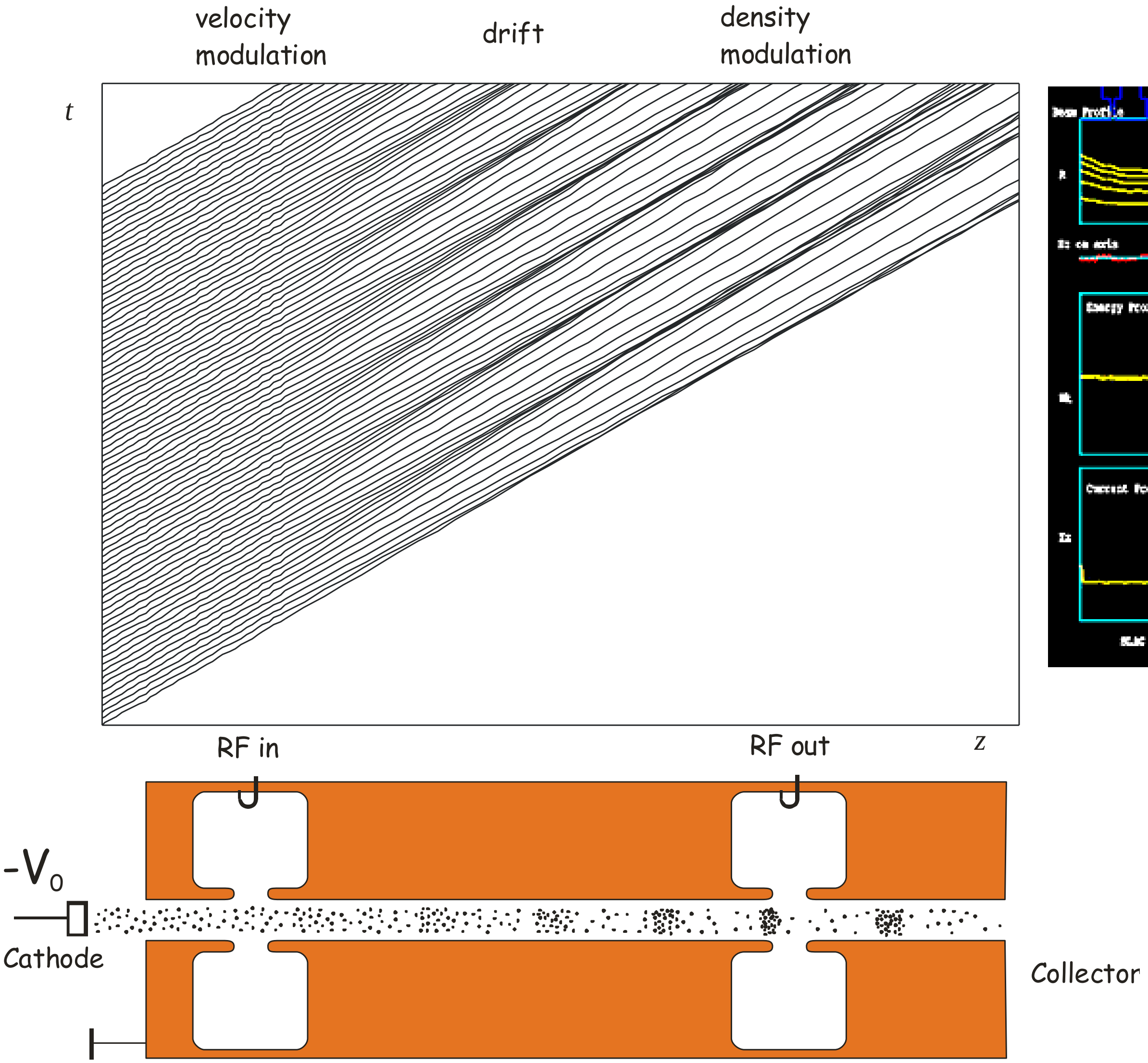
CERN Linac3: 100 MHz, 350 kW

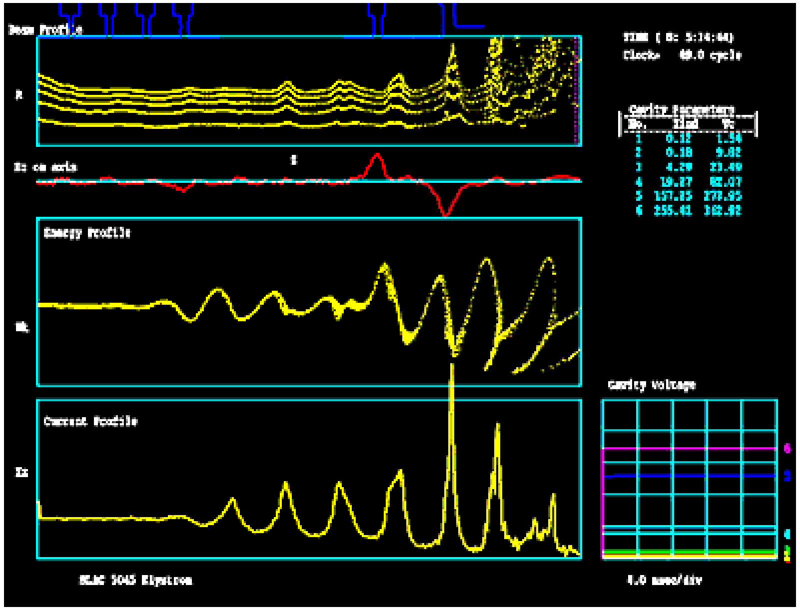
50 kW Driver: TH345, Final: RS 2054 SK

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 %

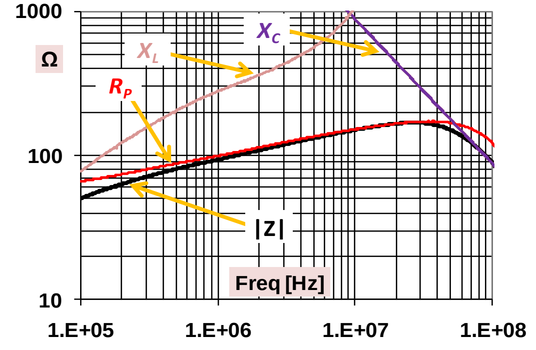
Some examples

Some Power RF systems at CERN

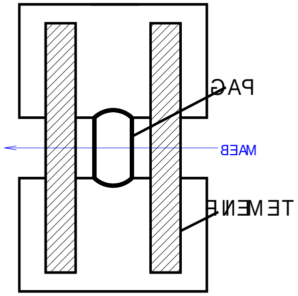
Finemet® based wide-band cavity

Finemet exhibits wideband response

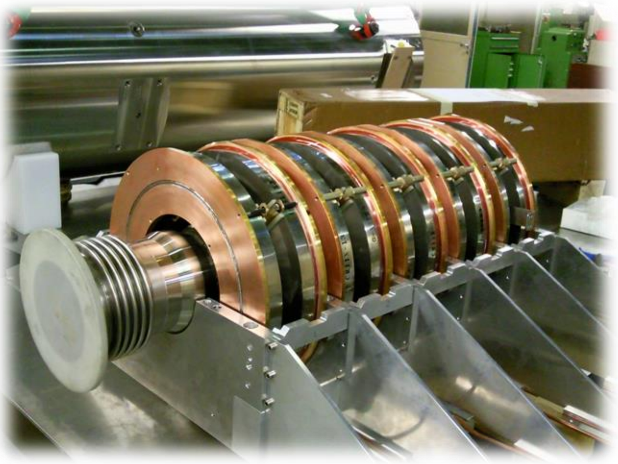
C_P mostly depends on geometry and drives the high frequency response. The capacitive effect is enhanced by the final stage output capacitance.



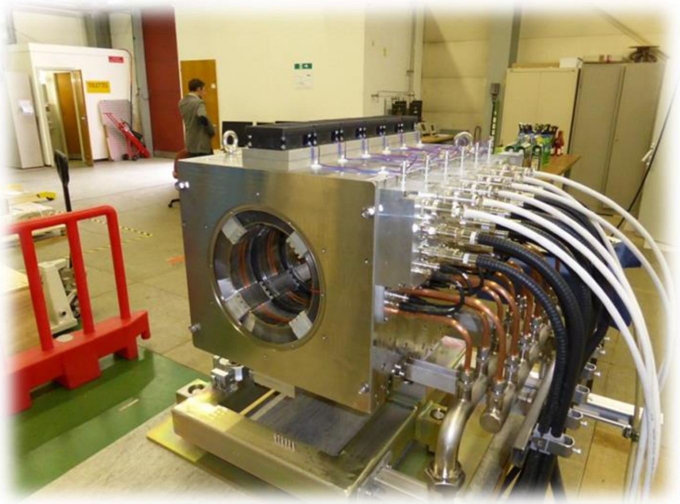
R_P and L_P drive the low frequency response. They and are mostly dependent on Finemet® Characteristics.



5-gap finemet cavity



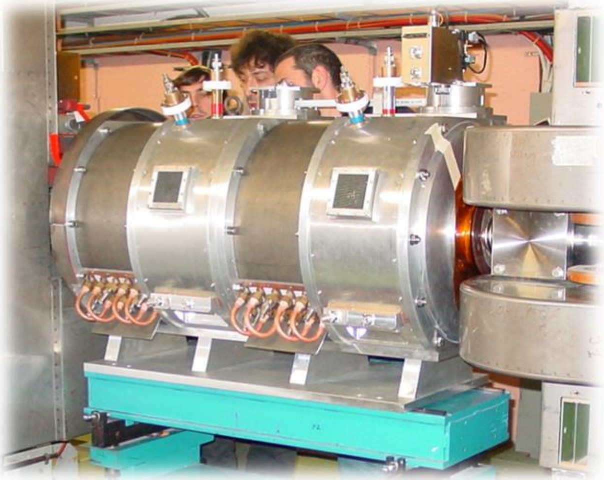
6-gap finemet cavity for MedAustron



Prototype system installed in ring 4 of CERN PSB

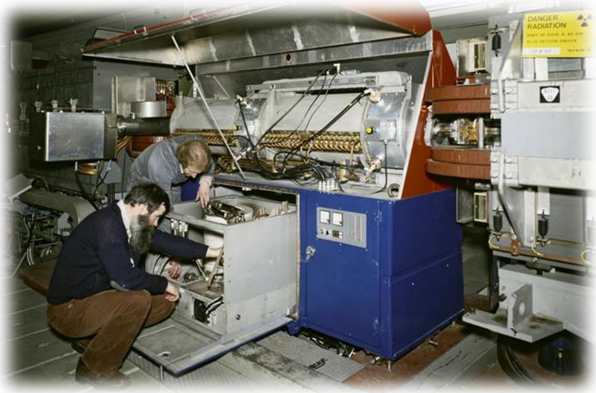
CERN PS RF Systems

10 MHz system, *h*=7…21

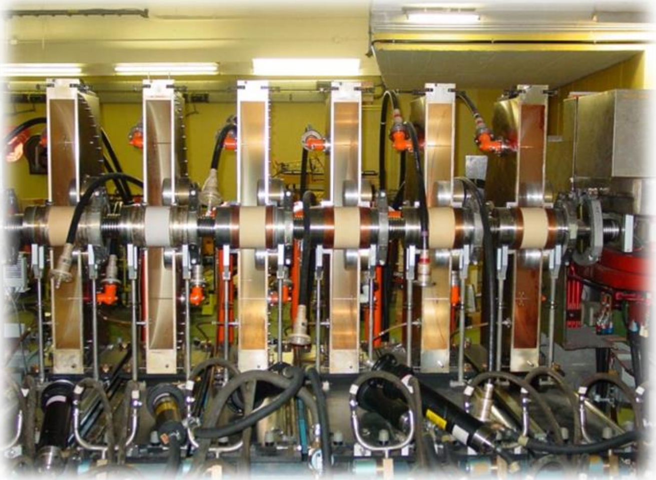


13/20 MHz system, *h*=28/42

40 MHz system, *h*=84



80 MHz system, *h*=168



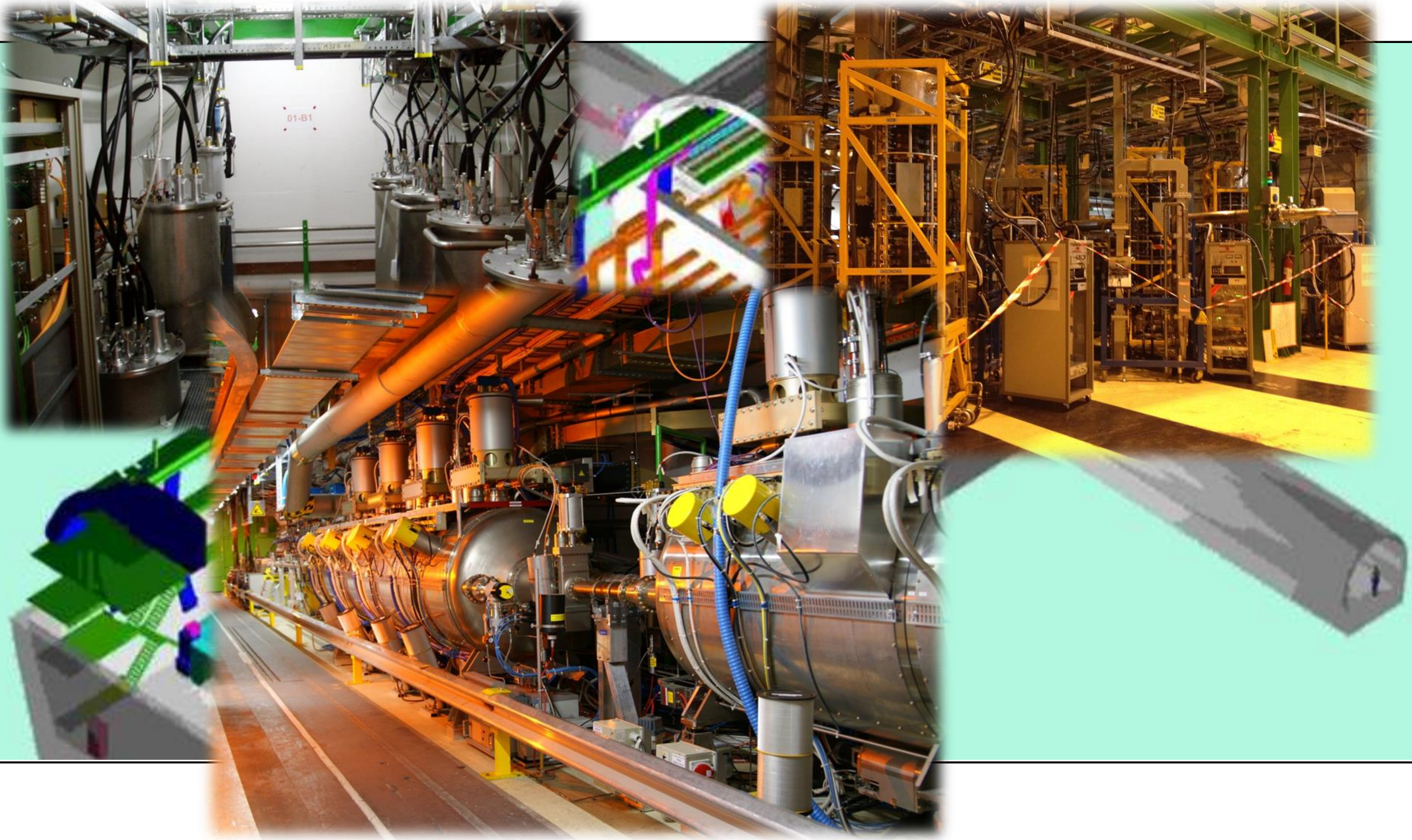
200 MHz system

SPS 200 MHz RF system

“Siemens”:
4 x 550 kW (28 tetrode amplifiers)

“Philips”:
4 x 550 kW (72 tetrode amplifiers)

LHC 400 MHz High-Power RF System



End of RF Systems II

Thank you for your attention!