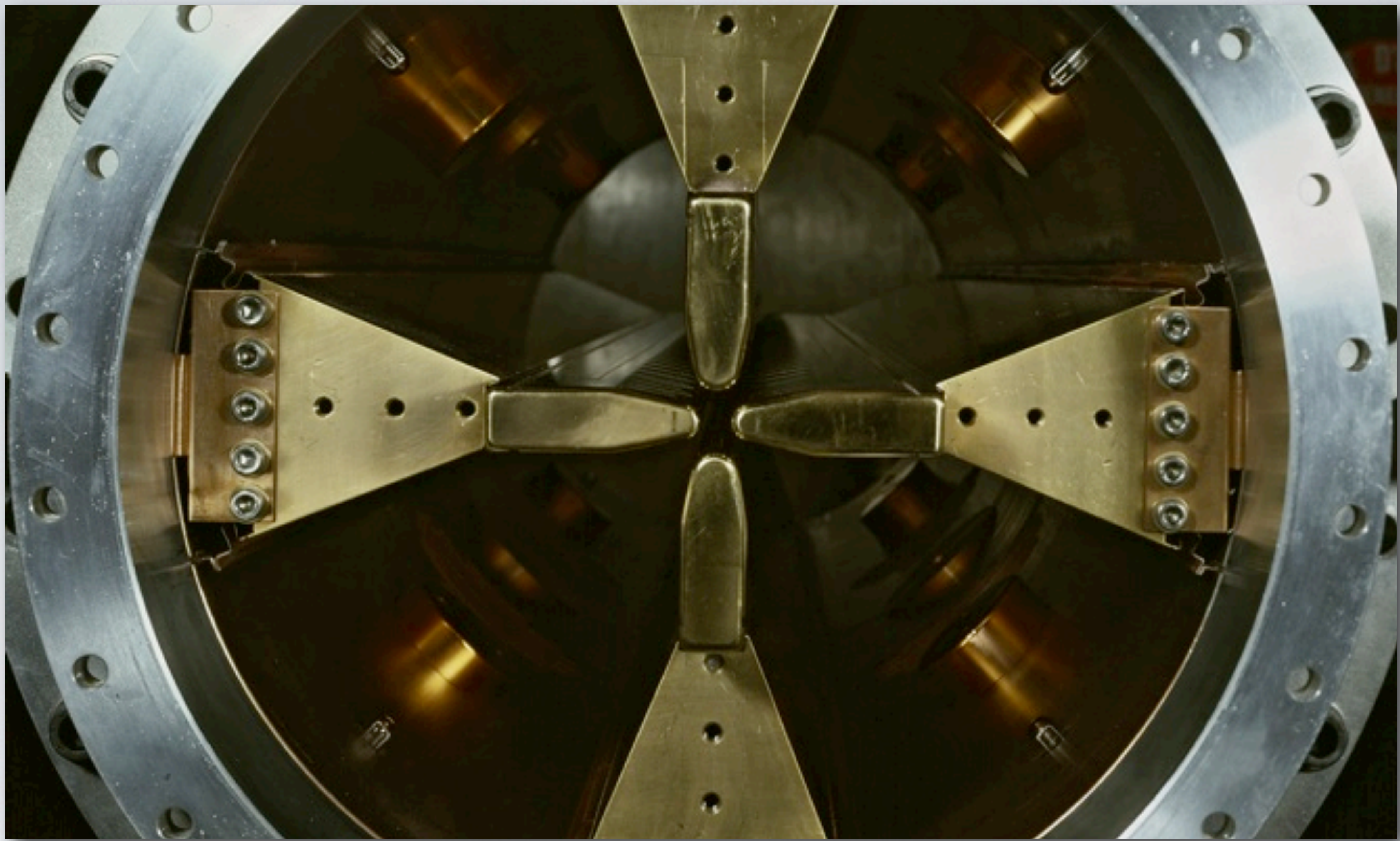


CAVITY TYPES

CAS, RF for Accelerators, Ebeltoft, Denmark, 11 June 2010

F. Gerigk (CERN/BE/RF)

OVERVIEW

- RF cavities for different types of accelerators,
- The first accelerators/why we put RF fields in a box,
- From a waveguide to an RF cavity,
- Standing wave and traveling wave acceleration,
- What are TE, TM, and TEM type cavities?,
- Superconducting cavities,

ACCELERATING CAVITIES ARE USED IN:

- low-β synchrotrons (protons, ions)
- low-β FFAGs (protons, ions)
- cyclotrons
- low-β proton/ion linacs
- electron linacs
- high-β synchrotrons (electrons, protons, ions)
- high-β FFAGs (electrons, protons, ions)

ACCELERATING CAVITIES ARE USED IN:

changing velocity

- low-β synchrotrons (protons, ions)
- low-β FFAGs (protons, ions)
- cyclotrons
- low-β proton/ion linacs

constant velocity

- electron linacs
- high-β synchrotrons (electrons, protons, ions)
- high-β FFAGs (electrons, protons, ions)

ACCELERATING CAVITIES ARE USED IN:

changing velocity

variable RF frequency (~revolution frequency)

- low-β synchrotrons (protons, ions)
- low-β FFAGs (protons, ions)

fixed RF frequency

- cyclotrons
- low-β proton/ion linacs

constant velocity

fixed RF frequency

- electron linacs
- high-β synchrotrons (electrons, protons, ions)
- high-β FFAGs (electrons, protons, ions)

ACCELERATING CAVITIES ARE USED IN:

changing velocity | **constant velocity** / **fixed RF frequency**

variable RF frequency (~revolution frequency) + changing velocity:

needs material with adjustable permeability in the cavity to tuning f,
low voltages, high losses,

fixed frequency + changing velocity:

- same RF system for all cavities,
- cell length is adapted to particle velocity,

constant velocity, fixed RF frequency:

- only one structure type needed,
- highest field gradients,
- can be mass produced

NON-ACCELERATING CAVITIES FOR

RF deflection:

I) beam chopping at low energies,
II) suggested for beam funnelling at low energy,
III) CRAB crossing of colliding beams,

see "Transverse Deflecting Cavities", Monday 14. June, G. Burt

RF bunching:

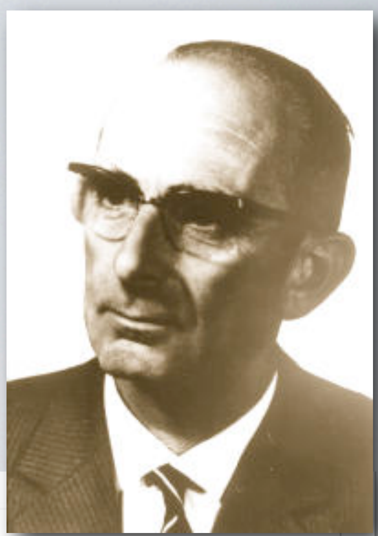
I) forming bunches out of a continuous beam (coasting beam or ion source beam),
II) keep bunches longitudinally confined during transport,

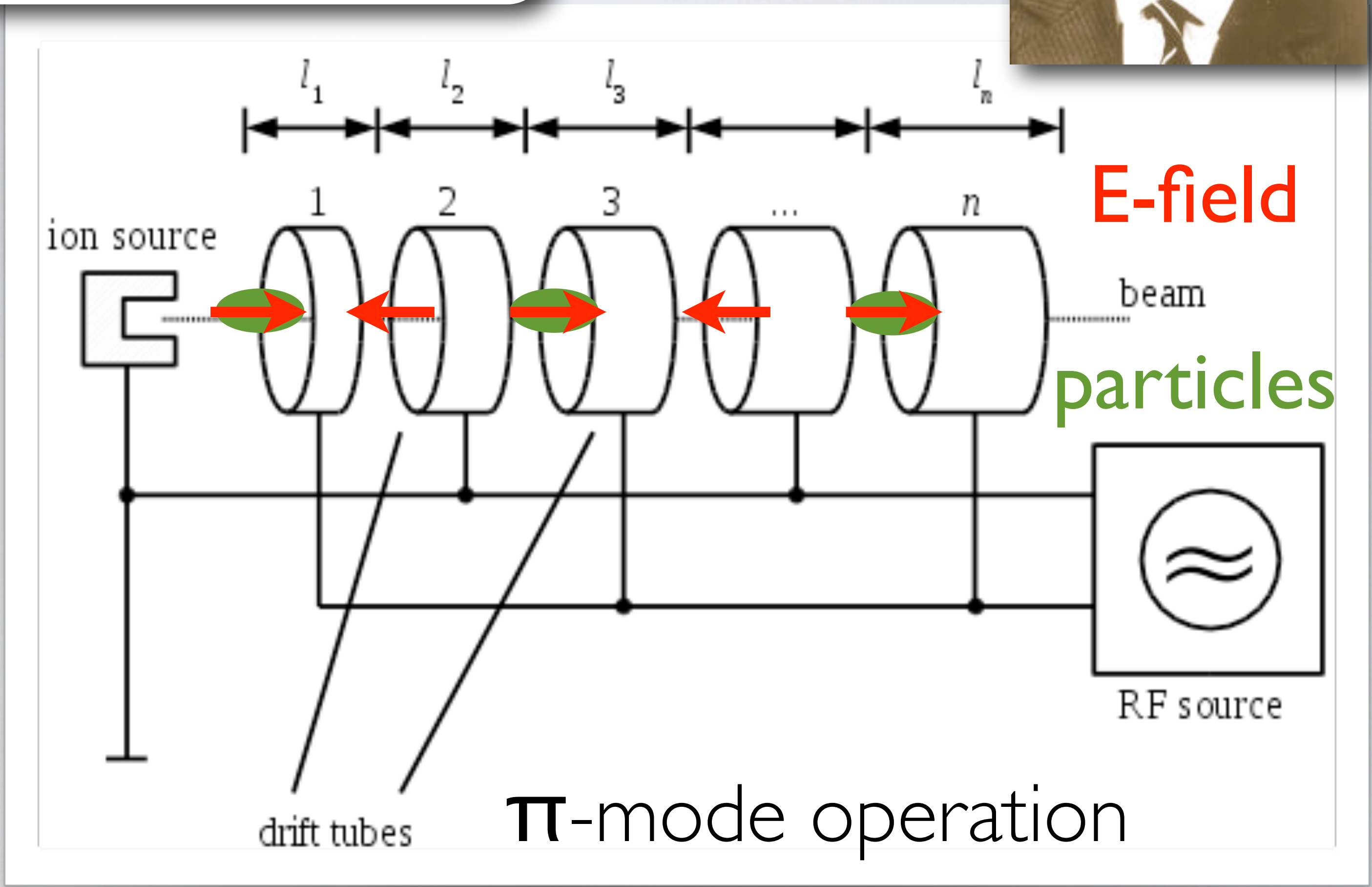
always used for the same beam velocity at the same frequency

THE FIRST ACCELERATING CAVITIES

or why we put RF fields in a box...

NOT YET A CAVITY: THE WIDERÖE LINAC (1927)

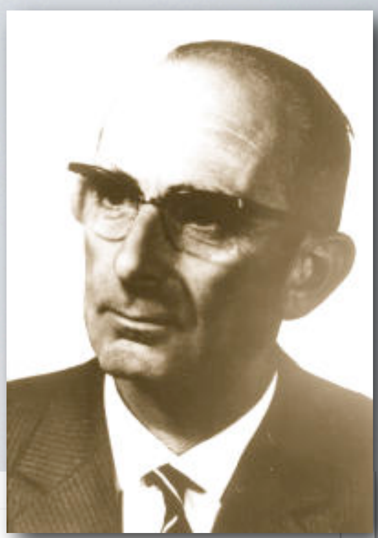


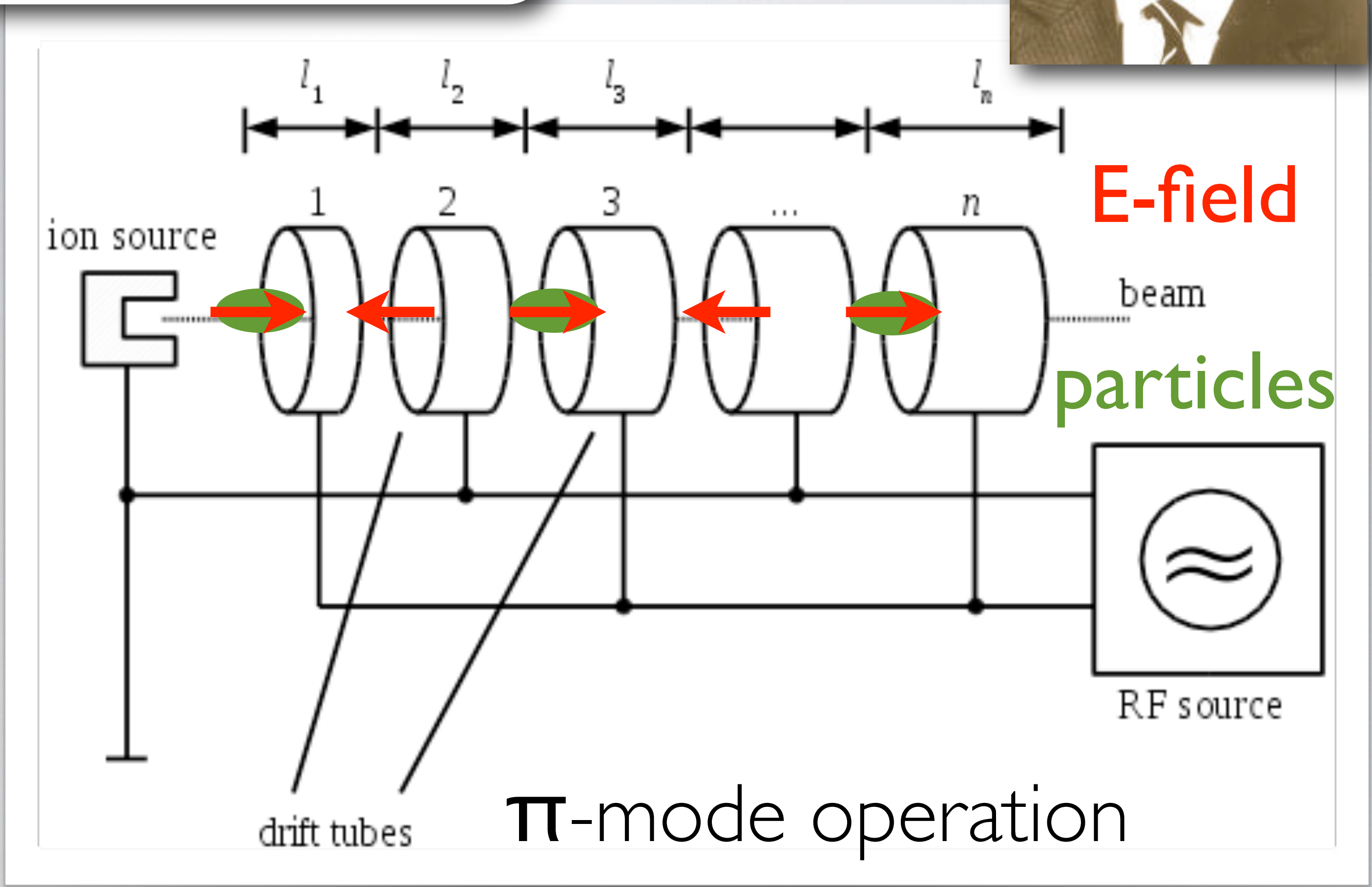


the RF phase changes by 180°, while the particles travel from one tube to the next

NOT YET A CAVITY: THE WIDERÖE LINAC (1927)

energy gain: $E = eN_{gap}V_{RF}$



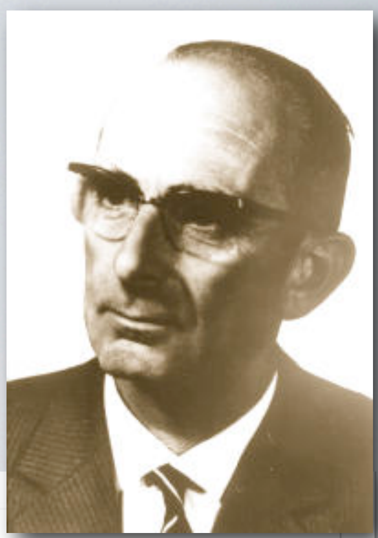


period length increases with velocity:

$$l = \frac{v}{2f}$$

the RF phase changes by 180°, while the particles travel from one tube to the next

NOT YET A CAVITY: THE WIDERÖE LINAC (1927)



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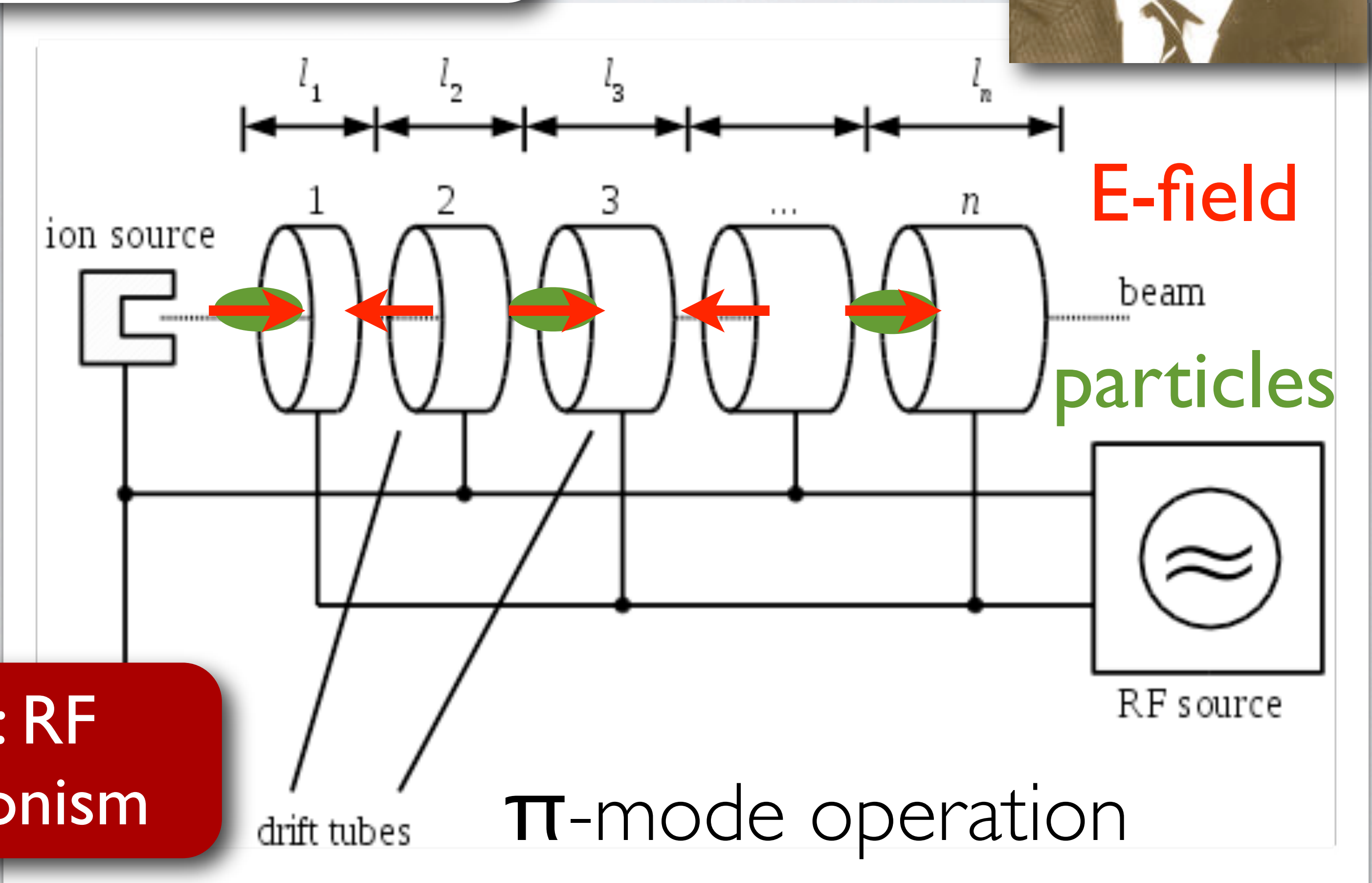


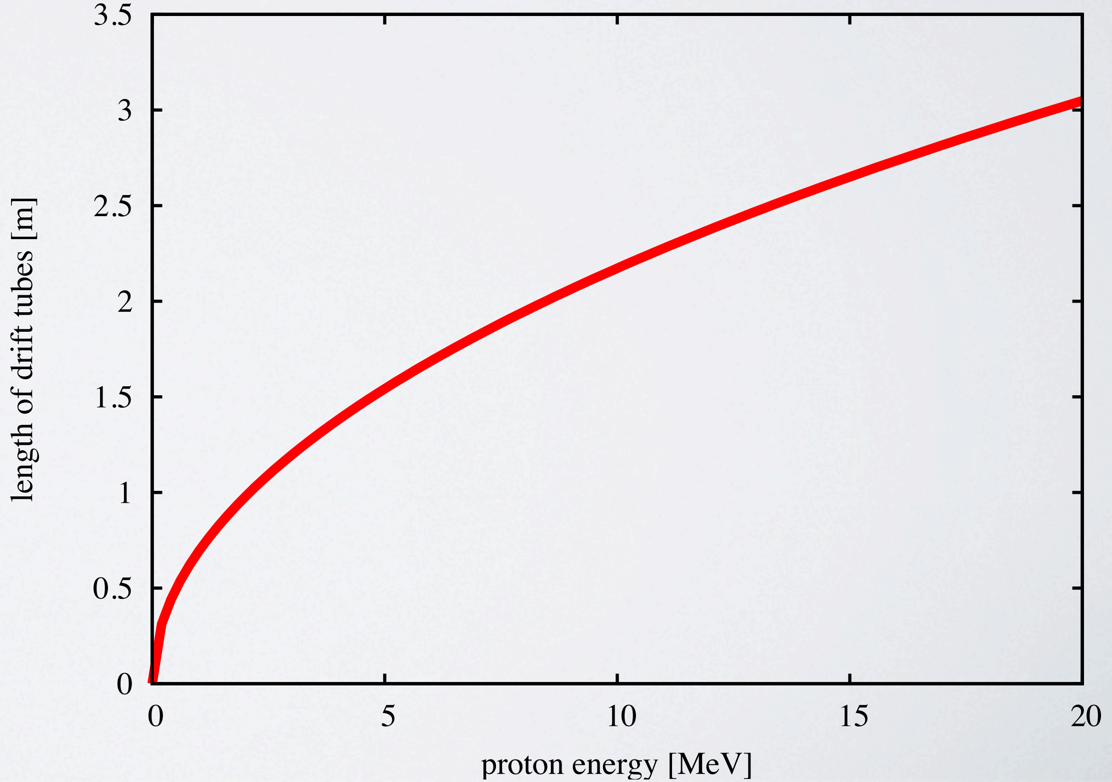
crucial technology: RF oscillators & synchronism

the RF phase changes by 180°, while the particles travel from one tube to the next

BUT:

- the Wideröe linac was only efficient for low-velocity particles (low-energy heavy ions),
- **higher frequencies (> 10 MHz) were not practical, because then the drift tubes would act more like antennas and radiate energy instead of using it for acceleration**,
- when using low frequencies, the length of the drift tubes becomes prohibitive for high-energy protons:

e.g. 10 MHz proton acceleration

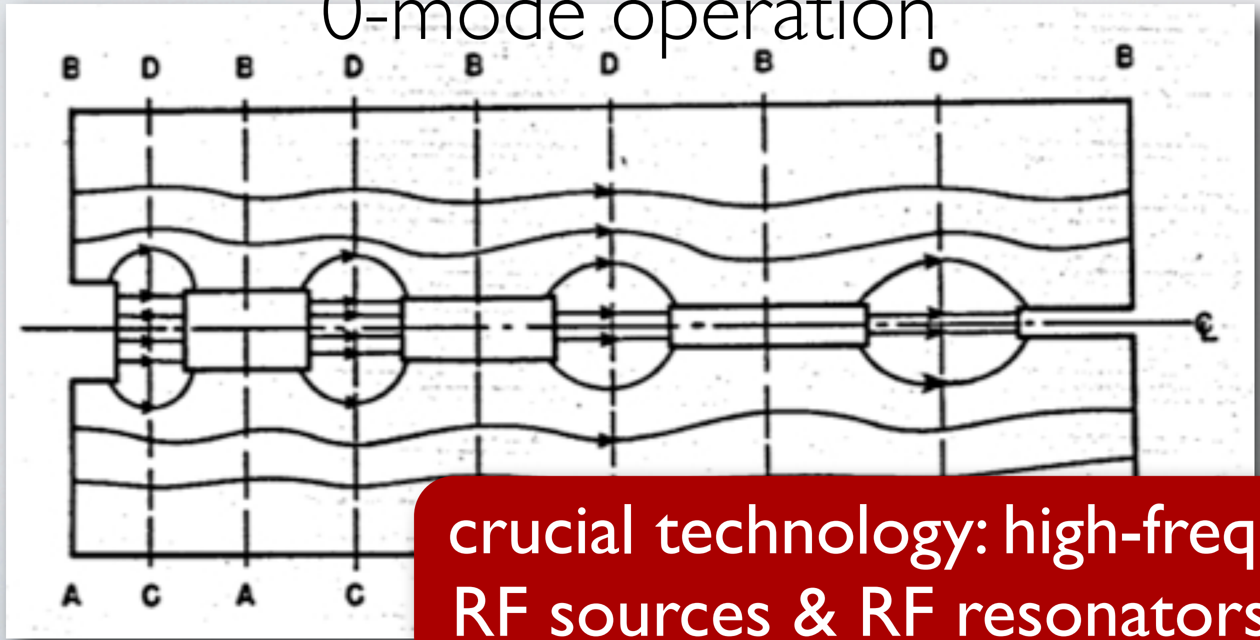


TRANSFORMING THE WIDERÖE LINAC INTO AN **RF CAVITY**: THE ALVAREZ LINAC (1946)

after WW2 high-power high-frequency RF sources became available (radar technology):

most old linacs operate at 200 MHz!

0-mode operation

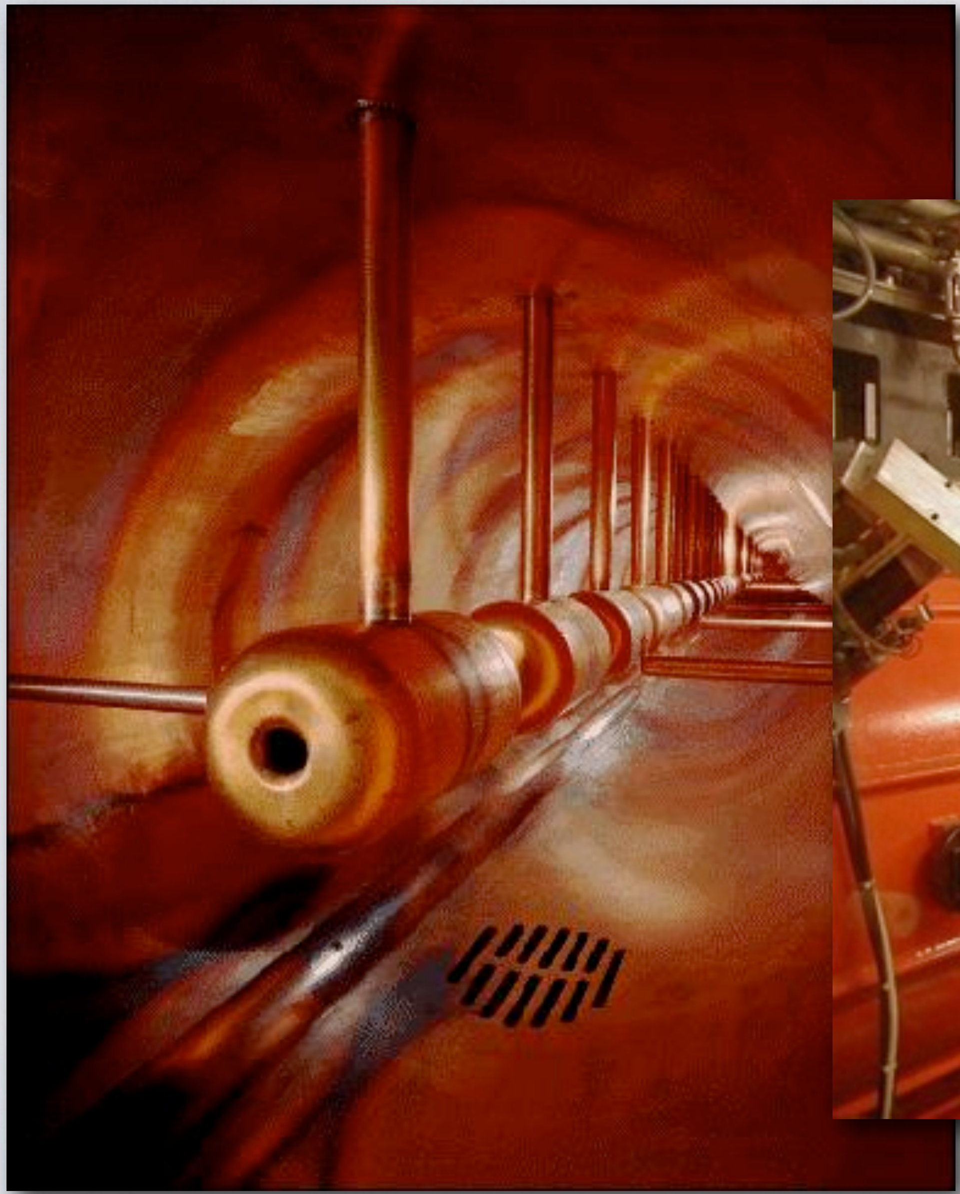


crucial technology: high-freq. RF sources & RF resonators

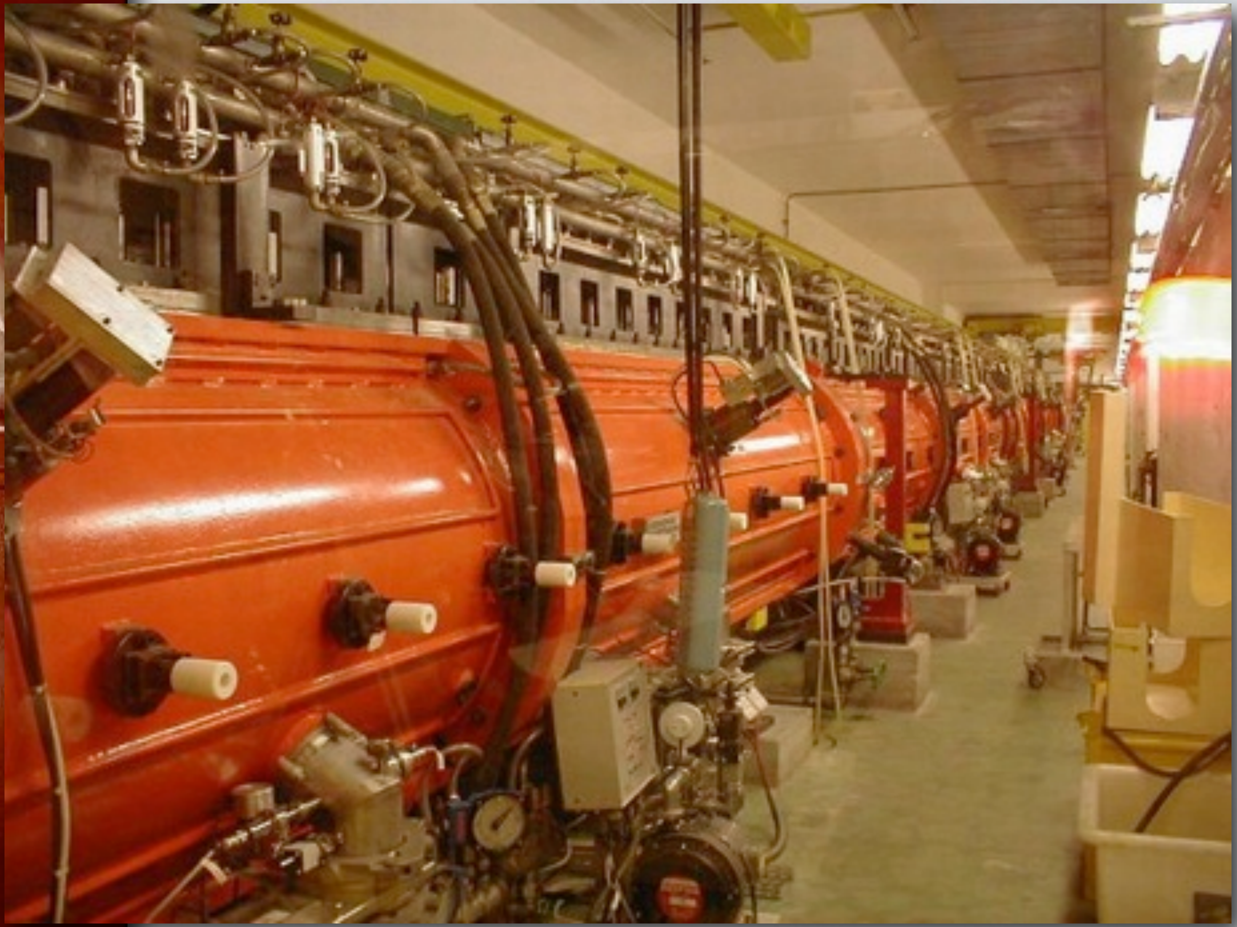
the RF field was enclosed in a box: RF resonator

While the electric fields point in the "wrong direction" the particles are shielded by the drift tubes.

inside a drift tube linac



Linac2 at CERN, 50 MeV



BACK TO BASICS

from a waveguide to RF cavities

WAVE PROPAGATION IN A CYLINDRICAL PIPE

Maxwells equations

$$\begin{aligned}\nabla \times \mathbf{H} &= \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}\\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t}\\ \nabla \cdot \mathbf{D} &= q_v\\ \nabla \cdot \mathbf{B} &= 0\end{aligned}$$

solved in cylindrical coordinates for the simplest mode with E-field on axis: TM01

$$\begin{aligned}E_z &= E_0 J_o(k_c r) e^{-jk_z z} e^{j\omega t}\\ E_r &= j\frac{k_z}{k_c} E_0 J_1(k_c r) e^{-jk_z z} e^{j\omega t}\\ H_\phi &= j\frac{k}{Z_0 k_c} E_o J_1(k_c r) e^{-jk_z z} e^{j\omega t}\end{aligned}$$

propagation constant: $k_z^2 = k^2 - k_c^2$

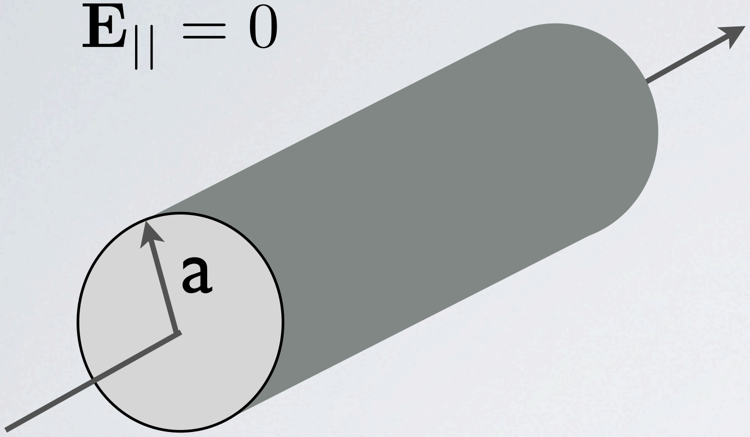
cut-off wave number: $k_c = \frac{2\pi}{\lambda_c} = \frac{\omega_c}{c}$

wave number:

$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$$

+ boundary conditions on a metallic cylindrical pipe: $E_{tangential}=0$

$\mathbf{E}_{||} = 0$



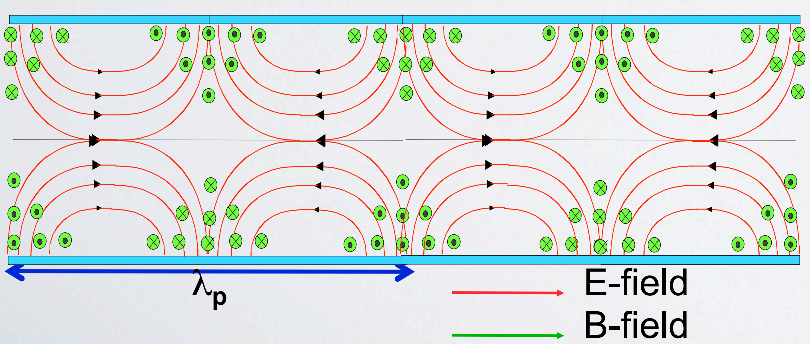
cut-off wavelength in a cylindrical wave-guide (TM_{01} mode)

$$\lambda_c = 2.61 \cdot a$$

- TM_{01} waves propagate for: $\omega > \omega_c$
- and are exponentially damped for: $\omega < \omega_c$
- the phase velocity is: $v_{ph} = \frac{\omega}{k_z}$

propagation constant: $k_z^2 = k^2 - k_c^2$

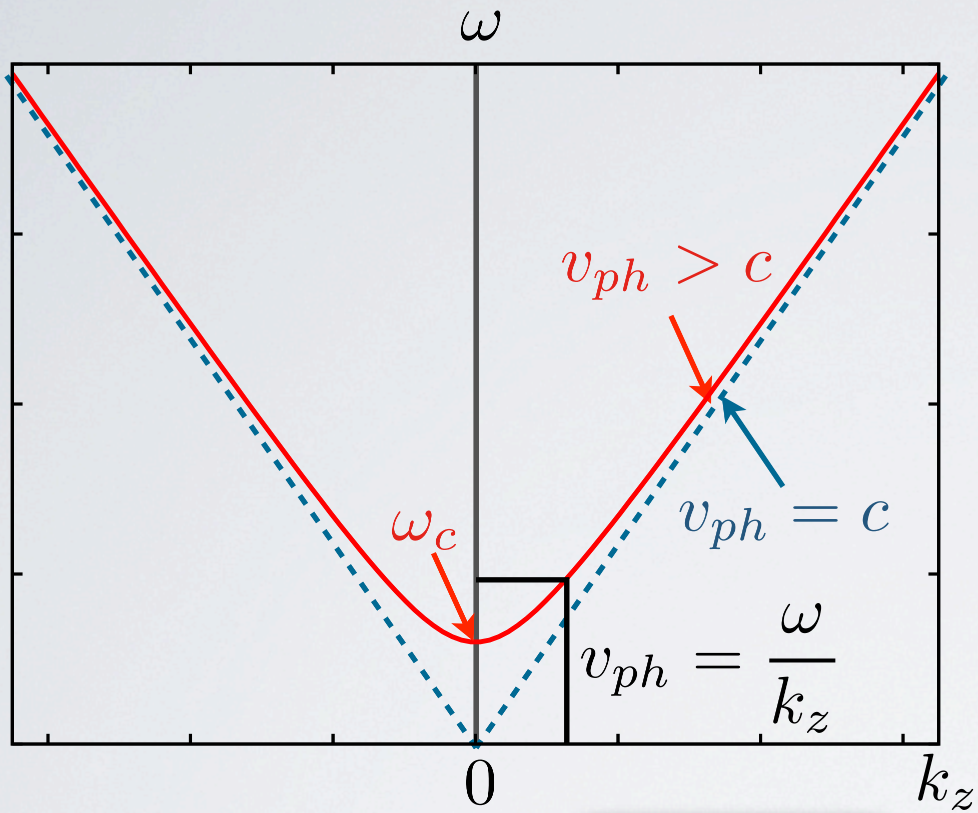
TM01 field configuration



$$k_z^2 = \frac{\omega^2}{v_{ph}^2} = \frac{\omega^2}{c^2} - \frac{\omega_c^2}{c^2}$$

dispersion relation

Brioullin diagram (dispersion relation)



group velocity: $v_{gr} = \frac{d\omega}{dk_z}$

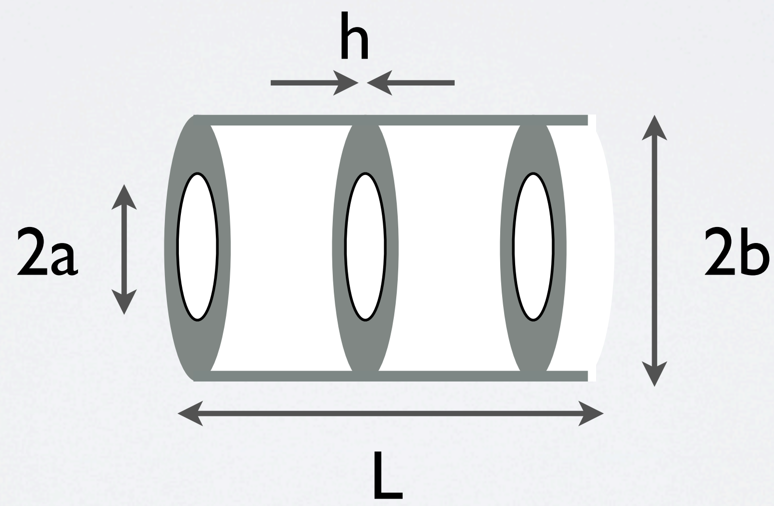
phase velocity: $v_{ph} = \frac{\omega}{k_z}$

- no waves propagate below the cut-off frequency, which depends on the radius of the cylinder,
- each frequency corresponds to a certain phase velocity,
- the phase velocity is always larger than c! (at $\omega=\omega_c$: $k_z=0$ and $v_{ph}=\infty$), $v_{ph}^2 = c^2 \frac{\omega^2}{\omega^2 - \omega_c^2}$
- synchronism with RF (necessary for acceleration) is impossible because a particle would have to travel at $v=v_{ph}>c$!
- energy (and therefore information) travels at the group velocity $v_{gr}<c$,

We need to slow down the phase velocity!

We need to slow down the phase velocity!

put some obstacles into the wave-guide: e.g: discs



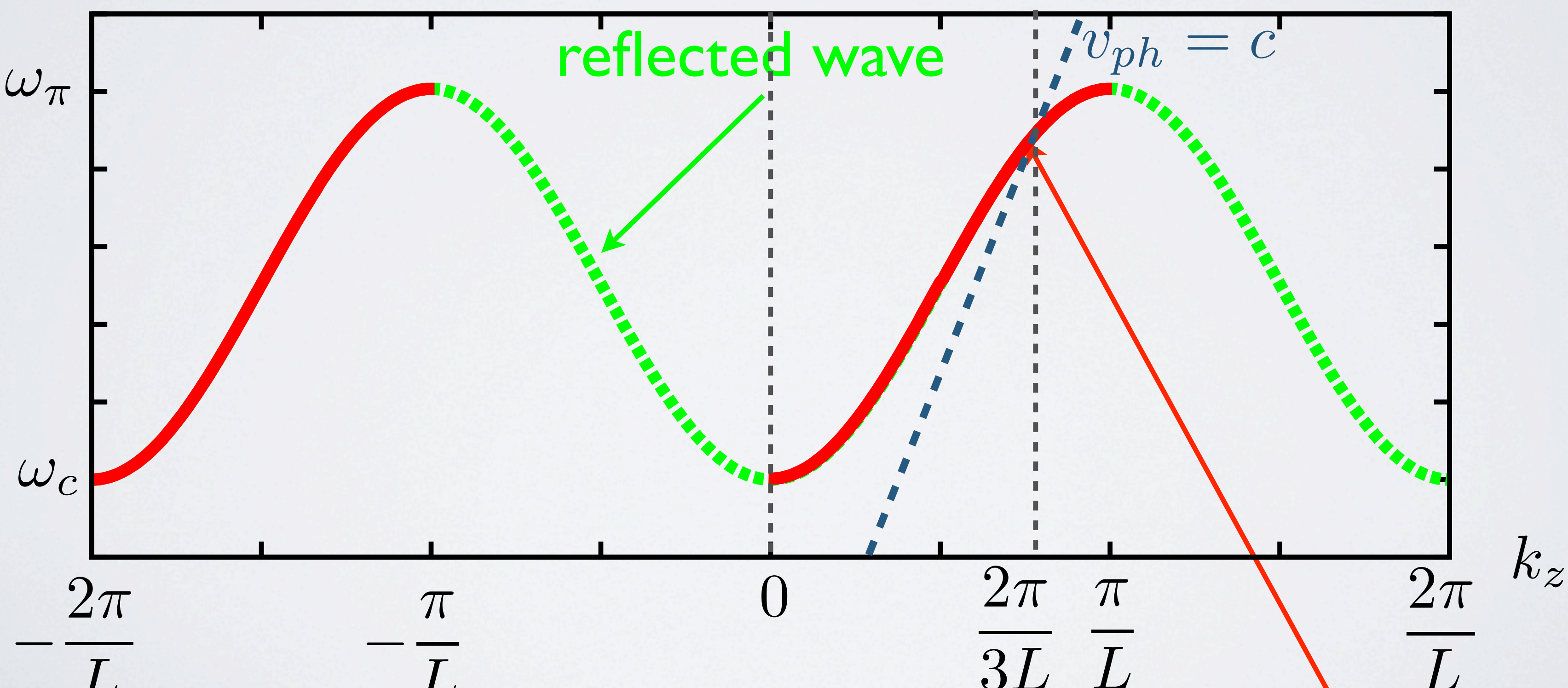
Dispersion relation for disc loaded travelling wave structures:

$$\omega = \frac{2.405c}{b}\sqrt{1+\kappa(1-\cos(k_z L)e^{-\alpha h})}$$

$$\kappa = \frac{4a^3}{3\pi J_1^2(2.405)b^2 L} \ll 1$$

damping: $\alpha \approx \frac{2.405}{a}$

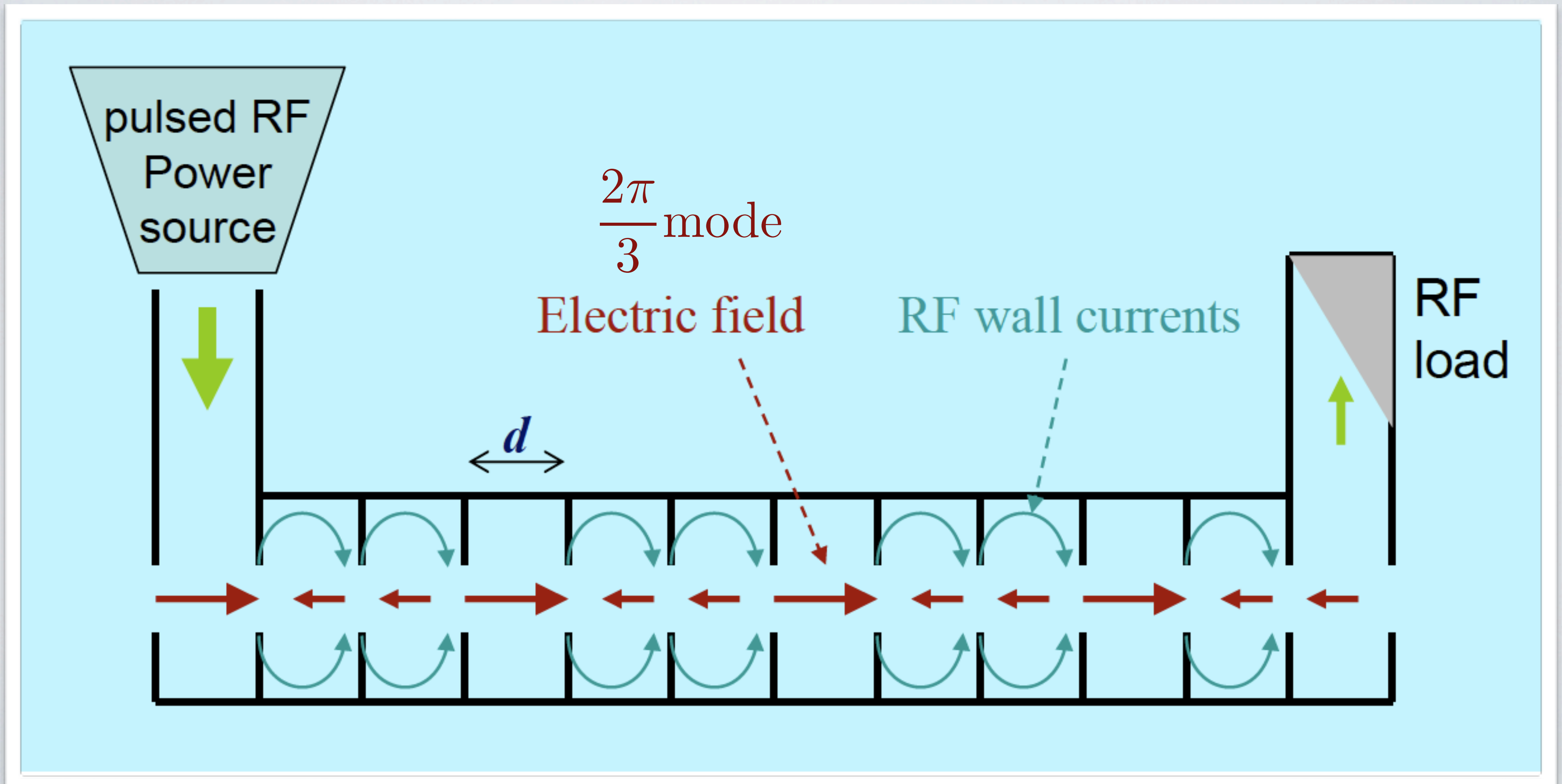
Brioullin diagram



structure with: $v_{ph}=c$ at $k_z= 2\pi/3$ (SLAC/LEP injector)

Example of a 2/3 travelling wave structure

synchronism condition: $d = \frac{(\beta)\lambda}{3}$ with $\beta \approx 1$

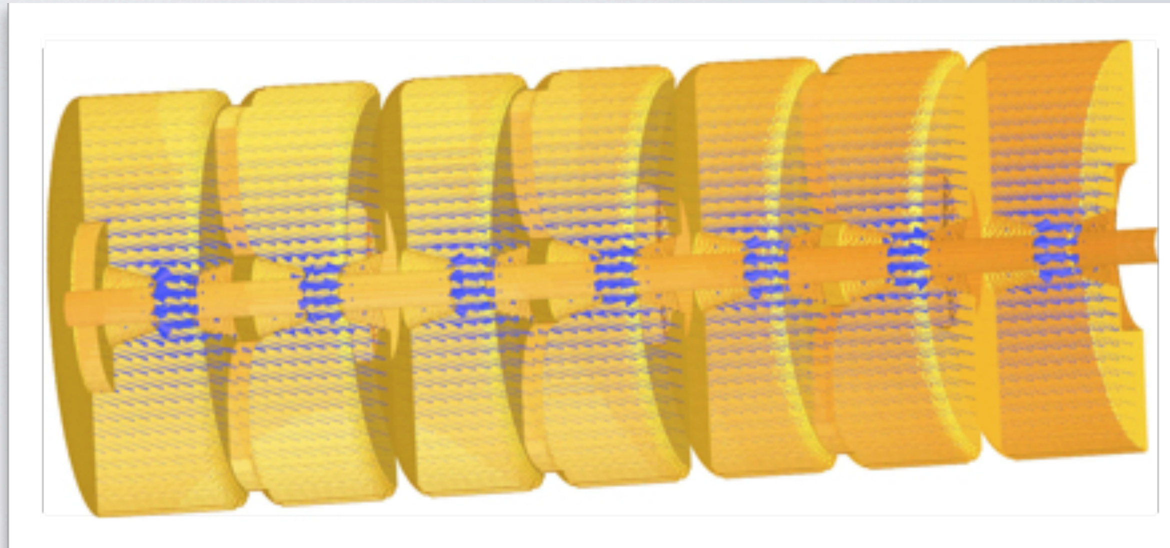


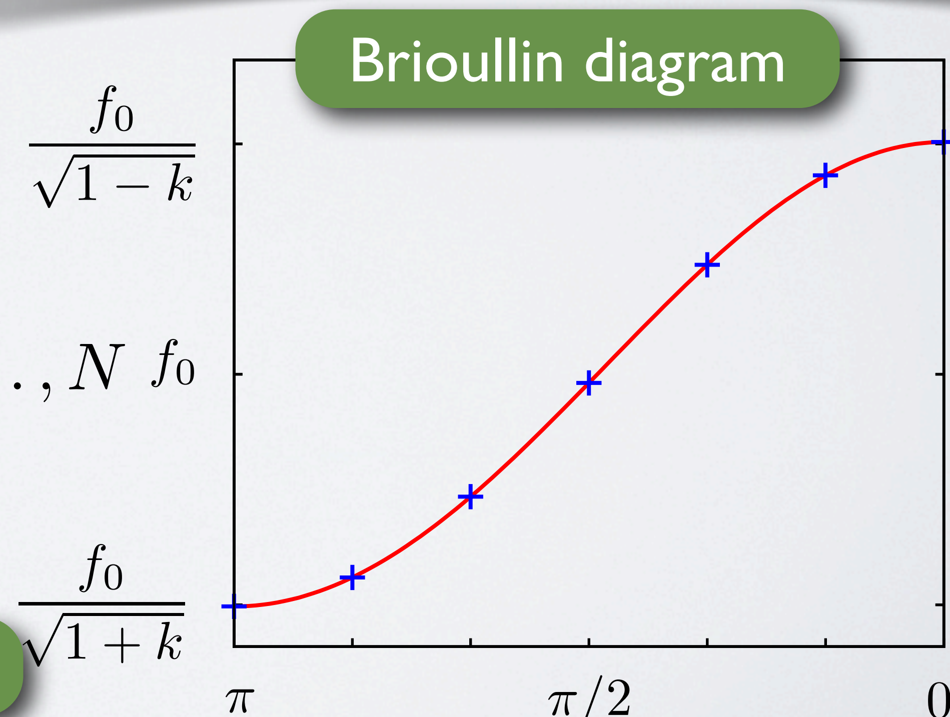
TRAVELLING WAVE STRUCTURES

- Since the particles gain energy the EM-wave is damped along the structure (“**constant impedance structure**”). But by changing the bore diameter one can decrease the group velocity from cell to cell and obtain a **“constant-gradient”** structure. Here one can operate in all cells near the break-down limit and thus achieve a higher average energy gain.
- Travelling wave structures are often used for very short (us) pulses, and can reach high efficiencies, and high accelerating gradients (up to 100 MeV/m, CLIC).
- are generally used for electrons at $\beta \approx 1$,
- difficult to use for ions with $\beta < 1$: i) constant cell length does not allow for synchronism, ii) long structures do not allow for sufficient transverse focusing,

STANDING WAVE

- Closing of the walls on both sides of the waveguide or disc-loaded structure yields multiple reflections of the waves.
- After a certain time (the filling time of the cavity) a standing wave pattern is established.
- Due to the boundary conditions only certain modes with distinct frequencies are possible in this resonator.
- The mode names (0, ..,**π**/2, .., **π**) correspond to the phase difference between the modes.





$$n = 0, 1, \ldots, N$$

$$f_n = \frac{f_0}{\sqrt{1 - k\cos(n\pi/N)}}$$

dispersion relation (magn. coupl.)

TRAVELLING WAVE VS. STANDING WAVE

- TW structures are filled with power "in space": the power fills one cell after another with typically 1-3% of *c* (<μs, depending on f).

- SW structures are filled "in time": the reflected waves build up in time until the final standing wave pattern is achieved at the desired amplitude: (~10 μs range for NC, depending on f).

- for very short beam pulses (< μs), there is a clear power efficiency advantage for TW structures, for longer pulses (μs range) both structure types can be optimised to similar efficiencies and cost. Depending on the specific parameters SW structures can be more cost efficient from the μs range onwards.

- Due to the extremely short RF pulse lengths, TW can typically sustain much higher peak fields than any SW structure (CLIC advantage over ILC).

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- Due to the extremely short RF pulse lengths, TW can typically sustain much higher peak fields than any SW structure (CLIC advantage over ILC).

do the optimisation + cost exercise for your specific application!!

TRAVELLING WAVE VS. STANDING WAVE

two excellent comparisons between SW and TW:

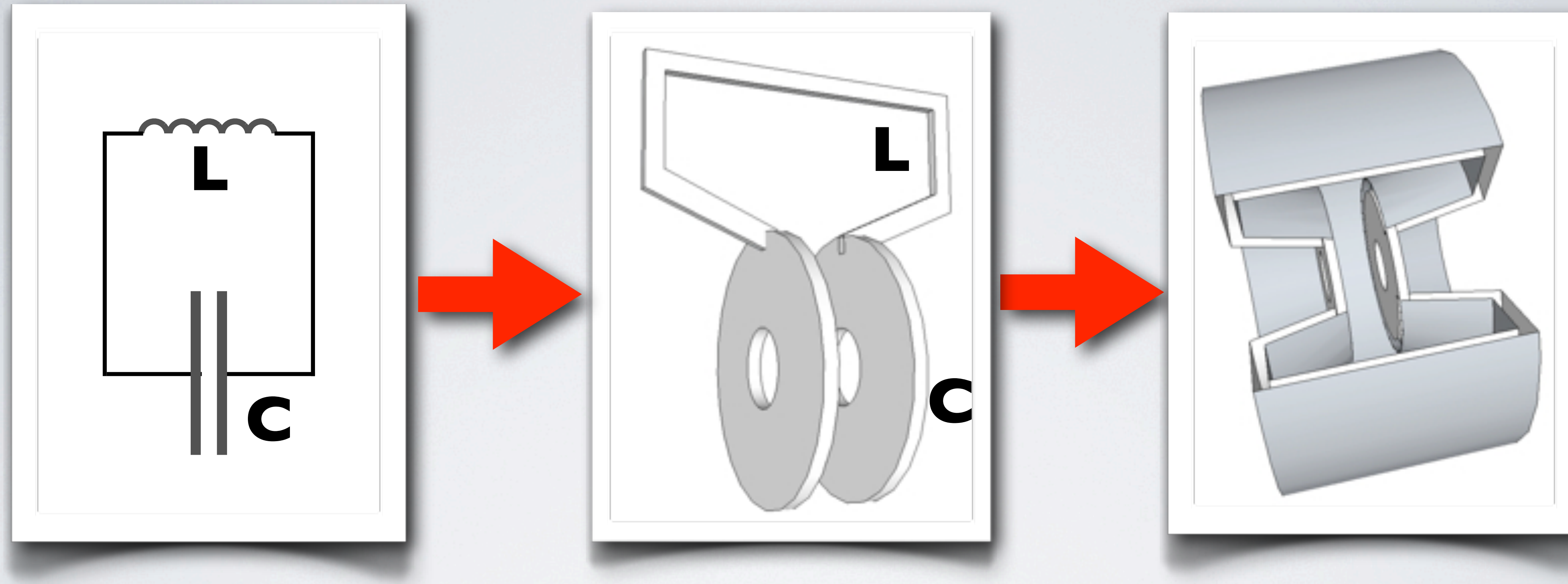
“Comparison of Standing Wave and Traveling Wave Structures”, Roger H. Miller (SLAC), LINAC86

“Comparison of Standing and Traveling Wave Operations for a Positron Pre-Accelerator in the TESLA Linear Collider”, V.A. Moiseev, V.V. Paramonov (INR Moscow), K. Floettmann (DESY), EPAC 2000

BASIC CAVITY TYPES

classified by the electromagnetic modes

THE PILLBOX CAVITY



$$\omega_{res} = 2\pi f_{res} = 1/\sqrt{LC}$$

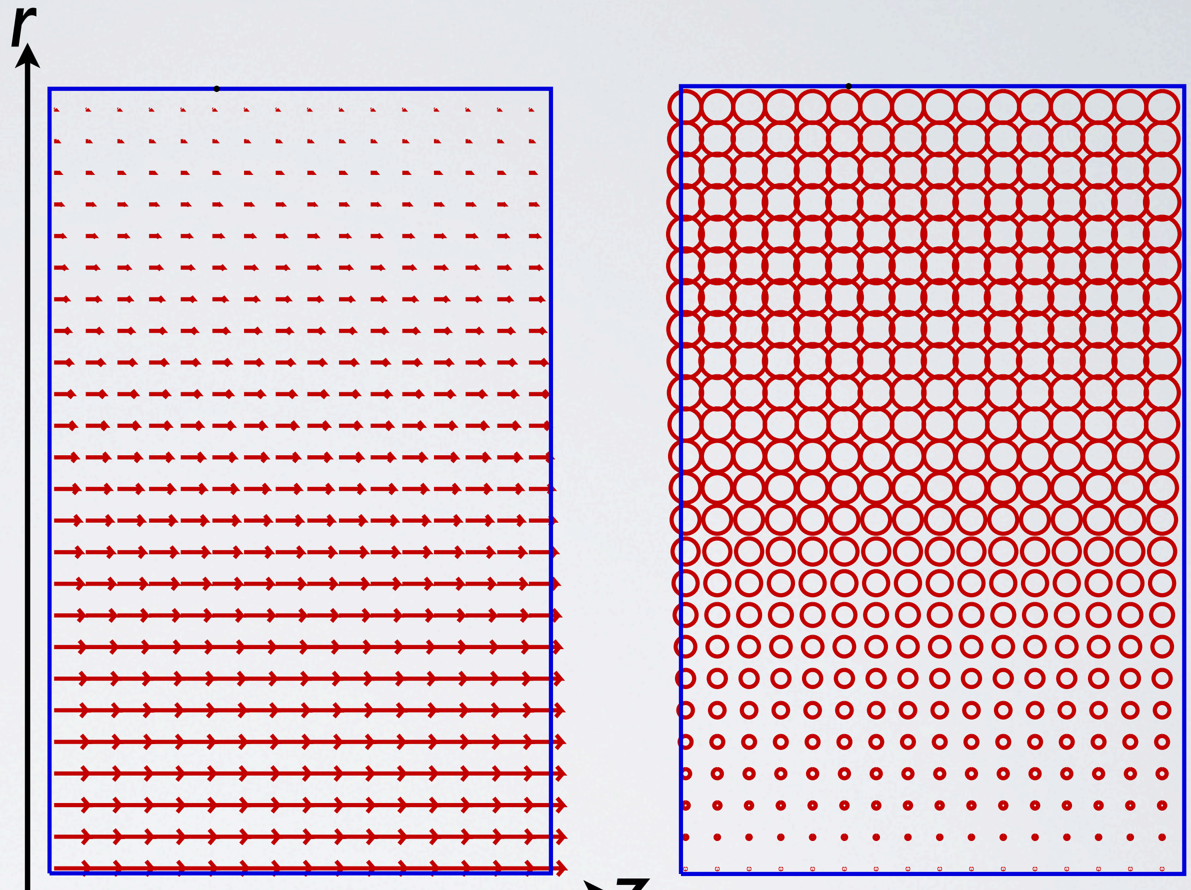
A lumped element resonator transformed into a pillbox cavity

IN THE SIMPLEST CASE...

...the pillbox cavity is just an empty cylinder:

- with longitudinal electric field and transverse magnetic fields: TM_{010} mode (ϕ,r,z),
- no field dependence on ***z and* ϕ**, frequency is determined by radius ***$r=R_{cav}$***:

$$\omega_c = k_r c = \frac{2.405 \cdot c}{R_{cav}}$$



electric fields

magnetic fields

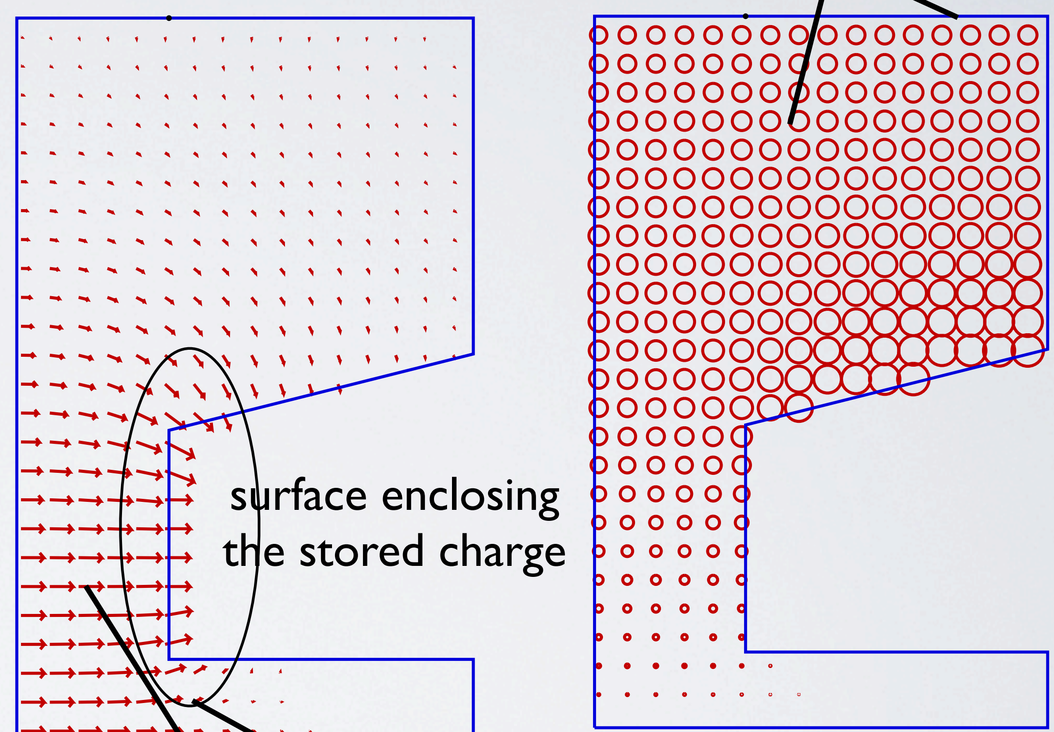
$$\begin{aligned} E_z &= E_0 J_0(k_r r)\cos(\omega t) \\ B_\phi &= -\frac{E_0}{c} J_1(k_r r)\sin(\omega t) \end{aligned}$$

see: A. Wolski “Theory of EM fields”

THE PILLBOX CAVITY: **A TM-MODE CAVITY**

$$L = \frac{\phi}{I} = \frac{\oint_s \vec{B} \cdot d\vec{S}}{\oint_l \vec{H} \cdot d\vec{l}}$$

- usually *C* is increased to concentrate the electric field lines along the axis,
- diameter of the cavities is in the order of λ/2, which makes them suitable for frequencies >100 MHz - GHz range,
- exist as single/multi-cell, normal/superconducting,
- usually fixed frequency,



$$C = \frac{Q}{V} = \frac{\varepsilon \oint \vec{E} \cdot d\vec{S}}{\int \vec{E} \cdot d\vec{s}}$$

line integral along axis

$$\omega_{res} = 2\pi f_{res} = 1/\sqrt{LC}$$

NOMENCLATURE OF MODES

TM_{mnp}-mode = E_{mnp}-mode → E-field parallel to axis, B_z =0, only transverse magn. (TM) components

TE_{mnp}-mode = H_{mnp}-mode → B-field parallel to axis, E_z =0, only transverse el. (TE) components

- number of full-period variations of the field components in the azimuthal-direction

$$\mathbf{E} \text{ or } \mathbf{B} \propto \cos(m\phi) \text{ or } \sin(m\phi)$$

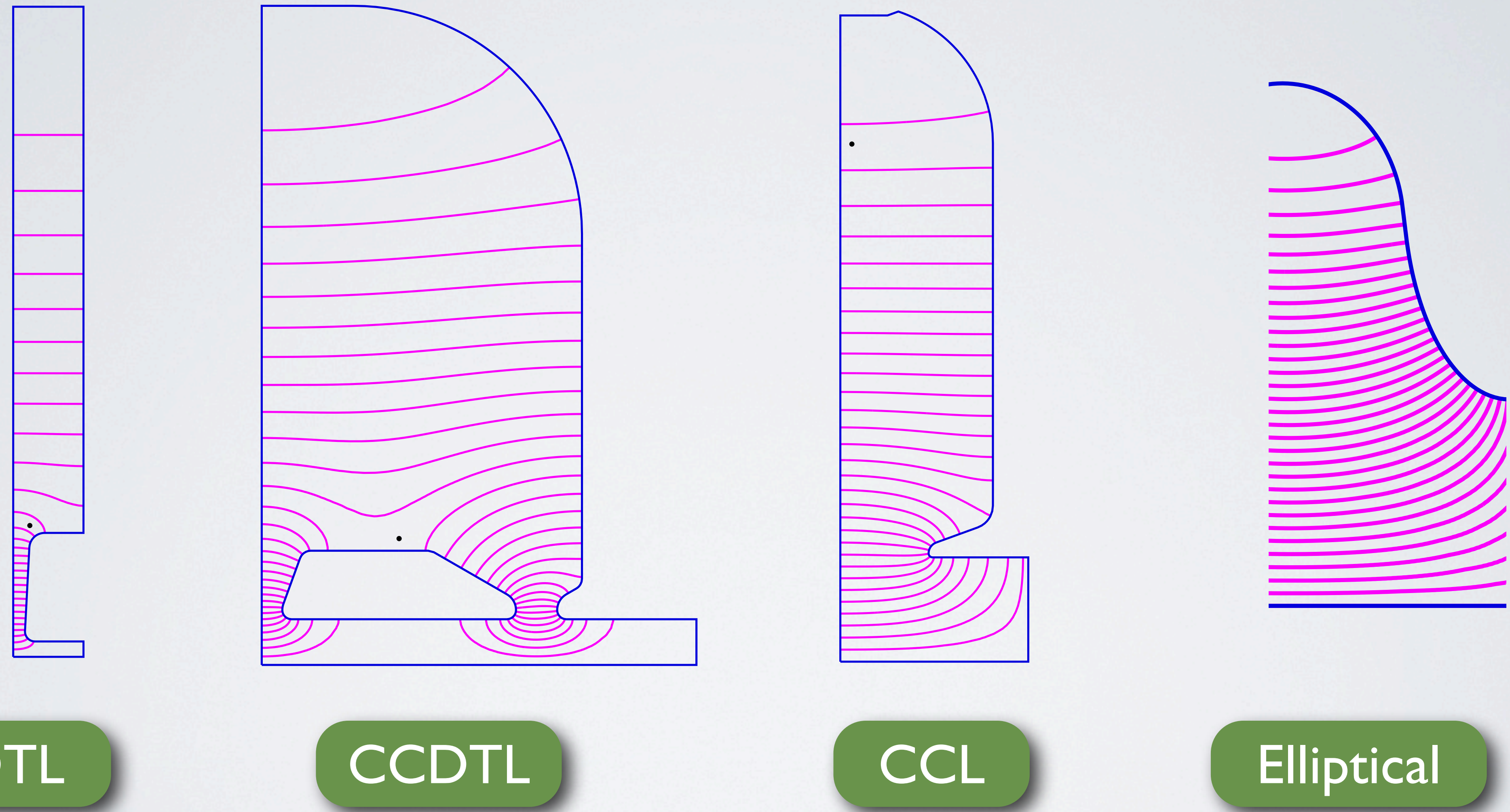
- number of zeros of the axial field component in radial direction.

$$E_z \text{ or } B_z \propto J_m(x_{mn} r/R_c)$$

- number of half-period variations of the field components in the longitudinal-direction

$$\mathbf{E} \text{ or } \mathbf{B} \propto \cos(p\pi z/l) \text{ or } \sin(p\pi z/l)$$

EXAMPLES OF TM-MODE CAVITIES:



more in: "Low-Beta Cavities", M.Vretenar

TE-MODE (H-MODE) CAVITIES

high shunt impedance at low energies...

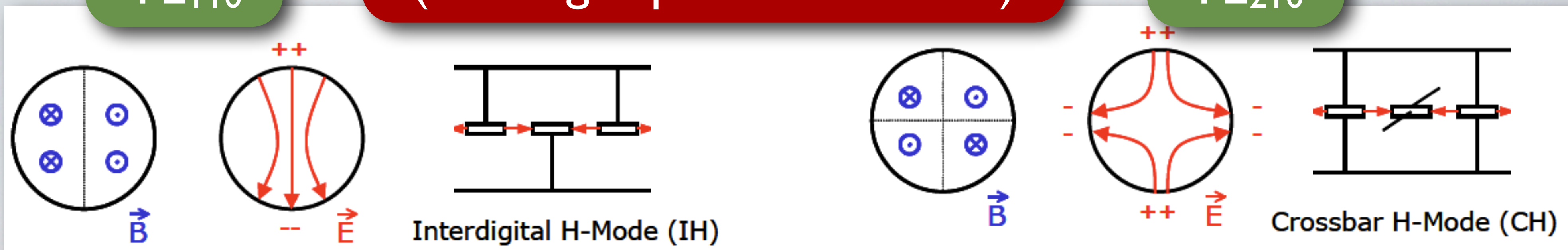
... or how to accelerate with a non-accelerating mode

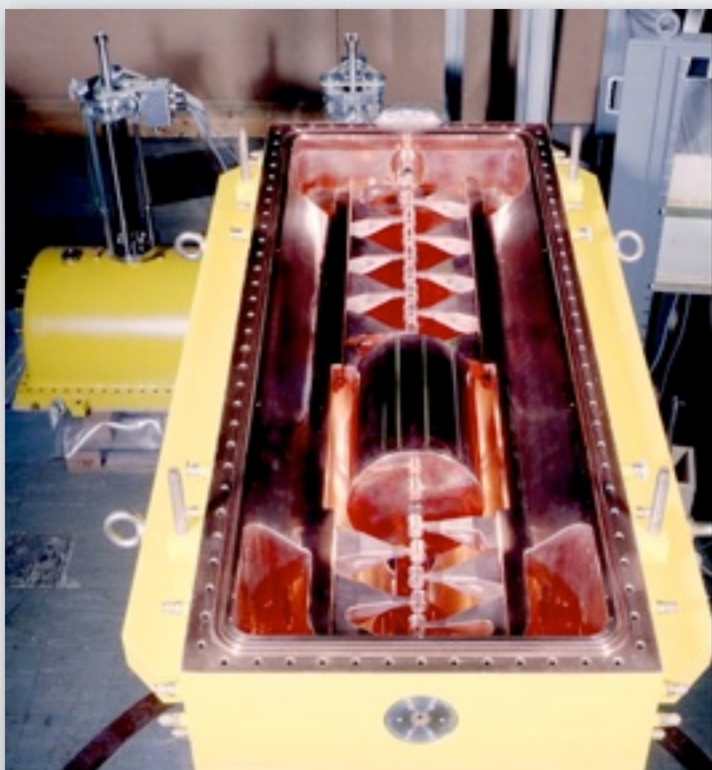
TE-MODE STRUCTURES

TE_{110}

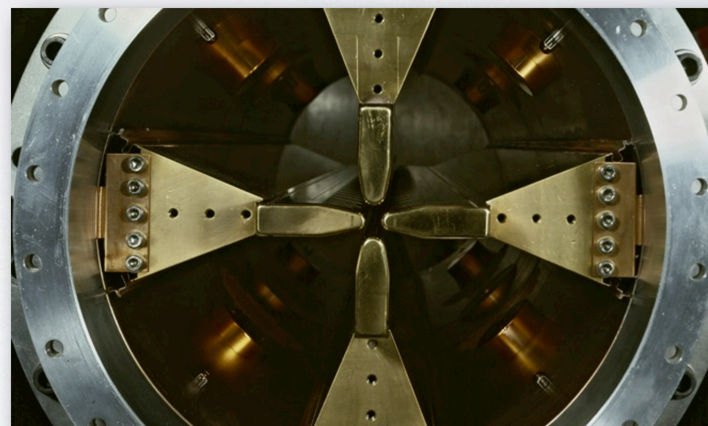
(no longer pure TE cavities!)

TE_{210}



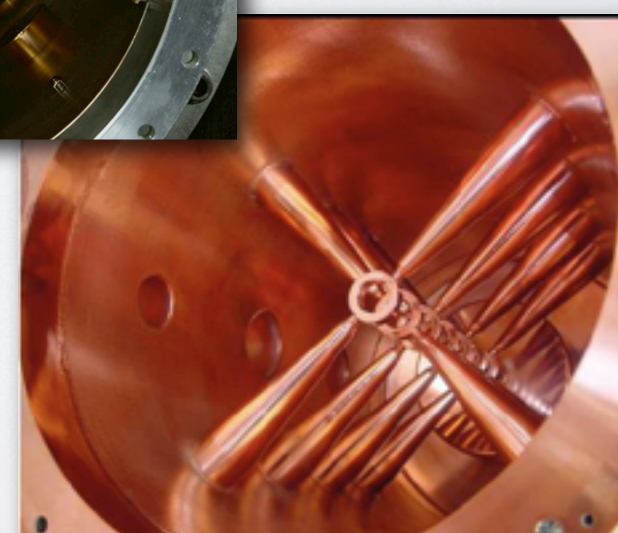


REX IH cavity at CERN/ISOLDE



RFQ

CH-DTL

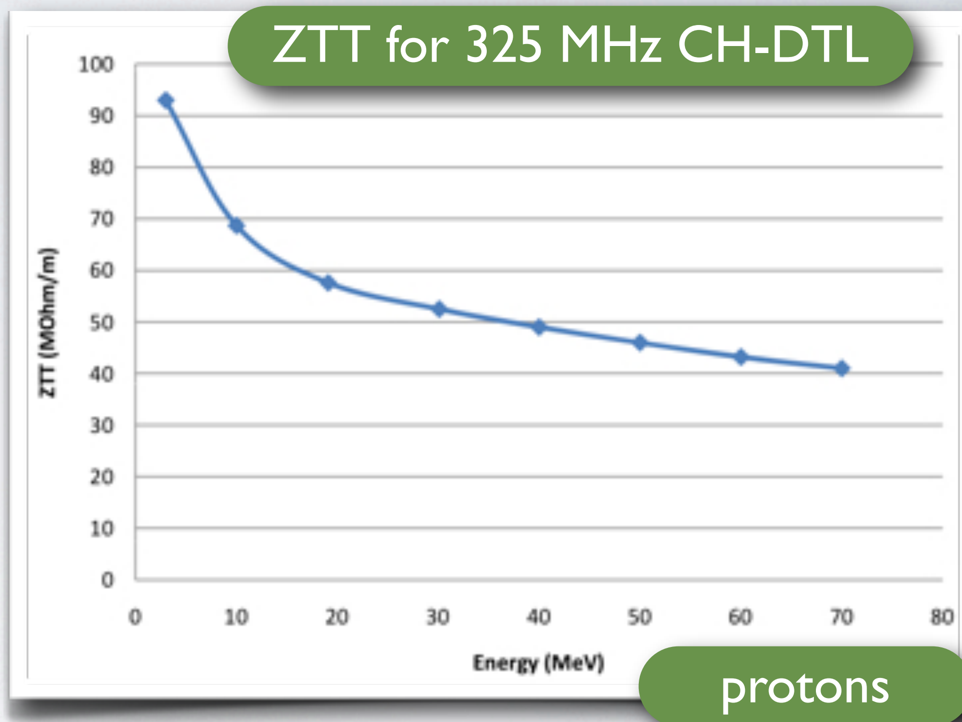


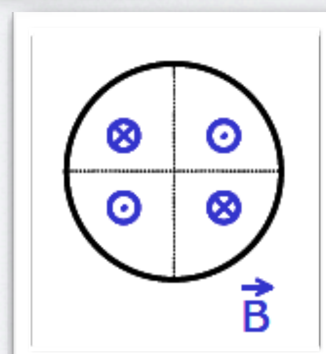
material from: *A. Bechtold, HIPPI meeting, CERN 10/2008*

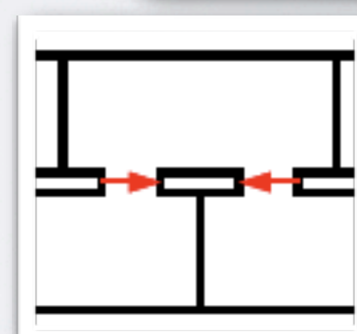
HOW (AND WHY) TO ACCELERATE WITH TRANSVERSE ELECTRIC FIELDS?

- TE-Modes have less magnetic fields on the inner cavity surface -> lower losses -> higher shunt impedance (at low energies)!

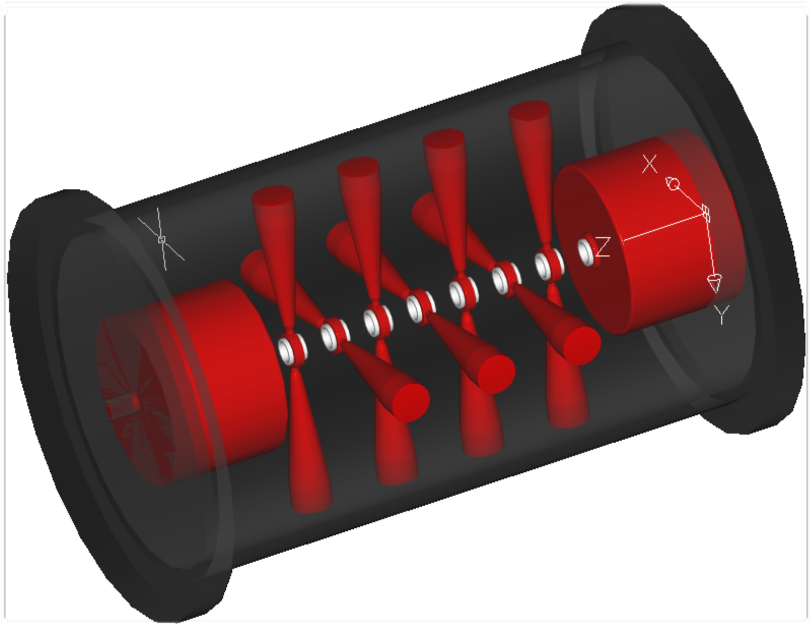
- But you need to bend the electric field onto the axis -> at the cavity end walls no axial field is allowed, which complicates the end-cell design-> most efficient for large number of cells between focusing elements or when used with integrated focusing (e.g. PMQs, see Kurennoy, Rybarcyk, Wangler PAC07).







EXAMPLE: CH-DTL



Design example from Frankfurt University (Clemente, HB 2008)

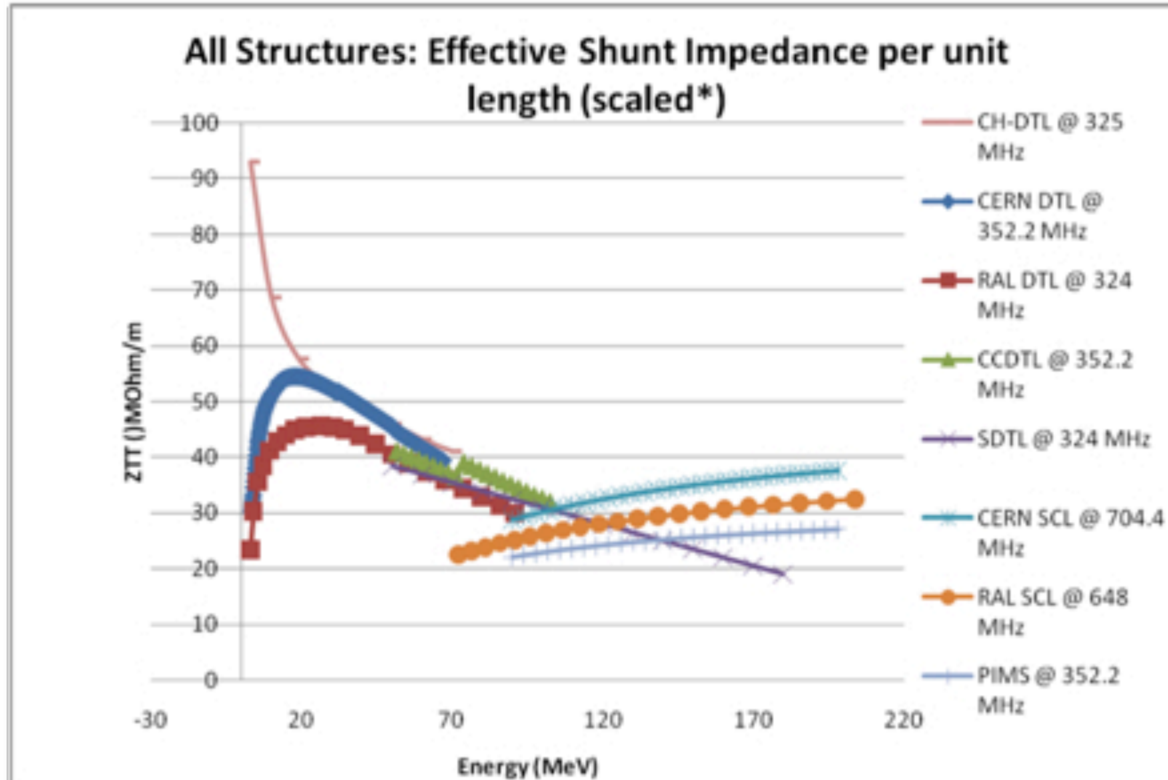


Figure 17. Effective Shunt Impedance per unit length for all structures.

* Calculated ZTT values scaled down to take into account additional losses. The following factors have been used:

DTL – a 20% reduction which doesn't include the contribution of the post-couplers.

CH-DTL – simulations in good agreement with measurements .A 5% reduction has been used.

CCDTL – a 17% reduction.

SCL – a 20% reduction.

PIMS – a 30% reduction.

Shunt impedance comparison for various structures (CARE-report-08-071-HIPPI)

TEM-MODE CAVITIES

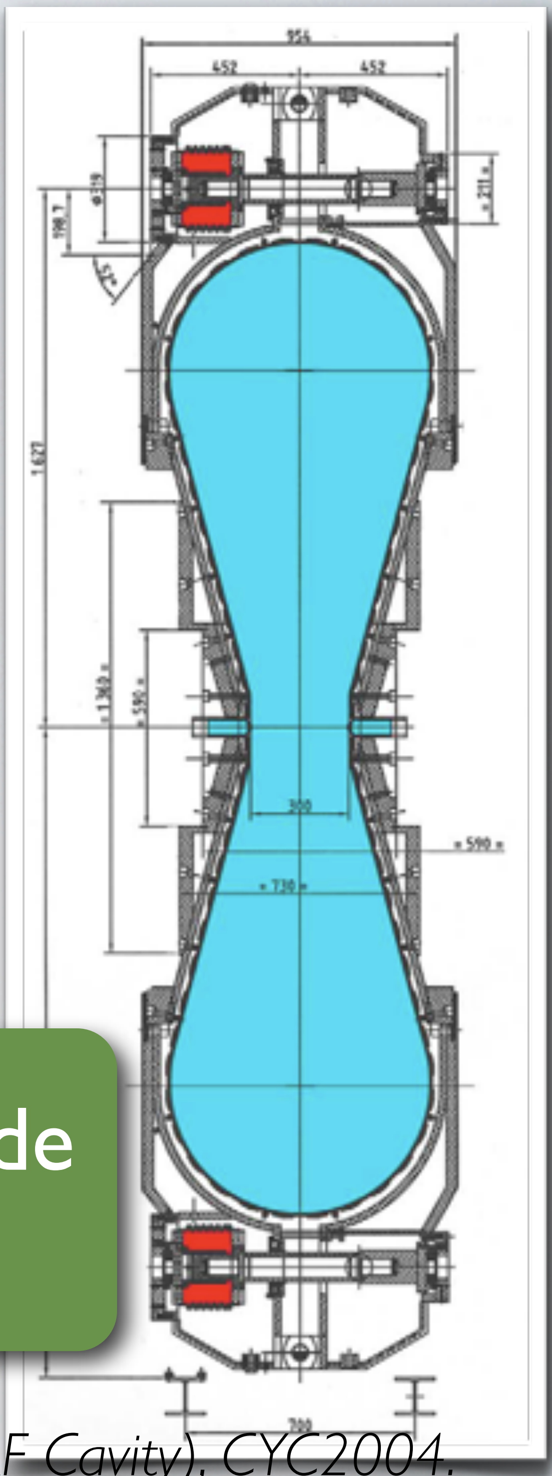
neither electric nor magnetic fields on axis?

- TE and TM mode cavities are ideal for frequencies in the several 100 MHz range.
- For lower frequencies the cavity dimensions become excessively large.
- Lower frequencies are often needed for synchrotrons (MHz-range), even combined with the ability to change the frequency as the particles gain speed in successive turns, the main challenge is not he gradient, but compactness and fast frequency tuning.
- Due to their low speed heavy ion linacs often use low frequencies (<100 MHz), which forbid TE/TM mode type cavities.

an exception:

CYCLOTRON CAVITY (E.G: PSI UPGRADE IN 2004)

parameter	value
frequency	50.6 MHz
V_{acc}	1 MV
P_{diss}	500 kW
E_{acc}	~1.7 MV/m
size	5.6x3.9x0.95 m



TM-mode cavity

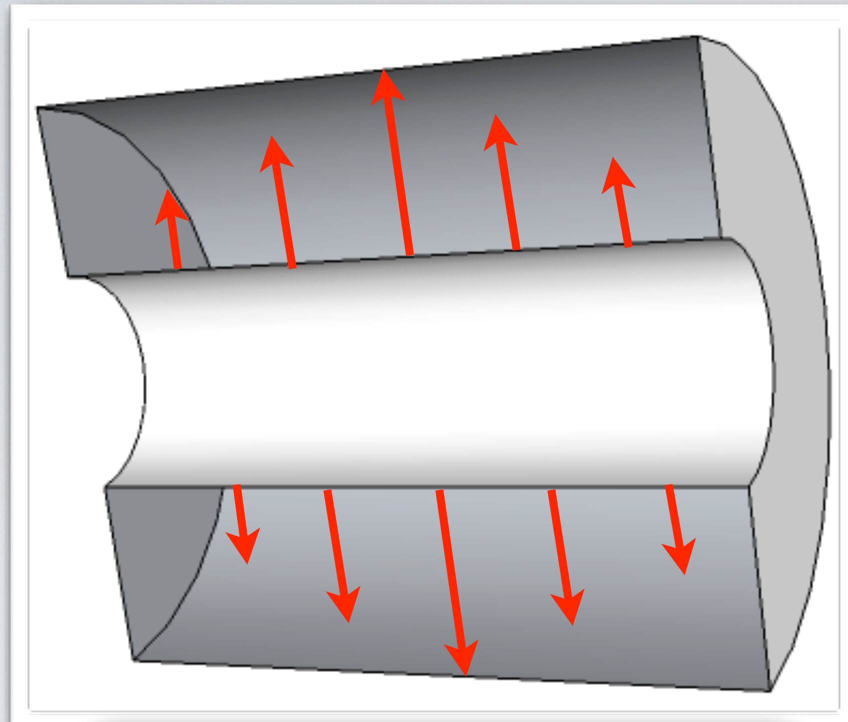
from: *H. Fitze et al: Developments at PSI (including new RF Cavity), CYC2004.*

completed cavity: 25 tons!

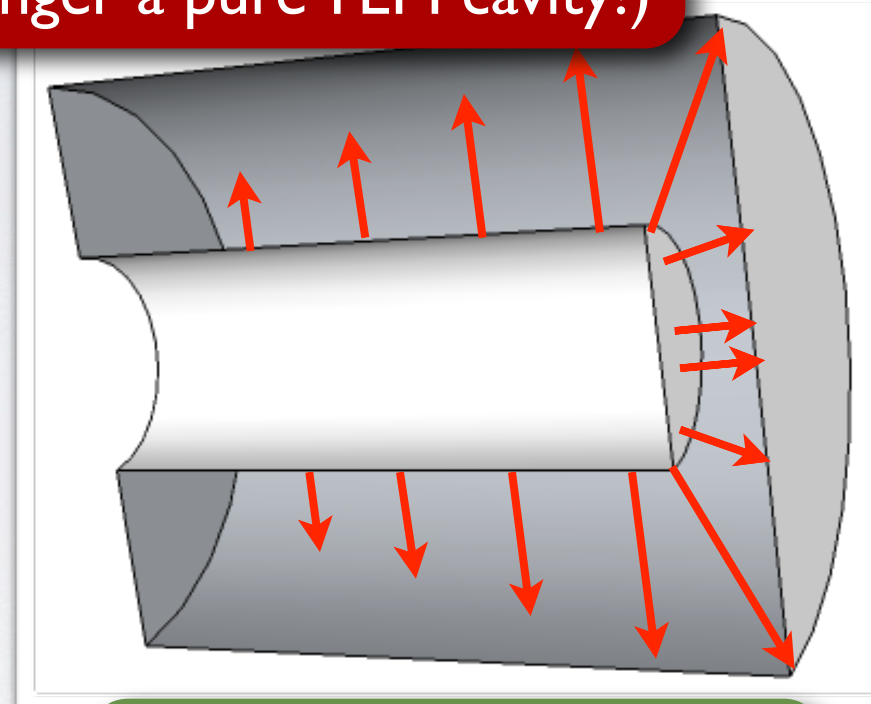
from: *H. Fitze et al: Developments at PSI (including new RF Cavity), CYC2004.*

TEM-MODE CAVITIES

(no longer a pure TEM cavity!)



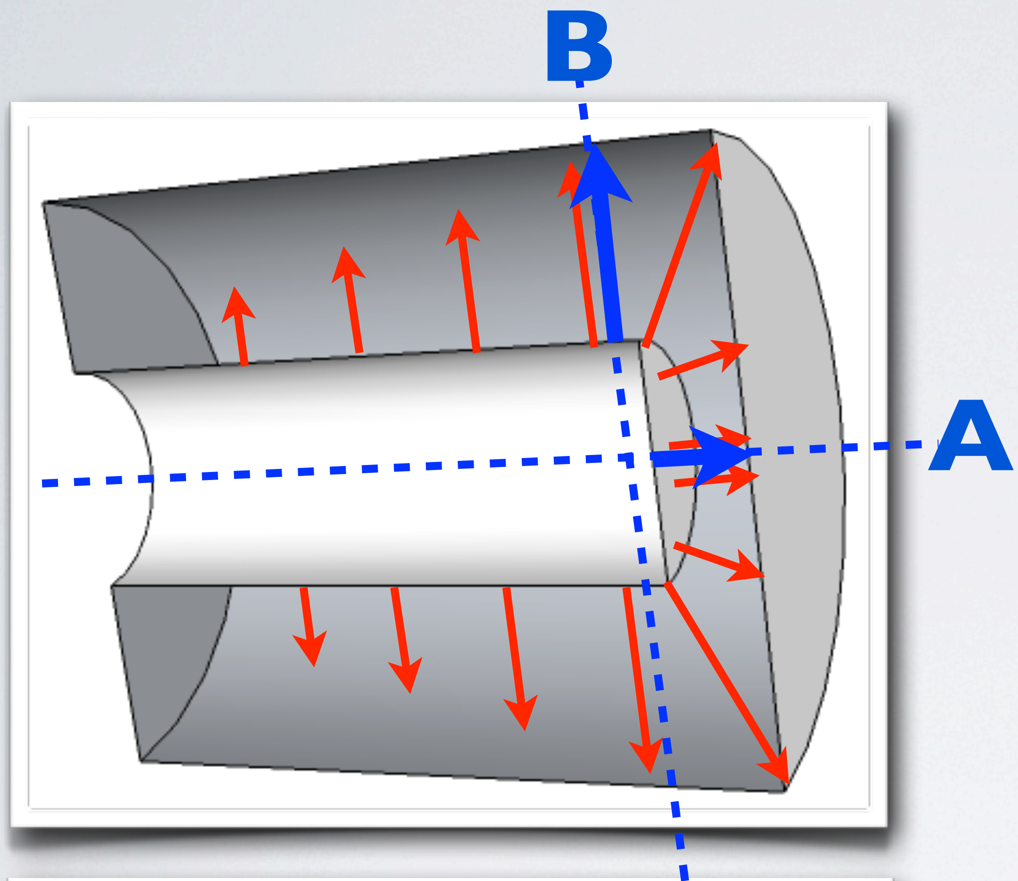
coaxial resonator, e.g: 1/2-wave



"coaxial" 1/4-wave cavity

- the frequency is now determined by the longitudinal dimensions and no longer by the transverse dimensions,
- the electric field is bent on axis, such that it can accelerate charged particles

1/4 WAVE RESONATOR (QWR)



Along path B:

- often found in low-frequency ion accelerators (NC and SC),
- tighter synchronisation between RF frequency and particle passage

Along path A:

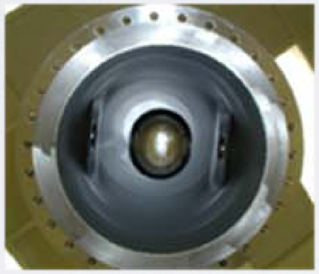
- typical synchrotron cavity

EXAMPLES OF QWRS

A. Facco, Low and intermediate β cavity design, SRF 2009

TRIUMF

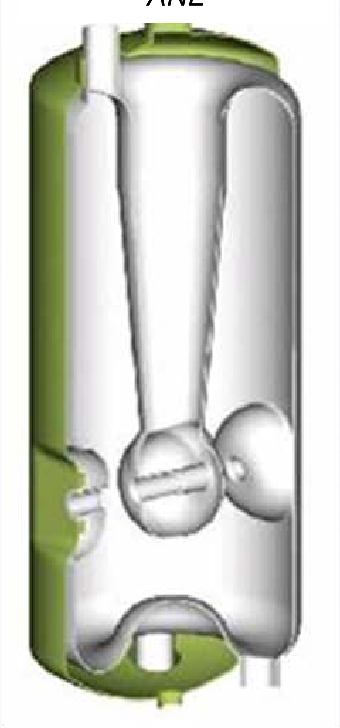
INFN LNL-MSU



MSU

New Dehli

ANL



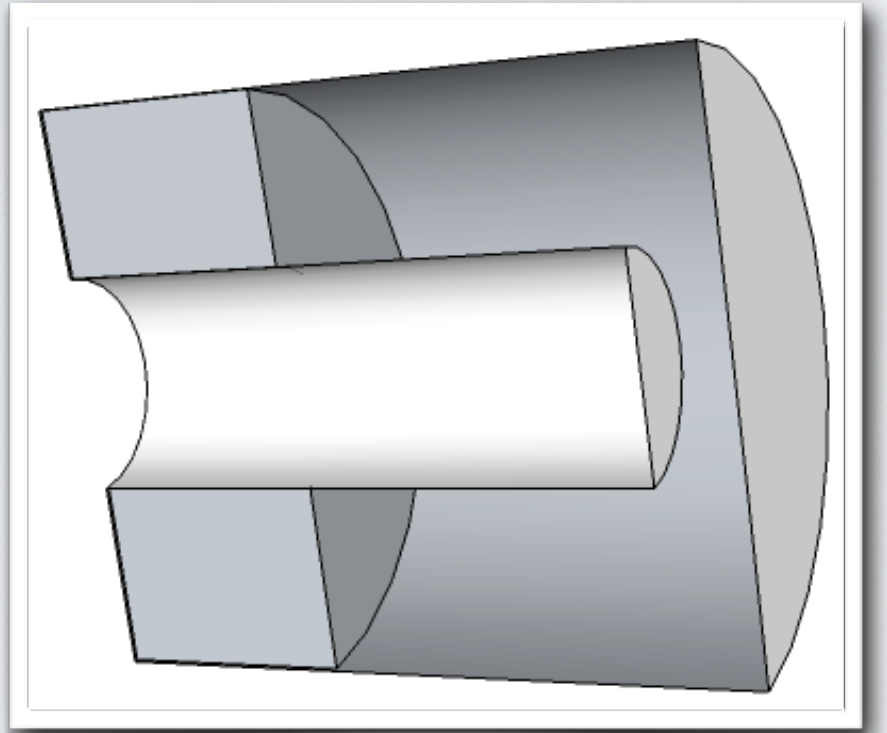
INFN LNL (sputtered)

INFN LNL

Saclay

IPNO

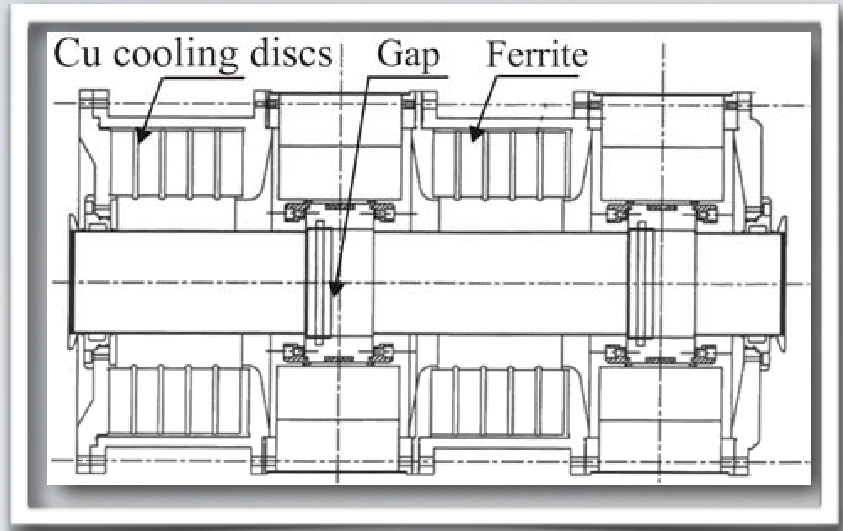
SYNCHROTRON CAVITY

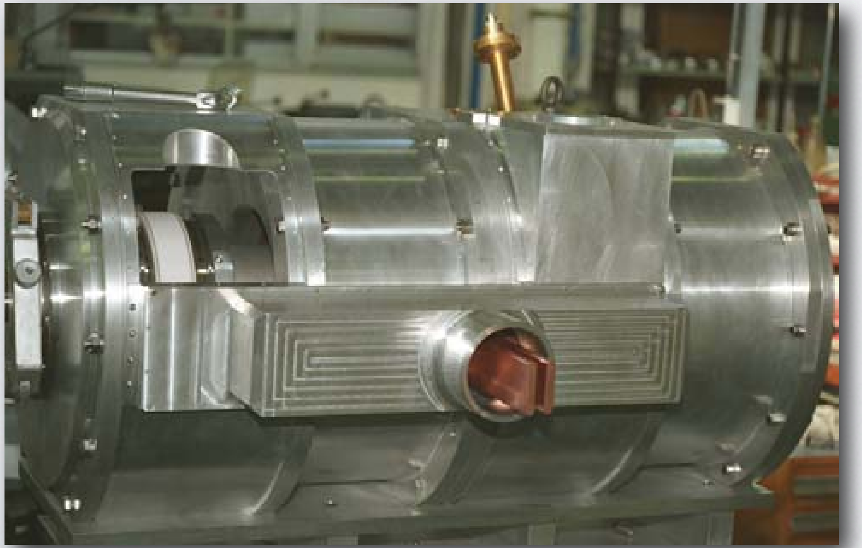


more in: "Ferrite Cavities", H. Klingbeil

- By filling part of the volume with a dielectric or magnetic material, one can shorten the cavity at the expense of higher losses.
- By filling it with ferrites, one can change the frequency by changing the permeability of the ferrite with external fields.
- Lossy materials reduce the Q (and the stored energy) and make it possible to rapidly change the frequency.

EXAMPLE: CERN PS 13.3/20 MHZ CAVITY

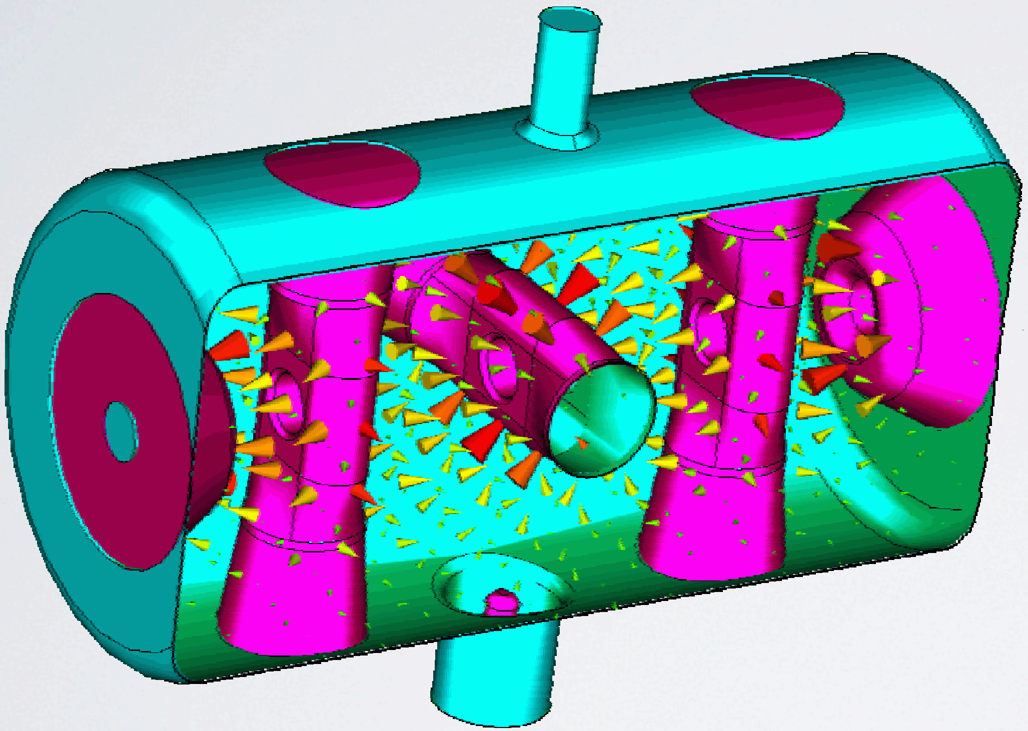




- maximum voltage: 20 kV,
- max. power dissipation: 30 kW,
- length: 1.5 m,
- operation either at 13.3 or at 20 MHz

M. Morvillo et al: "The PS 13.3-20 MHz RF System for LHC" PAC 2003

ANOTHER TEM TYPE RESONATOR: SPOKE CAVITIES



E. Zaplatin et al: "Triple Spoke Cavities at FZJ" EPAC 2004

- spoke cavities consist of 1-n combined 1/2 wave TEM cavities,
- typically 1-3 spokes, and usually superconducting.
- are used for lower to medium β.
- (not to be confused with Crossbar H-mode cavities).

ANL triple spoke cavity

SUPERCONDUCTIVITY

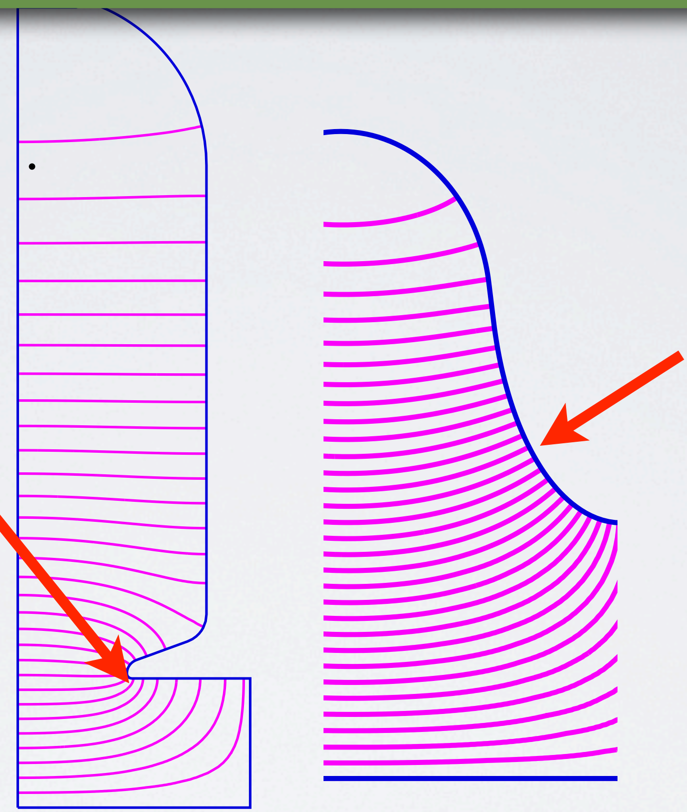
more in: "SC Cavities", J. Sekutowicz

NC & SC CAVITIES

normal conducting:

- nose cones reduce the gap length & increase the transit time factor and eff. shunt impedance ZT^2,
- high peak fields,
- $P_{beam} \lesssim P_{diss}$
- **design goal:** maximise ZT^2 and keep Kilpatrick below a certain value (1.2 - 2.4)

NC and SC half cells (typical shapes)



superconducting:

- ZT^2 has no big importance ($P_{beam} \gg P_{diss}$),
- cryogenic losses (P_{diss}) can be optimised with the temperature (2 K/ 4.5 K),
- keep the ratio **$E_{peak,surface}/E_{peak,axis}$ as small as possible** (for $\beta=1 \Rightarrow P_s/P_a \approx 2$),

$$P_d = \frac{V_{acc}^2}{ZT^2 L}$$

$$P_d = \frac{V_{acc}^2}{(R/Q) Q_0}$$

WHEN ARE SC CAVITIES ATTRACTIVE?

Instead of Q values in the range of ~10^4, we can now reach 10^9 - 10^{10}, which drastically reduces the surface losses (basically down to ~0) ➜ high gradients with low surface losses

$$P_d = \frac{V_{acc}^2}{(R/Q)Q_0}$$

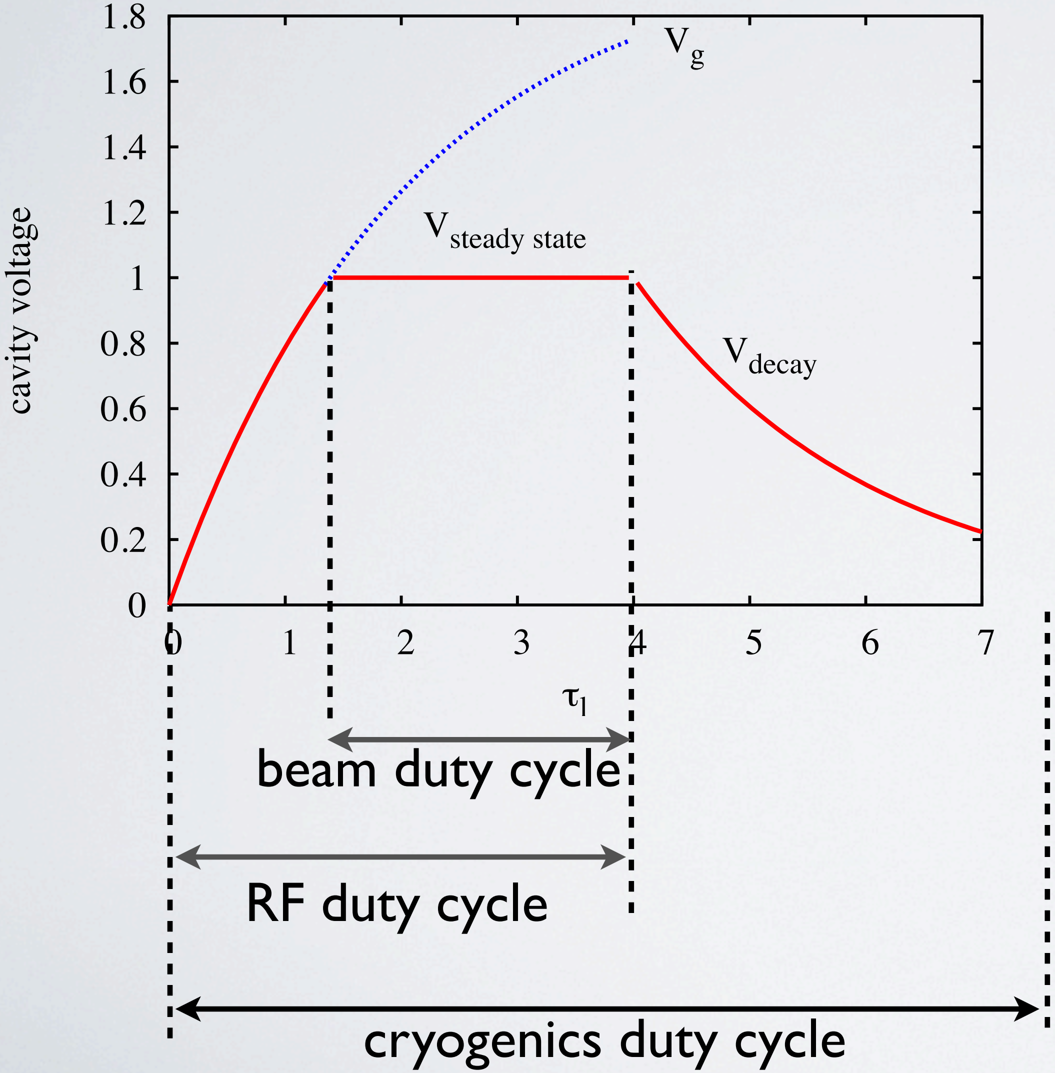
However, due to the large stored energy, also the filling time for the cavity increases (often into the range of the beam pulse length):

$$\tau_l = \frac{Q_l}{\omega_0} = \frac{Q_0}{\omega_0(1+\beta)} \approx \frac{Q_0}{\omega_0 \cdot P_b/P_d}$$

using: $\beta = 1 + \frac{P_b}{P_d} \approx \frac{P_b}{P_d}$

↑ only for SC cavities!

PULSED OPERATION & DUTY CYCLES FOR RF, CRYO, BEAM DYNAMICS



- **beam duty cycle:** covers only the beam-on time,
- **RF duty cycle:** RF system is on and needs power (modulators, klystrons)
- **cryo-duty cycle:** cryo-system needs to provide cooling (cryo-plant, cryo-modules, RF coupler, RF loads)
- RF and cryo-duty cycle have to be calculated as **integrals** of voltage over time.

SOME USEFUL FORMULAS TO CALCULATE ENERGY CONSUMPTION:

with $P_b = I_{beam} V_{acc} \cos\phi_s \quad \Rightarrow \quad \tau_l \approx \frac{V_{acc}}{\omega_0 (R/Q) I_{beam} \cos\phi_s}$

assuming a generator power, which exactly covers the power needed in the cavity, the total filling time of a SC cavity becomes: $t_{fill} = \ln(4)\tau_l$

now one can calculate the **reflected power during charging and discharging** of the cavity as:

$$W_{r,charging} = P_{generator} \int_0^{\ln(4)\tau_l} \left(1 - 2e^{-\frac{t}{2\tau_l}}\right)^2 dt = P_{gen.}\tau_l \underbrace{(ln(4) - 1)}_{\approx 0.39}$$

$$W_{r,decay} = P_{generator} \int_0^{\infty} e^{-\frac{t}{\tau_l}} dt = P_{gen.}\tau_l$$

For the **dissipated power** on the cavity surface one gets the following expressions for charging and decay:

$$W_{d,charging} = P_d \tau_l \underbrace{(8\ln(2) - 5)}_{\approx 0.55} \qquad W_{d,decay} = P_d \tau_l$$

Finally one can express the various duty cycles as:

beam duty cycle:

$$D_{beam} = \frac{t_{beam}}{t_{cycle}}$$

generator (power) duty cycle:

$$D_{gp} \approx \frac{1}{t_{cycle}}(1.39\tau_l + t_{beam})$$

cryogenics duty cycle:

$$D_{cryo} \approx \frac{1}{t_{cycle}}(1.55\tau_l + t_{beam})$$

reflected power duty cycle:

$$D_{refl} \approx \frac{1.39\tau_l}{t_{cycle}}$$

EXAMPLE: SPL CAVITIES

expected cavity parameters for 5-cell β=1 cavities	
frequency	704.4 MHz
R/Q	570 Ω
E_{acc}	25 MV/m
I_{beam}	40 mA
ϕ_s	-15°
t_{beam}	0.4 ms
rep rate	50 Hz

$$\begin{aligned} \tau_l &= 0.27\,ms \\ t_{fill} &= 0.38\,ms \\ D_{beam} &= 2\% \\ D_{gp} &= 3.89\% \\ D_{cryo} &= 4.11\% \end{aligned}$$

$$\Rightarrow \quad \tau_l \approx \frac{V_{acc}}{\omega_0 (R/Q) I_{beam} \cos \phi_s}$$

- Depending on the velocity-range, electric gradient, beam current, particle velocity, and pulse rate, SC cavities can be less cost efficient than NC cavities!
- Higher currents decrease the filling time but increase the needed peak power (⇒more klystrons).
- SC cavities generally need more inter-cavity space, leading to a lower "packing factor" of cavities.
- Nevertheless, one can generally get higher gradients (for high beta) than with NC standing-wave cavities! (E.g. XFEL cavities: ~23.6 MeV/m in a 9-cell 1300 MHz cavity, vs 3-4 MeV/m in traditional NC standing wave cavities.)

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do the optimisation + cost exercise for your specific application!!

GO CREATE !!

MATERIAL USED FROM:

- M. Vretenar: Introduction to RF Linear Accelerators (CAS lecture 2008)
- T. Wangler: Principles of RF Linear Accelerators (Wiley & Sons)
- D.J. Warner: Fundamentals of Electron Linacs (CAS lecture 1994, Belgium, CERN 96-02)
- Padamsee, Knobloch, Hays: RF Superconductivity for Accelerators (Wiley-VCH).
- F. Gerigk: Formulae to Calculate the Power Consumption of the SPL SC Cavities, CERN-AB-2005-055.
- H. Fitze et al: Developments at PSI (including new RF Cavity), CYC2004.