RF Engineering
Accelerating Structures

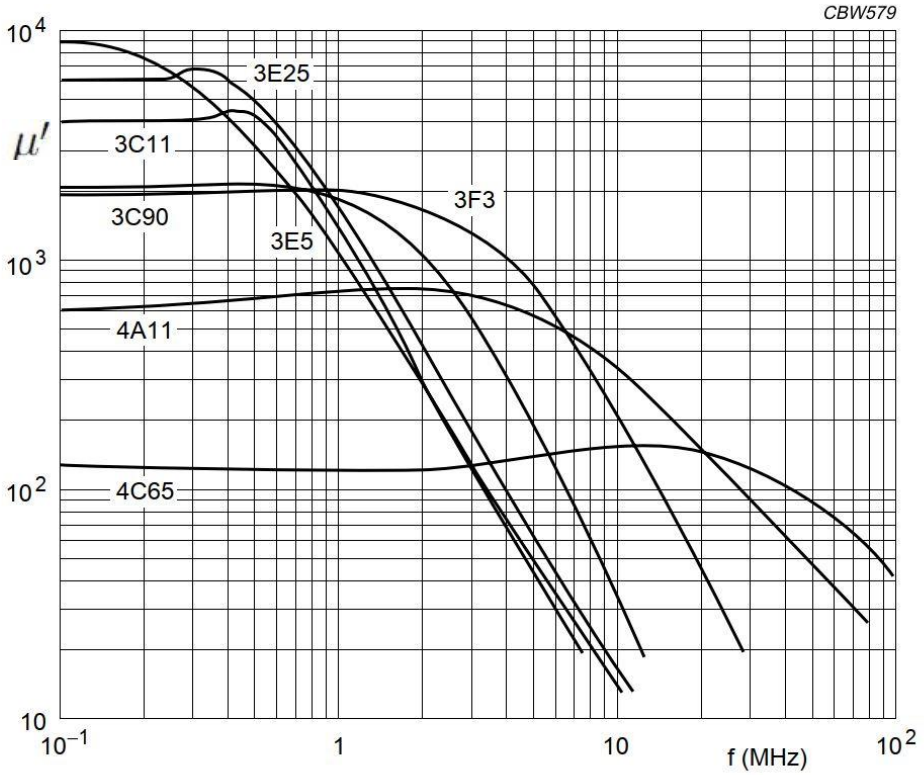
Christine Völlinger (CERN) & Manfred Wendt (BNL)

Contents of this lecture

- Dispersion diagram.
- General accelerating structures, and the concept of standing wave and travelling wave cavities.
- Higher order mode (HOM couplers) on the example of the SPS 200 MHz TWC.

Dispersion (1/3)

- *Dispersion* generally denotes frequency dependent behaviour.
  Best known example is dispersive media, changing its characteristics as a function of frequency.



$$\boxed{\tan \delta_m = \frac{\mu''}{\mu'}}$$

magnetic loss tangent

Transmission lines and waveguides also show dispersive behaviour.

Source: *Ferroxcube Data Handbook*

Dispersion (2/3)

If phase velocity and attenuation of a transmission line or wave guide are constants that do not change with frequency, *THEN* the phase of a signal that contains more than one frequency will not be distorted (= *no dispersion*).

If the phase velocity is different for different frequencies, *THEN* the line is dispersive.
This means that individual components of a wave will not maintain their original phase relationship when they propagate.
We will experience a signal distortion if the signal contains more than one frequency.

Dispersion = no single phase velocity can be attributed to the signal as a whole.

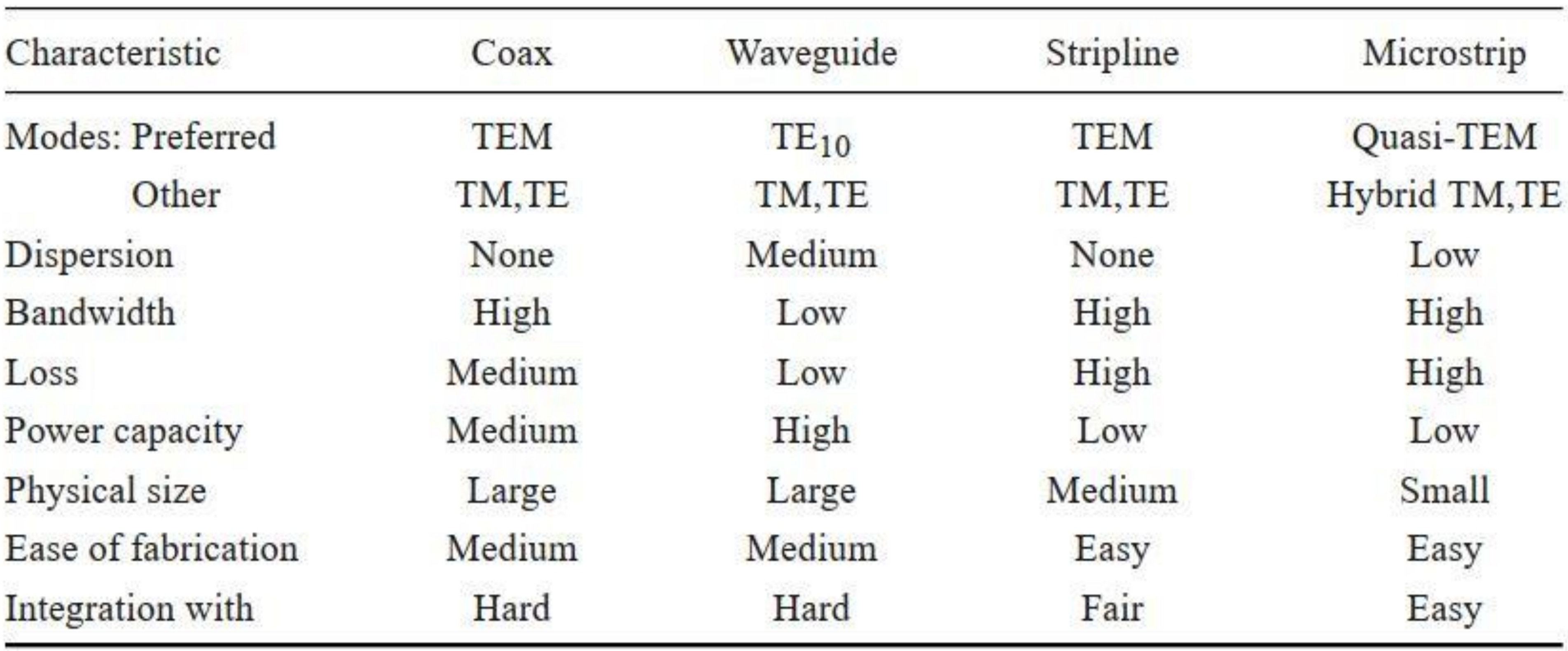
Different v_p means that some signal components travel faster than others.

If dispersion is small, a group velocity can be defined: v_g.
Group velocity = speed at which a signal propagates and at which power is transported.

For more details see: lecture of Andrea Mostacci or textbooks, for example: Pozar, *Microwave engineering*, Wiley

Dispersion (3/3)

Comparison of Transmission lines and waveguides



Characteristic	Coax	Waveguide	Stripline	Microstrip
Modes: Preferred	TEM	TE_{10}	TEM	Quasi-TEM
Other	TM,TE	TM,TE	TM,TE	Hybrid TM,TE
Dispersion	None	Medium	None	Low
Bandwidth	High	Low	High	High
Loss	Medium	Low	High	High
Power capacity	Medium	High	Low	Low
Physical size	Large	Large	Medium	Small
Ease of fabrication	Medium	Medium	Easy	Easy
Integration with	Hard	Hard	Fair	Easy

Source: Pozar, *Microwave engineering*, 4th ed., Wiley

Dispersion – Remark to Waveguides

Recall phase velocity:

$$v_p = \frac{\omega}{k} = \frac{\omega}{\beta}$$

defined

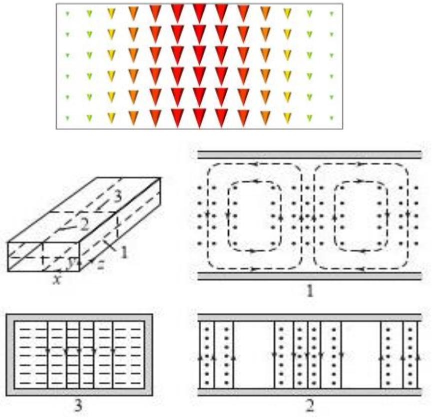
Phase constant of rectangular waveguide

$$\beta_{m,n} = \sqrt{\omega^2 \mu \epsilon - \left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

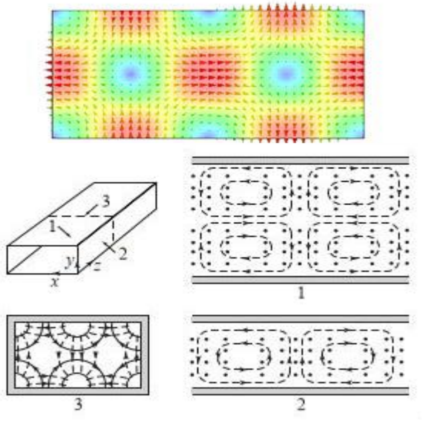
Phase constant of round waveguide

$$\beta_{nm} = \sqrt{\omega^2 \epsilon \mu - \left(\frac{p'_{nm} \text{ or } p_{nm}}{R}\right)^2}$$

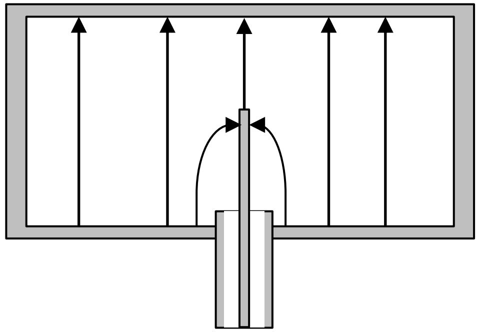
TE$_{10}$-mode



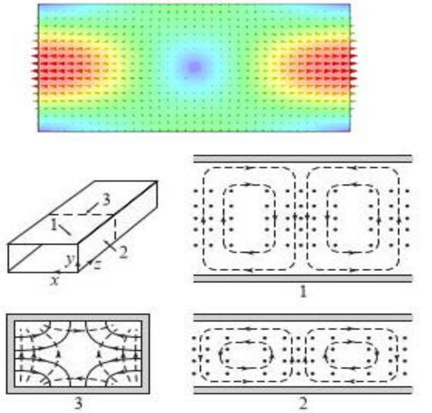
TE$_{21}$-mode



Coax to waveguide transition… will excite all modes that “fit” this field pattern.



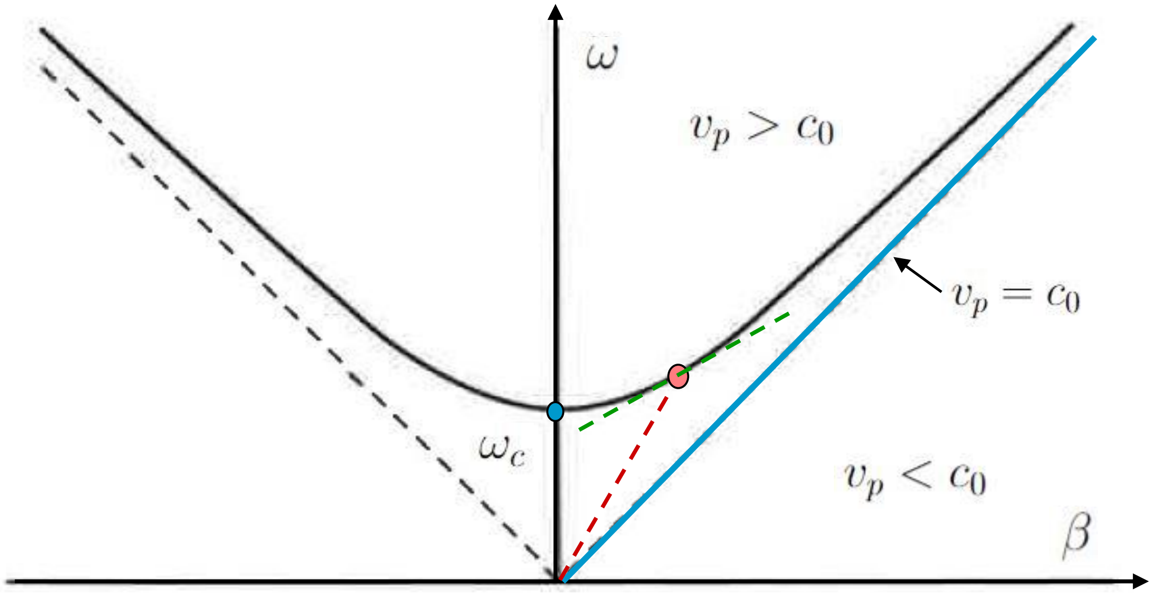
TE$_{11}$-mode

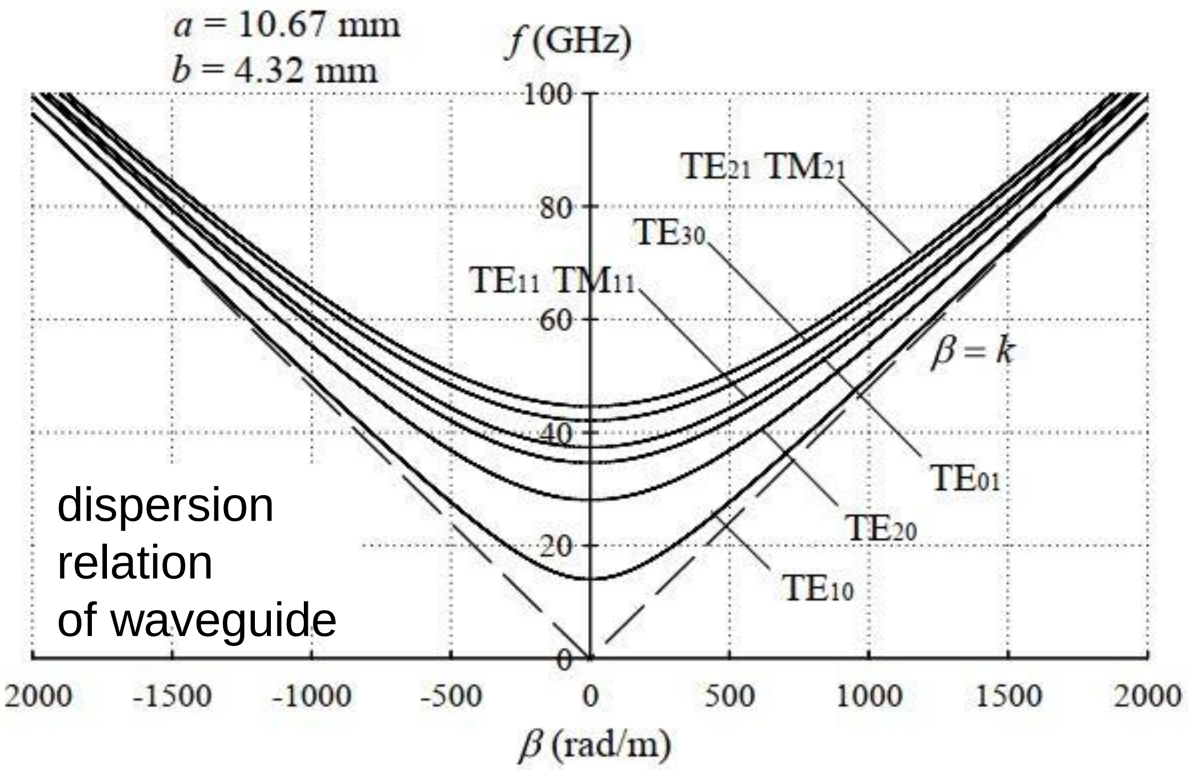


- Any discontinuity will need all possible modes to fulfill the boundary condition on the discontinuity, thus “excite” all modes.
- *Mode conversion* (one mode converting into another mode) happens “easily” and not only unintentionally. *Mode converters are built to convert from one mode to another.*

Dispersion Diagram

general dispersion relation





dispersion relation of waveguide

Source: Zhang, *Electromagnetic Theory for Microwaves and Optoelectronics*, Springer

Tangent at point on the dispersion curve

$$\boxed{v_p = \frac{\omega}{\beta}}$$

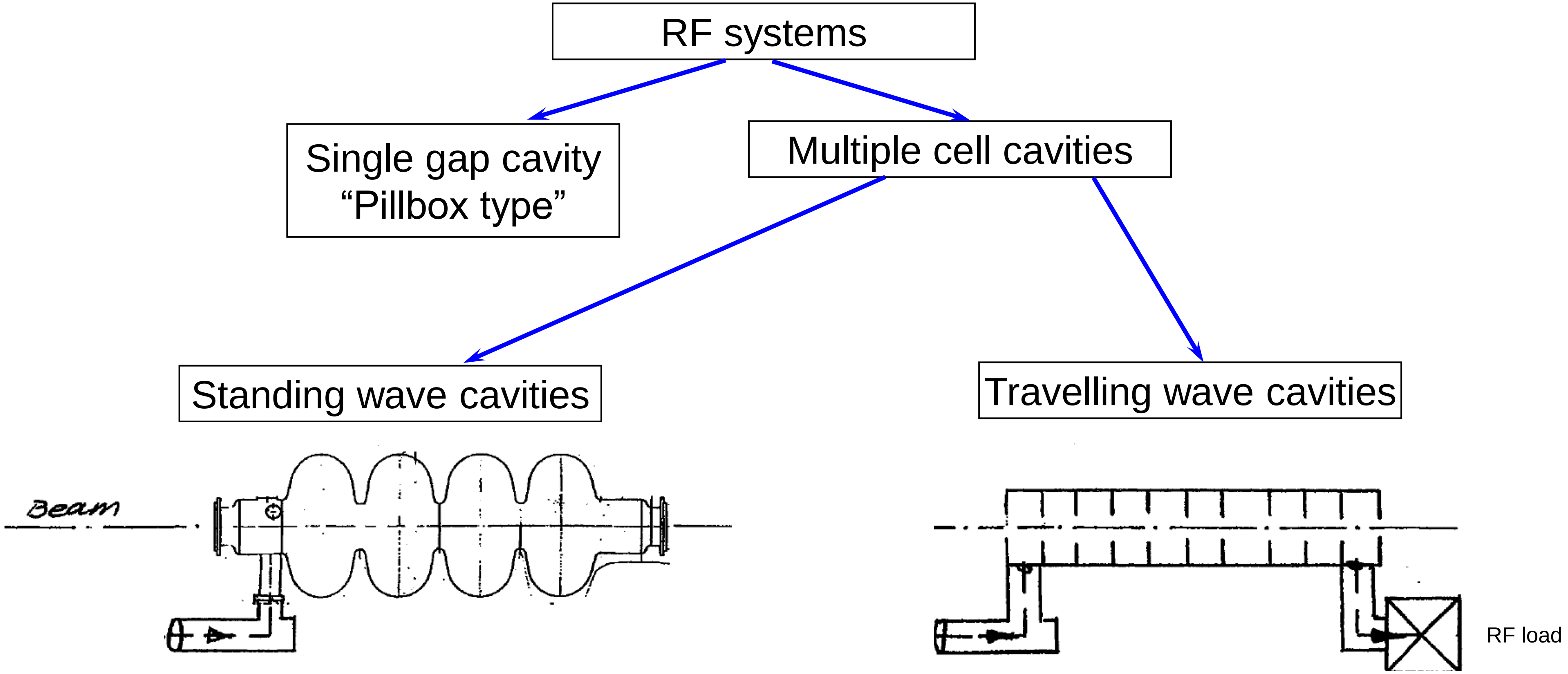
$$\boxed{v_g = \frac{\partial \omega}{\partial \beta}}$$

From origin to point on the dispersion curve

- v_g is zero at cut-off frequency
- v_g is smaller than c_0
- v_p can be larger than c_0

RF-systems

source: F. Caspers et al., *JUAS 2021*



RF systems

Single gap cavity
“Pillbox type”

Multiple cell cavities

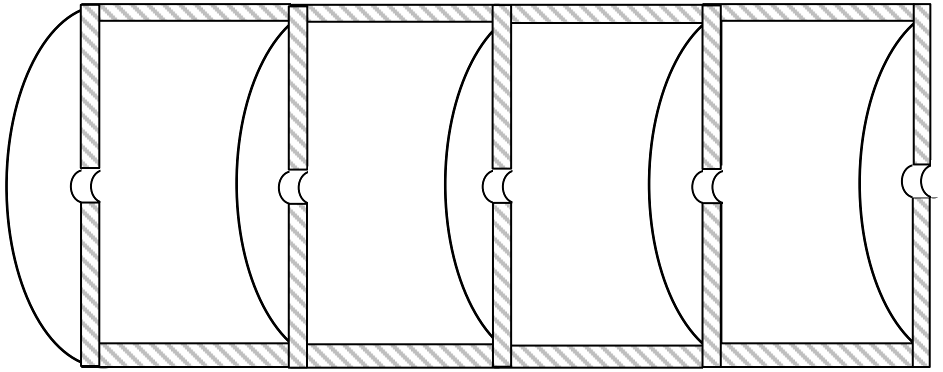
Standing wave cavities

Travelling wave cavities

Typically used in applications with low beam loading,
e.g. ring accelerators (storage rings)

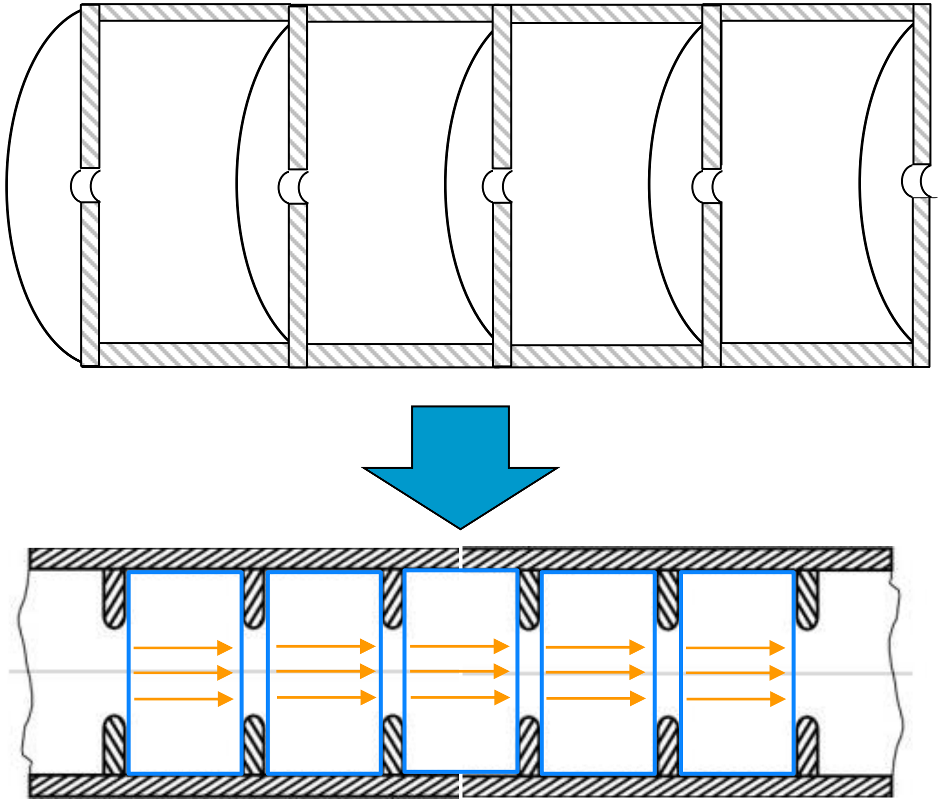
Typically used in applications with high beam loading,
e.g. linear accelerators (linacs)

Disc-loaded circular waveguide (1/2)



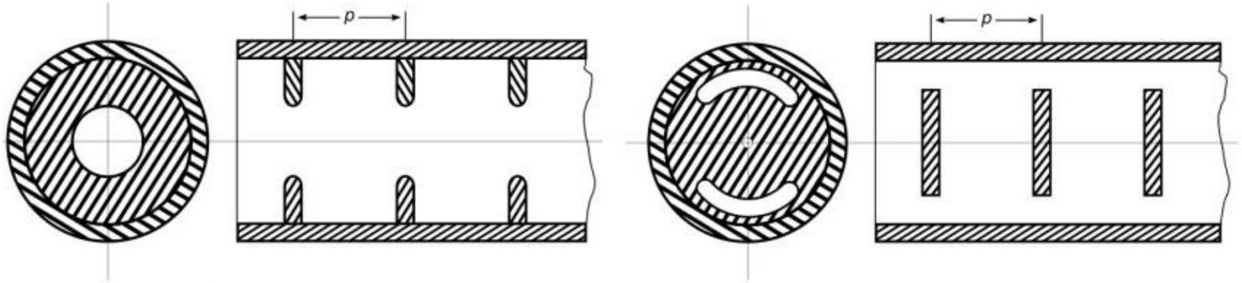
- Disc-loaded waveguide is a circular metallic waveguide with periodically added metallic discs and holes for particle passage and for coupling of the cells.
- We speak of a coupled-cavity chain structure.
- EM-fields need to fulfill boundary conditions on the metallic discs.
- Disc-loaded waveguide *can operate in travelling-wave as slow wave structure or in standing-wave mode*.
- In standing wave mode, the cells present a “concatenation” of TM_{010}-mode “pillbox”-type cavities.

Disc-loaded circular waveguide (2/2)



Example: 0-mode structure in standing wave (SW) … can be derived from pillbox TM$_{010}$-mode.

Source: Kramer, *Studies of HOM-couplers for the Upgrades Travelling Wave Acceleration System in the CERN SPS*, PhD, CERN-THESIS-2019-371



(a) Iris coupled structure.

(b) Slot coupled structure.

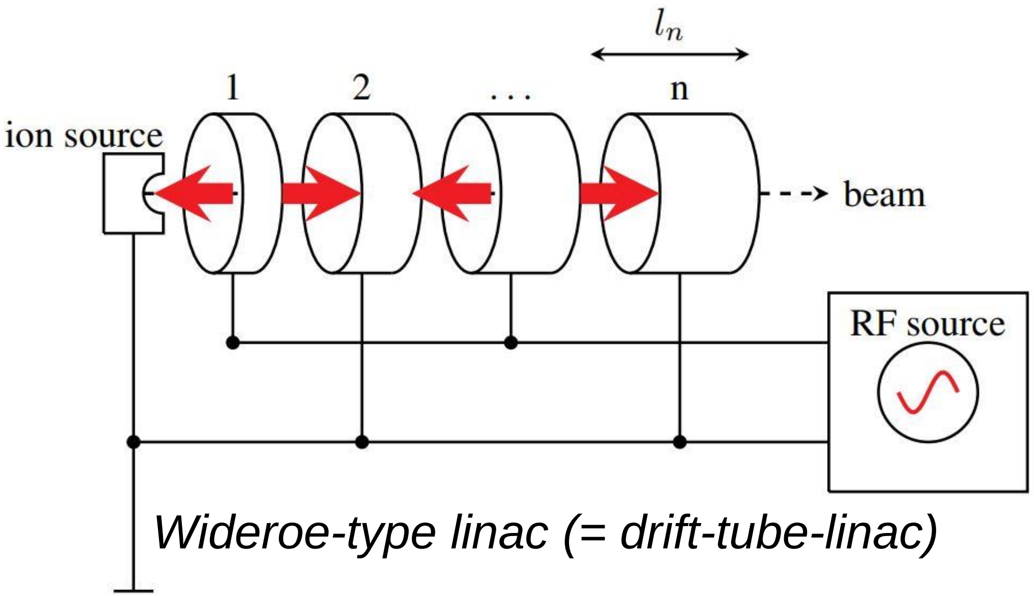
- Different coupling mechanisms between the individual cells exits, either on the side or in the center.
- We speak of iris-coupled-structure and slot-coupled-structure.
- For slot-coupled-structures, the center opening for the beam can be very small and is often ignored in the EM-calculations.

- *The name of the resonant mode is given by the phase advance between two consecutive cells.*

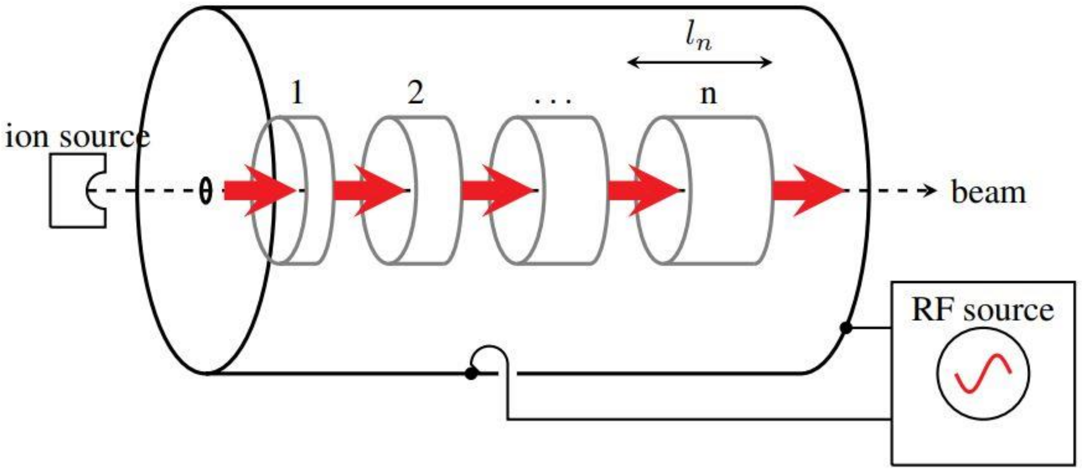
Example of 1st Accelerating Cavities (SW, 1/3)

How does this work?

source: F. Gerigk, CAS Ebeltoft, *Cavity Types*, 2010



Wideroe-type linac (= drift-tube-linac)

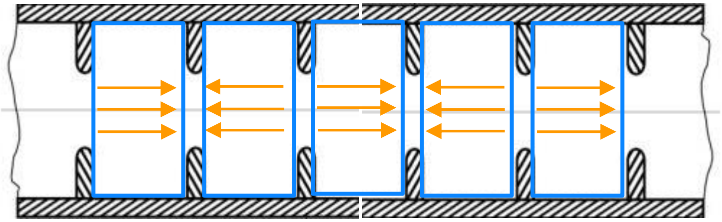


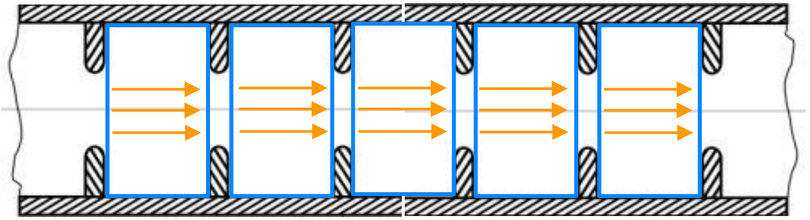
Alvarez-type linac (= drift-tube-linac)

Pi-mode structure

0-mode structure

Remember: The name of the resonant mode is given by the phase advance between two consecutive cells.





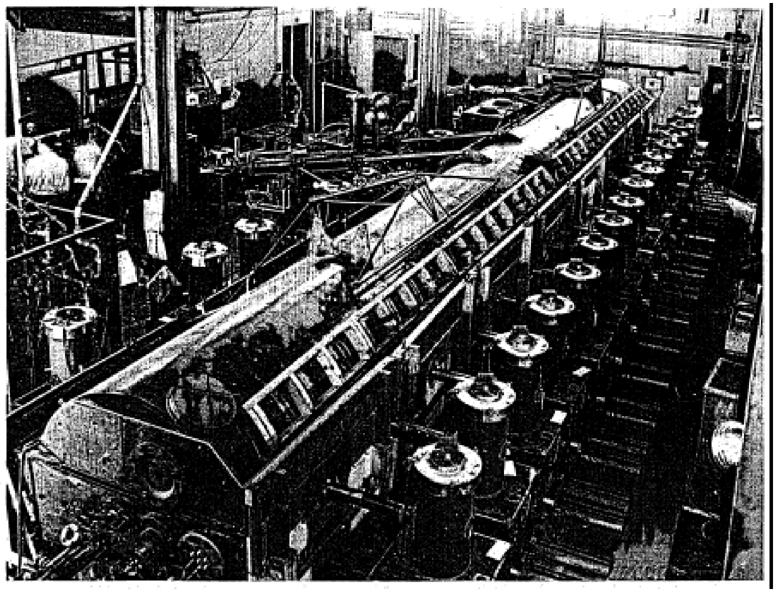
Side Remark about the linac-frequency…

Luis Alvarez and the Drift Tube Linac

The WW2 effort forced many scientist to develop the competences and gave the components to go to higher frequencies (in the MHz – GHz range) .

Alvarez tried acceleration of a proton beam to the MeV range using the Wideröe principle.

He worked at MIT on radar during the war. In 1945, he had the tools and the competences to build his own accelerator.



The 1st Drift Tube Linac by L. Alvarez and his team at Berkeley, reaches 32 MeV in 1947.

Following M. Vretenar, RF CAS 2023

Choice of Frequency :

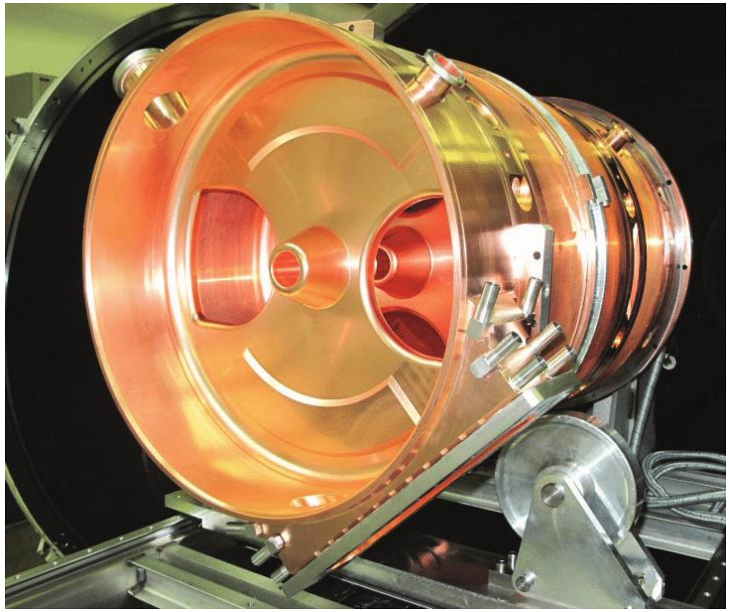
Alvarez received from the US Army a stock of 2’000 (!) surplus **202.56 MHz** transmitters, produced for a radar surveillance system.

26 were installed to power the DTL with a total of 2.2 MW.

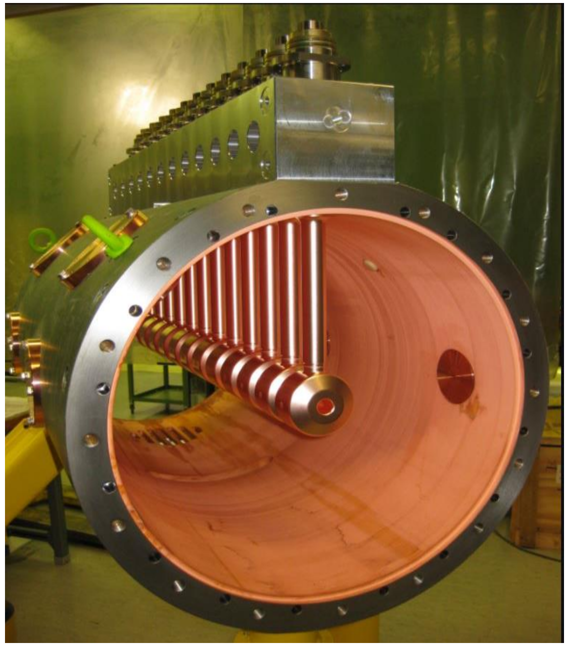
They were soon replaced because unreliable, but this frequency remained as the standard linac frequency.

Example of Pi-mode Cavities (SW, 2/3)

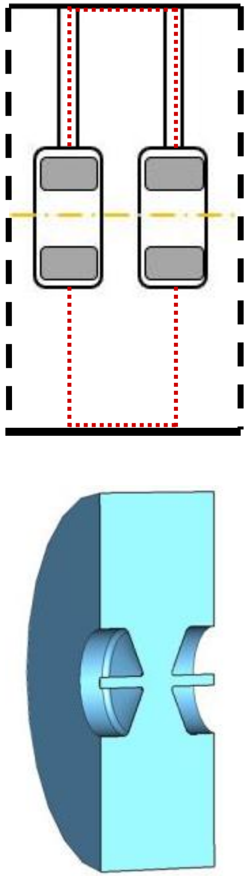
How does this look in reality?

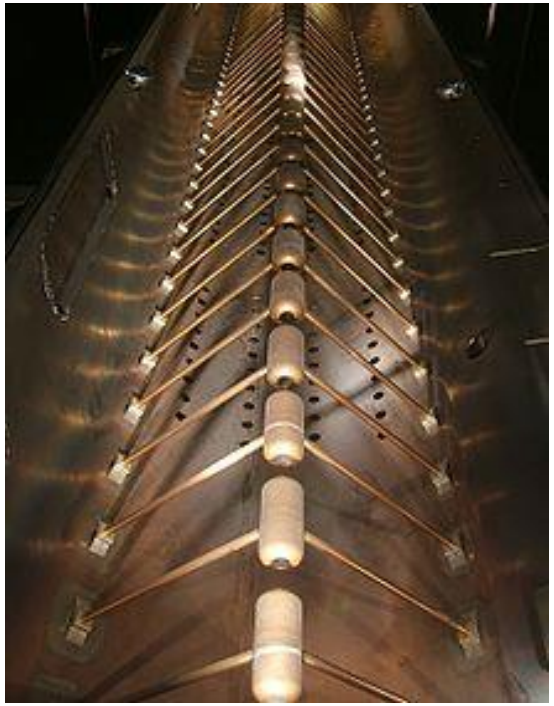


Slot-coupled-structure (PIMS) at CERN



Drift tube structure, CERN





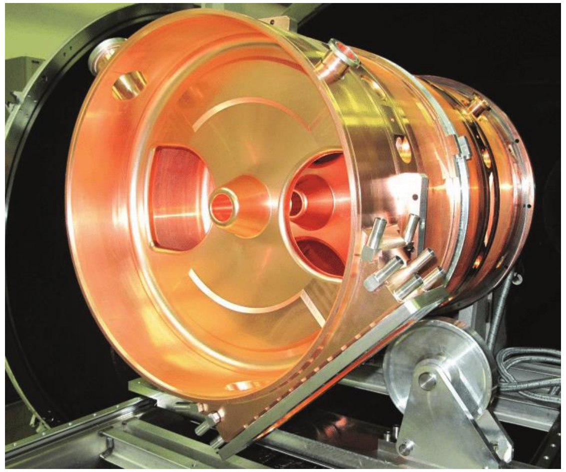
Picture of Linac1, CERN

Note that a ‘cell’ is not necessarily a pillbox-type shape. In drift tube structures, a cell is the area between two drifttubes and looks in principle like a pillbox with nose cones.

sources: P. Bourquin et al., *Development Status of the Pi-mode Accelerating Structure (PIMS) for LINAC4, Proc. Of LINAC08, Canada.*
C. Plostinar (ed.), Comparative Assessment of HIPPI Normal Conducting Structures, CARE-report-2002-0771

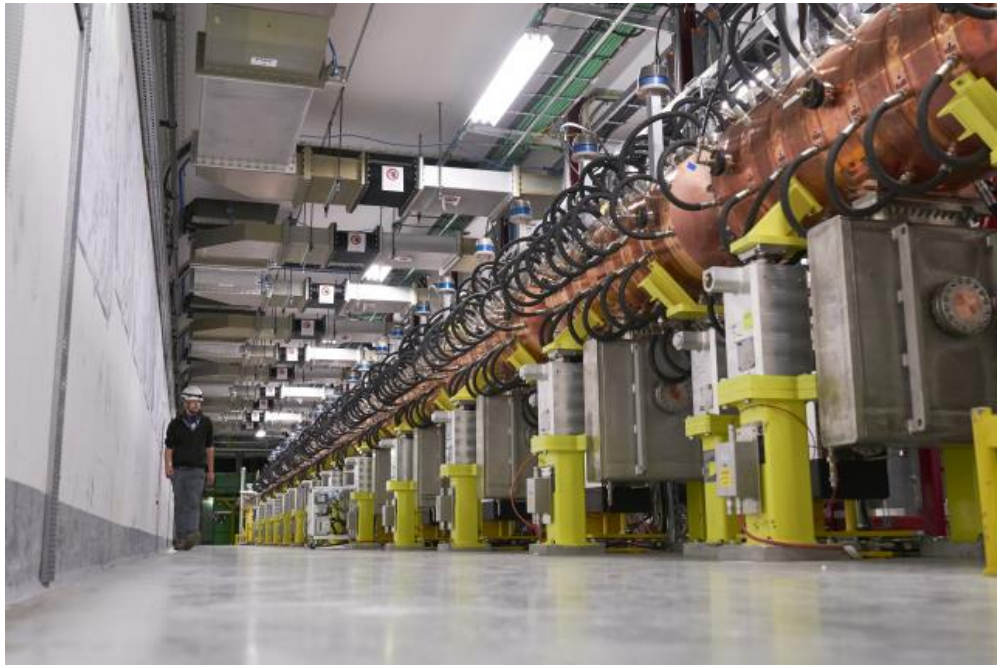
Example of Pi-mode Cavities (SW, 3/3)

Slot-coupled-structure (PIMS) at CERN



PIMS cell

PIMS test set-up



Completed LINAC4, CERN

Picture sources: CERN cds
R. Wegner et al., *Linac4 PIMS Construction and First Operation*, IPAC2017, Copenhagen.
P. Bourquin et al., *Development Status of the Pi-mode Accelerating Structure (PIMS) for LINAC4, Proc. Of LINAC08, Canada*

Waveguide becomes Slow Wave Structure

- To get power transferred to the beam, *the accelerating field needs to be kept in phase* with the charged particle.

- For single gap cavities, this means that the resonance needs to be synchronous with the particle phase. We can then concatenate many “pillbox cavities” to one multi-cell pattern.

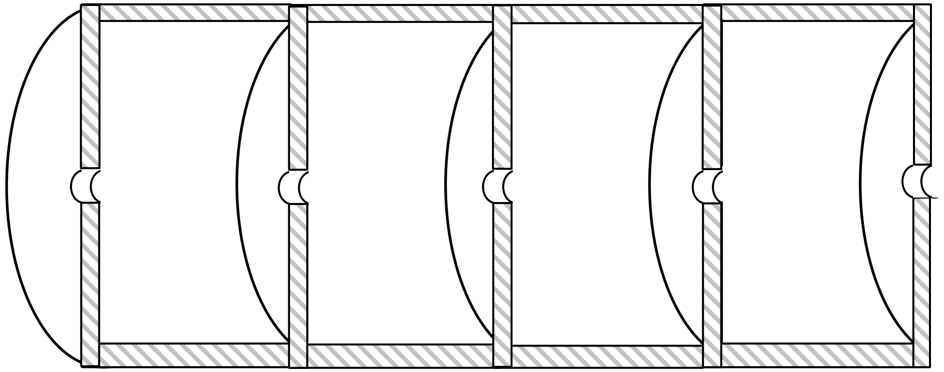
- Another way to reduce phase velocity is to build the disc-loaded waveguide where discs are added in a periodic pattern (schematic pictures look the same).

- As for the concatenated “pillbox cavities”, a multi-cell pattern builds up. The addition of discs inside the cylindrical waveguide induces multiple reflections between the discs and results in a change of the dispersion curve. The structure can then be used in travelling wave mode.

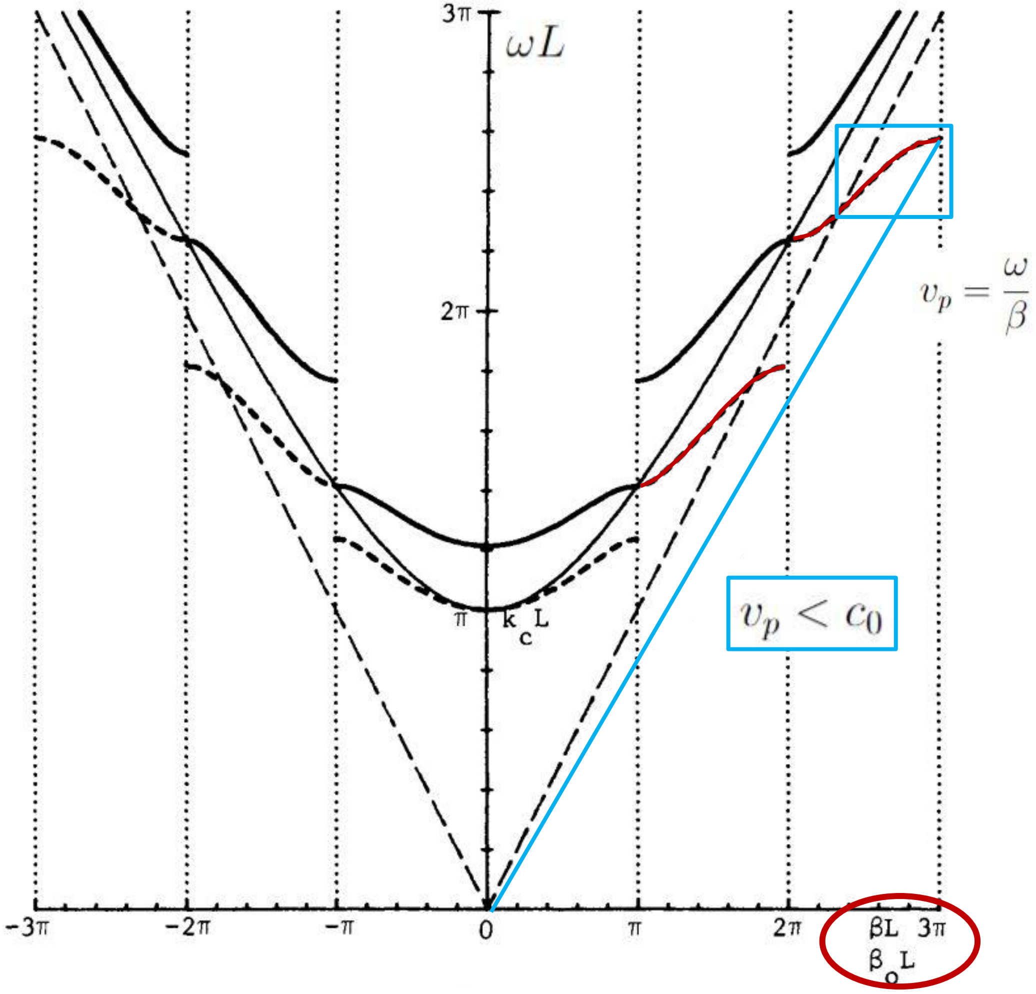
- If the wave is travelling with speed-of-light, and we slow down this wave *(=reduce phase velocity), we obtain* so-called slow wave structures (SWS).

- Slow wave structures are known from dielectrics (where the EM-wave slows down due to permittivity ϵ_r), but here we will discuss slow-wave structures with metallic boundaries used for particle acceleration.

Slow wave structure (1/7)



source: G. Dome, *RF Systems: Waveguides and Cavities, aip-conf-proc.153-1296*

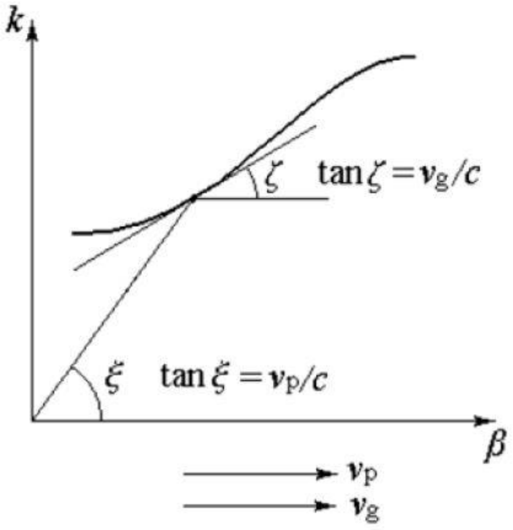


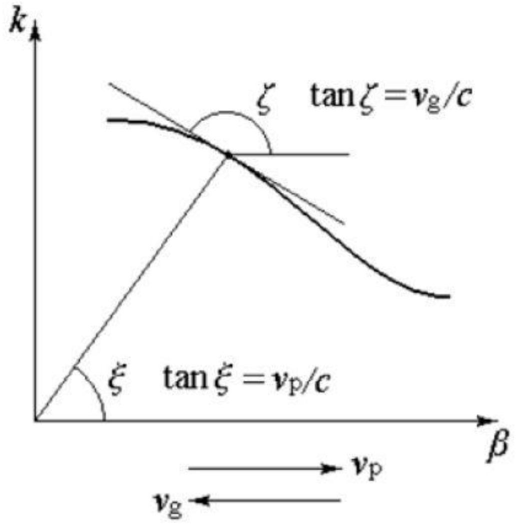
- Slow wave structures work in the range of $v_p < c_0$.
- The addition of discs inside the cylindrical waveguide induces multiple reflections between the discs and results in a change of the dispersion curve.
- The disc-loaded structure can then be used in travelling wave mode.
  The dispersion curve changes from continuous to splitting up into different modes which are slowed down. We speak of pass-bands. These modes are separated by stopbands.

Slow wave structure (2/7)

Dispersion Curves, phase- and group velocity for FW and BW wave in periodic structure.

Forward wave (FW)
v_g *and* v_p *point in the same direction.*





Backward wave (BW)
v_g *and* v_p *point in the opposite direction.*

For the advanced RF-fans:

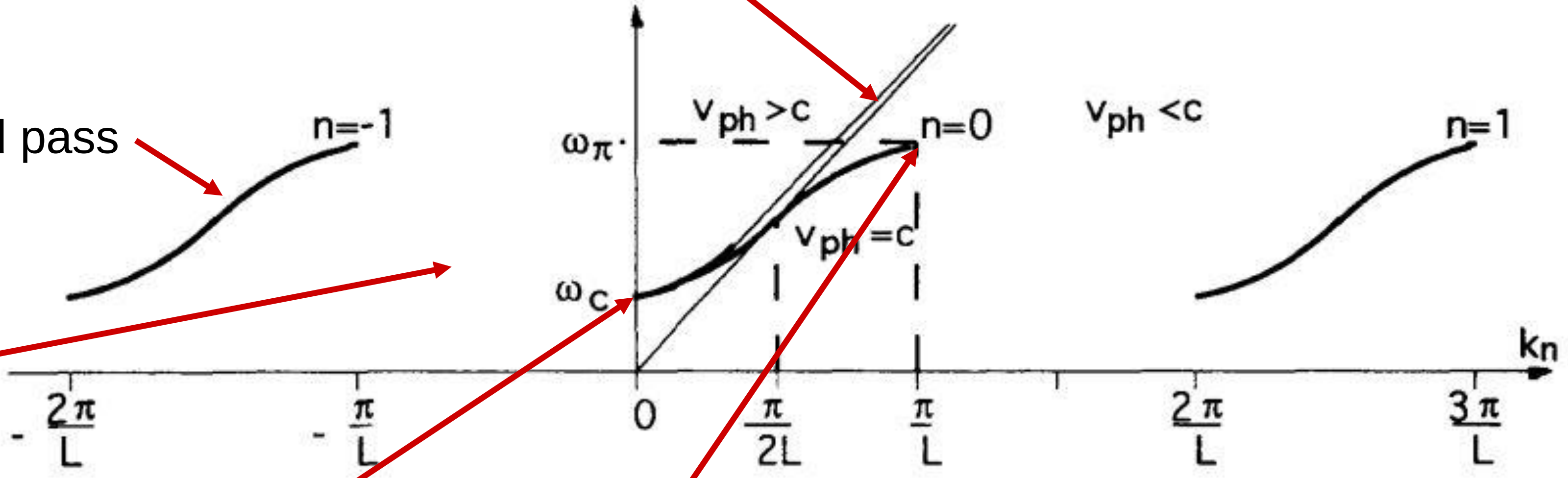
1. All guides modes in common transmission lines, metallic and dielectric waveguides are forward waves.
2. For transmission lines of “high-pass filter” type, the phase constant β decreases with increasing frequency.
3. “High-pass filter” type lines are modelled with a distributed series capacitance and a shunt inductance (i.e., opposite of what we did in the transmission line modelling!).
4. Forward and backward type of waves – this makes no difference for the direction of the beam.

Source: Zhang, *Electromagnetic Theory for Microwaves and Optoelectronics*, Springer

Slow wave structure (3/7)

Dispersion diagram of periodic structure (uniform waveguide is shown for orientation)

source: M. Weiss, *Introduction to RF Linear Accelerators.*

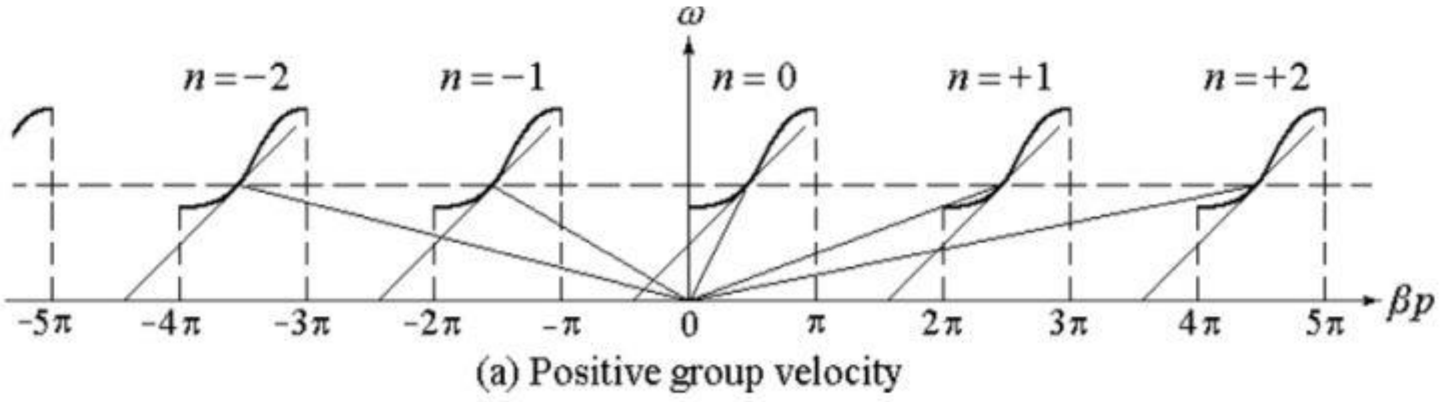


- Dispersion diagram shows the periodicity of the structure.
- For a given mode, there is a limited pass band of possible frequencies.
- The passbands are separated by stopbands where the specific mode cannot propagate.
- At both ends of the passband, the group velocity is zero and wave propagation stops.
- When group velocity and phase velocity are in the same direction, we speak about forward waves, if they are in different direction, we speak about backward waves. This has nothing to do with the direction of the particle travelling.

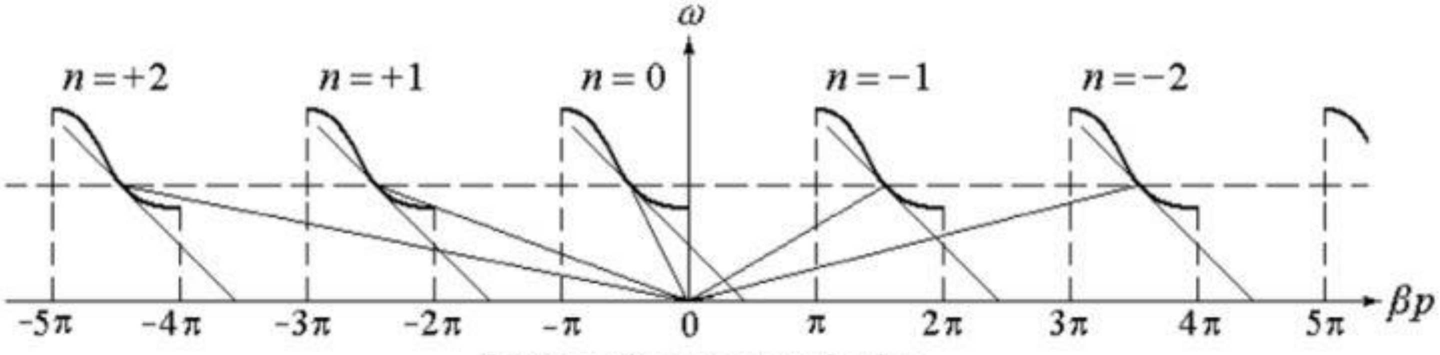
Slow wave structure (4/7)

- The request to fulfill the periodic boundary conditions leads to the concept of *space harmonics* (instead of wave modes).

- Space harmonics are closely connected the so-called *Floquet Theorem* (we will not cover this here).



(a) Positive group velocity



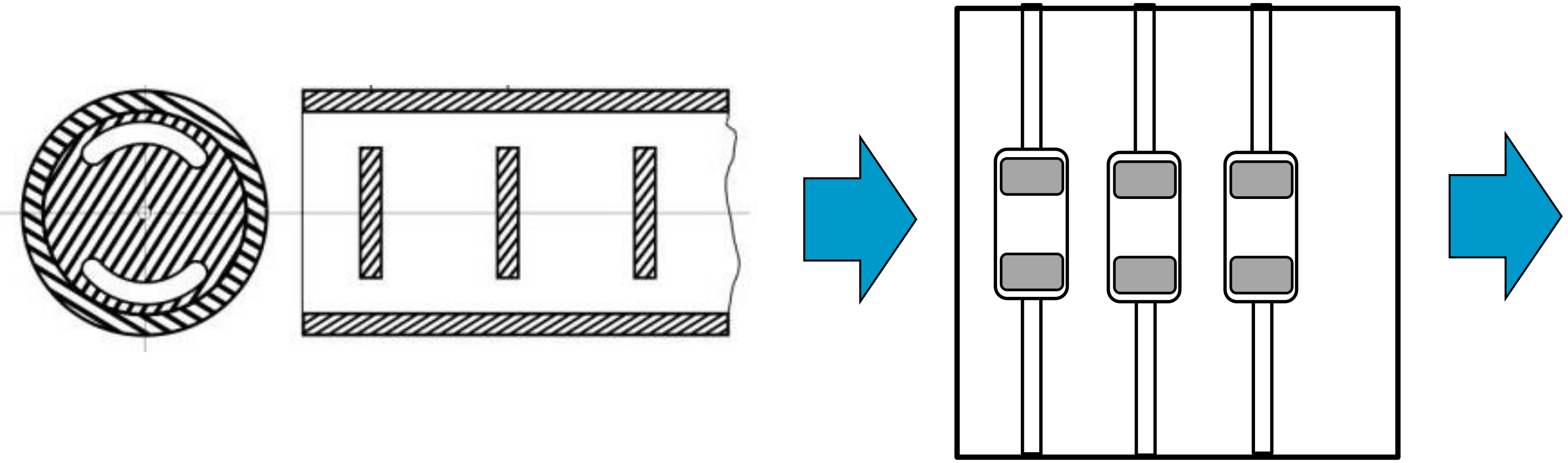
(b) Negative group velocity

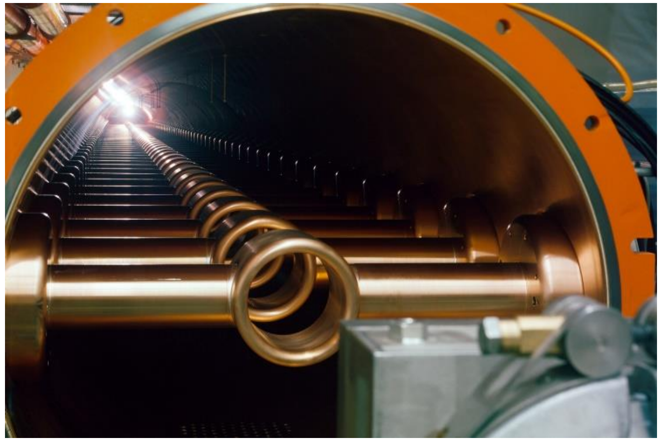
- The *Floquet Theorem* describes the relation between the phase constant of the n-th space harmonic and is a fundamental theorem of periodic structures.

Source: Zhang, *Electromagnetic Theory for Microwaves and Optoelectronics*, Springer

Slow wave structure (5/7)

- As was shown before, drift tubes can be used instead of separating discs to slow down the EM-field. The theory for drift tubes is very similar to calculating a slot-coupled structure. Just imagine that the slot is very large.





Inside view of the SPS travelling wave structure © CERN.

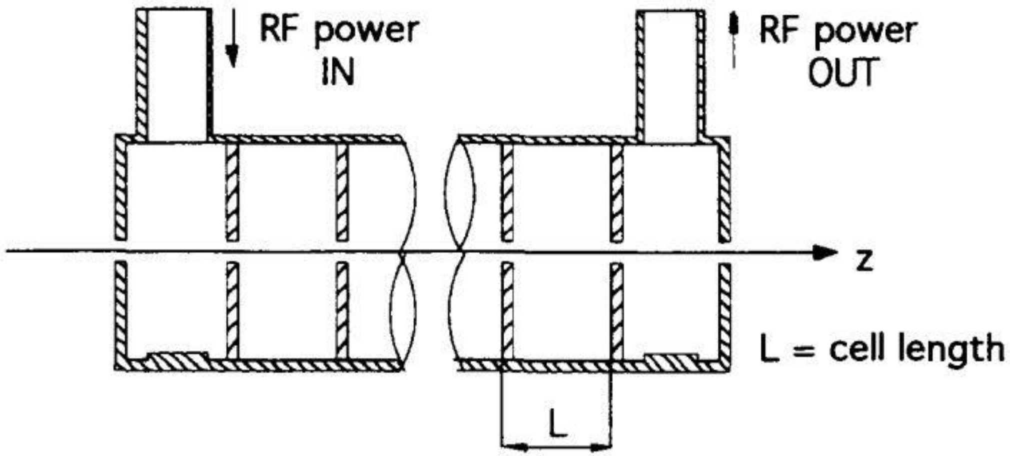
- In travelling wave (TW) mode, the field propagates through each cell.
- The phase advance per cell (distance between the discs, or periodic spacing of drift tubes) determines the length of the cell:

$$\Delta\varphi = \frac{2\pi}{\beta\lambda} l$$

Remember? $\beta\lambda$ was already introduced for the single gap cavity as distance that a particle travels during one RF-period.

Slow wave structure (6/7)

- The only missing component for our travelling wave system are the input and output couplers.
- These have to be matching the structure to avoid that standing waves are building up inside the periodic structure.



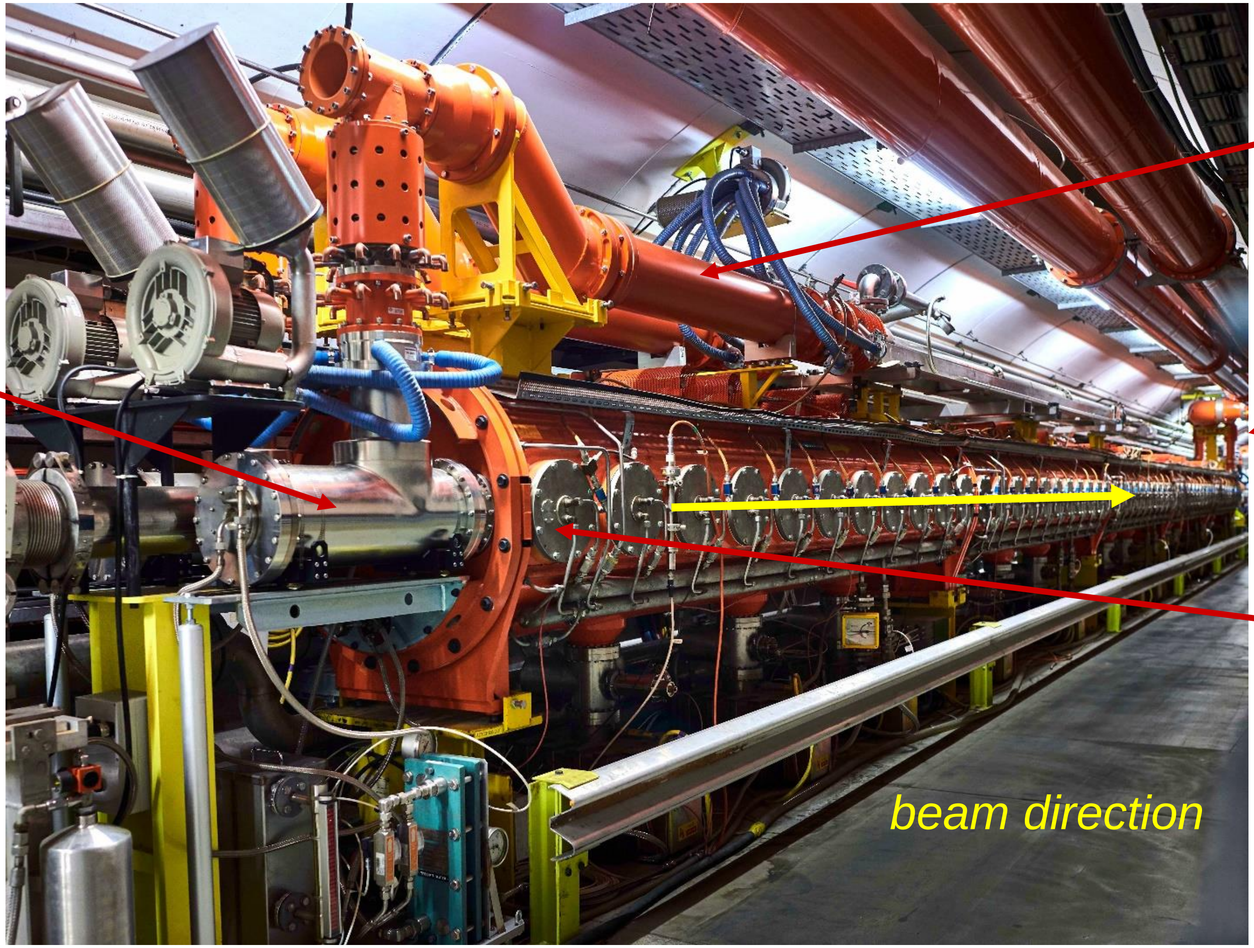
- Often, higher order modes (HOMs) are building up in the structure due to the finite length (end covers are put there).

  Note that a matching network is used to obtain the travelling state. This network is only matching the fundamental mode and not the HOMs!
  I.e. the fundamental mode is travelling, others might be travelling, partially travelling or standing modes.

Slow wave structure (7/7)

SPS 200 MHz travelling wave cavity (16m long).

Backward wave structure



Water cooled coaxial load

RF OUT side

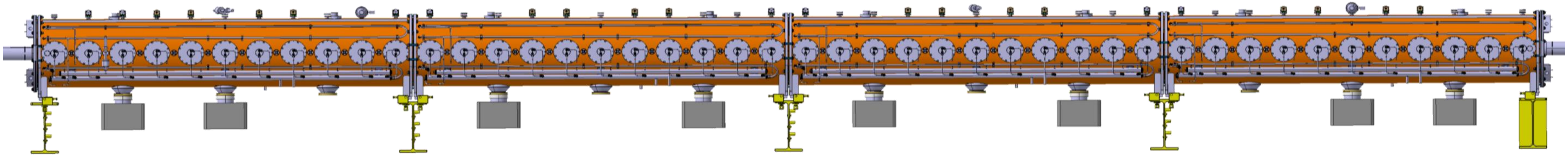
RF IN side

Drift tube with water cooling

© CERN

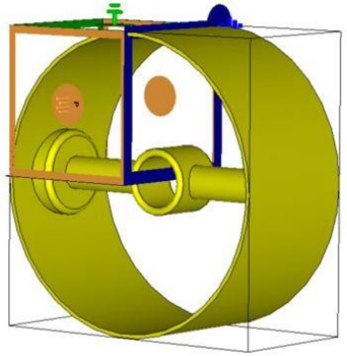
200 MHz TWC of SPS (1/3)

courtesy: E. Montesinos, CERN

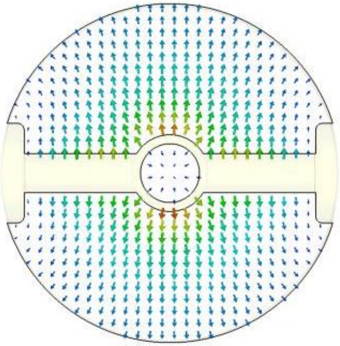


- Cavity is part of the LHC injector chain and was upgraded recently and equipped with new power amplifiers to reach a higher accelerating voltage.
- The cavity was entirely modelled in CST, so that we could well see the fields of the fundamental and the HOMs.

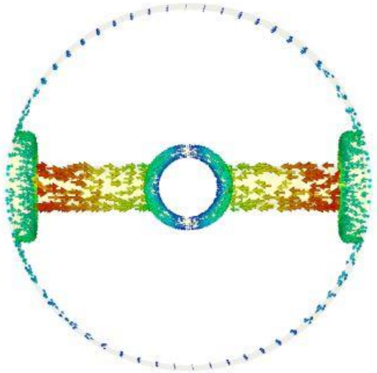
Modelling in CST (P. Kramer, CERN)



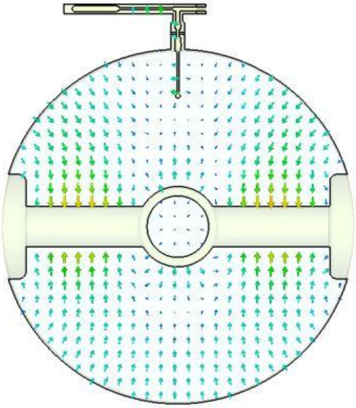
Single cell CST model with symmetries (no HOM coupler)



Electric field of fundamental mode in the Cross-section



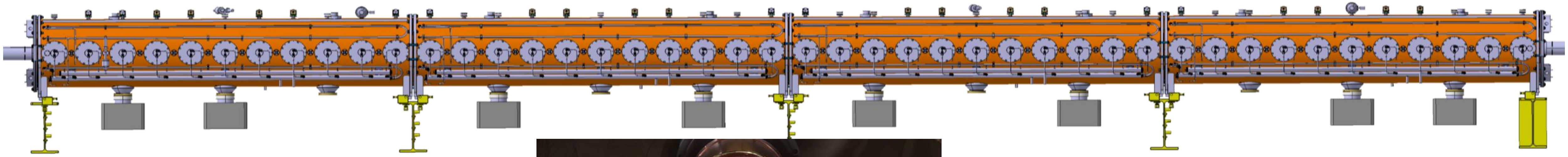
Surface currents on the Drift tube

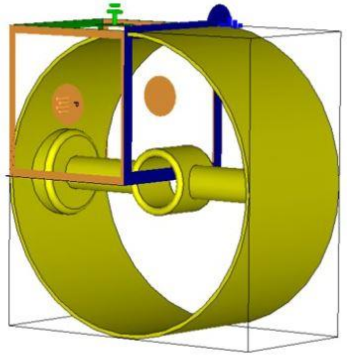


E-field in a cell with HOM-coupler (22π/33 mode)

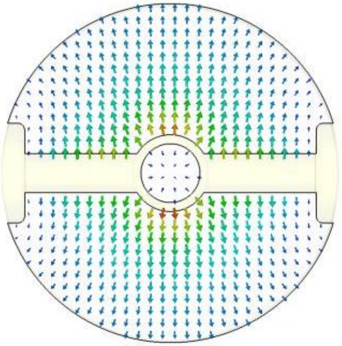
200 MHz TWC of SPS (2/3)

courtesy: E. Montesinos, CERN





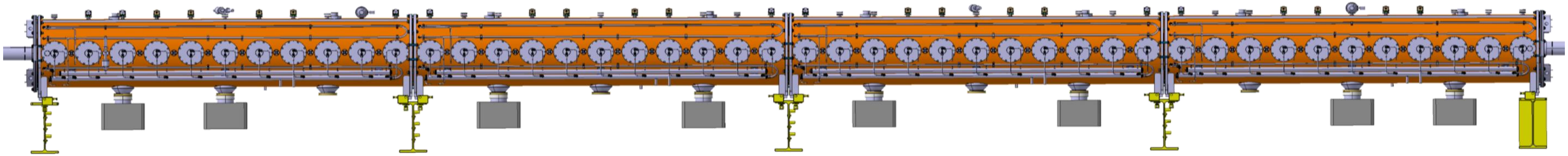
Single cell CST model with symmetries (no HOM coupler)



Electric field of fundamental mode in the Cross-section

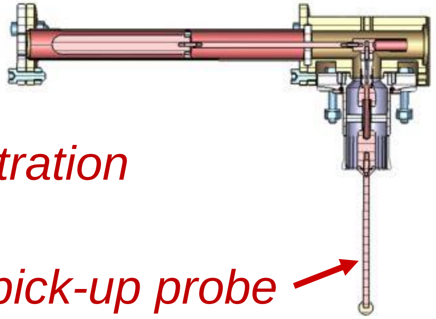
200 MHz TWC of SPS (3/3)

courtesy: E. Montesinos, CERN



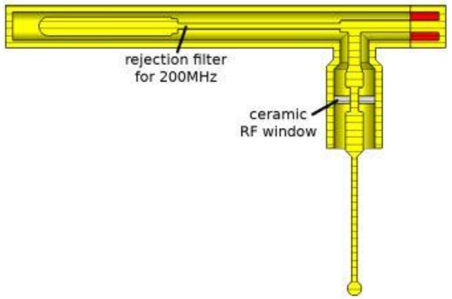
- Cavity is part of the LHC injector chain and was upgraded recently and equipped with new power amplifiers to reach a higher accelerating voltage.

- A number of HOMs are developing, mostly as standing wave and these were taken out by HOM-couplers.
  Most harmful was the mode at 630 MHz, each section of the cavity has a number of these Hom couplers installed:



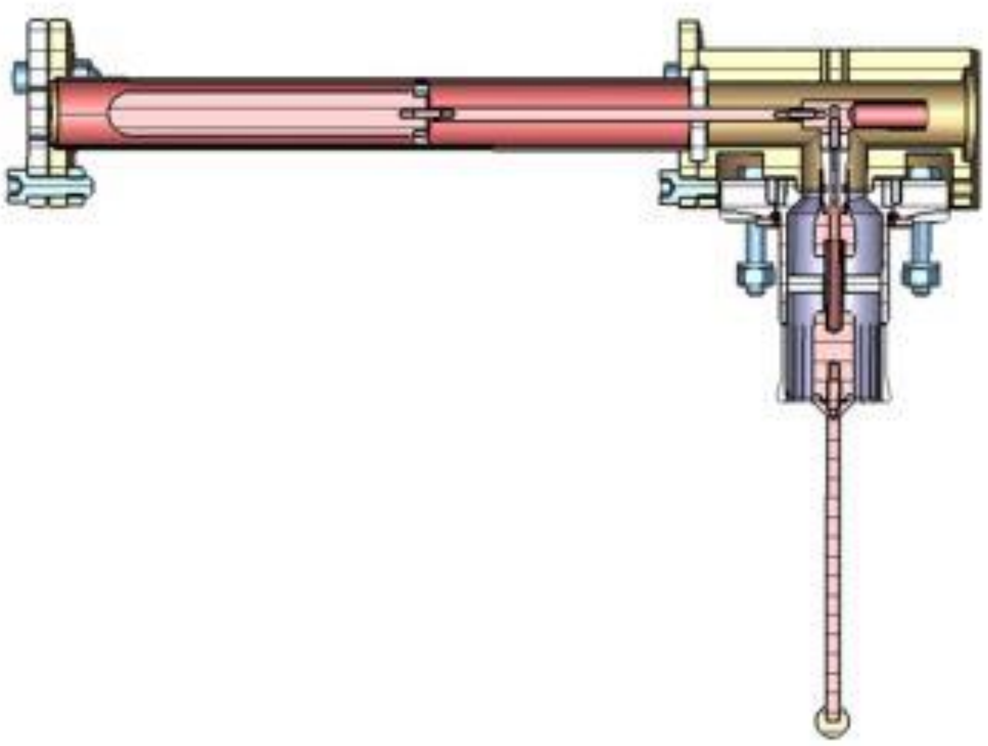
Schematic illustration

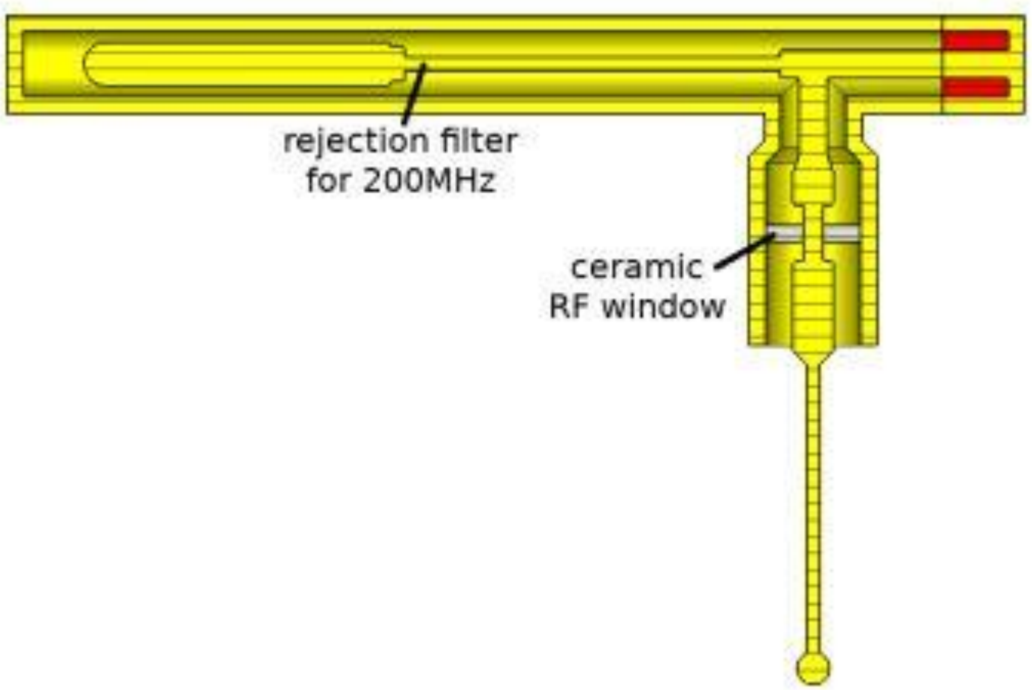
E-field pick-up probe



Modelling in CST
(P. Kramer, CERN)

630 MHz - HOM Couplers

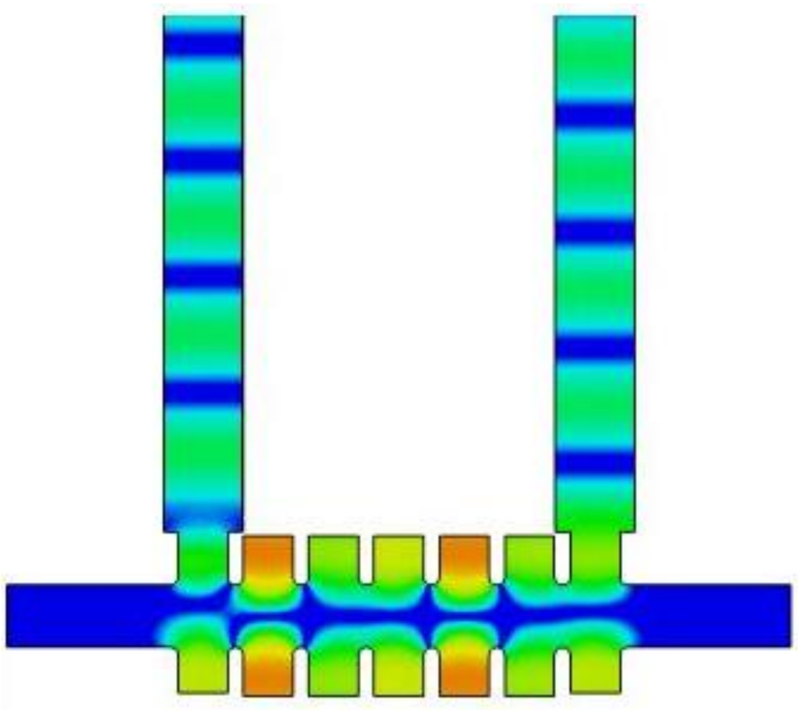




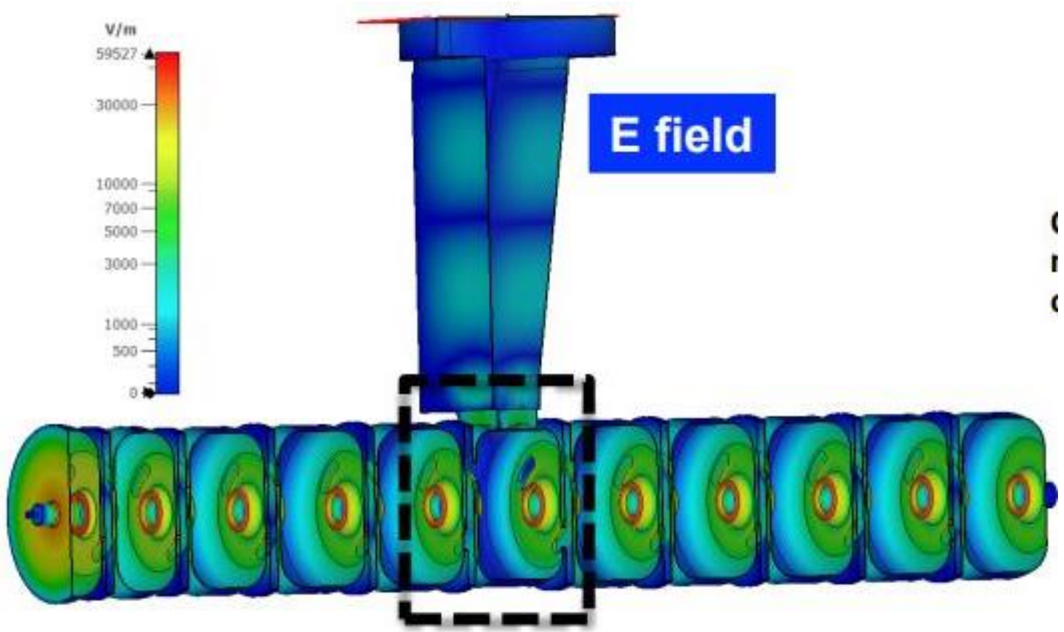
courtesy: E. Montesinos, CERN

Travelling vs. Standing wave

Just to recall: Andrea has already demonstrated the principle of standing and travelling waves in a multi-cell structure with fantastic animations!



travelling wave



standing wave

Large Pillbox-geometries

PS 19 MHz cavity (picture from 1966)

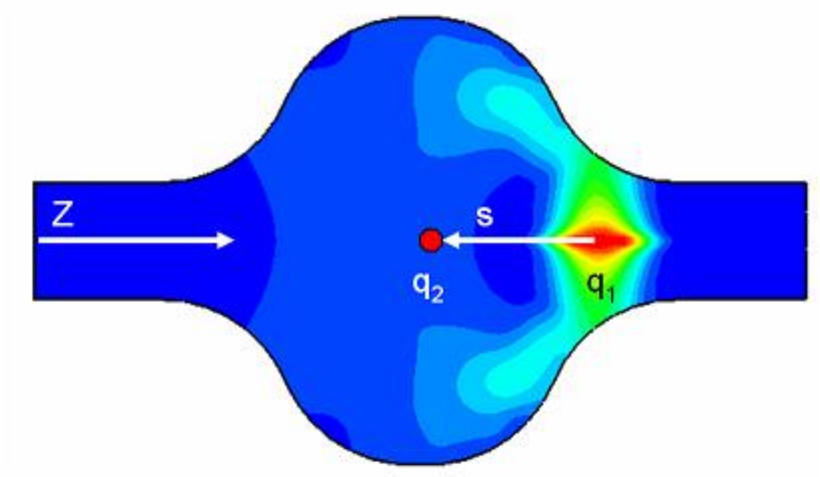
courtesy: E. Jensen, CERN

Inductive coupling loops

courtesy: E. Jensen, CERN

L. Stigelin
Taken from CAS lecture
of H. Damerau, CERN

Beam impedances (from mitigation side…)



Picture from CST indicating a lead charge q1 and a “test charge” q2 following the wake at a distance s.

CST is the program which is most used by our team for wake field calculation.
(www.cst.com)

- Wakefields and beam impedances are used to describe EM-interaction of charged particle beams with its environment.
- Moving particles lead to EM-fields trailing behind which impact on the following particles.

wakefields $\xrightarrow{\text{lead to}}$ wake potentials

$\xrightarrow{\text{Fourier transform to}}$ beam impedance

$$\vec{W}(r_1, s) = \frac{1}{q_1} \int_{-\infty}^{\infty} dz \left[\vec{E}(r_1, z, t) + c\vec{e_z} \times \vec{B}(r_1, z, t) \right]_{t=(s+z)/c}$$

Wake potential calculation from CST

Derivation e.g. in Zotter & Kheifets Impedances and Wakes in High Energy Particle Accelerators, World Scientific, 1998

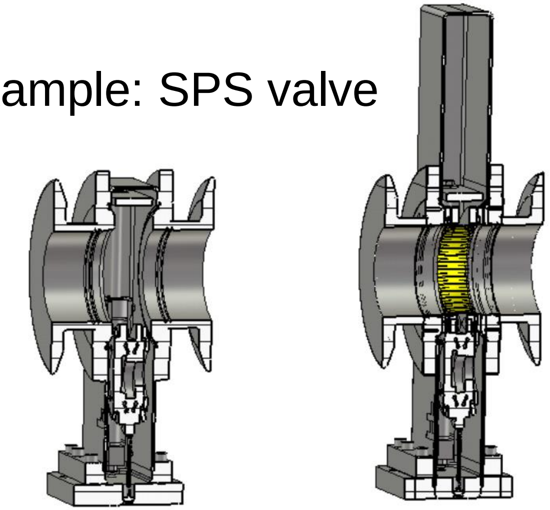
Very good explanations by of M. Migliorati at JUAS lectures!

Beam impedances (from mitigation side…)

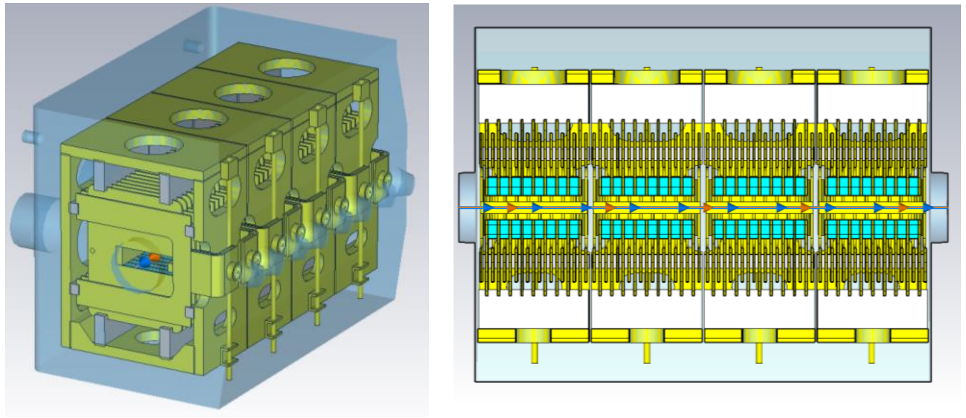
- Beam impedances are problematic since they can cause performance limitations in (mostly circular) accelerators.
- For example: contribution to beam instabilities (see talk of B. Salvant during 1st JUAS lectures).

Charged particle beam generates EM-fields at any cross-sectional change of the vacuum pipe. Therefore, all elements which interrupt the smooth beam pipe gives a contribution to beam impedance and potentially needs to be mitigated.

Example: SPS valve



Example: PS kicker magnet



Beam impedances (from mitigation side…)

Longitudinal EM-fields can impact on:

- Effective amplitude and phase of the accelerating RF-field leading to an impact on the rate of acceleration, the energy distribution in the bunch and the effective bunch length…
- Secondary effect can be an impact on accelerator optics (due to change of momentum), a change of beam focusing or change of closed orbit, and…

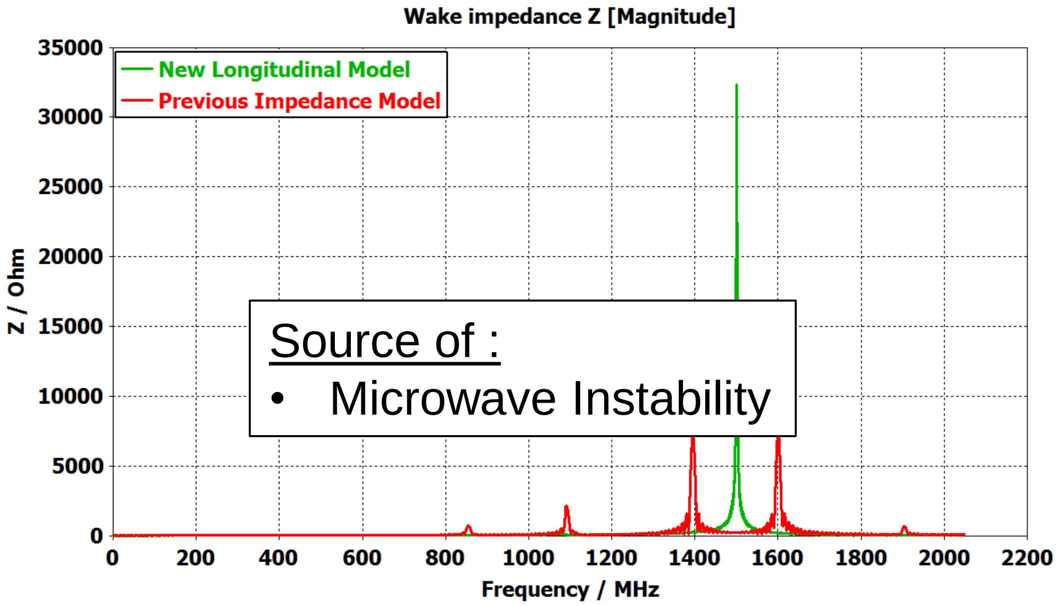
Transverse EM-fields can impact on:

- Cross-section of the particle bunch, change of closed orbit, change of betatron frequency, and…

Both effects increase with higher beam currents and can lead to transverse
or longitudinal beam instabilities.

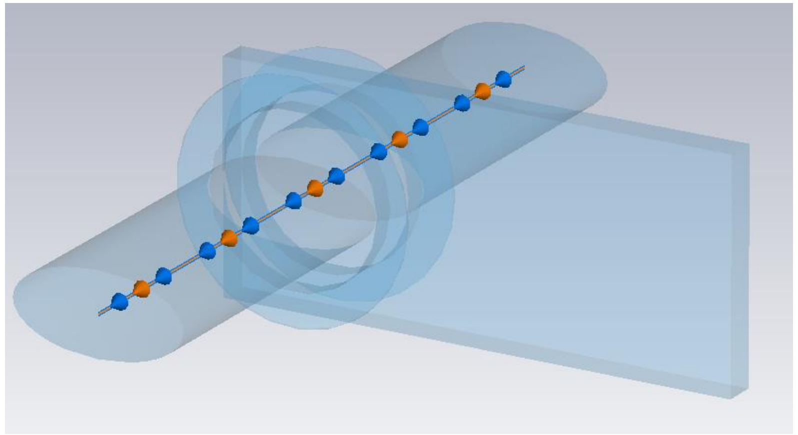
Mitigation of sector valve PS (1/3)
UHV Gate Valve: CST Models

- **10 Valves total**
- **No internal model available**
  - **Not included in previous model**
  - **Proprietary**
  - **Drawn using datasheet**
  - **Measurements necessary**

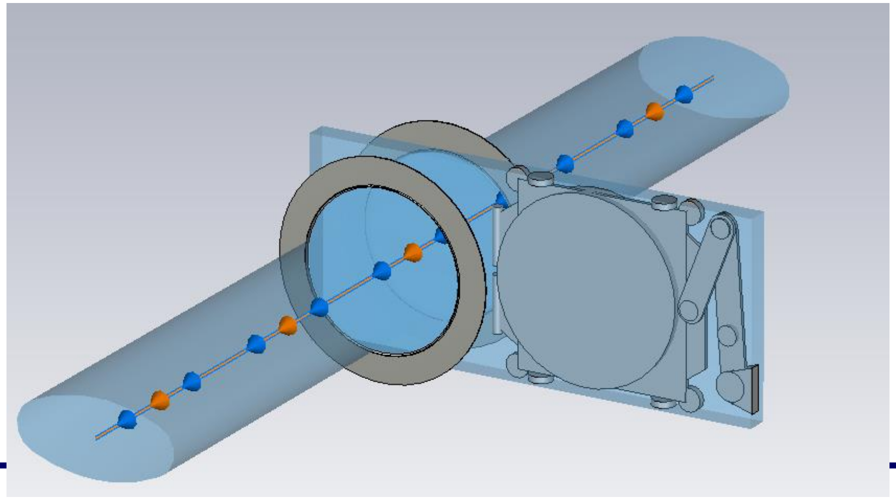


Source of :
- Microwave Instability

Previous Impedance Model



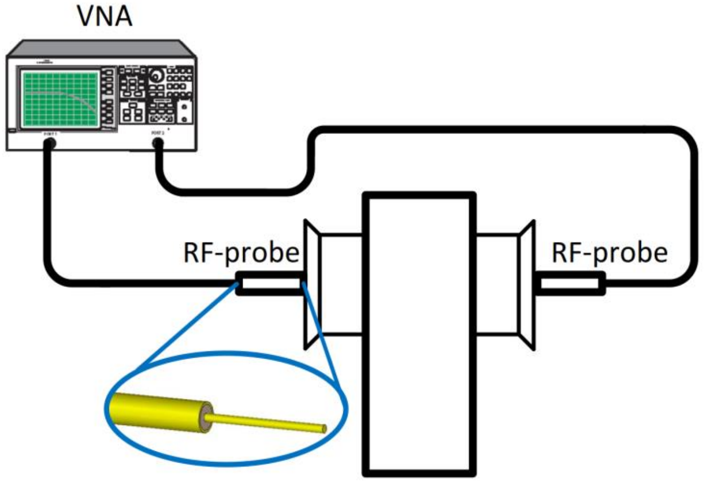
New Longitudinal Impedance Model



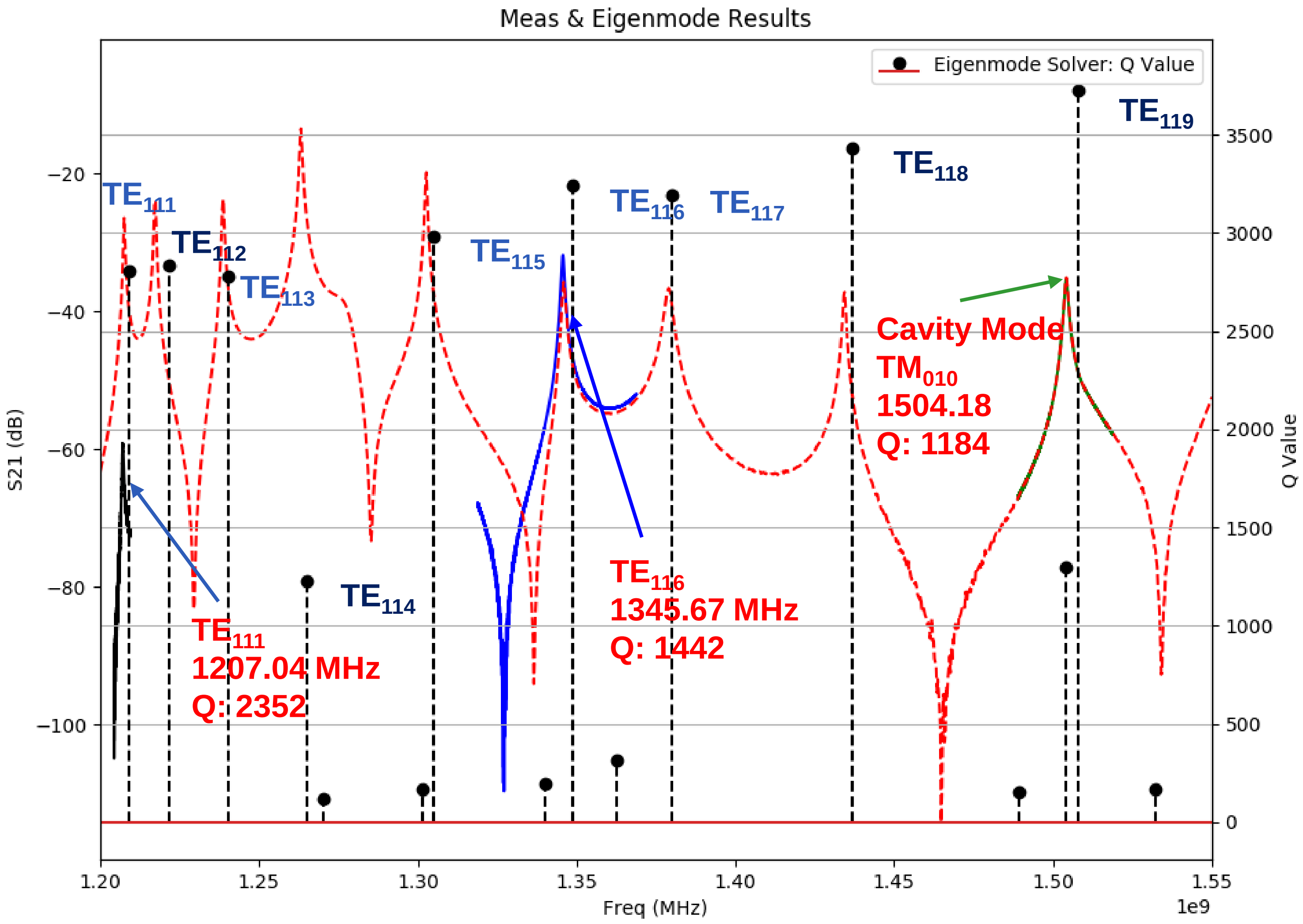
B. Popovic

UHV Gate Valve: Measurement Setup

- Measured using probe method
- Setup closed at both ends
  - Traps travelling wave modes
  - TE_{11p}
- Investigated resonances at
  - 1.2 GHz, 1.34 GHz & 1.5 GHz



Mitigation of sector valve PS (3/3)



TE$_{111}$
1207.04 MHz
Q: 2352

TE$_{116}$
1345.67 MHz
Q: 1442

Cavity Mode
TM$_{010}$
1504.18
Q: 1184

UHV Gate Valve: Comparing Measurement & Simulation Results

Thank you for your attention!