HOM Mitigation

Dealing with Higher Order Modes in Accelerating Structures

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CAS course on 'RF in Accelerators'
Berlin, Germany
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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Wakefields

HOMs

Issues due to HOMs

1. Intro: What do you know about HOMs?

From this school only!

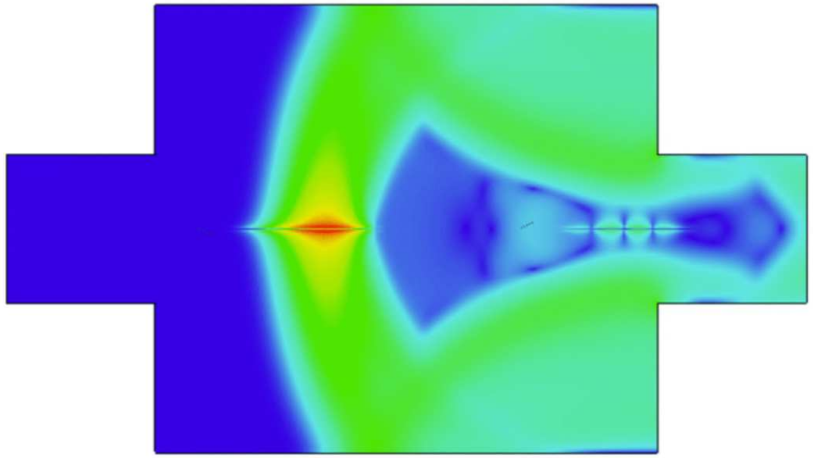
?

1. Intro: Wakefields

Brief reminder

- **Wake**: definition from Merriam-Webster
  (https://www.merriam-webster.com/dictionary/wake)
  (among other meanings)
  - 1: the track left by a moving body (such as a ship) in a fluid (such as water); broadly: a track or path left
  - 2: aftermath (the period immediately following a usually ruinous event)

- **In an accelerator**
  - 1: Electromagnetic "track" left behind by the beam
  - 2: "Usually ruinous"? → can be → one has to know the possible danger in order to avoid it



Courtesy of S.A. Udongwo

⇒ Know your wakefields

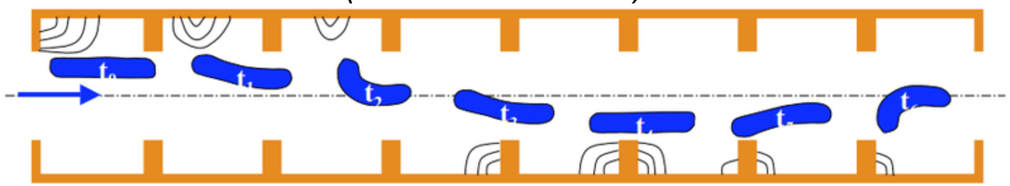
1. Intro: Wakefields

Brief reminder (2)

- Different types:
  - Geometrical, resistive wall, rugosity
  - Longitudinal or transverse
  - Short or long range
- Short-range wakefields:
  - effects within the bunch:
    increase in energy spread, emittance
  - Often treated in time domain
- Long-range wakefields:
  - effects from bunch to bunch:
    increase of multi-bunch
    energy spread or emittance
  - Usually treated in frequency domain
    → HOMs

see lecture on
"Impedances and wakefields"
by Andrea Mostacci
and many others!

Single bunch beam breakup
("banana" effect)



W. Barletta, USPAS 2010

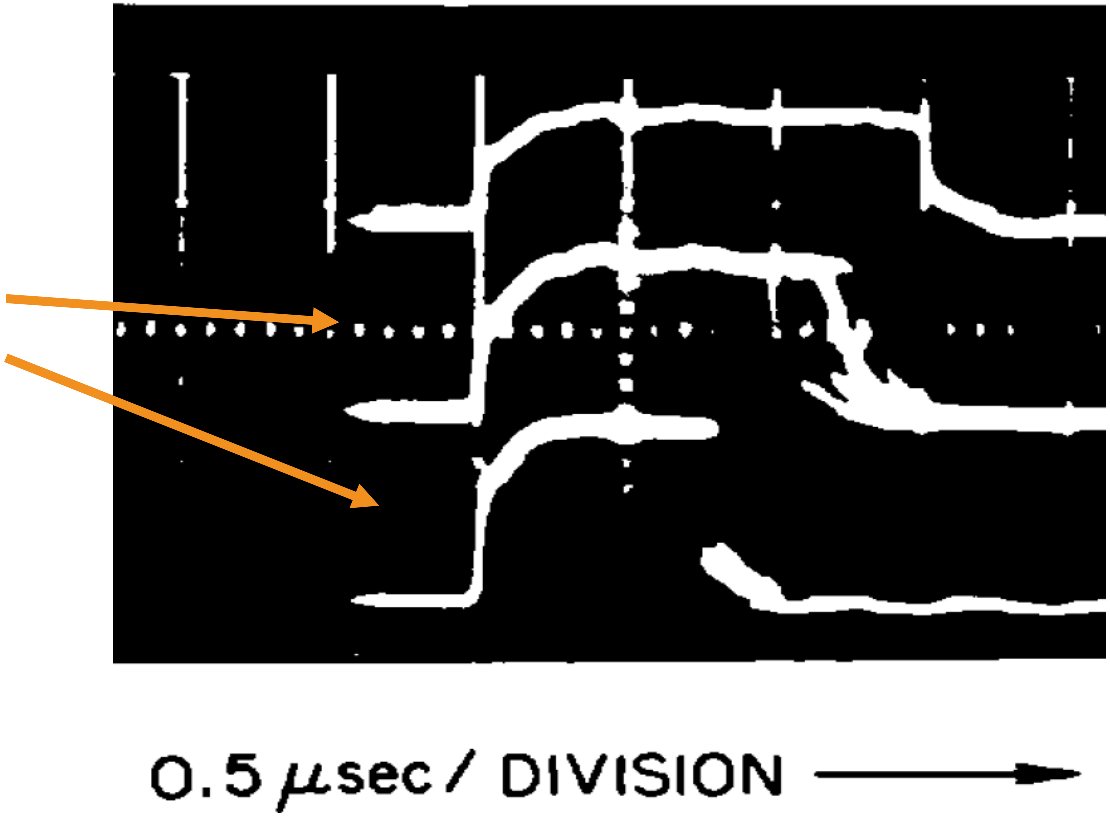
- **This lecture**
  - Long-range wakes/multi-bunch effects
  - Geometrical wakes
  - In accelerating structures

1. Intro: Wakefields

Why worry with long-range wakes?

Beam breakup observed at SLAC 1966

pulse cut for currents above some threshold



R.B. Neal (ed.), The Stanford two mile accelerator, 1968

- Found to be due to the beam interaction with one dipole mode

1. Intro: Higher Order Modes

Brief reminder: Longitudinal long-range wakefields

- Longitudinal wakefields can be described as a sum of HOMs for cylindrically symmetric structures

$$W_{||}(s) = \sum_n 2k_n \cos\left(\omega_n \frac{s}{c}\right) e^{-\frac{\omega_n}{2Q_n}\frac{s}{c}}$$

n = mode count

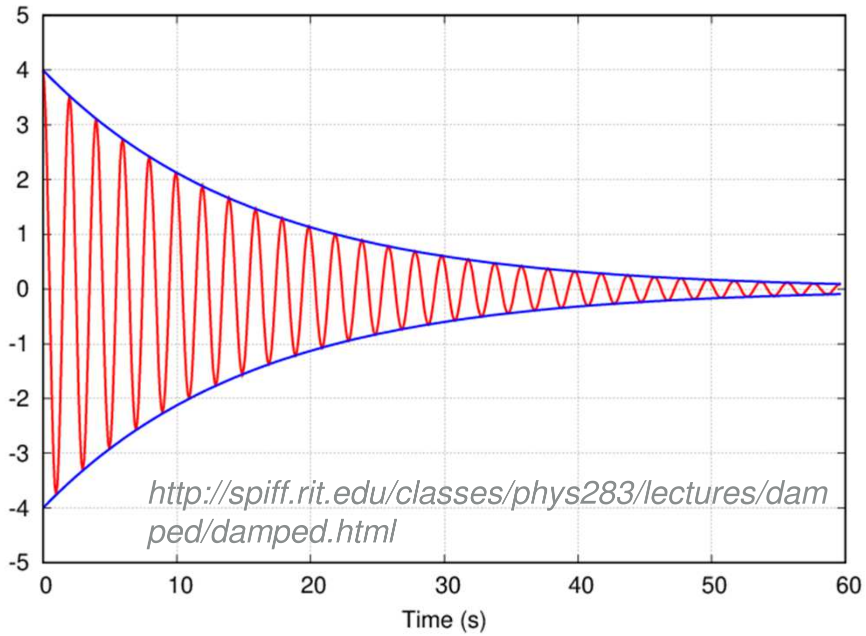
- Longitudinal **loss factor**: $\boldsymbol{k_n = \frac{|V_n(r,\omega_n)|^2}{4U_n}}$ (V/pC)

  or equivalent R/Q factor (linac definition):

$$k_n = \frac{\omega_n}{4}\left(\frac{R}{Q}\right)_n$$

→ Strength of interaction between beam and mode
→ Given only by geometry

s: distance behind the excitation particle
U_n: energy stored in the mode
V_n: voltage seen by the particle



http://spiff.rit.edu/classes/phys283/lectures/damped/damped.html

1. Intro: Higher Order Modes

Brief reminder: Longitudinal long-range wakefields (2)

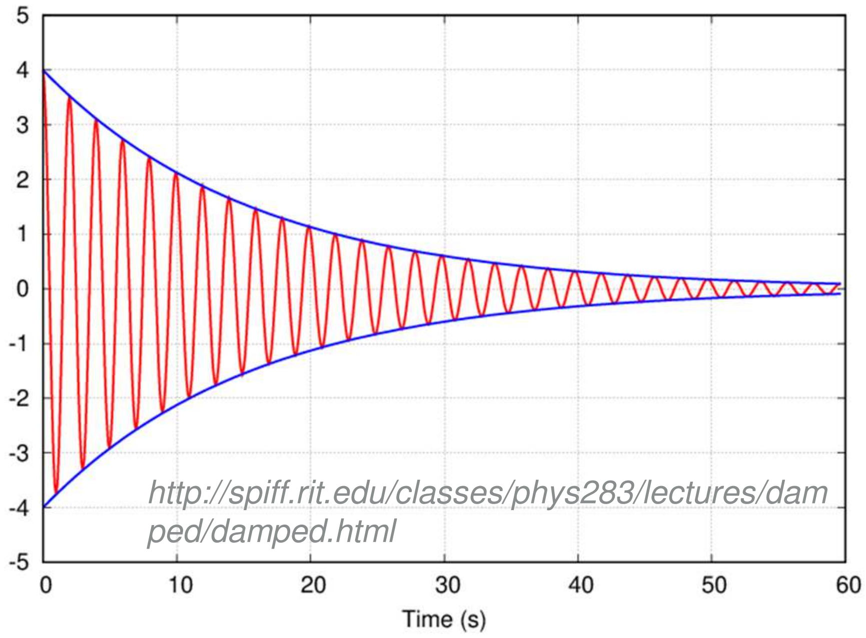
$$W_{||}(s) = \sum_n 2k_n \cos\left(\omega_n \frac{s}{c}\right) e^{-\frac{\omega_n}{2Q_n}\frac{s}{c}}$$

- The **quality factor** gives the decay time

$$Q_n = \omega_n \cdot \frac{stored\ energy}{power\ loss}$$

- → The material of the structure gives the intrinsic Q_0 of a mode
- Additional components (ports) can also damp the HOMs → Q_{ext}

$$1/Q_{total} = 1/Q_0 + 1/Q_{ext}$$



1. Intro: Higher Order Modes

The CERN Accelerator School

Brief reminder: Transverse long-range wakefields

- Transverse wakes:
  strongest contribution is usually given by dipole modes

$$W'_{\perp}(r,s) = \sum_n 2k'_{n\perp}(r)\sin\left(\omega_n \frac{s}{c}\right) e^{-\frac{\omega_n}{2Q_n}\frac{s}{c}}$$

(transverse dipole wake)

- Transverse dipole kick factor:

$$k'_{n\perp} = \frac{ck_n}{\omega_n r^2} \quad \text{(V/pC/mm}^2\text{)}$$

(normalized to beam offset squared,
sometimes also to the structure length)

$\Rightarrow$ It is enough to calculate the longitudinal loss factor (or R/Q)
(Panofsky-Wenzel theorem)

1. Intro: Higher Order Modes

Brief reminder: Characteristics of resonant modes

- Resonant frequency $f_n = \omega_n/2\pi$

- Loss factor k_n or equivalent $(R/Q)_n$

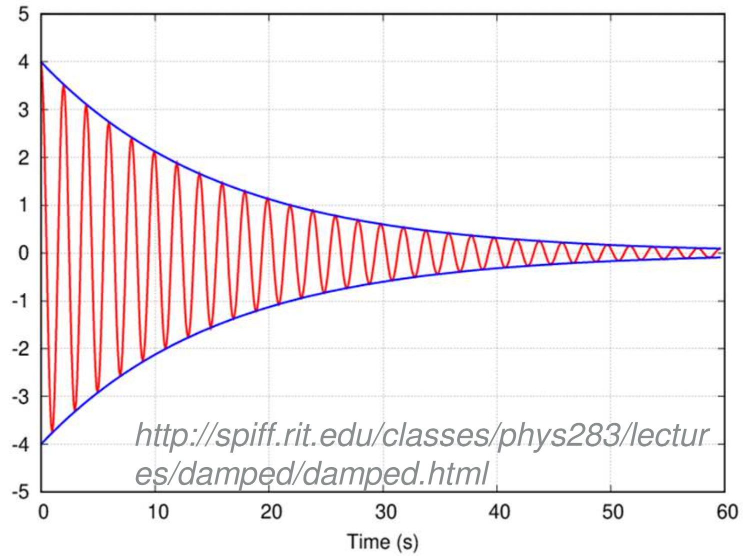
$$k_n = \frac{|V_n(r,\omega_n)|^2}{4U_n};\ k_n = \frac{\omega_n}{4}\left(\frac{R}{Q}\right)_n$$

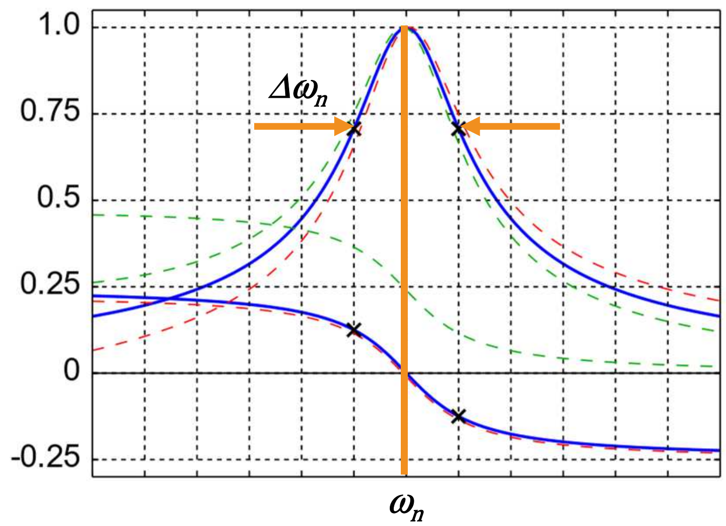
- Quality factor: $Q_n = \omega_n \cdot \frac{stored\ energy}{power\ loss}$

$$Q_n = \omega_n/(\Delta\omega_n);\ \tau_n = 2Q_n/\omega_n$$

- Field distribution, polarization etc.

Know your HOMs!



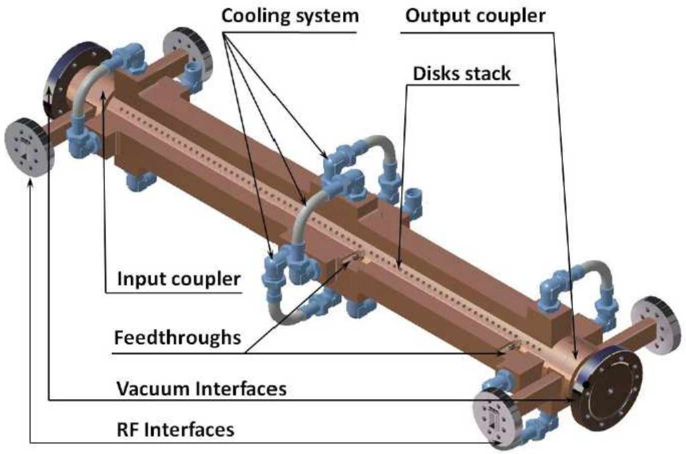


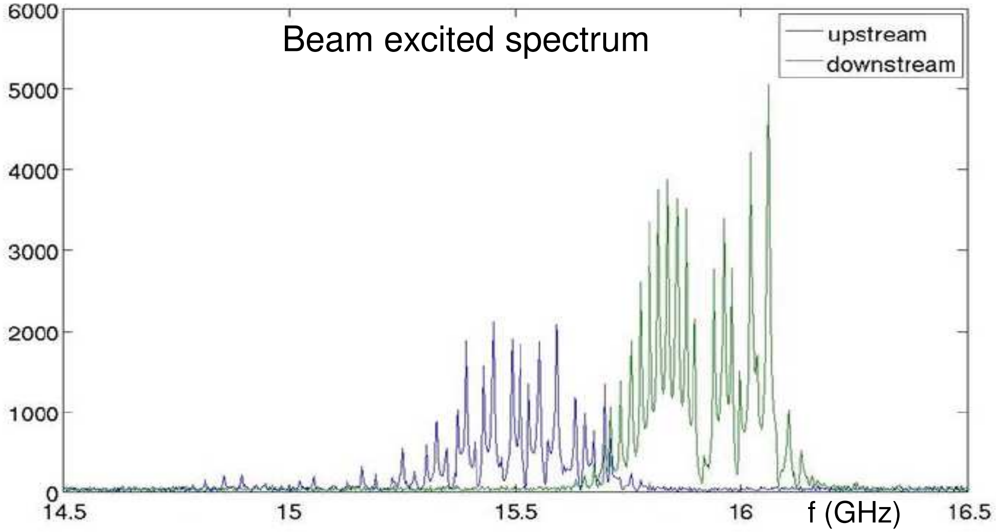
https://en.wikipedia.org/wiki/Resonance

1. Intro: Higher Order Modes

Brief reminder: HOM spectra (examples)

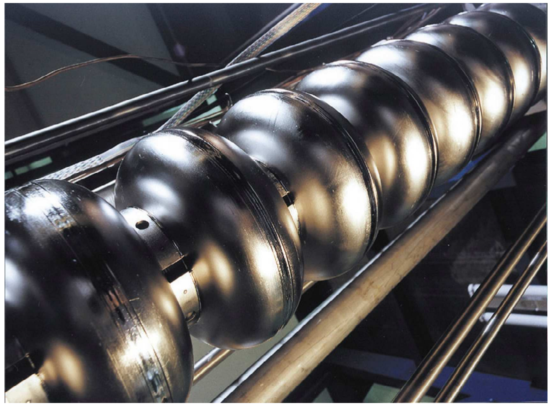
- X-band structure at the Swiss-FEL



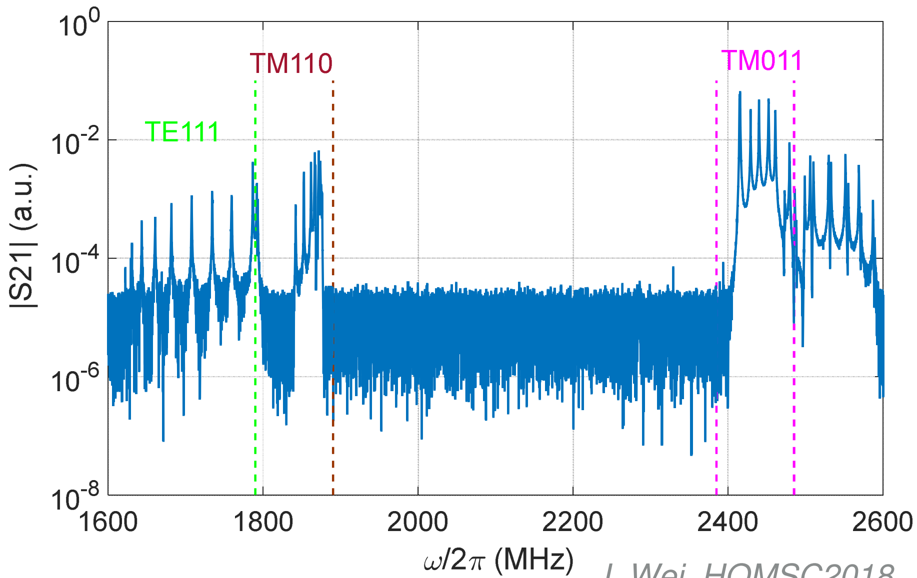


M. Dehler, IBIC2013, WEBL3

- TESLA cavity at FLASH/European XFEL



DESY

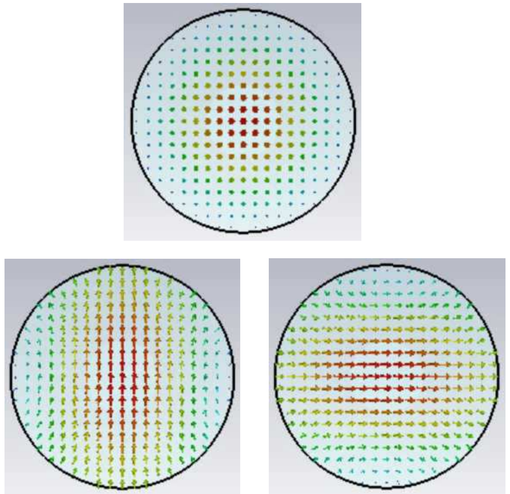


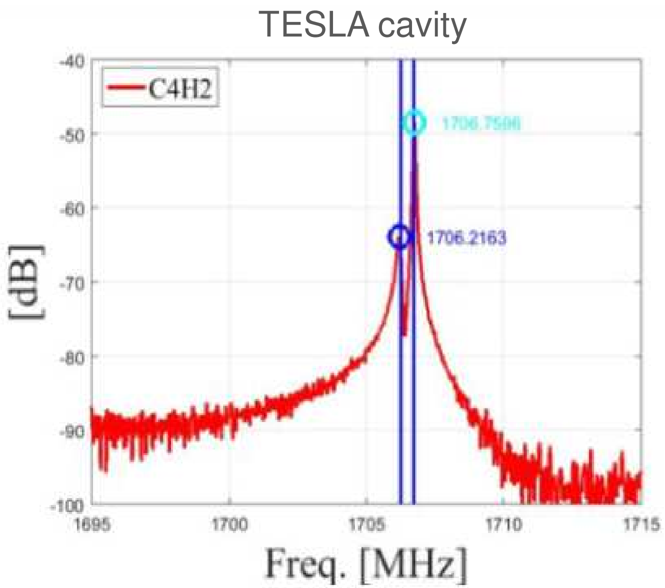
J. Wei, HOMSC2018

1. Intro: Higher Order Modes

Brief reminder: Dipole modes

- Monopole modes:
  - Always excited
- Dipole, quadrupole modes etc.
  - Excited only by off-axis beams
  - Come in pairs (polarizations) with equal frequencies for circularly symmetric structures
- Zoom into measured spectrum (dipole mode)
  - Frequency split due to asymmetries
  - Polarization not always horizontal and vertical



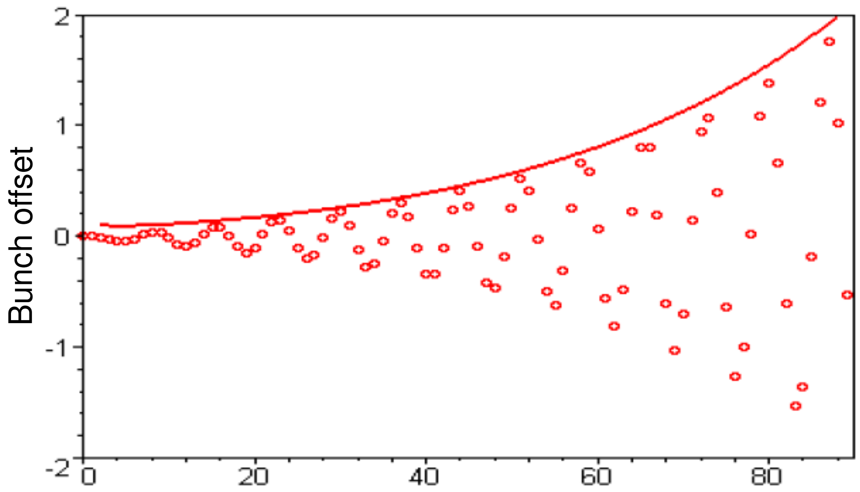


J. Wei, FEL Seminar, DESY, 20.08.2019

1. Intro: Issues due to HOMs

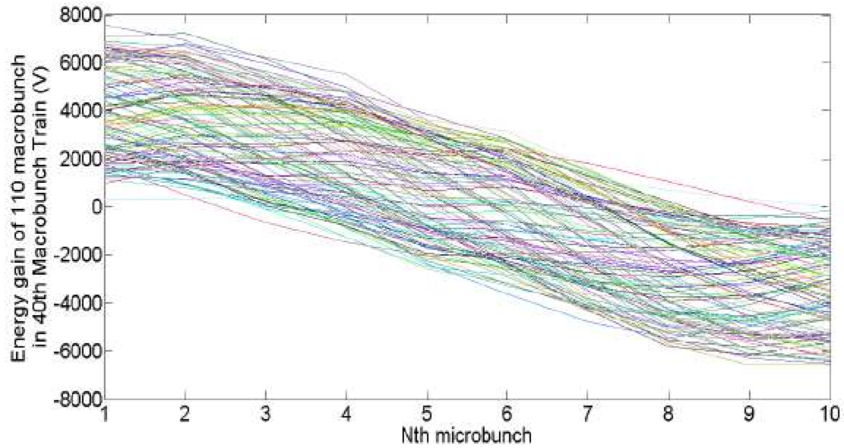
HOM effects on the beam

- Transversely:
  increase in multi-bunch emittance



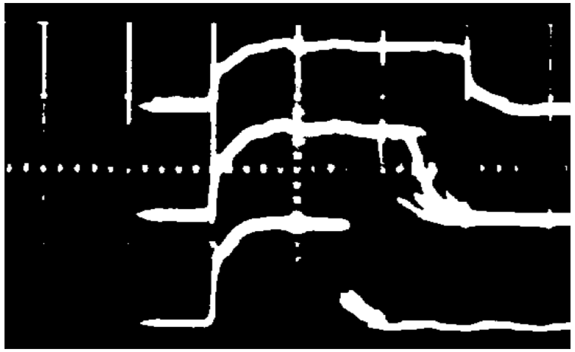
C. Bohn, K. Ng, LINAC 2000

- Longitudinally:
  increase in multi bunch energy spread



Chen Xu, AAC 2016

Extreme case: beam breakup



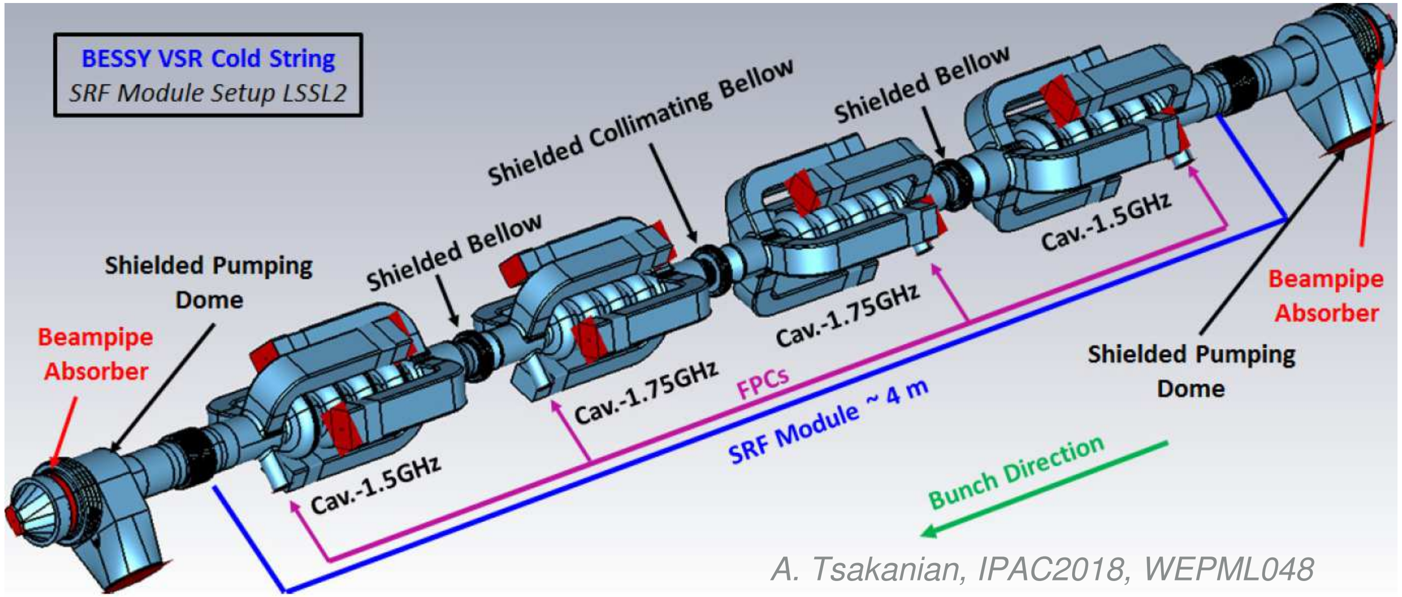
Worst effects at low energies

1. Intro: Issues due to HOMs

Further HOM effects

- Power damped into the accelerating structures or other components

BESSY VSR cold string



- BESSY VSR: HOM power estimated: of the order of 1 kW propagating out of the cold string; tens of W in each HOM load

1. Intro: HOM Mitigation

Ways to deal with HOMs

- Avoid them
- Compensate their effects
- Use them

Contents

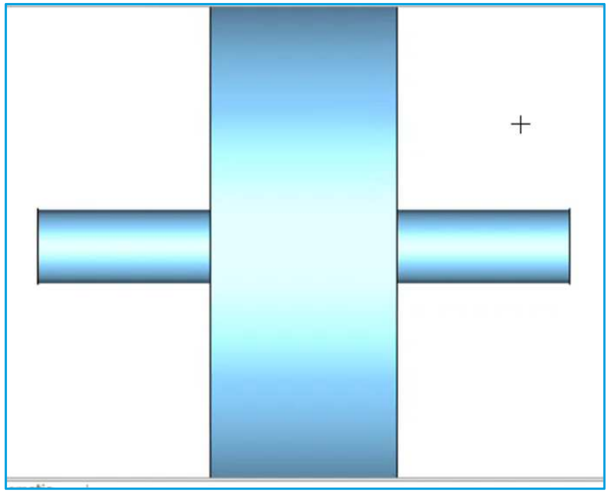
Accelerating Structure Design

Accelerator Design

2. Avoid HOMs: Structure Design

Geometry

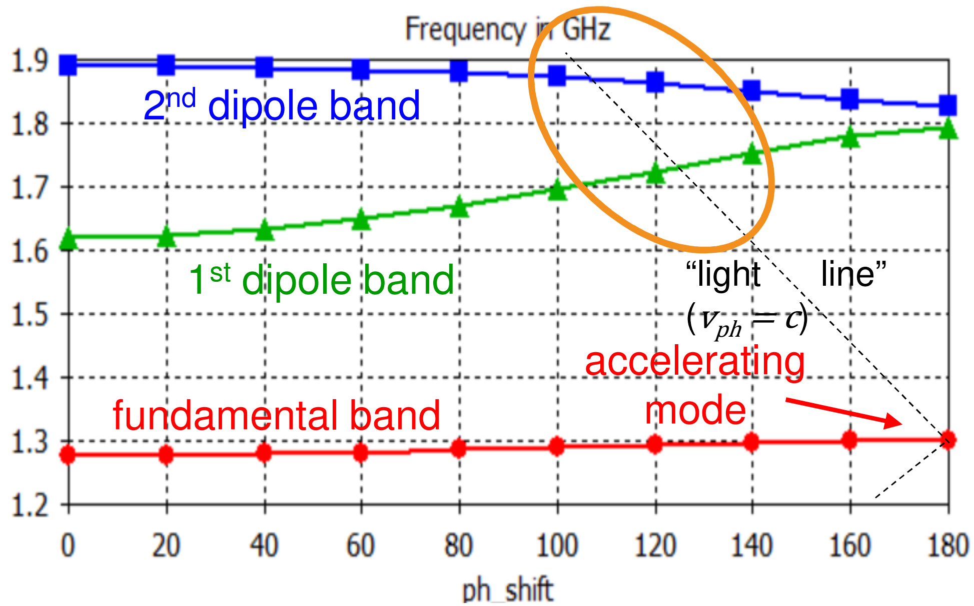
- Optimize the cell geometry for low loss factors for HOMs, while aiming at high value for the accelerating mode
  - Remember: the loss factor depends only on the geometry



Courtesy of S.A. Udongwo

- For multi-cell structures pay particular attention to the quasi synchronous modes

Dispersion diagram of a TESLA cavity
(single cell simulation with periodic boundaries)



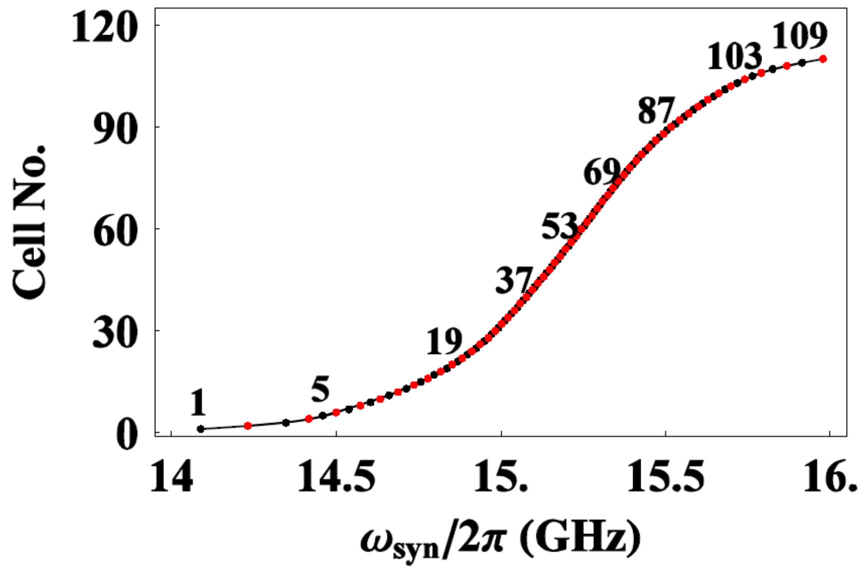
2. Avoid HOMs: Structure Design

Geometry (2)

- Avoid to have HOMs with frequency matching a bunch harmonics
  - That would give a resonant amplification along bunch train

- Detune cells along (long) structure
  - Vary cell dimensions along a NC structure
    ⇒ overall HOM effects decohere

Interleaving of cell frequencies
of a structure for CLIC



R.M. Jones, CAS 2010

2. Avoid HOMs: Structure Design

Material

- Choose material of the cavity walls for low HOM quality factors Q_0.

- However this is decided by the purpose of the cavity:
  choice of technology, type of beam to be accelerated, etc.

- This determines the Q_0 of the HOMs

2. Avoid HOMs: Structure Design

HOM damping: Requirement

- Add something to extract HOM fields, but leave accelerating fields untouched

$$\mathbf{1/Q_{total} = 1/Q_0 + 1/Q_{ext}}$$

  - if $Q_{ext} \ll Q_0 \Rightarrow Q_{total} \cong Q_{ext}$

- How much damping is enough?
- Requirement: from BBU models or beam dynamics calculations

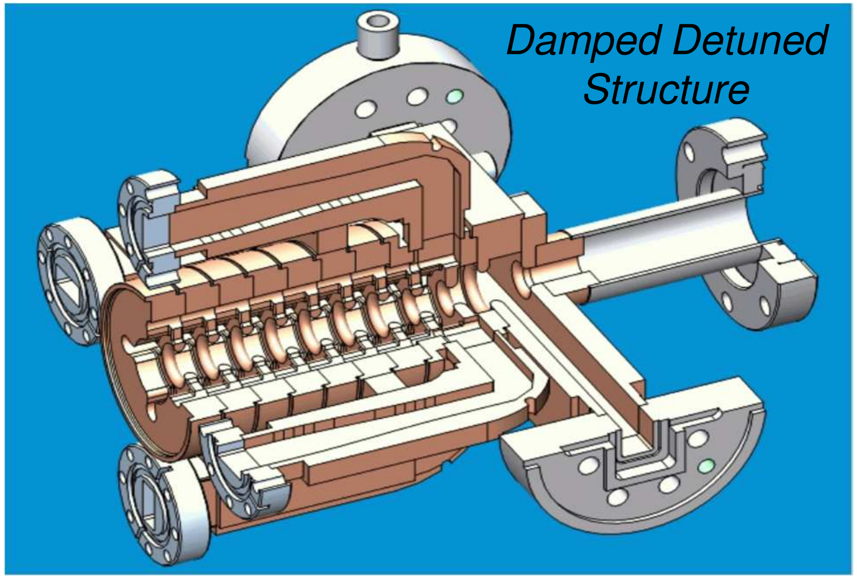
  e.g.

  - lecture on “*Longitudinal instabilities & Intensity effects*” *by Elena Shaposhnikova*
  - *W. Lou et al., PRAB-ST **22**, 112801 (2019)*
  - *N. Baboi, EPAC2000, THP3B05*

2. Avoid HOMs: Structure Design

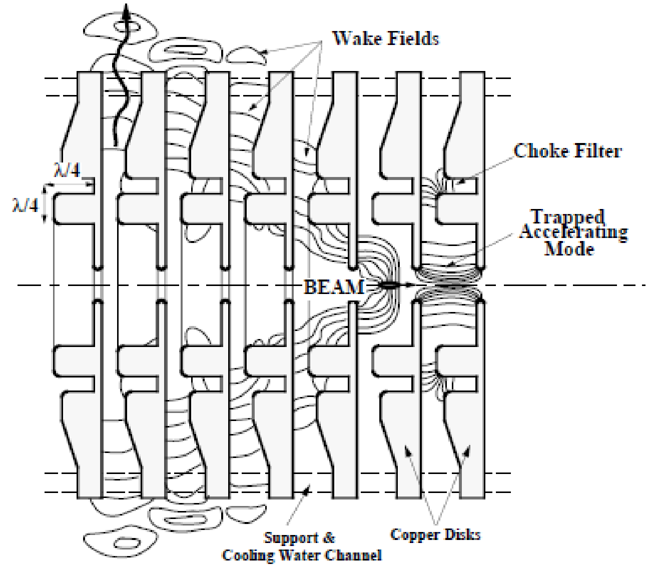
HOM damping in each cell

- Add ports in each cell: waveguides, couplers
- Notch filter at the accelerating frequency



R.M. Jones, CAS 2010

HOM-free linear accelerating structure using choke mode cavity



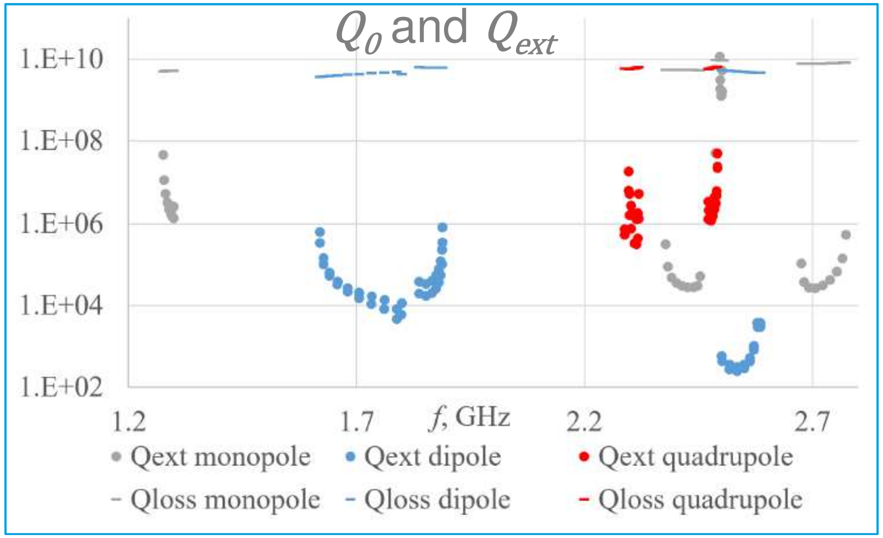
T. Shintake, PAC'95

- Particularly good for trapped modes in detuned structures

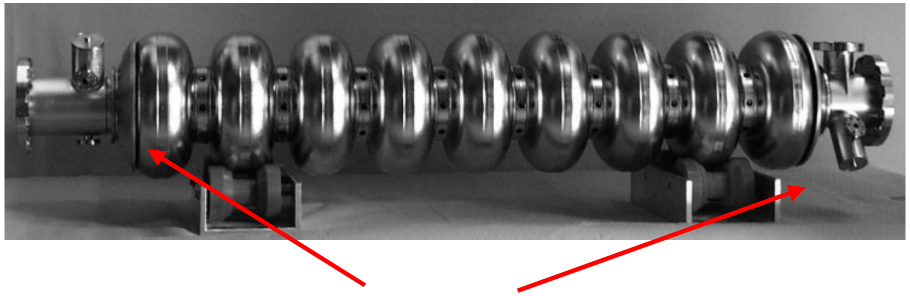
2. Avoid HOMs: Structure Design

HOM damping at end of structure

- Add ports at the end of the accelerating structure: waveguides, couplers



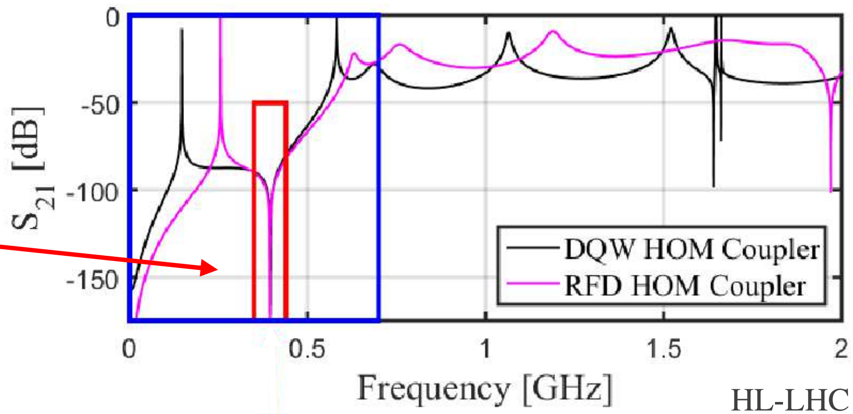
TESLA cavity used in MESA



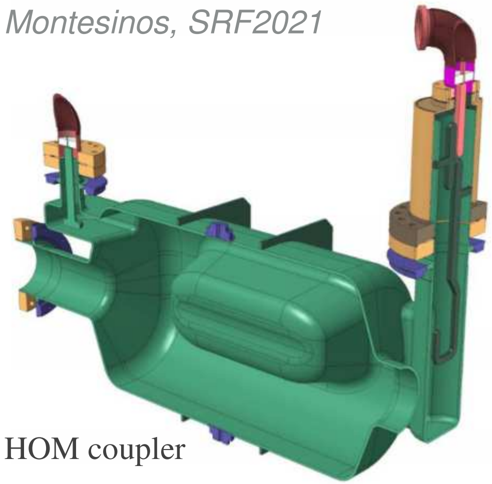
HOM couplers

S. Glukhov, PhD thesis, TU Darmstadt, 2022

- Notch filter at the accelerating frequency



E. Montesinos, SRF2021



HL-LHC RFD HOM coupler

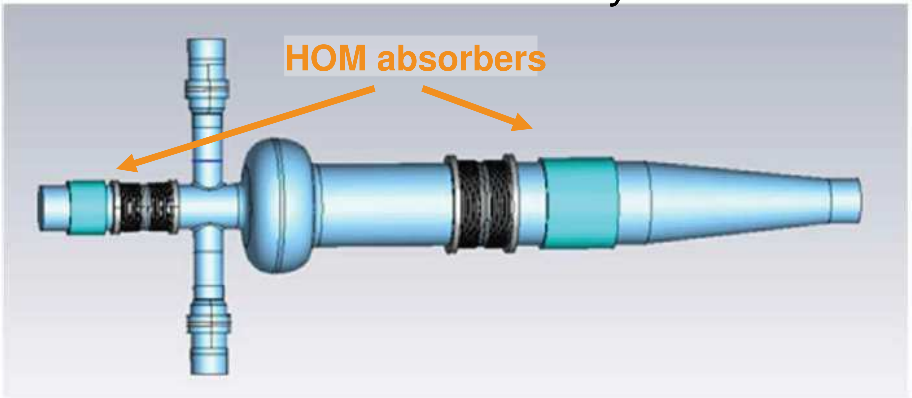
2. Avoid HOMs: Structure Design

HOM damping in the beam pipe

- Damping materials:
  HOM absorbers in the beam pipe

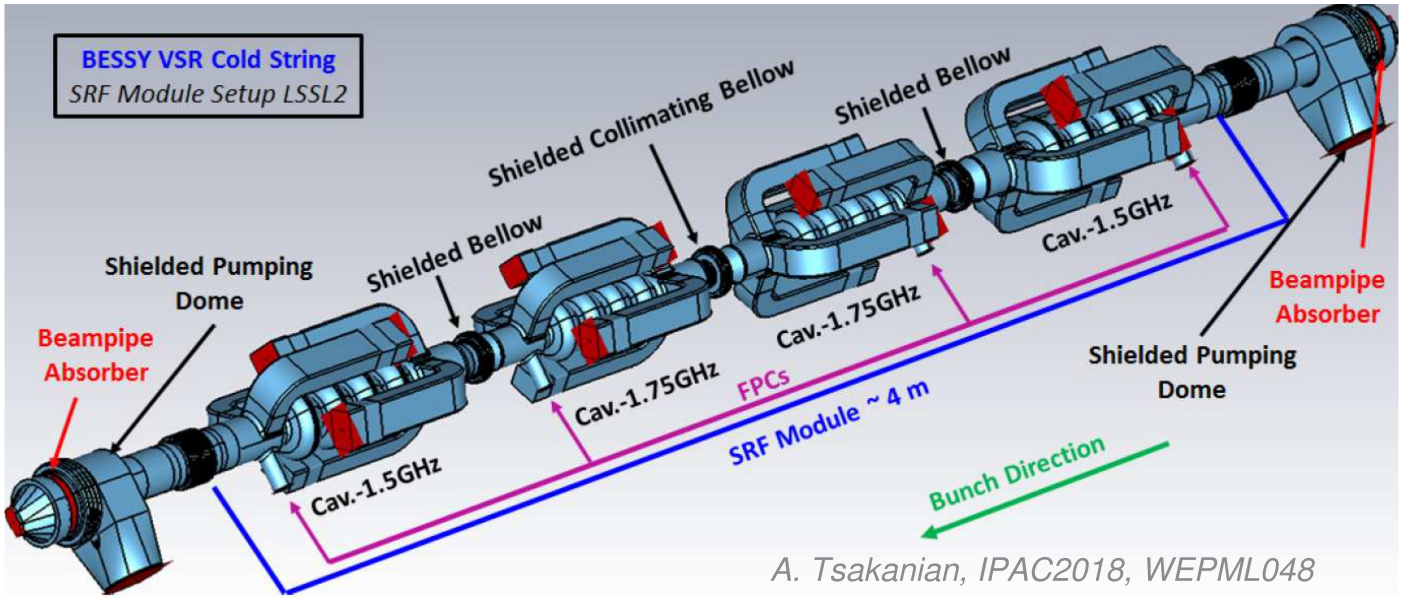
- The accelerating frequency is below the cut off of the beam pipe

591 MHz 1-cell SRF cavity at BNL



R. Rimmer, eeFACT2022, WEXAS0101

BESSY VSR cold string



A. Tsakanian, IPAC2018, WEPML048

2. Avoid HOMs: Accelerator design

The CERN Accelerator School

Accelerator design

- Design optics such that the HOM effects are not dramatic
  - E.g. Recirculation Arcs Lattice Optimization in ERLs
  - Add non-linear elements etc.

- Choose bunch frequency (or design accelerator) such that the strongest HOMs are not at bunch multipoles, so that they do not add up coherently
  - Often not a real option

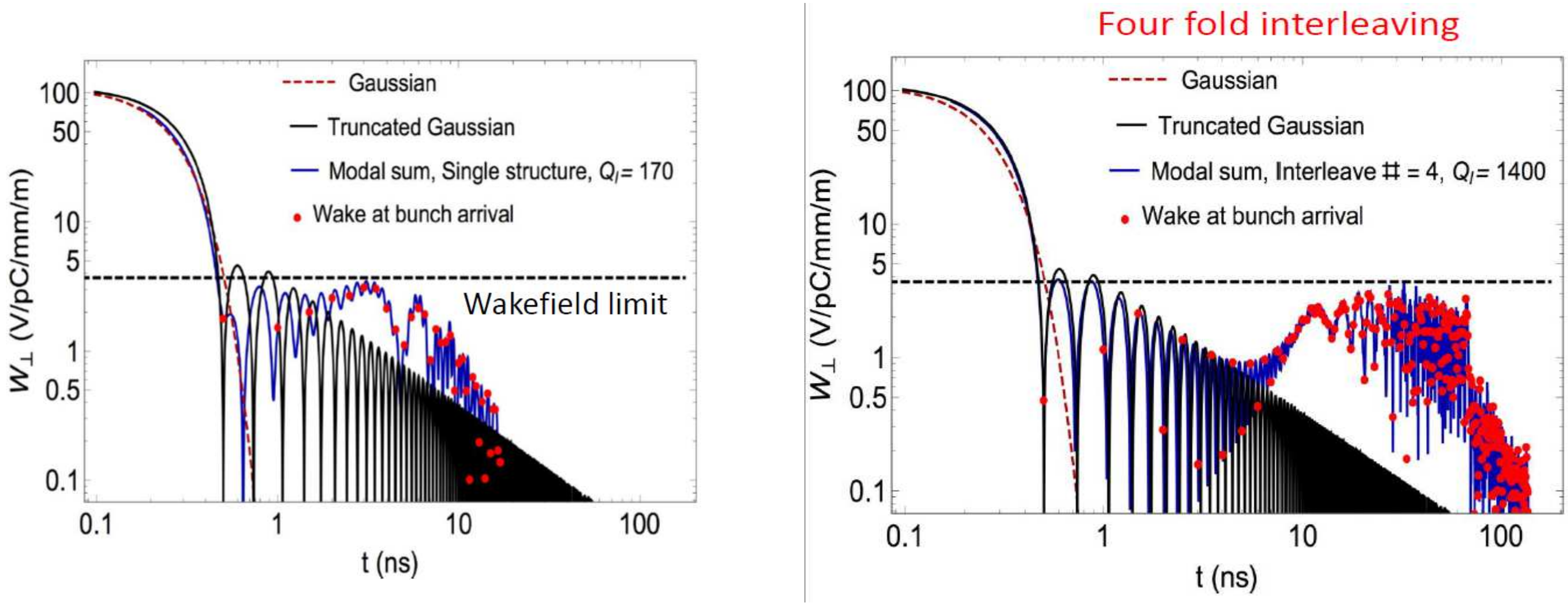
S. Glukhov, PhD thesis, TU Darmstadt, 2022

2. Avoid HOMs: Accelerator design

Structure interleaving

- Make 2 or more slightly different designs (classes) for the accelerating structure such that the long-range wakefields do not add up coherently from structure to structure

Interleaving for CLIC structures



N. Joshi, EuCARD-2 Meeting, 2017

Contents

Fast Feedbacks

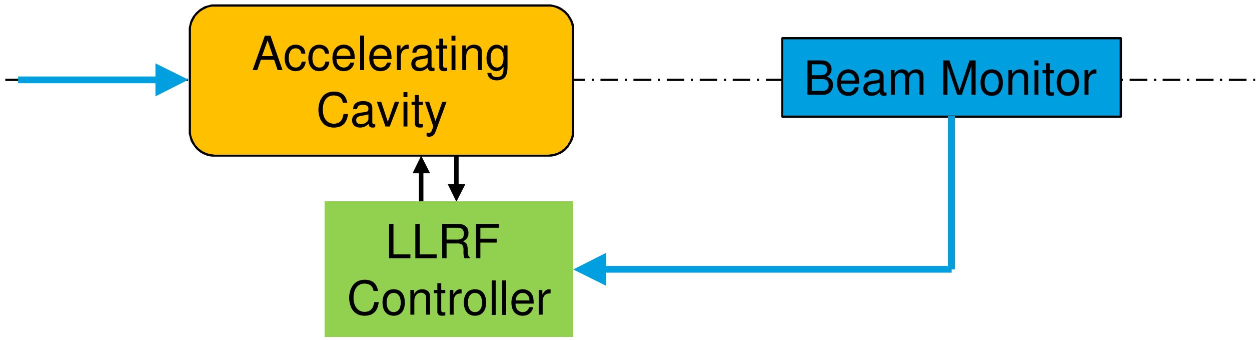
Beam Alignment

Cavity detuning and retuning

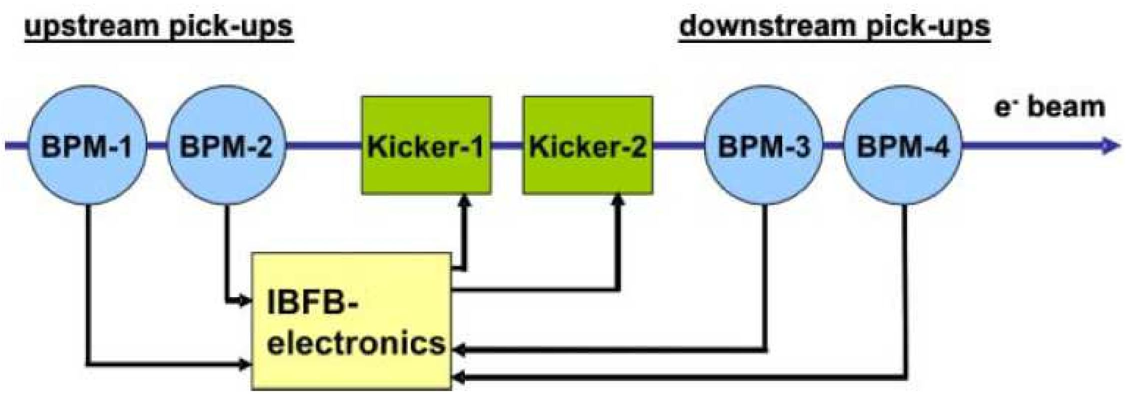
3. Compensate HOMs: Fast Feedbacks

Compensation of spread in bunch arrival time and beam offset

- Longitudinal HOMs induce a variation of the bunch energy, and therefore the bunch arrival time (or beam phase)
  - Measure beam arrival time, energy etc. → feedback to LLRF



- Transverse HOMs induce a spread in the bunch orbit (multi-bunch emittance growth)
  - Fast orbit feedback



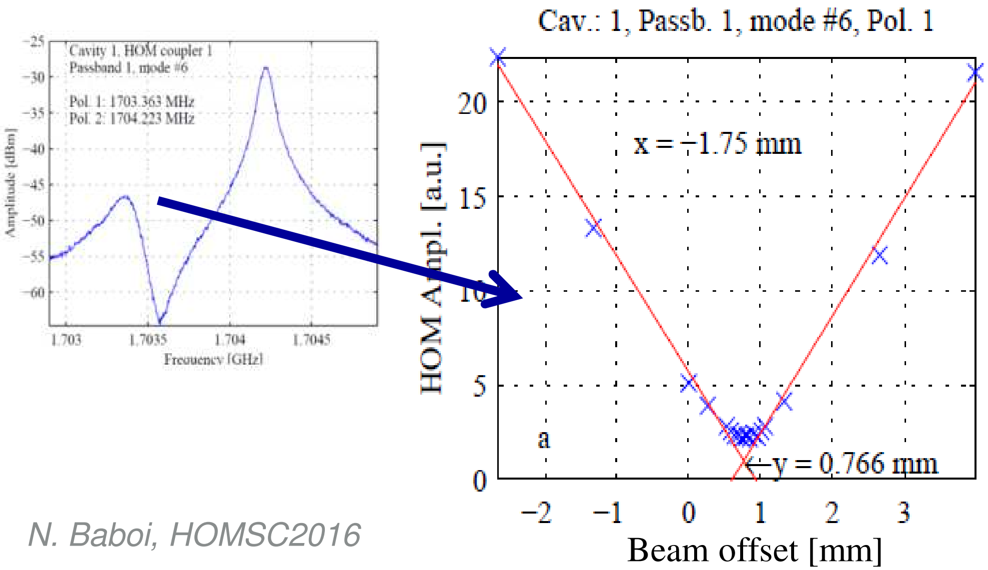
V. Schlott, EPAC 2006, THPCH096

3. Compensate HOMs: Beam Alignment

Beam alignment to avoid transverse HOM excitation

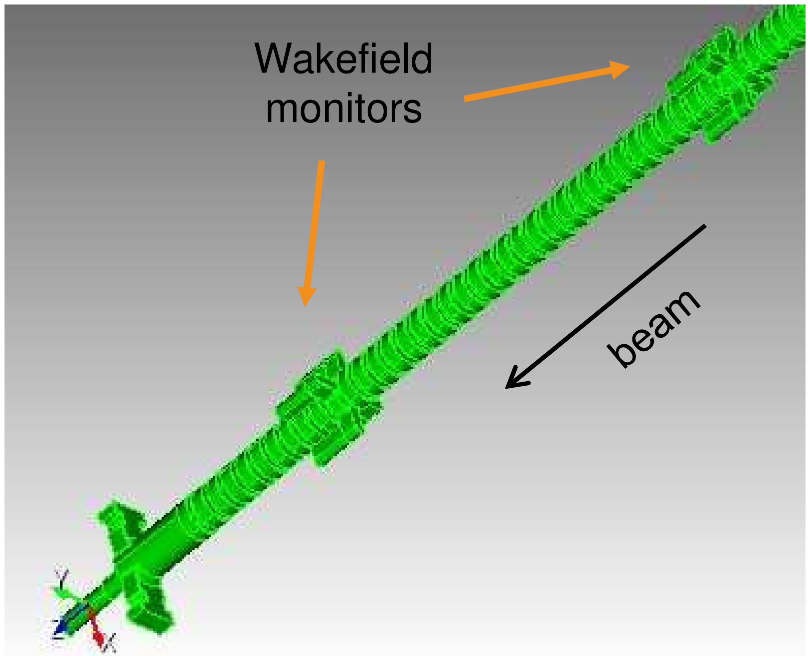
- Transverse effects mainly from dipole modes
- The dipole fields depend only on the offset of the exciting bunch
- ⇒ Monitor dipole modes through couplers, and align the beam to minimize their strength

Amplitude of dipole mode signal versus exciting bunch offset for a TESLA cavity



N. Baboi, HOMSC2016

Dedicated alignment monitors in a X-band structure



M. Dehler, PRST-AB 12, 062001 (2009)

3. Compensate HOMs: Retuning

Cavity detuning and retuning

- It may happen that one HOM unluckily hits a beam spectrum line
  - $\Rightarrow$ Resonant amplification of HOM field

- Detune and retune the operating mode back to the resonance
  - HOMs move because of small inelastic deformation

Detuning and retuning a 1.3 GHz ILC-type cavity

F, MHz	ΔF, kHz	δF, Hz	Passband
1300	90	0	1Monopole
1600.093	-218	360	1Dipole
1604.536	-215	240	1Dipole
1607.951	-214	360	1Dipole
1612.189	-210	360	1Dipole
1621.344	-211	240	1Dipole
1625.458	-208	370	1Dipole
1830.836	-185	370	2Dipople
1859.882	-36	120	2Dipople

N. Solyak, IPAC10, TUPEA020

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1. Introduction

2. Avoid HOMs

3. Compensate HOM effects

4. Uses of HOMs

   Diagnostic of Accelerating Structures

   Diagnostic of Beam

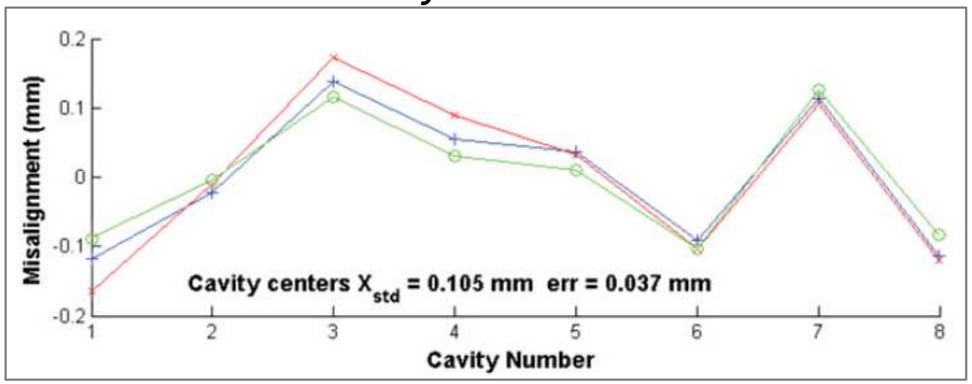
5. Summary

4. Use HOMs

Diagnostic of accelerating structures

- Monitor HOMs through damping couplers
  - Measure cell alignment
    - Due to varying cell dimensions along detuned structure, the modes are localized in part of it giving information on different cells
  - Monitor SC cavity alignment in cryo-module
    - Monitor dipole mode

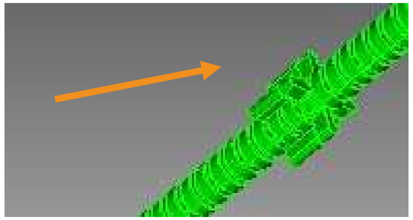
Transverse offset of SC TESLA cavities in cryo-module

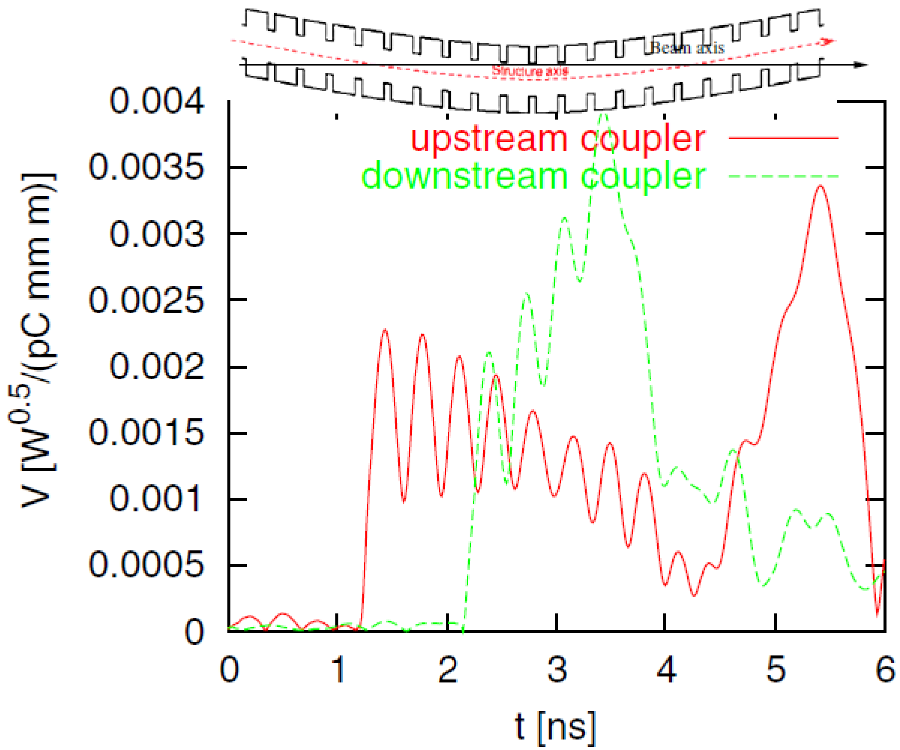


S. Molloy, Meas. Sci. Technol. 18, 2314 (2007)

X-band rf structure with integrated alignment monitors

Wakefield monitors



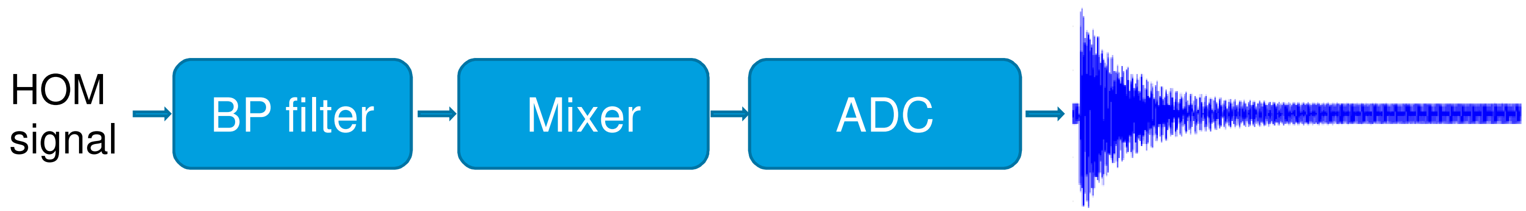


M. Dehler, PRST-AB 12, 062001 (2009)

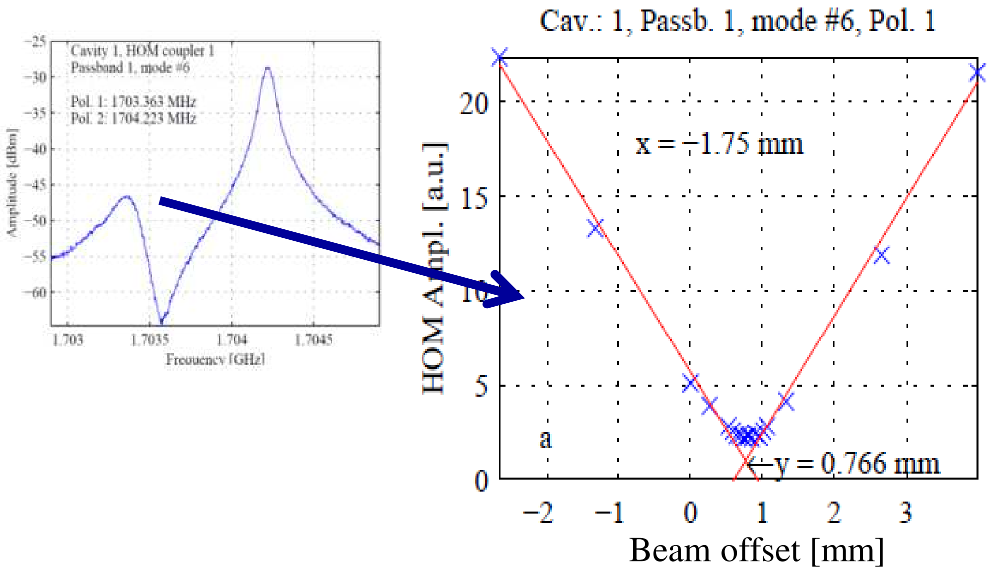
4. Use HOMs

Diagnostic of beam

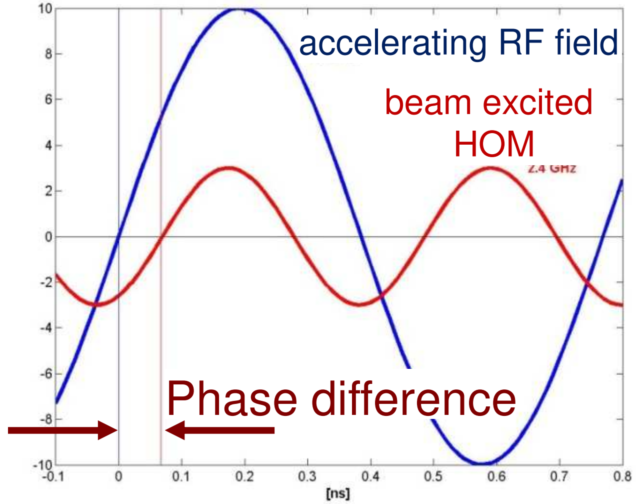
- Monitor selected HOMs (e.g. with downconverting electronics)



Beam position measurement with dipole modes (like with a cavity BPM)



RF phase measurement wrt to beam



N. Baboi, HOMSC2016

Contents

Summary

HOM mitigation

- HOMs can decrease the beam quality to an unacceptable degree
- Avoid HOM excitation
  - Design of accelerating structure
  - Design of accelerator
- Compensate excited HOMs
  - Feedbacks
  - Beam alignment
  - Detune and retune cavity
- Use the excited HOMs
  - Measure the cell or cavity alignment
  - Measure beam offset, beam phase

- Only a selection of methods was shown
- There are many more methods to mitigate HOMs

Know your HOMs!

Thank you!

Contact

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

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