# 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

# Contents

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The CERN Accelerator School

# 1. Intro: What do you know about HOMs?

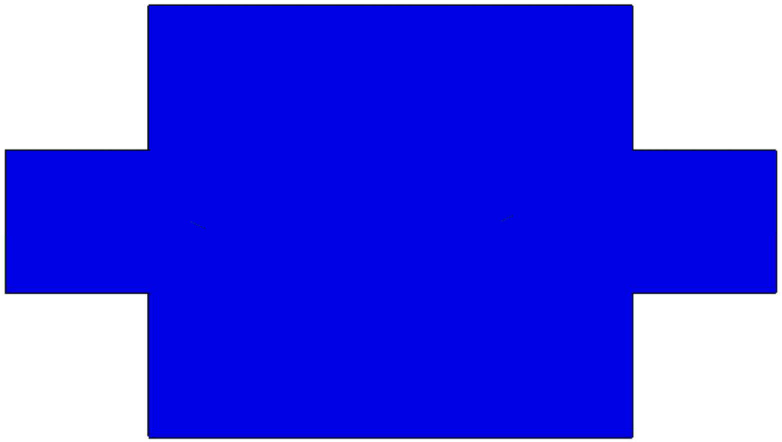
**From this school only!**

?

# 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**

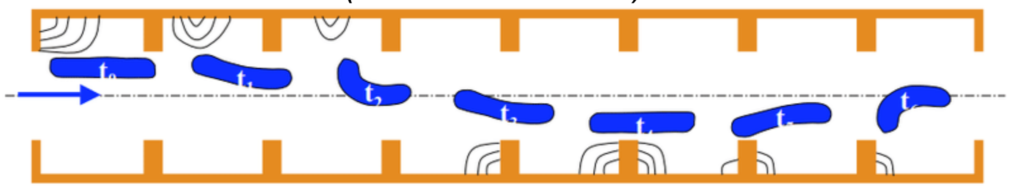
# 1. Intro: Wakefields

## 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)*



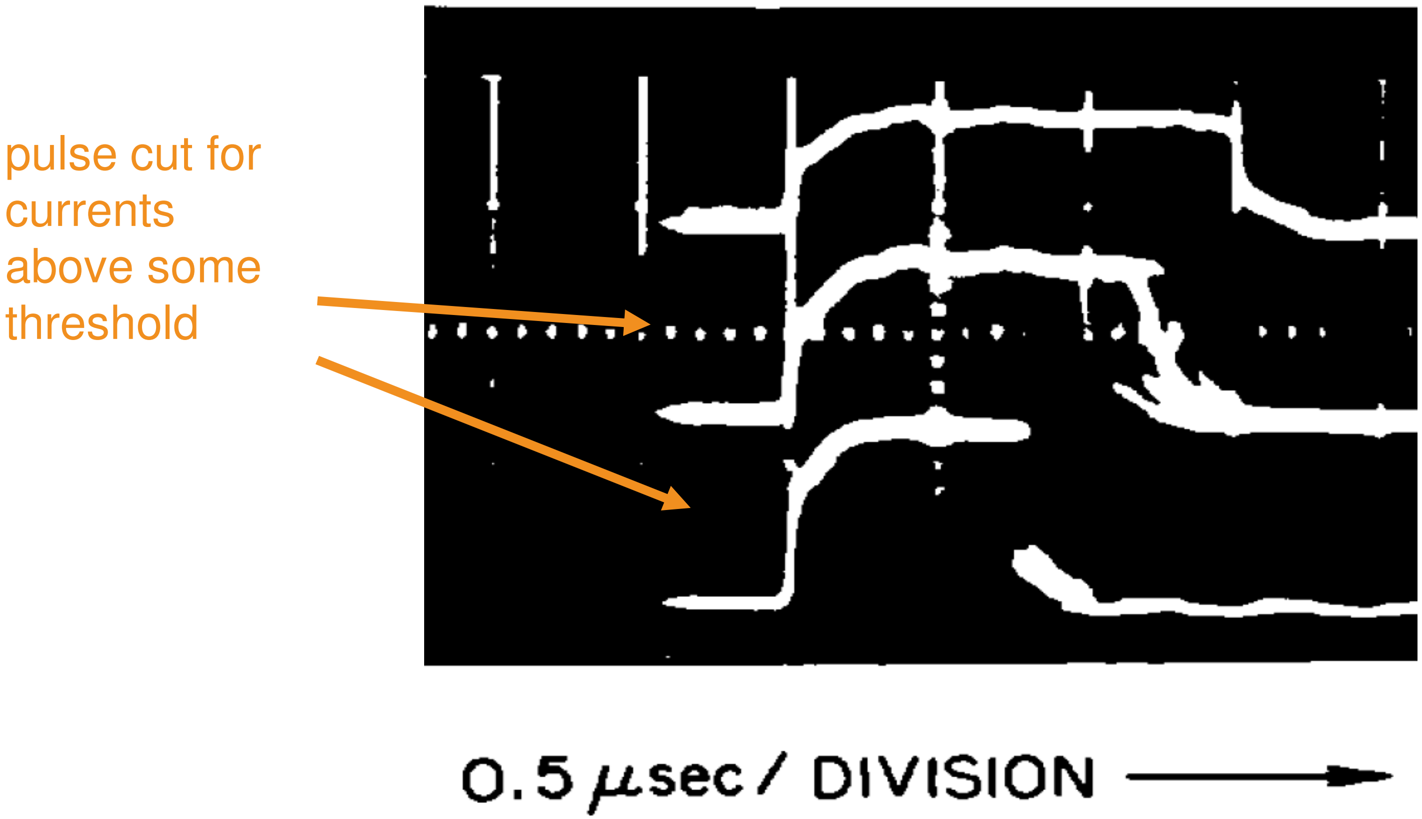
*W. Barletta, USPAS 2010*

- **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




*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

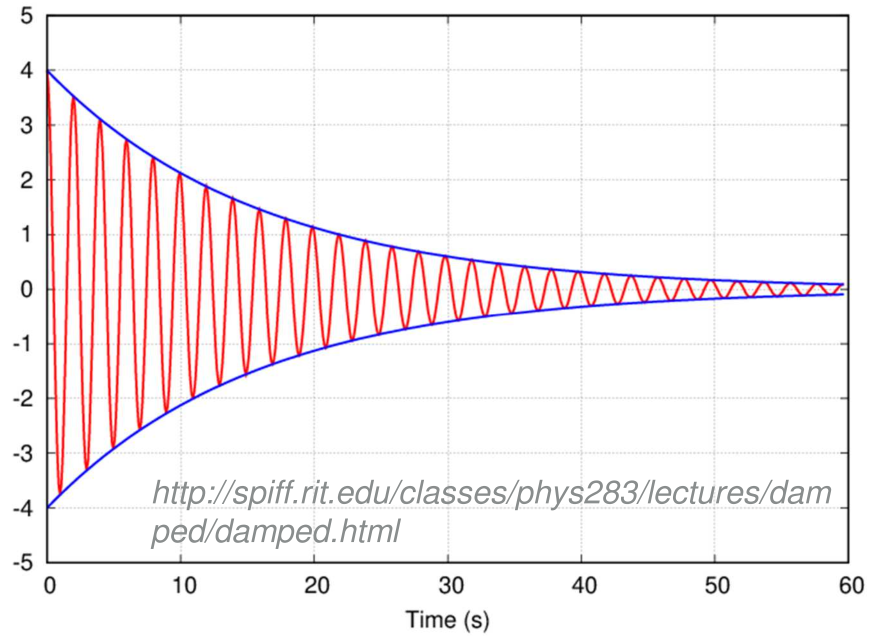
- Longitudinal **loss factor**: $k_n = \frac{|V_n(r,\omega_n)|^2}{4U_n}$ (V/pC)

  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*



# 1. Intro: Higher Order Modes

## Brief reminder: Longitudinal long-range wakefields (2)

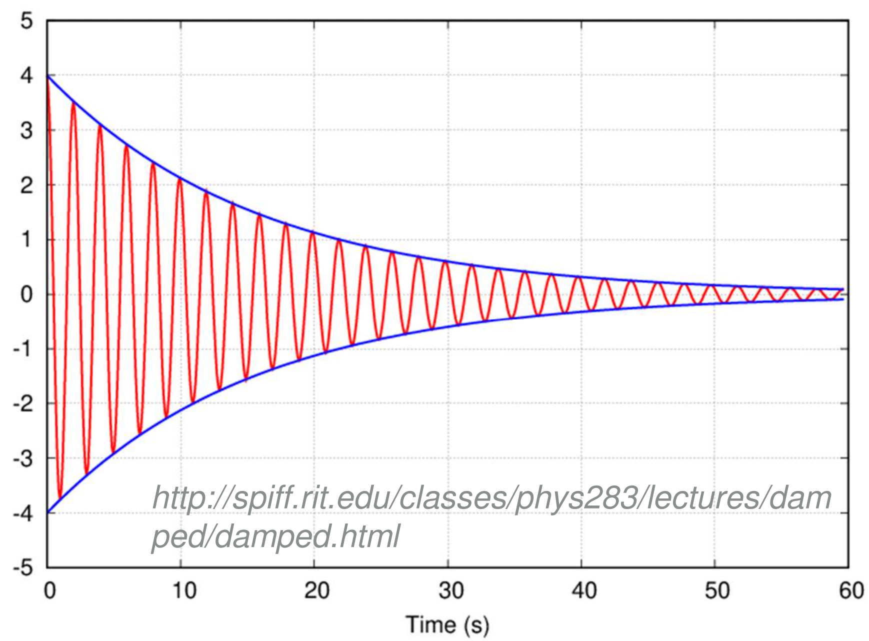
$$W_{||}(s) = \sum_n 2k_n \cos\left(\omega_n \frac{s}{c}\right) e^{-\frac{\omega_n}{2Q_n}\frac{s}{c}}$$

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

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

- → 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

## 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:

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

(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 $(R/Q)_n$

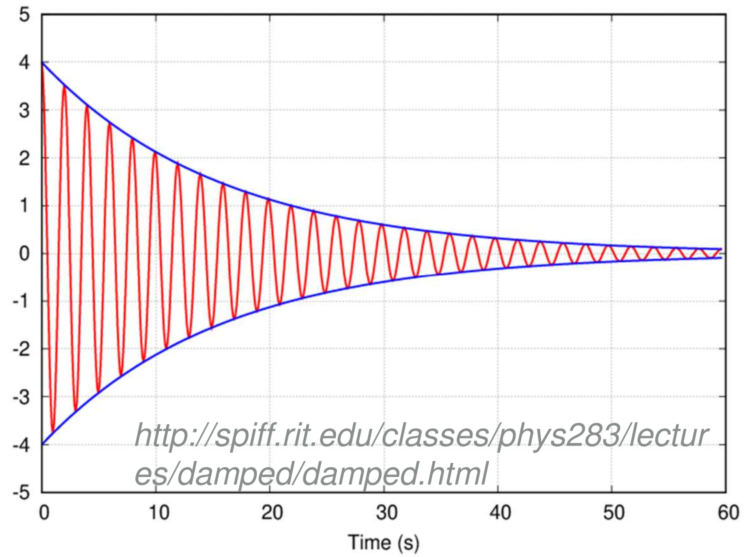
$$k_n = \frac{|V_n(r,\omega_n)|^2}{4U_n};\ k_n = \frac{\omega_n}{4}\left(\frac{R}{Q}\right)_n$$

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

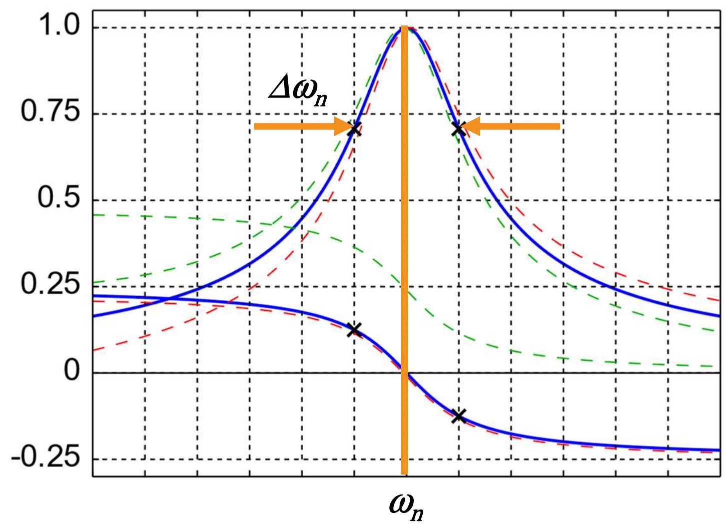
$$Q_n = \omega_n/(\Delta\omega_n);\ \tau_n = 2Q_n/\omega_n$$

- Field distribution, polarization etc.

**Know your HOMs!**




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

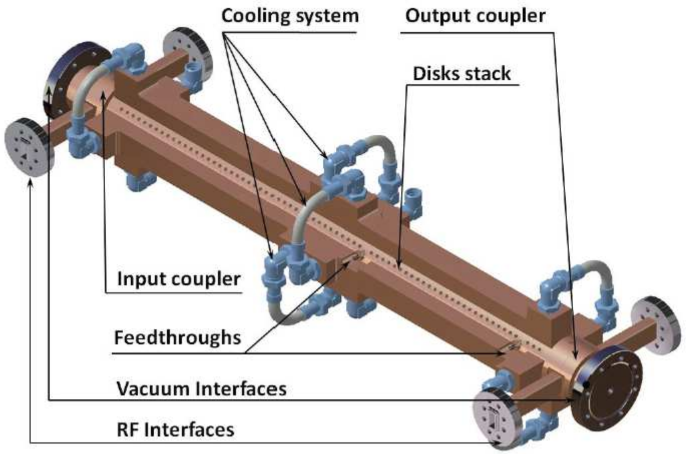


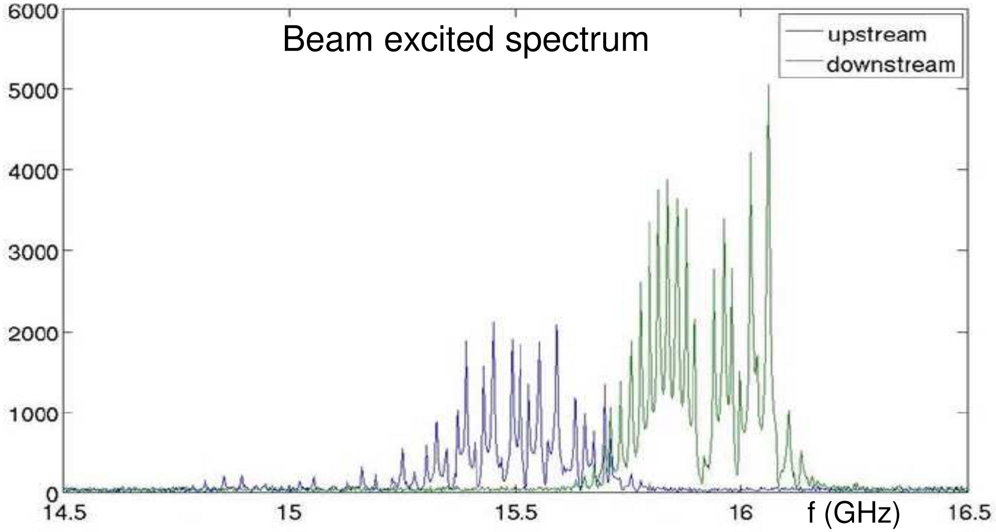

https://en.wikipedia.org/wiki/Resonance

# 1. Intro: Higher Order Modes

## Brief reminder: HOM spectra (examples)

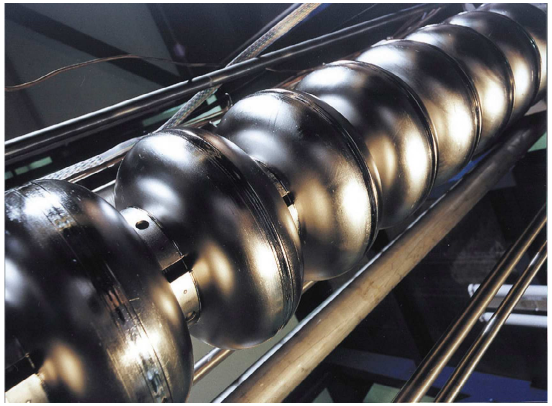
- X-band structure at the Swiss-FEL



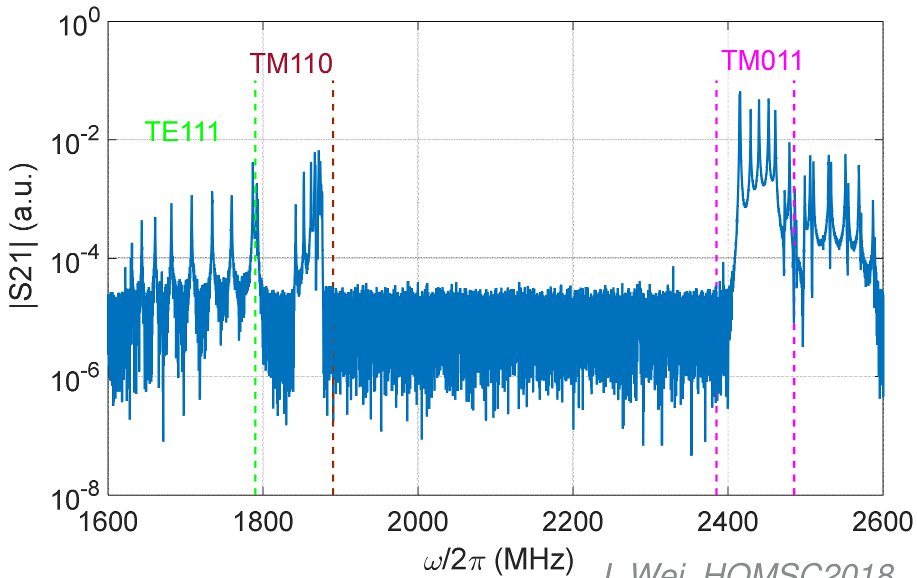




*M. Dehler, IBIC2013, WEBL3*

- TESLA cavity at FLASH/European XFEL



*DESY*

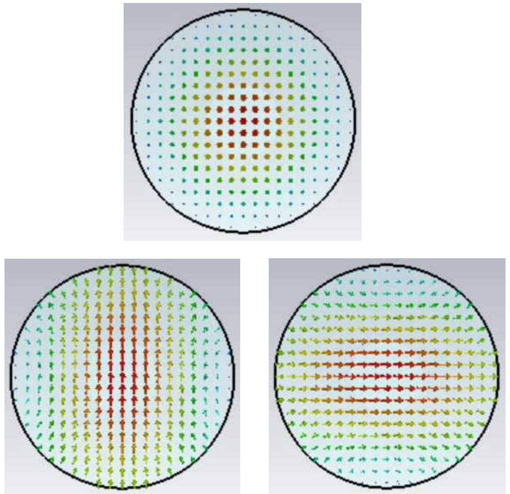



*J. Wei, HOMSC2018*

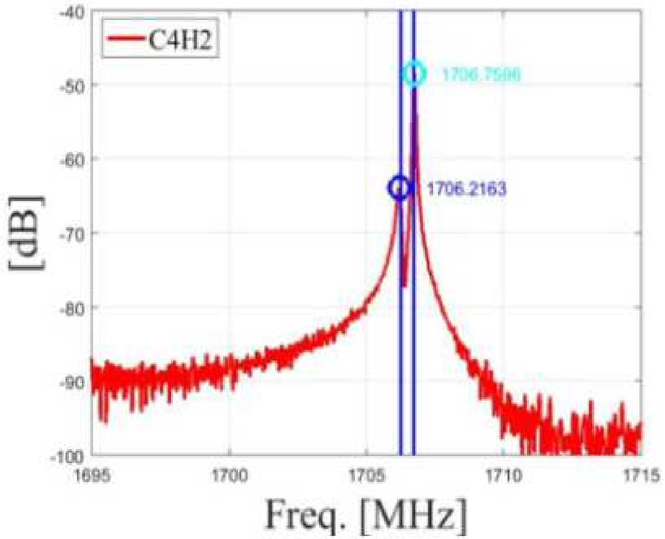
# 1. Intro: Higher Order Modes

## 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



TESLA cavity

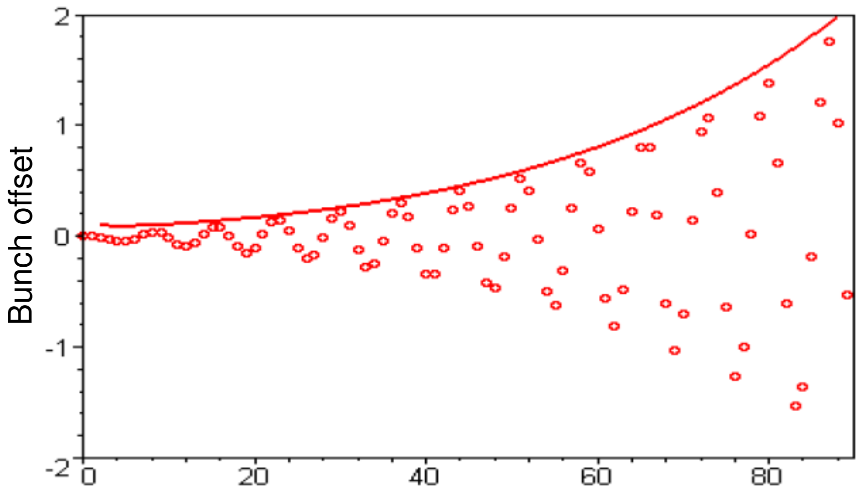



*J. Wei, FEL Seminar, DESY, 20.08.2019*

# 1. Intro: Issues due to HOMs

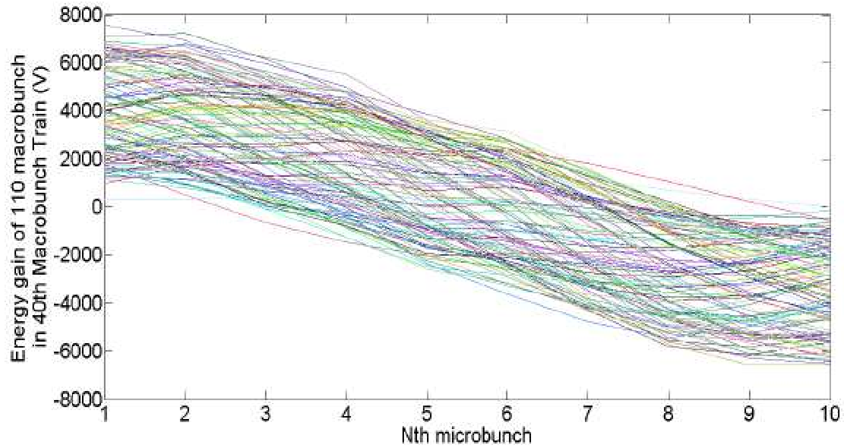
## HOM effects on the beam

- Transversely:
  increase in multi-bunch emittance



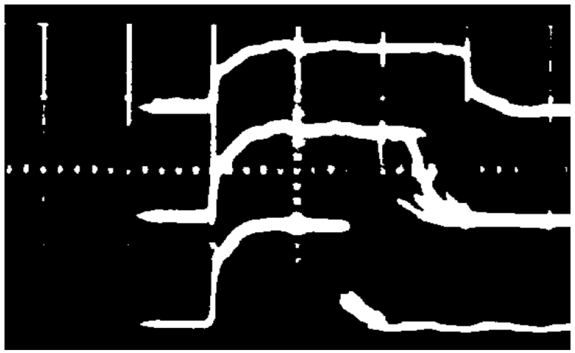

*C. Bohn, K. Ng, LINAC 2000*

- Longitudinally:
  increase in multi bunch energy spread




*Chen Xu, AAC 2016*

Extreme case: beam breakup



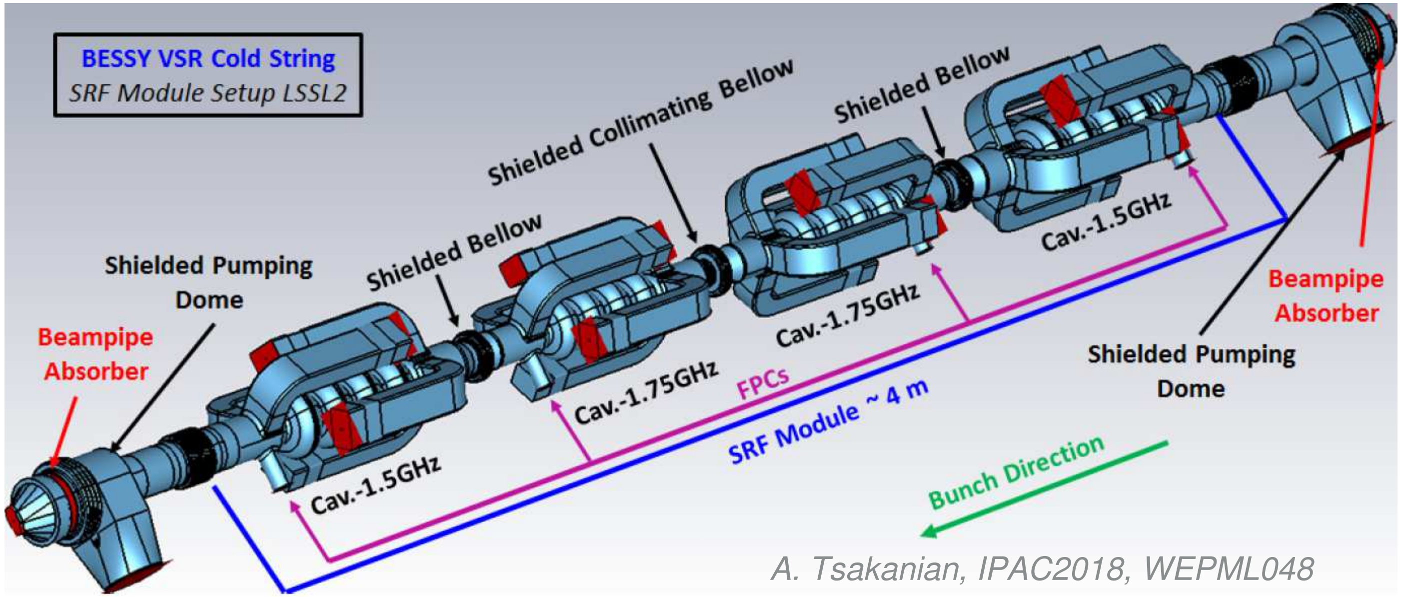
Worst effects at low energies

# 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



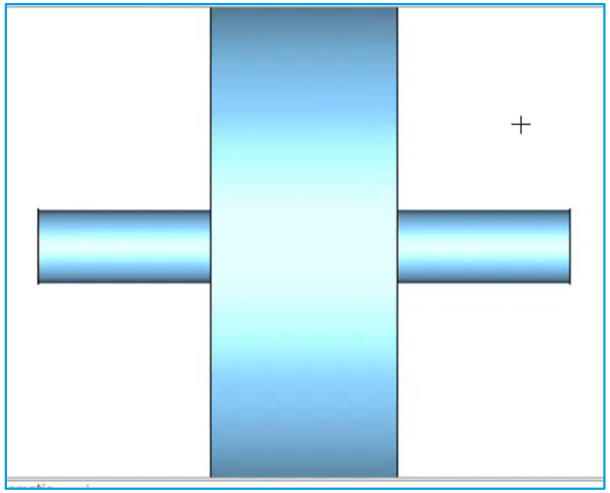
**Accelerating Structure Design**

**Accelerator Design**

# 2. Avoid HOMs: Structure Design

## Geometry

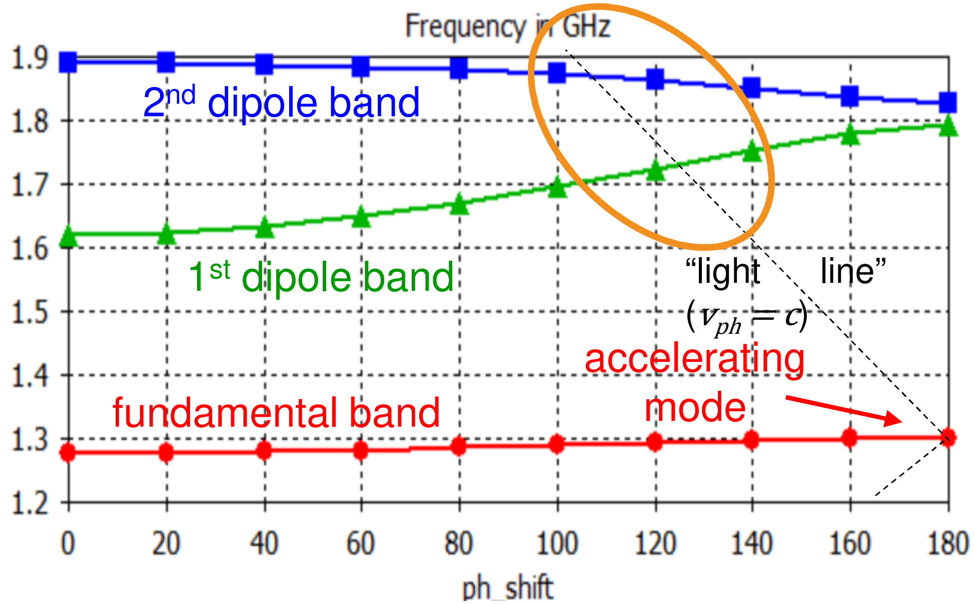
- Optimize the cell geometry for low loss factors for HOMs, while aiming at high value for the accelerating mode
  - Remember: the loss factor depends only on the geometry



*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)



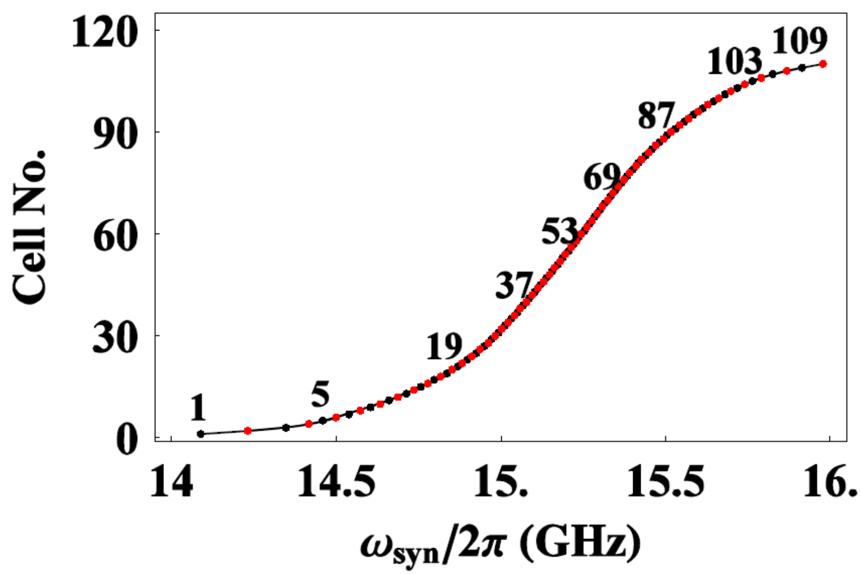
# 2. Avoid HOMs: Structure Design

## 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

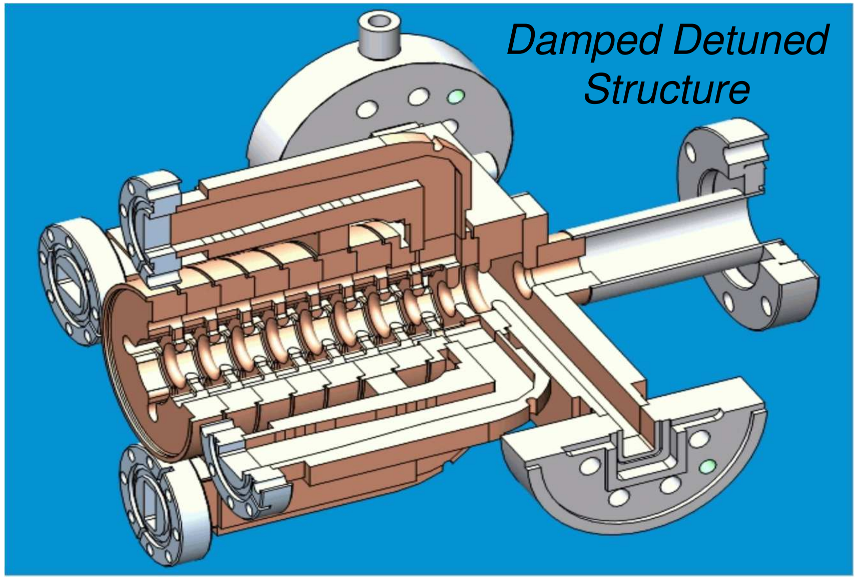
  e.g.

  - 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

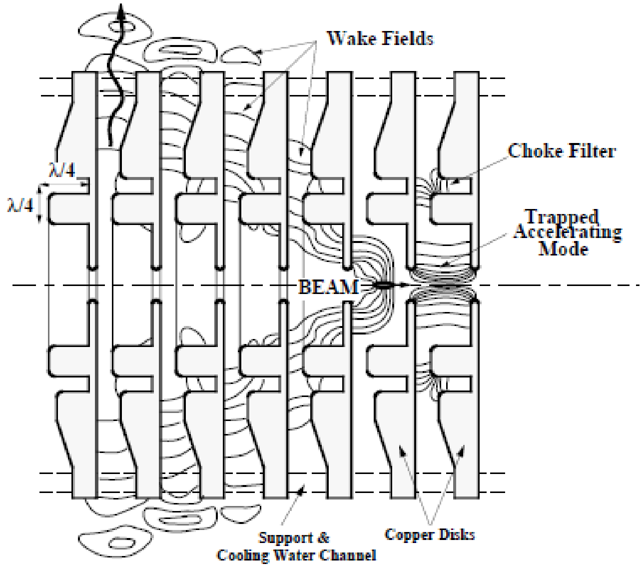
## HOM damping in each cell

- 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*



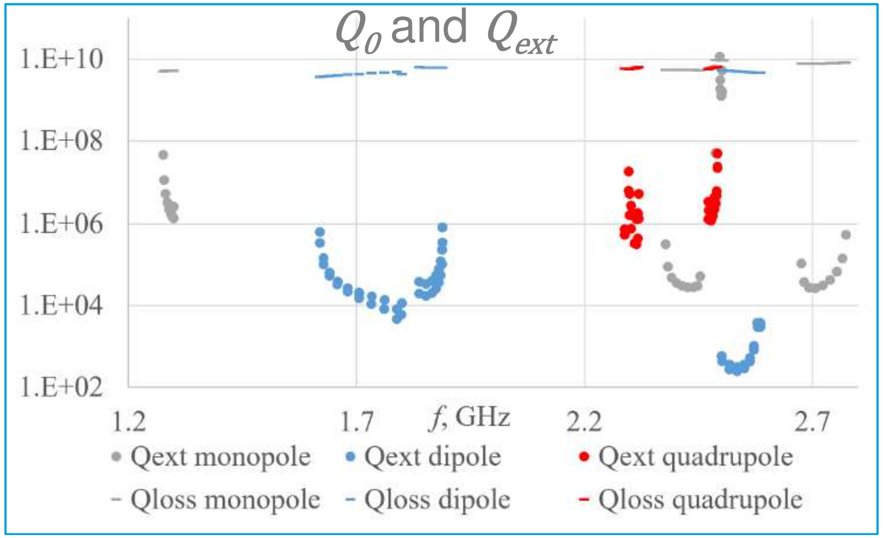

T. Shintake, PAC'95

- Particularly good for trapped modes in detuned structures

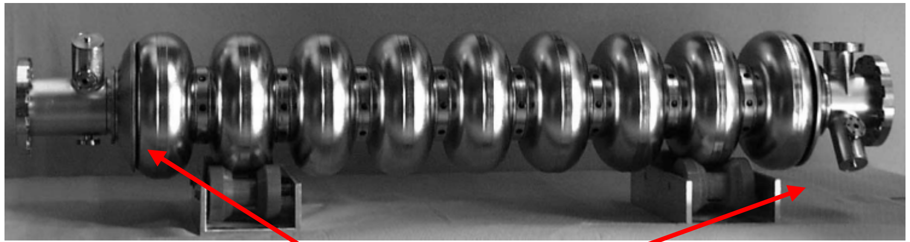
# 2. Avoid HOMs: Structure Design

## HOM damping at end of structure

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




TESLA cavity used in MESA

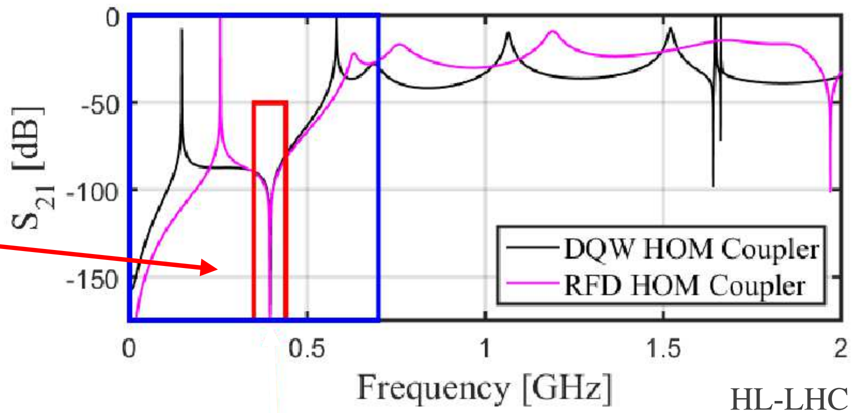


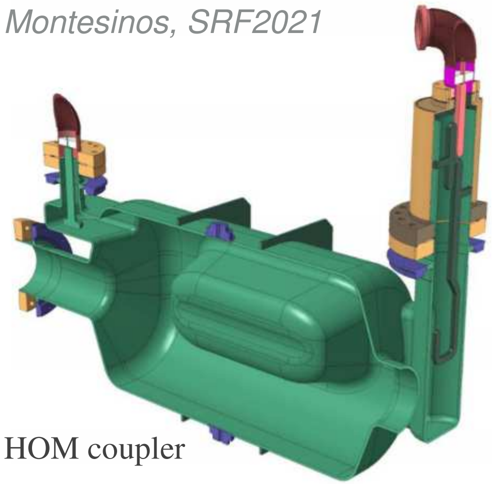
HOM couplers

S. Glukhov, PhD thesis, TU Darmstadt, 2022

- Notch filter at the accelerating frequency

E. Montesinos, SRF2021



HL-LHC RFD HOM coupler

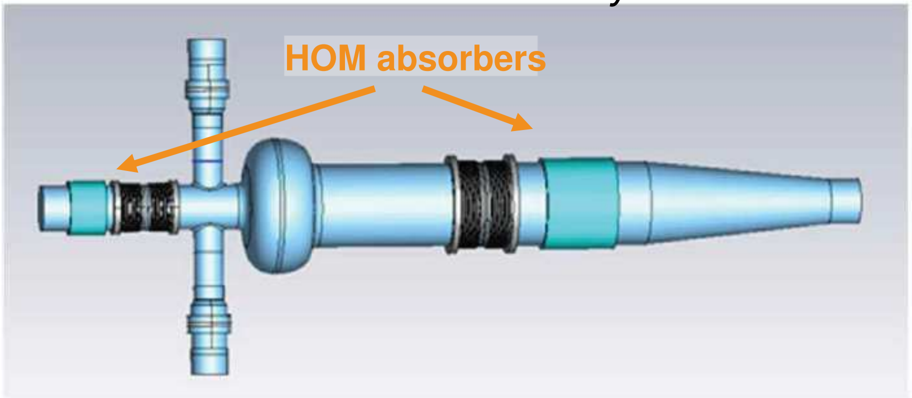
# 2. Avoid HOMs: Structure Design

## HOM damping in the beam pipe

- Damping materials:
  HOM absorbers in the beam pipe

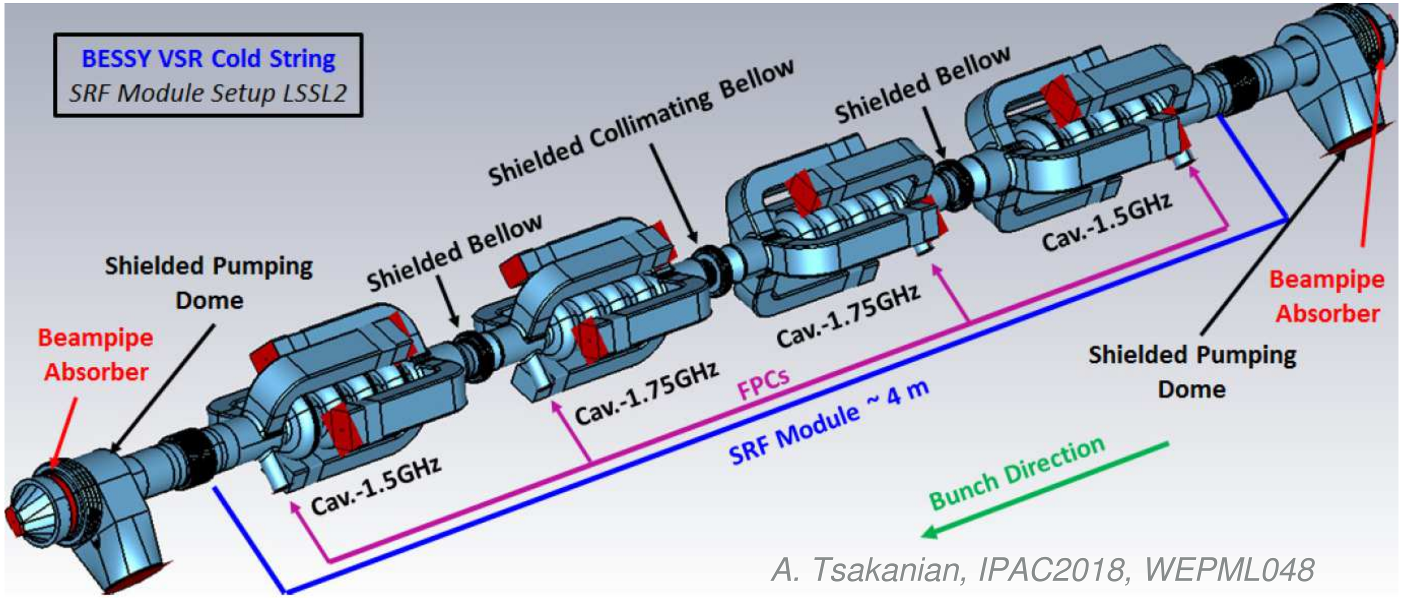
- The accelerating frequency is below the cut off of the beam pipe

*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

## 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

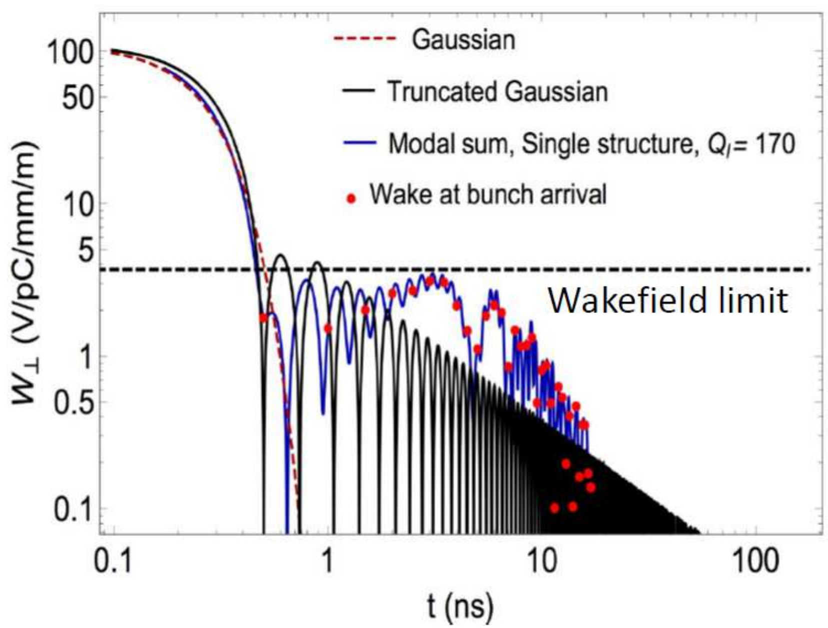
*S. Glukhov, PhD thesis, TU Darmstadt, 2022*

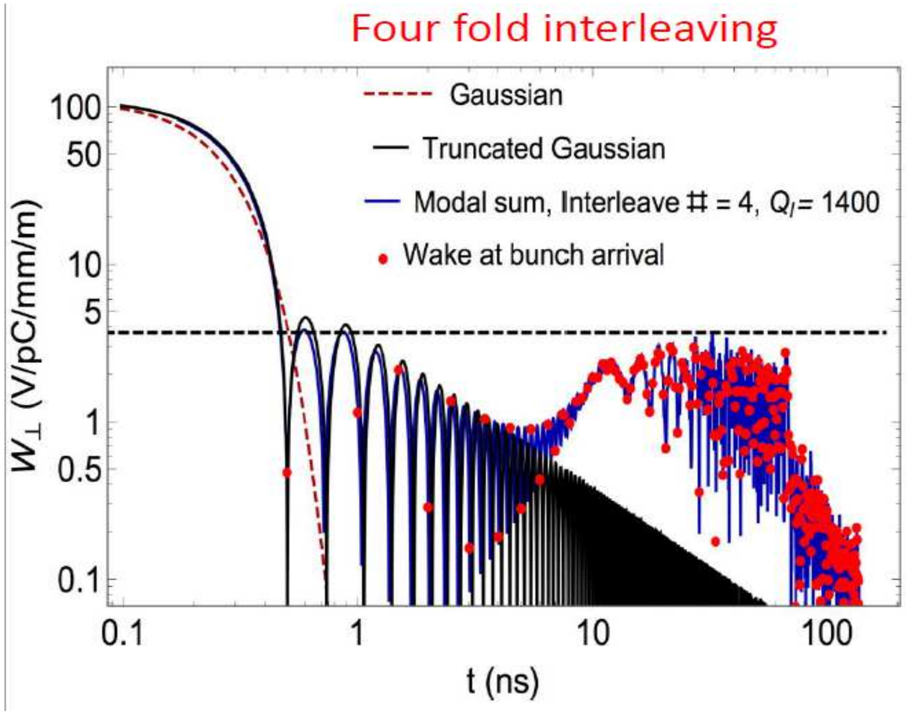
# 2. Avoid HOMs: Accelerator design

## 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

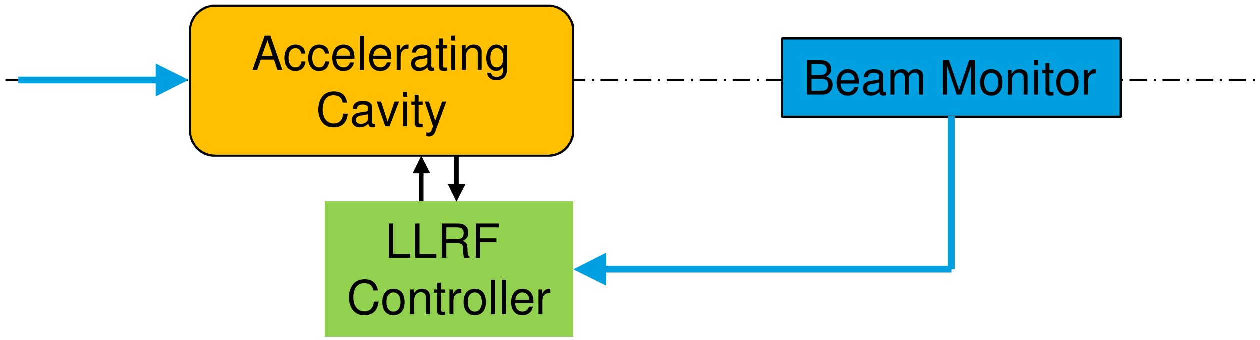
Beam Alignment

Cavity detuning and retuning

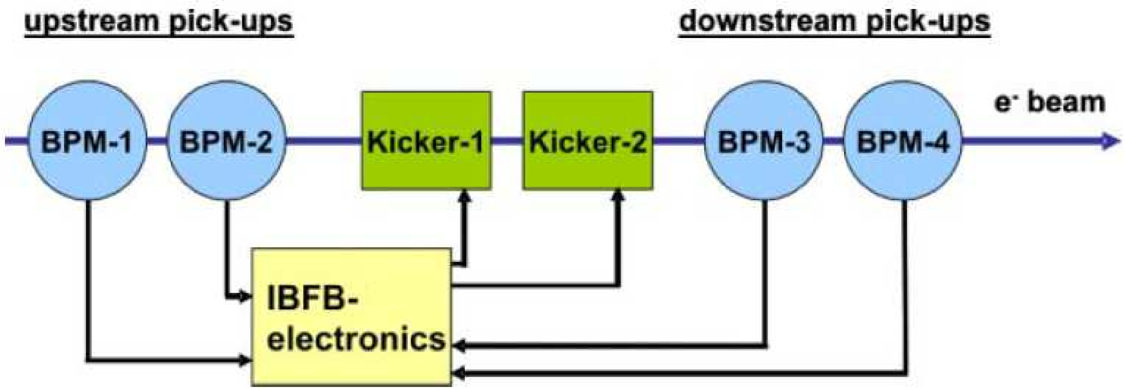
# 3. Compensate HOMs: Fast Feedbacks

## 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



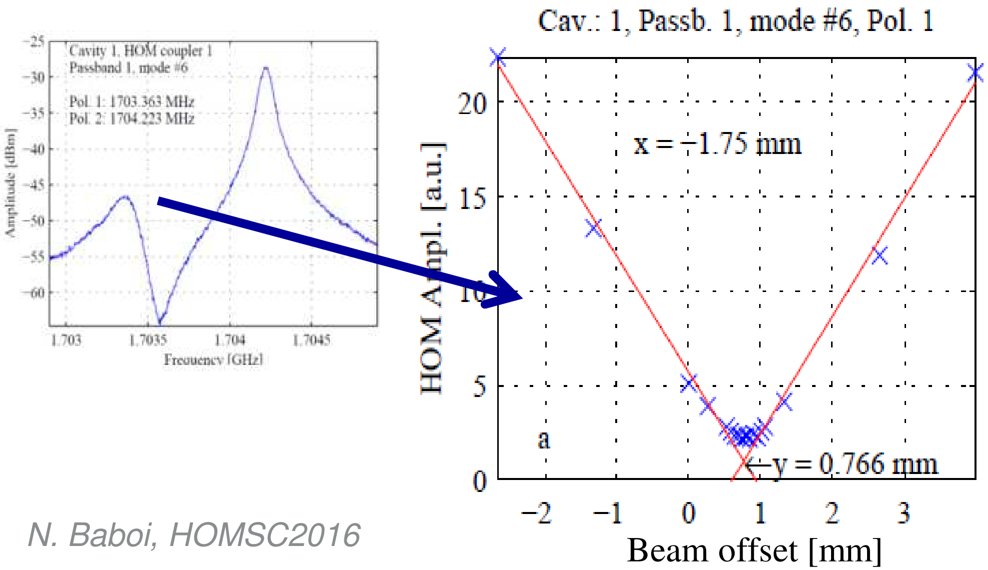

*V. Schlott, EPAC 2006, THPCH096*

# 3. Compensate HOMs: Beam Alignment

## Beam alignment to avoid transverse HOM excitation

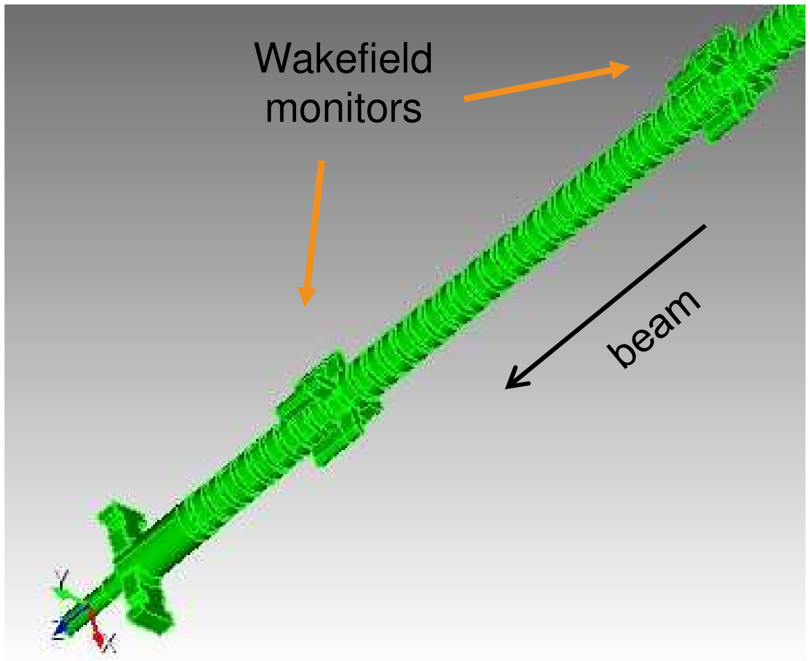
- Transverse effects mainly from dipole modes
- The dipole fields depend only on the offset of the exciting bunch
- ⇒ Monitor dipole modes through couplers, and align the beam to minimize their strength

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
  - ⇒ 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*

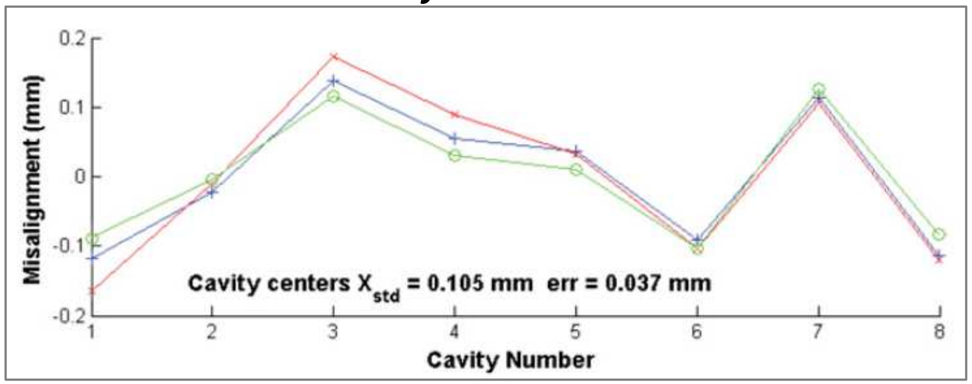
# Contents

# 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

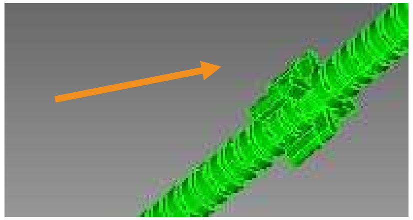
*Transverse offset of SC TESLA cavities in cryo-module*

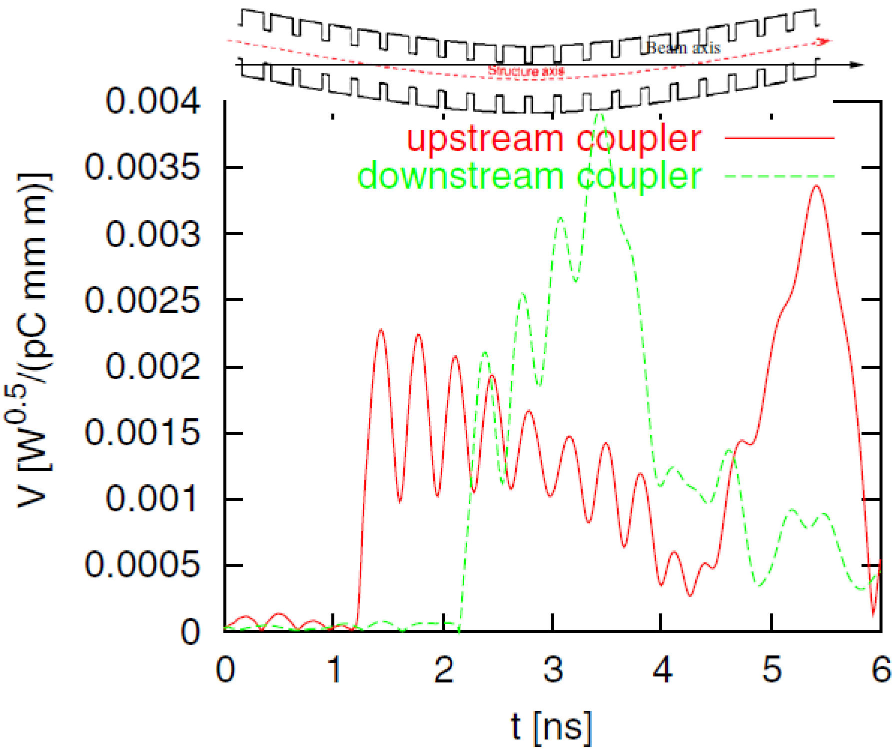



*S. Molloy, Meas. Sci. Technol. 18, 2314 (2007)*

*X-band rf structure with integrated alignment monitors*

Wakefield monitors



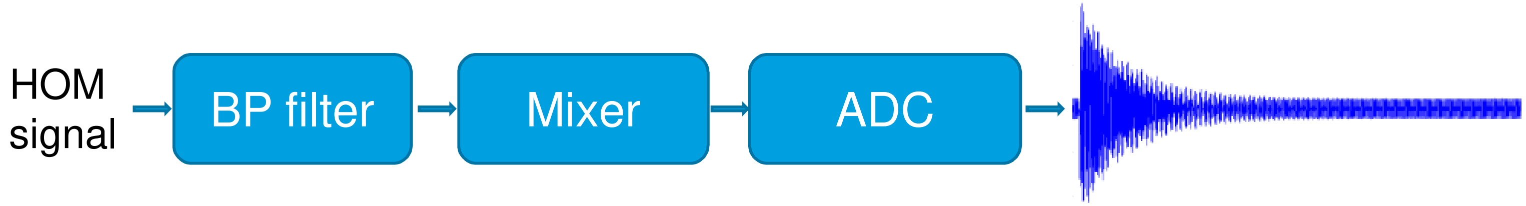



*M. Dehler, PRST-AB 12, 062001 (2009)*

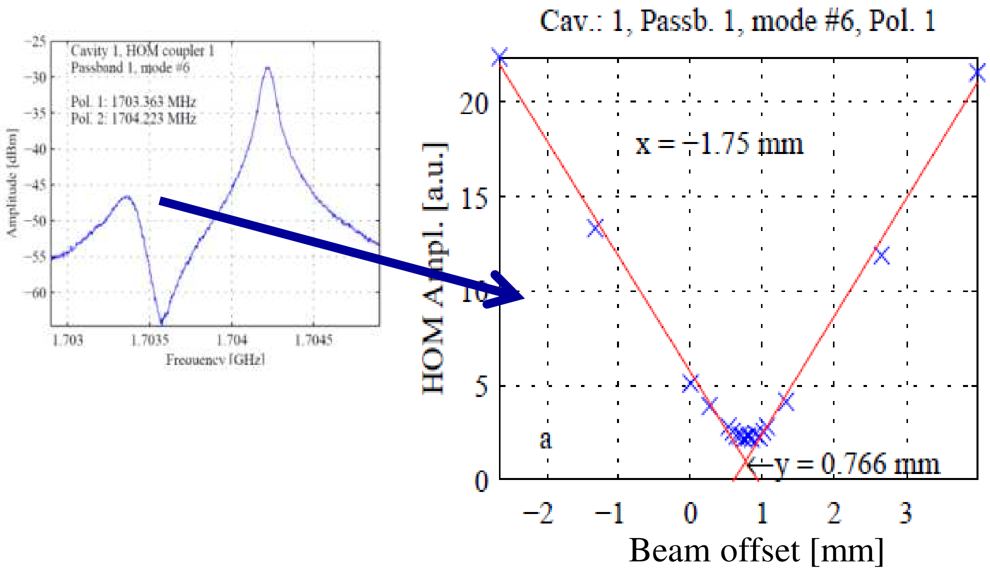
# 4. Use HOMs

## Diagnostic of beam

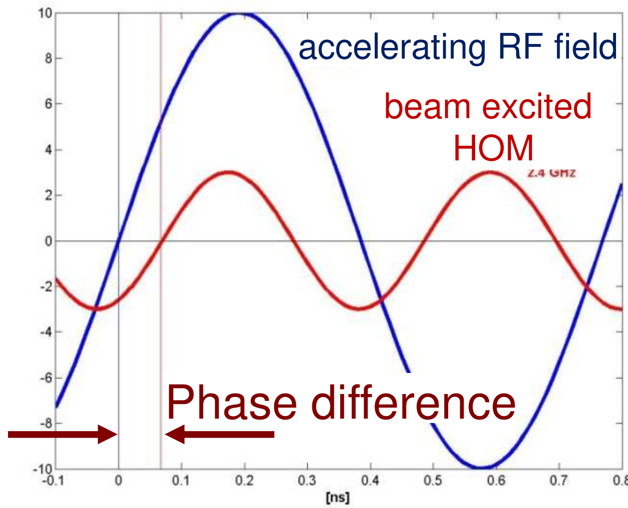
- Monitor selected HOMs (e.g. with downconverting electronics)




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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