STUDIES on HIGHER ORDER MODES in ACCELERATING STRUCTURES for LINEAR COLLIDERS

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DESY

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Linear Colliders

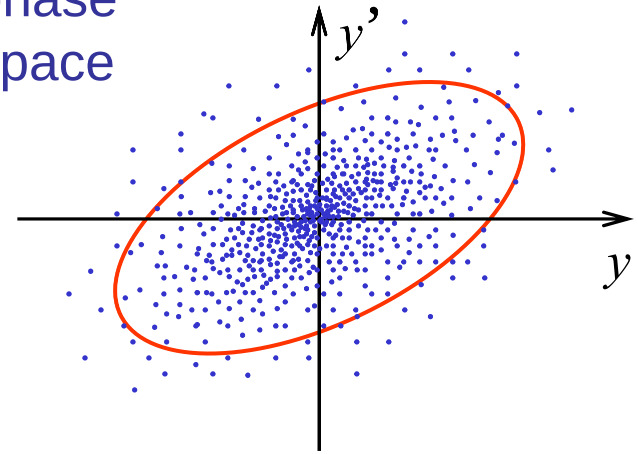
- Synchrotron radiation ($P_{loss} \propto E^4/R^2$)

  → limitation in energy for e$^+$e$^-$ circular accelerators
- Luminosity $L \propto dN_p/dt$

  ➢ for flat beams $\boxed{L \propto \frac{P_b}{E_{cm}} \frac{\sqrt{\delta_E}}{\sqrt{\varepsilon_{y,n}}}}$

P_b - beam power
E_{cm} - CM energy
δ_E - beamstrahlung
$\varepsilon_{y,n}$ - vertical normalized emittance

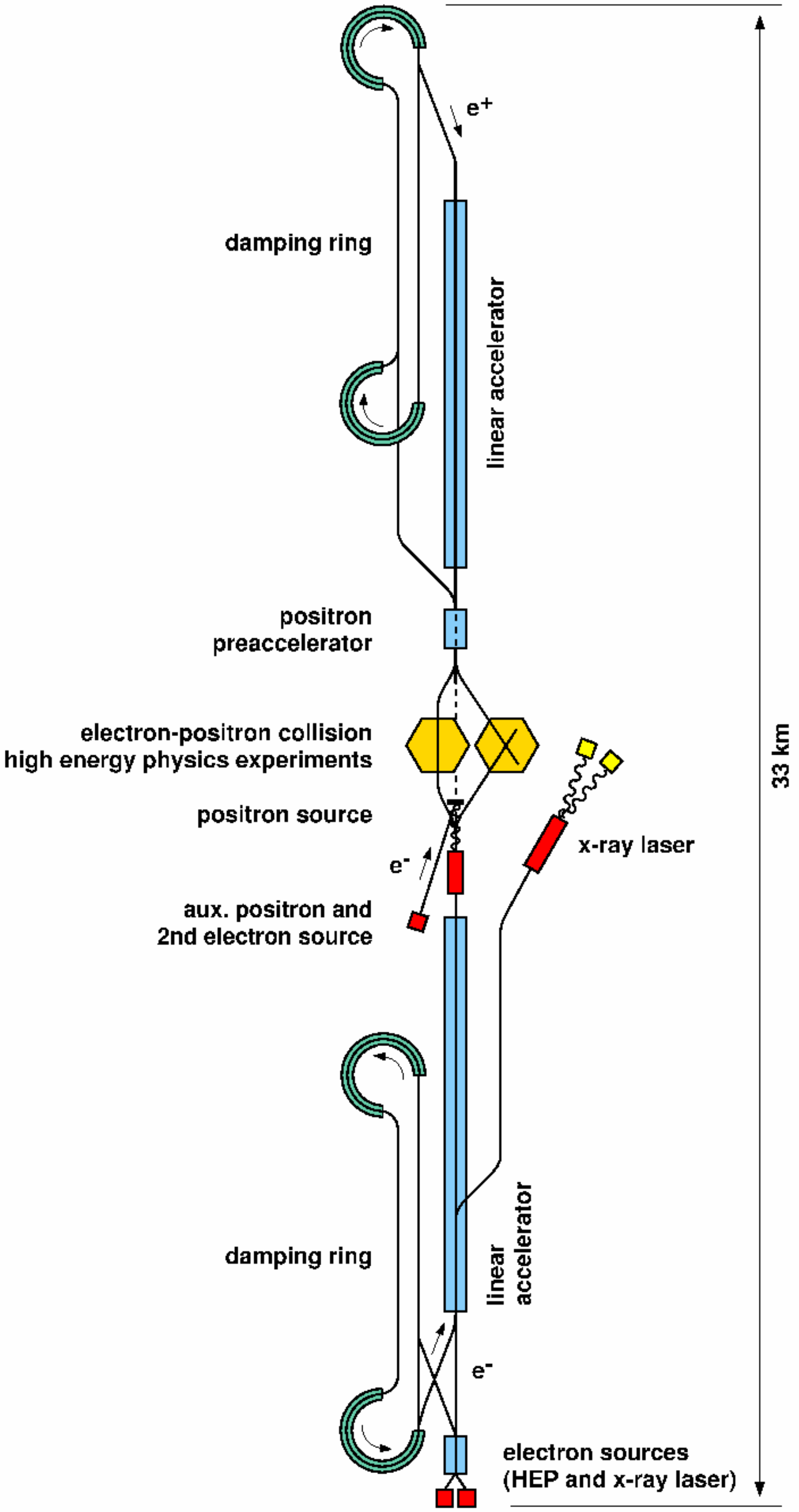
phase space



Transverse emittance:

$$\varepsilon_y = \sqrt{\langle y^2\rangle\langle y'^2\rangle - \langle yy'\rangle^2}; \qquad \varepsilon_{y,n} = \beta\,\gamma\,\varepsilon_y$$

TESLA

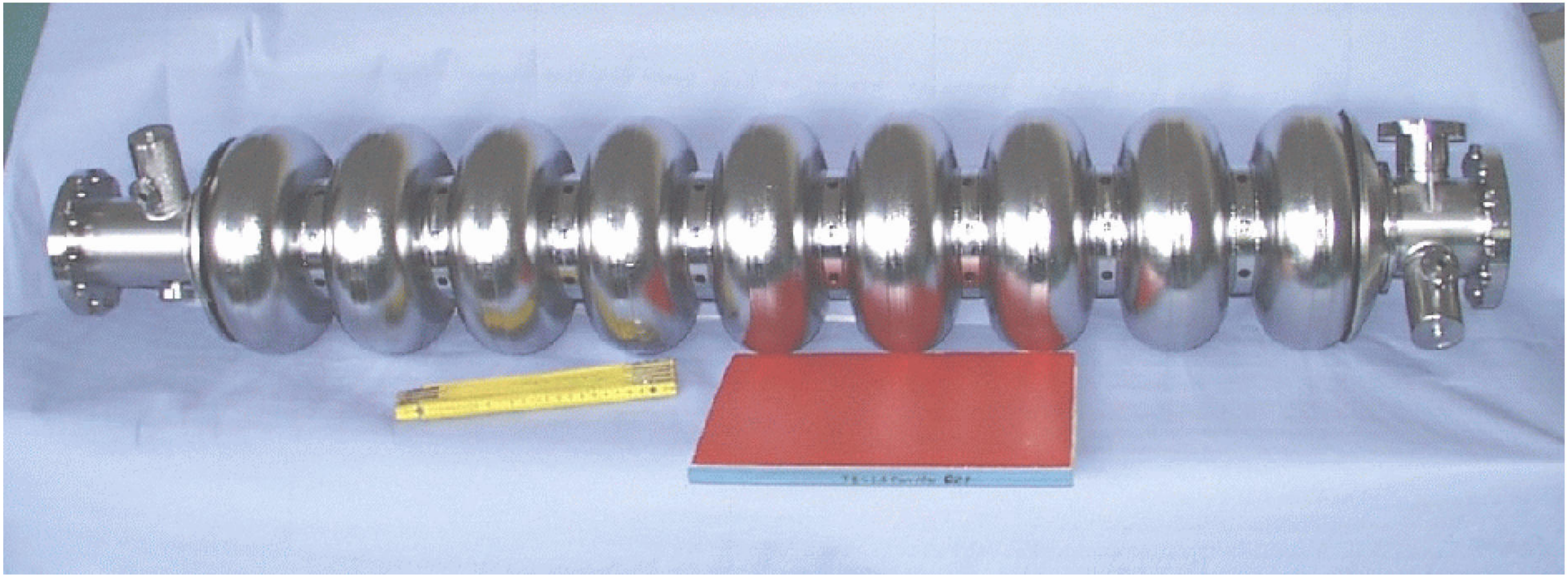


H.Weise 3/2000

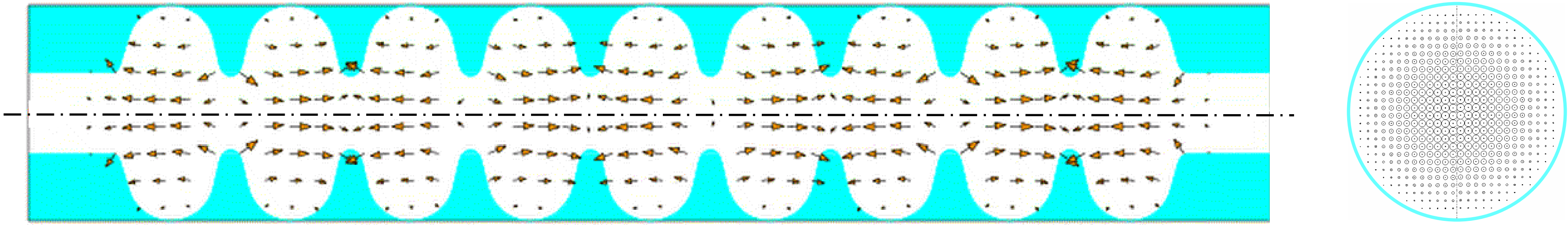
The TESLA cavity

- 1 m long, 9-cell
- 1.3 GHz
- standing waves

- superconducting (Nb, 2 K)
  - low losses, high efficiency
  - gradients achieved : > 23.4 MV/m (design)
  - high luminosity ($3.4 \cdot 10^{34}$ $cm^{-2}s^{-1}$)

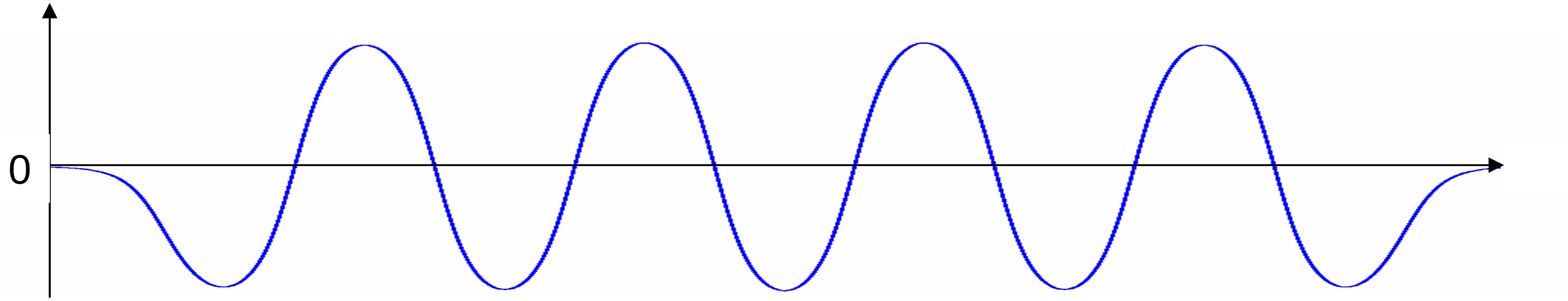


Accelerating mode



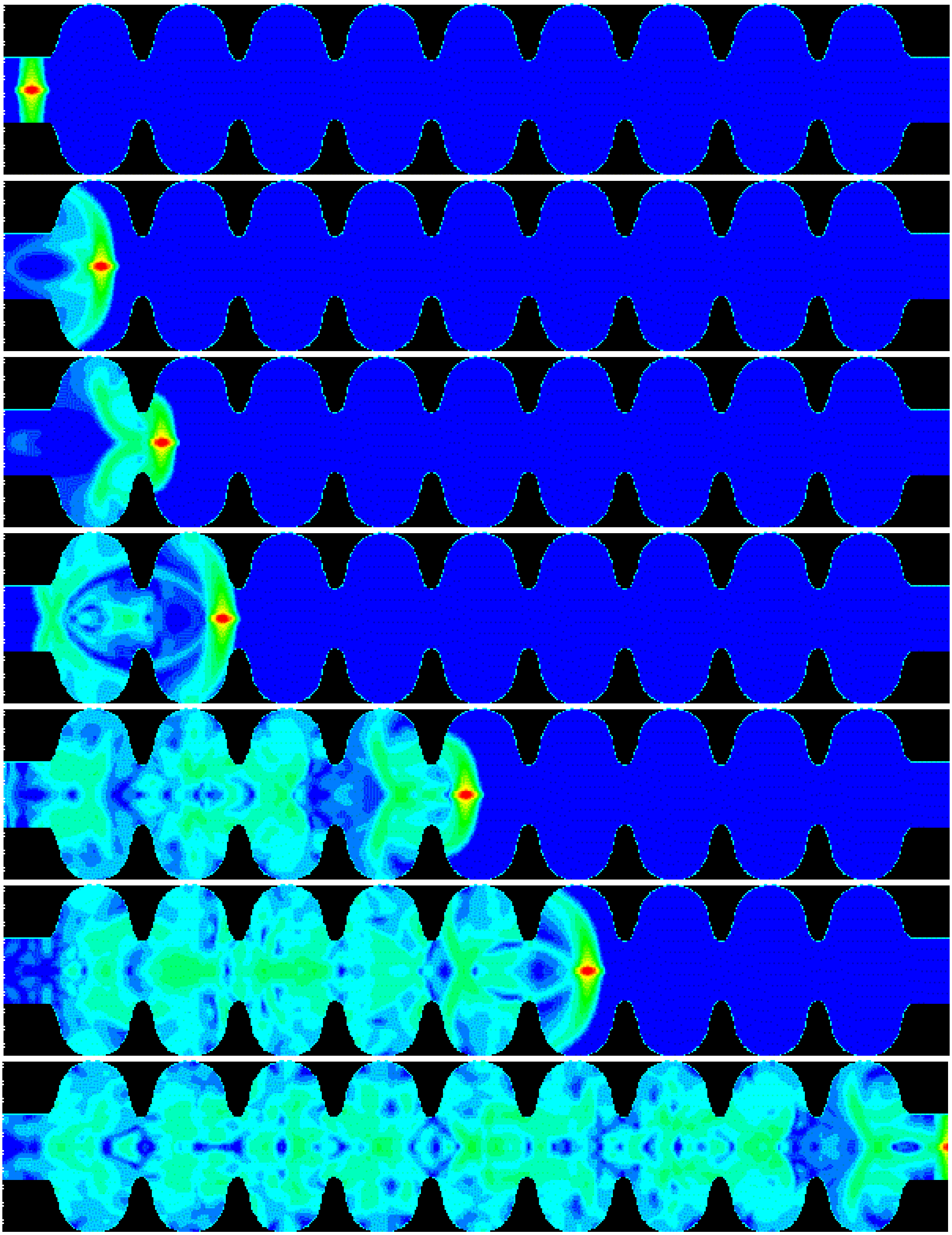
monopole mode

Electric field profile on the axis:



phase advance per cell: π

Wake fields



Higher Order Modes (HOMs)

- The long range wake field = ∑ resonant fields (HOMs)
- Transverse dipole wake field:

$$\boxed{W_\perp^\delta(\zeta) = \sum_l 2\underbrace{k_l}_{\text{loss factor}}\frac{c}{\omega_l}\sin\left(\underbrace{\omega_l}_{\text{frequency}}\frac{\zeta}{c}\right)\exp\left(-\frac{\omega_l}{2\underbrace{Q_l}_{\text{quality factor}}}\frac{\zeta}{c}\right)}$$

($\zeta > 0$)
l: HOM index

$$\boxed{k_{\perp l} = \frac{|V_l|^2}{4W_l a^2}} \Leftrightarrow \left(\frac{R}{Q}\right)_l = \frac{4k_l}{\omega_l}$$

(for dipole modes)

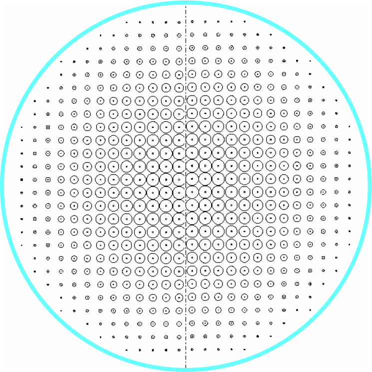
$$\boxed{Q_l = \frac{\omega_l W_l}{P_{\text{loss}\,l}}}$$

$$\Rightarrow \quad \tau_l = \frac{2Q_l}{\omega_l}$$

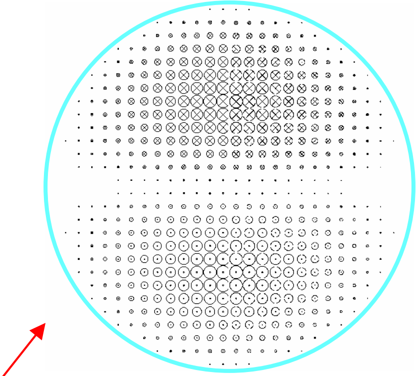
- Calculated with the help of simulation programs (MAFIA, URMEL)

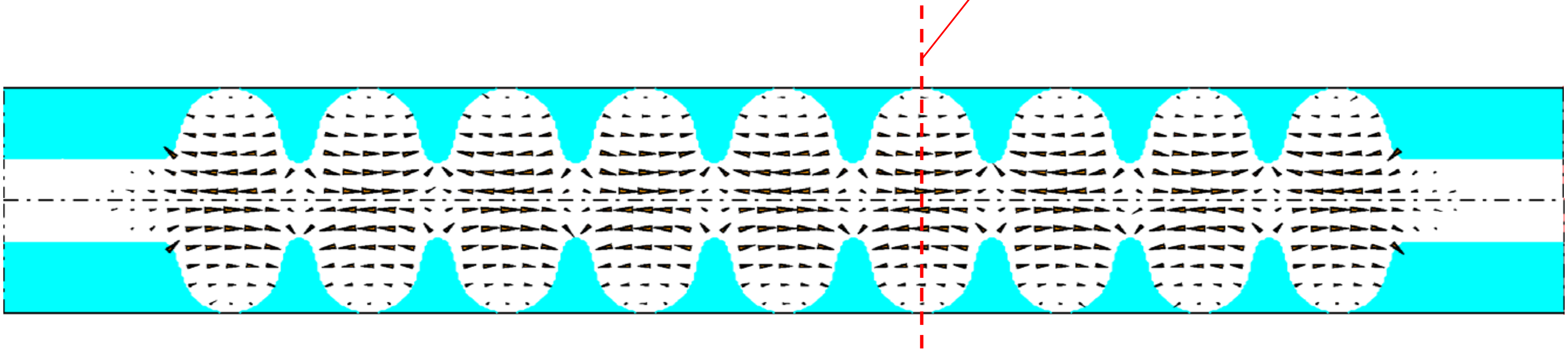
Higher Order Modes

Monopole mode



Dipole mode



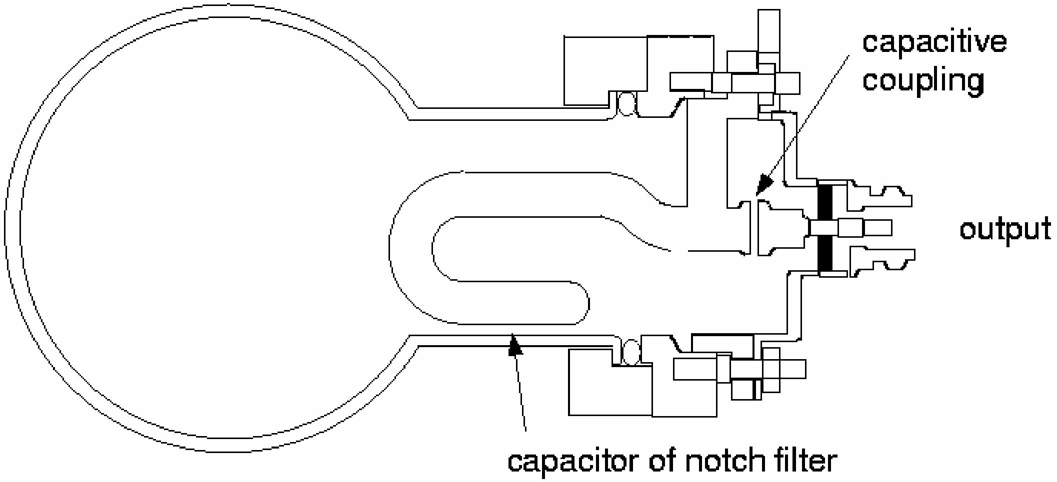


HOM damping

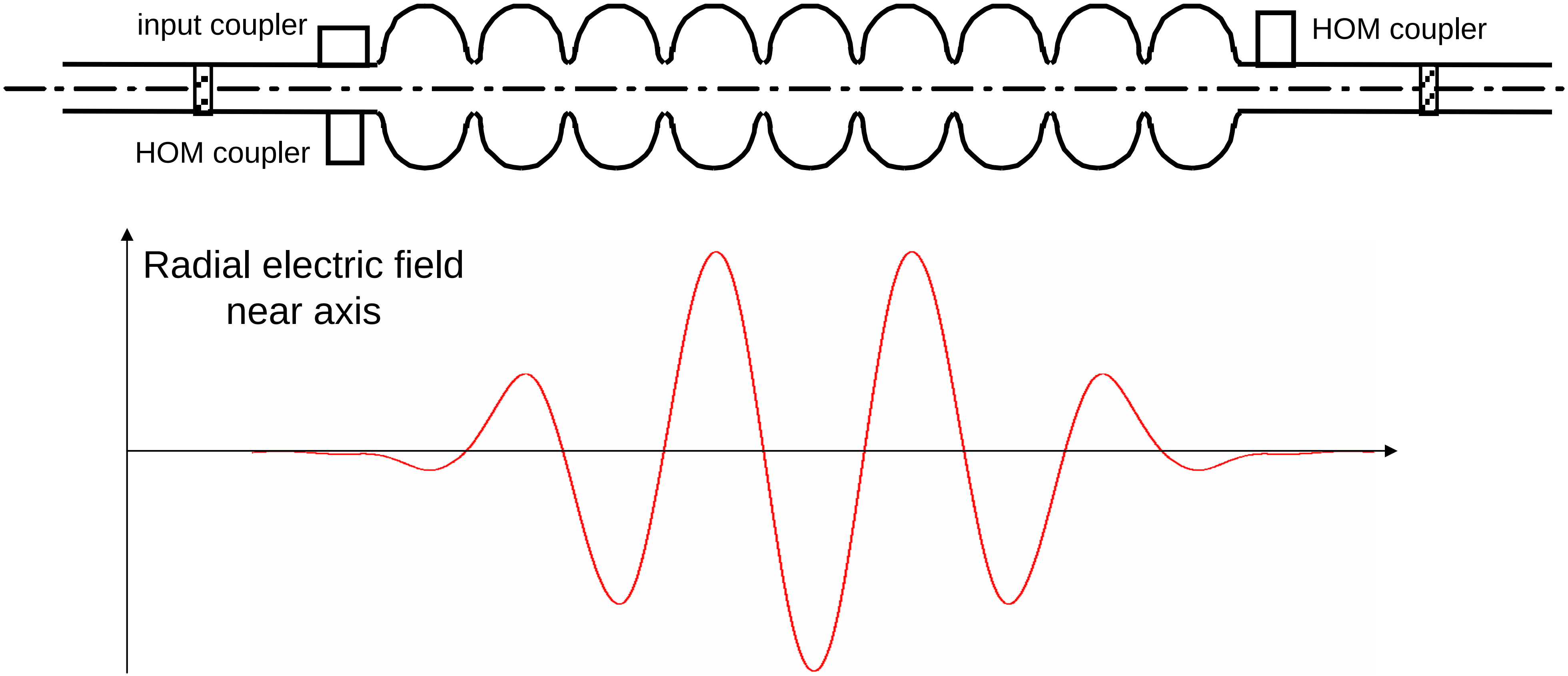
- Extract mode energy ⇒
  - reduce Q
  - reduce damping time

$$\tau = \frac{2Q}{\omega}$$

- with HOM couplers



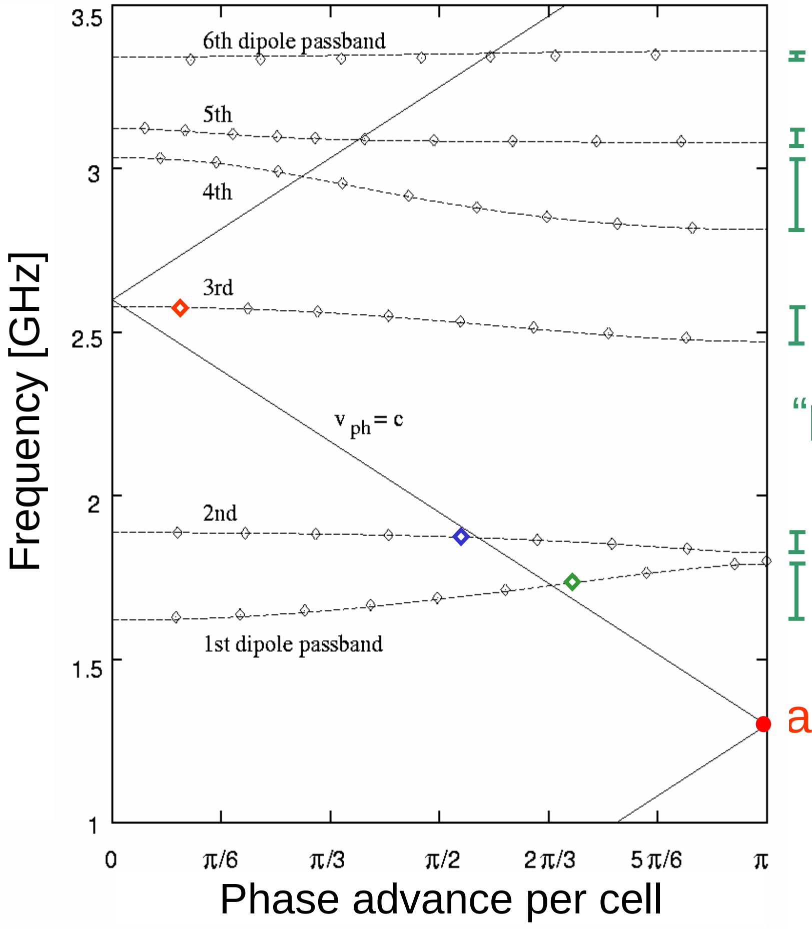
Trapped modes



- most difficult to damp

Dipole modes

Dispersion diagram



dipole “passbands”

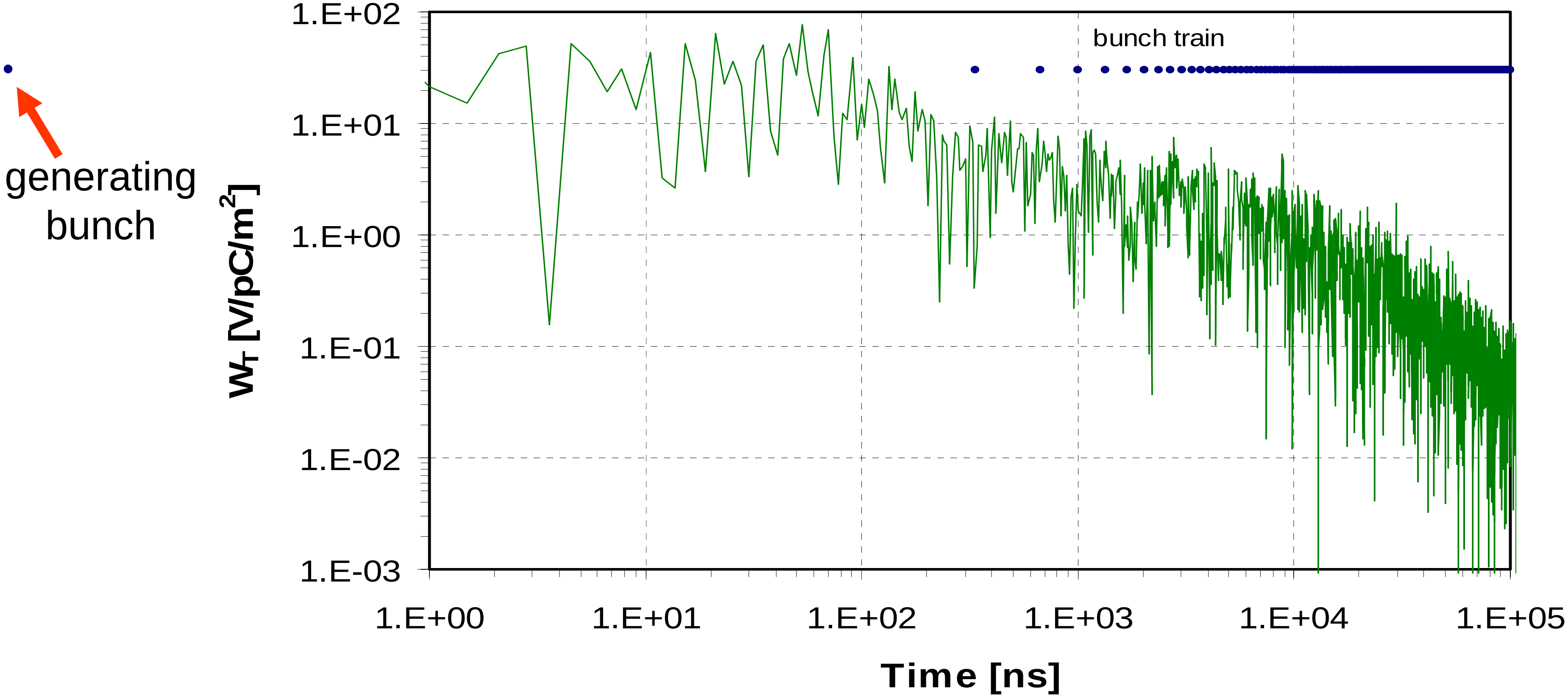
accelerating mode

Modes with highest R/Q

$\omega_l/2\pi$ [GHz] (measurement)	$(R/Q)_l$ [Ω/cm^2] (simulation)	Q_l (measurement)
1st dipole passband		
1.6506	0.76	$7.0 \cdot 10^4$
1.6991	11.21	$5.0 \cdot 10^4$
1.7252	15.51	$2.0 \cdot 10^4$
1.7545	2.16	$2.0 \cdot 10^4$
1.7831	1.75	$7.5 \cdot 10^3$
2nd dipole passband		
1.7949	0.77	$1.0 \cdot 10^4$
1.8342	0.46	$5.0 \cdot 10^4$
1.8509	0.39	$2.5 \cdot 10^4$
1.8643	6.54	$5.0 \cdot 10^4$
1.8731	8.69	$7.0 \cdot 10^4$
1.8795	1.72	$1.0 \cdot 10^5$
3rd dipole passband		
2.5630	1.05	$1.0 \cdot 10^5$
2.5704	0.50	$1.0 \cdot 10^5$
2.5751	23.80	$5.0 \cdot 10^4$

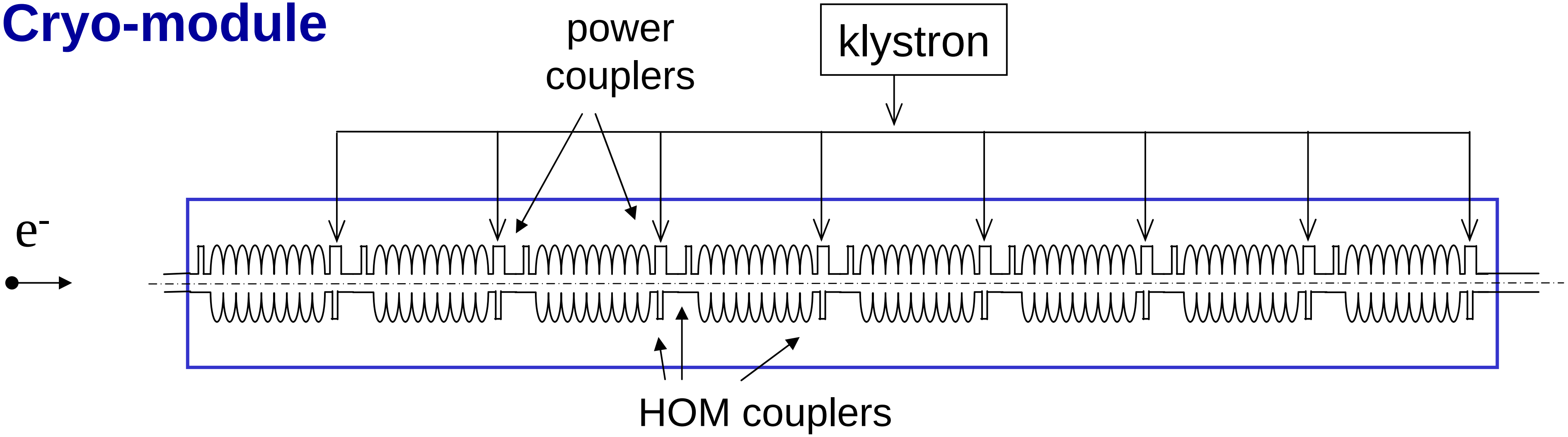
Transverse long range wake field for TESLA cavities

Obtained with dipole modes with highest R/Q measured on TTF cavities; averaged over 36 cavities with 0.1 % frequency spread



TESLA main linac

Cryo-module

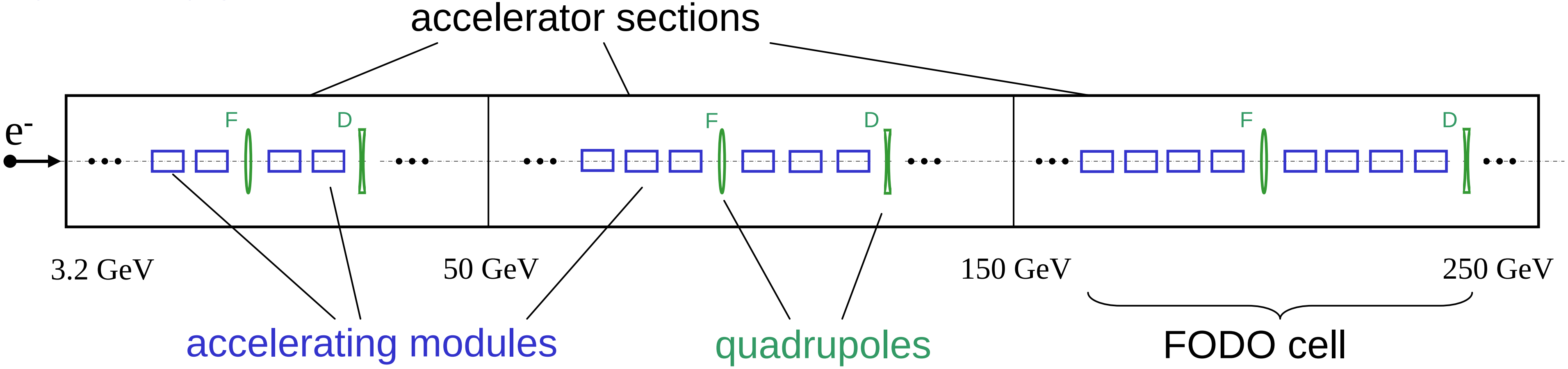

power couplers

klystron

e^-

HOM couplers

Main linac


accelerator sections

e^-

F

D

F

D

F

D

3.2 GeV

50 GeV

150 GeV

250 GeV

accelerating modules

quadrupoles

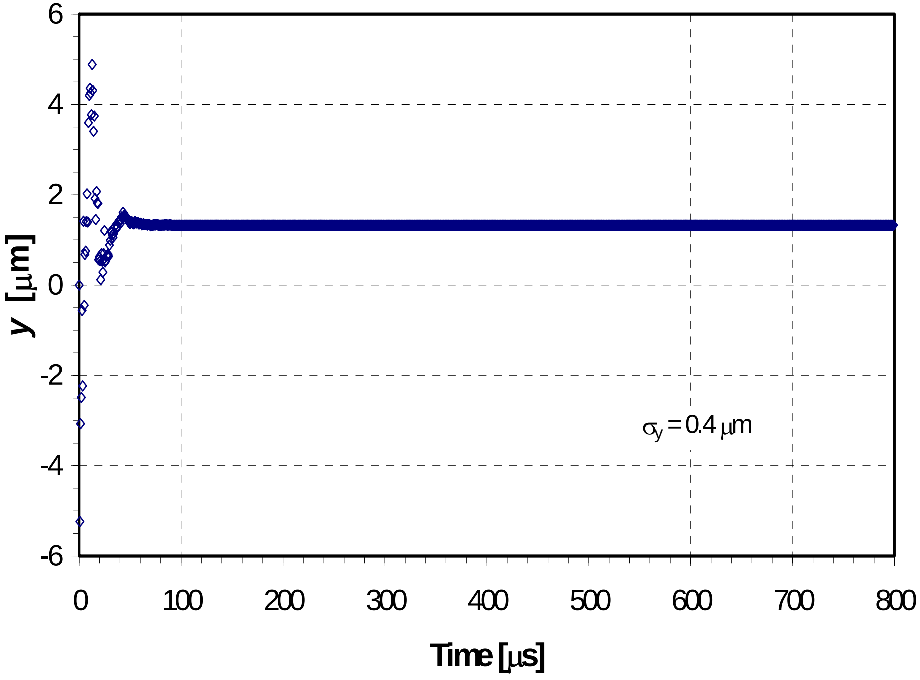
FODO cell

Multi-bunch beam dynamics

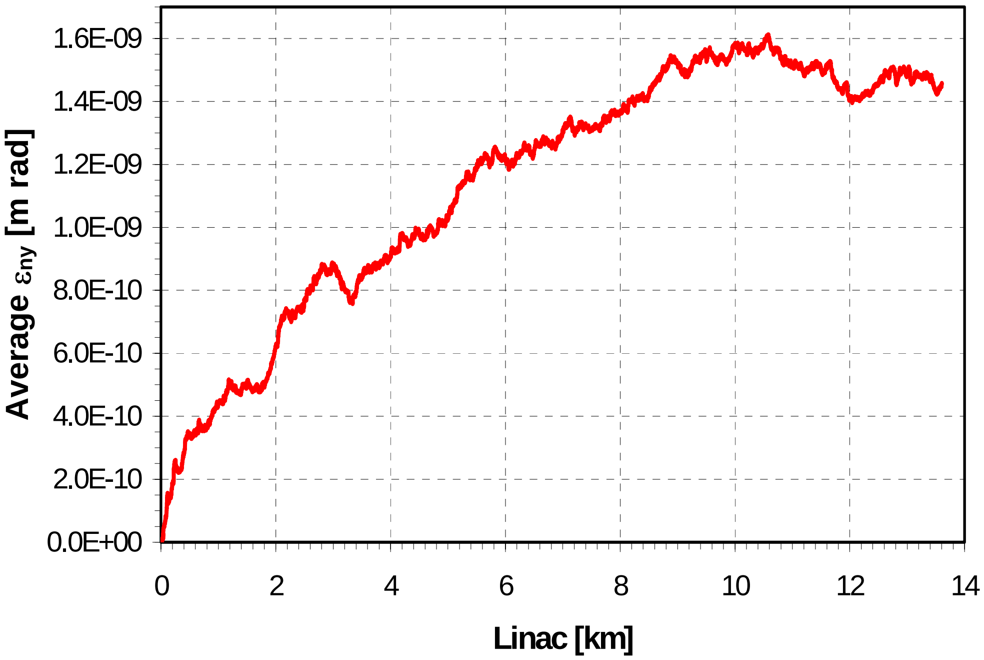
- Steady state achieved after about 7 % of beam
- Multi-bunch emittance growth $\Delta\varepsilon/\varepsilon_0 \approx 5\%$ (negligible)

  ($\varepsilon_0 = 3\cdot10^{-8}$ m·rad)

Bunch train



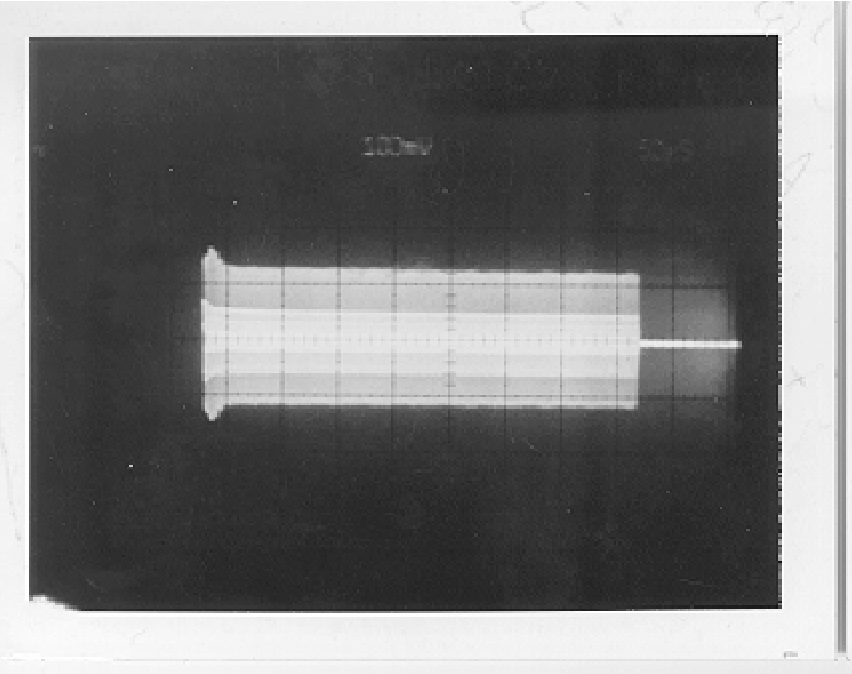
Multi-bunch emittance



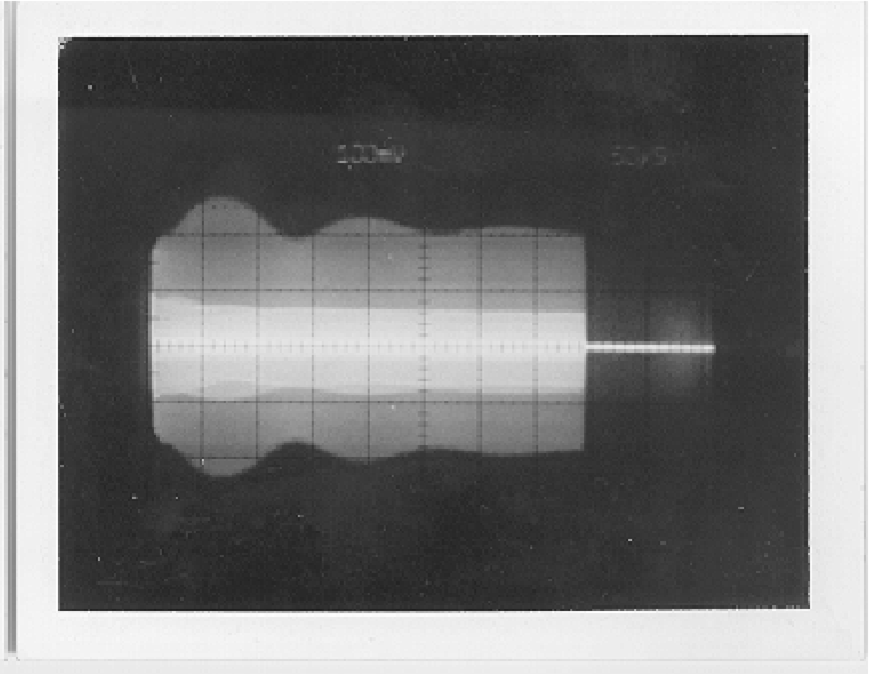
High-Q mode

- High-Q mode in the 3rd dipole passband excited resonantly by a beam with modulated intensity
  - $\omega_l/2\pi = 2.584$ GHz, $(R/Q)_l = 23.8\ \Omega/\text{cm}^2$, $Q_l = 10^6$

no HOM resonance



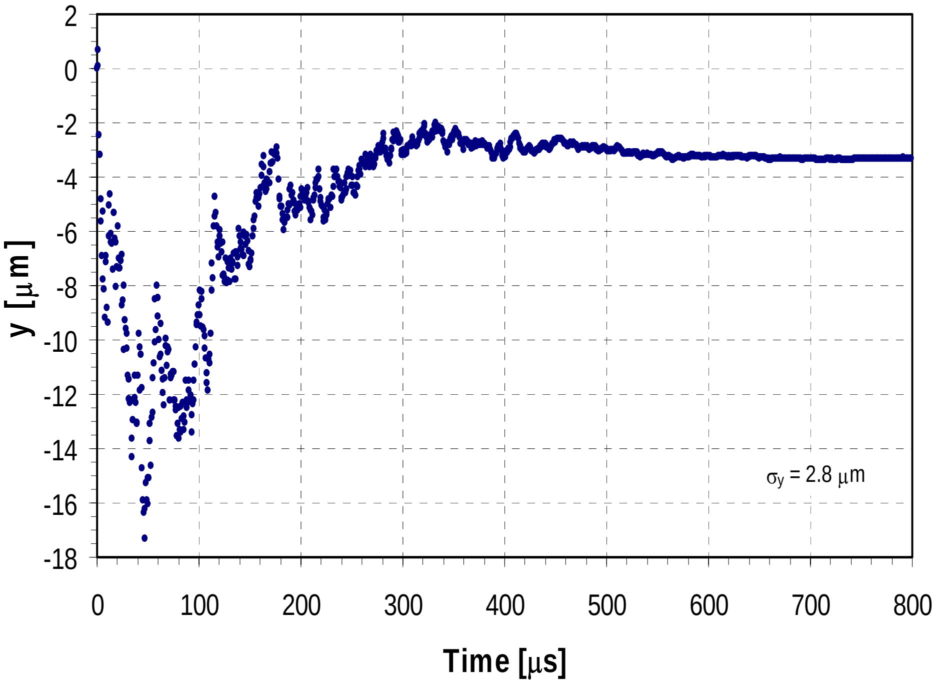
HOM resonance

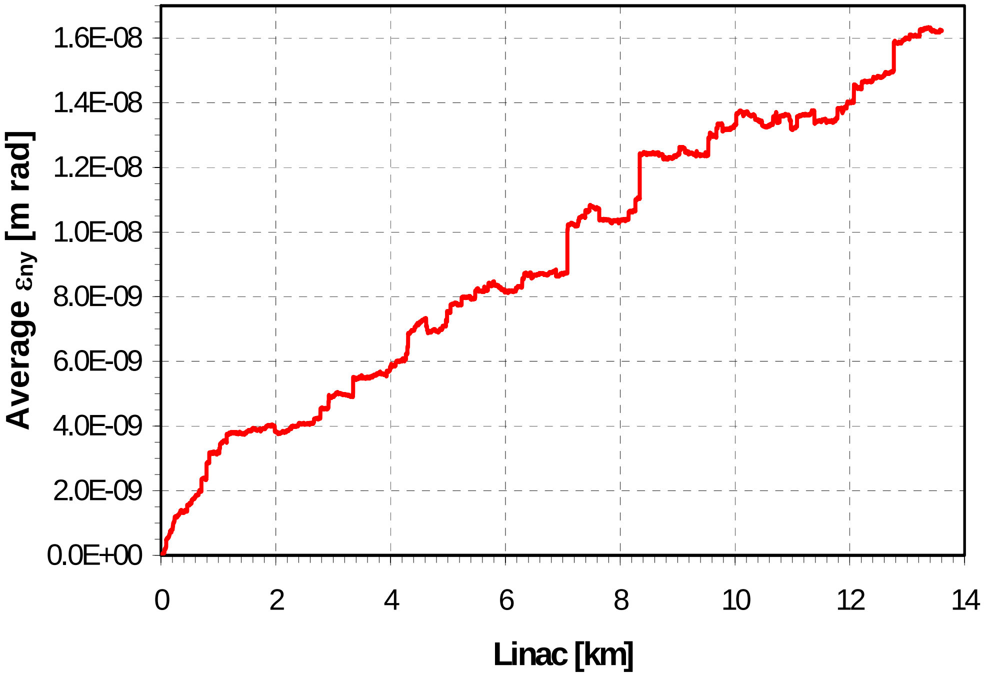


Beam dynamics with high-Q mode

- 1 cavity in each cryo-module → high Q mode in 3rd passband:

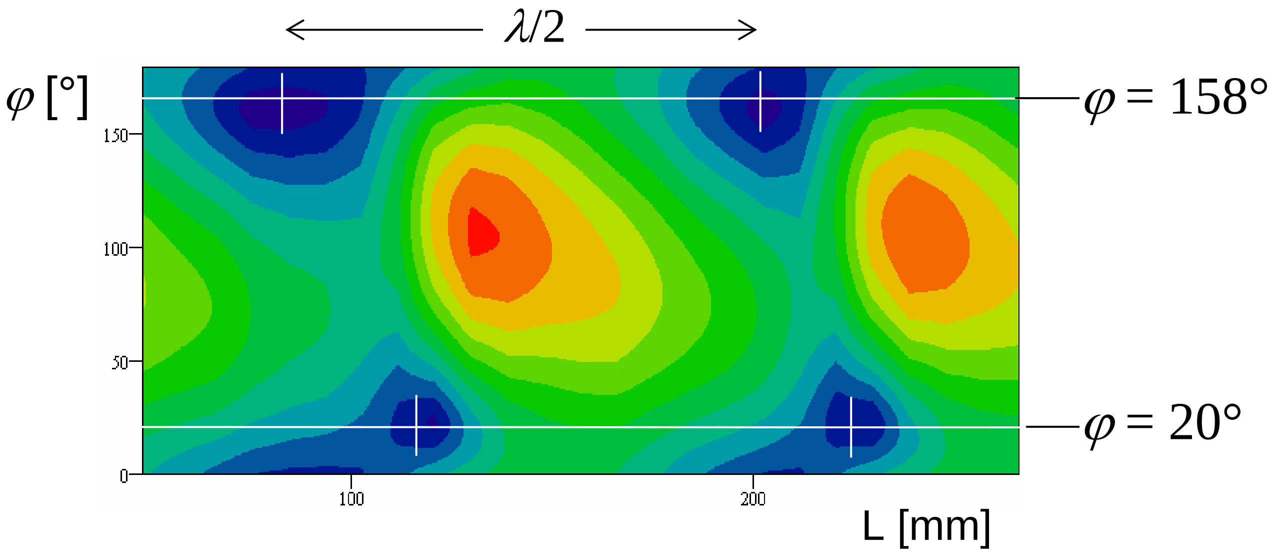
⇒ average $\Delta\varepsilon/\varepsilon_0 > 50\%$ ⇒ stronger damping is needed





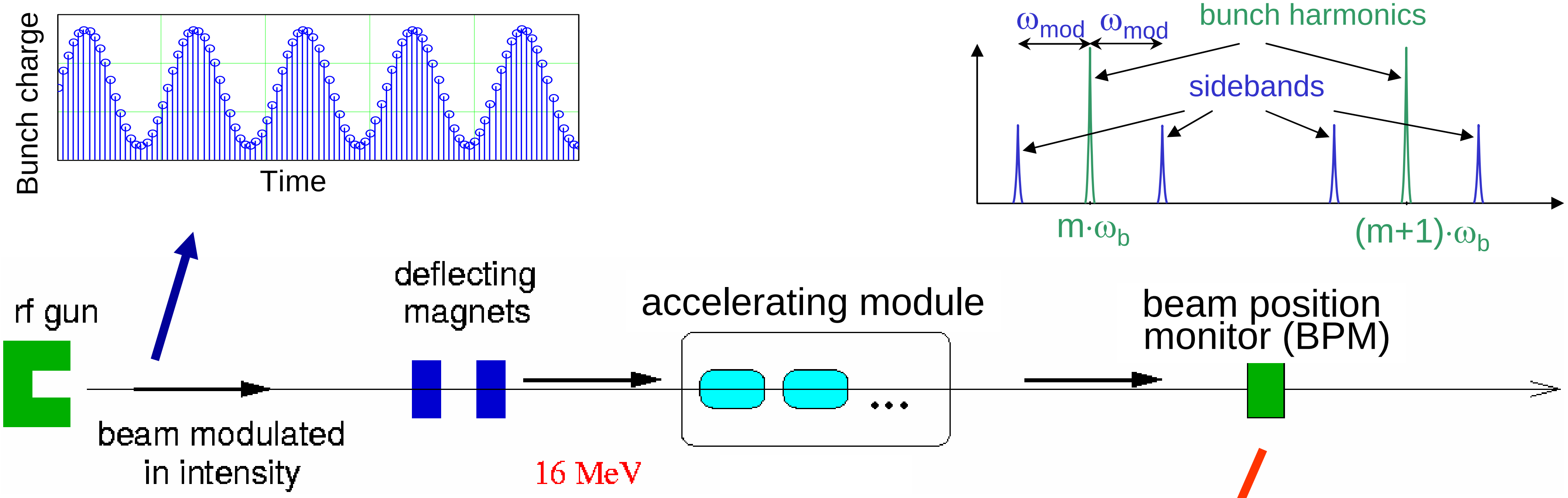
Cause of insufficient damping of mode in the 3rd dipole passband

- Effective absorption of the HOM couplers



⇒ field minima at both couplers for 2 angles ⇔ high Q

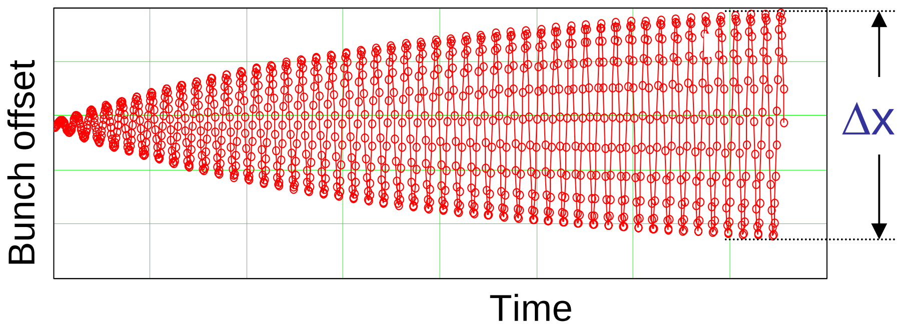
Excitation of single modes



If $\boxed{\omega_{\text{mod}} = \left|\omega_l - m\cdot\omega_b\right|} \le \omega_b/2$:

$$\boxed{\Delta x'_{res\,\max} = c\,\frac{e}{E}\,\delta x_0\left(q_0\,\frac{\omega_b}{2\pi}\right)\lambda\,\frac{1}{\omega_l}\left(\left(\frac{R}{Q}\right)Q\right)_l}$$

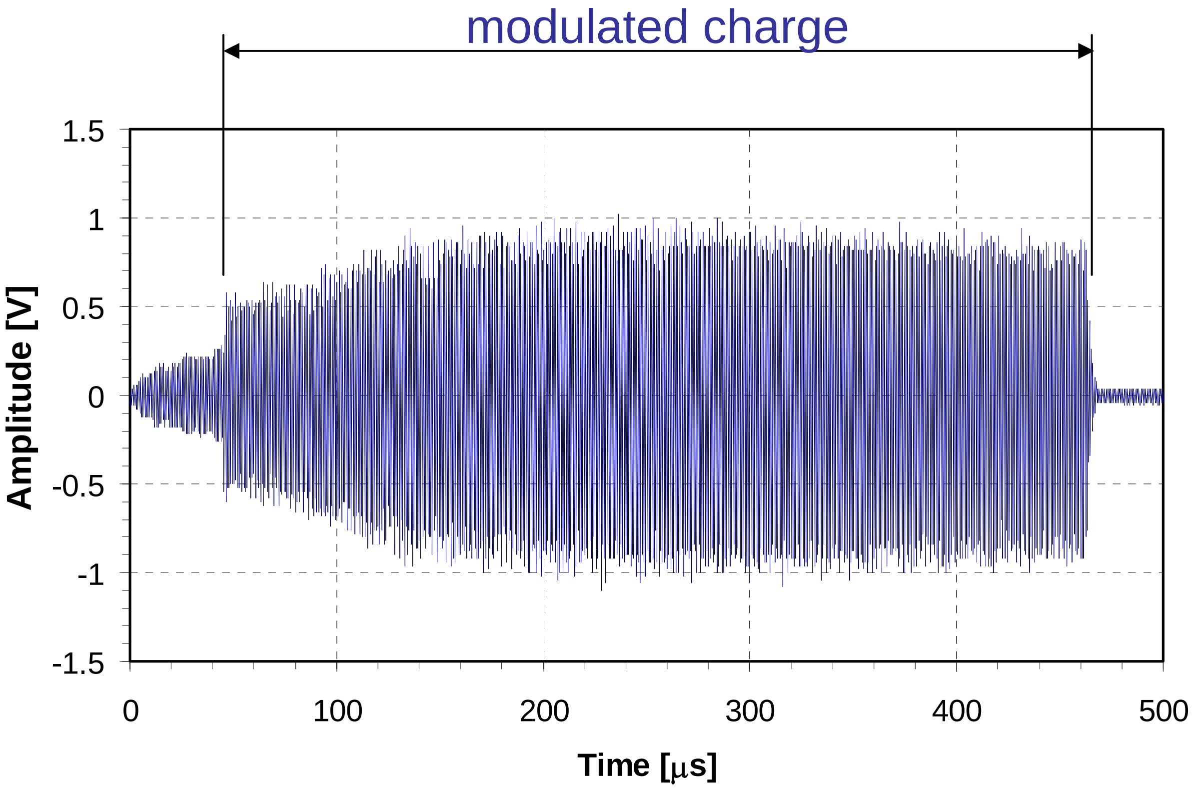
(for long bunch trains)



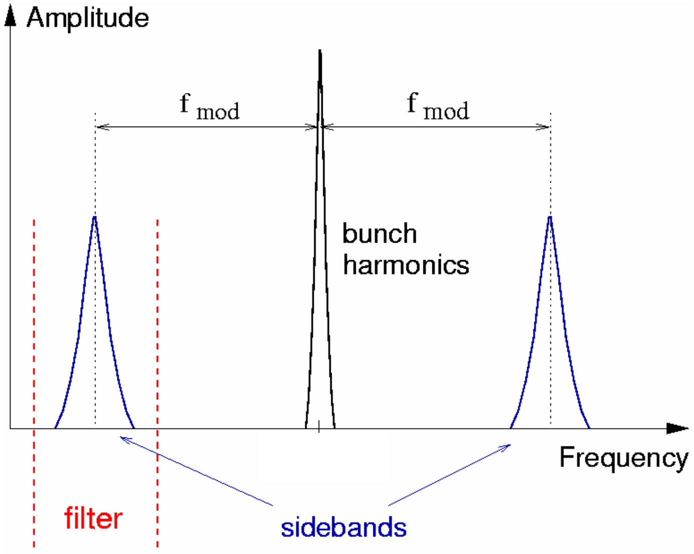
BPM difference signal

- change with ω_{mod} are comparable to the fluctuations in beam charge and position
- rejection of sum signal in difference signal

$\omega_{mod}/2\pi$ = 23.775 MHz



BPM filtered signal

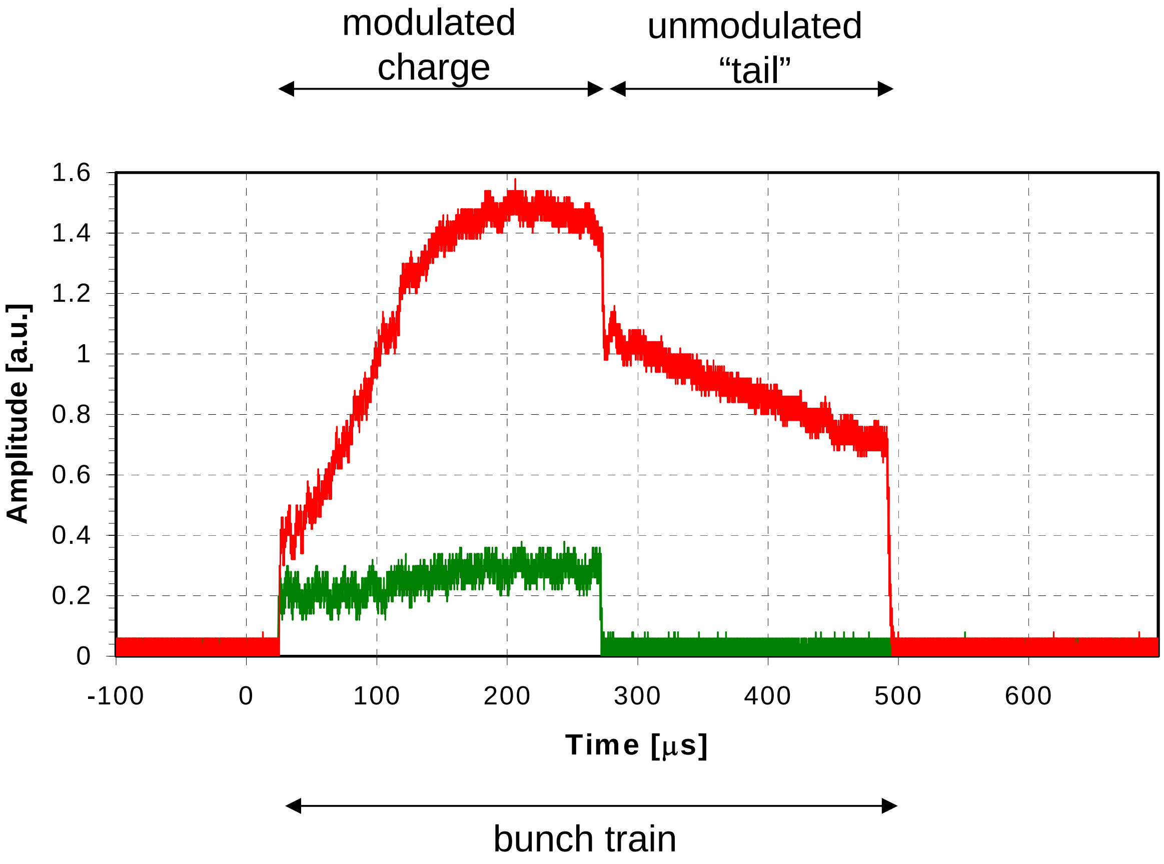


$\omega_{\mathrm{mod}}/2\pi = 23.629$ MHz

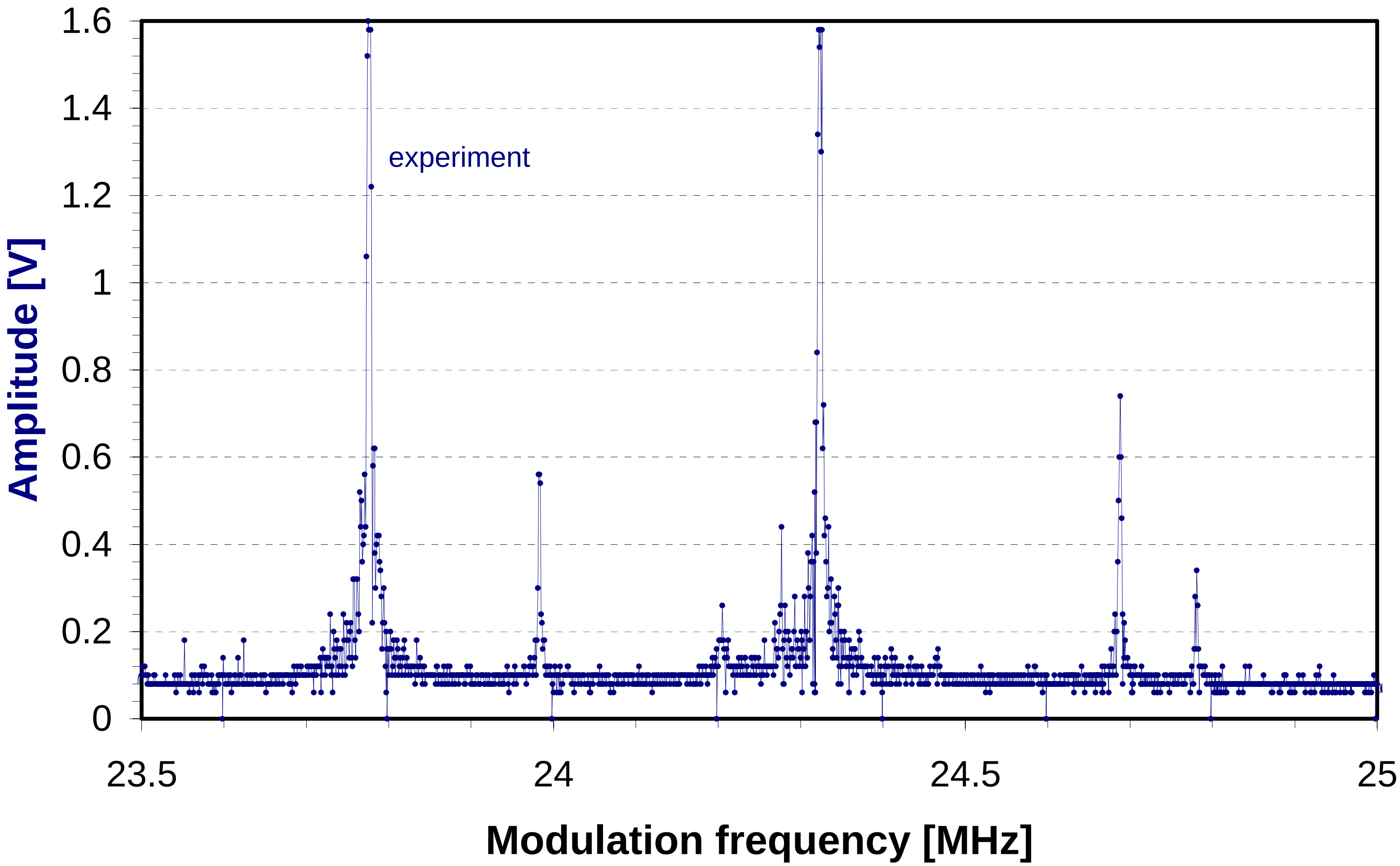
(off resonance)

$\omega_{\mathrm{mod}}/2\pi = 23.776$ MHz

(on resonance)

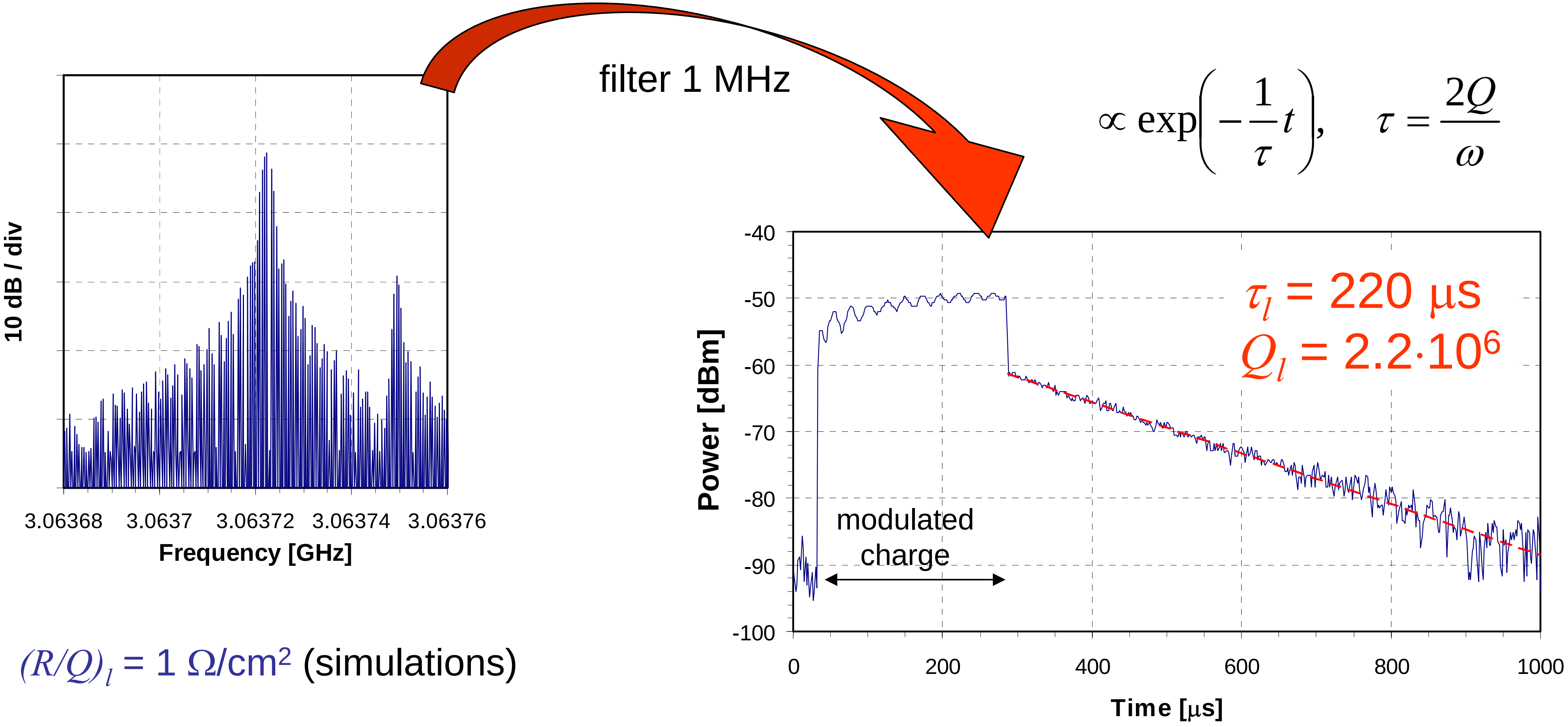


Modulation frequency scan



Spectrum from HOM couplers

$\omega_{mod}/2\pi = 23.775$ MHz, $\omega_l/2\pi = 3.063724$ GHz $= (57 \cdot \omega_b - \omega_{mod})/2\pi$



filter 1 MHz

$$\propto \exp\left(-\frac{1}{\tau}t\right), \qquad \tau = \frac{2Q}{\omega}$$

$\tau_l = 220$ μs

$Q_l = 2.2 \cdot 10^6$

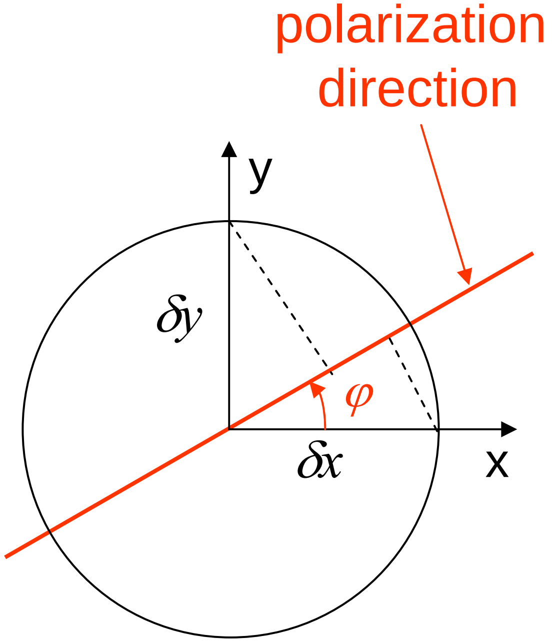
$(R/Q)_l = 1\ \Omega/\mathrm{cm}^2$ (simulations)

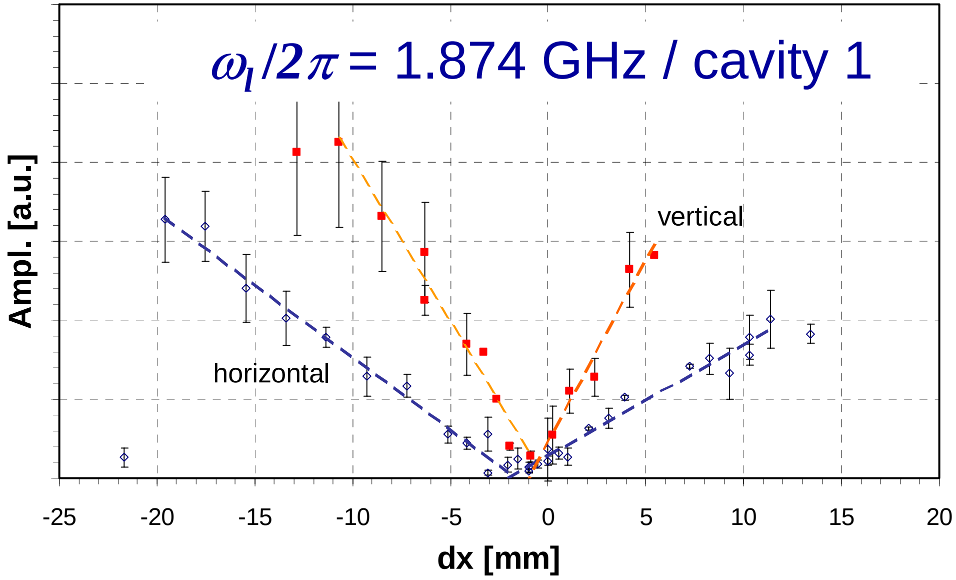
Polarization angle

- Signal amplitude at coupler

$$A(\delta x, \delta y = 0) \propto \delta x \cdot \cos\varphi; \quad A(\delta x = 0, \delta y) \propto \delta y \cdot \sin\varphi$$

$$\delta x = \delta y \quad \Rightarrow \quad \boxed{\tan\varphi = \frac{A(\delta x = 0, \delta y)}{A(\delta x, \delta y = 0)}}$$





$\Rightarrow \varphi = 70° \pm 7°$

R/Q

- Kick amplitude:

$$\Delta x'_{\max} = c\,\frac{e}{E}\,\delta x_0\,(q_0 f_b)\,\lambda\,\frac{1}{\omega_l}\left(\left(\frac{R}{Q}\right)Q\right)_l \cos\varphi$$

polarization angle

- For $\omega_l/2\pi$ = 1.874 GHz / cavity 1:

Δx = 1.8 mm ⇒ $\Delta x'$ = 200 μrad ⇒ $(R/Q)_l \cos\varphi$ = 3.3 Ω/cm^2

⇒ **$(R/Q)_l$ = 9.3 Ω/cm^2** ± **3 Ω/cm^2** (simulations: 8.7 Ω/cm^2)

Conclusions

- HOMs in accelerating structures for TESLA
- Beam dynamics in the TESLA main linac
  - ok for modes of 1st + 2nd dipole passbands
  - mode in 3rd passband needs better damping in all cavities
  - high-Q induced by boundaries imposed by neighboring cavities
- Method to study modes individually
  - modes excited and identified → 5th dipole passband
  - polarization direction was measured
  - *R/Q* estimated with good agreement with simulations

- Correction techniques will minimize HOM effects