Operational Aspects of SC RF Cavities with Beam

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And there was beam…

- **Two different points of view:**
  - **The SRF cavity view:**
    - **I could function so nicely if the beam wouldn't cause such a mess…**
  - **The beam view:**
    - **OK, gaining energy is nice, but why do these cavities also have to disturb me so much?**

The Cavity and the Beam…

Impact on the SRF cavity:

- Beam loading, field perturbations, increased RF power
- Beam based field calibration
- HOM power handling and heating issues
- Beam induced trips
- Cavity performance with beam

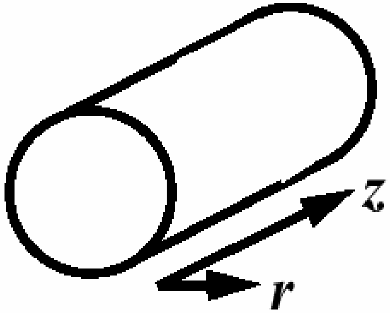
Impact on the Beam:

- Energy gain, energy stability
- Emittance growth
  - Short range wake fields
  - HOM fields, BBU
  - Transverse kick fields
    - Cavity misalignment
    - Asymmetry from couplers, …
  - RF focusing
- Beam loss due to RF trips

Let's start "simple": The Fundamental mode (passband) and the beam

- Accelerating field
- Beam induced fields: Single bunch and bunch train
- Beam loading and optimal loaded Q
- Beam induced field perturbations
- LLRF field control
- Beam based field calibration

The mode we love so much: TM$_{010}$

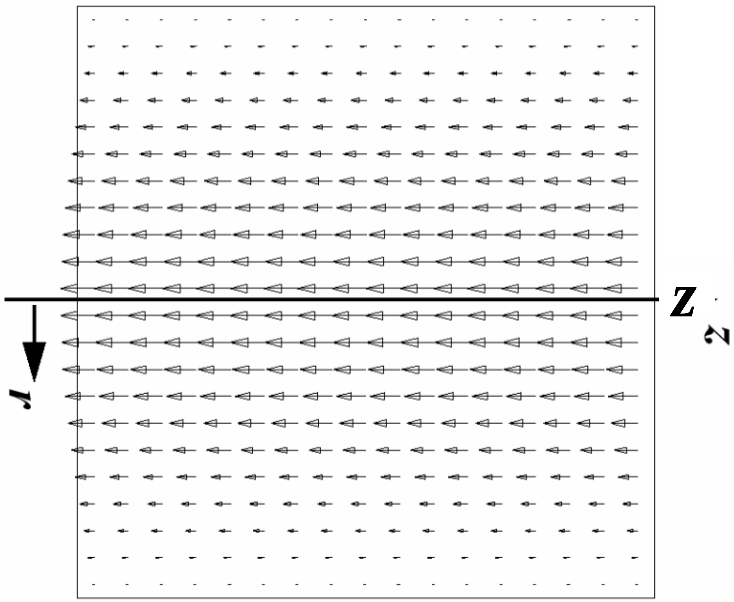


lowest frequency mode: ***TM010*** — z

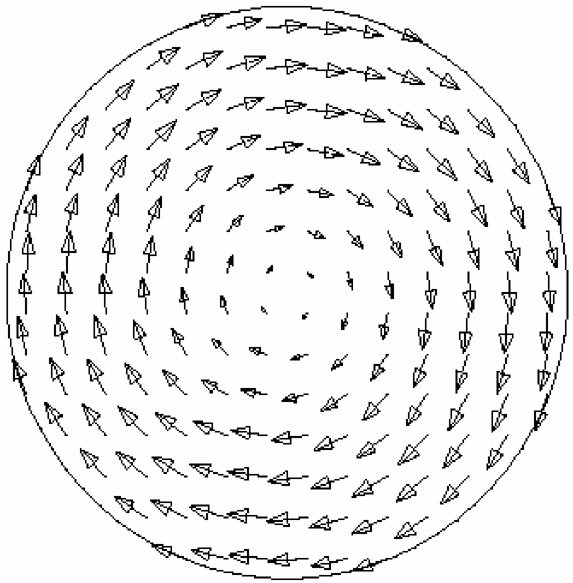
transverse magnetic — r

0 $\Rightarrow$ monopole mode

electric field



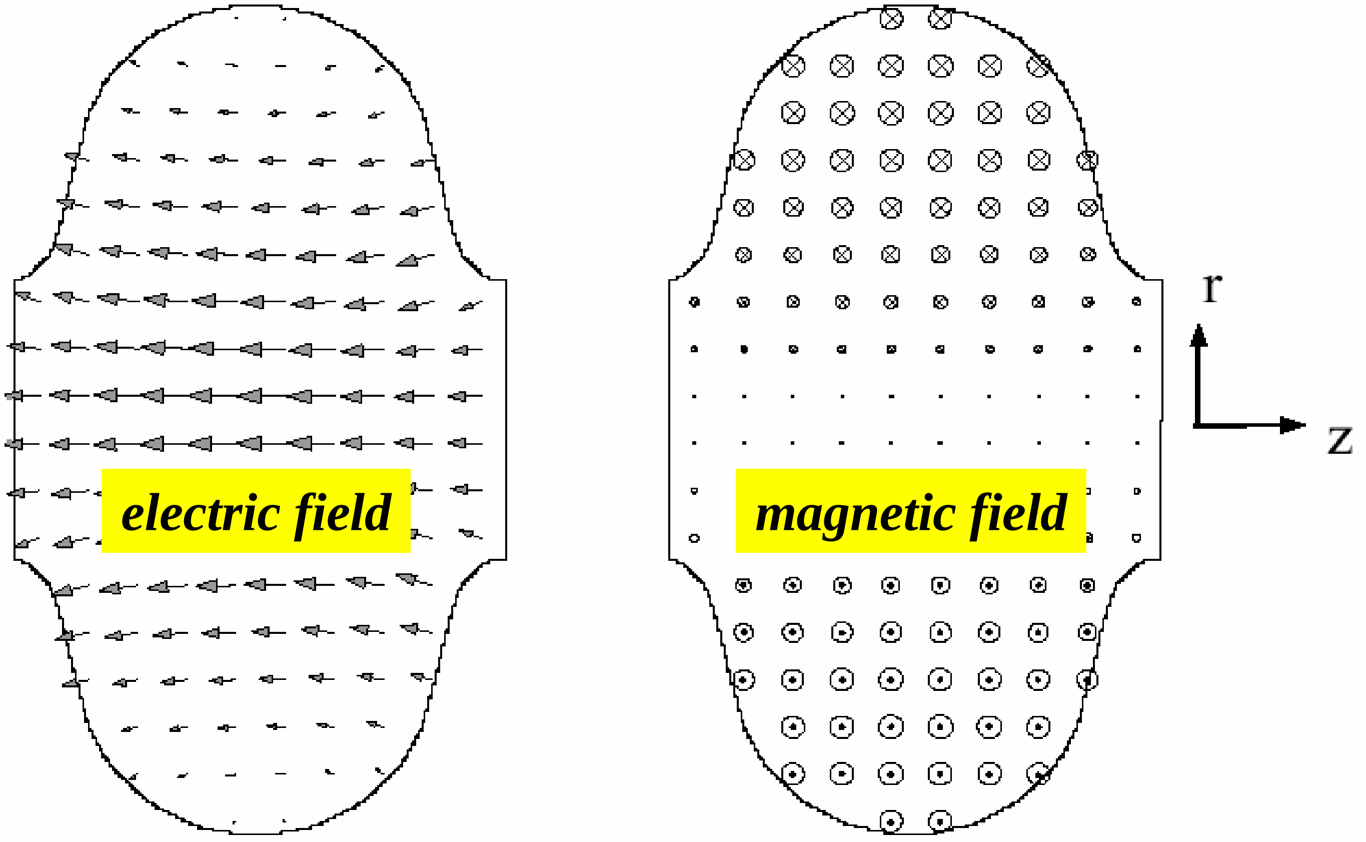
magnetic field



$$\vec{E}(r,t) = E_0 J_0\left(\frac{\omega_0}{c} r\right)\cos(\omega_0 t)\vec{e}_z$$

$\Rightarrow$ acceleration

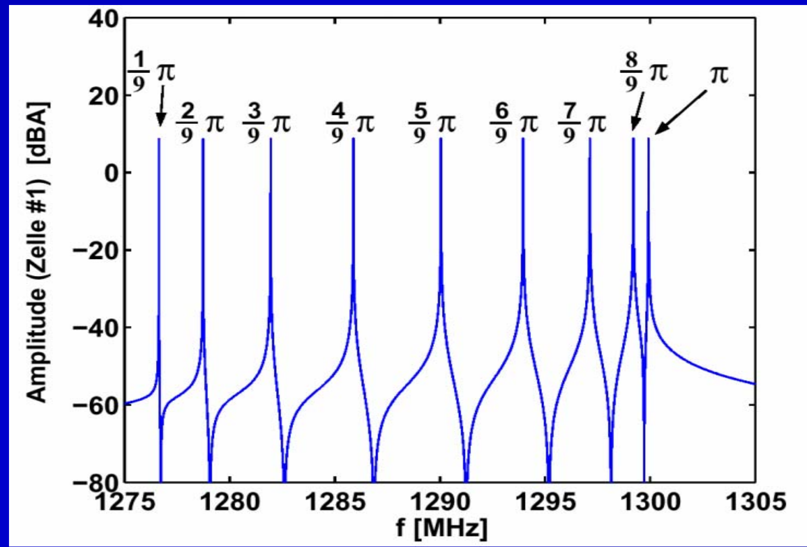
The Accelerating Mode in an Elliptical RF Cavity

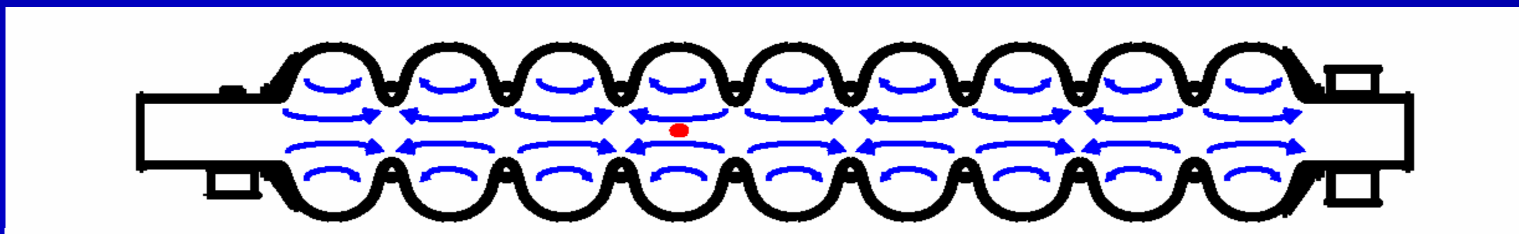


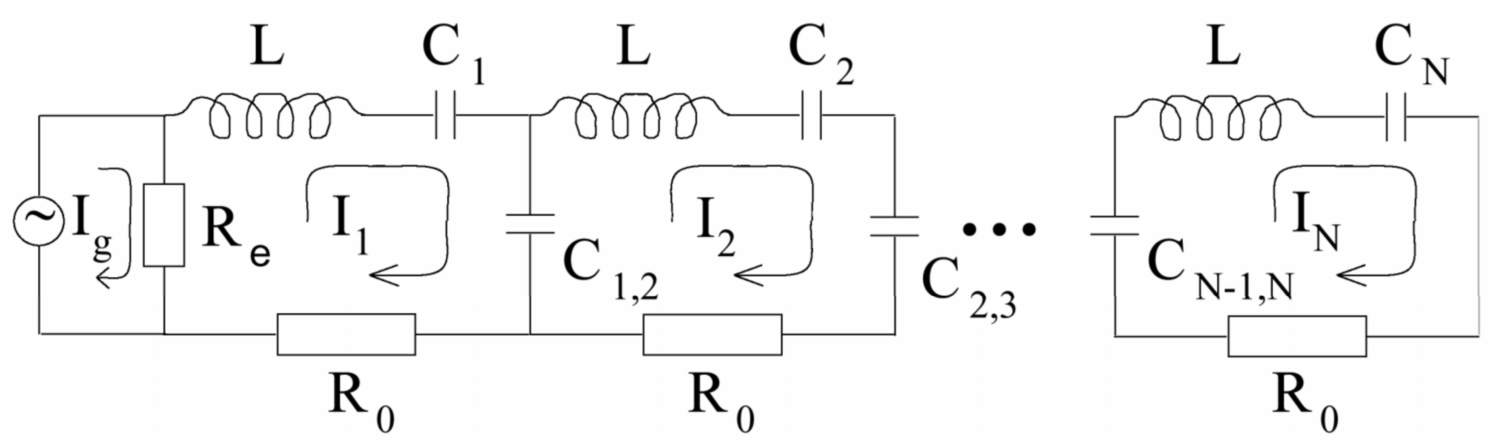
$f_0 = 1.3$ GHz for ILC cavities

Multi-cell Cavities

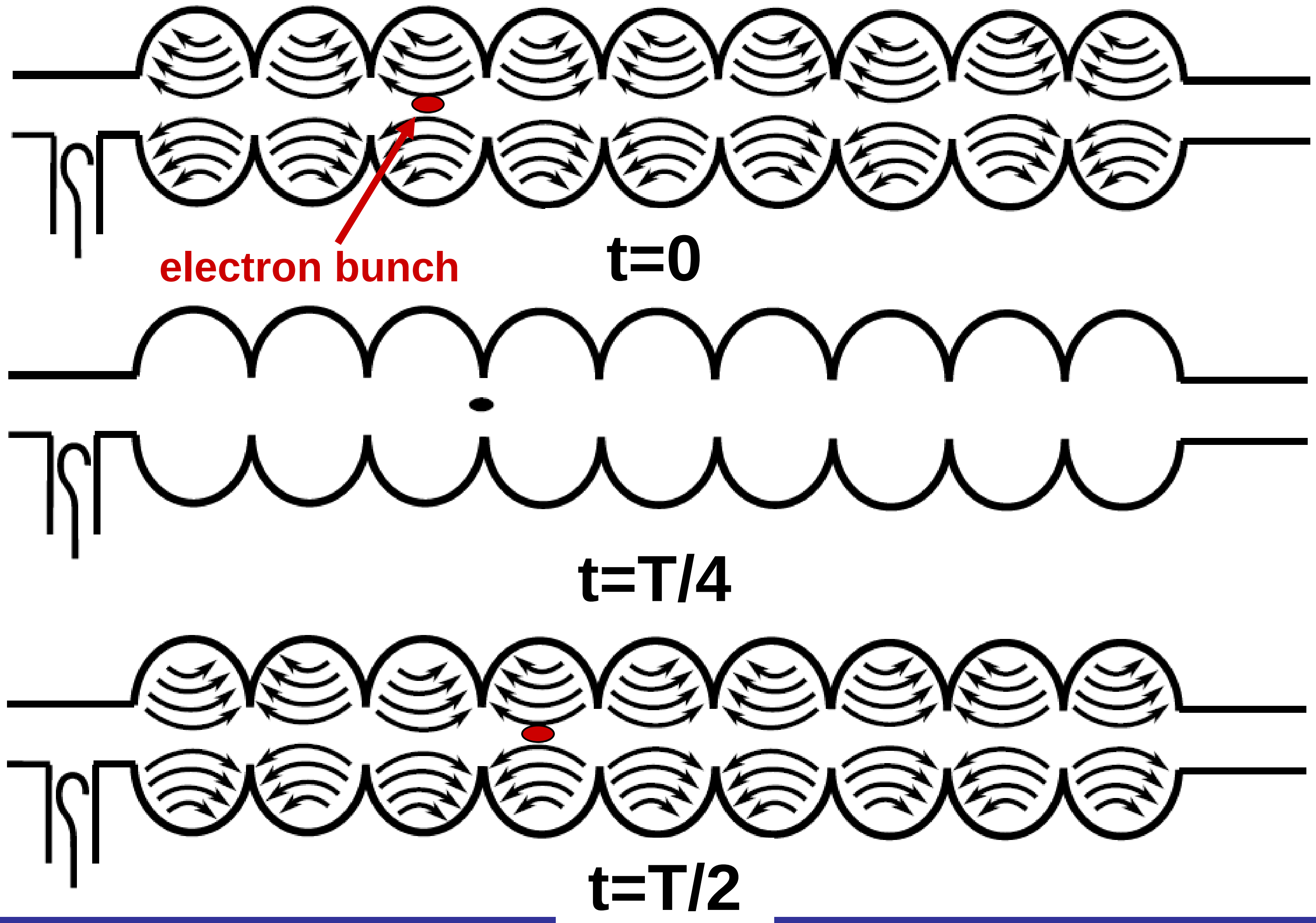
- **N coupled cells $\Rightarrow$ N TM_{010} modes = TM_{010} passband!**
- **Highest frequency mode (π-mode) is the accelerating mode**





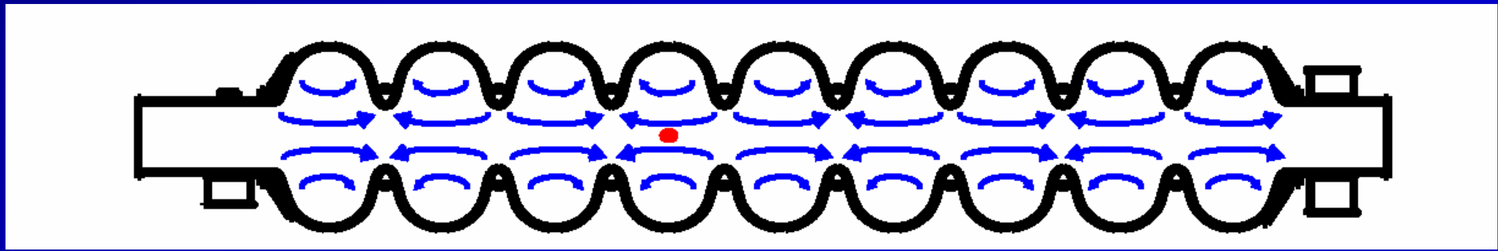


The Accelerating Mode



Accelerating Voltage

Accelerating π-mode:



Accelerating voltage:

$$V_{acc} = \frac{\text{maximum energy gain}}{\text{charge}} = \left| \int_{-L/2}^{+L/2} E_z e^{i\omega(z/c)} dz \right|$$

Accelerating field gradient:

$$E_{acc} = \frac{V_{acc}}{\text{active cavity length}}$$

Coupling Strength: R/Q

Shunt-impedance:

$$R_{sh} = \frac{(V_{acc})^2}{2P_{dis}}$$

Quality factor:

$$\boldsymbol{Q_L = \frac{\omega U}{P_{dis}}}$$

$$\frac{R_{sh}}{Q_L} = \frac{R}{Q} = \frac{(V_{acc})^2}{2\omega U}$$

Note: Here I use the circuit definition of the shunt impedance. The so-called accelerator definition of it is a factor of 2 larger!

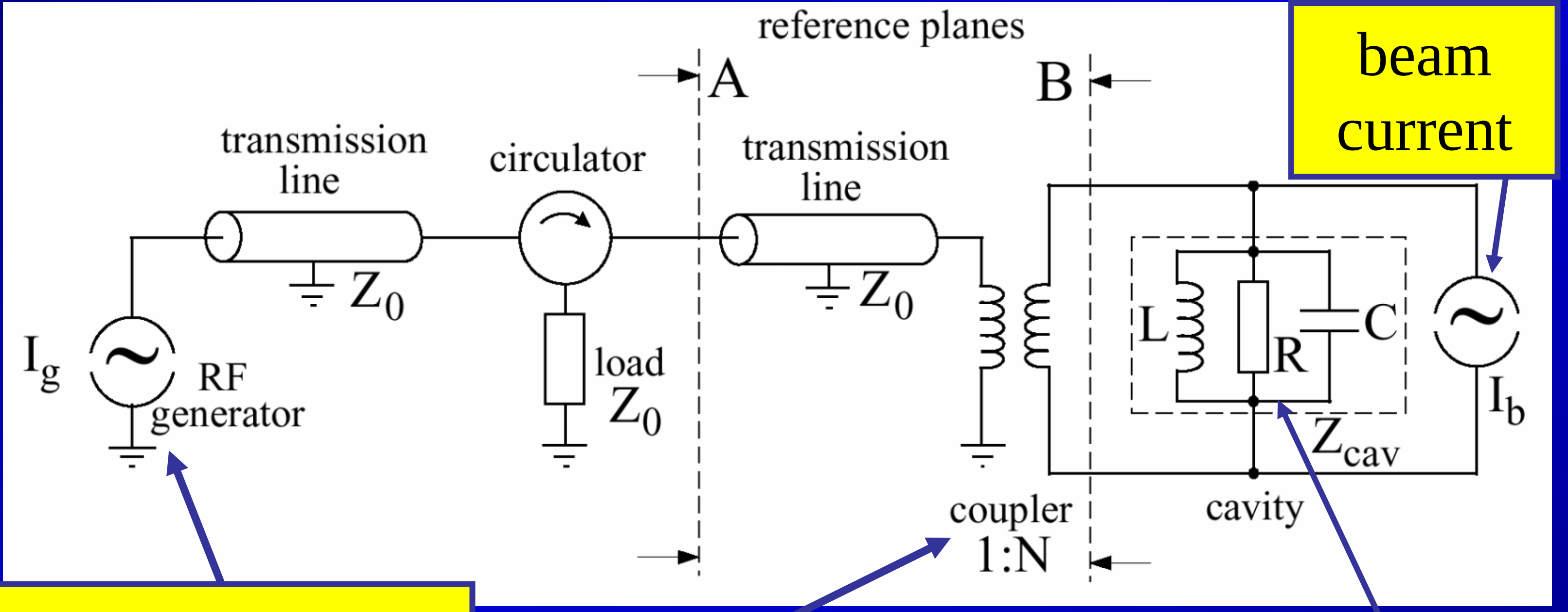
Excitation of the Fundamental Mode

Two different sources excite the accelerating mode:

- **RF Generator (power source)**
  - **RF power at the fundamental mode frequency is coupled into the cavity via the input coupler**
- **Beam current**
  - **Bunches / bunch train excites the fundamental mode**

Equivalent Circuit Model

The full picture: **generator - transmission line - coupler - cavity**



beam current

generator:

$$P_g = \frac{1}{2} Z_0 I_g^2$$

coupler acts like a transformer:

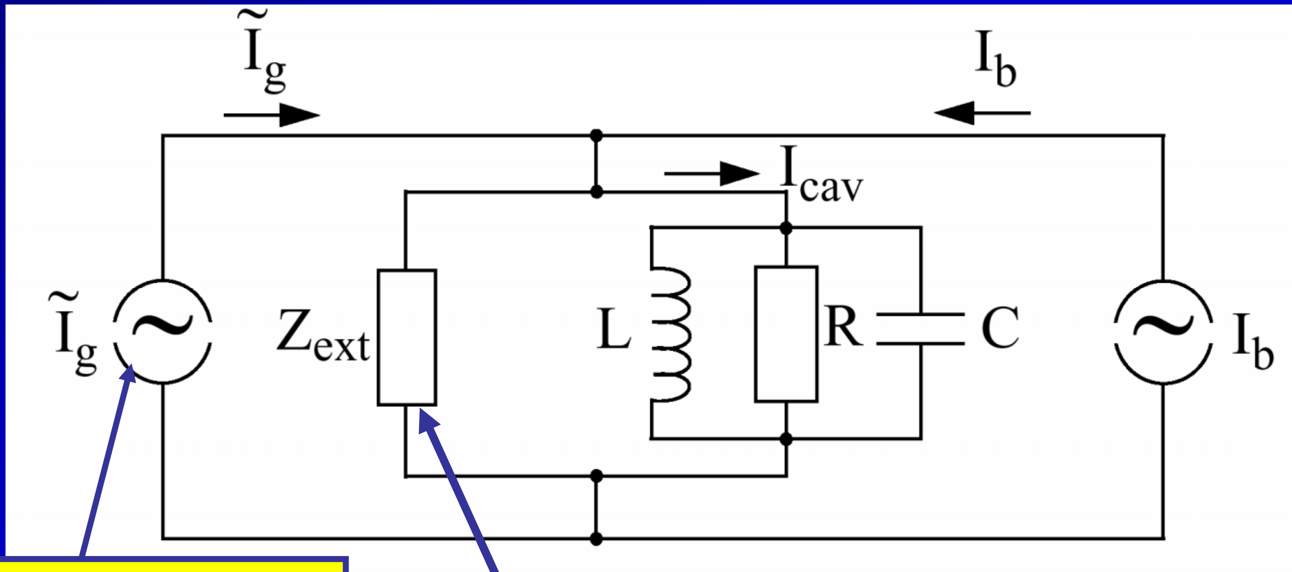
$V_2 = N\ V_1$

$I_2 = 1/N\ I_1$

cavity modeled as LCR circuit:

Note: R is the shut impedance, not R_{surf}!

Simplified Circuit Model



fictitious generator current:

$$\tilde{I}_g = 2/NI_g$$

transformed external load:

$$Z_{ext} = N^2 Z_0$$

⇒ Use this model to simulate cavity filling, RF field control, beam loading, …

More Figures of Merit…

Resonance frequency: $\omega_0 = 2\pi f_0 \approx 1/\sqrt{LC}$

Intrinsic quality factor: $Q_0 = \frac{\omega U}{P_{wall}} = \frac{R}{\omega_0 L}$

External quality factor: $Q_{ext} = \frac{\omega U}{P_{ext}} = \frac{Z_{ext}}{\omega_0 L}$

Loaded quality factor: $Q_L = \frac{\omega U}{P_{total}} = \frac{1}{\omega_0 L}\left[\frac{RZ_{ext}}{R+Z_{ext}}\right]$

Bandwidth of mode: $\omega_{1/2} = \omega_0 / 2Q_L$

Cavity detuning: $\Delta\omega = \omega_0 - \omega_{drive}$

Generator and Beam Induced Voltage

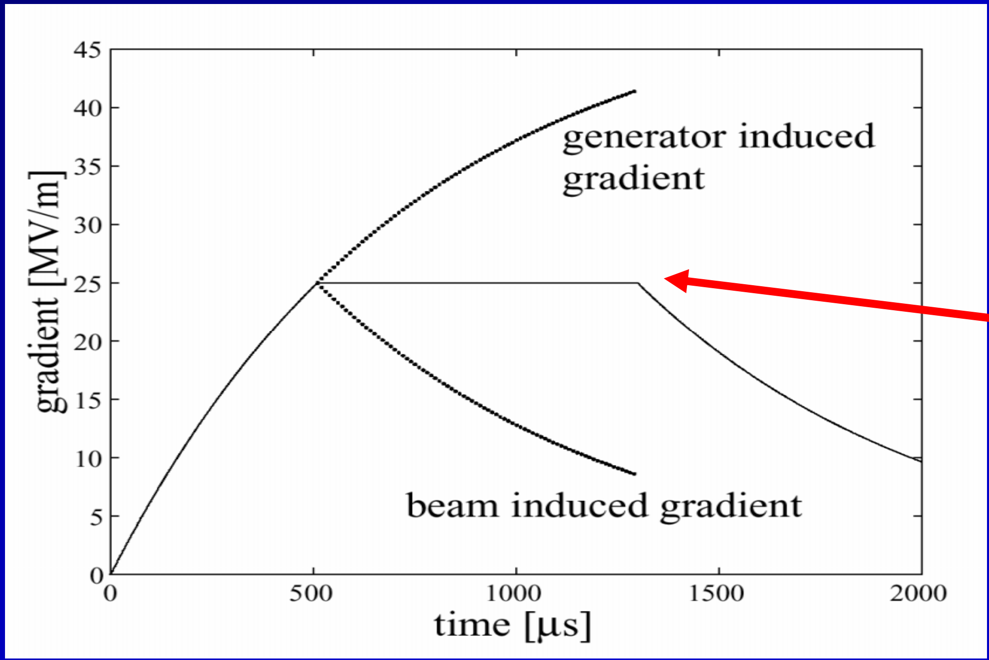
- Generator induced voltage (for constant generator power):

$$V_g(t) = \frac{\sqrt{8\frac{R}{Q}Q_L P_g}}{1 - i\frac{\Delta\omega}{\omega_{1/2}}}\left(1 - e^{-(\omega_{1/2} - i\Delta\omega)t}\right) e^{i\omega_g t}$$

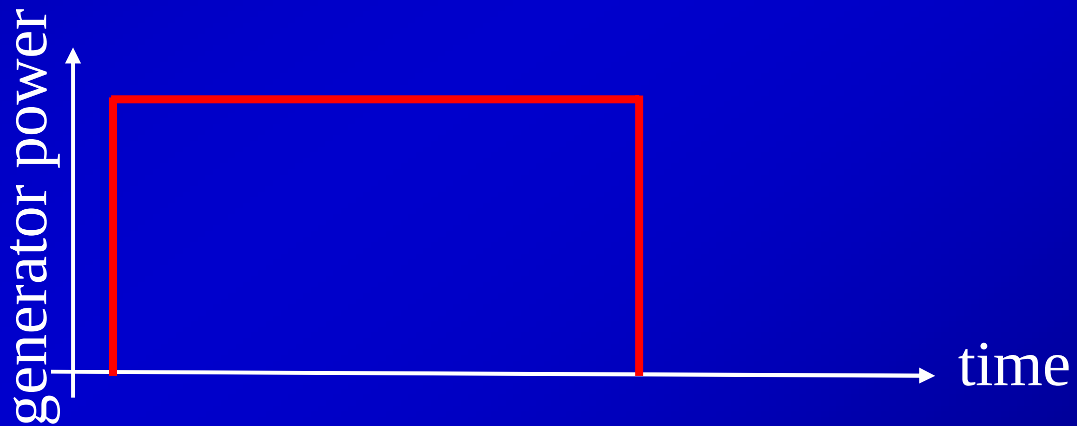
- Beam induced voltage (beam starts at t = 0):

$$V_b(t) = \frac{2\frac{R}{Q}Q_L I_b}{1 - i\frac{\Delta\omega}{\omega_{1/2}}}\left(1 - e^{-(\omega_{1/2} - i\Delta\omega)t}\right) e^{i\omega_b t}$$

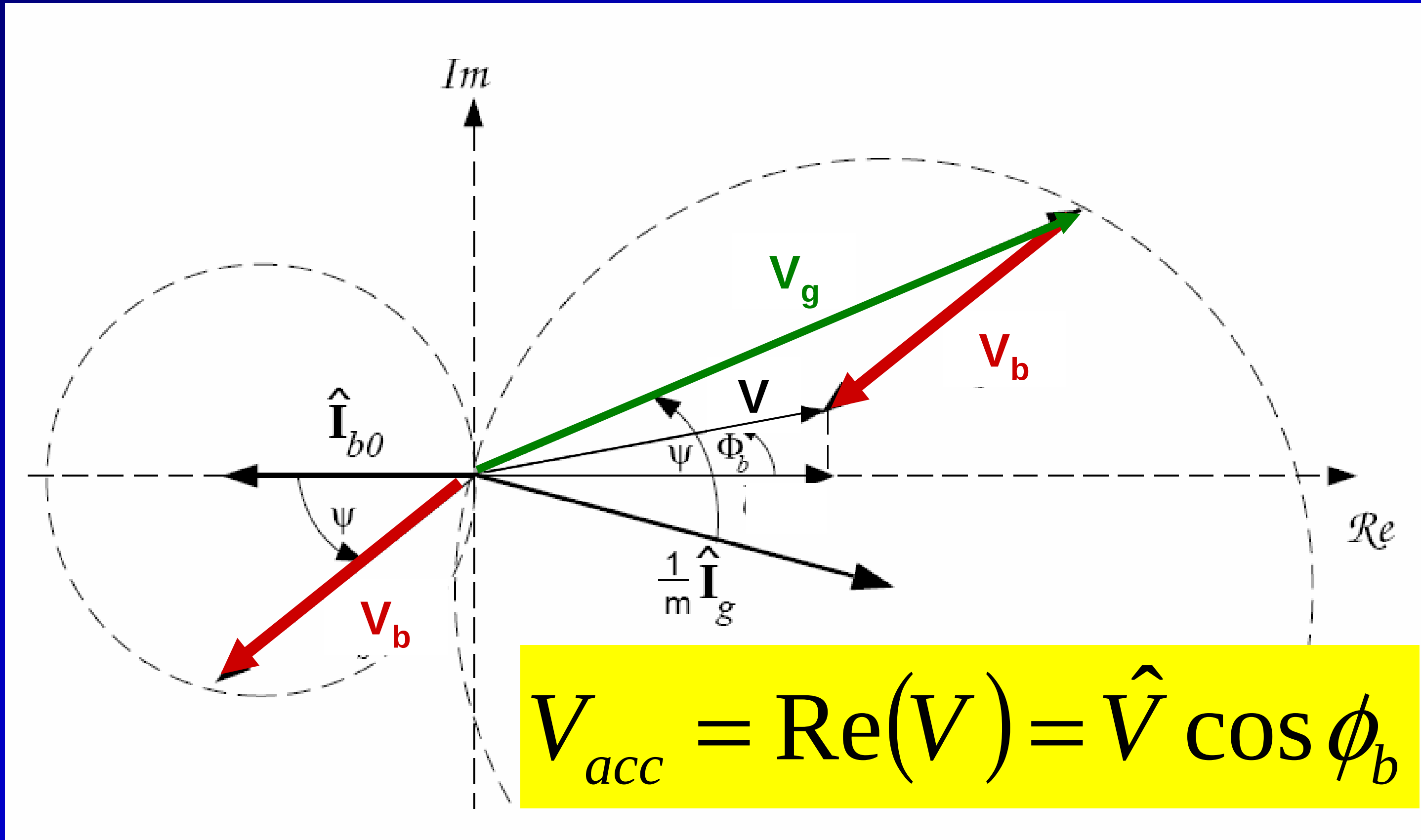
Example: FLASH



The generator and the beam induced voltage compensate each other if Q_L is properly adjusted.



Complex Phasor Diagram



$$V_{acc} = \mathrm{Re}(V) = \hat{V}\cos\phi_b$$

$$\Psi = \tan^{-1}\left(\frac{\Delta\omega}{\omega_{1/2}}\right) = \text{tuning angle}$$

Single Bunch

- So far: treated beam as an AC current
- Reality: bunches!
- Accelerating mode voltage induced by a single bunch: $$\Delta V_{bunch} = \omega_0 \frac{R}{Q} q_{bunch}$$
- On average, bunch "sees" half of its own induced field: $$V_{acc} = \hat{V} \cos\phi_b - \frac{1}{2} V_{bunch}$$

(fundamental theorem of beam loading)

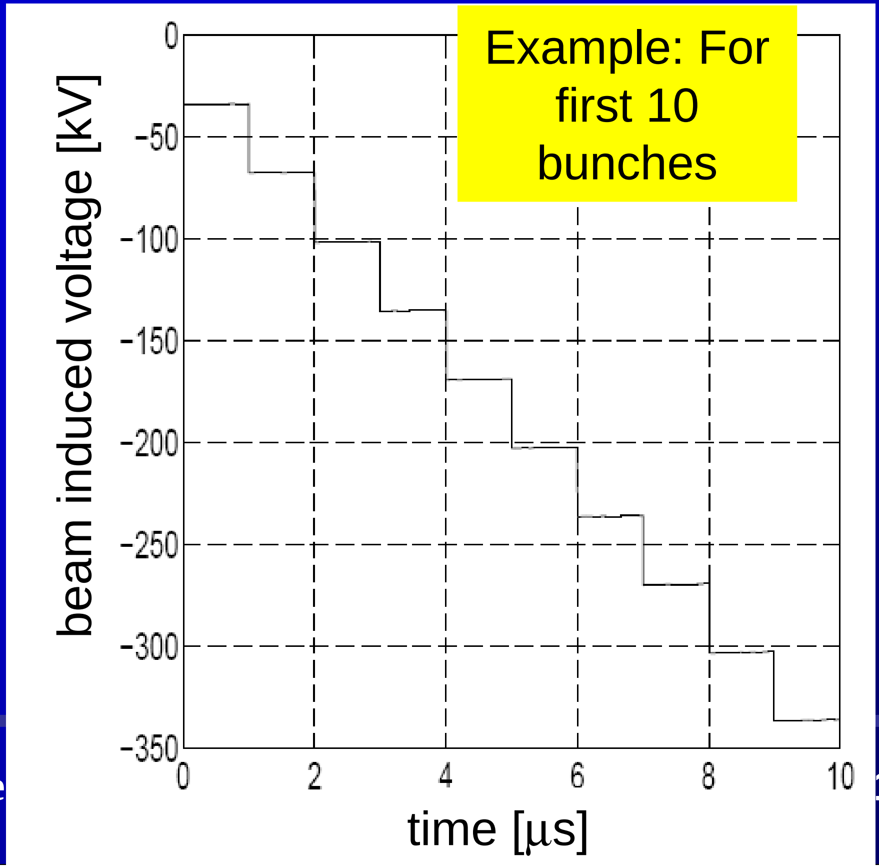
Bunch Train

- **Need to sum individual bunch induced voltages:**

$$V_{train} = V_{bunch}\left[1 + e^{-\omega_{1/2}\Delta T_b} e^{-i\Delta\omega\Delta T_b} + e^{-\omega_{1/2} 2\Delta T_b} e^{-i\Delta\omega 2\Delta T_b} + \ldots\right]$$

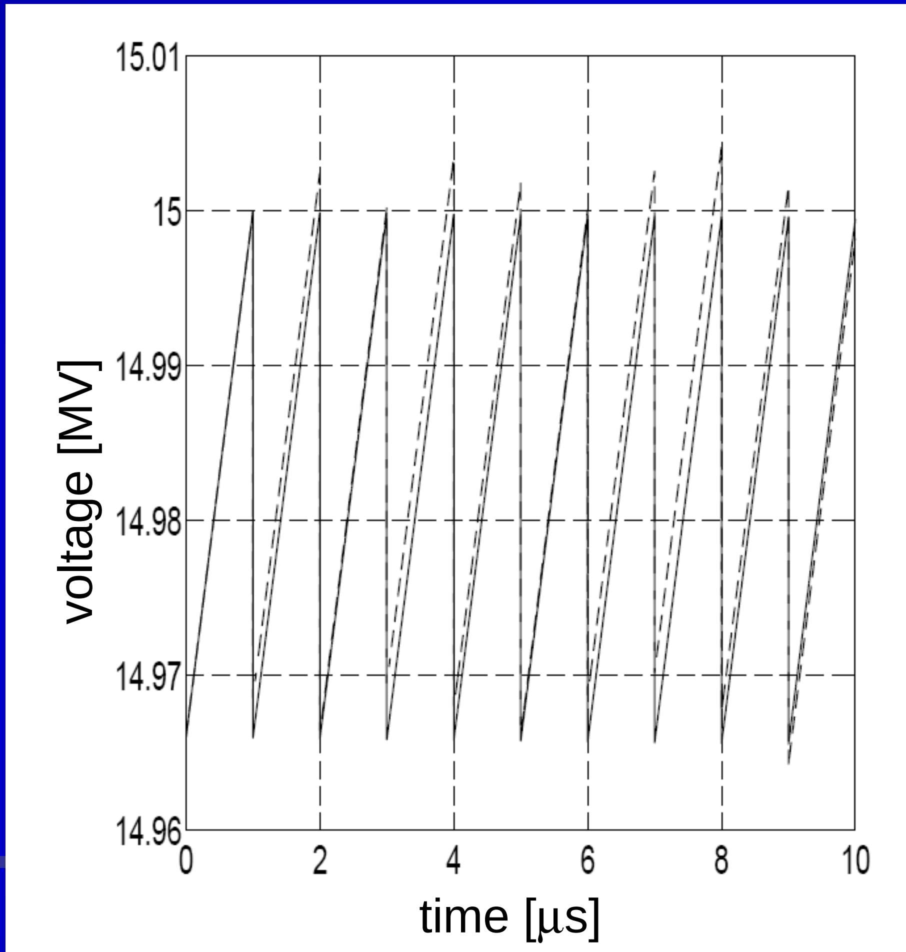
$\Rightarrow$ **Substructure!**

$\Rightarrow$ **Envelope given by previous equation**



Steady State

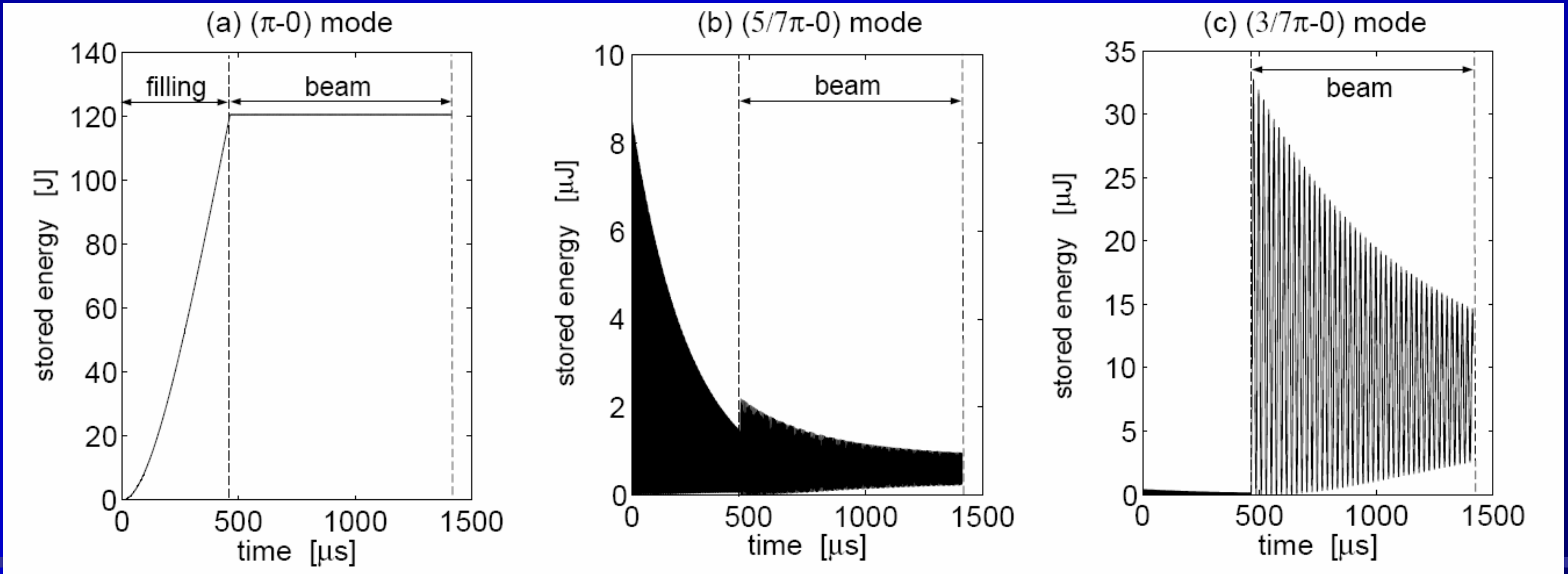
- **Sum of beam induced and generator induced voltage is not constant, but shows saw-like shape!**

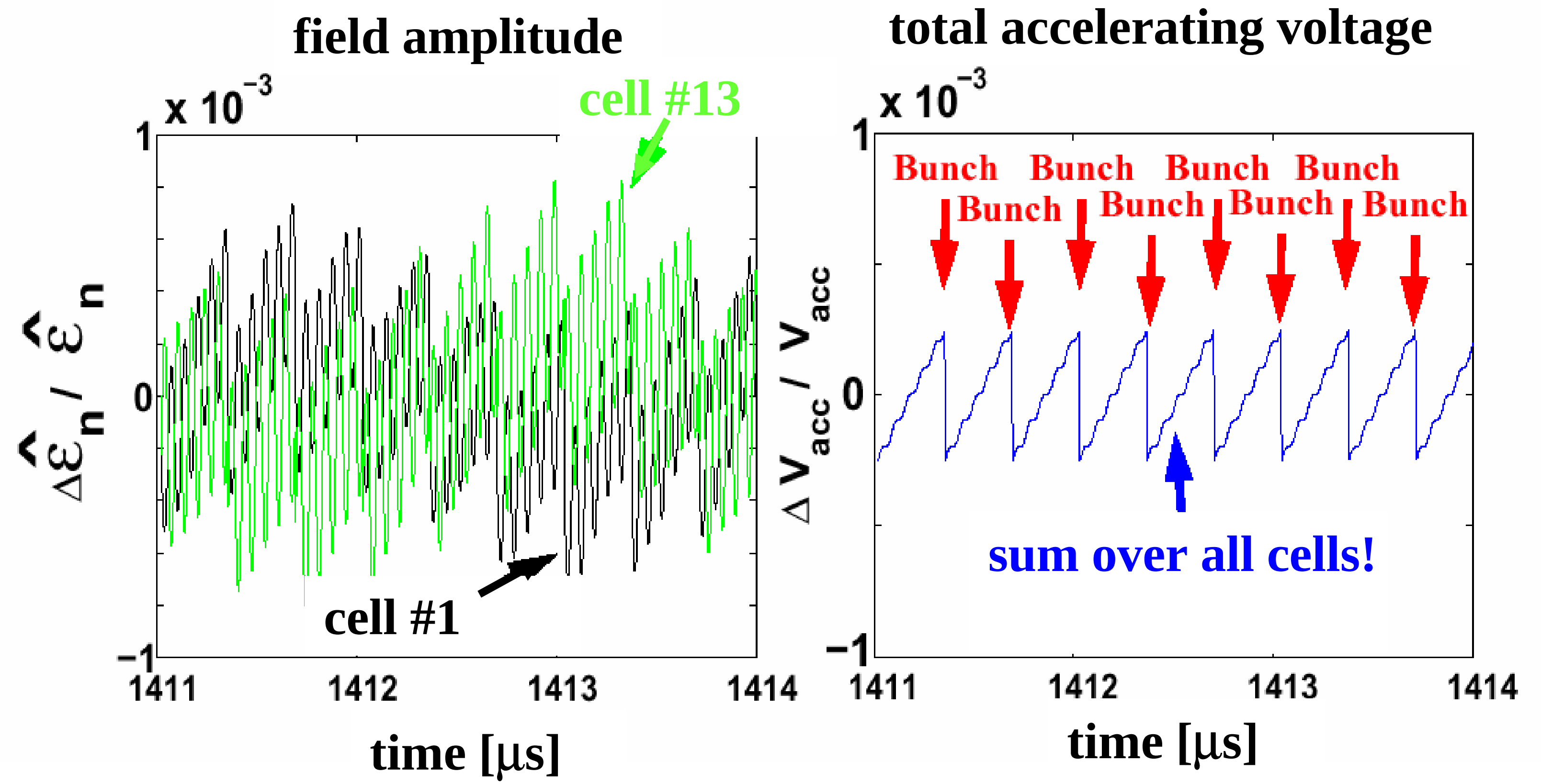


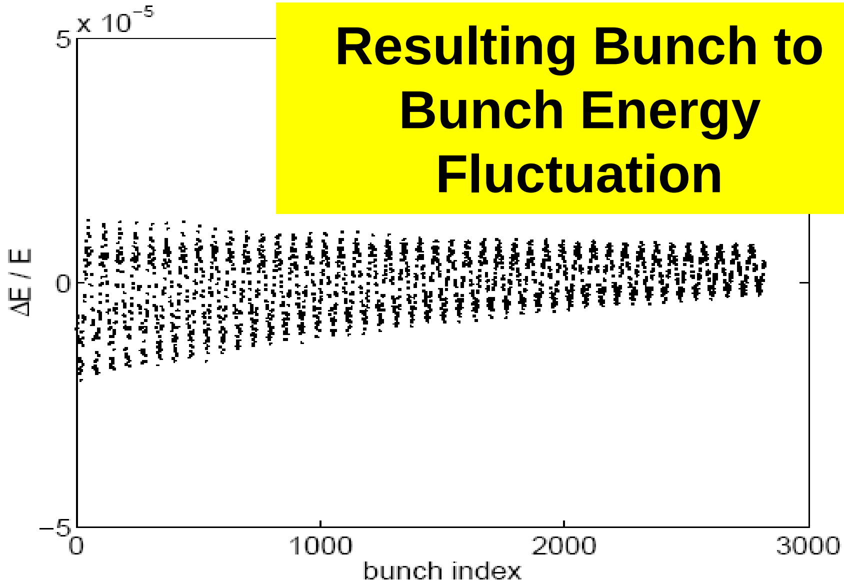
But there are N TM_{010} modes in a N-cell Cavity…

➢ **Both, the generator and the beam will not only excite the accelerating TM_{010} mode, but with small amplitudes also all other TM_{010} modes:**

Example: TTF 2x7-cell superstructure







Resulting Bunch to Bunch Energy Fluctuation

Note:

- Energy transport from one cell to another requires excitation of more than one mode!

RF Power Requirements with Beam

- *The RF power required to maintain an accelerating voltage V_{acc} is given by:*

$$P_g = \frac{V_{acc}^2}{8\frac{R}{Q}Q_{ext}}\left\{\left(1+2\frac{R}{Q}Q_{ext}\frac{\bar{I}_b}{V_{acc}}\cos\varphi_b\right)^2+\left(\frac{\Delta\omega}{\omega_{1/2}}+2\frac{R}{Q}Q_{ext}\frac{\bar{I}_b}{V_{acc}}\sin\underset{\text{beam phase}}{\varphi_b}\right)^2\right\}$$

- *From this one can calculate, that the minimum RF power is required if:*

<u>**optimal loaded Q:**</u>

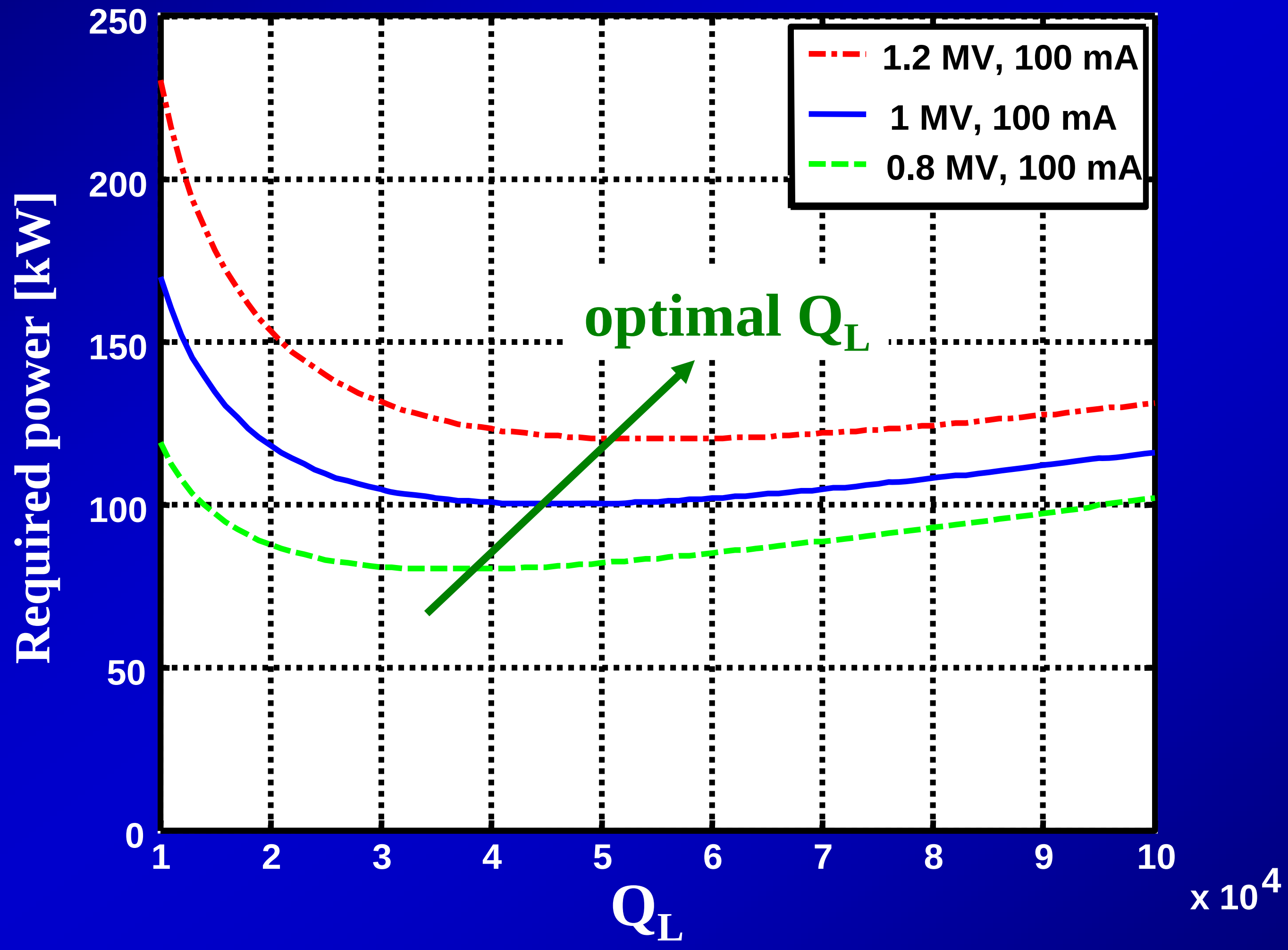
$$Q_{opt} = \frac{V_{acc}}{2\left(\frac{R}{Q}\right)\bar{I}_b\cos\varphi_b}$$

<u>**optimal cavity detuning:**</u>

$$\Delta\omega_{opt} = -\frac{R}{Q}\omega_0\frac{I_b}{V_{acc}}\sin\varphi_b$$

All power is transferred to the beam (no reflected power)

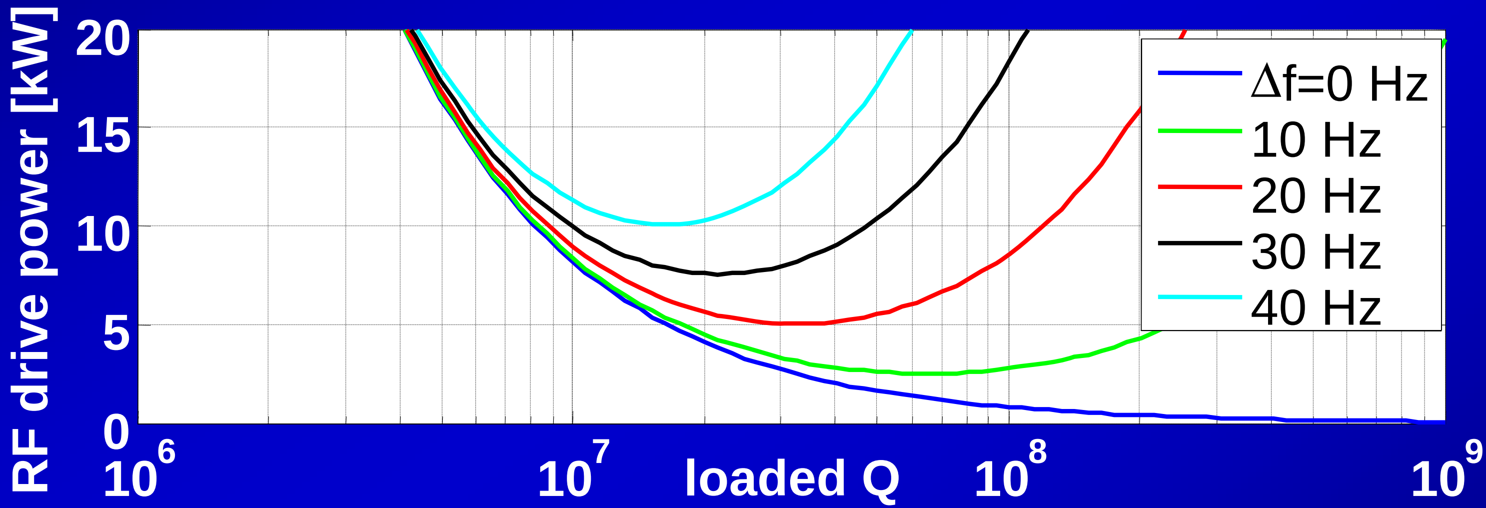
Example 1: Cornell ERL 2-cell Cavity (on-crest acceleration):



Example 2: Cornell ERL Main Linac

ERL: $\Rightarrow$ No effective beam loading in main linac!

(accelerated and decelerated beam compensate each other)

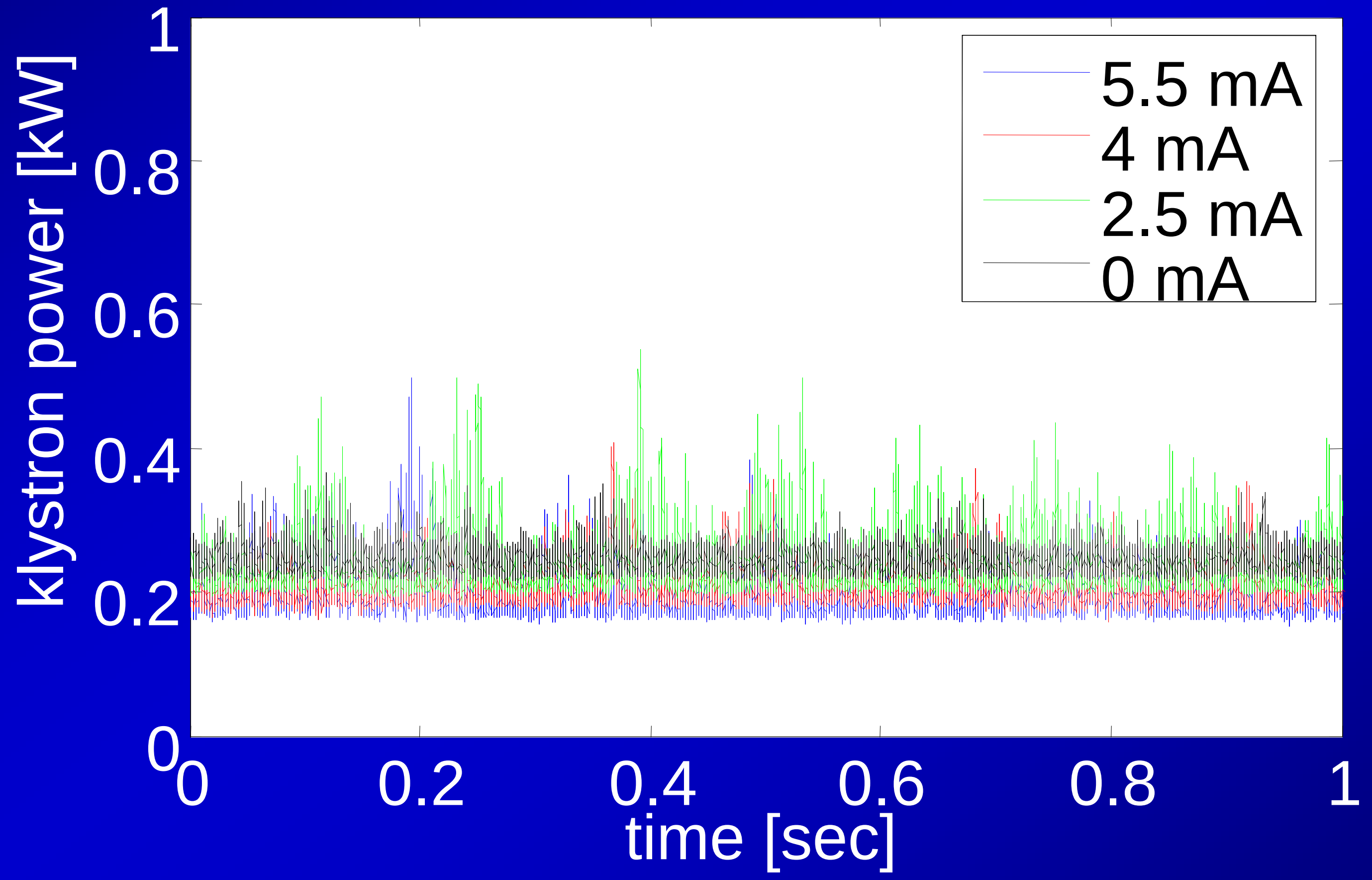


$$P_g = \frac{V^2}{8\frac{r}{Q}Q_L}\left(1+\left(\frac{\Delta f}{f_{1/2}}\right)^2\right)$$

$$Q_{opt} = \frac{1}{2}\frac{f_0}{\Delta f}$$

ERL Cavity Operation at Q_L=10^8

Power for cavity operation at 12.3 MV/m at the JLAB FEL:



Beam induced Field Perturbations

From

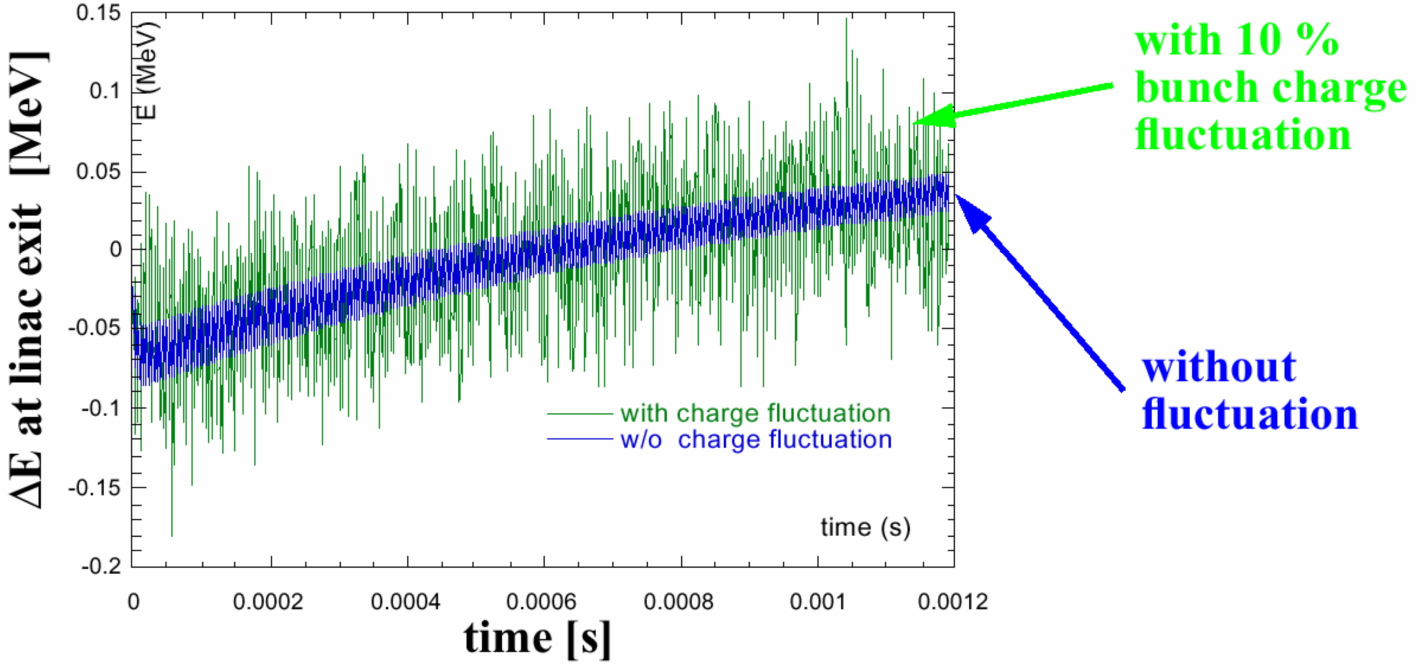
- Beam current modulations
- Bunch to bunch charge fluctuations
- Return phase fluctuation of the decelerated beam in and ERL
- Potential instabilities in storage rings (coupling of energy and path length)
- Pulsed beam transients (FLASH, ILC, SNS)
- Excitation of other passband modes

$\Rightarrow$ Beam energy fluctuation!

Example 1: Bunch Charge Fluctuations

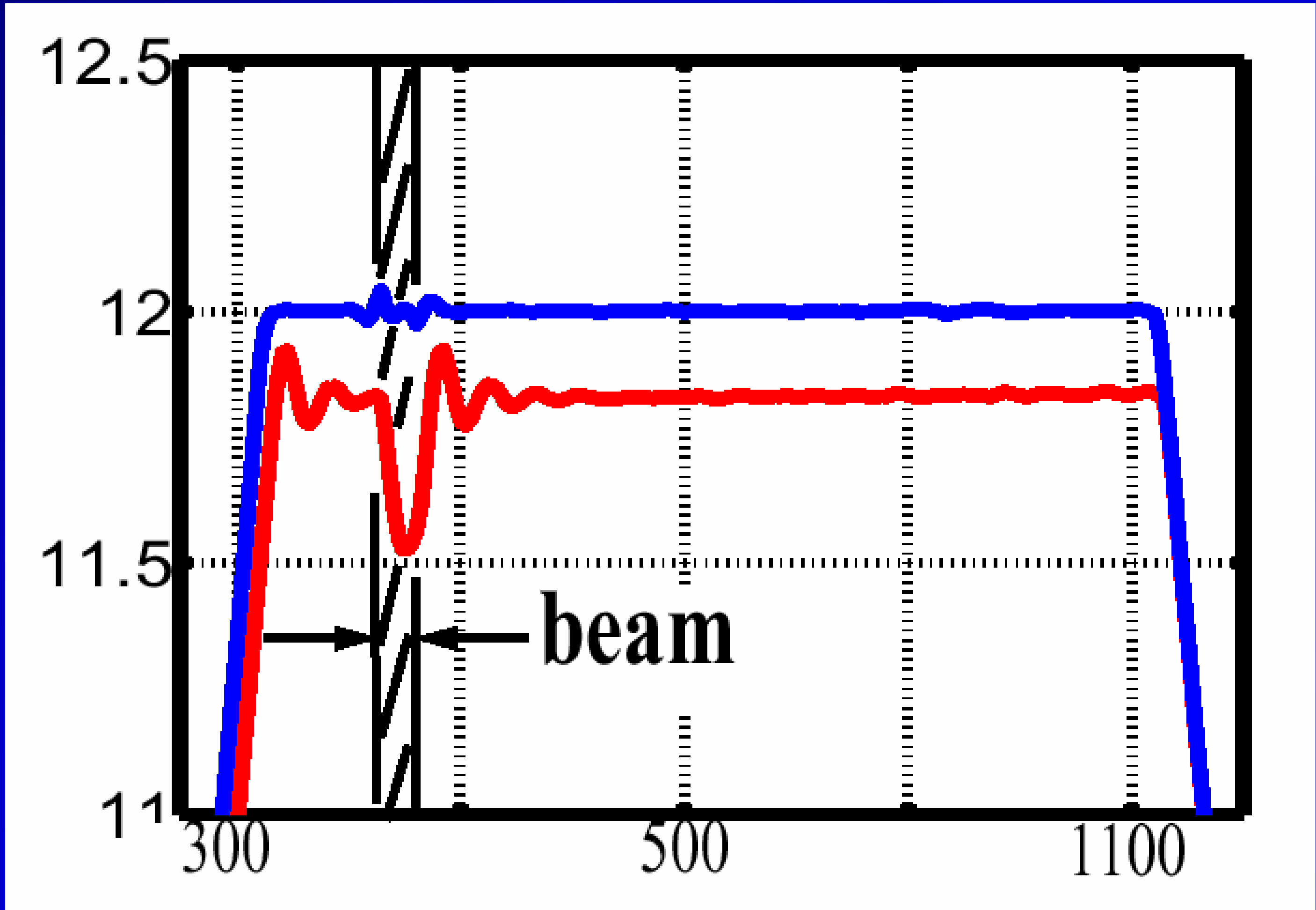
bunch charge fluctuations ⇒ beam loading fluctuations
⇒ *correlated* amplitude and phase fluctuations

Example: pulsed sc proton linac (A. Mosnier et al.)



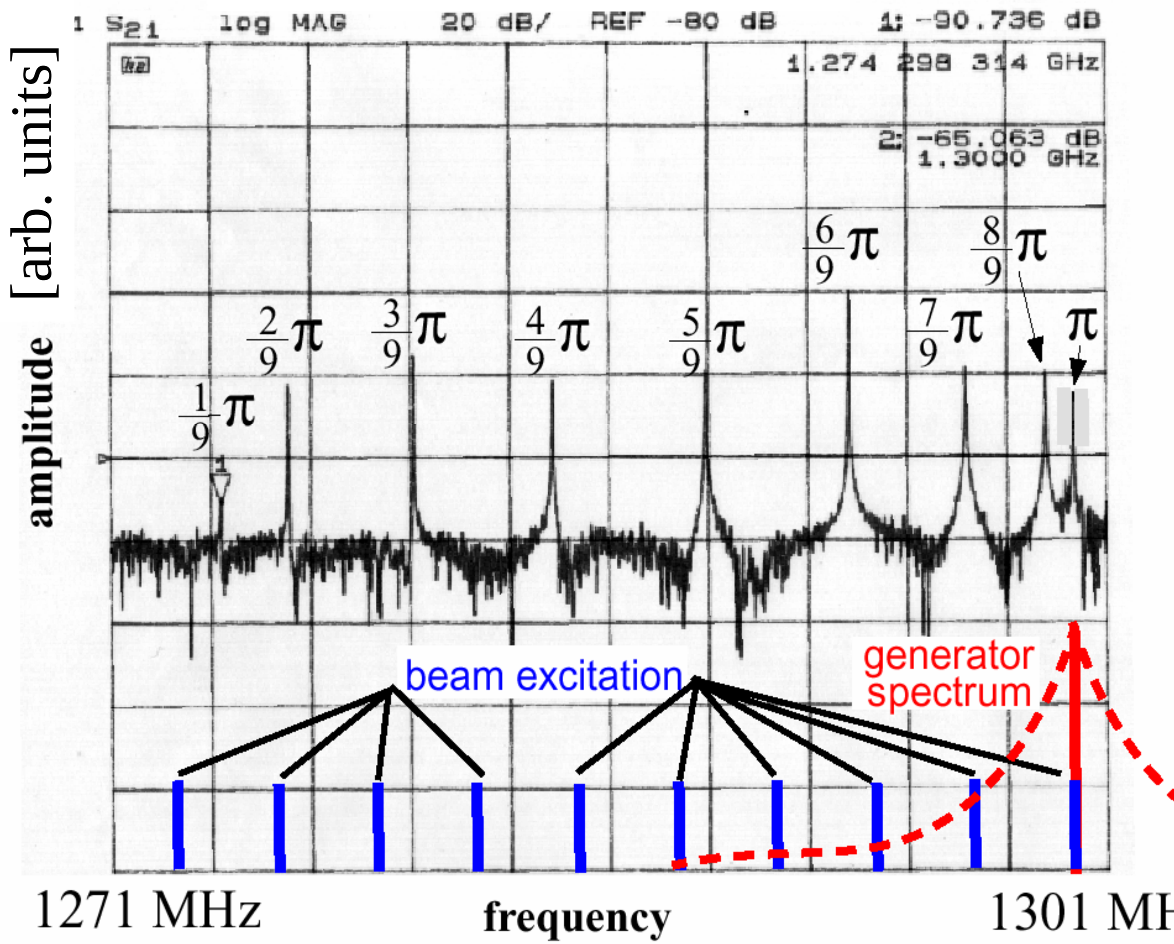
Bunch energy deviations at linac exit
(with Lorentz forces + 10% bunch charge fluctuation)

Example 2: Beam Transients



Example 3: Excitation of Passband Modes (I)

Example: TTF/Flash 9-cell cavity



f_{π} = 1300.091 MHz

$f_{8/9\pi}$= 1299.260 MHz

$f_{7/9\pi}$= 1296.861 MHz

$f_{6/9\pi}$= 1293.345 MHz

$f_{5/9\pi}$= 1289.022 MHz

$f_{4/9\pi}$= 1284.409 MHz

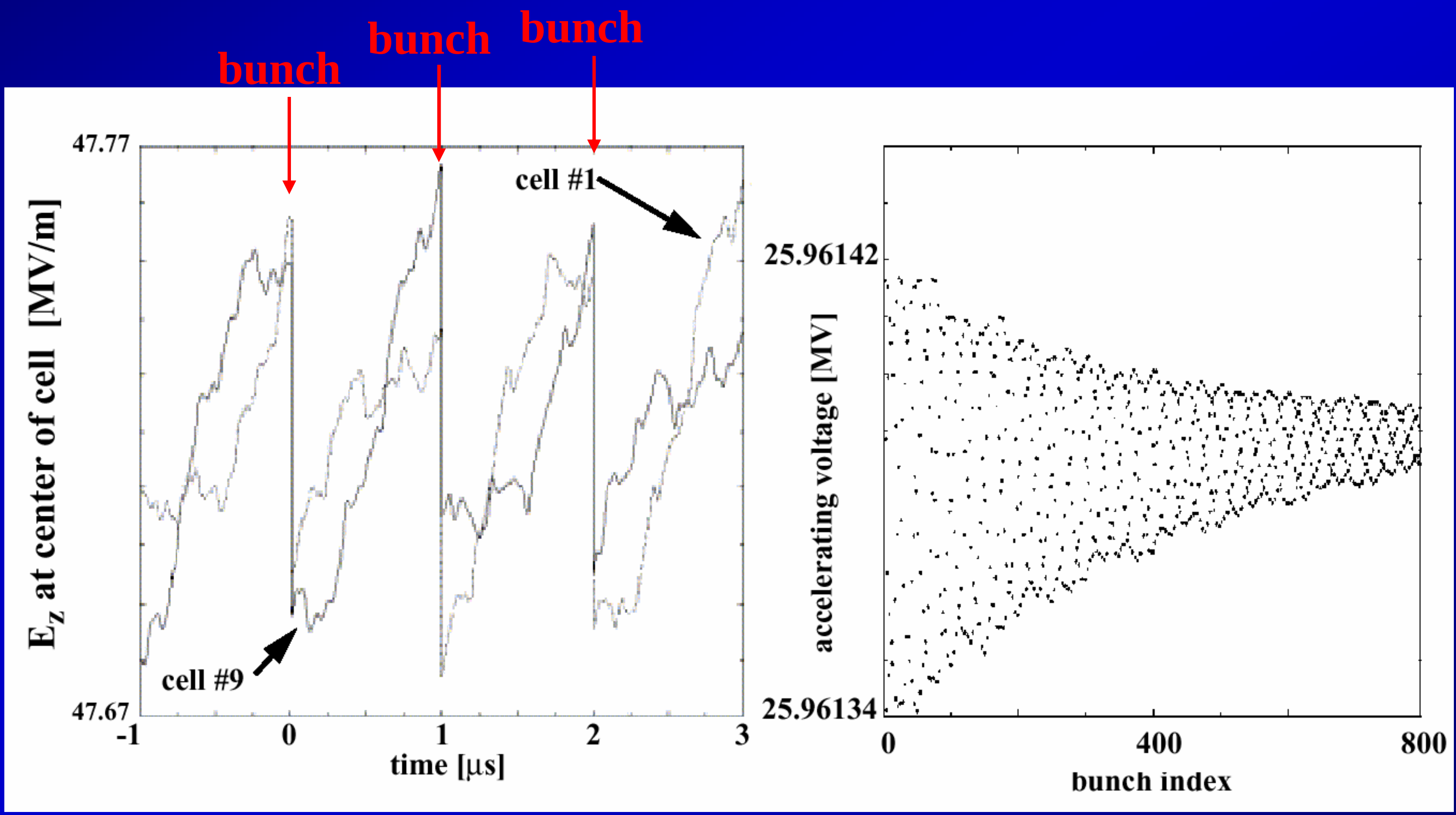
$f_{3/9\pi}$= 1280.206 MHz

$f_{2/9\pi}$= 1276.435 MHz

$f_{1/9\pi}$= 1274.387 MHz

Example 3: Excitation of Passband Modes (II)

Example: TTF 9-cell cavity with 1 MHz beam

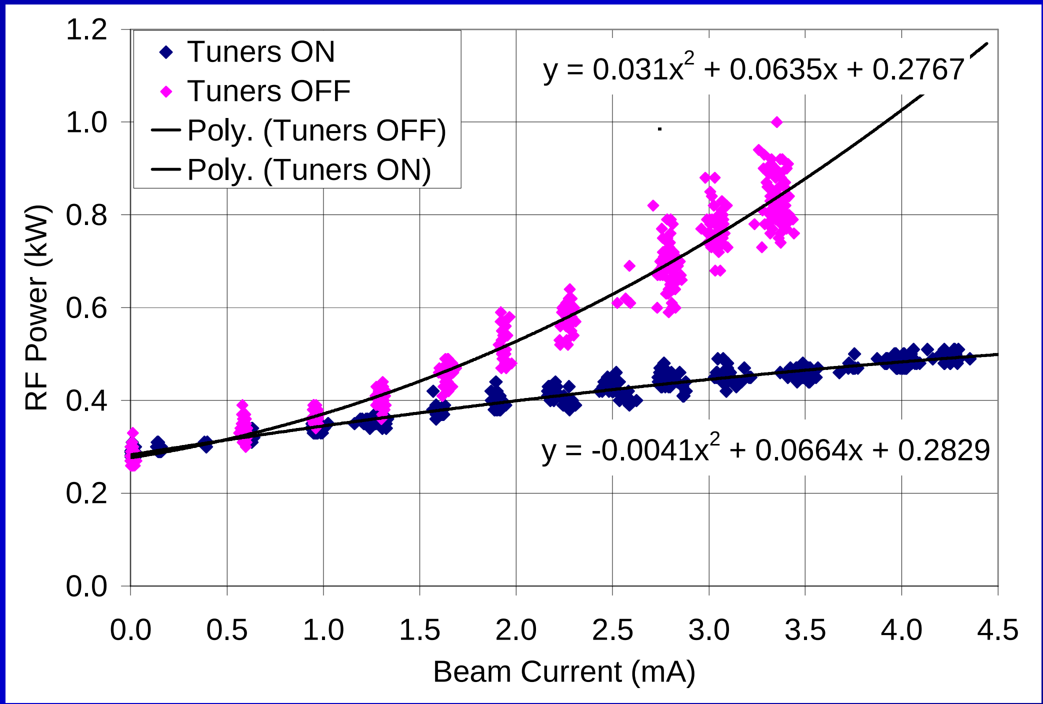


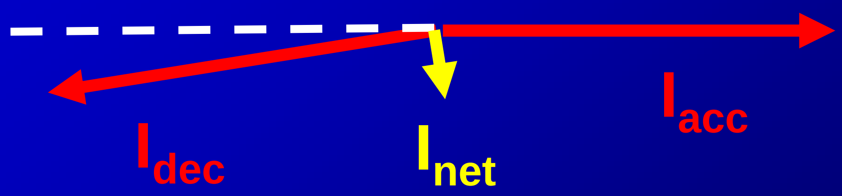
M. Ferrario et al.

Example 4: ERL with Return Phase Error

Cavity tuners need to adjust the cavity detuning to its optimal value to compensate for the reactive loading

Tom Powers, Chris Tennant; TJNAF FEL

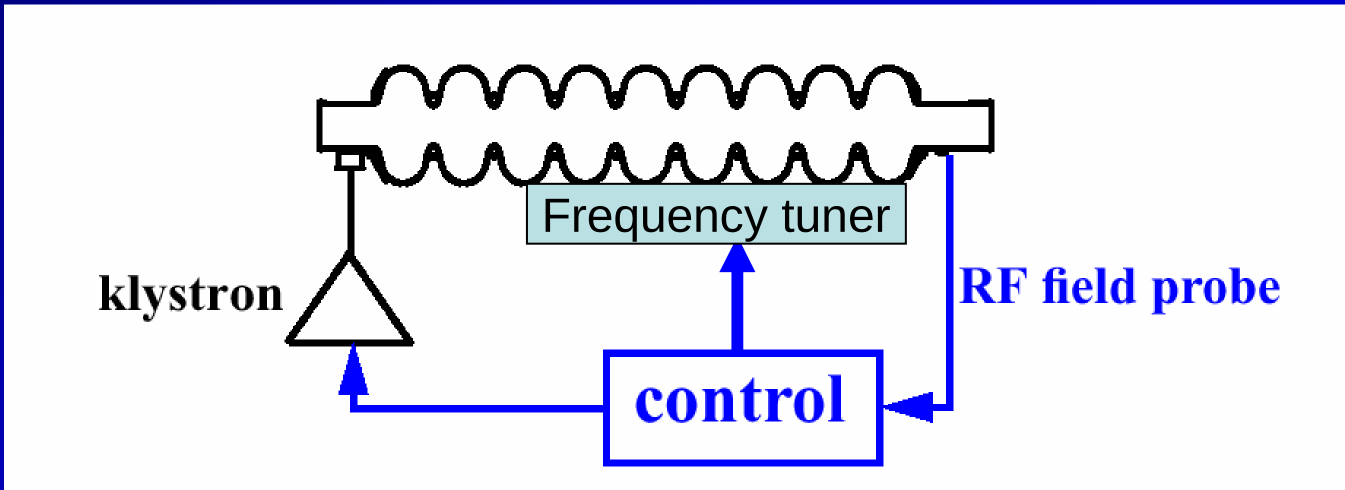




Field Stability Requirements

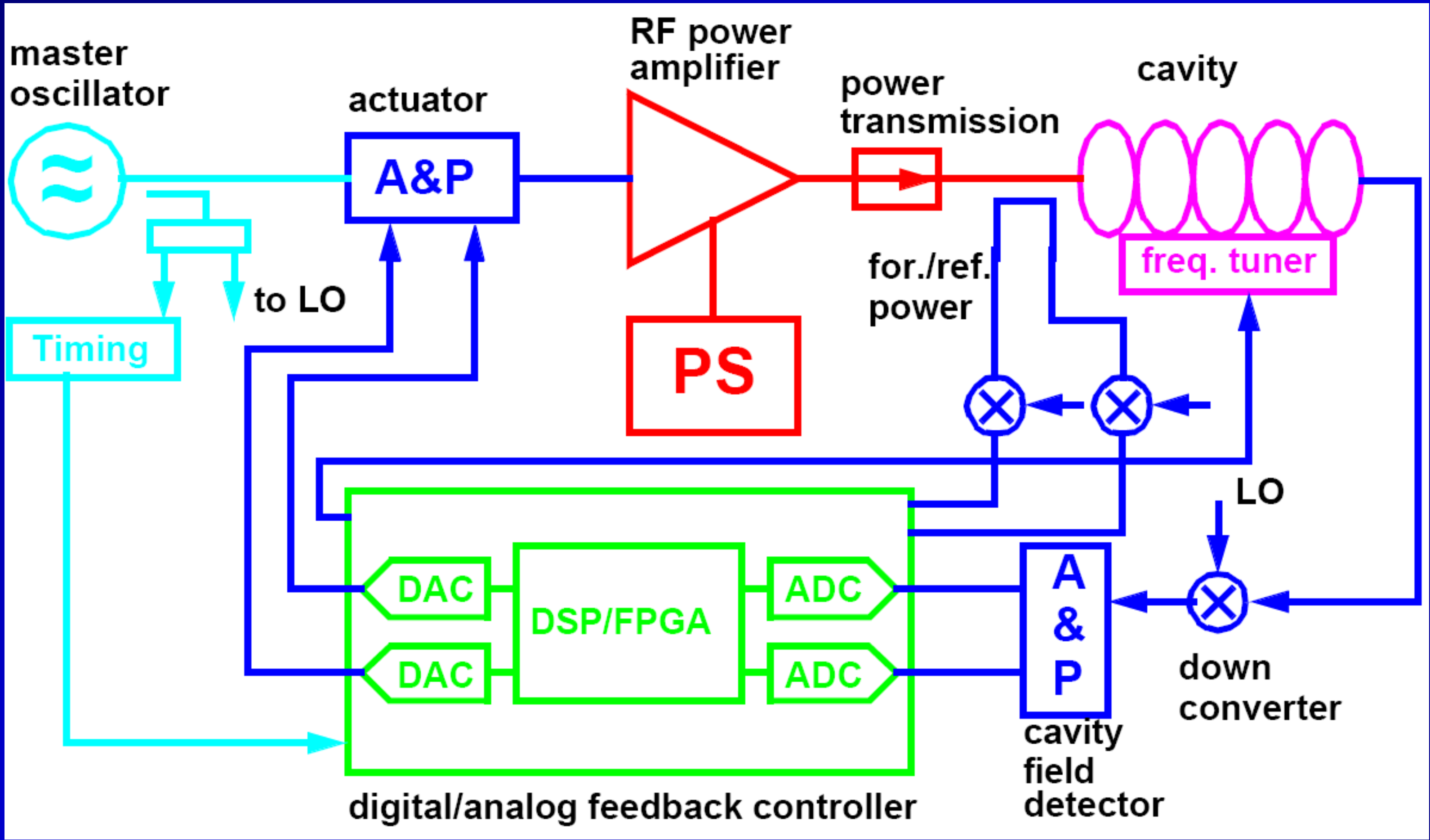
- Different accelerators have different requirements for field stability!
- approximate RMS requirements:
  - 1% for amplitude and 1 deg for phase (storage rings, SNS)
  - 0.1% for amplitude and 0.1 deg for phase (linear collider, …)
  - down to 0.01% for amplitude and 0.01 deg for phase (XFEL, ERL light sources)

LLRF Field Control: Concept



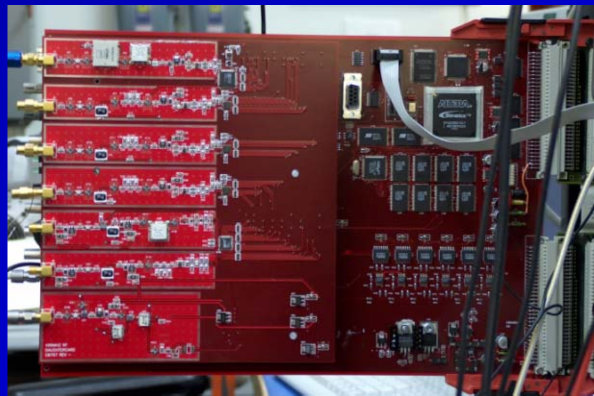
- Measure cavity RF field.
- Derive new klystron drive signal to stabilize the cavity RF field.
- Derive new frequency control signal.

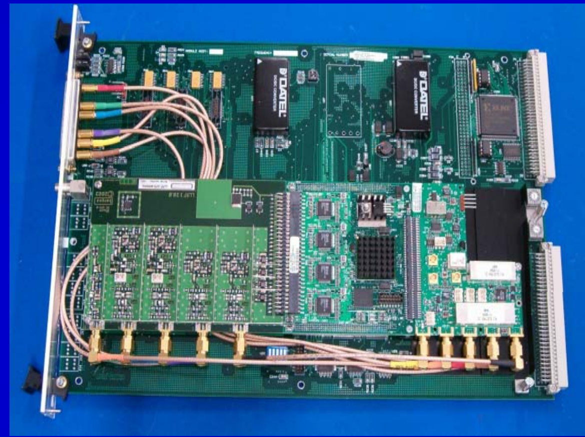
LLRF Control: A complex System

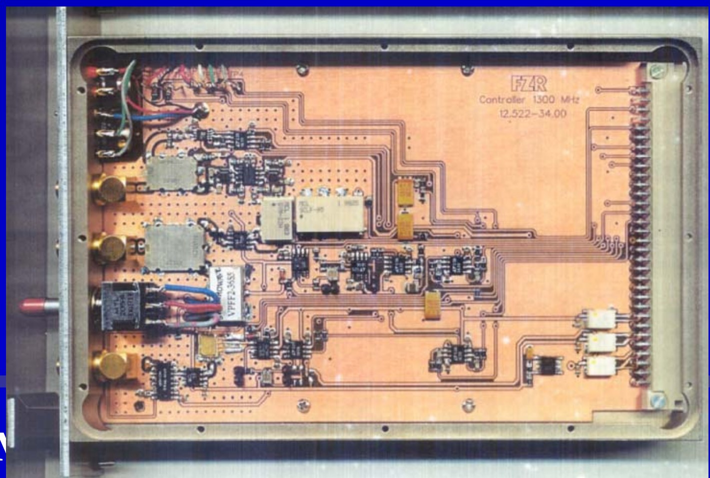


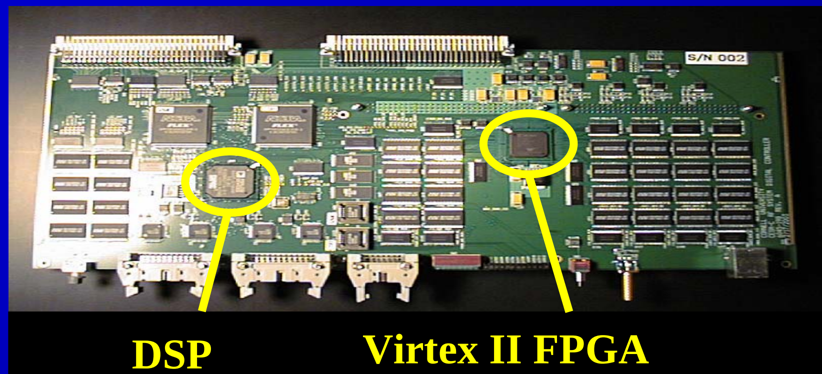
Many connected subsystems…

LLRF Hardware









Perturbation Compensation: Feedback and Feedforward

- ***Active Control of Perturbations***
  - Feedforward: (fixed or adaptive)

    - Vibration signals
    - Beam current
    - HV PS ripple

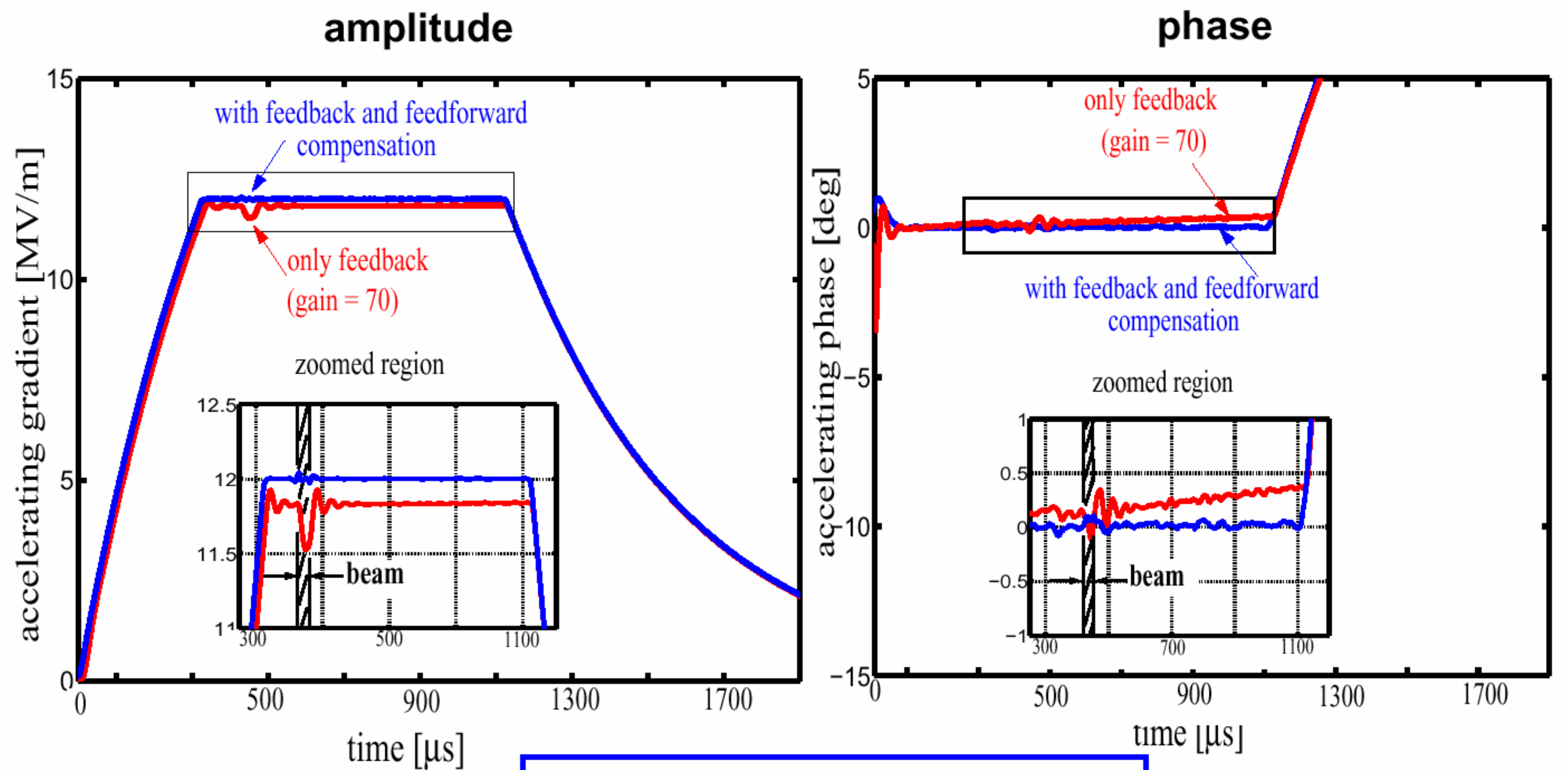
    - Klystron drive
    - Frequency tuner drive

  - Feedback:

    - Measured cavity field
    - Klystron output
    - Cavity detuning
    - Beam energy
    - Bunch length

    - Klystron drive
    - Frequency tuner drive

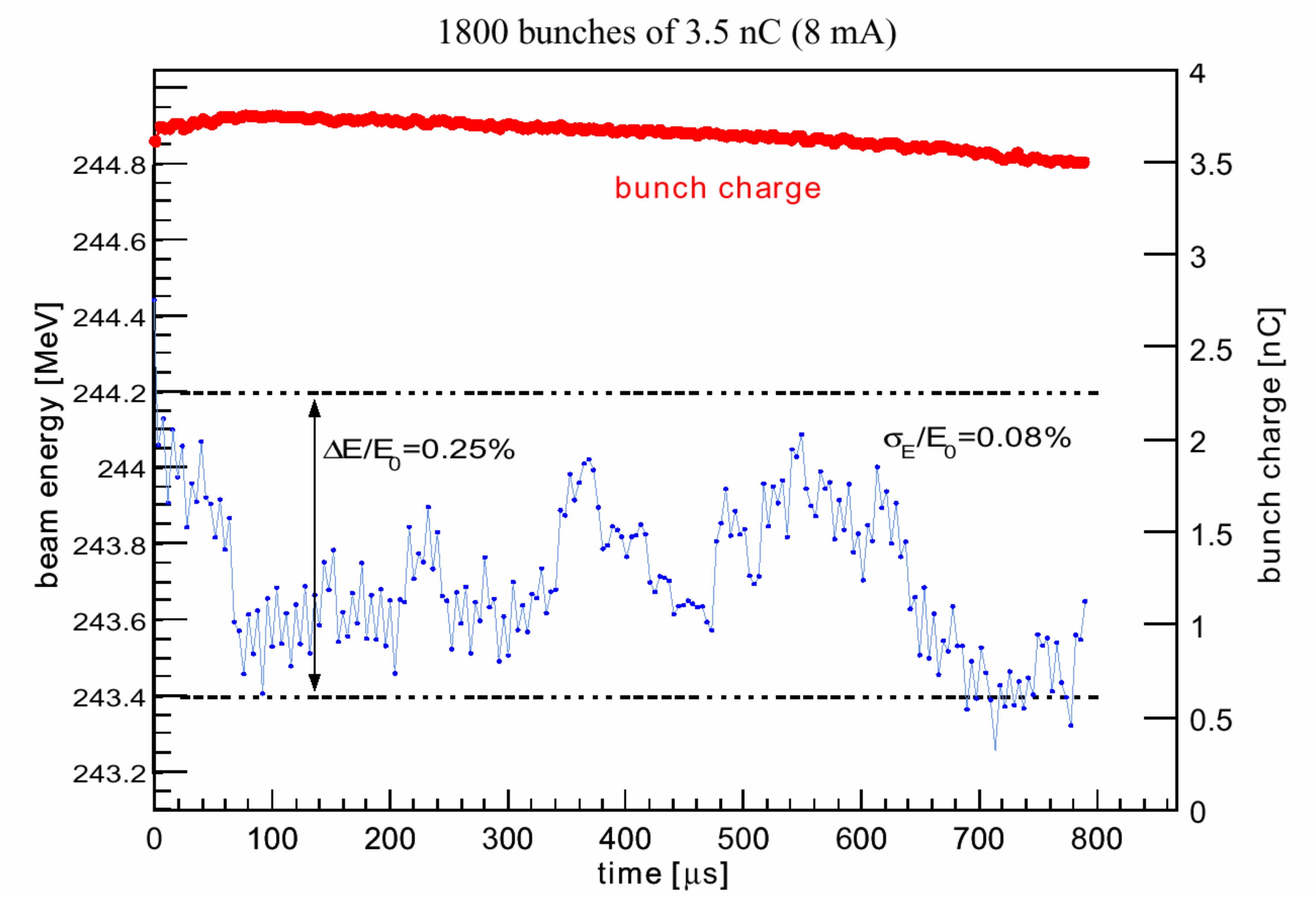
Achieved Energy Stability: TTF/FLASH



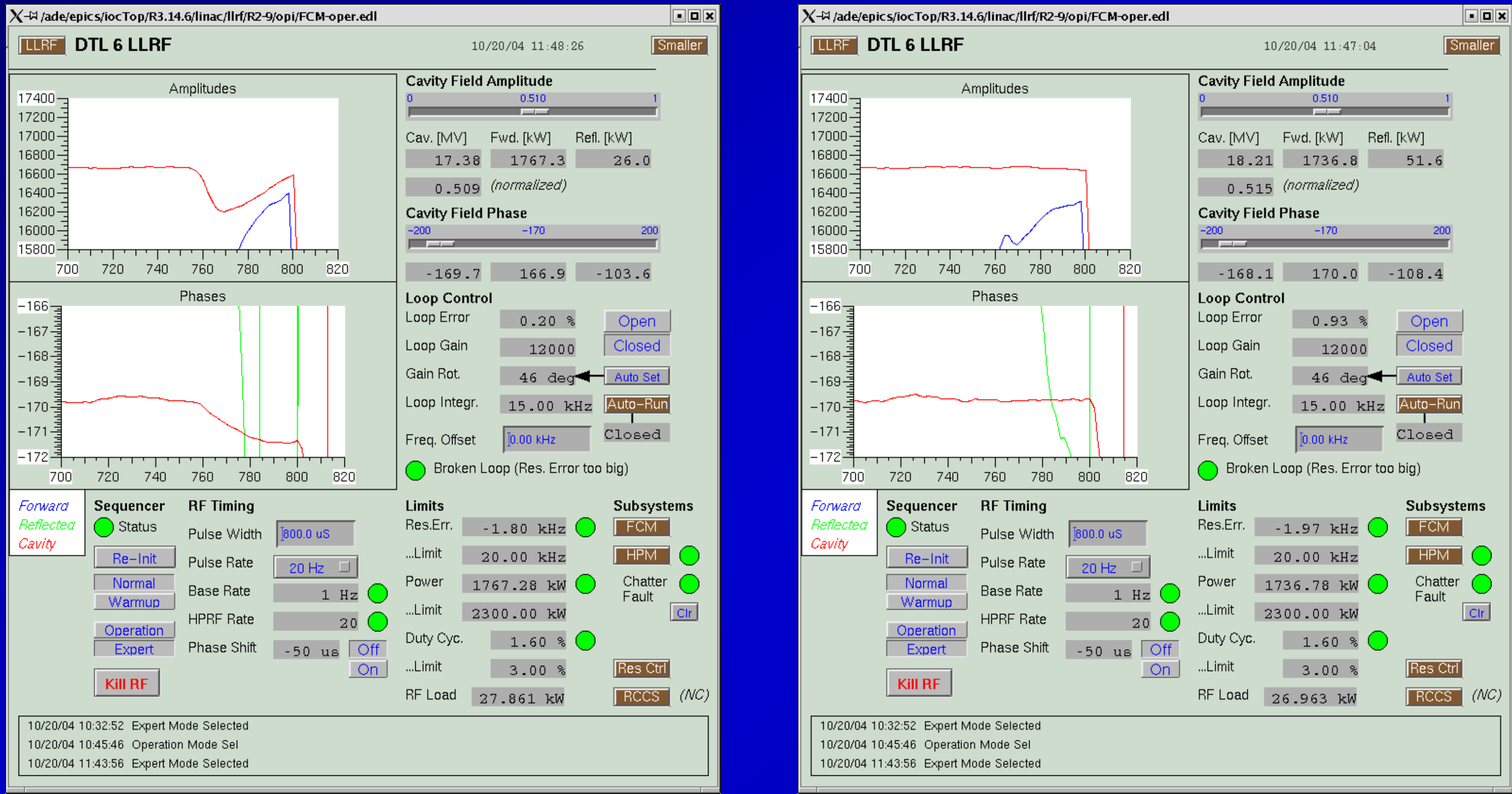
Vector-sum controlled

$$\frac{\sigma_A}{A} < 2 \cdot 10^{-4} \quad \textbf{and} \quad \sigma_\phi < 0.1^\circ$$

Achieved Energy Stability: TTF/FLASH



Adaptive Feedforward (SNS, FLASH)

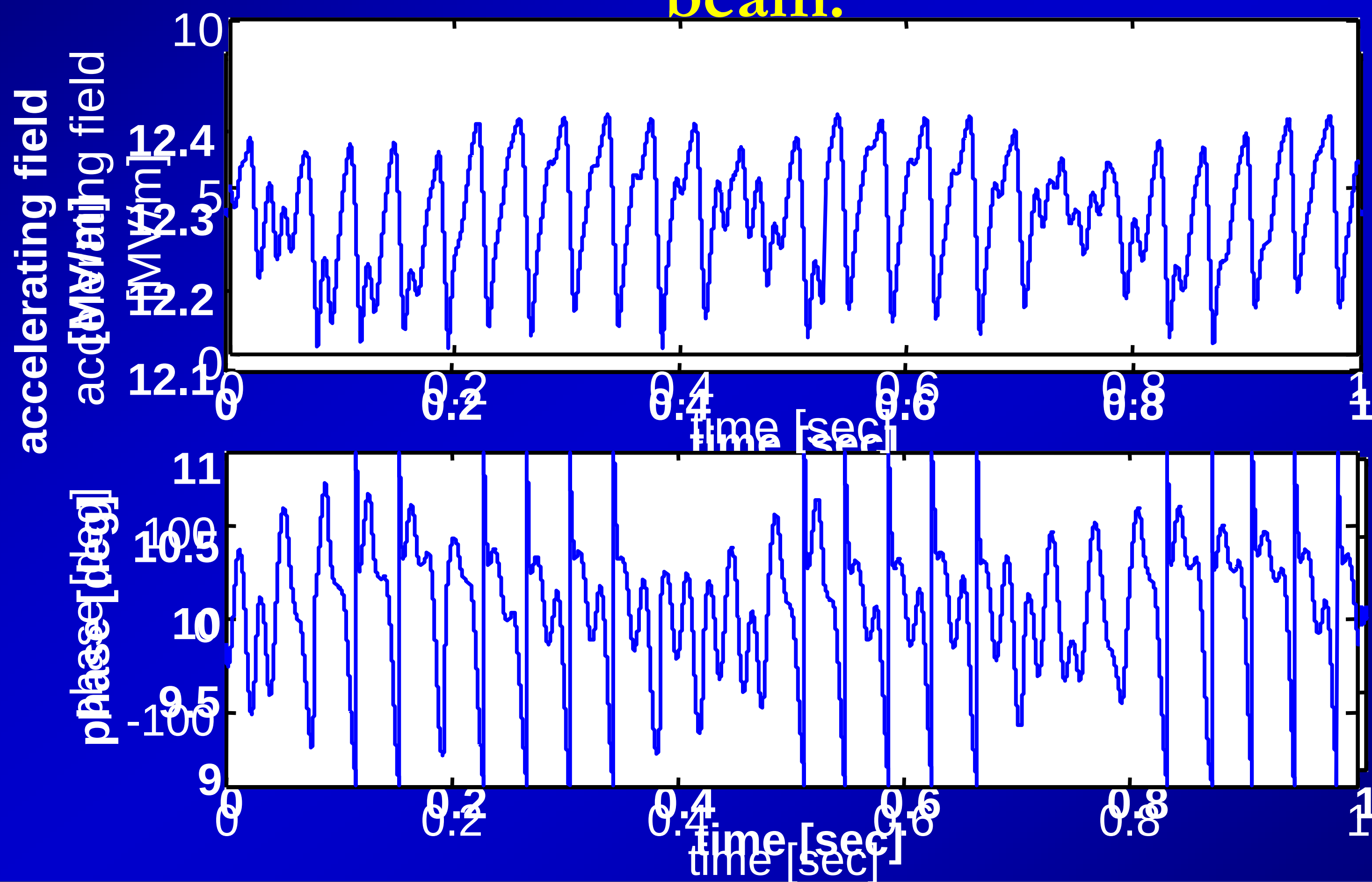


- **Adaptively adjusted forward power to compensate beam transients in pulsed mode operation**

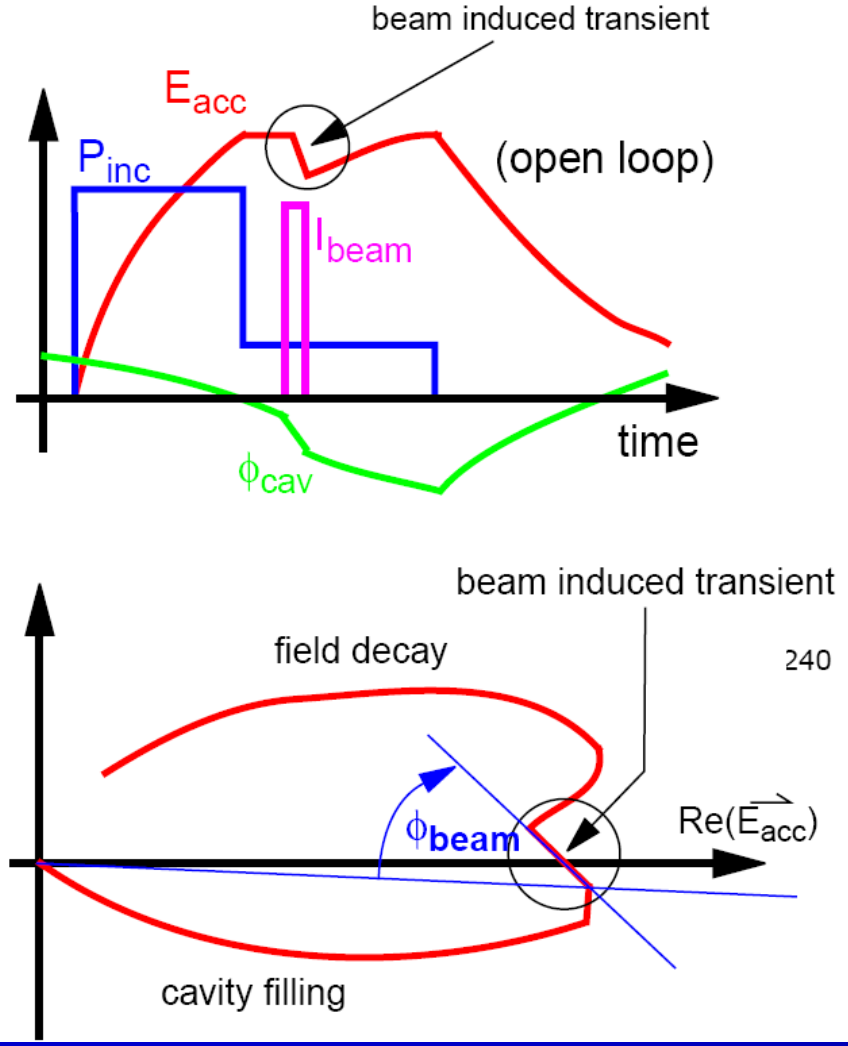
ERL high Q_L Cavity Test Operation

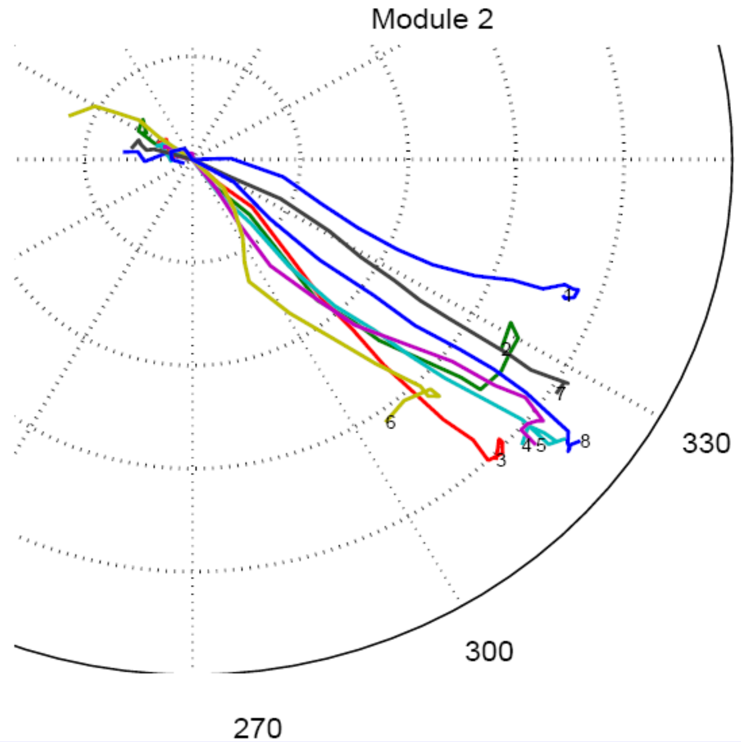
With feedback: Very good field stability with 5 mA ERL beam:

Without feedback:



Beam Based Calibration

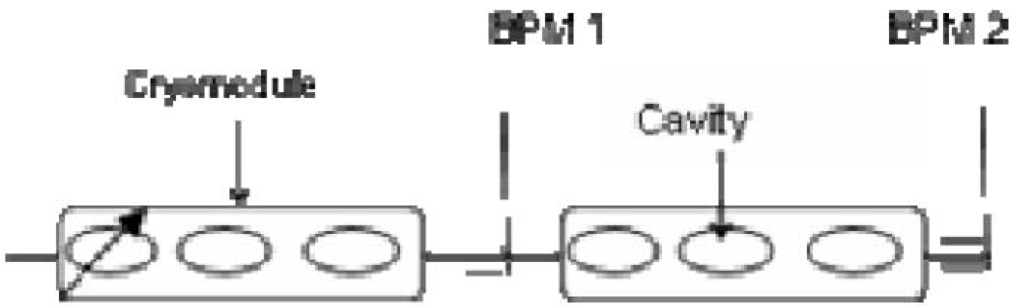




for $\Delta t << \tau_{cav}$:

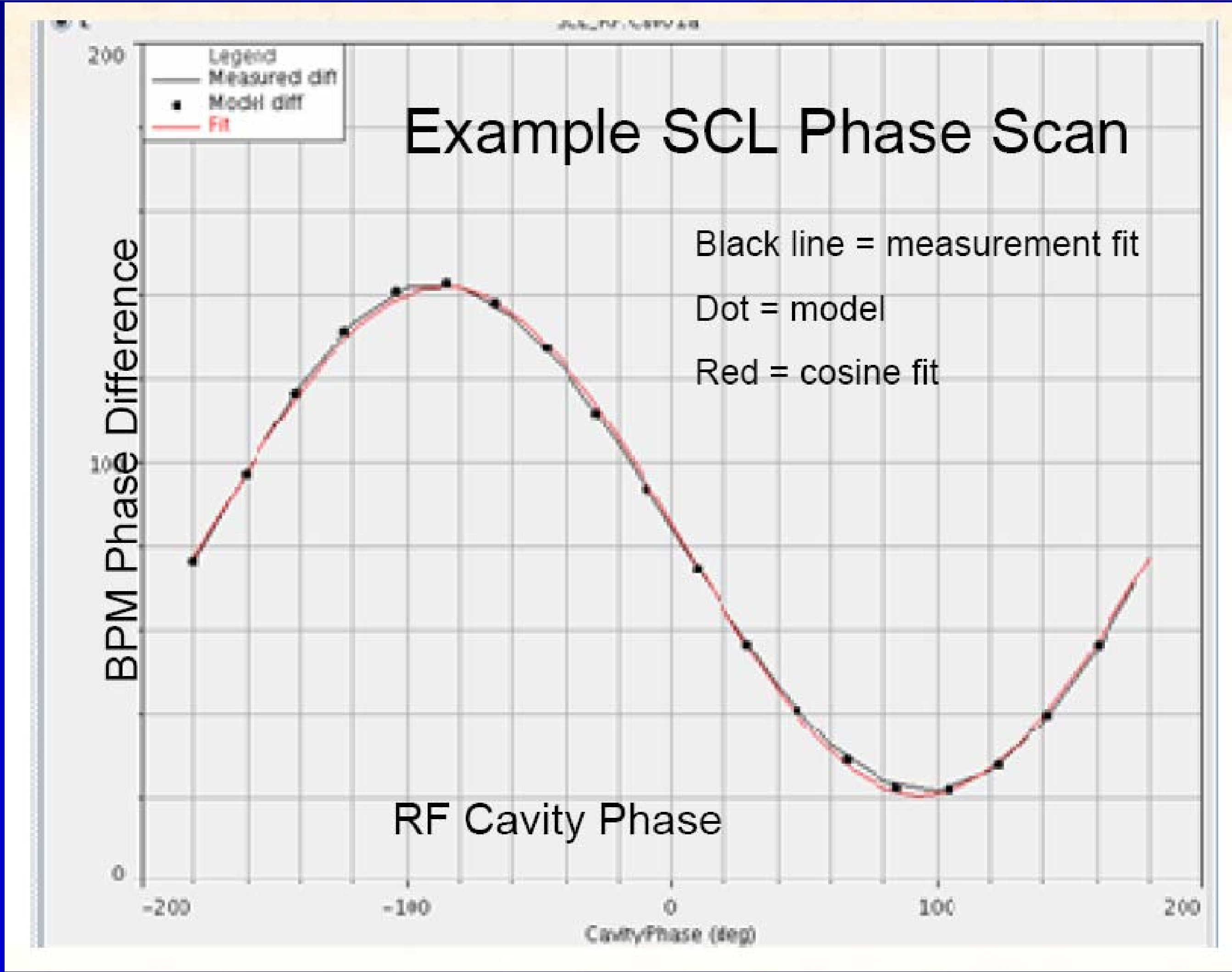
$$\Delta V_{ind} = I \cdot \Delta t \cdot \left(\frac{r}{Q}\right) \cdot \pi \cdot f$$

Setting the RF Phase at SNS (I)



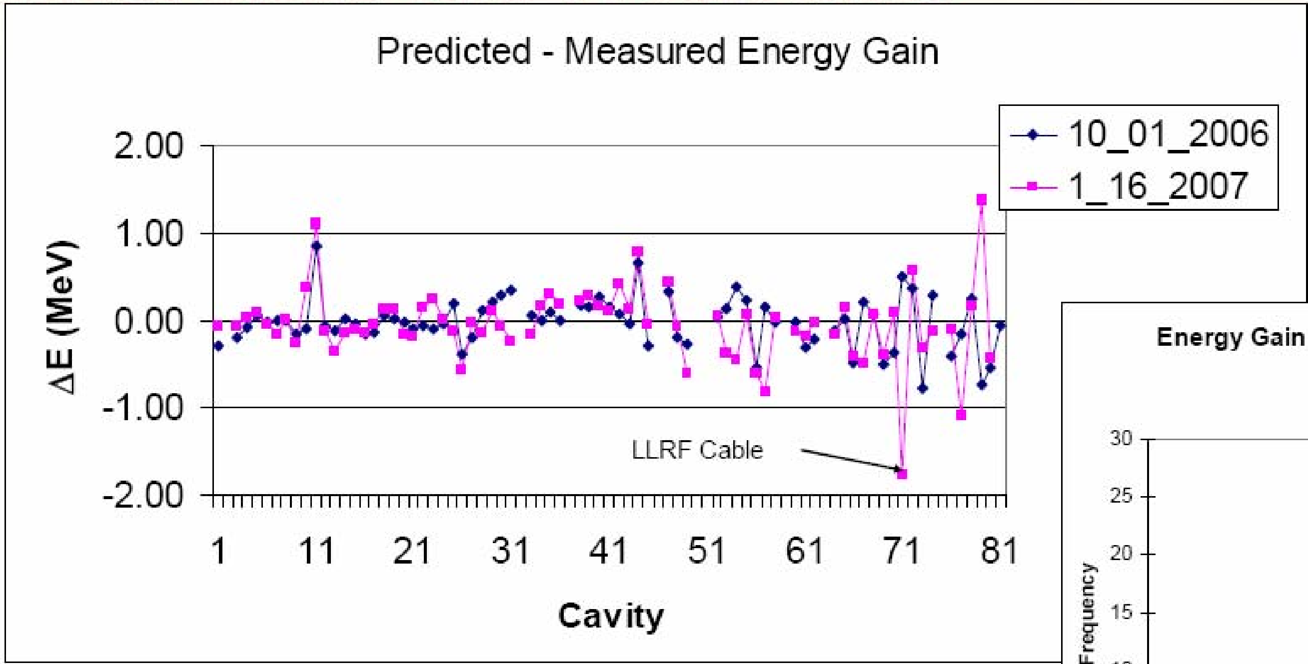
- A beam based measurement must be done to initially set each cavity RF phase setpoint
- Scan the cavity phase of a cavity 360, and observe the resultant change in the Time of Flight (TOF) between 2 downstream detectors
  - Compare this difference with a model calculations.
  - Gives the input beam energy, cavity voltage and RF phase offset calibration
  - Need good relative phase measurements from the detectors (~ 1degree!)
- Scan each cavity sequentially

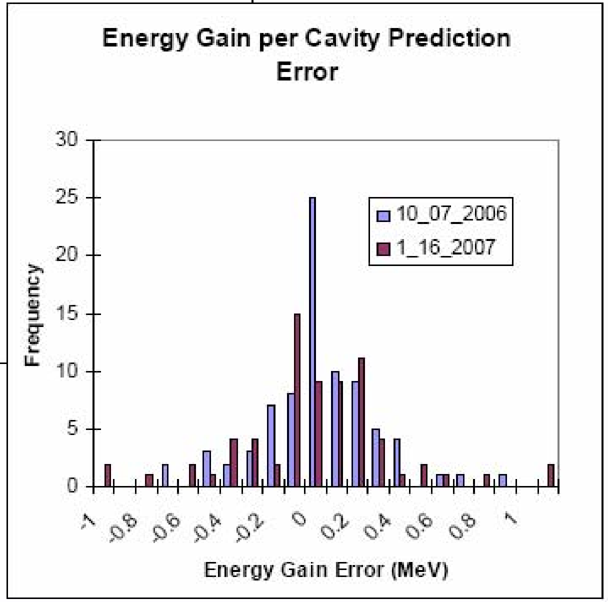
Setting the RF Phase at SNS (II)



Setting the RF Phase at SNS (III)

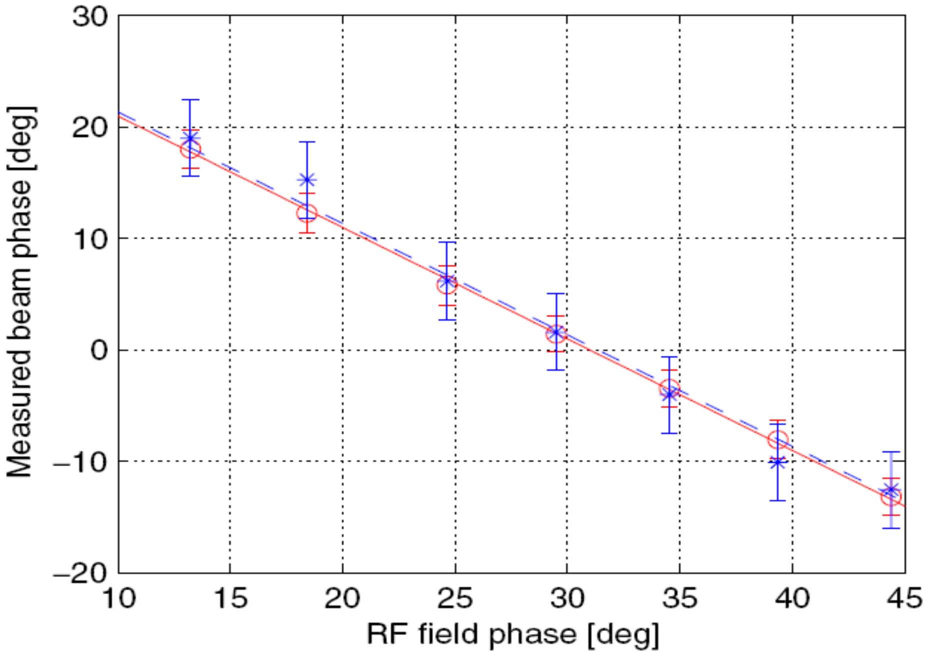
SCL Tune-up – Linac Energy Gain is Understood and Predictable

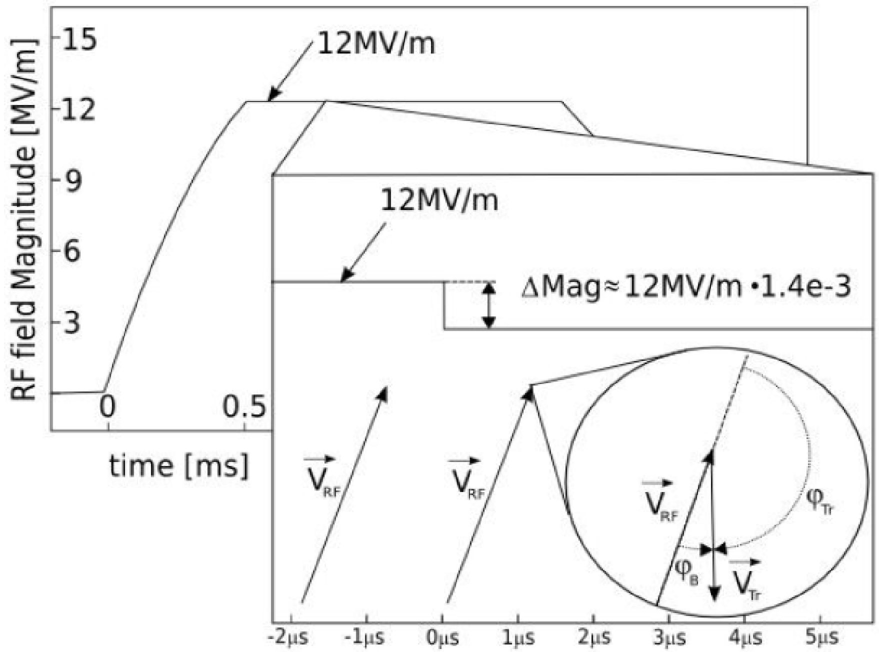




- **Energy gain per cavity is predictable to a few 100 keV and distributed about 0.**
- **Final energy is predictable to within a few MeV**

Field Calibration based on Single Bunch Transients





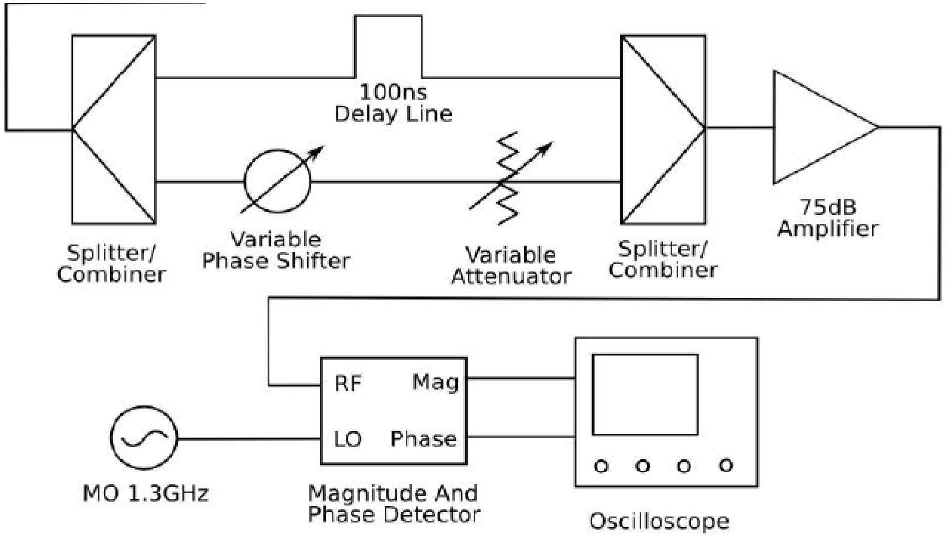
$\vec{V}_{RF}$ - RF field vector without transient

$\vec{V}_{Tr}$ - transient vector

φ_{Tr} - transient vector phase

φ_{B} - beam phase

$\varphi_{B} = \varphi_{Tr}$ - 180°



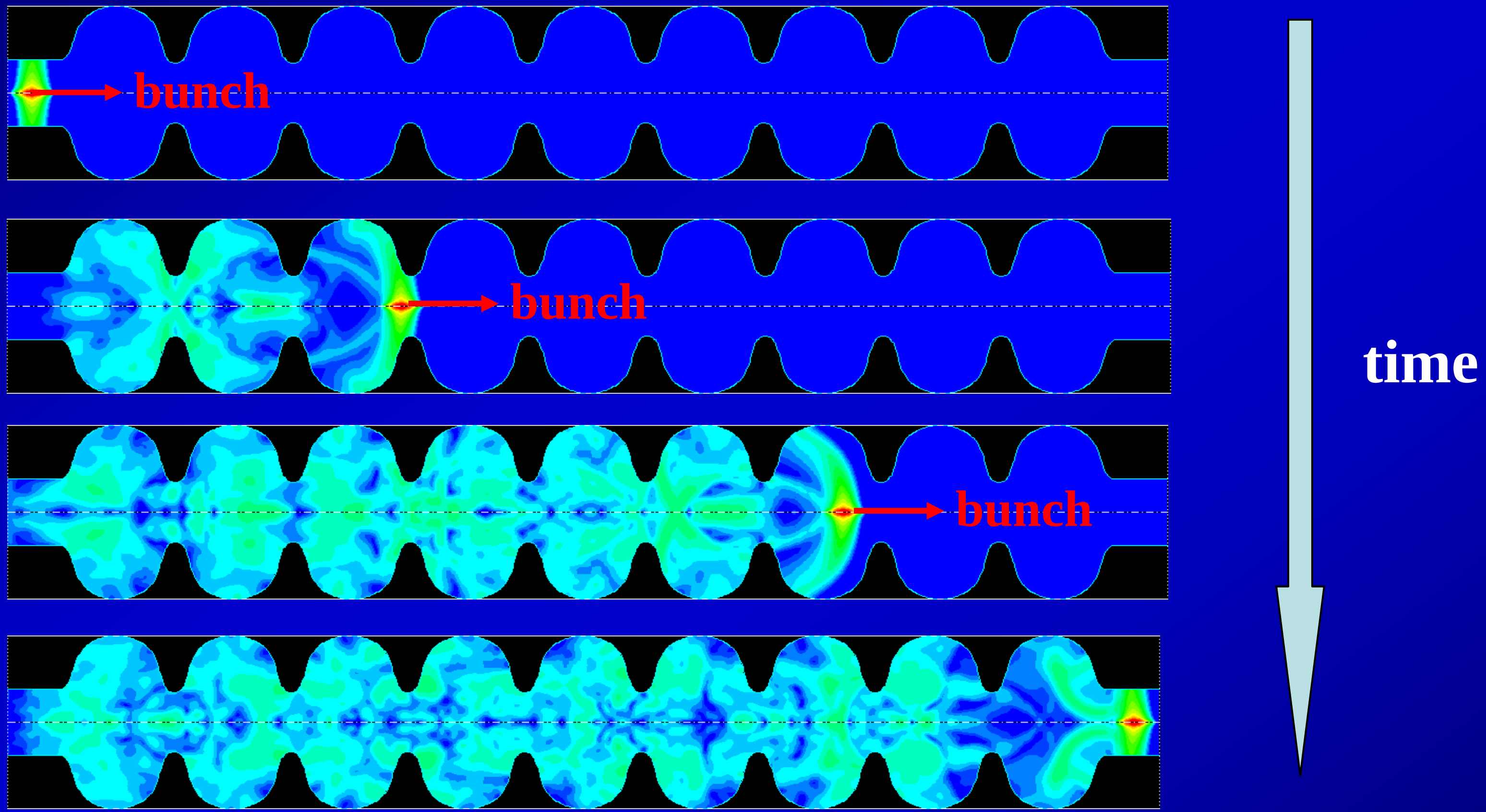
P. PAWLIK, M. GRECKI, S. SIMROCK

$$\begin{bmatrix} V_{\text{tr}} \\ V_{\text{ti}} \end{bmatrix} = 2 \cdot \omega_{1/2} \cdot q_b \cdot R_L \begin{bmatrix} \cos(\varphi_b) \\ \sin(\varphi_b) \end{bmatrix}$$

More cavity eigenmodes: Higher-Order-Modes

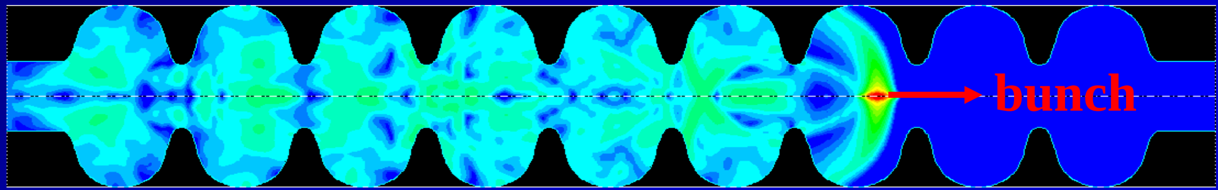
- Beam excitation
- HOM heating issues
- Beam based HOM damping measurements
- HOM based BPM

Higher-Order-Mode Excitation



The bunched beam excites higher-order-modes (HOMs) in the cavity.

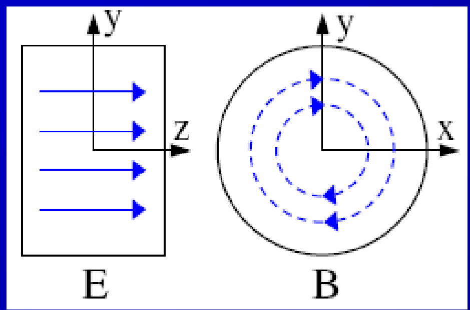
Higher-Order-Mode Excitation

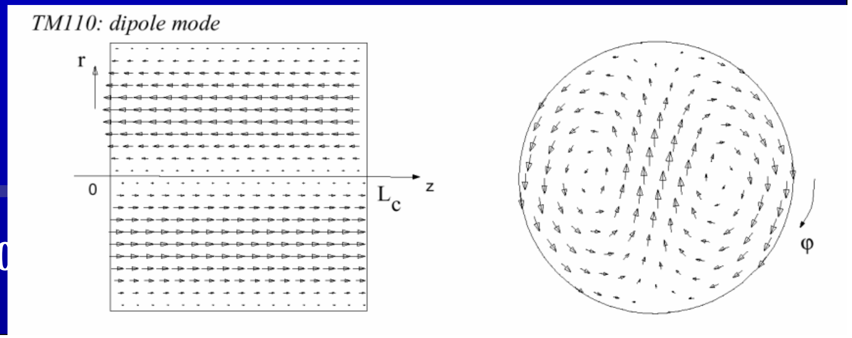


- Short range wake-field: Fields inside the bunch and just behind it

- Long range wakes (Higher-Order-Modes)
  - Monopole modes: RF heating and longitudinal emittance dilution

  - Dipole modes: transverse emittance dilution and beam break-up

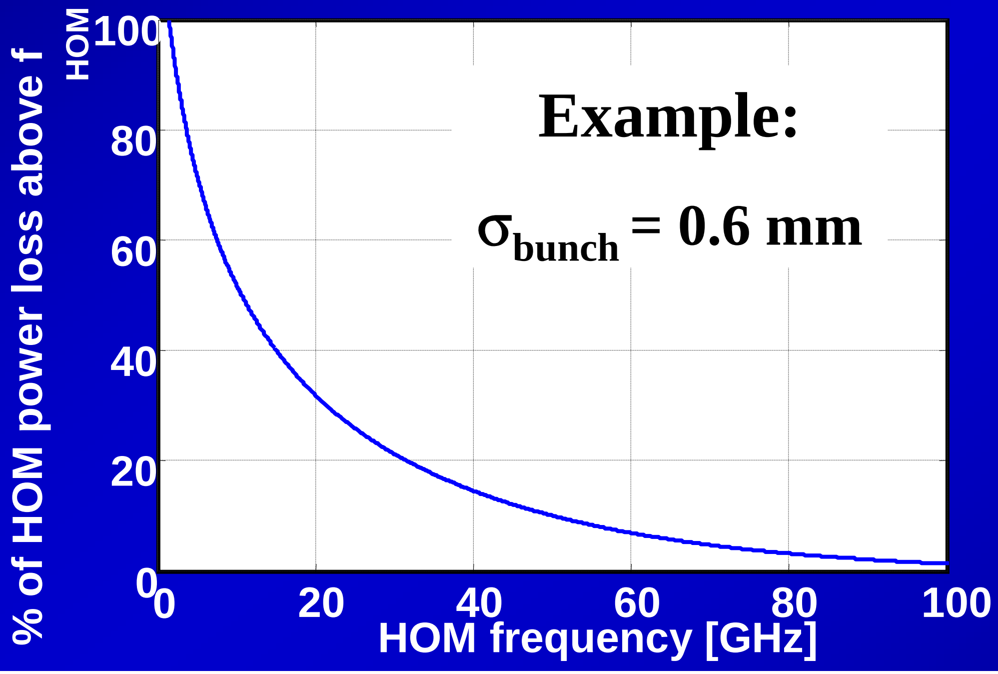




HOM Excitation by a Single Bunch

The HOM power excited by a single bunch depends on:

- the HOMs of the cavity (cavity shape),
- the bunch charge ($P_{HOM} \propto q^2$),
- the bunch length (i.e. the spectrum of a bunch).



$\Rightarrow$ Short bunches can excite very high frequency modes!

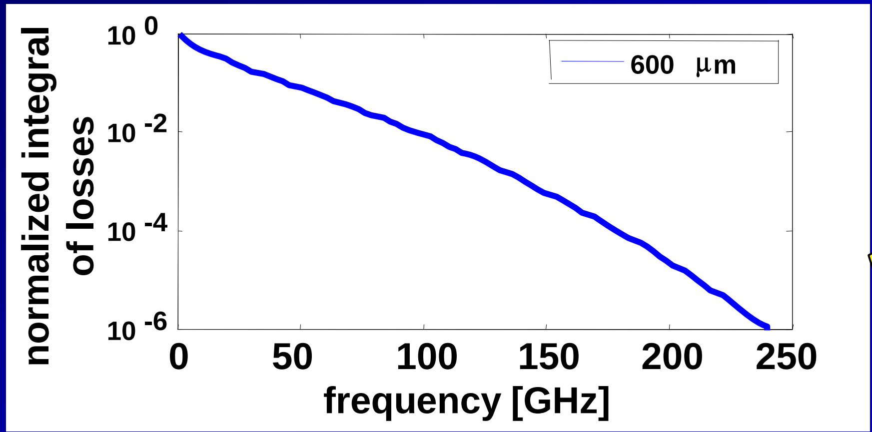
$$\Delta V_{acc,b}^{(m)} = \omega^{(m)} \left(\frac{R_{sh}}{Q_0} \right)^{(m)} Q_b \exp\left(-\frac{(\omega^{(m)})^2 \sigma_b^2}{2} \right) \exp(i\omega^{(m)} t)$$

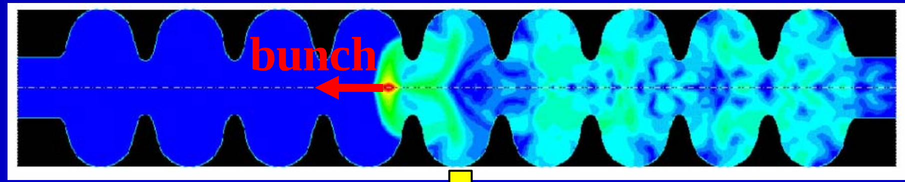
HOM Excitation by a Bunch Train

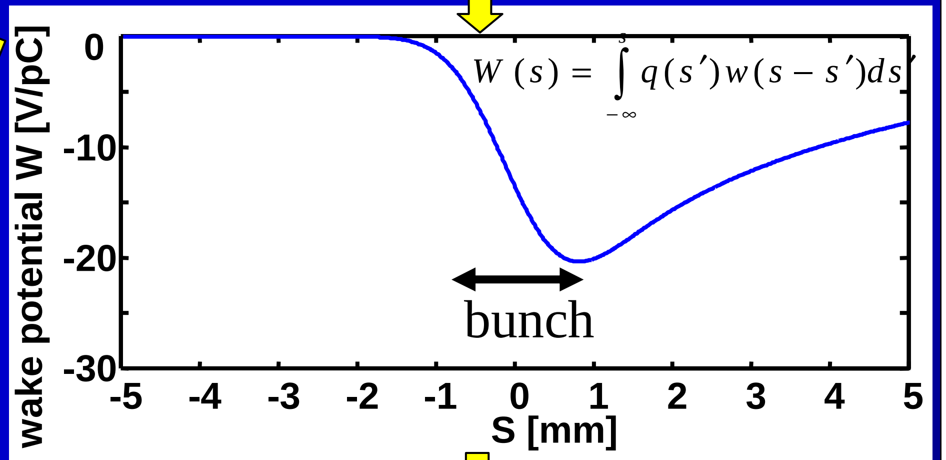
The excited HOM power of a bunch train depends on:

- **the HOM excitation by the individual bunches,**
- **the beam harmonic frequencies and the HOM frequencies (resonant excitation is possible!),**
- **the bunch charge and the beam current**
- **and the external quality factor, Q_{ext} of the modes.**

Average Monopole Power







- **Bunch excites EM cavity eigenmodes (Higher-Order Modes)**
- **Single bunch losses determine the *average* monopole HOM power per cavity.**

Loss Factor:

$$k_{\|} = \int_{-\infty}^{\infty} q(s) W(s) ds$$

$$P_{\|} = k_{\|} Q_{bunch} I_{beam}$$

Resonance Monopole Mode Excitation

Resonant Monopole Mode Excitation if $f_{HOM}=N \cdot f_{bunch}$

If a monopole mode is excited on resonance, the loss for this mode can be very high:

$$P = 2\left(\frac{R}{Q}\right) Q I_{beam}^2$$

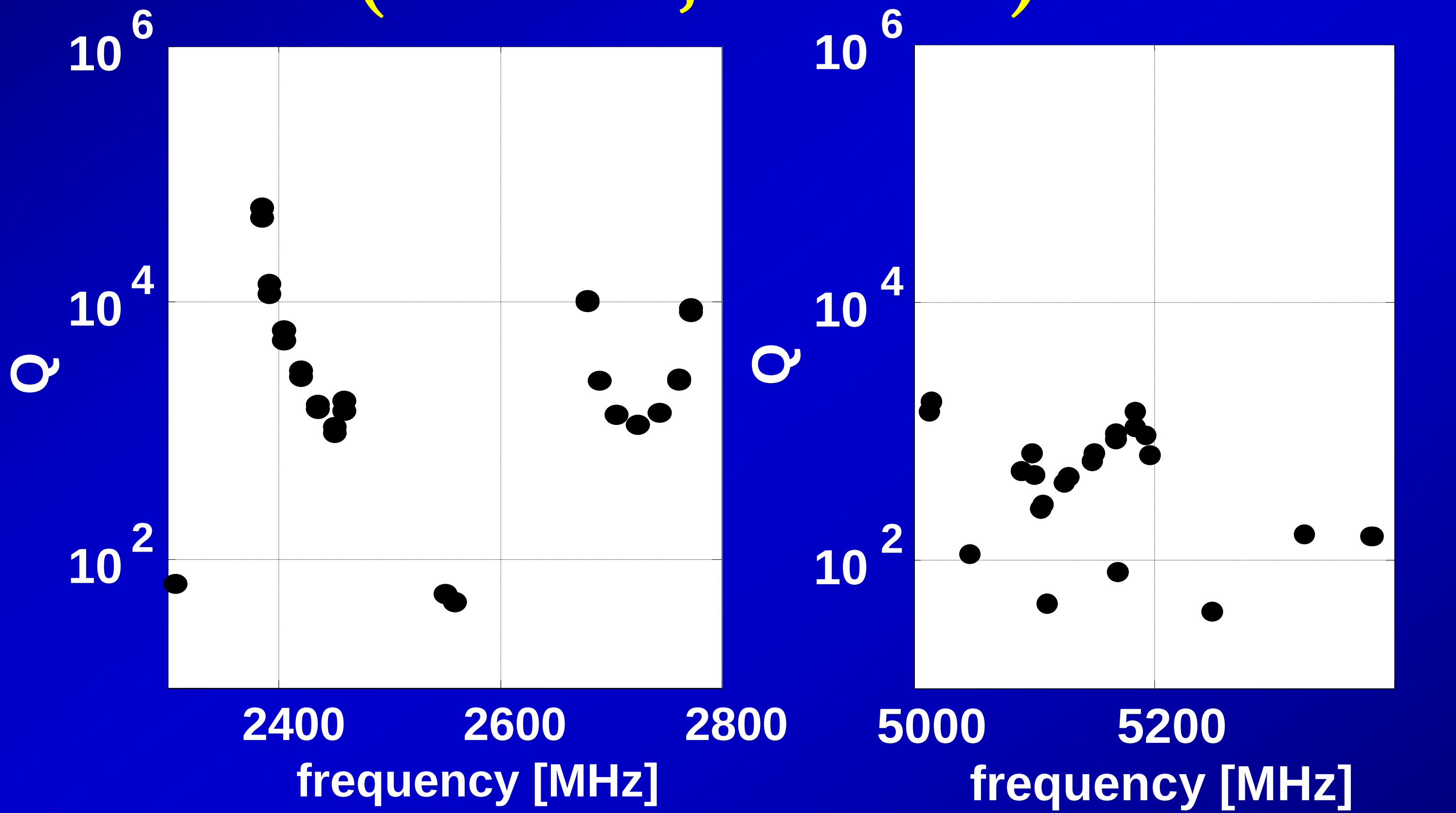
Need strong HOM damping!

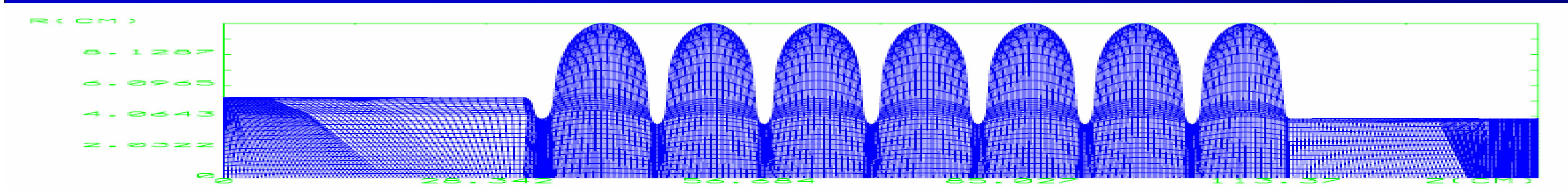
$\Rightarrow$ Example: To stay below 200 W with I=200 mA:

- achieve (R/Q)Q < 2500 Ω,
- or avoid resonant excitation of the mode.

Example: ERL Main Linac Cavity

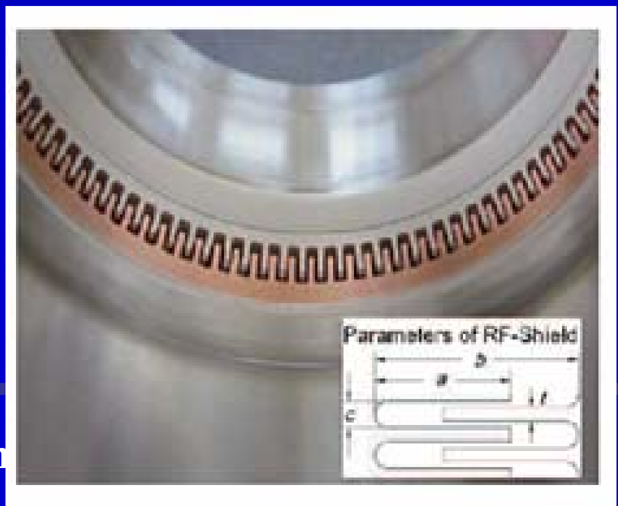
- No high Q monopole modes near first beam harmonics (2.6 GHz, 5.2 GHz)

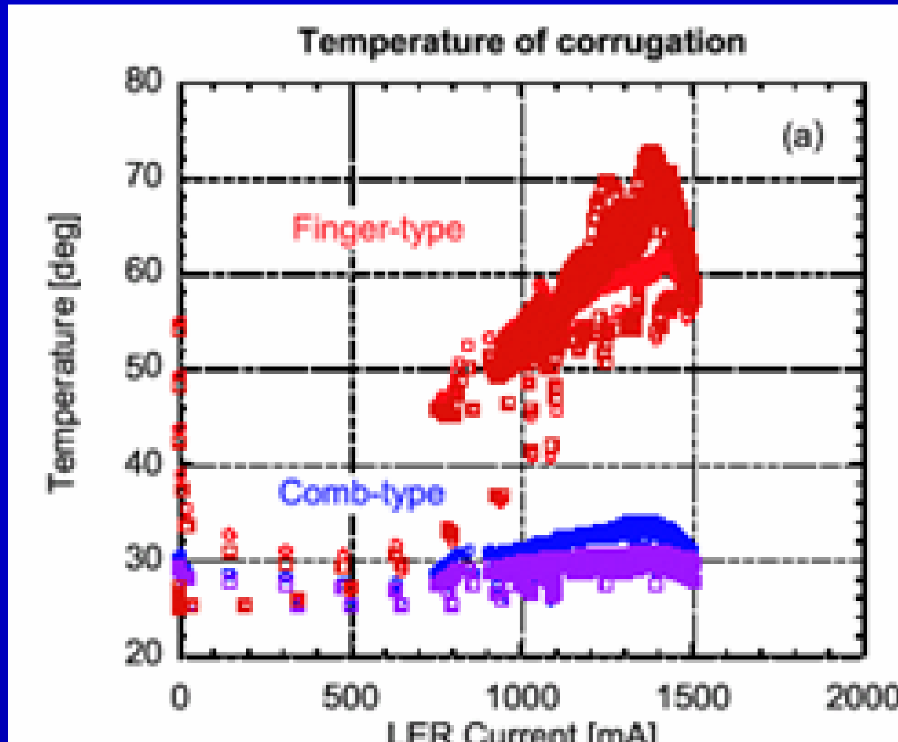




Example: HOM Power Heating

- **Example: Shielded bellows at KEK-B:**
  - Comb-type RF shield developed to replace RF fingers.

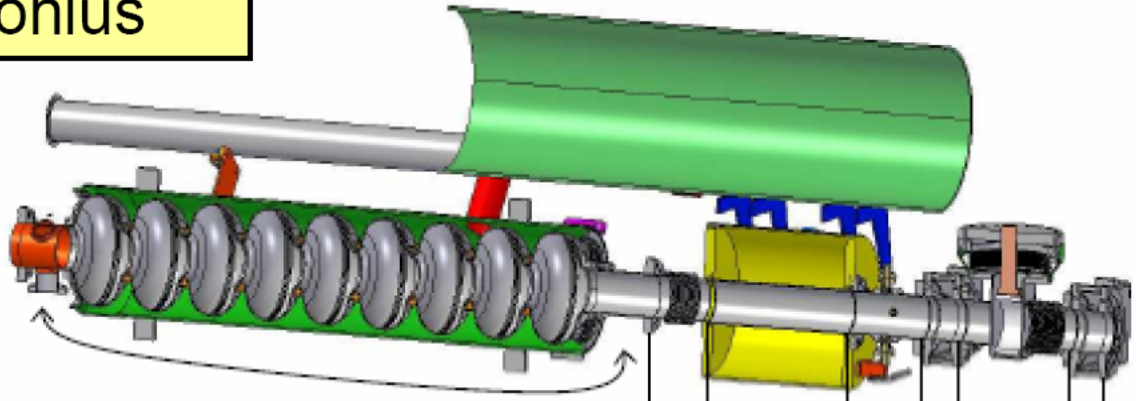




Absorbing High Frequency HOM Power

Calculations
M. Dohlus

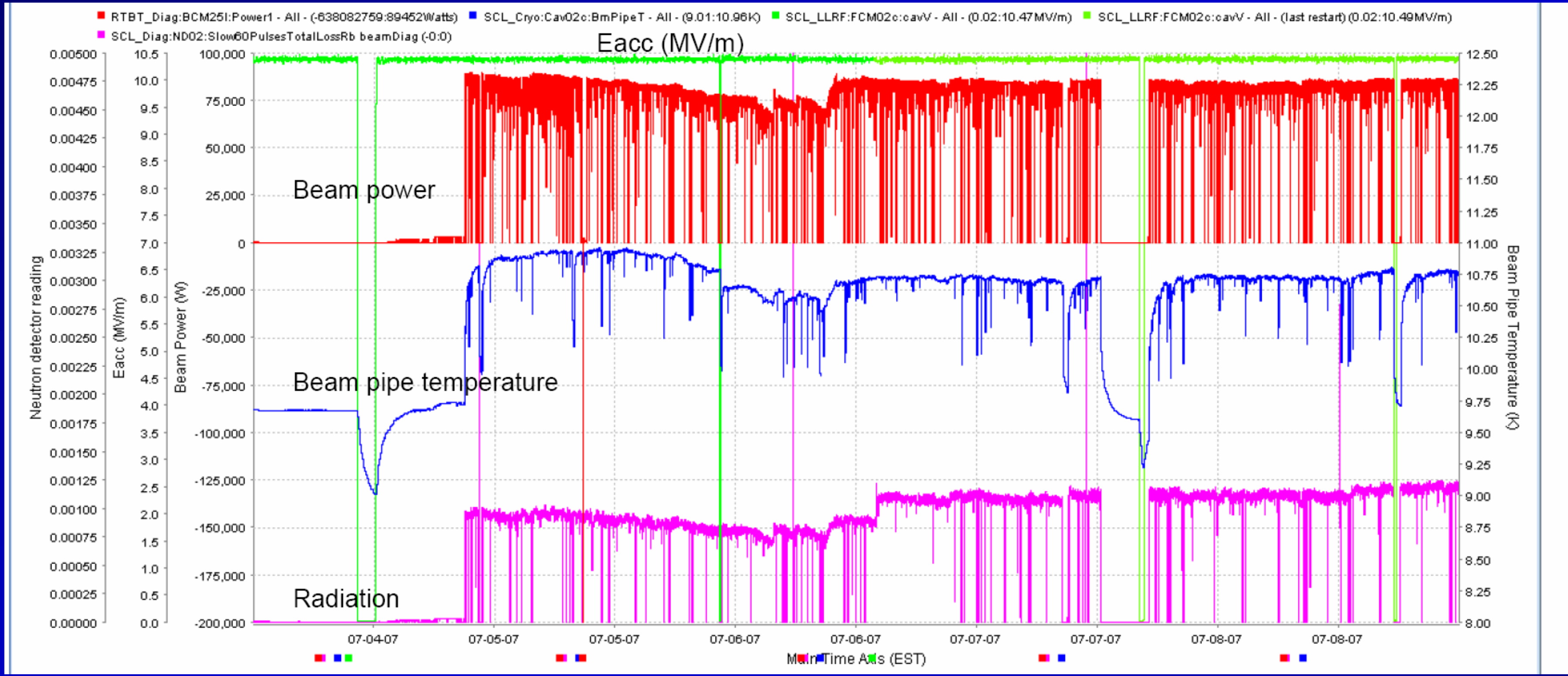
HOM absorption: all = 1000



<table>
<tr><td>72.2</td><td>cu
2.4</td><td>3.0</td><td>1.5</td><td>10.4</td><td>0.7|
1.5|894.4|1.5|
|2.0</td><td>10.4</td><td>$\eta = 79.4\%$</td></tr>
<tr><td>rest</td><td>bellows
24</td><td>quadrupole
30</td><td>bpm
15</td><td>shutter
8</td><td>absorber
7|15|..|15|20</td><td>shutter
8</td><td>(effective length / cm)</td></tr>
<tr><td>68.1</td><td>st
26.4</td><td>32.8</td><td>16.2</td><td>8.6</td><td>7.6|
16|777.9|16.3|
|21.4</td><td>8.7</td><td>$\eta = 67.8\%$</td></tr>
</table>

absorption efficiency (including 10% safty margin)

Example: HOM Heating at SNS



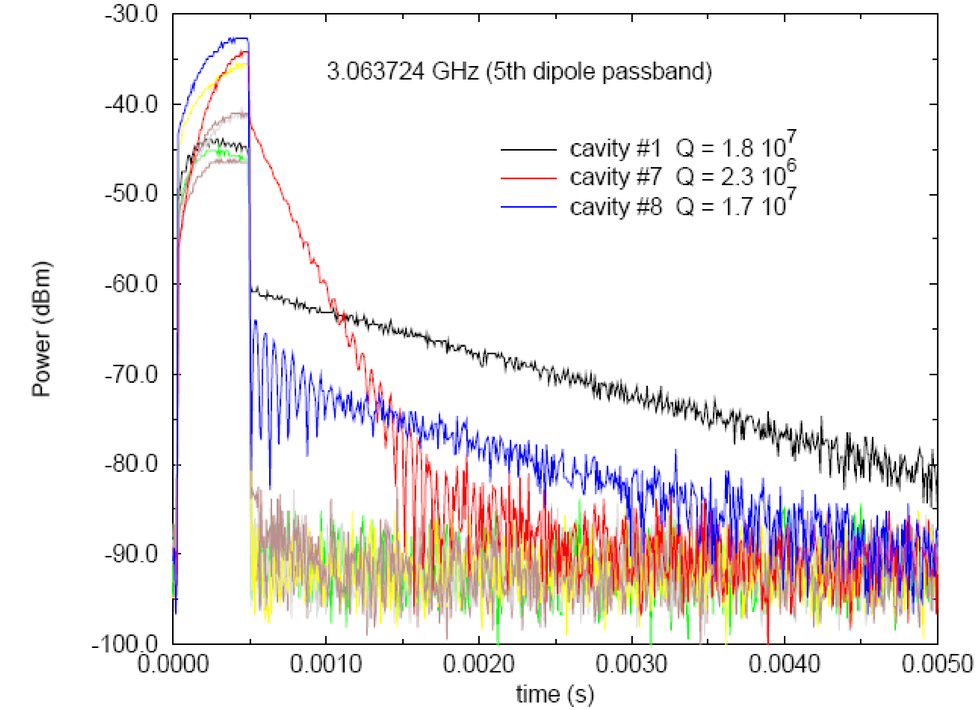
Beam pipe temperature increases by beam induced heating

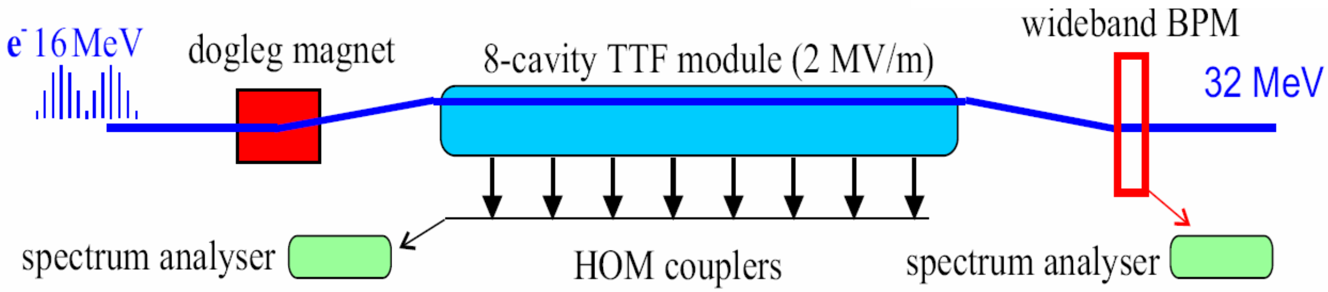
Beam Based HOM Damping Measurements

- The beam can be used to excite HOMs on purpose to search for weakly damped / trapped HOMs.

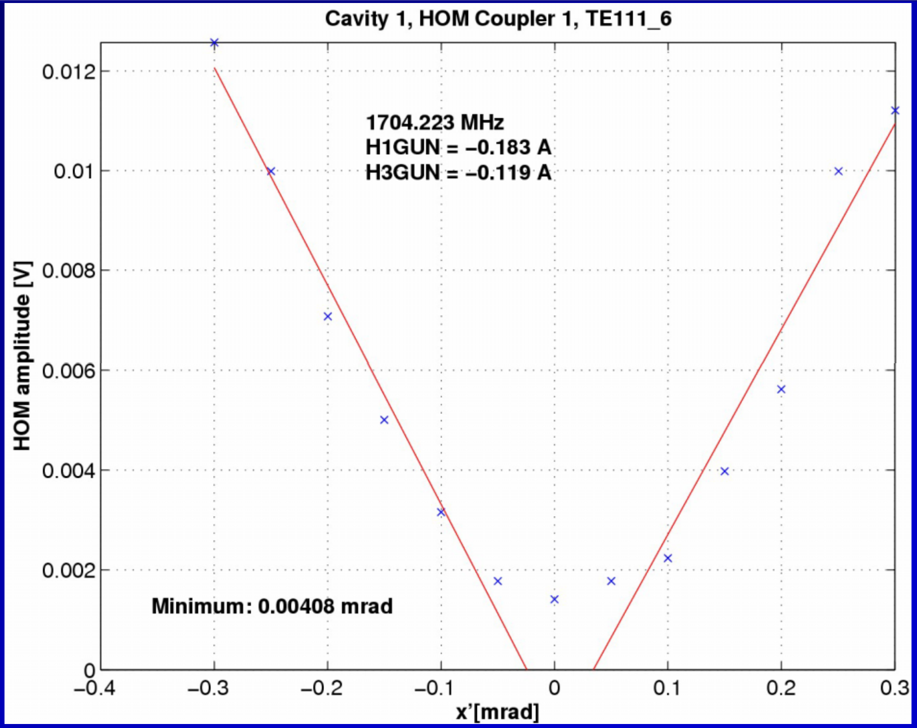
TTF/Flash results with current modulated beam reveled several weakly damped modes.

Some of them where initially not predicted by numerical HOM calculations!

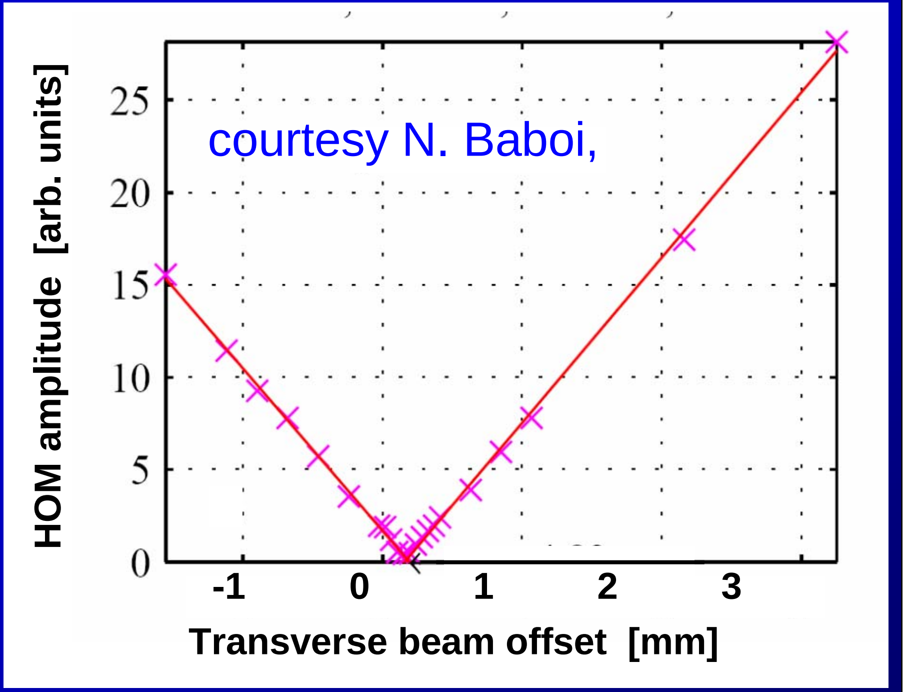




Cavity HOMs can be used as a BPM



Angular scan resolution and accuracy < 50 µrad



Relative position resolution ~ 4 µm

(*cf. M. Ross and J. Frisch*).

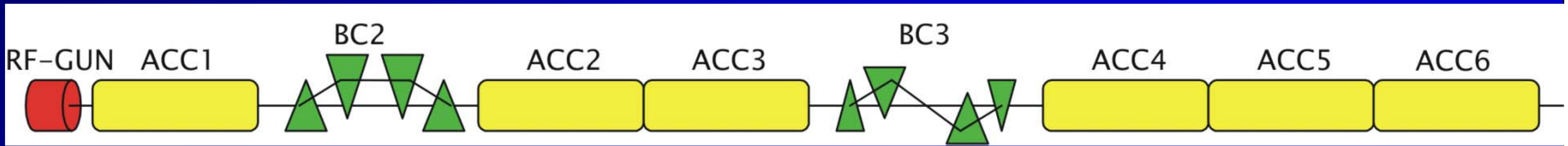
Cavity Performance and Performance Degradations

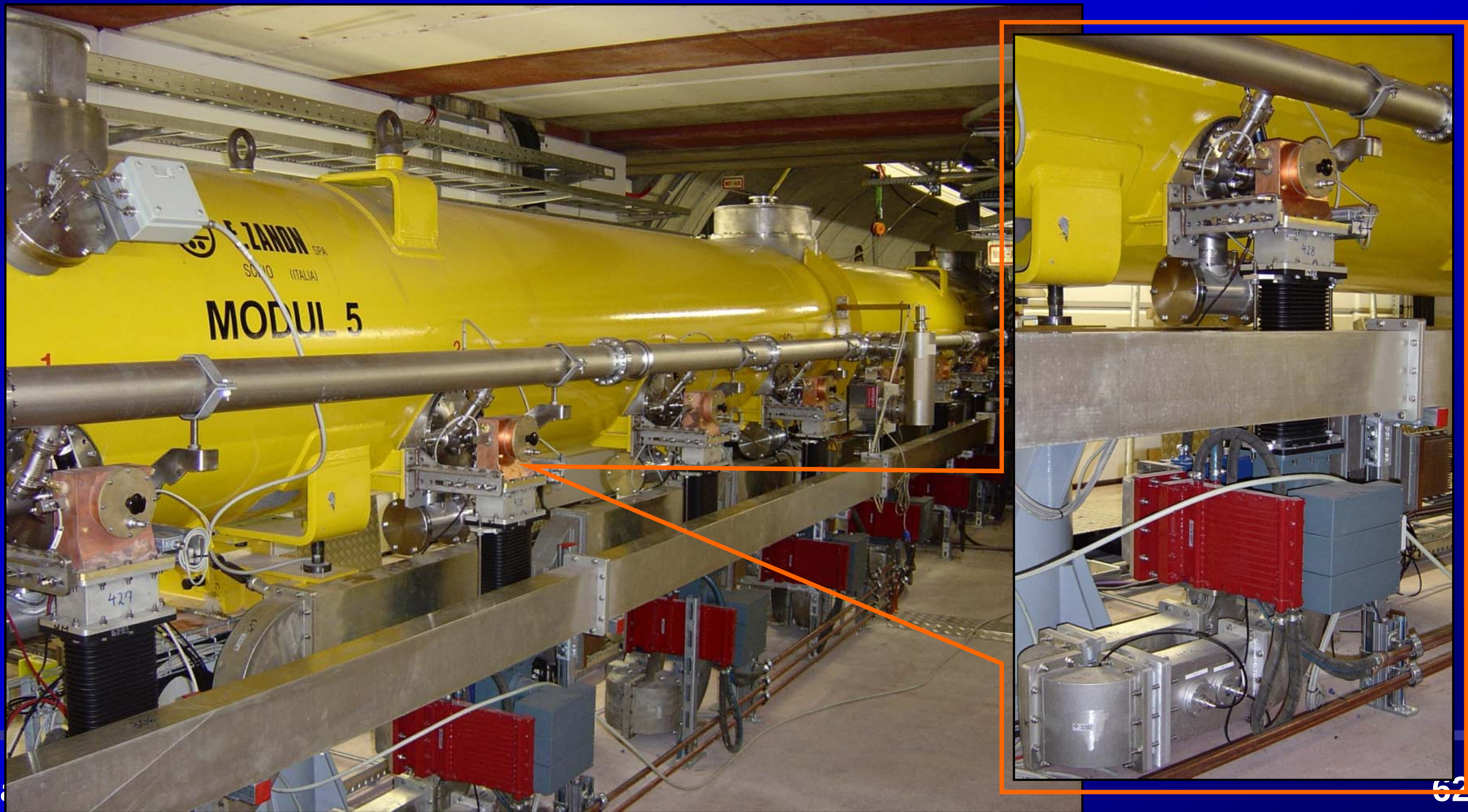
- Some Examples -

Linac Cavity Performance

- SRF cavity performance can change over time:
  - "Dust" can propagate through beam pipe into cavity (beam fields)
  - Field emitter can turn on suddenly
  - Special events (vacuum leaks…)
  - Collective effects
  - …

Example 1: FLASH Linac



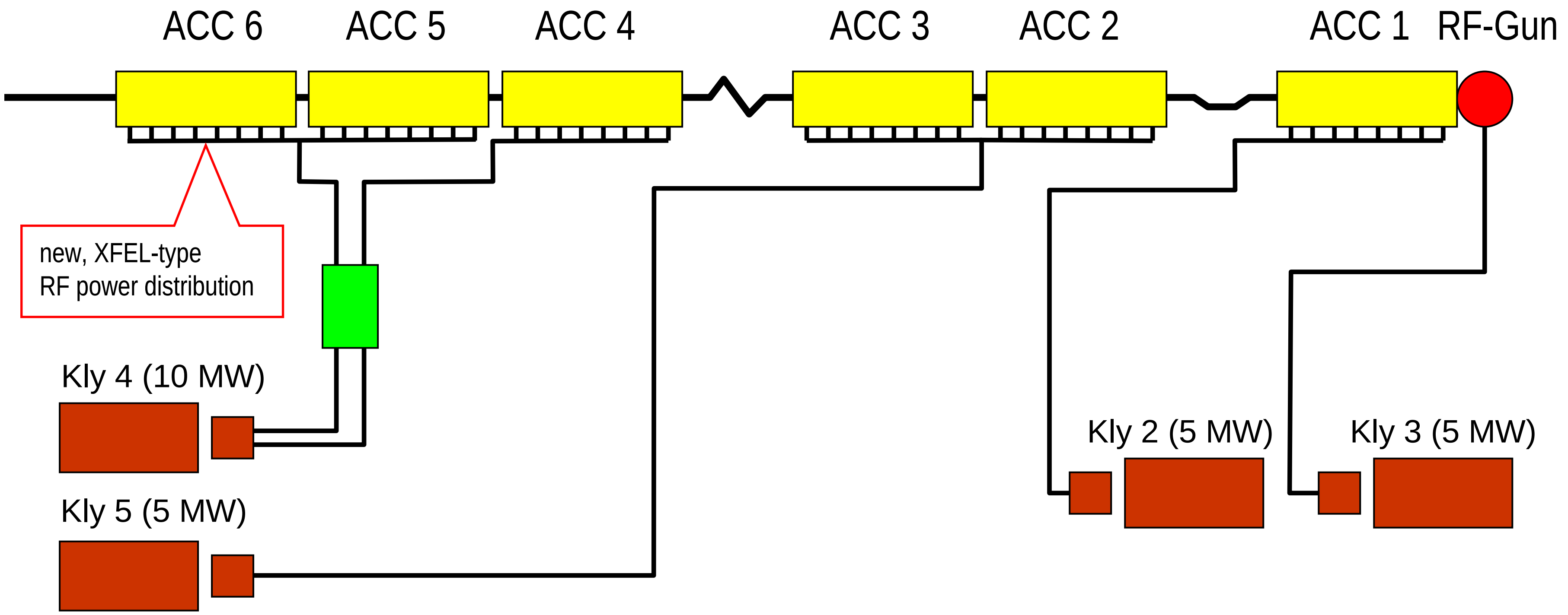


Experience from FLASH

- Recent measurements show that there is basically no degradation in gradient vs. time.
- Never had vacuum failures or dirt/dust contaminating the cavities. Also no problems after conditioning etc.
- Conditioned state is preserved also after some time of operation and after some time off.
- So far, there was no need to replace modules due to degradation or failure (but destroyed tuning motors)

$\Rightarrow$ **Whole machine is assembled "dust free"!**

FLASH: Vector Sum Control!

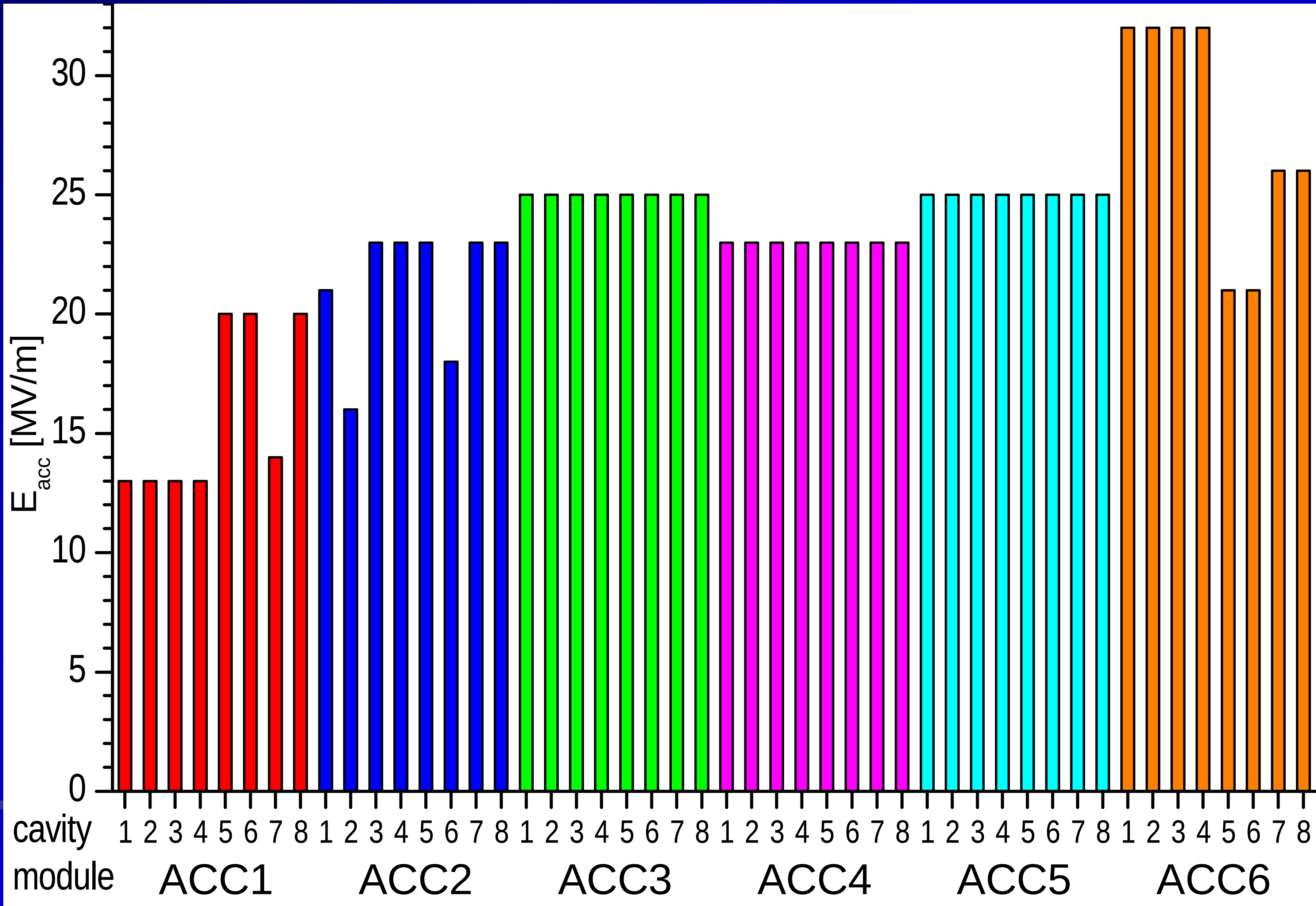


- **Need to adjust power distribution according to cavity performance, or weakest cavity will limit all other cavities!!**

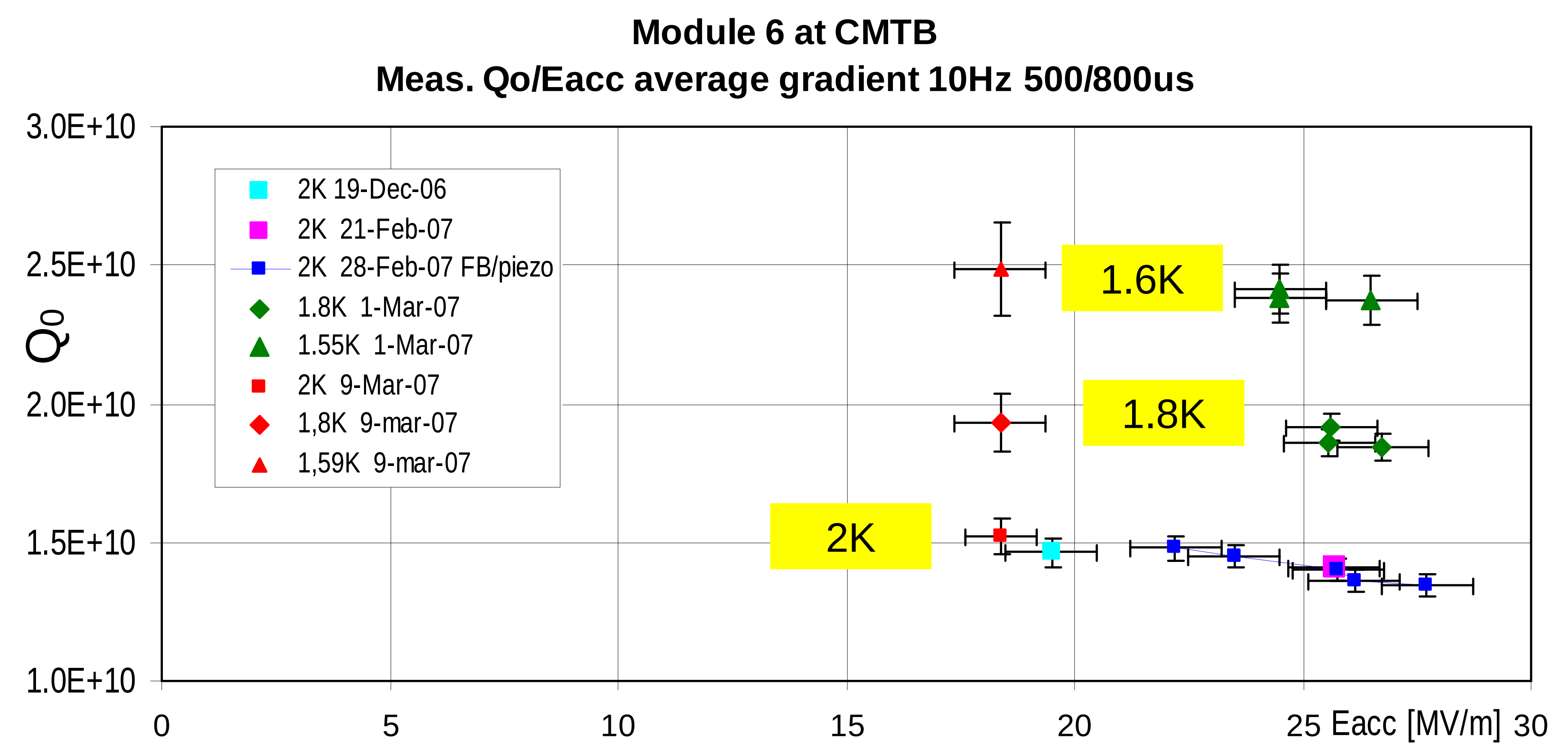
FLASH Operation

module	cavity	E_{acc} [MV/m]	attenuator [dB]	comment
ACC1	1, 2, 3, 4	13	—	capture section, lower gradient
	5, 6, 8	20	—	
	7	14	3	too high FE
ACC2	3, 4, 5, 7, 8	23	—	limited at 24 .. 25 MV/m
	1	21	1	quench
	2	16	3	quench
	6	18	2	quench
ACC3	1 ... 8	25	—	limited at 25.5 MV/m
ACC4	1 … 8	23	—	limited at 23.5 MV/m
ACC5	1 … 8	25	—	limited at 26.0 MV/m
ACC6	1 ... 4	32	XFEL type RF power distribution	limited at 33.0 MV/m
	5, 6	21		limited at 22.0 MV/m
	7, 8	26		limited at 27.0 MV/m

FLASH Operation

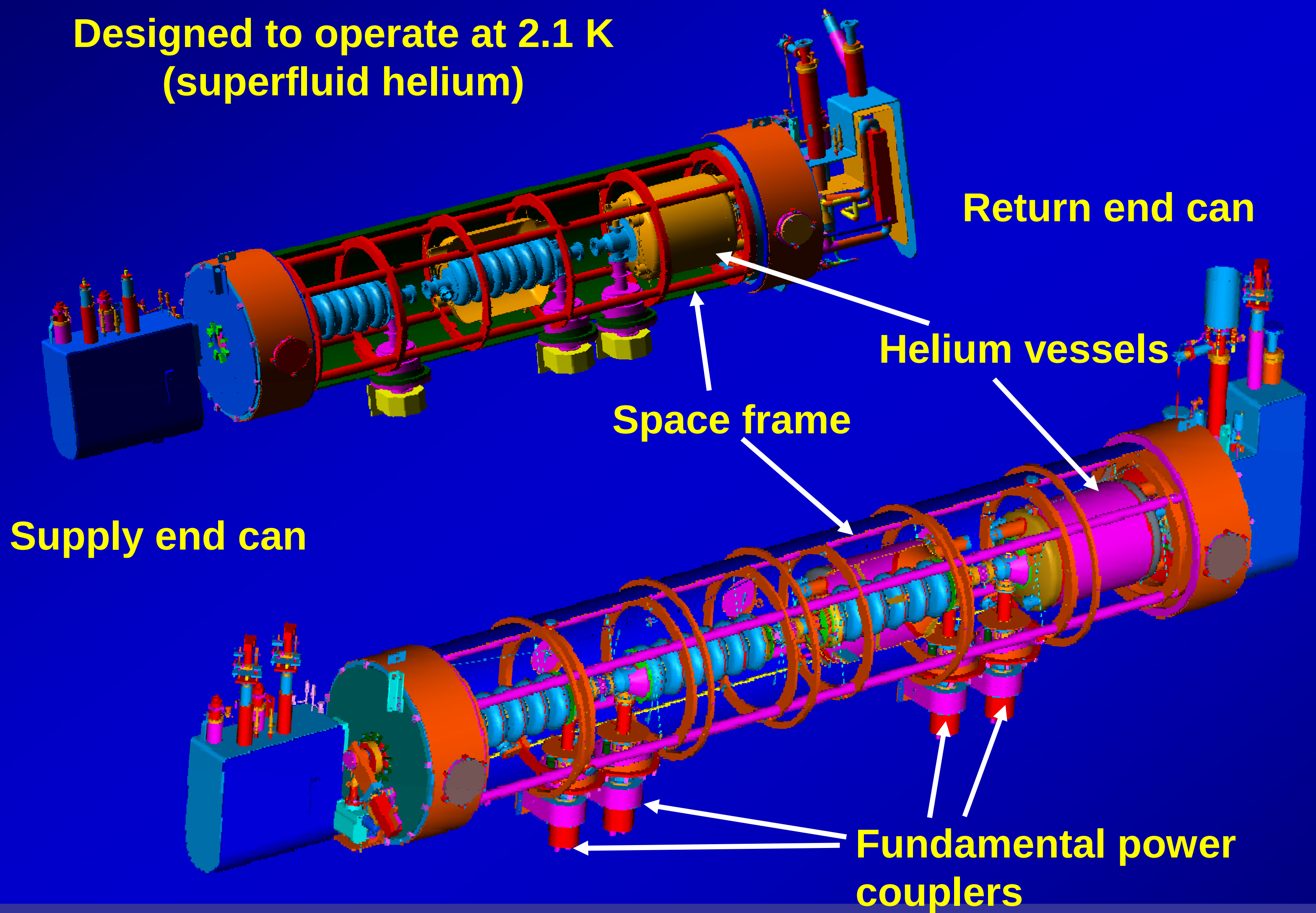


FLASH: Module Operation vs. Temperature



Example 2: SNS

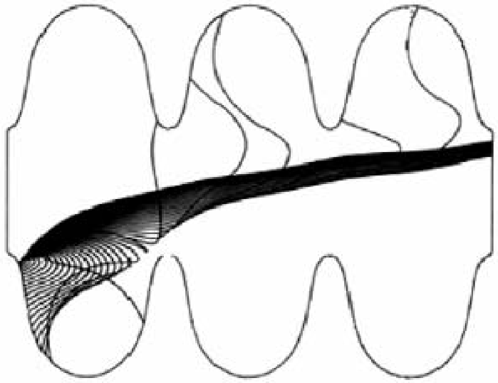
Designed to operate at 2.1 K (superfluid helium)



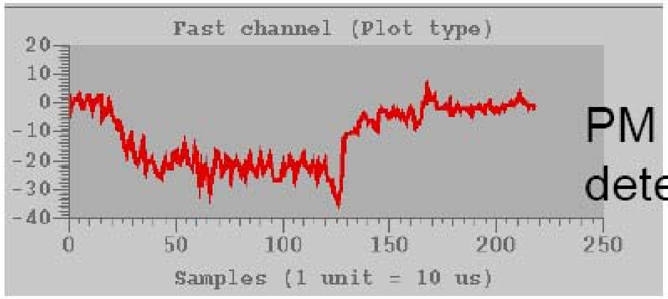
Cavity Limitations at SNS (I)

Cavity Limitations I – Field Emission (radiation→ heating)

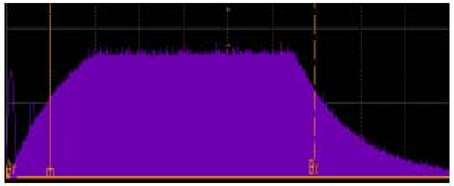
Electrons emitted from high field surface



Radiation ~ constant throughout the RF pulse



PM Radiation detector



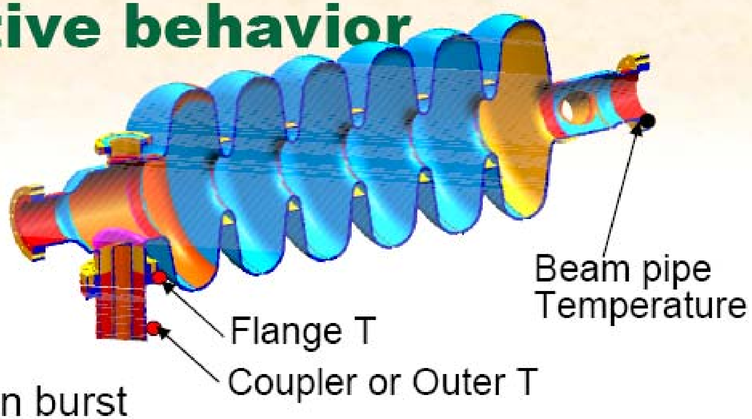
RF waveform

- **The primary cavity gradient limitation**

Cavity Limitations at SNS (II)

Field emission and Collective behavior

(clear indication at higher rep. rate)

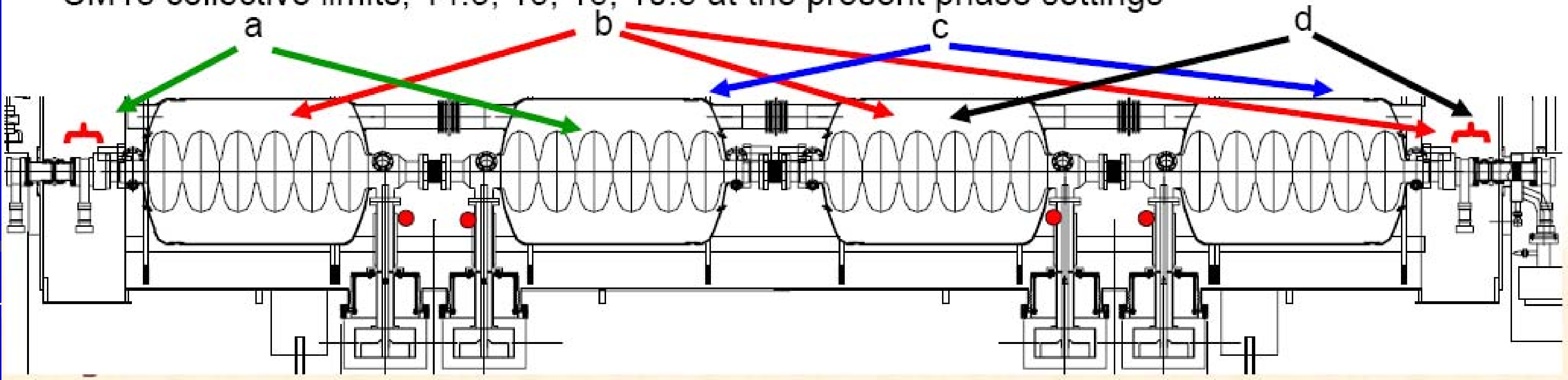


- **Field Emission +**
  electrons from cavity coupler interaction;
  - steady state electron activity + sudden burst
  - affects other cavities
  - electron landing place (relative phase, amplitude)
  - leads continuous gas activity, even though all signals look quiet
  - hits intermediate temperature region (5-20K); H2 evaporation (burst of gas)
  - redistribution of gas→ changes cavity/coupler conditions

Ex.

CM13 individual limits; 19.5, 15, 17, 14.5

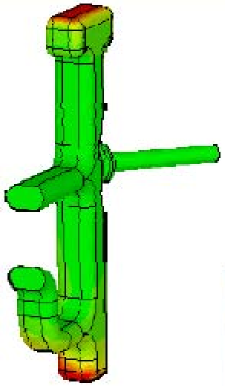
CM13 collective limits; 14.5, 15, 15, 10.5 at the present phase settings



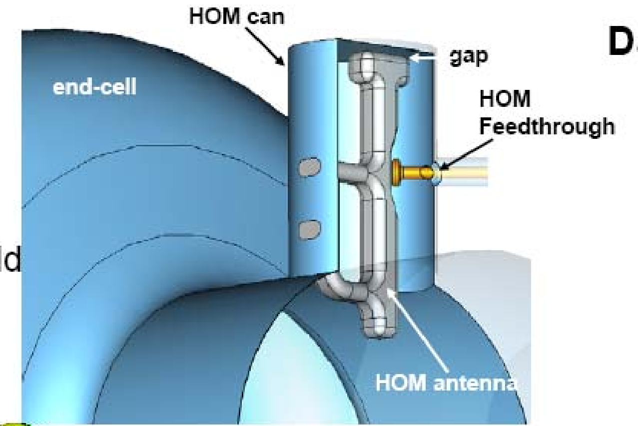
SNS: HOM Loop-Coupler Problems

HOM Coupler (subcomponent concern I)

Electric Field



- When Q>10^5, there's a concern.
  - but the probability is very low
- Extra insurance
- Coaxial type notch filter scaled from TTF was chosen and installed.
- Low power tests confirmed its functionality
  - Damping; dangerous modes to have Q≤~10^4

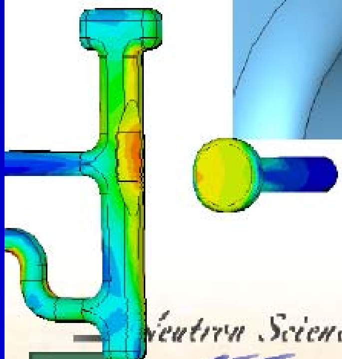


Damage/deterioration

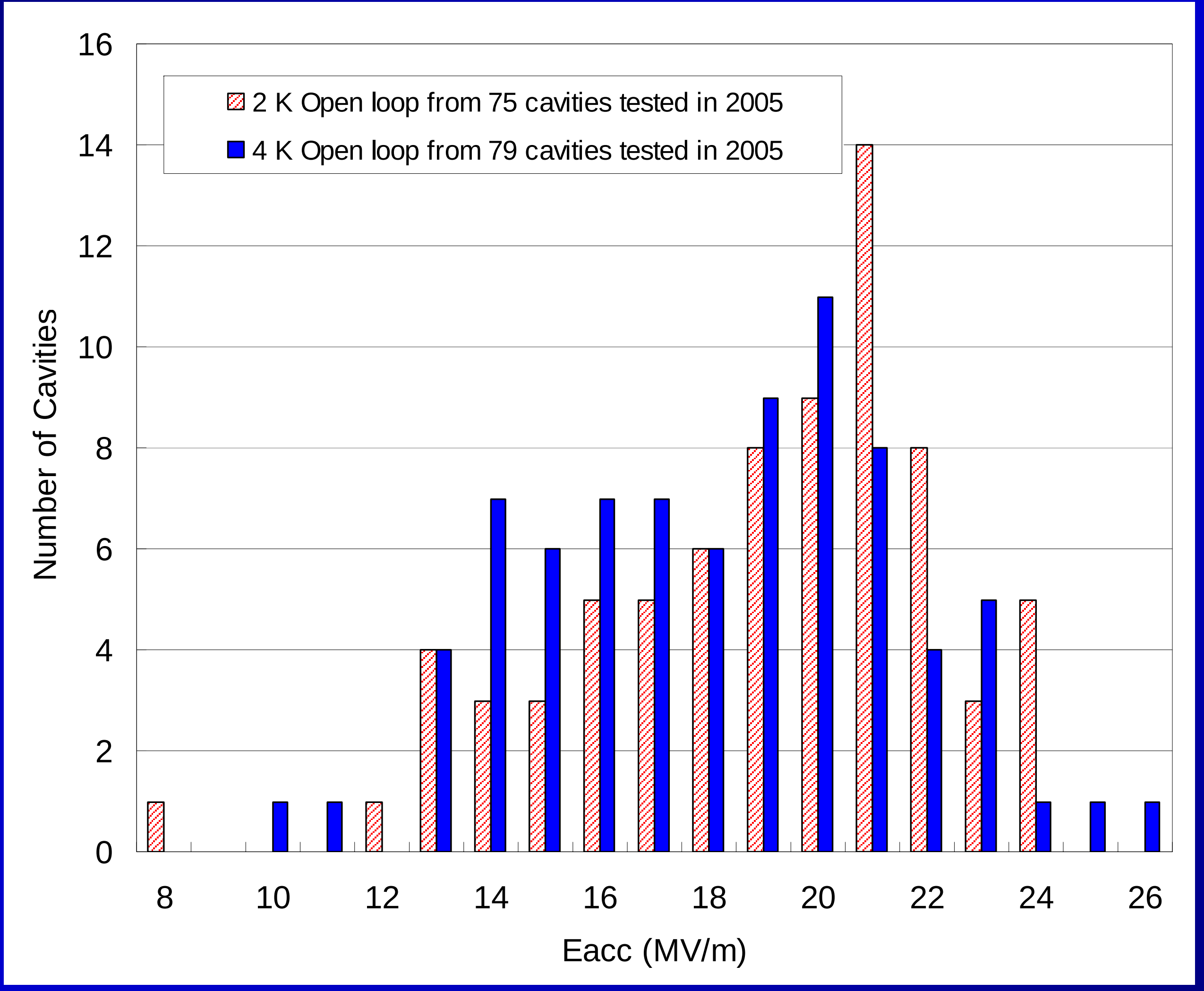
Hypothesis;
interactions between
electronic activity (MP, FE)
+ fundamental mode standing wave
(from stray field)

Should reevaluate
advantages vs. disadvantages
Since HOM coupler in SNS is
Not a critical device

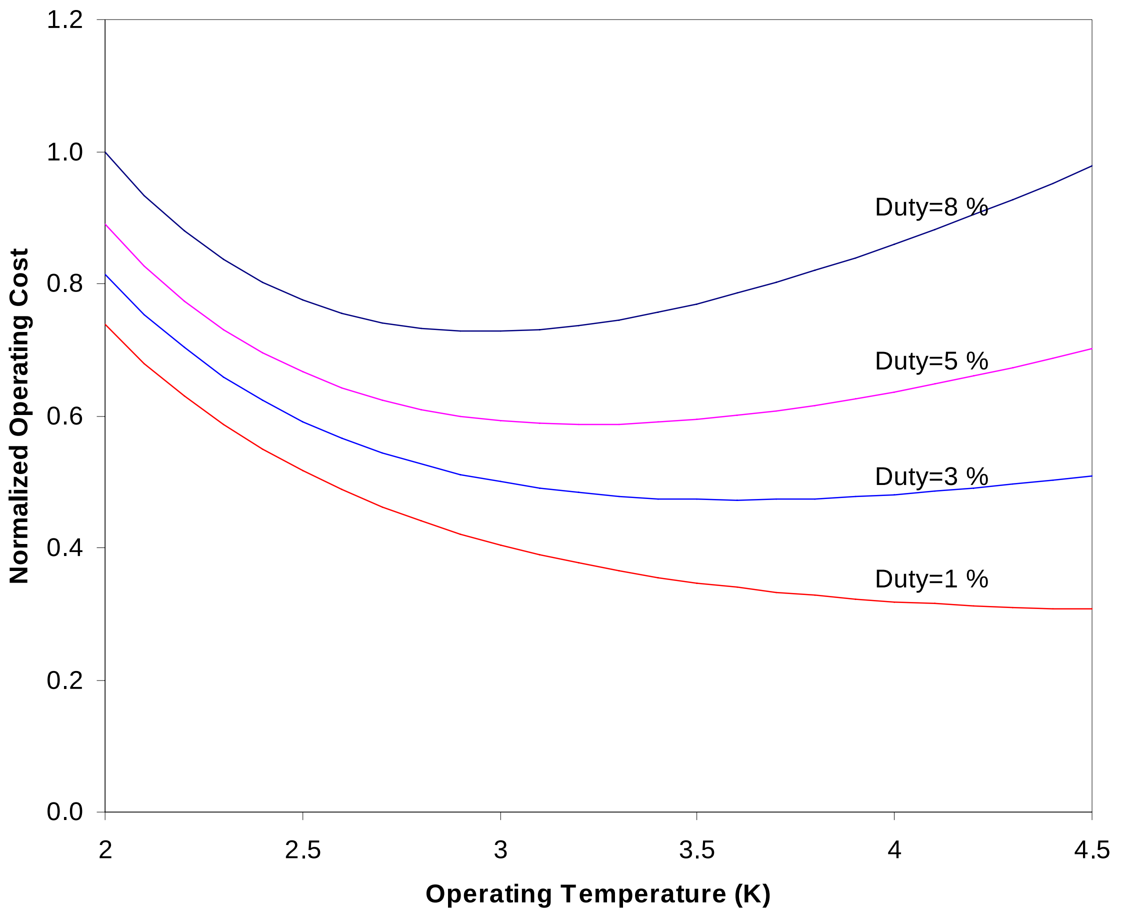
Magnetic field



SNS: Operating Temperature (I)



SNS: Operating Temperature (II)



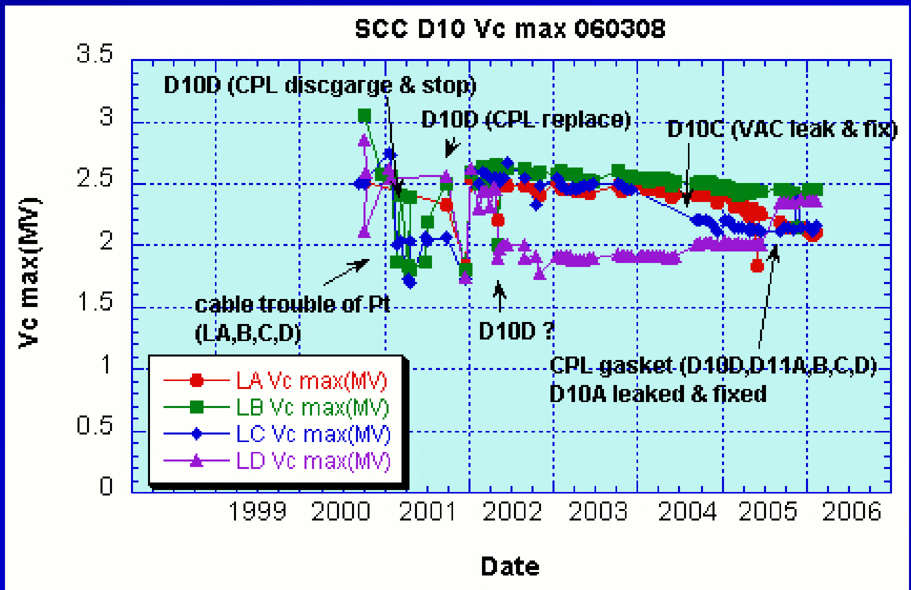
For SNS, operation at 4.2 K is overall more economical up to about ½ of the design beam power
(if achieved by reducing repetition rate to 30 Hz)

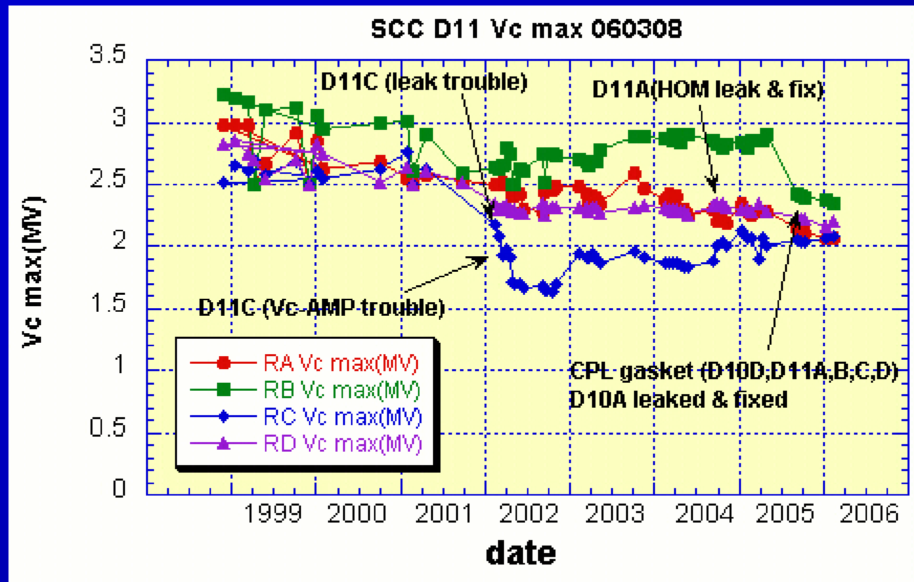
Example 3: KEK-B, Long Term Cavity Operation (I)

(1) maximum accelerating voltage

T. Furuya, S. Mitsunobu

- All cavities can provide Vc >2 MV after 7 years operation.
- Vc of D11C degraded after the vacuum trouble.
- Vc of D11B degraded after changing the coupling of the input coupler.



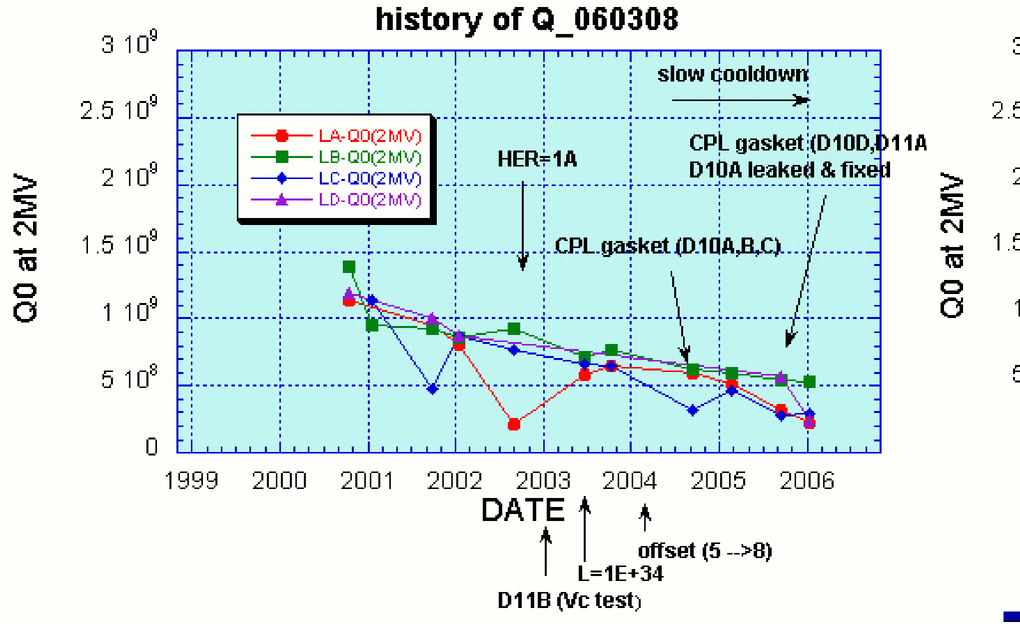


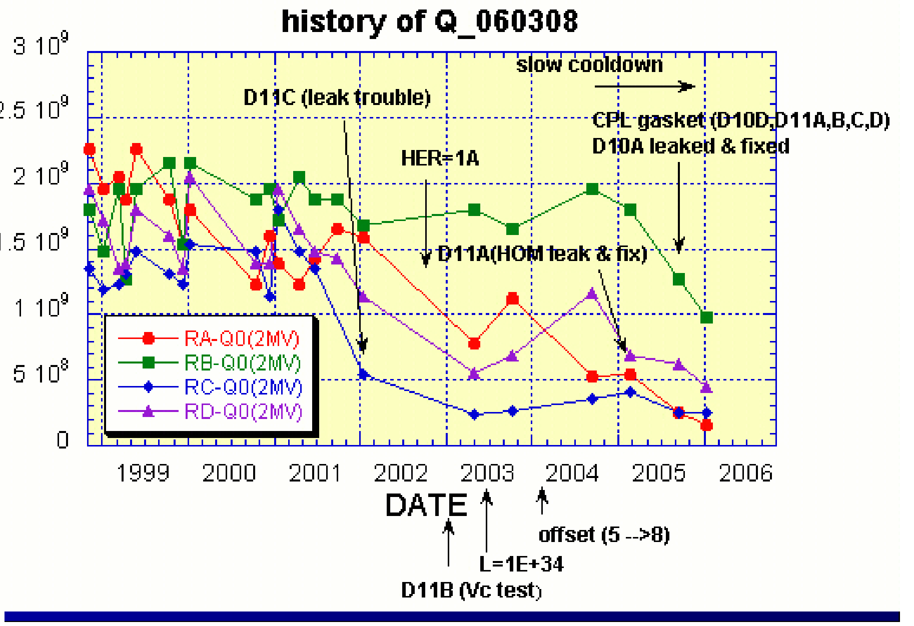
Example 3: KEK-B, Long Term Cavity Operation (II)

(2) Intrinsic Q

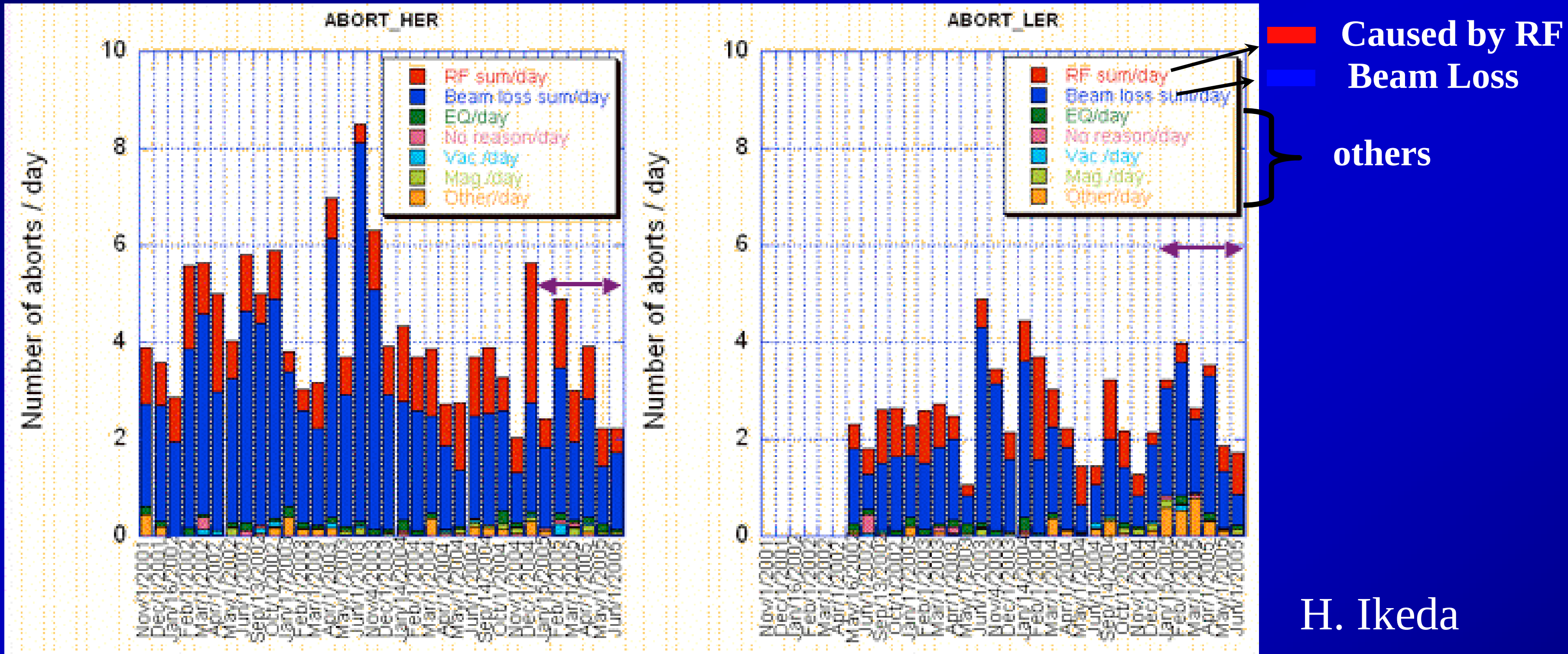
T. Furuya, S. Mitsunobu

- Unloaded Q at 2MV (8MV/m) has gradually degraded to 3-5x10^8.
- Huge amount of out gas from the ferrite dampers has degraded the cavity performance?
- Baking may recover the performance, but we have to consider the risk of vacuum leak at the indium seals.
- The Q at the operating voltage (1.4MV) still keeps Q >1x10^9.





KEK-B: Beam Aborts

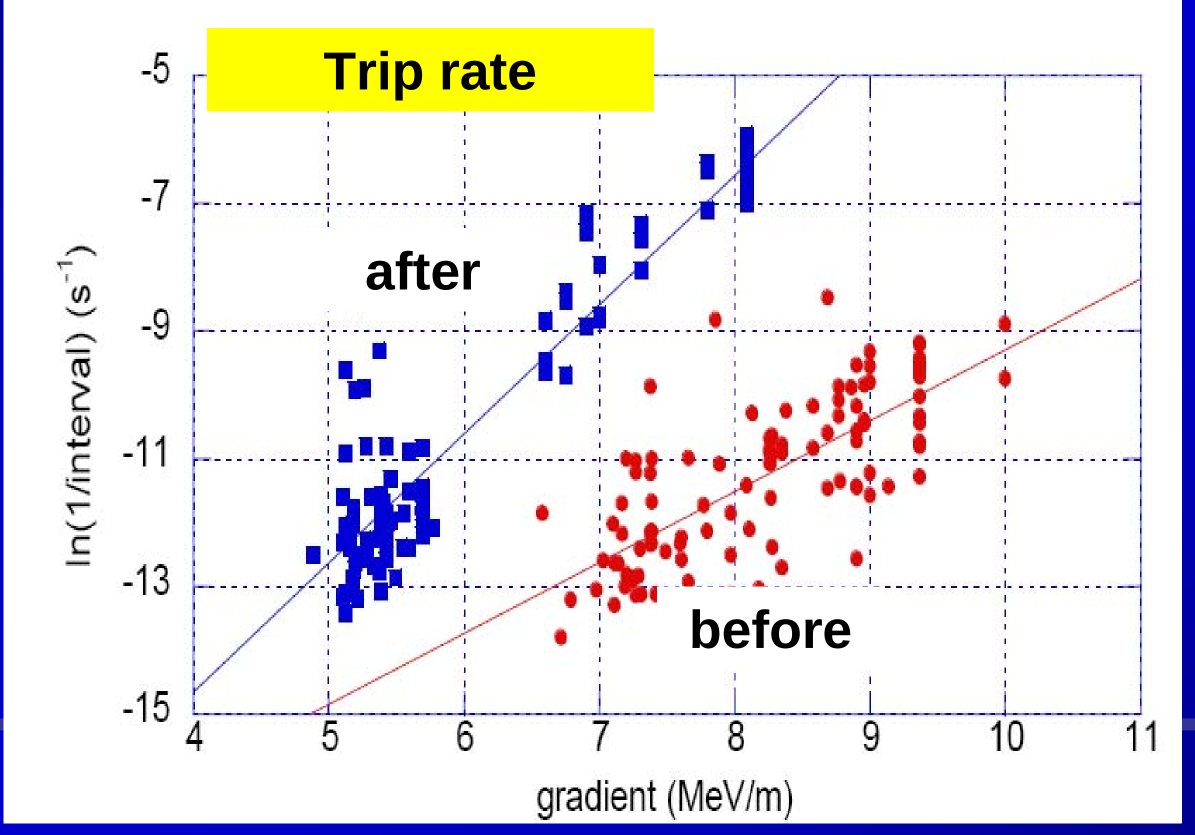


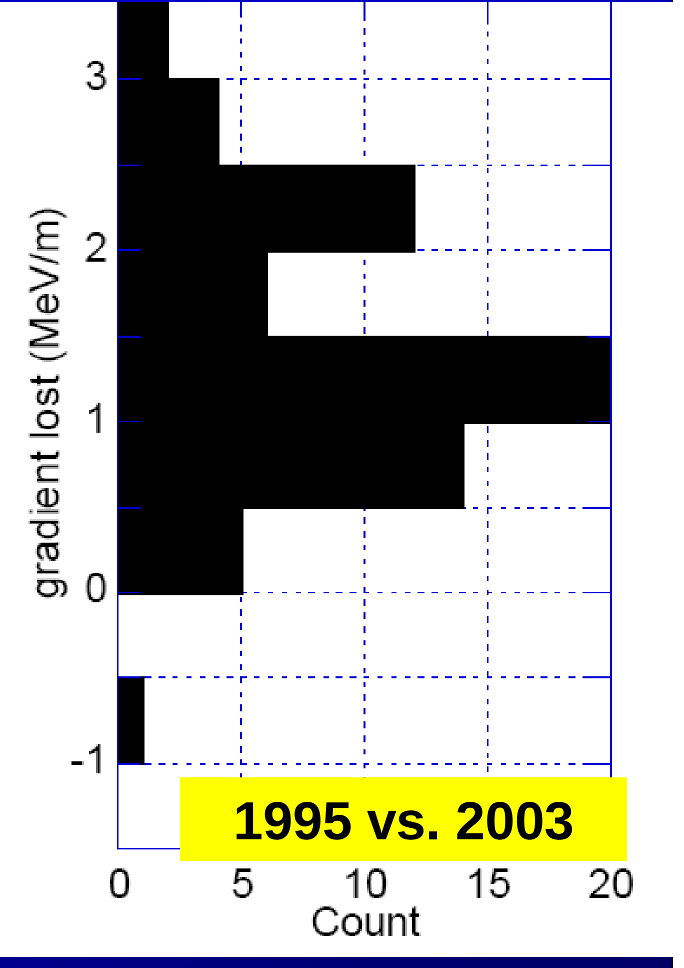
H. Ikeda

- The cause of every beam abort is analyzed immediately.
- Caused by beam loss (60%), RF (28%), or others (12%).
- Average number of beam aborts in two rings caused by any RF reasons is about once or twice /day.

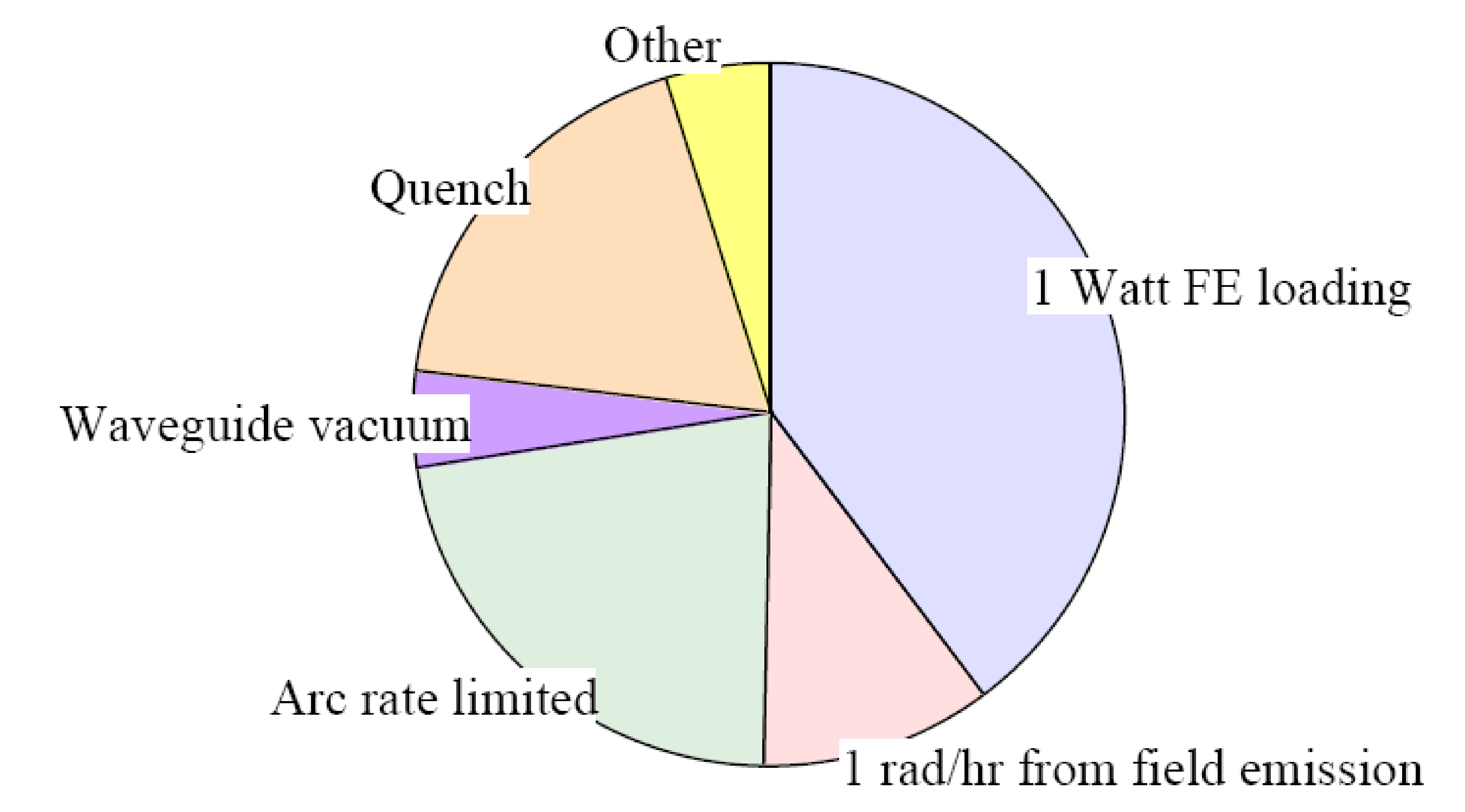
Example 4: CEBAF

- See changes in cavity performance vs. time
- Not all of these changes are correlated to external disturbances (warm up, ..)!

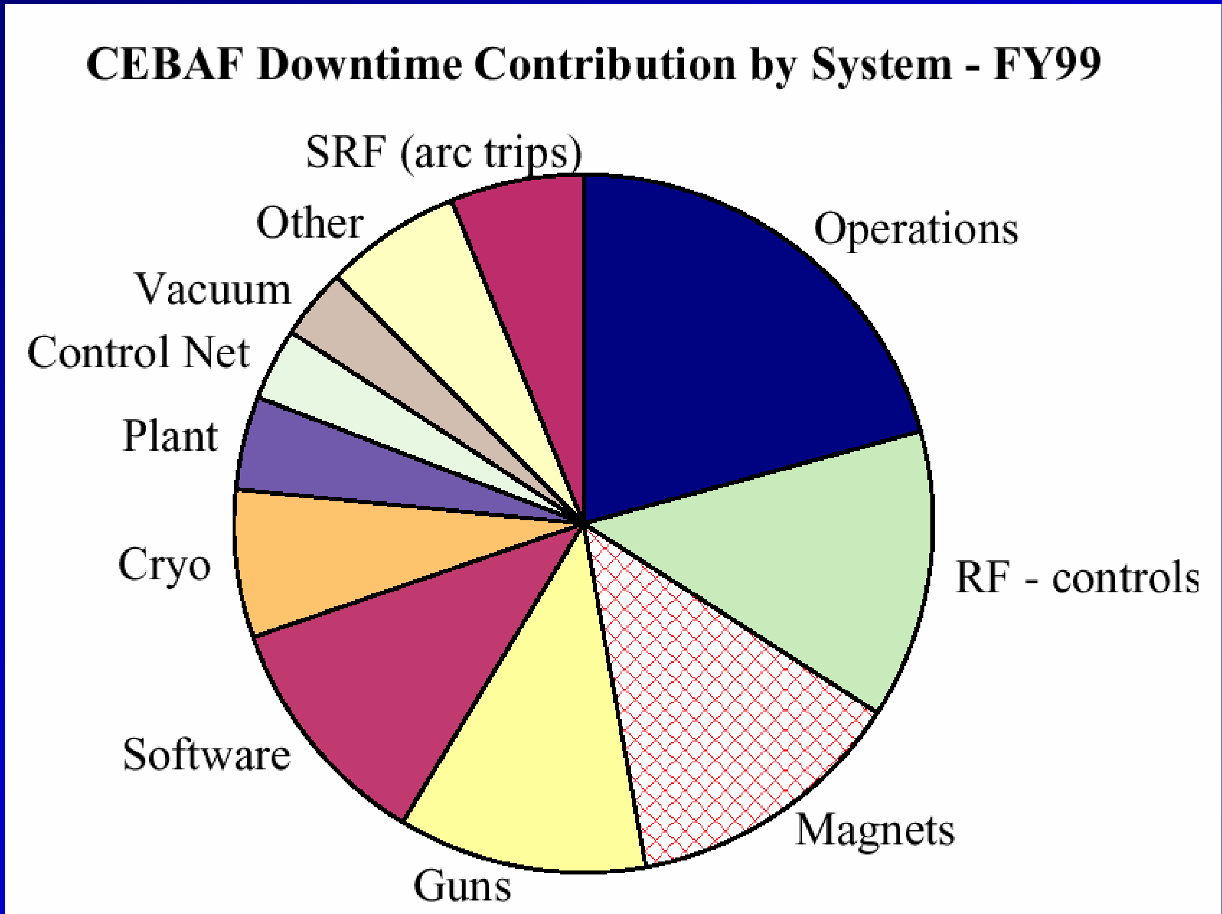




CEBAF: Type of Cavity Performance Limitation



CEBAF Downtime (1999)



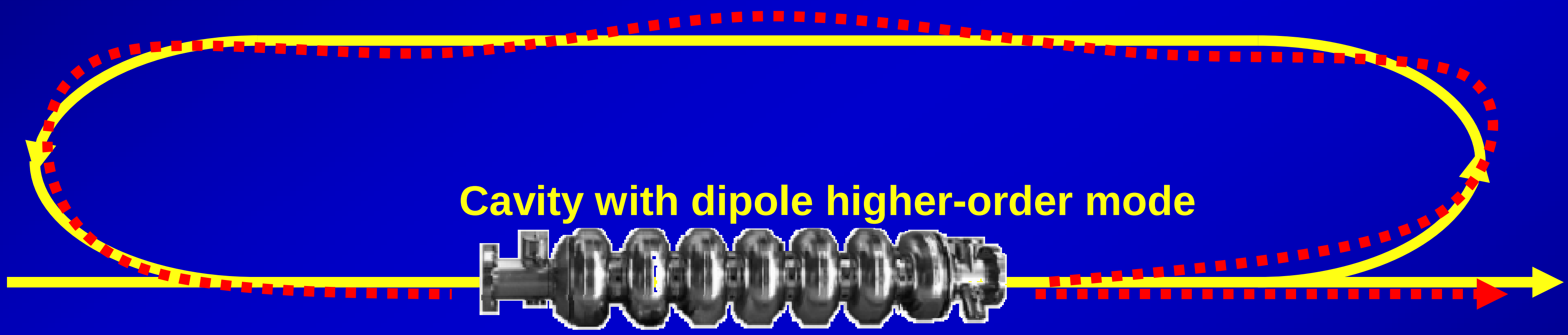
Other than the arc trips, the SRF system directly contributed 48 minutes (less than 0.1%) of the 1620 hours of unscheduled downtime.

Emittance Dilution caused by SRF Cavities

- Some Examples -

Example 1: Transverse BBU in ERLs

- In an ERL a feedback system formed between cavities and the beam is closed. ⇒ Instability at sufficient high currents (BBU threshold)!



- Simple model for instability beam current:

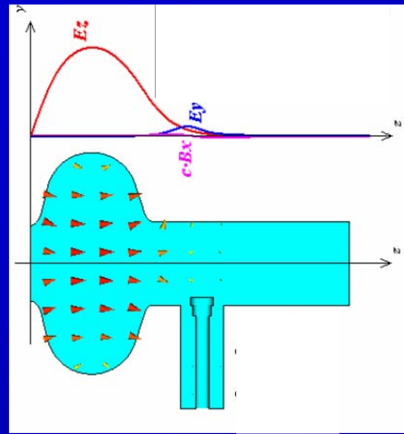
$$I_{BBU} \propto \frac{\omega}{(R/Q)\,Q}$$

For I_{BBU} > 100 mA, need strong HOM damping ($Q \approx 10^4$ to 10^5)!

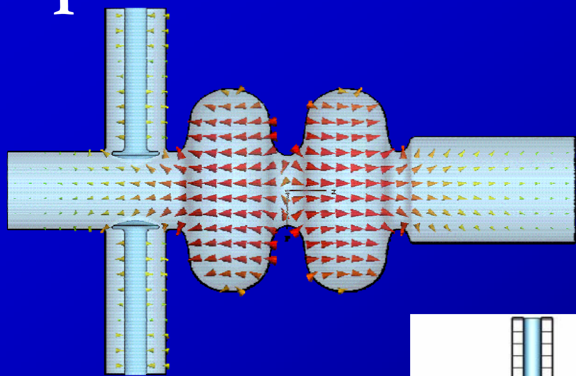
Example 2: Coupler Kicks

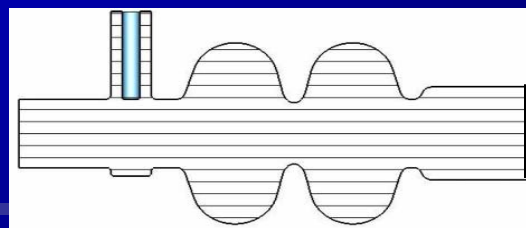
- Input couplers cause transverse, time dependent kick fields on axis, and thereby emittance growth.

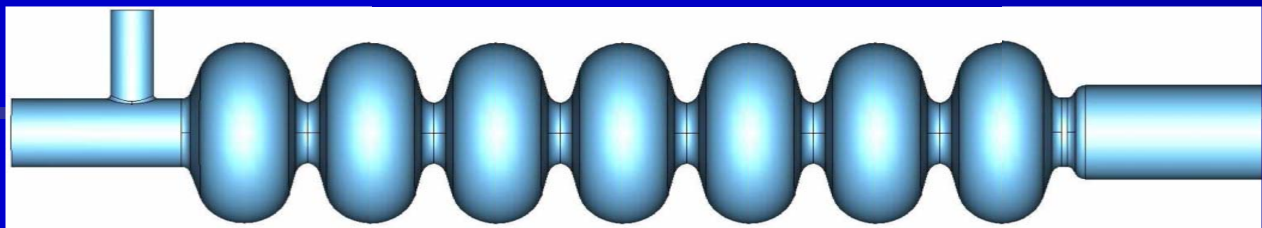
$$\boxed{\kappa = \frac{\Delta P_y}{\Delta P_{||}}}$$



- Solutions
  - Optimize distance coupler – first cell
  - Symmetry
  - Compensating stub

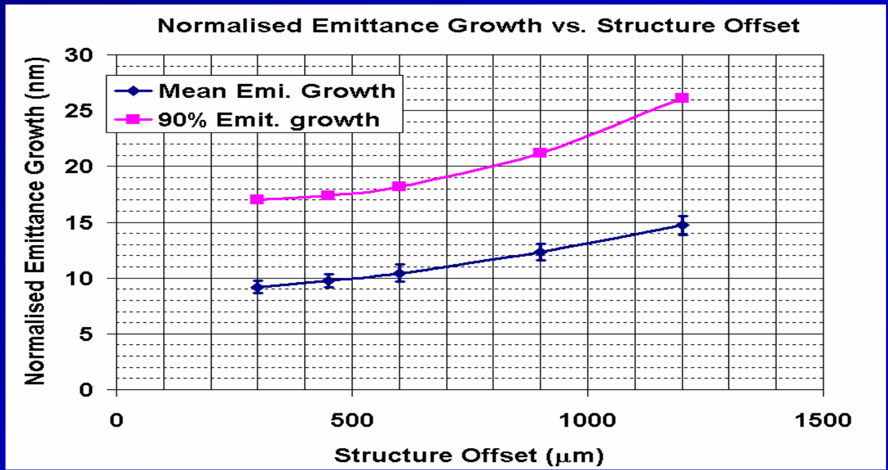


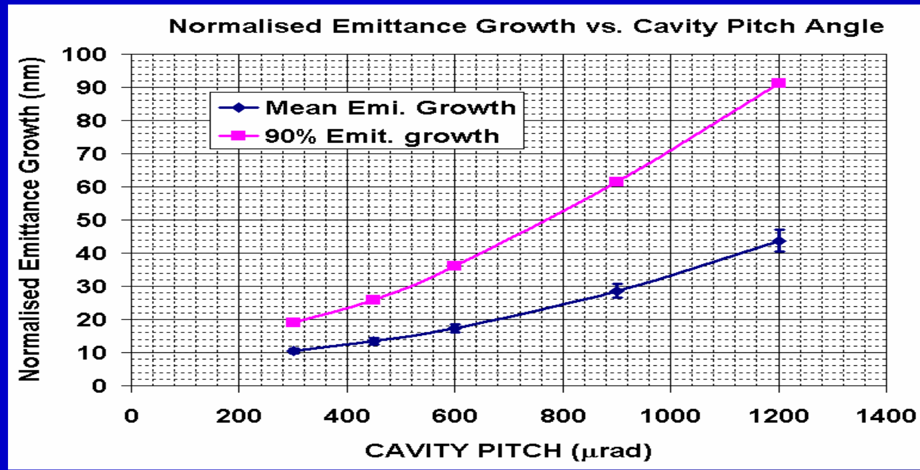


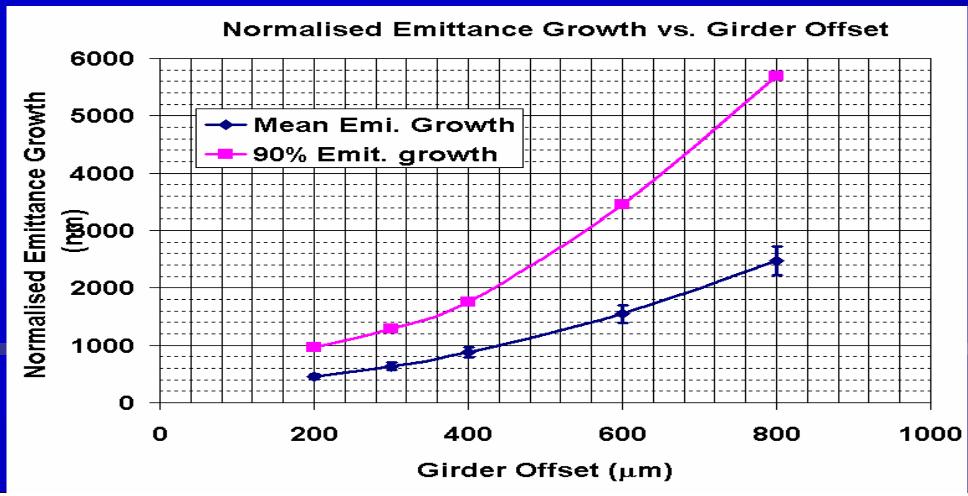


Example 3: Cavity Misalignment

- Cavity and cryomodule offset and tilt cause emittance growth

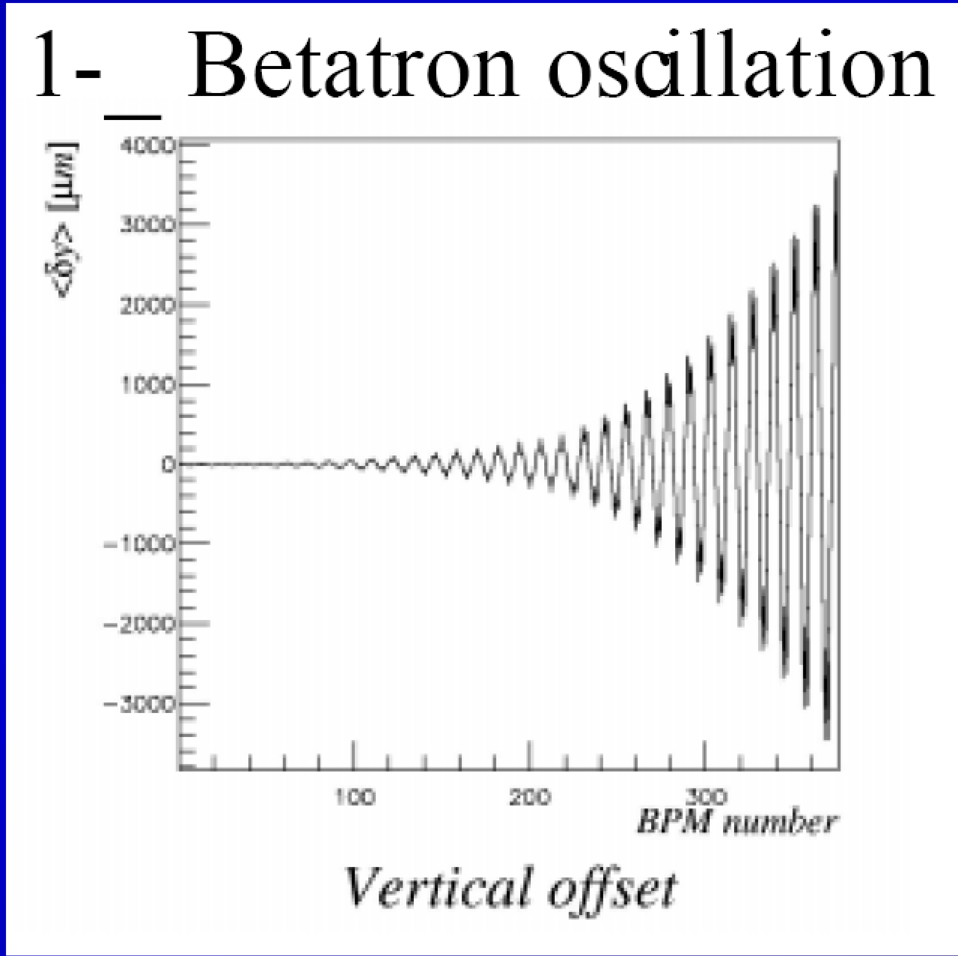






Example 4: BBU from high Q HOM

- Insufficiently damped dipole modes can cause emittance growth and even beam break-up



Conclusion

SRF Cavity and Beam

What would be one without the other?

If we do it right, they both can be happy…