Determining Loaded-Q for SRF Cavities Used In ERLs

(What do you mean it is not perfect energy recovery?)

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Outline

- Loaded Q for on crest beam.
- Loaded Q for complete energy recovery
  - Microphonic Effects
- Loaded Q for incomplete energy recovery
  - Why Incomplete energy recovery
  - Implications in RF loading and control
  - Implications for high current applications.
- Conclusions

Basic Equations For RF Source Power

$$P_{Kly} = \frac{(\beta+1)\,L}{4\beta\, Q_L(r/Q)}\left\{\left(E + I_0 Q_L(r/Q)\cos\psi_B\right)^2 + \left(2Q_L\frac{\delta f}{f_0}E + I_0 Q_L(r/Q)\sin\psi_B\right)^2\right\}$$

$$\psi_{Kly} = \arctan\left(\frac{2Q_L\frac{\delta f}{f_0}E + I_0 Q_L(r/Q)\sin\psi_B}{E + I_0 Q_L(r/Q)\cos\psi_B}\right)$$

E, I_0 are the electric field and current in the caivty respectively

(r/Q) is the shunt impedance per unit length (Ω/m)

Ψ_B is the phase of the beam relative to the field in the cavity

δf is the differernce between the cavity frequency and that of the RF source f_0

Q_L is the loaded - Q of the cavity

β is the cavity coupling factor with no beam loading

L is the length of the cavity in meters.

Case 1 Standard Beam Loading

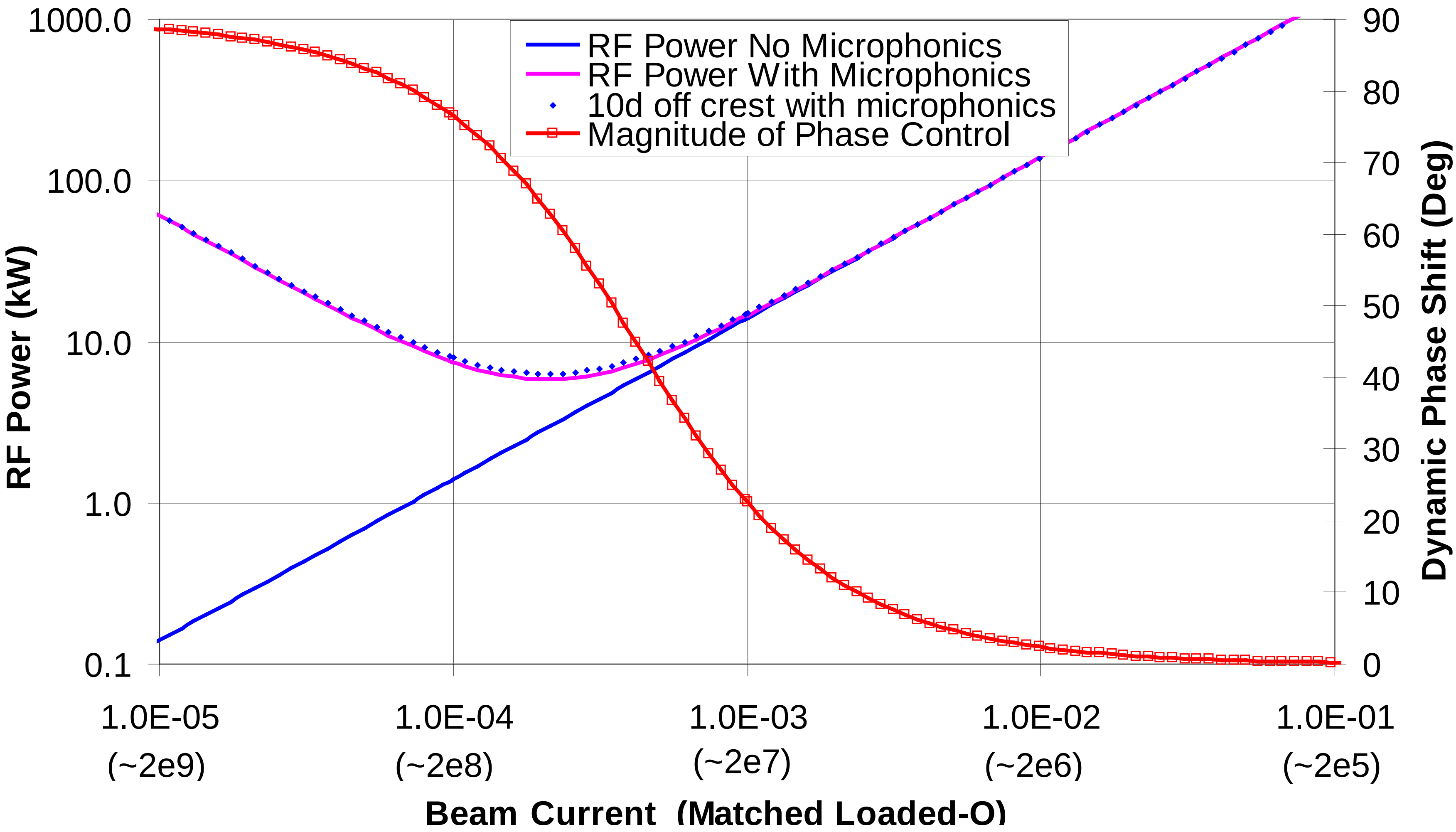
$$P_{Kly} \cong \frac{(\beta+1)\,L}{4\beta\, Q_L(r/Q)}\left\{\left(E + I_0 Q_L(r/Q)\right)^2\right\}$$

$$\psi_{Kly} \cong \arctan\left(\frac{2Q_L \dfrac{\delta f}{f_0} E}{E + I_0 Q_L(r/Q)}\right)$$

$$Q_L matched \cong \frac{E}{I(r/Q)}$$

- Beam at or near on crest
- Power to beam is much greater than wall losses.
- Microphonics control power small compared to beam power
- Matched condition when cavity reflected power is zero and all klystron power goes into the beam.

RF Power and Phase Control Requirements as a Function of Matched Condition Loaded-Q



For this example gradient = 20 MV/m, CEBAF upgrade cavity, microphonics equal 15 Hz peak

Case 2 Complete Energy Recovery

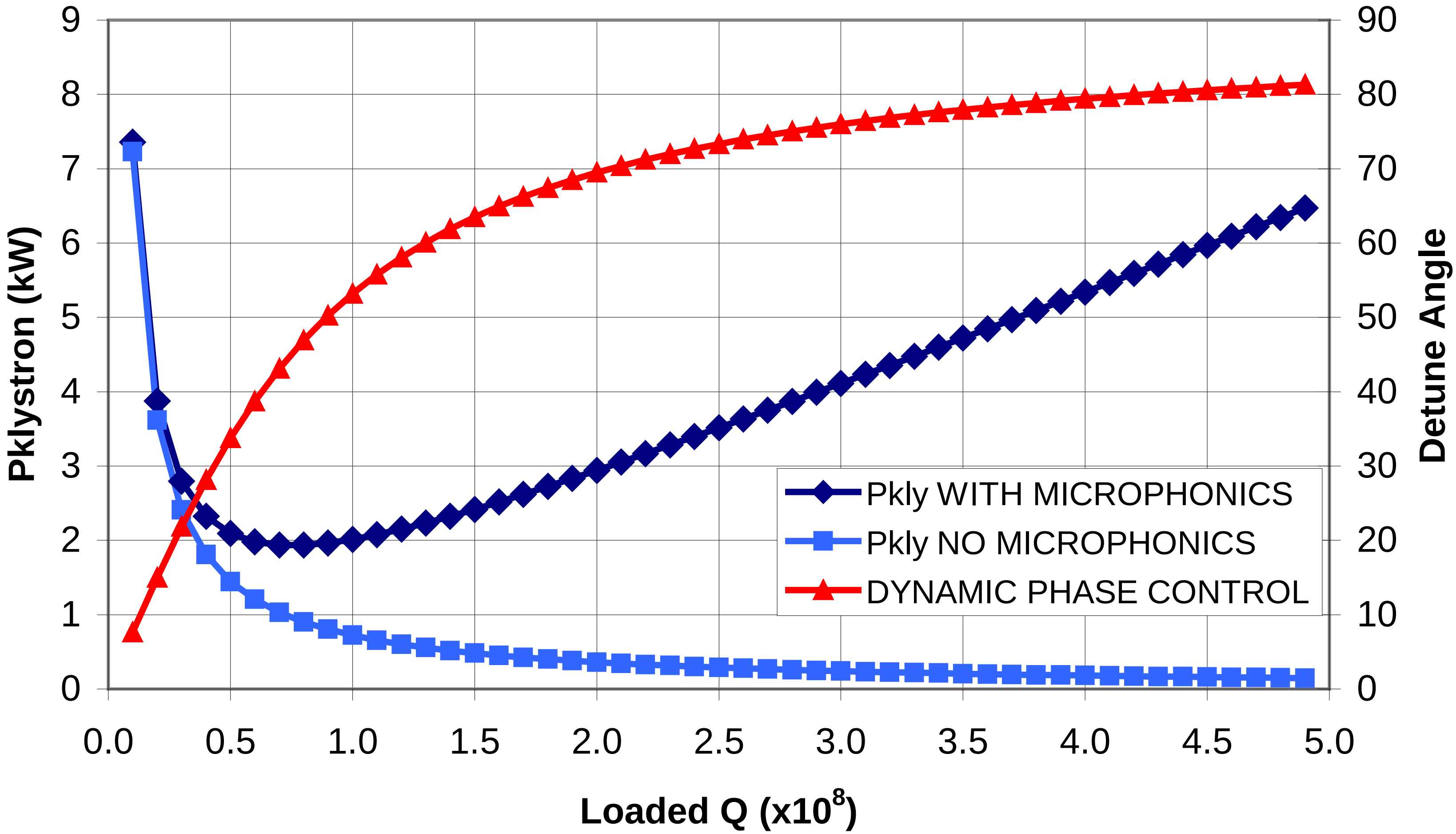
$$P_{Kly} = \frac{(\beta+1)L}{4\beta\, Q_L\, (r/Q)} \left\{ \left(E + \cancelto{0}{I_0} R_C \cos\psi_B\right)^2 + \left(2Q_L \frac{\delta f}{f_0} E + \cancelto{0}{I_0} R_C \sin\psi_B\right)^2 \right\}$$

$$P_{Kly} = \frac{(\beta+1)EL}{4\beta\, Q_L\, (r/Q)} \left(1 + \left(2Q_L \frac{\delta f}{f_0}\right)^2\right)$$

$$\psi_{Kly} = \arctan\left(\frac{2Q_L \frac{\delta f}{f_0} E + \cancelto{0}{I_0} Q_L (r/Q)\sin\psi_B}{E + \cancelto{0}{I_0} Q_L (r/Q)\cos\psi_B}\right) = \arctan\left(2Q_L \frac{\delta f}{f_0}\right)$$

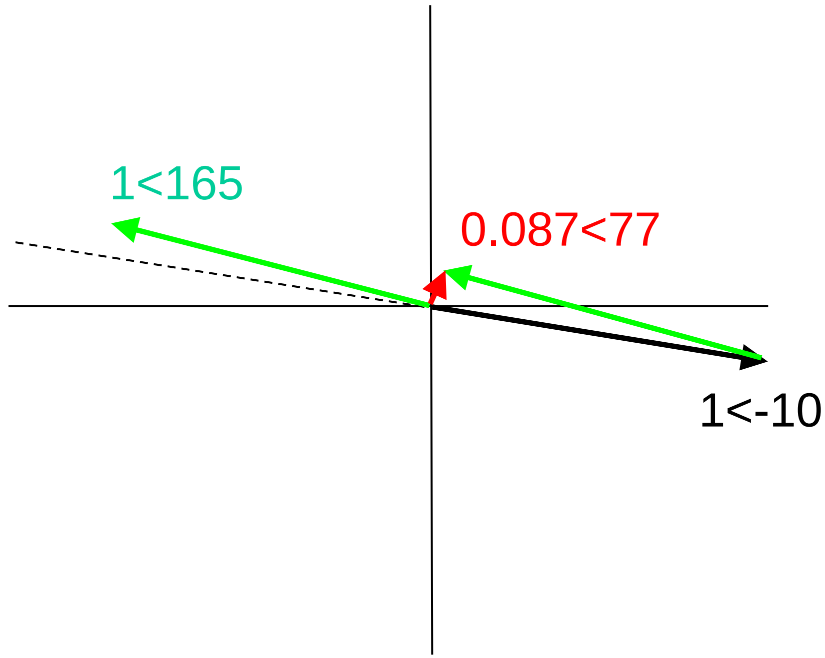
- Net beam current equals zero
- Possible to run at very high loaded Q values
- Note above loaded Q's above 5×10^8 β is no longer >> 1 and must be accounted for.
- Microphonic Control becomes critical.

Klystron and Phase Control Requirements as a Function of Loaded-Q, Ideal Energy Recovery



- Example is a CEBAF 7-cell upgrade cavity operated at 20 MV/m.
- Microphonics 10 Hz-peak excursion in frequency.

2-Pass Beam Incomplete Energy Recovery



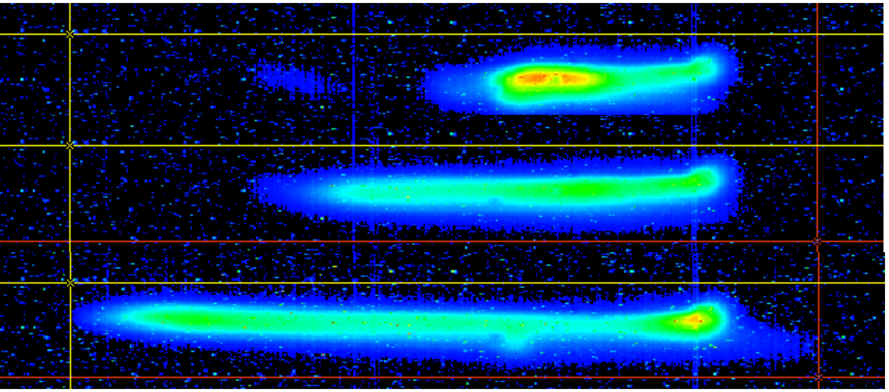
Incomplete Energy Recovery

$$P_{Kly} = \frac{(\beta+1)L}{4\beta\, Q_L\,(r/Q)}\left\{(E + I_0 R_C \cos\psi_B)^2 + \left(2Q_L \frac{\delta f_D}{f_0} E + I_0 R_C \sin\psi_B\right)^2\right\}$$

$$\psi_{Kly} = \arctan\left(\frac{2Q_L \frac{\delta f_D}{f_0} E + I_0 R_C \sin\psi_B}{E + I_0 R_C \cos\psi_B}\right)$$

- All terms of the power and phase equations now apply.
- In the case where the beam is close to 180º out of phase with each other the resultant beam current is near 90º off crest.
  - A substantial fraction of the power takes the form of “reactive” power
  - There is substantial phase variation in the klystron power.
- The cavity tuners respond such that the reactive power effects are short term in nature.

Why Would Anyone Have Incomplete Energy Recovery?



Synchrotron Light from Second Arc JLAB FEL

No Lasing

Weak Lasing

Strong Lasing

Increase in Energy →

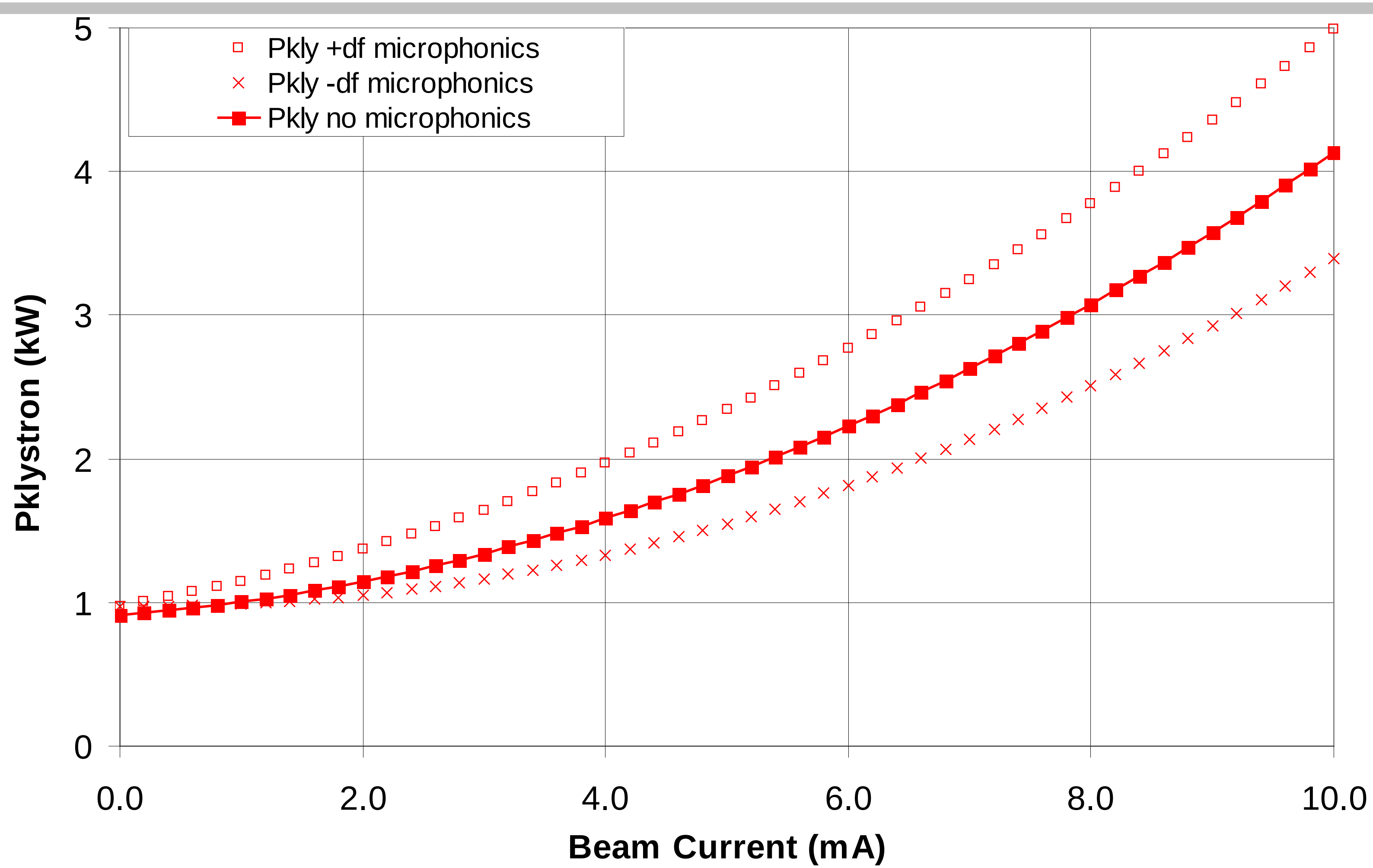
Intentionally (An Example)

- When an FEL lases the energy of the exhaust beam changes in energy as shown above.
- This translates to a change in the path length and thus a phase shift in the second pass beam.
- In the JLAB FEL we have to do energy compaction on both the first and second pass beam. The first for bunch compression for improved lasing. The second so that we can comply with the energy acceptance of the dump bend.

Unintentionally

- Because you do not get the phase of the second pass beam correct or it drifts.

Theoretical Power Requirement for Two Pass Beam



CEBAF upgrade cavity, E=10 MV/m, QL=2.0e7, peak microphonics = 10 Hz

First pass at -10d, second pass 165d from crest.

The Effects of Cavity Tuning

Our Tuning Algorithm

- In our machine the cavity is tuned with no beam loading such that the forward power is minimized.
- The RF phase difference between the forward power and the field probe power is then considered the reference phase. (For the purposes of this discussion the difference between this phase and the actual value is the detune phase.)
- The detune phase is then monitored and kept as a minimum during operations.

Tuning Effects With Off Crest Beam Loading

$$\psi_{Kly} = \arctan\left(\frac{2Q_L \dfrac{\delta f_D + \delta f_S}{f_0} E + I_0 R_C \sin\psi_B}{E + I_0 R_C \cos\psi_B} \right) \xRightarrow{\text{Tuning}} 0$$

δf_D is the dynamic detuning, i.e. microphonics

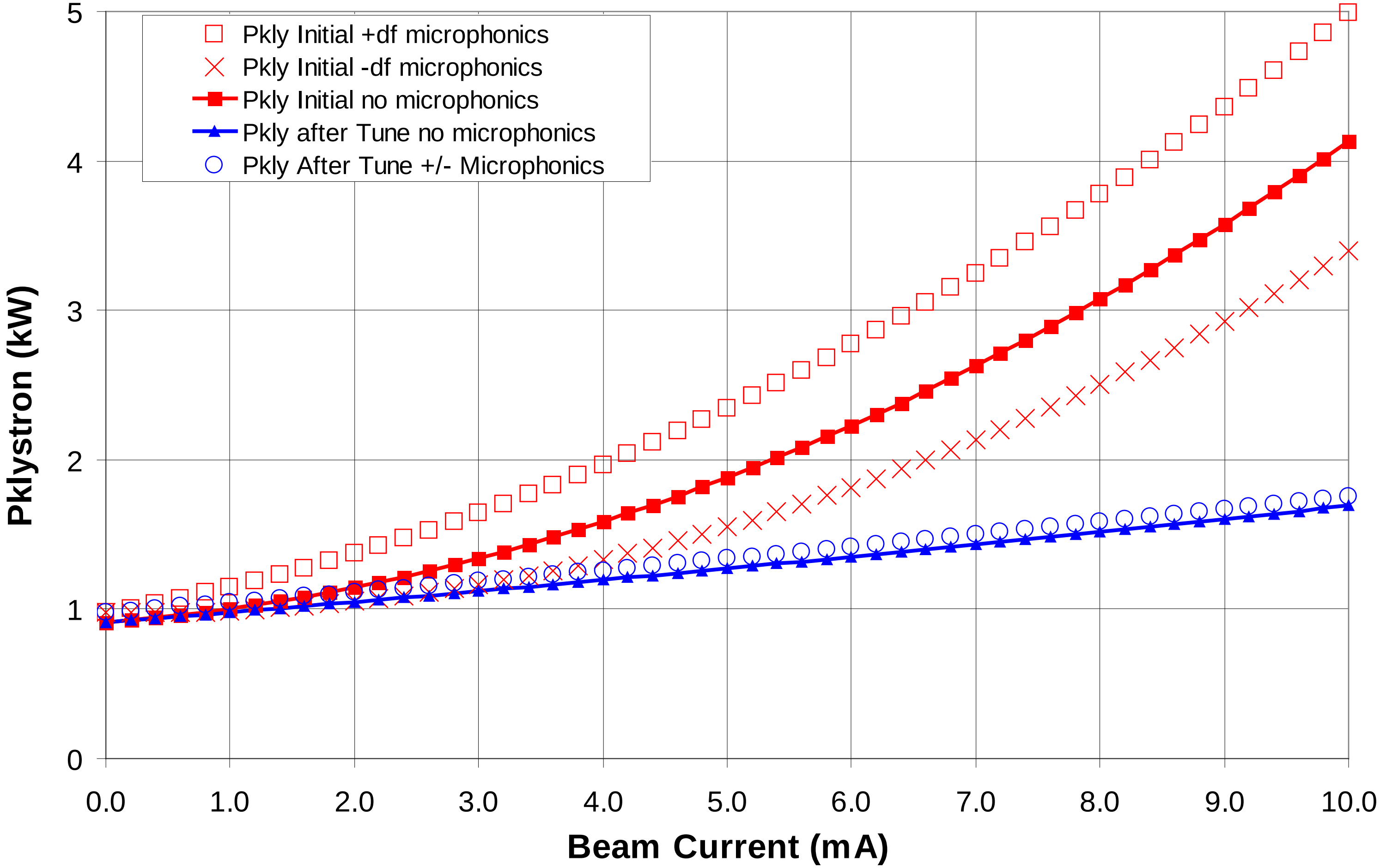
δf_S is the static detuning, i.e. the mechanical tuner driven by tuner alogrithm

$$\delta f_S = -\frac{f_0 I_0 R_C \sin\psi_B}{2Q_L E}$$

Substituting this in leads to the following (after tuning)

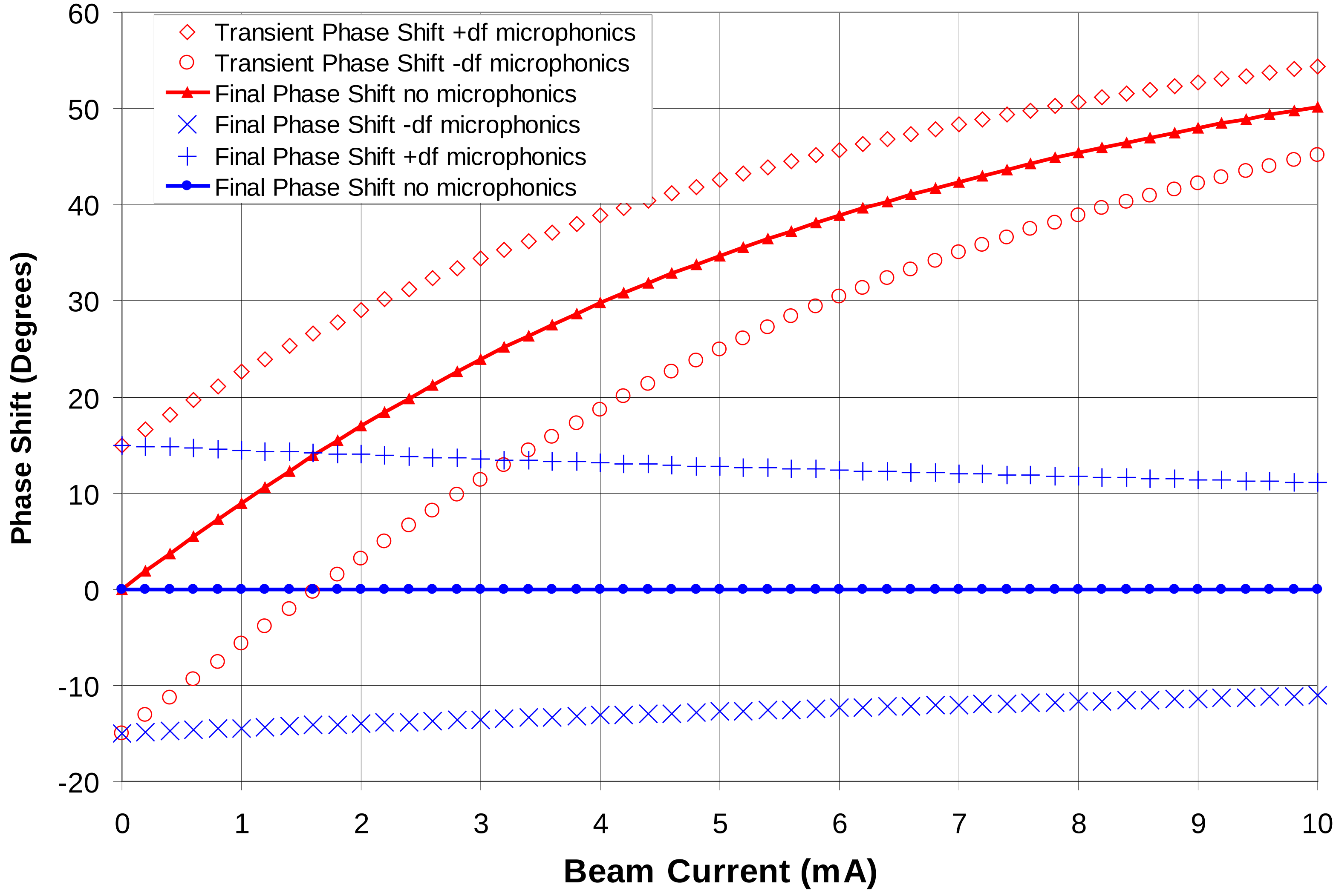
$$P_{Kly} = \frac{(\beta+1)L}{4\beta\, Q_L (r/Q)} \left\{ \left(E + I_0 Q_L (r/Q)\cos\psi_B\right)^2 + \left(2Q_L \frac{\delta f_D}{f_0} E\right)^2 \right\}$$

Theoretical Power Requirement for Two Pass Beam Including Tuning Effects

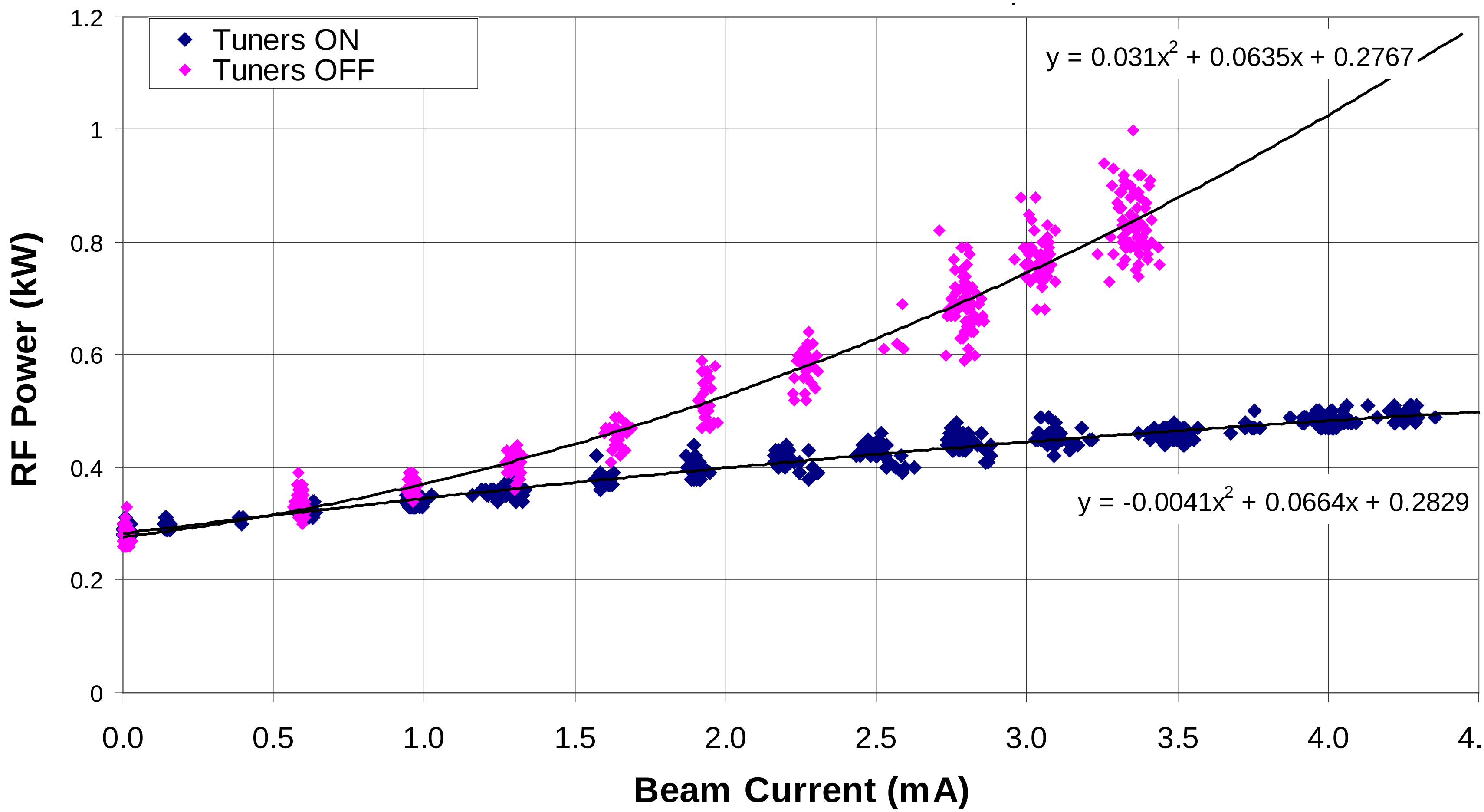


CEBAF upgrade cavity, E=10 MV/m, QL=2.0e7, peak microphonics = 10 Hz
First pass at -10d, second pass 165d from crest.

Theoretical Dynamic Phase Control Requirement for Two Pass Beam Including Tuning Effects



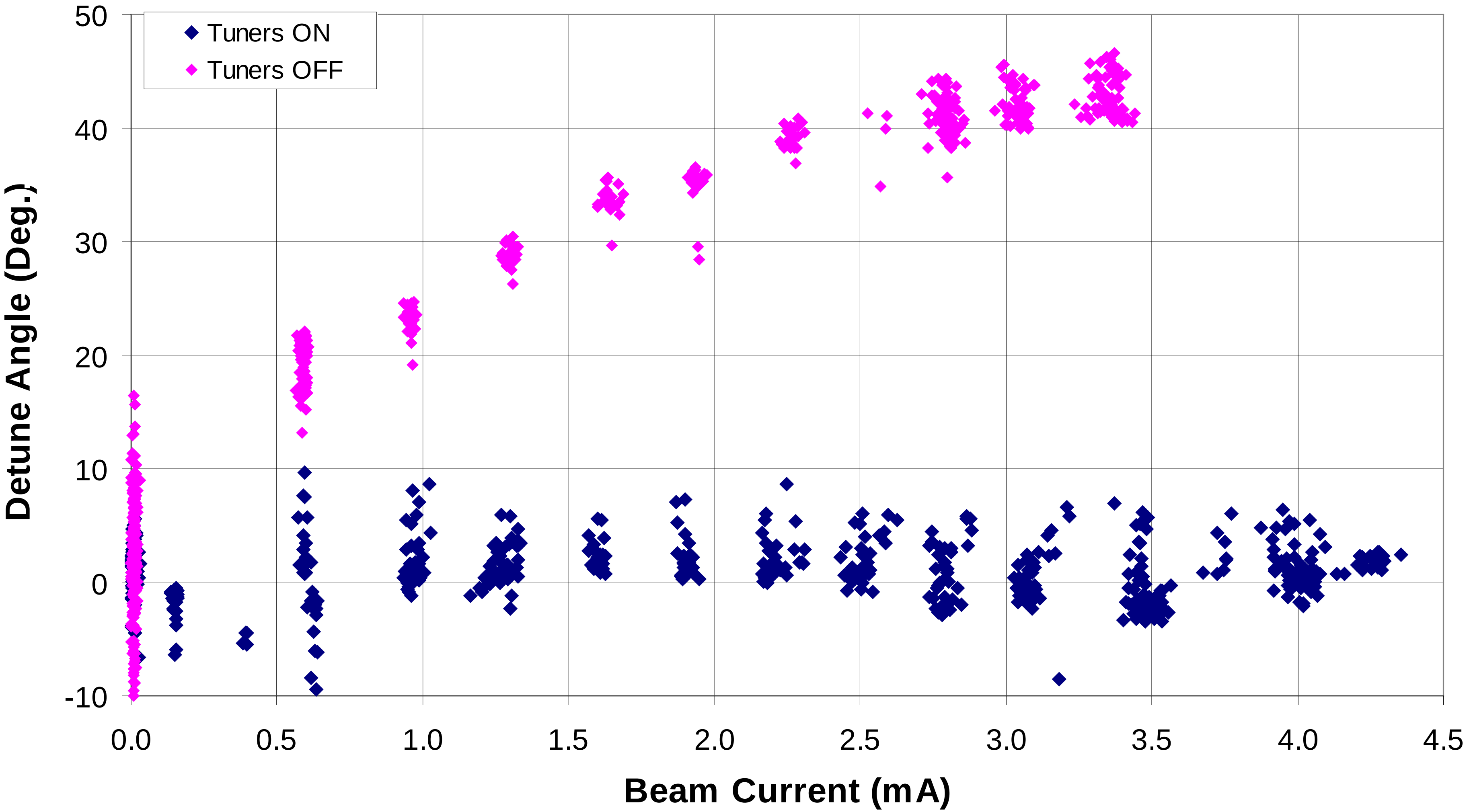
Real Data From FEL3-5 Forward Power



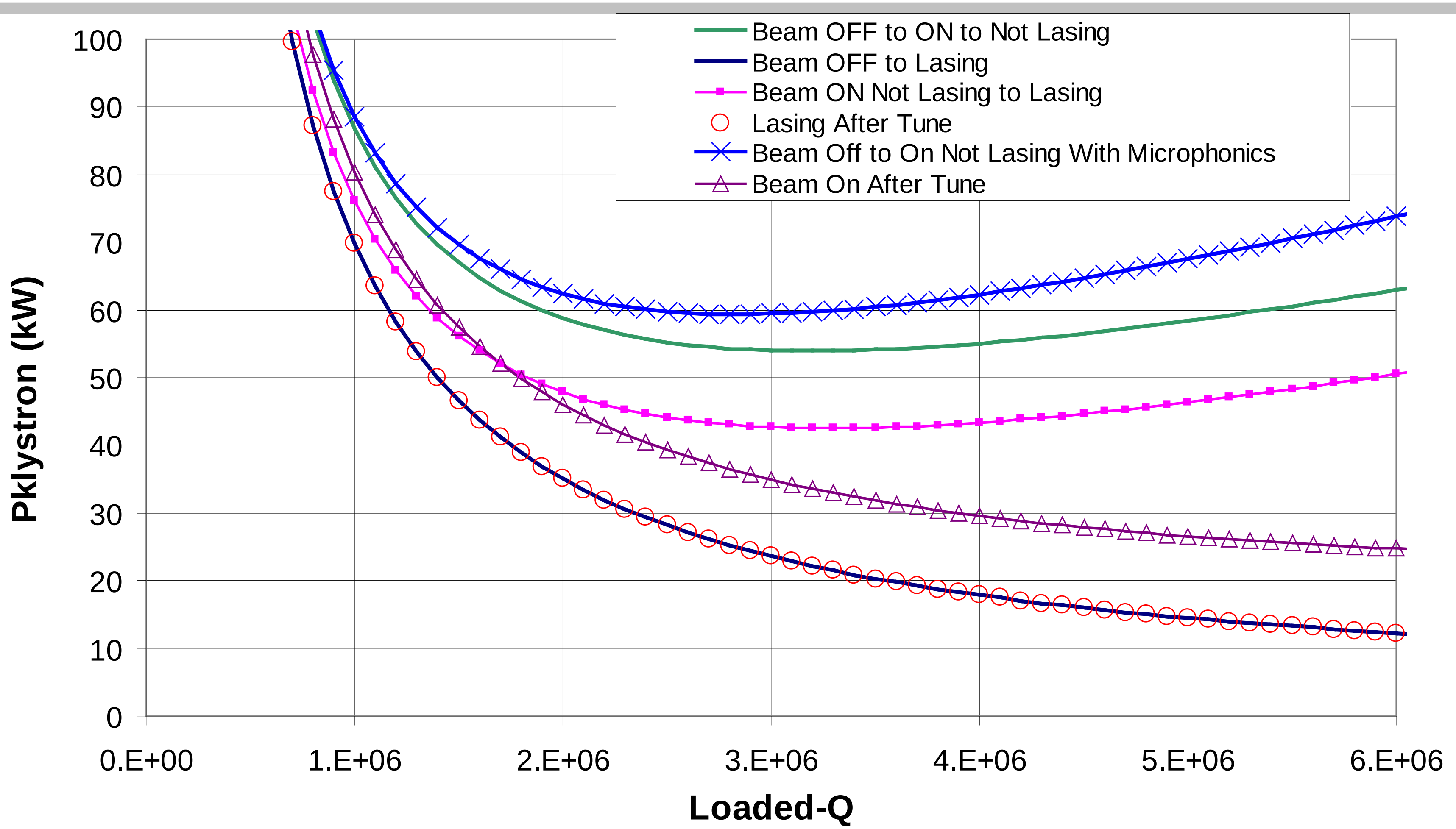
E=5.6 MV/m, QL=2.1e7, RF power calibration ~20% but linear

First pass beam -10d second pass beam not well known.

Real Data From FEL3-5 Detune Phase

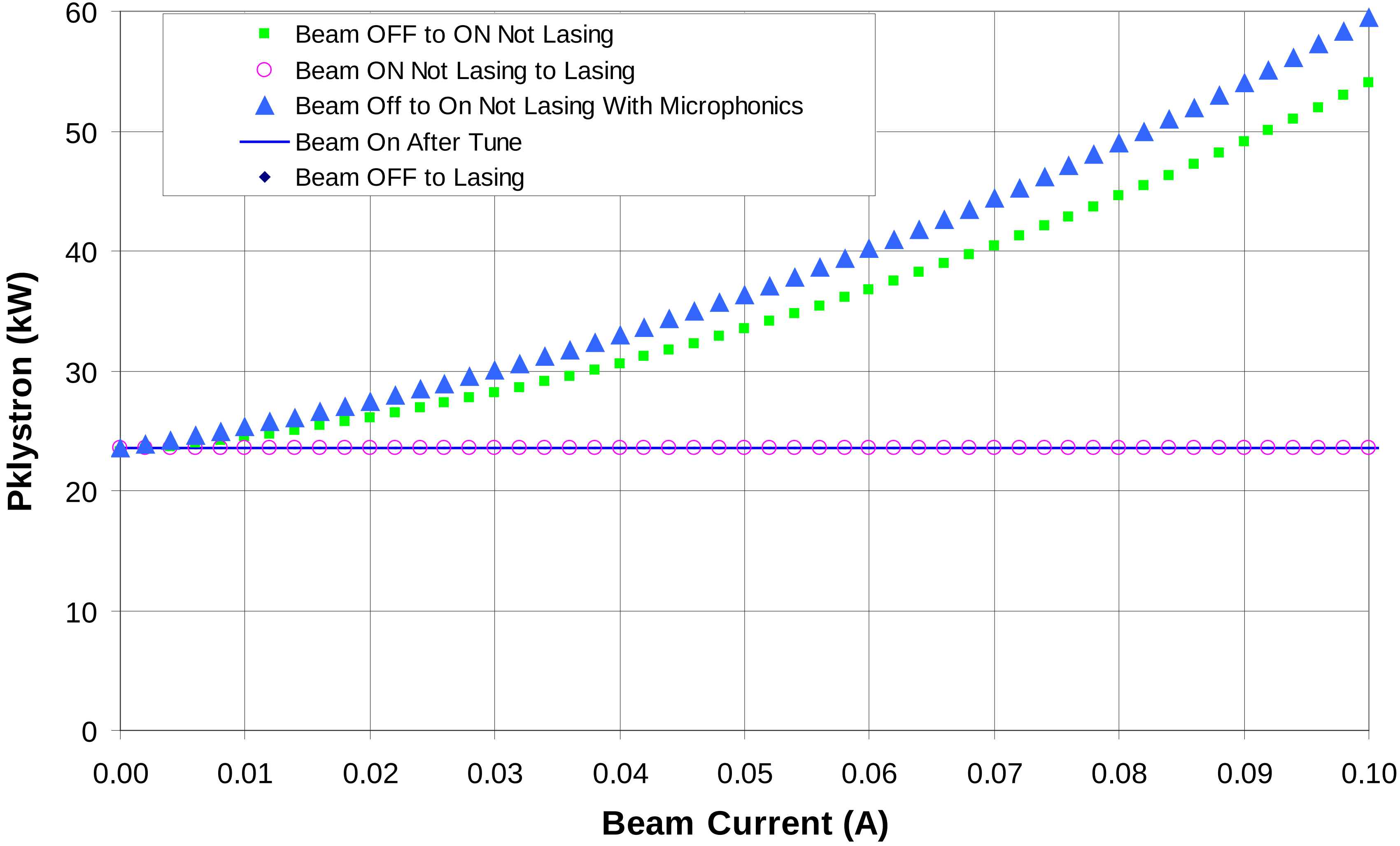


100 kW FEL Example Loaded-Q Selection



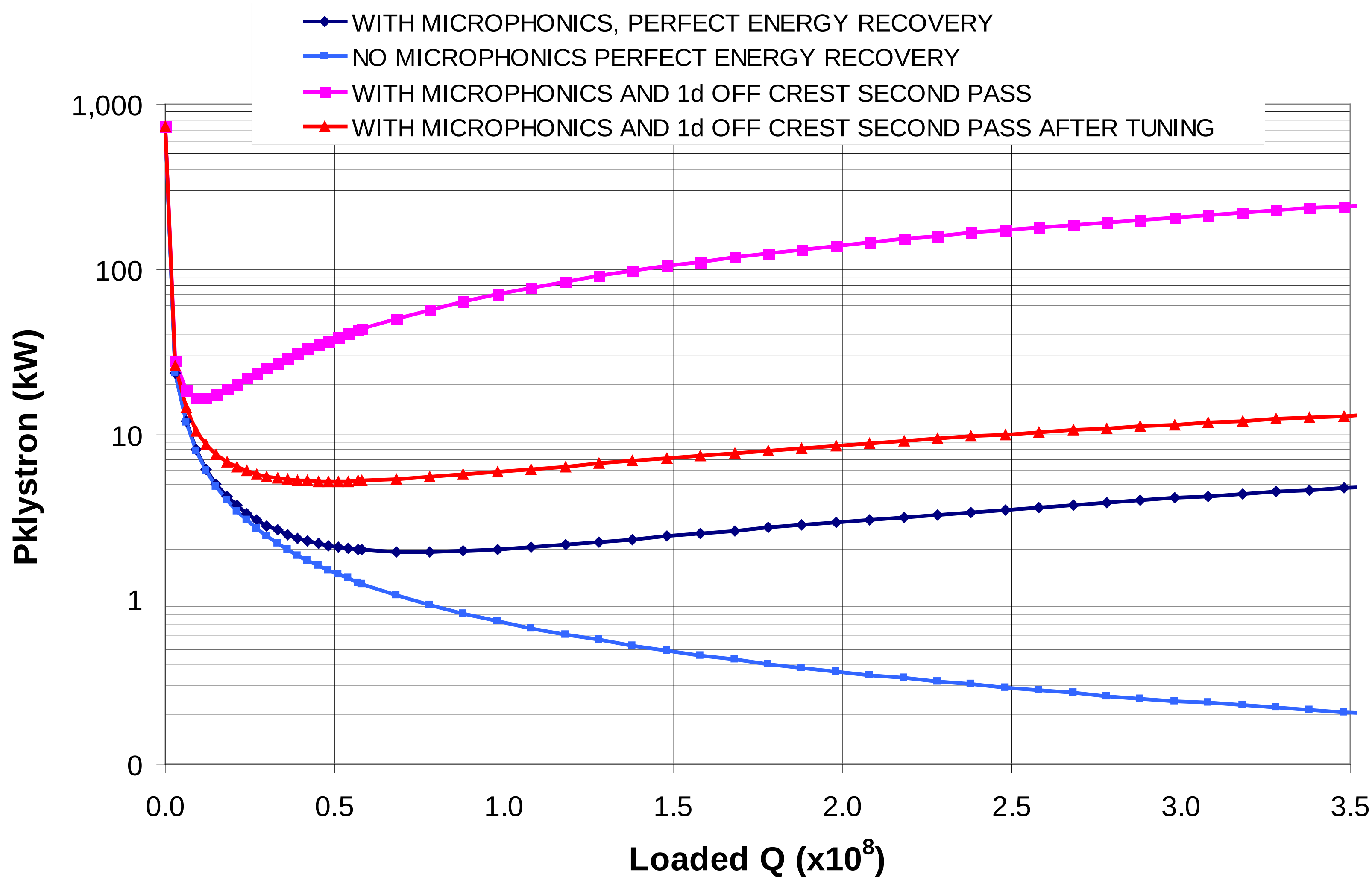
748.5 MHz, 5-Cell, (r/Q)=1000, 17 MV/m, E=16.7 MV/m, first pass phase -10d, second pass phase lasing 165d, not lasing 168. Resultant beam Not Lasing 5.2mA at 76.5d

100 kW FEL Pkly and Phase vs Current



QL=3e6, dF=15 Hz,

Effect of 1d of Phase Slip on 100 mA Cavity Designed for Perfect Energy Recovery



7-Cell, 1500 MHz, 20 MV/m, dF=10 Hz, (r/Q)=960 Ω/m

Conclusions

- Dynamic loading due to incomplete energy recovery is an issue for all machines
- Some machines it is due to unintentional missmatch of second pass beam
- Some machines it is due to intentional missmatch due to changing beam conditions.
- Dynamic loading would be difficult to completely control using fast tuners, etc.
- Many systems will be effected by this.
  - LLRF system
  - Klystron selection
  - Fundimental Power Couplers
  - Machine design and prudent selection of phase parameters is important.
- Tools need to be implemented to measure this effect at low or pulsed current.