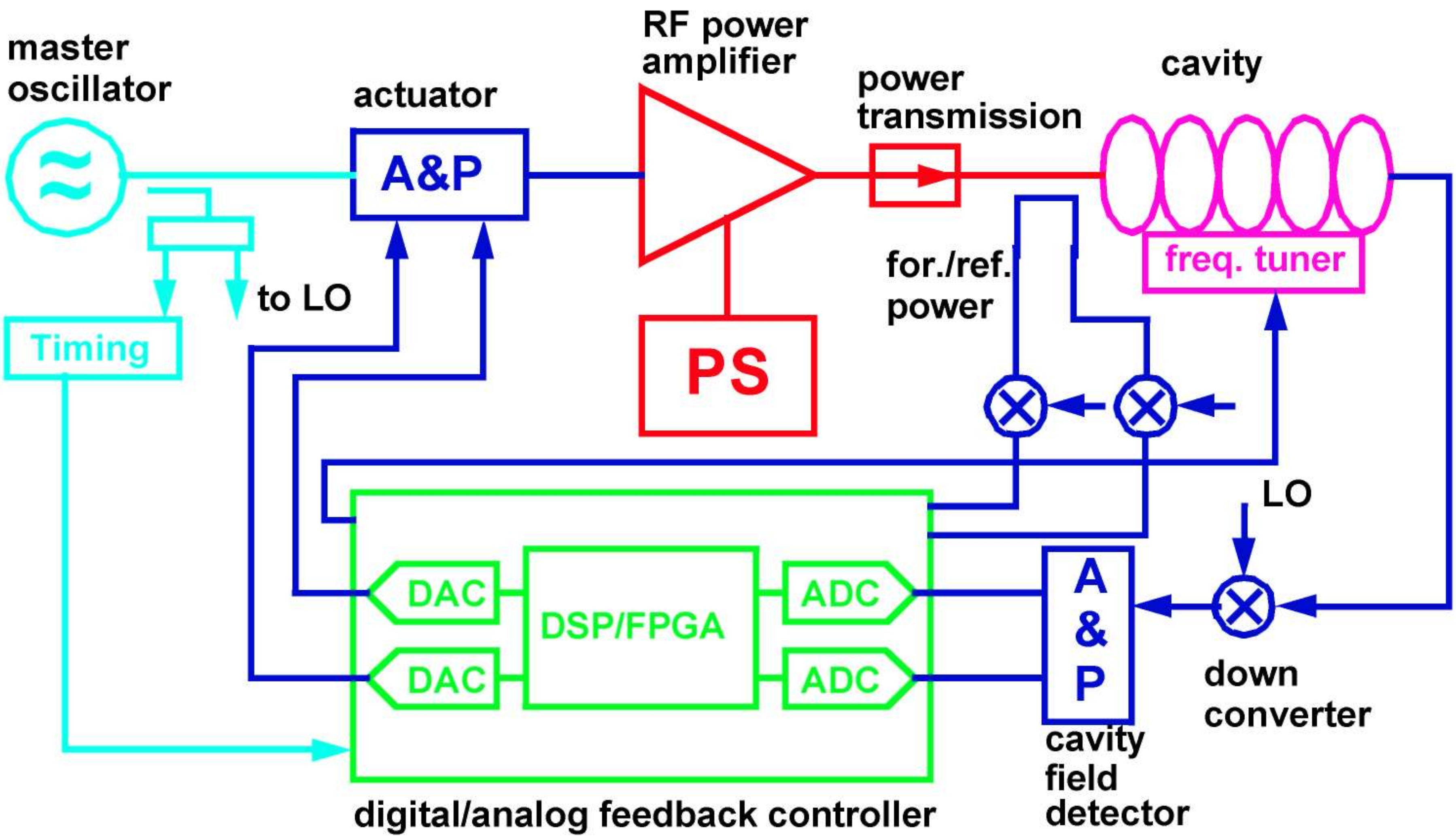
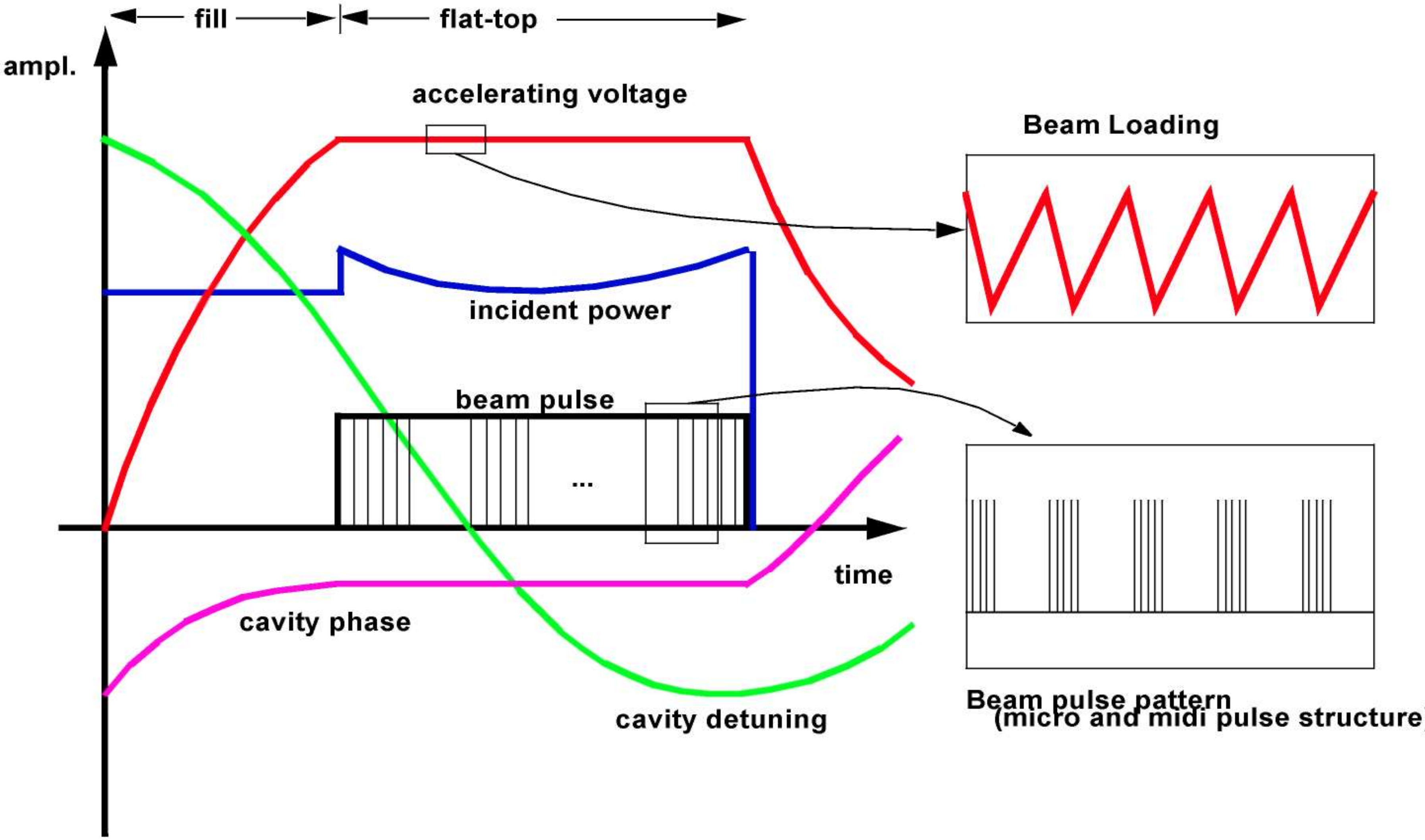
# Power Requirements for RF Control

S. Simrock, DESY
S. Michizono, KEK
B. Chase, FNAL

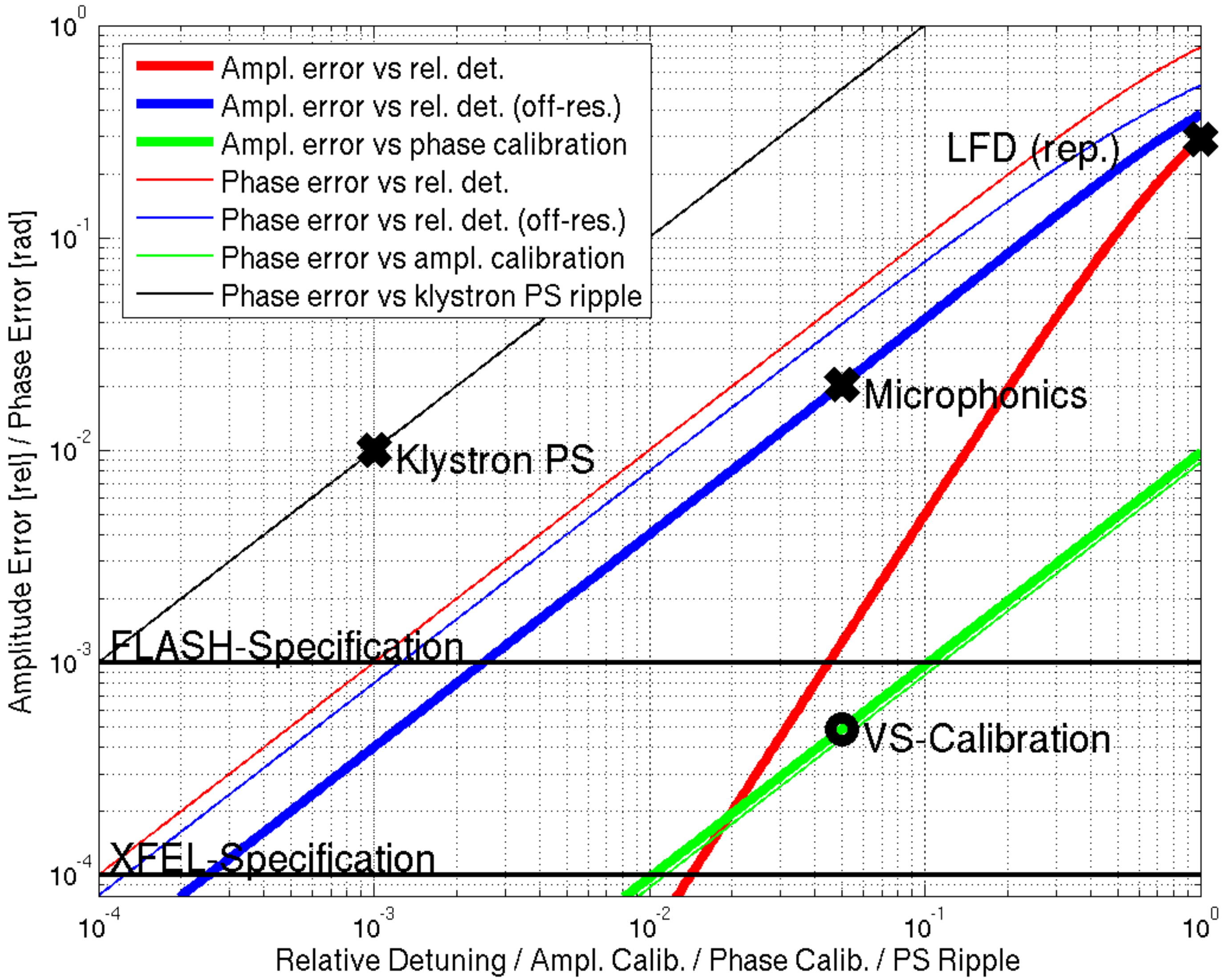
# RF System Architecture (Simplified)



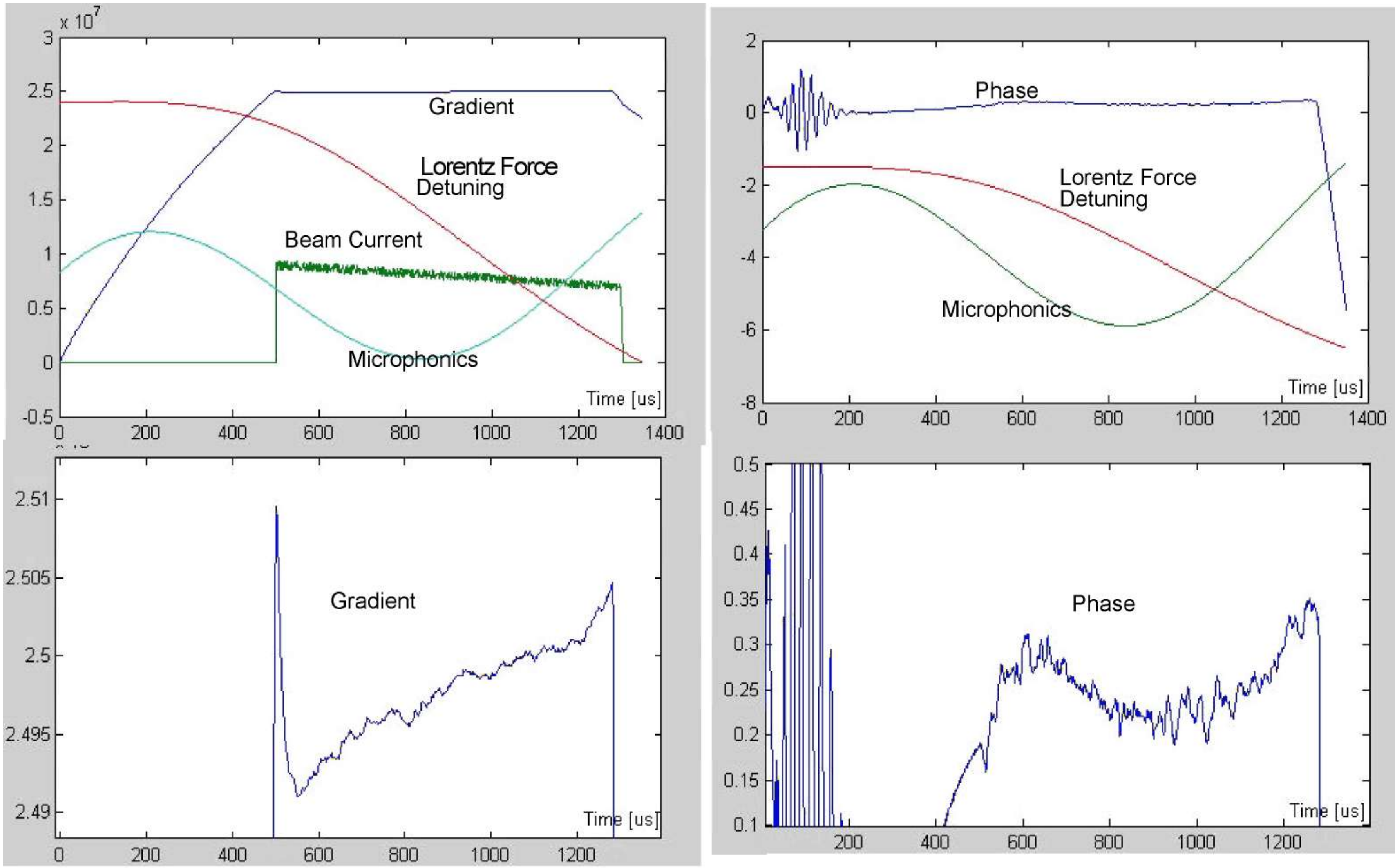
# Typical Parameters in a Pulsed System



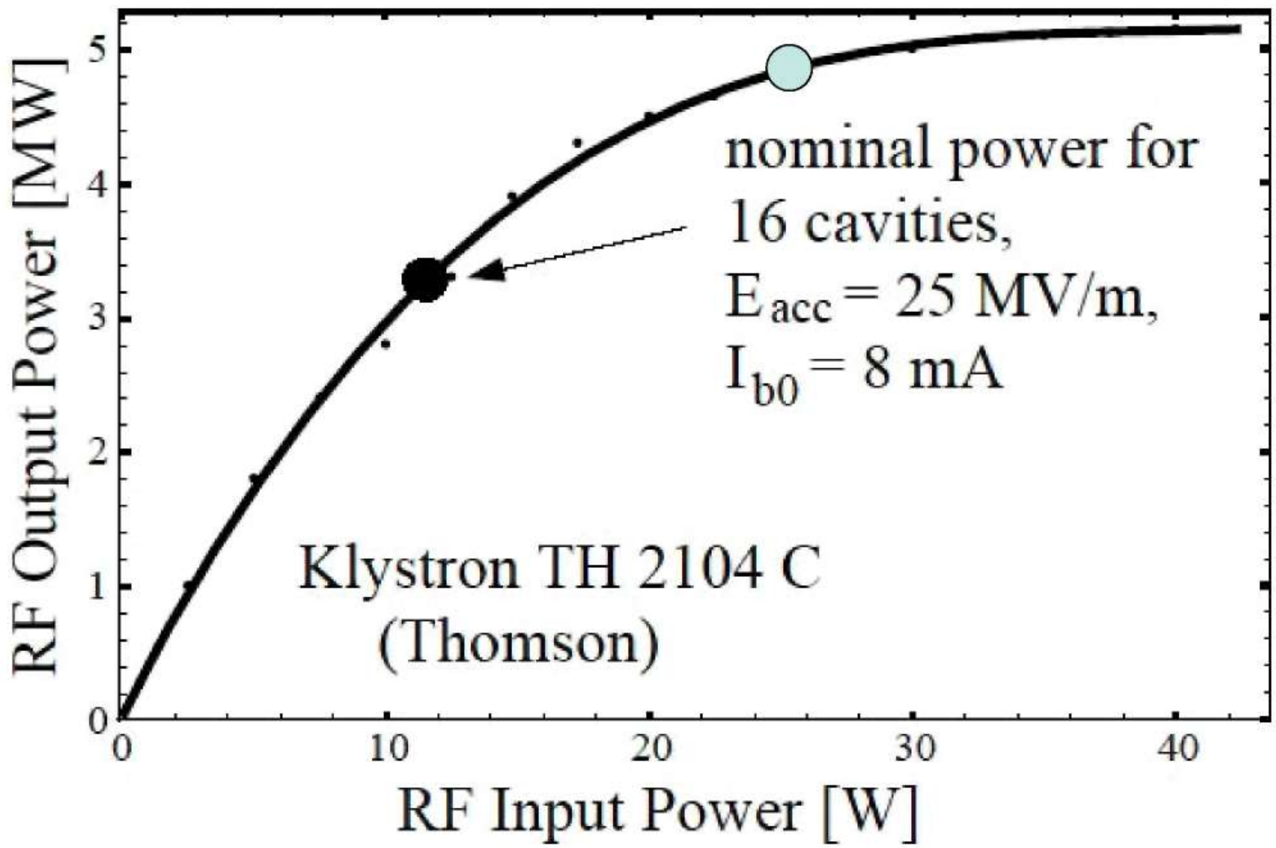
# Sources of Field Perturbations



# RF Field Regulation (Simulation)

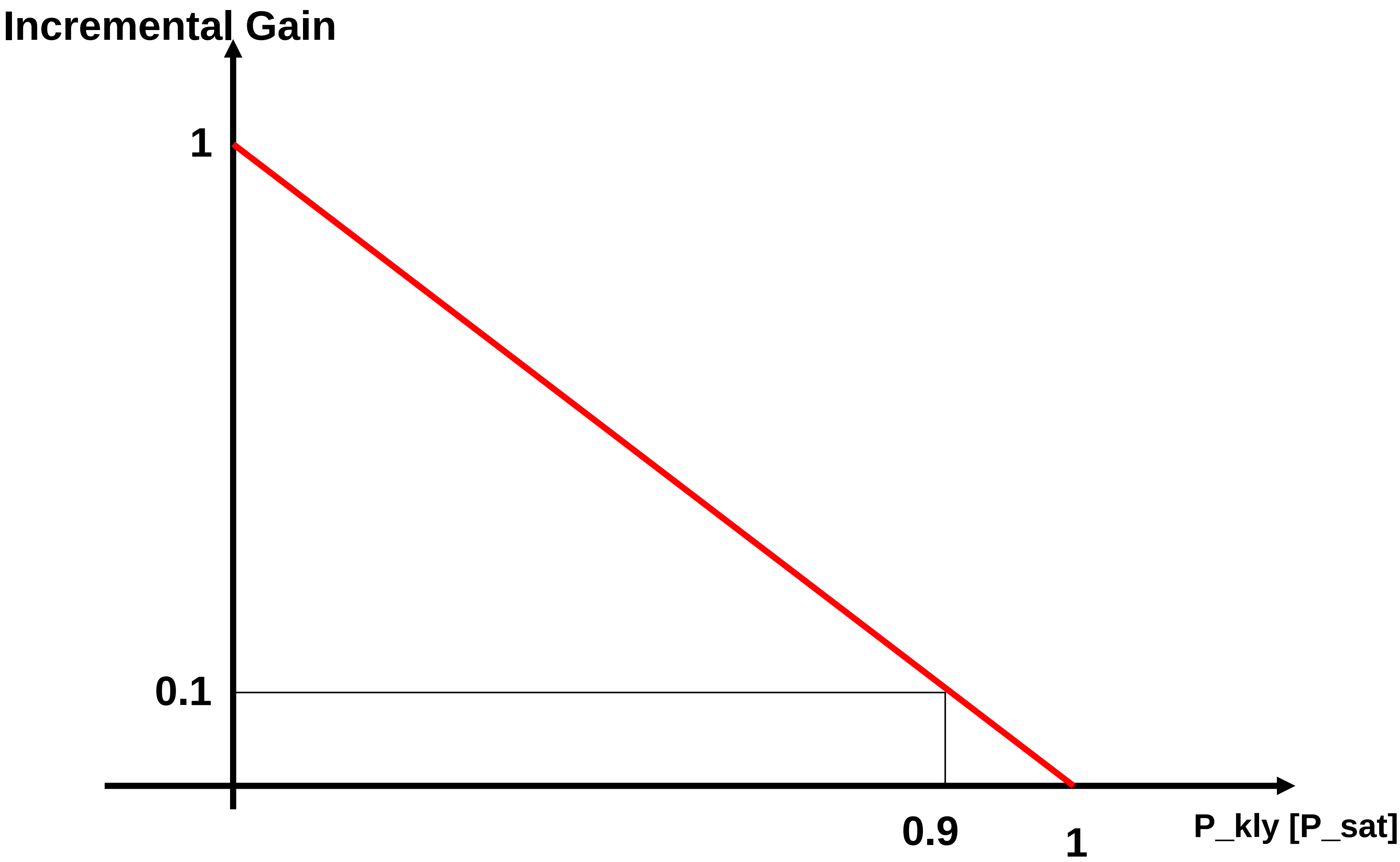


# Typical in/out at 5 MW klystron



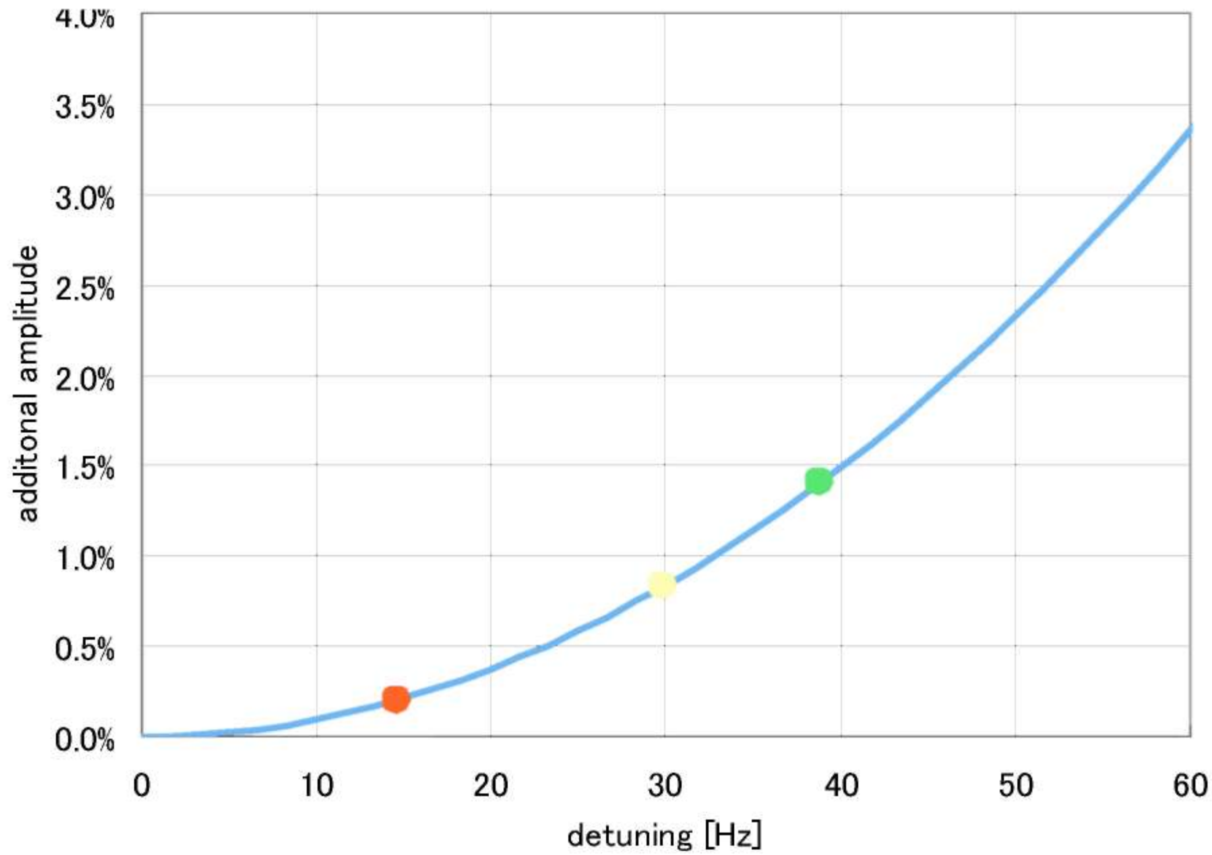

Klystron saturation en live of the 5 MW klystron TH 2104 C made bv Thomson {TTF klystron). The power of the output *RF* signal is plotted versus the input RF signal. The cathode voltage is 126 kV and the current 95 A.

# Incremental Gain



# Additional Power as function of detuning

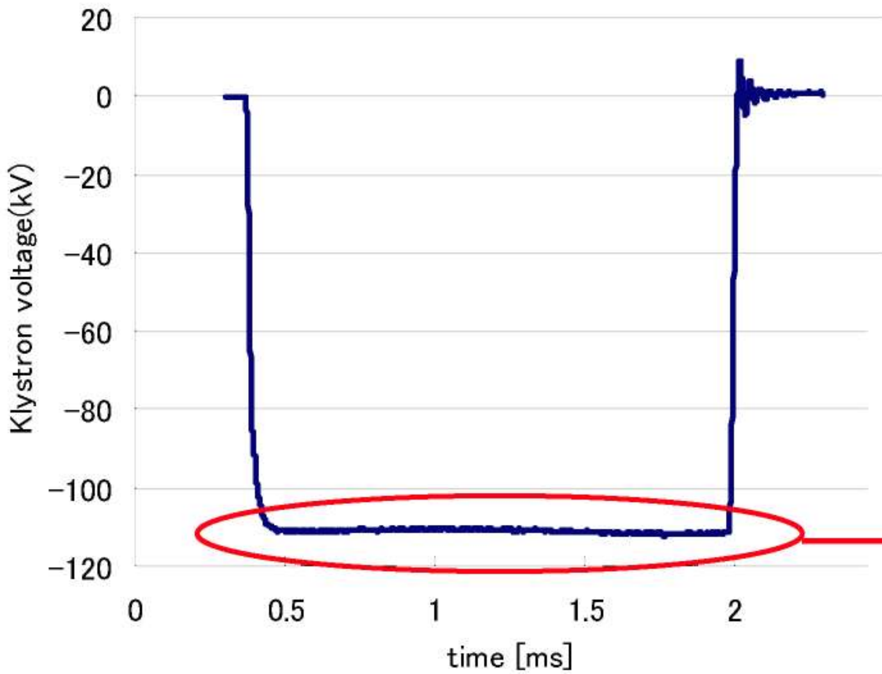
$$P_g = \frac{V_{cav}^2}{\left(\frac{r}{Q}\right) Q_L} \frac{1}{4} \left( \left[ 1 + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \cos \phi_b \right]^2 + \left[ \frac{\Delta f}{f_{1/2}} + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \sin \phi_b \right]^2 \right) \qquad (3.46)$$

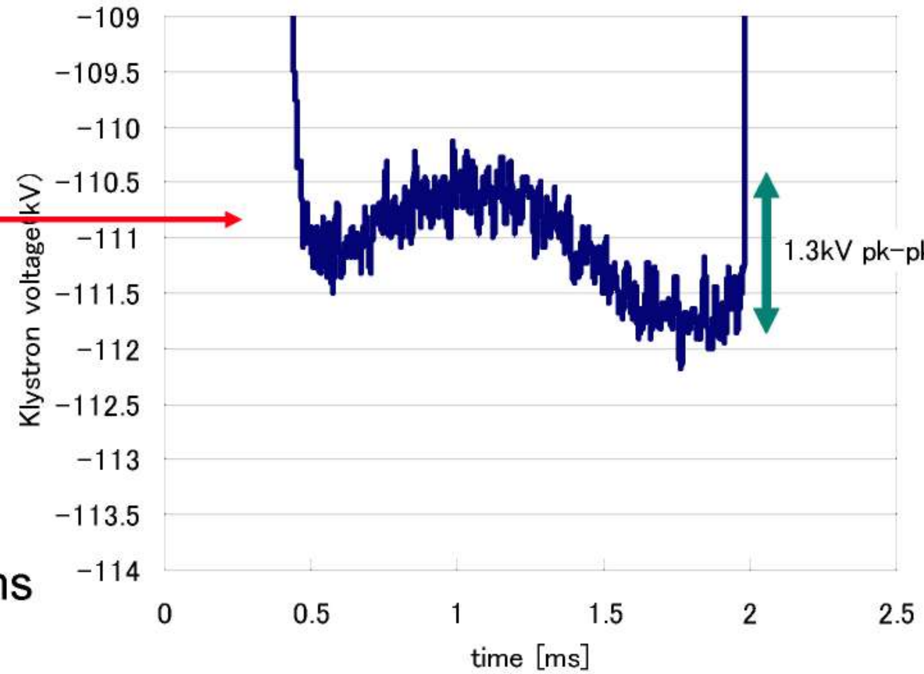



Detuning control <15Hz will be necessary for the 0.2%rms compensation.

# Flatness of Modulator Voltage

Present KEK' s bounce modulator has a flatness of 1.3 kV (1.2% pk-pk, 0.2%rms). If the amplitude overhead becomes 3%, requirements for voltage stability is 0.16%rms.




Assumption:
Pout~uVmod^2.5
RF amplitude~ Vmod^1.25
0.2%rms (amp.) ->0.2/1.25=0.16%rms

# RF Power Budget

| | Voltage loss | Power loss | Available Power (MW |
|---|---|---|---|
| | | | |
| **High Level RF Loss Factors** | | | |
| Maximum Klystron Output Power | | 0,0% | 10,00 |
| De-rating of klystron for end of life time | | 5,0% | 9,50 |
| Modulator Ripple Spec = 1% (Often worse) | 1% | 2,5% | 9,26 |
| Waveguide and circulator losses | | 8,0% | 8,52 |
| Power loss due to cavity gradient variation | | 2,0% | 8,35 |
| Parameter variation | 1,0% | 2,0% | 8,18 |
| | | | |
| **Low Level RF Loss Factors** | | | |
| Peak power headroom | 1,0% | 2,0% | 8,02 |
| Dynamic Headroom | 2,0% | 4,0% | 7,70 |
| Beam current fluctuations of 1% | 2,0% | 4,0% | 7,40 |
| Detuning errors of 30 Hz | 1,0% | 2,0% | 7,25 |
| Klystron drive noise sidebands | 1,0% | 2,0% | 7,11 |
| | | | |
| **Beam Power Requirments** | | | |
| Power Required for 9.5ma @ 33.5 MV/m | | | 0,330344 |
| Power for 26 cavities | | | 8,59 |
| | | | |
| **Excess Power Headroom** | | | (1,48) |

**Courtesy: Brian Chase, Shin Michizono**

# RF Power Budget

| | Adolphsen (20061106) | | | Chase (20061116) | | | Toge (20061120) | | | FNAL (20061122) | | | MICHIZONO (20061124) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Voltage loss | Power loss | Available Power (MW) | Voltage loss | Power loss | Available Power (MW), when 5% derating of klys is considered | Voltage loss | Power loss | Available Power (MW), when no derating of klys is considered | Voltage loss | Power loss | Available power (MW) | Voltage loss | Power loss | Available power (MW) |
| **Power Source and High Level RF Loss Factors** | | | | | | | | | | | | | | | |
| Maximum Klystron Output Power | | 0,0% | 10 | | 0,0% | 10,00 | | 0,0% | 10,00 | | 0,0% | 10,00 | | 0,0% | 10,00 |
| De-rating of klystron for end of life time | | 0,0% | 10 | | 5,0% | 9,50 | | 0,0% | 10,00 | | 10,0% | 9,00 | | 0,0% | 10,00 |
| Modulator Ripple Spec = 1% (Often worse) | | 0,0% | 10 | 1% | 2,5% | 9,26 | 1% | 2,5% | 9,75 | 1% | 2,5% | 8,78 | 1% | 2,5% | 9,75 |
| Waveguide and circulator losses | | 7,0% | 9,3 | | 8,0% | 8,52 | | 10,0% | 8,78 | | 8,0% | 8,07 | | 8,0% | 8,97 |
| Power loss due to cavity gradient variation | | 0,0% | 9,3 | | 2,3% | 8,33 | | 2,3% | 8,57 | | 2,3% | 7,89 | | 2,3% | 8,76 |
| Parameter variation | | 0,0% | 9,3 | 0,5% | 1,0% | 8,24 | 0,5% | 1,0% | 8,49 | 0,5% | 1,0% | 7,81 | 0,0% | 0,0% | 8,76 |
| **Total HLRF Loss and Available Power** | | **7%** | **9,3** | | **18%** | **8,24** | | **15%** | **8,49** | | **22%** | **7,81** | | **12%** | **8,76** |
| **Low Level RF Loss Factors** | | | | | | | | | | | | | | | |
| Peak power headroom | | | | 1,0% | 2,0% | 8,08 | 1,0% | 2,0% | 8,32 | 1,0% | 2,0% | 7,65 | 2,5% | 5,0% | 8,33 |
| Dynamic Headroom | | | | 3,0% | 5,9% | 7,60 | 3,0% | 5,9% | 7,83 | 3,0% | 5,9% | 7,20 | 0,0% | 0,0% | |
| Beam current fluctuations of 1%pk | | | | | 1,0% | 7,52 | | 1,0% | 7,75 | | 1,0% | 7,13 | | 1,0% | |
| Detuning errors of 30 Hz | | | | 1,0% | 2,0% | 7,38 | 1,0% | 2,0% | 7,59 | 1,0% | 2,0% | 6,99 | 1,0% | 3,0% | 8.55/8.71 |
| parameter variation | | | | | | | | | | | | | | 4,0% | |
| Klystron drive noise sidebands | | | | 1,0% | 2,0% | 7,23 | 1,0% | 2,0% | 7,44 | 1,0% | 2,0% | 6,85 | 0,0% | 0,0% | 0,00 |
| **Total LLRF Loss (linear sum) and Available Power** | | **10,9%** | **8,29** | | **12,3%** | **7,23** | | **12,3%** | **7,44** | | **12,3%** | **6,85** | | | |
| **Total LLRF (square sum) and Available Power** | | **10,9%** | **8,29** | | **6,7%** | **7,69** | | **6,9%** | **7,90** | | **6,7%** | **7,29** | | **5,1%** | **5,19%** |
| **8-8-8 Configuration Case** | | | | | | | | | | | | | | | |
| Power (kW) Required for 9.5ma @ 35 MV/m | | | 0,345135 | | | 0,345135 | | | 0,345135 | | | 0,345135 | | | 0,345135 |
| Power (MW) for 24 cavities | | | 8,28 | | | 8,28 | | | 8,28 | | | 8,28 | | | 8,28 |
| Simulated rf power (MW) for 24 cavities | | | | | | | | | | | | | | | |
| **Excess Power Headroom (when linear sum of LLRF losses assumed)** | | | **0,00** | | | **(1,05)** | | | **(0,84)** | | | **(1,44)** | | | **(0,38)** |
| **Excess Power Headroom (when square sum of LLRF losses assumed)** | | | **0,00** | | | **(0,59)** | | | **(0,38)** | | | **(1,00)** | | | |
| **Peak Gradient (MV/m) at 9.5mA with 24cavities, when zero power headroom is assumed for linear-sum LLRF loss** | | | **35,01** | | | **30,54** | | | **31,45** | | | **28,94** | | | |
| **Peak Gradient (MV/m) at 9.5mA with 24cavities, when zero power headroom is assumed for square-sum LLRF loss** | | | **35,01** | | | **32,50** | | | **33,38** | | | **30,79** | | | |

Note: Lower power per cavity -> higher Ql and longer fill and decay times
This requires a longer modulator pulse and higher cryo loading
30 Hz detuning errors are the sum of microphonics and Lorentz force detuning. (Even if microphonics=0, we have to compensate 97% of LFD)

# Typical Power Overhead for Various Accelerators

- FLASH(TTF): 20% (in amplitude)
- XFEL: 28% (in amplitude) (5.2 MW/10 MW)
- SNS: =~25% (in amplitude)
- J-PARC (NC): >10% (in amplitude)

# Prerequisites for RF Control

1. Need stable llrf feedback gain of at least 100 for sufficient error suppression
2. Feedback gain must be (almost) independent of klystron output power to
   a. guarantee sufficient error suppression independent of klystron power
   b. guarantee feedback loop stability independent of klystron power
3. Klystron phase should be (almost) independent from klystron power to
   a. Ensure that no significant phase error are induced
   b. Loop phase is constant to guarantee feedback stability
4. Power headroom required for exception handling
   Example: Quench in cavity can require up to 10% extra power to maintain vector-sum
5. Power headroom to compensate for klystron aging or protection
6. The required klystron incremental gain and phase stability can be achieved by
   a. Operation sufficiently far below saturation
   b. Operation with klystron linearization scheme

Note: Does not work well if less than 10% from klystron saturation

# Comments

1. Without klystron linearization feedback gain will be lowered by factor of 3 if headroom is reduced from 10% to 3% => residual error goes up by factor of 3. Response time of feedback is 3 times longer.
   - a. Simply increasing gain is not possible since robustness of feedback loop will be sacrificed.
2. Feedback gain becomes extremely sensitive to rf power (function of beam loading, gradient and cavity detuning, klystron HV) =>
   - Frequent loss of regulation
   - Potential instabilities in feedback loop due to large loop gain changes
3. LLRF cannot react well to loss in gradient with low rf power overhead. Recovery is very slow.
4. Exception handling capability is severely sacrificed with low power overhead.
5. No gradient spread can be accepted. All cavities must operate within about 1% of same gradient. Power distribution must be very precise (about 1%) to allow for optimal use oif each cavity.

1. Various subsystems must be extremely stable to guarantee field stability
   a. Klystron voltage to << 1 k (i.e. desired 100) during flat-top
   b. Beam loading to << 1 %
   c. Lorentz force detuning must be held < 10 Hz with piezo tuner

- NOTE: With klystron linearization the linearity can be improved by about a factor of 10.
  - Unfortunately the compensation degrades rapidly close to saturation (robustness, noise). While it works well at 10% from saturation it does not at 3%.
  - Klystron linearization requires very reproducible operating parameters
  - Klystron linearization will be sacrificed by broadband noise which increases linear with 1/headroom. Noise power bands will be clipped by peamp. and klystron leading to severe signal distortion and amplitude to phase coupling

# Conclusion

If the rf power headroom is reduced to 3% one **dramatically increases the risk of loosing several percent in maximum energy and/or beam current capability (= luminosity)** because the rf system will not operate with the required stability at the desired linac operating gradient and beam current.

In simple words: **The rf system will not work (well) with an rf power overhead of 3% but it will work well with an overhead of 10-20 %.**