Whither will SL21 and NL11 Take Us?

CASA Seminar

February 14, 2003

Outline

- Maximum Energy Reach
- Maximizing Operating Envelop
  - Operational considerations
  - Limits on maximum current
    - Optimum Q
    - RF power
    - Detuning
- Putting it all together
- Summary

Disclaimer

Most technical details have been checked by other folks.

- **I'll blame <u>them</u> if somebody takes issue with a detail.**

Improved Energy Envelope

SL21:

- This cryomodule was intended to have ~80 MV capability.
  - "70 MV" label was based on what was possible in one of the old 12 GeV Upgrade scenarios
  - Gradient target came from cryogenics budget
- But…….we've got real data to work with now: 82 MV!
- "Old" SL21 delivered 42 MV.
  - Net gain is 40 MV.
  - 40 MV x 5 passes ⇒ 200 MV

<u>Old SL21</u> ⇒ <u>New SL21</u>

"Old" 5.5 GeV ⇒ "New" 5.7 GeV

"Old" 5.7 GeV ⇒ "New" 5.9 GeV

"Old" 5.8 GeV ⇒ "New" 6.0 GeV

Equivalent trip rates

Harwood; CASA seminar; 2/14/034

Improved Energy Envelope (cont'd)

Renascence (NL11):

- 12 GeV planning assumes a minimum on-line performance of 100 MV per cryomodule (17.5 MV/m)
- 10 MV was added to the specification to allow for 10% of the cavities (aggregate) to be off-line. (19.2 MV/m)
- Planning includes having sufficient RF power to support 10% more gradient. (21.2 MV/m)

<u>121 MV is the "top end"</u>

Improved Energy Envelope (cont'd)

Renascence (cont'd)

- "Old" NL11 delivered ~36 MV
  - Gain is 85 MV
  - 85 MV x 5 passes ⇒ 425 MV
- Net from SL21 + NL11 = 625 MV

Old SL21 & NL11 ⇒	New SL21 ⇒	New SL21 & NL11
"Old" 5.1 GeV ⇒	"New" 5.3 GeV ⇒	"New-new" 5.7 GeV
"Old" 5.4 GeV ⇒	"New" 5.6 GeV ⇒	"New-new" 6.0 GeV
"Old" 5.7 GeV ⇒	"New" 5.9 GeV ⇒	"New-new" 6.3 GeV

Caveat

To get the energies listed on the previous slides I have assumed that the cryomodules have been swapped around so that the voltage capabilities of the two linacs are balanced.

Note: they have not been balanced in the past.

Yeah….but……

The numbers on the preceding slides's ignored any limitations from the availability of finite RF power.

In particular, and Hall B notwithstanding, being able to reach 6.3 GeV doesn't buy us much if we can deliver only 1 uA.

We need sufficient rf power to:

1. Drive the beam
2. Provide phase and amplitude control

There must be sufficient power on a cavity-by-cavity basis, i.e one underpowered cavity causes problems.

Let's look at the issues now.

Beam power vs RF Power (I = P/V)

	RF power	5-pass Beam current
SL21 (17.7 MV/m)	5.0 kW	80 uA
	6.5 kW	105 uA
NL11 (21 MV/m)	5.0 kW	70 uA
	6.5 kW	90 uA
	13.0 kW	180 uA

Looks pretty good!

What about control power?

What if there's not enough power?

The cavity phase & amplitude loops lose "lock", then phase and amplitude start to "wander"

- **Amount of "wandering" depends on:**
  - **How "short" we are of having sufficient power**
  - **How long the situation persists.**
- **Beam quality is affected when we lose "lock"**
  - **Energy droops**
  - **Energy spread increases**
  - **Degraded beam quality could cause scraping $\Rightarrow$ BCM trips.**
- **Nb: Cavity doesn't trip off…necessarily.**

Down and Dirty: How much current?

$$I = 2\sqrt{\frac{P}{\frac{R}{Q}Q_L} - \left[\left(\frac{GL}{\frac{R}{Q}}\right)\frac{\delta f}{f}\right]^2} - \frac{1}{Q_L}\left(\frac{GL}{\frac{R}{Q}}\right)$$

Correct iff:
$Q_0 >> Q_{ext}$ &
Beam is on crest

GL = Voltage (gradient * length)

P = RF power

R/Q = cavity shape factor

$\delta f/f$ = how much the cavity's resonant freq. differs from rf freq
= Tuning error = detuning

Q_L = Loaded Q

Must choose an envelop for planning.

f we want to maximize the possible current…….

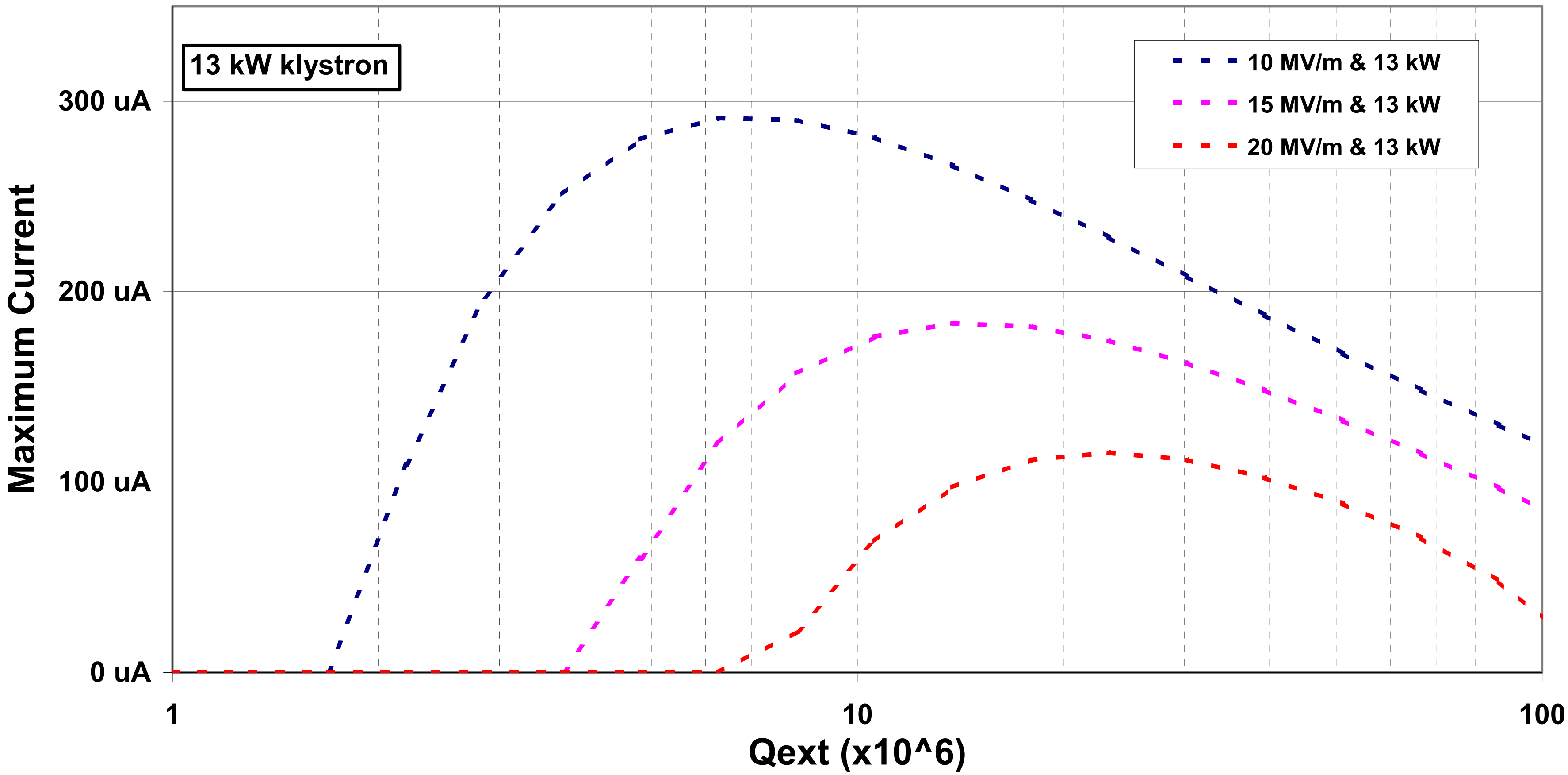
For a given cavity voltage (GL) and cavity shape (R/Q), we increase the maximum current if we:

- Decrease detuning "budget"
  - Constrain the detuning (needs active control of some sort)
  - Decrease headroom (affects beam quality)
- Increase the rf power ($$$)
- Use the optimum Q_L
  - Optimum changes with conditions
  - Historically have used a fixed value
  - Running at optimum requires development and implementation of a way to adjust the Q's remotely

I'll now go thru how each parameter affects things and options for dealing with any limitations.

Optimizing Q_L

There is an optimum Q for each set of operating conditions:



Using a fixed value for Q limits the operating envelop.

Variable Q

Optimum performance can be had if we install a system that gives variable Q.

Possible solutions:

- **Tief's variable reactance idea (needs some R&D)**
  - **Originally conceived for resonance control**
  - **Might be hard to do both Q and resonance control simultaneously**
- **Develop remotely adjustable stub tuners**
  - **We presently use manually adjustable stub tuners to set the Q for "good" cavities. (Adjustment is done with micrometers.)**
  - **Could automate them (add stepper motors?)**
  - **~$15k & ½ M-Y including software and procedures (LH WAG)**
- **?????**

Adjustable Q has other benefits (later in the presentation)

Operational consideration: Turn-on

After a major off-normal event (e.g. CHL trip), the cavities' resonant frequencies can shift so far that normal procedures and software (PTUNE, TUNE22/24/…..) can't "find" them.

- If ya don't know the frequency, ya can't adjust it to the right value.

These procedures presently fail for Q's > 8 x 10^6 and someone has to go out with a network analyzer.

Optimized Q's for SL21 and NL11 are > 2 x 10^7.

Without a change in how we do things, we won't be able to operate at optimum Q.

⇒ Greater power draw at a given current

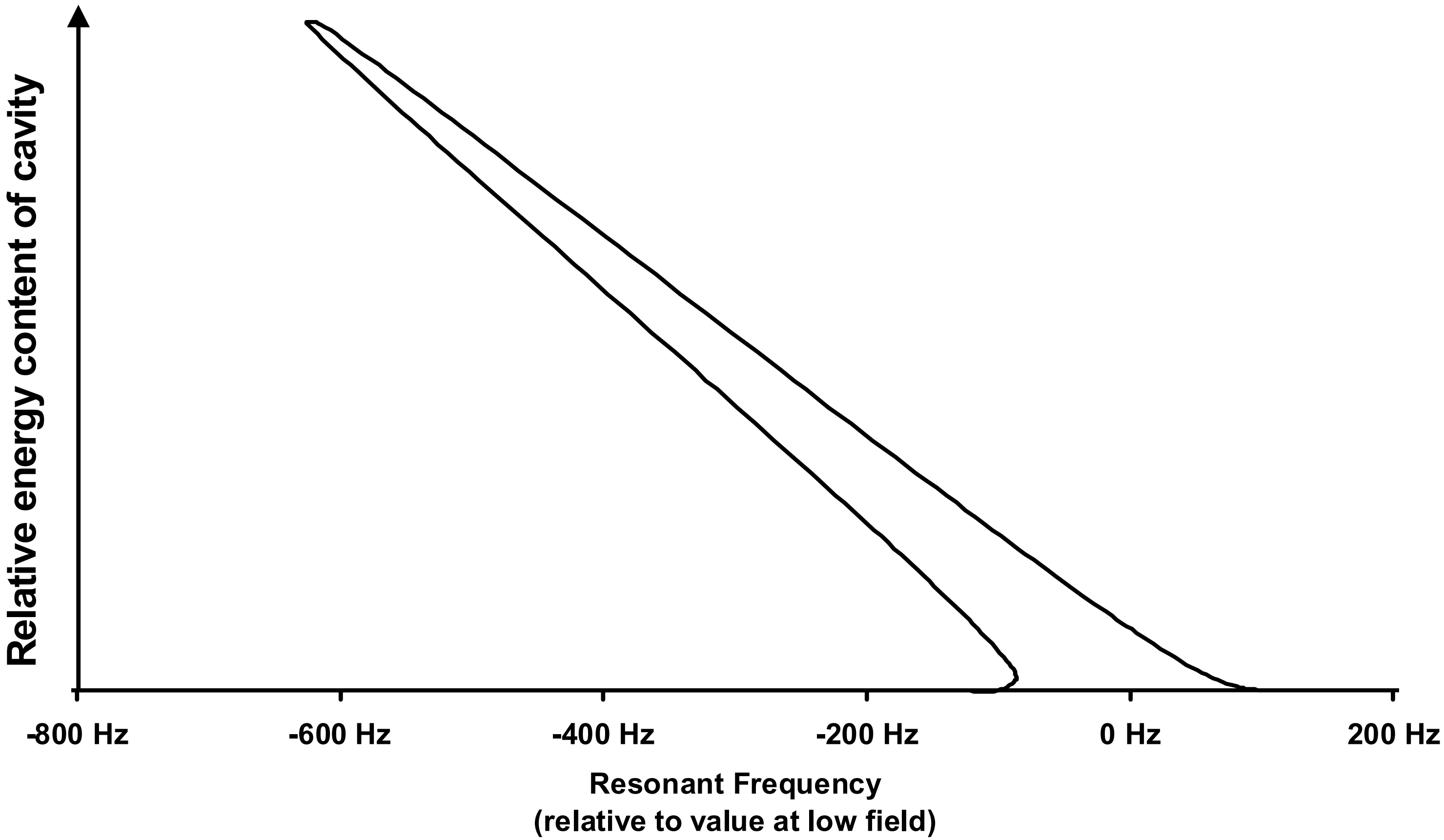
⇒ Less current at a given klystron power

Potential solutions for turn-on problem

1. **Control with a self-excited loop instead of the present generator-driven loop**
   - Not possible with present control module
   - Potentially useful for 12 GeV
2. **Have a way to vary Q_L remotely.**
   - If we do this, then recovering from a CHL crash becomes about as simple as it is now. The process would look something like:
     - Start turn-on as is done now.
     - If "normal" procedures fail, drive the Q's to low Q_L
     - Recover the cavity as now.
     - Return the Q's to the optimized values.
   - Nb: This could also be done on the "really good" 5-cell cavities that are presently limited by the Q< 8 x 10^6 restriction (cost/benefit is likely to be worse than for SL21 or NL11)

Operational considerations: Trip recovery

At 17.7 MV/m and near-optimal Q's, the detuning curve leans substantially.



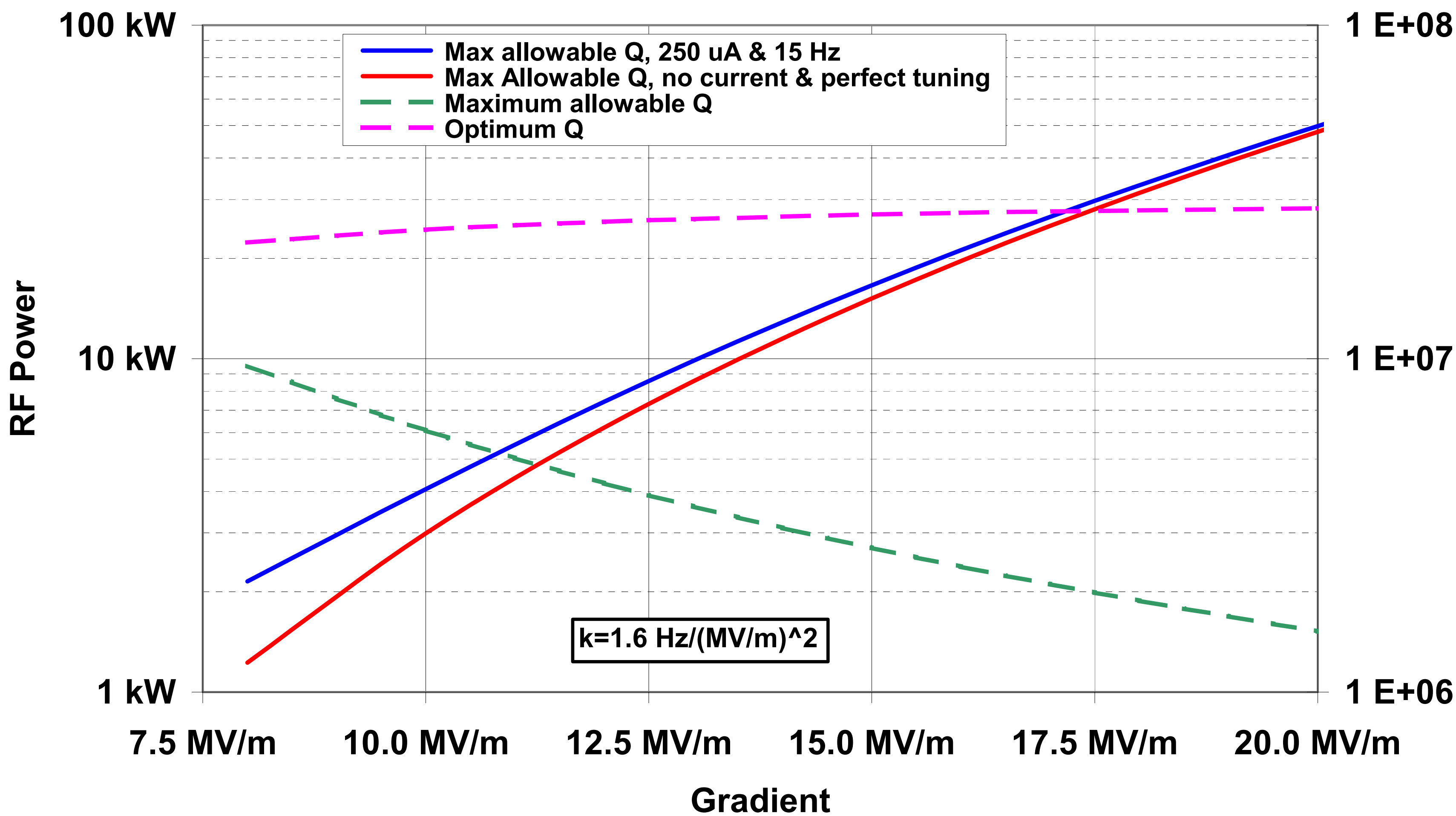
Trip recovery (cont’d)

With the “leaning” detuning curve, we can’t energize the cavity after a trip unless something is done, i.e. shift the resonant frequency.

Options?

As with turn-on, a SEL would solve the problem, but isn’t going to be available for several years.

Trip recovery (cont'd)



Klystron options (above 5 kW)

	Klystron cost (with 2 spares)	HPA cost	Building cost	Total
6.5 kW	0	0	0	0
~~8 kW klystron; "steal" HPA from FEL~~	~~0~~	~~0~~	~~$50k~~	~~$50k~~
~~8 kW klystrons; build new HPA~~	~~0~~	~~$300k + 3 M-Y~~	~~$50k~~	~~$350k + 3 M-Y~~
~~10 kW~~	~~$300k~~	~~$400k + 5 M-Y~~	~~$50k~~	~~$750k + 5 M-Y~~
13 kW	$600k	$400k +5 M-Y	$50k	$1050k + 5 M-Y

LH estimate (Building cost)

FY05-06 AIP funds are an option for more RF power

Detuning

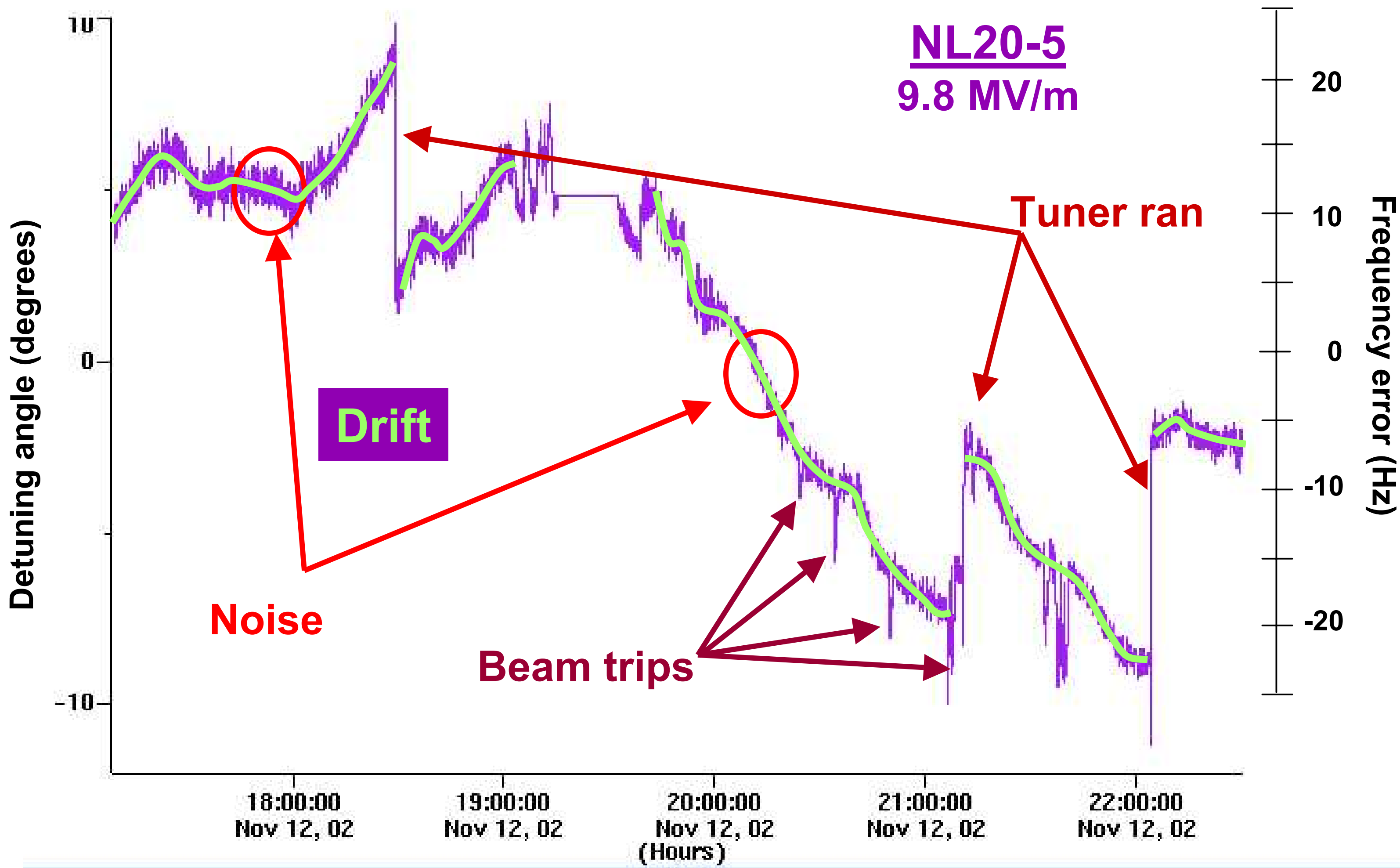
The cavities are never exactly on resonance.

- Helium pressure drifts
- Microphonics
- Tuner limitations
  - Finite lifetime
  - Could induce microphonics

Need a model for before we can predict how much the cavities might be out-of-lock for a given combination of gradient, rf power, and current.

What happens right now?

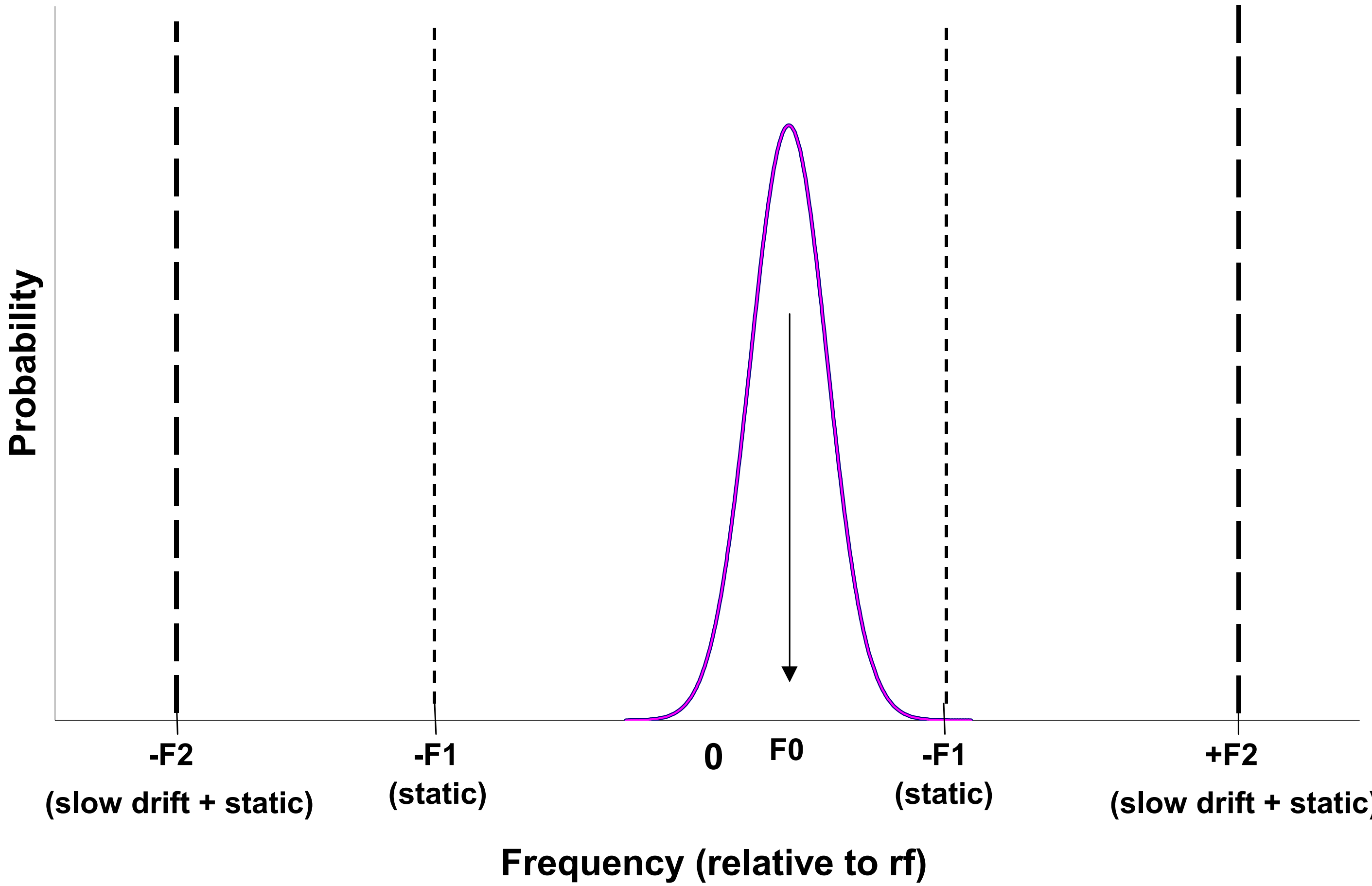
Detuning in Existing Cavities



Detuning Model

Model for detuning vs time:

static (tuner error) + slow drift + microphonics (Gaussian)

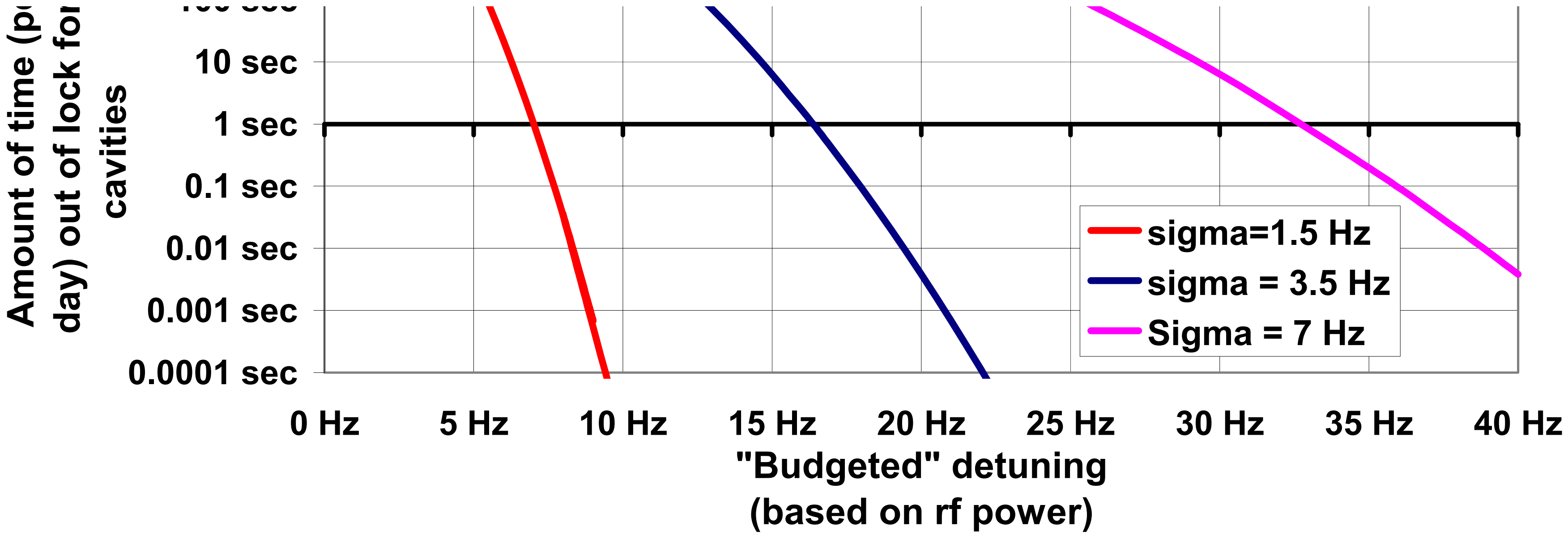


Detuning (cont'd)

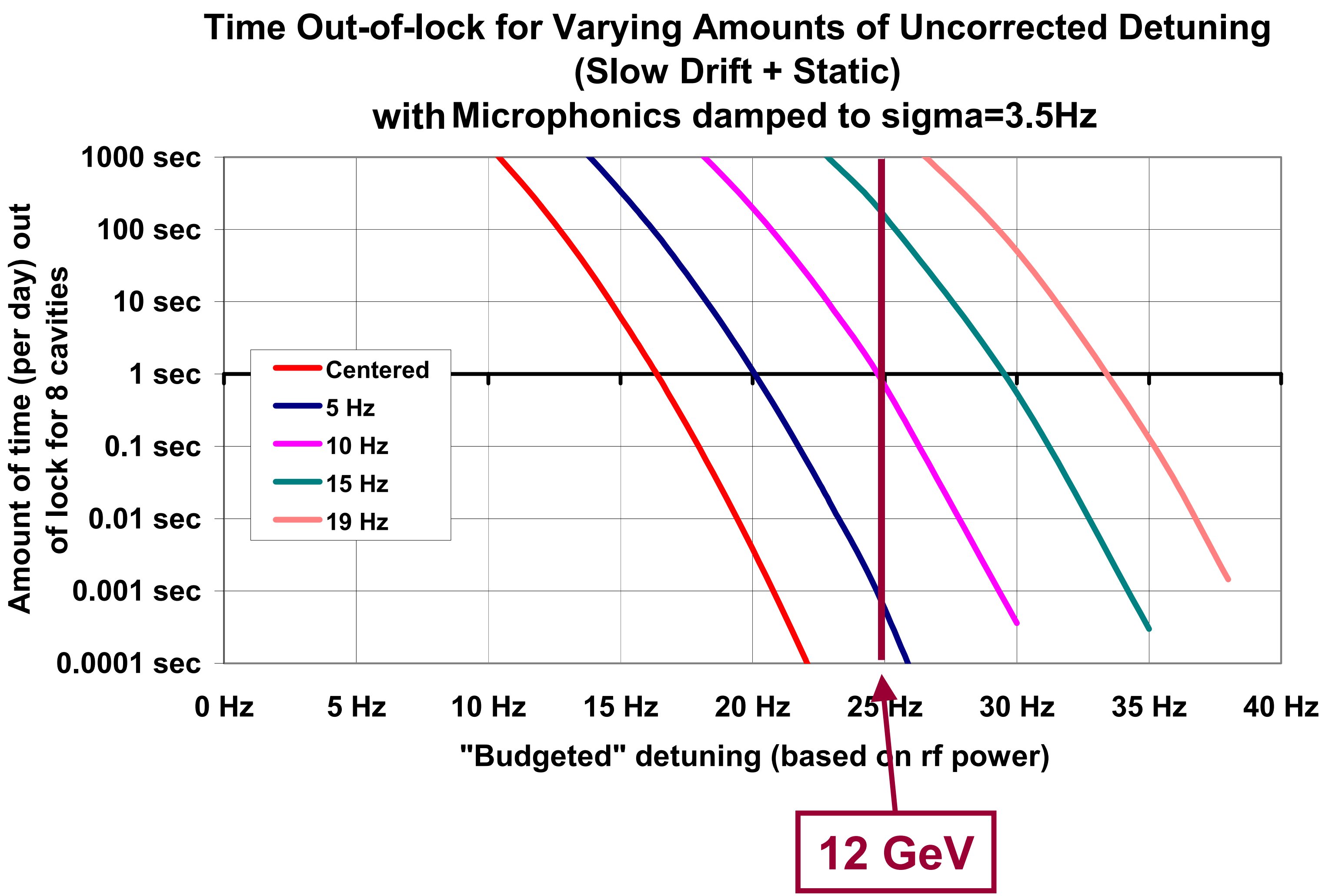
Microphonics has a huge impact on required "budget", i.e the detuning value used in calculating the rf power requirements.

LLRF Performance for Varying Widths of the Microphonics Distribution.

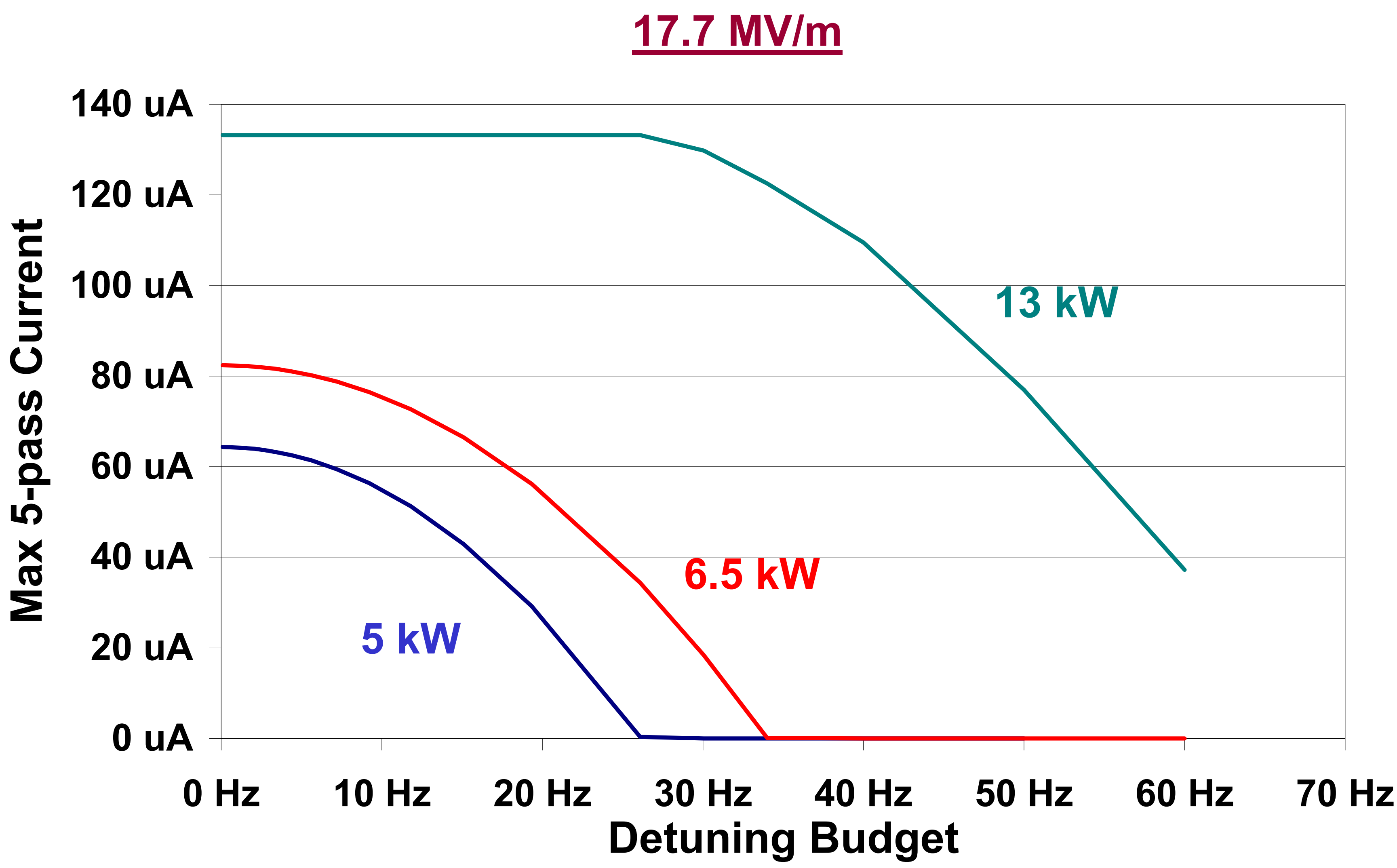
For now I'll use 3.5 Hz for sigma (value was measured on CEBA by Doolittle; data for SL21 is clouded by CTF behavior)



Choosing a "Budget" for the Detuning.



Effects of Detuning Budget on Maximum Currents



Routes to Reducing Terms in Detuning Budget

Dealing with static and slow drift

- Mechanical tuner
  - Pro
    - No new hardware of software development needed
  - Con
    - May induce microphonics
    - May wear out steppers quickly
- Piezo
  - Pro
    - Smooth
    - Better resolution than mechanical tuner
  - Con
    - Need to develop software and buy & install hardware

Recommendation: start with mechanical but develop piezo

Reducing terms in detuning budget (cont'd)

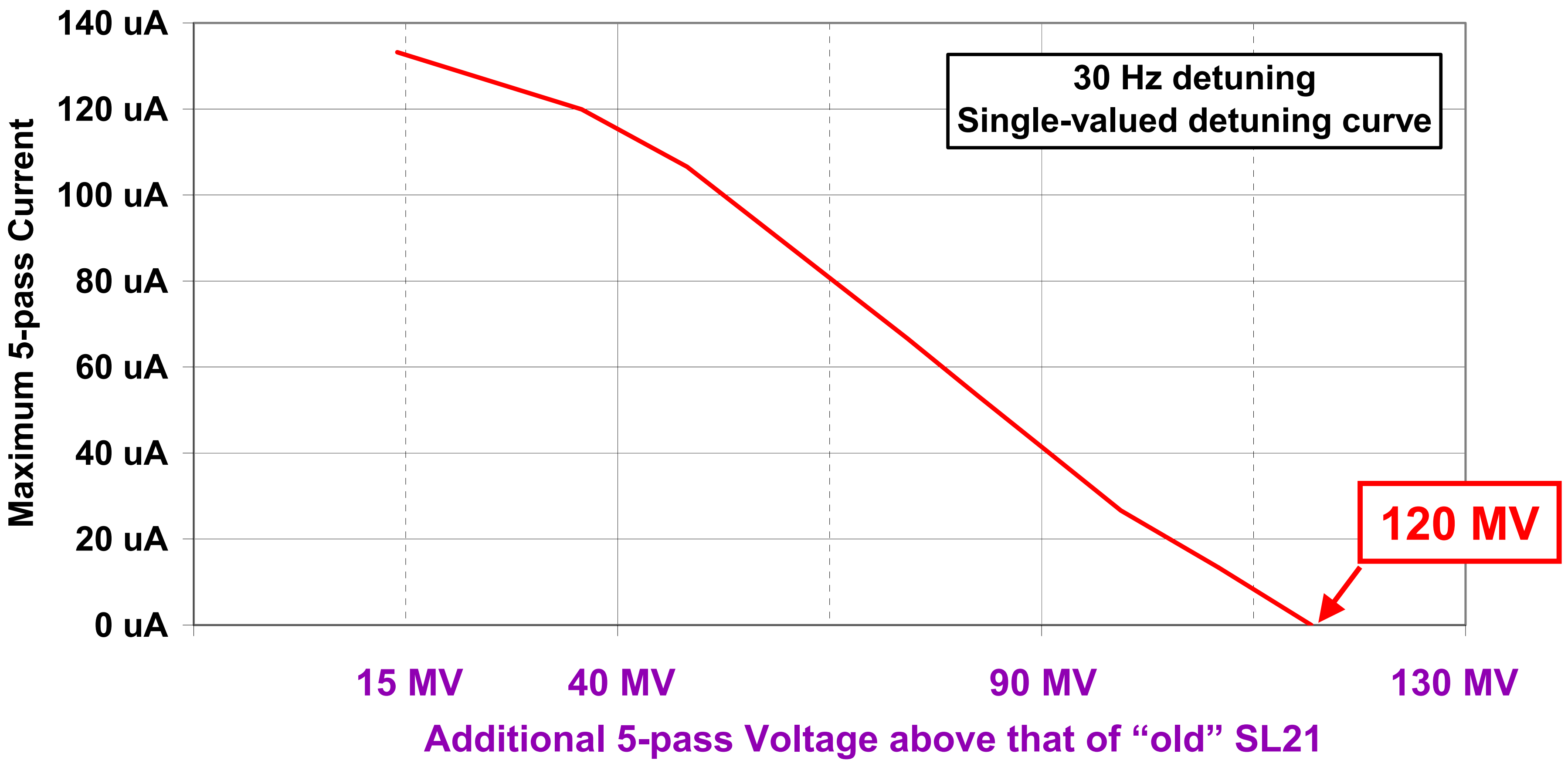
Dealing with microphonics

- Gamble:
  - Might have a really quiet system
  - Tolerate a bit more time out-of-lock (SOS'ing)
- Damp them somehow
  - Three options that I know of; all need R&D
    - Jean's electronic option (needs a new LLRF control module for implementation)
    - Tief's variable reactance
    - ENERGEN's SBIR for magnetostrictive tuner

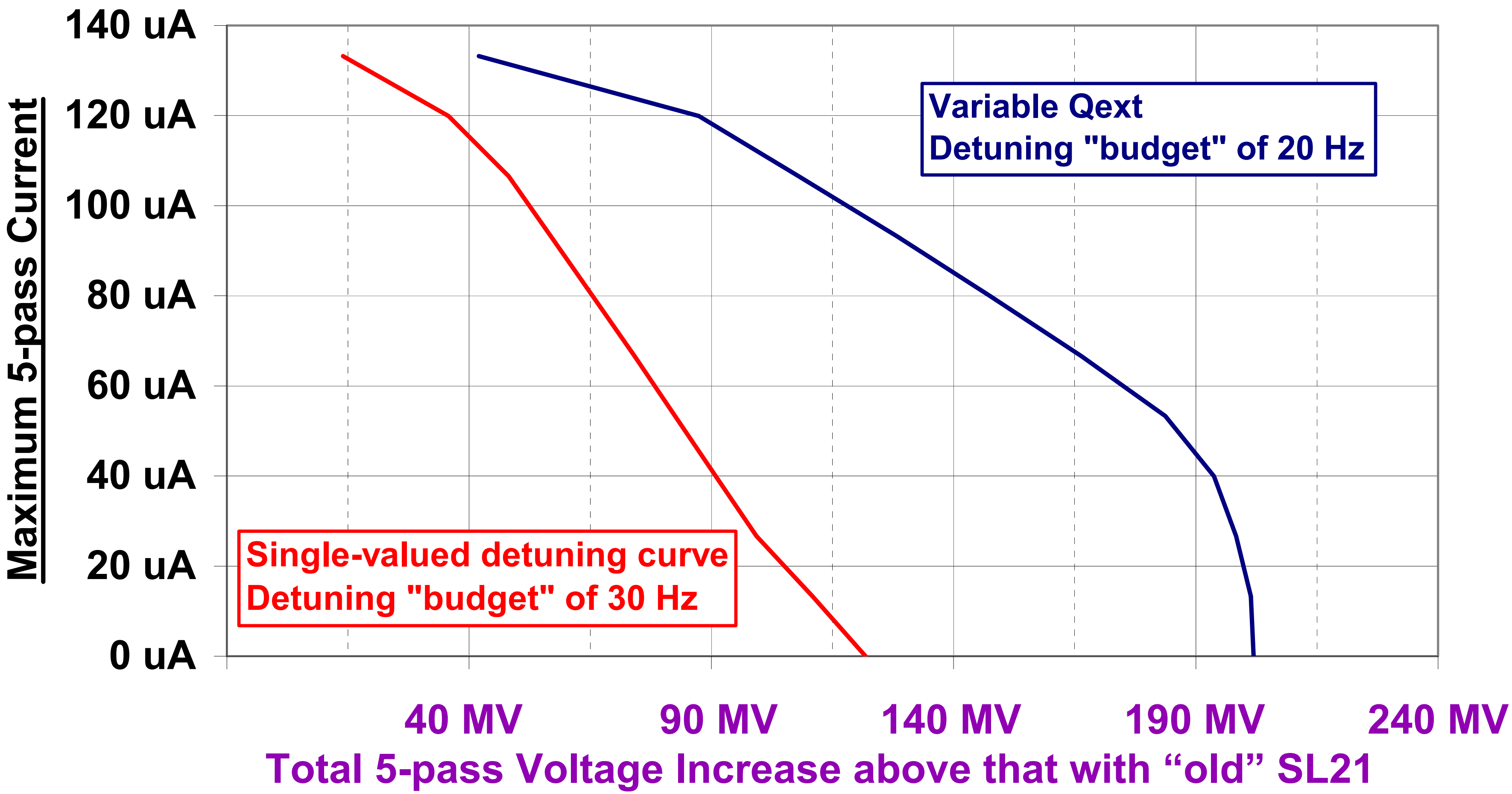
25 Hz is the total "budget" for 12 GeV.

For now will evaluate with 20 Hz and 30 Hz (span the 12 GeV spec.).

What if we installed SL21 today?



SL21 with New Support Systems



What about NL11?

For now I'll focus on what we can get with BOTH new cryomodules installed.

- **Both cryomodules have to drive the same beam current.**
- **Must do a balancing act of voltage in each cryomodule with it's klystron.**

Potential scenarios:

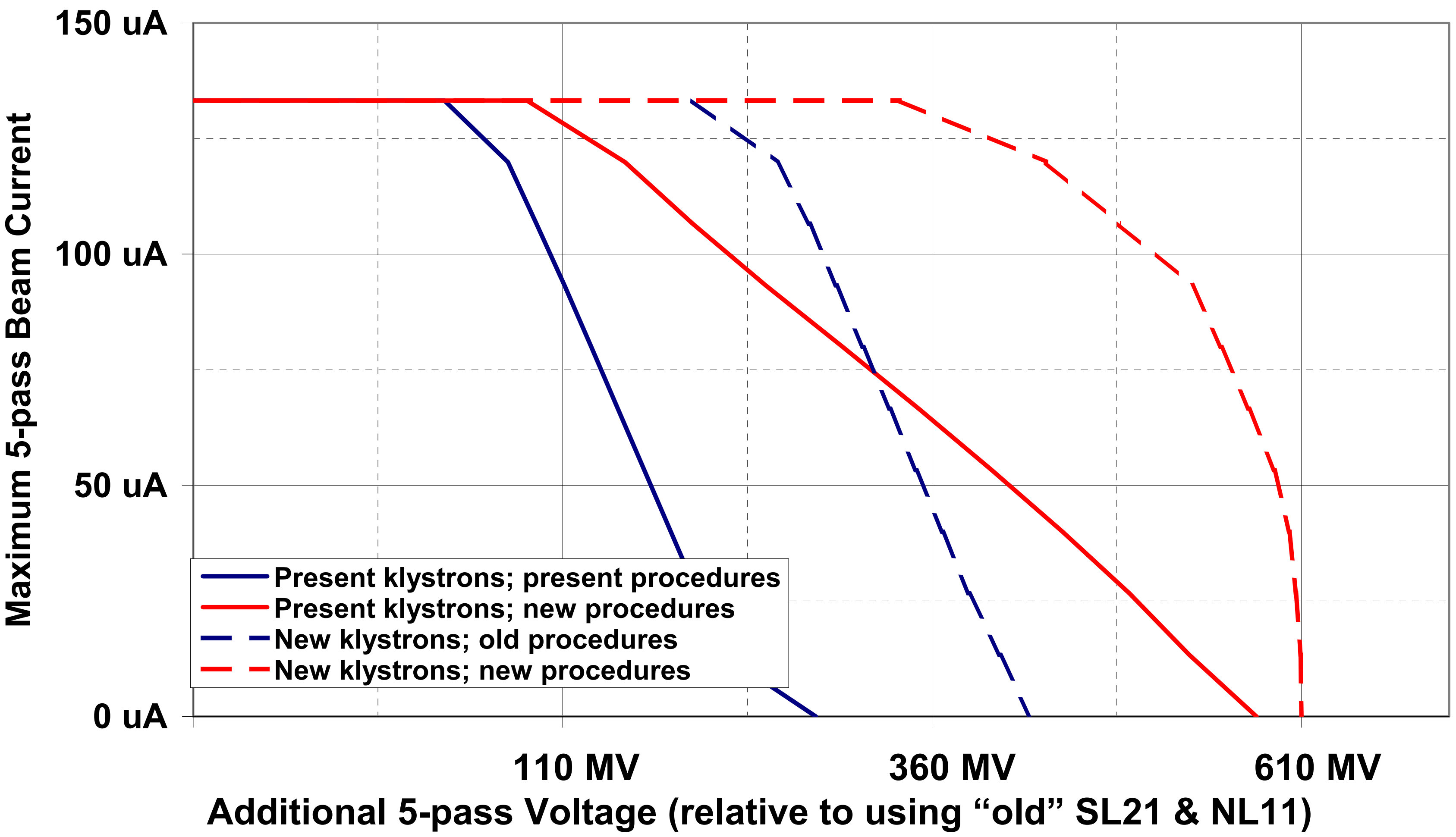
Klystron power

- Use what we have
  - SL21 5 kW
  - NL11 6.5 kW
- Have one zone of 13 kW klystrons
  - SL21 6.5 kW
  - NL11 13 kW

Q_{ext}, Turn-on, Detuning budget

- What we've got now
  - Single-valued detuning curve
  - Detuning budget of 30 Hz
- Add new systems & procedures
  - Variable Q_{ext}
  - Detuning budget of 30 Hz

SL21 + NL11



150 uA
100 uA
50 uA
0 uA
Maximum 5-pass Beam Current
110 MV
360 MV
610 MV
Additional 5-pass Voltage (relative to using “old” SL21 & NL11)
Present klystrons; present procedures
Present klystrons; new procedures
New klystrons; old procedures
New klystrons; new procedures

Summary

SL21 and NL11 will each add substantially to our energy reach.

- How much depends on the desired current

The performance envelop is greatly extended by

- Adding variable Q_{ext} and some detuning drift control
- Building one zone of 13 kW klystrons (plus HPA)

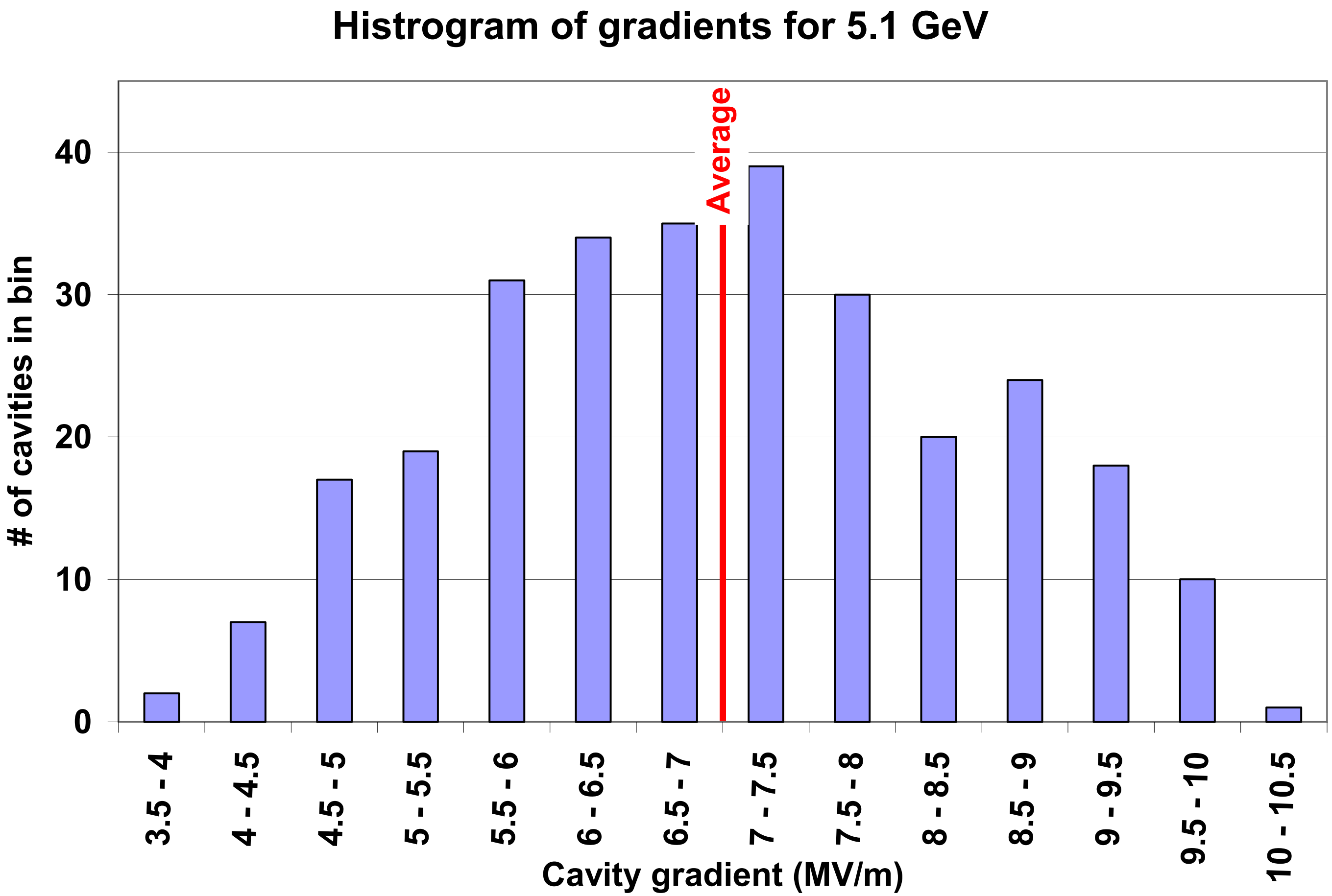
Additional Energy

	Present stuff	Enhanced RF
0 uA	0.2 GeV	0.6 GeV
100 uA	0.1 GeV	0.5 GeV

Is that all?

What about what we've already got?

Many of the cavities have quite limited performance



Note:

"Weird" distribution because of absence of SL21

Enhancements Other than New Cryomodules

Improving the existing cavities' performance could greatly extend the energy reach of the machine

Assume we can get an average 1 MV/m improvement on the "weaker" cavities (those at less than 7.5 MV/m)

- **Adds ~80 MV to the voltage**
- **About the same as adding a full SL21-ish cryomodule**
- **<u>0.4 GeV</u> for the 5-pass energy.**

May be worth doing another round of helium processing.

How about <u>pulsed</u> helium processing?