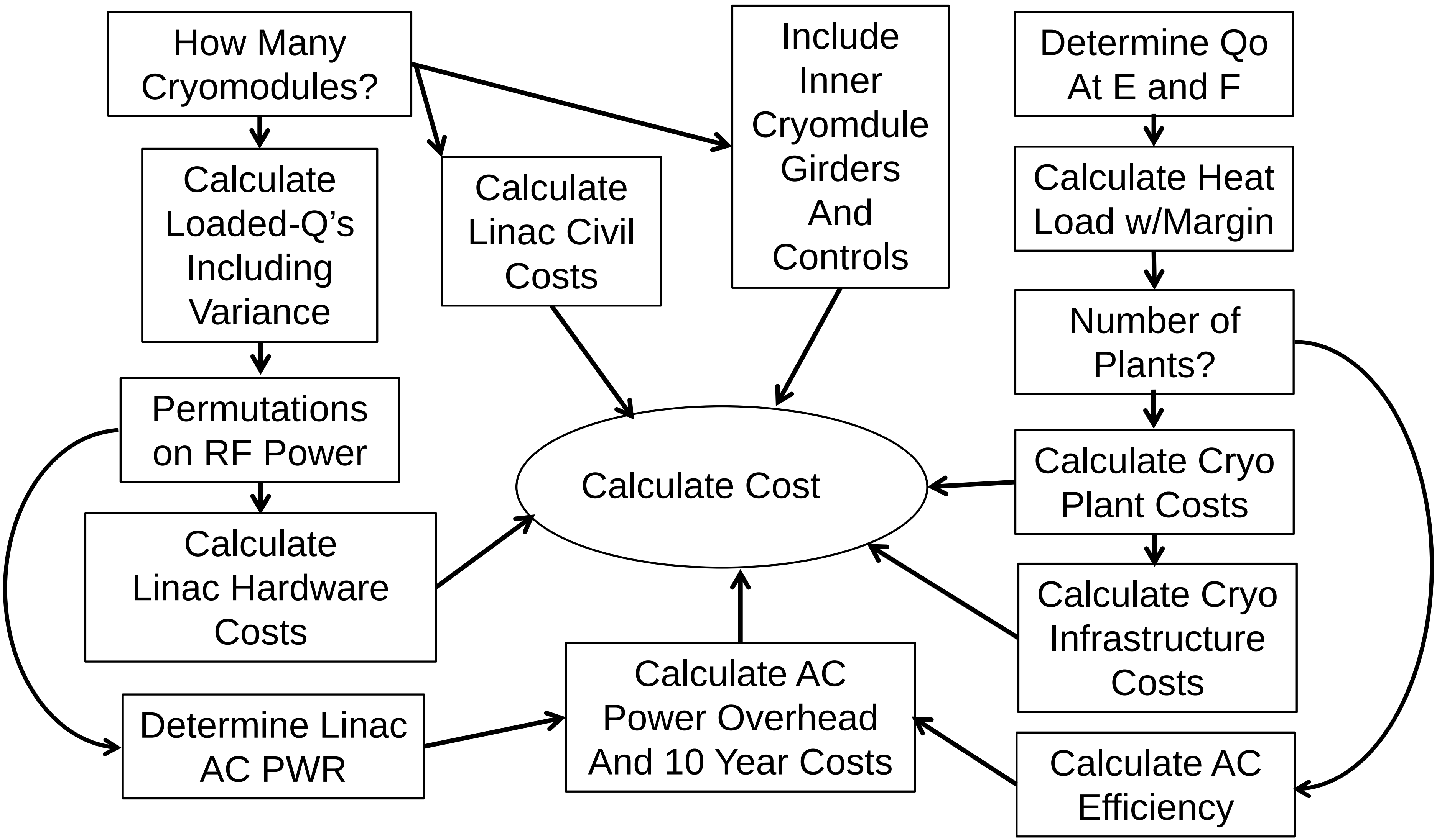
Cost Optimization Models for SRF Linacs

(or what I did on my winter vacation)

Tom Powers

Overall Cost Calculation



Cryogenic Plant Considerations*

- A 2 K liquid helium cold box is limited by transportation infrastructure to about 18 kW at 4 K which equates to 5 kW at 2 K, and 3.8 kW at 1.8 K.*
- It is beneficial from a design and maintenance standpoint to build mulitple copies of the same plant.
- For these reasons in the model, any time that the plant exceeds a multiple of 5kW @ 2K the plant was split into two identical plants and the efficiency will come from the following curve.
- The cost of a cryo plant doubles (at least) if you buy it turn key rather than buying the components, (compressors, coldboxes, oil removal systems, etc.) seperately.*

*Dana Arenius, Jefferson Lab, Personal Communication

Cryogenic Plant Considerations*

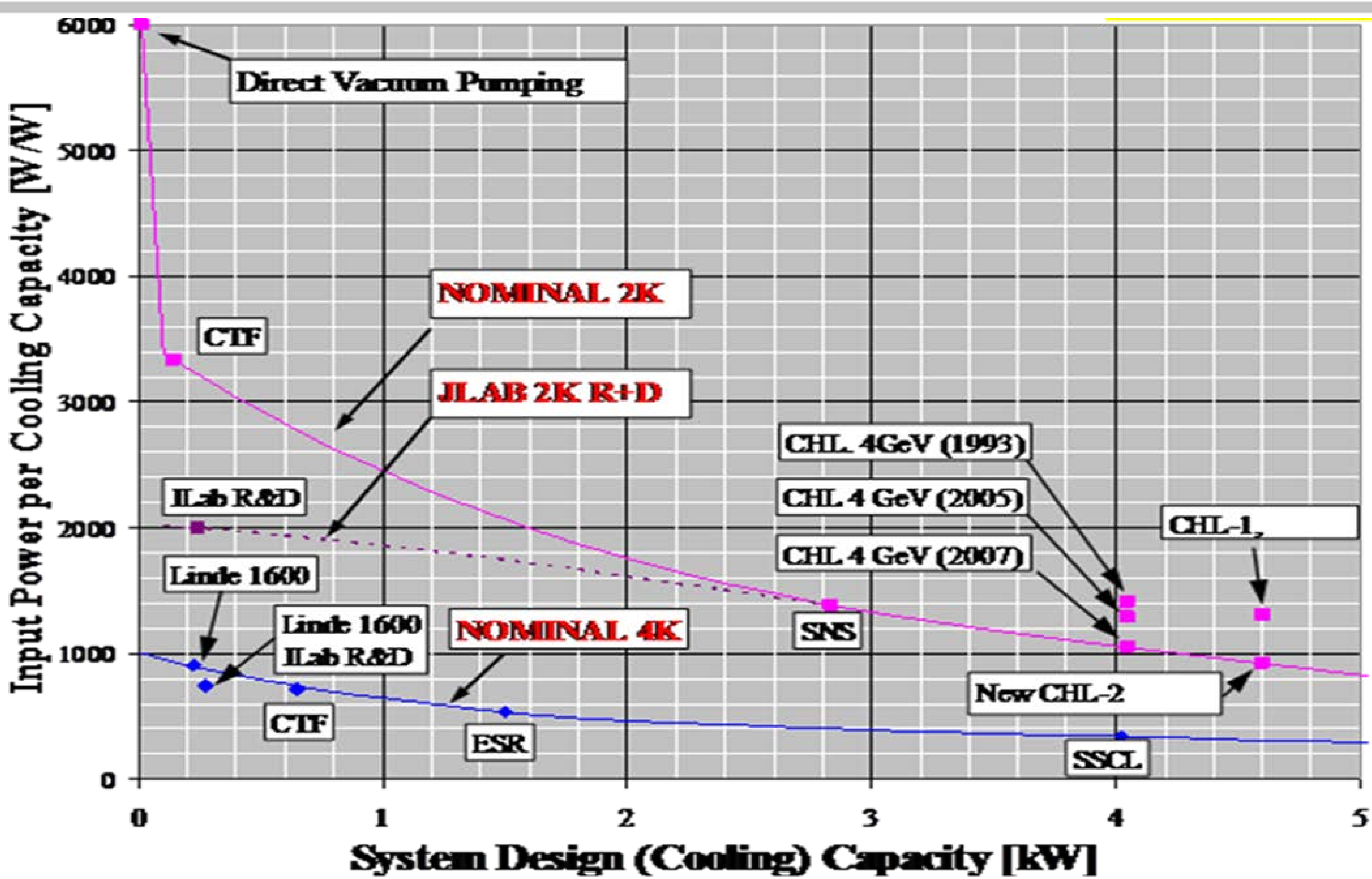
- For this model we used $25M for the cost of a 5 kW@2K plant and $5M for civil and infrastructure costs (based on the CEBAF 12 GeV project).
- The costs were escalated by 30% at 1.8K.
- The overall cost was from 5 kW 2K load was reduced by the following:

$$Cost_{Power} = Cost_{2.05K}\left(\frac{Power_{2.05K}}{5{,}000}\right)^{0.7}$$

- The efficiency was fitted to the magenta curve on the next slide and was adjusted only for Carnot effects by the following:

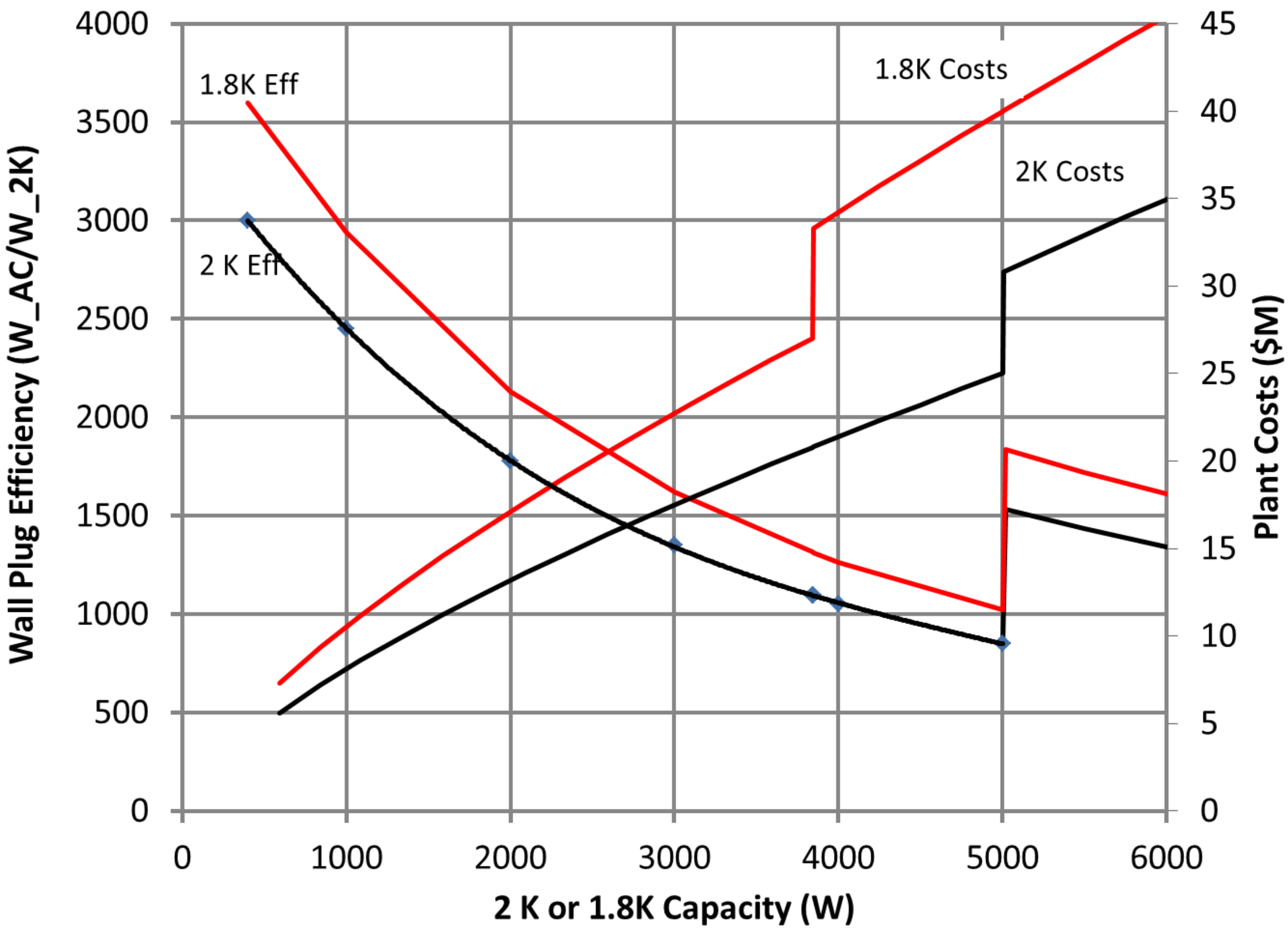
$$\Delta Eff_{Temp} = \frac{T}{2.05}(0.4T + 1.8)$$

Cryo Plant Efficiency at 2.05K as a Function of Heat Load



Ganni, R., et. al., “Cryogenic Systems Improvements,” JLAB Science and Technology Review, May, 2008.

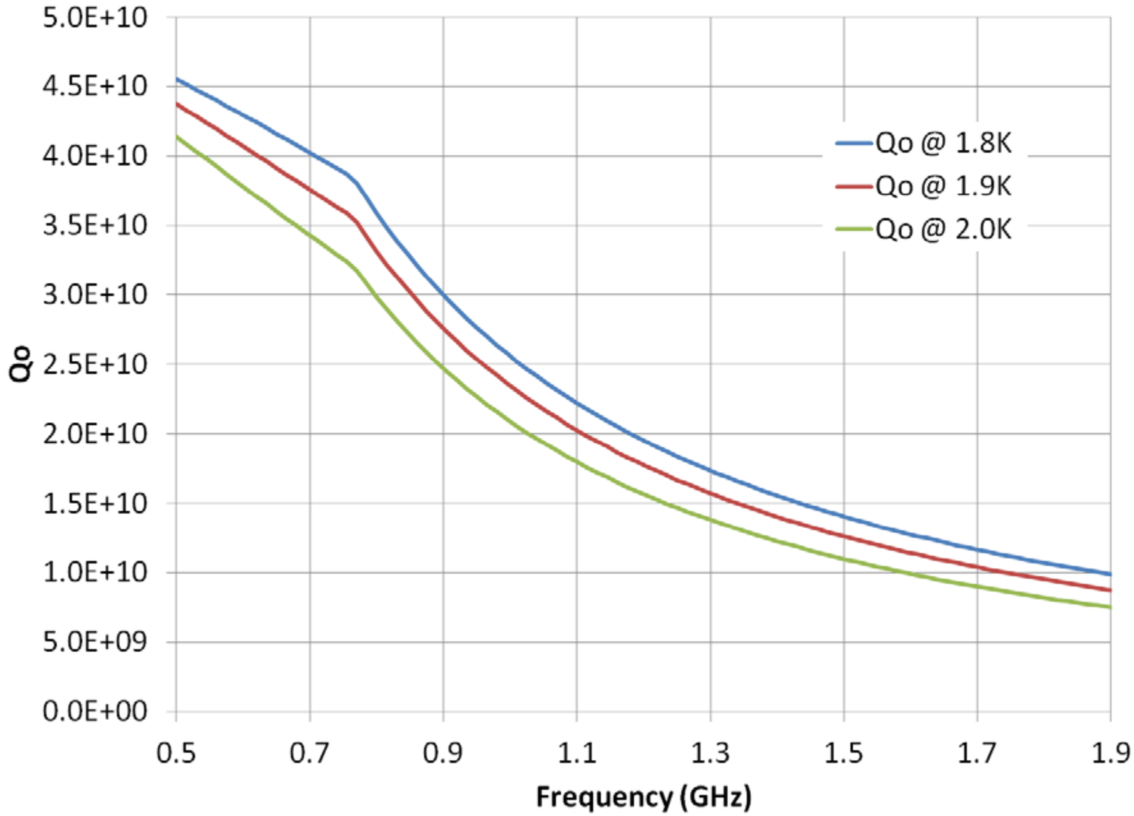
Resultant Cost and Efficiency Curves for the Cryo Plant



Different Approaches for Optimization.

- **Non causal cryomodules. Smooth curves of frequency dependence by.**
  - Using a fixed active length per cryomodule and thus a fixed number of cryomodules,
  - Using fractional number of cavities within each cryomodule.
- **Variable number of cells per cavity and cavities per cryomodule.**
  - Scale shunt impedance as 1/f.
  - Provides curves that have steps as you change cavity parameters and number of cryomodules
- **Variable gradient for specific cavity/cryomodule designs**
  - Effectively optimizes on the number of cryomodules to reach the design energy gain.
  - Provides smooth results with steps for cryo plant configurations.

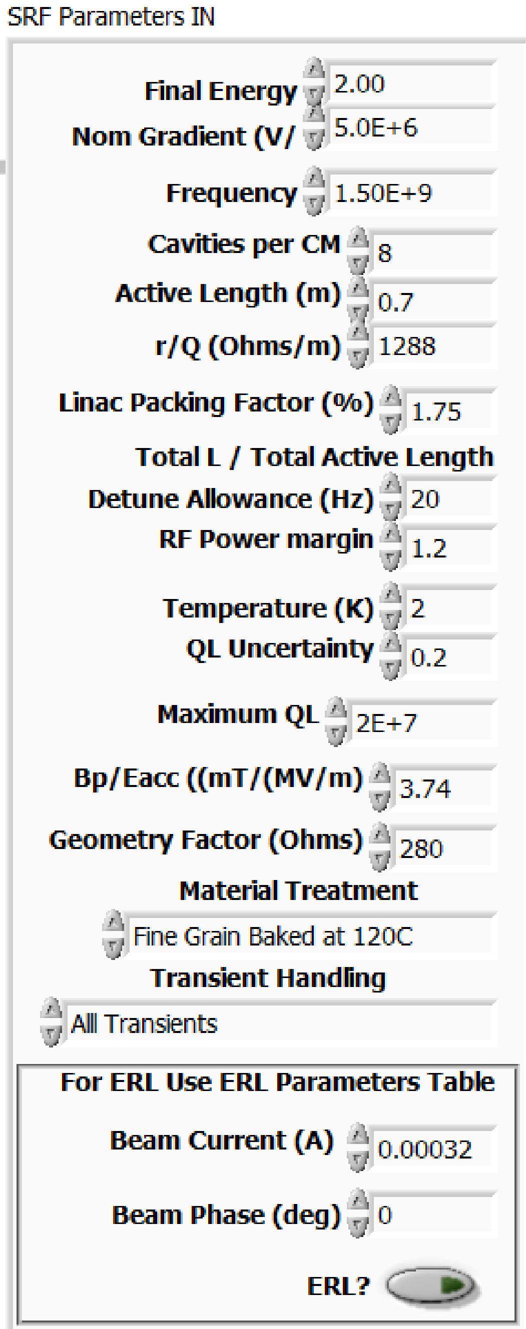
Qo Calculations



Q_0 as a function of frequency and temperature at 16 MV/m. All frequencies scaled from CEBAF C100 upgrade cavity.

Q_0 is calculated for each data point, and is based on a compilation of historic data. This historical data is a compilation from measurements taken in the vertical test area at Jefferson Lab.*

*Ciovati, G., et. al., "Residual Resistance Data from Cavity Production Projects at Jefferson Lab," IEEE Transactions on Applied Superconductivity, Vol 21, No. 3, June 2011



SRF Parameters Variables

- General cavity parameters
- Beam current and phase
- Detune allowance for microphonics, helium pressure variations, tuning uncertainty, etc.
- RF power margin
- Maximum allowed loaded-Q
- Material type and treatment
- Linac energy
- Linac Packing factor (Total L / Active L)
- ERL? Uses resultant current and tune up beam for RF Power calculations

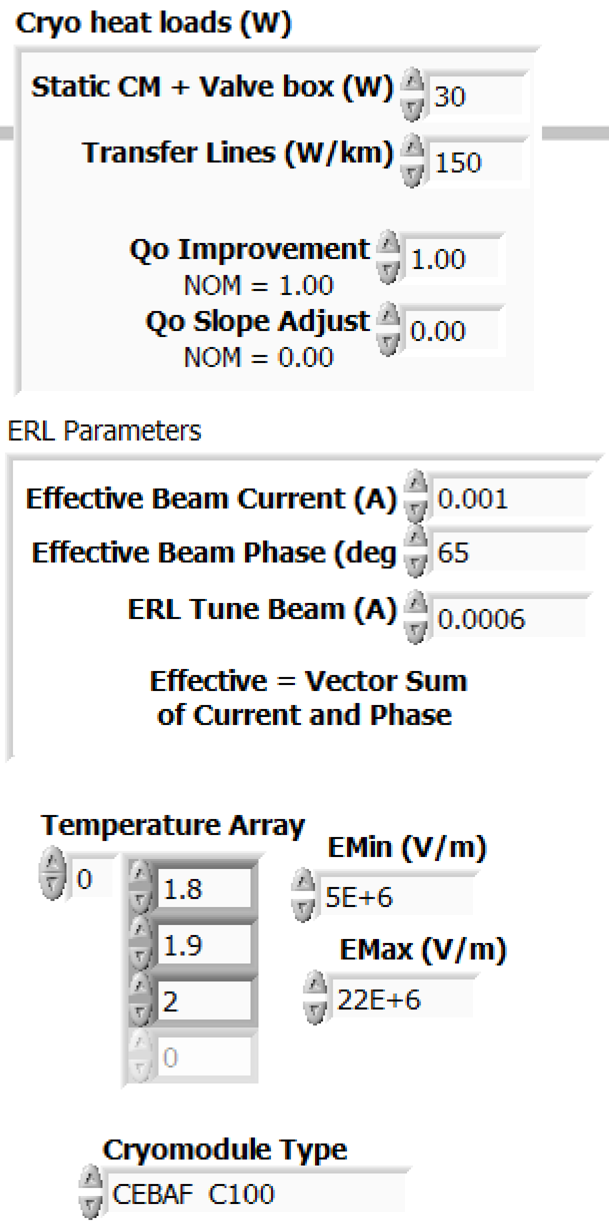
Baseline Costs Variables

Baseline Costs

Cryomodule ($M each)	3
RF Power ($/W)	12
RF Controls($k/cavity	40
Inner CM Girder ($k each)	265
Tunnel Civil ($k/m)	150
AC Power ($/MW-Hr)	65
5kW @ 2K cryo plant	25
Cryo Margin	1.5
5kW CryoPlant infrastructure ($M)	5
Transfer line costs (k$/m)	3.3
%inc in Plant cost 2K to 1.8K	0.3
%inc in cryo AC 2K to 1.8K	0.3
Cryo Wall plug Efficiency (W/2KW)	1207.8
Linac R&D costs ($M)	20
RF Wall Plug Efficiency	0.5
Controls AC pwr per CM/Girder(kW)	0.5
Operations Weeks	44
Power Overhead For LCW, HVAC, Lights, etc.	1.25
Spare Cryomodules	0

- Cryomodule fixed cost includes installation and testing.
- RF power costs includes transmission lines, circulators, etc.
- Inner cryomodule girder includes magnets, controls, valves, viewers, etc.
- Tunnel civil costs includes service buildings, AC power, LCW, etc.
- Cryo plant is based on CEBAF upgrade costs assumes you buy the major components double or triple the cost if you buy a turn-key plant.
- Linac R&D costs includes prototype cryomodule as well as remainder of electronics.
- Costs in the model come from 12 GeV upgrade cost book, and various engineering estimates.
- Baseline costs should be modified to fit the target machine cost estimates.

Other Inputs/Controls



- Ability to what if Qo improvements by adjusting scale and slope.
- ERL parameters to adjust resultant current and tune beam.
- Temperature array allows one to change the parameter.
- Cryomodule type allows one to select between several types with one being user defined. This is only used on the sweep gradient module.
- Also have buttons to pause, save results, save and restore set up parameters.

Linac overall parameters out

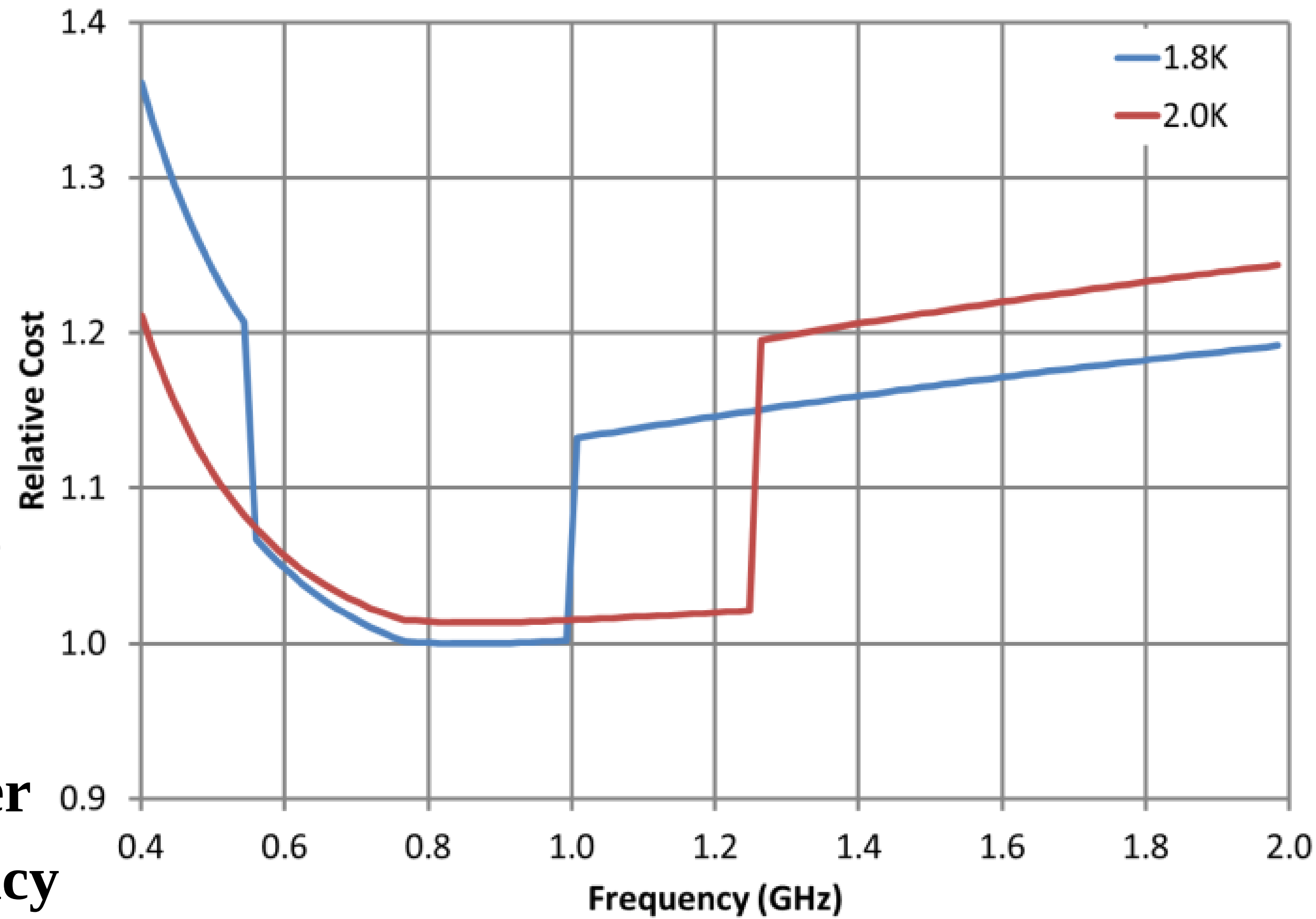
Linac Costs ($M)	455
Cryomodules($M)	213
RF PWR & Ctls Costs ($M)	32.3
Inner CM Girders ($M)	18.6
Tunnel Civil ($M)	104.4
Cryo plant and facility ($M)	27.6
10 yr Linac & Cryo AC pwr cost ($M)	38.8
Linac Length (m)	696
Number Cryomodules	71
Number Cavities	568
Number inner CM Girders	70
Linac Active Length	397.6
CM dynamic heat load	8
Linac 2K heat load (W)	2859
CryoPlant with Margin (W)	4289
CryoPlant Eff (ACW/2KW)	992
Qo	1.35E+10
Matched Loaded-Q	1.16E+7
RF pwr per Cavity (kW) Includes QL variance and Margin	1.4
Total RF Power (kW)	798
Cryo AC Power (MW)	5.32
RF, Magnets and Cntls AC (MW)	2.04
Actual Gradient (MV/m)	5.03E+6

Output Parameters

- Costs of different components of the overall costs.
- 10 year AC power costs
- Linac Length
- Match Loaded Q
- Qo at E and F
- RF power per cavity
- All output parameters during a sweep can be written to a file or viewed on live graphs.

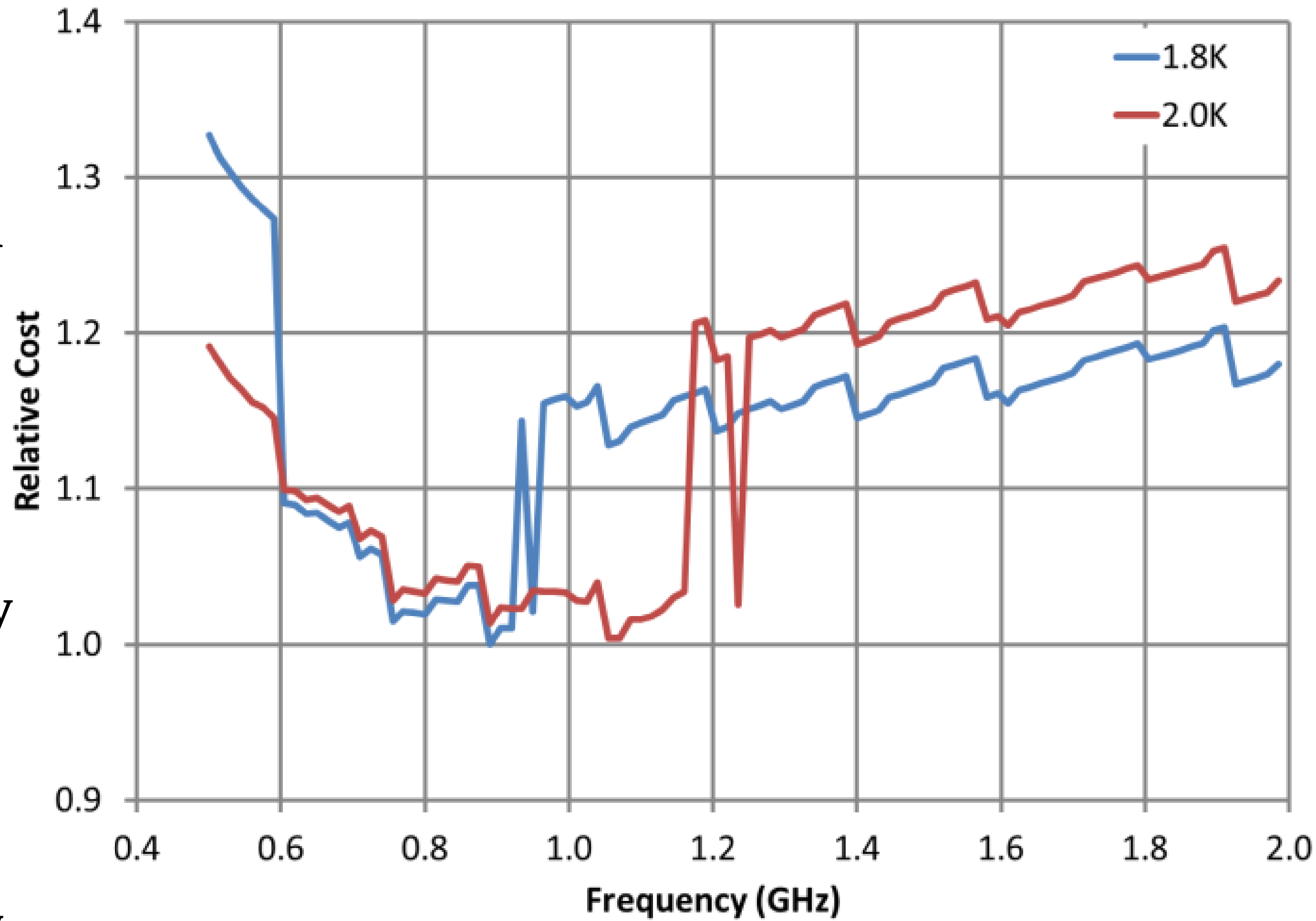
Fractional Cavity Model Relative Cost

- 118 m active length
- 21 cryomodule
- 2 GeV linac
- 10 years of electrical power
- Sweep frequency
- Two temperatures



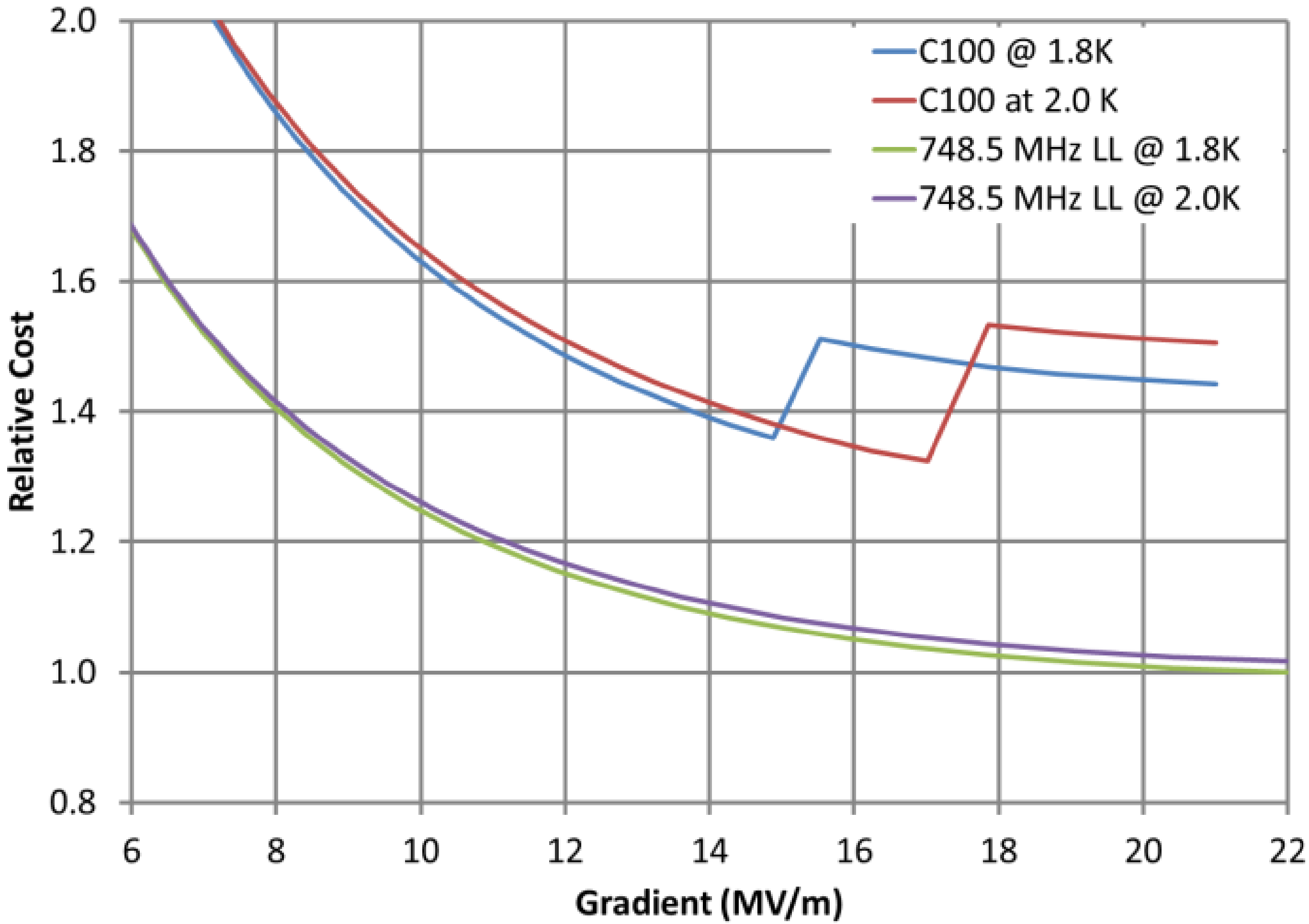
Fractional Cavity Model Relative Cost

- 10 – 12 m cryomodules
- Each with a maximum of 6 m of active length
- Integer number of cavities.
- Various number of cells per cavity
- 2 GeV linac
- 10 years of electrical power
- Sweep frequency
- Two temperatures



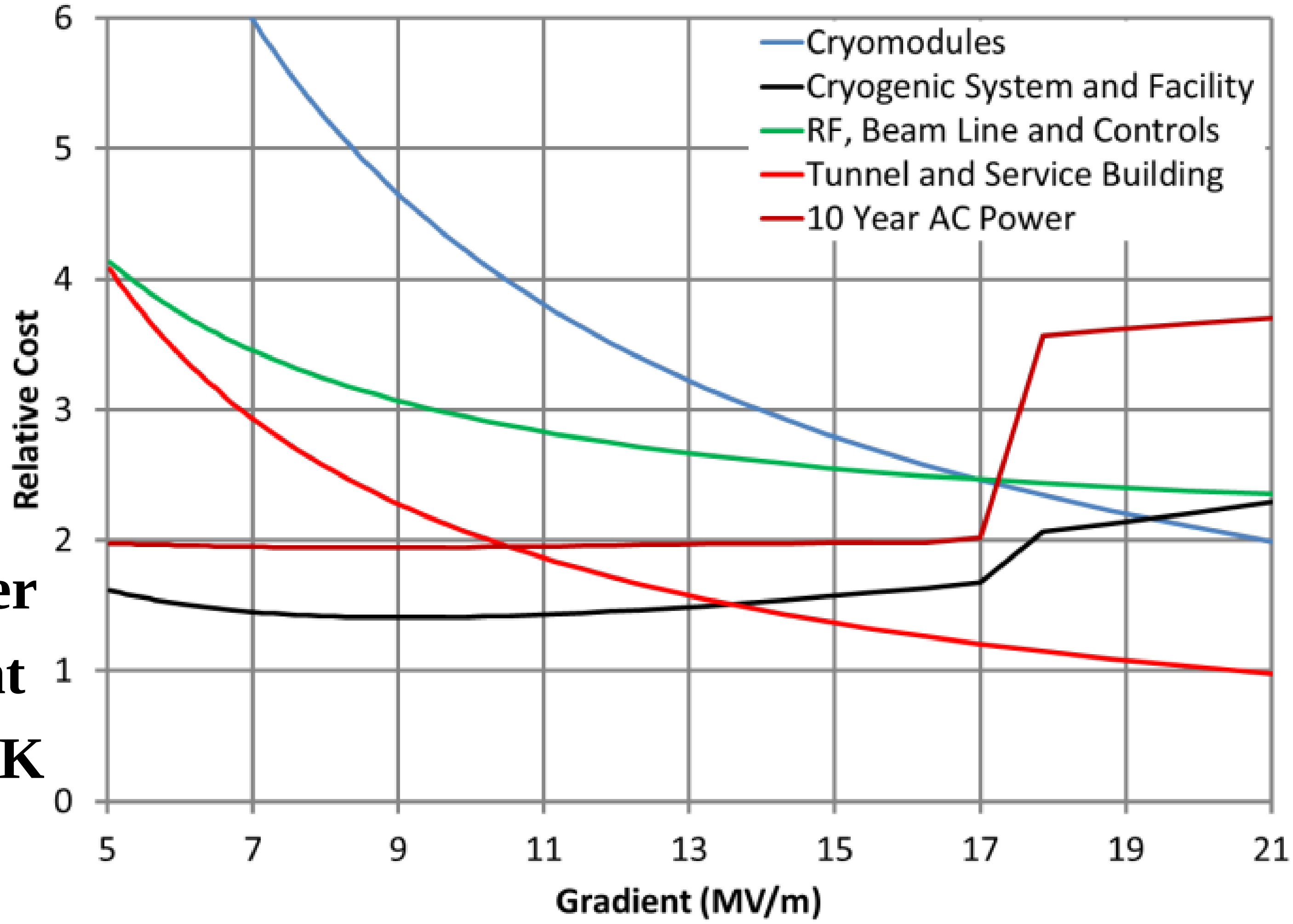
Sweep Gradient Defined Cryomodule Relative Cost

- **CEBAF C100 Cryomodule,**
  - **7 cells**
  - **8 cavities/CM**
- **C100 scaled to 748.5 MHz,**
  - **5 cells**
  - **7 cavities/CM**
- **2 GeV linac**
- **10 years of electrical power**
- **Sweep gradient**
- **Two temperatures**



Relative Costs of Sub Elements From C100 CM

- **CEBAF C100 Cryomodule,**
  - **7 cells**
  - **8 cavities/CM**
- **2 GeV linac**
- **10 years of electrical power**
- **Sweep gradient**
- **Operated at 2 K**



Summary

- **Tools allow the user to understand the cost drivers for given operating modes, cyromodule and cavity types.**
- **Tools allow user to change the input parameters.**
- **Tools allow user to save input and output parameter sets**
- **Executable files are available at:**

https://userweb.jlab.org/~powers/

- **Comments and suggestions welcome.**

Acknowledgements

I would like to thank Dana Arenius, Gigi Ciovati, Rao Ganni, and Bob Rimmer, from Jefferson Lab as well as Frank Marhauser from Muons, Inc. for support and discussions related to this topic. Additionally, to thank Gigi Ciovanti for his help in developing the section of the code that calculates Q_0 as a function of gradient, cavity parameters and temperature.

Backup Slides

Efficiency Adjustments for Temperature*

- The wall plug efficiency for a 2.05 K plant was calculated using a 3rd order fot to the mengenta curve from the previous slide.
- It includes all AC power including warm compressors.
- Cooling tower power is included in the overall power overhead budget.
- Scaling from 2.05 K efficiency only takes into account the thermodynamic efficiency changes. The equation used is:

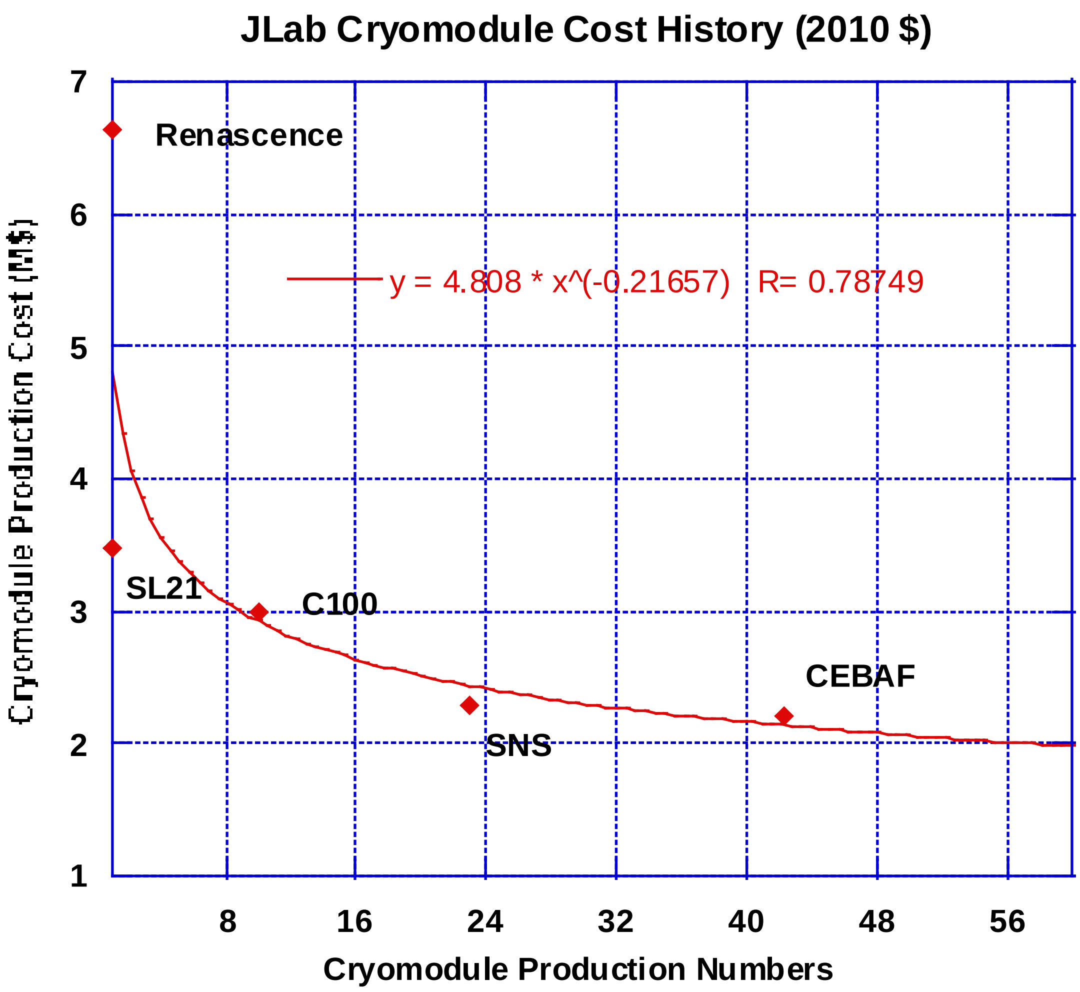
$$T_{Eff} = \frac{T}{2.05}(0.4T + 1.8)$$

- The first term is the temperature effect on the Carnot work.
- The second is the change in the Carnot efficiency which goes from approximately 20% at 2.05 K to 19% at 1.8k.

*Rao Ganni Jefferson lab personal communication

Jlab Cryomodule Cost History

A. McEwen



- Data taken from closed projects, C100 is estimated
- Engineering costs included
- Overhead Rates lowered for C100,SNS,CEBAF projects
- XFEL estimate ~$1.7M?
- ILC estimate ~$1M?

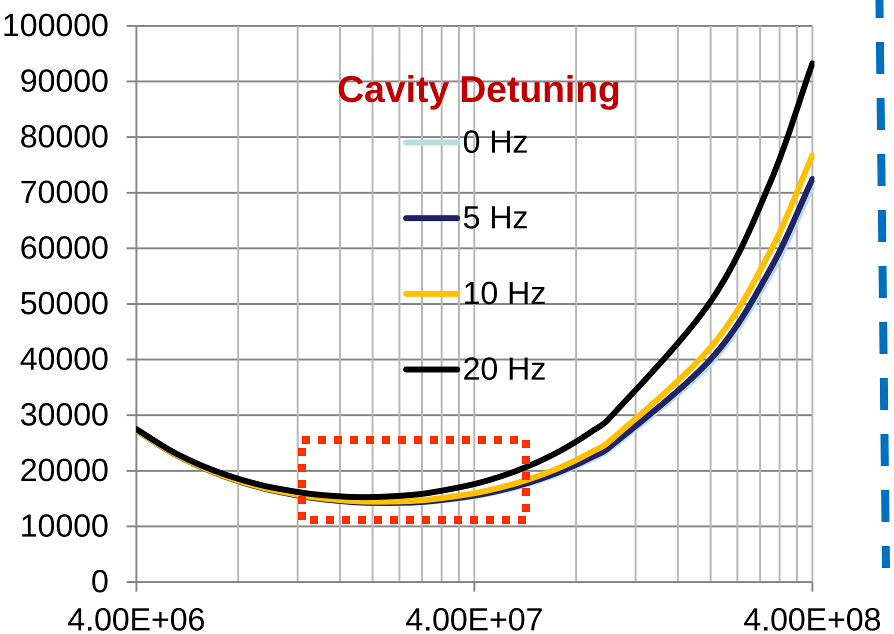
Q_L Optimization for Minimum Power

Depending on the application (injector/LINAC or ERL) the cavity Q_L must be optimized for minimum power.

$$Q_L\Big|_{MinPower} = \frac{E}{\sqrt{\left\{ \left(I_0 (r/Q)\cos\psi_B\right)^2 + \left(2\frac{\delta f}{f_0}E + I_0\,(r/Q)\sin\psi_B\right)^2 \right\}}}$$

Beam Loaded Cavity

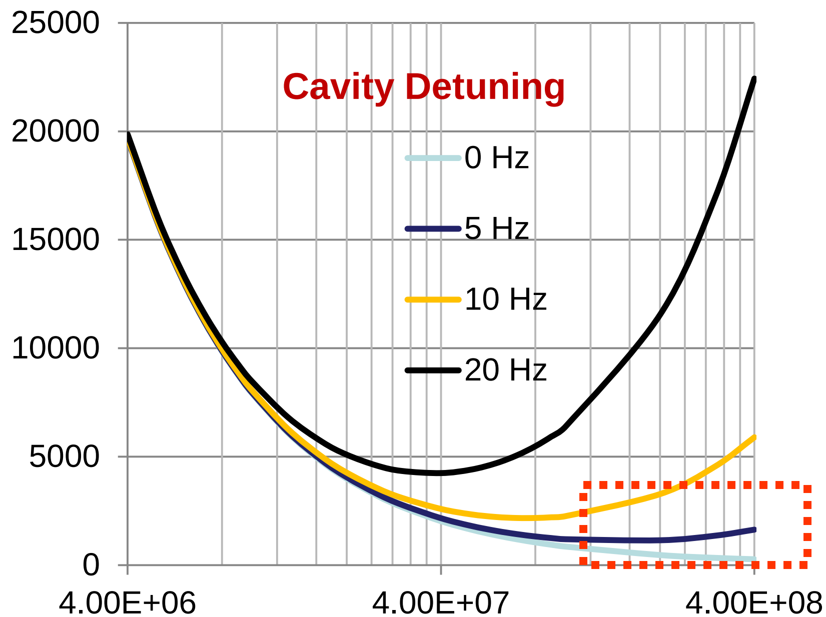
$$Q_{Lopt} \cong V / I_O(R/Q)$$



I = 1 mA

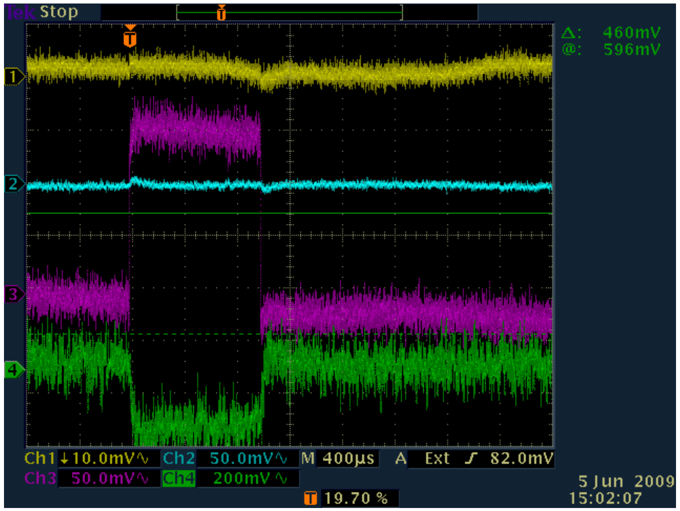
Lightly-non beam loaded Cavity

$$Q_{Lopt} \cong f_o / 2\delta f$$



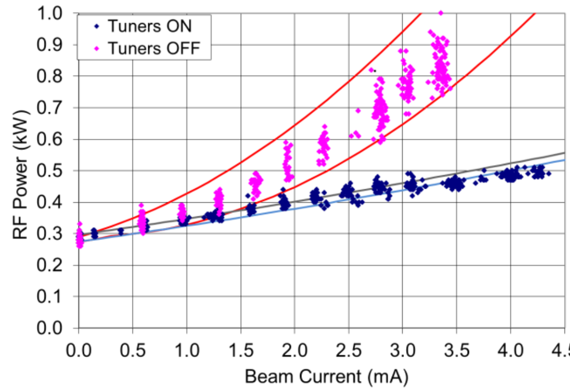
I = 10 μA

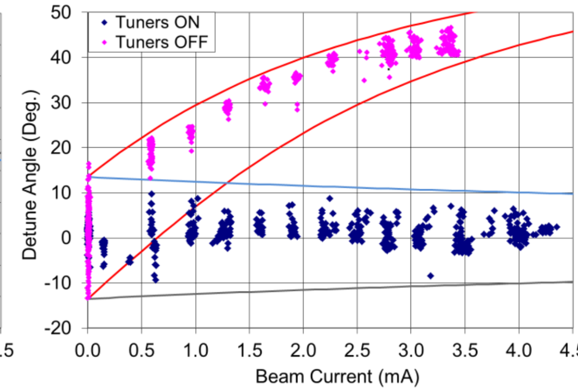
Allow for Transient Beam Loading?



Tune Beam Transient, 600 uA, Phase ≅ 0°

1 Measured gradient
2 Measured phase
3 Magnitude drive
4 Phase drive





Measured and predicted RF drive amplitude and phase due to CW beam loading in an ERL where the effective current is approximately 7% of the single pass beam at 75º.

0

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

No Transient Loading