Cost and efficiency of the TLEP RF system based on the CEBAF upgrade experience

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Jlab

TLEP 13 workshop, 7-25-13

Outline

- Significant parameters for TLEP
  - (Compared to existing or past machines)
- Options for technical implementation
- Major cost drivers
- Cost dependence on key parameters
  - Frequency, cavity type, material
- Options for improvement via targeted R&D
- Conclusions

Significant parameters for TLEP

(Compared to existing or past machines)

Voltage	2-6 GV per ring or 12 GV combined	
Current	5.4-1180 mA	like B-factories
RF power	2x 50 MW	(4x SLAC w. PEP-II)
Circumf.	80kM	3 x LEP
Cryo	~15kW@2K	3 x original CEBAF

Options for technical implementation

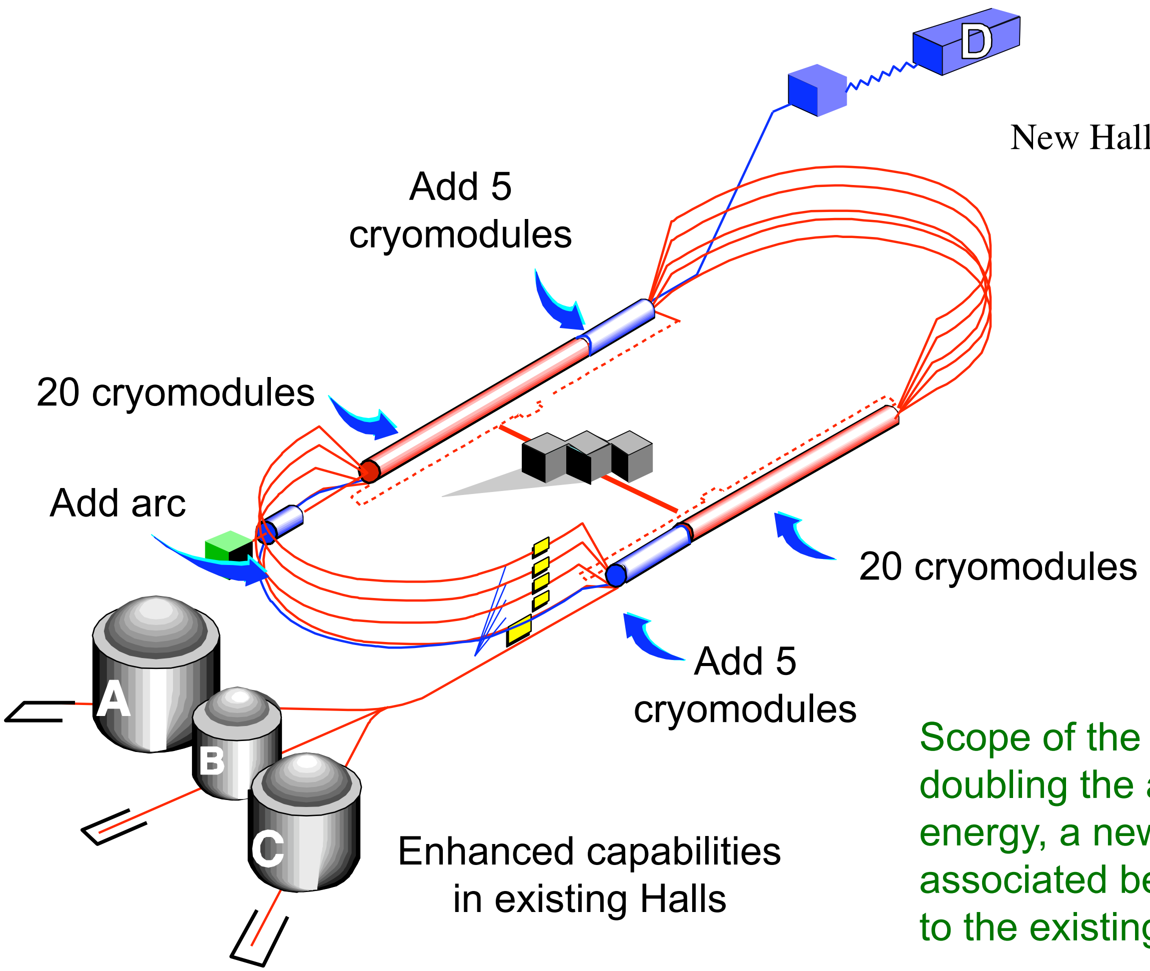
- Single-cell cavities (Like B-factories)
  - –High current, low packing factor, large number required
  - –Maybe a new design would help? (MEIC R&D)
- Multi-cell cavities (like HERA and LEP2)
  - –Higher packing factor, limited current?
  - –Can we park the other fundamental passband modes safely in a bigger ring?
- Multi-cell low-HOM cavities (like ERLs, LHeC)
  - –High current, high packing factor (JLab/BNL3)
  - –Have to deal with high HOM power at high current
  - –Still have to park the other fundamental passband modes
- Some combination? Phased approach? Harmonic/passive cavities?

Major cost drivers

- RF, cryomodules, cryo plant, tunnel, facilities
- Wall plug power is a major operating cost
- JLab costs reported here are approximate and scaled from
  - Original CEBAF production (42.25 CM's)
  - SNS (23 CM's) 805 MHz
  - C100 (10 CM's) added 1 GeV, one 5 kW 2K plant

SCOPE OF 12 GeV UPGRADE

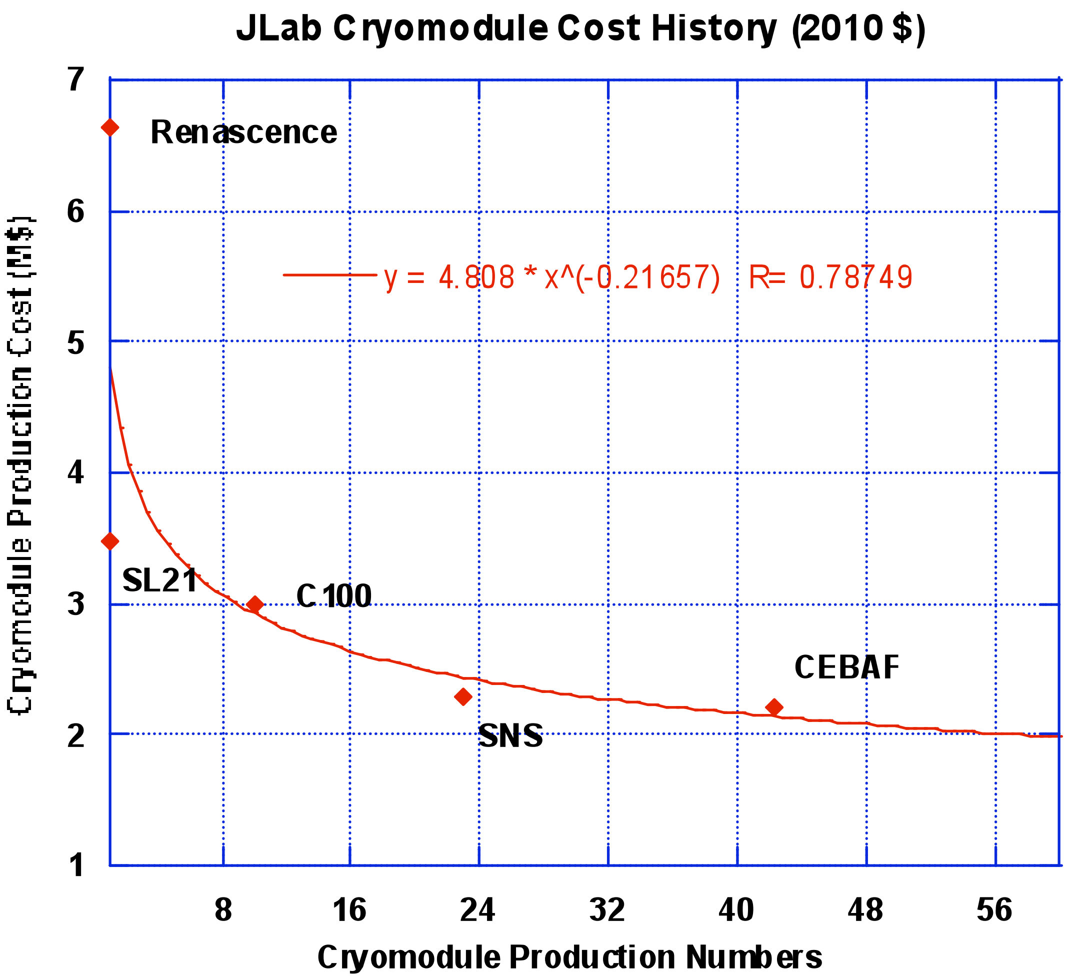
Upgrade is designed to build on existing facility:
vast majority of accelerator and experimental equipment have continued use



Scope of the proposed project includes doubling the accelerator beam energy, a new experimental Hall and associated beamline, and upgrades to the existing three experimental Halls.

Jlab Cryomodule Cost History

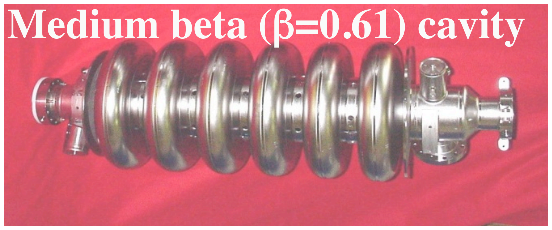
A. McEwen

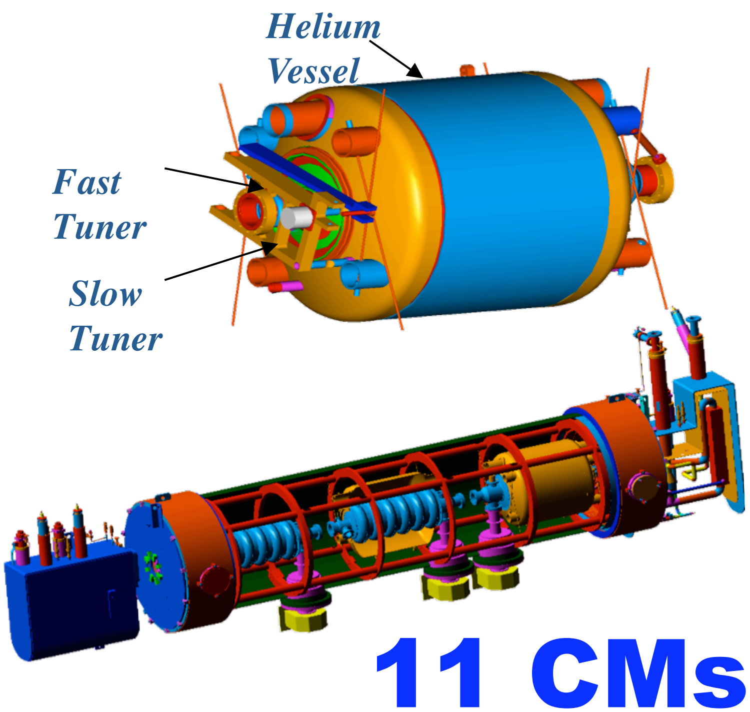


- Data taken from closed projects, C100 is estimated
- Engineering costs included
- Overhead Rates lowered for C100,SNS,CEBAF projects
- XFEL estimate ~$1.7M?
- ILC estimate ~$1M?

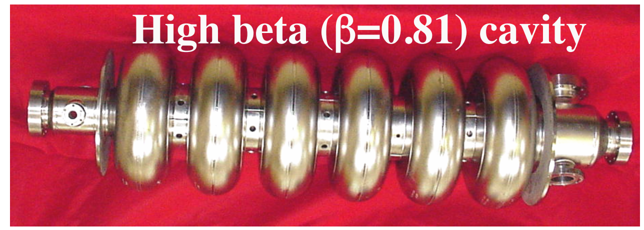
SNS Cavities and Cryomodules

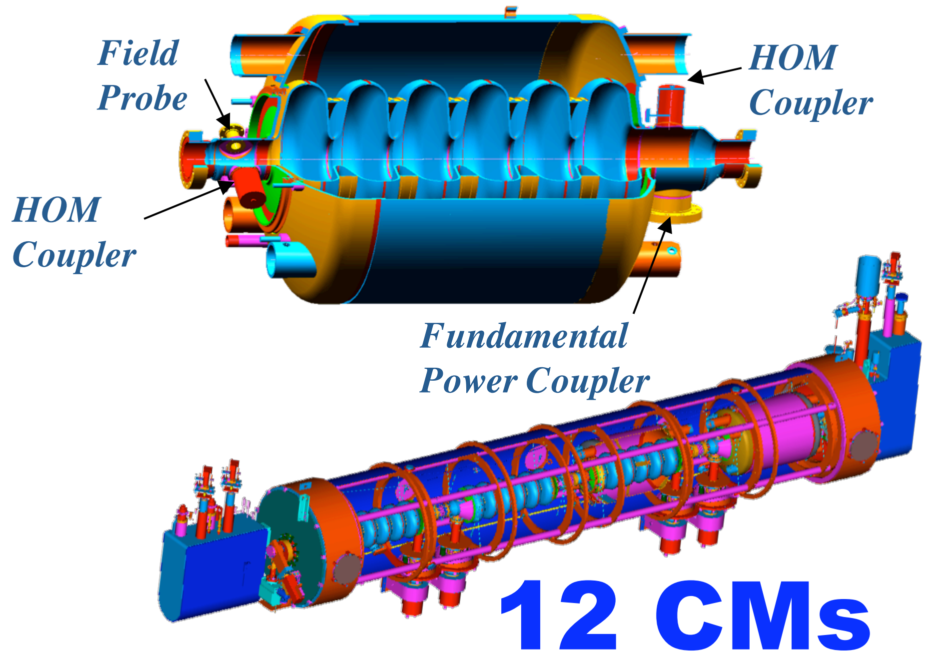
β=0.61 Specifications:
E_a=10.1 MV/m, Q_o> 5E9 at 2.1 K



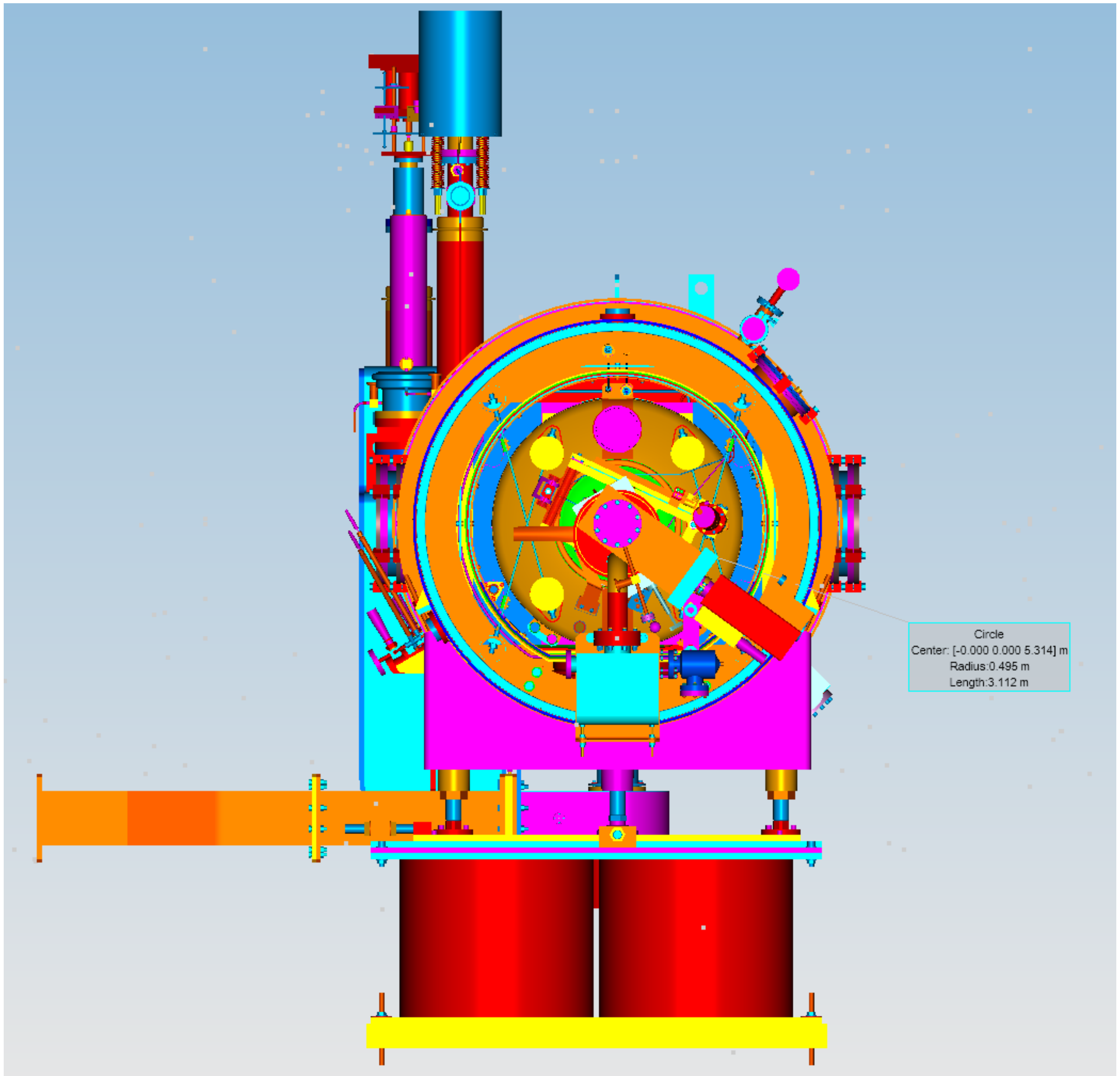


β=0.81 Specifications:
E_a=15.8 MV/m, Q_o> 5E9 at 2.1 K





SNS Cryostat Layout



Unique Features:

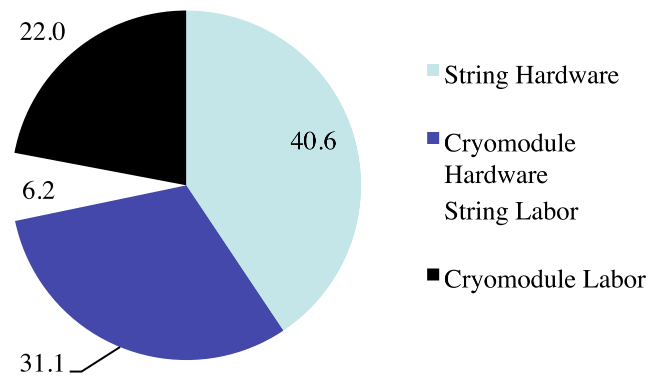
- Segmented
- No separate gas return pipe
- Coaxial coupler (KEK type)
- Space frame mechanical support
- Similar to Jlab C100

Advantages:

- Cavity has large helium inventory
- Individual alignment of cavities up to insertion into vacuum shell

Comparison of SNS cost breakdown to C100 project:

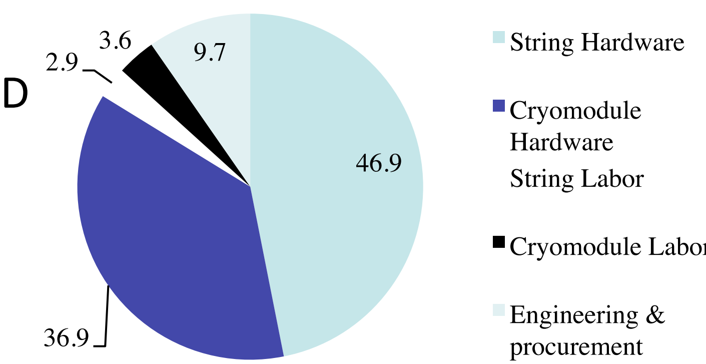
SNS Project (4 -805MHz cavities)		Cost (%)	Cost ($)
String Hardware		40.6	$904,000.00
Cryomodule Hardware		31.1	$692,000.00
String Labor		6.2	$139,000.00
Cryomodule Labor		22.0	$490,000.00
		100.0	$2,225,000.00



Engineering Labor Included

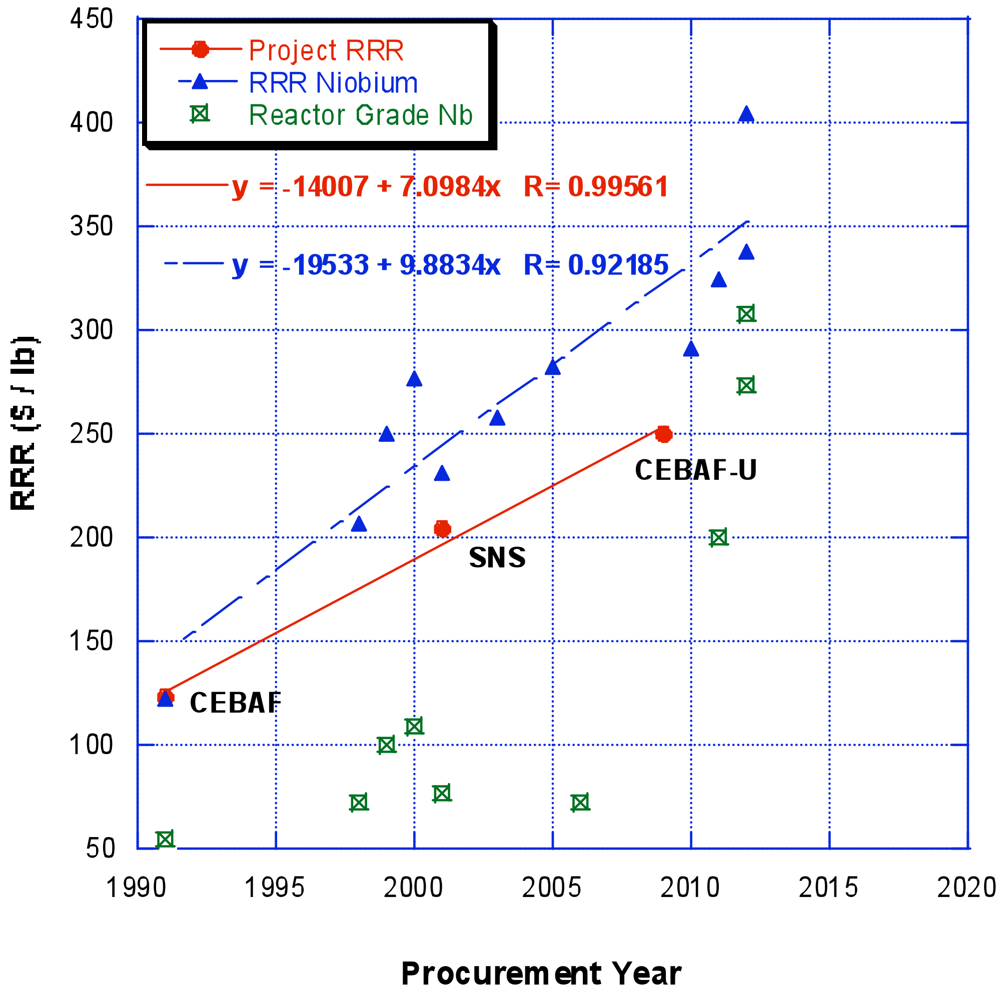
Additional services not added, no R&D

C100 Project (8 1.5GHz cavities)		Cost %
String Hardware		46.9
Cryomodule Hardware		36.9
String Labor		2.9
Cryomodule Labor		3.6
Engineering & procurement		9.7
		100.0



Project not complete and may change over time

Cavity Raw Material Cost:



- Data from Jlab cavity projects over time shows a steady increase in RRR niobium prices
- Large quantity (80-360) cavity material prices are lower then small quantity pricing but the gap is increasing
- Reactor grade material (small quantity) seem to be rising as well

Some typical CW parameters (JLab upgrade)

- Frequency 1.5 GHz
- 15-20 MV/m CW (~10 MV/m real estate gradient)
- Q_o ~ 10^{10} at 20 MV/m (has been demonstrated)
- CM Cost ~$2.6M*/100 MeV (Jlab upgrade module)
- RF ~$1.7M/cryomodule (8x13kW RF stations)** @~1mA
- 2K cryogenic plant ~$30M/GeV (CHL2) excluding distribution. JLab as integrating contractor
- ~7.3 cents/volt or $73M/GeV (excluding tunnel costs)
- ~$73/watt electron beam power (1ma @ 1GeV =1MW)

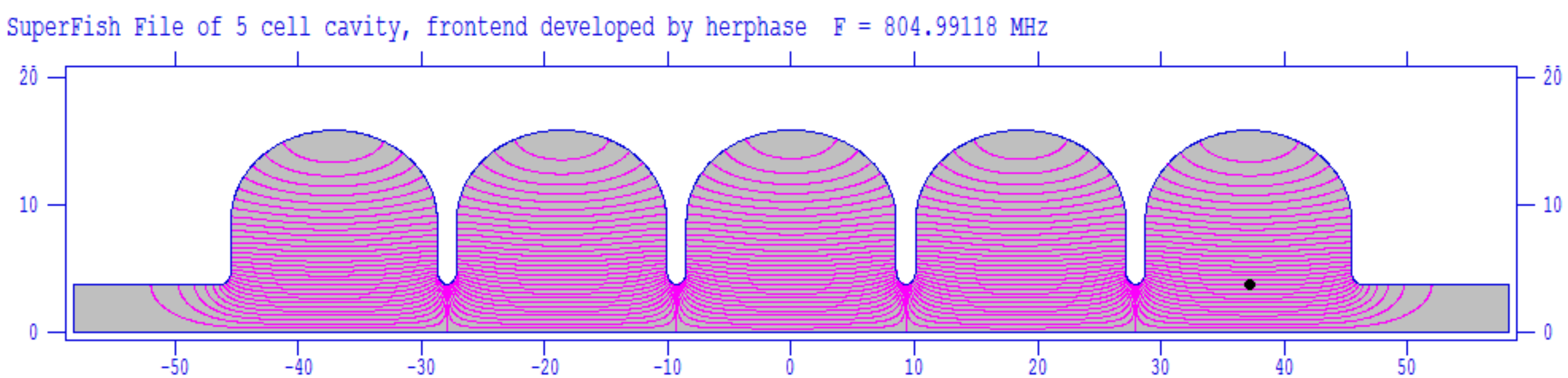
*FY08 loaded dollars, actual 12 GeV project costs will be known soon

**$16/W

805 MHz low-loss Cavity parameters

- 0 degree wall angle, small iris
- Same shape for mid&end cell
- Could use SNS type cryomodule
- N^2/k~3000, better than JLab-LL
- Assuming Ea=15MV/m, then Ep=36MV/m, Bp=50mT.
- Assume Rres~10nΩ at 2K, so Q_0~2.0e10, P_{loss}~12.6W at 15MV/m
- MP and HOM NOT investigated yet

Frequency [MHz]	805
Cavity inner diameter [mm]	316.7
Beam pipe diameter [mm]	75.74
Cavity total length [mm]	1165
Cavity active length [mm]	925.2
Ep/Ea	2.40
Bp/Ea [mT/(MV/m)]	3.34
Geometry factor [Ω]	288
Ra/Q [Ω]	764
Ra*Rs (=G*Ra/Q) [$Ω^2$]	2.20×10^5
Cell-to-cell coupling k	0.84%



TLEP parameters and costs

- Costs: manual scaling from previous projects

	Energy	$Loss_{SR}$	Vtot/ ring	SR power per ring	#cavs per ring	total cavs	grad.	power per coupler	Current	#CM's	Cryo*	RF cost*	CM cost	LLRF*	cryo cost*	Cap cost	10 years ops*	total cap+10 years
	GeV	GeV	GV	MW			MV/m	kW	mA	(8/cm)	kW@2k	$M	$M	$M	$M	$M	$M	$M
TLEP Z	45	0.04	2	50	100	200	20	500	1180	25	5	1000	60	8	30	1098	650	1748
TLEP W	80	0.4	4	50	200	400	20	250	119	50	10	1000	103	16	60	1179	650	1829
TLEP H	120	2	6	50	300	600	20	167	24.3	75	15	1000	142	24	90	1256	650	1906
TLEP t	175	9.2	12*	100	600	600	20	167	5.4	75	15	1000	142	24	90	1256	650	1906
LEP3	120	6.99	12*	100	600	600	20	167	5.4	75	15	1000	142	24	90	1256	650	1906
			*shared								*200W/cm	*$10/W		*$40k/cav	*$30M/5kW		$65/MWH 50% eff.	

- Also ran through Tom Powers' calculator

General Input Parameters For Model

Tom Powers

General I/O parameters | Parameter arrays | Page 2 | Page 3

SRF Parameters IN

Final Energy	2.00
Nom Gradient (V/	5.0E+6
Frequency	800E+6
Cavities per CM	8
Active Length (m)	0.9252
r/Q (Ohms/m)	825.76
Linac Packing Factor (%) Total L / Total Active Length	1.75
Detune Allowance (Hz)	20
RF Power margin	1
Temperature (K)	2
QL Uncertainty	0
Maximum QL	2E+7
Bp/Eacc ((mT/(MV/m)	3.34
Geometry Factor (Ohms)	288
Material Treatment	Fine Grain Baked at 120C
Transient Handling	After Transients

For ERL Use ERL Parameters Table

Beam Current (A)	0.0243
Beam Phase (deg)	70
ERL?	

Baseline Costs

Cryomodule ($M each)	2
RF Power ($/W)	10
RF Controls($k/cavity	40
Inner CM Girder ($k each)	265
Tunnel Civil ($k/m)	75
AC Power ($/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)	1076.7
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

Cryo heat loads (W)

Static CM + Valve box (W)	30
Transfer Lines (W/km)	150
Qo Improvement (NOM = 1.00)	4.00
Qo Slope Adjust (NOM = 0.00)	-6.00

Temperature Array: 0 | 1.8, 1.9, 2, 0

EMin (V/m)	5E+6
EMax (V/m)	25E+6

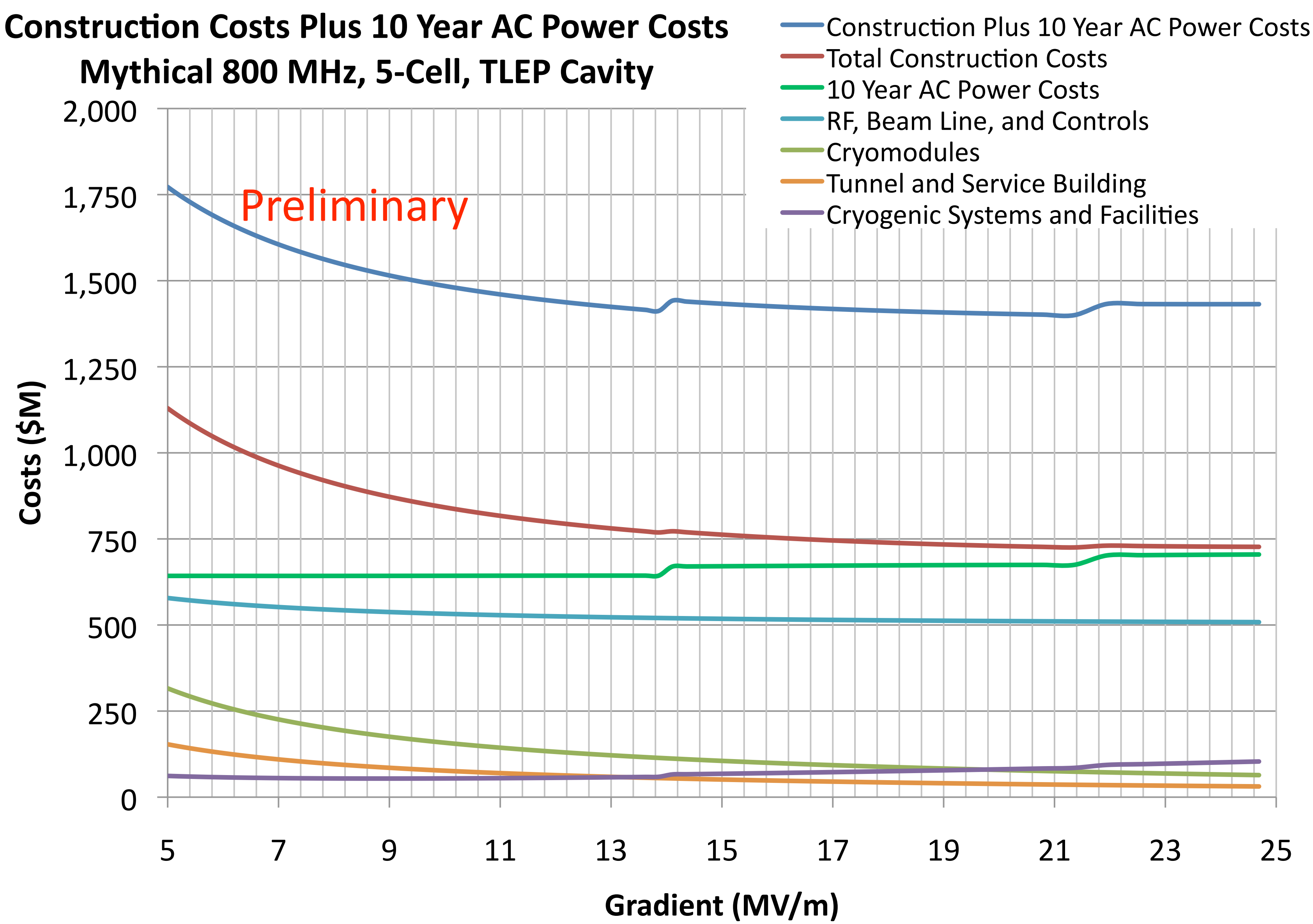
Consider loaded Q bandwidth when setting maximum loaded Q.

Linac overall parameters out

Linac Costs ($M)	1764
Cryomodules($M)	316
RF PWR & Ctls Costs ($M)	536.8
Inner CM Girders ($M)	41.6
Tunnel Civil ($M)	153.5
Cryo plant and facility ($M)	54.1
10 yr Linac & Cryo AC pwr cost ($M)	642
Linac Length (m)	2047
Number Cryomodules	158
Number Cavities	1264
Number inner CM Girders	157
Linac Active Length	1169.5
CM dynamic heat load	2
Linac 2K heat load (W)	5221
CryoPlant with Margin (W)	7831
CryoPlant Eff (ACW/2KW)	1077
Qo	1.07E+11
Matched Loaded-Q	7.28E+5
RF pwr per Cavity (kW) Includes QL variance and Margin	38.5
Total RF Power (kW)	48616
Cryo AC Power (MW)	10.54
RF, Magnets and Cntls AC (MW)	121.64
Actual Gradient (MV/m)	5E+6

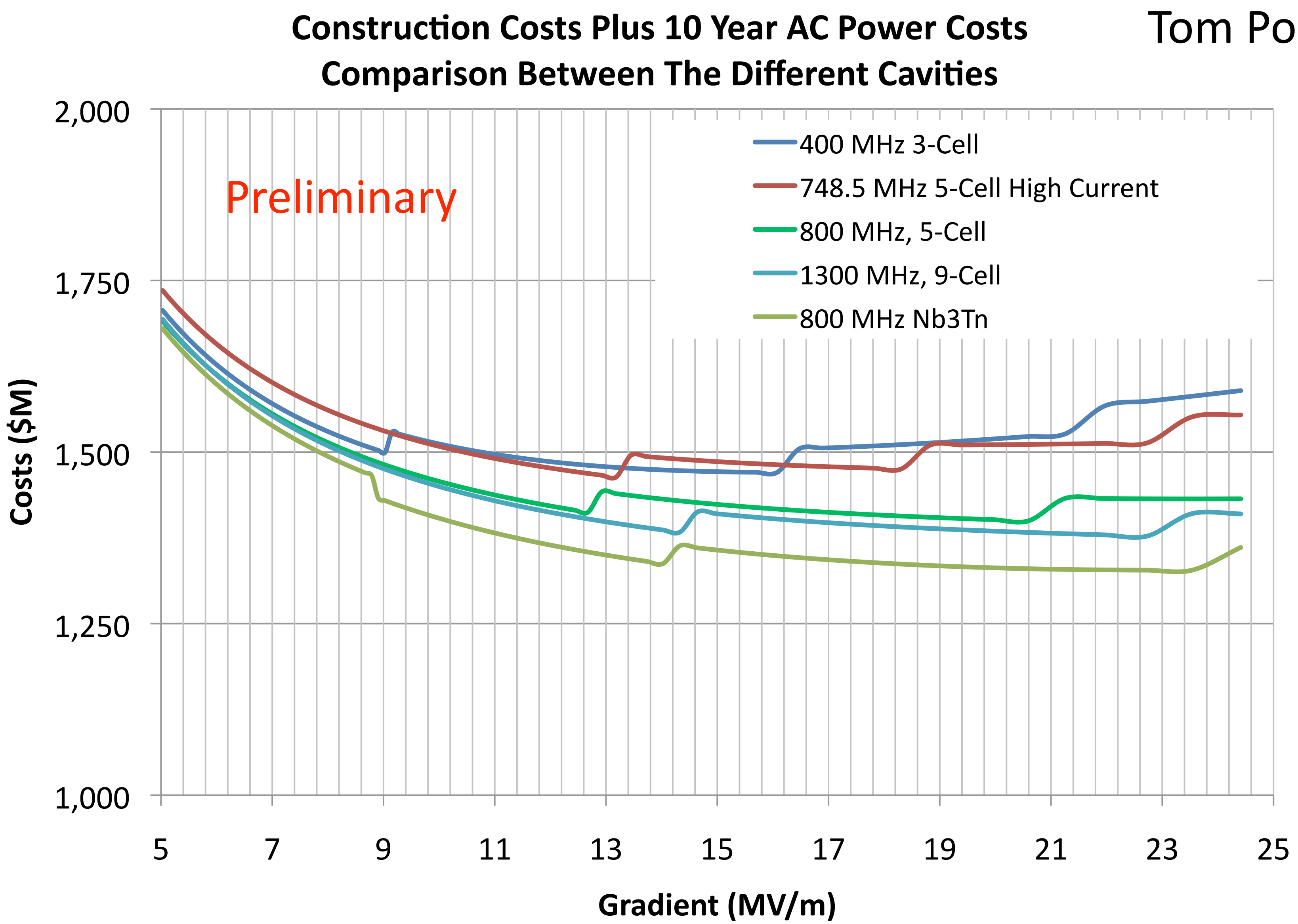
Cost vs. Gradient, 800 MHz

Tom Powers

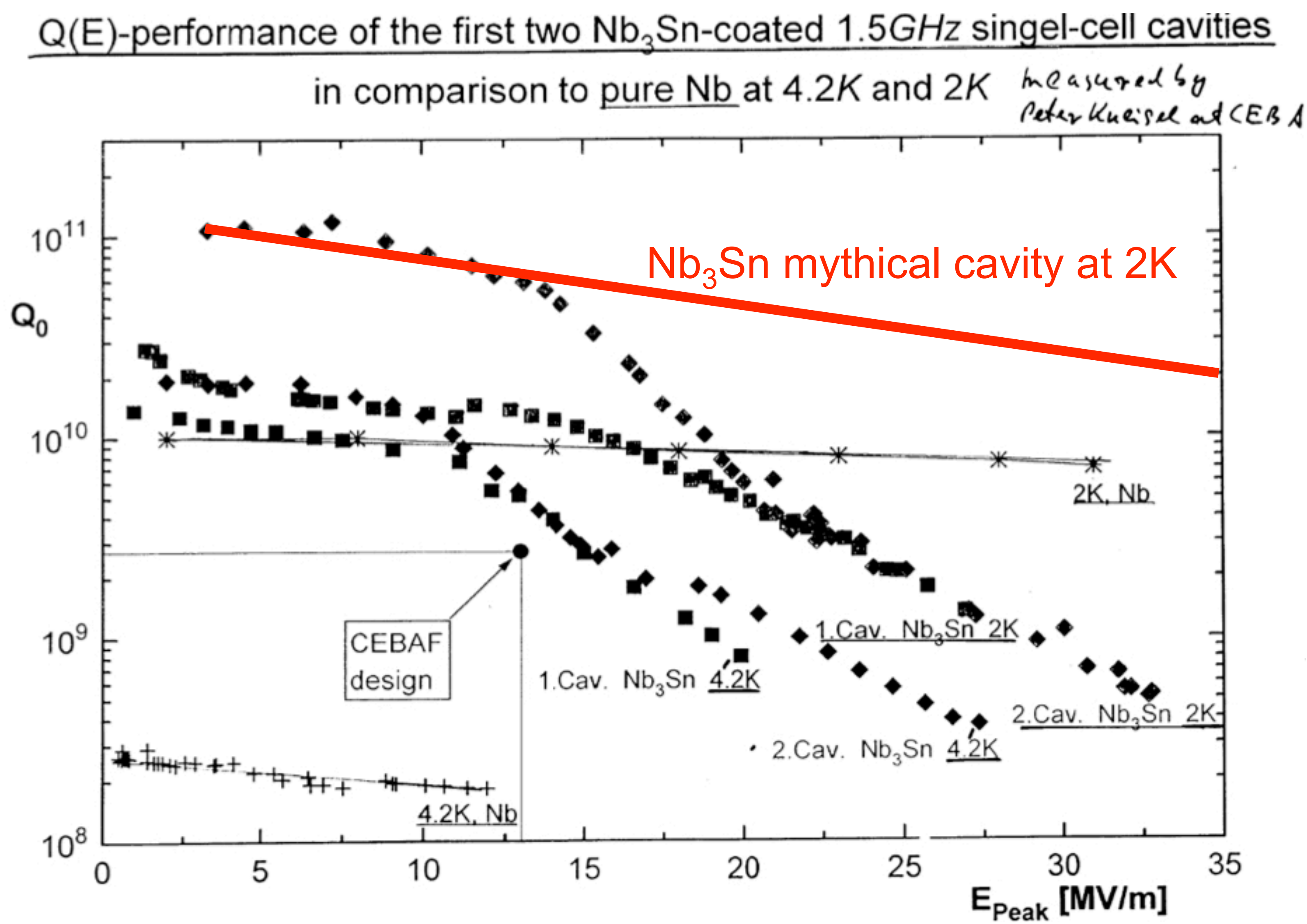


Comparison of options

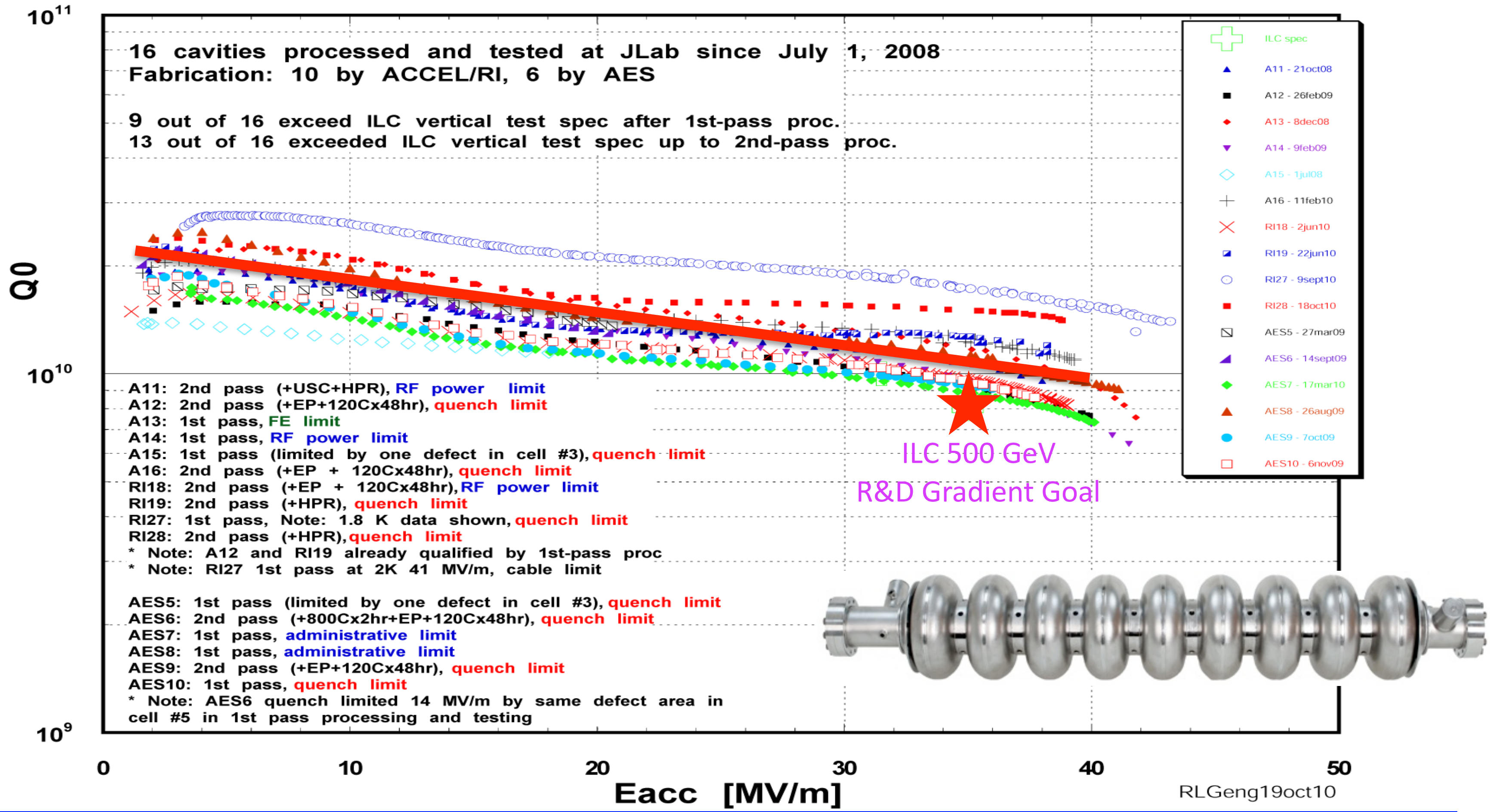
Tom Powers



Potential of Niobium Tin for SRF cavities



State-of-the-Art Gradient Results



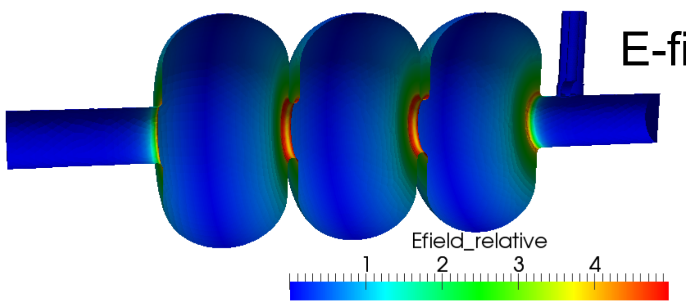
As a result of continued SRF cavity R&D at CERN, Cornell, DESY, JLAB, KEK, SACLAY and other labs, modern 9-cell TTF-style cavities increasingly exceed 35 MV/m at Q_0 P 8×10^9. Gradient in the range of 40-43 MV/m demonstrated and confirmed independently in real 9-cell (and 7-cell) cavities, corresponding to a surface magnetic field of 160-180 mT.

400 MHz Elliptical Cavity Development

Highly efficient cell shape

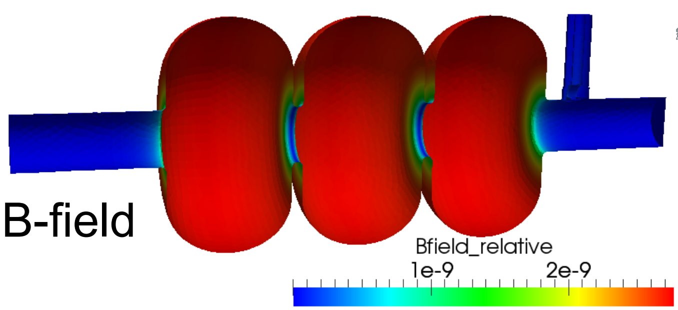
- 0 degree wall angle, small iris
- Same shape for mid & end cell
- E_p=20MV/m, B_p=25mT,
- Q_0=3.5e9 at 4K (P_{loss}=44W) @12.5 MV/m
- Q_0=2.6e10 at 2K (10 nΩ R_{res}) 16W

Frequency [MHz]	400
Cavity inner diameter [mm]	636
Aperture diameter[mm]	150
Beam pipe diameter [mm]	150
Cavity active length [mm]	1109
Ep/Ea	2.55
Bp/Ea [mT/(MV/m)]	3.26
Geometry factor [Ω]	288
Ra/Q [Ω]	468
Ra*Rs (=G*Ra/Q) [$Ω^2$]	1.35×10^5
Cell-to-cell coupling k	0.78%

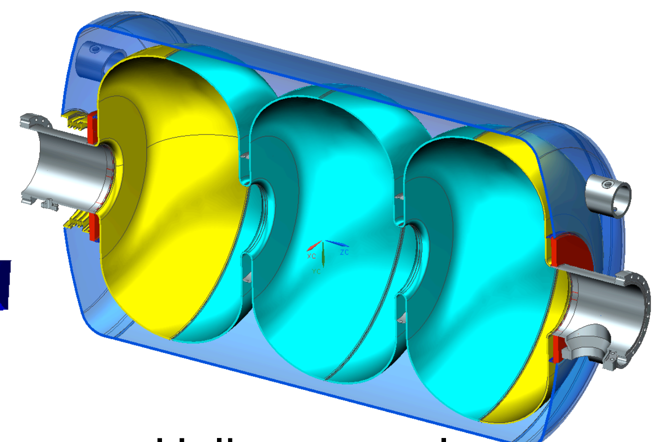


E-field

Feisi He, PKU

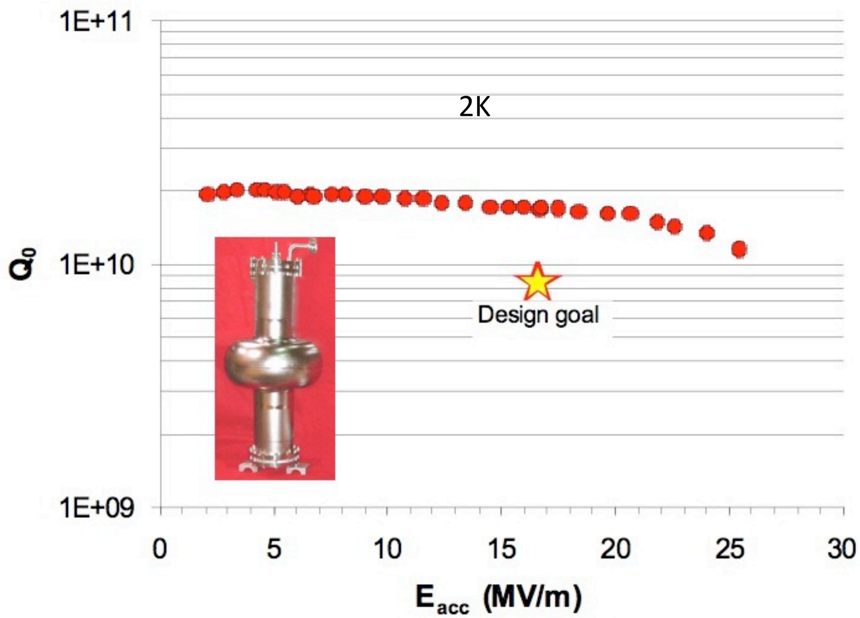


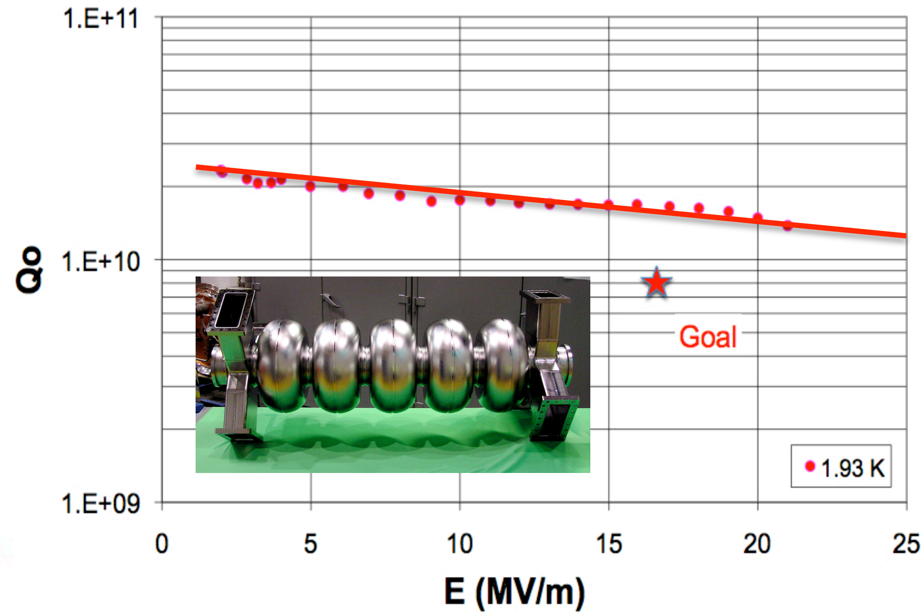
B-field

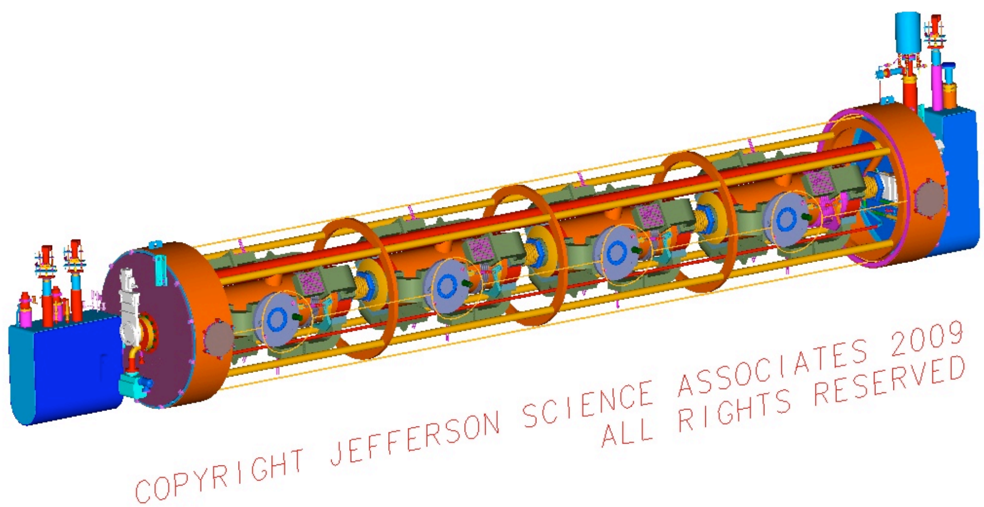


Helium vessel

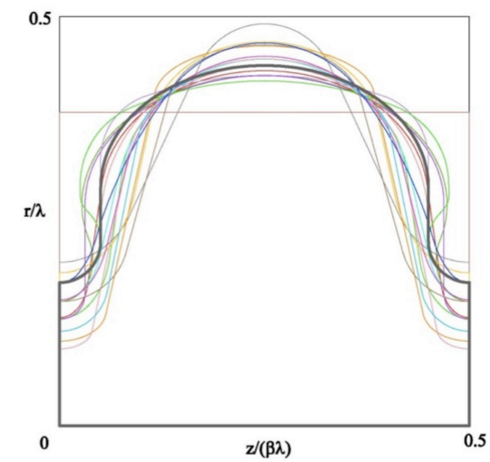
Jlab High-current 750 MHz ERL cavity





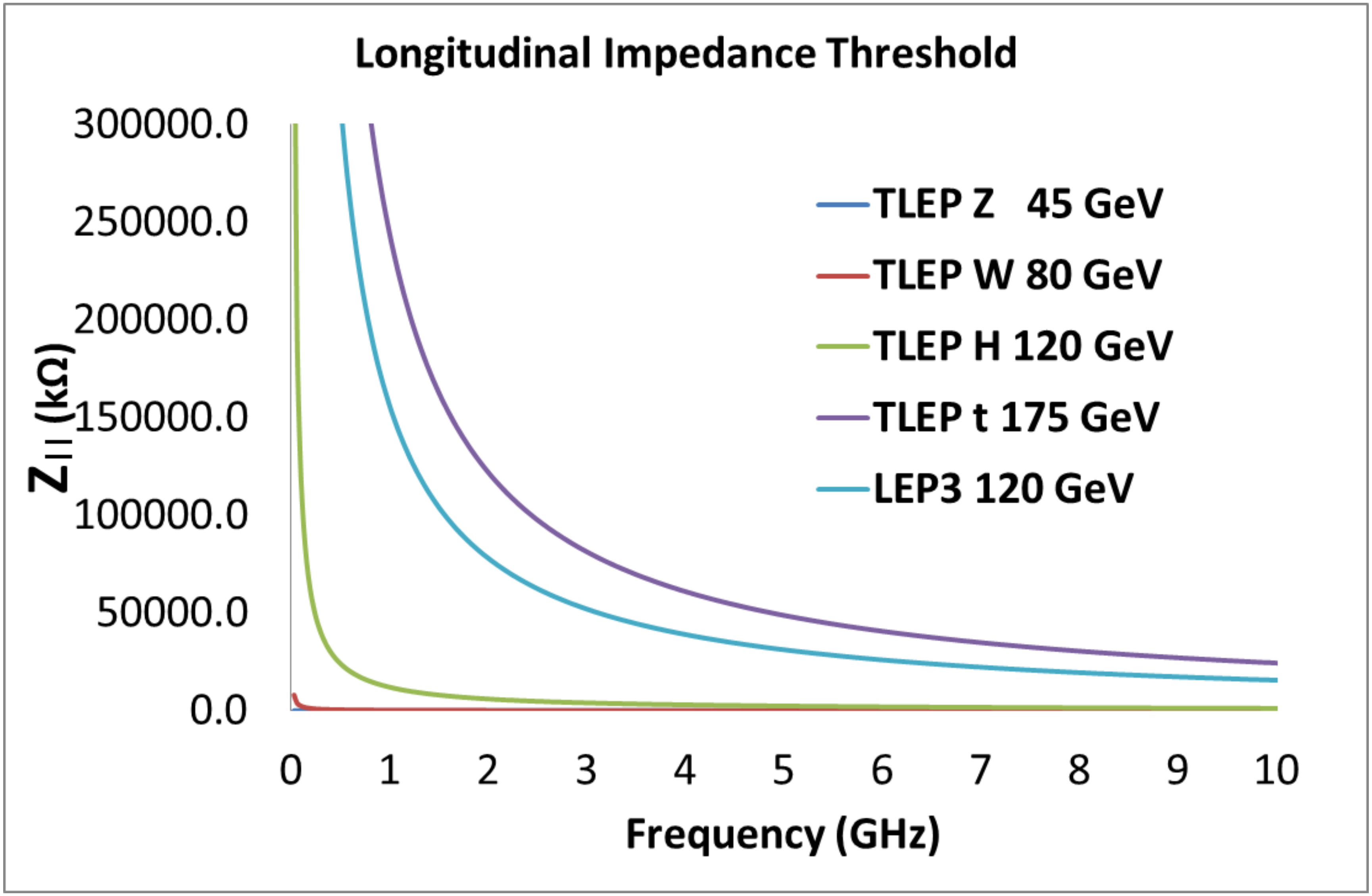


Multipacting seen from low gradient but processed away

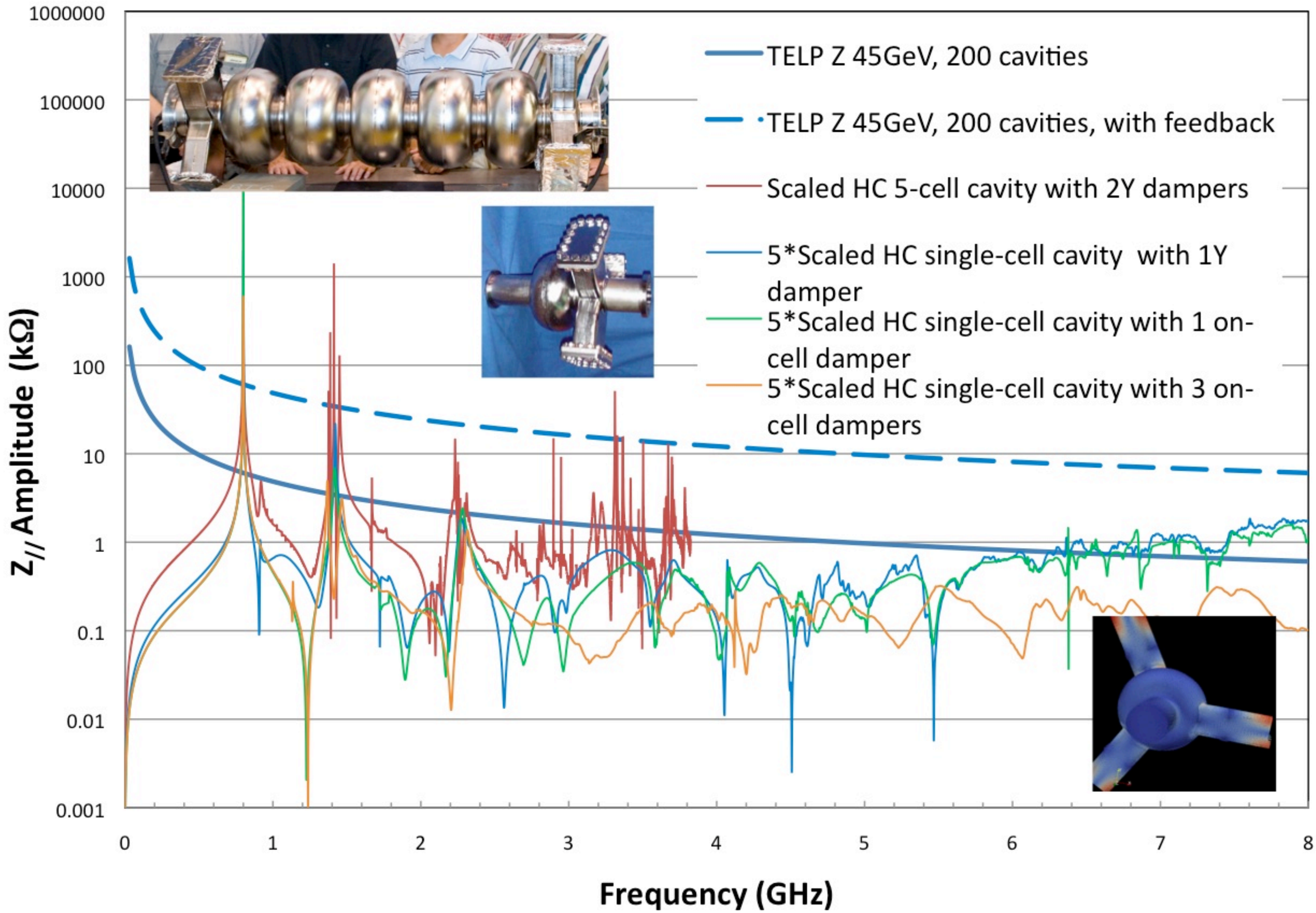


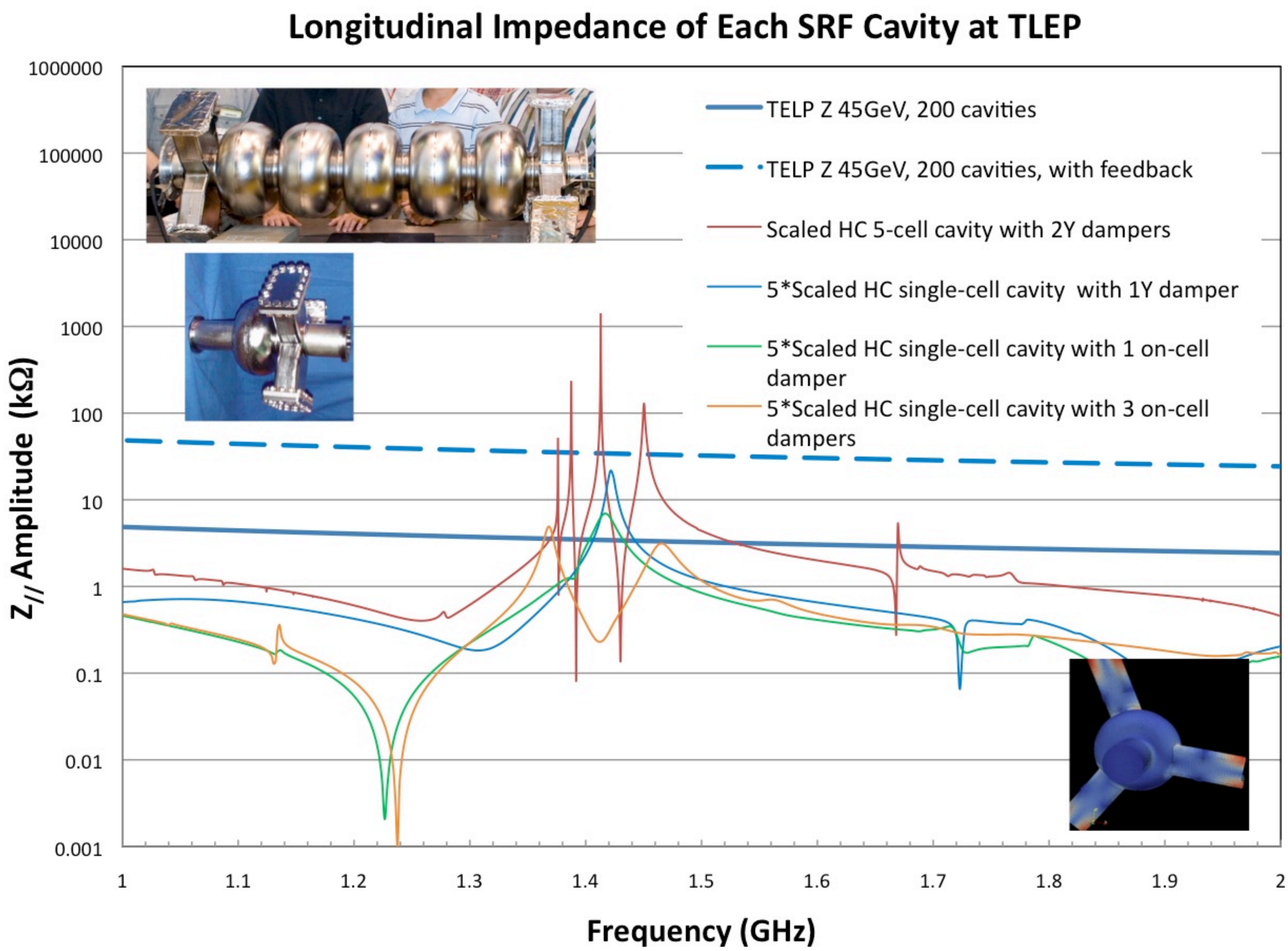
Longitudinal Coupled-bunch Instability threshold

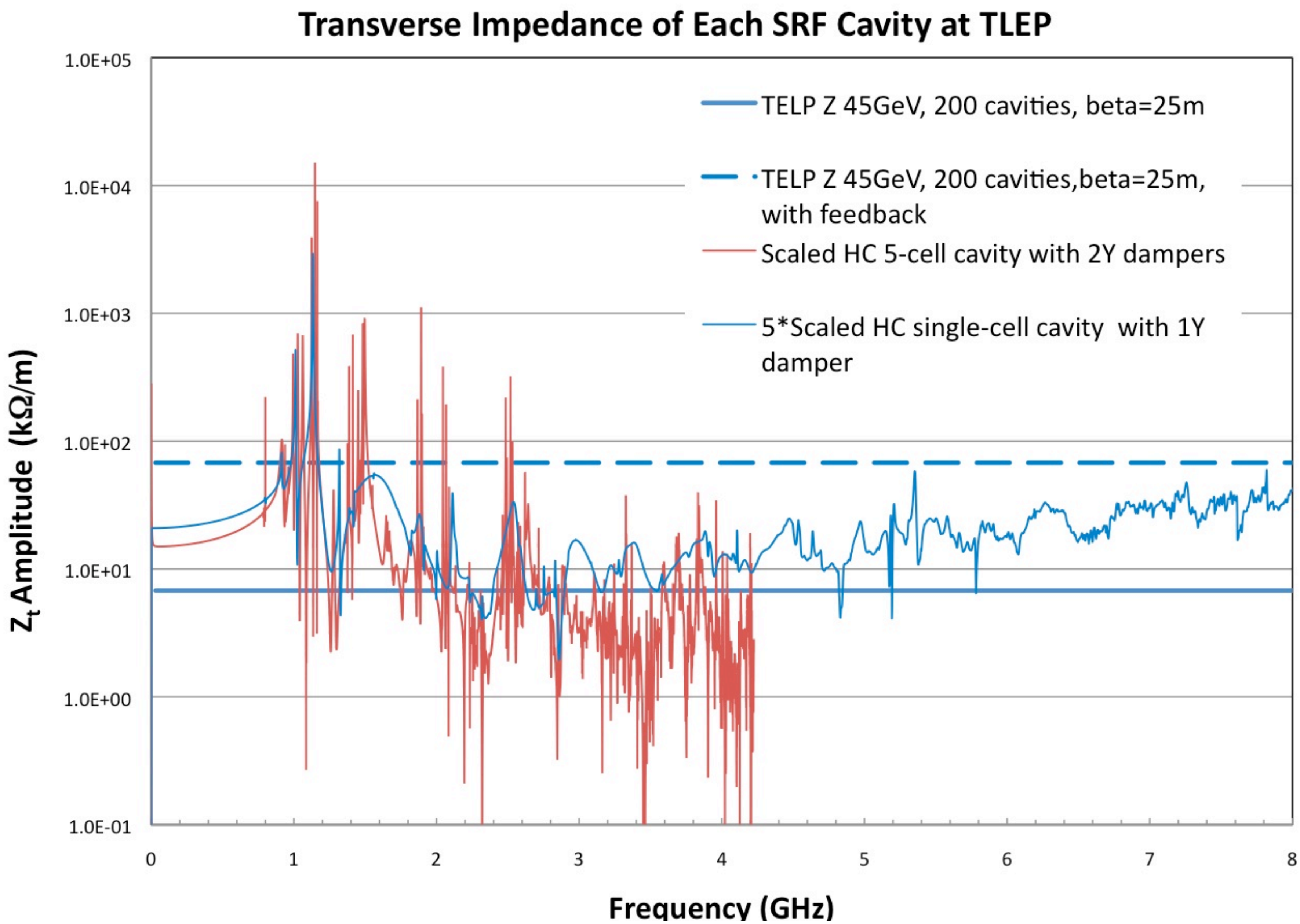
(per cavity, assuming 600 cavities)



Longitudinal Impedance of Each SRF Cavity at TLEP

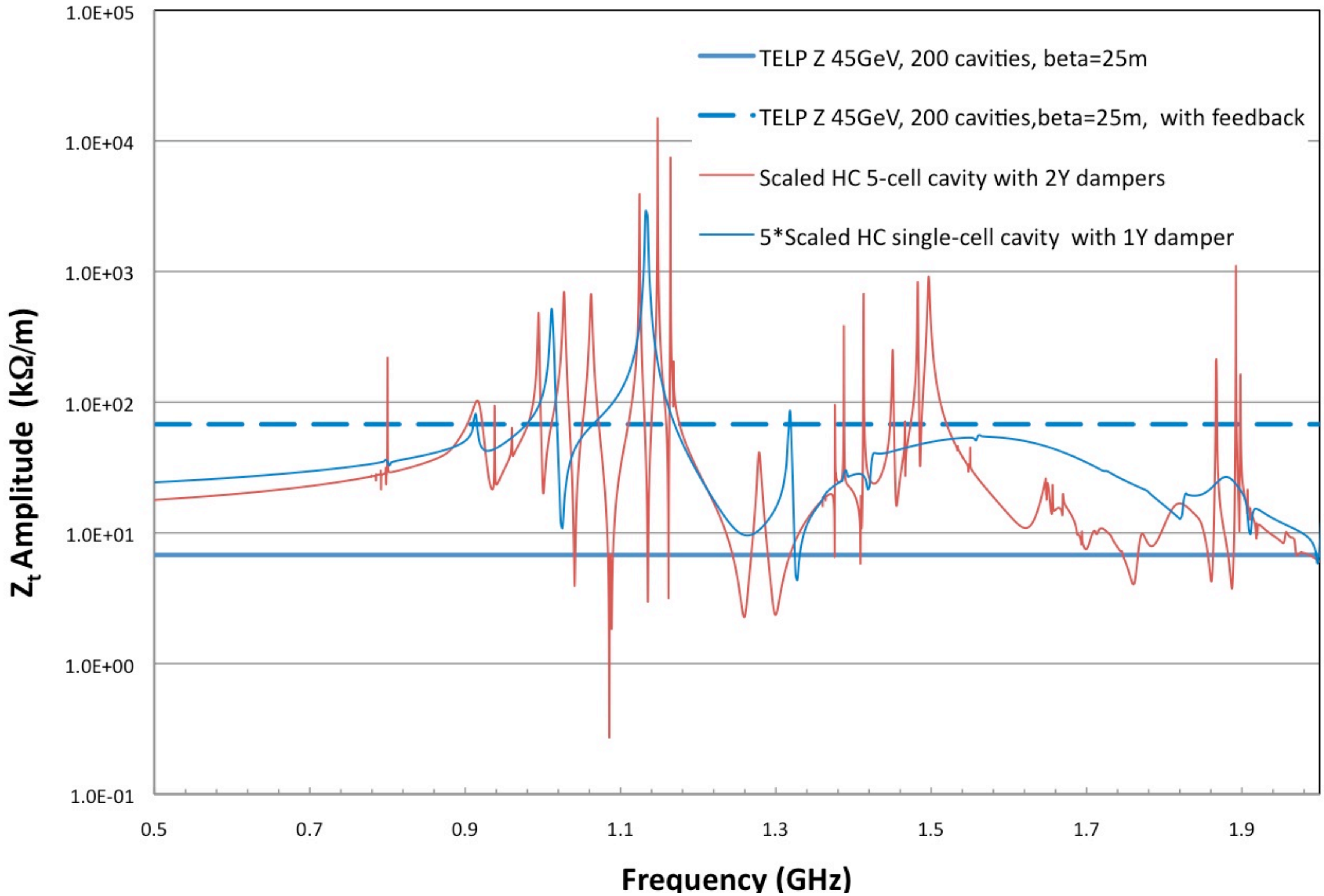



Longitudinal Impedance of Each SRF Cavity at TLEP
1000000
100000
10000
1000
100
10
1
0.1
0.01
0.001
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
$Z_{//}$ Amplitude (kΩ)
Frequency (GHz)
TELP Z 45GeV, 200 cavities
TELP Z 45GeV, 200 cavities, with feedback
Scaled HC 5-cell cavity with 2Y dampers
5*Scaled HC single-cell cavity with 1Y damper
5*Scaled HC single-cell cavity with 1 on-cell damper
5*Scaled HC single-cell cavity with 3 on-cell dampers



Jefferson Lab

Transverse Impedance of Each SRF Cavity at TLEP



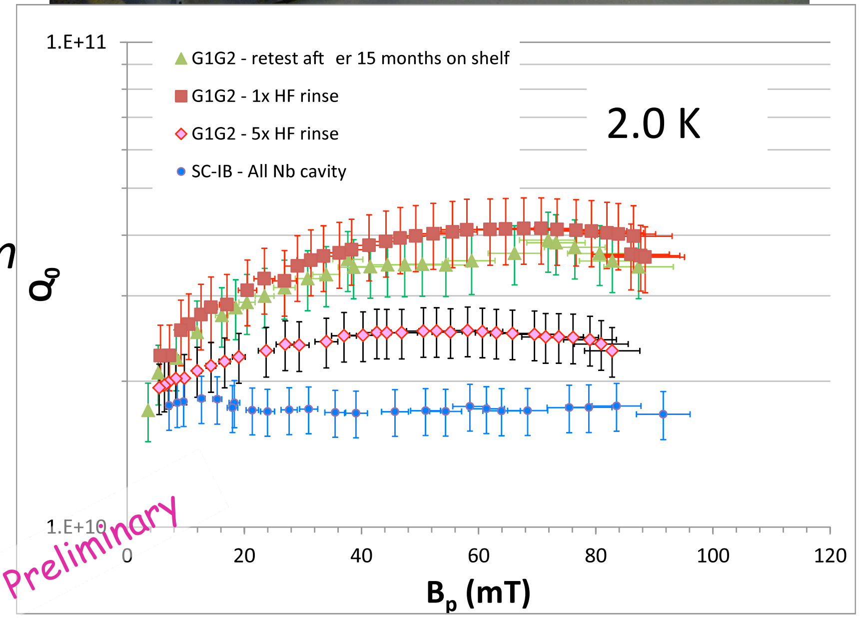
Options for improvement via targeted R&D

- Lower cost, higher efficiency RF sources
  - IOT's, magnetrons, solid state?
- Higher Q_0
  - High temp furnace treatments
  - Nb_3Sn (nice new result from Cornell)
  - MgB_2 or something new?
- Improved HOM damping (on-cell dampers?)
  - First tried on ANL crab cavity, plan to try on MEIC
  - Higher packing factor
- Reduced cryomodule costs
  - Cheaper materials, reduced labor
- Find a way to use the same RF for the booster ring?

High Q_0 R&D

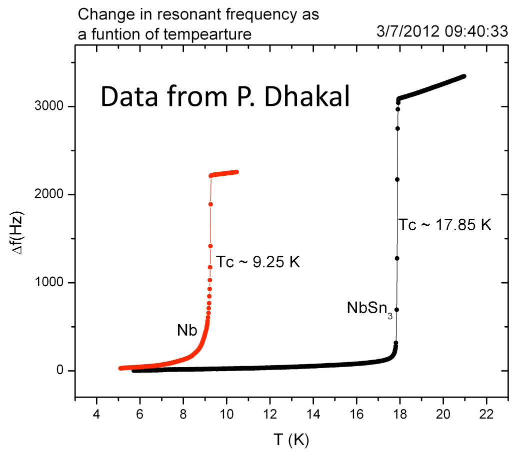
G. Ciovati et. al.

- Induction furnace successfully re-commissioned in Test Lab North Annex
  - *New Ultra-High Purity gas delivery system (H_2, O_2, Ar, N_2)*
  - *New ISO 4 soft-wall clean room*
  - *New water cooling system*
- Investigation of "low-field Q-rise" by sequential nanoremoval and HT of "all Nb" cavity
  - *The effect is confined to the top ~10 nm*
  - *~1 at.% Ti within the RF penetration depth seems necessary*

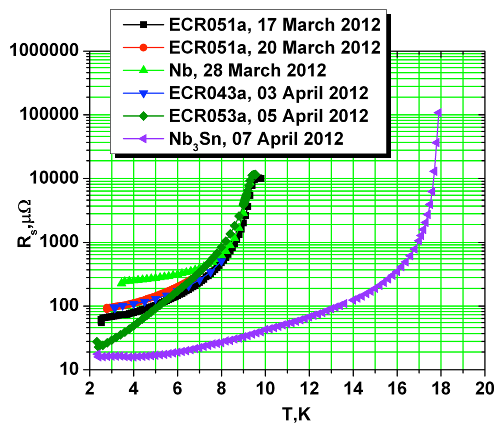


Nb_3Sn progress at JLab

Grigory Eremeev



Transition temperature is ~ 17.85 K. The best of three samples shows very smooth surface with no residual tin contamination

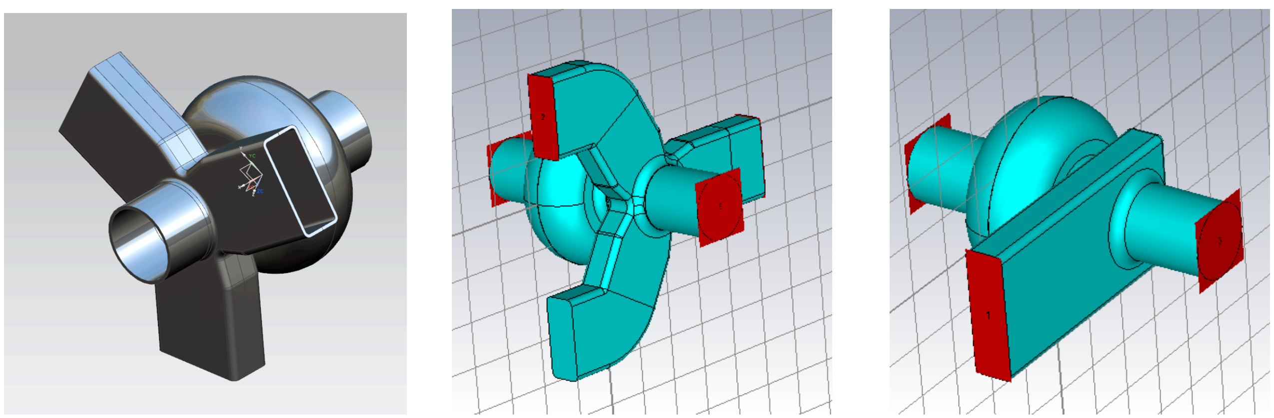


Recent measurements of surface resistance of several ECR films, bulk Nb sample, and Nb_3Sn sample as a function of temperature at 7.4 GHz.

- Preliminary studies with samples have been done. RF measurements on a sample indicated the transition temperature of 17.9 K and RF surface resistance of about 30 $\mu\Omega$ at 9 K and 7.4 GHz.
- The horizontal insert has been built and inserted in the furnace. The first furnace run has been done at 1200 °C for 2 hours.
- R&D furnace for Nb_3Sn development has been ordered in October 2012. It is expected to be delivered in August 2013.

Possible future improvements: structures

- KEK 9-cell, Cornell 7-cell, BNL 5-cell, HZB, etc.
- Simplify waveguide end groups?
  - Reduce static load
  - Maintain high power handling
  - Extend JLab "on-cell" damping to multi-cell cavities?

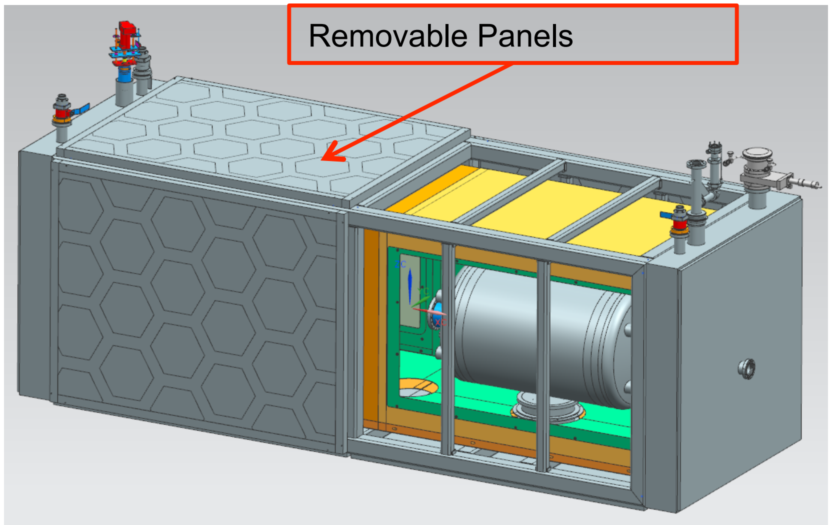


750 MHz MEIC e-ring concepts

ANL SPX prototype with on-cell damper

Low Cost Box Cryostat Design

John Mammosser

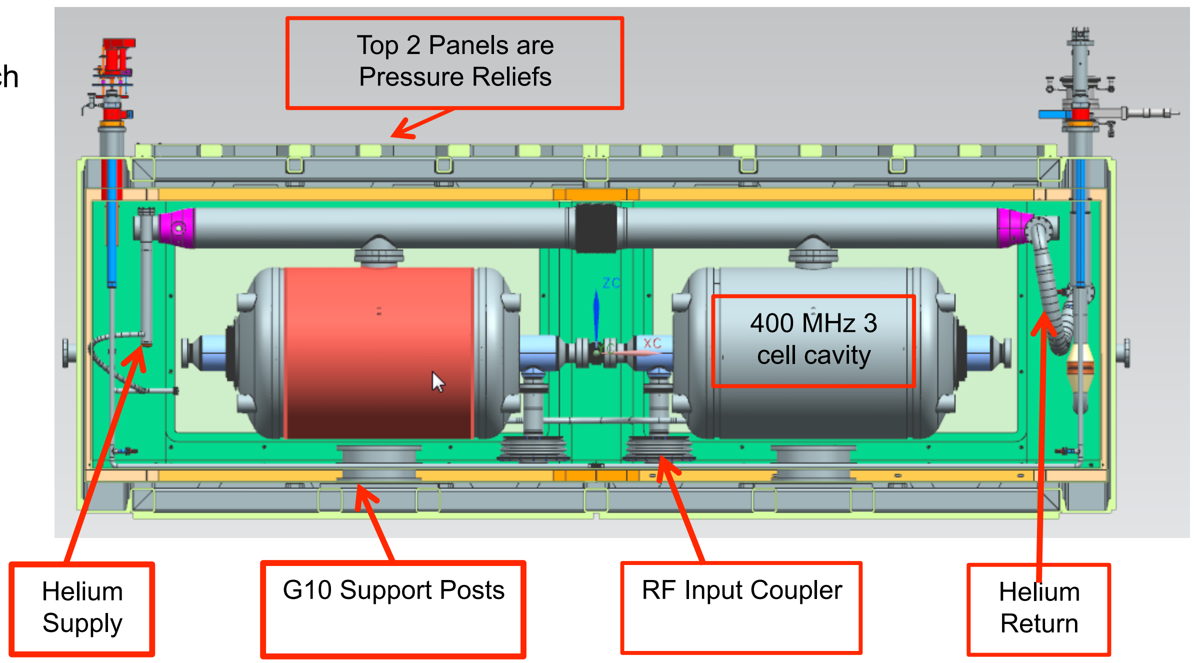


Basic concept is a simple box:

- Structure is square tube stainless steel frame
- Removable panels for servicing and upgrading
  - Removable support struts
  - Removable thermal shield panels
  - Vacuum sealing o-ring fabricated in face
- Bottom and ends are stainless steel plate

Panel Options:

- Honeycomb sandwich
- Stainless sandwich



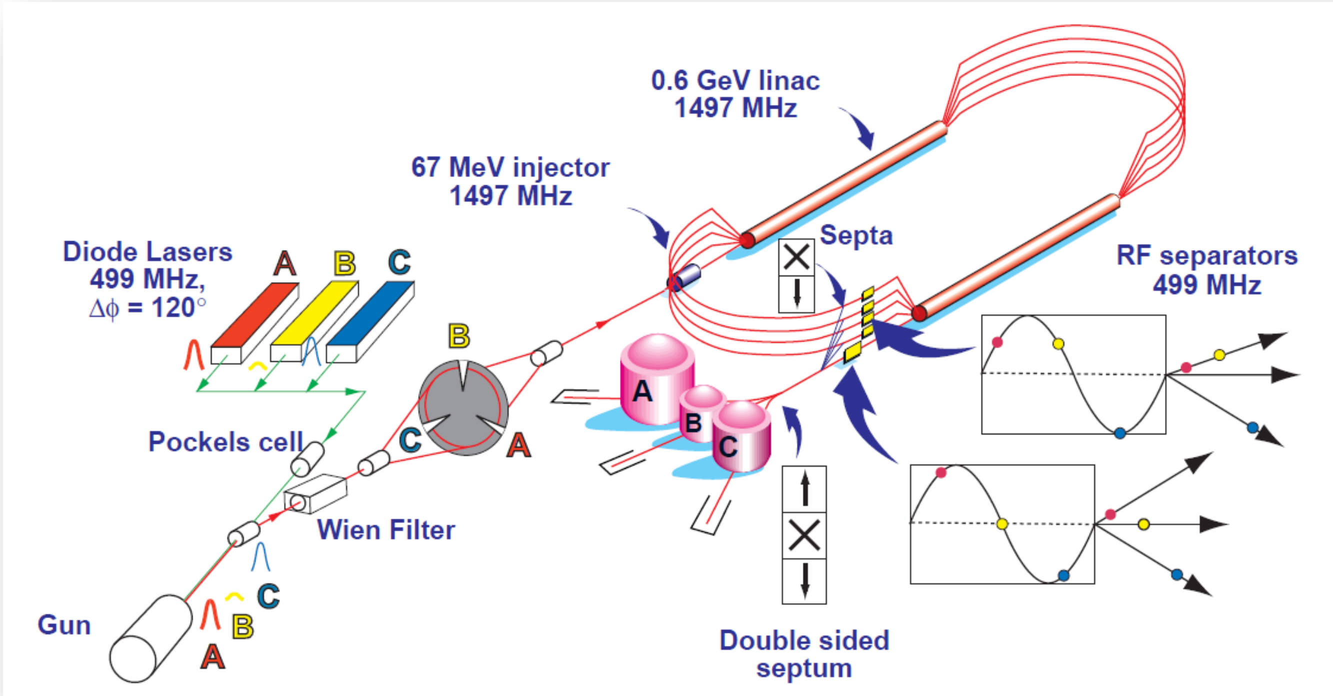
Conclusions

- Combination of high voltage and high current is challenging
- RF costs dominate (capital and operating)
- Beam stability is a concern at high current
- R&D can address the issues

Thank you!

Back up

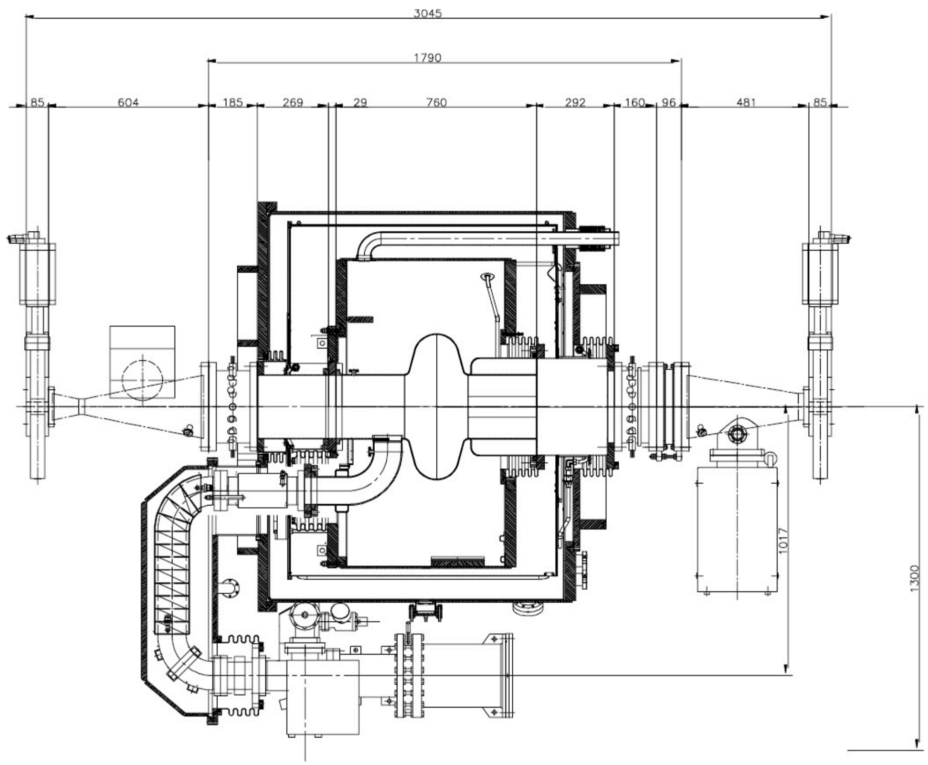
CEBAF overview



First large high-power CW recirculating e-linac based on SRF technology
In operations since **1995** → served ~1400 nuclear physics users
Capabilities: 5 passes, multiple energies, beam characteristics, polarization
3 Halls running simultaneously
Upgrade to 12 GeV: proposal late 1990's → approved and funded in 2004

Storage ring SRF cavities

- Cornell CESR 500 MHz cavity, KEK B cavity
- High average power delivered to beam
- High reliability for user operations



Formula

TLEP and LEP3 are e^+e^- circular colliders capable of very high luminosities in a wide centre-of-mass (ECM) spectrum from 90 to 350 GeV, TLEP and 240 GeV, LEP3. LEP3 intends to use the LHC tunnel.

The threshold impedance spectrum for the excitation of multibunch instabilities in electron ring can be obtained by equating the radiation damping time with the respective multibunch instability rise time

$$Z_{\parallel}^{\text{thresh.}} = \frac{1}{N_C} \cdot \frac{1}{f_{\parallel,HOM}} \cdot \frac{2 \cdot E_0 \cdot Q_s}{I_b \alpha \tau_s} \quad (1)$$

$$Z_{x,y}^{\text{thresh.}} = \frac{1}{N_C} \cdot \frac{2 \cdot E_0}{f_{rev} I_b \beta_{x,y} \tau_{x,y}} \quad (2)$$

Parameters used in Calculation

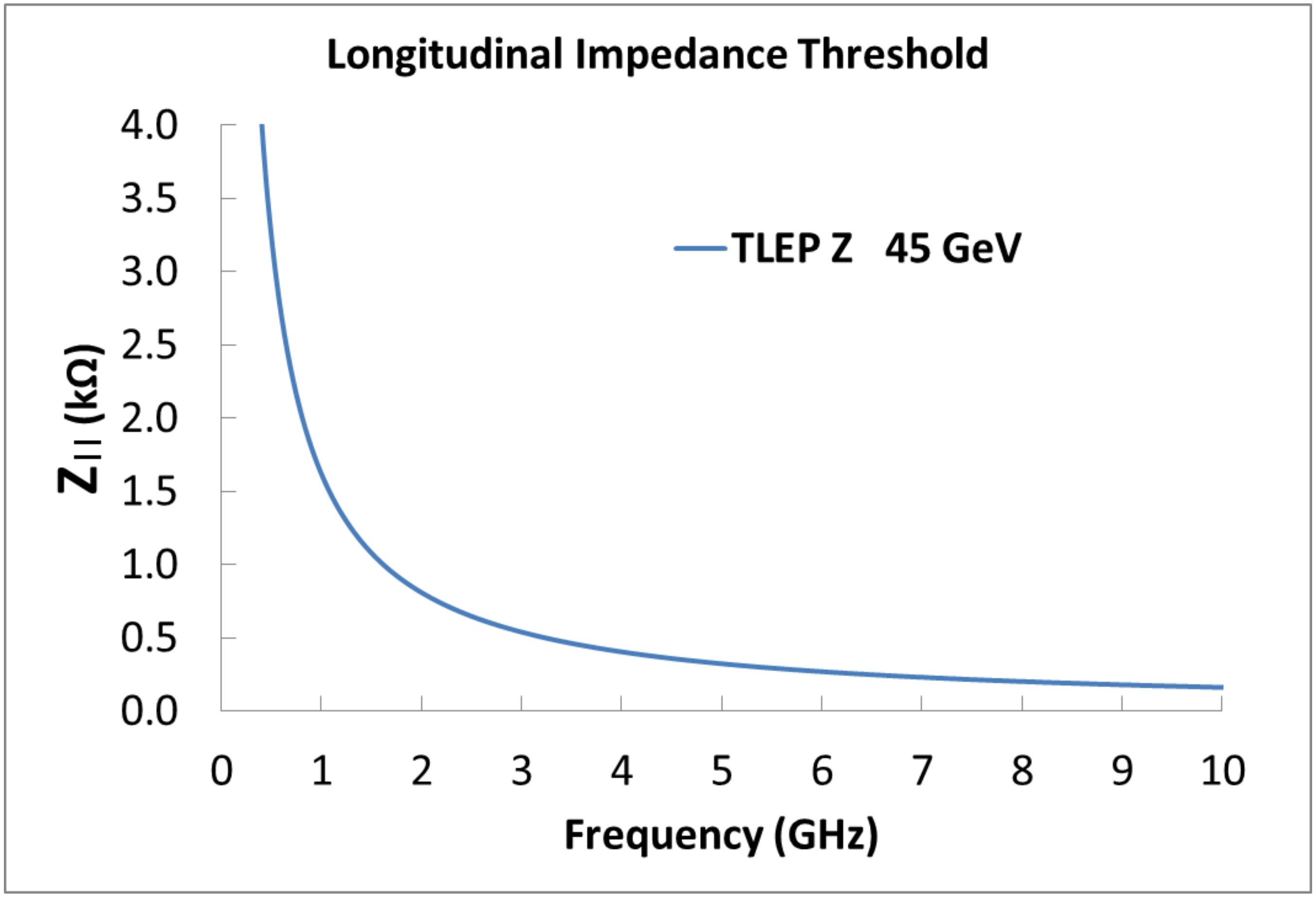
	Energy GeV	Synchrotron Tune	Current A	Moment. compact	τs sec	τt sec	$Loss_{SR}$ GeV
TLEP Z	45	0.344	1.18	9.0E-05	0.30000	0.60000	0.04
TLEP W	80	0.120	0.124	2.0E-05	0.05333	0.10667	0.4
TLEP H	120	0.1170	0.0243	1.0E-05	0.01600	0.03200	2
TLEP t	175	0.110	0.0054	1.0E-05	0.00507	0.01014	9.2
LEP3	120	0.348	0.0072	8.1E-05	0.00153	0.00306	6.99

Cavity number: 600

TLEP circumference: 80 km
LEP3 circumference: 26.7 km

Beta function at RF cavity is assumed to be 4m, which influence the transverse impedance threshold only.

Longitudinal Impedance threshold



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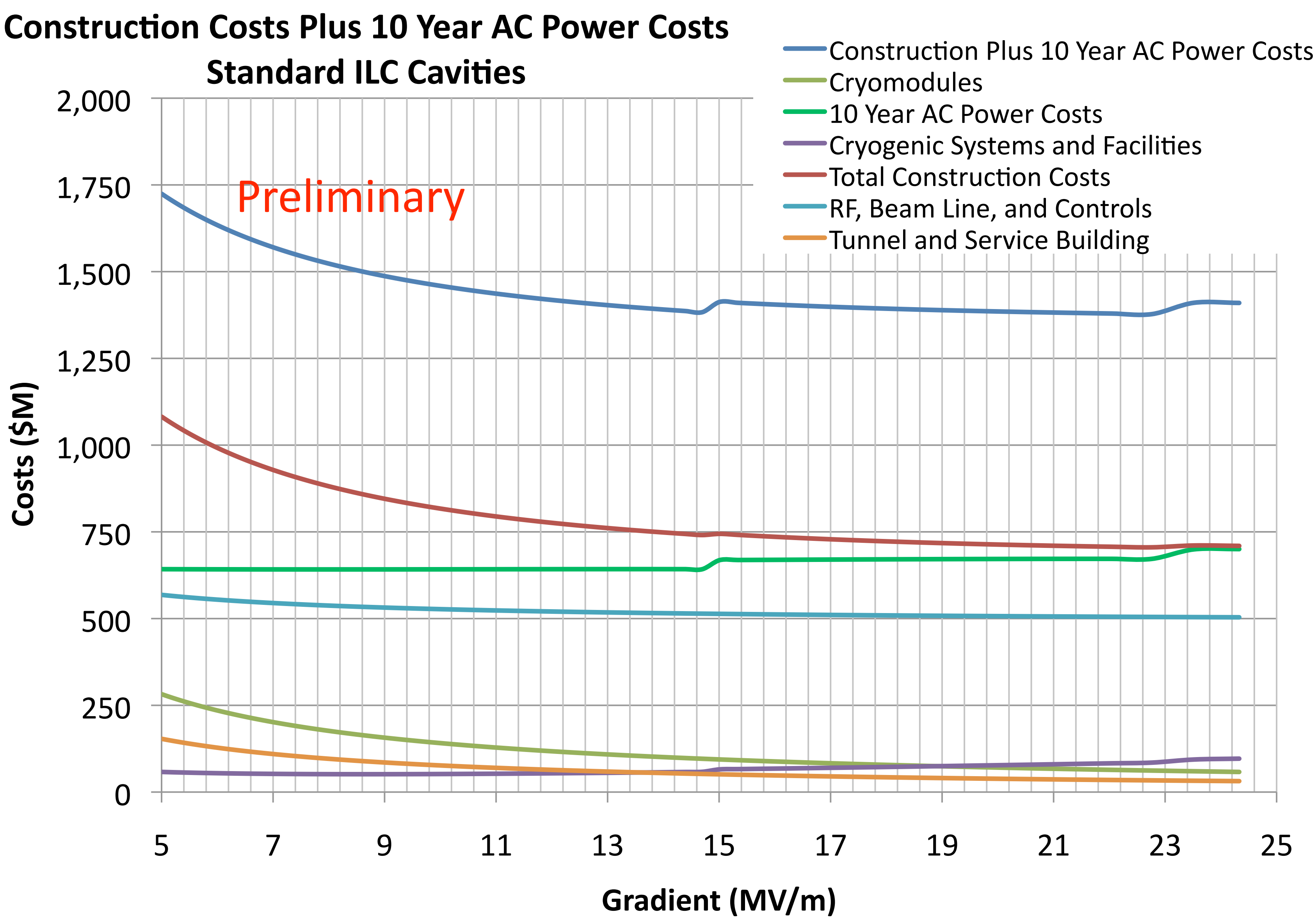
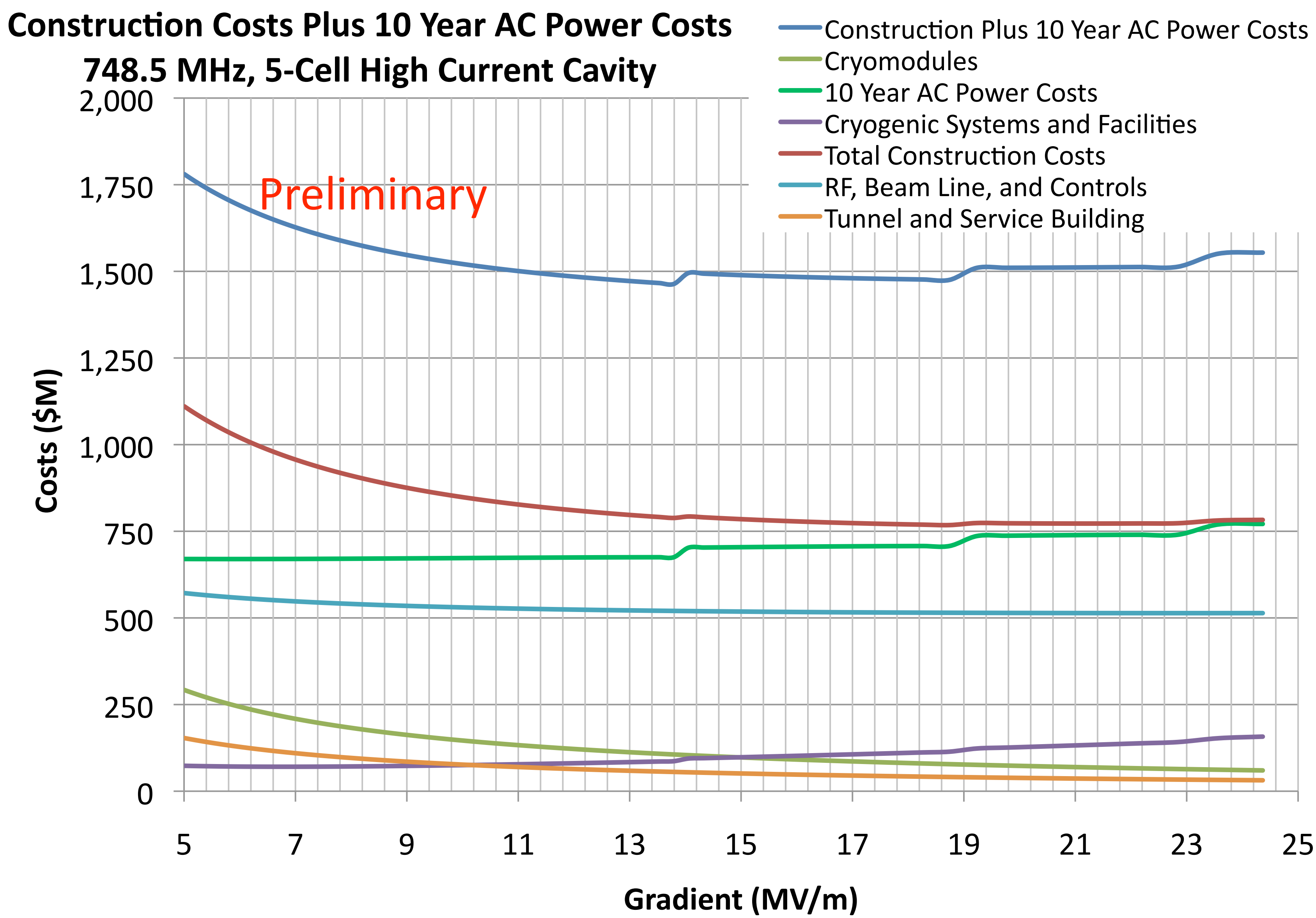
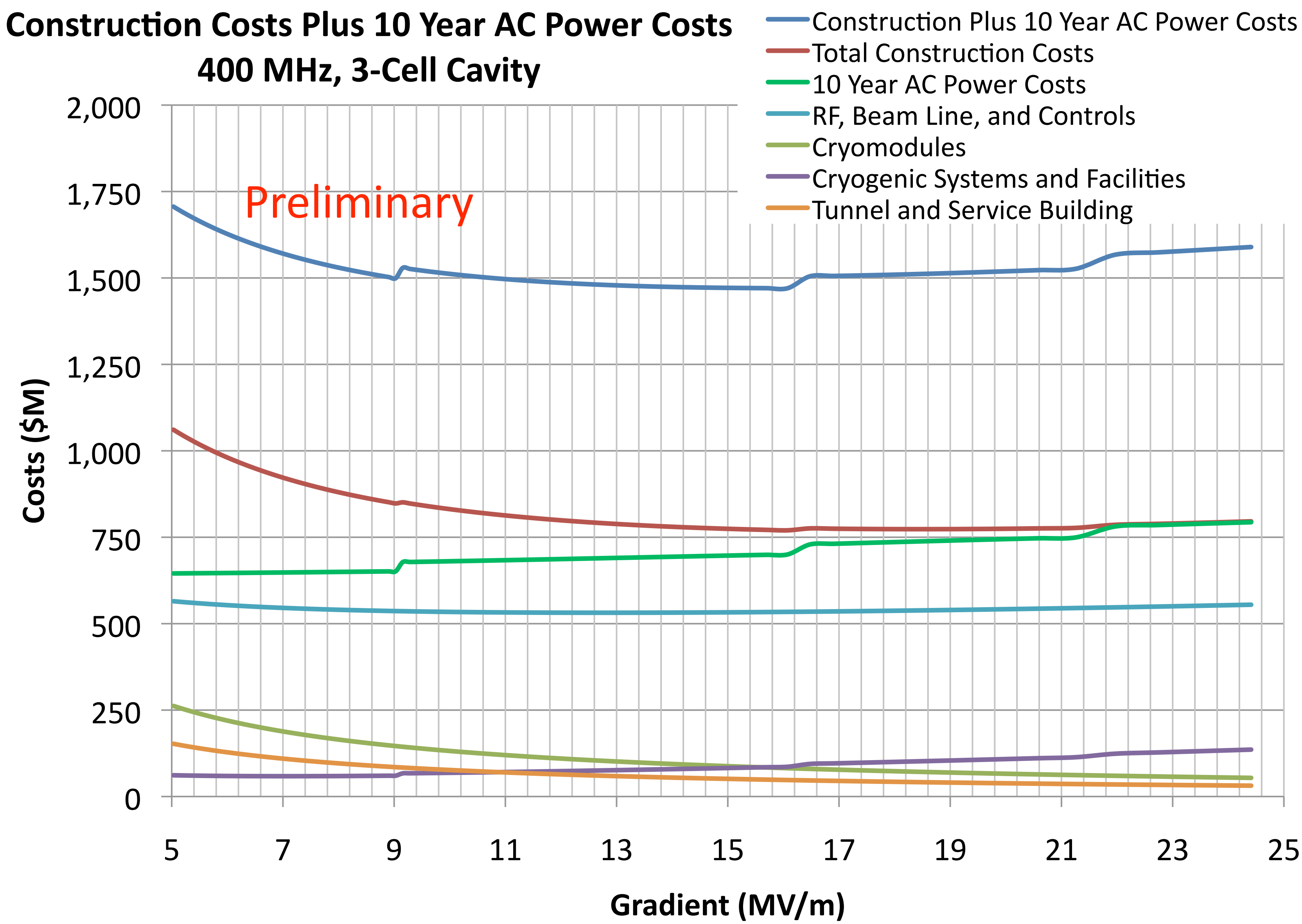


Construction Costs Plus 10 Year AC Power Costs
Standard ILC Cavities
Preliminary
Construction Plus 10 Year AC Power Costs
Cryomodules
10 Year AC Power Costs
Cryogenic Systems and Facilities
Total Construction Costs
RF, Beam Line, and Controls
Tunnel and Service Building
Costs ($M)
2,000
1,750
1,500
1,250
1,000
750
500
250
0
5
7
9
11
13
15
17
19
21
23
25
Gradient (MV/m)

Tom Powers

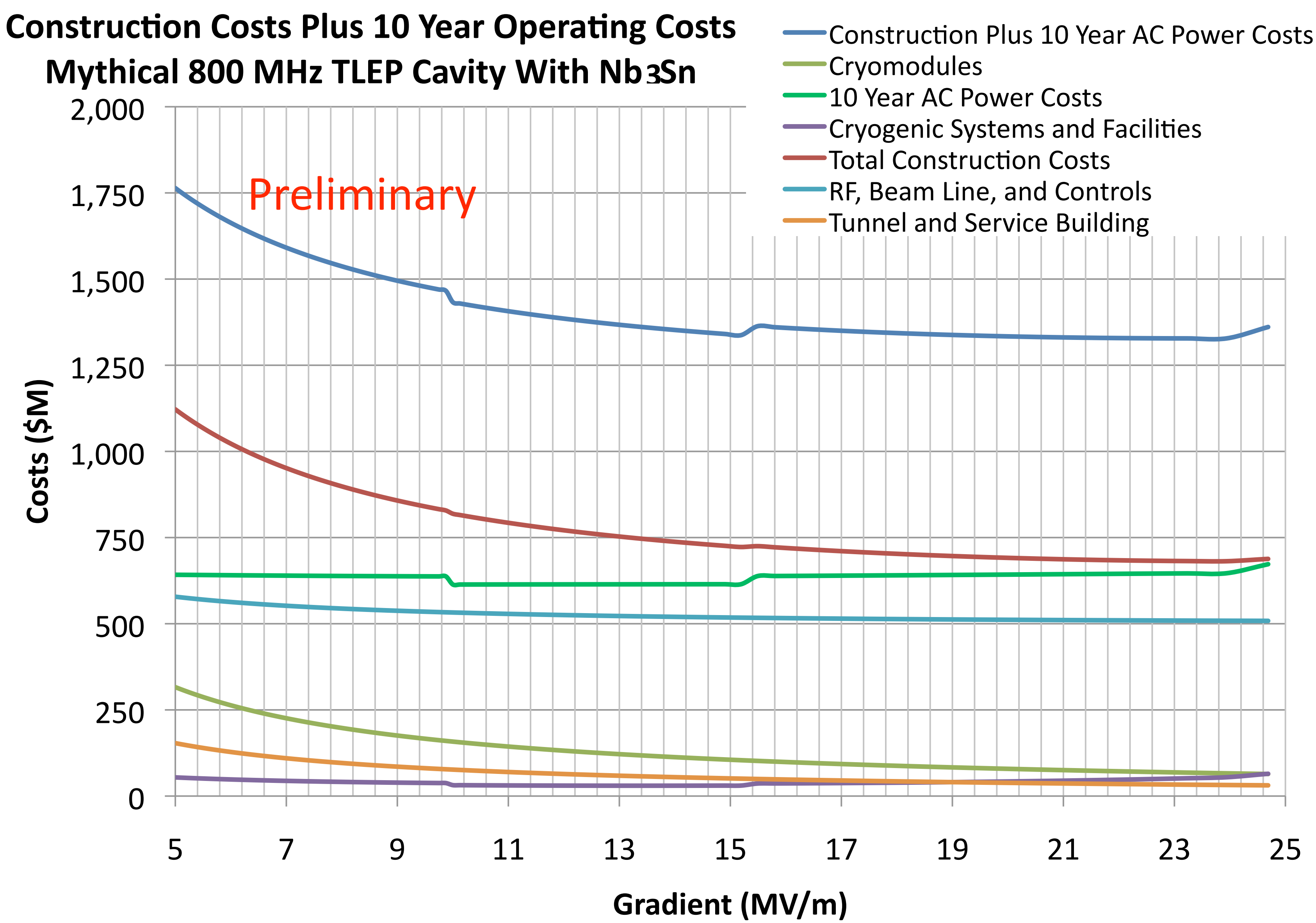

Construction Costs Plus 10 Year AC Power Costs
748.5 MHz, 5-Cell High Current Cavity
Preliminary
Construction Plus 10 Year AC Power Costs
Cryomodules
10 Year AC Power Costs
Cryogenic Systems and Facilities
Total Construction Costs
RF, Beam Line, and Controls
Tunnel and Service Building
Costs ($M)
2,000
1,750
1,500
1,250
1,000
750
500
250
0
5
7
9
11
13
15
17
19
21
23
25
Gradient (MV/m)

Tom Powers



Construction Costs Plus 10 Year AC Power Costs
400 MHz, 3-Cell Cavity
Preliminary
Construction Plus 10 Year AC Power Costs
Total Construction Costs
10 Year AC Power Costs
RF, Beam Line, and Controls
Cryomodules
Cryogenic Systems and Facilities
Tunnel and Service Building
Costs ($M)
2,000
1,750
1,500
1,250
1,000
750
500
250
0
5
7
9
11
13
15
17
19
21
23
25
Gradient (MV/m)

Tom Powers


Construction Costs Plus 10 Year Operating Costs
Mythical 800 MHz TLEP Cavity With Nb3Sn
Preliminary
Construction Plus 10 Year AC Power Costs
Cryomodules
10 Year AC Power Costs
Cryogenic Systems and Facilities
Total Construction Costs
RF, Beam Line, and Controls
Tunnel and Service Building
Costs ($M)
2,000
1,750
1,500
1,250
1,000
750
500
250
0
5
7
9
11
13
15
17
19
21
23
25
Gradient (MV/m)