Frequency Choice for PERLE and Coupler Simulations

F. Marhauser

Workshop PERLE at LAL - Orsay

23-24. February 2017

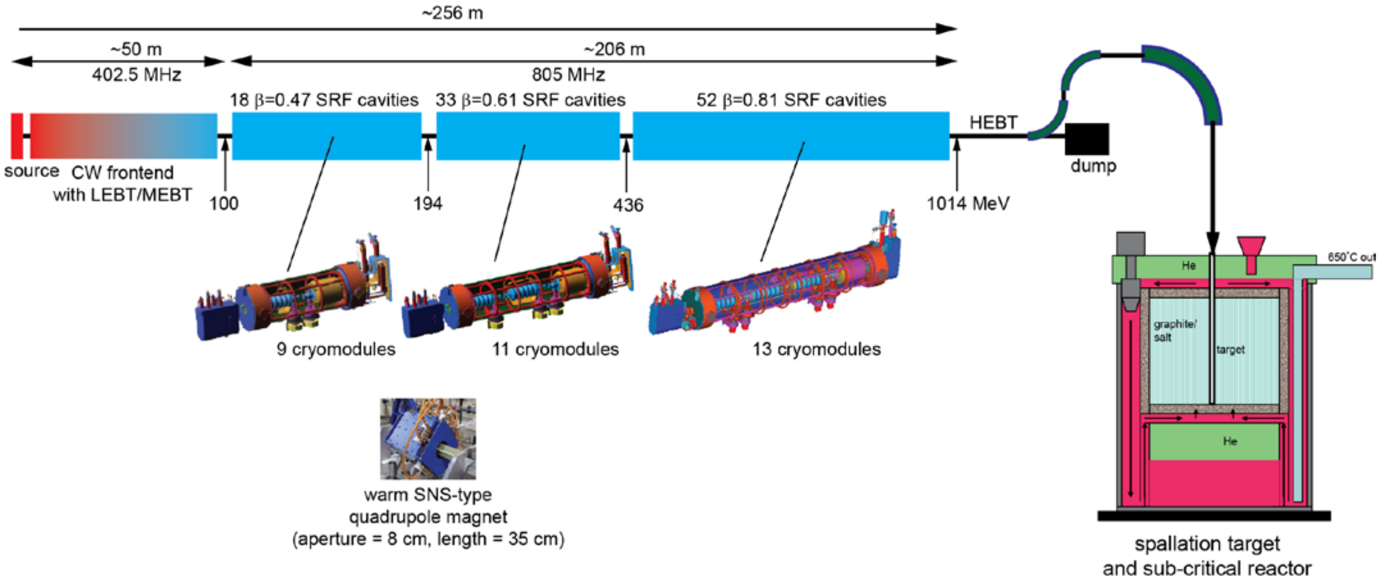
RF Frequency Choice

- For PERLE it has been decided to use an RF Frequency of **801.6 MHz**
- This considers compatibility with LHC RF frequency (400.8 MHz cavities) (considers SPS RF frequency at 200.4 MHz)
- Is 801.6 MHz a choice good?
- For a large quantity of cavities the cavity RF frequency and operating field (E_{acc}) should be chosen to minimize operational and capital costs
- In CW the dynamic heat losses in cryomodules ($P_{RF} \sim E_{acc}^2$) are dominant (>> static heat losses), which is a cost driver
- These losses determine both operational costs and required refrigeration capacity (cryoplant expenditures)

Preliminary Conceptual Design Report
of the Proton Linac
for the GEM*STAR
Accelerator Driven Subcritical Reactor

F. Marhauser, Muons, Inc., 2013-2014, 153 pages

- Past work: Cost optimization for the cold section of a 1GeV 10 MW proton linac
  (GEM*STAR = Green Energy Multiplier*Subcritical Technology for Alternative Reactors)
- SRF cryomodules (CM) envisioned are based on segmented SNS-type CMs operated at 805 MHz, so all similar to PERLE



Dynamic/RF Cavity Heat Loss

$$P_{RF} = \frac{U_{eff}^2}{\left(R/Q \cdot G\right)} \cdot R_s = \frac{\left(E_{acc} \cdot L_{act}\right)^2}{\left(R/Q \cdot G\right)} \cdot \left(R_{BCS} + R_{res}\right)$$

$$R_{BCS}(T,f) = \frac{A}{T} \cdot f^2 \cdot e^{-\frac{\Delta}{k_B \cdot T_C} \cdot \frac{T_c}{T}} \quad \text{for } T < \frac{T_c}{2}$$

Δ = energy gap

A = material-dependent parameter

- For a given accelerator one seeks to minimize the RF losses per unit length (E_{acc} yet unknown, will be optimized later)

$$P_{RF}^* \equiv \frac{P_{RF}}{E_{acc}^2 \cdot L_{act}} = \frac{L_{act}}{\left(R/Q \cdot G\right)} \cdot \left(R_{BCS} + R_{res}\right)$$

$$P_{RF}^* = \frac{\frac{\beta}{2} \cdot \frac{c_0}{f}}{\left(R/Q \cdot G\right)_{\text{per cell}}} \cdot \left(\frac{A}{T} \cdot f^2 \cdot e^{-\frac{\Delta}{k_B \cdot T_C} \cdot \frac{T_c}{T}} + R_{res}(f)\right)$$

- How to describe frequency-dependent R_{res} ?

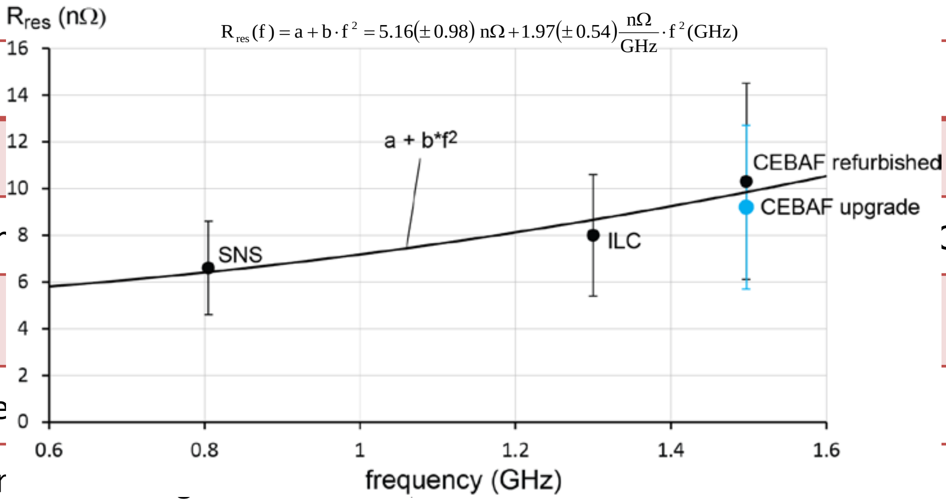
Residual Resistance

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 21, NO. 3, JUNE 2011

Residual Resistance Data From Cavity Production Projects at Jefferson Lab

Gianluigi Ciovati, Rongli Geng, John Mammosser, and Jeffrey W. Saunders

- Experimental approach: Use large set of cavities tested at JLab from 805-1500 MHz
- All cavities made from fine-grain high-purity Nb (RRR ≥ 250)
- Measurements:
    - Q_0 measured at low field (prior medium-Q slope)
    - Surface resistance is determined ($R_s = G/Q_0$)
    - $R_{BCS}(T)$ is computed applying full BCS theory (Halbritter code) with material assumption well describing Nb (sys. error ~15%)
    - This yield residual resistance $R_{res}=R_s-R_{BCS}$
- R_{res} does not significantly depend on surface treatment (BCP/EP)
- Yet, a low-T bake (120 deg. C for 2 days) in UHV reduces R_{BCS} by ~50% due to an increase in the energy gap value (Δ/k_BT_c) and a significant reduction of the normal electron mean free path length



Frequency	**1497**
Project	CEBAF Upgrade
Surface treatmer	CP + light EP + bake
R_{res} (avg ± stdev)	9.2 ± 3.5
# of cavities teste	86

* only for a small fr

Optimum Frequency to Minimize RF Losses

- Dynamic cavity heat losses for frequency-dependent residual resistance:

$$P_{RF}^{*} = \frac{\frac{\beta}{2} \cdot \frac{c_0}{f}}{\left(R\!/\!_{Q} \cdot G \right)_{\text{per cell}}} \left(\frac{A}{T} \cdot f^{2} \cdot e^{-\frac{\Delta}{k_B \cdot T_C} \cdot \frac{T_c}{T}} + \left(a + b \cdot f^{2} \right) \right) \longrightarrow \boxed{f_{opt} = \sqrt[+]{\frac{a \cdot T}{\left(A \cdot e^{-\frac{\Delta}{k_B \cdot T_C} \cdot \frac{T_c}{T}} + b \cdot T \right)}}}$$

- The minimum total surface resistance then is

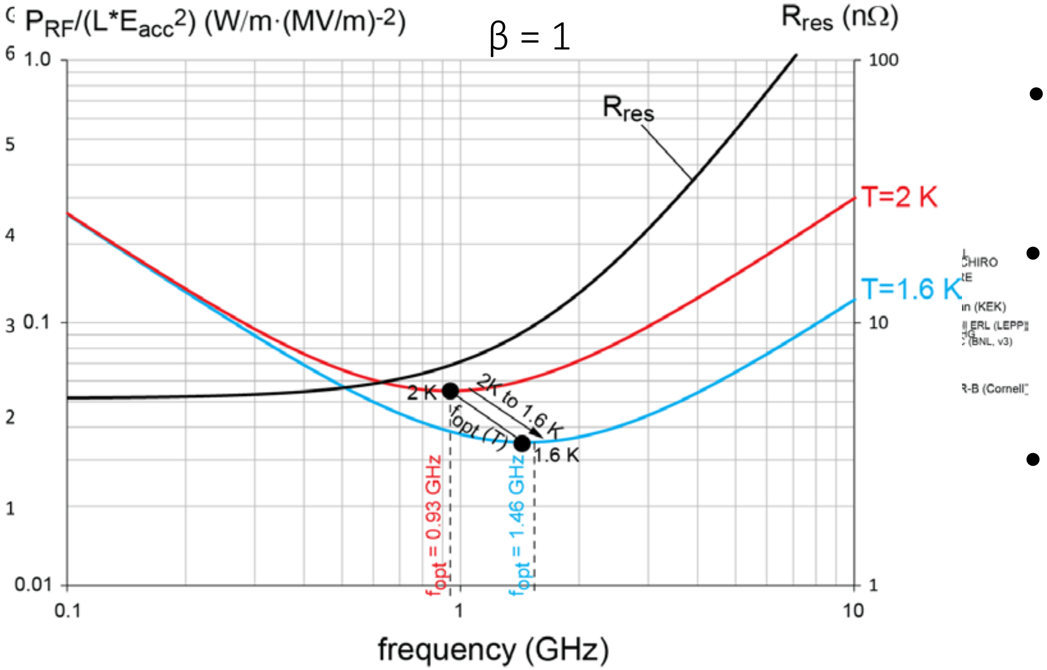
$$R_S(f_{opt}) = f_{opt}^{2} \left(\frac{A}{T} \cdot e^{-\frac{\Delta}{k_B \cdot T_C} \cdot \frac{T_c}{T}} + b \right) + a = 2 \cdot a$$

- At low frequencies a+b·f² ≈ a and $R_{res}(f_{opt}) \approx a \approx R_{BCS}(f_{opt})$

- If residual resistance would be constant, then $R_{res}(f_{opt}) = R_{BCS}(f_{opt})$

Optimum Frequency to Minimize RF Losses

- Use material properties of fine-grain high-RRR Nb (BCP or EP, low-T baked)
- Use reasonable (R/Q·G) to quantify losses even without final cavity design in hand
- E_{acc}, f and T can now be optimized to minimize RF losses



- In case $R_{res} < R_{BCS}$ the losses are not minimal at given T
- To counteract this behavior one may reduce the operating temperature, thus R_{BCS}
- Increased complexity of the refrigerator has to be considered when lowering the T

Cold Compressor Costs

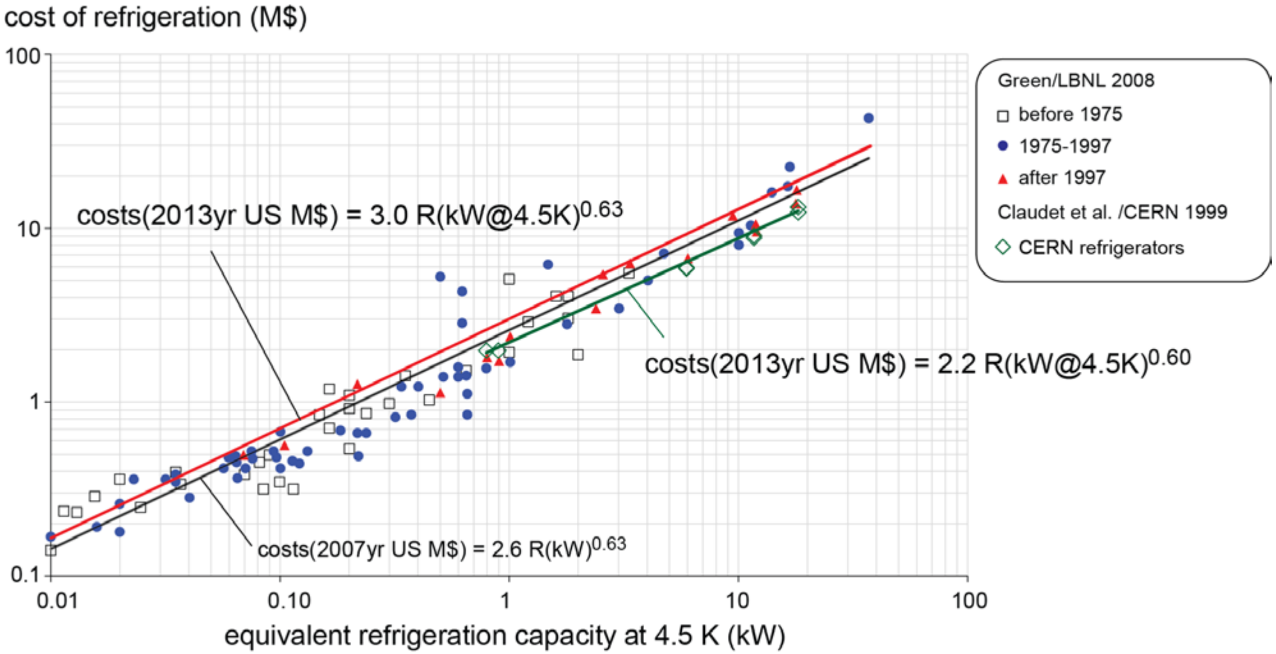
- Lower temperature seems favorable, but one it comes with more costs and complexities for the cryogenic refrigerator plant (e.g. CCB)
- Capital costs of CCB are assessed separately depending on compressor stages

He temperature (K)	Saturated vapor pressure (atm)	Overall compression ratio (CPR)	Required compressors	
			PR = 2 (each)	PR = 3 (each)
1.6	0.0075	133.6	8 (7.1)	5 (4.5)
1.7	0.0113	88.5	7 (6.5)	5 (4.1)
1.8	0.0164	61	6 (6.0)	4 (3.7)
1.9	0.023	43.5	6 (5.5)	4 (3.4)
2	0.0313	32	5 (5.0)	4 (3.2)

Saturated vapour pressure at various He temperatures and CPRs (referred to 1 atm discharge). Assuming a PR of 2 and 3 per compressor, respectively, results in the required number of compressors

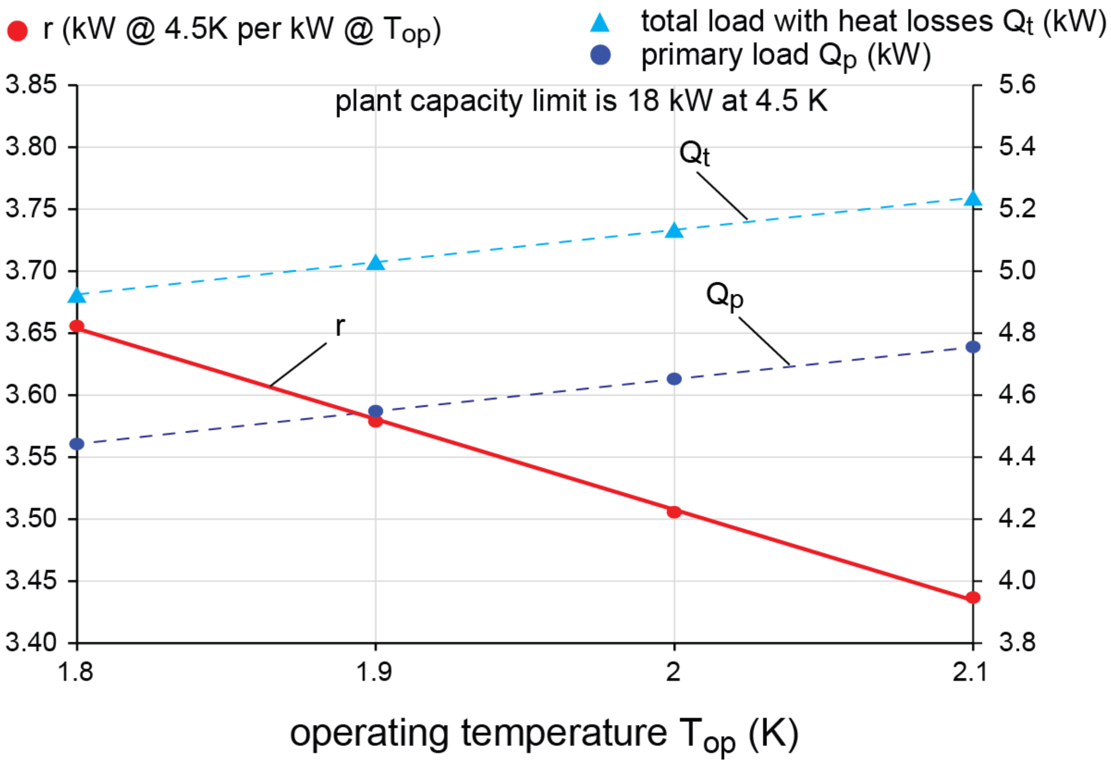
Costs for Refrigerator Plant

- General difficulty of a cost estimate of the refrigerator is the choice of the parameter from which to calculate the costs
- More complex large-scale systems may have several cooling cycles at various temperature levels as well as liquefaction at low temperatures
- The refrigeration capacity is typically normalized to the equivalent refrigeration capacity at 4.5 K, for which cost scaling law exists



Costs for Refrigerator Plant

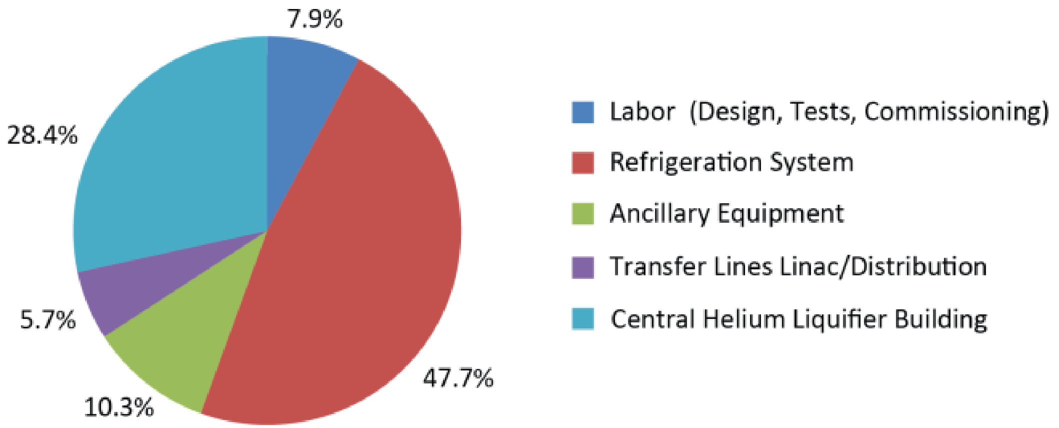
- Main task was to assess the scaling law for the equivalent load at 4.5 K in dependence on a variable operating temperature (T_{op})
- Equivalent 4.5 K heat load (**r**) generated by CCB (1.8 K $\leq T_{op} \leq$ 2.1 K),
  5 cold compressors used throughout (CCs between 2-2.9)
- Constraint: Max. equivalent load is 18 kW at 4.5 K (at constant T, P)



heat loss estimate is 480W based on measurements at CEBAF CHL

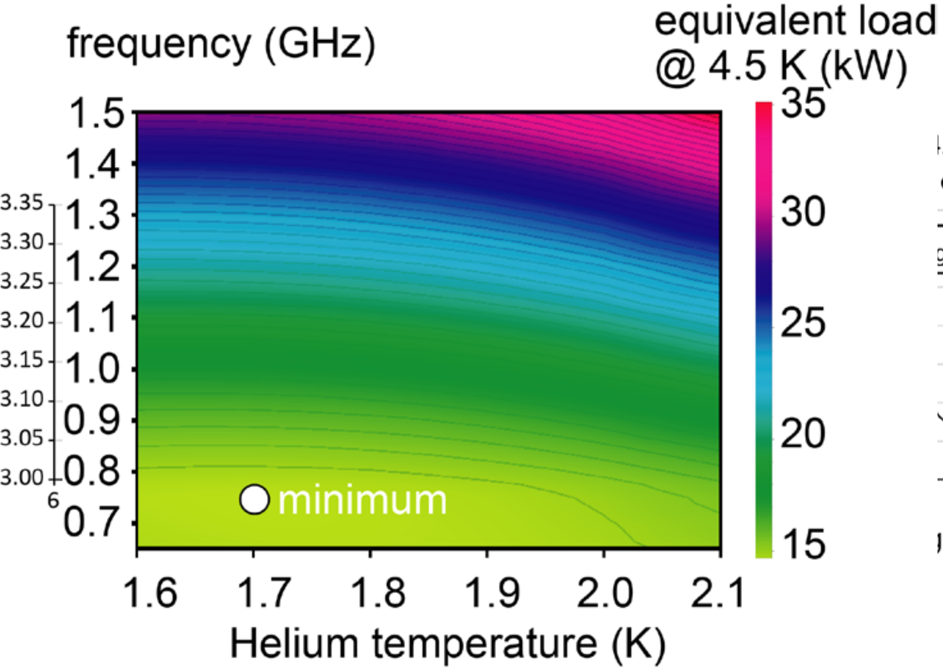
Costs for Refrigerator Plant

- The costs for the refrigerator plant comprised minimal piping between compressors, expansions engines, while capital costs for He dewars, external He distribution lines, computer process control hardware and software needs to be added
- Expenses for LHe storage and transfer lines may contribute as much as the main cold box and compressor stages
- Costs for main building need to be added
- Labor expenses for design, test and commissioning need to be considered
- Cannot be put in simple equations
- To realistically account for such major expenditures, the work breakdown structure (WBS) for the SNS refrigeration system has been engaged

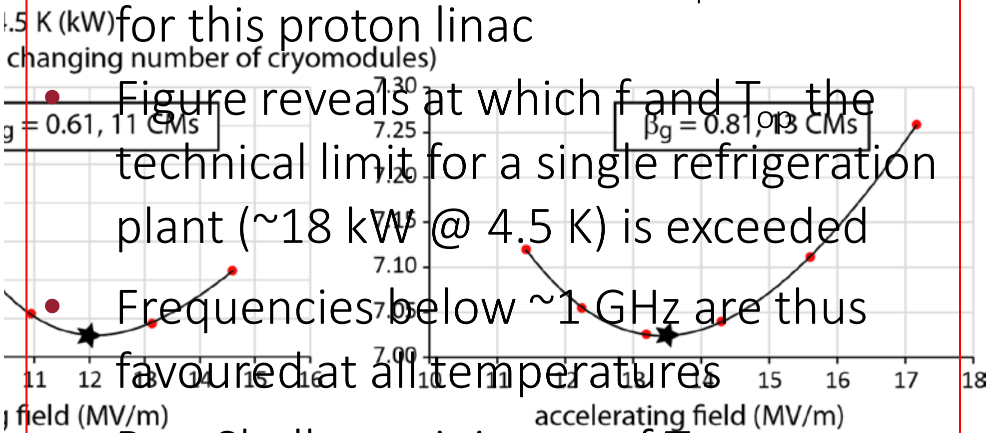


Optimum Frequency and Temp. to Minimize RF Losses

- One can sum up P*(β_g, f, T) over all CMs to evaluate the equivalent losses at 4.5 K in order to estimate the costs for the refrigerator plant
- One also needs to assess the dynamic losses arising from other components (such as input and HOM couplers)
- Moreover all static losses dissipated via conduction and radiation as well as intercepted at thermal shield(s) within the CM need to be assessed and converted to 4.5 K



Equivalent dynamic and static losses at 4.5 K for the proton linac covering three β_g-sections



Main observations:

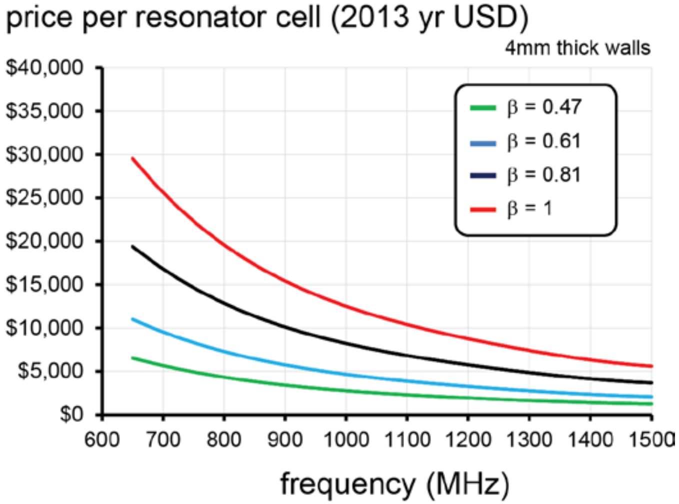
- Optimum f ~ 750 MHz at T_{op} ~1.7 K for this proton linac
- Figure reveals at which f and T_{op} the technical limit for a single refrigeration plant (~18 kW @ 4.5 K) is exceeded
- Frequencies below ~1 GHz are thus favoured at all temperatures
- But: Shallow minimum of T_{op}
- One may rather choose T_{op} to reduce complexity of CCB (# of compressors)

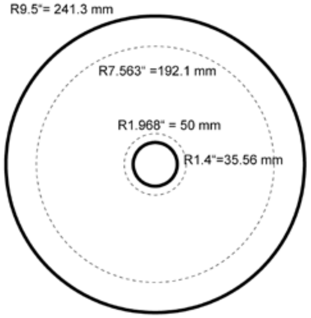
Capital Costs for Cavities(f)

- Cost optimization need price tag for cavities(f) and cryomodules(f)
- For cavities and cryomodules one principally pays for the amount of metal/mass
- How do cavity costs scale with frequency?
- **Bare cavity** material costs (cavity plus beam tubes (1.5 $\beta_g \cdot \lambda/2$ each side)

$$\boxed{C_{cav} = N_c \cdot Nb_{cav} \cdot 3.68 \cdot t_w \cdot \beta_g^2 \cdot f^{-2} + Nb_{tubes} \cdot 3.01 \cdot t_w \cdot \beta_g \cdot f^{-2.13} \quad \text{[in US\$].}}$$

t_w = wall thickness, β_g = geometrical beta, N_C = number of cavity cells, Nb = price for Niobium (US$/kg), using generic beam tube diameter Ø(m) = 248.2/f(MHz)$^{1.13}$, which is a fit function to known cavity geometries

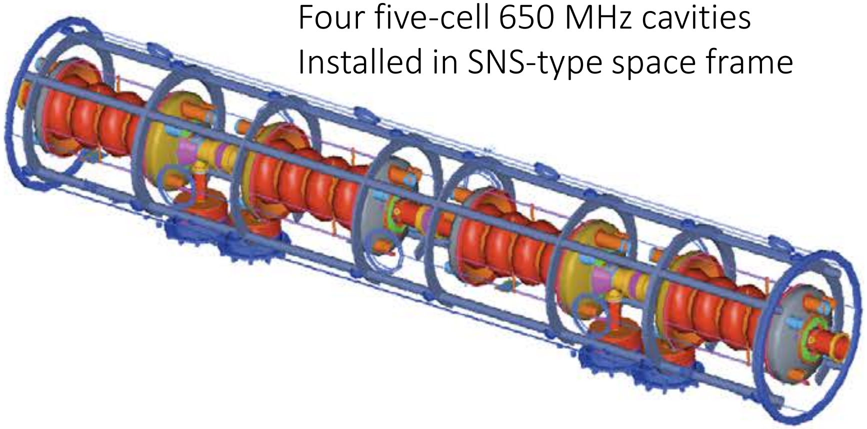




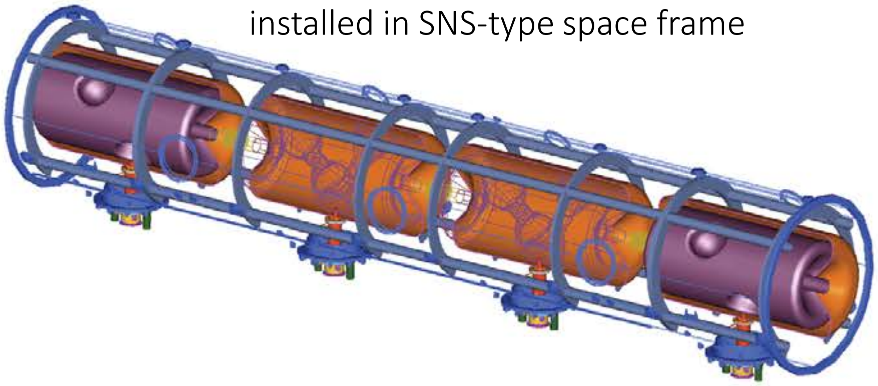
- For string hardware costs one needs to add Helium vessel, tuner, main coupler, HOM couplers, stiffening rings (if any)…add significantly to costs

Capital Costs Cryomodules(f)

- For CM hardware (no cavity string) the scaling of costs to 1st order depends on total length
- In SNS-type CMs one can accommodate differently sized cavities in the same space frame down to a certain frequency (practicable length limit applies)
- Lower frequency/larger size may require more expensive tooling and post-processing equipment



Four five-cell 650 MHz cavities
Installed in SNS-type space frame

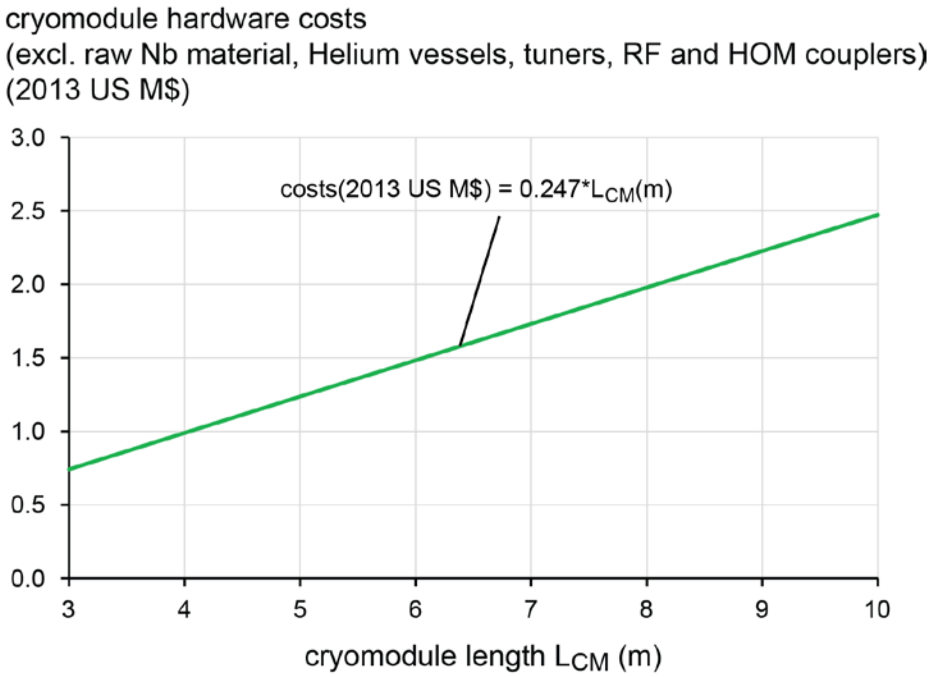


Four 325 MHz double spoke cavities
installed in SNS-type space frame

R. Rimmer, “Costs for a CW SRF Linac for ADS”
A. McEwan, “SNS Project Estimated Costs in 2010 Dollars”, ADS workshop, VTech, 2010

Capital Costs Cryomodules(L(f))

- Based on existing projects and equipment costs, the following scaling law has been used for cryomodule hardware

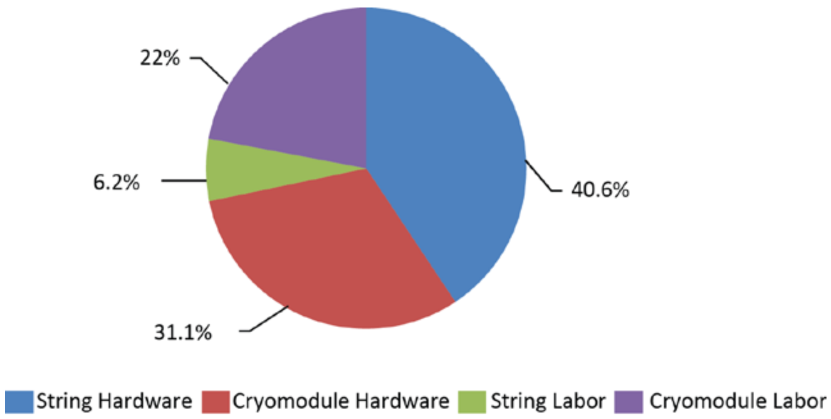


L_{CM} is CM length [in m] valve to valve*

*An extra $0.102 \cdot N_{cav} + 0.723$ (in m) is added beyond $(N_{cav} \cdot L_{cav})$ to account for overall beam line space requirements based on SNS (CEBAF CMs are packaged denser to save real estate)

Labor Costs and Other Expenditures

- WBS for large-scale project such as SNS considered again



Relative cost breakdown for SNS CMs

1) **Cavity string hardware** – Cavities, helium vessels tuner, FPC, HOM couplers, bellows…

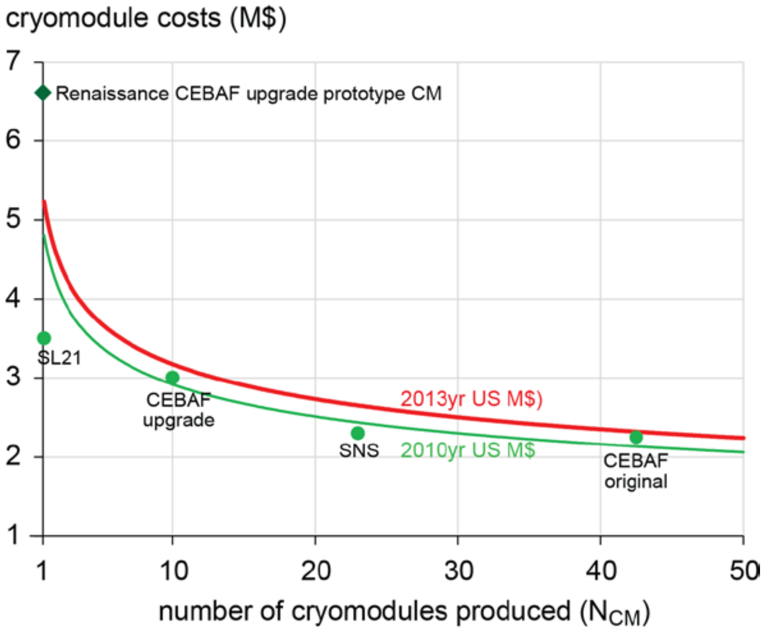
2) **CM hardware** - insulating vacuum vessel, space frame, thermal shielding, magnetic shielding, He piping, instrumentation, He supply/return end cans…

Cryomodule Costs with Cavity String

- Combing CM and cavity string hardware costs and based on the WBS the overall CM costs can be evaluated as a function of frequency and number of cavity cells

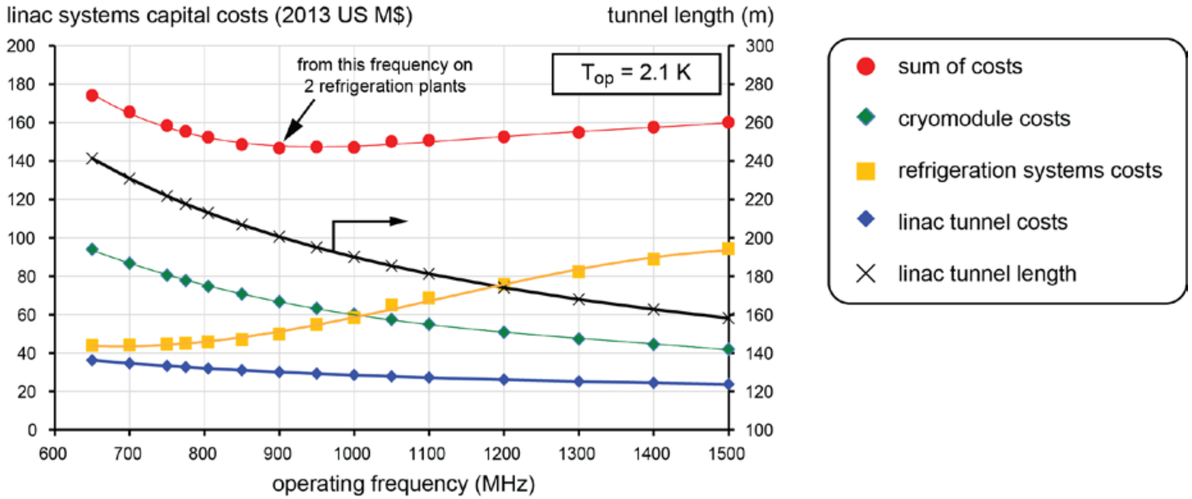
Average costs per CM

Project	Frequency (MHz)	Number of cavities per CM	Number of cells per cavity	Real costs (2013 US M$)	Functional estimate (2013 US M$)
SNS	805	6	6	**3.26**	3.4
CEBAF Upgrade	1497	6	7	**2.5**	2.4

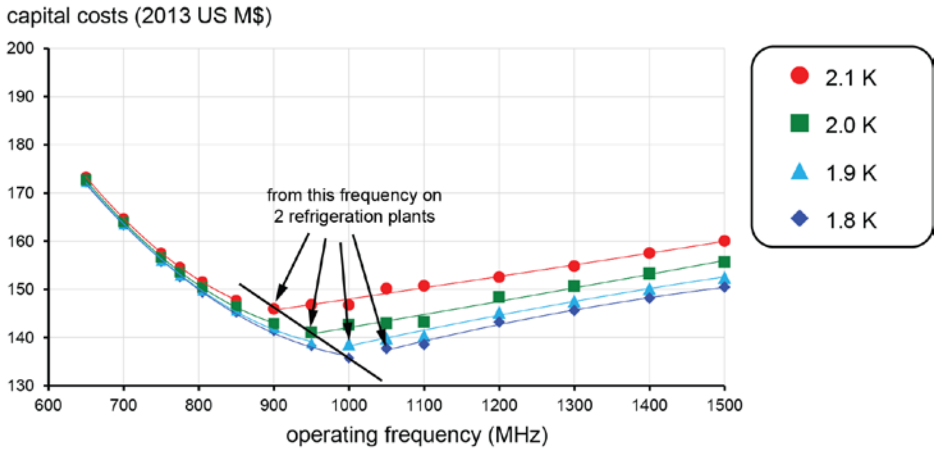


Total Capital Linac System Costs incl. Tunnel

- E.g. T_{op} = 2.07 K (CEBAF temperature) → shallow minimum at 900-1000 MHz

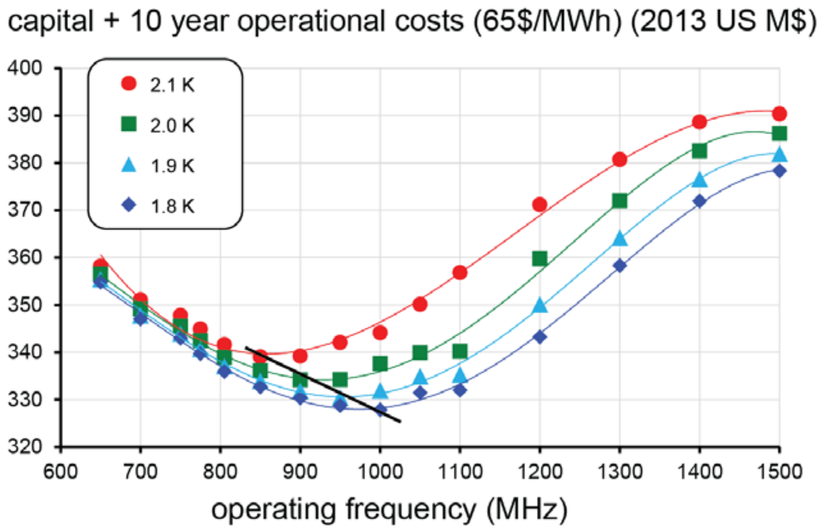


ADS SRF linac (0.1-1 GeV) system capital costs



Total Capital and Operational Costs

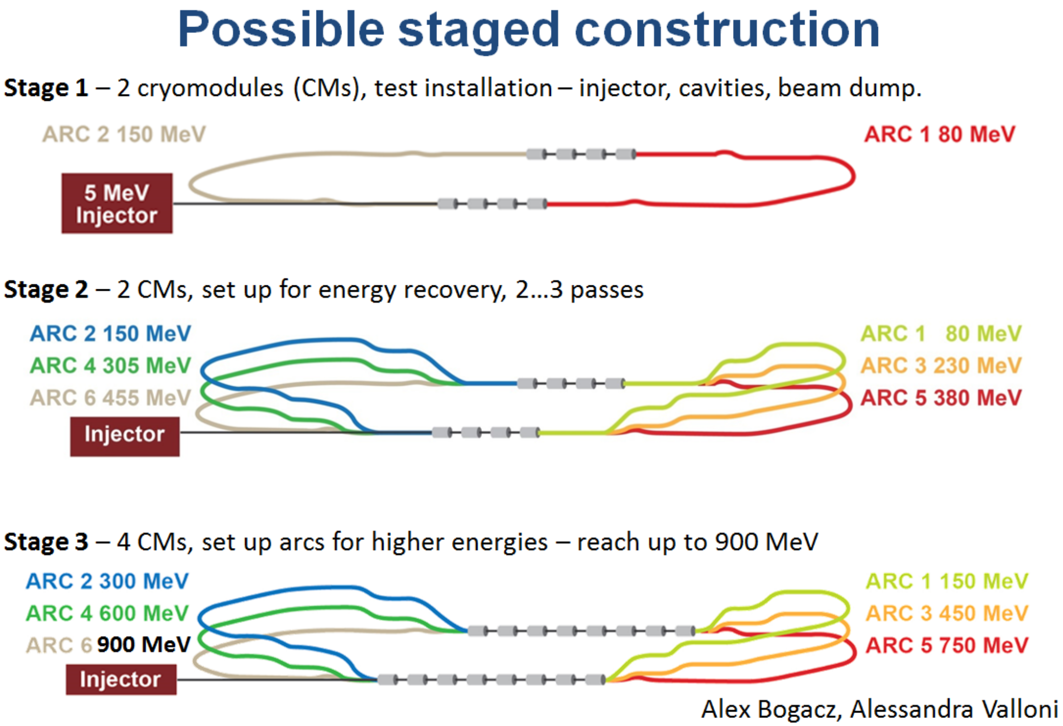
- Operational costs add significantly over time
- Considering Low Loss (LL) cavities (maximizing R/Q·G) becomes important for large-scale machines, e.g. on the verge from 1 to 2 refrigeration plants



ADS SRF linac (0.1-1 GeV) system capital plus 10 year operational costs

PERLE

- 801.6 MHz seems a good choice cost-wise, though much less CMs are utilized while it benefits from the inherent energy recovery advantages



Possible staged construction

Stage 1 – 2 cryomodules (CMs), test installation – injector, cavities, beam dump.

Stage 2 – 2 CMs, set up for energy recovery, 2…3 passes

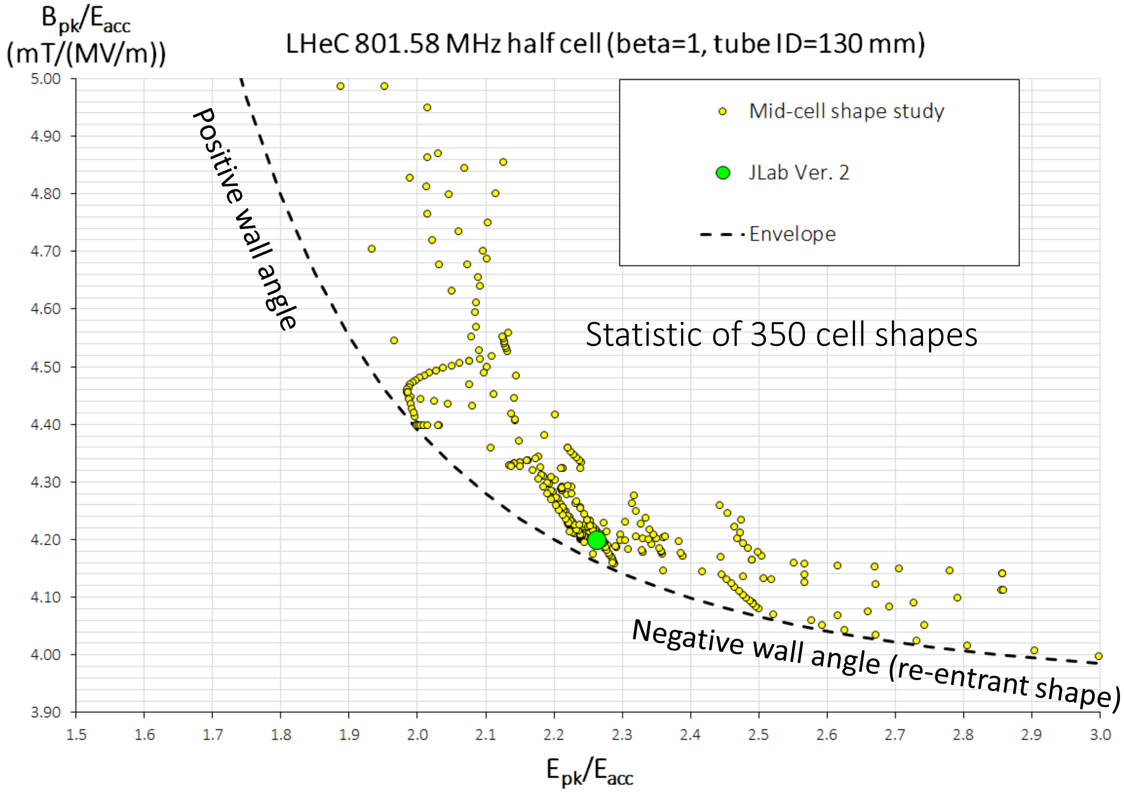
Stage 3 – 4 CMs, set up arcs for higher energies – reach up to 900 MeV

Alex Bogacz, Alessandra Valloni

Cavity Design

Surface Peak Fields

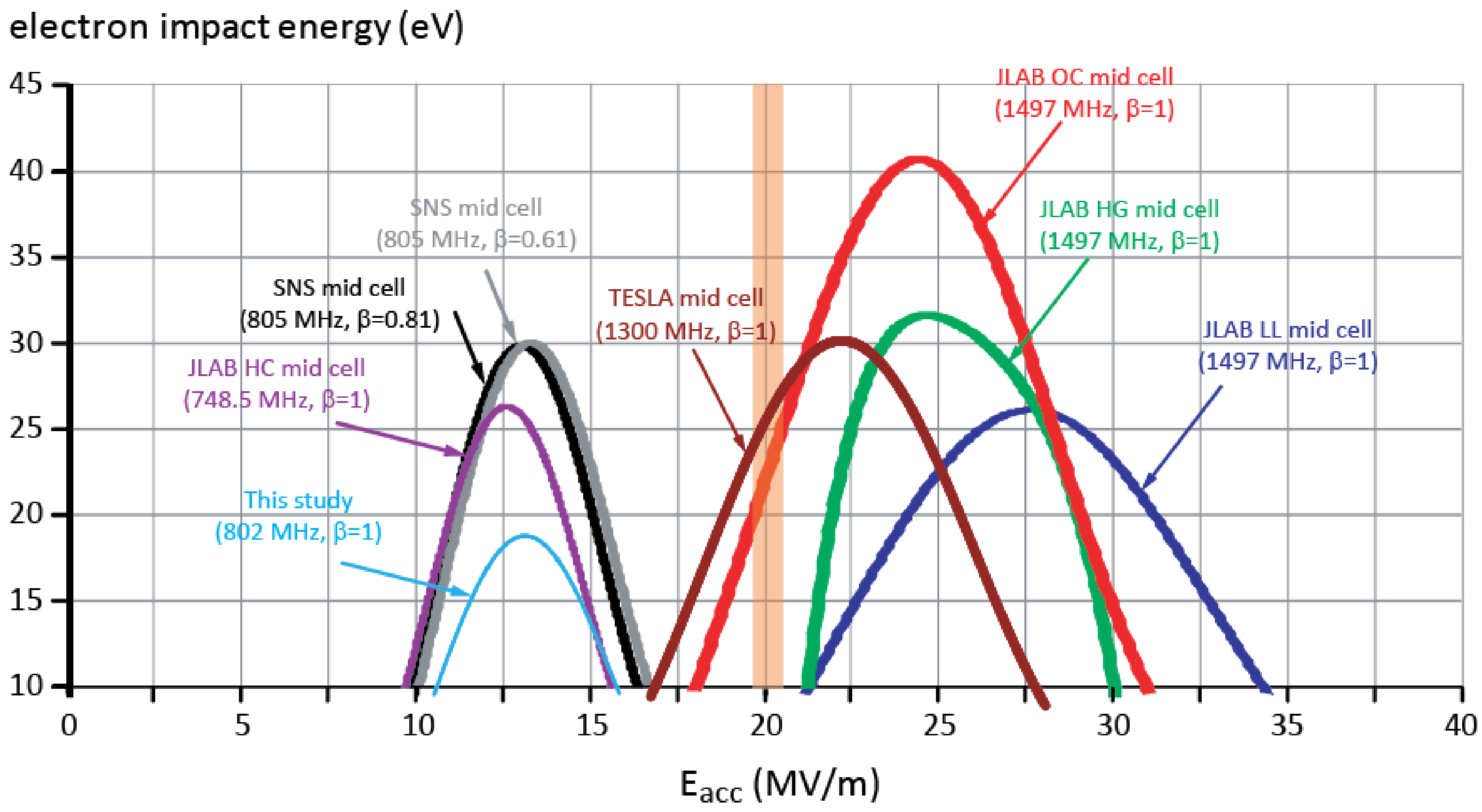
- At E_{acc} ≈ 20 MV/m and avoiding potential Q_0-slope, B_{pk} ~80-90 mT
  → B_{pk}/E_{acc} ~ 4 mT/(MV/m)
- Danger at 20 MV/m is field emission, small E_{pk}/E_{acc} can become important
- Main parameter to minimize peak field ratios is cavity iris diameter (ID) → small ID
- However, small ID will compromise HOM-damping



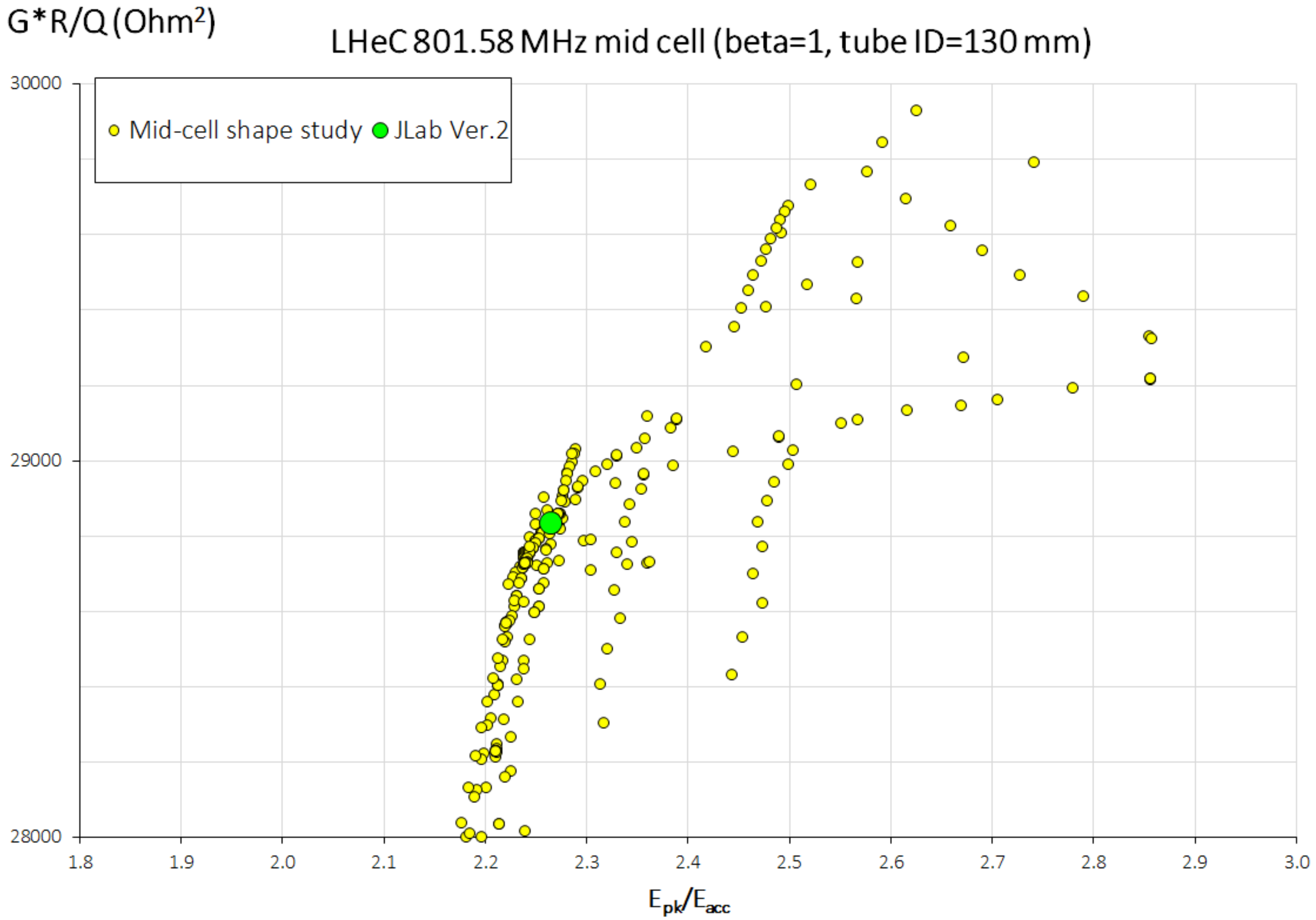
ID: 130 mm (fixed)

Typical Cell Multipacting Barrier

- Flat equator will lower secondary impact energy



R/Q·G


G*R/Q (Ohm²)
LHeC 801.58 MHz mid cell (beta=1, tube ID=130 mm)
○ Mid-cell shape study
● JLab Ver.2
30000
29000
28000
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
Epk/Eacc

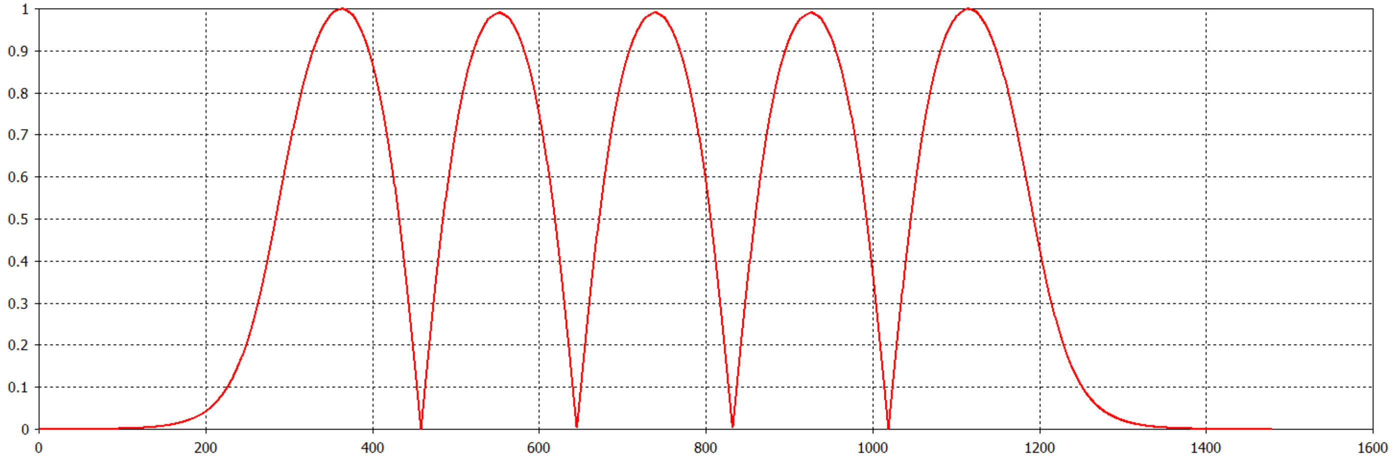
Parameter Table for Cavity Versions

Parameter	Unit	Value	Value	Value
Cavity type		JLab Ver. 2	CERN Ver. 1	CERN Ver. 2
Frequency	MHz	801.58		
Number of cells		5		
L_{active}	mm	917.9	935	935
Long. loss factor (2 mm rms bunch length)	V/pC	2.742	2.894	2.626
$R/Q = V_{eff}^2/(\omega * W)$	Ω	523.9	430	393
R/Q/cell	Ω	104.7	86.0	78.6
G	Ω	274.6	276	283
R/Q·G/cell		**28788**	**23736**	**22244**
Eq. Diameter	mm	328.0	350.2	350.2
Iris Diameter	**mm**	**130**	**150**	**160**
Tube Diameter	mm	130	150	160
Eq./Iris ratio		2.52	2.19	2.19
Wall angle (mid-cell)	degree	0	12.5	12.5
E_{peak}/E_{acc} (mid-cell)		**2.26**	**2.26**	**2.40**
B_{peak}/E_{acc} (mid-cell)	**mT/(MV/m)**	**4.20**	**4.77**	**4.92**
k_{cc}	%	3.21	4.47	5.75
N^2/k_{cc}		7.78	5.59	4.35
cutoff TE_{11}	GHz	1.35	1.17	1.10
cutoff TM_{01}	GHz	1.77	1.53	1.43

JLab Ver. 2

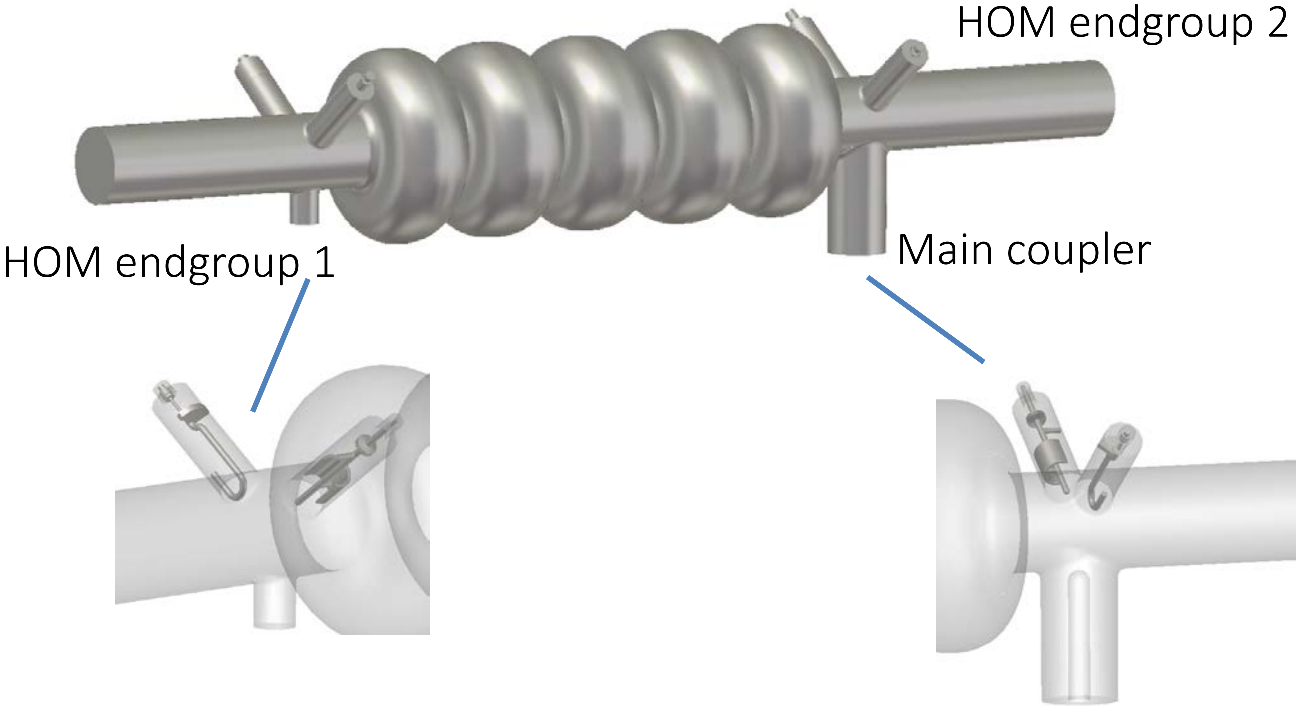
- For the prototype cavity we have chosen a single-die design (end cells will just be trimmed shorter)
- Final version may consider different end cell geometries (may help HOM damping)

On axis |Ez|



Which HOM-Coupler Technology ?

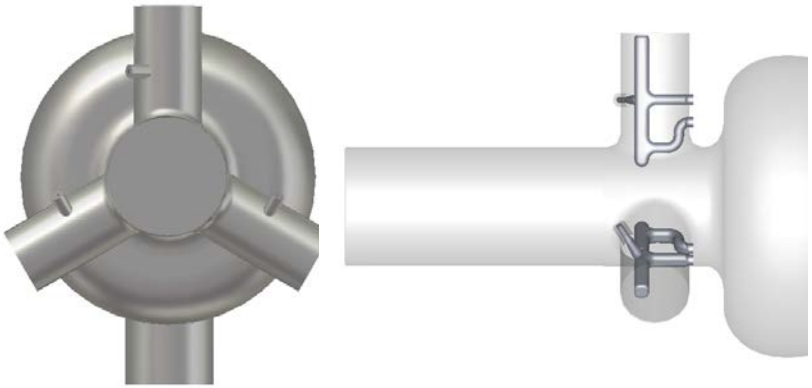
- First approach could be to utilize existing coupler technology, but this needs scaling to new frequency and tube ID
- For instance: Scale LHC HOM couplers (and FPC)



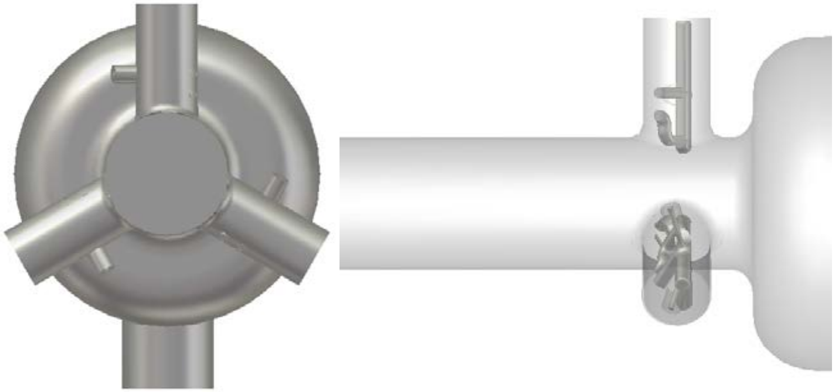
- 4 HOM couplers per cavity ?
  - LHC-type coaxial loop coupler is narrowband coupler for dipole modes
  - LHC-type coaxial antenna/capacitive coupler is more broadband

Which HOM-Coupler Technology ?

- 3 couplers for HOM endgroup could suffice and are favorable to minimize dependence on mode polarization

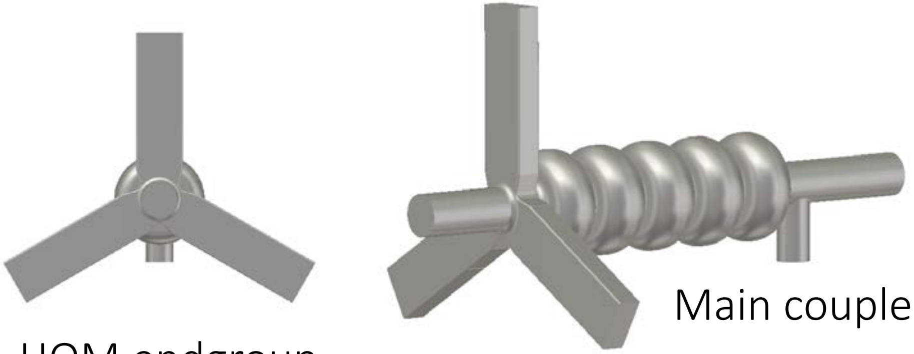


Scaled JLab-type couplers



Scaled TESLA-type coaxial couplers

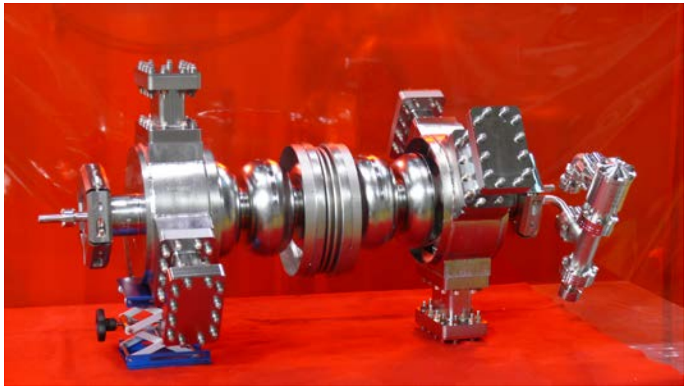
Which HOM-Coupler Technology ?



Main coupler

HOM endgroup

Scaled JLab High Current (HC) waveguide couplers

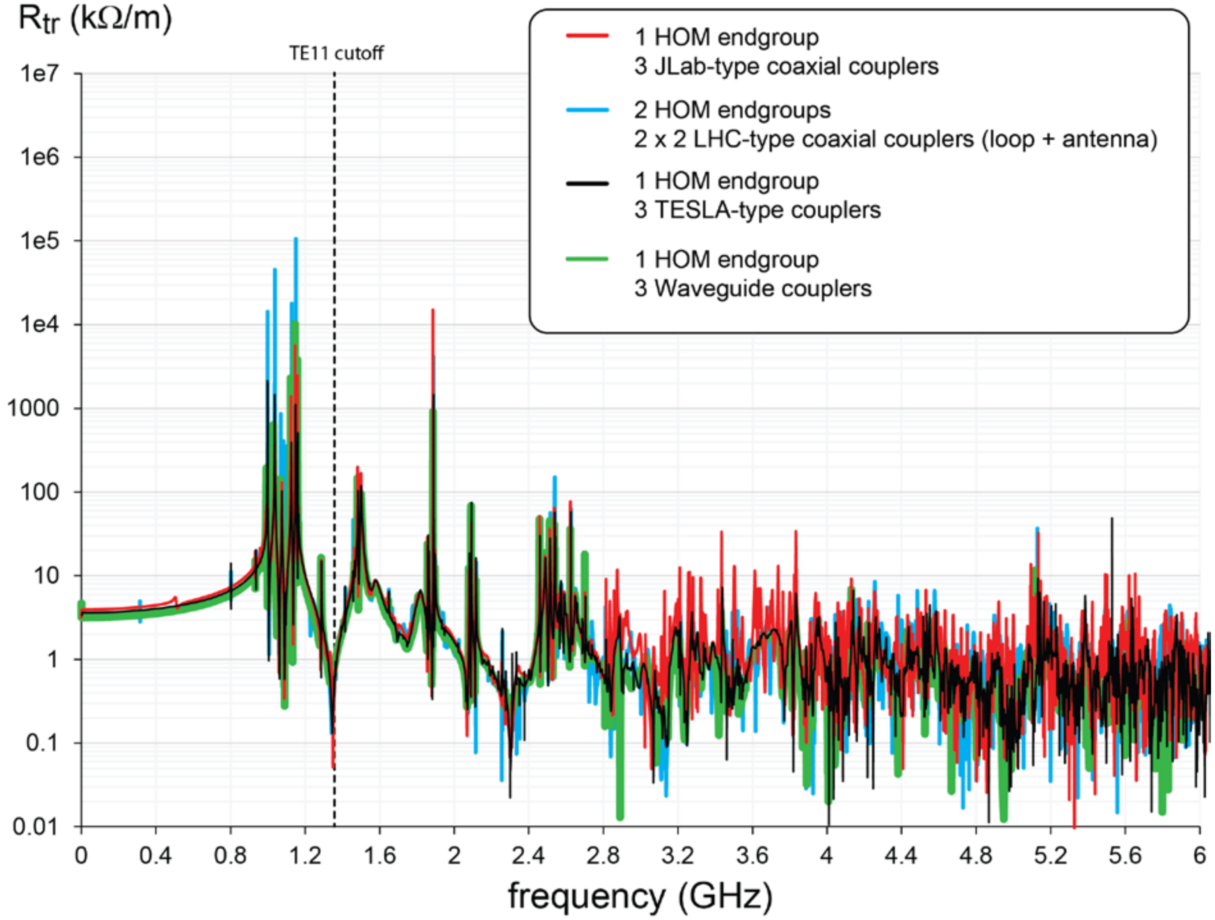


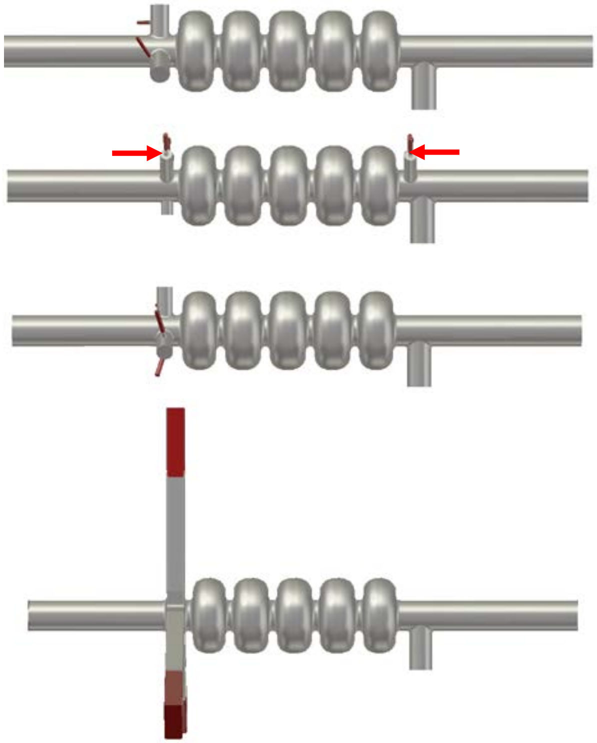
1.5 GHz HC cavity prototype

750 MHz HC cavity prototype

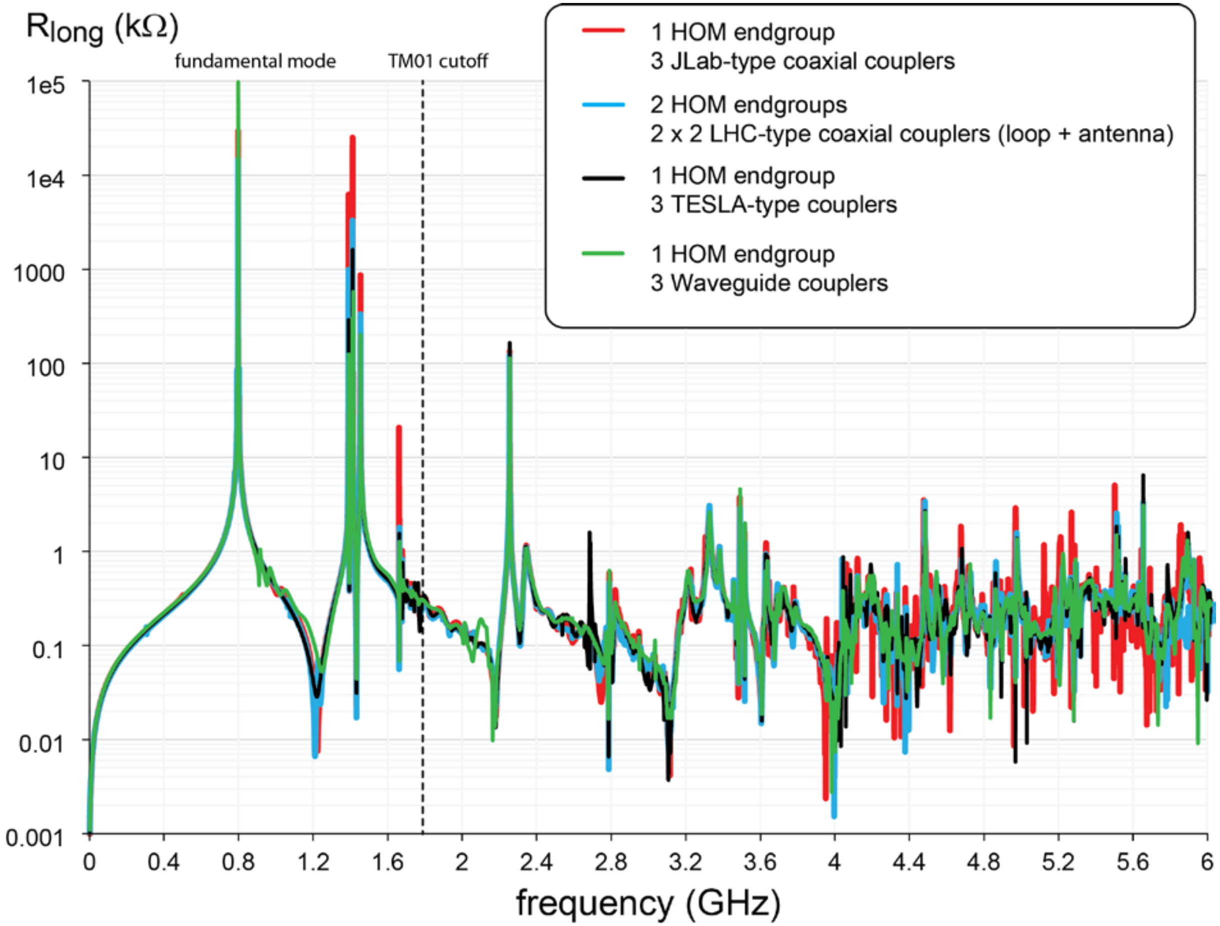
Dipole Spectra

- Distance of HOM-endgroup to iris always same, except for LHC endgroups (5 cm closer)



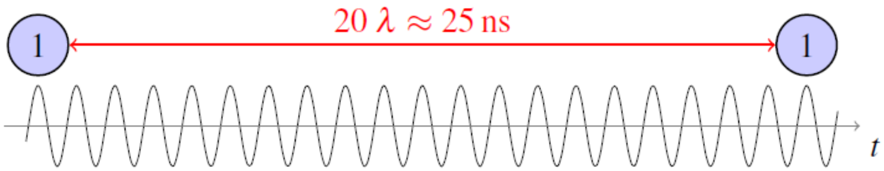


Monopole Spectra

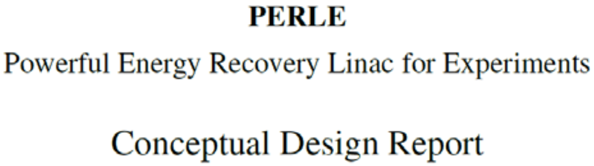


Beam Spectral Lines Important for HOM-Power Assessment

- 801.6 is the 20th harmonic of the bunch frequency (40.1 MHz)



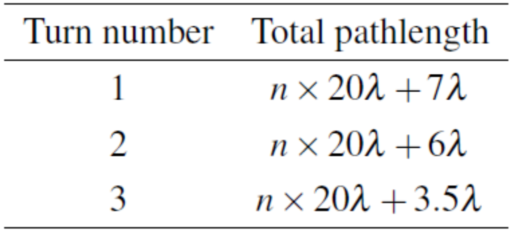
Beam structure without recirculation



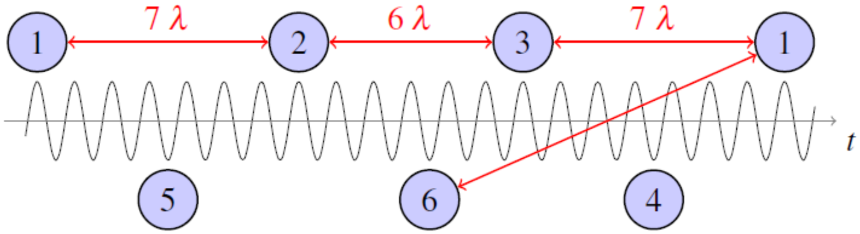
PERLE

Powerful Energy Recovery Linac for Experiments

Conceptual Design Report



Turn number	Total pathlength
1	$n \times 20\lambda + 7\lambda$
2	$n \times 20\lambda + 6\lambda$
3	$n \times 20\lambda + 3.5\lambda$

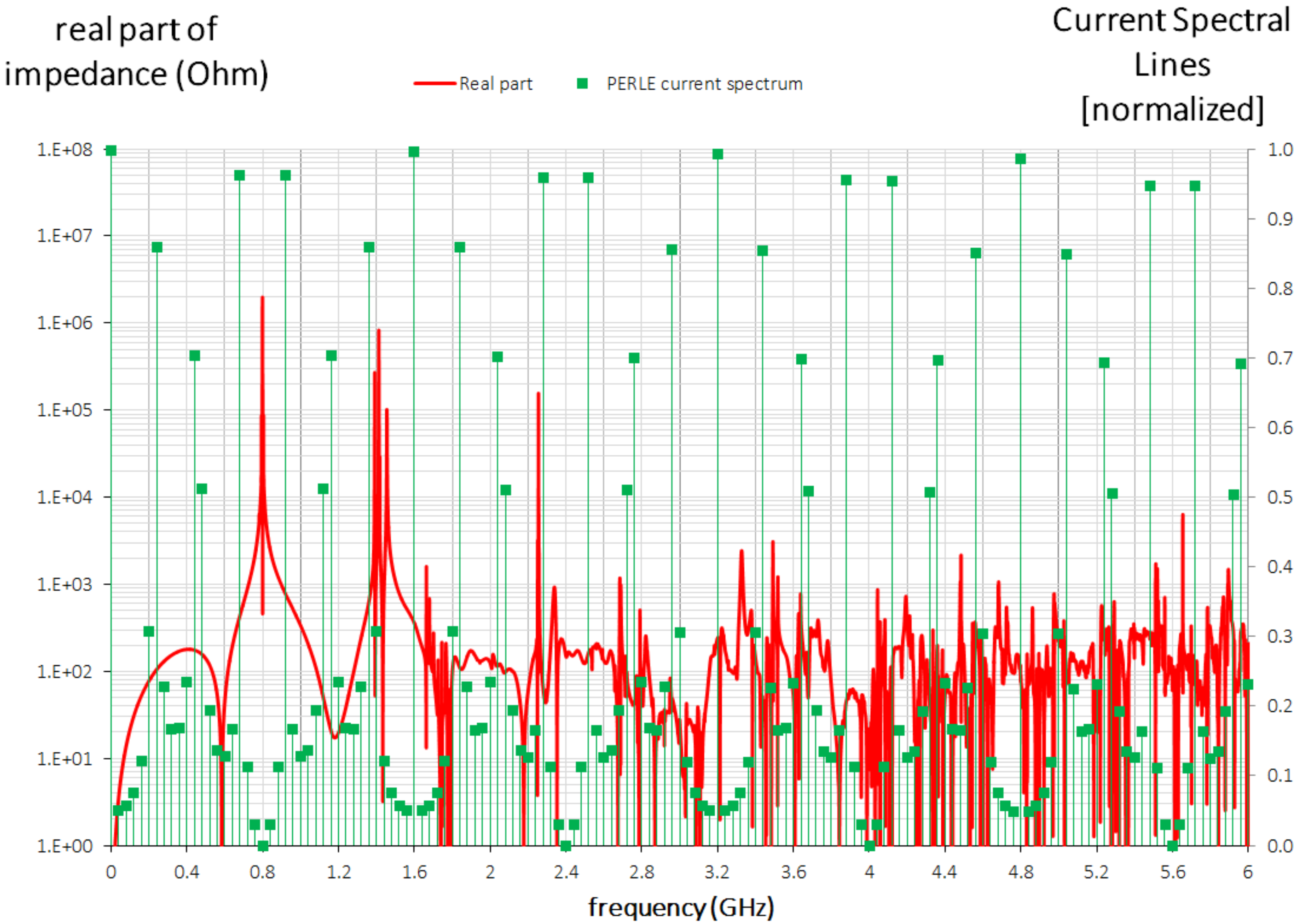


Beam structure with ERL recombination pattern
(nearly constant bunch spacing)

- For the power calculation, one needs to look into the corresponding spectral lines

Beam Spectral Lines Important for HOM-Power Assessment

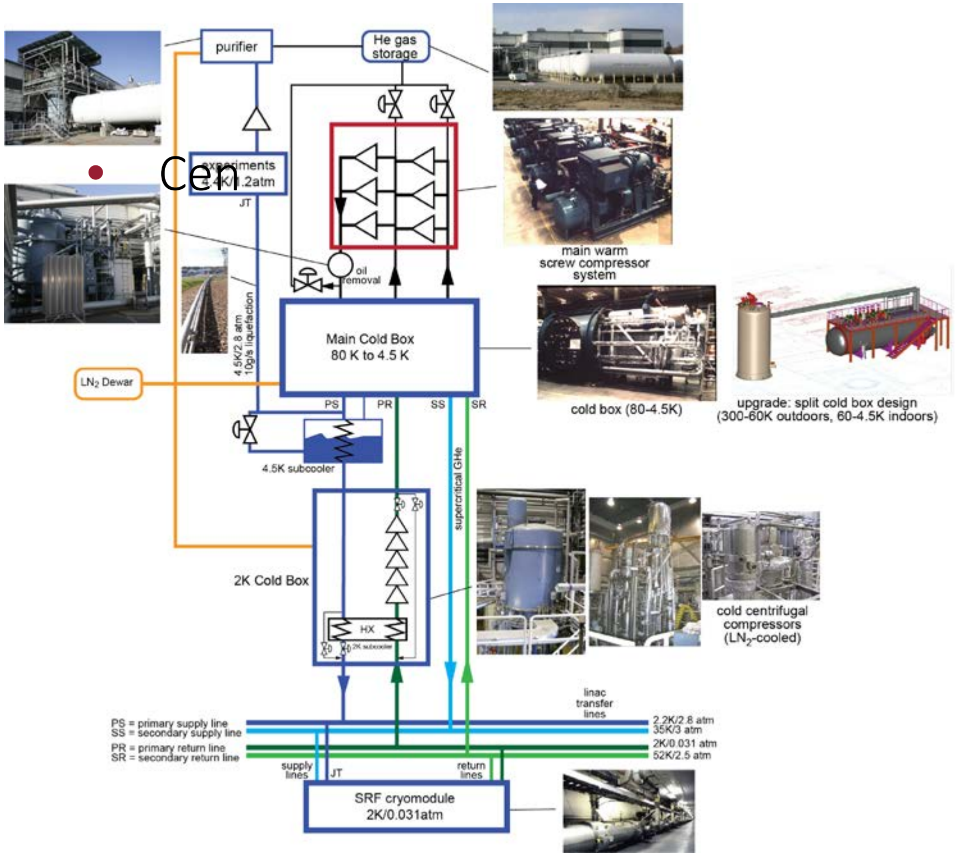
- Thanks to Dario Pellegrini to provide the current spectral lines for the PERLE recombination pattern (today)

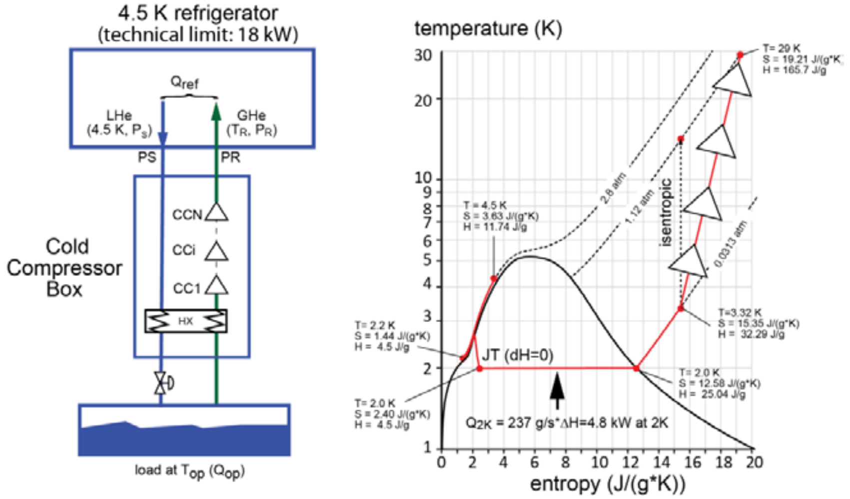


Backup Slides

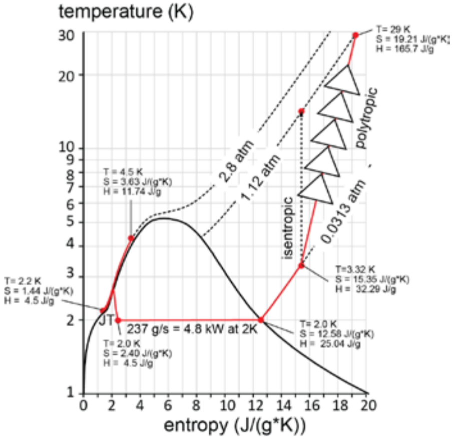
Central Liquefier Plane

- Cen





Integral cold compressor box and T-S diagram based on the original CHL design at CEBAF (top figures) and with one added cold compressor (bottom figure)



Broadband HOM Coupler Performance w/o Cavity

- Scaled LHC endgroup not efficient above cutoff, would need modification