Choice of Frequency, Gradient, and Temperature for a Superconducting Proton Linac

using the example of the CERN SPL

F. Gerigk, O. Brunner, S. Calatroni, E. Ciapala, M. Eshraqi, R. Garoby, A. Lombardi, R. Losito, V. Parma, J. Tückmantel, M. Vretenar, U. Wagner, W. Weingarten

HB'08, August 25-29, 2008, Nashville, Tennessee, USA

Outline

- basic SPL parameters,
- possible SC linac architectures,
- beam dynamics,
- HOMs,
- SC cavity properties (frequency, temperature, Q-slope),
- RF equipment,
- cryo-modules & cryogenics,
- overall performance & summary.

SPL parameters

operation type	low-power (nominal)	full-power (nominal)	full-power (red. energy)
E [GeV]	4	5	2.5
P_{beam} [MW]	0.192	4	4
f_{rep} [Hz]	2	50	50
$I_{average}$ [mA]	20	20/40	40
I_{source} [mA]	40	40/80	60
chopping	yes	3/8	no
t_{pulse} [ms]	1.2	0.8/0.4	0.8
$n_{protons/pulse}$ [10^{14}]	1.5	1	2
filling time PS2 [ms]	1.2	1.2/0.6	n.a
main user	PS2/ISOLDE	PS2/neutrinos	EURISOL

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

possible SC architectures

basic choices:

- use a multiple of 352 MHz (Linac4 frequency), but not 3x352.2 MHz or mixtures of 704 and 1408 MHz,
- replace 5-cell 704 MHz cavities by 9-cell 1408 MHz cavities to keep approximately the same length,
- use b<1.0 cavities (e.g. 0.92/0.94) for high-energy section (10% saving in linac length!),
- assume 25 MV/m @ β=1 for 704 and 1408 MHz,
- include beam dynamics matching section for all scenarios,

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

possible SC architectures II

SPL type	nominal improved	high-frequency option	spoke option
frequency [MHz]	704.4	1408.8	352.2/1408.8
beta families	0.65/0.92	0.6/0.76/0.94	0.67/0.8/0.94
cells/cavity	5/5	7/9/9	4/5/9
trans. energies [MeV]	160/581	160/357/884	160/392/758
output energy [MeV]	5122	5144	5075
gradients [MV/m]	18.7*/24*	17.5*/21.3*/24.2*	8.5/9.5/24.2*
cavities p. module	6/8	4/4/8	3/4/8
cavities p. period	3/8	2/4/8	3/4/8
cavities p. family	39/200	30/40/208	27/24/216
cavities in total	**239**	**278**	**267**
length [m]	**439**	**499**	**485**

* corresponds to 25 MV/m @ β=1

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

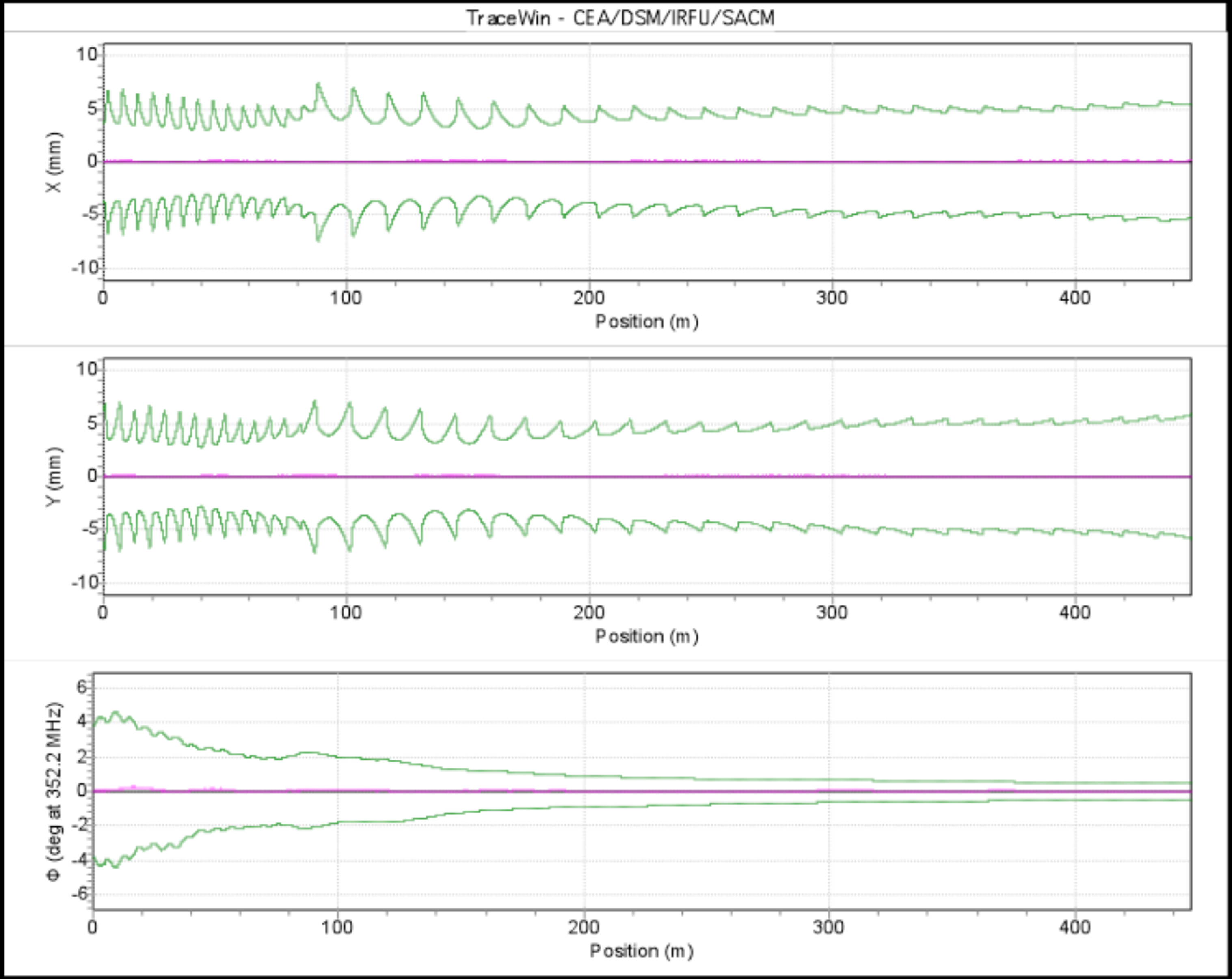
Beam dynamics

(A. Lombardi, M. Eshraqi)

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

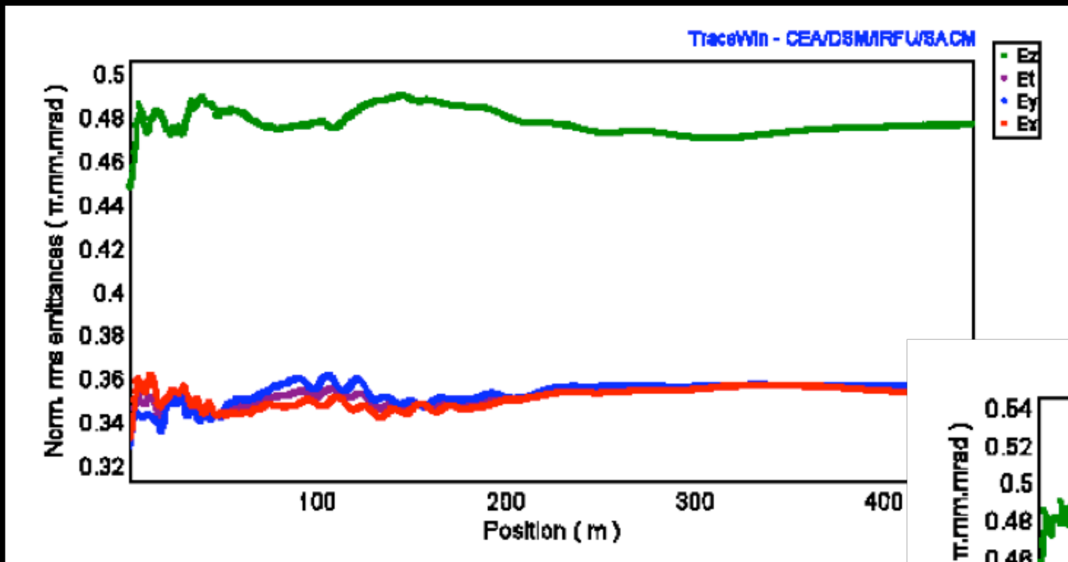
beam dynamics: 5 x rms envelopes

nominal:



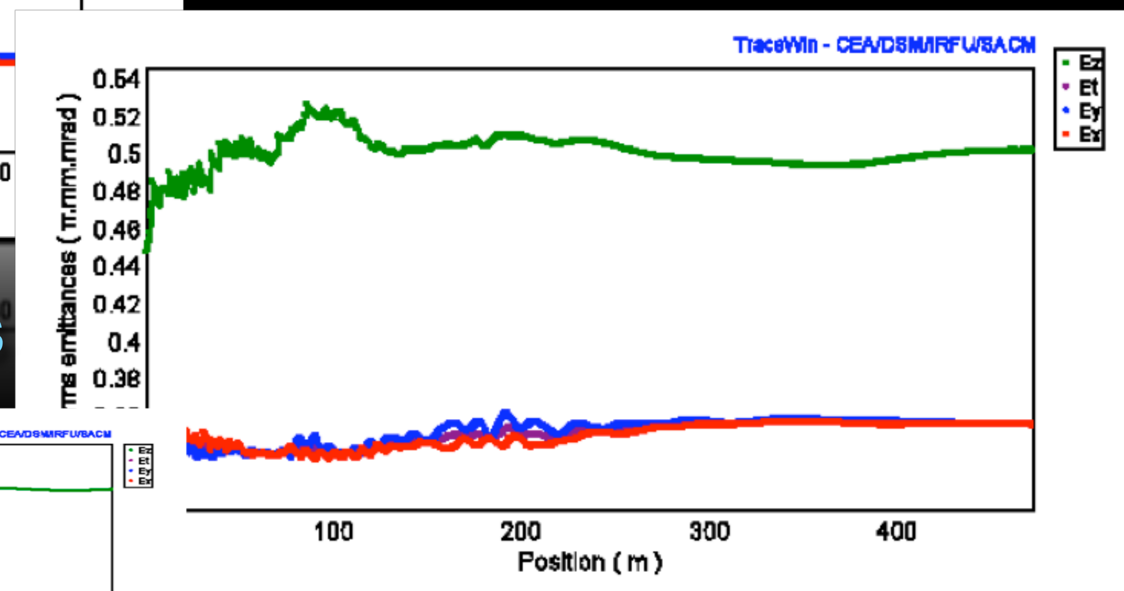
“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

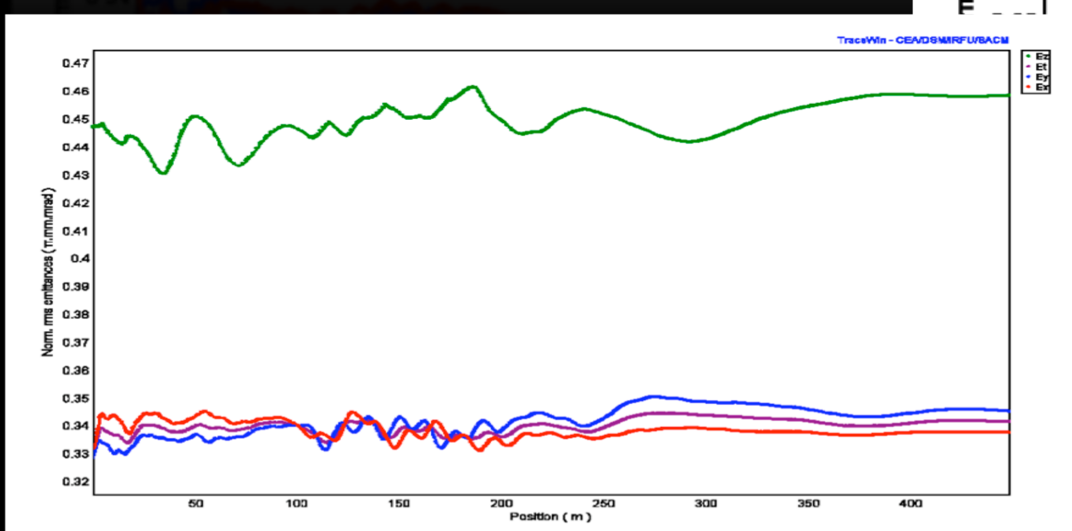
rms emittances



nominal

1408 MHz elliptic cavities





spoke + 1408 MHz elliptic

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

beam dynamics nominal beam

SPL type	nominal improved	high-frequency	spoke/elliptical
frequency [MHz]	704.4	1408.8	352.2/1408.8
beta families	0.65/0.92	0.6/0.76/0.94	0.67/0.8/0.94
$\Delta\varepsilon_x$ [%]	5.6	6.3	1.5
$\Delta\varepsilon_y$ [%]	8.2	7.8	5.3
$\Delta\varepsilon_z$ [%]	6.8	12.1	2.5
Lossy runs	-	-	-

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

beam dynamics: longitudinal errors

Case I: ΔE (1σ)= 125 keV/±0.5 deg from Linac4, ±0.5%/±0.5 deg in SPL. **Case II:** ΔE (1σ)= 125 keV/±1 deg from Linac4 ±1%/±1deg in SPL.

SPL type	nominal improved		high frequency		spoke/elliptical	
	case I	case II	case I	case II	case I	case II
frequency [MHz]	704.4		1408.8		352.2/1408.8	
beta families	0.65/0.92		0.6/0.76/0.94		0.67/0.8/0.94	
$\Delta\varepsilon_{x,rms}$ [%]	0.07±0.27	0.21±0.41	0.24±0.62	1.02±1.11	0.05±0.22	0.24±0.49
$\Delta\varepsilon_{y,rms}$ [%]	0.18±0.26	0.59±0.53	0.10±0.38	0.42±0.75	0.09±0.24	0.33±0.50
$\Delta\varepsilon_{z,rms}$ [%]	0.40±0.58	1.13±1.33	0.27±0.70	1.90±1.88	0.19±0.36	0.81±0.76
ΔE [MeV]	±2.0	±3.8	±1.8	±3.5	±1.8	±3.5
Δϕ [deg, st.dev.]	0.26	0.57	0.30	0.61	0.30	0.61
Lossy runs	0	0	9/500	21/500	0	0

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

beam dynamics: summary

- **transverse plane:** reducing the aperture due to higher frequency cavities (1408 MHz) is unlikely to influence transverse beam loss: beam pipe/rms radius > 20,

➡ even for strong mismatch, the outermost halo particles are usually confined to beam pipe/rms radius < 12,

- **longitudinal:** ε-growth and energy/phase jitter does not seem to be a show-stopper for any architecture (thanks to a careful matching and longer matching sections for 1408 MHz!),

➡ the largest longitudinal ε-growth and the only longitudinal losses (at all) were observed for the 1408 MHz version.

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

Higher Order Modes

(J. Tuckmantel)

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

Higher-order modes (BBU) I

step I: pure frequency scaling: same number of cells

	704 MHz	1408 MHz
number of cells	n	n
cavity length	L	L/2
areas	A	A/4
volumes	V	V/8
frequency	f	2 x f
stored energy	W	W/8

scaling only with freq.

$$Q_{ex} \propto \frac{V_{acc}}{(R/Q)I_{beam}}$$

$$\Delta V_{ind} = 0.5q\omega(R/Q)$$

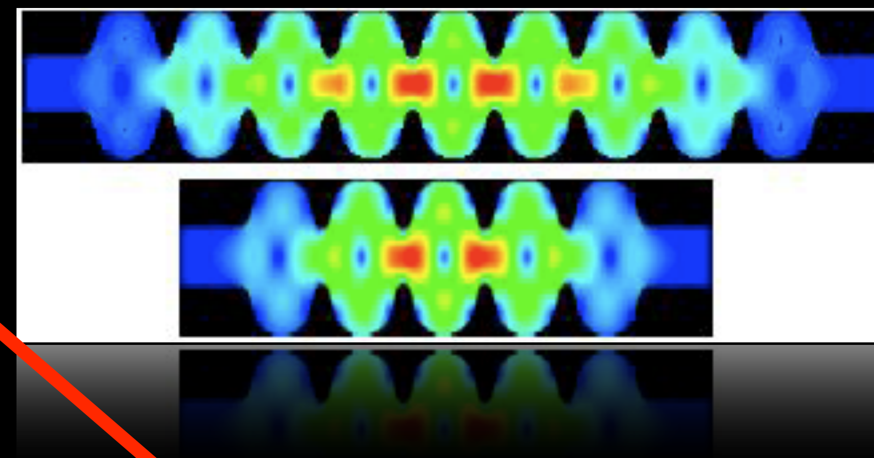
	704 MHz	1408 MHz
$(R/Q)_{\|\|}$	1	1
Q_{ex}	1	1
ΔV_{ind} (monop., short range, p. cav.)	1	x2
$Z_{\|\|}/L$ (monop., long range)	1	x2
Δp_x (dip., long range, p.cav.)	1	x2
$Z_{\perp}/L$ (dip. long range)	1	x4
I_{BBU}	1	/4

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

Higher-order modes (BBU) II

step II: doubling the cell number (still perfect cavities)

- Q_{ex} doubles because the stored energy doubles
- Some modes have higher amplitudes in the centre than in the end-cells (worse for higher cell numbers!).
- HOM coupling is proportional to the square of the fields.
- When doubling the number of cells, the coupling can go down by 8:1!!



	704 MHz	1408 MHz
ΔV_{ind} (monop., short range, p. cav.)	1	x4
$Z_{\parallel}/L$ (monop., long range)	1	x4..16
Δp_x (dip., long range, p.cav.)	1	x8..32
$Z_{\perp}/L$ (dip. long range)	1	x8..32
I_{BBU}	1	/(8..32)

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

Higher-order modes (BBU) III

step III: imperfect structures

- The end-cell tuning will flatten the field for accelerating mode but will make things worse for the HOMs ("crooked" field profiles).
- Increases the risk for HOMs, with "uneven" field profile (e.g. field only on one side of the structure, or completely trapped modes with almost no field in the end cells).
- Frequency difference between neighbouring modes is halved when cell number doubles: with nearly quadratic frequency distribution towards the pass-band borders, the Δf for the last 2 modes is reduced by almost 4!

	704 MHz	1408 MHz
$I_{BBU,threshold}$	1	/(8-128)
risk of trapped modes	1	x 2-4

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

Higher-order modes (BBU) IV

scaling from SNS results:

- SNS simulated that longitudinal instabilities are ok, if Q_{ex}(all HOMS) < 10^8, 6-cell, 806 MHz, I_{beam} = 20 mA,

➡ scaling with current, frequency, n_{cells}, linac length means: Q_{ex} (all HOMS) $\lesssim 10^6$,

➡ including end-cell problems & worst cases: $Q_{ex} \lesssim 10^5$

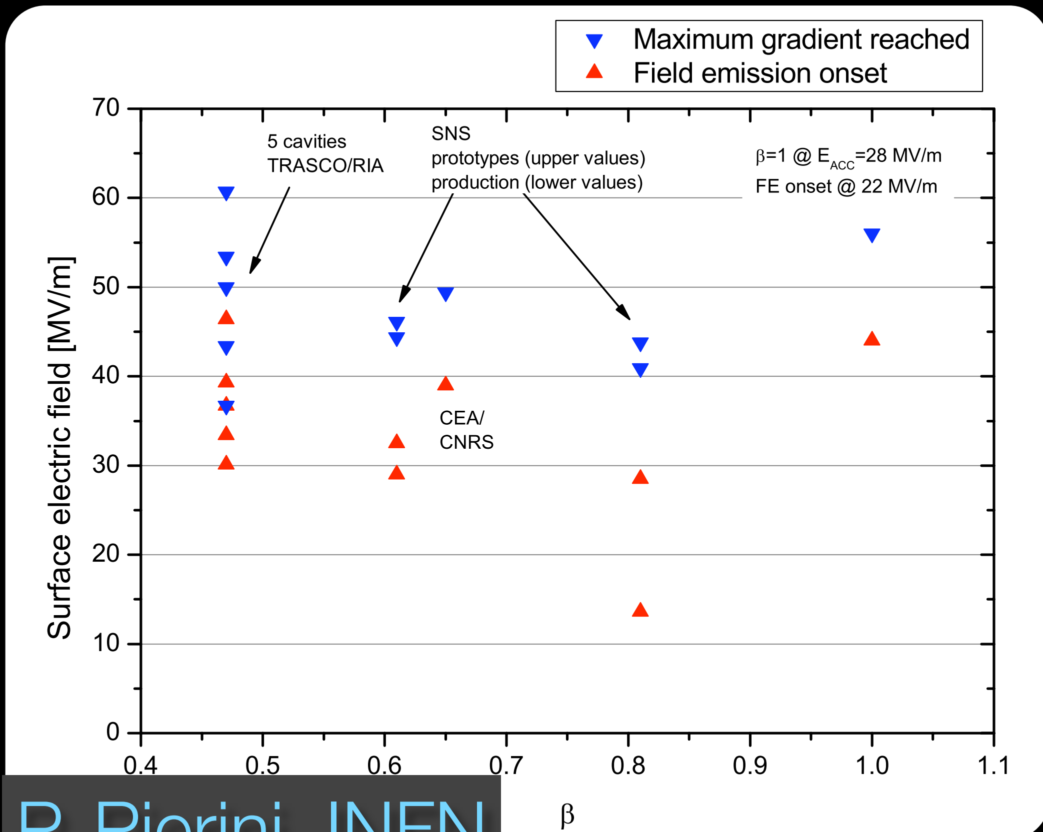
“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

Cavity properties

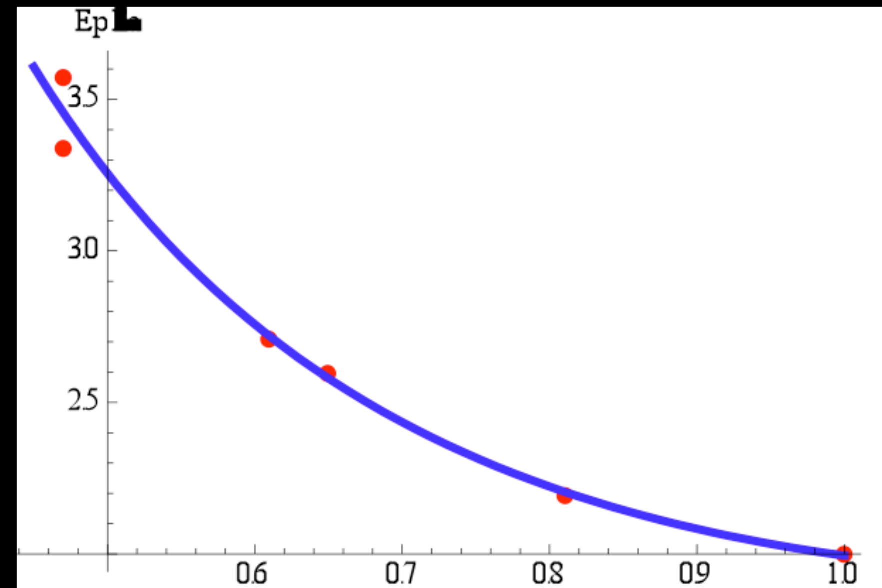
(W. Weingarten, S. Calatroni)

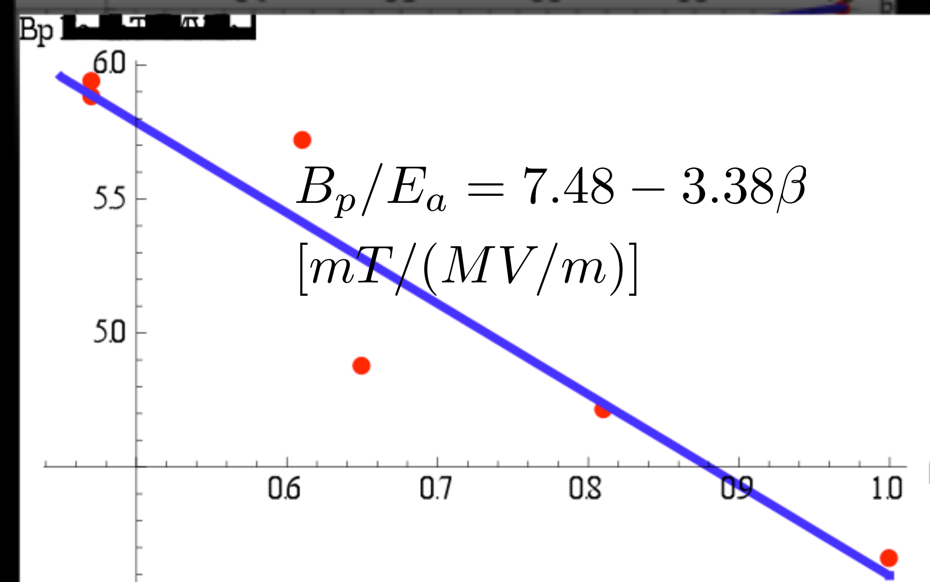
“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

SC cavity performance for β<1



P. Pierini, INFN



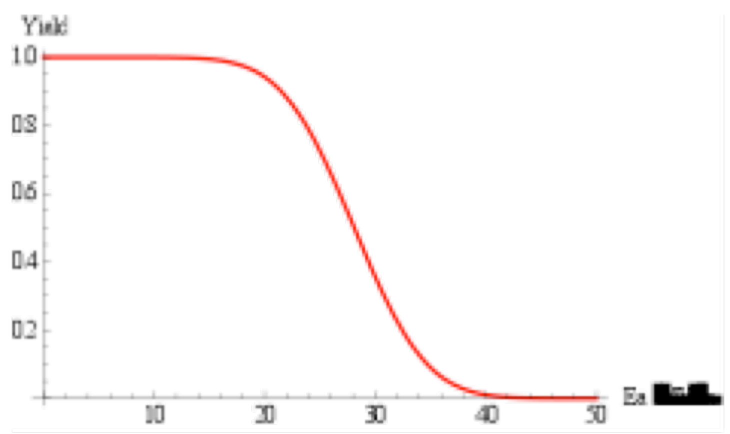


gradient independent of freq.

25 MV/m looks challenging but not impossible!

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

yield vs performance



for electropolished ILC cavities at 1300 MHz:

- at 28.1 MV/m the yield is ≈ 50%,
- at 25 MV/m the yield is ≈ 75%,

but basically no difference between single cell and multi-cell results!

Laboratory	freq. [MHz]	$\langle E_{acc} \rangle$ [MV/m]	ΔE_{acc} [MV/m]	$\Delta E_{acc}/E_{acc}$ [%]	E_{acc} at 90/50% yield
DESY, 9-cell	1300	28	5.2	19	22/28
ORNL/JLAB, 6-cell β=0.61, (extrapolated to β=1)	805	17.1 (23)	1.9 (2.6)	11 (11)	15/17 (20/23)
ORNL/JLAB, 6-cell β=0.81, (extrapolated to β=1)	805	18.2 (20)	2.6 (2.8)	14 (14)	15/18 (16/20)

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

Q dependance on f,T,B_p ?

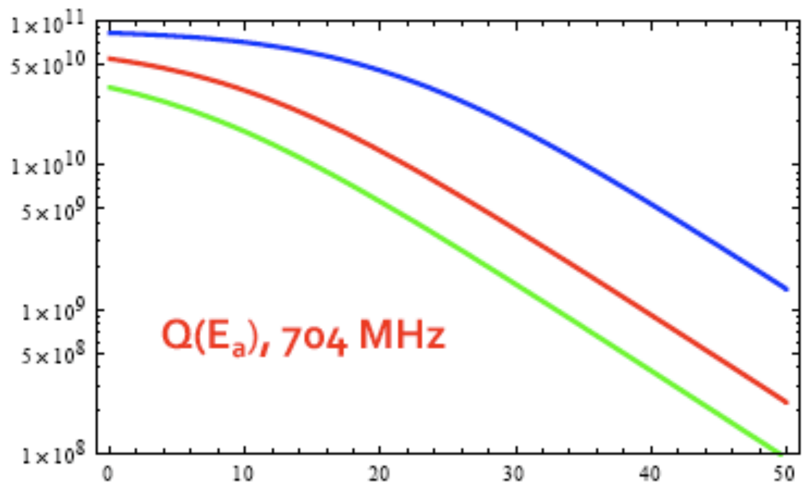
$$
\begin{aligned}
Q &= G/R_s \\
R_s &= \underbrace{R_{BCS}(f,T) + R_{s,mag,trapped}(f,T,B_{trapped})}_{\text{known (e.g. Wikipedia!)}} + \underbrace{R(f,T,B_p)}_{\text{new addition}} + R_{res}
\end{aligned}
$$

Evaluating test results of elliptical, spoke, quarter-wave resonators between 80 and 1300 MHz and 1.4 and 4.6 K a "phenomenological" parametrisation for the field dependance of Q was introduced as:

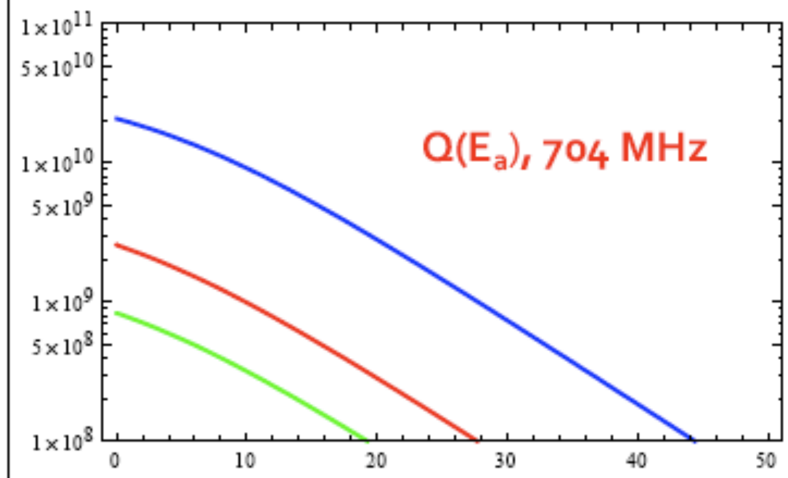
$$R(f,T,B_p)[n\Omega] = (0.73 \pm 0.22) \cdot 10^5 \cdot (f[GHz])^{1.5} \exp(0.035 B_p[mT]) \cdot \exp(-18/(T[K]))/(T[K])$$

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

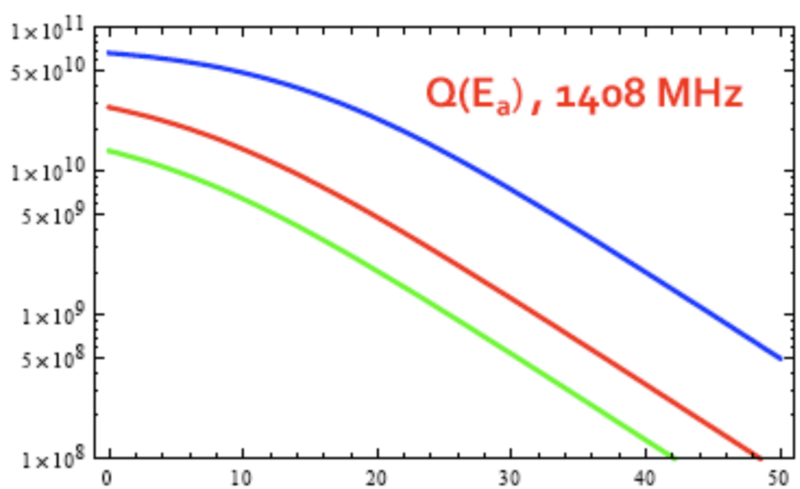
Superfluid helium
T = 1.5, 1.8, 2.0 K
R_{res} = 3 nΩ



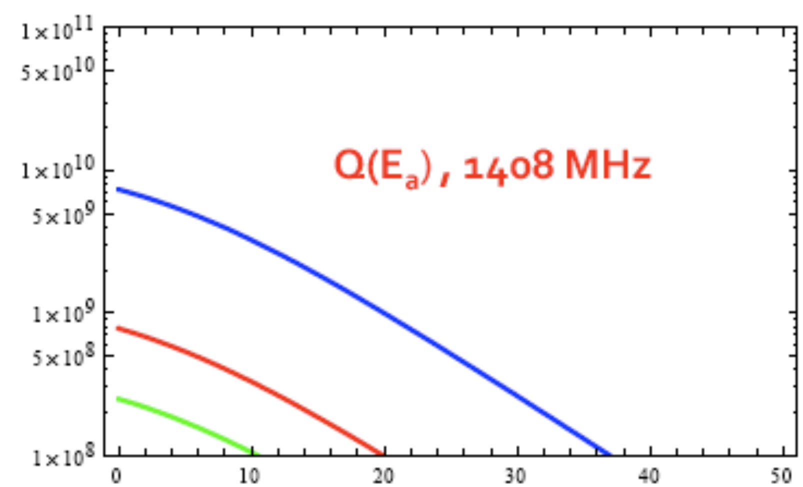
Normal helium
T = 2.2, 3.3, 4.5 K
R_{res} = 3 nΩ



Superfluid helium
T = 1.5, 1.8, 2.0 K
R_{res} = 3 nΩ



Normal helium
T = 2.2, 3.3, 4.5 K
R_{res} = 3 nΩ



Q dependance at 25 MV/m

at 2K: $Q_{704\ MHz} = 2.7 \times Q_{1408\ MHz}$

at 4.5K: $Q_{704\ MHz} = 3 \times Q_{1408\ MHz}$

at 704 MHz: $Q_{2\ K} = 45 \times Q_{4.5\ K}$

at 1408 MHz: $Q_{2\ K} = 49 \times Q_{4.5\ K}$

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

summary cavity performance:

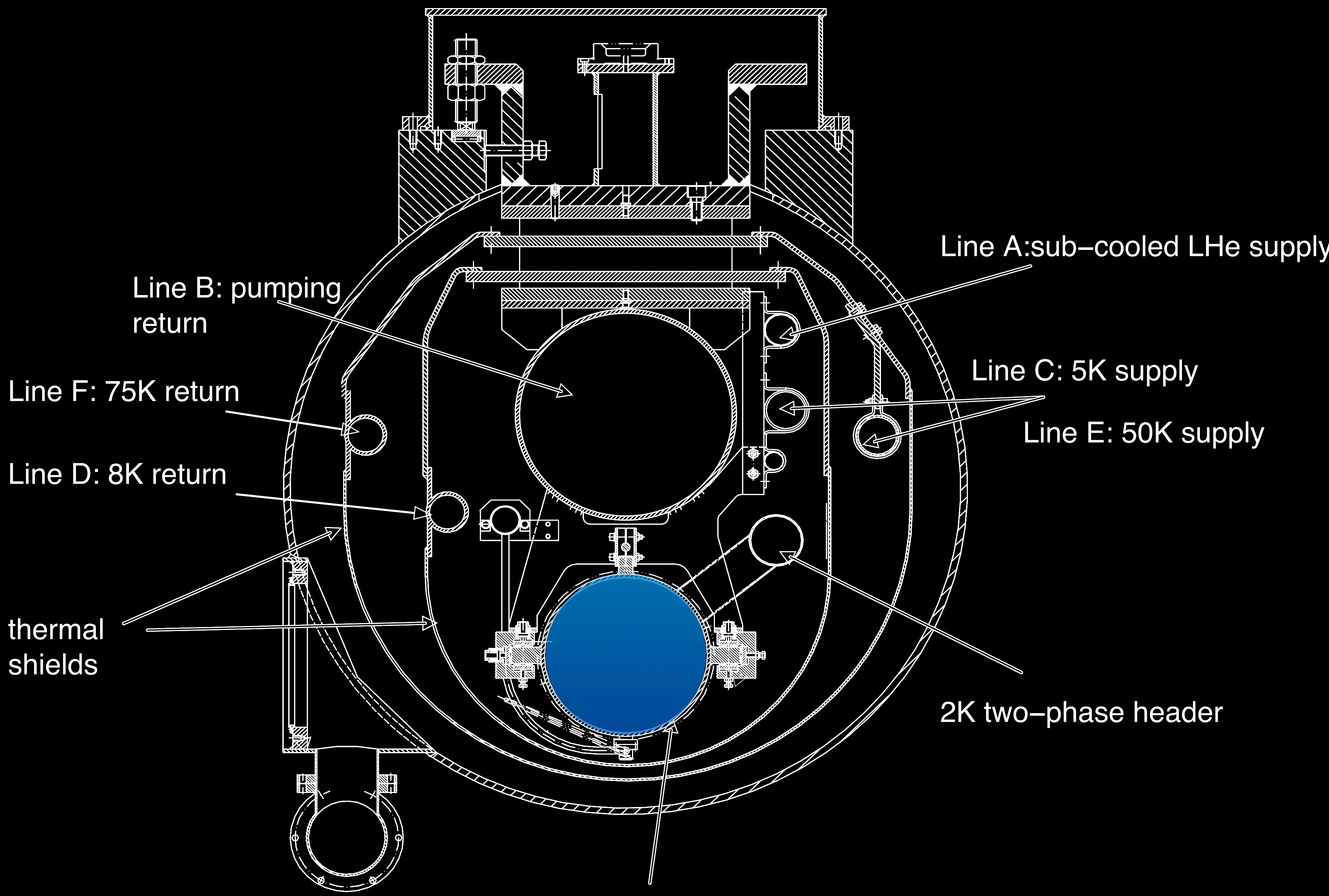
- ➡ assume that the same gradients can be reached at 704 and 1408 MHz,
- ➡ 25 MV/m at 704 MHz looks possible but may mean to accept a yield of 75%,
- ➡ assume Q_0 of 10^{10} at 2K at 704 MHz (may even be conservative),
- ➡ Q-values at 4.5 K (25 MV/m) are up to 50x lower than at 2 K!
- ➡ Q-values are ~3x higher at 704 MHz than at 1408 MHz (25 MV/m).
- ➡ We do not save R&D effort, nor do we gain in performance when going to 1408 MHz instead of 704 MHz.

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

Cryogenics

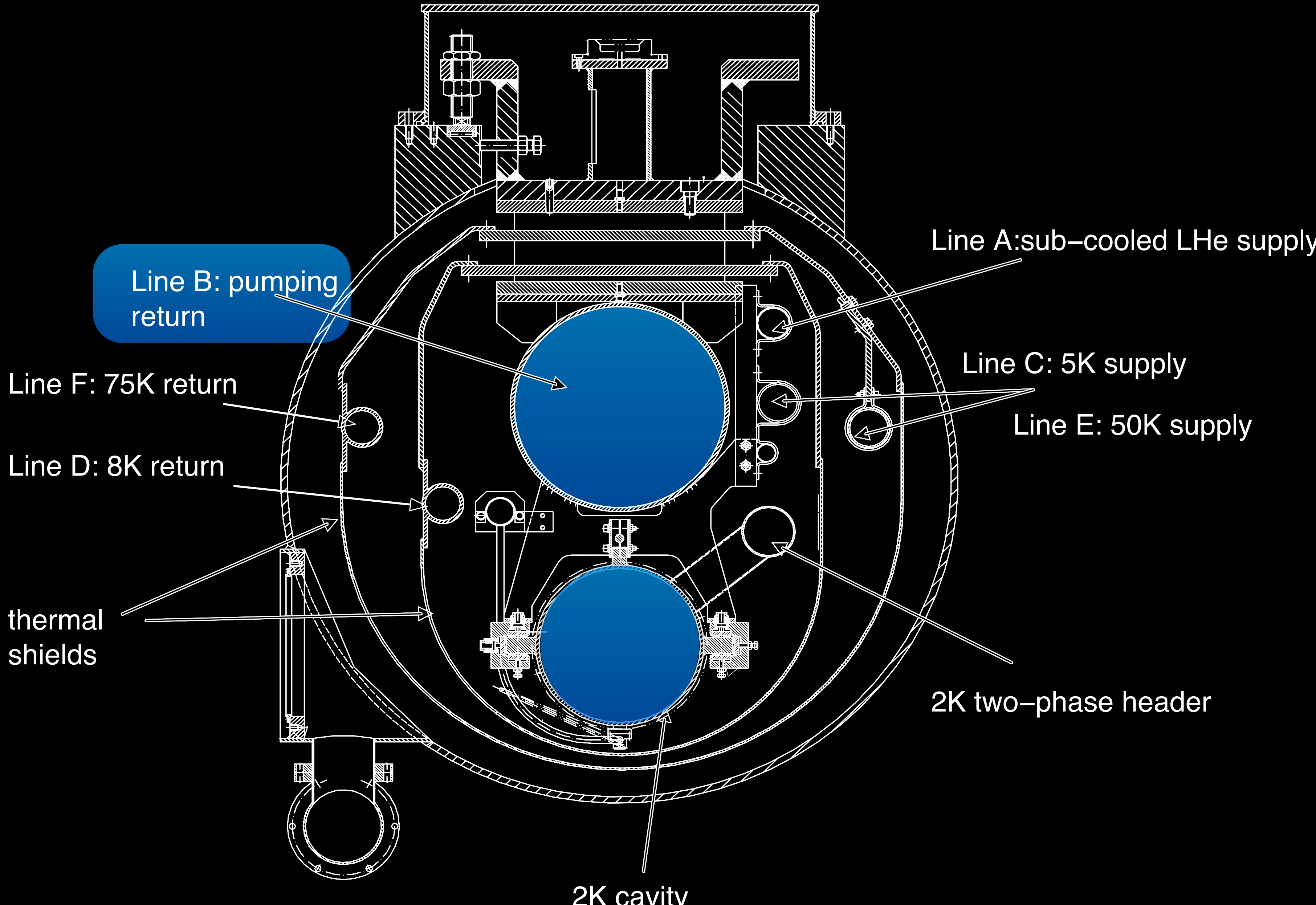
(V. Parma, U. Wagner)

Can we re-use the ILC cryo-module?



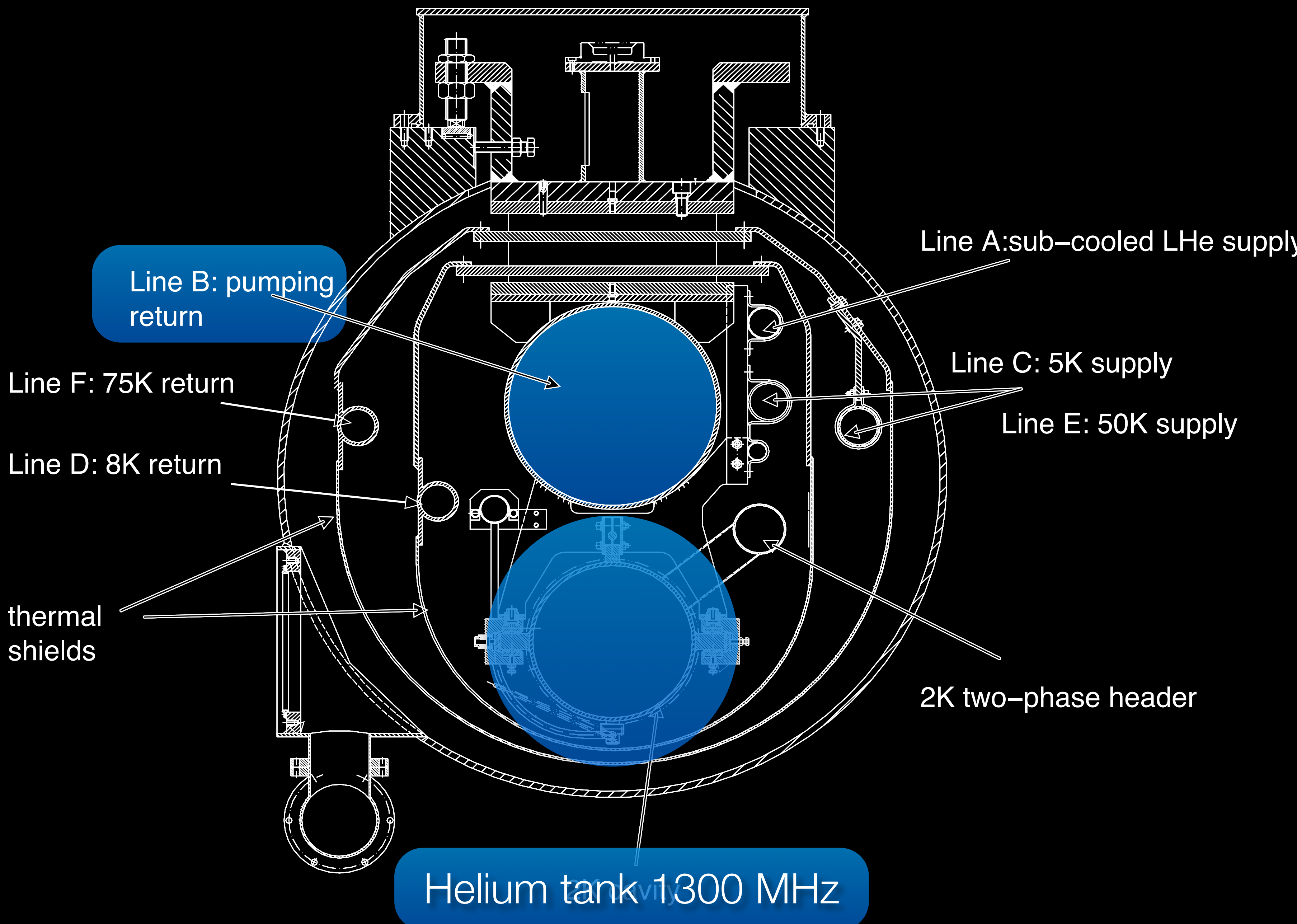
“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

Can we re-use the ILC cryo-module?



“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

Can we re-use the ILC cryo-module?



“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

Can we re-use the ILC cryo-module?

At 2K we can re-use the ILC design principle for both frequencies, but:

- the port openings will have to be adapted to the SPL cavities (power coupler, HOM coupler, ...),
- the design has to be adopted for the SPL slope of 1.7 deg,
- dynamic heat load of the HPSPL is estimated to be ~10 times higher than for ILC,

➡ an identical copy of the ILC cryo-module cannot be used!

➡ unlikely that we can have a major saving on the cryo-module cost, when going to 1408 MHz!

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

cryogenic infrastructure

assuming: ~45..50 x $Q_{0,\,4.5\,K} = Q_{0,\,2\,K} = 10^{10}$

		eq. capacity @ 4.5 K [kW]		el. power [MW]	
	T [K]	704 MHz	1408 MHz	704 MHz	1408 MHz
HP SPL, 2% beam d.c. (4% cryo d.c.)	2	15.3	15.5	3.8	4.0
HP SPL, 2% beam d.c. (4% cryo d.c.)	4.5	139	138	34.5	34.5
HP SPL, 6% beam d.c. (8% cryo d.c.)	2	24.8	29	6.2	7.3
HP SPL, 6% beam d.c. (8% cryo d.c.)	4.5	276	354	69	88.4

excessive!

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

cryogenics summary

- 4.5 K leads to an excessively large cryo-plant (size and power consumption),
- the development of a SPL specific cryo-module is recommended and it will be based on the ILC design,
- the design effort, size, and cost for 704 and 1408 MHz seems similar,
- installed capacities are similar for both frequencies,

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

RF hardware

(O. Brunner, E. Ciapala)

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

RF hardware: klystrons

for both frequencies we want ~5 MW peak power, ~10% duty cycle

704 MHz:

- for Linac4, Thales, CPI, and Toshiba were contacted,
- expected beam power: 4-5 MW @ SPL duty cycle,
- similar to SNS klystrons at 805 MHz,
- no off-the-shelf device exists on the market,
- for single-beam the specifications are at the limit for MBK they should be straight forward.

1408 MHz:

- Toshiba, CPI, and Thales have built 10 MW (150 kW) klystrons for DESY @ 1300 MHz,
- They expect around 5 MW peak power for 10% duty cycle,
- likely to be more expensive than 704 MHz,
- no off-the-shelf device exists on the market.

limits given by average power density (cooling): advantage for 704 MHz MBK!

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

RF hardware: power distribution

704 MHz:

- large wave-guide components,
- 5 MW circulators for high duty cycle exist (SNS),
- ferrite loads look feasible,
- high average power vector modulator easier at lower frequencies,

1408 MHz:

- smaller wave-guide components,
- no high duty cycle circulators available for 5 MW,
- phase shifters need at least volume,
- ferrite loads unrealistic, no suitable water loads available,

unlikely to gain in size when going to 1408 MHz, because power density enforces bulky components, can even be more difficult at 1408 MHz!!

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

RF hardware: coupler

for both frequencies we need ~1 MW peak power, ~10% duty cycle

704 MHz:

- $P_{av} \approx 40/80$ kW (0.4/1.2 ms pulses @ 40 mA),
- A 1 MW coupler has been developed at CEA within HIPPI, and will be tested soon.
- If this does not work it will be further developed with money from FP7.

1408 MHz:

- $P_{av} \approx 26/66$ kW (0.4/1.2 ms pulses @ 40 mA)
- Cornell is using a modified TTF coupler, gas cooled was tested with average power up to 61 kW CW (should support up to 75 kW).
- Main geometry remained the same, should achieve the same peak power as TTF (1.5 MW) but was not yet tested at this level.

some R&D needed at both frequencies, no show-stopper!

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

Facility optimisation: electrical power consumption

(W. Weingarten, F. Gerigk)

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

facility optimisation: el. power

$$P_{diss} = \frac{V_{acc}^2}{(R/Q)Q_0}$$

$$\tau_f = \frac{Q_l}{\omega_0} \approx \frac{V_{acc}}{(R/Q)I_{beam}\cos(\phi_s)\omega_0}$$

cryogenics power!

electrical + cryogenics power!

assuming cavities of approximately equal length

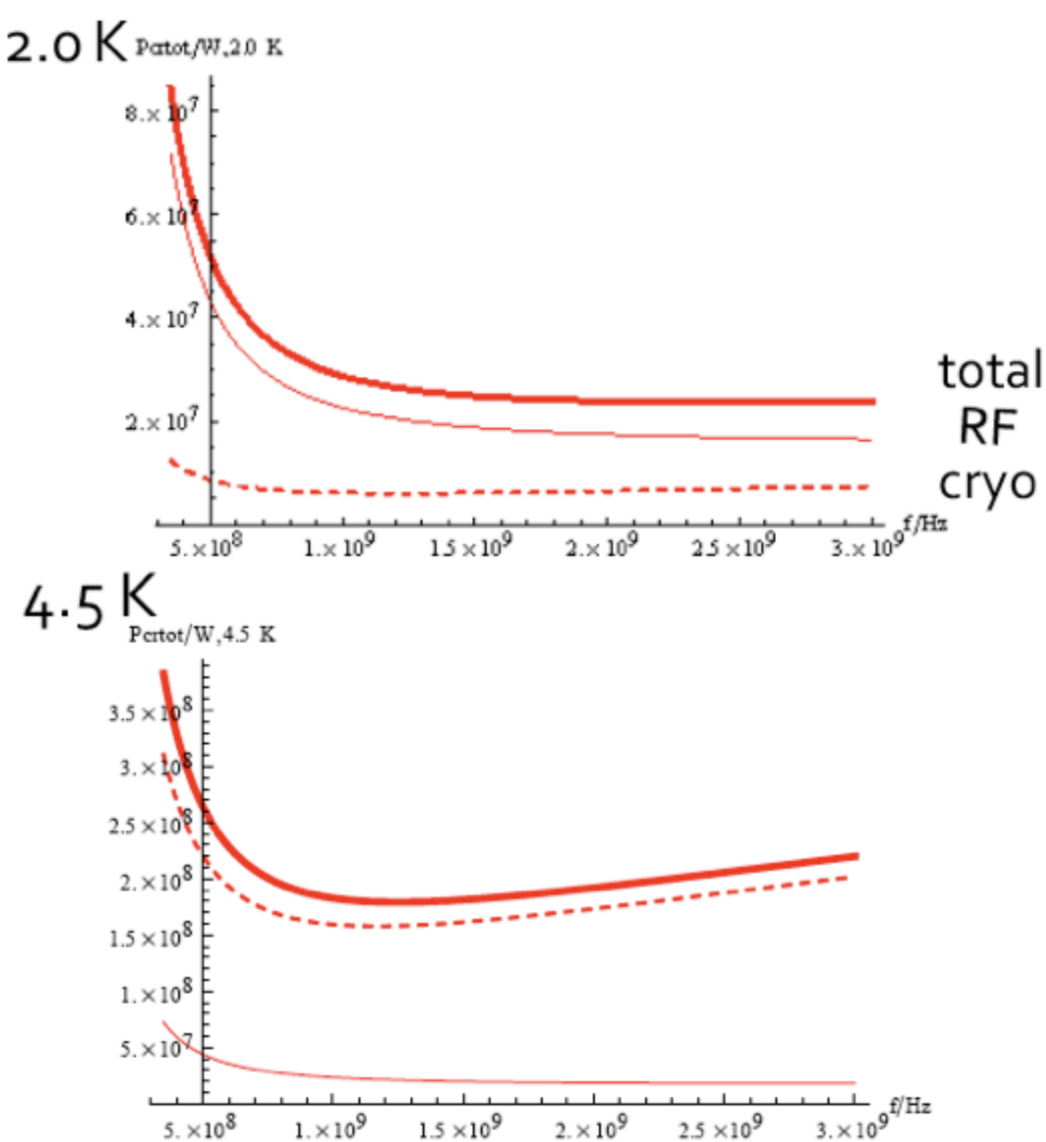
$$(R/Q) \propto f$$

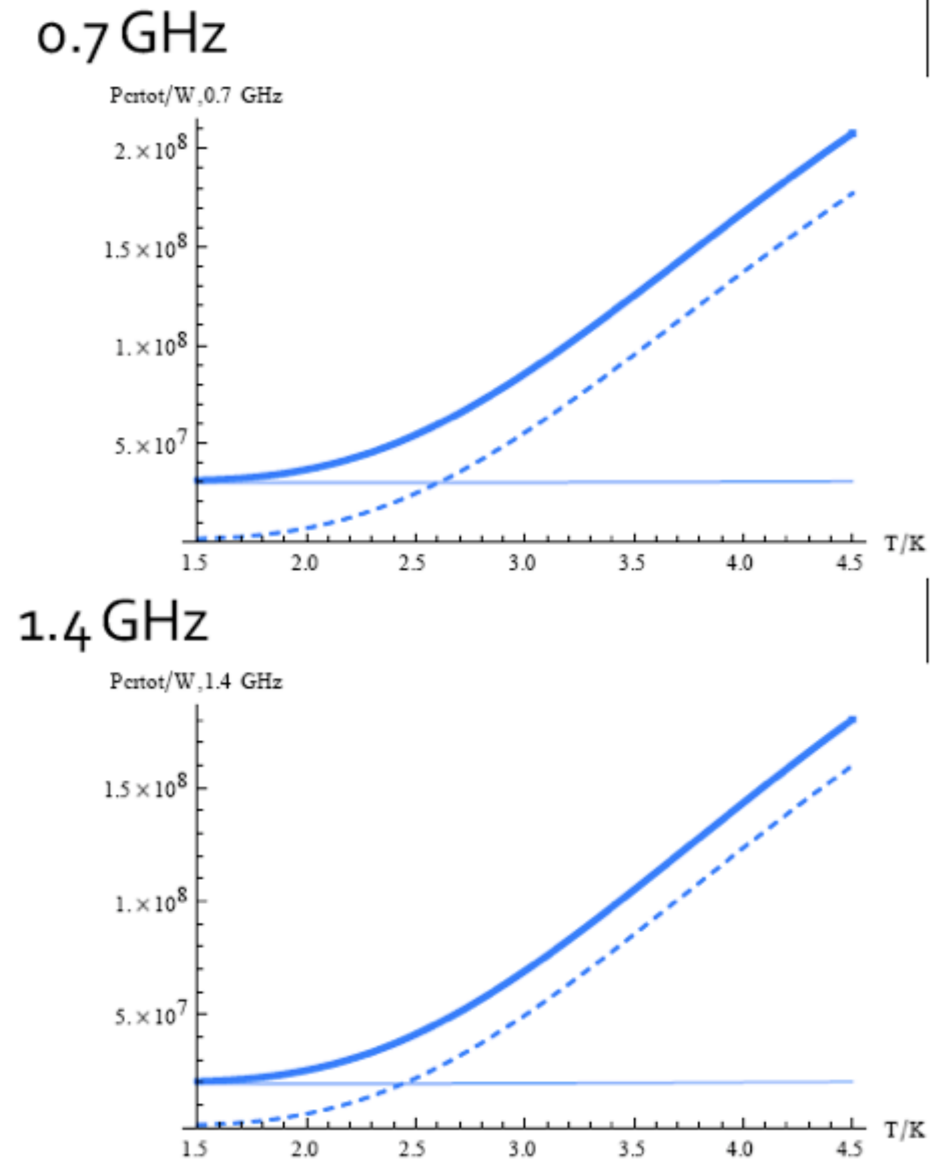
	704 MHz	1408 MHz
P_{diss}	$P_{diss,704\ MHz}$	~3/2 $P_{diss,704\ MHz}$
τ_f	$\tau_{f,\ 704\ MHz}$	1/4 $\tau_{f,\ 1408\ MHz}$

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

el. Power vs freq.

el. Power vs temperature





facility optimisation: el. power

4 MW, 5 GeV, neutrinos:

HPSPL: I_b=40 mA, t_P=0.4 ms, 50 Hz, 5 GeV, 4 MW	**704 MHz**	**1408 MHz**
P_{el} (RF + cryo 2K/4.5K)	24.1 MW + 3.8/34.5	16.0 MW +4.0/34.5
P_{cryo} @2 K (eq.@4.5 K)	15.3 kW	15.5 kW
P_{cryo} @4.5 K	139 kW	138 kW

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al

Summary

overall summary (assuming 2 K):

	704 MHz	1408 MHz	352 MHz (spoke) + 1408 MHz
length	439 m	+14%	+10%
$N_{cavities}$	239	+16%	+12%
$N_{\beta\text{-families}}$	2	3	2+1
tr. beam loss	-	-	-
jitter	medium	medium	medium
ε-growth (x/y/z)	5.6/8.2/6.8	6.3/7.8/12.1	1.5/5.3/2.5
trans. beam loading	-	-	-
BBU (HOM)	$I_{BBU,704}$	1/(8..128)	higher/lower
trapped modes	normal risk	2..4 higher risk	?/higher
SC gradients	-	-	-
field control		more complex	

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

...continued (assuming 2 K)

	704 MHz	1408 MHz	352 MHz (spoke) + 1408 MHz
cryo-modules	follow ILC	follow ILC	2 different types
cooling power @4.5 K	15.3 kW	15.5 kW	?
klystrons	comfortable: MBK	difficult	existing/difficult
RF power coupler	feasible	feasible	feasible
RF power density limit (distribution)	ok	problematic	bulky/ problematic
overall power consumption (RF +cryo, nom. SPL)	28 MW	-30%	?
power converter	more bulky	saves tunnel space	-
synergy with ESS	yes	no	no

“Choice of Frequency, Gradient and ...”, HB’08, F. Gerigk et al

for high-current, multi-MW proton linacs:

- 2 K is mandatory,
- lower frequencies entail higher RF power consumption despite the higher Q values (longer cavity filling time),
- the cryogenic power consumption does not change with f,
- beam dynamics (HOMs), cavity control, and RF power generation & distribution clearly benefit from lower frequencies,
- spoke option seems interesting but requires mastering of 2 cavity types (3 cavity families), yields long filling times, and results in a longer linac,
- no significant savings or simplifications expected when going to 1408 MHz, on the contrary!
- for the SPL we choose 704 MHz and 2 K!

"Choice of Frequency, Gradient and ...", HB'08, F. Gerigk et al