Some aspects of the layout and optimization for the cryogenic supply of superconducting linacs

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Working Group 3

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Overview

- Introduction
- High Q-Cavities Q = Q(T)
- 2 K principle cooling scheme
- Helium plant coefficient of performance COP = COP (T)
- Cold Compressors
- HeII Parameters = f(T)
- Critical gas flow conditions = f (T)
- Kapitza thermal resistance = f (T)
- European XFEL-Linac as an example
- Cryoplant parameters = f(T)
- Conclusions

Introduction

ERL superconducting linacs will dissipate power

in the order of some kW at temperatures < 2.17 K

In view of conversion factors to primary power consumption

in the order of 1000 = primary power / load at low temperatures

it seems to be worth while to try some optimization

Introduction (cont.)

My talk is restricted to SL-linacs operated around 1.3 – 1.5 GHz

and to liquid helium II bath cooling below 2.17 K

The optimization is focused on the T< 2.17 K cooling circuit

(the 5-8 K / 40-80 K thermal shield niveaus are not discussed)

The discussion is coupled to the believe that we can assume a

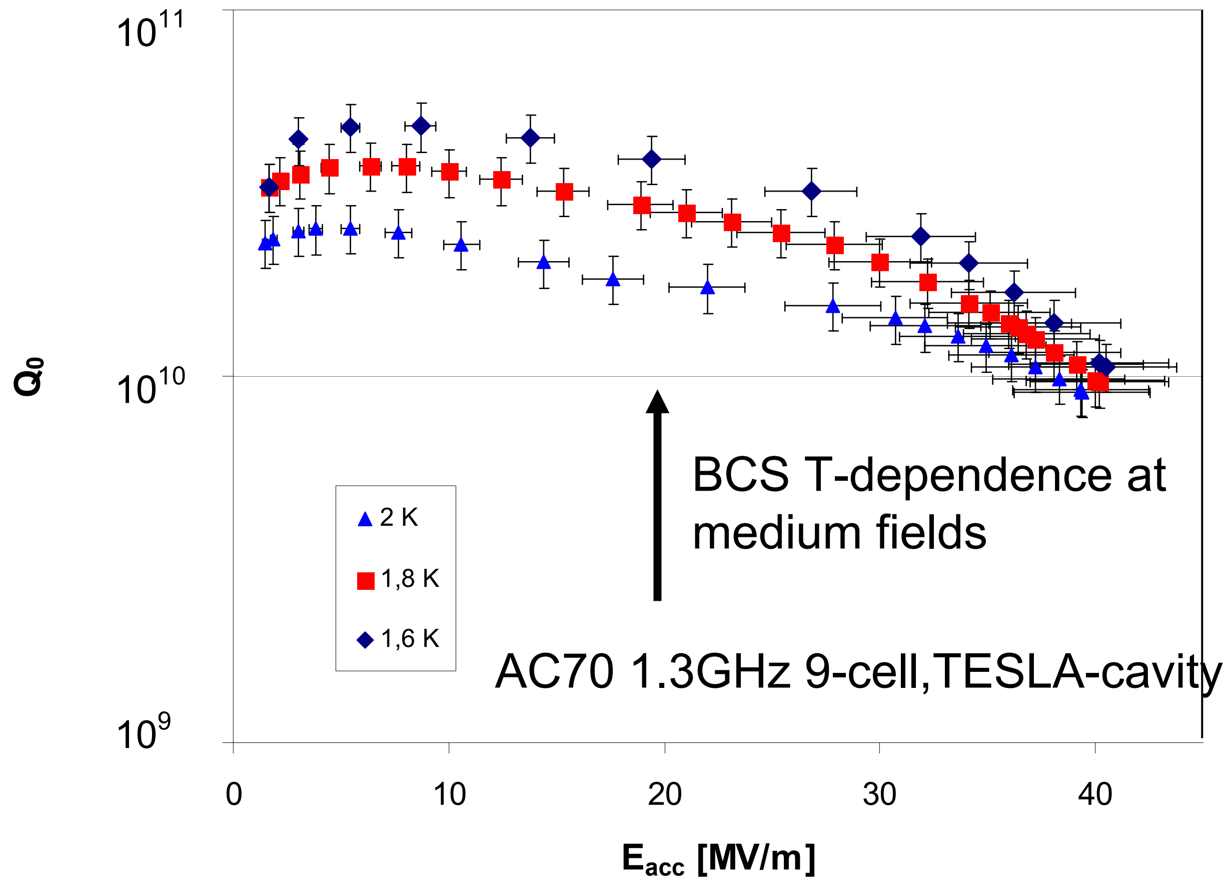
BCS Q = Q (t) dependence and the temperature dependent dynamic loads are dominating

DISCLAIMER:

Some XFEL-parameters, which are shown here, are in no way ‚official' project parameters. Often ‚hand-waving' argumentation is used to get qualitative results. Do not base the design of your machine on these data !

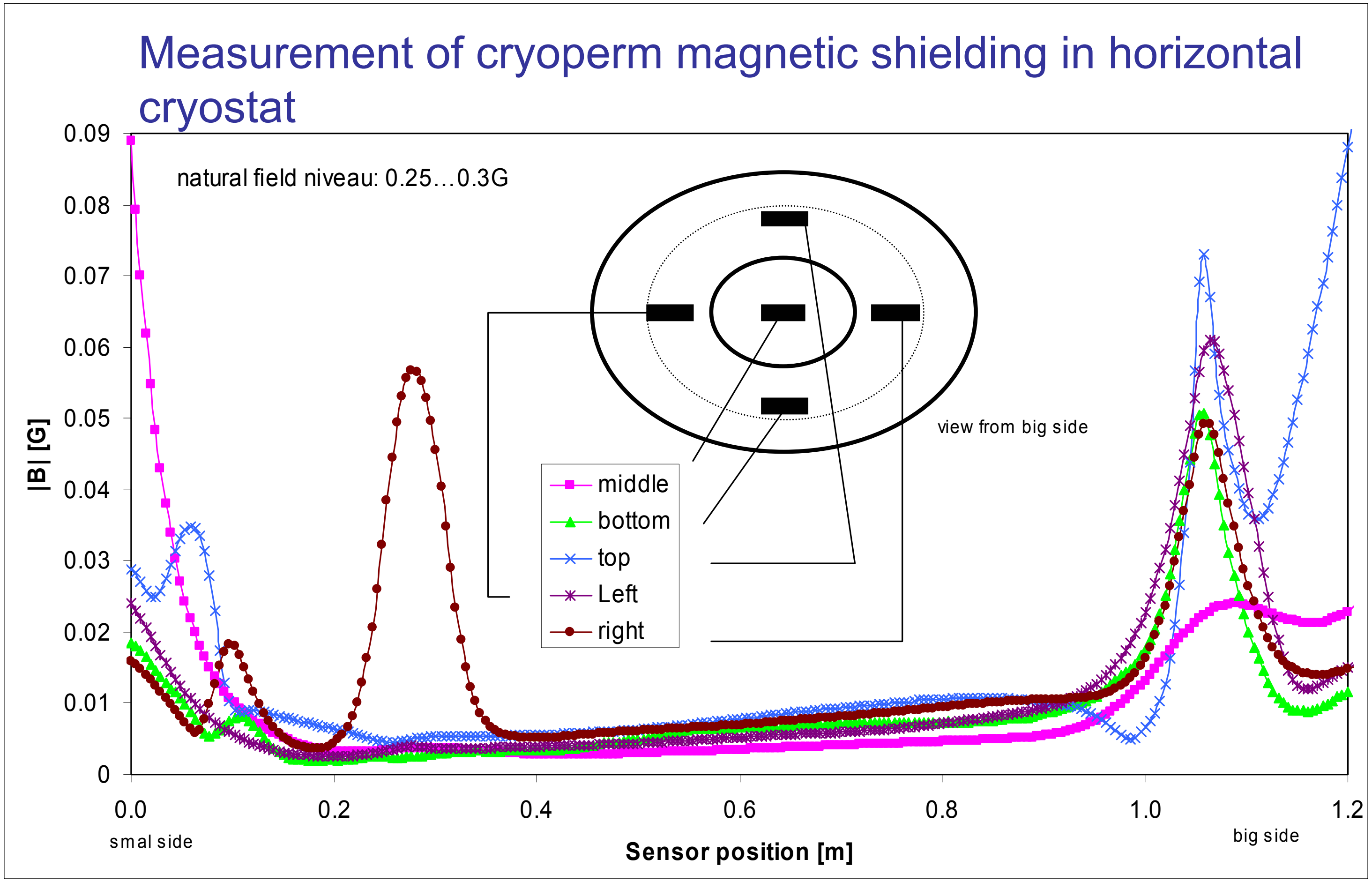
High Q Cavities

About factor 2 dynamic load reduction at 0.2 K temperature reduction below 2.17 K !



High Q requries proper magnetic field shielding !

AC70 result achieved by reduction of earth magnetic field to about 3 %



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Q (T) is linked to the BCS surface resistance

$$R_s = A\, f^2 \exp^{-\Delta/kT} \quad (+ R_0)$$

R_s : BCS surface resistance
A : material constant
f : frequency

R_0: residual resistance

Δ : BCS energy gap
k : Boltzmann constant
T : temperature

1.5 K is taken here as a reasonable lower limit of BCS Q=Q(T) dependence

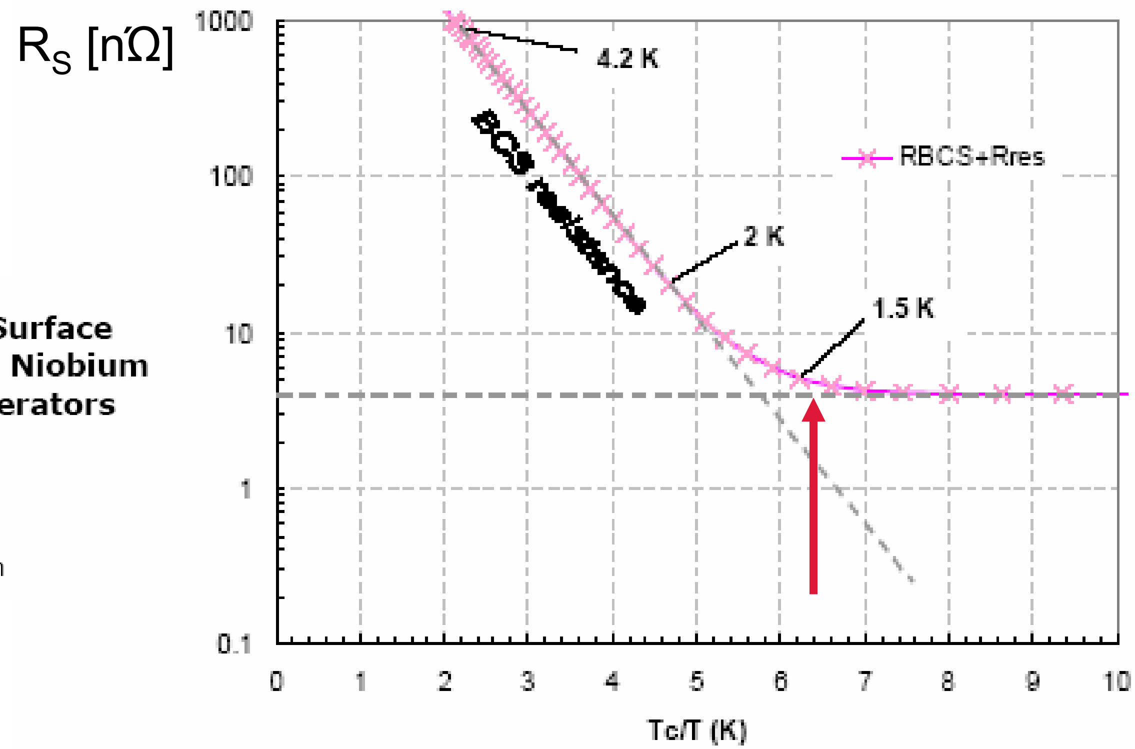


Diagramm taken from:

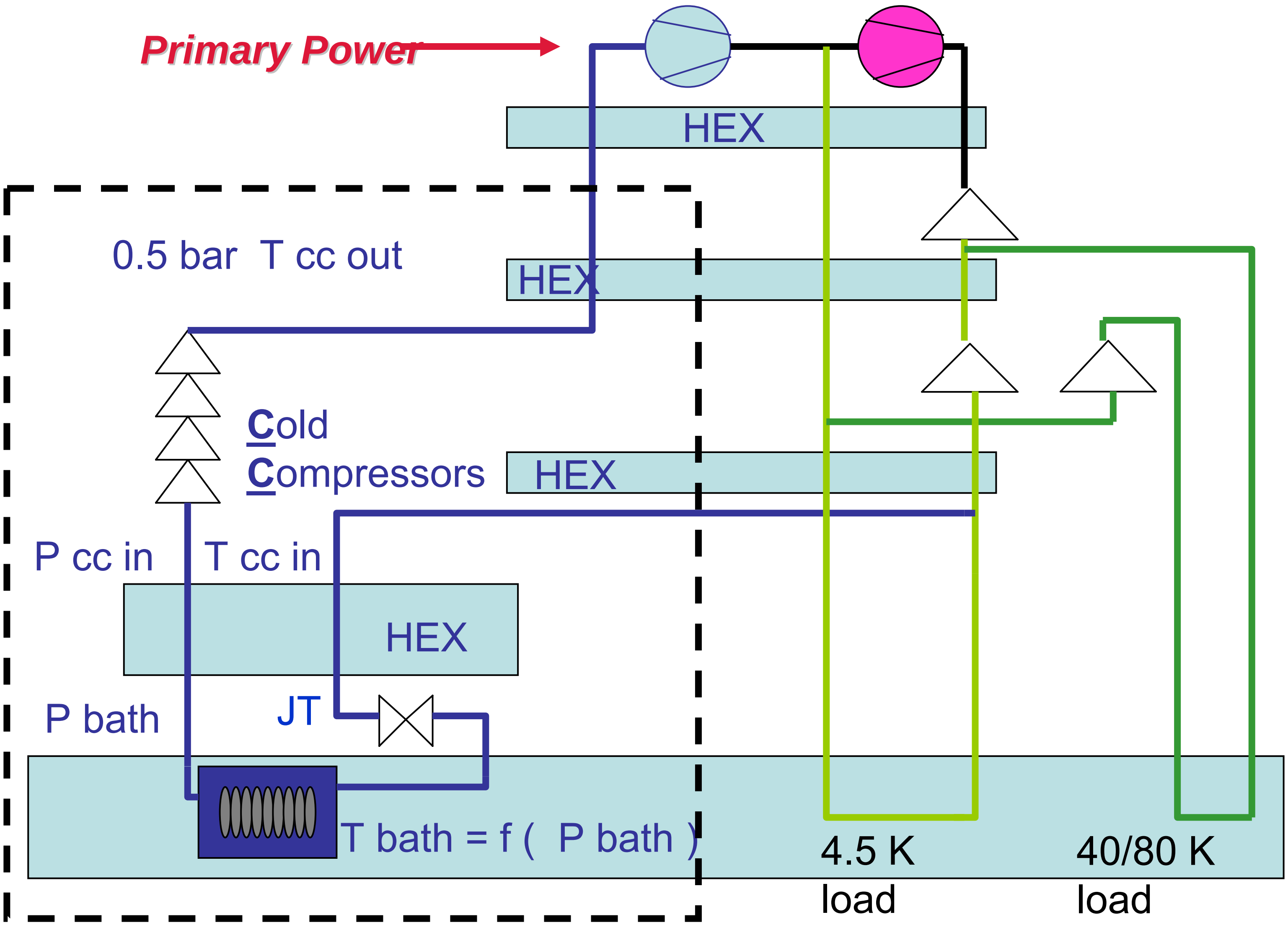
Review of Models of RF Surface Resistance in High Gradient Niobium Cavities for Particle Accelerators

P. Bauer

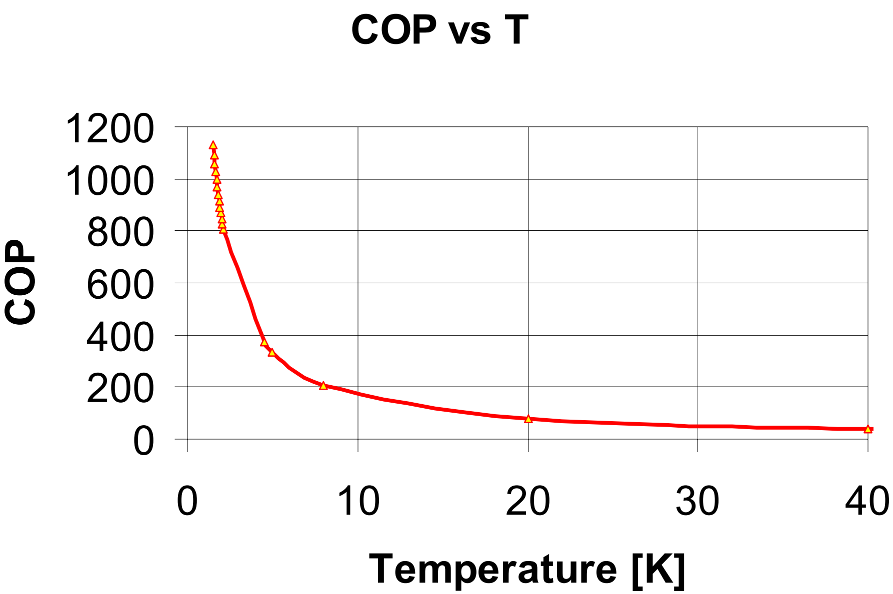
Fermilab, Technical Division

TD-04-014, June 2004

2K Cooling Scheme (simplified)



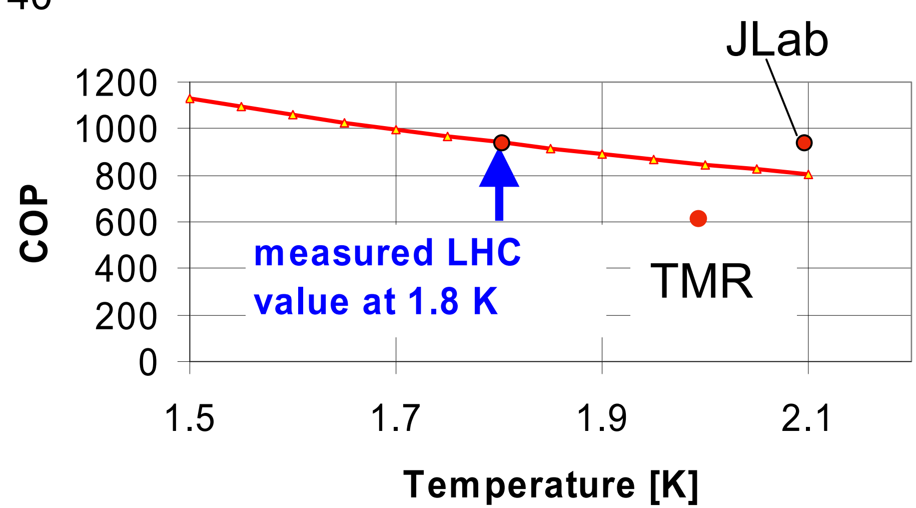
Coefficient of Performance



COP=1/(K * η CARNOT)

η CARNOT = T/(300 -T)

K= 0.176 (from latest LHC measurements at 1.8 K)



COP= Primary Power/ Power at TT

Power Consumption of the TESLA Model Refrigerator

Example for the required power at different T levels

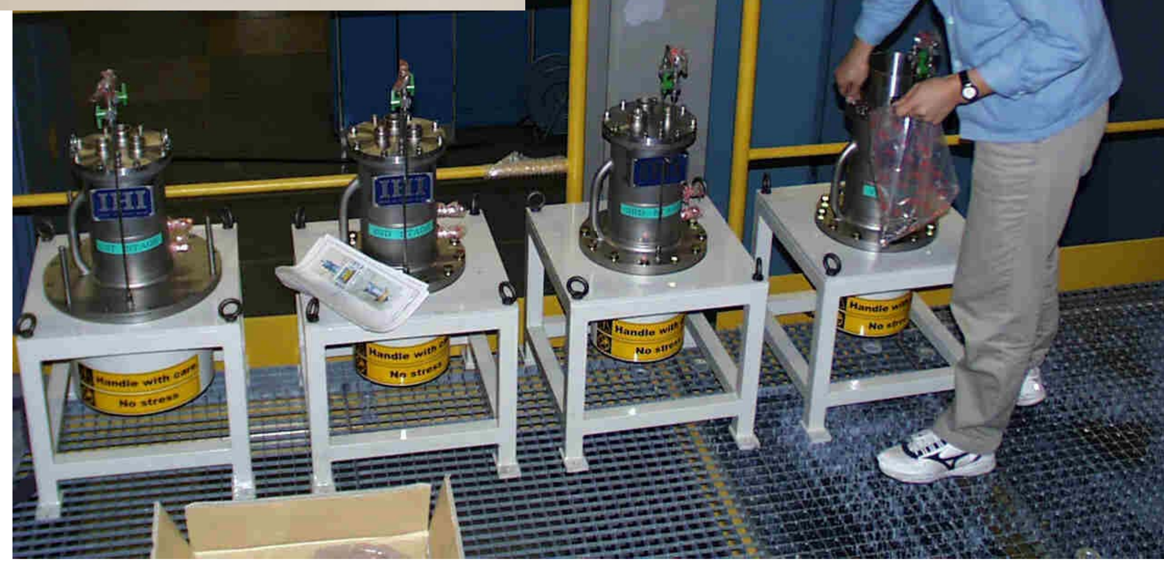
Power Consumption	Refriger-ation	COP W / W	Specific Load	% of Power
2 K	4.3 kW	588	2500 kW	**49 %**
5 – 8 K	7.5 kW	168	1254 kW	**24 %**
40 – 80 K	80.8 kW	17	1373 kW	**27 %**
Total			5147 kW	100 %

Cold Compressor Cartridges of 2.4 kW @ 1.8 K Refrigeration Units

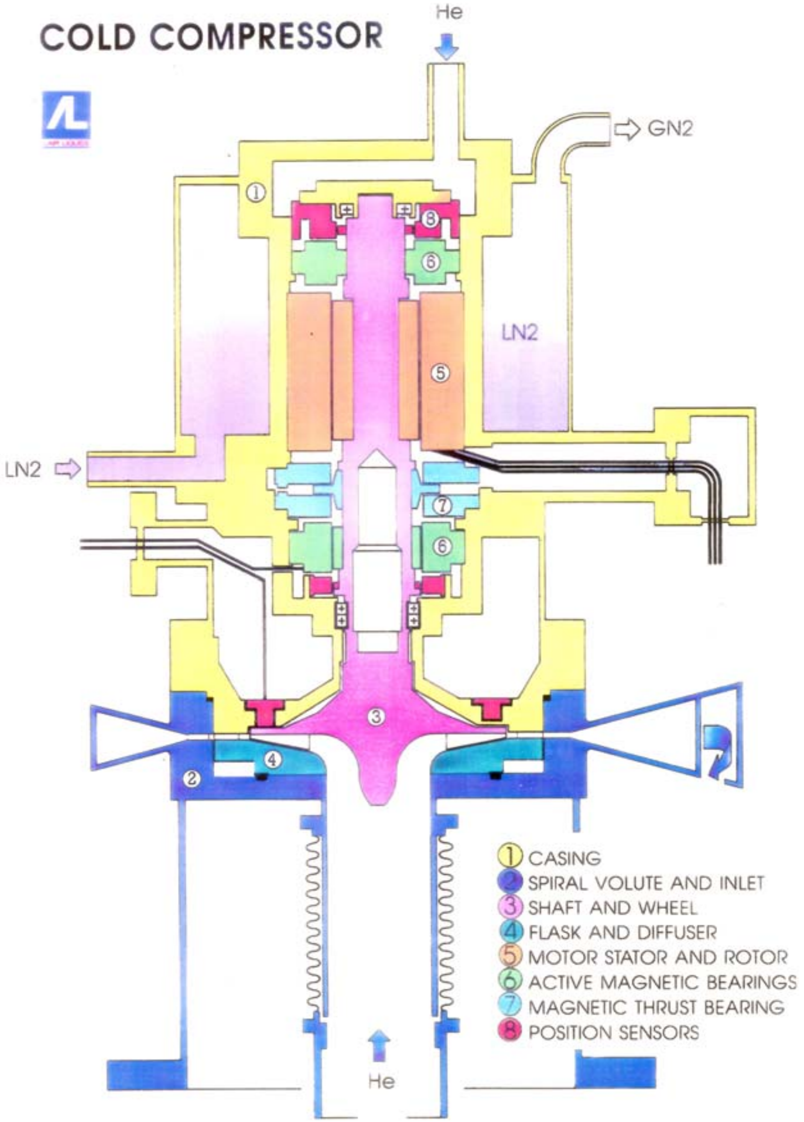
IHI-Linde

Cold compressor impeller

1st stage

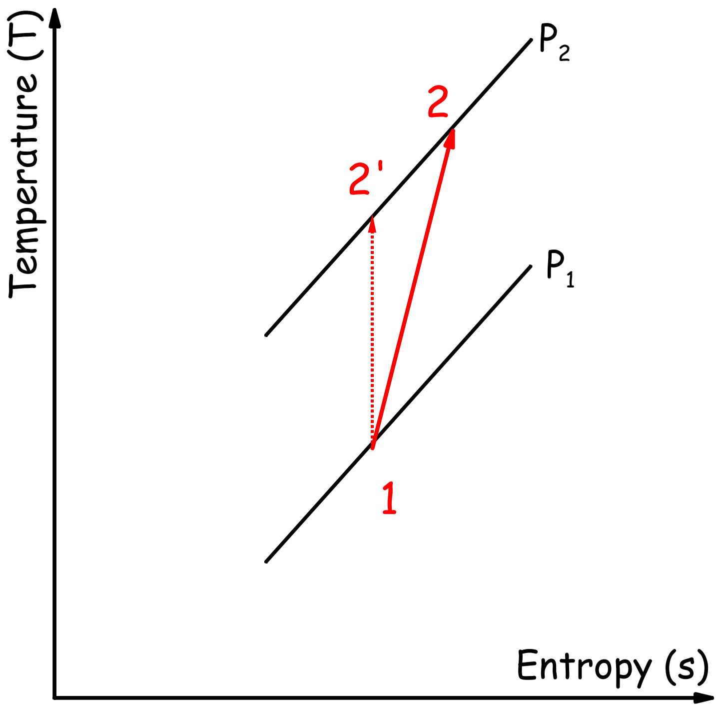


The four-stage LHC cold compressors

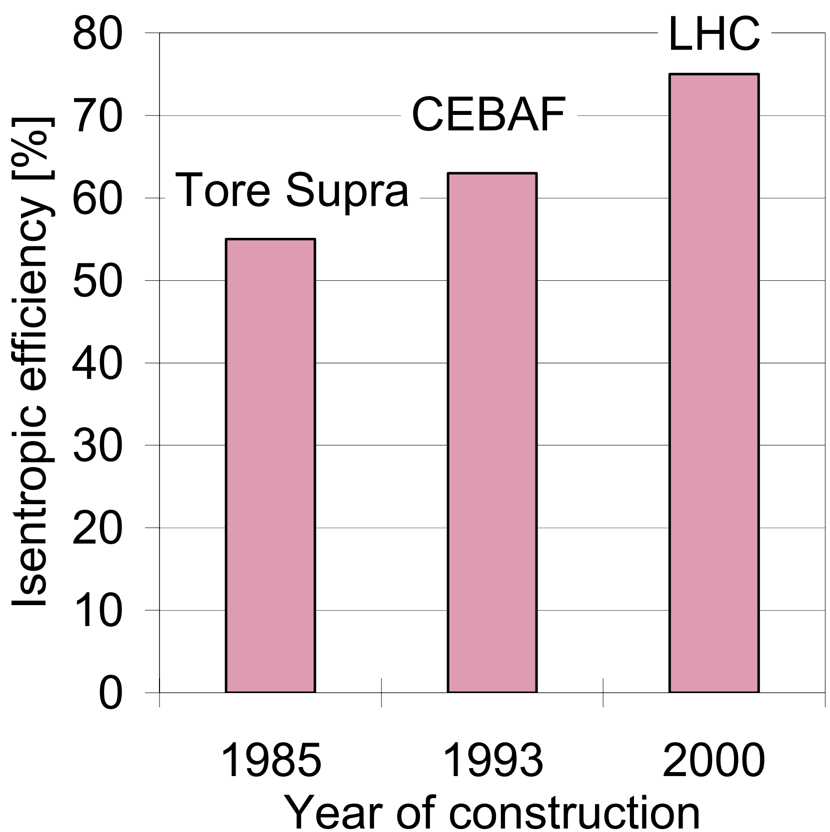


Example of a cold compressor with active magnetic bearings used at Tore Supra, CEBAF and Oak Ridge

Development of the Efficiency of Cold Compressors



$$\eta_{is} = \frac{H_{2'} - H_1}{H_2 - H_1}$$



Cold Compressor Parameters

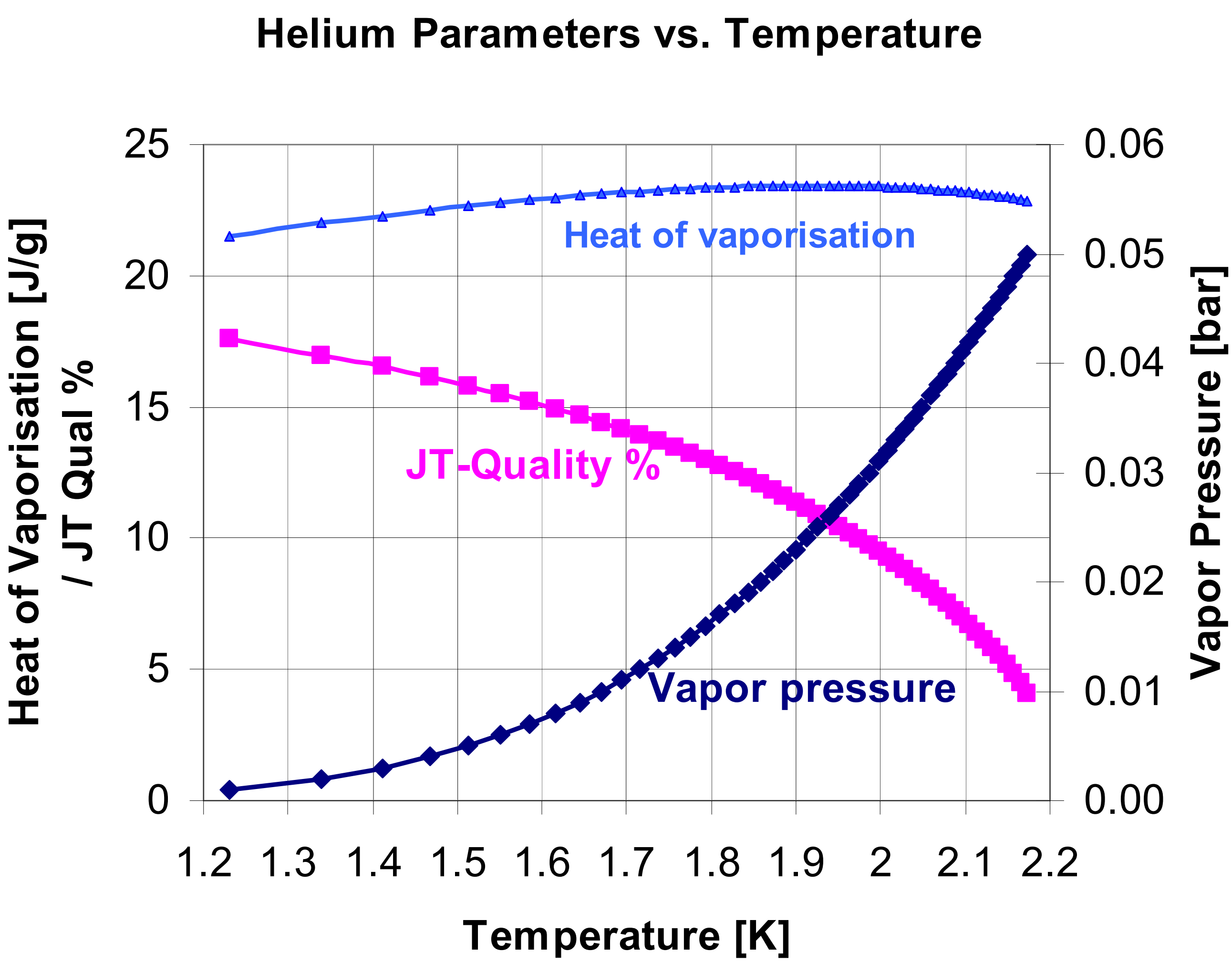
Insentropic efficiency of 0.7 assumed

Maximum compression ratio per single CC around 3 !

TEMP K	PRESS Pa	ENTROPY J/gK	ENTHALPY J/g	XFEL MASS FLOW g/s	KOMPRESSION POWER W	XFEL cw MASS FLOW g/s	KOMPRESSION POWER W
1.6	746	14.49	23.32				
4	746	19.36	36.01				
21.53	50000	19.36	126.8				
28.99	50000	20.91	165.71	26.7	3462.99	135	17509.5
1.8	1638	13.43	24.2				
4	1638	17.72	35.96				
15.73	50000	17.72	96.54				
20.7	50000	19.15	122.5	34.8	3011.592	264	22846.56
2	3129	12.58	25.04				
4	3129	16.36	35.88				
12.14	50000	16.36	77.7				
15.56	50000	17.66	95.62	48	2867.52	466	27838.84

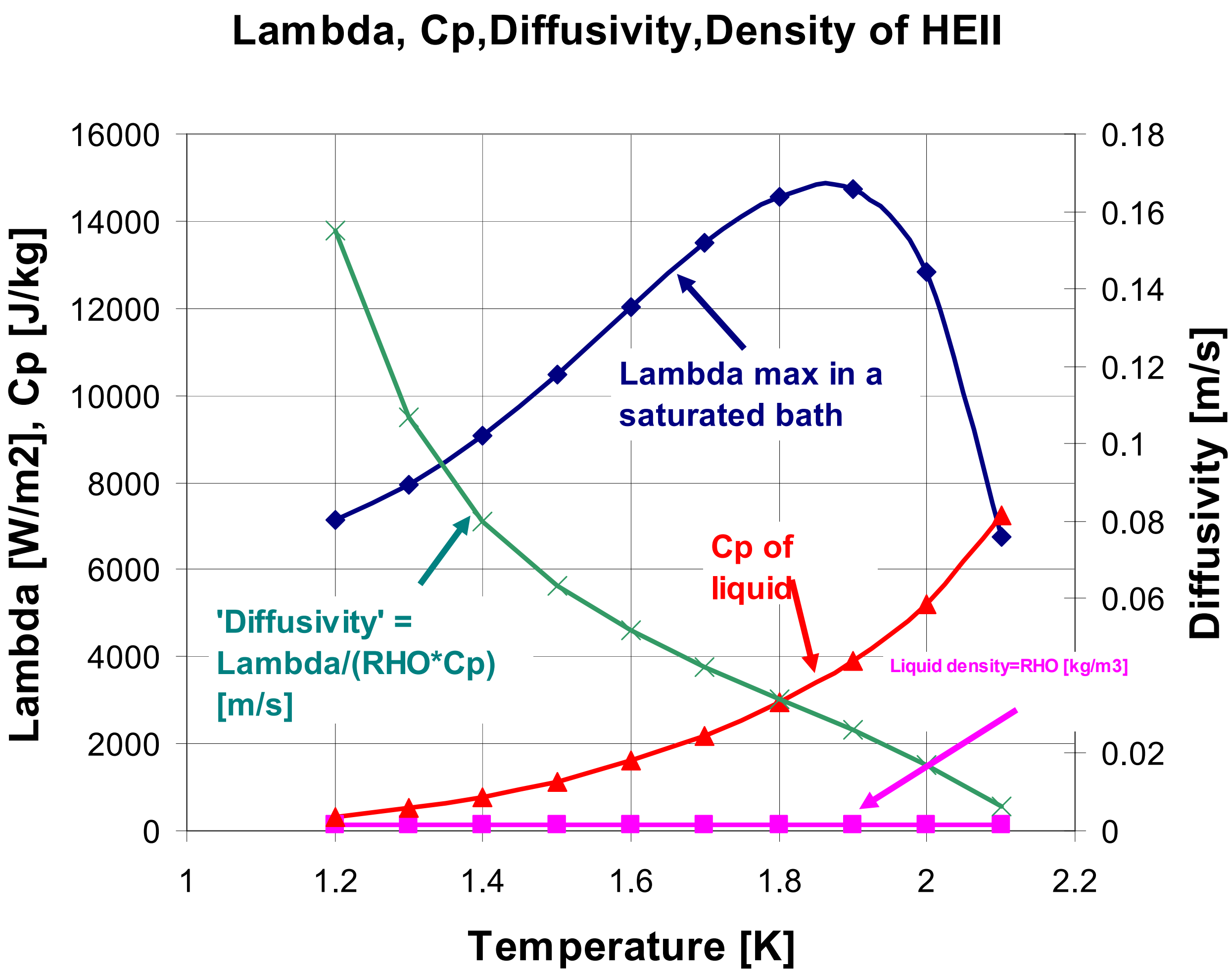
Helium II parameters = f(T)

-> more mass flow needed at LT



Helium II parameters = f(T) (cont.)

-> Cooling instable below 1.8 K ? Test required !



Definition of Lambda max in a HEII bath

Heat conductivity in HeII $q^{m} = f(T) * dT/dx$

T-Temperature, x-length

$m \approx 3$

f(T) Germany = f(-1) (T) USA**

$$q_{max} * L^{1/3} = \left[\int_{T1}^{T2} f(T)\, dT \right]^{1/3}$$

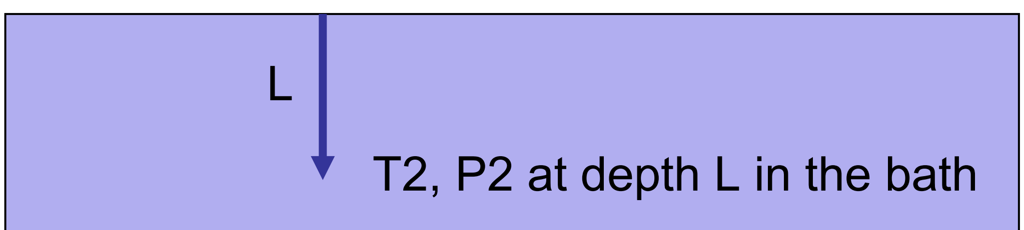
T1 = F (P1) **Temperature function of vapour pressure**

T2 = F (P1 + Δ P)

Δ P = ρ*L*g **ρ= density of liquid** **g=9.81 m/s2**

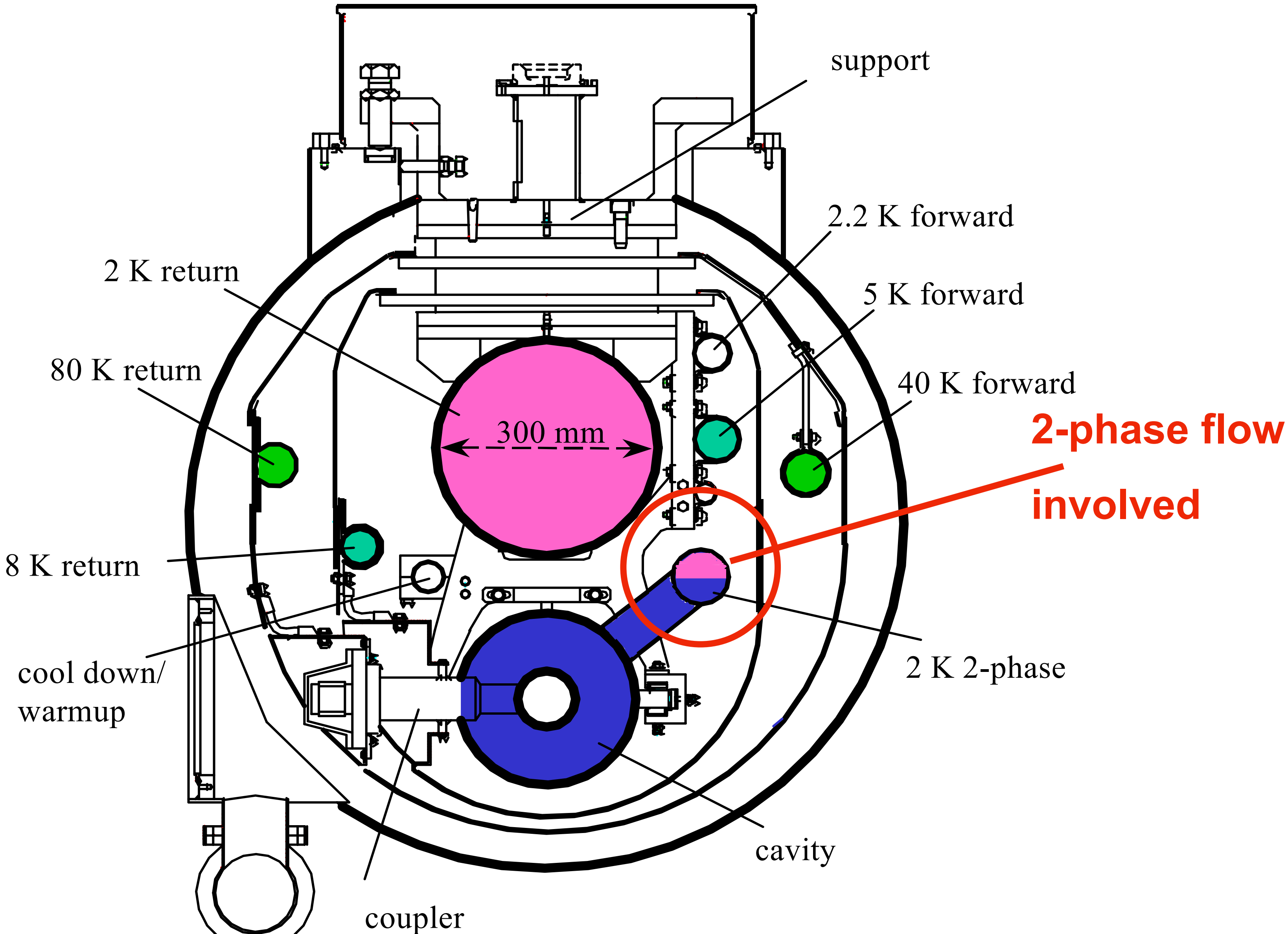
L= depth in bath

T1, P1 at liquid surface

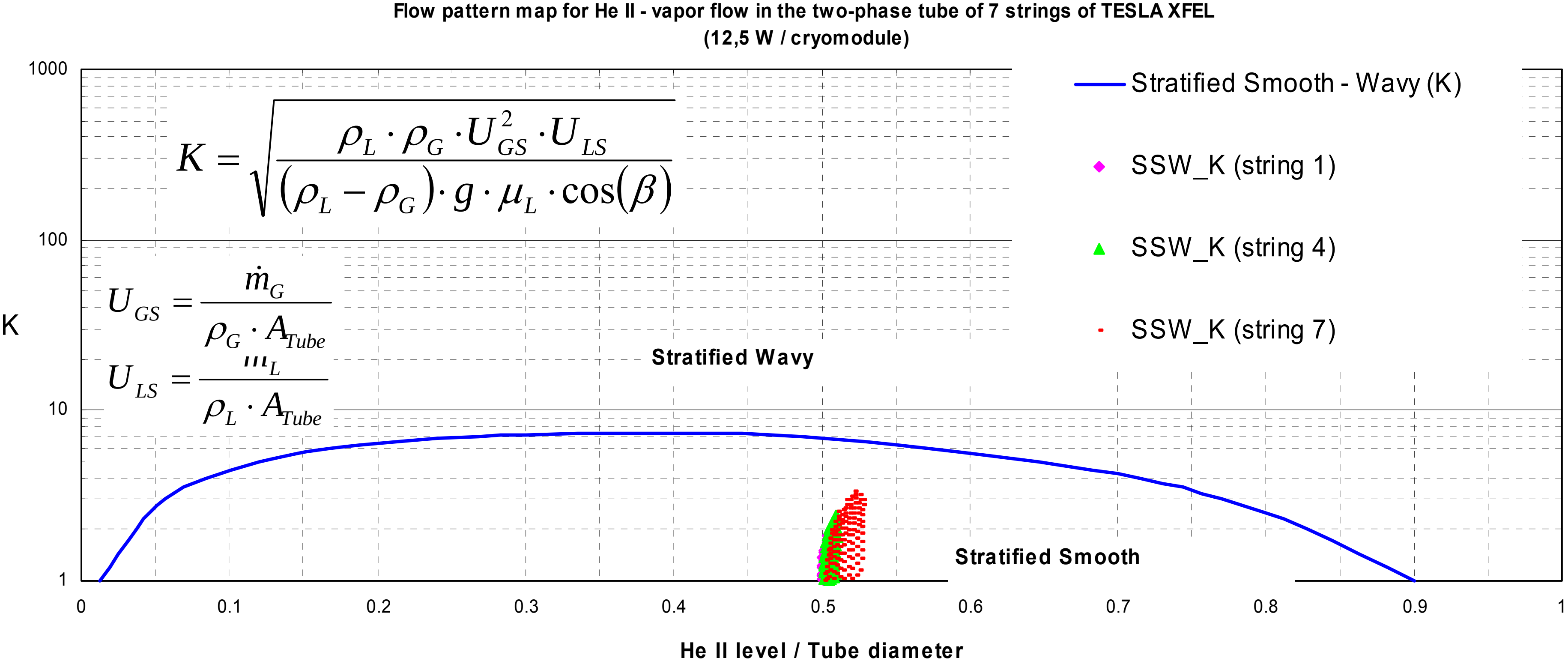


T2 must not be exceeded to avoid bubbles !

XFEL-Cryomodule



2-phase flow characteristics for XFEL-Cryomodules



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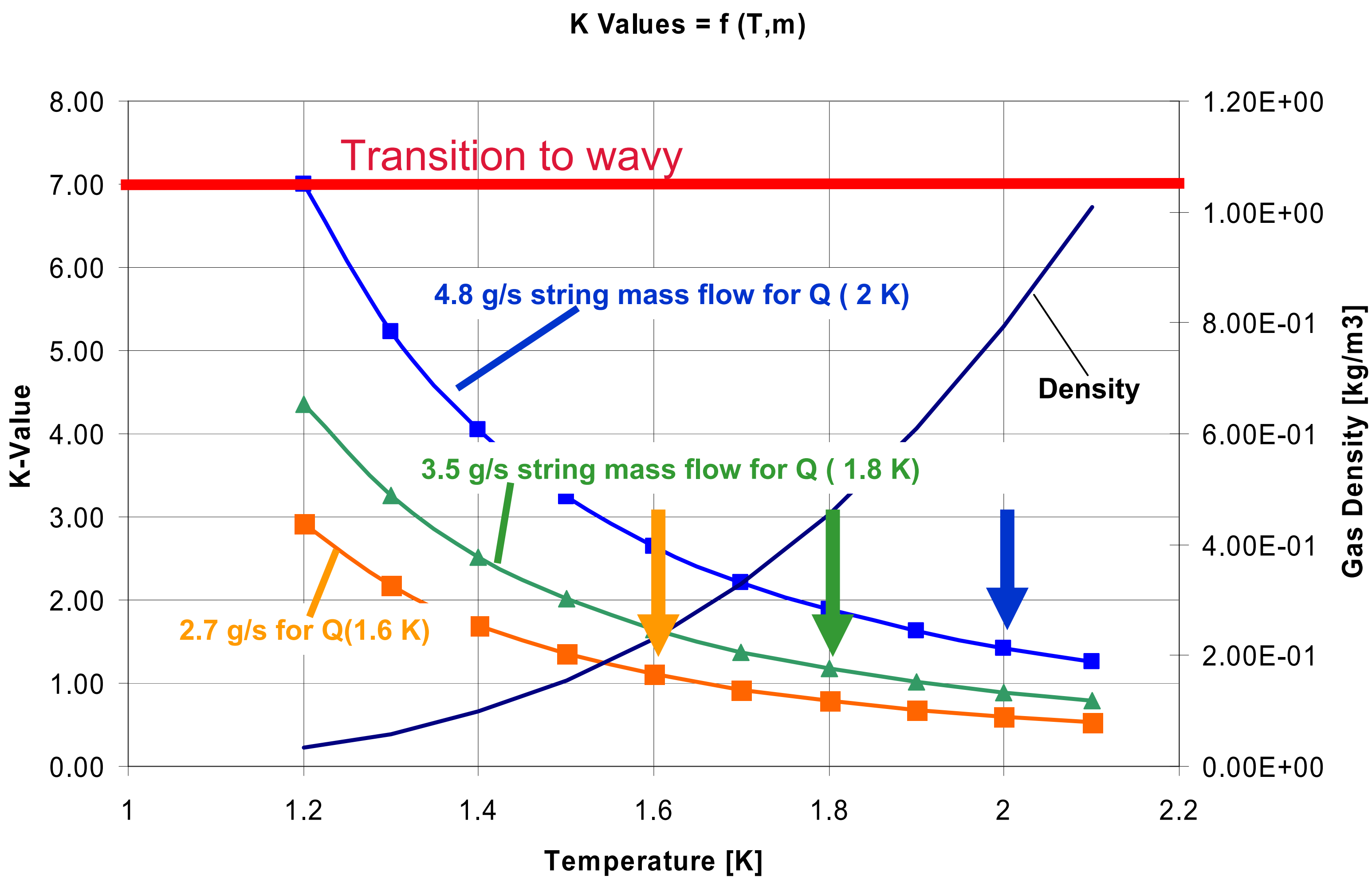
2-phase flow characteristics for XFEL-Cryomodules

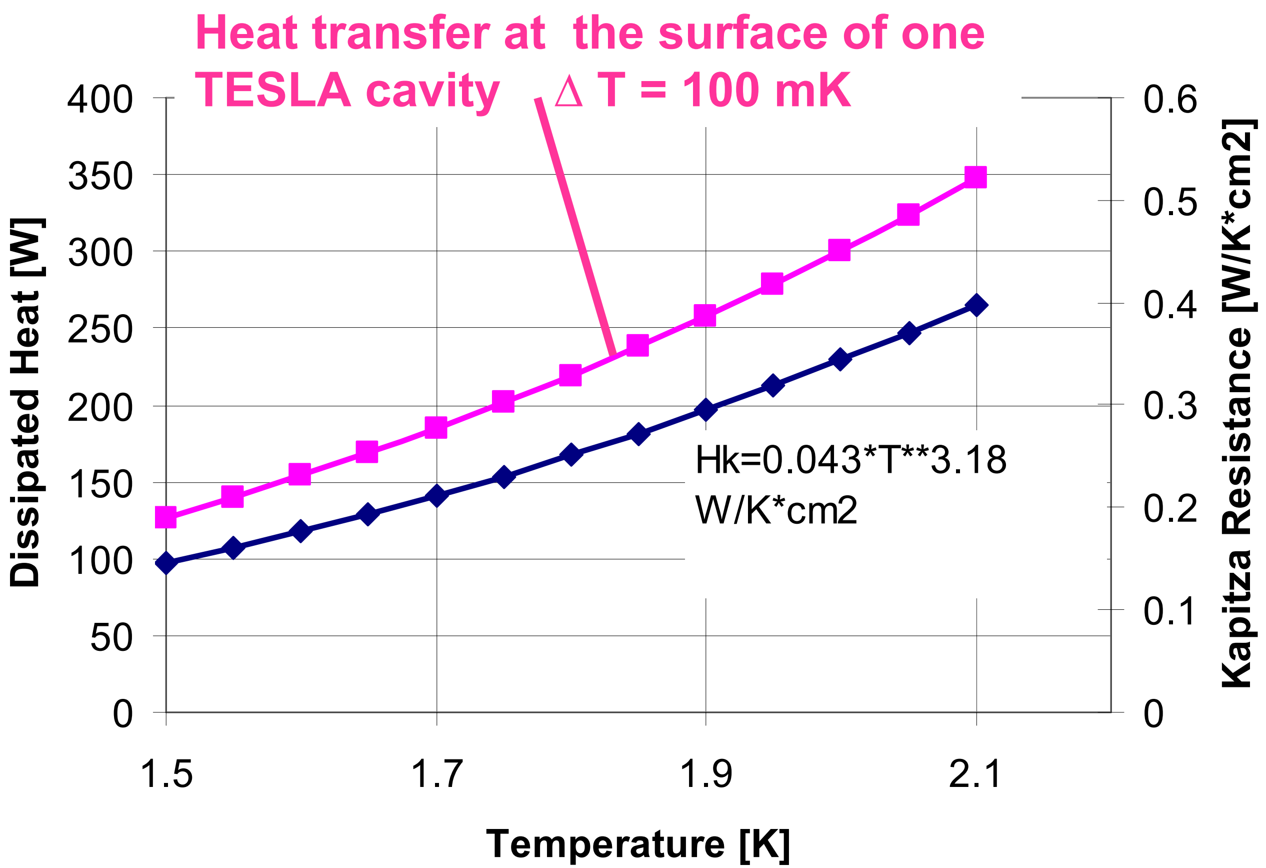
- > Lower densities balanced by smaller flows ?



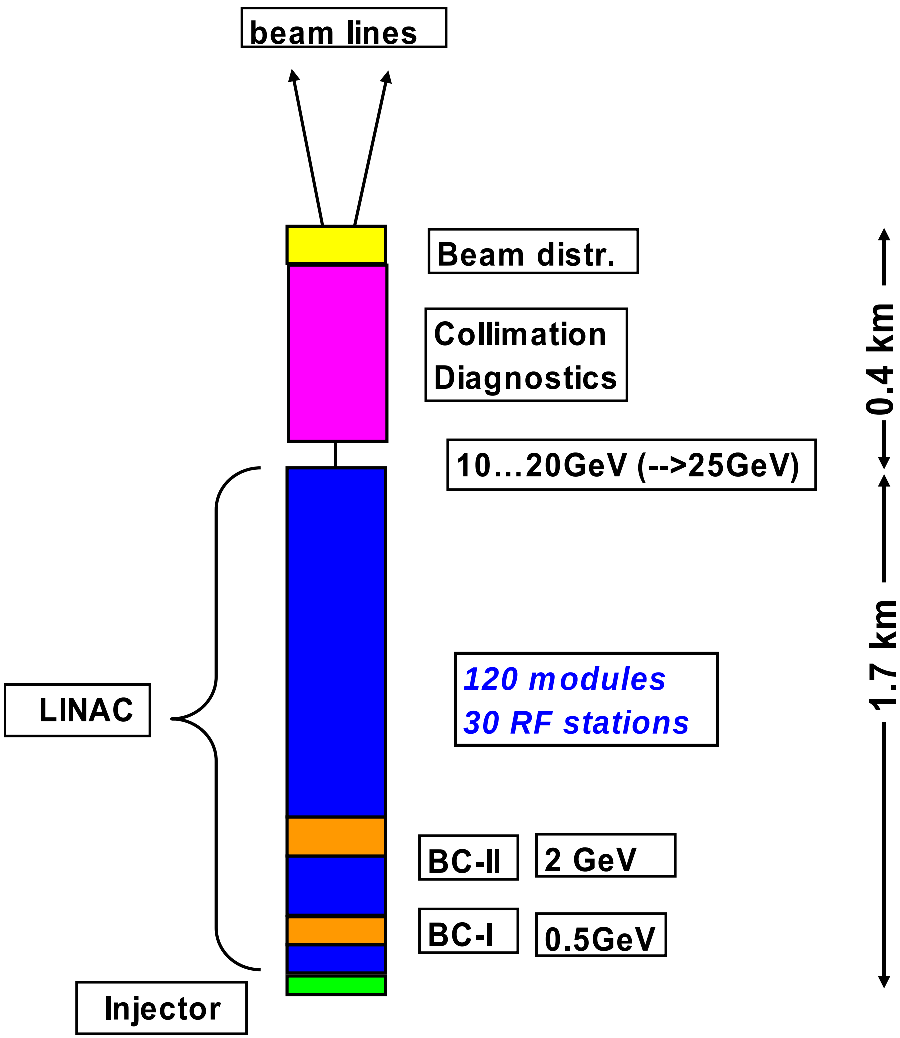
Simplified dependencies : K ~ m_G sqrt (m_L / ρ_L* ρ_G)

Kapitza Heat Transfer

-> Seems to be no limit under reasonable boundary conditions

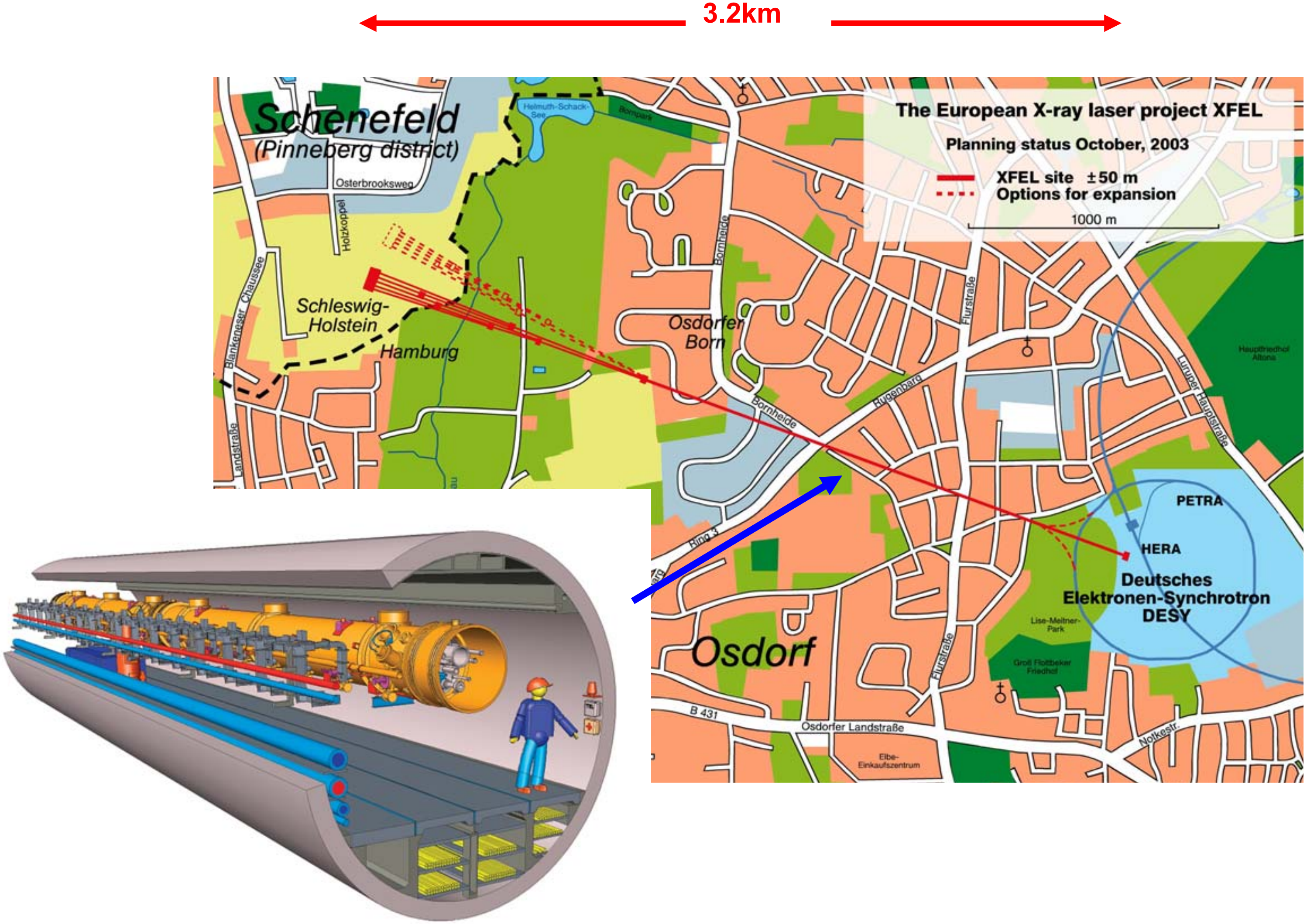


XFEL-Accelerator schematic layout

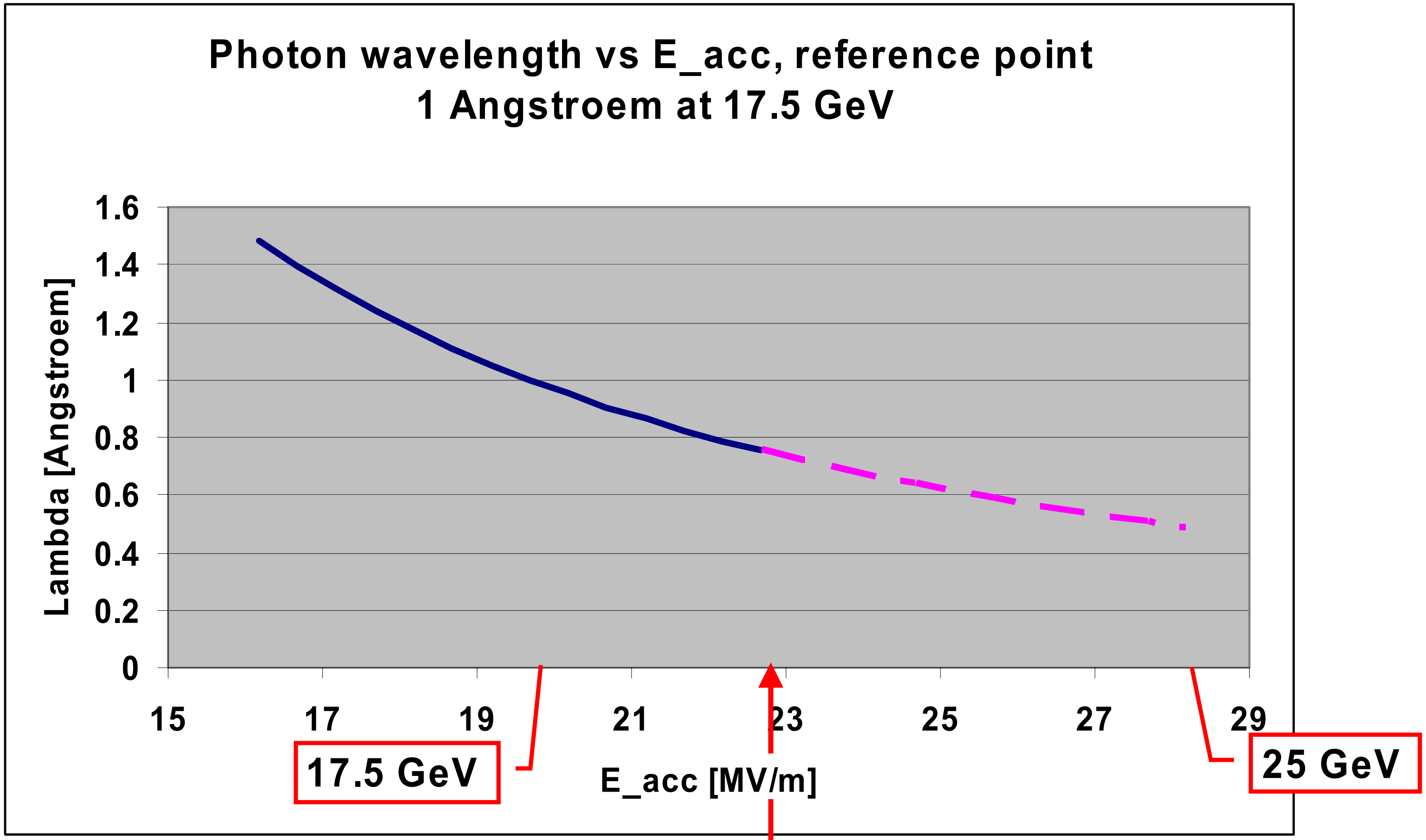


Main linac	
Beam energy	20 GeV
acc gradient	22.9 MV/m
Bunch spacing	200 ns
beam current	5 mA
power→beam p. klystron	3.8 MW
incl. 10% + 15% overhead	4.8 MW
matched Q_{ext}	$4.6 \cdot 10^6$
RF pulse	1.37 ms
Beam pulse	0.65 ms
# bunches p. pulse	3250
Rep. rate	10 Hz
Av. Beam power	650 kW

Site near DESY laboratory



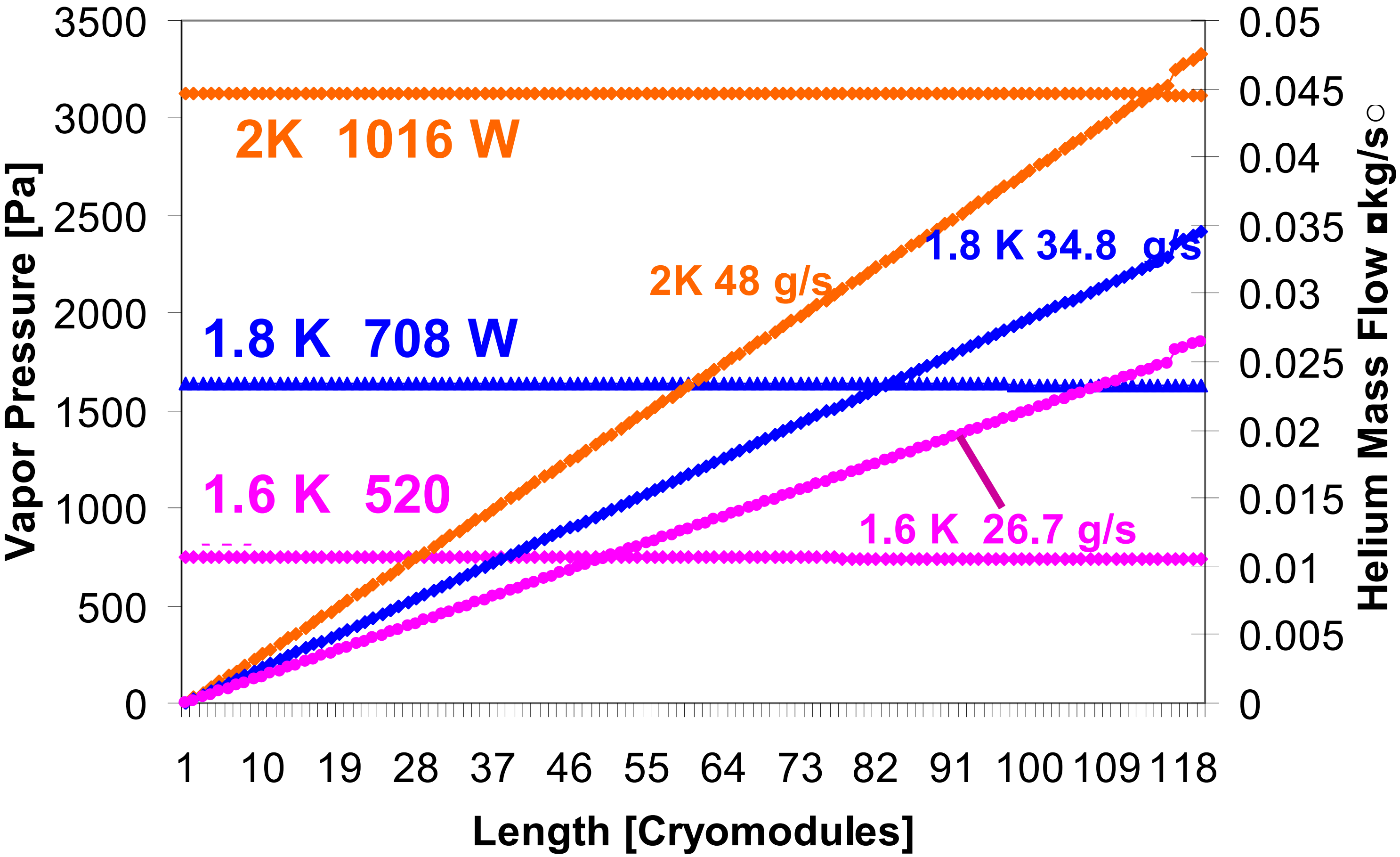
Wavelength vs. acc gradient



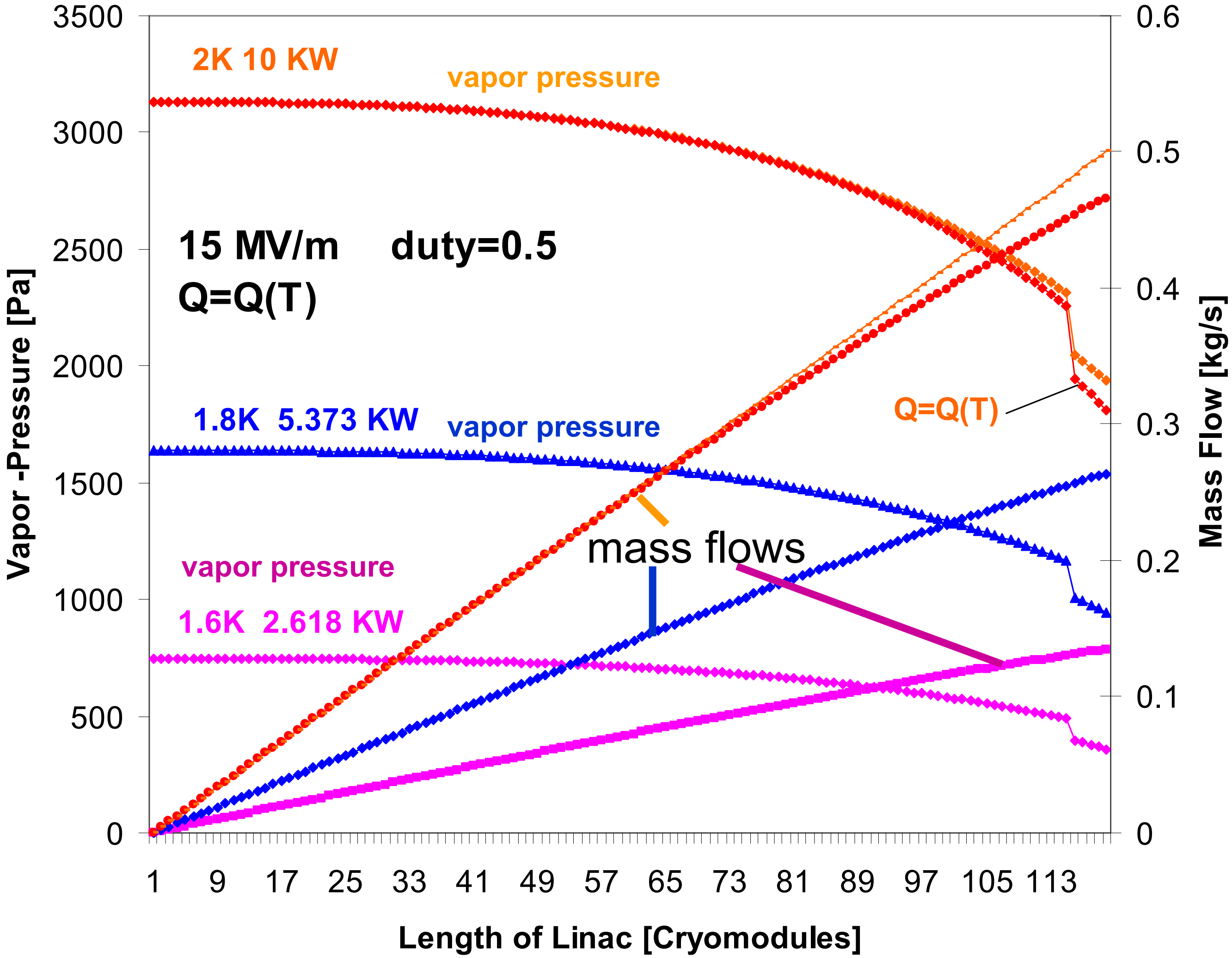
Nominal linac energy 20 GeV, includes ^{57}Fe line @ 0.8Å

Expected better cavity performance permits higher energy/smaller wavelength

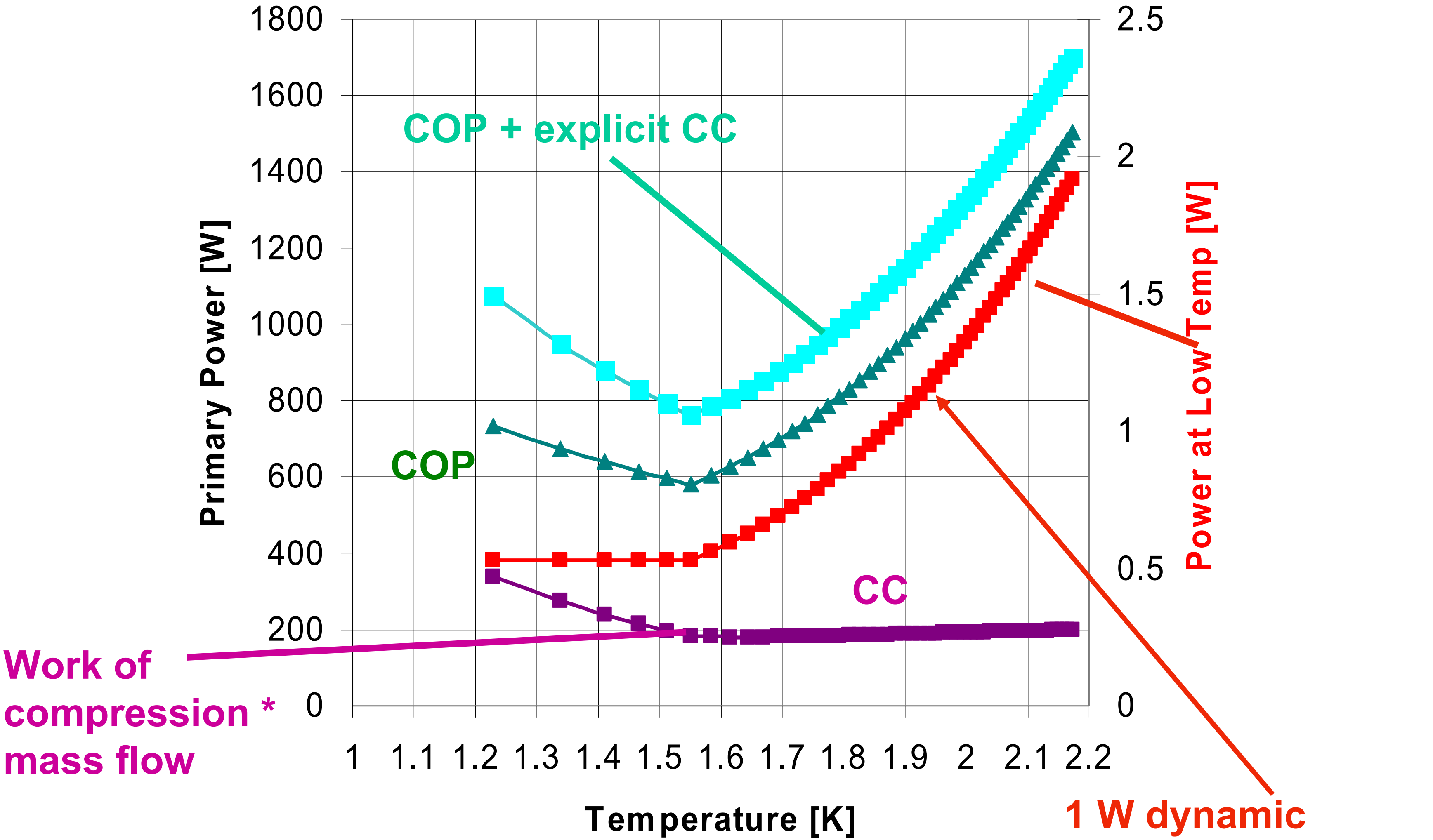
20 GeV XFEL parameters 10 Hz
650 µs Pulse 23.5 MV/m



XFEL ERL-up-grade ?



All in one – the lower the better !?



Conclusions

- Lowering the temperature seems to be effective as long as Q = Q(T) follows BCS and the temperature dependent dynamic loads dominate (reasonable lower limit 1.5 K)
- Watch the temperature independent loads: HOMs, couplers…, static
- The long term stability of the Q = Q(T) characteristic has to be proven
- HeII cooling might become unstable below 1.8 K – tests required
- Another cold compressor stage is required for each 0.2 K temperature step to lower temperatures – investment costs and system complexity increase
- In view of pressure drops, critical gas velocities, work of compression and general sizing the lower gas densities at lower temperatures seem to be balanced by the lower cooling loads and the related lower mass flows
- If the cryogenic layout is suited for 2 K operation, it should also allow operation at lower temperatures as long as Q = (T) works (beside the necessity of more CC stages) – for the time beeing this is our baseline for the XFEL