Thermal and mechanical analysis for compact cavities cryomodules

(very first thoughts)

V.Parma,
CERN, TE-MSC

Outline

- Geometrical considerations: compact cavities candidates and beam spacing
- Envelope in IR5
- Alignment
- Heat Loads and cryogenics
- Summary and Outlook

Introduction

Content: rather than a "thermal and mechanical analysis", as suggested in the mandate, this presentation covers a number of issues (certainly not an exhaustive list). It is premature to start any engineering design at this stage but it's useful to anticipate engineering needs at an early stage of the cavity development and understand intrinsic constraints that will have to be coped with in the design and integration of a cryomodule. Far from being systematic, the aim of this presentation is to stimulate brainstorming and discussion.

Disclaimer

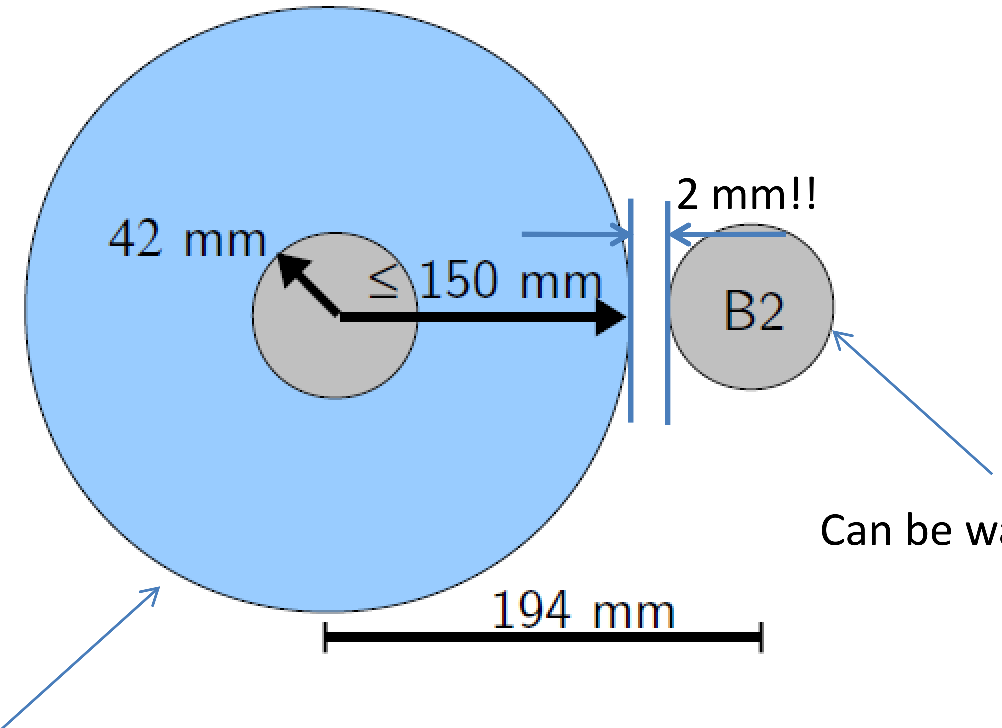
- I present personal views with the limited knowledge I have on the subject. I have not been involved in crab cavities earlier.
- I have been thinking over this subject only in the last few week
- Statements in this talk should not be taken as decisions, but rather as general considerations

Thanks:

- To R.Calaga for his effort in trying to compile a set of consistent data for the cavity candidates
- To B.Vullierme, W.Weigarten, V.Baglin, P.Maesen for the instructive discussions

“Chasing after the mm”

LHC IR 1,5 constraints (input R.Calaga)

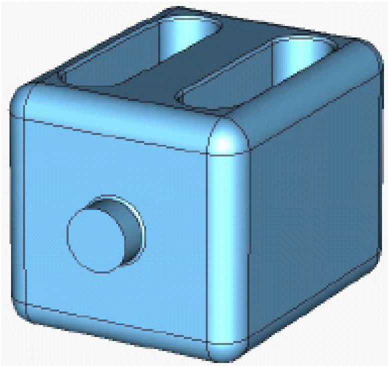


Can be warm or cold

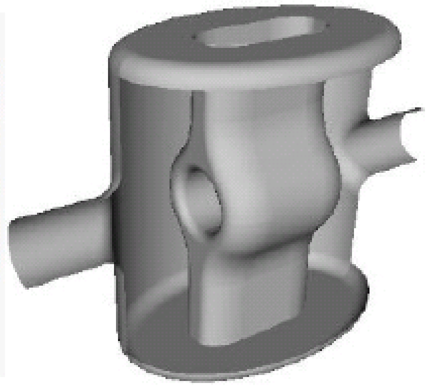
Cavity space limitation (not He vessel, as I initially thought)

Technical Candidates

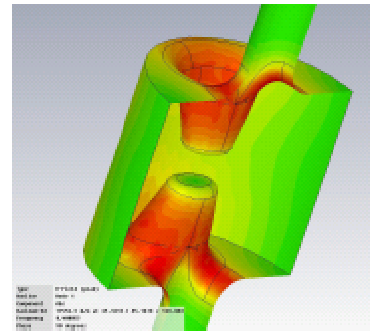
HWDR, JLAB,OD



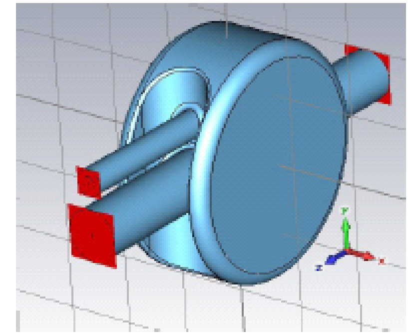
HWSR, SLAC-LARP



DR, UK, TechX



Kota, KEK



Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity

		HWDR (J. Delayen)	HWSR (Z. Li)	4-Rod (G. Burt)	Rotated Pillbox (N. Kota)
Geometrical	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Cavity Height [mm]	380	391	280	668
	Beam Pipe [mm]	42	45	45	[illegible]
RF	Peak E-Field	29	52	62	85
	Peak B-Field	105	97.5	113	328
	R_T/Q	413	215	802	-

Large! Not latest figure for LHC?

These are 1 yr old
Kota-san will have update at workshop

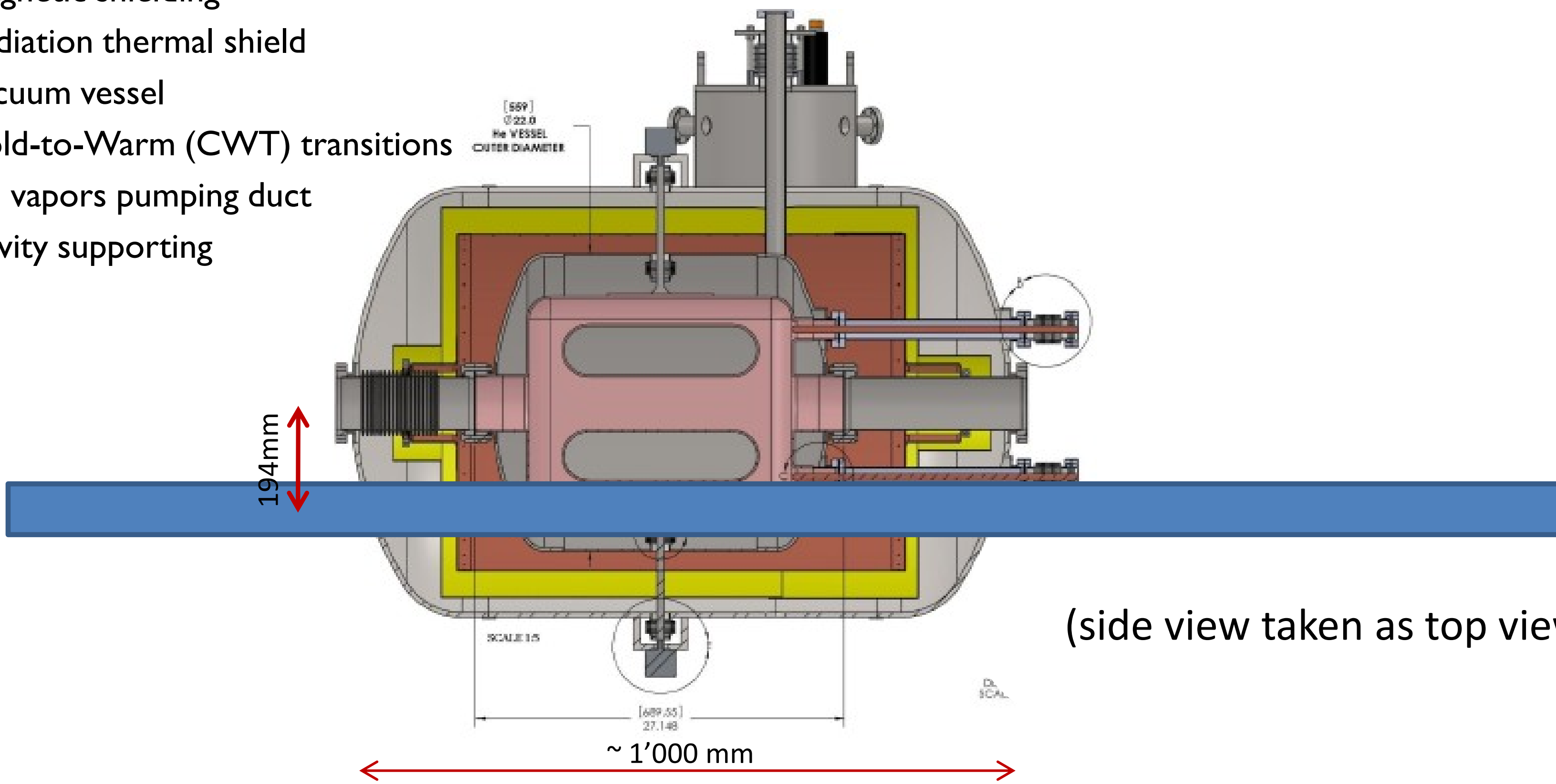
Input: R.Calaga

†Exact voltage depends on cavity placement & optics
†Cavity parameters are evolving

An example of compact cavity in its cryostat (JLAB's test cryostat)

All main elements cryo-module shown:

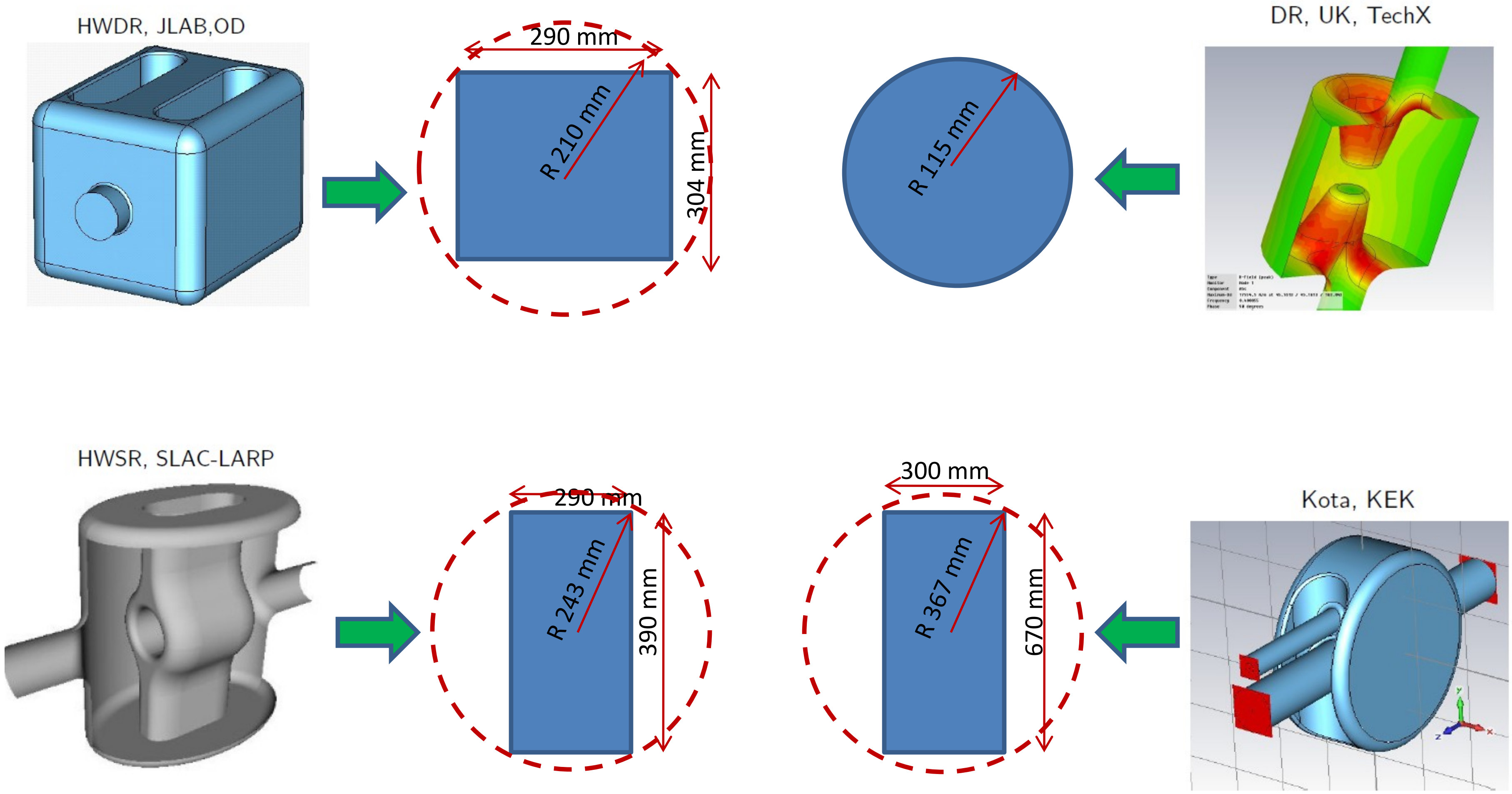
- Helium vessel
- Magnetic shielding
- Radiation thermal shield
- Vacuum vessel
- Cold-to-Warm (CWT) transitions
- He vapors pumping duct
- Cavity supporting



(side view taken as top view)

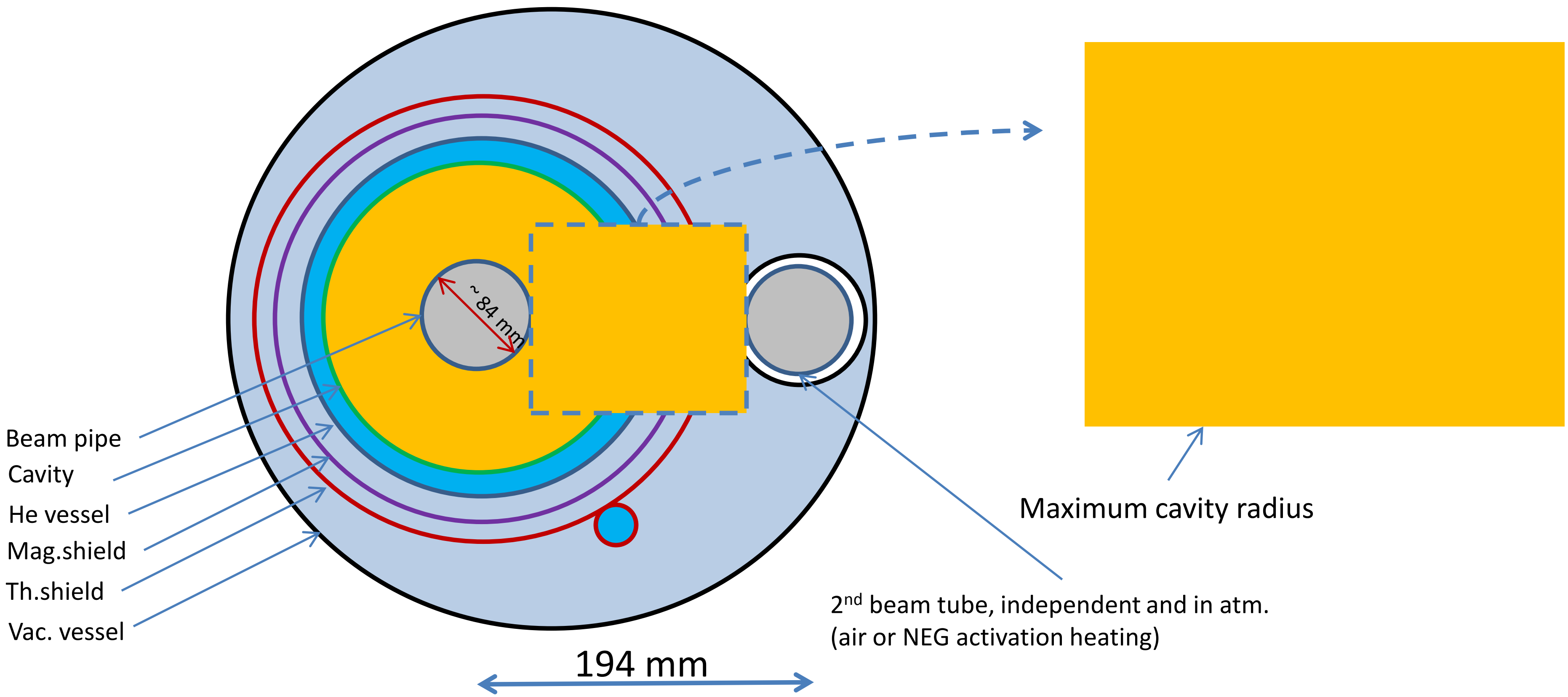
Note: this cryo-module was not intended for LHC use!

Candidates and “footprints”



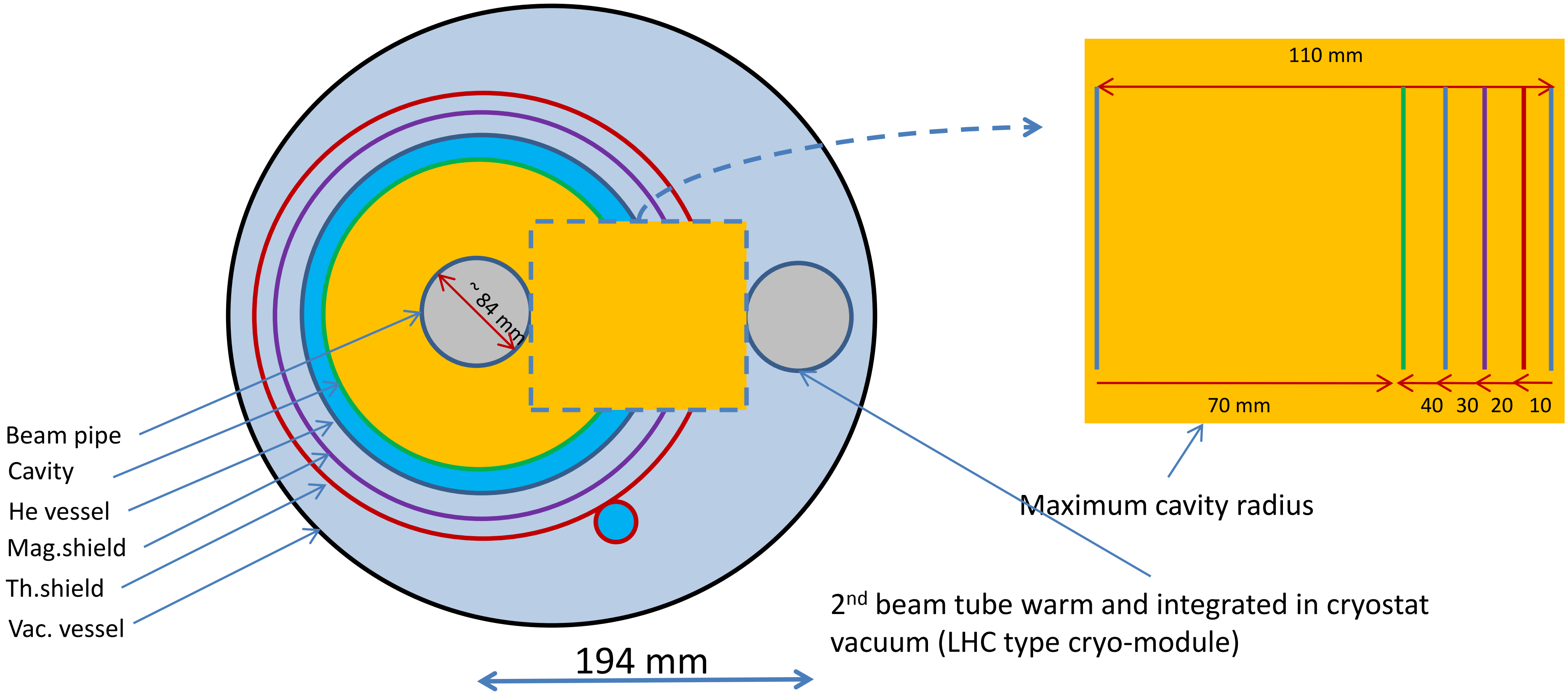
Important note: assuming circular footprint (for cylindrical He vessel)

Double beam line cryostat (concept I)



Note: not a design! rather a list if items needed, with tentative spacing

Double beam line cryostat (concept II)



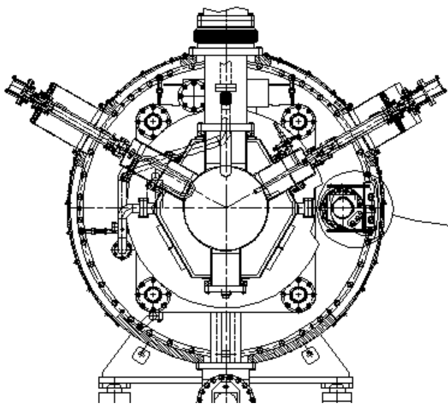
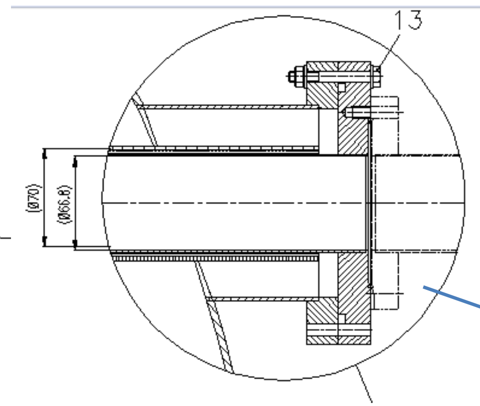
Space considerations:

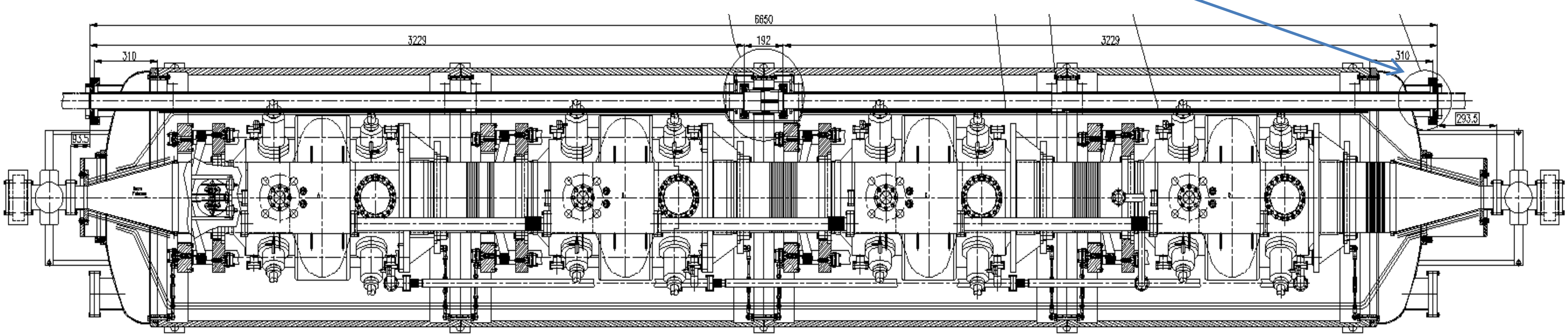
- 10 mm gain
- But NEG heating and MLI insulation→ screen needed? (LHC)

→ Space gain uncertain

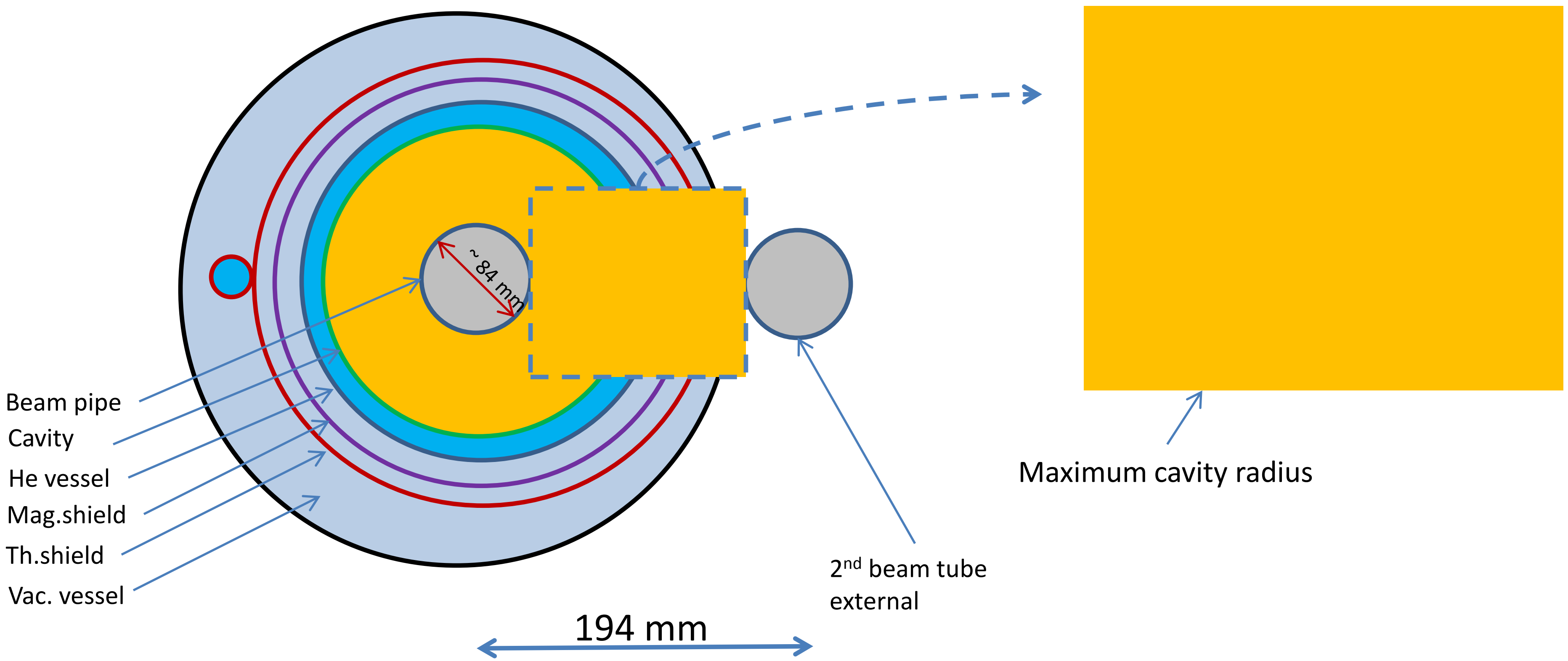
LHC cryo-modules (concept II)

- Warm tube integrated
- NEG + activation heaters (~200deg.)
- MLI for radiation protection of tube
- Shield for MLI protection from heaters

Single beam line cryostat (concept III)



Space drawbacks:

Interference with vessel flanges/reinforcements (not shown)

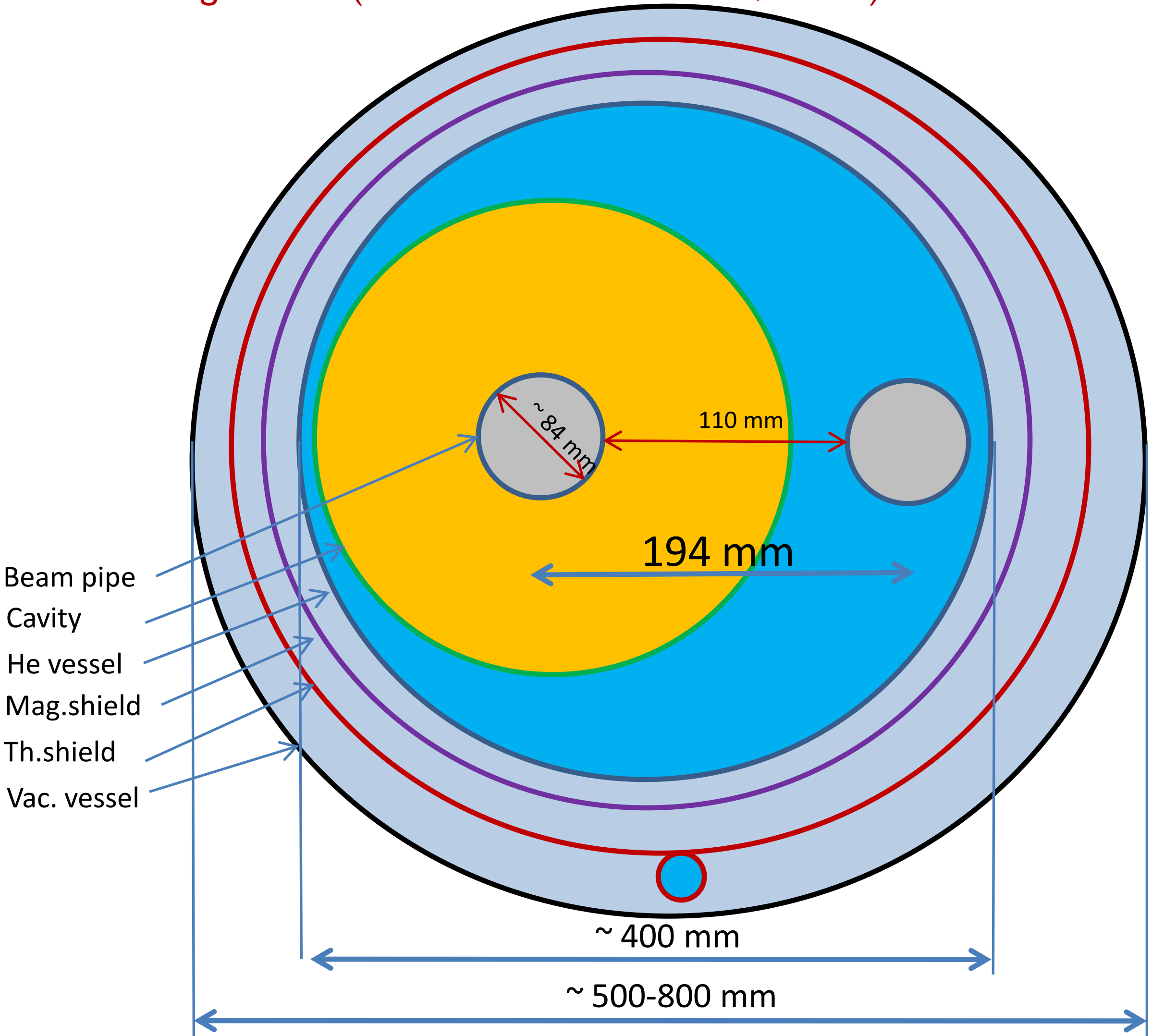
Pros:

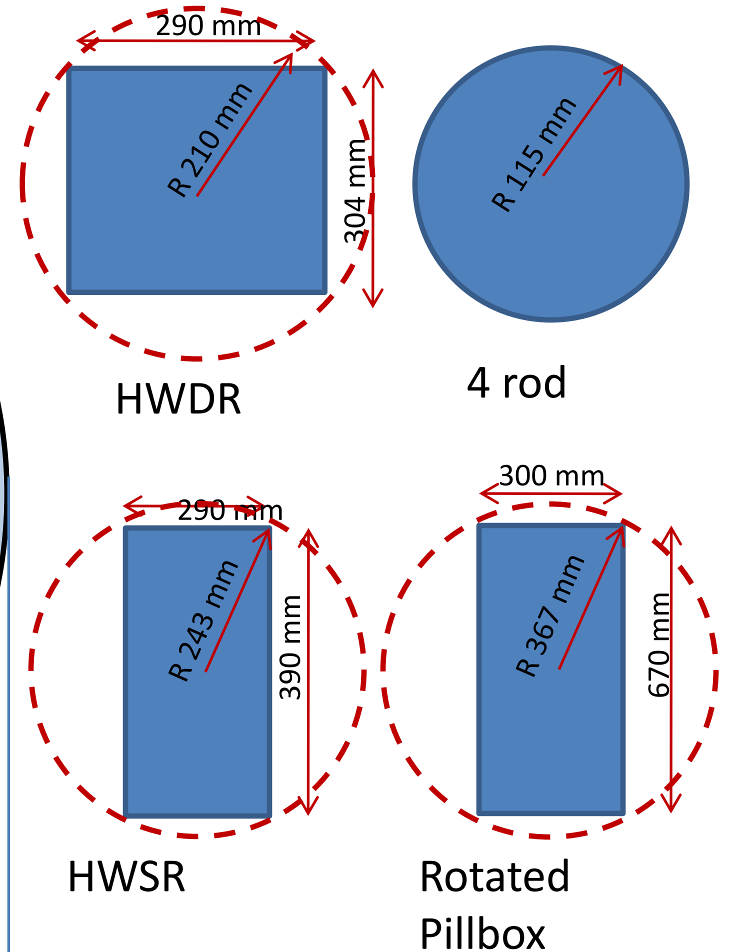
Easier cryostat construction

External tube really warm

Double beam line in same He vessel (concept IV)

- Beam tubes in same He vessel
- Cavity radius can be increased up to 152 mm (say 140mm?).
- Any proximity limitation between cavity and beam tube? Apparently not.
- Magnetic shielding between beam tubes? Apparently not necessary.
- Long cold drift tube: This is <u>not an LHC existing solution</u>: anything wrong with it? (vacuum/beam interaction, other?)





All concepts fit

Summary on Inter-beam space

- Design for 194 mm beam spacing:
  - Concepts I to III. Cavity radius: ~70 mm about maximum footprint acceptable for integration
  - All present cavities (round) footprints are 2-to-4 times larger!
  - HWSR and Kota (KEK), using rectangular He vessels, remain 2 times larger
  - → Margin for further transversal compacting ? 70 mm an achievable goal?
  - → Concept IV. Double beam line in same He vessel. Cavity radius up to 152mm

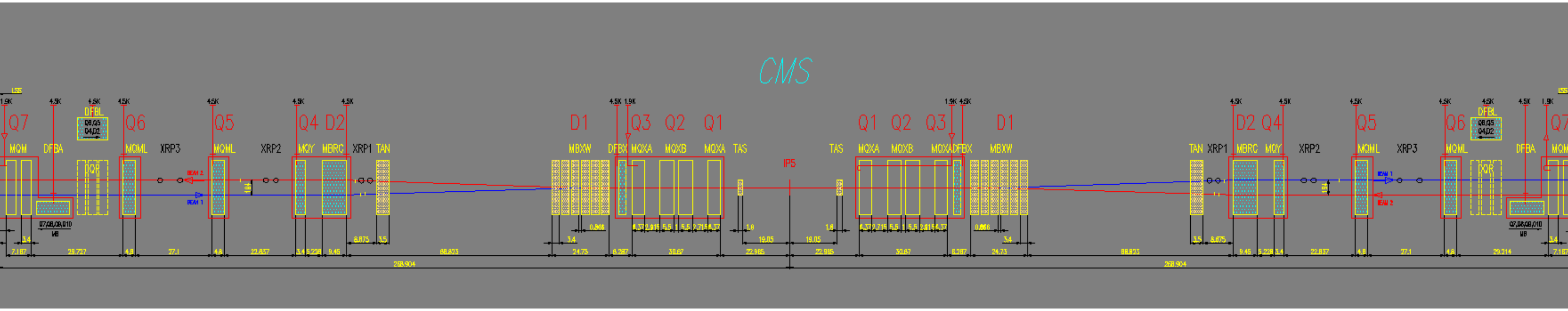
In case of show stopper on concept IV…

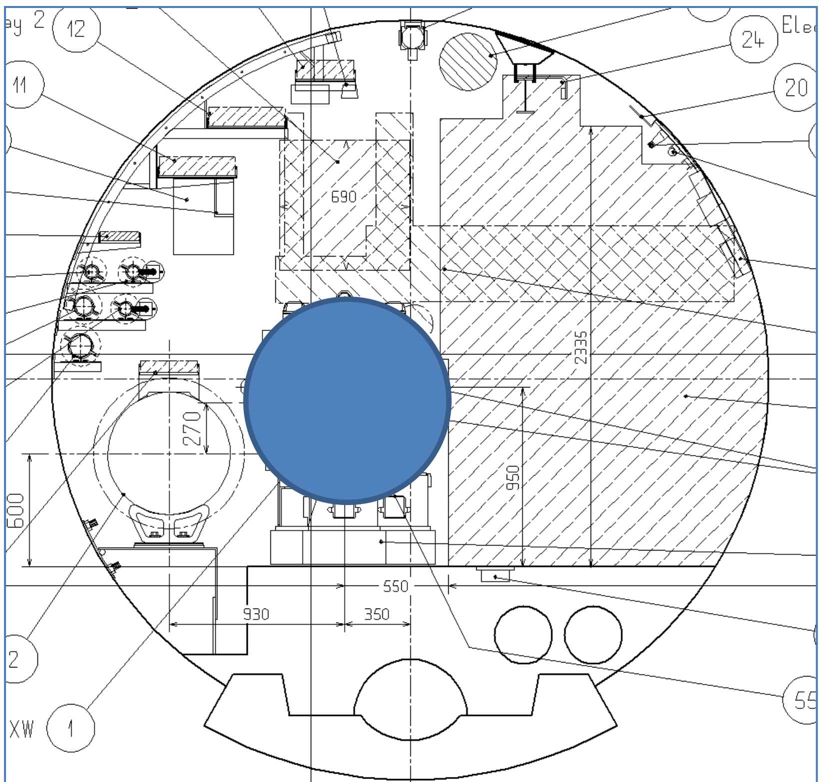
- Dogleg to increase beam separation (i.e. additional complexity, what about reliability??)
- Minimum goal: increase separation from 194mm to say ~294mm → 2 dogleg beam deflections ~50mm each

Otherwise…

- Reconsider a Global scheme in IR4:
  - 420 mm beam spacing (up to 296mm cavity radius)

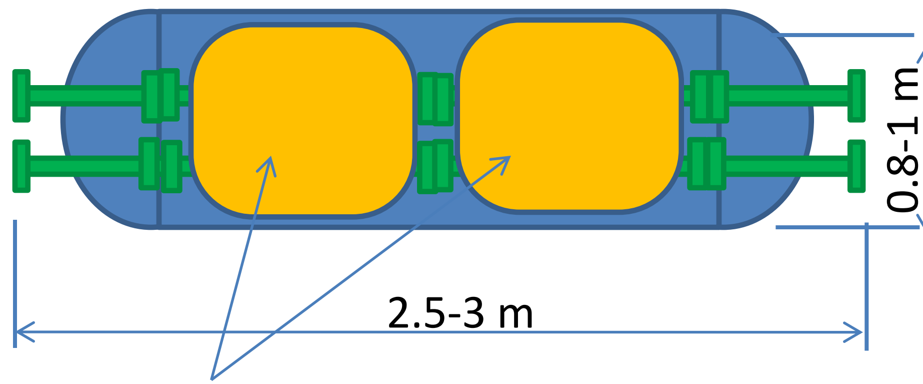
Layouts: IP 5 CMS





3.8 m diameter tunnel, QRL in high position

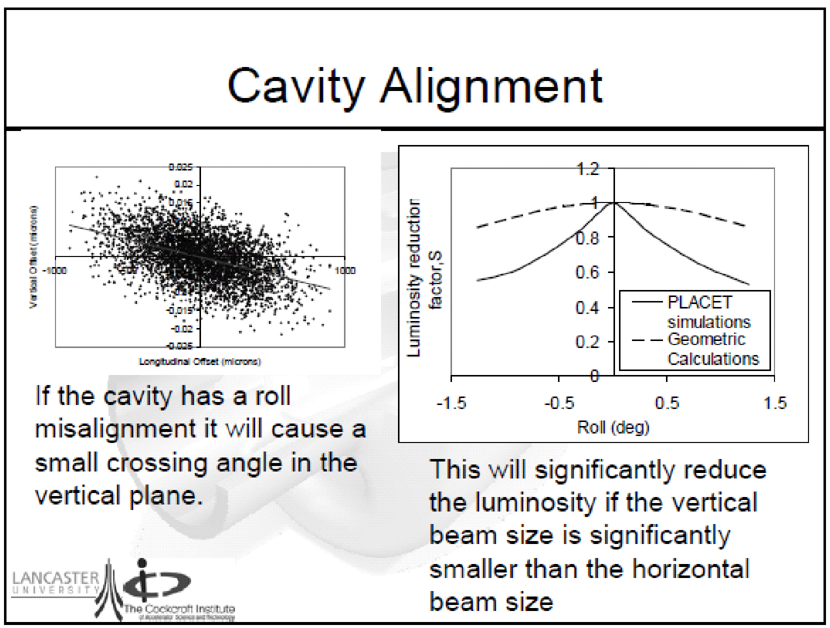
- Typical envelope (2 cavity one cryo-module), strongly depends on choice of cavity



2 5 MV kick CC

Alignment (cavity w.r.t. vacuum vessel)

- Positioning accuracy:
  - construction tolerances → cost
  - Not an issue for few units
- Positioning stability:
  - Design features, choice of materials, assembly techniques…
  - This is the real challenge!
- If too stringent:
  - Online monitoring (optical methods, stretched wires, etc.)
  - Remote alignment (e.g. LHC triplets)



(G.Burt, *RF CAS 2010*)

Tentative requirements:

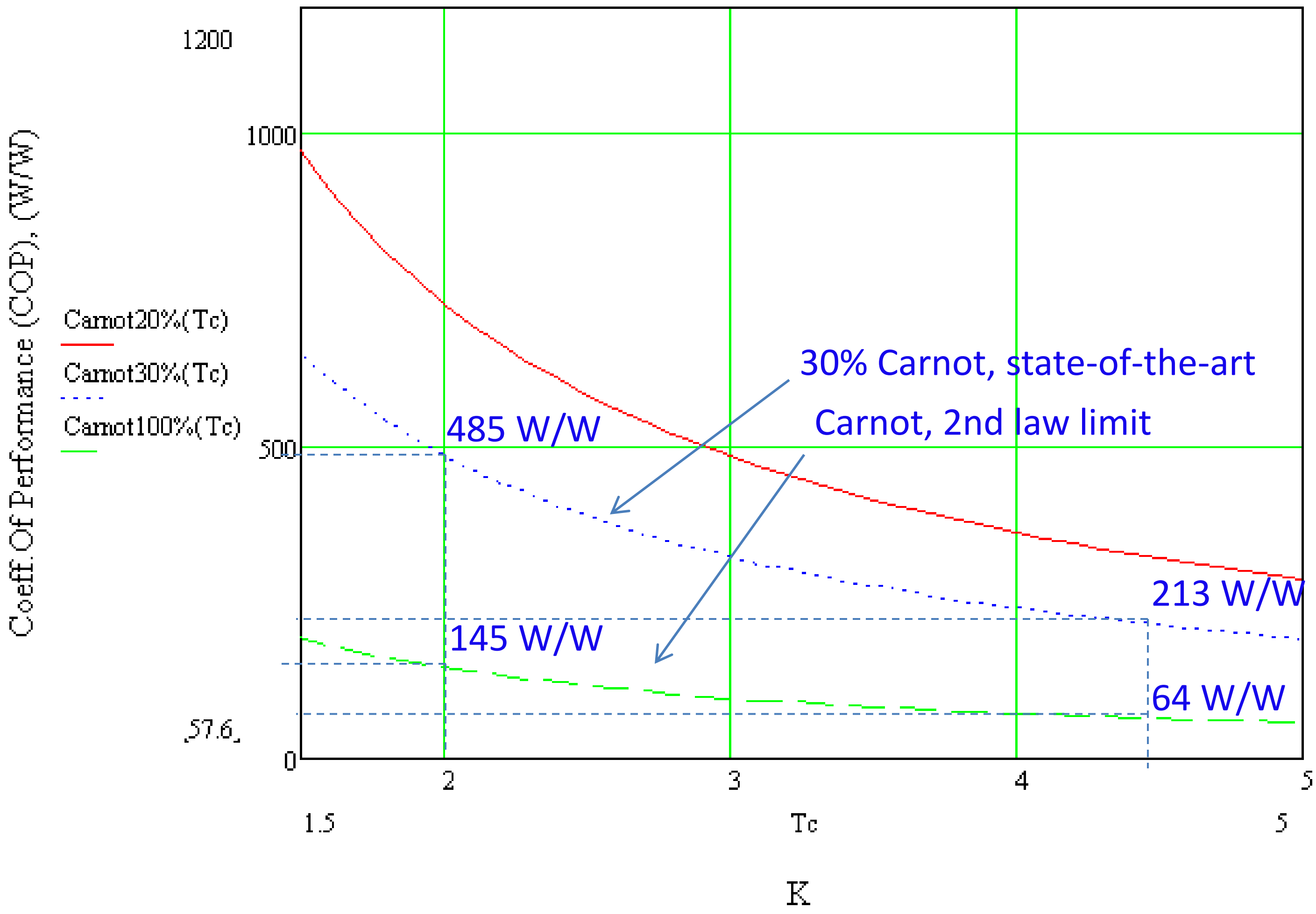
- Positioning stability?
  - ± 0.5 mm transversal feasible
  - Sufficient?
- Pitch, Yaw:
  - ± 1 mrad feasible
  - Sufficient?
- Roll limit: < 0.25mrad? (~1% Lumi. reduction):
  - 0.25 mrad → 0.25 mm/m
  - ~0.5 m He vessel → thermo-mechanical dimensional stability of supporting system:

  < 125μm → tough!
- Online alignment monitoring probably needed

Heat load budgets

- Premature to give a full assessment at this stage
- Dynamic load of deflecting mode, the only mode of interest, is dumped into the He bath (see next slide)
- If possible, all other unwanted modes (LOM, SOM, HOM) to be filtered and dumped at higher temperature: (remember Carnot!)
  - Complex design and integration of couplers on cavity helium vessel
  - Need for ~4.5 K thermalisation helium circuit ? (~50 K needed for thermal shielding anyway)
  - Use of gas-cooling between 2 K and 300 K (feed-throughs) is a thermodynamically efficient (but technically complex) solution.
- Cavity supporting systems: a range of solutions exist (tie-rods, composite supports…). Choice depends on alignment goals.
- Cold-to Warm transitions, due to large aperture, are source of high static heat loads
- Radiation thermal shielding with MLI, a "standard" solution

Carnot efficiencies

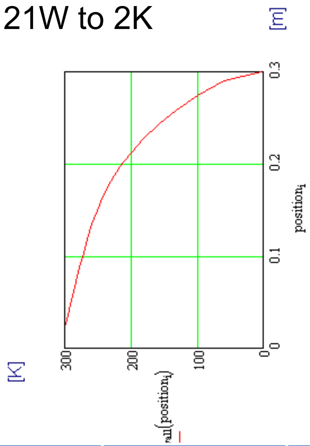


SPL: Vapour-cooled RF coupler tube

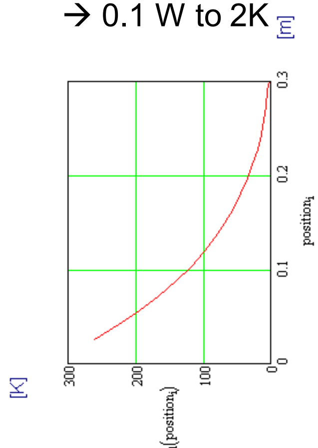
SPL coupler double walled tube, active cooling to limit static heat loads

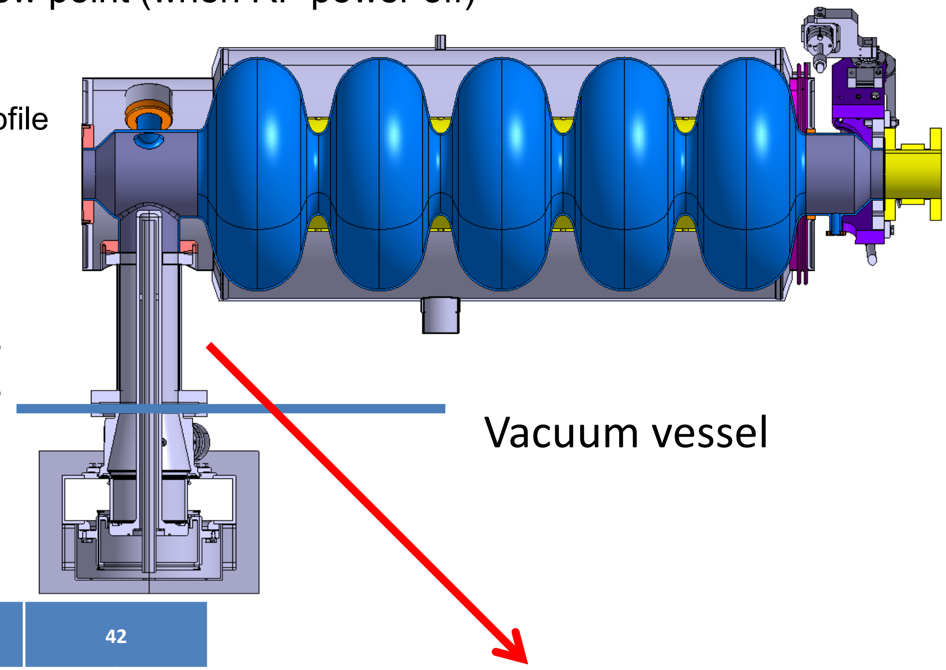
- Connected at one end to cavity at 2K, other end at RT (vessel)
- Requires elec. Heater to keep T > dew point (when RF power off)

No cooling T profile
→ 21W to 2K



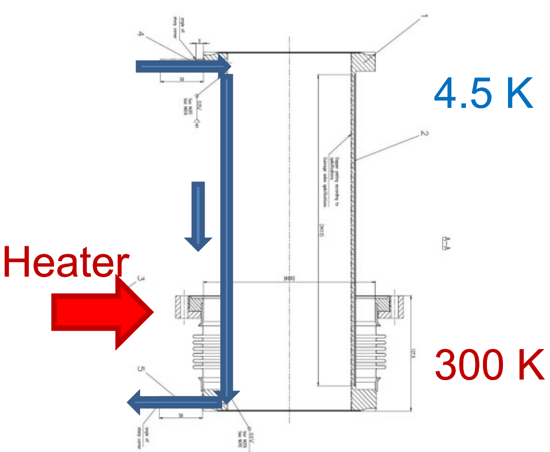
(42 mg/sec) T profile
→ 0.1 W to 2K





Massflow mgram/sec	21		23		28		35		42	
Power	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
Temp. gas out	286 K	277 K	283 K	273 K	271 K	242 K	255 K	205 K	232 K	180 K
Q thermal load to 2K	2.4 W	0.1 W	1.7 W	0.1 W	0.4 W	0.1 W	0.1 W	0.1 W	0.1 W	0.1 W
Q heater	19 W	32 W	21 W	34 W	29 W	38 W	39 W	41 W	46 W	44 W
ΔL	0.1 mm (0.63-0.53)mm				0.05 mm (0.66-0.61)		~ 0 mm (0.67-0.67)			

→ Yields a certain degree of position uncertainty (<0.1 mm?)



Helium gas cooling the double wall

Heat loads budgets

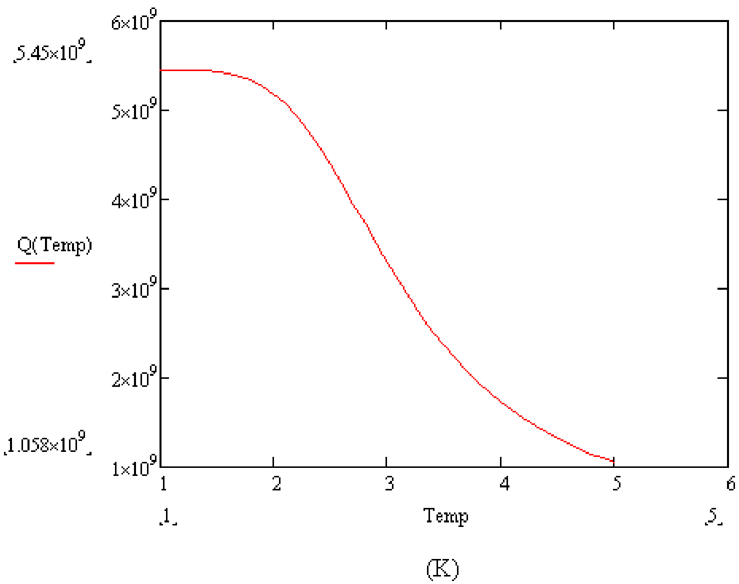
(example: HWSR rectangular design)

Parameter	Unit	Value	Remark
Ro	nΩ	20	My guess, conservative but for well prepared surface
Rmag	nΩ	0	Perfect shielding
$(R/Q)_T$	Ω	109	JLAB data
G=Q x Rs	Ω	263	JLAB data
Vacc	MV	4.9	JLAB data

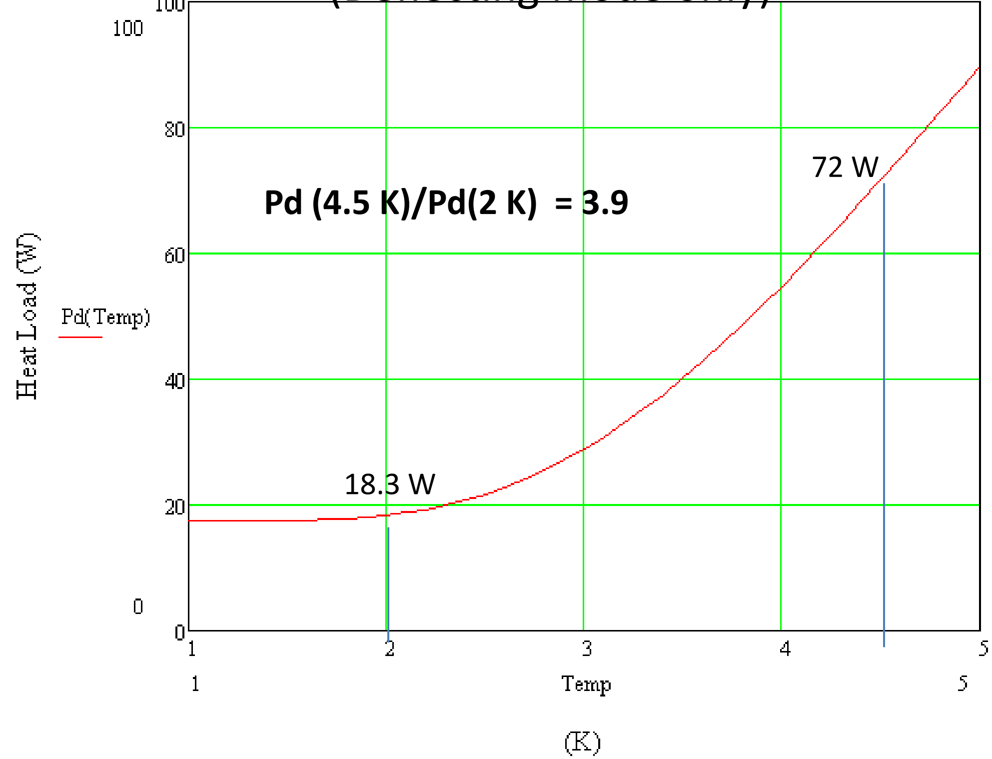
$$R_s = R_s^{BCS} + R_0 + R_{mag}$$

$$R^{BCS}{}_s(\mathrm{Ohm}) = 2\times10^{-4}\,\frac{1}{T}\left(\frac{f\,[\mathrm{GHz}\,]}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right)$$

$$Q(T) = G/Rs(T) \qquad Pd(T) = \frac{\mathrm{Vacc}^2}{\frac{R}{Q}\cdot Q(T)}$$



(Deflecting mode only)



Data from: http://indico.cern.ch/getFile.py/access?contribId=30&sessionId=6&resId=1&materialId=slides&confId=83532

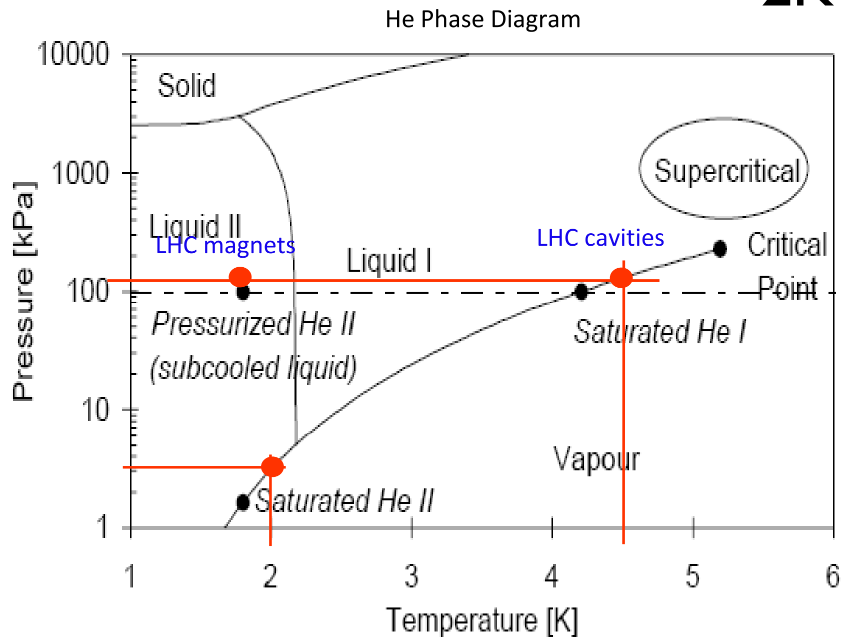
Heat Loads budget (minimum)

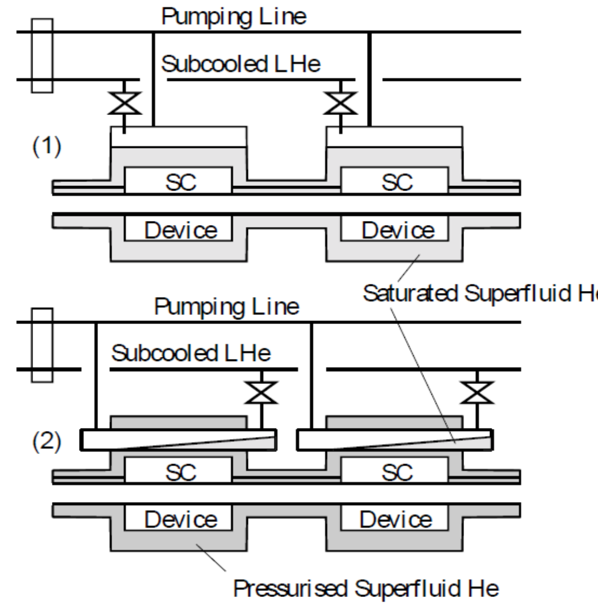
- Assuming operation at 2K, 2 cavities/cryo-module (3m long)

HL/cryo module		HL @ 2 K (W)	HL @ 4.5K (W)	HL @50K(W)	Comment
Dynamic	Deflecting mode	36.6 (2x18.3)	-	-	
	LOM+SOM+HOM couplers	TBD	TBD	TBD	
	RF coupler	TBD	TBD	TBD	
	Beam current	3	-	-	1 W/m: Correct?
Static	Radiation (vessel)	3	-	60	1 W/m @ 2K; 20 W/m @ 50K
	Radiation (end caps)	1	-	15	0.5 W/cap @2K; 15 W/cap @ 50K
	Beam tubes (rad.+cond.)	9	10	40	Rescale from LHC
	Supporting system	1	-	30	Tentative figures
	RF coupler	TBD	TBD	TBD	
	LOM+SOM+HOM couplers	TBD	TBD	TBD	
	Totals	**~54 + TBD**	**10 + TBD**	**~145+ TBD**	

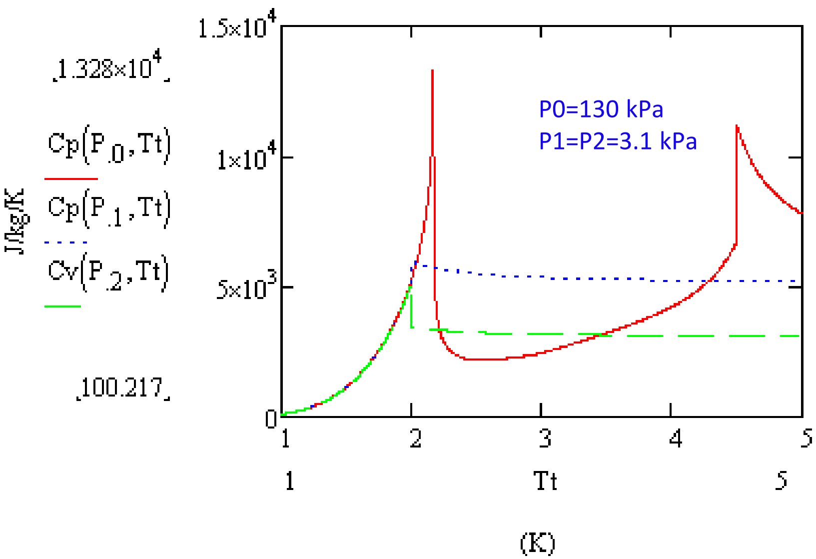
- What is the fraction of 2 K capacity upgrade allocated to CC ? (→ **talk on cryogenics by B.Vullierme tomorrow**)

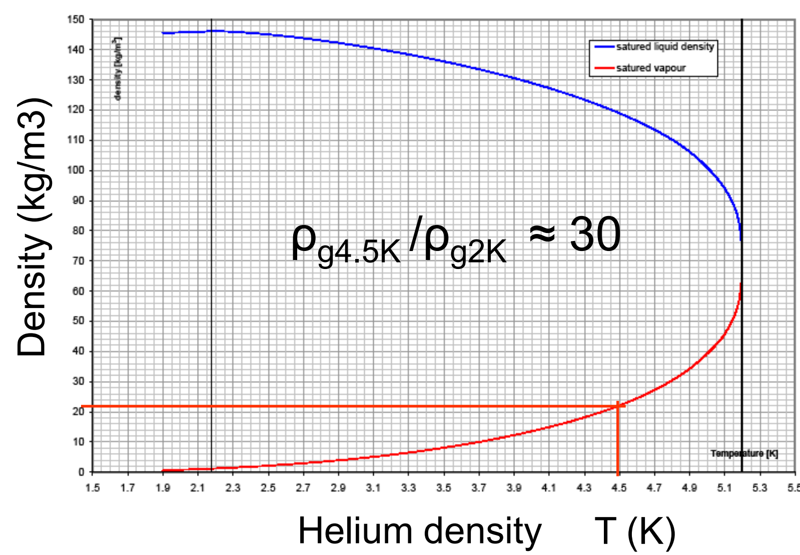
General considerations on operating T: 2K or 4.5K ?





(L.Tavian, EPAC2000)





General considerations on operating T: 2K or 4.5K ?

Property/Issue	4.5 K saturated	2 K saturated	2 K pressurized
Pressure	130 kPa (1.3 bar)	3.1 kPa (31 mbar)	130 kPa (1.3 bar)
Air leak prevention	-	-	+
Dielectric strength	-	-	+
Enthalpy margin for transients	-	-	+
Technical simplicity	+	+	-
Vapour density/pressure vs. pumping capacity	tbd	tbd	tbd
Surface wetting on complex geometries (trapped gas)	-	+	+
Sensitivity to micro-phonics (boiling, pressure stability)	-	+	+

The choice of T ?

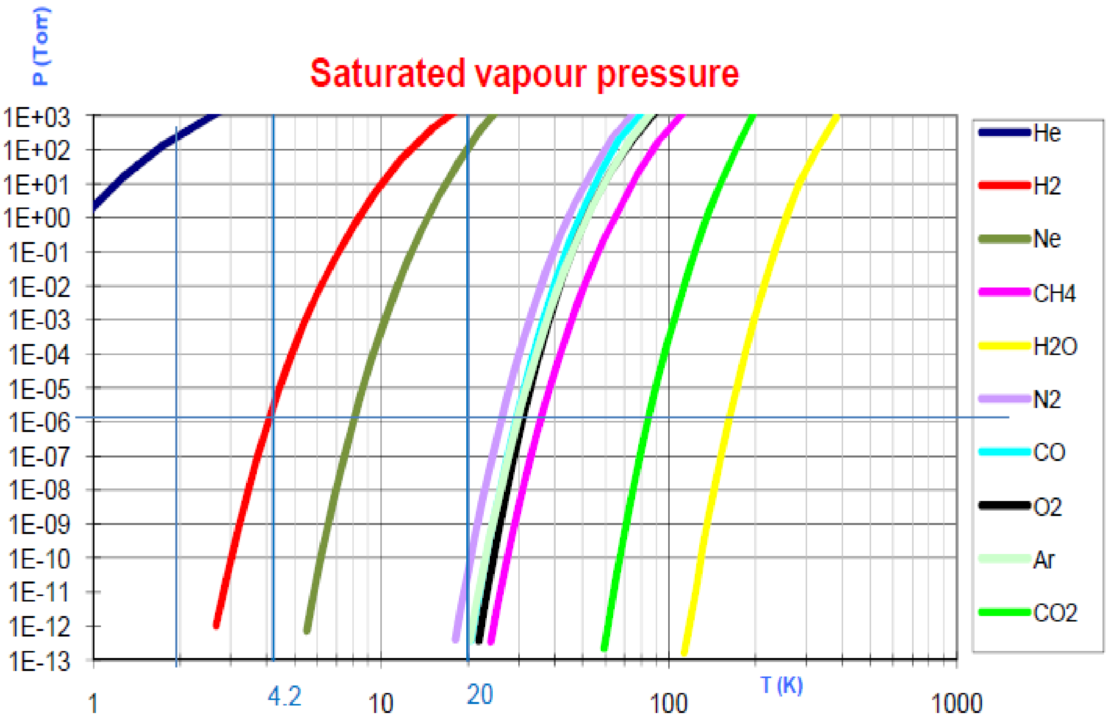
- x4 (?) lower dynamic loads for 2K
- Premature at this stage, but both 2 K and 4.5 K sat. seem possible.
- Advantages of 2K pressurized? Not clear at this stage but not to be excluded "a priori"
- What T do the other users (new triplets, D2, SC links…) need? A common and consistent choice should be made.

Other issues:

- Pressure stability requirements (probably depends on cavity geometry)? Pressurizes HeII can provide better stability (pumping in heat exchanger, not on cavity bath).

Vacuum aspects (cold beam tube)

- 4.5 K would require cryo-sorption for H_2 (filament type, not ideal)
- 2 K cryo-condensation of H_2
- Since beam tube is > 0.5m and cold, a beam screen has to be foreseen (LHC beam vacuum policy)
- Beam screen with pumping slots ensures local pumping



Summary and Outlook

- From geometrical considerations on candidate compact crab cavities and their integration in the 194 mm beam spacing a “2 beam tube in same He vessel” seems to be the only viable solution.
- Are there any show stoppers inherent to this technical option ? Needs further studies.
- The geometry of the helium vessel, due to the many penetrations (RF couplers, dampers, tuners…) will be complex
- Figures of a tentative (!) envelope for a cryo-module housing 2 cavities was shown, but these figures may (=will) evolve, essentially depending on the retained candidate.
- Alignment requirements have to be defined. This is the starting point for engineering studies of the cryo-module. Need for online alignment?
- Operating temperature: premature for making a final choice, but 2 K is preferable to limit dynamic loads (some candidates assume 2K). A common and consistent choice has to be made including the needs of other users (new triplets, D2, SC links…).
- Premature for Heat load analysis (though partial figures were presented for one candidate) . Important to know what is the fraction of the cryogenic capacity available .
- Due to the wide specificities between cavity candidates, further engineering work needs the selection of <u>THE</u> crab cavity candidate.

Thank you
for your attention!