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Cooling the FCC beam screens

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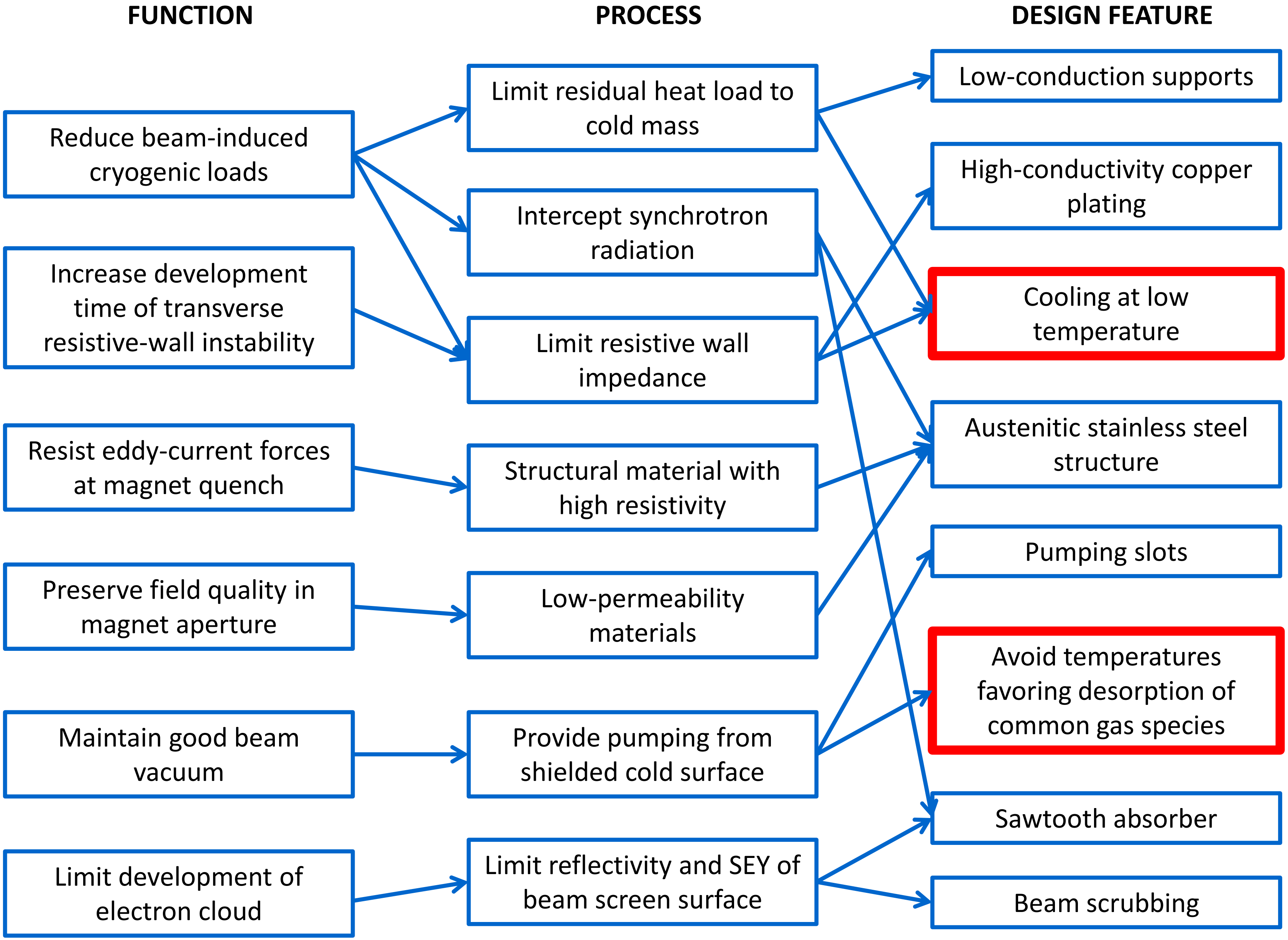
Content

- Beam screen cooling requirements and constraints
- Cooling and main sources of exergetic inefficiency
- Cooling of half-cell beam screen: first results
- Conclusions

Functional design map of beam screen



FUNCTION

- Reduce beam-induced cryogenic loads
- Increase development time of transverse resistive-wall instability
- Resist eddy-current forces at magnet quench
- Preserve field quality in magnet aperture
- Maintain good beam vacuum
- Limit development of electron cloud

PROCESS

- Limit residual heat load to cold mass
- Intercept synchrotron radiation
- Limit resistive wall impedance
- Structural material with high resistivity
- Low-permeability materials
- Provide pumping from shielded cold surface
- Limit reflectivity and SEY of beam screen surface

DESIGN FEATURE

- Low-conduction supports
- High-conductivity copper plating
- Cooling at low temperature
- Austenitic stainless steel structure
- Pumping slots
- Avoid temperatures favoring desorption of common gas species
- Sawtooth absorber
- Beam scrubbing

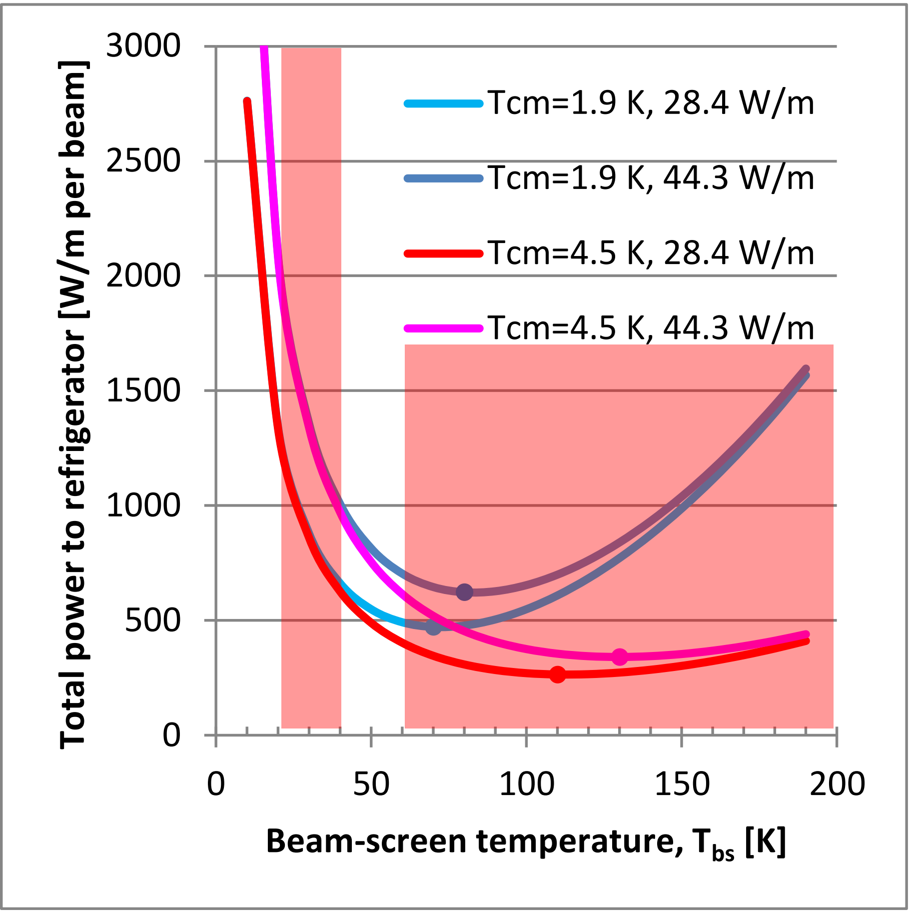
Ph. Lebrun

The synchrotron radiation

	LHC	FCC (100 km)	FCC (83 km)
P_{SR} in W/m	0.17	28.4	44.3
P_{SR} total in MW	0.008	4.8	5.8

- If this load is falling directly on the magnet cold masses working at 1.9 K, the corresponding total electrical power to refrigerators is 4.3 to 5.2 GW
- Beam screens are mandatory to stop the synchrotron radiation at a higher temperature reducing the electrical power to refrigerator.
  - → Is there a optimum operating temperature?

Main considerations



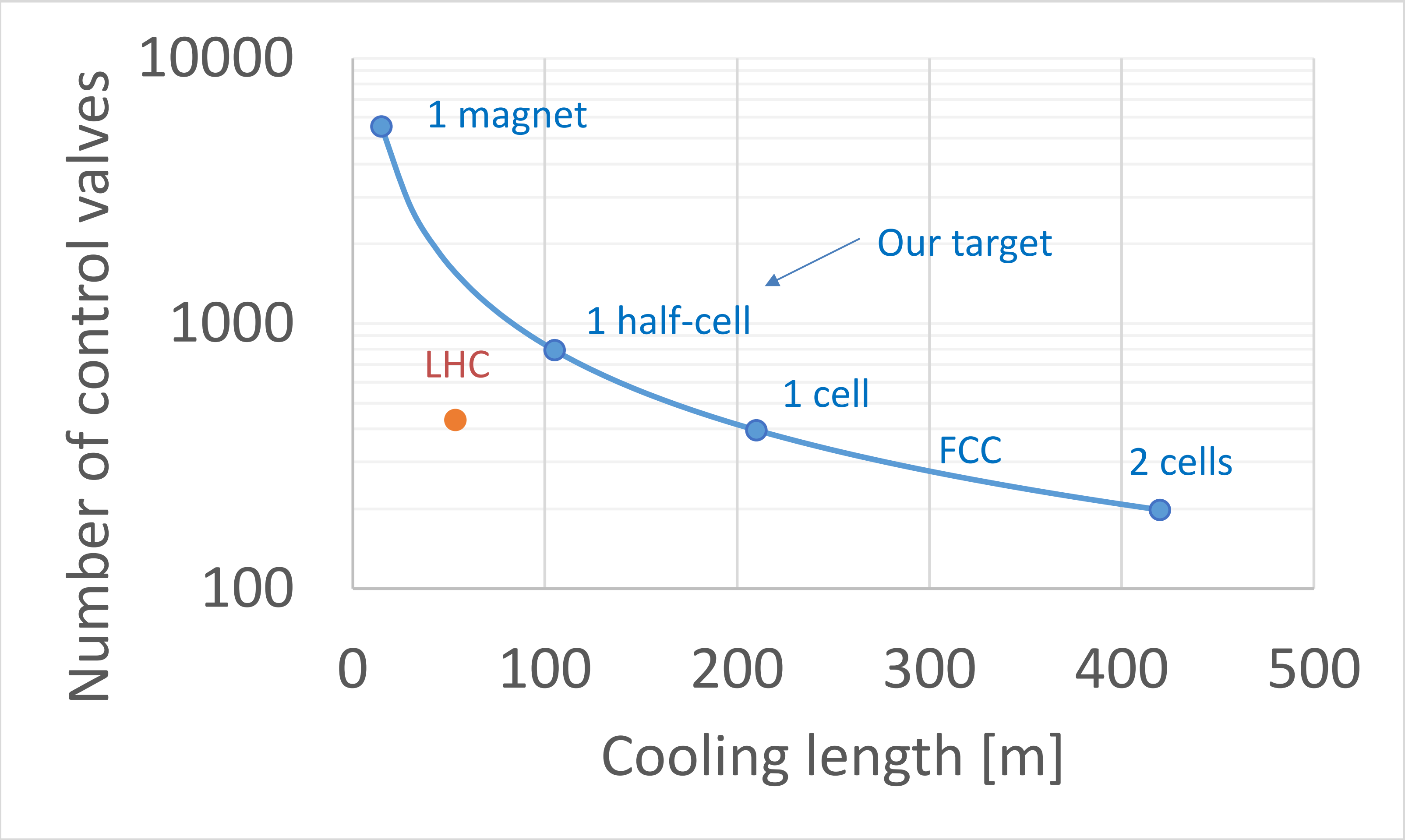
🟥 Forbidden by vacuum
and/or by surface impedance

Entropic load ratio for FCC

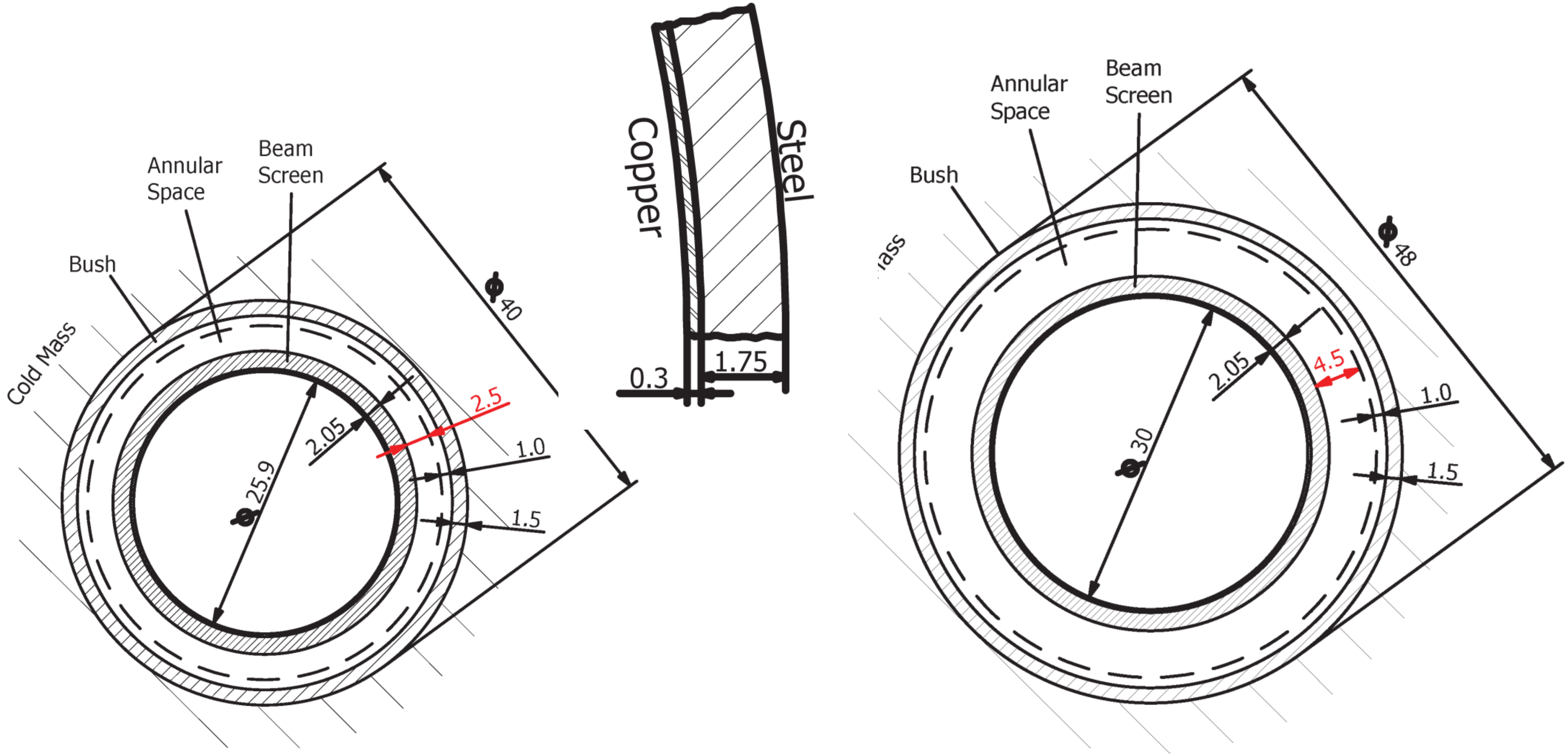
Cold-mass @ 1.9 K	46 %
Beam screen and thermal shield	51 %
Current lead	3 %

Beam screen and thermal shield cooling is the largest refrigeration load of FCC which will required more than 100 MW of electrical power to the refrigerator: Optimization of the corresponding cooling is mandatory.

Control valve number vs cooling length



Beam screen geometry



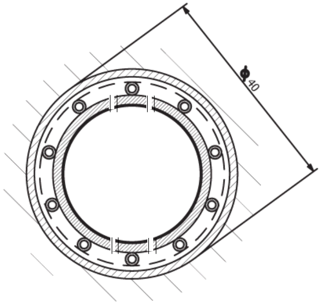
Inner coil diameter: 40 mm
Beam aperture: 26 mm
Remaining annular space: 2.5 mm

Inner coil diameter: 50 mm
Beam aperture: 30 mm
Remaining annular space: 4.5 mm

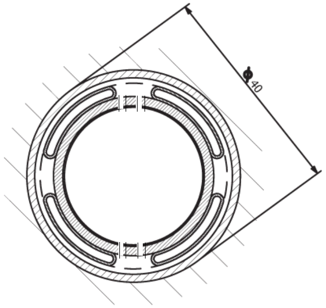
Beam screen cross-section and cooling constraints

- 2 different cold bore diameters
- Cylindrical or oval cooling channels
- Design constraints: free space for pumping slot and beam welding process (LHC type)

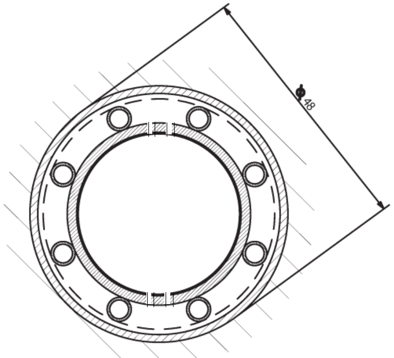
Small CB C10



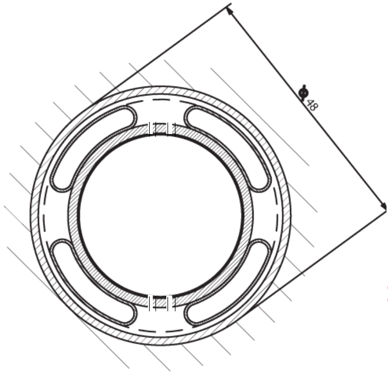
Small CB O4

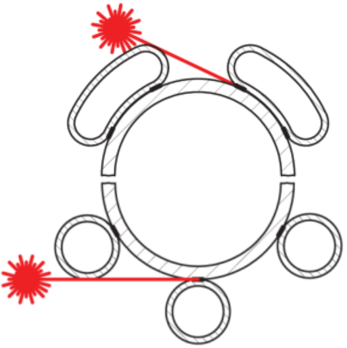


Big CB C8



Big CB O4



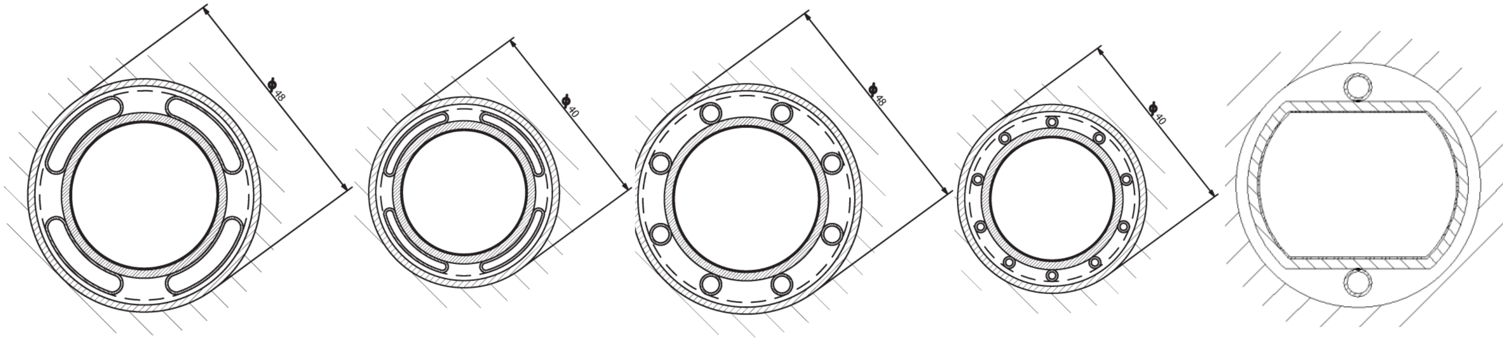


- 2 different cryogens (helium or neon)
- Different supply pressures (4 with helium, 2 with neon)
- 2 different heat loads (28.4W/m and 44.3 W/m)
- Cooling constraint:
  - Maximum pressure drop: 80 % of the absolute supply pressure (remaining 20 % for the valve controllability)
  - Maximum flow velocity: 10 % of the sound velocity (to avoid vibrations)

Hydraulic impedance

$\Delta P \sim 1/(A^2.Dh)$, A Section, Dh Hydraulic diameter

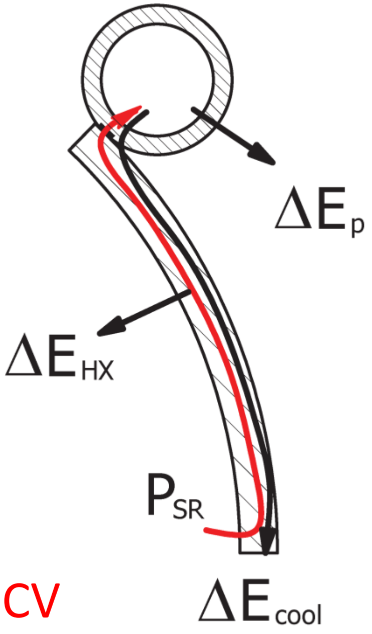
	Big CB O4	Small CB O4	Big CB C8	Small CB C10	LHC type
A [mm^2]	274	105	77	18	22
Dh [mm]	6.3	2.7	3.5	1.5	3.7
A^2.Dh [mm^5]	471856	30215	20735	468	1711
A^2.Dh ratio w/r to LHC	276	18	12	0.3	1



BS cooling efficiency

Exergy balance for cooling

Exergy balance only for the BS cooling



Exergy difference between inlet and outlet consists of

- Exergy flow to the Beam Screen
- Exergy loss due to pressure drop in channels and CV
- Exergy loss due to heat transition in Beam Screen (i.e. temperature difference between cryogen and BS)
- Exergy losses in the mixing chambers (unbalanced cooling)

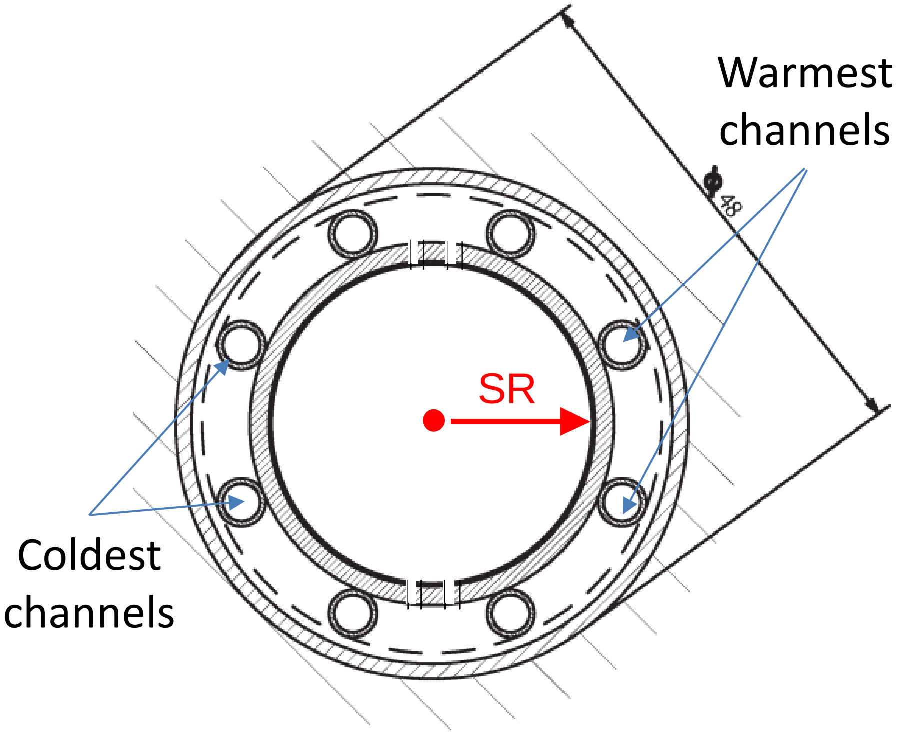
$$\text{Exergetic efficiency} = \frac{\text{Exergy of extracted heat at } T_{BS}}{\text{Exergy difference of cryogen}}$$

Main sources of unefficiency: Unbalance cooling

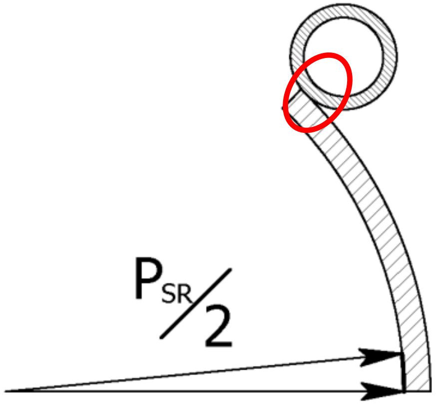
- Thanks to the copper layer (0.3 mm), the heat is well redistributed in the different parallel cooling channels.

Mass-flow ratio between warmest and coldest channel: < 1 %

Temperature ratio between warmest and coldest channel: < 2 %



Main sources of unefficiency: BS thermal impedance



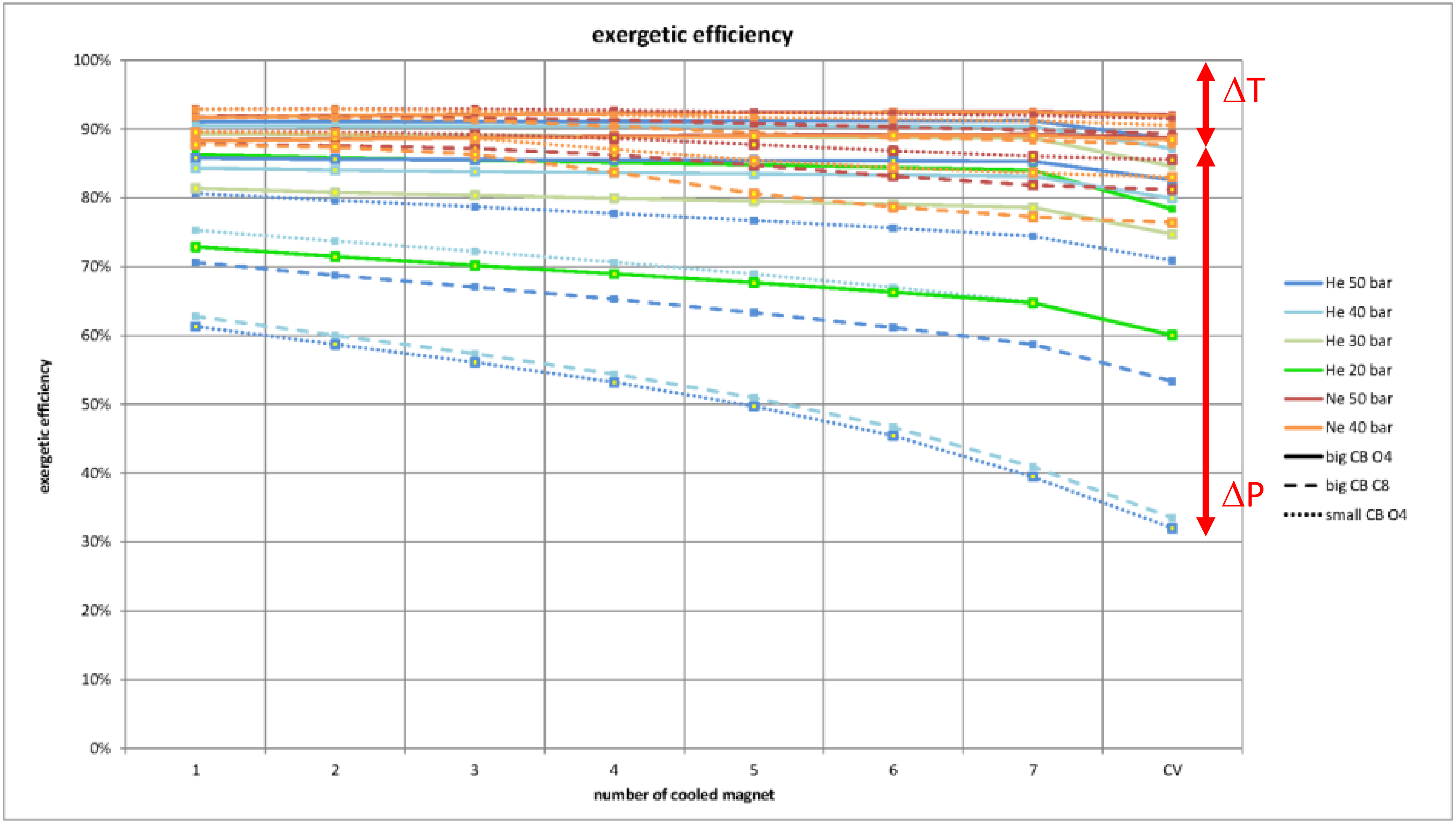
- The thermal impedance of the stainless steel part is preponderant in particular at the welding interface with the cooling channel:
  - Thermal impedance: 0.8 W/K.m per welding interface,
  - i.e. for beam screen with 8 welding interfaces, we have a temperature difference of:
    → ~4 K to extract a SR of 44 W/m
    → ~3 K to extract a SR of 28 W/m
  - - i.e. for beam screen with 2 welding interfaces (LHC type), we have a temperature difference of:
    → ~17 K to extract a SR of 44 W/m
    → ~11 K to extract a SR of 28 W/m
- To guaranty a Tmax of 60 K, we have to lower the cooling temperature of the cryogen, i.e. increase the refrigeration cost.

Main sources of inefficiency: pressure drop

- Pressure drop is a source of irreversibility, which requires to be compensated by additional compression power dissipated:
  - at cold temperature in case a cold circulator/compressor
  - at cold and ambient temperature in case of a warm circulator/compressor.

Calculation results

Out of the 48 possible combinations 21 were able to meet the half-cell cooling conditions

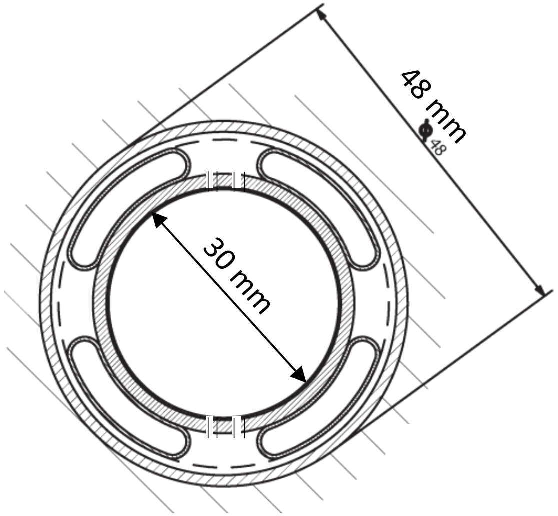


Cooling conclusion

- Considering the cooling performance in nominal condition, the optimum configuration is large oval channels cooled with neon.

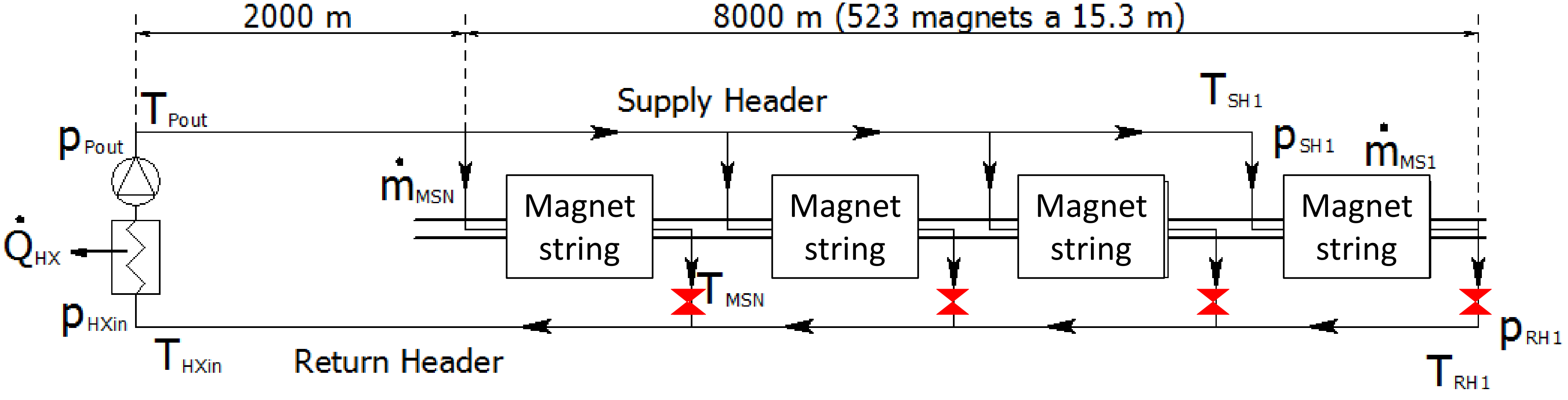
- But considering:
  - off design operation with neon becoming solid after a cooling stop (power cut).
  - cost and availability of neon,
  - possible activation of neon by the beam losses,

The best compromise is large oval channels cooled with helium. (loss of few points on the exergetic efficiency)



Supply pressure [bar]	Exergetic efficiency [%]	
	He	Ne
20	78	87
30	84	89
40	87	91
50	89	91

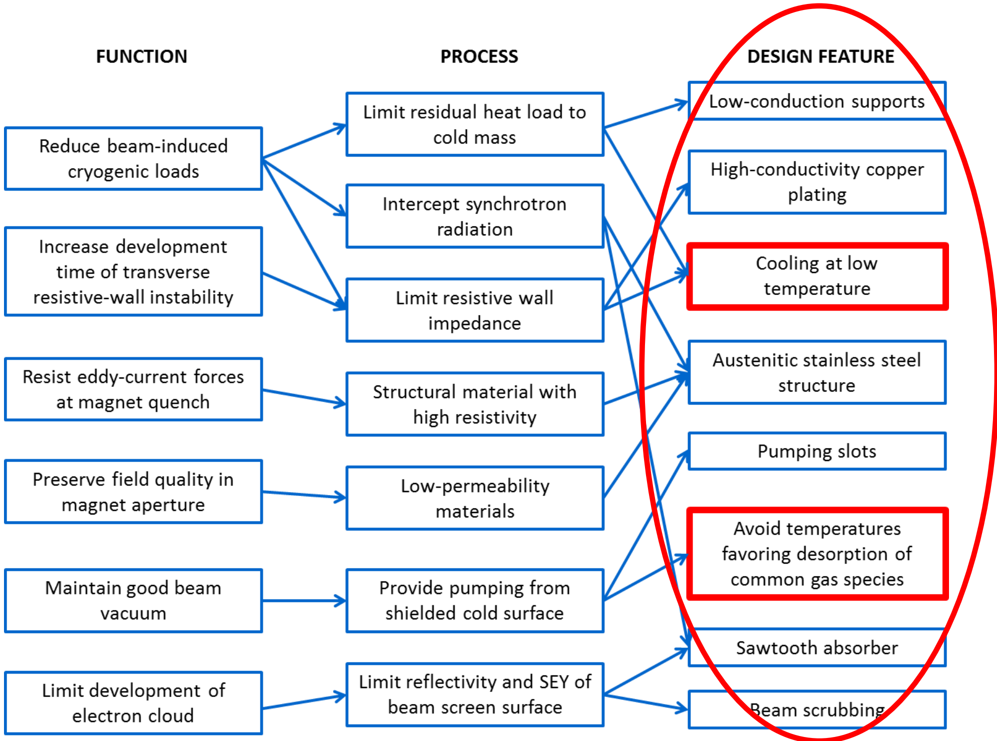
Can we avoid control valve ?



- Removing control valve could allow to decrease the cooling length (one loop per magnet ?) and consequently the required cooling channel diameter/number. In addition it will reduce the capital and maintenance cost.
- However, pressure drop in supply/return headers could create unbalances in the loop cooling which will impact the exergetic efficiency. In addition, off-design operation (no beam, ramp-up/down, operation at reduced beam energy…) must be carefully analysed.
- Study is in progress…

Conclusion

- Study of the beam screen cooling is in progress.
- Different beam screen geometries have been studied: large oval channels cooled with helium at 40-50 bar is recommended for efficient cooling.
- Iteration with other design features must continue in collaboration with vacuum colleagues.



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Avoid temperatures favoring desorption of common gas species

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Beam scrubbing