Exergetic analyses of the Cold Mass Cooling and the Beam Screen Cooling systems of the Future Circular Collider (FCC)

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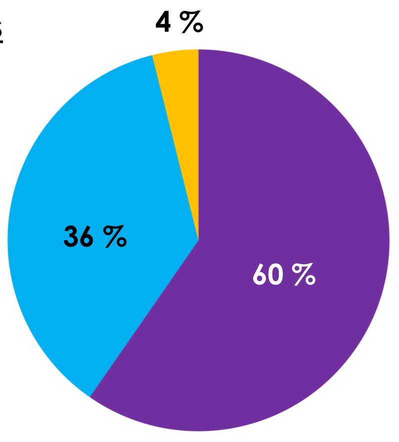
Introduction

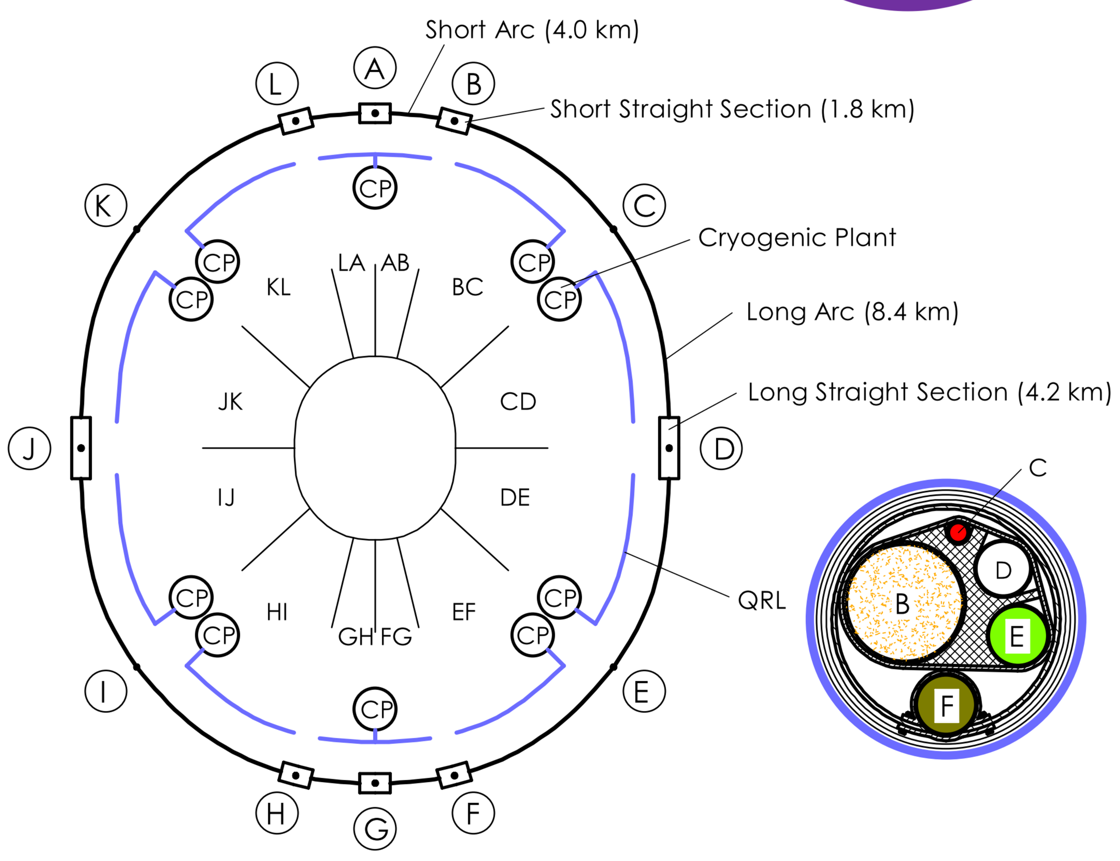
Electrical Power Consumptions of Cryogenics

Cold Mass Cooling System (132 MW)

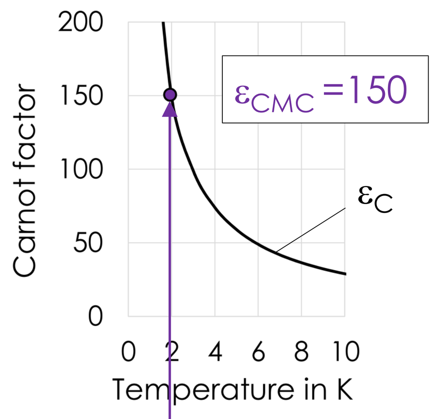
Beam Screen Cooling System and Thermal Shielding (80 MW)

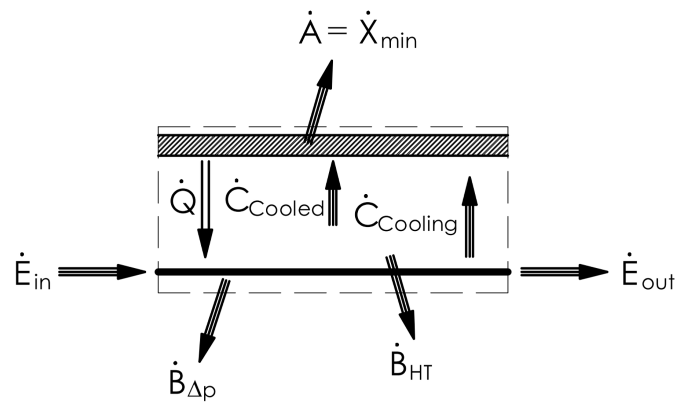
Current Lead Cooling (7 MW)





Minimal exergy effort and exergy losses





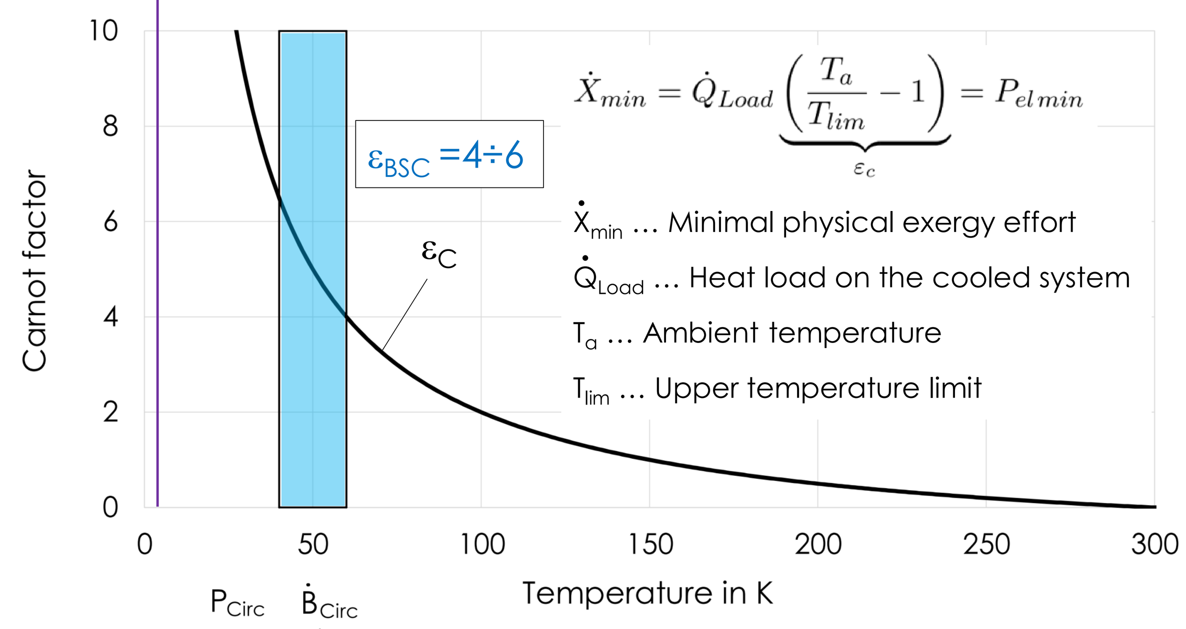
$\dot{E} = \dot{m}e = \dot{m}\left[h - h_a - T_a\left(s - s_a\right)\right]$ ... Exergy flux contained in the cryogen flow

$\dot{C}_{Cooled} = \dot{Q}\left(\frac{T_a}{T_{Cooled}} - 1\right)$

$\dot{C}_{Cooling} = \dot{Q}\left(\frac{T_a}{T_{Cooling}} - 1\right)$

$\dot{B}_{HT} = \dot{C}_{Cooling} - \dot{C}_{Cooled} = \dot{Q}T_a\left(\frac{1}{T_{Cooling}} - \frac{1}{T_{Cooled}}\right)$ ... Exergy loss due to driving temperature differences of cryogen cooled object

$\dot{B}_{\Delta p} + \dot{C} = \underbrace{\frac{\dot{m}}{\rho}\frac{T_a}{T}\Delta p}_{\dot{B}_{\Delta p}} + \underbrace{\left(\frac{T_a}{T} - 1\right)\dot{Q}}_{\dot{C}}$ ... Exergy loss due to (frictional) pressure losses



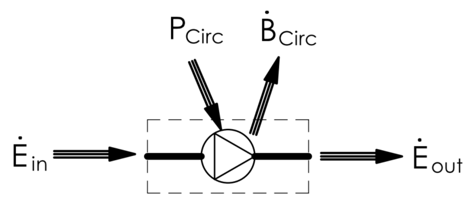
$\dot{X}_{min} = \dot{Q}_{Load}\underbrace{\left(\frac{T_a}{T_{lim}} - 1\right)}_{\varepsilon_c} = P_{el\,min}$

$\dot{X}_{min}$ ... Minimal physical exergy effort

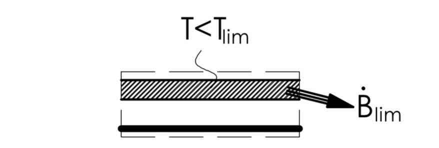
$\dot{Q}_{Load}$ ... Heat load on the cooled system

T_a ... Ambient temperature

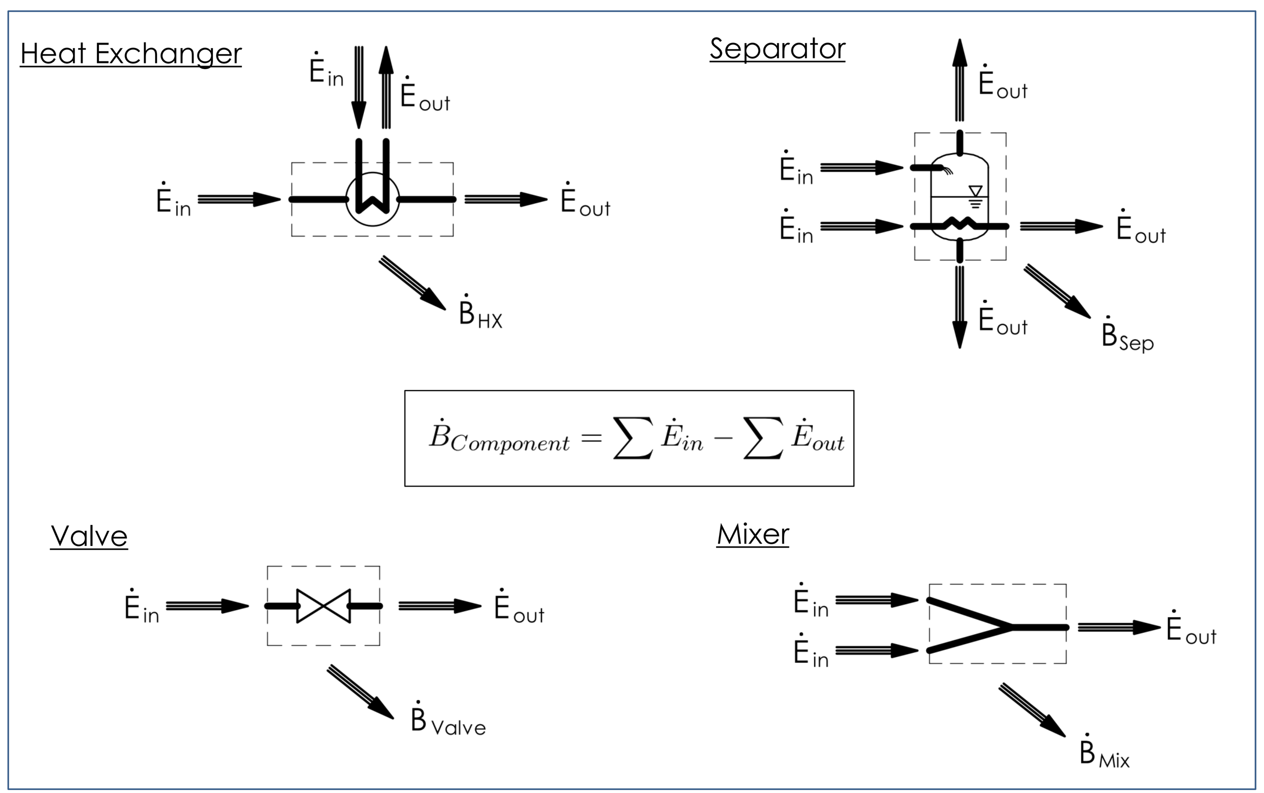
T_{lim} ... Upper temperature limit



$\dot{B}_{Circ} = P_{Circ} - \left(\dot{E}_{out} - \dot{E}_{in}\right) = -\dot{m}T_a\left(s_{out} - s_{in}\right)$



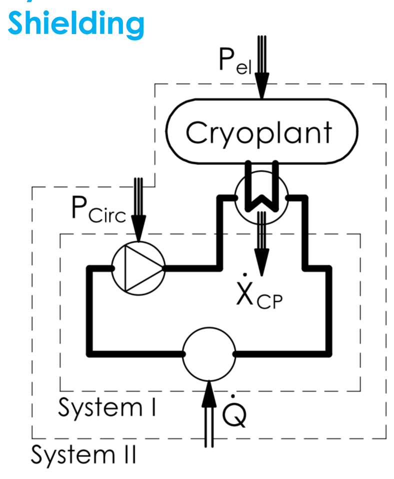
$\dot{B}_{lim} = \dot{Q}T_a\left(\frac{1}{T_{Cooled}} - \frac{1}{T_{lim}}\right)$



$\dot{B}_{Component} = \sum \dot{E}_{in} - \sum \dot{E}_{out}$

Cryoplant Designs and Efficiencies

Beam Screen Cooling System and Thermal Shielding



P_{el} ... Electrical power consumption of the cryoplant

$\dot{X}_{CP}$ ... Exergy supplied by the cryoplant

$\dot{X}_{tot}$ ... Total exergy supplied to the cryogenic system

P_{Circ} ... Electrical power consumption of the circulator (CP-Design I)

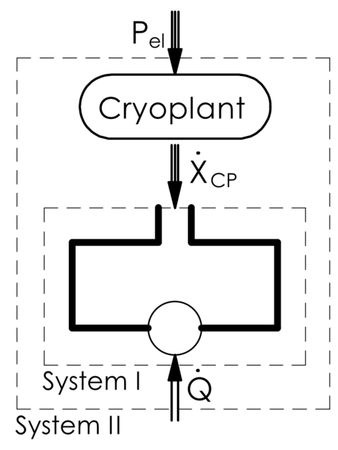
ζ_I ... Exergetic efficiency of the cryogenic distribution system w/o Carnot efficiency of the cryoplant

ζ_{II} ... Exergetic efficiency of the cryogenic distribution system with Carnot efficiency of the cryoplant

ζ_{CP} ... Carnot efficiency of the cryoplant

$\zeta_{CP} = \frac{\dot{X}_{CP}}{P_{el}}$

Cold Mass Cooling



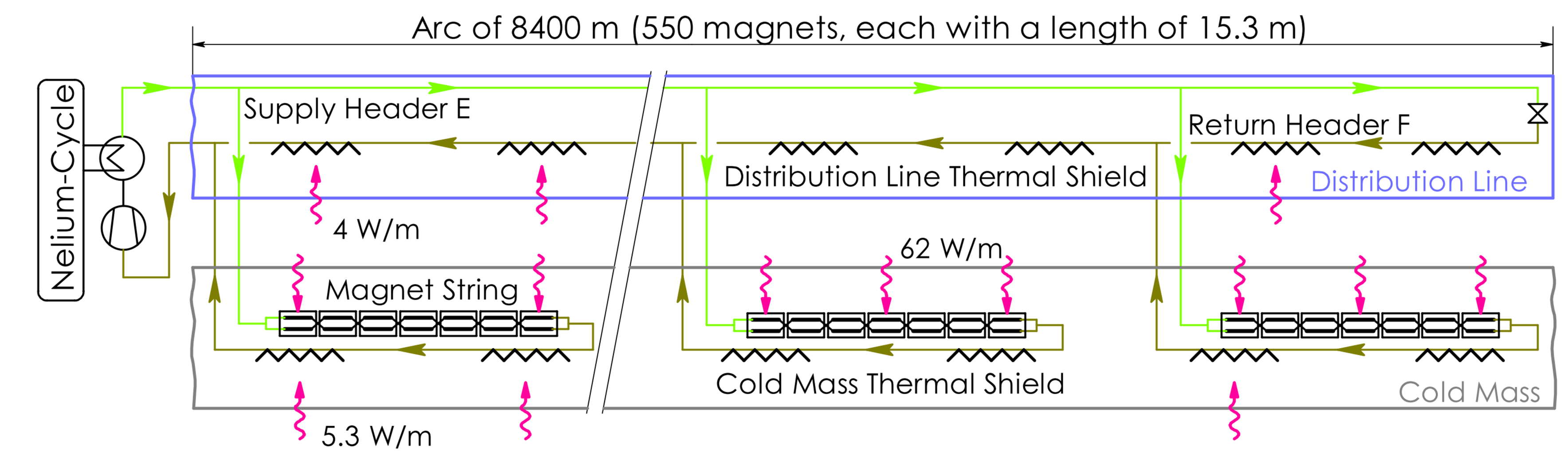
$\dot{X}_{tot} = P_{Circ} + \dot{X}_{CP} = P_{Circ} + \dot{m}\left(e_{in} - e_{out}\right)$

$\zeta_I = \frac{\dot{A}}{\dot{X}_{tot}} = 1 - \frac{\sum_{i=1}^{n} \dot{B}_i}{\dot{X}_{tot}}$

$\zeta_{II} = \zeta_{CP}\zeta_I\frac{\dot{X}_{CP}}{\dot{X}_{tot}}$

$\dot{X}_{tot} = \dot{X}_{CP} = \dot{m}\left(e_{in} - e_{out}\right)$

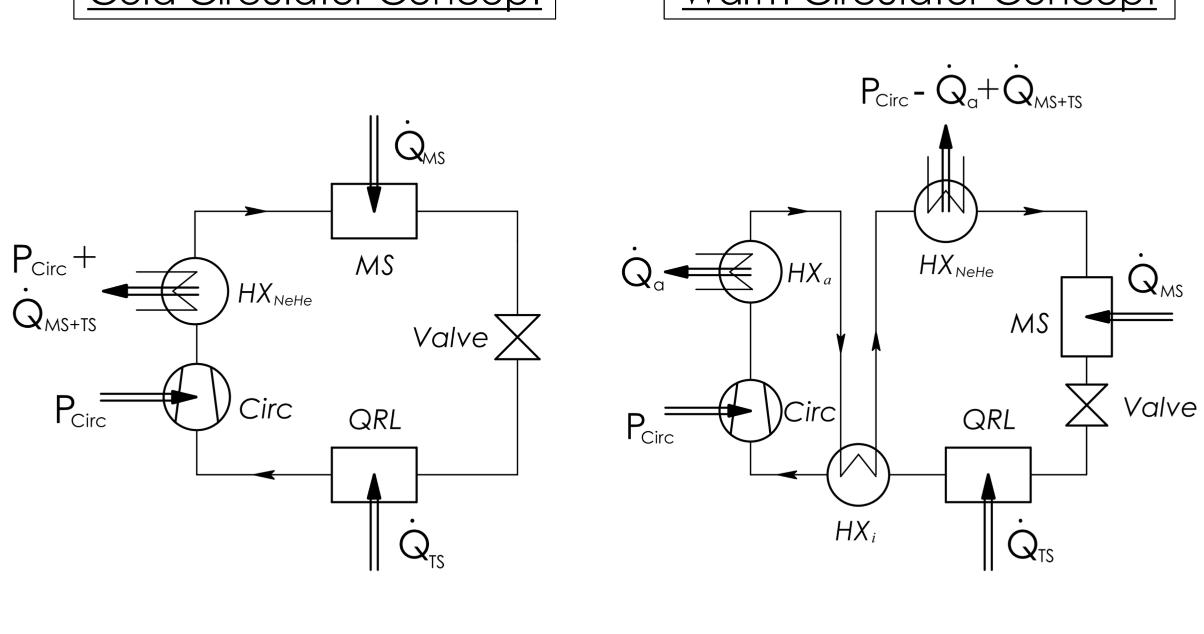
Beam Screen Cooling and Thermal Shielding

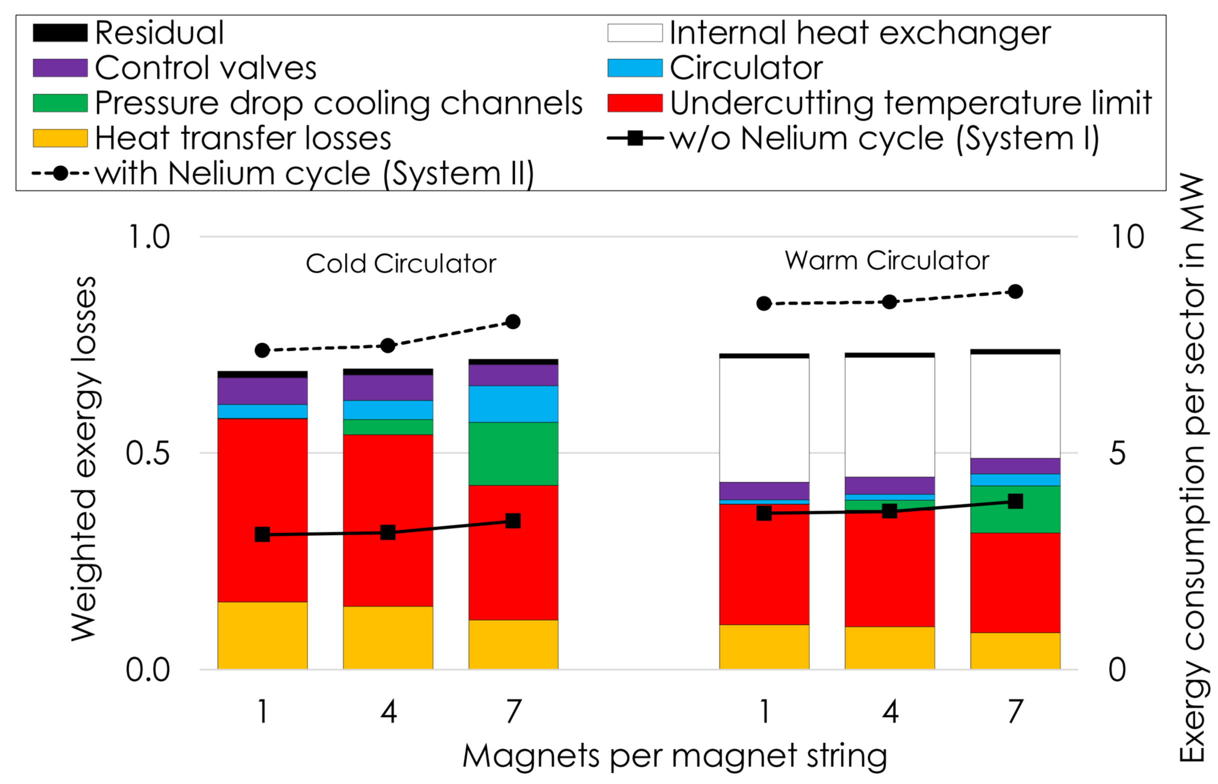


Due to similar temperature requirements, the thermal shielding is integrated into the beam screen cooling system. Helium is pressurized to 50 bar by the circulator and cooled down by the cryoplant (Nelium-Cycle) to 40 K and delivered thermally well-insulated to the magnets in parallel. After extracting the heat load on the beam screen (mainly due to synchrotron radiation), the helium flow passes thermal shielding pipes of the cold mass installed in series after the beam screen cooling channels. The warmed up helium is discharged to the return header F and returns to the cryoplant, thermally shielding the cryogenic distribution line.

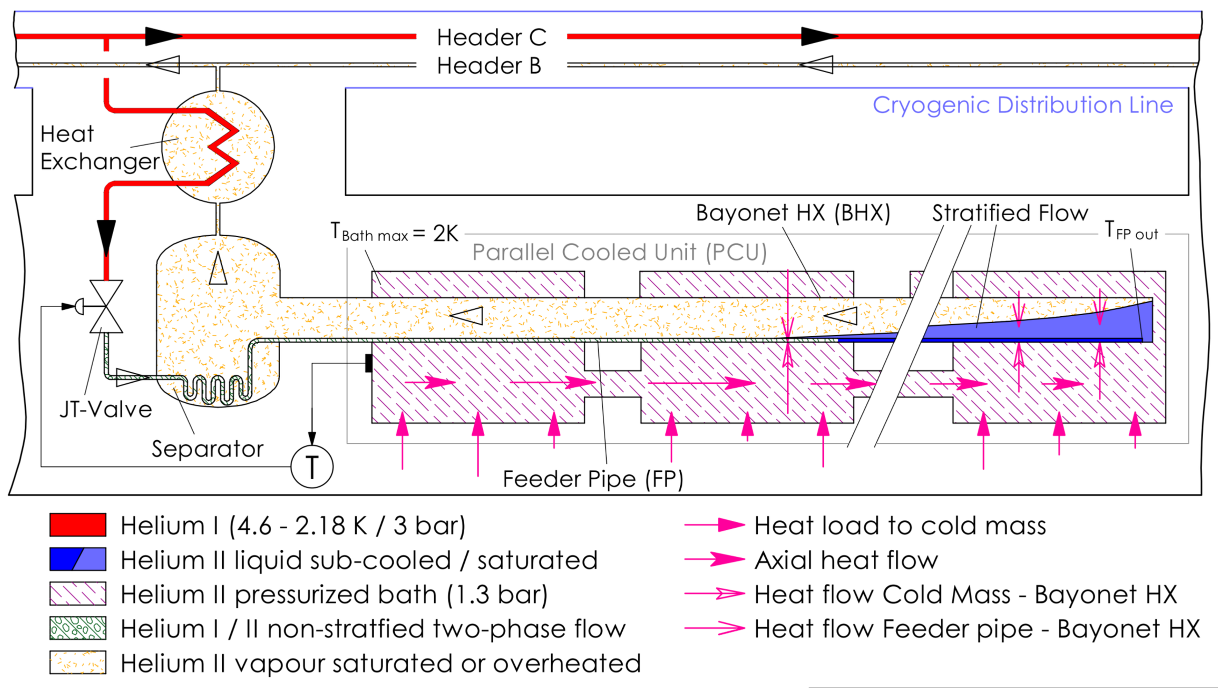
The Beam Screen Cooling Cycle is connected to the cryoplant via a heat exchanger. Two circulator concepts were compared: a cold circulator operating at cryogenic temperature and a warm circulator operating at ambient temperature to reduce the entropic load on the low temperature side.

The combination of several magnets to continuously cooled magnet strings in parallel changes the requirements to the cryogenic distribution system depending on their length. To reduce the necessary amount of technical components, a magnet string length of seven magnets was chosen, despite the increase of the exergy consumption.



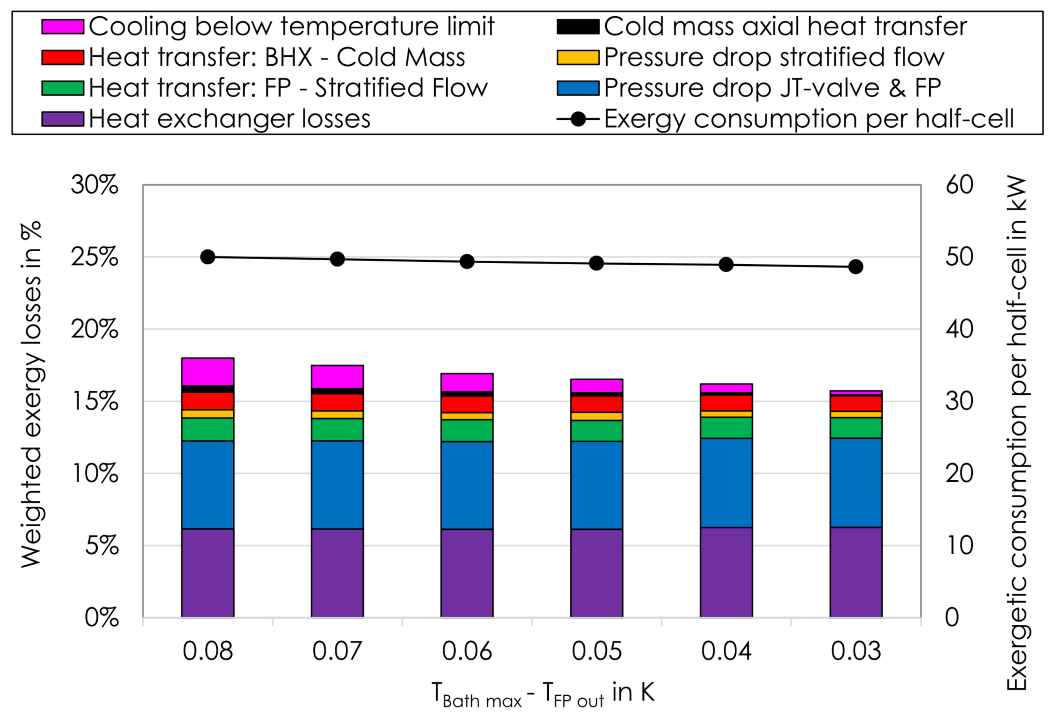


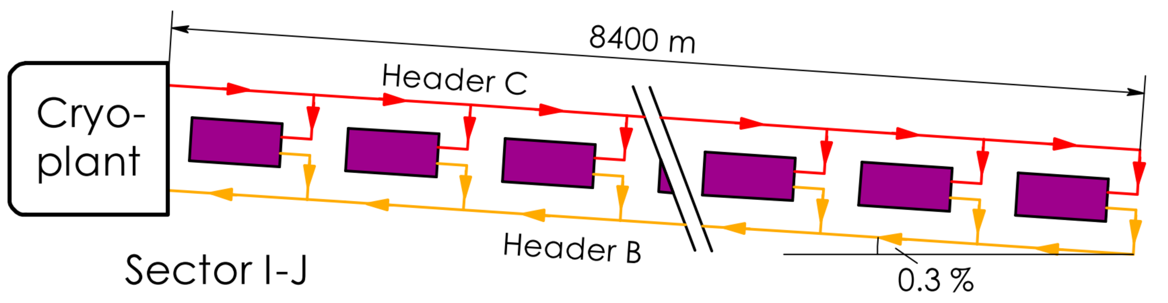
Cold Mass Cooling

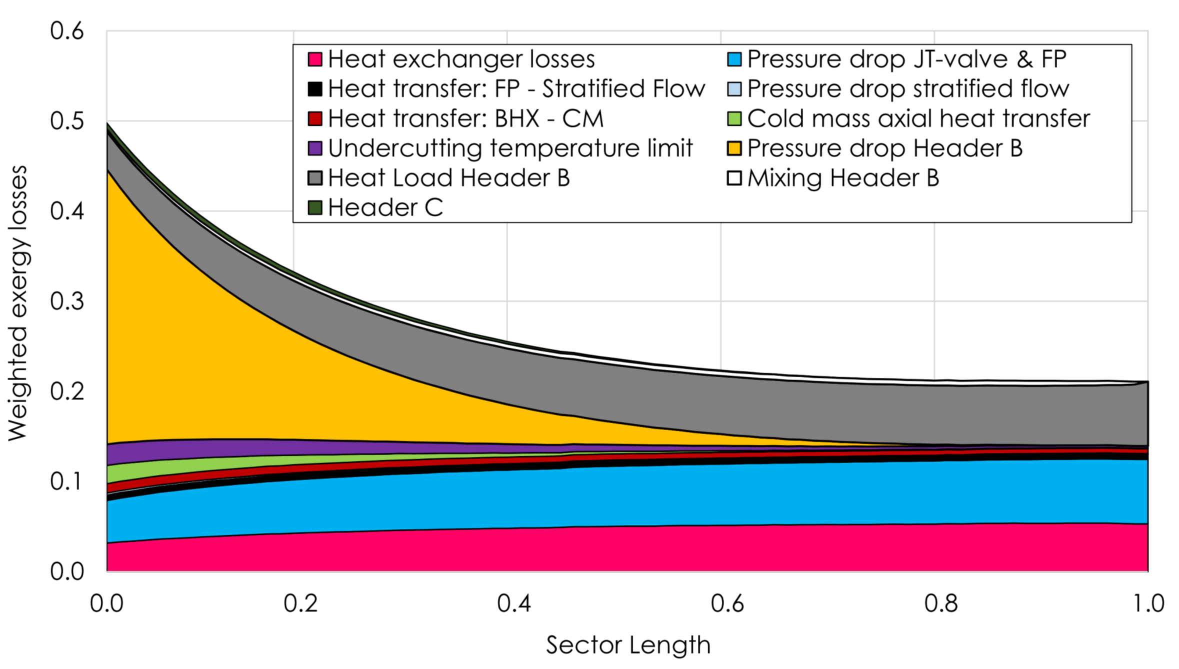


One parallel cooled Cold Mass Cooling unit corresponds to the length of an optical half-cell consisting of six dipoles and one quadrupol in series (≈107 m). The cold mass is immersed into a static bath of superfluid helium at 2 K (= $T_{Bath\ max}$). The heat load is extracted by a two-phase helium flow via the bayonet heat exchanger (BHX).

The helium is supplied by the header C, passes a heat exchanger and is expanded in a Joule Thomson-valve. It then is delivered to the PCU's end in a feeder pipe (FP). The exergy losses in cold mass cooling design are already close to the technical minimum. The efficiency of the two major contributors (heat exchanger and JT-valve) are limited by the thermal conductivity of superfluid helium and the state of the supplied helium by header C.







The arc of one long sector consists of 79 half-cells in series. Due to the slope of 0.3 % of the FCC tunnel, the sector I-J cryoplant is about 30 m higher elevated than the last half-cell. Any low pressure helium vapour generated at the sector end has to overcome the hydrostatic pressure in addition to the frictional pressure drop. To avoid choking of the pumping line (header B), the sector I-J determines the requirements to reach the cryoplant suction pressure.

Exergetic efficiencies and consumptions

The table below summarizes the efficiencies and the electrical power needed. The values for the Current Lead Cooling (CLC) were scaled, based on the LHC data. The cryoplant Carnot efficiencies are assumed to be: ζ_{CP} (T < 2 K)=0.18 ζ_{CP} (T < 40 K)=0.29 ζ_{CP} (T ≥ 40 K)=0.42

Value	Symbol	Unit	CMC	BSC	CLC	Σ
Exergy consumption per long arc w/o cryoplant	$\dot{X}_I$	MW	2.44	3.43	0.21	6.08
Exergetic efficiency of a long arc w/o cryoplant	ζ_I	-	0.714	0.7	0.842	0.71
Electric power consumption long arc	$\dot{X}_{II}$	MW	13.55	8.03	0.56	22.14
Exergetic efficiency of a long arc with cryoplant	ζ_{II}	-	0.129	0.299	0.311	0.195
Electric power consumption FCC	P_{el}	MW	131.5	80.3	6.8	218.5
Fraction of the total power consumption	-	-	0.602	0.367	0.031	1
Total exergetic efficiency FCC	ζ_{FCC}	-	0.133	0.299	0.311	0.199

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