Future Circular Collider (FCC)
Sector cool-down and warm-up studies

Hugo Rodrigues, Claudio Kotnig, Laurent Tavian
CERN, Technology Department
Geneva, Switzerland

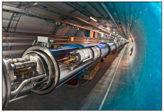
Rome, 15th April 2016

Outline

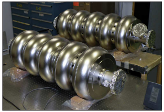
1. **Introduction:** Cryogenic system layout
2. **Modelling considerations**
3. **Results:**
   - Sector cool-down and warm-up timescales
   - Required nitrogen storage facilities
4. **Conclusions and Outlook**

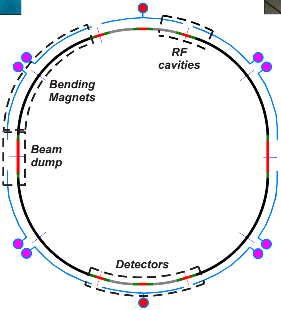
Preliminary FCC layout

Bending magnets

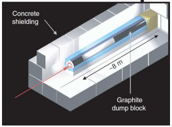


RF cavities

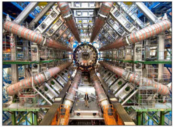




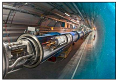
Beam dump

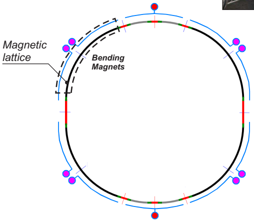


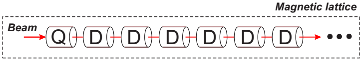
Detectors



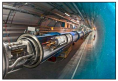
Preliminary FCC layout

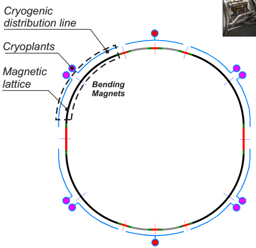


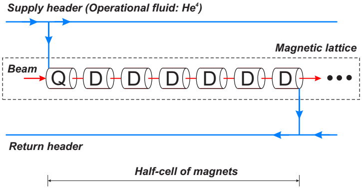




Preliminary FCC layout







Baseline parameters:

Sector:

- 8430 m
- 79 half-cells
- 23.600 tons (2.8tons/m)

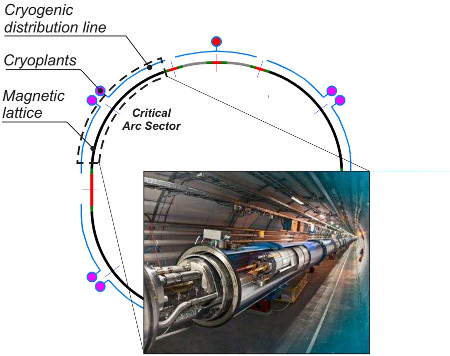
Cryoplants power:

- 2500 kW (300 - 80 K)
- 620 kW (80 - 40 K)
- 12 kW (40 - 4.5 K)

Motivation

Estimate and optimize:

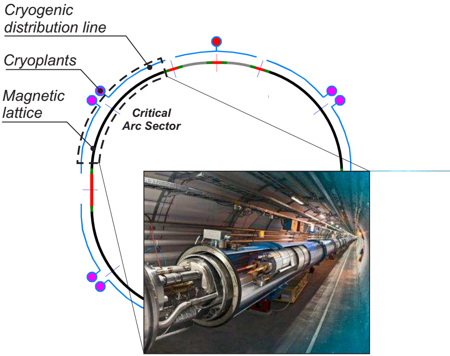
1. Cool-down timescales:
   - 300 to 80 K
   - 80 to 40 K
   - 40 to 4.5 K
2. Nitrogen consumption
3. Warm-up timescales



Motivation

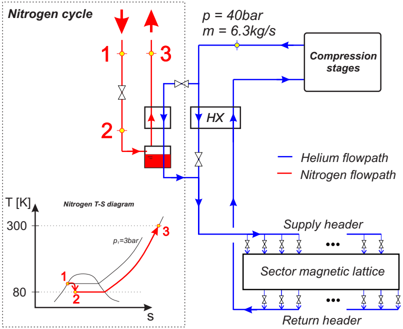
Estimate and optimize:

1. Cool-down timescales:
   - 300 to 80 K
   - 80 to 40 K
   - 40 to 4.5 K
2. Nitrogen consumption
3. Warm-up timescales



Mathematical modelling considerations:

N_2 refrigeration unit (300 - 80 K)



- **Maximum power:** 2500 kW
- **Cool-down rate constant over the sector length:**

$$\dot{m}_i = \dot{m}/N_{Cells}$$

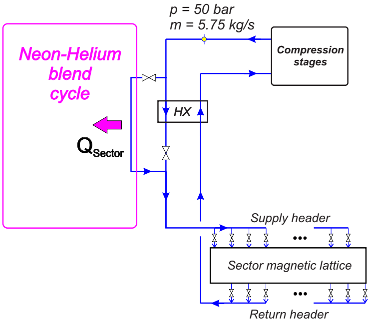
$$T^{Headers} = \text{Constant}$$

$$\text{(No heat-inleaks)}$$

$$\dot{Q}_i = \dot{Q}_{Sector}/N_{Cells}$$

Half-cell cool-down rate representative of the sector.

Ne-He[4] blend cryoplant (80 - 40 K)



- **Maximum power:**
  620 kW
- **Cool-down rate constant over the sector length:**

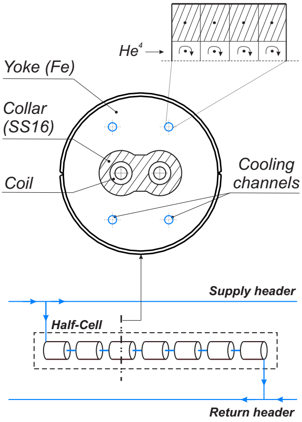
$$\dot{m}_i = \dot{m}/N_{Cells}$$

$$T^{Headers} = \text{Constant (No heat-inleaks)}$$

$$\dot{Q}_i = \dot{Q}_{Sector}/N_{Cells}$$

Half-cell cool-down rate representative of the sector.

Magnet design and half-cell layout



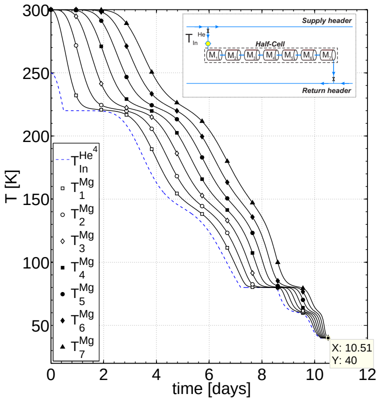
$$M \cdot c_p\,(T^M) \cdot \frac{\partial T^M}{\partial t} = -\alpha \cdot (T^M - T^{He})$$

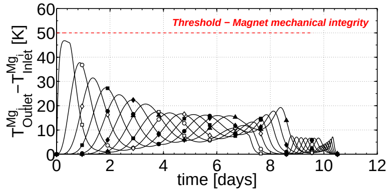
$$\underbrace{\frac{\partial h}{\partial t}}_{\mathcal{T}} + \underbrace{u\frac{\partial h}{\partial x}}_{\mathcal{P}} = \underbrace{\frac{1}{\rho A} \cdot \alpha \cdot (T^M - T^{He})}_{\mathcal{Q}}$$

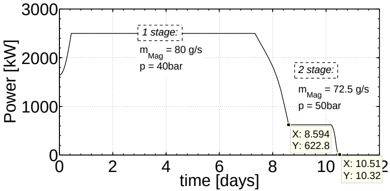
$\mathcal{T}$: Net rate of heat added to the fluid element
$\mathcal{P}$: Convective transport
$\mathcal{Q}$: Source term (heat exchange with the magnet)

- **Numerical method:** Finite-differences
- **Materials:** 70% Iron (Fe) and 30% Stainless steel 316 (SS16)
- **Maximum thermal gradient:** 50 K (over the magnet length)

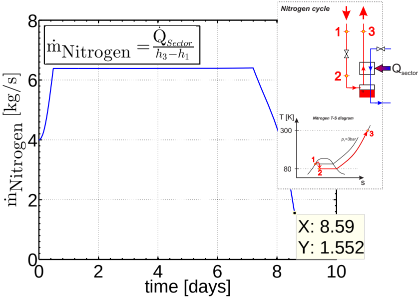
Results: Half-cell cooldown timescales (300 - 40 K)







Results: FCC N_2 consumption



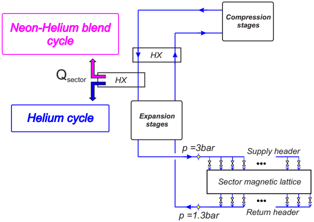
Key figures (10 sectors):

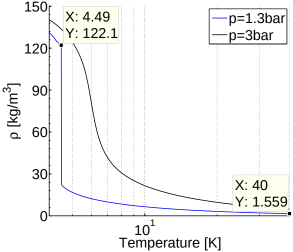
- 44.500 tons N_2
- 58.9 Million liters N_2 (equivalent to 5.7 globes)

Figure: The Globe of Science and Innovation (Geneva, Switzerland)

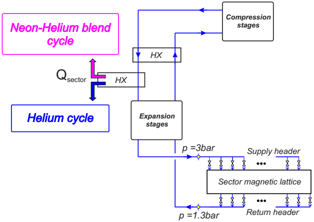
Mathematical modelling considerations:

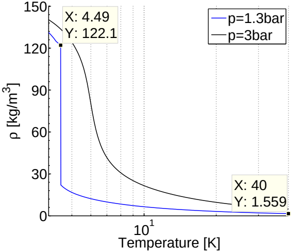
Ne-He^4 blend and He^4 cryoplants (40 - 4.5 K)





Ne-He^4 blend and He^4 cryoplants (40 - 4.5 K)





Lumped model:

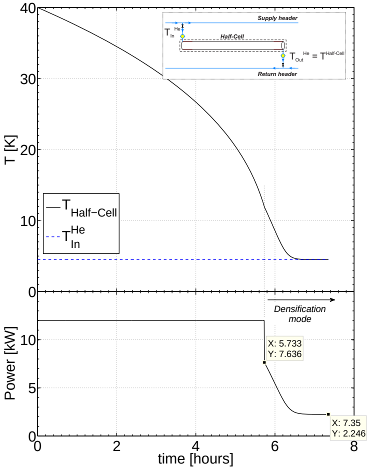
$$\underbrace{M \cdot c_p\left(T^M\right)}_{\mathcal{T}} \cdot \frac{\partial T^{HC}}{\partial t} = -\underbrace{\dot{Q}}_{\mathcal{Q}}$$

$\mathcal{T}$: Half-cell thermal inertia

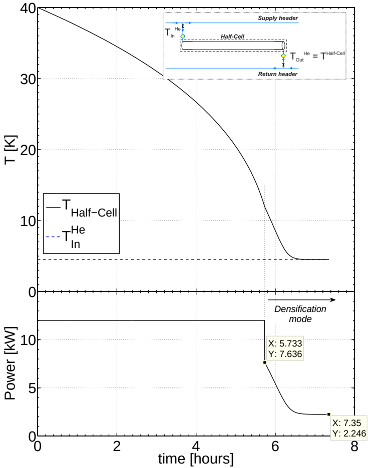
$\mathcal{Q}$: Cryoplant power

- $\dot{Q}_{T \geq 12K} = 12$ kW
- $\dot{Q}_{4.5 \leq T < 12K} = \frac{\dot{m}_{liq}}{h_3 - h_1}$

Results: Half-Cell cool-down timescales (40 - 4.5 K)



Results: Half-Cell cool-down timescales (40 - 4.5 K)



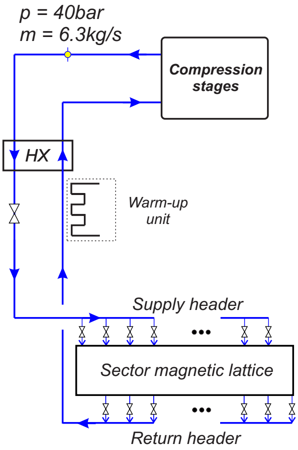
FCC sector filling:

- Magnet diameter: 800 mm
- Void fraction: 51.2 L/m
- $\dot{m}_{liq} = 120$ g/s

Filling time : 6.1 days

Mathematical modelling considerations:

Warm-up unit (4.5 - 300 K)



- **Maximum power:** 2500 kW
- **Warm-up rate constant over the sector length:**

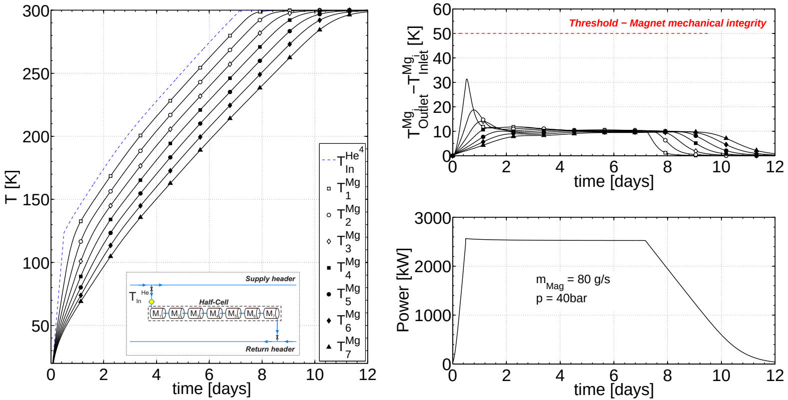
$$\dot{m}_i = \dot{m} / N_{Cells}$$

$$T^{Headers} = \text{Constant (No heat-inleaks)}$$

$$\dot{Q}_i = \dot{Q}_{Sector} / N_{Cells}$$

- **No liquid helium inside the magnets**

Results: Half-cell warm-up timescales (4.5 - 300 K)



- Cool-down and warm-up timescales are comparable to those of the Large Hadron Collider (LHC).

	FCC	**LHC**[1]
Cool-down:		
300 - 4.5 K	10.9 days	11.0 days
Warm-up:		
4.5 - 300 K	12.0 days	9.5 days
Sector filling:	6.1 days	2.0 days

[1] L. Liu et al. *Numerical analysis of cooldown and warmup for the Large Hadron Collider*. Cryogenics, Vol. 43-6, Pag. 359-367, 2003.

- Cool-down and warm-up timescales are comparable to those of the Large Hadron Collider (LHC).

	FCC	**LHC**[1]
Cool-down:		
300 - 4.5 K	10.9 days	11.0 days
Warm-up:		
4.5 - 300 K	12.0 days	9.5 days
Sector filling:	6.1 days	2.0 days

- The temperature gradients over the half-cell length comply with the established requirements ($\leq$ 50 K).

[1] L. Liu et al. *Numerical analysis of cooldown and warmup for the Large Hadron Collider*. Cryogenics, Vol. 43-6, Pag. 359-367, 2003.

- Cool-down and warm-up timescales are comparable to those of the Large Hadron Collider (LHC).

	FCC	LHC[1]
Cool-down:		
300 - 4.5 K	10.9 days	11.0 days
Warm-up:		
4.5 - 300 K	12.0 days	9.5 days
Sector filling:	6.1 days	2.0 days

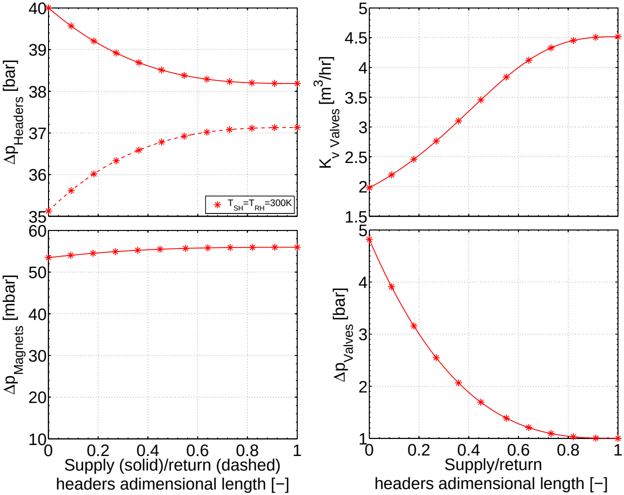
- The temperature gradients over the half-cell length comply with the established requirements (≤ 50 K).

- Nitrogen delivery by semi-trailers is not viable (12 trucks/hr).

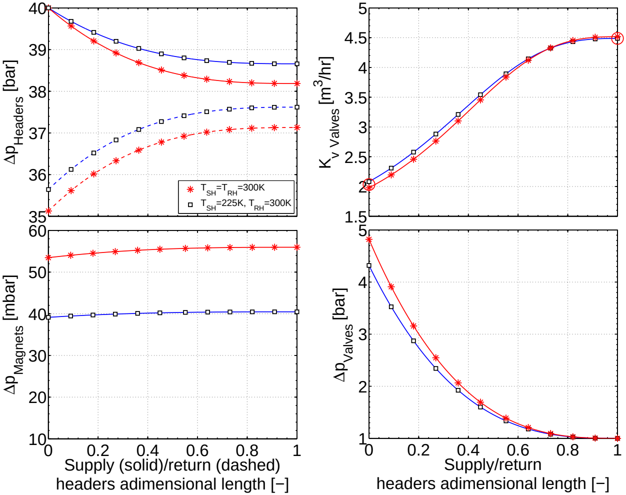
[1] L. Liu et al. *Numerical analysis of cooldown and warmup for the Large Hadron Collider*. Cryogenics, Vol. 43-6, Pag. 359-367, 2003.

Thank you for your attention.

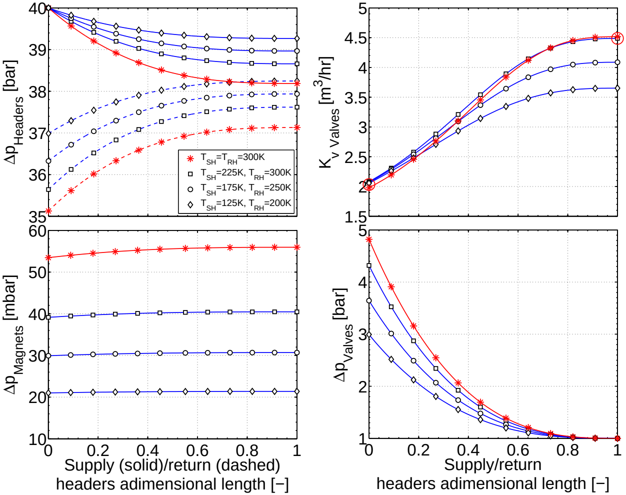
Results: $p_{discharge}$=40 bar, D=250 mm, m = 6.3kg/s



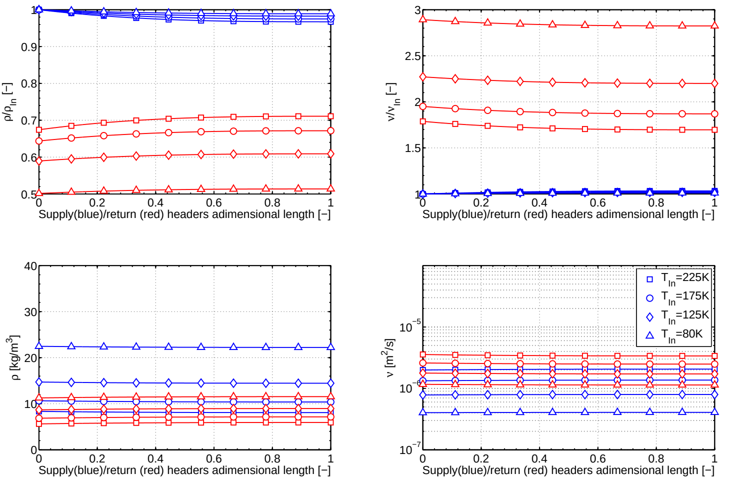
Results: $p_{\mathrm{discharge}}$=40 bar, D=250 mm, m = 6.3kg/s

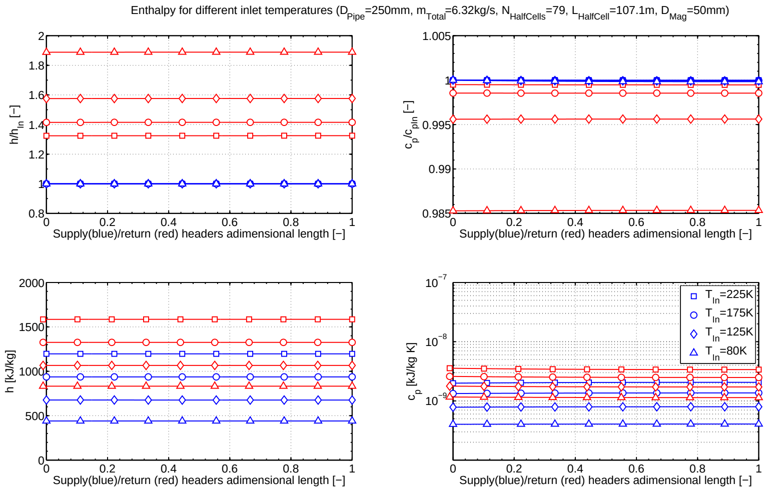


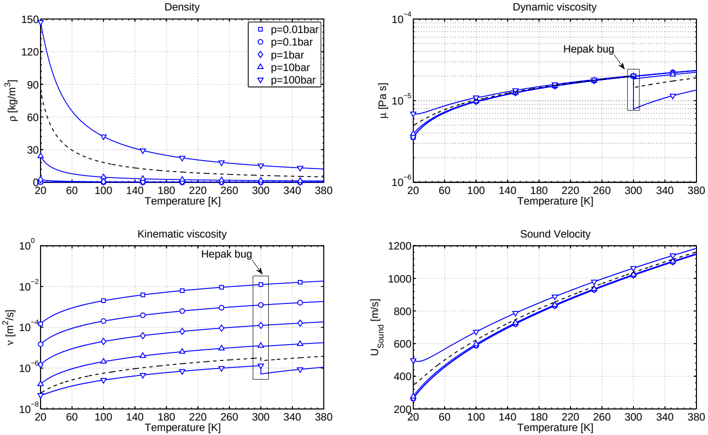
Results: $p_{discharge}$=40 bar, D=250 mm, m = 6.3kg/s



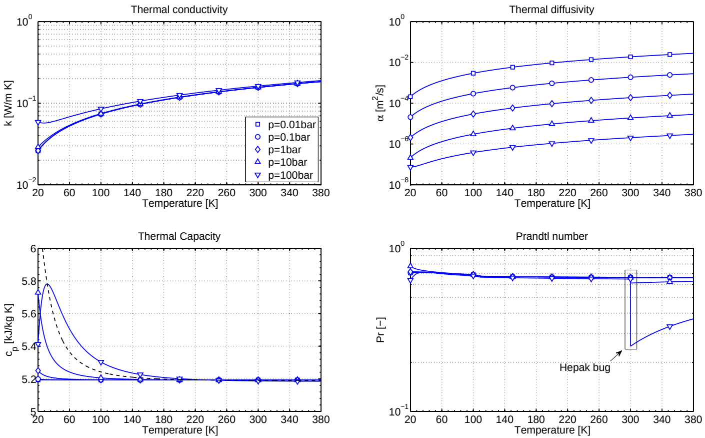
Density for different inlet temperatures (D_{Pipe}=250mm, m_{Total}=6.32kg/s, $N_{HalfCells}$=79, $L_{HalfCell}$=107.1m, D_{Mag}=50mm)



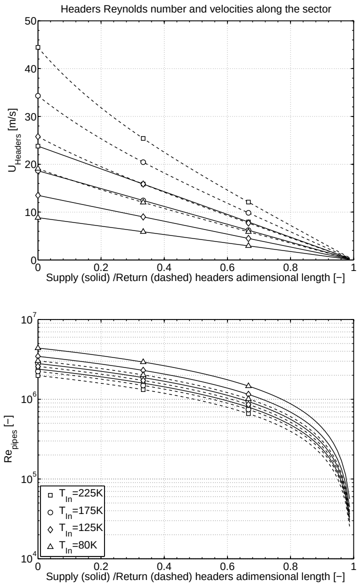

Enthalpy for different inlet temperatures (D_Pipe=250mm, m_Total=6.32kg/s, N_HalfCells=79, L_HalfCell=107.1m, D_Mag=50mm)
h/h_In [–]
c_p/c_pIn [–]
h [kJ/kg]
c_p [kJ/kg K]
Supply(blue)/return (red) headers adimensional length [–]
T_In=225K
T_In=175K
T_In=125K
T_In=80K
0
0.2
0.4
0.6
0.8
1
0.8
1.2
1.4
1.6
1.8
2
0.985
0.99
0.995
1.005
500
1000
1500
2000
10^−7
10^−8
10^−9



Density
p=0.01bar
p=0.1bar
p=1bar
p=10bar
p=100bar
ρ [kg/m3]
Temperature [K]
Dynamic viscosity
Hepak bug
μ [Pa s]
Temperature [K]
Kinematic viscosity
Hepak bug
ν [m2/s]
Temperature [K]
Sound Velocity
U_Sound [m/s]
Temperature [K]



Thermal conductivity
k [W/m K]
Temperature [K]
p=0.01bar
p=0.1bar
p=1bar
p=10bar
p=100bar
Thermal diffusivity
α [m^2/s]
Temperature [K]
Thermal Capacity
c_p [kJ/kg K]
Temperature [K]
Prandtl number
Pr [−]
Temperature [K]
Hepak bug



- Decrease of the Reynolds numbers along the return header. This effect yields a marginal impact on the Darcy factors (5%).
- Higher fluid velocities in the headers and, consequently, higher pressure drop.

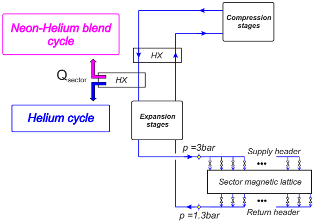
TABLE 1. Channel structures of Main Dipoles and Quadrupoles

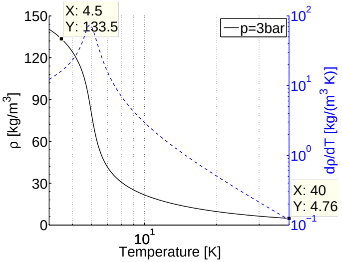
Channels	Main Dipole			Main Quadrupole		
	D_w [m]	A_f [m^2]	D_h [m]	D_w [m]	A_f [m^2]	D_h [m]
1	0.377	2.83×10^{-3}	3.00×10^{-2}	2.808	9.30×10^{-3}	1.32×10^{-2}
2	0.293	7.98×10^{-4}	1.09×10^{-2}	2.288	3.30×10^{-3}	5.80×10^{-3}
3	0.248	5.65×10^{-4}	9.10×10^{-3}	0.372	5.73×10^{-4}	6.20×10^{-3}
4	0.274	5.33×10^{-4}	7.80×10^{-3}	0.685	5.14×10^{-4}	3.00×10^{-3}
5	0.259	4.22×10^{-4}	6.50×10^{-3}	0.371	1.85×10^{-4}	2.00×10^{-3}
6	0.168	2.68×10^{-4}	6.40×10^{-3}	0.096	4.00×10^{-5}	1.70×10^{-3}
7	0.355	3.74×10^{-4}	4.20×10^{-3}	--------	--------	--------
8	0.372	5.73×10^{-4}	6.20×10^{-3}	--------	--------	--------
9	0.694	5.16×10^{-4}	3.00×10^{-3}	--------	--------	--------
10	0.382	3.07×10^{-4}	3.20×10^{-3}	--------	--------	--------
11	0.341	3.04×10^{-5}	4.00×10^{-4}	--------	--------	--------

TABLE 2. Mass of Materials of a Main Dipole and Quadrupole

Magnets	Mass of Materials [kg/m]					
	Iron	Copper	Nb-Ti	Teflon	Glass	St. Steel
Dipole	1.18×10^{3}	8.11×10^{1}	1.95×10^{1}	1.78×10^{1}	6.87	5.90×10^{2}
Quadrupole	7.79×10^{2}	6.27×10^{1}	2.52×10^{1}	5.06×10^{1}	9.18	4.40×10^{2}

Ne-He^4 blend and He^4 refrigeration units (40 - 4.5 K):





Lumped model:

$$\underbrace{M \cdot c_p \cdot \frac{\partial T^{HC}}{\partial t}}_{\mathcal{T}} = -\underbrace{\dot{m}^{He} \cdot \left(h^{He}_{Out} - h^{He}_{In}\right)}_{\mathcal{Q}}$$

$\mathcal{T}$: Half-cell thermal inertia
$\mathcal{Q}$: Net rate of heat extracted by the helium

- $T^{He}_{Out} \approx T^{HC}$
- $\delta\rho^{Headers} \leq 2.7\ \mathrm{kg/m^3}$
- Phase-change neglected

Results: Half-Cell cooldown timescales (40 - 4.5 K)