LhARA Capture Meeting

Preliminary analytical model for the LhARA solenoids

16th June 2022

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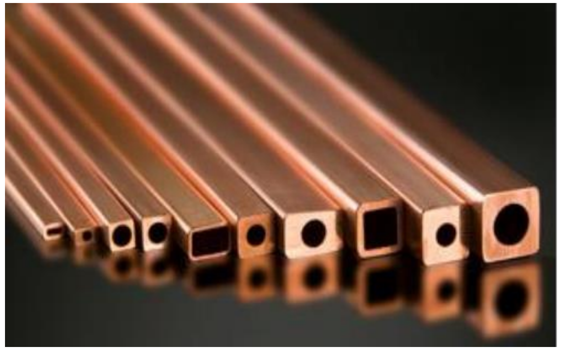
Solenoid requirements

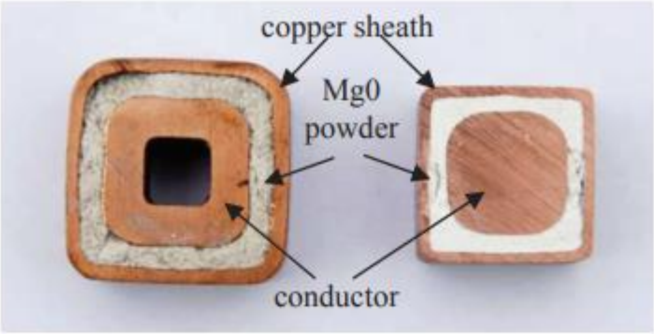
- 1.3 T, 1 m long coil
  - $\int Bdz \leq 1.233\ \mathrm{Tm}$ (1.2 T, 1.05 m as alternative)
- Vacuum bore ID: 60 mm
  - Limited for the 1^{st} solenoid due to the close proximity to the target
- Coil inner radius: 38 mm

- Relatively large number of turns (e.g 4140 for 250 A)
  - Choose water-cooled hollow conductors (oxygen-free copper) to allow for higher current density $j > 3$ A/mm^2

  - Insulation: polyimide resin + boron free glass tape (up to 1 MGy)

  - Alternative cable:
    - mineral-insulation (MgO) magnet cables, for radiation hard magnets (up to 100 MGy)
    - extensive use at PSI, JHF/J-PARC; solid/hollow conductor, nominal current up to ~ 2500 A, outward size 14-28 mm
    - direct/indirect cooling





1^{st} design iteration

Table 1: Summary specifications of the solenoid (see Section 1)

Parameter	**Value**	**Units**
Maximum field strength	1.3	T
Coil length	1036	mm
Coil thickness	196	mm
Maximum coil current	250	A
Total number of turns	4144	
Number of layers	28	
Vacuum bore ID	$60^*, 80^{**}$	mm
Coil inner radius	$38^*, 48^{**}$	mm
Current density	6	A/mm^2
Hollow-conductor size	7×7	mm^2
Conductor inner hole diameter	3	mm
Winding bed thickness	2	mm

* first solenoid in the capture section

** rest of the solenoids

1^{st} design iteration

Table 2: Other parameters of interest (see Section 2)

Parameter	**Value***	**Value****	**Units**
Coil length	3450	3710	m
Total cable mass	1293	1391	kg
Electric resistance	1.41	1.52	Ω
Power dissipated	88.2	94.9	kW
Total water flow rate	0.848	0.848	$\mathrm{L\,min^{-1}}$
Water velocity	2	2	m/s
Temperature increment†	53	57	°C
Reynolds number	1.2×10^4		
Pressure drop	–	–	L/s

* first solenoid in the capture section

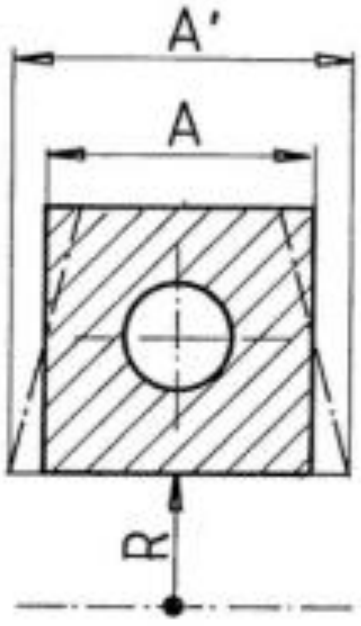
** rest of the solenoids

† if each layer is cooled by a separate cooling circuit

- Relatively large number of turns ⟹ large length of the cooling circuit ⟹ large temperature increment & number of cooling circuits

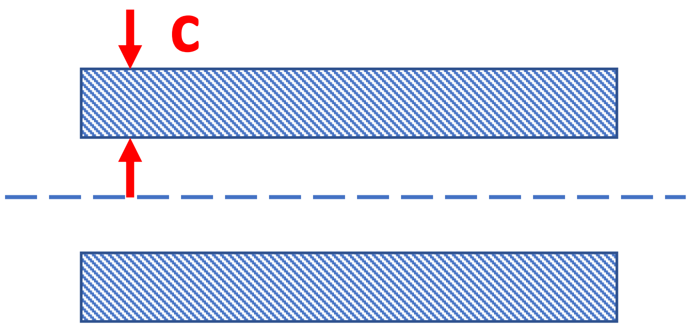
Keystone effect – an issue (?)

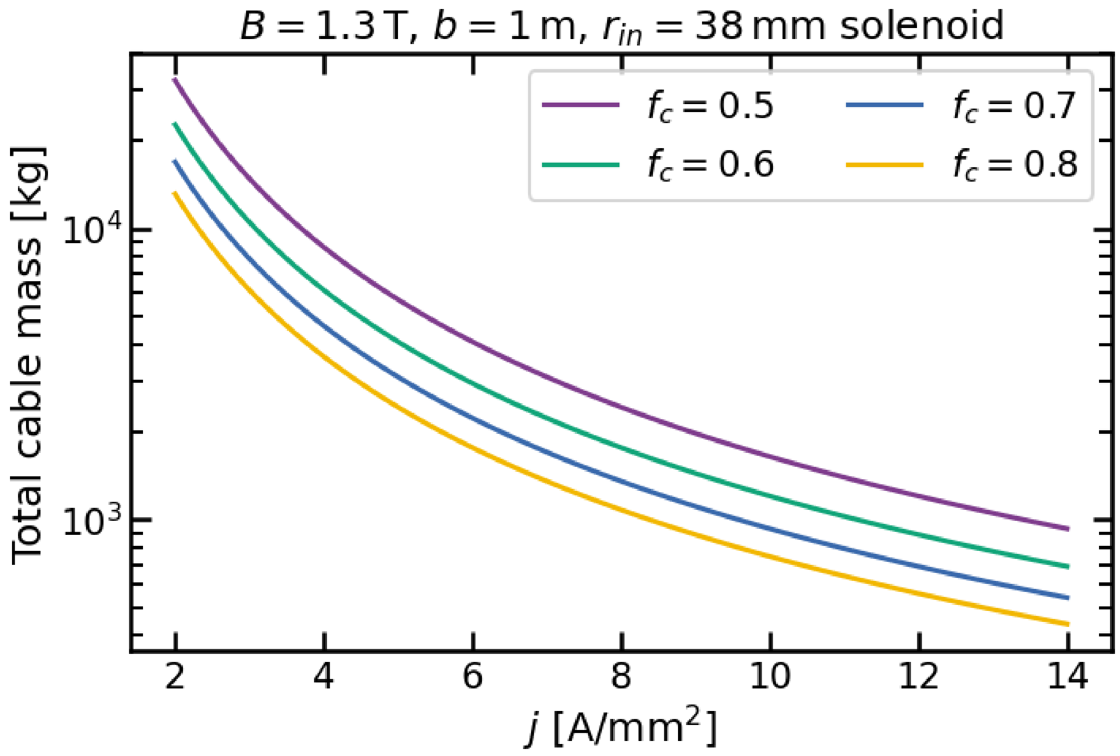
- Rule of thumb: choose a bending radius four times larger than the conductor width
  - for an inner coil radius ~ 4 cm, cable width limited to ~ 1 cm

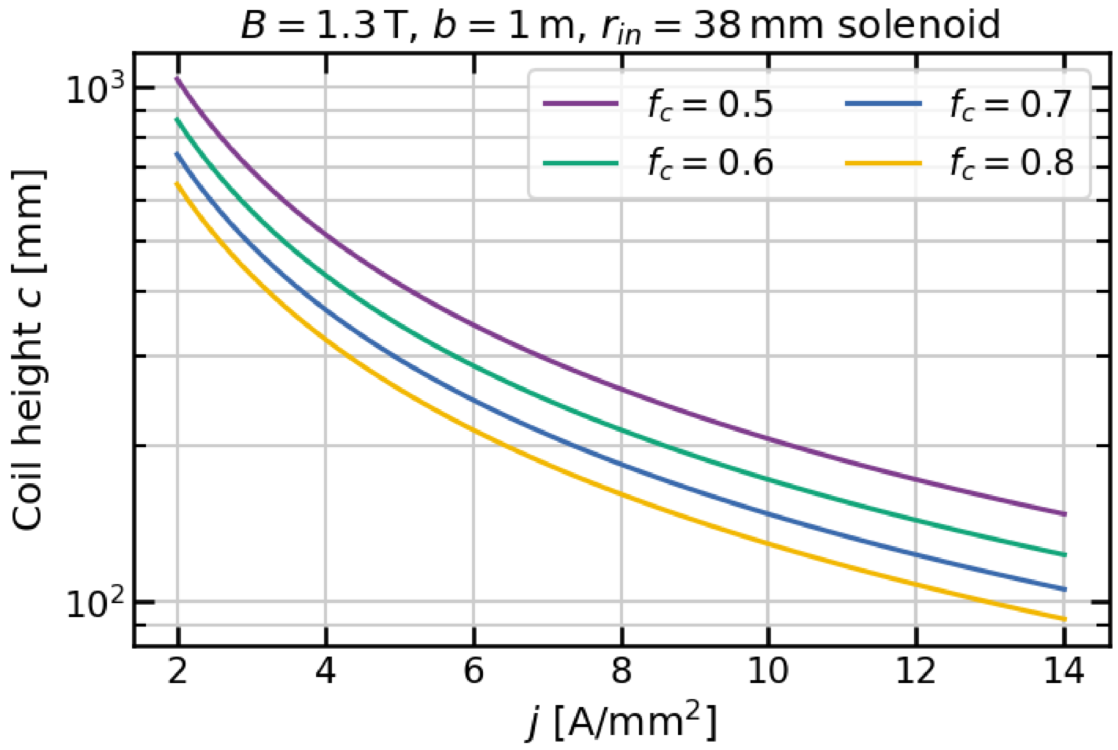


Scaling studies: magnet size

- Filling factor $f_c = \frac{\text{net conductor area}}{\text{coil cross section}}$ (typically $0.6 \leq f_c \leq 0.8$)







Space constraints for the 1st solenoid in the beamline

CERN Summer Student Programme 2021 Report

Supervisors: Kenneth Long, Colin Whyte, Josef Boehm

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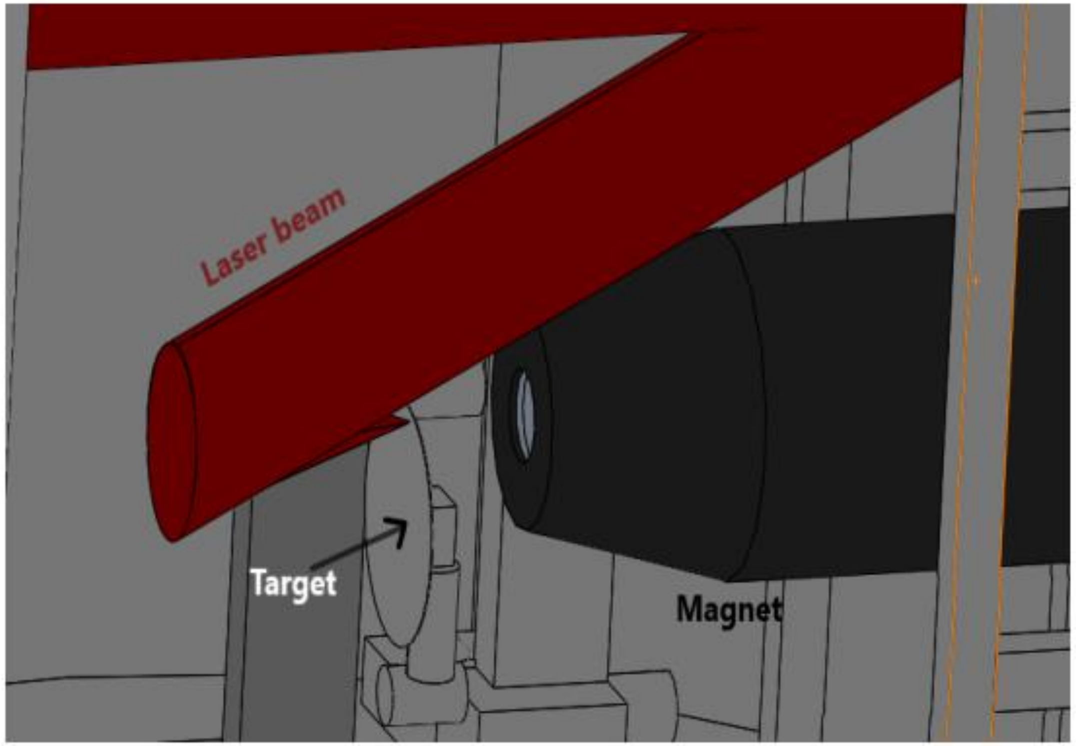
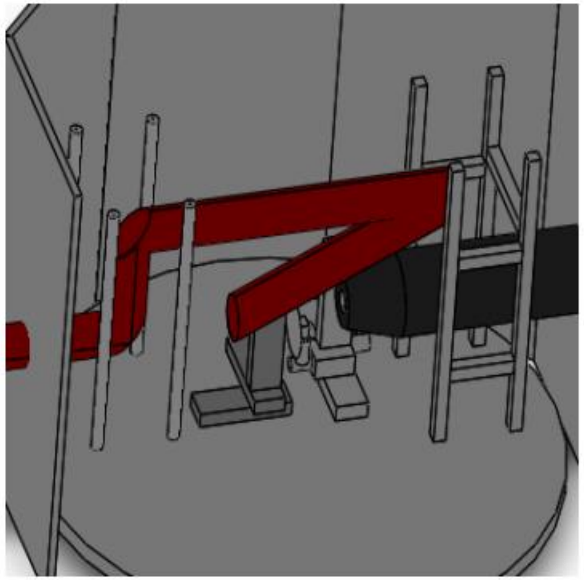
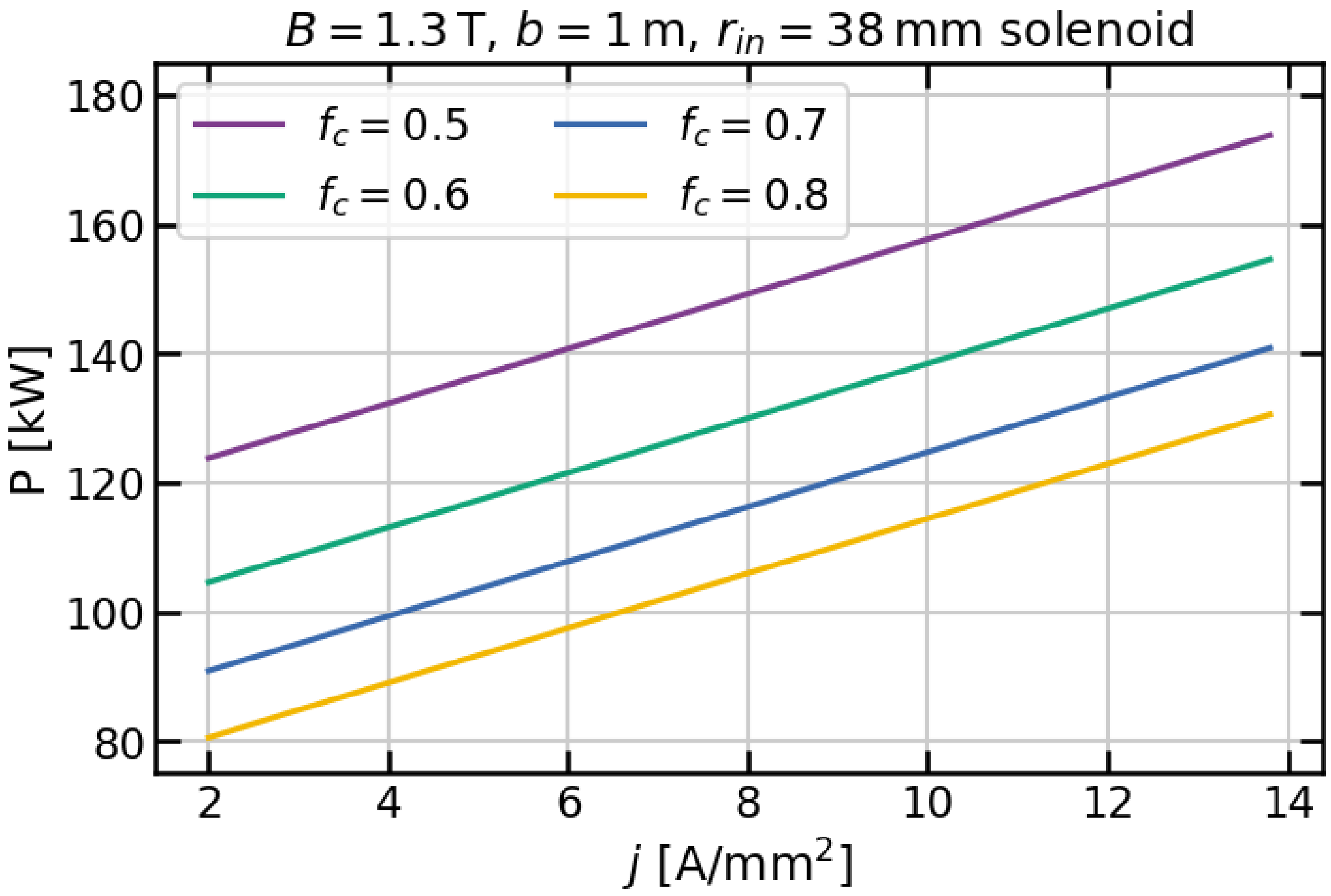


Figure 2 – Minimum distance between the magnet and the target



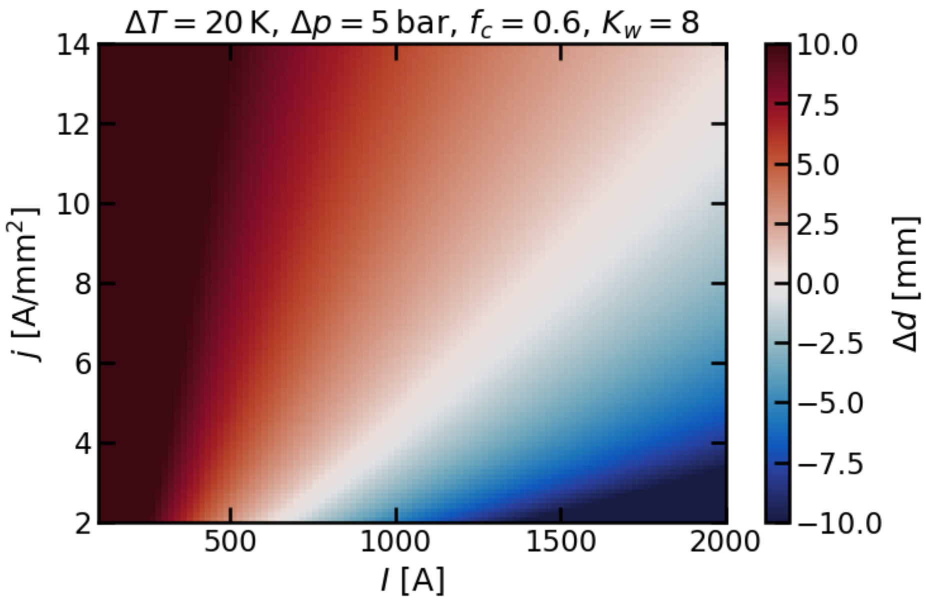
- Solenoid OD < 150 mm
  - For magnet entrance to be placed 150 mm from target

Scaling studies: power

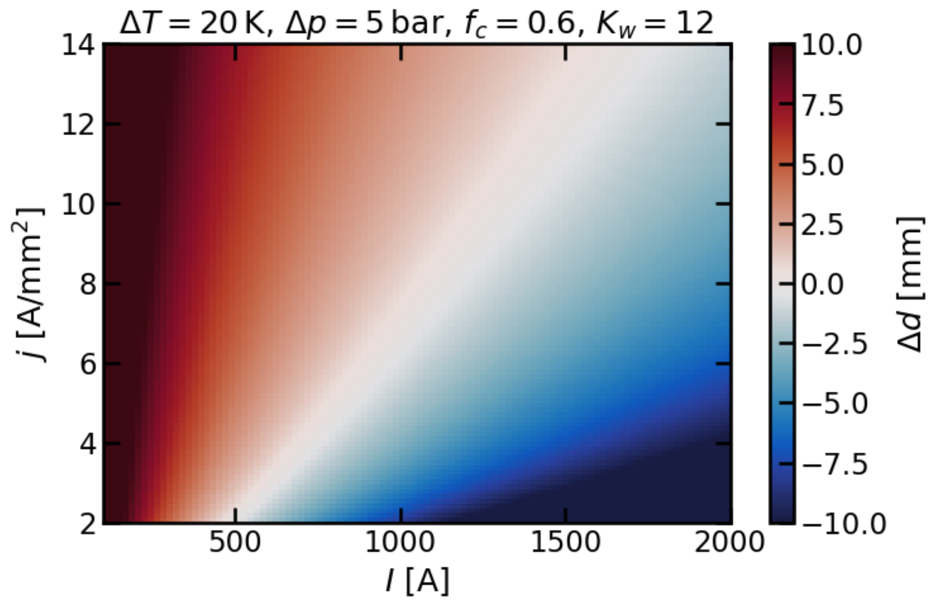


Cooling requirements

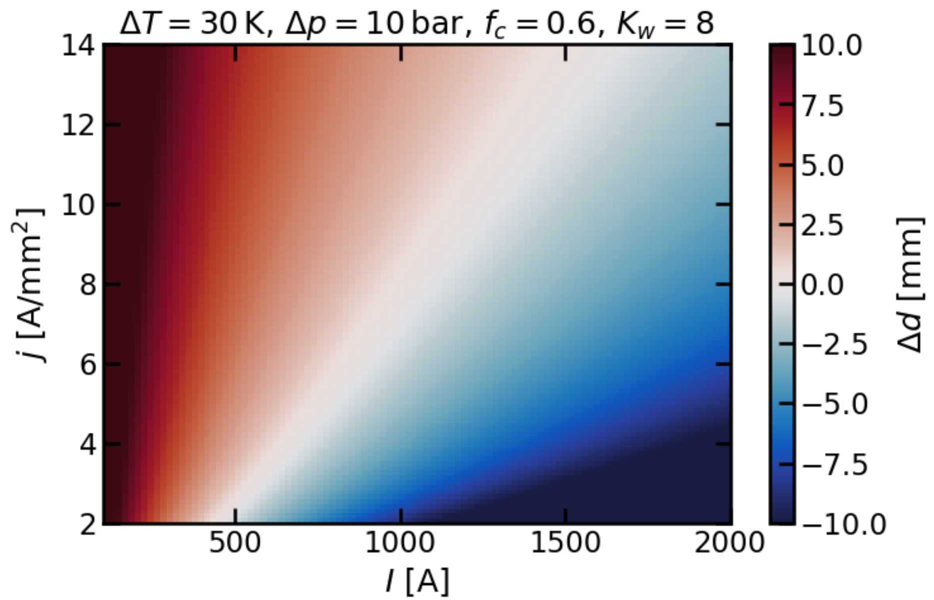
- Good practice: less than 60℃ on coil surfaces (maximum $\Delta T \approx 30$℃)
- Modern cooling plants: 1 bar < Δp < 10 bar
- Number of cooling circuits: K_w



Higher K_w

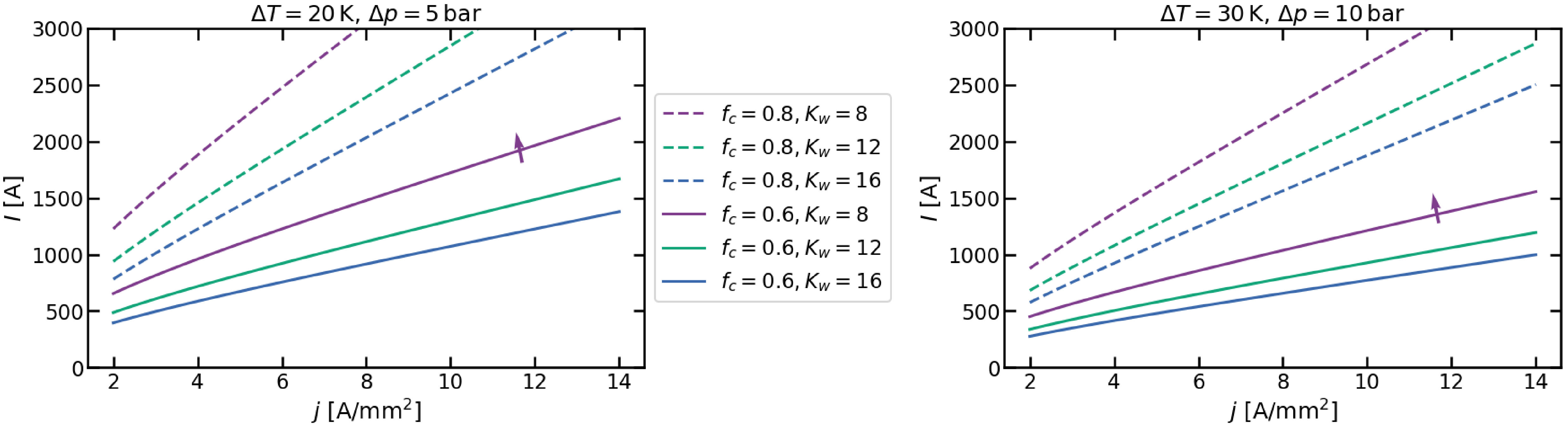


Higher $\Delta T, \Delta p$



Cooling requirements

- Keeping the water temperature down constraints the area needed for the cooling pipe
  - For fixed j, f_c the constraint propagates into the current which must be chosen on/above the lines plotted below

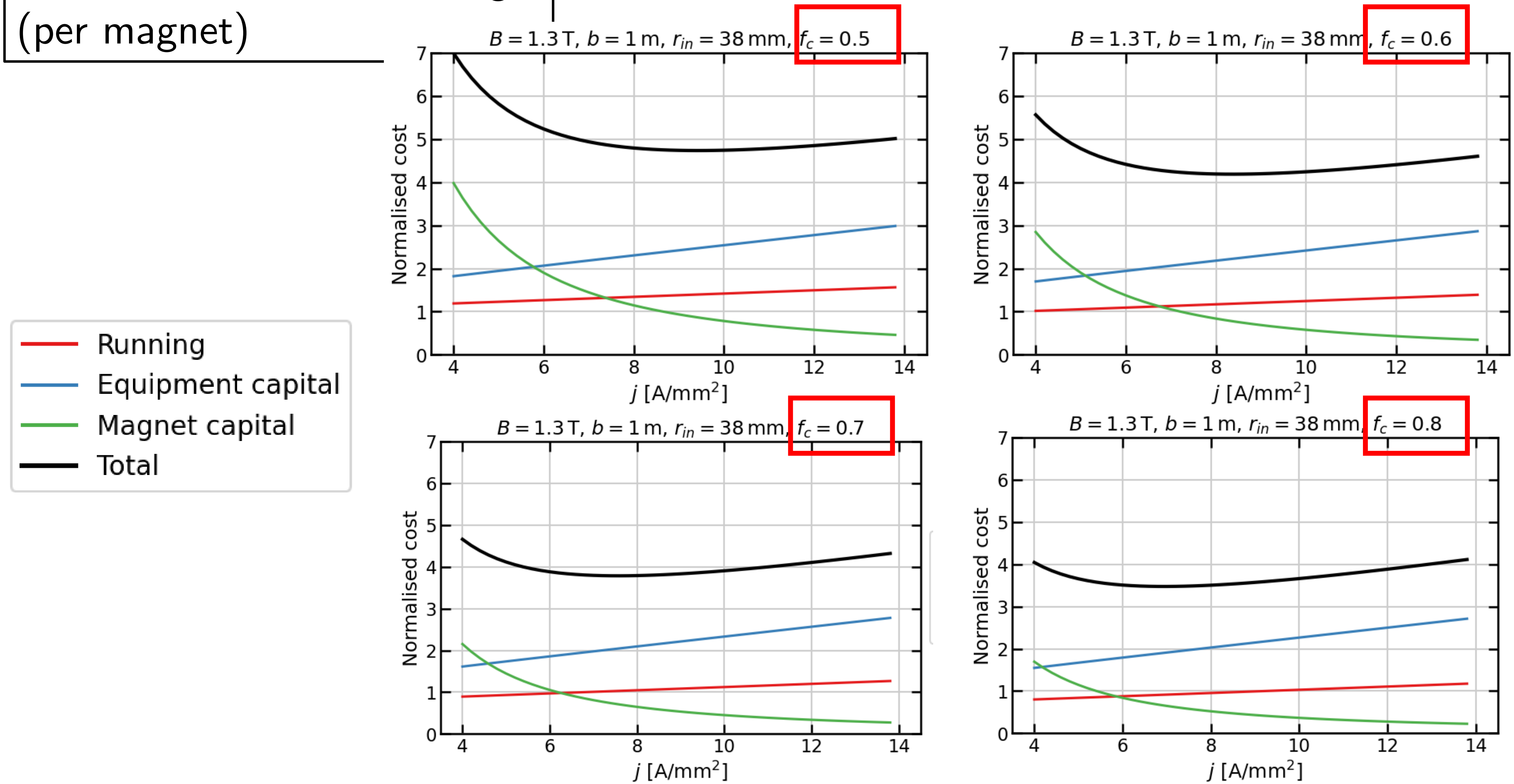


Estimate of the cost scaling

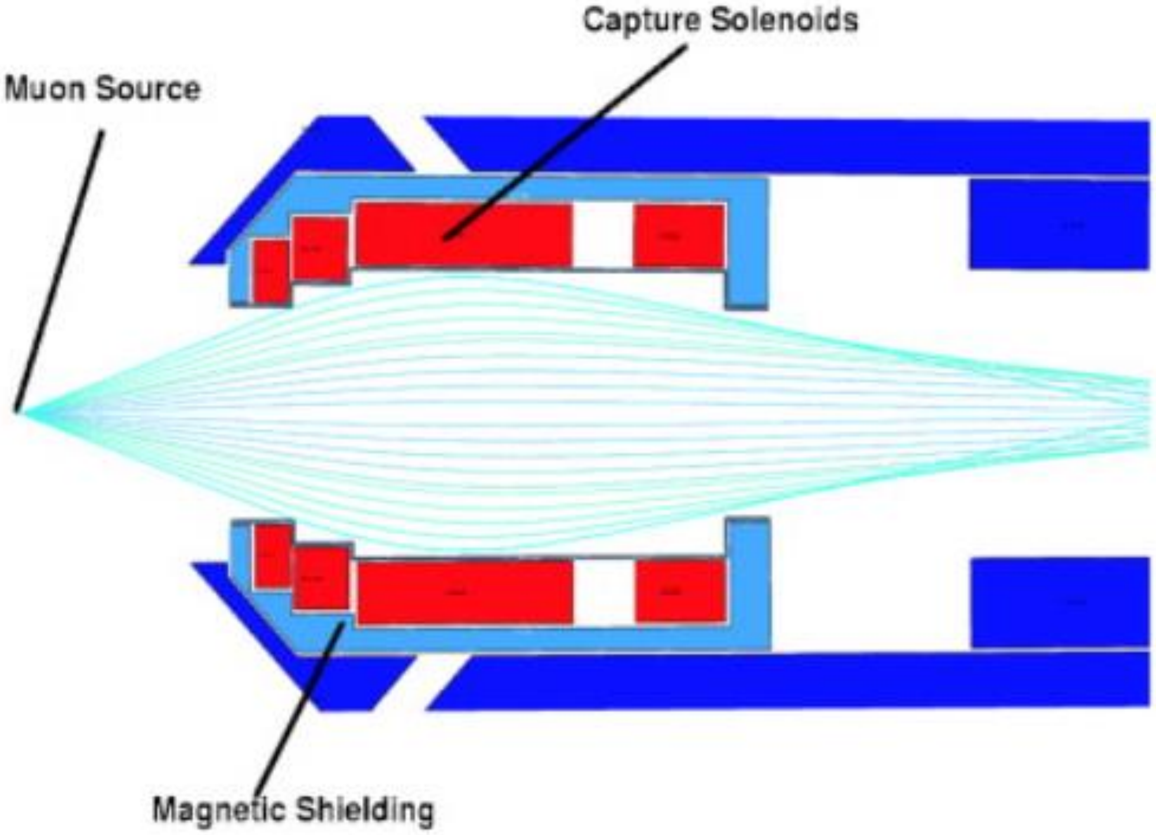
- Cost scaling based on a procedure from:
  - *G. Brianti and M. Gabriel, Basic expressions for evaluating iron core magnets – A possible procedure to minimize their cost, CERN/SI/Int. DL/70-10 (1970).*
  - $+$ a few modifications to account for the increase in the power supply with the current
    - Assumption: the cost doubles when going from 250A to 1000A

- 60,000 hours of running (~ 15 years of 12 hours/day)
- Iron return yoke/cover included
- One power supply per magnet
- Equipment cost includes
  - Cost of power supply
  - Cost of d.c. power distribution
  - Cost of cooling
- Absolute cost is not specified (only the approximate relations between various cost components)

Estimate of the cost scaling (per magnet)



- Possible configuration near the target



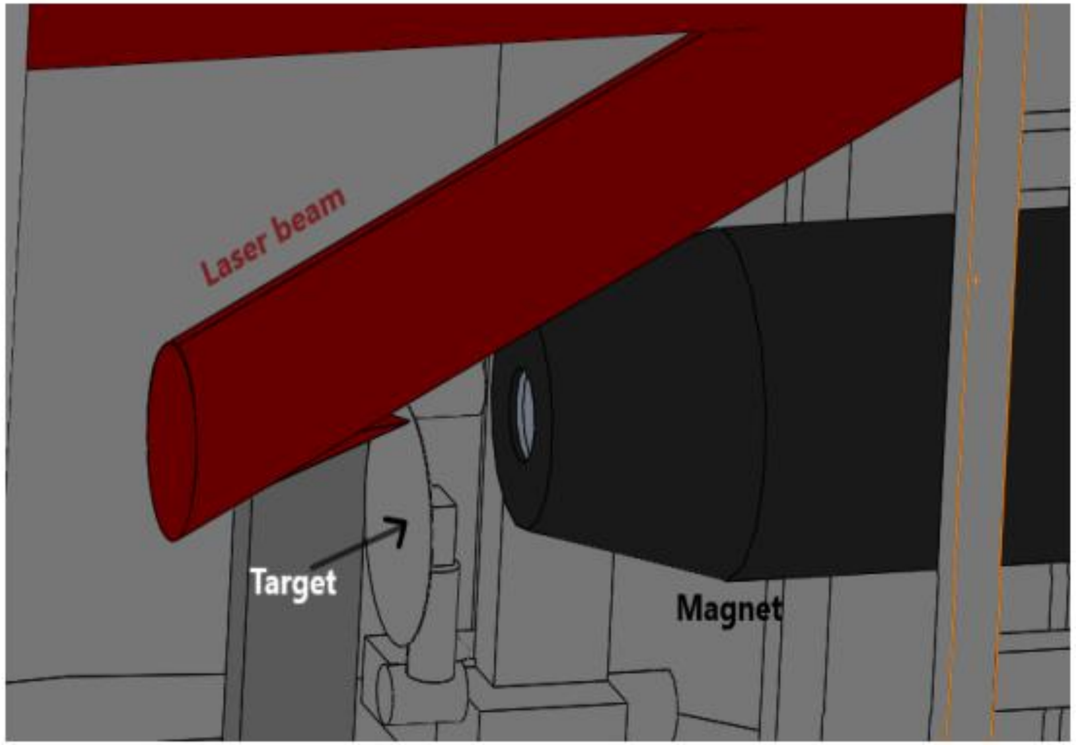


Figure 2 – Minimum distance between the magnet and the target