EPFL

Quench protection of EDIPO 2 using LEDET

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SWISS PLASMA CENTER

Outline

- EDIPO2
- Simulation of two-stage cables with LEDET
- Quench protection of EDIPO2
- Conclusions

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EDIPO 2

- EDIPO is a test facility. Usual samples:
  - High-current **forced flow superconductors for fusion magnets**
  - **Accelerator insert coils**
- The facility operated until 2016, when its magnet assembly (12.35 T dipole) was irreversibly damaged
- **The rest of the EDIPO infrastructure remains intact**:
  - Cryoplant
  - Magnet power supply
  - Superconducting transformer (~sample power supply)
  - Vacuum vessel
- EDIPO 2 will be the upgraded test facility. Main targets:
  - **15 T** in a **large aperture**
  - Operation at **4.2 K** and **85%** of **short sample limit**
  - Homogeneous field length (1%) of 1000 mm
  - **Wide range of temperature**: T_{sample} = 4.2 - 80 K
  - **High-current**: $I_{sample} \leq 100$ kA

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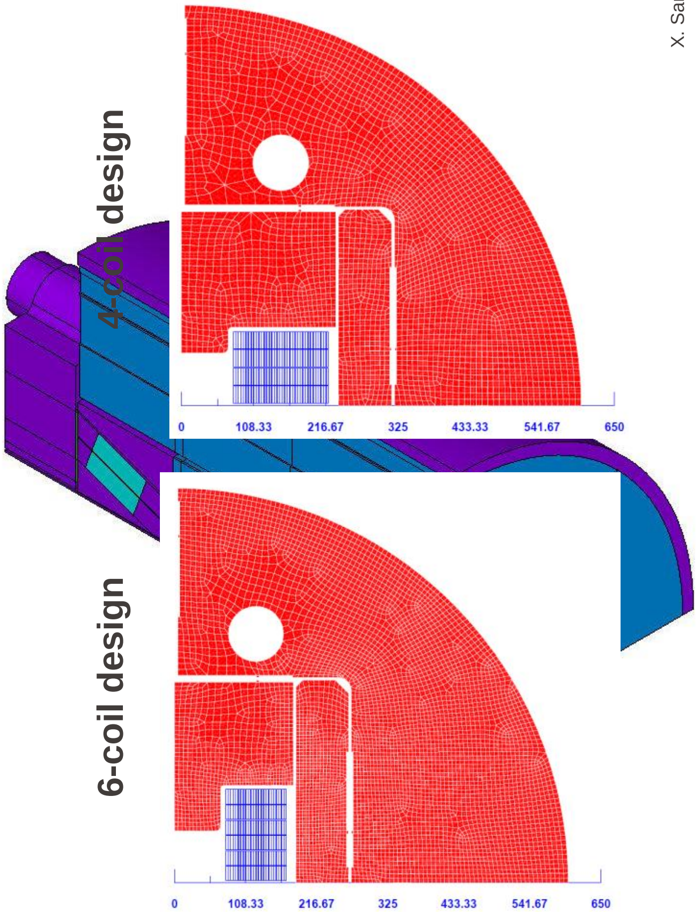
EDIPO 2: Magnet design

- Unlike accelerator magnets, the **field quality** of the generated background field is **not a crucial design target** in a test facility
- Magnet design:
  - **Flared-end block coil** design
  - **Shell-based** mechanical structure:
    - Outer **shell** made of **steel**
    - **Adjustable pre-compression**
    - Use of **detachable winding poles**
  - If **pre-compression** is kept at a **minimum level**, during operation:
    - A gap opens between the test well and the coils
    - The test well is stress-free
- **4 and 6-coil designs are considered** (windings aligned in low and high field side)



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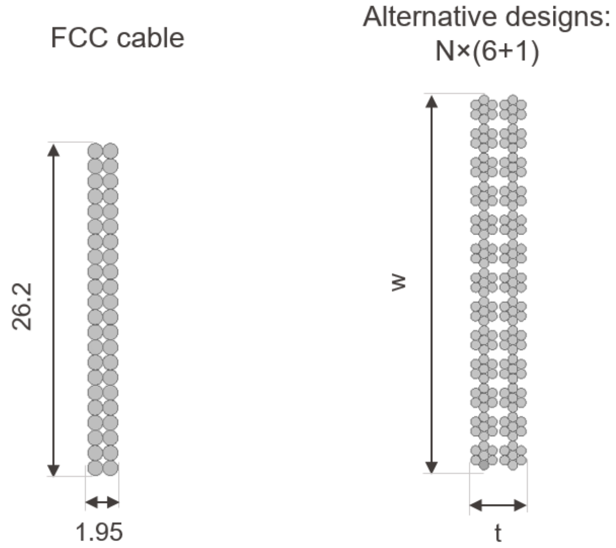
Cable design

- Rutherford cable considered until 2020 (44×1.1 mm FCC strands):
  - I_{op} limited to ~10.6 kA
  - One of the largest aspect ratio Rutherford cables ever built (quite stiff)
- A two-stage cable layout can operate at a current closer to 18 kA and might result in a more flexible design.



Cable alternatives

		Strand diam. (mm)	Cu:nCu	Cable layout	# strands	Cable width (mm)	Cable thick. (mm)	Void fraction (%)
4-coil layouts	FCC cable	1.1	1.0	Rutherford	44	26.2	1.95	16%
	Alternative 1	0.8	1.0	20×(6+1)	140	22.8	3.98	20%
	Alternative 2	0.7	1.0	26×(6+1)	182	25.9	3.48	20%
	Alternative 3	0.65	1.0	28×(6+1)	196	25.9	3.23	20%
	Alternative 4	0.6	1.0	32×(6+1)	224	27.4	2.98	20%
6-coil layouts	Alternative 5	0.9	1.0	14×(6+1)	98	18.0	4.47	20%
	Alternative 6	0.8	1.0	16×(6+1)	112	18.2	3.98	20%
	Alternative 7.A	0.7	1.0	20×(6+1)	140	20.0	3.48	20%
	Alternative 7.B	0.7	1.0	22×(6+1)	154	21.9	3.48	20%
	Alternative 8.A	0.6	1.0	26×(6+1)	182	22.2	2.98	20%
	Alternative 8.B	0.6	1.0	28×(6+1)	196	23.9	2.98	20%

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Simulation of two-stage cables in LEDET

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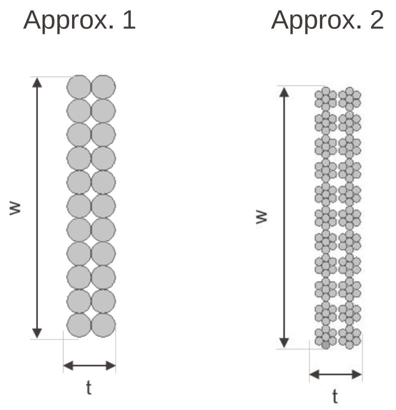
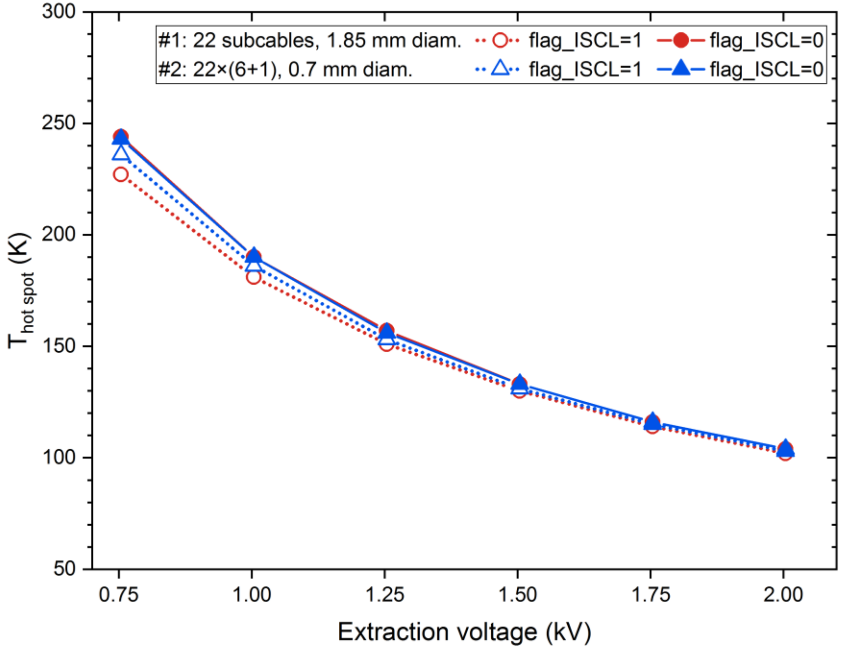
- Two approaches were used:
  1. Simulation of 22 sub-cables of equivalent cross-section (1.85 mm diameter)
  2. Simulation of the actual cable: 22×(6+1) 0.7 mm diam. The magnetic field had to be interpolated at the center of each of the 154 strands.
- Inter-strand coupling losses (ISCL) in two stage cables are not precisely simulated
- The additional resolution (and computation time) didn't change the results





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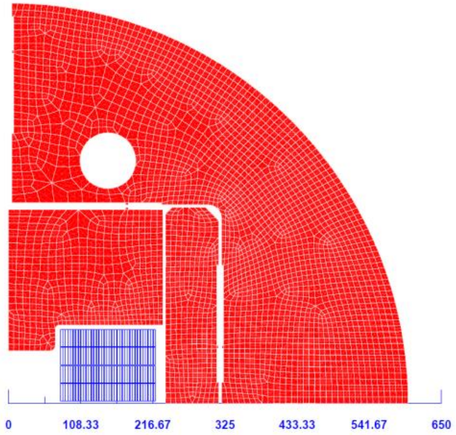
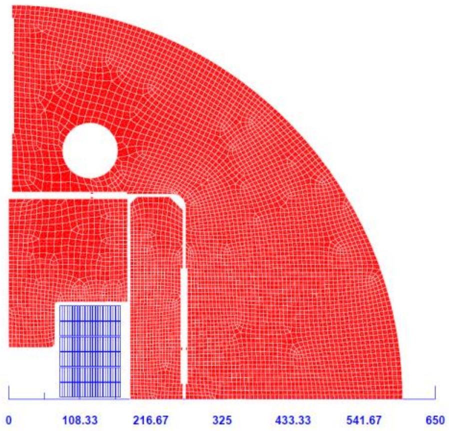
EDIPO 2: Alternative designs analyzed with LEDET

	4 coils	6 coils	Units
Strand diameter	0.7	0.7	mm
Cable layout	26×(6+1)	22×(6+1)	
Operating current, I_{op} (85%*I_{ss})	17.51	17.73	kA
B field in the aperture center, B_{center}	15.00	15.02	T
Peak field in the winding pack, B_{peak}	16.21	15.74	T
Number of turns per pancake, $n_{turns,pan}$	37	24	
Total number of turns, $n_{turns,total}$	296	288	
Total ampere-turns, I_{total}	5.18	5.11	MAt
Total stored energy in the magnet, E_{total}	7.51	6.50	MJ/m
Magnet self inductance, L	49.0	41.4	mH/m
Current density insulated conductor, j_{eng}	171.4	204.9	A/mm^2
Copper current density, j_{Cu}	500.0	598.3	A/mm^2
Lorentz stress in the coils, $\sigma_{Lorentz\ coils}$	130	111	MPa

4-coil design



6-coil design



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Assumptions

- Simulations performed with STEAM-LEDET [1], [2] (v1.08.03)
- 2D model
- Energy extraction protection scheme:
  - Quench detection + validation time: 15 ms
  - Energy extraction triggering time: 1 ms
- Cu:nCu: 1.0
- Inter-strand coupling losses in a two stage cable are not precisely simulated in LEDET and they are “turned-off” (flag_ISCL = 0)

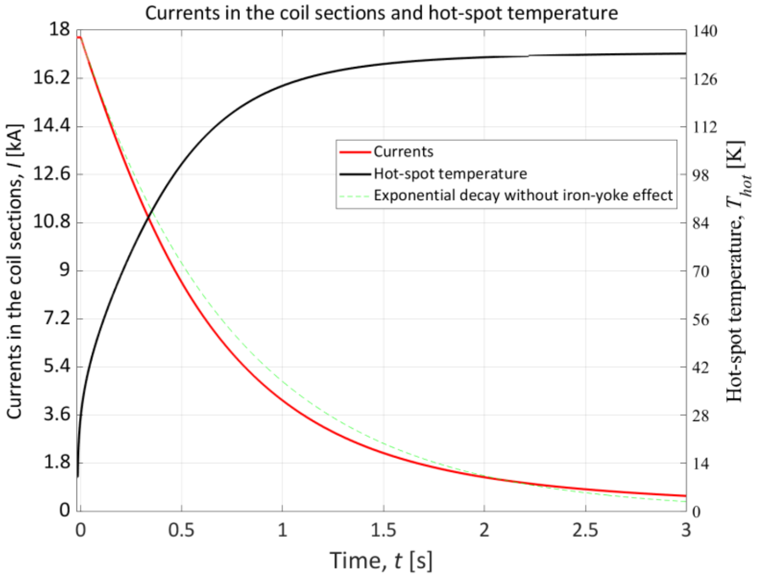
	Nominal	Parametric variation
RRR	100	100 - 300
Filament twist-pitch	14 mm	10 - 30 mm
Effective transverse resistivity factor	1	0.5 - 2

[1] E. Ravaioli, “CLIQ”, PhD thesis, 2015
[2] E. Ravaioli et al., Cryogenics 2016 https://cern.ch/steam/LEDET/

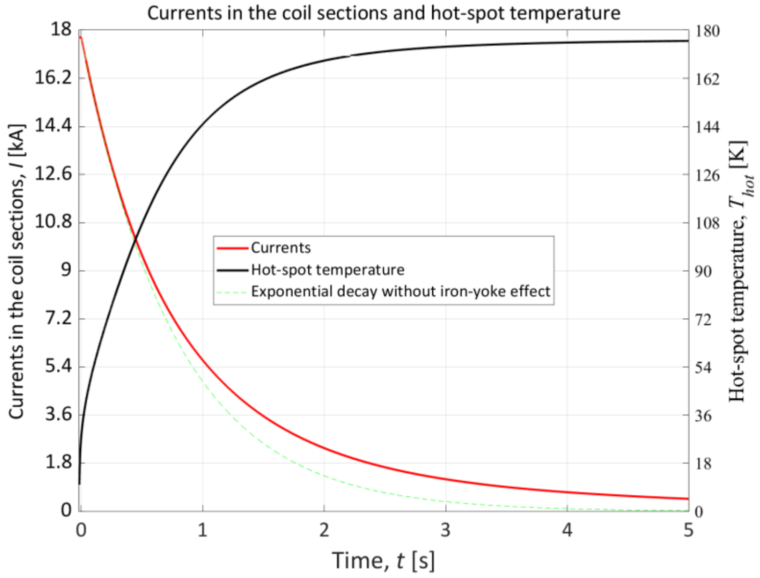
Discharge with V_{ext} = 1.5 kV (V_{ground} = ±0.75 kV)

- R_{dump} = 84.4 mΩ
- Adiabatic hot-spot temperature:
  - Including IFCC: 133 K
  - No IFCC: 176 K

Including contribution of IFCC



No contribution of IFCC



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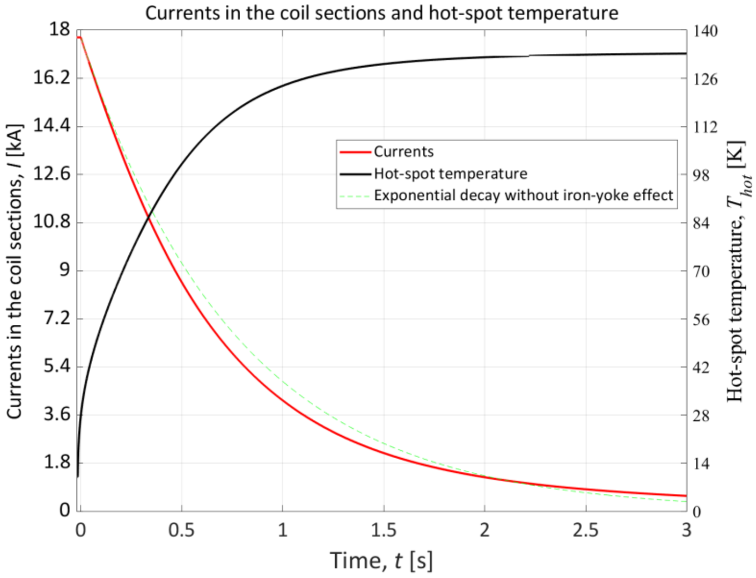

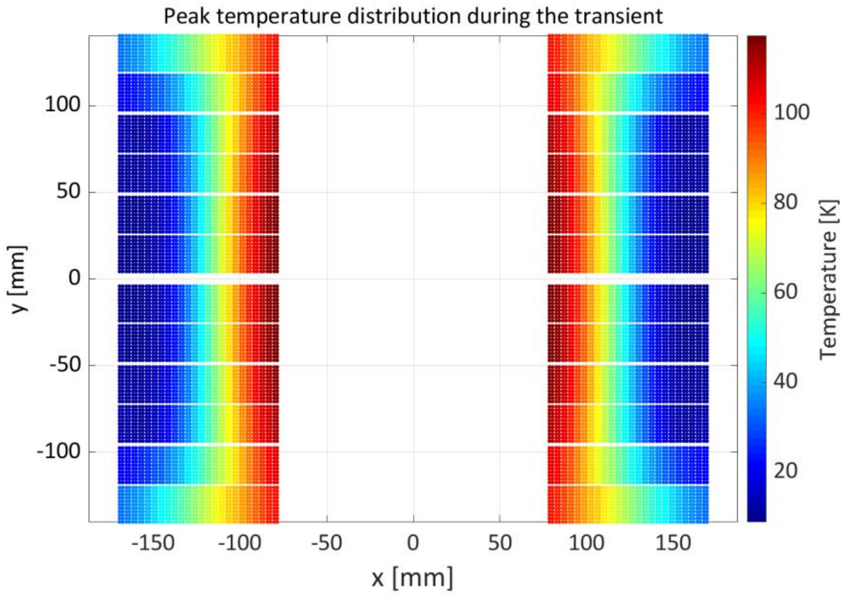

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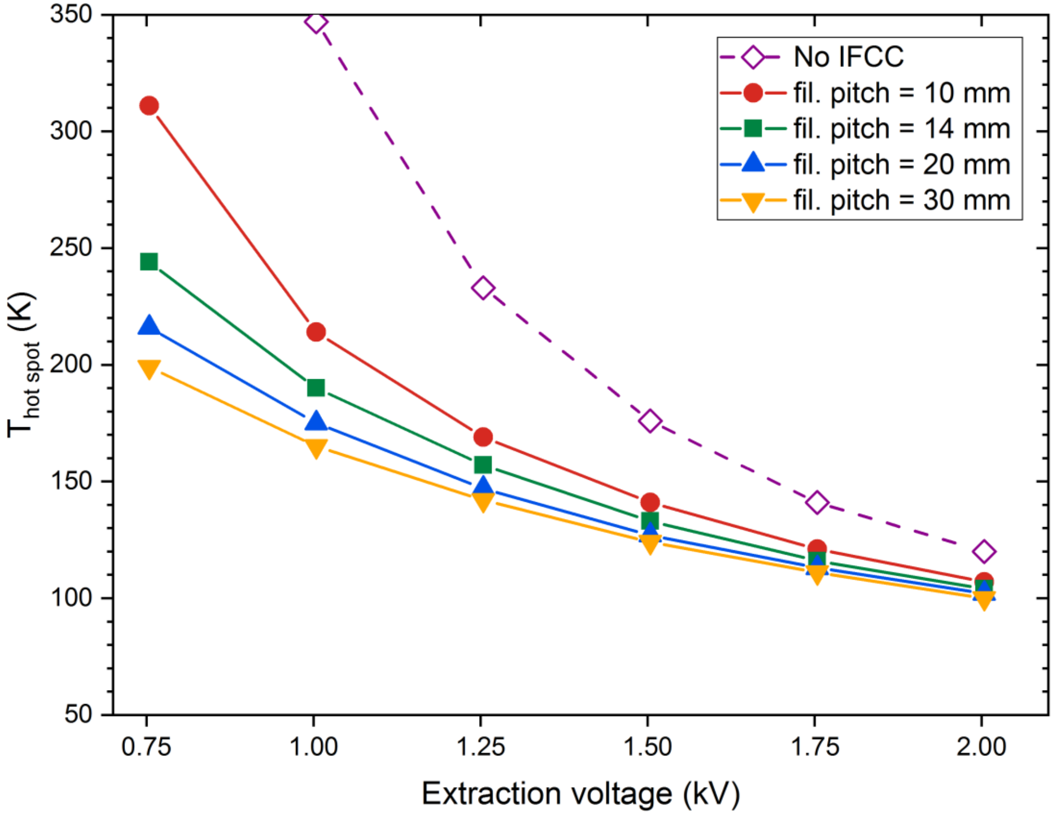
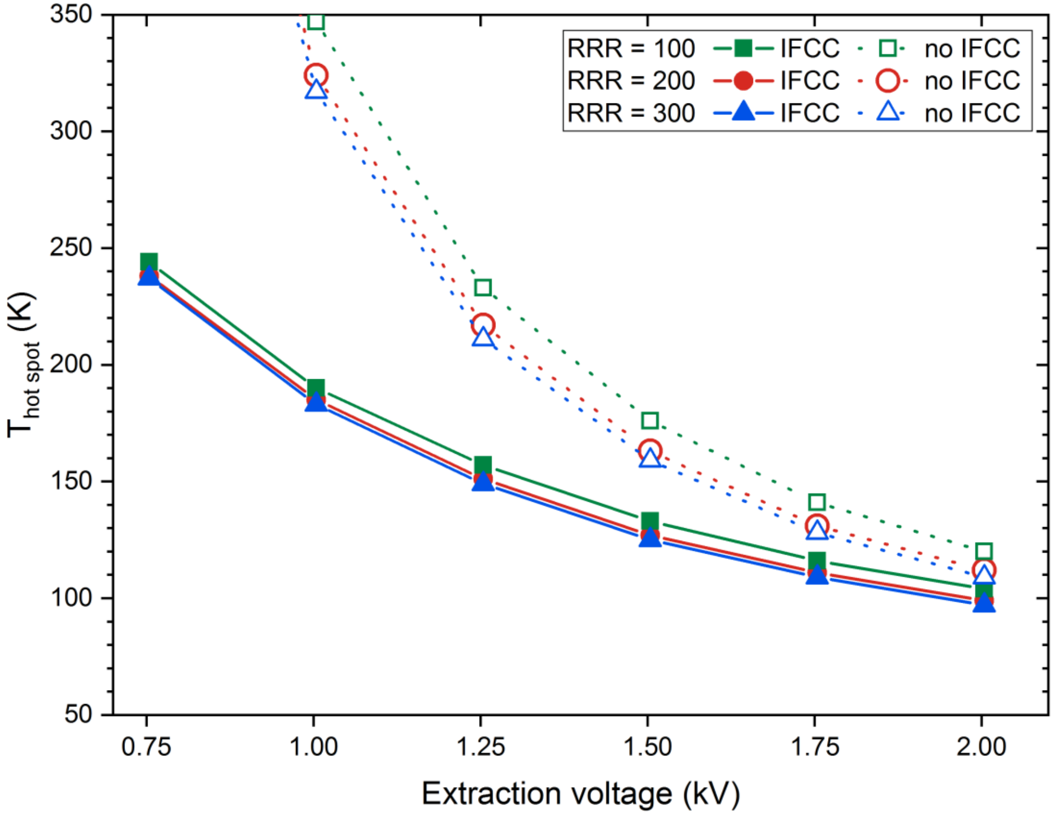
Parametric analysis: filament twist pitch

- 6 coils, RRR = 100, ρ_{eff} = 1, flag_ISCL = 0



Parametric analysis: RRR

- 6 coils, fil. pitch = 14 mm, ρ_{eff} = 1, flag_ISCL = 0



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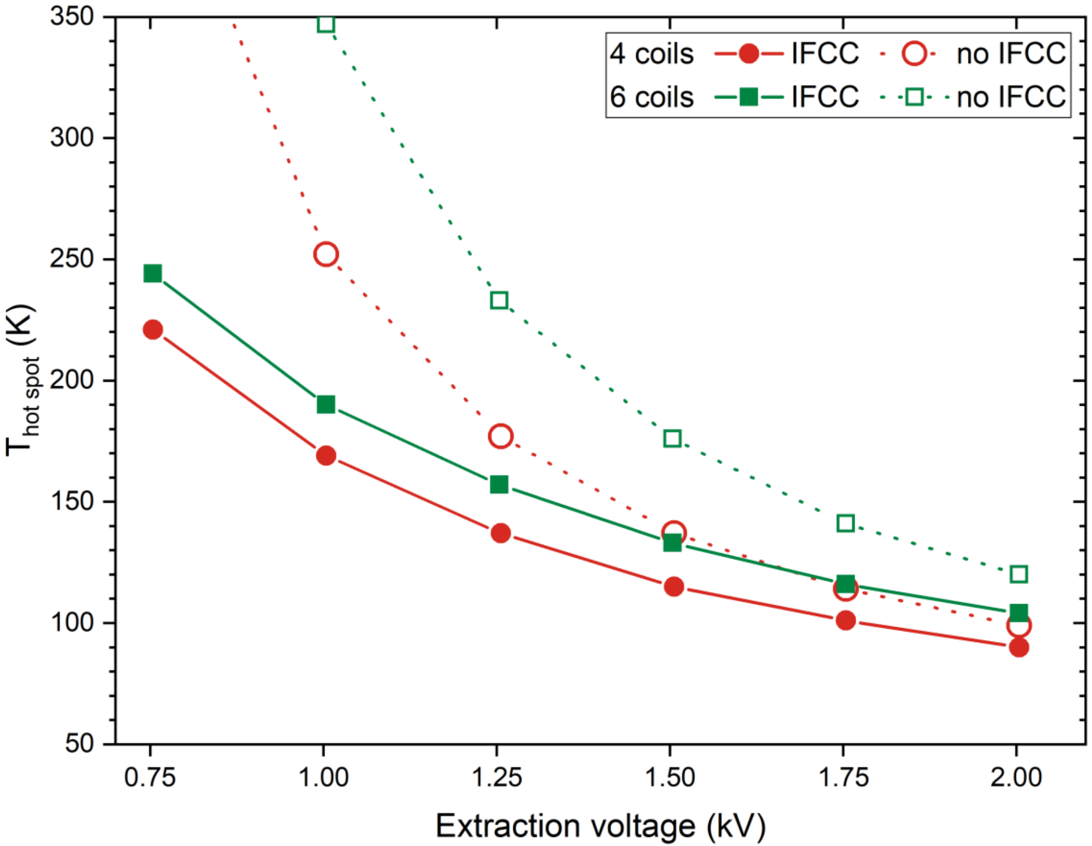
Hot spot temperature: 4 coils vs 6 coils designs

- Fil. pitch = 14 mm, ρ_{eff} = 1, RRR = 100, flag_ISCL = 0



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Conclusions

- We are developing a new magnet design for EDIPO 2
- It relies on a flared-end block coil design, but it includes some innovative features:
  - Use of a two-stage cable layout
  - Minimal pre-compression applied to the coils
- Quench protection of the EDIPO2 magnet was studied using STEAM-LEDET:
  - Simulation of two-stage cables successfully done using sub-cables of equivalent cross-section
  - The filament twist pitch is the key parameter in the hot spot simulations
  - A protection scheme based on energy extraction should work (even without interfilametary coupling currents)