Progress on the design of 15 T magnet of the EDIPO test facility

X. Sarasola, **P. Bruzzone, R. Guarino, K. Sedlak and E. Solodko**

École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-5232 Villigen, Switzerland

Abstract

- The magnet assembly of EDIPO was irreversibly damaged in 2016.
- However, the cryostat, cryo-plant, power supply and high current transformer of the test facility remain intact.
- **EDIPO 2** (the upgraded EDIPO test facility) will provide a unique test bed for superconducting cables for fusion and accelerator magnets, as well as, other applications.
- **Enhanced features** compared to previous magnet design:

	EDIPO 1	EDIPO 2
$B_{center\ aperture}$	12.35 T	15 T
Aperture size	90×141 mm²	144×144 mm²
Homogeneous field length (1%)	680 mm	1000 mm

SULTAN samples + insert dipoles

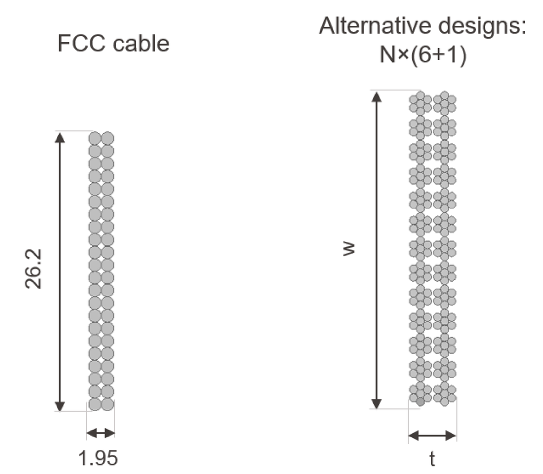
- **Retained key features:**
  - **Wide range of sample temperature**: T_{sample} = 4.2 - 80 K.
  - **High sample current**: I_{sample} ≤ 100 kA.

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)
- An **alternative cable design** operating at **higher current** will allow us to:
  - **Reduce the maximum voltage** (V_{max}) during an emergency discharge of the magnet:

$$V_{max} = L\frac{dI_{op}}{dt} = \frac{2E}{I_{op}\tau}$$

  - Make a better use of the **existing 18 kA power supply**
- The proposed designs are **two-stage flat** cables, based on a **6+1** layout, which might also result in a **more mechanically flexible** design.



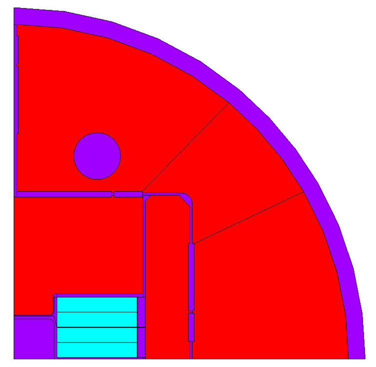
	Strand diam. (mm)	Cu:nCu	Cable layout	# strands	Cable width (mm)	Cable thick. (mm)	Void fraction (%)
FCC cable	1.1	1.0	Rutherford	44	26.2	1.95	16%
4-coil alt.	0.7	1.0	26×(6+1)	182	25.9	3.48	20%
6-coil alt.	0.7	1.0	22×(6+1)	154	21.9	3.48	20%

2D magnet design

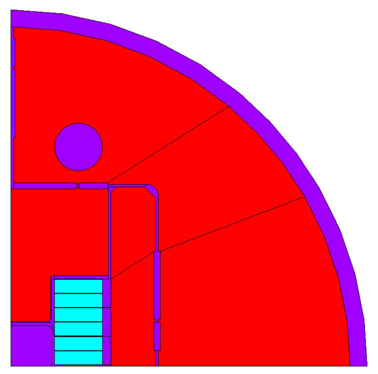
- Unlike accelerator magnets, the **field quality** of the generated background field is **not a crucial design target** in a test facility.
- 2D magnet design:
  - **Shell-based** mechanical structure:
    - Outer **shell** made of steel
    - **Adjustable pre-compression**
    - Use of **detachable winding poles**
  - If **pre-compression** is kept at a **minimum level**, during operation:
    - A ~1.5-mm 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)
- Assumptions:
  - $j_{c,nc}$ = 3093 A/mm² @ 12 T, 4.2 K
  - 15 T reached in the bore center operating at 85% of short sample
- **2D magnetic finite element analyses:**

	4-coil (FCC cable)	4-coil design	6-coil design	Units
Strand diameter	1.1	0.7	0.7	mm
Cable layout	Rutherford	26×(6+1)	22×(6+1)	
Area of insulated conductor, A_{cond}	30504	30251	24919	mm²
Operating current, I_{op} (85%*I_{ss})	10.64	17.51	17.73	kA
B field in the aperture center, B_{center}	14.99	15.00	15.02	T
Peak field in the winding pack, B_{peak}	16.17	16.21	15.74	T
Number of turns per pancake, $n_{turns,pan}$	61	37	24	
Total number of turns, $n_{turns,total}$	488	296	288	
Total ampere-turns, I_{total}	5.19	5.18	5.11	MAt
Total stored energy in the magnet, E_{total}	7.51	7.51	6.50	MJ/m
Magnet self inductance, L	132.6	49.0	41.4	mH/m
Current density insulated conductor, j_{eng}	170.3	171.4	204.9	A/mm²
Copper current density, j_{Cu}	509.1	500.0	598.3	A/mm²
Lorentz stress in the coils, $\sigma_{Lorentz\ coils}$	129	130	111	MPa

4-coil design

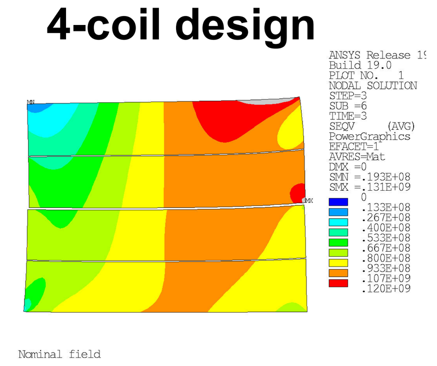


6-coil design

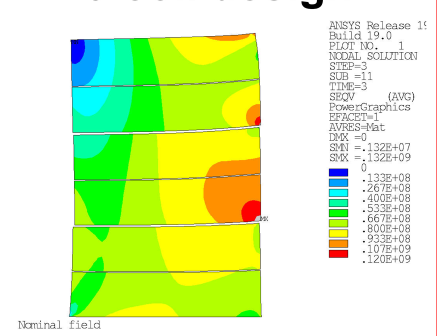


- **2D mechanical finite element analyses:**
  - The stress in the coils is below 130 MPa
  - Also below allowable limits in other components

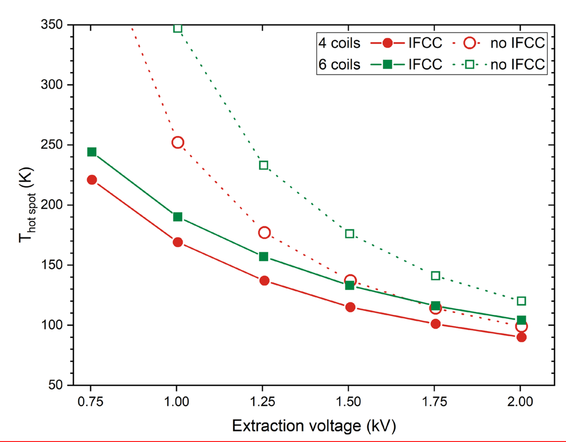
4-coil design



6-coil design

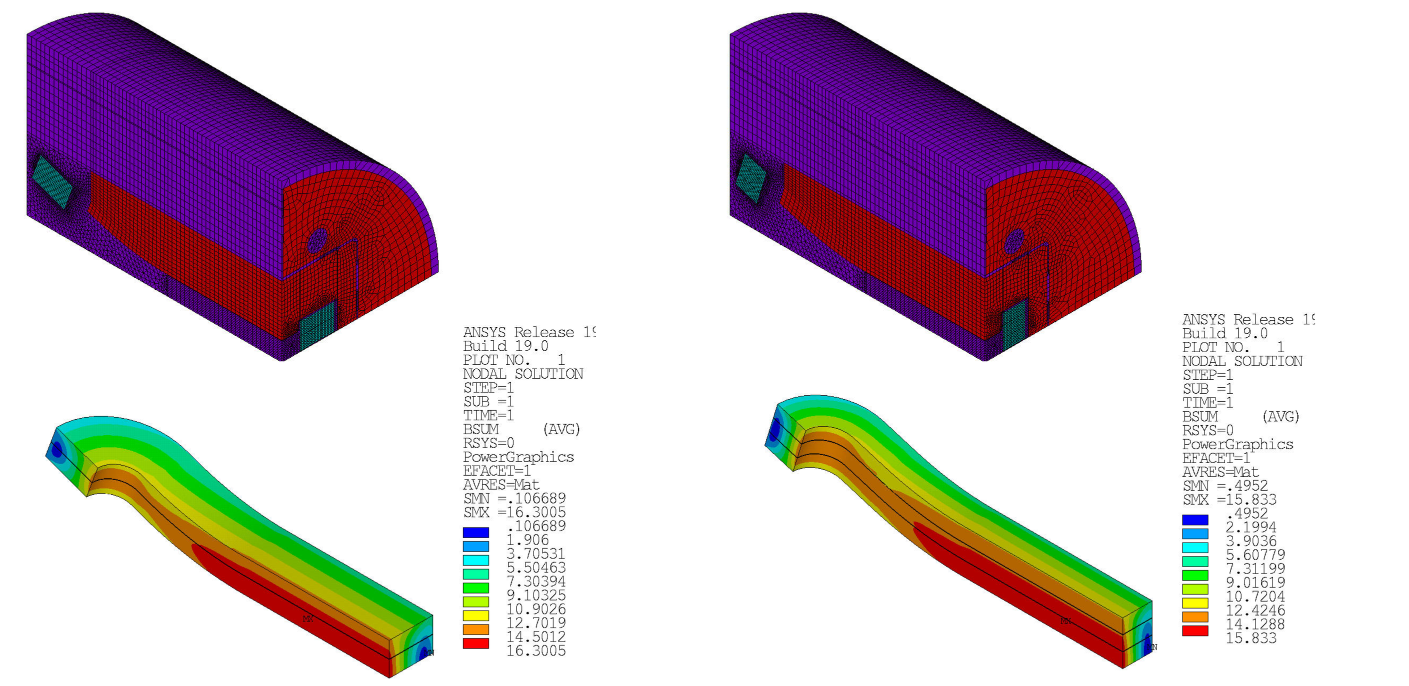


- **Quench protection** studies conducted with **STEAM-LEDET**:
  - Key parameter: filament twist pitch
  - EDIPO 2 can be successfully protected with an energy extraction scheme



3D magnet design

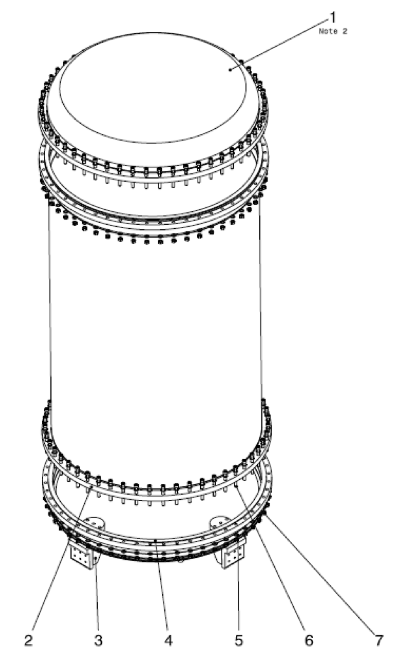
- **4-coil design:**
  - Straight section: 960 mm
  - Hardway radius: 1000 mm
  - Angle flared ends: 20 degrees
  - Straight ramp: 25 mm
  - Uniform field length: 959 mm
- **6-coil design:**
  - Straight section: 1000 mm
  - Hardway radius: 1000 mm
  - Angle flared ends: 17 degrees
  - Straight ramp: 100 mm
  - Uniform field length: 956 mm



- **Field in the ends** more than **1.5 T lower** than in the straight section
- **Preliminary 3D mech FEA** show unacceptable stress in the coil ends

He vessel and pressure relief system

- The EDIPO 2 magnet will be **bath-cooled at 4.2 K**.
- The liquid helium **vessel** is **under construction**.
- Main **design parameters**:
  - Operating pressure: 1 bar
  - Accident pressure: 3 bar
  - Leak rate < 10^{-8} l·bar/s
- The **pressure relief system** follows a **staged pressure protection** concept.
- Both a **loss of vacuum** and an **unprotected quench** are considered as worst-case accidents.
- A **DN65 bursting disc** is chosen as safety relief device (based on EN 13648-3 and EN ISO 4126-6).



Conclusions

- **Status of the magnet design**:
  - The magnet of EDIPO 2 relies on a **flared-end block coil design** (similar to accelerator magnets), but it includes some **innovative features**:
    - Use of a **two-stage flat cable** layout
    - **Minimal pre-compression** applied to the coils
  - The mechanical design of the **coil ends** is under study to **minimize the stress** in that region.
  - **Other design aspects satisfy the stringent design criteria** to generate a background field of 15 T in a large aperture.
- The **liquid He vessel** that will host the magnet is **under construction.**
- The **emergency pressure relief system** is **under design**.

Swiss Plasma Center

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.