HFM
High Field Magnets

HFM Forum meeting

FALCON-D CERN 12T dipole status & update plan (HFM RD3 WP3.1)

CERN, Geneva, September 19th 2024

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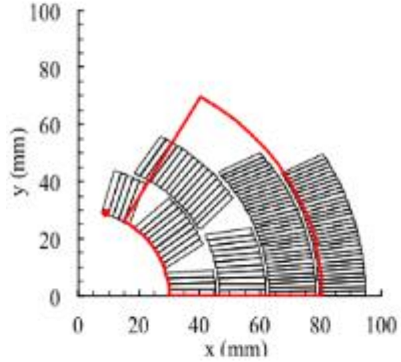
Outline

- Introduction
- Update of WP3.1 FALCON-D 12T dipole scope
- Achievements within CERN & INFN collaboration
- Deliverables, development plan, 2024-2026 Schedule
- Summary

Introduction

- HFM program entrusted CERN WP3.1 to developed a **12T Nb_3Sn Cos-theta dipole based on models (< 2 m)** by 2028, as potential technology for further prototype (~ 5 m long), 14T dipole magnet design by horizon 2030. (indico/1430998/)
- **Strategic knowledge and mastering of the cos ϴ technology** for dipoles as a back-up.
- **Uniformized HFM design parameters** applied in update design :
  - Around 80%.Iss loadline operation at 1.9K
  - Mid plane stress @RT < 120 Mpa, 150 Mpa @ 4K,
  - Current design J_c (16T @4.2K) = 1200 A/mm^2
  - 50 mm aperture, 50 mm equivalent 60° sector width

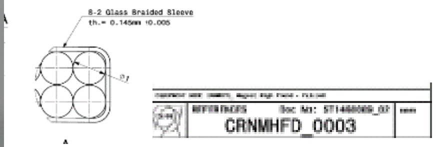
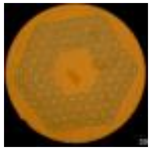


- Decision from mid 2024 to enhance **alignment of both FalconD coils design at INFN (WP3.2) and CERN (WP3.1)** to share coil design, gain in margin and field capability, enhance development synergy and favor technical exchanges.

Update of FALCOND WP3.1 dipole scope

- **Following June 2024 HFM steering board** endorsement, **scope of HFM WP3.1 12T Cos-theta Nb_3Sn** dipole scope has been aligned with following key guidelines:
  - *FalconD **coil manufacture both at B927-CERN and ASG (It) industrial site**;*
  - ***Baseline magnet models assembly** (1-in-1, 2-in-1) based **on optimized B&K structure** then **cold tested at both CERN SM18 and INFN LASA***
  - *Design of 12T dipole coils based on **larger Rutherford Falcon D cable made of 40 x 1.0 mm RRP 162/169 strands, Cu:nCu 0.9**. The **structures are designed for 14T e.m loads level including 2-in-1.***
  - *In case of major winding issue due to narrow bending radii, use of previous 0.85 mm QXF cable RRP 108/127 Cu:nCu 1.2.*
- CERN FalconD dipole development plan includes early investigation **of cos-theta magnet structure candidates (B&K, alu bars + SS shells) on mechanical mockups**.
- **Note: for long magnet protection purpose (> 5 m), further use of optimised cable** (cu/noncu: 1-1.2, **low-field stability) needed.** Further cable development for 14T 2-in-1 dipole design based on enhanced RRP108/127 strand, and available strands RRP 162/169 - Φ1.1 mm, RRP 60/91 - Φ 0.7 mm

RRP Nb_3Sn wire for WP3.1

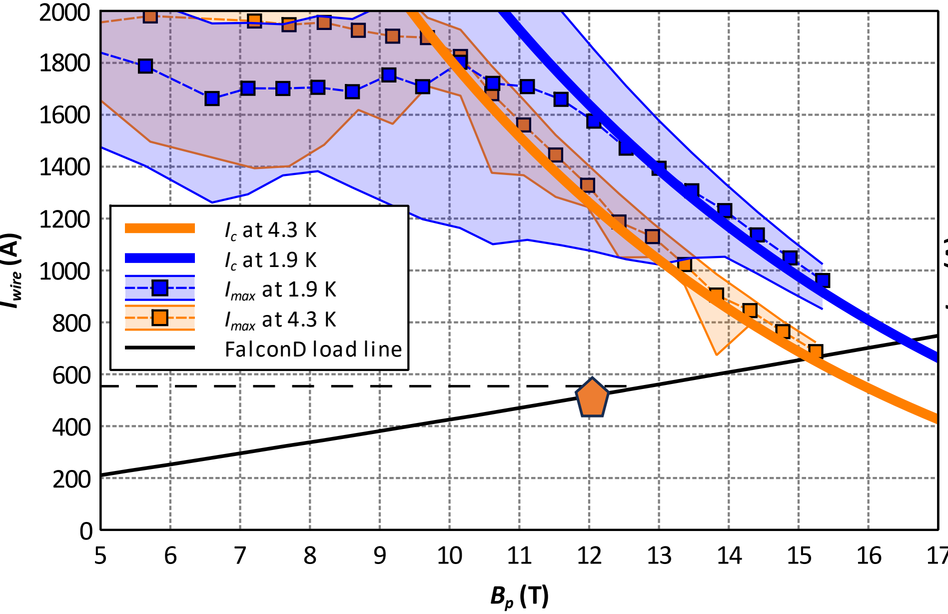
Cable	Units	Past WP3.1 12T cos theta	2024 baseline WP3.1 & WP3.2 12T FALCON D (1-in-1)
			
Material		**Nb_3Sn (RRP 108/127)**	**Nb_3Sn (RRP 162/169)**
Strand type name		MQXF	DEM 1 (ERMC-1)
No. strand		40	40
Strand diam.	[mm]	0.850 ± 0.003	**1.000 ± 0.003**
Cu/NonCu		1.2 ± 0.1	**0.9 ± 0.2**
Keystone	[º]	0.4	0.5
Jc (@4.2K, 16T)	[A/mm^{-2}]	1200	1200
Heat treat.		665 °C 50 h	**650 °C 30-50 h**
Ic (A)	4.22 K, 12.0 T	> 590	
	4.22 K, 15.0 T	> 331	**> 508**
Bare cable th. (R)	[mm]	1.59	1.893
Bare cable wd. (R)	[mm]	18.500	21.420
RRR	Round	> 150	> 150
Insulation th.	[mm]	0.150	0.150
Filling factor		0.29	0.35

Reference S Hopkins et al. : doi: 10.1109/TASC.2023.3254497

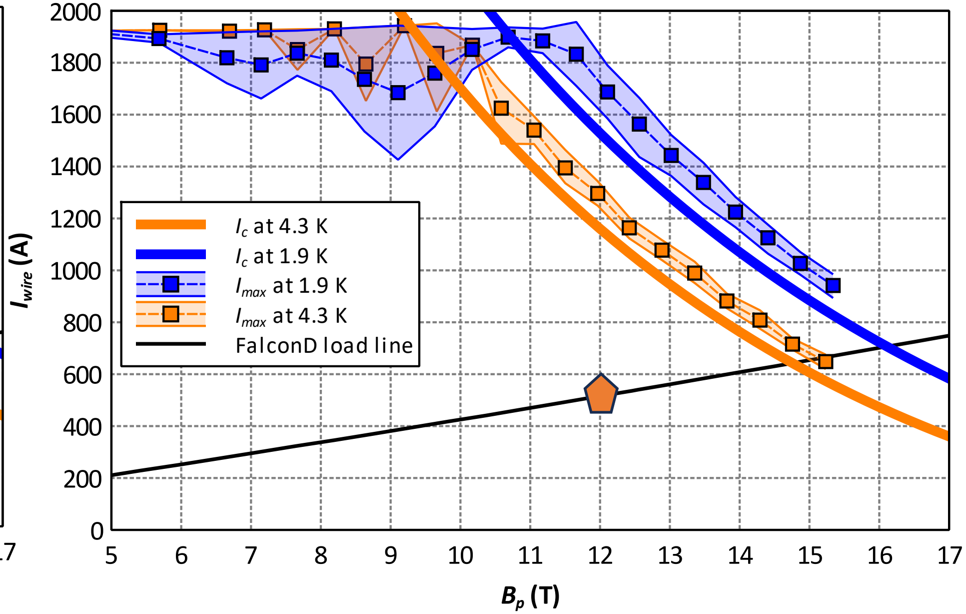
Current stability versus field

- **Although RRP162/169 strand shows Jc(B) instability at low field, conductor team found improved heat treatment (reduced plateau time at 650 deg C)** which offers **factor x2 margin at 12 T @ 4K on critical current for** magnet model. (Need an optimized cable for design of 14 T dipole).

3_650_A heat treatment cycle



3_650_I heat treatment cycle



Courtesy CERN Simon Hopkins

Note: Includes reduction of 6 % from cabling degradation in fitting Jc(B)

Achievements at CERN & INFN collaboration

- **Development and procurement efforts are mutualised** following FALCOND dipole HFM strategy (cern.ch/event/1430998/) and last CERN INFN collaboration meeting (/event/1431283/):
- Last progress within CERN-INFN collaboration on key WP3.1 items:
  - **Global procurement of insulated RRP® 162/169 Nb_3Sn cable 150 m unit lengths (5 out of 12) - in Progress.**
  - **Mutualised ten stacks fabrication**, properties testing at RT and cold **- in Progress.**
  - **On-going coils parts procurement route** common to WP3.2 first sets of machined SS spacers, Glidcop Cu wedges. with further 3D printed spacer investigation;
  - **Further dummy winding trial test** of multiturns collective blocks behavior
  - **Supporting mechanical WP3.1 mock ups** to answer pending questions :
    - optimised slit iron yoke structure, separate layers impact, preloading structure variants (B&K + Alu ring vs. Al bar + SS shell)
  - **Optimised tooling to minimise coil movement** (common base for both winding and HT tooling, detachable / non- detachable & impregnated pole option)

FALCOND WP3.1 12T design parameters

Coil		12T cos	Falcon D 1-in-1
No. of turns per pole		15+22 = 37	12+24 = 36
No. Blocks		6	5
Insulated cable surface	[mm²]	5259	6859
Equivalent coil width	[mm]	31.0	37.5
Physical length	[m]	1.5	1.5
Coil efficiency	[T.mm/A]	0.00078	0.00071

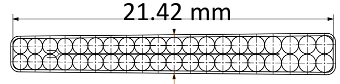


Fig.1 Reacted DEM1 conductor size

Magnet		12T collar. (2023)	Falcon 12T b&k (2024)	1-in-1 Falcon 12T collar. (option)	1-in-1 Falcon Ult. 14T b&k	2-in1 Falcon D 12T
Aperture / interbeam	[mm]	50	50	50	50	50 / 204
Operating temperature	[K]	1.9	1.9	1.9	1.9	1.9
Outer diameter	[mm]	620	640	640	640	640
Nominal current	[kA]	17.750	20.991	20.400	24.906	20.400
Strand eng. Je	[A/mm²]	782	668	650	793	650
Overall Je	[A/mm²]	489	454	454	554	454
Nominal field	**[T]**	**12.01**	**12.00**	**12.00**	14.00	**12.3**
Peak field	[T]	12.42	12.53	12.55	14.63	12.56
Ap. to peak field ratio	[%]	3.4	4.4	4.5	4.5	4.5
Load line fraction	**[%]**	**83.2**	**77**	**76**	**91**	**76.1**
Temperature margin	[K]	4.3	5.11	5.17	**2.72**	**5.14**
Inductance	[mH/m]	2.64	2.24	2.23	2.19	
Stored energy	[MJ/m]	0.451	0.543	0.52	0.741	1.04
Hot spot temp. adia.	[K]		< 150 K	< 150 K	< 150 K	< 150 K
Horizontal force (per quadr)	[MN/m]	3.32	3.57	**3.75**	4.920	**3.88**
Vertical force (per quadr)	[MN/m]	-2.40	-1.78	**-1.76**	-2.580	**-1.77**

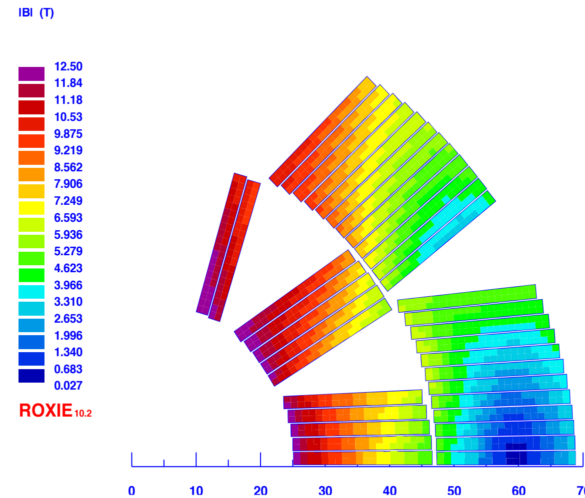


Fig. 2 5 blocks Falcon D coil section

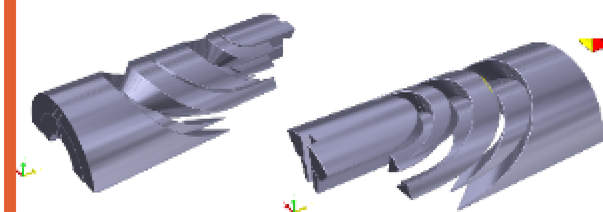
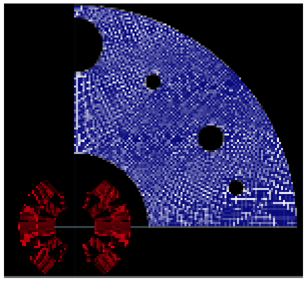
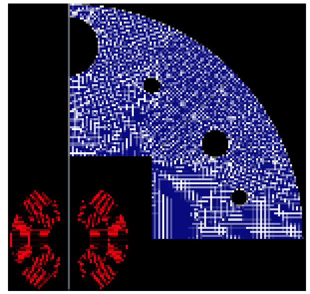


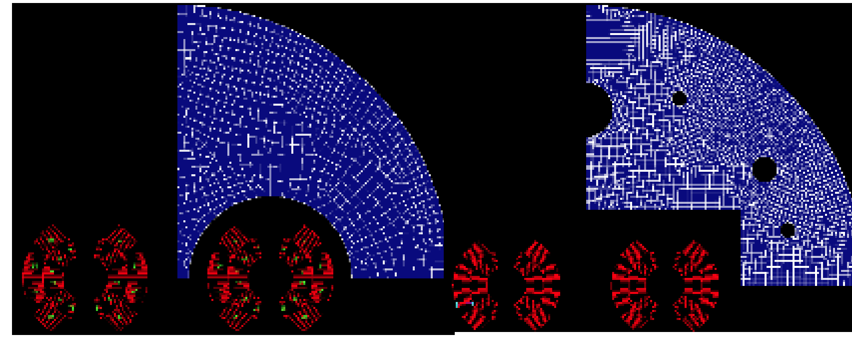
Fig.3 LR and LE end, Roxie API models

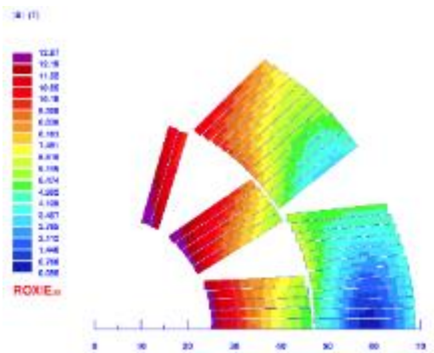

Fig.4 Falcon D 3D machined spacer vs R&D 3D printed development

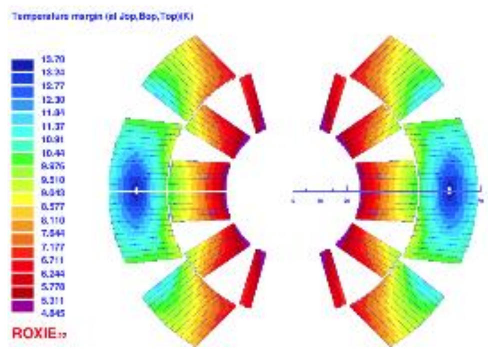
Field quality for reference yoke layouts











- On going magnetic optimization of 2-in-1 b&k baseline

NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	10000.00000	b 2:	0.00000	b 3:	6.17941
b 4:	0.00000	b 5:	-5.44894	b 6:	-0.00000
b 7:	12.26451	b 8:	0.00000	b 9:	2.76912
b10:	0.00000	b11:	1.27581	b12:	-0.00000
b13:	-0.76305	b14:	-0.00000	b15:	-0.23338
b16:	-0.00000	b17:	0.06851	b18:	-0.00000
b19:	-0.01166	b20:	-0.00000	b	

SKEW RELATIVE MULTIPOLES (1.D-4):

a 1:	0.00000	a 2:	-0.00000	a 3:	0.00000
a 4:	-0.00000	a 5:	0.00000	a 6:	-0.00000
a 7:	0.00000	a 8:	-0.00000	a 9:	0.00000
a10:	0.00000	a11:	0.00000	a12:	-0.00000
a13:	-0.00000	a14:	0.00000	a15:	-0.00000
a16:	0.00000	a17:	-0.00000	a18:	-0.00000
a19:	-0.00000	a20:	-0.00000	a	

NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	10000.00000	b 2:	-0.00000	b 3:	-0.35560
b 4:	0.00000	b 5:	-5.28073	b 6:	-0.00000
b 7:	12.59299	b 8:	0.00000	b 9:	2.84277
b10:	-0.00000	b11:	1.30973	b12:	0.00000
b13:	-0.78333	b14:	-0.00000	b15:	-0.23959
b16:	0.00000	b17:	0.07033	b18:	-0.00000
b19:	-0.01196	b20:	0.00000	b	

SKEW RELATIVE MULTIPOLES (1.D-4):

a 1:	0.00000	a 2:	-0.00000	a 3:	0.00000
a 4:	0.00000	a 5:	0.00000	a 6:	0.00000
a 7:	-0.00000	a 8:	-0.00000	a 9:	-0.00000
a10:	0.00000	a11:	0.00000	a12:	-0.00000
a13:	0.00000	a14:	0.00000	a15:	0.00000
a16:	-0.00000	a17:	0.00000	a18:	-0.00000
a19:	-0.00000	a20:	0.00000	a	

b&k structure

NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	10000.00000	b 2:	-6.36052	b 3:	1.19488
b 4:	-0.27219	b 5:	-5.62243	b 6:	-0.00504
b 7:	14.00333	b 8:	-0.00006	b 9:	3.28857
b10:	-0.00000	b11:	1.57626	b12:	-0.00000
b13:	-0.98079	b14:	-0.00000	b15:	-0.31209
b16:	0.00000	b17:	0.09531	b18:	0.00000
b19:	-0.01687	b20:	-0.00000	b	

Collared structure

NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	10000.00000	b 2:	7.64871	b 3:	12.01884
b 4:	0.29926	b 5:	-5.62559	b 6:	0.00931
b 7:	13.50776	b 8:	0.00027	b 9:	3.17224
b10:	0.00001	b11:	1.52050	b12:	0.00000
b13:	-0.94609	b14:	0.00000	b15:	-0.30105
b16:	0.00000	b17:	0.09194	b18:	0.00000
b19:	-0.01627	b20:	-0.00000	b	

Cos-Θ dipole development plan

- CERN-MSC and INFN-Ge, LASA proposed from 2024 the synergetic plan below towards a twin-aperture 12 T, 1.5 m long Nb_3Sn dipole design by 2028.

Date	Description	Length	Remarks	Goals	Institute
Q2-2026	1-in-1 demonstrator magnet (WP3.2)	1.5 m	Construction at INFN LASA, test at INFN, CERN	Cable technology Coil technology Quench performance New b&k structure design	INFN WP3.2
Q3-Q4 2025	**Long mechanical mock ups**	< 0.5 m	CERN B&K & collars coils section mock up assembly (use 11T coils)	Benchmarked concepts of mechanical cross section structures at RT and cold. Measurement of residual stress	**CERN WP3.1**
Q3- 2026	**1-in-1 demonstrator magnet M1**	1.5 m	CERN B&K coils magnet assembly	Novel dipole b&k structure design	**CERN WP3.1**
Q2-Q4 2027	**1-in-1 demonstrator magnet M2a – (option M2b)**	1.5 m	CERN B&K coils magnet assembly (CERN collared coils magnet assembly optional)	**Optimization of** b&k structure design **Reproducibility** Structure pro's & con's vs scale up	**CERN WP3.1**
Q2-2028	**2-in-1 demonstrator magnet M3**	1.5 m	CERN B&K coils 2-in-1 magnet assembly, **structure around 12T coils**	**New 2-in-1 structure, Field optimization, fabrication process, scale-up design inputs for 14T design**	**CERN WP3.1**

Exploratory FE mock-up modelling

- ***Parametrized FE Dipole quadrant model*** (fig.1) to investigate impacts on coil stress (RT & cold) of key ***B&K*** structure parameters (**yoke splits V, H, 45°, 0/90 °**, key positions, pads thicknesses), mockups pre-dimensioning. **- in Progress.**
- **Sensitivity analysis** through methodology of Design of Experiment (DOE) to study material properties ranges.
- **Bilinear mechanical properties** benchmarking from next Falcon-D cable stack test, smeared model properties inputs.

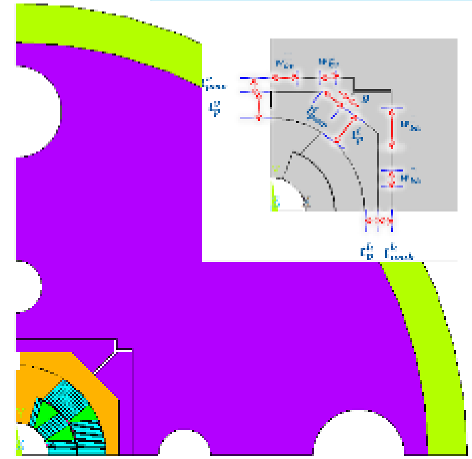


Fig.1 – FE quadrant parametrized model of FalconD-C (S Gowrishankar)

	Unit		R.T.			4.5 K	
		Elastic	Plastic	Avg.	Elastic	Plastic	Avg.
E_x	GPa	52.6	11.3	31.9	48.0	12.0	30.0
E_y	GPa	37.4	11.6	24.5	40.2	12.0	26.1
E_z	GPa	66.1	28.1	47.1	77.2	38.4	57.8
G_{xy}	GPa	18.8			17.7		
G_{yz}	GPa	19.8			22.5		
G_{xz}	GPa	22.9			24.1		
ν_{xy}	/	0.19			0.24		
ν_{yz}	/	0.17			0.16		
ν_{zx}	/	0.23			0.18		
α_x	mm/m	3.65					
α_y	mm/m	4.03					
α_z	mm/m	2.33					

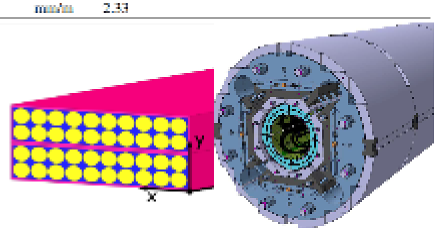


Fig.2 - QXF cable smeared properties (Courtesy G. Vallone)

DOI: 10.1109/TASC.2023.3248544

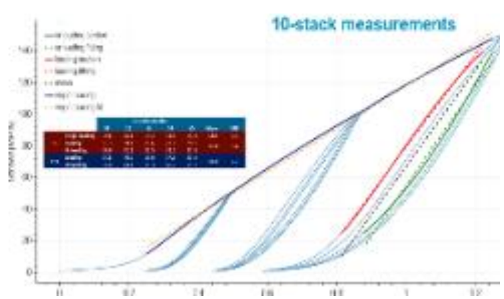


Fig.3 - bilinear FE stress strain stack (11T) measurement (Courtesy O.Sacristan)

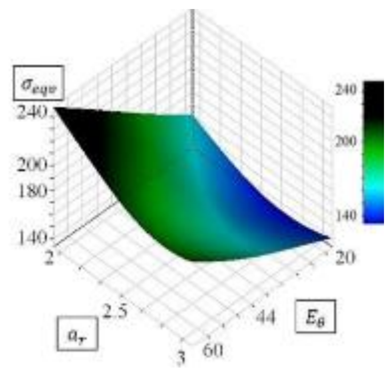


Fig.4 DOE sensitivity methodology used in structure design (US-FNAL A Zlobin)

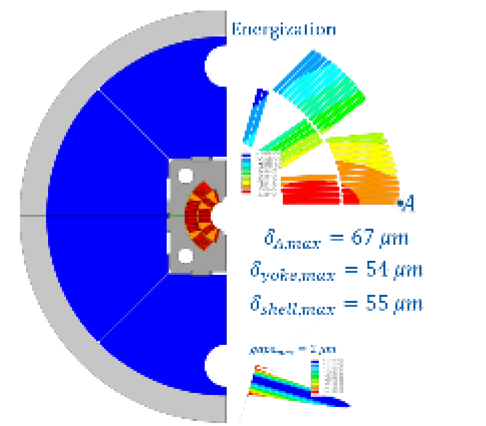
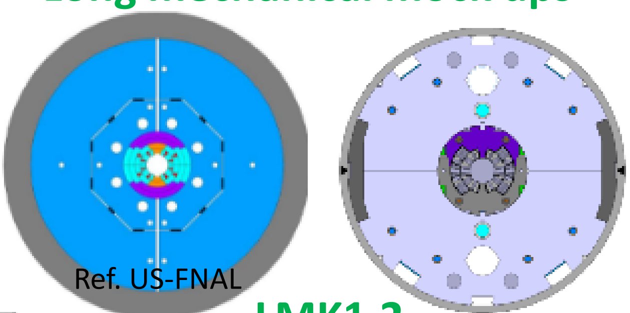


Fig.5 Pole pressure contact and coil stress criteria used in Falcon D-INFN assessment (Courtesy N.Sala)

WP3.1 FalconD 12T dipole roadmap

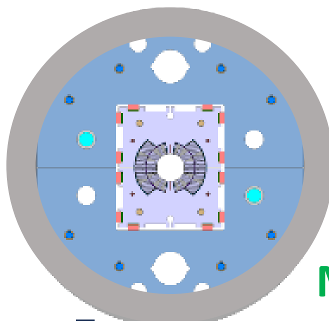
- **B&K structure models design with Alu ring** (ex: QXF, US-MDP concepts)
- Early **mechanical properties dedicated tests** and **exploratory design of structure on mechanical mock ups** (B&K + Alu ring, option of collars with SS shell + Alu bars)
- **Future optimization on single magnet design of 1-in-1 models towards 2-in-1 dipole**

Long mechanical mock ups

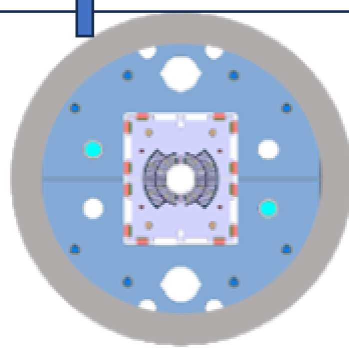


LMK1,2

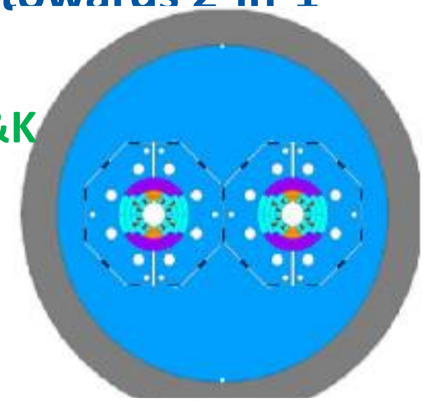
Single Aperture B&K magnet models



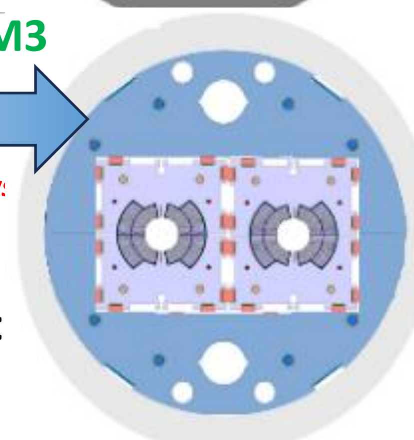
M1,2



Double aperture B&K 12T dipole magnet



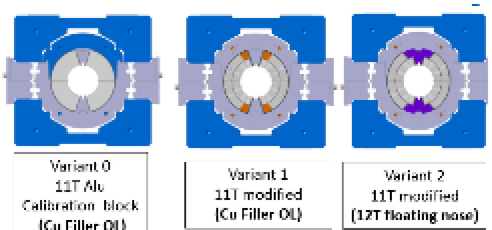
M3



Conceptual cross sections views (H yoke split vs V)

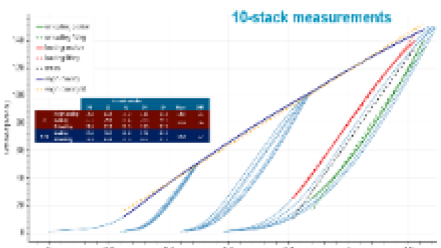
2-in-1 magnet models b&k options

Short mechanical mock up



SMKs

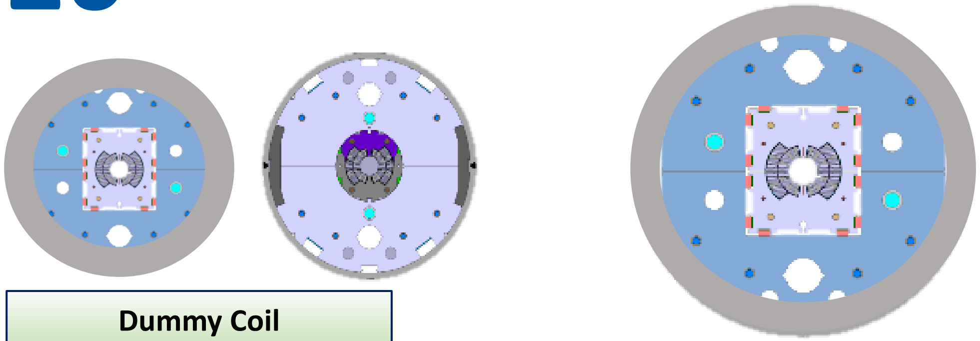
FALCON D at CERN
Focus on 2024-2026



10-stacks
moulds fabrication

Winding trials
on optimised end-spacers

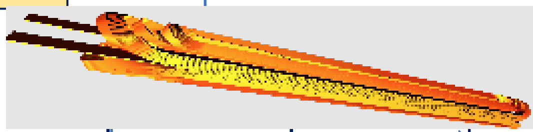
3D printed
end-spacers
development



Dummy Coil
Winding trial

2 Practise Coils

2 +3 Series Coils



Q3_2024

Today

Q4_2024

Q1_2025

Q2_2025

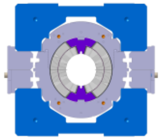
Q3_2025

Q4_2025

Q1_2026

Q2_2026

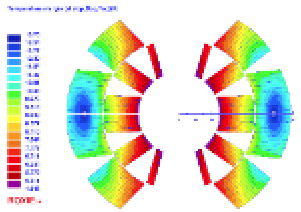
Q3_2026



Long Mechanical mock-ups

Magnet model M1

10-stacks assembly



Short Mechanical mock-ups

Tooling coil, assembly Production

Overview provisional schedule

- Update schedule of CERN WP3.1 **FALCOND-C subtasks on coils and dipole models production**

	2024			2025				2026				2027				2028			
Development and Demonstrators	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1 - Mechanical mock ups																			
Short mock ups coils sections SMK (11T mod., 12 T) (circ 130mm l		F	T	D	D	D	F	T											
Long mock ups coil section LMK 1 & 2 (cir. 0.3-0.7 mm long)			D	D	F	T	F	T											
Task 2- Coils production																			
Ten stack, E coil modulus measurement			D	F	T	D	F	T											
winding trial, multi turns on 3D printed end spacers			D,T	T															
Production coil tooling			D	F	F	T													
Production of 1 dummy Cu coil				D	D	F													
Production of 2 practise coils						D	F	F											
Production of 3 coils (single AP)								D	F	F									
Production of 2 coils (D-AP)										D	F	F							
Task 3- Magnet models production																			
Single aperture magnet model M1					D	D	F	F	T	C -P									
Single aperture magnet model M2						D	D	D	D	F	F	T	C -P						
Single aperture magnet model M3 (Optional)											D	F	F	T	C -P				
Task 4 - 2-In-1 magnet																			
Double aperture magnet Falcon D model											D	D	F	F	T	T	C-P		

D	Design	T	test assembly		
F	Fabrication	C	Cold test	P	Power test

WP3.1 cable production need

Delivery dates

	Bare conductor **<u>for insulation</u>**	Insulated cable **to CERN**
1 Dummy Cu cable	March 2025	May 2025
2 units (practise)	Sept-25	Oct-25
3 units	Janv-26	Mars-26
2 units	Jun 2026	Sept-26

Note: Start of first dummy coil WP3.2 winding at ASG on FALCON D-I from Oct.24

WP3.1 CERN coils production schedule

Start of production equipment procurement	Nov’ 2024 – May 25
Dummy winding trial tests	Oct’ 24 - Mar 25
1st dummy pole *	June 2025
2 practice coils	Nov 25 - Mar’ 26
2 aperture coils	Apr’ 26 - Aug’ 26
3 aperture coils	Nov’26 - Mar’27

* Start of first dummy pole WP3.2 winding at ASG from 10.24

Summary

- **Mutualization of** WP3.1 (CERN) and WP3.2 (INFN) **FalconD 12T dipole coils designs** following last HFM steering board,
- WP3.1 is used **to investigate few structure variants**, provide benchmarked **inputs for single design optimization** towards **2-in-1 magnet construction**.
  - Step-by-step approach with mechanical mock ups for specific parameters impacts study.
- **Baseline design and roadmap strategy clarified** for an integrated design of 1-in-1 then 2-in-1 12T dipole magnet models till 2028 based on past experience.
- **Updated schedule with procurement plan from 2025** for 12T coils WP3.1 manufacture scope (dummy, 2p + 5 coils) and structure.
- Dedicated **collaboration CERN-INFN group meetings on FALCOND activities** on design, tooling, parts procurement and production QA follow up.

References

- 2023 TE-MSC Strategy & Implementation Update for High Field Magnet (HFM) Part 1: LTS, EDMS 2816918 3-0
- 12 T VE Preliminary Design Review report , July 5, 2023, CERN : https://indico.cern.ch/event/1294868/
- IPAC 2024 conference, *Mechanical design of the 12 T superconducting dipole. An accelerator-fit, Nb_3Sn double aperture magnet,* M Masci, D Perini, L Baudin , DOI: 10.18429/JACoW-IPAC2024-WEPS63
- 12-14T cos theta HFM WP3.1 Working indico directory: //indico.cern.ch/category/15243/
- Technical Design Report of the FalconD Nb3Sn Cos-Theta Dipole Model for the FCC-hh at CERN, INFN/Code-19/001, Indico1086175
- 2024 update HFM program structure. https://hfm.web.cern.ch/
- INFN CERN collaboration ADDENDUM FCC-GOV-CC-CC-0004/17.10.2014 (KE4102/FCC) : Design and manufacturing of a single-aperture, 12 T short model superconducting Nb3Sn dipole magnet, designed and assembled according to the bladder-and-key technology

Publications:

- R. Valente et al., Status on the Development of the NbSn 12 T Falcon Dipole for the FCC-hh, IEEE trans. Appl. Supercond., 34 (3), 2024
- R. Valente et al., Optimization of Electromagnetic Design After Winding Tests for the Nb3Sn Cos-Theta Dipole Model for FCC-hh, IEEE trans. Appl. Supercond., 33 (5), 2023
- F. Levi et al., Updates on the Mechanical Design of FalconD, a Nb3Sn Cosθ Short Model Dipole for FCC-hh, IEEE trans. Appl. Supercond., 33 (5), 2023
- A. Pampaloni et al., Mechanical Design of FalconD, a Nb3Sn Cosθ Short Model Dipole for the FCC, IEEE trans. Appl. Supercond., 32 (6), 2022
- A. Pampaloni et al., Preliminary Design of the Nb3Sn cosθ Short Model for the FCC, IEEE trans. Appl. Supercond., 31 (5), 2021

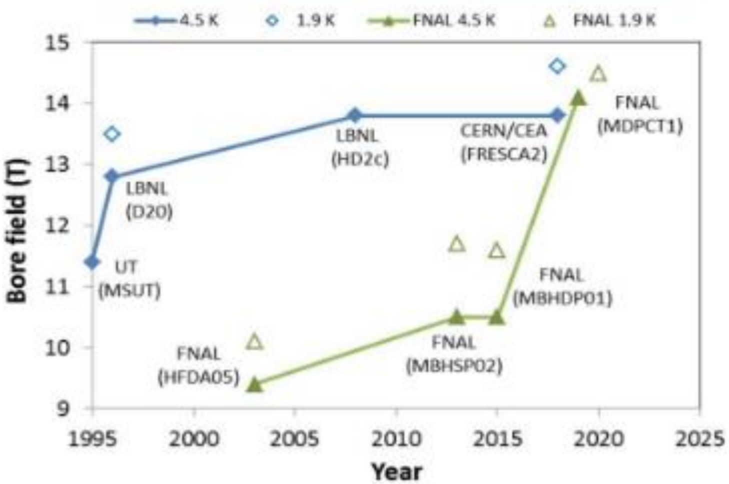
Thank you for your attention

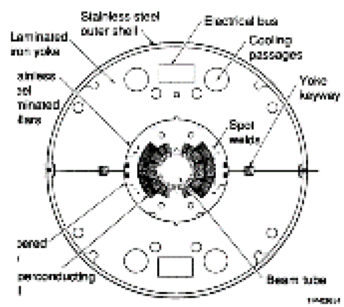
WP3.1-FALCOND-C main tasks

- **Task 1: Mechanical mock ups (using existing 11T coil sections)**
  - Short mock ups (150 mm) mechanical test with new separate 11T layers collared coil sections. Benchmarking with FE analysis.
  - Long structure test mock ups concept (0.3-0.6 m)
  - LMK1 mock up to investigate B&K on selected CERN design variant (Alu shell, pads, B&K), cool down at 77K
  - LMK2 mock up to provide fast-track preliminary technical assessment on a collared coil design with Alu safety bars.
- **Task 2: Coils production**
  - Impregnated ten-stacks (5) for mechanical and thermal properties (under progress)
  - **1-in-1 models: 1 dummy copper, 2 practises + 5 coils** of 1.5 m long, UL of 140 m,
- **Task 3: Single aperture 12T dipole FALCOND-C models**
  - Two models single aperture (AP 50 mm) dipoles (M1, M2) with B&K structure being optimised, as a variant of FALCOND-I. Any alternative structure under review.
- **Task 4: Double aperture 12T dipole FALCOND-C model**
  - Magnetic and mechanical design of the double aperture in line with the single aperture models design baseline, optimised cables, possible grading, cold tested

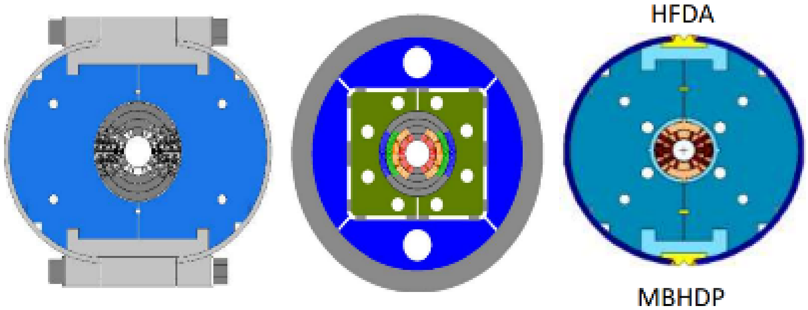
Design legacy

- The 12 T HFM FalconD dipole development magnet finds legacy from past development of high field dipole magnet at FNAL (HD, HFDA), ELIN CERN dipole magnet (1986) SSC (1992) and the last MBH dipole development (2015-2021) on CERN HL-LHC Project

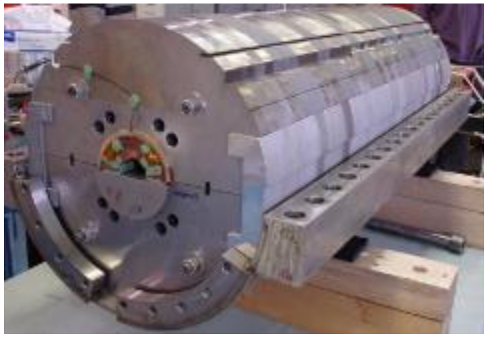




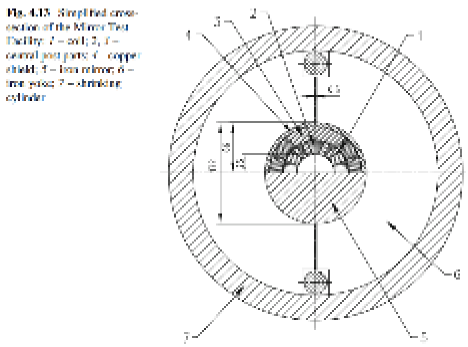
SSC dipole (BNL)



Dipole magnet topology development at FNAL,



MBH test mirror (FNAL, Zlobin)



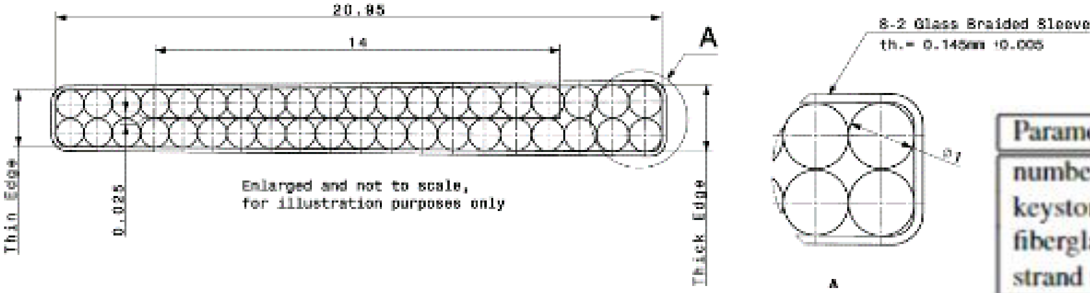
Elin – CERN 10.2 T Nb3sn dipole model (1986) tested in magnetic mirror (AP diameter 50 mm)

Drawings CDD equipment code

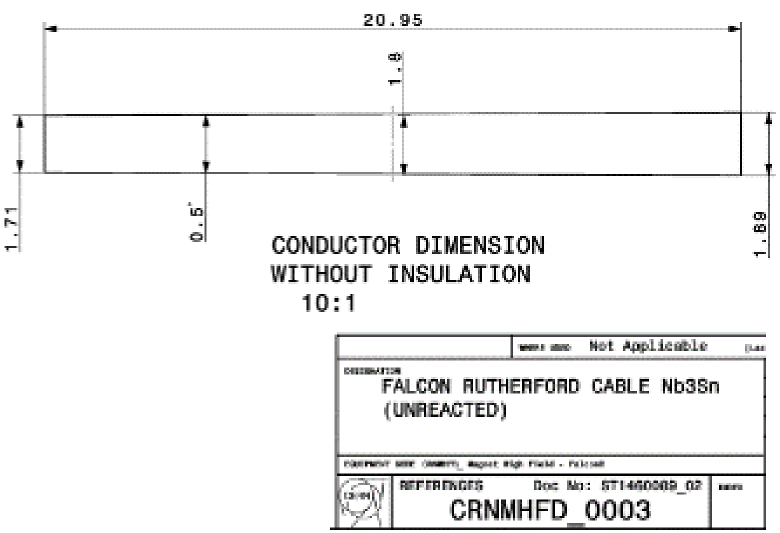
- Newly FALCON-D equipment codes CRNMHFD_ for manufacture drawings management both at CERN and INFN/ASG

Equipment code	CAD topic
CRNMHFDA	• CERN Coil components & Assembly for High Field 12T Dipole Short model (HFM - Falcon D).
CRNMHFDB	• INFN Coil components & Assembly for High Field 12T Dipole Short model (HFM - Falcon D).
CRNMHFDAM	• CERN Magnet components & Assembly for High Field 12T Dipole Short model (HFM - Falcon D).
CRNMHFDBM	• INFN Magnet components & Assembly for High Field 12T Dipole Short model (HFM - Falcon D).
CRNMHFDMK	• Mock-ups for High Field 12T Dipole Short model (HFM - Falcon D).
CRNMHFDTA	• CERN Tooling for High Field 12T Dipole Short model (HFM - Falcon D).
CRNMHFDTB	• INFN Tooling for High Field 12T Dipole Short model (HFM - Falcon D).

FalconD cable features



Non reacted conductor dimensions



Parameter	Expected Values
number of strand	40 (2 × 20)
keystone angle	0.5°
fiberglass insulation thickness	0.15 mm
strand twist pitch	120 mm
bare width (unreacted/reacted)	21.000 mm / 21.420 mm
bare thin edge (unreacted/reacted)	1.720 mm / 1.797 mm
bare mid-thick edge (unreacted/reacted)	1.812 mm / 1.893 mm
bare thick edge (unreacted/reacted)	1.903 mm / 1.989 mm
Nb_3Sn area	16.53 mm² (34.7766%)
Cu area	14.88 mm² (33.1516%)
fiberglass insulation area	6.844 mm² (15.2461%)
void area	6.629 mm² (14.7671%)
tot. area of cable	44.89 mm² (100%)
θ_{pitch}, strand twist pitch angle	19.29°
PF, packing factor	0.747
c_t, deformation cable edge	-9.4%
c_w, deformation cable width	-4.2%
c, overall deformation	86.8%
k_t, thin edge compaction (keystoned cable)	91.3%

Table 1: FalconD DEM-1 conductor type parameters

WP3.1 procurement plan

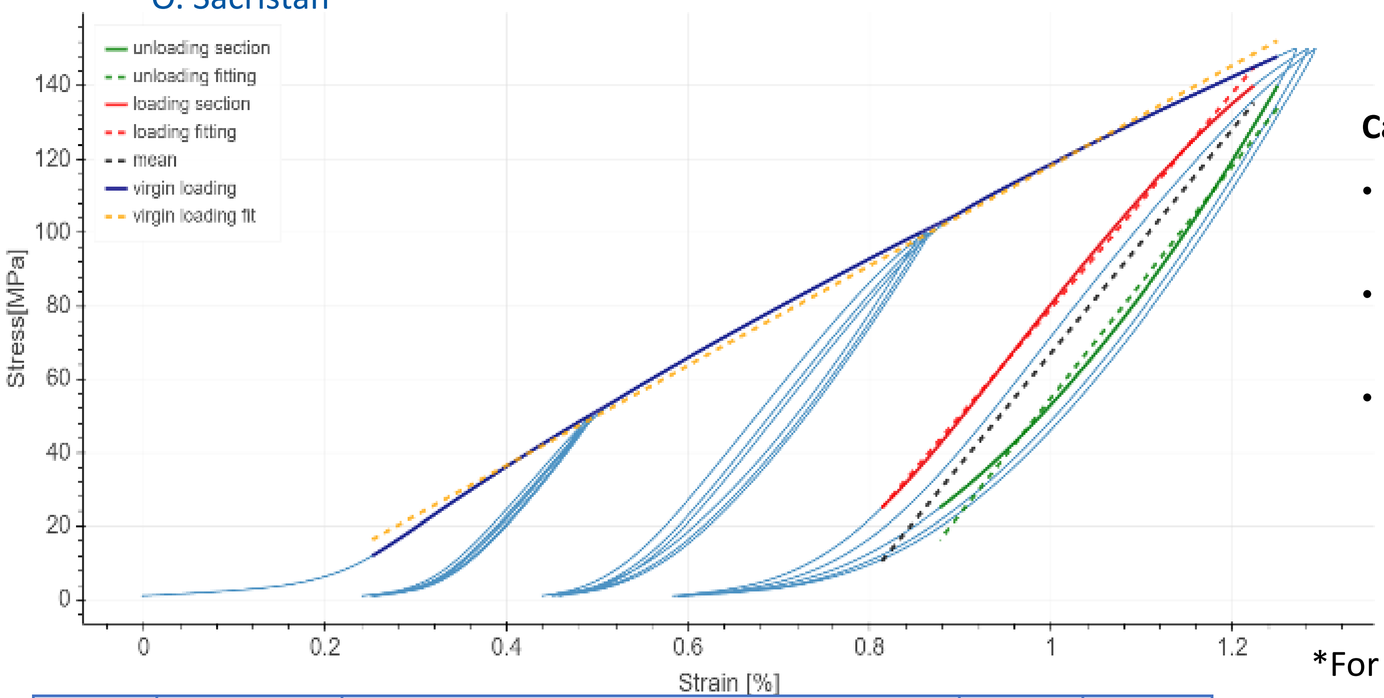
Planning of procurement	Groups	2024										2025												
		M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J
SHORT Mockups																								
MK1 - OFH wedges, loadplate shims, Kapton sheets	MSC																							
MK2 - collar nose,, shims, Kapton sheets	MSC																							
MK3 - collars, packs shims, Kapton sheets	ENMME, MSC																							
MK4 - collars, packs, shims kapton sheet	MSC																							
MK4 - 12T wedges	MSC																							
MK4 - 12T short coils section (2)	MSC																							
LONG mock ups																								
Iron yoke laminations	ENMME																							
Alu shells	EN MME																							
shims, Kapton sheets, protection sheets	MSC																							
LMK1 - coils pads, B&K, pole	MSC																							
LMK2 - Alu stoppers bars	ENMME																							
LMK2 - 11T long coil sections metrology	EN MME																							
LMK 2 - Half shells (4), protec strips	MSC																							
Production tooling																								
winding mandrel, jigs	EN MME																							
Heat treatment mould	EN MME																							
Curing jig	EN MME																							
Impregnation mould	EN MME																							
Coils components and practise coils																								
Dummy coil (1)																								
Practise coils (2)	MSC																							
End spacers WP3.1 WP3.2	MSC, EN MME																							
Copper wedges WP3.1 WP3.2	MSC, EN MME																							
Bare cable WP3.1 WP3.2	MSC																							
Insulated cable WP3.1 WP3.2	MSC																							

Planning of procurement	Groups	2024	2025	2026
Model Single aperture 12T B&K				
M1 - 12T model coils wedges, spacers	MSC, ENMME			
M1 - 12T coil pads, bladders & keys	EN MME			
M1 - 12T quench heaters	MSC			
M1 Interlayer splice (option)	MSC			
M1- model coils (2)	MSC			
M1 - yoke laminations	EN MME			
M1 - end plates, rods	EN MME			
M1 - Alu shells	MSC, EN MME			
Model Single aperture 12T collared				
M2 - 12T model coils wedges, spacers	MSC, ENMME			
M2 - 12T coil pads, bladders & keys	EN MME			
M2 - Quench heaters	MSC			
M2- model coils (2)	MSC			
M2 - yoke laminations	EN MME			
M2 - end plates, rods	EN MME			
M2 - Alu shells	MSC, EN MME			
Model double aperture 12T collared				
M3 - 12T model coils wedges, spacers	MSC, ENMME			
M3 - 12T coil pads, bladders & keys	EN MME			
M3- 2-in-1 model coils (4)	MSC			
M3 - yoke laminations	EN MME			
M3 - end plates, rods	EN MME			
M3 - Alu Shell	MSC, EN MME			

Ten-stack 11T cable properties

25/10/2019
O. Sacristan

10-stack measurements



Calculated Stiffness

- Virgin Loading (RT and 77K*):
  14 ±2 GPa
- RT Loading/unloading phase:
  31 ±3 GPa
- 77K Loading/unloading phase:
  39 ±3 GPa

*For the virgin loading at cold: tests performed on a different batch than the rest of the tests matrix

		10-stack samples						
	Segment	**S1**	**S2**	**S3**	**S4**	**S5**	**Mean**	**STD**
RT	**Virgin Loading**	**13.6**	**13.3**	**14.2**	**13.3**	**13.4**	**13.5**	**0.3**
	Loading	**29.3**	**29.1**	**30.6**	**28.8**	**29.1**	**30.8**	**0.6**
	Unloading	**31.6**	**32.1**	**33.5**	**32.0**	**32.3**		
77 K	**Loading**	**34.6**	**40.0**	**36.0**	**37.6**	**33.8**	**38.0**	**2.2**
	Unloading	**37.8**	**43.1**	**39.3**	**40.7**	**37.1**		

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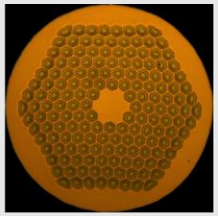
Wire properties

DEM. 1 Strand		
		
d (mm)		1.000 ± 0.003
Layout		162/169
d_s (µm)		< 60
Cu/non-Cu		0.9 ± 0.2
Nb:Sn		3.4 (std. Sn)
Heat treat.		650 °C 50 h
I_c (A)	4.22 K, 12.0 T	
	4.22 K, 15.0 T	> 508
	4.22 K, 16.0 T	> 395
n-value		> 30
RRR	Round	> 150
	Rolled	> 100

Property	HL-LHC		HFM	
	11 T	MQXF	ERMC-1	DEM-1.1
Diameter (mm)	0.7	0.85	1.0	1.1
RRP® Layout	108/127		162/169	
d_s (µm) [a]	45	55	58	64
Cu/non-Cu [b]	1.15 ± 0.1	1.2 ± 0.1	0.9 ± 0.2	0.9 ± 0.2
Nb:Sn	3.6 (reduced Sn)		3.4 (standard Sn)	
Standard heat treatment [c]	650 °C 50 h	665 °C 50 h	650 °C 50 h	665 °C 50 h
RRR, round [d]	309 ± 35	345 ± 40	290 ± 33	266 ± 39
RRR, rolled [d]	174 ± 29	215 ± 29	206 ± 27	203 ± 36

[a] Geometrical sub-element diameter
[b] Range of Cu/non-Cu permitted by specification
[c] Final plateau of the manufacturer's final recommended heat treatment cycle; RRP® heat treatments begin with plateaus of 48 h at 210 °C and 48 h at 400 °C
[d] Residual resistivity ratio measured in CERN acceptance tests (mean ± standard deviation) after the standard heat treatment, for round wire and after rolling with a diameter reduction of 15 %

Characteristics of RRP wires

Reference ERMC-1 wire S Hopkins et al. : doi: 10.1109/TASC.2023.3254497

Field quality / protection

- field quality is considered a secondary objective of the project, therefore the cable block longitudinal position is not optimized to minimize the integrated harmonics

Field quality		Falcon 12T single	Falcon 14T double *
Harmonic b3 at I_{nom}	[10^{-4}]	-0.35	0.106
Harmonic b5 at I_{nom}	[10^{-4}]	-5.28	0.18
Harmonic b7 at I_{nom}	[10^{-4}]	12.59	0.18
Harmonic b2 max	[10^{-4}]	0	0.025
Harmonic b3 at I_{ini}	[10^{-4}]	?	?

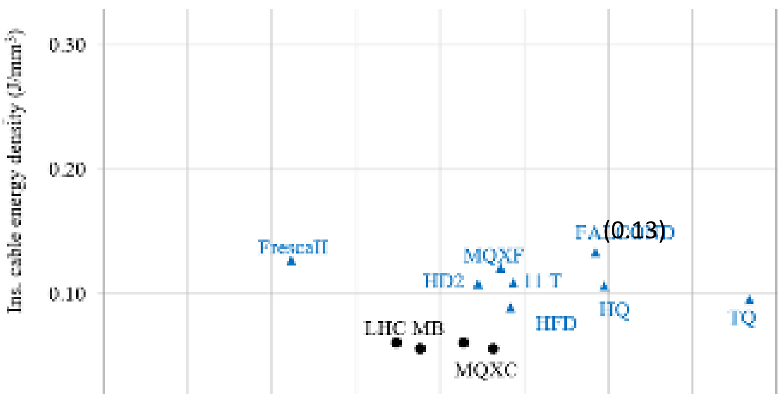
Protection		Falcon 12T single
Coil energy density	[J/mm^3]	0.09
J copper	[A/mm^2]	1439
Time margin	[ms]	45
Hotspot (adiab.)	[K]	130
Harmonic b3 at I_{ini}	[10^{-4}]	?

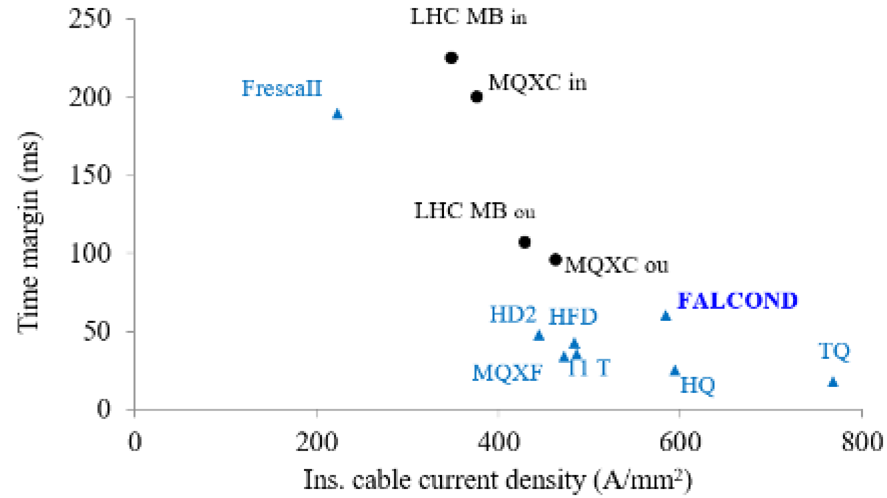
** Under progress, design discussion within FALCON D*

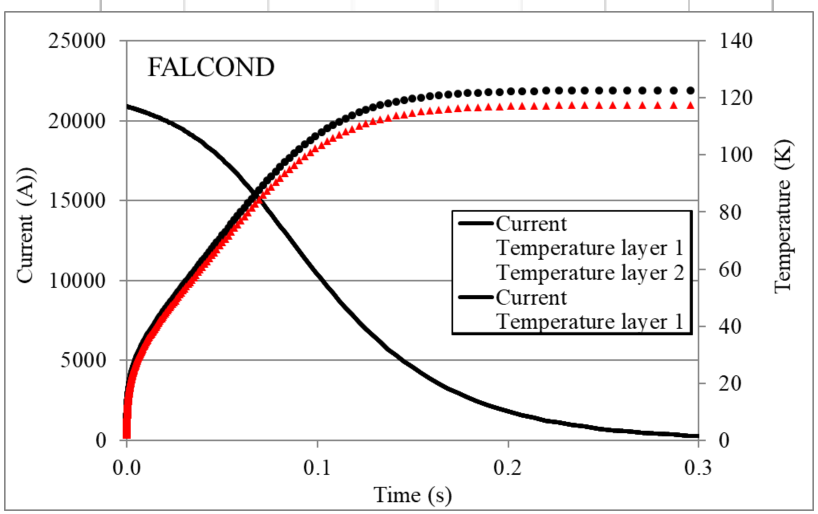
Falcon D quench protection range (adiabatic)

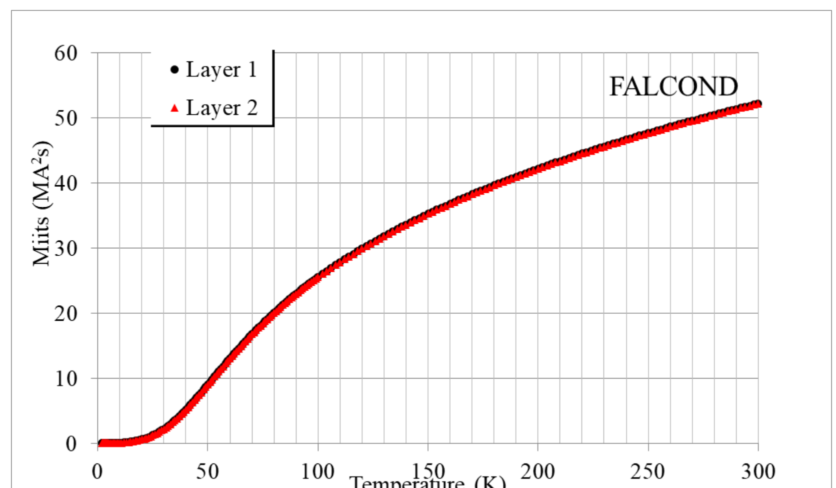
- Adiabatic temperature case of 1.5 m Falcon D 0.9 mm RRP162/169 strand based coil model w/o dump
- About 44-50 ms left to quench during validation time

$$MIITs\,(T) = A^2 \int_{T_0}^{T} \frac{\gamma\,(T)\,C_p\,(T)}{\varrho\,(B, RRR, T)} dT = \int_{t_0}^{\infty} I^2 dt$$









Open items

- Well known instabilities observed on Falcon D cable and cumulative offset during first Cu dummy cable trial by INFN at CERN, to be further characterized.
- Further winding parameters need optimisation per winding machine, (ex: at ASG use rolling but not the yaw, with the spool rotating around the winding bench)
- Expected deviation of 4-5 mm of conductor block tip in coil heads wrt. envelop to be confirmed, filled for mechanical preload.

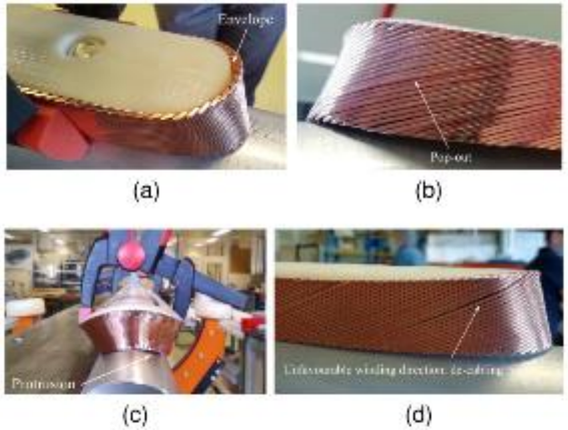
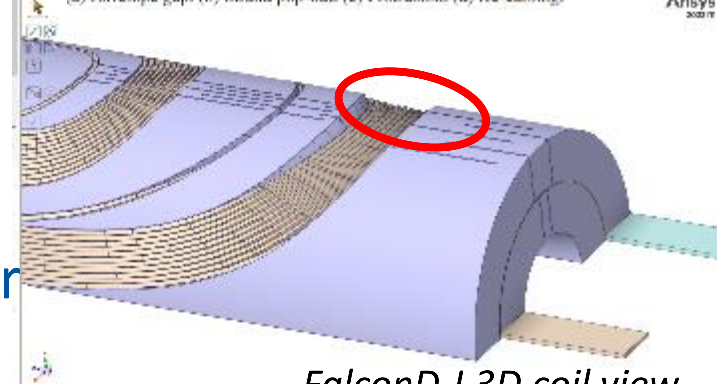
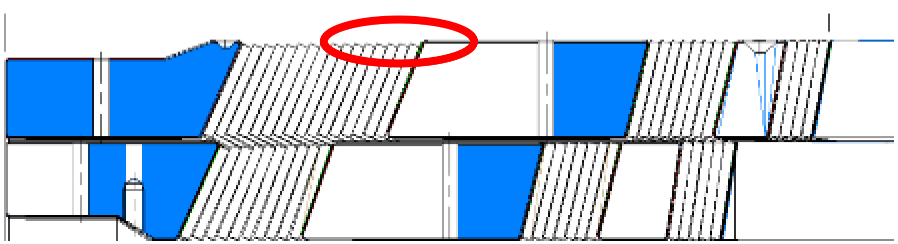


Fig. 4. The cable instabilities observed during the first winding test. (a) Envelope gap. (b) Strand pop-out. (c) Protrusion. (d) De-cabling.



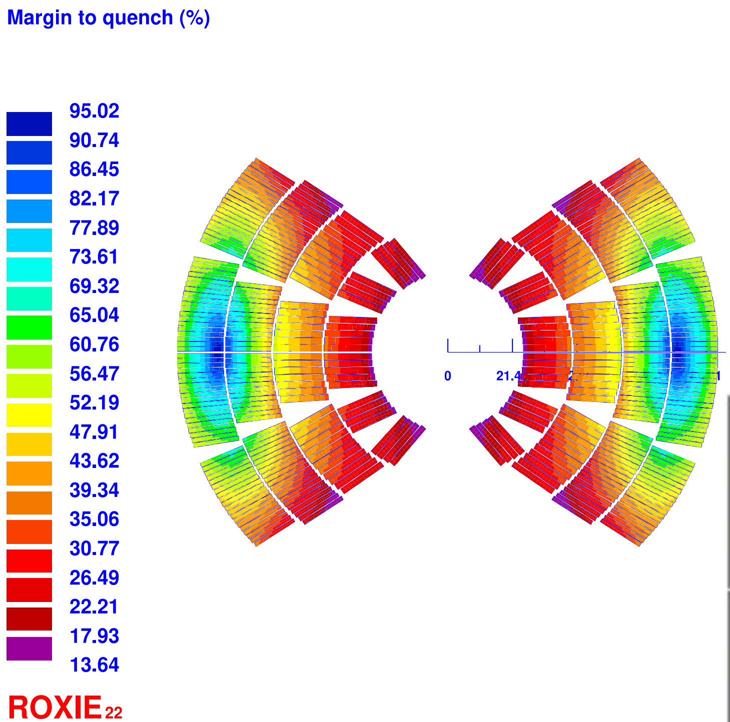
FalconD-I 3D coil view



QXF coil cut view, DWG M0223, maximum gap of 2 mm

FALCOND WP3.1 towards 14T design

- Design work in progress within collaboration, Option C, 1-in-1 presented by *R. Valente (INFN) at ASC conf. 2024*.
- Current design based on as of today existing strands using grading (22 strands **Ø 1.1 mm** HF, 38 strands **Ø 0.7 mm** LF)



Bore field 14 T	HF	LF
Peak field [T]	14.33	12.17
Temperature [K]	1.9	
j overall [A/mm^2]	329	448
j sc [A/mm^2]	939	1554
Loadline fraction [%]	78	75
Temperature margin [K]	4.51	5.34
Equivalent width [mm]	49.4	
N° of turn (per quadrant)	32	68

	ERMC-1		DEM-1.1	
High Field 162/169	Diameter	1.0 mm	Diameter	1.1 mm
	Cu/non-Cu	0.9 ± 0.2	Cu/non-Cu	0.9 ± 0.2
	I_c at 4.22 K, 16 T	≥ 395 A	I_c at 4.22 K, 16 T	≥ 475 A
	$d_{sub\text{-}el}$ (nom.)	58 µm	$d_{sub\text{-}el}$ (nom.)	64 µm
	ERMC-0.7		**DEM-0.7**	
Low Field /91	Diameter	0.7 mm	Diameter	0.7 mm
	Cu/non-Cu	1.2 ± 0.2	Cu/non-Cu	1.8 - 0.2
	I_c at 4.22 K, 12 T	≥ 430 A	I_c at 4.22 K, 12 T	≥ 315 A
	$d_{sub\text{-}el}$ (nom.)	54 µm	$d_{sub\text{-}el}$ (nom.)	54 µm

Glossary

Equivalent coil width: width of a 60° sector coil whose area is the same of the area of the layout that we are considering.

$$w_{eq} = r\left(\sqrt{1+\frac{3A}{2\pi r^2}}-1\right)$$

where r is the aperture radius and A the area of the insulated cable.

Coil efficiency: Ratio between the field and the current times the coil width, given in [T.mm/A].

$$\gamma = \frac{B}{j w_{eq}}$$

Can be compared with $\gamma_0 = 6.625 \times 10^4$ T.mm/A (found for a 60° 2-sector coil cancelling b3 and b5 [0 °,48 °], [60 °,72 °] case.

Peak field ratio: The ratio λ between peak field and central field can be used as a marker for good optimization. It is a function of the coil shape and can fit with the function:

$$\lambda = 1 + a\frac{w_{eq}}{r}$$

E. Todesco, Masterclass – Design of superconducting magnet for particle accelerator – Unit 4
L. Rossi and E. Todesco, Electromagnetic design of superconducting dipoles based on sector coils, Phys. Rev. STAB, 10 (11), 2007