DTT Magnet Integration

Giuseppe Ramogida
DTT S.c.a r.l. (ENEA)
on behalf of DTT Team

IOD - Industrial Opportunity Days 2022
June 9-10, 2022
INAF - Osservatorio Astronomico di Capodimonte - Napoli

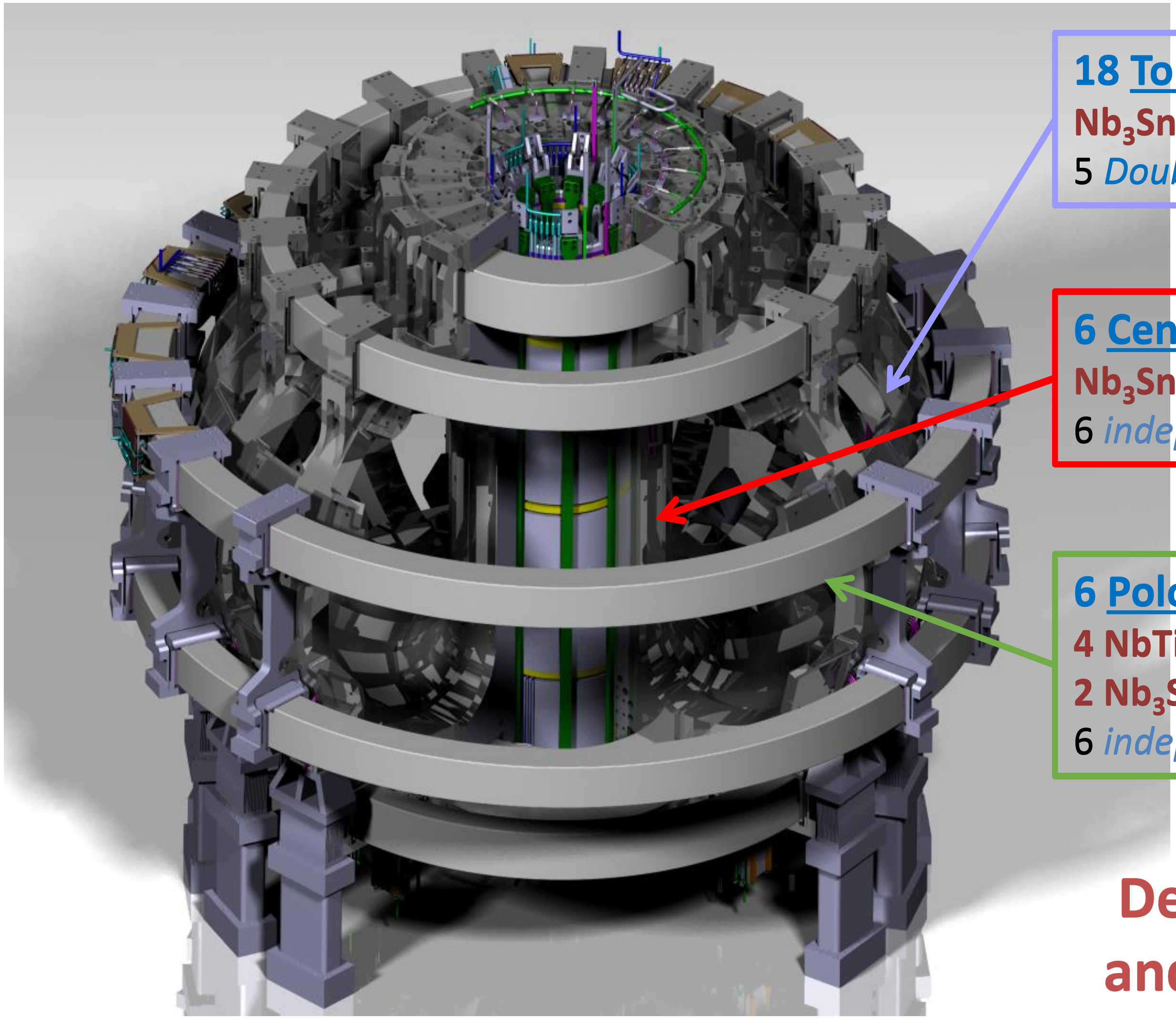
Outline

- DTT magnet system overview
- Main subsystems/procurements:
  - Superconducting and Copper strands
  - Coils conductors
  - Toroidal Field Coils (Winding pack, Casing, Integration, Testing)
  - Poloidal Field coils
  - Central solenoid coils
  - Superconducting feeders and current leads
  - Diagnostics
  - ENEA Cold Test Facility
  - Cryoplant

DTT magnet system requirements & constraints

- High magnetic fields -> use of Nb3Sn
- High flexibility for plasma shaping -> independent PF coils
- Confinement field 6 T @ plasma center -> High current TFCs
- Ripple < 0.5% -> 18 TF Coils
- Pulse length ~ 100 s -> High current density in CS modules
- Schedule & budget constraints -> Use of mature technologies

DTT magnet system at a glance



18 Toroidal Field coils
Nb_3Sn Cable-In-Conduit Conductors
5 *Double-Pancakes* (3 regular + 2 side)

6 Central Solenoid module coils
Nb_3Sn Cable-In-Conduit Conductors
6 *independent modules*

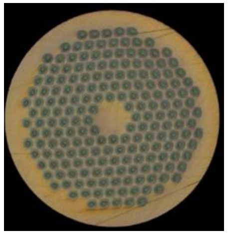
6 Poloidal Field coils
4 NbTi Cable-In-Conduit Conductors
2 Nb_3Sn Cable-In-Conduit Conductors
6 *independent modules*

Design based on proven and reliable technologies

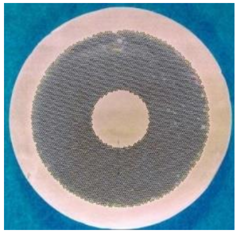
Superconducting and copper strands procurements outlook

- Tender negotiated procedure after market survey to set-up a list of qualified economic operators to be invited, 4 lots, most economically advantageous tender (MEAT) criterion adopted
  1. Nb_3Sn (chromium coated) for TF:
     Hi-Grade performance at 4.2K: Ic (4.2K, 12T, 0.0% applied strain) > **285 A**
     hysteresis losses < 1000 mJ/cm^3
  2. Nb_3Sn (chromium coated) for CS & PF1/6:
     Hi-Grade performance at 4.2K: Ic (4.2K, 12T, 0.0% applied strain(*)) > **260 A**
     hysteresis losses nts < 400 mJ/cm^3
  3. NbTi (nichel coated) for PF2/3/4/5:
     Required Performance at 4.2K: Ic (4.2K, 5T) ≥ 500 A
     hysteresis losses < 100 mJ/cm^3
  4. Cu (chromium coated) for TF, CS & PF1/6 and Ni (nichel coated) for PF2/3/4/5:
     0.82 ± 0.005 mm, Cr/Ni coating = 2 ± 1 μm
     RRR: > 300

0.82 mm



0.82 mm



- Nb3Sn strands for TF conductors (KAT) -> Deliveries completed on schedule (55 tons)
- Nb3Sn strands for PF/CS conductors (LUVATA) -> On going, 9 tons expected in 2022
- NbTi strands for PF conductors (FURUKAWA) -> Deliveries on schedule (14 tons), last 2 deliveries expected in 2022 (13.5 tons)
- Cu(Cr) strands for Nb3Sn conductors (LUVATA) -> On going, 9 tons delivered, 8 tons exp. in 2022
- Cu(Ni) strands for NbTi conductors (LUVATA) -> On going, 4 tons delivered, 6 tons exp. in 2022

Conductors procurement outlook

Superconducting conductors (ICAS), Phase I (qualification of design) on going

- Dummy (full Cu) conductors manufactured
- TF superdummy (first) delivered to TF integrator
- TF, PF2, PF3 samples ready, in preparation for testing in Sultan
- Sultan test results for TF conductors expected at end of July, then choice of design option and start of TF Phase II (Production) exp. in September
- Production rate: 1 WP set / 40 working days

All conductors and termination design options will be tested in Sultan in operative conditions for the design number of cycles

- TF - ULs:

  54 rDP + 36 sDP + 8 spare
- PF - ULs:

  18 DP-PF1/6 + 1spare + 16 DP-PF2/5 + 1 spare + 14 DP-PF3/4 + 1 spare
- CS - ULs:

  6 HF + 1 spare + 6 MF + 1 spare + 6 LF + 1 spare (tbc)

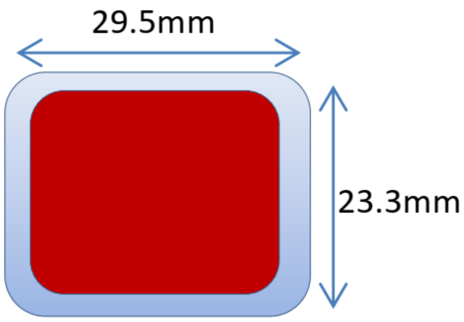
TF conductor features

Conductors manufacturing will consist in:

- Cabling
- Jacketing & insertion
- Spooling
- Testing
- Shipping to coil manufacturers

Key issues:

- 316 LN jacket (samples and dummies to be provided in advance for winding test)
- 100% welds testing
- He leak testing (pressure, flow)
- Jacketing line ~ 880 m (for CS & PF)



- Unit length (UL): 240 m (regular), 170 m (lateral)
- Total # of ULs: 54 (regular) + 36 (lateral) + 8 spare
- VF: 26.4%
- Nb_3Sn strands: 504
- Cu segregated strands: 144
- Cabling pattern:

  [(1Cu+2Nb3Sn)+(1Cu+2Nb3Sn)+3Nb3Sn]*3*4*6

  Wrapping: 0.05mm thick, overlap 30%

TF coils procurement outlook

- TF casings (SIMIC) -> On going, Materials procurement for mock-up started (includes manufacture of 18 sets of TF coil casing components, mock-ups, superbolts, supports and transport frames)
- TF WPs and integration (ASG) -> On going, winding line set-up and termination/joint design started

Conductor	Nb3Sn CICC
B_{max}	11.9 T
I	42.5 kA (N. turn = 84)
M	16 ton (w/o OIS and GS)
Height	6.3 m
Width	3.5 m
Case material	316 LN
Δ tmargin	> 1.4 K
DP winding	80 turns
Winding	5 DoublePancakes (3 regular + 2 side)
Max. hydraulic length	110 m

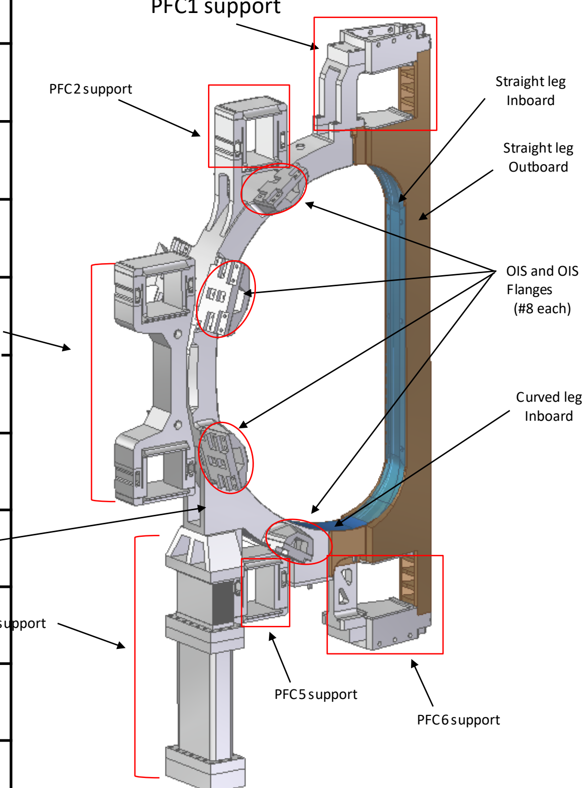
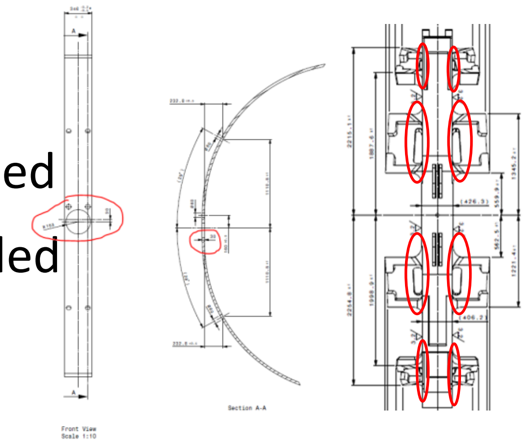
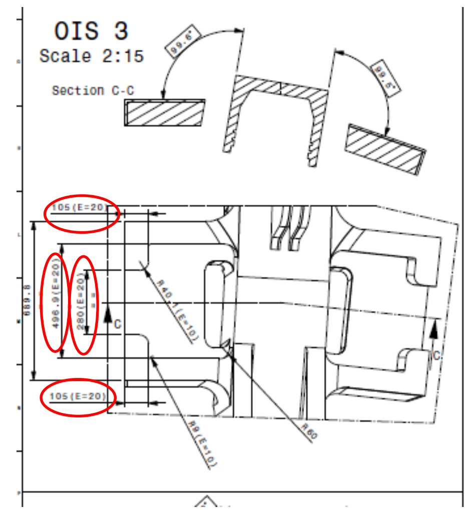


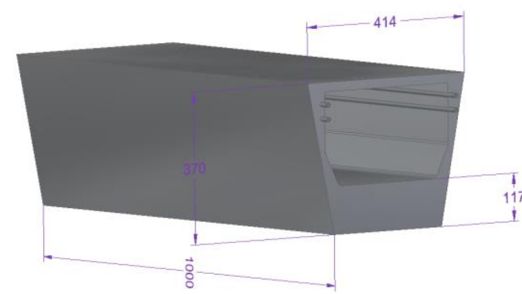
Figure 1 TF Coil casing and miscellaneous components

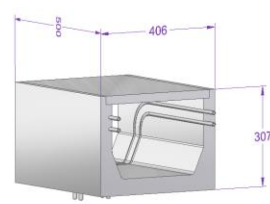
TF coil casings procurement

- Casing mass approx. ~ 10 tons
- Max thickness approx. 90 mm
- Support structures for PF included
- Outer Intercoil structures included
- Casing material 316LN
- 100% welds control
- Dimensional controls with laser track
- Channels for cooling machined inside and sealed
- Jigs for composition and trasnport
- Mock-ups for coil integration included
- Production rate; 1 casing/month









Qualification activities for TF Coils

Activities for WP qualification

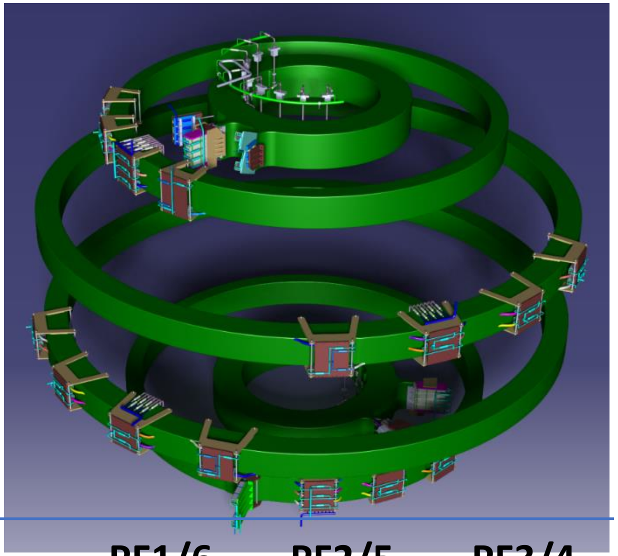
- Heat treatment (up to 650°C for ~ 2 weeks < 200 ppm O2 and other impurities)
- Insulation after heat treatment
- Internal joint (<2nOhm) to be tested in cryogenic conditions
- Vacuum pressure impregnation (VPI)
- Shear strenght test of insulation
- High voltage DC tests in vacuum (Paschen proof) -> Vacuum chamber

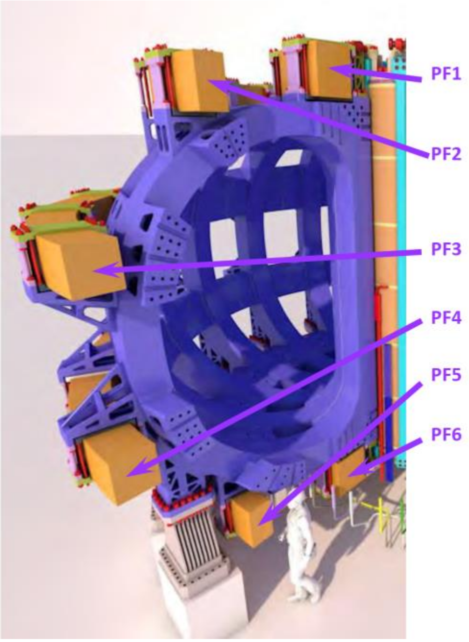
Activities for TF integration

- Welding process qualification record -> chamfer design
- WP insertion and embedding qualification
- Machining qualification and measurement (general medium tolerance class specified unless otherwise stated)
- Piping layout and welding process
- High voltage DC tests in vacuum (Paschen proof) for piping

PF coils procurement outlook

- 1 (inner) Nb_3Sn + 2 (outer) NbTi pairs of up-down symmetric coils
- Technical specifications in review, definitive drawings in preparation (S-DRM in 2022Q3)
- Independent verification analyses on going (2022Q2)
- Study of 9 m diameter PF3 & PF4 transportation on DTT site started
- Tender to be launched in 2022Q3





	PF1/6	PF2/5	PF3/4
CICC	Nb_3Sn	NbTi	NbTi
Iopmax [kA]	28.3	27.1	28.6
Bmax [T]	9.1	4.2	5.3
Turns (radial x vertical)	20 x 18	10 x 16	14 x 14
Dtmargin [K]	1.8	1.9	1.7
Mass [tons]	15	16	28

PF coils winding features

PF1/PF6:

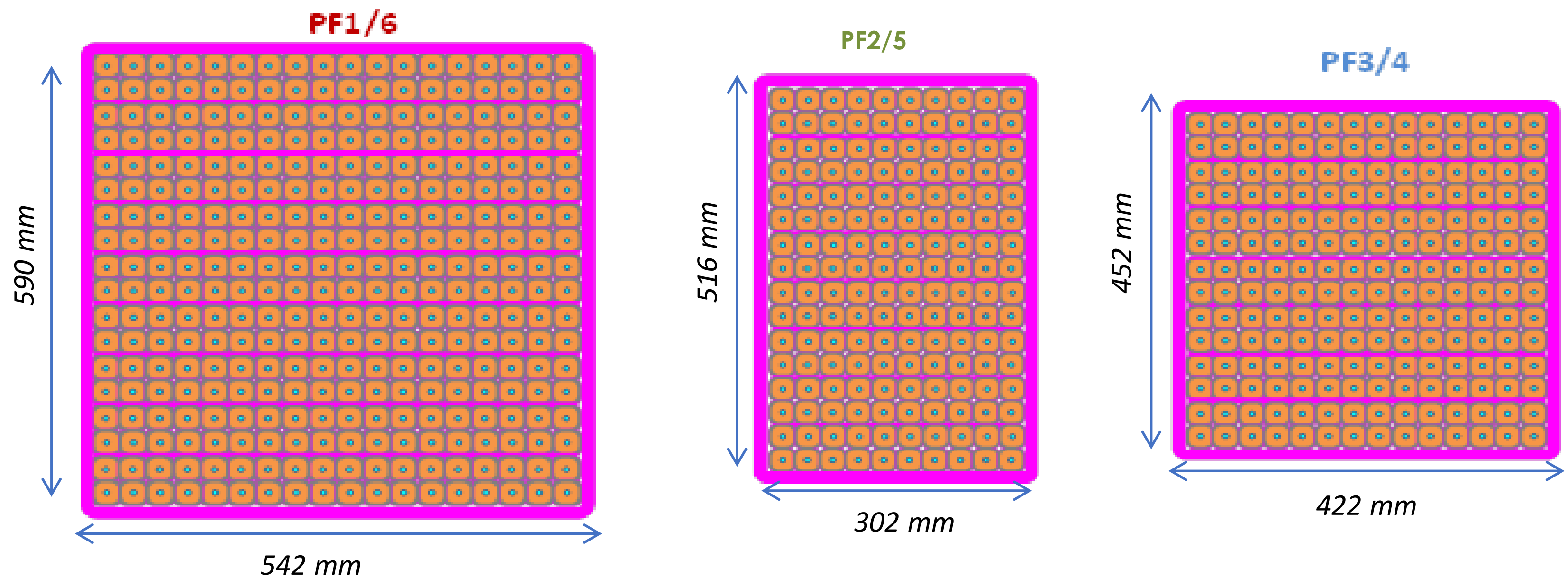
- Coil height ~ 590 mm
- Inner diameter ~ 2,3 m
- Outer diameter ~ 3,4 m
- Mass ~ 20 tons
- Double pancakes 9

PF2/PF5:

- Coil height ~ 516 mm
- Inner diameter ~ 5,8 m
- Outer diameter ~ 6,4 m
- Mass ~ 20 tons
- Double pancakes 8

PF3/PF4:

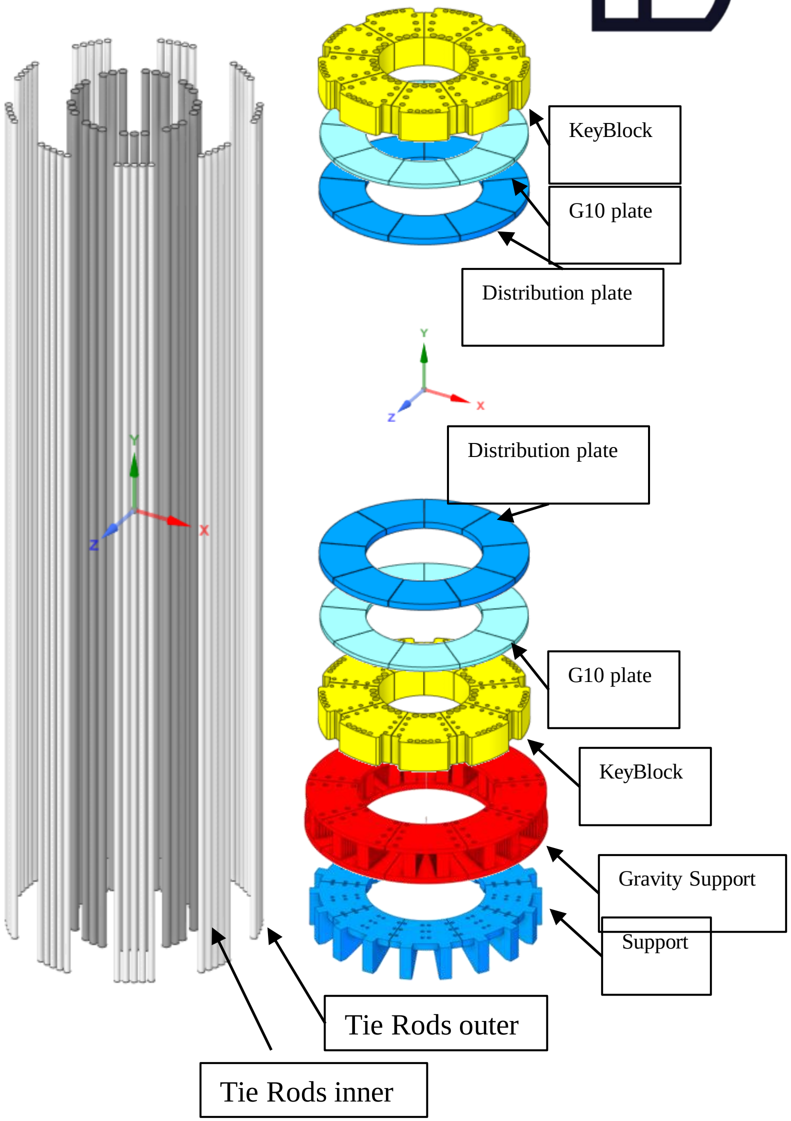
- Coil height ~ 452 mm
- Inner diameter ~ 8,2 m
- Outer diameter ~ 9 m
- Mass ~ 33 tons
- Double pancakes 7



<u>PF6 will be the first component to be tested and delivered</u>

Central Solenoid procurement outlook

- Stack of 6 independently fed modules, tied by a precompressed structure
- Minimum flux required 16 Wb (from max Iop to zero)
- Grading design
- Discussion on CS option (pancake vs layer wound with glass-only Insulation before heat treatment) design in C-DRM (2022Q2)
- Discussion on the pre-load (60 MN) applied at RT by tie-rods vs tie-plates
- CS Engineering and tender preparation to be completed by the end of 2022
- E-DRM in 2022Q4
- S-DRM in 2023Q1
- HV DC tests in vacuum (Paschen proof)
- Tight tolerance on current line diameter and center axis
- Assembly only after testing of each module in cryogenic conditions and full current



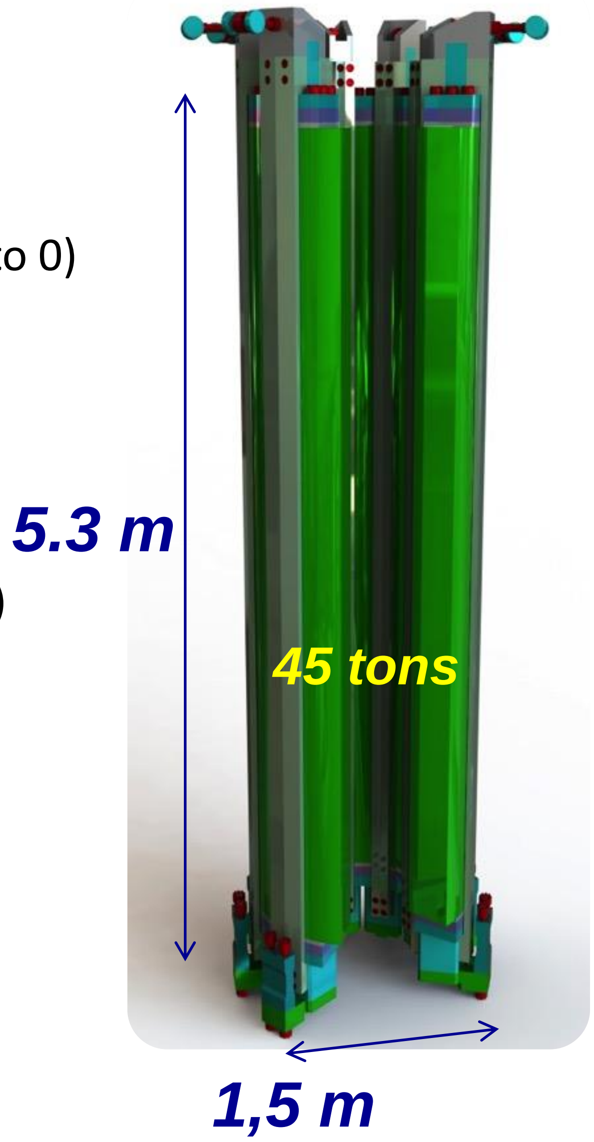
Central Solenoid features

Requirements

- Stack of 6 equals, independently fed modules, tied by a precompressed structure
- Minimum flux required 16 Wb (from max Iop to 0)
- Rmax < 824 mm (innermost TF radius)
- Rmin allowing a possible future insert of additional HTS module

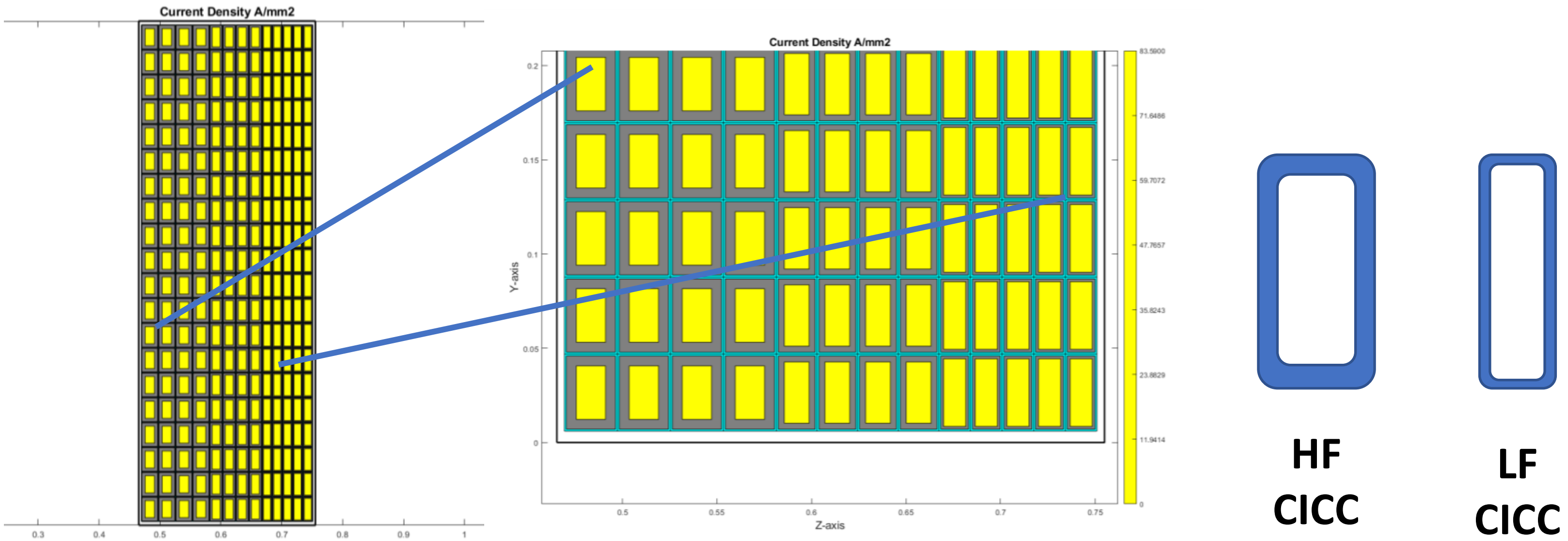
Design choices (tbc)

- Nb3Sn Cable-In-Conduit Conductors
- CICC Iop > 31.3 kA (35 kA with current strands)
- Bpeak: 13.2 T
- Rmin / Rmax: 443 mm / 755 mm
- ΔTmargin > 1.0 K
- Graded design to increase current density
- Module height ~ 0,9 m
- Module inner diameter ~ 0,9 m
- Module outer diameter ~ 1,5 m
- Module Mass ~ 7 tons
- Cycling loading conditions (> 25000 cycles)



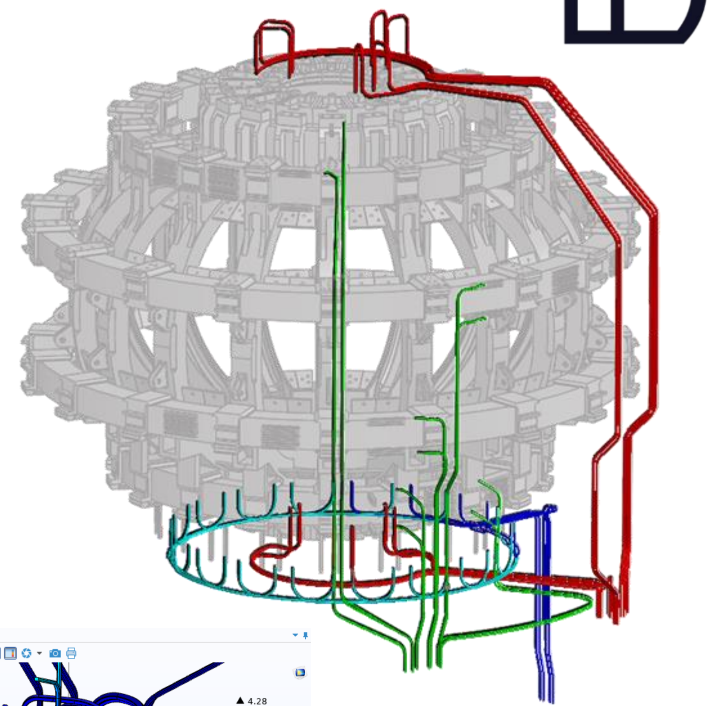
CS alternative design options

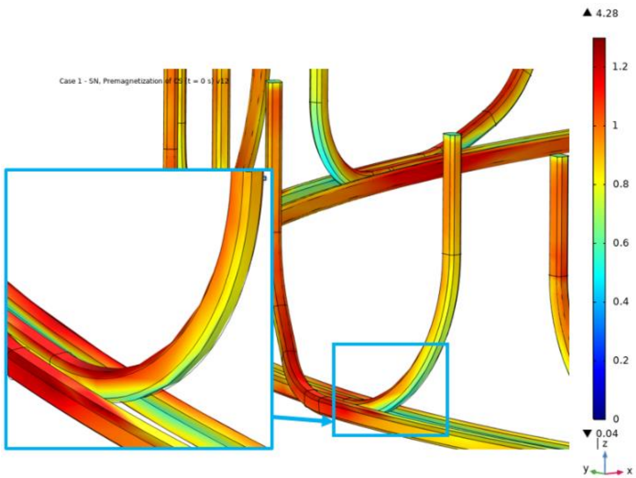
- External panel review triggered analysis of solutions based on Wind, React and Transfer approach, to allow Kapton in inter-turn insulation -> too much R&D required
- Alternative, non-standard hybrid pancake solution with I_{op} = 35.0 kA is being studied, that would allow a flux of 16.0 Weber, but reduce the risks on insulation -> some issues on CICC manufacturing to be clarified
- Some R&D on insulation materials and joints to be carried out in 2022

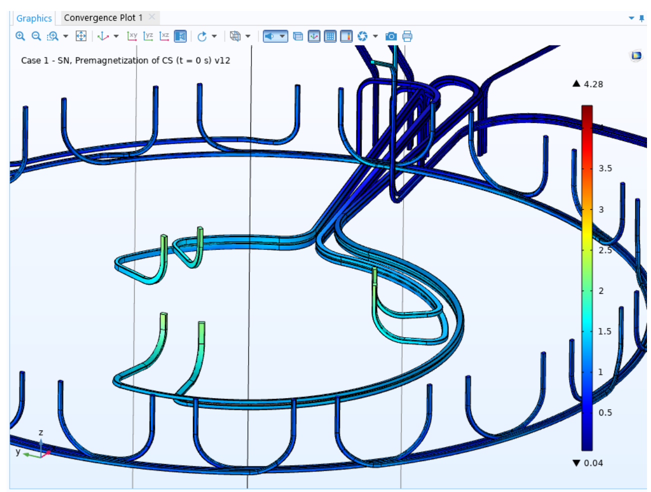


Superconducting Feeders overview

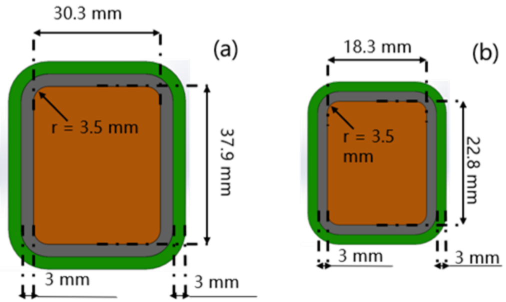
- Feeders routing updated to avoid high field regions
- Thermohydraulic and 3D EM analyses performed
- Feeders design completed
- Design of supports and clamps started (2022Q1)
- C-DRM in 2022Q3
- Main components:
    - NbTi conductors (ad-hoc procurement)
    - Clamps, supports, joints (assembly tender)
    - Current Leads (ad-hoc tender)
    - Coil Terminal boxes to be defined depending on current leads design







Super Conducting Feeders cable layout

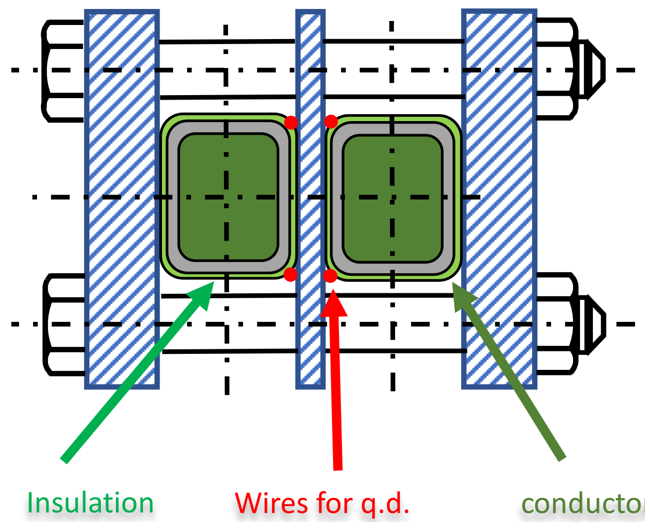


Jacket thickness to be confirmed through 3D mechanical analyses

Main Parameters of the DTT Feeder Design

Parameter	CS	PF	TF /jumpers
# SC strands	1350	162	
# pure Cu strands	0	324	
Cabling pattern	3 x 3 x 5 x 5 x 6	(1 SC + 2 Cu) x 3 x 3 x 3 x 6	
Strand diameter	0.82 mm	0.82 mm	
Void fraction (%)	35.4	34.9	
Twist pitch sequence	35/80/125/190/290		
Jacket thickness	3 mm	3 mm	
Insulation thickness	3 mm	3 mm	
Maximum field	5.5 T	3.1 T	
Maximum transport current	32 kA	32 kA	42.5 kA
Operating temperature	4.5 K		
Nominal mas flow rate	5 g/s		

- ⊕ & ⊖ feeders clamped together to counter the *e.m.* force
- Glass-Kapton-Glass tape and epoxy resin for insulation
- Voltage taps for quench detection attached along and wound around the conductor to cancel the inductive voltage



(Pre-preg fiberglass or ETFE/TEFZEL®)

Magnet signals and diagnostics outlook

About 2000 HV signals wires foreseen for TFC, PFC, CSC in total

Under analysis:

- HV cryostat feedthrough
- Signals grouping and conditioning
- Set of signals to be used in CTF
- Study of HV wires insulation in cryostat

HV wires included in coil procurements (up to cryostat) and in assembly tender (out of cryostat)

Item #	Coil/System/Component	N°	Flowmeter- TOLL [0.01 g/s]	Thermometer (3-300 K) - TOLL [0.01 K]	Voltage Tap(0-3kV) - TOLL [1 mV]	Cowound	Pressure (0-10 bar) - TOLL [0.1 bar]	Strain gauge	Notes
1	TF-Coil	18	36	36	36		18		
2	TF-Case	18		54				126*	*2xN(inner-leg)+x3N(outer-leg)+2*N(OIS)
3	TF-Cooling channels	144		19*					*1 in + 18 out (cooling channels)
4	CS-Modules	6	12	24*	48	168	12		*1 in + 3 out per module; ** 1 per module + 1 cowound
5	CS-Tie Plates	18						36	
6	CS-Support	9						18	
7	PF-Coil	6	12	12	48	192	12	54**	* 1 per DP + 1 cowound; ** 9 per coil
8	PF-Support	54						108*	*2 per support
9	Feeders	24	24	48	384	192			
10	Currents Leads HTS	6	6	30	60				
11	Current Leads Cu	24	24	120	24				
TOTALS			**114**	**343**	**600**	**552**	**42**	**342**	
			4wire	4wire	HV3	HV4	4wire	4wire	

				TOTAL	PF	CS	feeders
	cavi	passanti	cowound	552	192	168	192
4wire	841	3364	passanti	2208	768	672	768
HV3	600	1800					
HV4	552	2208	VT	480	48	48	384
	1993	7372	passanti	1440	144	144	1152

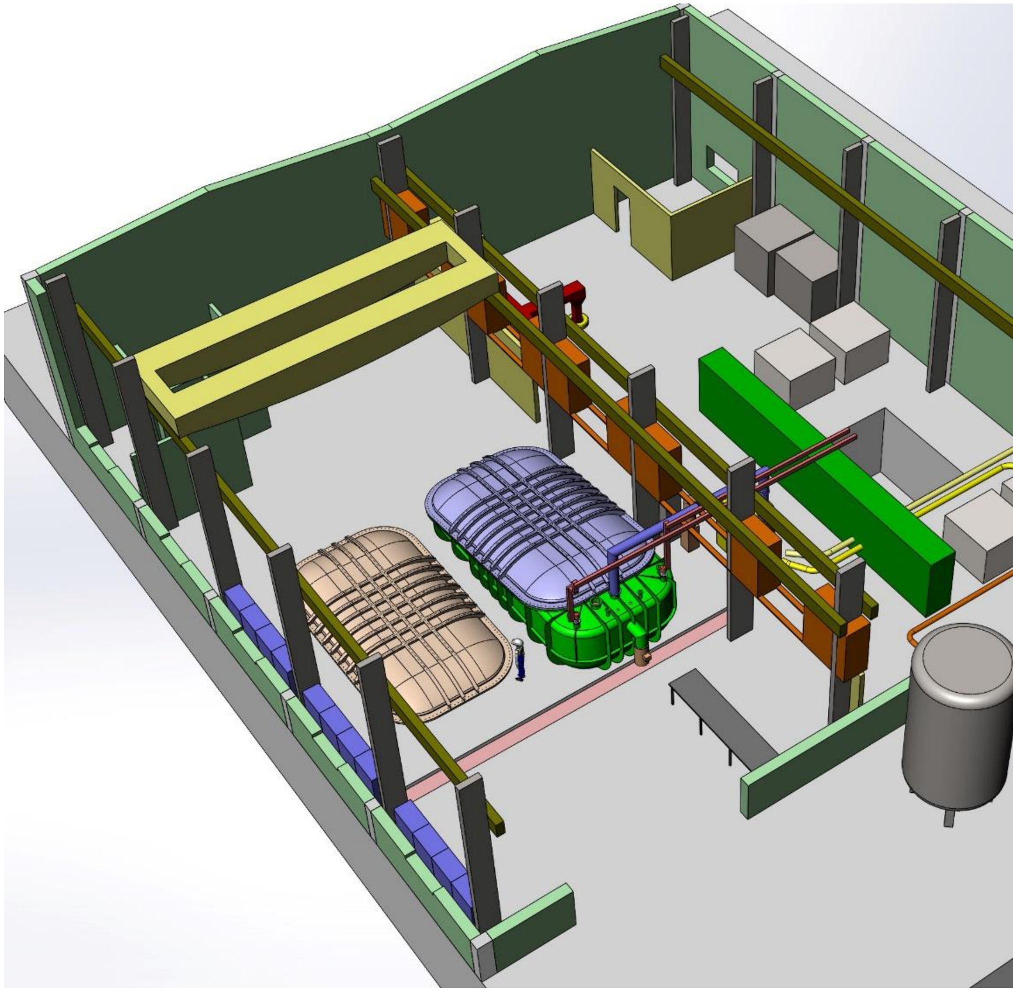
ENEA Frascati Cold Test Facility

All Nb3Sn coils will be cryogenc 4.5K tested in ENEA CTF

- Procurement by ENEA in progress
- Test rate: ~ 2 month per TFC including coil preparation, cool-down (1 week), testing (1 week), warm-up, coil release

Key issues:

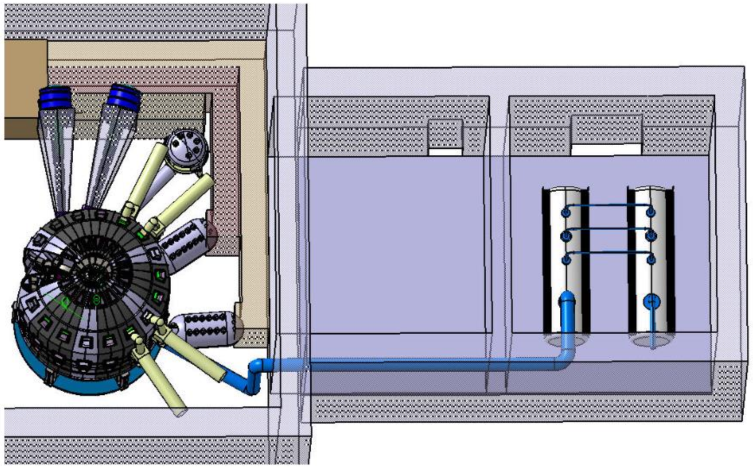
- High voltage DC tests in vacuum at Cryogenic 4.5 K, 6 bar, nominal current
- Quench test
- Insulation resistance test
- Joint resistance test (< 2 nOhm)

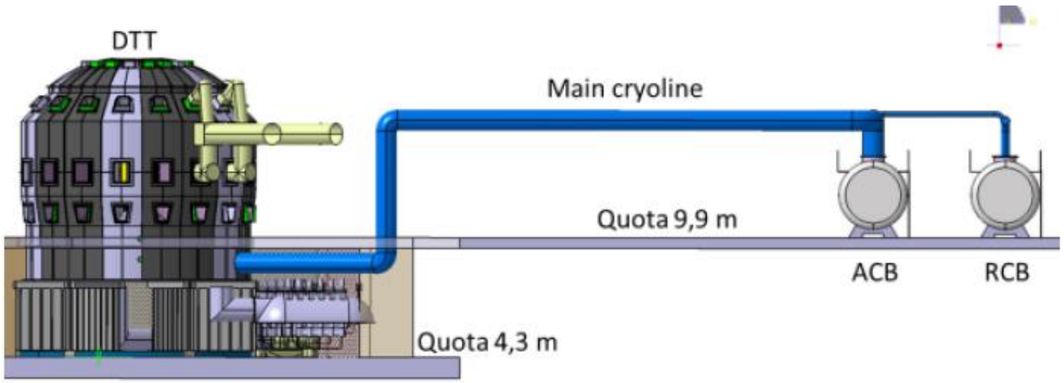


Cryoplant subsystem overview

DTT-CEA agreement divided in three steps devoted to Cryoplant design

- First step aimed at identifying by the end of 2022 the preliminary functional design suitable is close to start
- This preliminary design will be used as reference for launching a competitive dialogue with manufacturers in 2023
- Main components:
  - Cold boxes (RCB, ACB)
  - Cryolines
  - Cryogenic valve boxes
  - Coil terminal boxes
  - Warm compression station
  - Helium storage tanks
  - Quench recovery line
  - Nitrogen storage tanks





DTT Magnet Integration

G. Ramogida

Making DTT together

DTT Team

Thank you for attention and patience