ENEA
Agenzia nazionale per le nuove tecnologie,
l'energia e lo sviluppo economico sostenibile

AEIT 1897
SEZIONE di PALERMO

ORDINE DEGLI INGEGNERI
DELLA PROVINCIA DI PALERMO

ALIMENTAZIONI ELETTRICHE DI DTT

SEMINARIO “NUCLEARE: PRESENTE E FUTURO”

PALERMO,15 DICEMBRE 2022

Ing. Pietro Zito FSN-FUSEN-DIA/DTT S.c.a r.l. (per conto PSS Team di DTT)

Contenuti

Superconducting magnets system

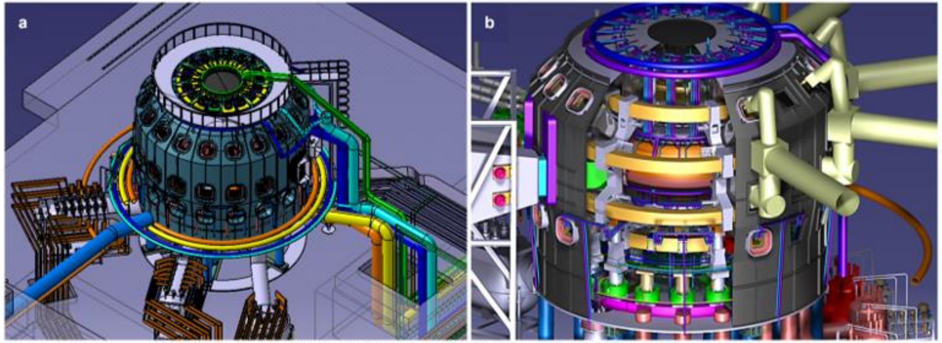


Fig. 1. Outside (a) and inside (b) view of the DTT tokamak.

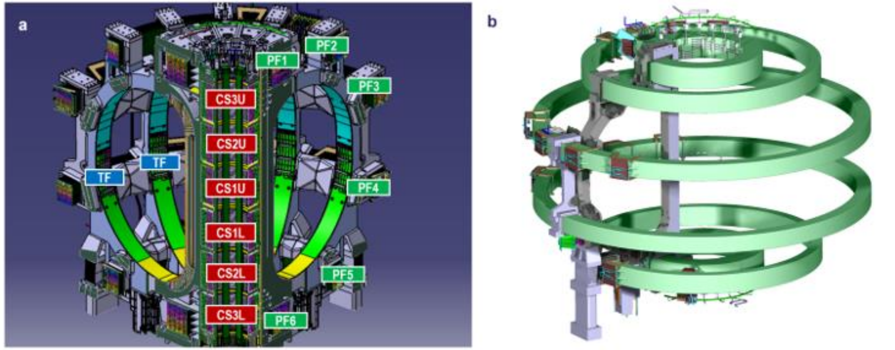
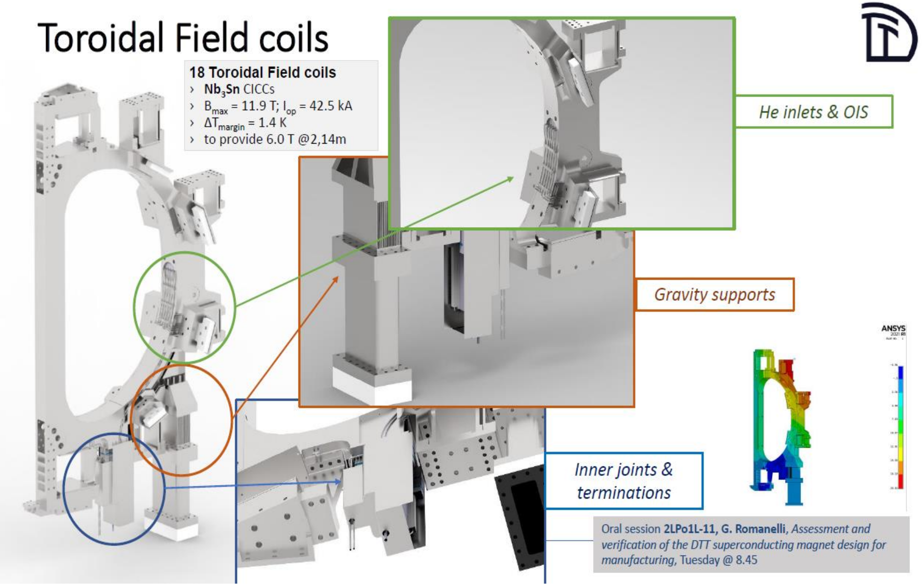


Fig. 2. Arrangement of the DTT superconductive coils (a), classified as TF (18 coils), CS (6 modules) and PF (6 coils), and details of the PF coils and their connection with the TF coils (b).



Toroidal Field coils

18 Toroidal Field coils

- **Nb_3Sn** CICCs
- B_{max} = 11.9 T; I_{op} = 42.5 kA
- ΔT_{margin} = 1.4 K
- to provide 6.0 T @2,14m

He inlets & OIS

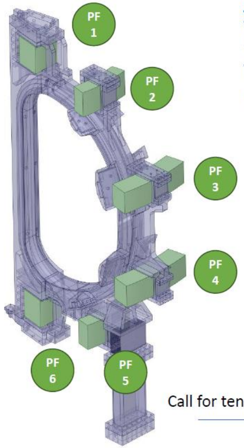
Gravity supports

Inner joints & terminations

Oral session **2LPo1L-11, G. Romanelli**, *Assessment and verification of the DTT superconducting magnet design for manufacturing*, Tuesday @ 8.45

Superconducting magnets system

PF Coils



PF coils (along with CS) provide flexibility to DTT performances, so:

The 6 coils and supports are designed at the reference conditions +10% operative current.

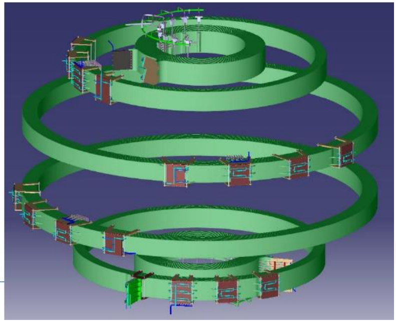
Top-down almost perfect simmetry is implemented in design.

Large temperature margins (around 2 K) are taken.

6 Poloidal Field coils
- **4 NbTi & 2 Nb_3Sn** CICCs
- B_{max} = 2.5 – 9.2 T; $I_{op\text{-}max}$ = 8.7 - 28.5 kA
- ΔT_{margin} = 1.5 K – 2.5 K

Pancakes winding technique.

For assembly and room occupancy reasons, some inner joints (those of PF1/6) are embedded into winding.



Call for tender to be launched within end of 2022

CS Coils

6 Central Solenoid module coils:
- **Nb_3Sn** CICCs
- B_{max} = 13.6 T, 10.7 T, 8.8 T; I_{op} = 31.3 kA
- ΔT_{margin} = 1.0 K

- ✓ The 1,5m bore diameter along with a requirement of 16.6Wb flux swing, require to work with high current densities (J_E up to 40 A/mm^2) and EM loads/stresses
- ✓ Room optimization is performed by conductor grading
- ✓ Layer-wound technique + use of embedded joints
- ✓ Some doubts on the insulation manufacturing quality linked to this technique, still requires further investigation

Alternative designs are under investigation.
(based on pancake winding or on reduction of number of grades)

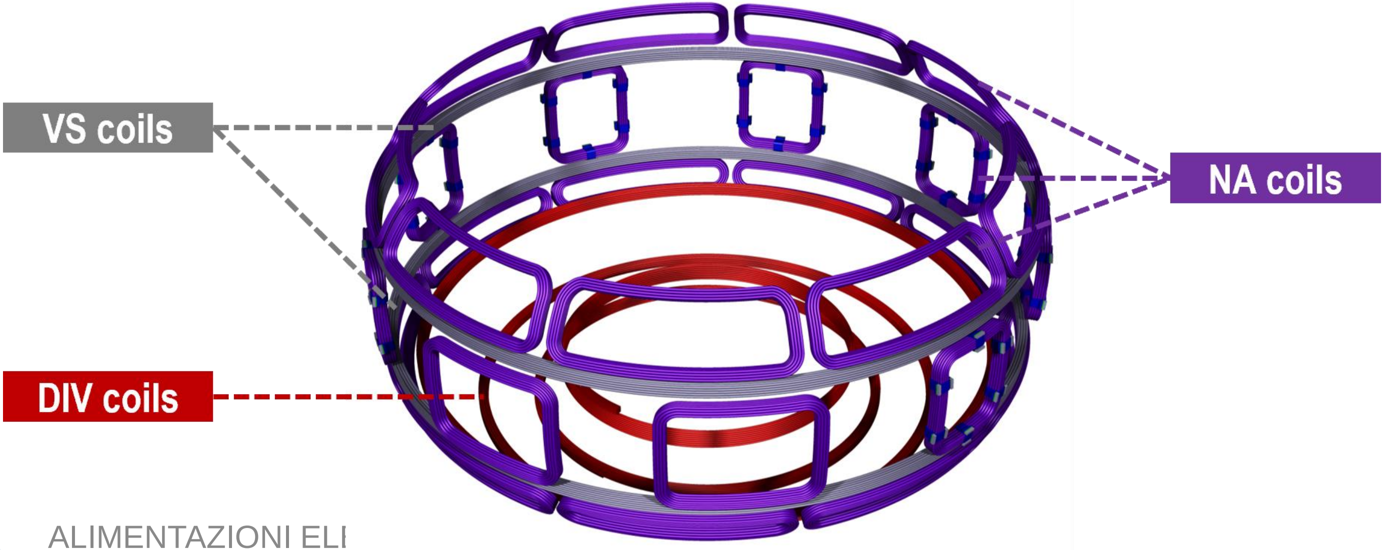
Request to provide 16.6 Weber magnetic flux is under discussion, as at present this is the most loaded SC component of the project.

Relaxation of this parameter, may open the way to design the modules with an higher degree of confidence in their reliability along the about 60.000 loading cycles they shall face in the machine's lifetime.

In-vessel coils system

The control of the plasma and power exhaust requires high-performance PSs for all the in-vessel coils. In DTT, there are 3 types of in-vessel coils:

1. Vertical Stabilization (VS) coils (ICA)
2. Divertor (DIV) coils (ICA)
3. Not-Axialsymmetric (NA) coils (ICN, saddle)



DTT superconducting magnet PSs

- A 44-kA 24-pulse AC/DC converter supplying the 18 toroidal field (TF) superconducting coils, protected by a bypass crowbar;
- Three fast discharge units (FDUs) to protect the TF coils in case of faults as quenches in the superconductors;
- Six PSs for the six superconducting modules of the central solenoid (CS), based on energy-conservation topologies to reduce the impact on the external grid;
- Six switching network units (SNUs), for both CS breakdown overvoltage and discharge protection;
- Six PSs for the poloidal field (PF) superconducting coils, partially based on energy storage, able to generate the breakdown voltage without a SNU;
- Six FDUs for the PF coils;

DTT In-vessel coil PSs

- Two PSs feeding the two vertical stabilization (VS) in-vessel copper coils;
- An additional branch including a PS or a large inductor to imbalance the VS coils for radial control and for protection in case of disruption;
- Three or four PSs for the four copper coils placed close to the divertor (DIV) in order to shape the field and plasma configurations in that zone;
- An additional inductive branch to protect the DIV coils in case of disruption;
- A system supplying 27 non-axisymmetric (NA) in-vessel copper coils for error field correction (EFC) and edge-localized mode (ELM) control.

DTT superconducting magnet PSs

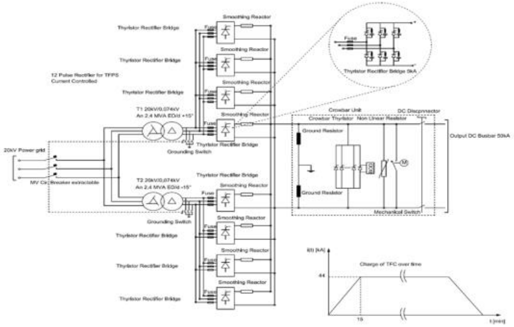
Coil group	TF	CS	PF1/6	PF2/5	PF3/4
Coil material	Nb_3Sn	Nb_3Sn	Nb_3Sn	NbTi	NbTi
Load inductance (mH)	48 for 1 coil 2200 for 18 coils	75	454	298	690
Quadrants in output	2	4	4	4	2
Regulation	I or V	I or V	I or V	I or V	I or V
Current (kA)	44	±32	±28.5	±22.7	27.9
Voltage (kV)	±0.1	±1	±2	±3	±3
Peak power to the load (MVA)	4.4	32	57	68	84
Peak power from the grid (MVA)	4.4	2.4	2	2	2
Maximum duration of operation (s)	Steady-state	200 s	200 s	200 s	200 s
Reference waveform	Constant current	Scenarios	Scenarios	Scenarios	Scenarios
Average current accuracy (%)	±1	±1	±1	±1	±1
Current ripple (%)	0.1	0.1	0.1	0.1	0.1
Breakdown voltage (kV)	Not requested	3	2	3	3
Energy stored in the coil (MJ)	46 for 1 coil 2050 for 18 coils	37	184	77	269
Discharge time constant τ (s)	6	4	5	5	5
Maximum FDU (discharge) voltage (kV)	5.5	3	3	3	3
Topology	Thyristor bridge	IGBT-based	IGBT-based	IGBT-based	IGBT-based

DTT In-vessel coil PSs

Coil group	VS	DIV	NA
Coil material	Cu	Cu	Cu
Number of independent load coils	2	3/4	27
Load inductance (mH)	6.7	0.7÷1.7	5
Additional branch inductance (mH)	20	1.32	Not present
Quadrants in output	4	4	4
Regulation	I or V	I or V	I or V
Current (kA)	±4.4 (+3 imbalance)	±5	±2.5
Voltage (V)	±3900 (+1100 imbalance)	±500	±400
Peak power to the load (MVA)	4.4	32	57
Peak power from the grid (kVA)	200	400	3000
Maximum duration of operation (s)	100	100	100
Reference waveform	Triangular	Constant	DC + sinusoidal
Bandwidth of current at -1 dB	40 Hz	4 Hz	7 Hz
Average current accuracy (%)	±0.5	±0.5	±0.5
Current ripple (%)	0.1	0.1	1
Topology	IGBT-based	Thyristor/IGBT-based	IGBT-based

DTT TF PS system

- The TFCPS is a 2-quadrants 24-pulses AC/DC converter thyristor based converter with an output DC current up to 44 kA.
- The FDUs are the quench protection system designed for the safe and the fast dissipation of magnetic energy stored in the TF superconducting magnets. The protection is implemented by connecting a dump/discharge resistor in series to each TFC sector through a redundant by-pass switch, in this case completely static IGCTs based.



TF PS Parameters

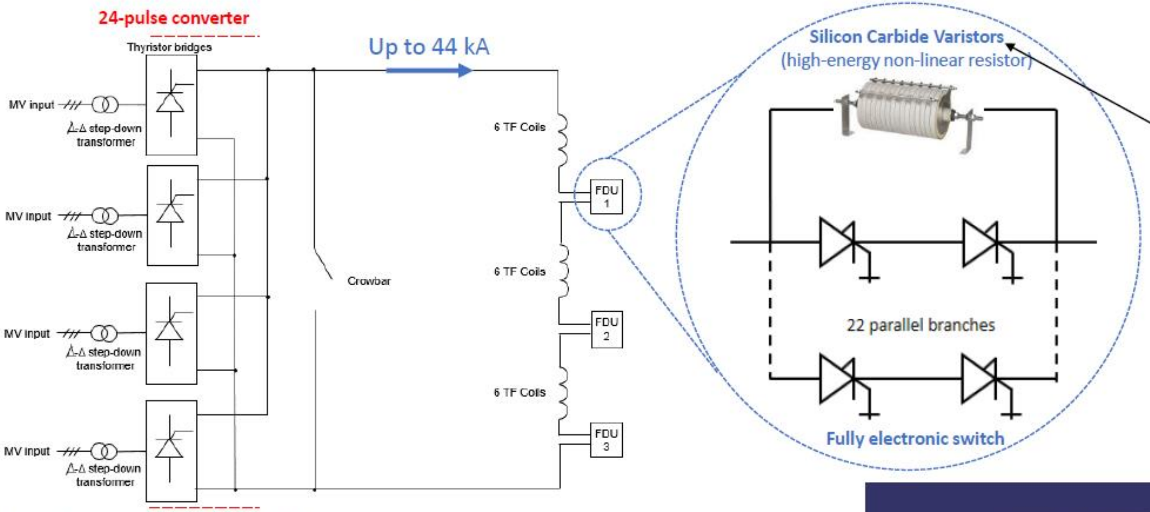
Parameter	Value
Base PS	
Operations	Steady State
Rated output voltage	± 100 V
Rated DC output current	42.5 kA + 3.5% (44 kA)
Current/voltage accuracy	≤ 1 %
Current ripple	≤ 0.1 %
Insulating voltage to ground	7.2 kV
Crowbar	
Type	Unidirectional
I^2t	7.23 GA^2s
Number of operations without maintenance	2000
Insulating voltage to ground	7.2 kV
Rated DC output current	42.5 kA + 3.5% (44 kA)

FDU Parameters

Parameter	Value
Type	Unidirectional
Operating current	42.5 kA
Total energy for one FDU	0.7 GJ
Specific energy through	7.23 GA^2s
Insulating voltage to ground	7.2 kV

DTT TF PS system

Toroidal Power Supply and Fast Discharge Units

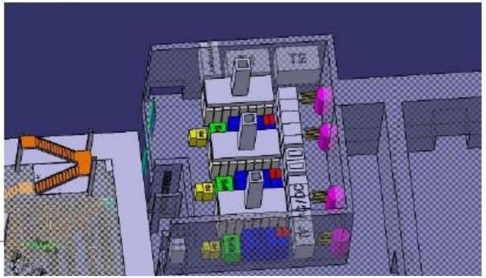


To obtain a quasi-linear safety discharge

Procurement contracts signed in 2022:

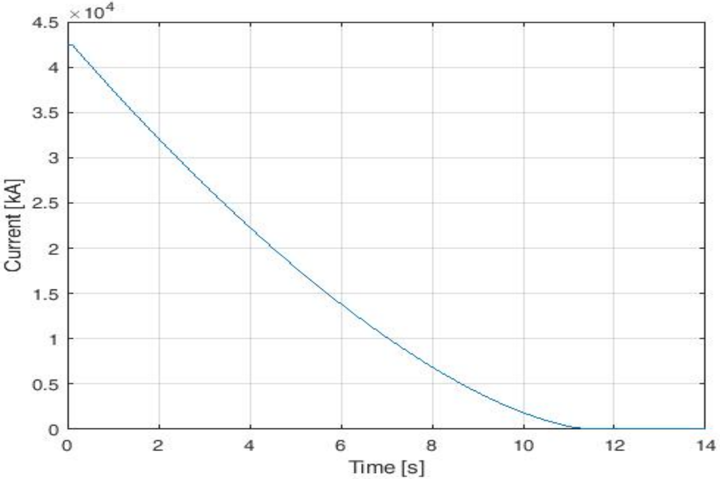
1. TF power supply system provided by JEMA (Spain)
2. TF FDUs provided by OCEM (Italy)

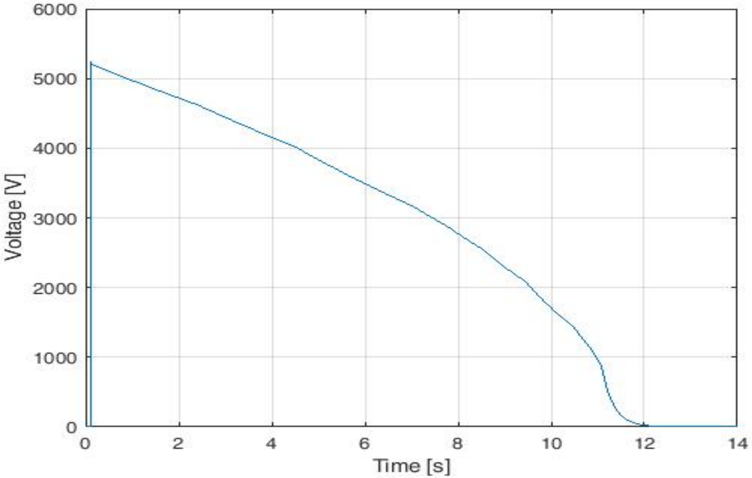
First deliveries from 2023 to be installed in the Frascati Coil Cold Test Facility @ ENEA, to test TF (and other) coils in nominal conditions.



DTT TF FDUs

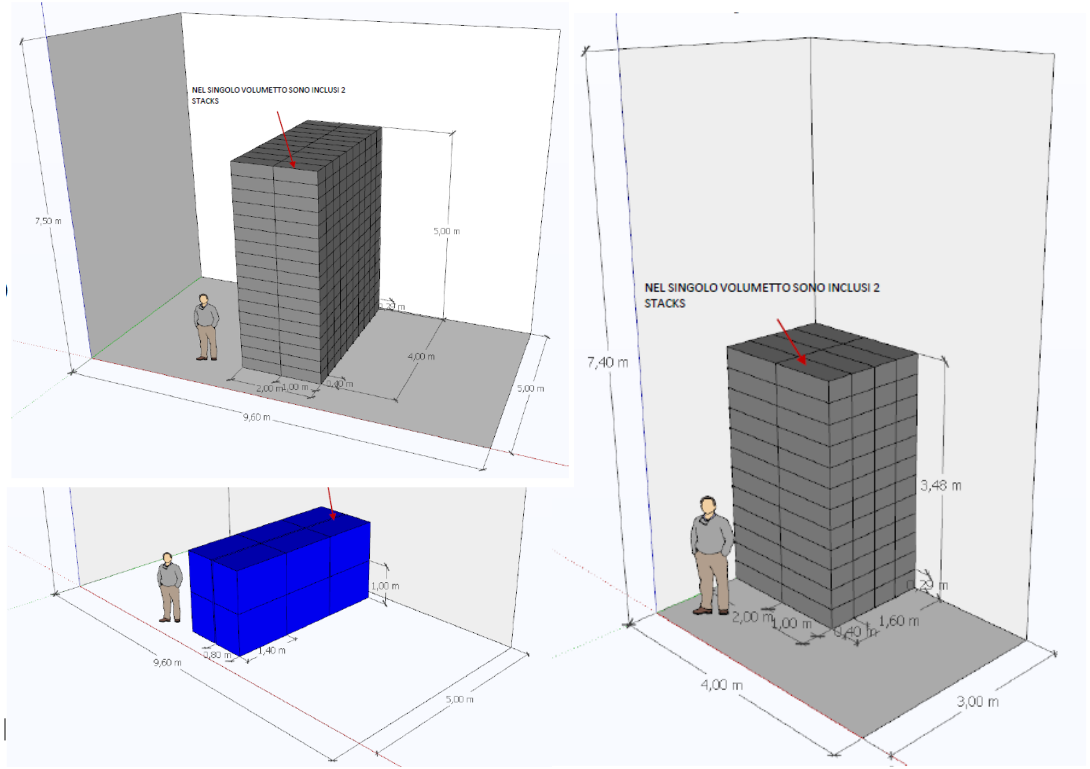
In DTT FDUs standard resistors were replaced by properly designed Silicon Carbide varistors achieving an almost linear and faster discharge instead of an exponential current discharge (implemented in ITER and JT-60SA). Also, standard resistors would produce a voltage across the switches ≥ 6.5 kV and would force to use two ICGTs in series.





DTT TF FDUs

The adopted technical solution allows a relevant reduction of the voltage stresses on components and reduced discharge time in a reliable way, with less volume occupation.



DTT TF PS system

Frascati Coil Cold Test Facility

Construction on-going @ ENEA, Superconductivity labs
Hall is undergoing preparation works.

All Nb_3Sn coils will be tested in close-to-operative conditions, aimed at checking electrical integrity of coils at cryogenic temperature, SC performances (even if at lower conditions), thermal-hydraulic characteristics, joints behaviour and resistance values, power supplies and quench protection systems (FDU or SNU).

Cold tests will minimize the risk associated to SC coils manufacturing.

Side beneficial effect, is to let a younger team practising with cryogenic aspects, magnets operations and data acquisition/quench detection systems.

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ctober 2022

32

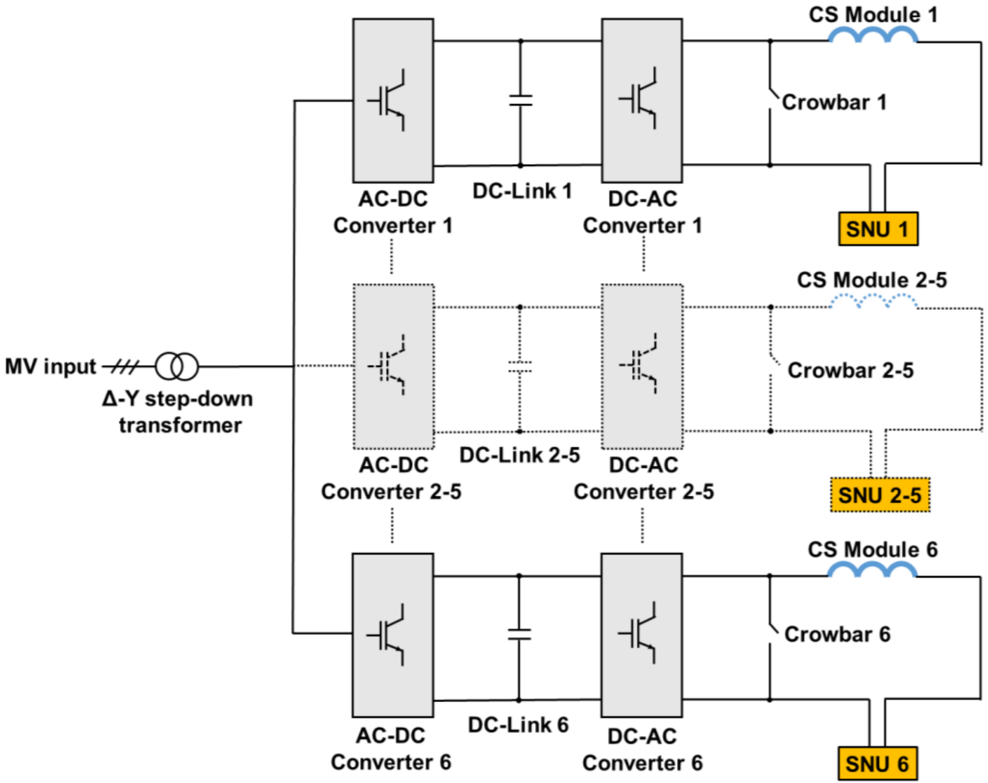
DTT CS PS system

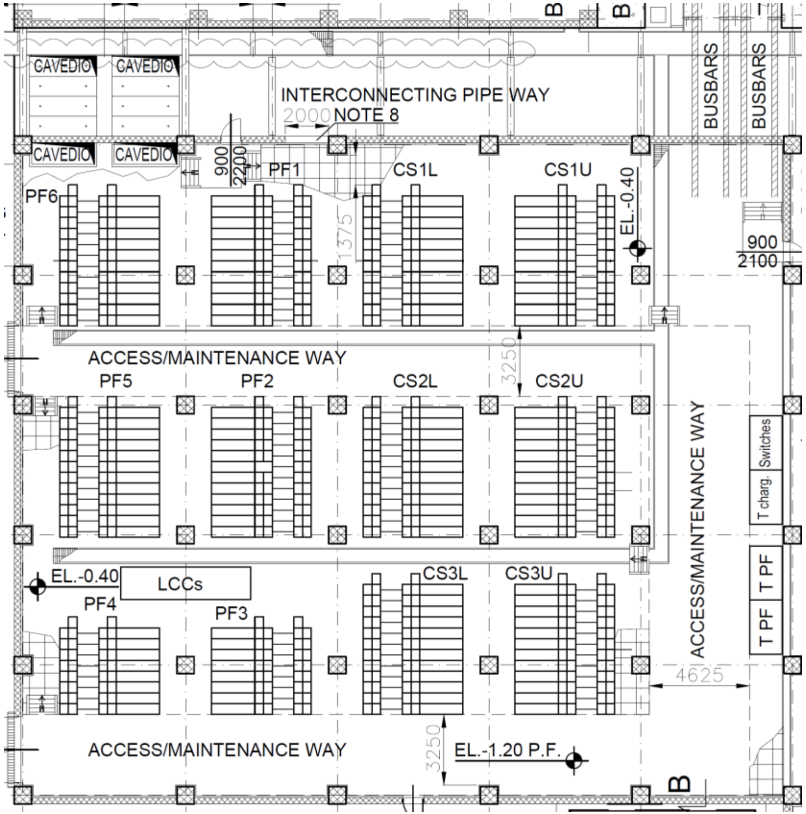
The DTT CS is divided in three symmetric couples of “upper” (U) and “lower” (L) modules (CS3U, CS2U, CS1U, CS1L, CS2L, and CS3L), with one independent PS each.

As the supercapacitor-based DC-link reduces the input power demand, a single transformer can provide sufficient power for all the six circuits. In order to not increase the CS PS output voltage, the SNUs are introduced to generate an overvoltage of about 2-3 kV at the plasma breakdown.

The SNUs support each CS circuit since the CS breakdown voltage is higher than the PS voltage.

DTT CS PS system

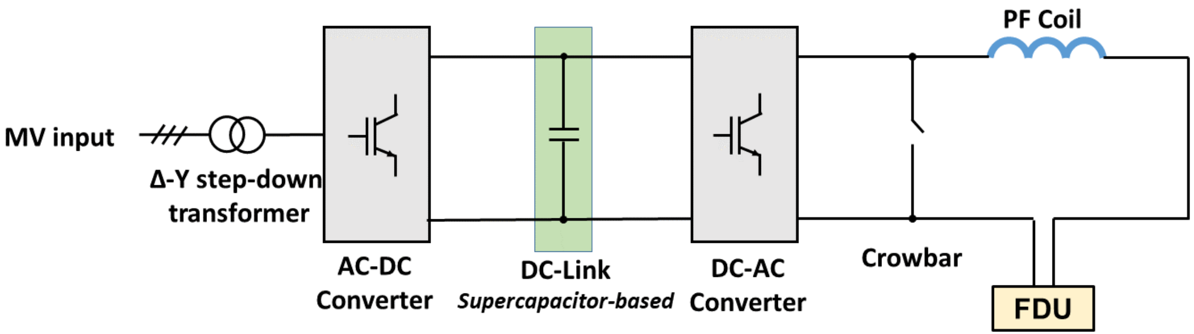


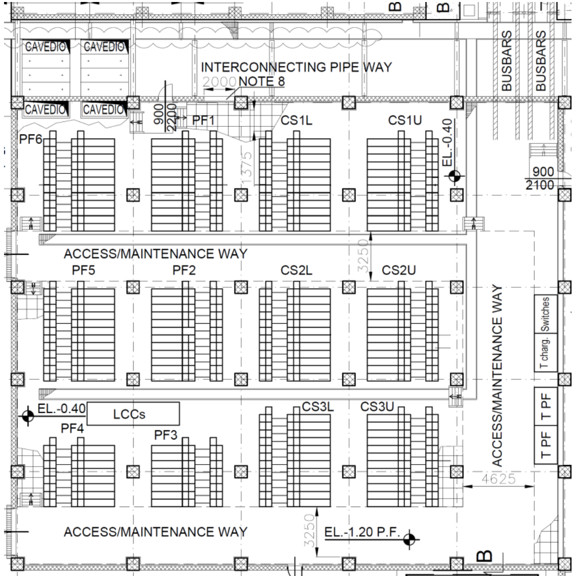


DTT PF PS system

The six PF coils (PF1 to PF6) are feed by independent PSs. The six PF power supplies can be grouped in three different set based on the electrical characteristics derived by the DTT plasma scenarios.

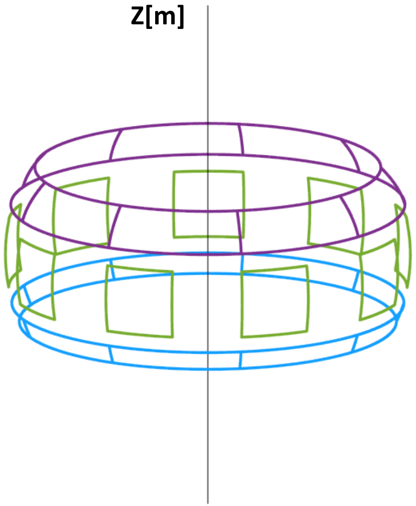
A supercapacitor-based energy storage solution is employed also for the PF PSs. In this case, the ratings were selected sufficiently high to produce the breakdown voltage without a SNU.

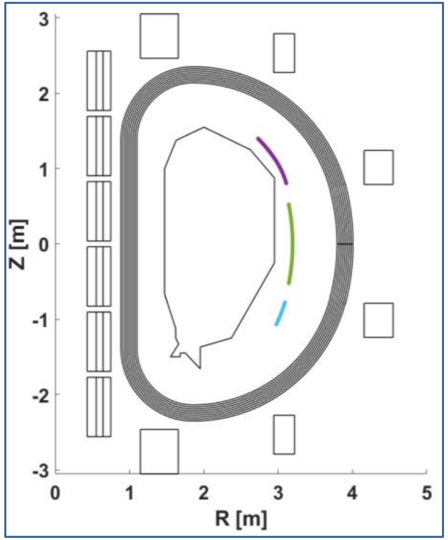




DTT NA PSs

- These will be financed by PNRR (Call for Tender to be launched in January 2023)
- Number of coils is defined to 3×9=9×3=27 coils
- Requirements in terms of EF and ELM defined
- Many activities on disruptions (last design choices to be defined)

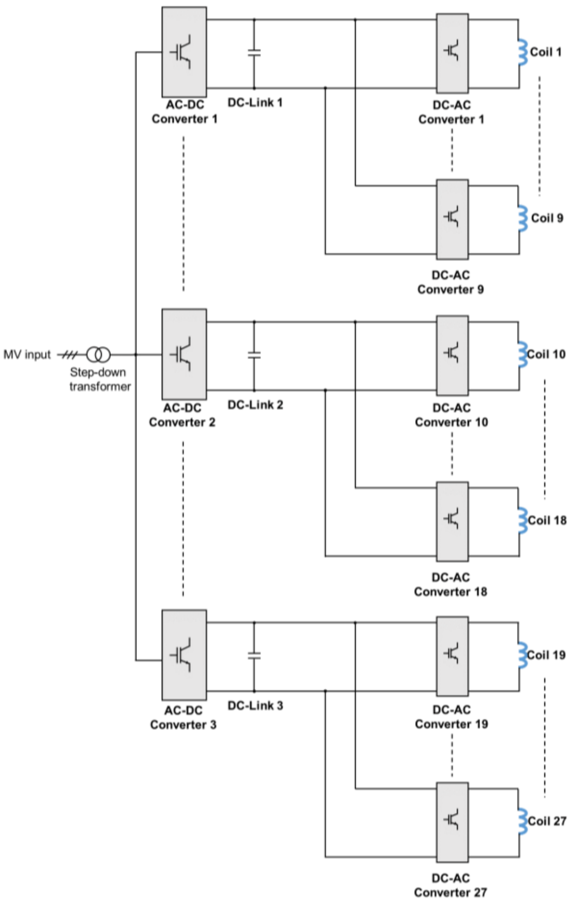




DTT NA PSs

General electrical scheme is similar to that implemented for JT-60SA EFCC.

JT-60SA	DTT
Totally independent PSs	✓
3×6=18 coils	3×9=27 coils
1500 A peak per coil	Much more
400 V	Probably same
7 Hz	✓
IGBTs (SCRs would be possible)	✓
Unidirectional AC/DC stage	✓
1 transformer 1 AC/DC 1 shared DC-link	3 transformers 3 AC/DC 3 DC-links (by row)
No Crowbar (control of disruption)	Much more induced voltage

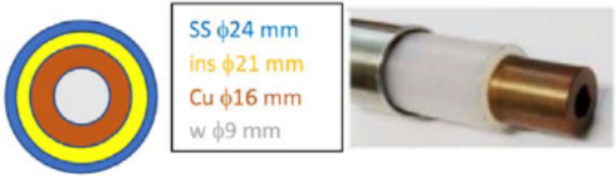


DTT NA PSs

- Problems of turns: in DTT maximum **23 turns**

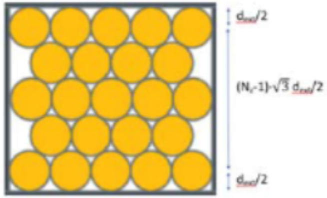
  (trying to optimize position)

(ASDEX-U-like conductor)



- Theoretical requirements on currents:
  - Error Field Correction:
    - 2.2 kA for 50 kAt
    - At lower frequencies, almost in DC
  - ELMs:
    - 0.87 kA for 20 kAt
    - At 7 Hz

23 turns



120 mm x 107 mm

- We agreed to fix the nominal maximum current **2500 A**
  - (< 0.87 kA + 2.2 kA), as EFC should not require all coils at full currents, leaving room to the optimization of the circuit connections

DTT NA PSs

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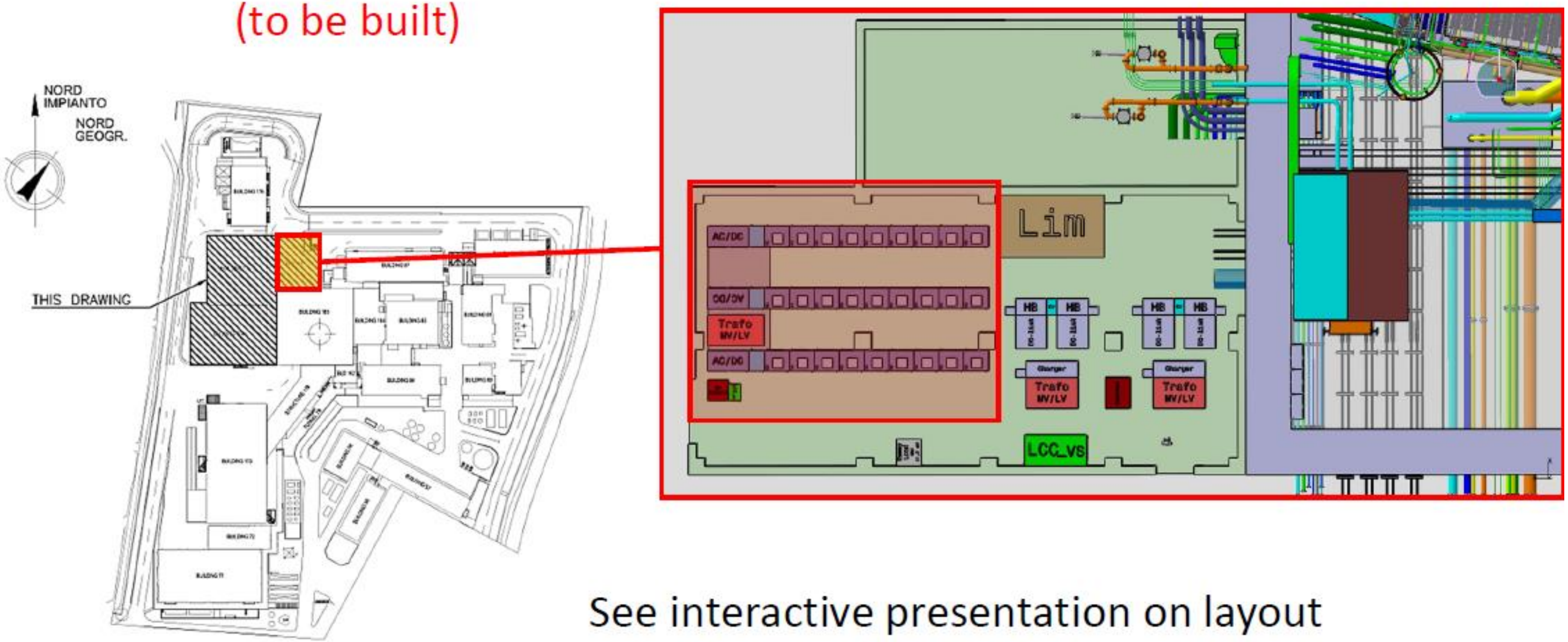
(to be built)

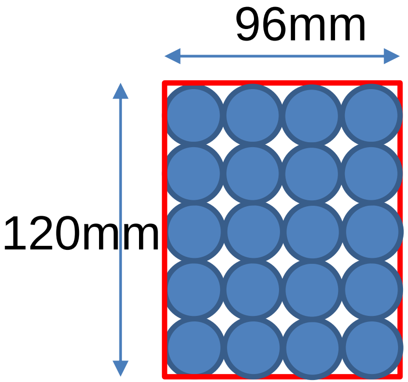


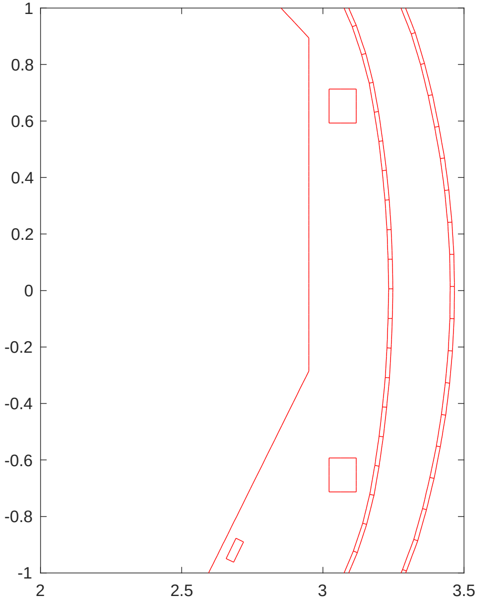
See interactive presentation on layout

DTT VS PS system

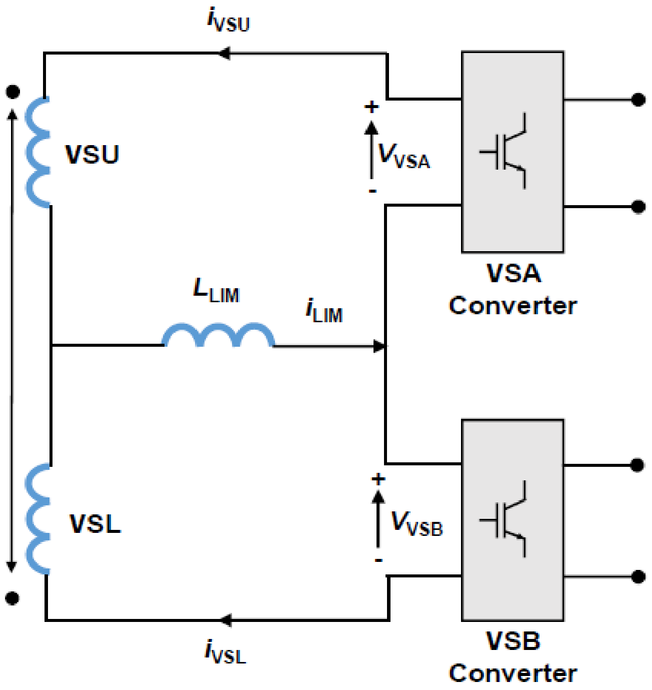
More complicated design:

- Assuming 20 turns, each VS load L=6.7 mH
- Fast control, but on two different phenomena: parameters under definitions
- Main problem is disruption protection
  - Maximum induced currents in conductors: ≈7 kA
  - Maximum induced currents on the imbalance branch: ≈5 kA
  - Assuming $I_{\text{operative}}$≈6 kA, the worst case in the circuit is ≈13 kA





DTT VS PS system



Requirements for radial control

- Imbalance inductance: $L_{\mathrm{IM}} = 30\ \mathrm{mH}$
- Imbalance resistance: $R_{\mathrm{IM}} = 200\ \mathrm{m\Omega}$
- Imbalance voltage: $V_{\mathrm{IM}} = 2\ \mathrm{kV}$
- Imbalance current: $I_{\mathrm{IM}} = 6\ \mathrm{kA}$

Good reduction

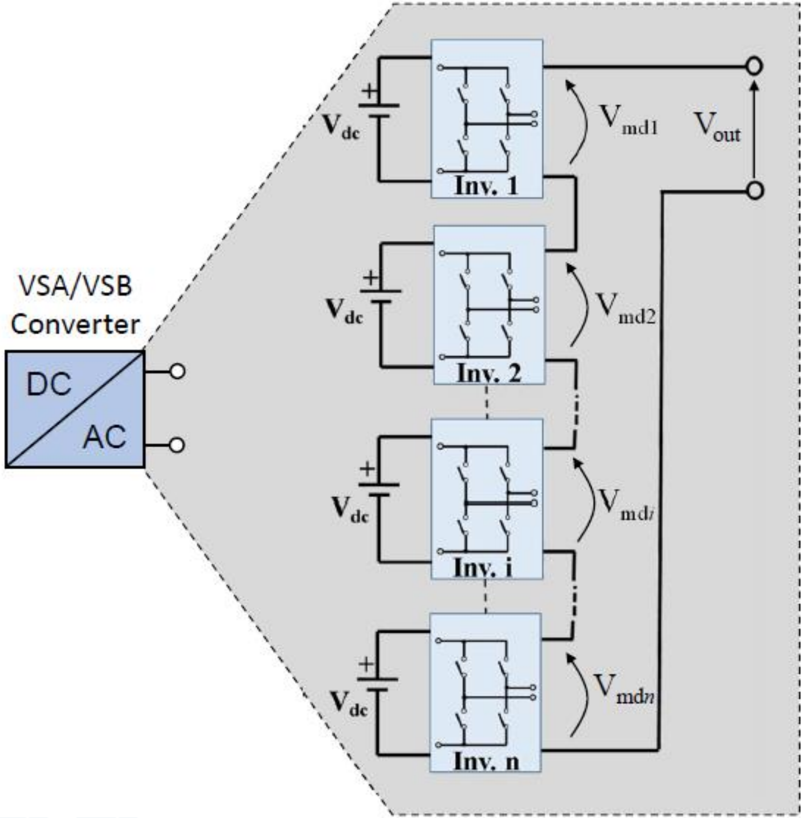
Requirements for vertical control

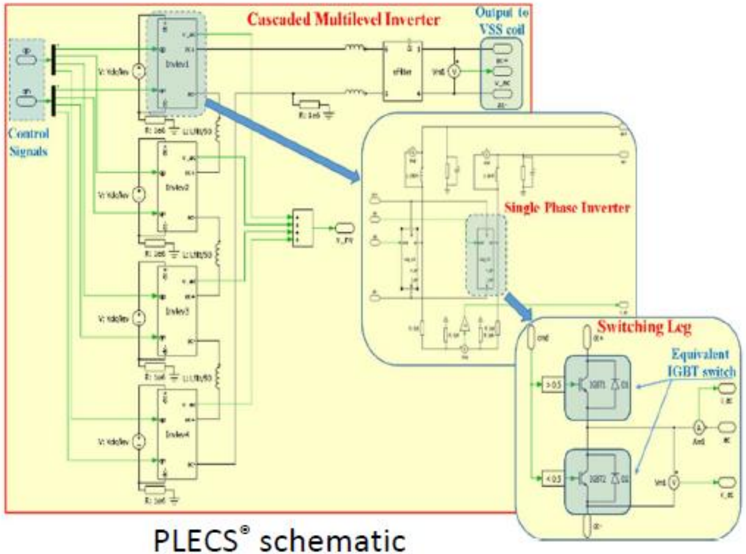
- Anti-series voltage: $V_{\mathrm{VS}} = 3.6\ \mathrm{kV}$
- Anti-series current: $I_{\mathrm{VS}} = 3\ \mathrm{kA}$

Requirements for the converters V_{VSA2} and V_{VSB2}

- Driven with the same voltage for vertical control
- Driven with opposite voltage to produce a radial control
- 4-quadrant IGBT-based
- Each with 4 kV
- Current reaches 6 kA in the most severe current unbalance conditions

DTT VS PS system

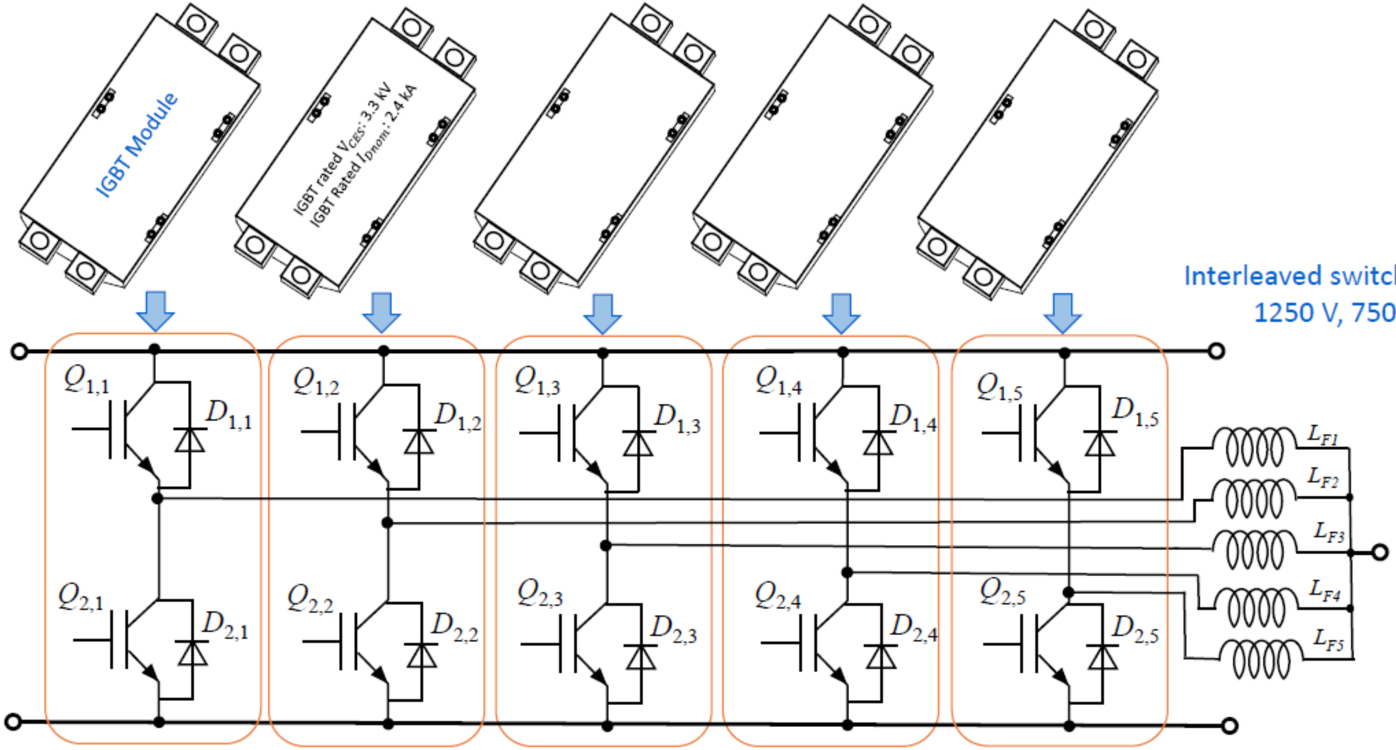




PLECS® schematic

DC/AC Multi-Level Converter with Full-Bridge Single Module
(4 H-bridges in series × 5 legs in parallel → 4×5×2 IGBTs)

DTT VS PS system



Interleaved switching pole
1250 V, 7500 A

DTT VS PS system

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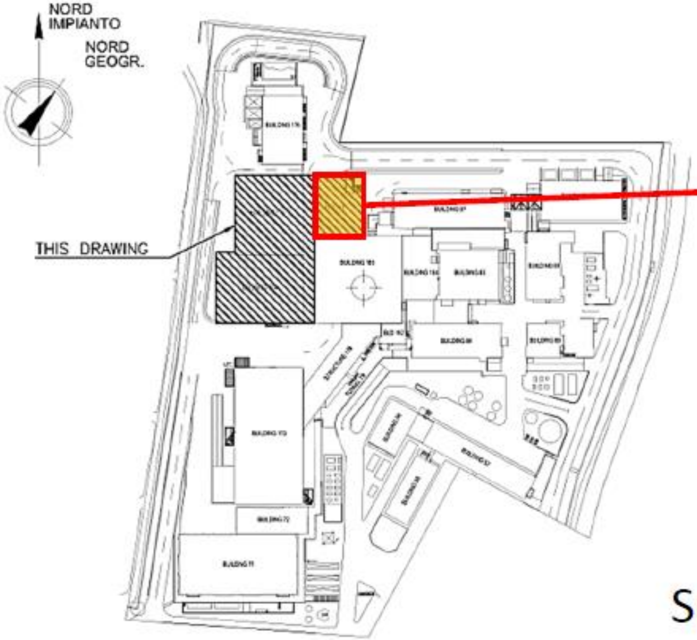

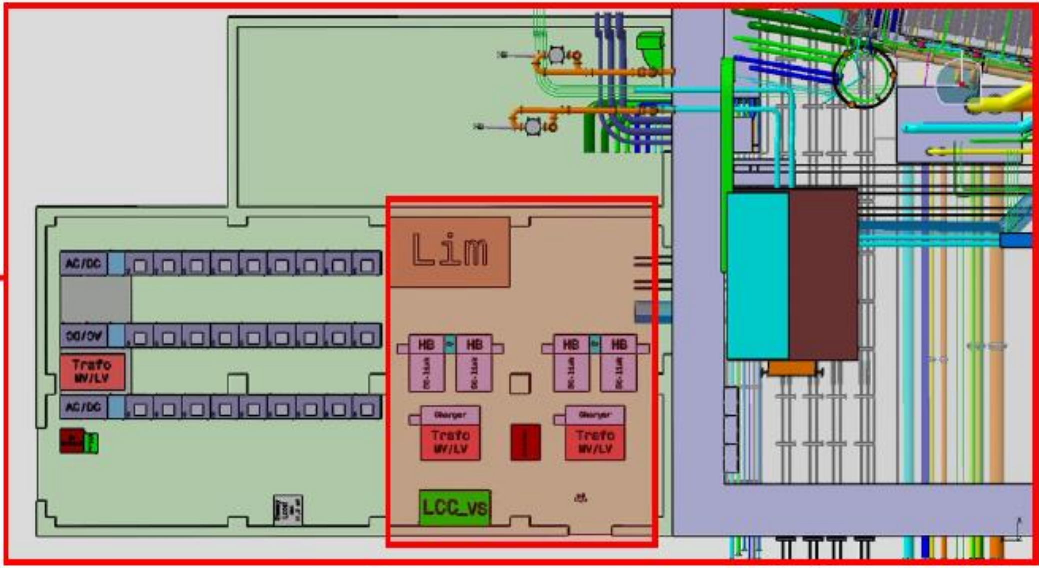

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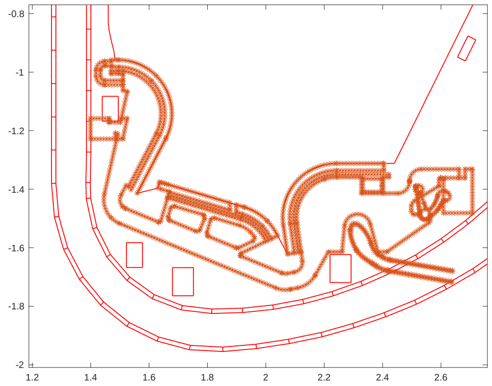
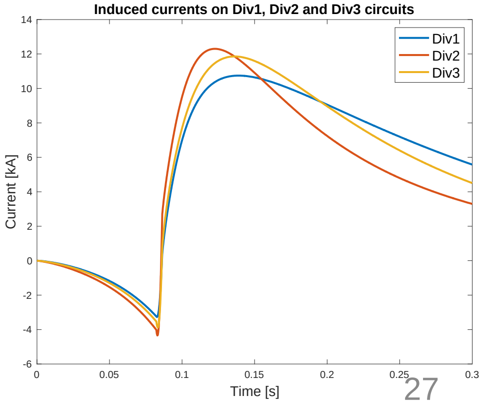
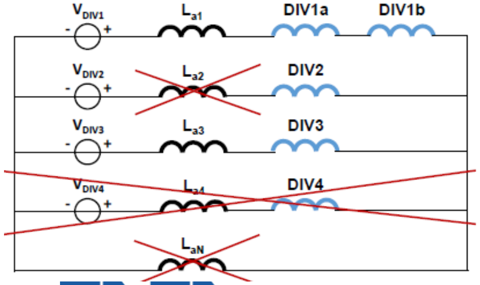
DTT DIV PS system

- Disruption is again the main problem
  - Maximum induced currents is ≈12 kA
  - $I_{operative}$≈5 kA → Worst case ≈17 kA
- Additional inductances (slowing effect tolerated?):
  - La1 on DIV1: 2 mH
  - La2 on DIV2: 0!
  - La3 on DIV3: 1 mH
- Under analysis possibility to slightly increase the inductance on DIV2 and DIV3 to reduce the peak current







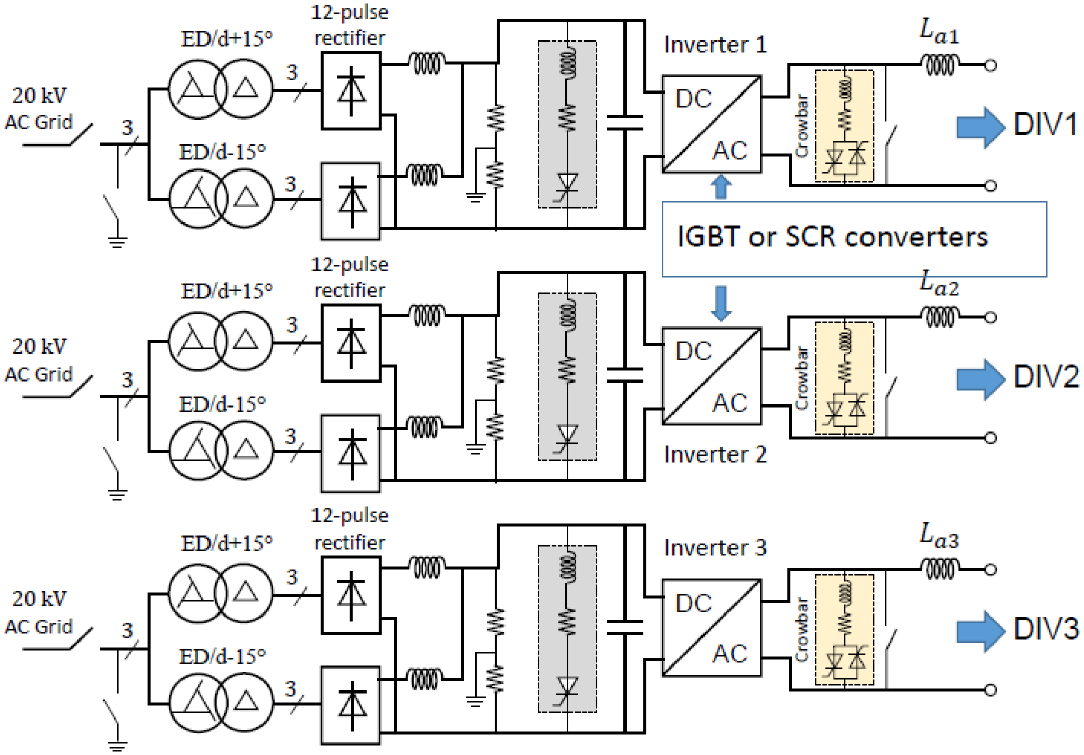
DTT DIV PS system

- All: 4-quadrants, 5 kA, 500 V
- Reference current waveform (for thermal analysis): sinusoidal current at 5 kA for flat-top (30s) → 3.5 kArms
- Overcurrent protection?

- Fine control of the divertor region
- Strike-point sweeping

- Maximum control speed: 4 Hz (7 Hz?)

- SCR converters cheaper and higher overcurrent, but IGBTs similar to NAS (choice mainly based on costs)



DTT DIV PS system

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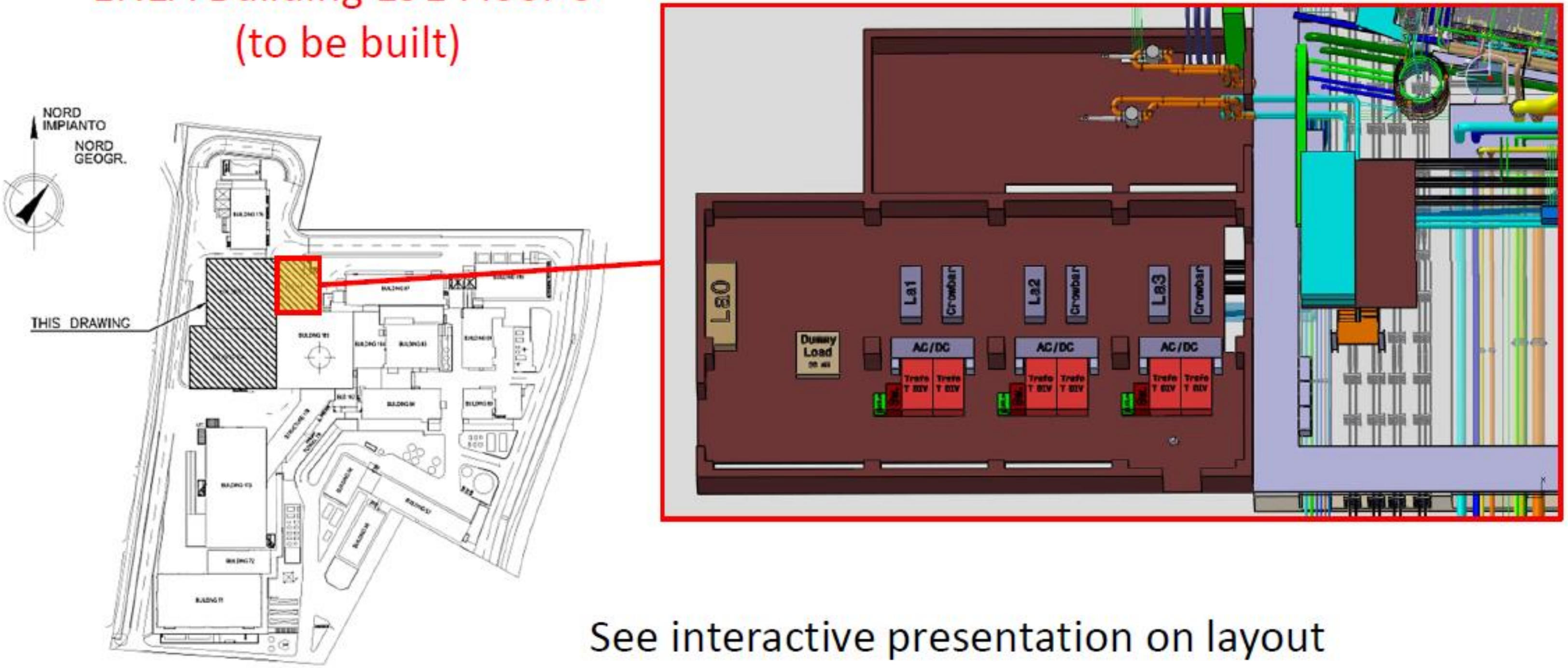

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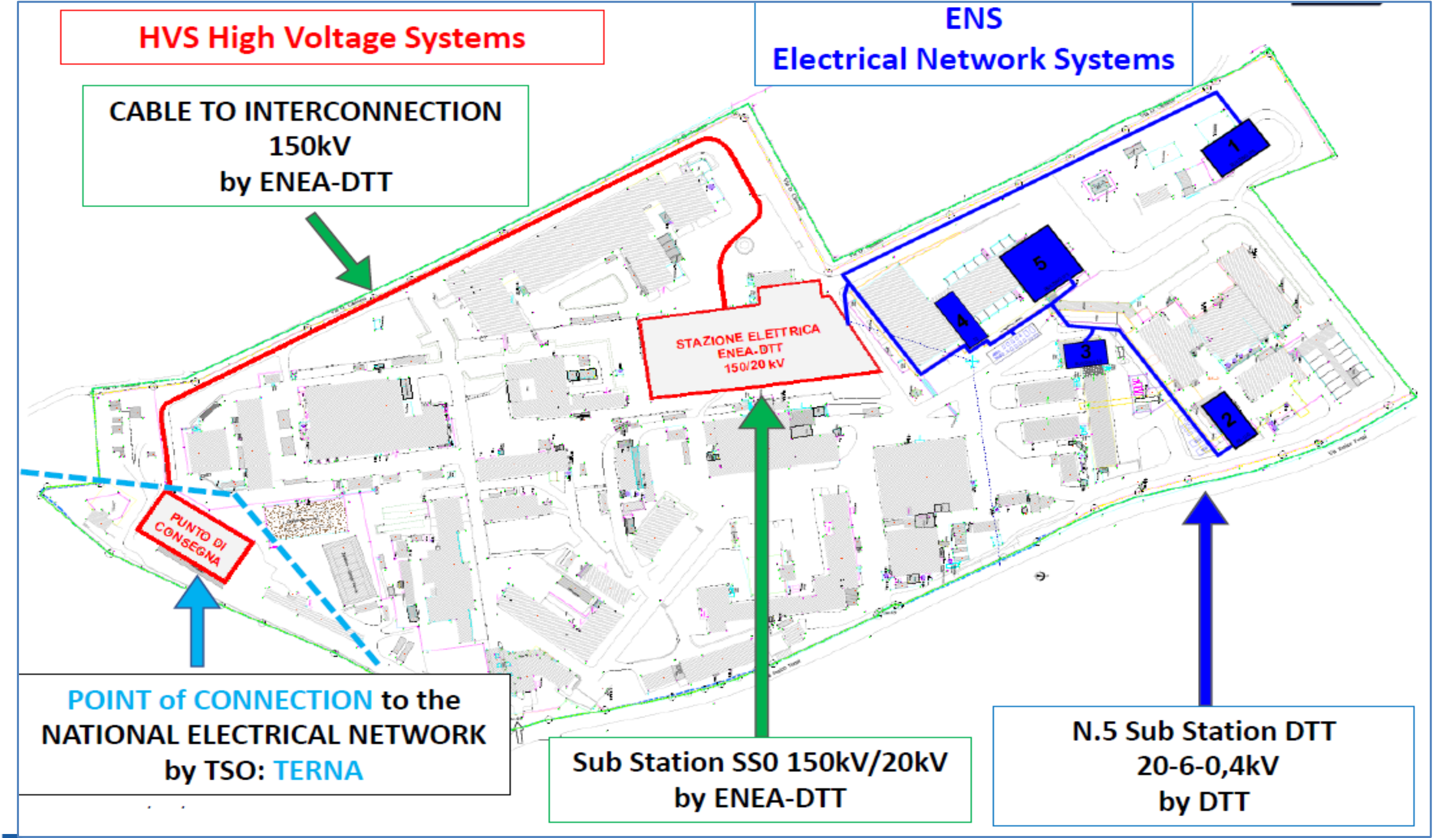
DTT EDS



HVS High Voltage Systems

ENS
Electrical Network Systems

CABLE TO INTERCONNECTION
150kV
by ENEA-DTT

POINT of CONNECTION to the
NATIONAL ELECTRICAL NETWORK
by TSO: TERNA

Sub Station SS0 150kV/20kV
by ENEA-DTT

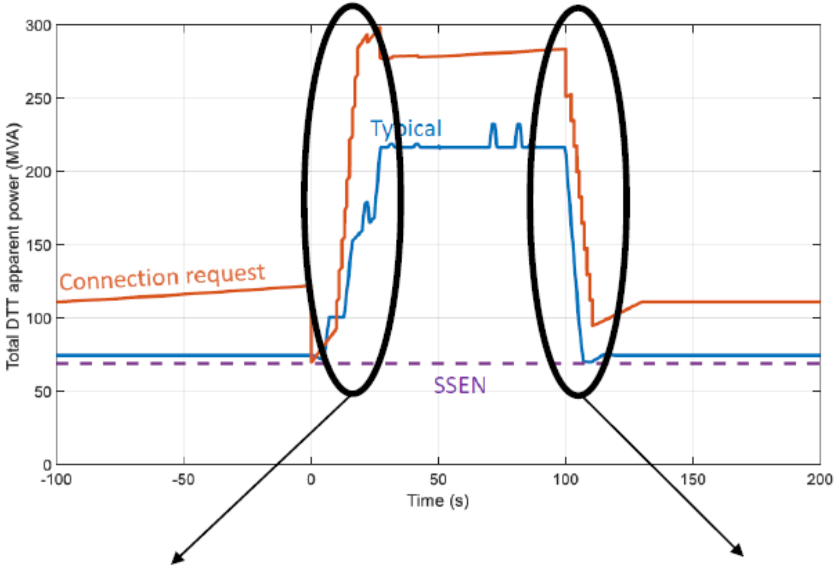
N.5 Sub Station DTT
20-6-0,4kV
by DTT

DTT EDS

SS-01	ELECTRICAL SUBSTATION 06080ZD001
SS-02	ELECTRICAL SUBSTATION 06080ZD002
SS-03	ELECTRICAL SUBSTATION 06080ZD003
SS-04	ELECTRICAL SUBSTATION 06080ZD004
SS-05	ELECTRICAL SUBSTATION 06080ZD005

DTT EDS

III. Dynamic Network Analysis: electrical load profile P->P(t), Q->Q(t):



Rump-UP

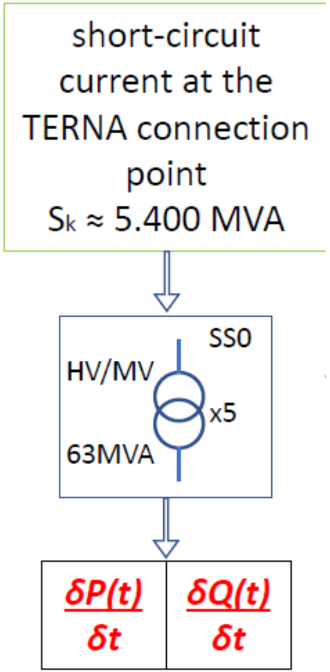
H&CD: **P(t), Q(t)**

PPS: **P(t), Q(t)**

Rump-Down

H&CD: **P(t), Q(t)**

PPS: **P(t), Q(t)**



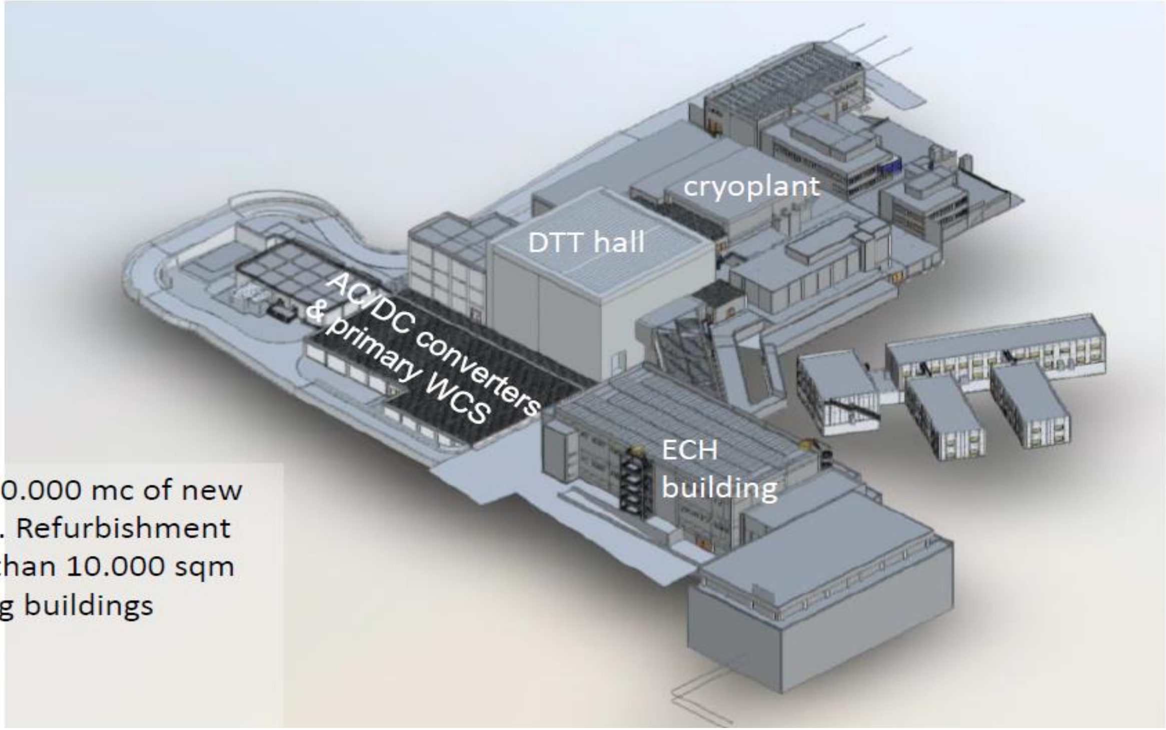
short-circuit current at the TERNA connection point

$S_k \approx 5.400$ MVA

$\frac{\delta P(t)}{\delta t}$ $\frac{\delta Q(t)}{\delta t}$

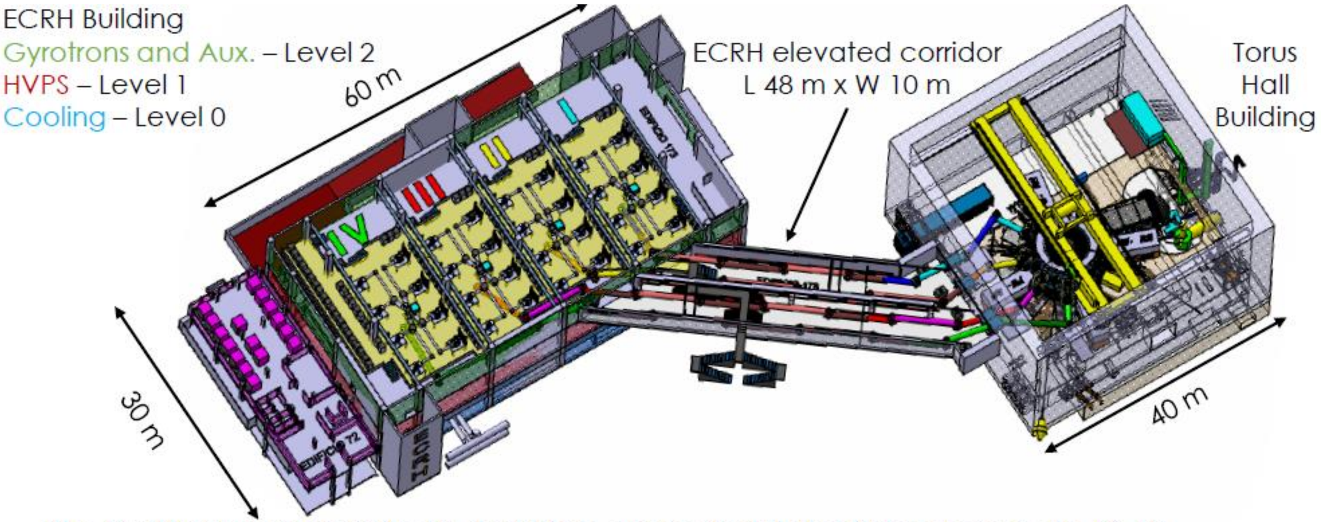
DTT EDS

Render of new buildings layout



- ✓ About 150.000 mc of new buildings. Refurbishment of more than 10.000 sqm of existing buildings

DTT ECH&CD

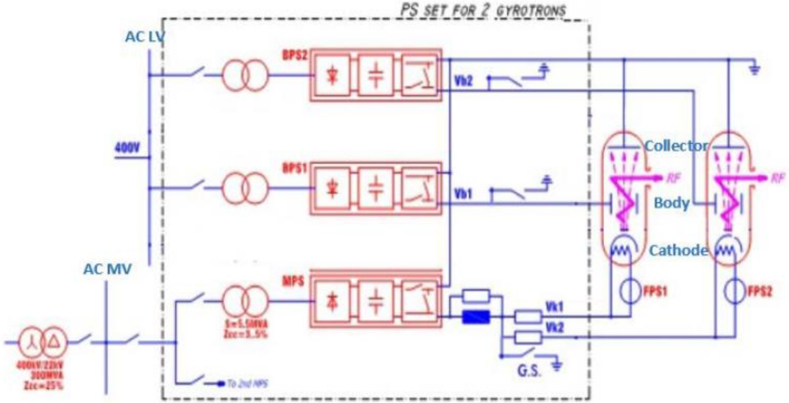


The ECRH system is organised in 4 Clusters, connected to the DTT sectors 12, 14, 16, 18, each one composed by:

- **8 Gyrotron sources** fed in pairs by **4 Main High Voltage Power Supply**.
- **1** Evacuated Quasi-Optical Single/Multi-Beam **Transmission Line** delivering the 8 microwave beams from gyrotrons to one tokamak sector.
- **8** Independent pairs of **launching mirrors** located in the equatorial (6 lines) and upper port (2 lines).

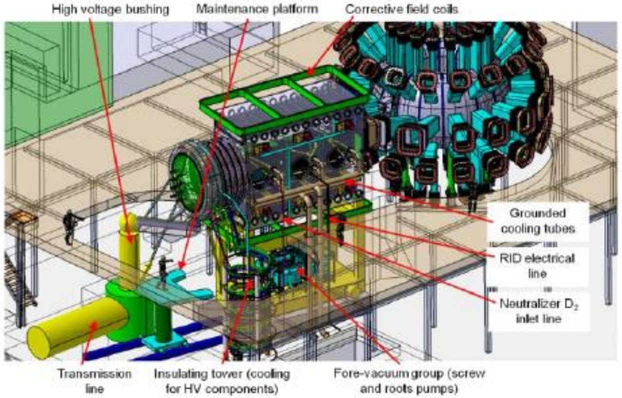
DTT ECRH

OCEM



Parameter type	Parameter	MPS	BPS
	Dimension	7.5 m (W) × 3.5 m (L) × 3.0 m (H)	2.0 m (W) × 1.0 m (L) × 2.32 m (H)
		Control Rack: 1.6 m (W) × 0.8 m (L) × 2.3 m (H)	
		Low Voltage Distribution: 0.6 m (W) × 0.4 m (L) × 2.0 m (H)	
		MW Switchgear: 1.6 m (W) × 1.6 m (L) × 2.5 m (H) – BUI72-L2	
	Weight	~28000 Kg for 1 MPS, 2 BPS, control rack and LV distribution	
	Nominal voltage	-55 kV	35 kV
	Voltage range	-55 - 0 kV	0 – 35 kV
	Nominal current	110 A	0.1 A
	Ramp-up/[ramp-down] time[1]	0.1 – 1 ms	0.1 – 1 ms
	Settling time	< 50 μs	< 50 μs
	Voltage accuracy	≤ ± 0.5 % of nominal value	≤ ± 0.5 % of nominal value
	Voltage ripple	≤ 1 % peak to peak of nominal value	≤ 1 % peak to peak of nominal value
	Modulation frequency	0 - 1 kHz	0 – 1 kHz / 1kHz – 5 kHz
	Modulation type	ON/OFF modulation	ON/OFF / Square partial modulation[2]
	Shutdown time[3]	<10 μs	<10 μs
	Pulse length	100 s	100 s
	Duty cycle	up to 25%	up to 25%

DTT NBI



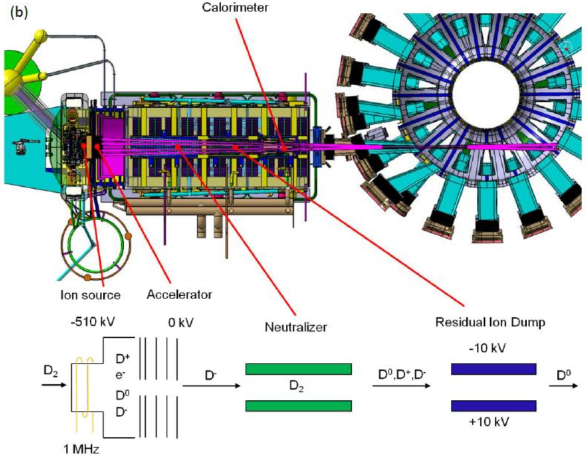
Main parameters:

- 510 keV beam energy (deuterium negative ions)
- 10 MW injected plasma
- Pulse duration 50s
- 5 Acceleration Grids fed by 3 stages HV PS
- RF drive plasma source
- Vacuum System based on NEG

The NBI system of DTT is in a design phase aiming to procure and install the system for the second phase of DTT operational program.

The System will be design exploiting the result of SPIDER/MITICA for the similar components: Ion Source, Neutralizer, Residual Ion Dump, Calorimeter , HV Power Supplies and HV transmission line.

For the components like Accelerator, HV Bushing and Vacuum System, that are unique for DTT a dedicated R&D activities is on-going, with the construction of prototypes and facilities for testing.



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