Alternative toroidal field coils conceptual design for tokamaks in the TRUST project framework

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TRUST Project

Outline

TUSCIA RESEARCH UNIVERSITY SMALL TOKAMAK

UNIVERSITÀ DEGLI STUDI DELLA TUSCIA

TRUST Project

- Academic and Scientific Goals
- Project Status
- Buildings
- Plasma Scenario
- Engineering Design

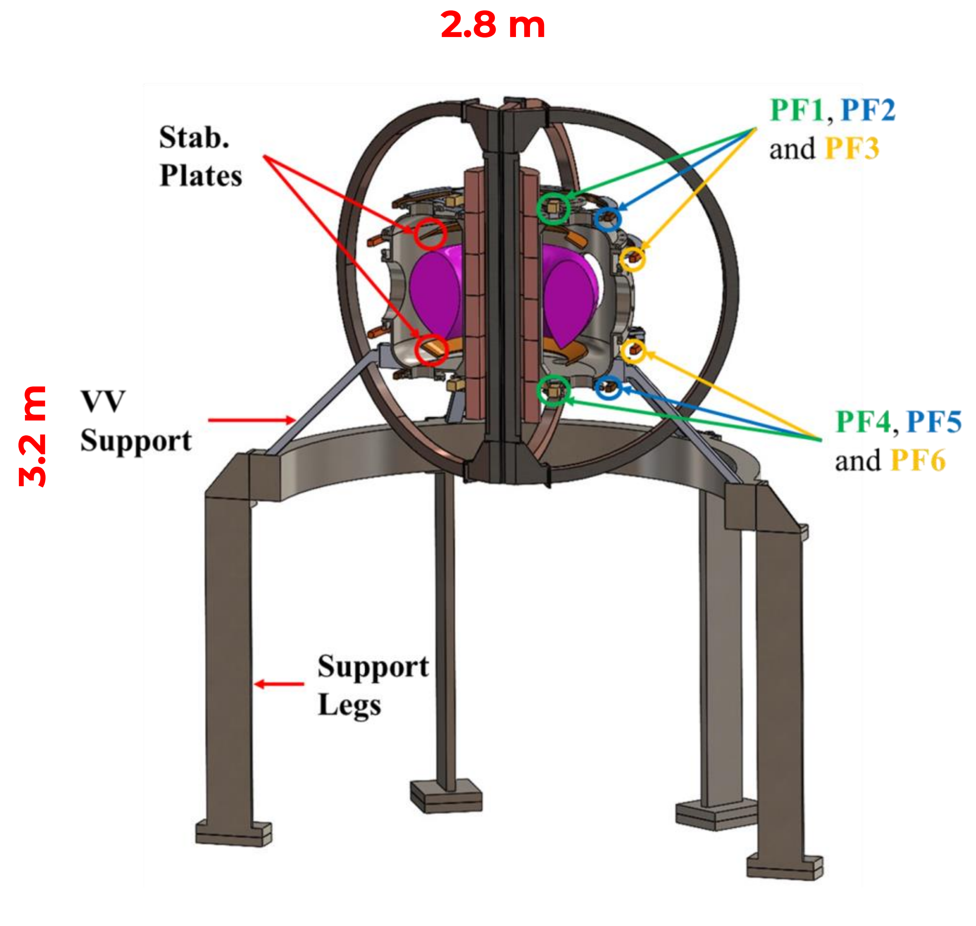
Alternative Magnetic Layout (AML)

- DEMO scaling
- Design and Scenario
- TF coils Characterization

Conclusions

TRUST Project
Goals

Tuscia **R**esearch **U**niversity **S**mall **T**okamak – New academic nuclear fusion experiment to better prepare the next generation of engineers allowing students to approach "real-world" experimental problems.



Besides the academic goal, TRUST include 3 different scientific research aims:

- Study an **alternative magnetic layout for future DEMO** reactor
- Perform test on **HTS coils and magnets**
- Integrate **Meta-Materials** as plasma facing components

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Project Status

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Three operational phases (OP):

- **OP1.** Test and commissioning of all the components, all the magnetic system in copper, testing of HTS coils in a dedicated testbed laboratory;
- **OP2.** Replacing of one copper PF coil with an HTS one, different plasma scenario and plasma performance will be investigated;
- **OP3.** Achieving the maximum performance and plasma discharges under steady-state conditions, all the magnetic systems in HTS material, addition of a radiofrequency system (ECRH) for sustaining the discharge.

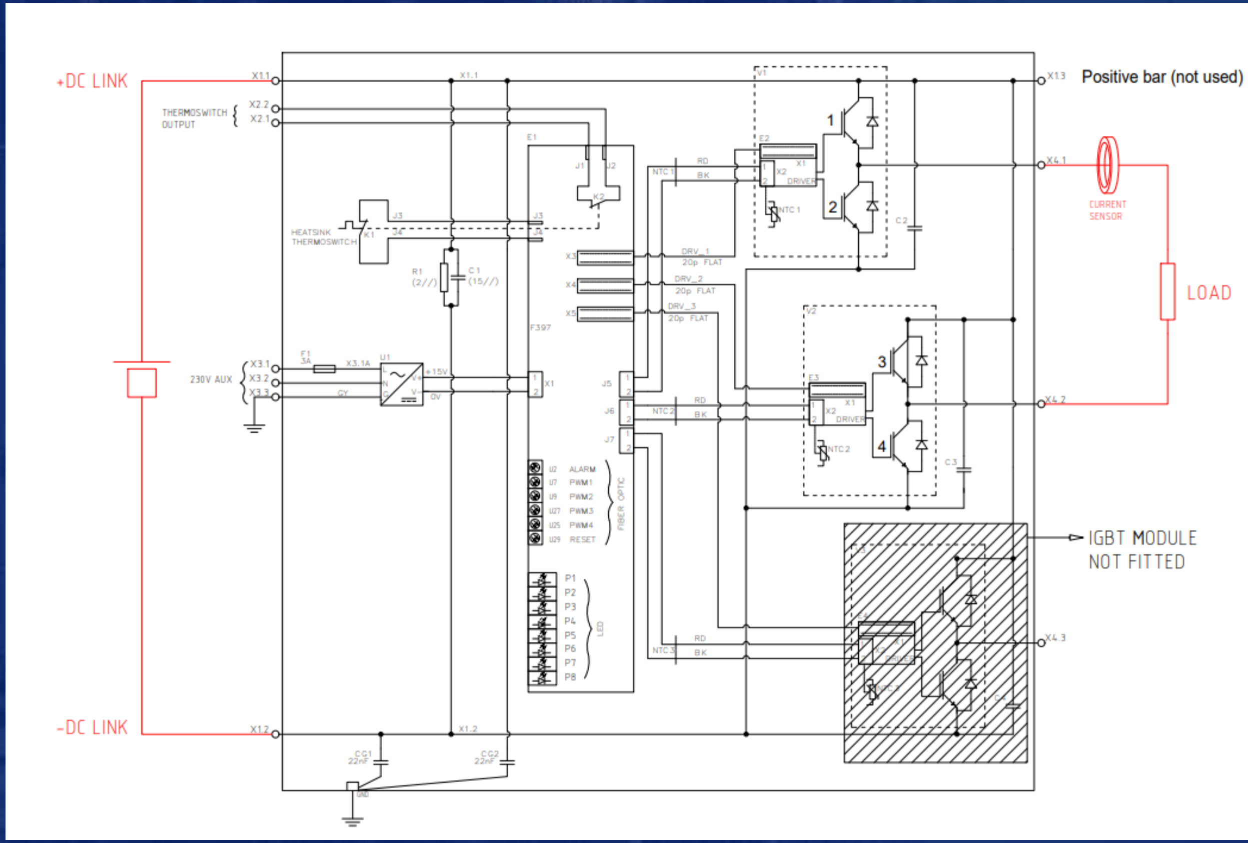
Currently we are moving from the conceptual design to the engineering design improving the design maturity level. The OP1 is already started !

TRUST Project

Project Status

New laboratory to test a **supercapacitor IGBT power supply system** (600A and 1200V) feeding a copper coil. The laboratory includes also a **DC controllable power supply** (120A and 40V).

Within the 2024 we are planning to **buy a small HTS coil** to starting the design and testing of this technology.



In this laboratory we are also **manufacturing and testing magnetic diagnostic and control systems** (both mandatory to operate a tokamak device)

TRUST Project

Project Status

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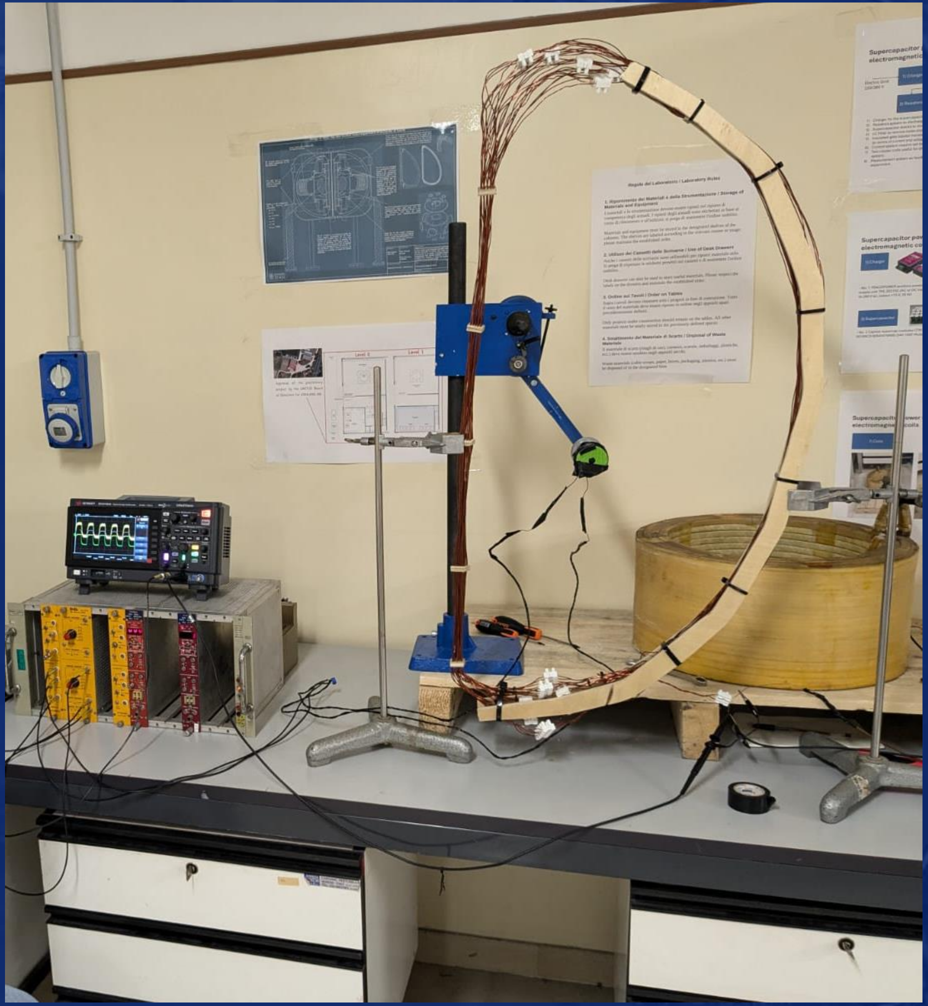

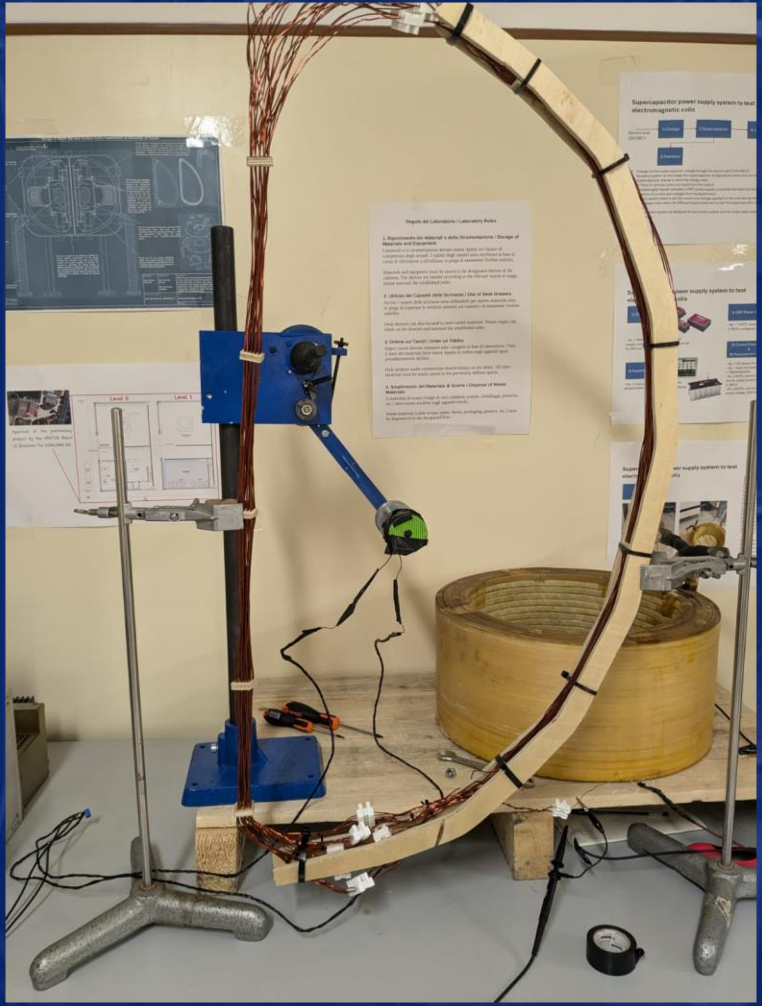

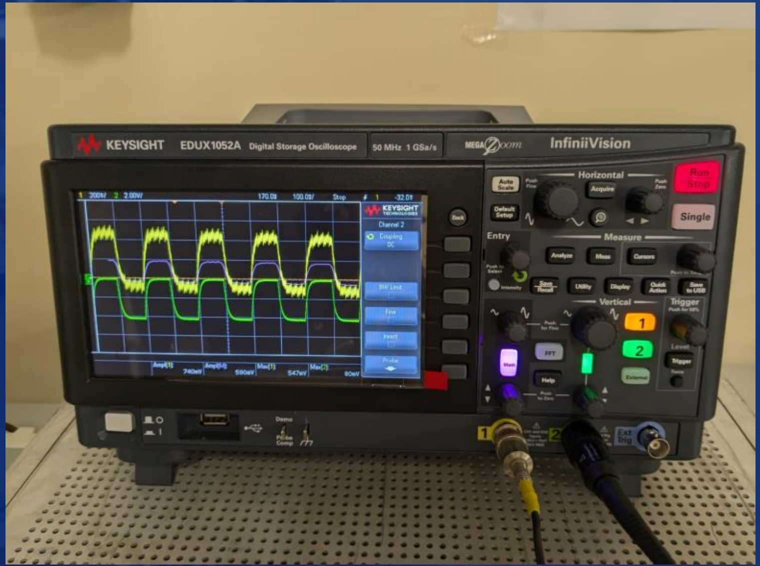

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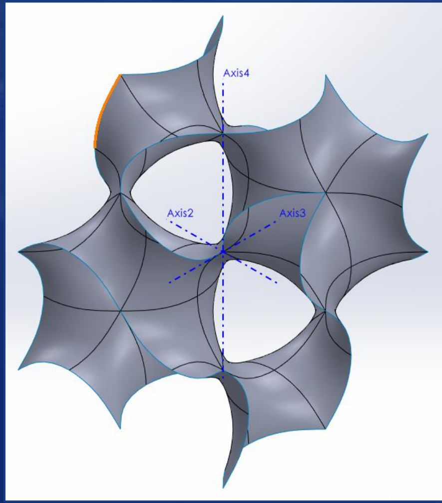
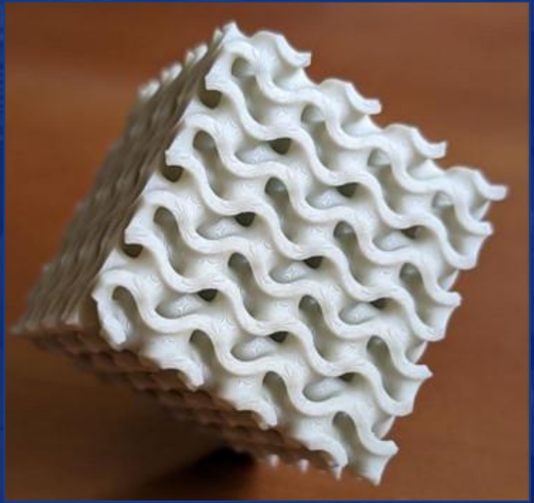
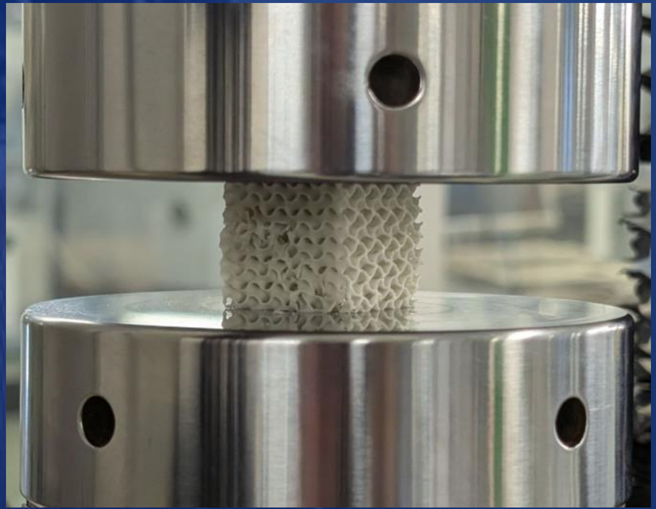
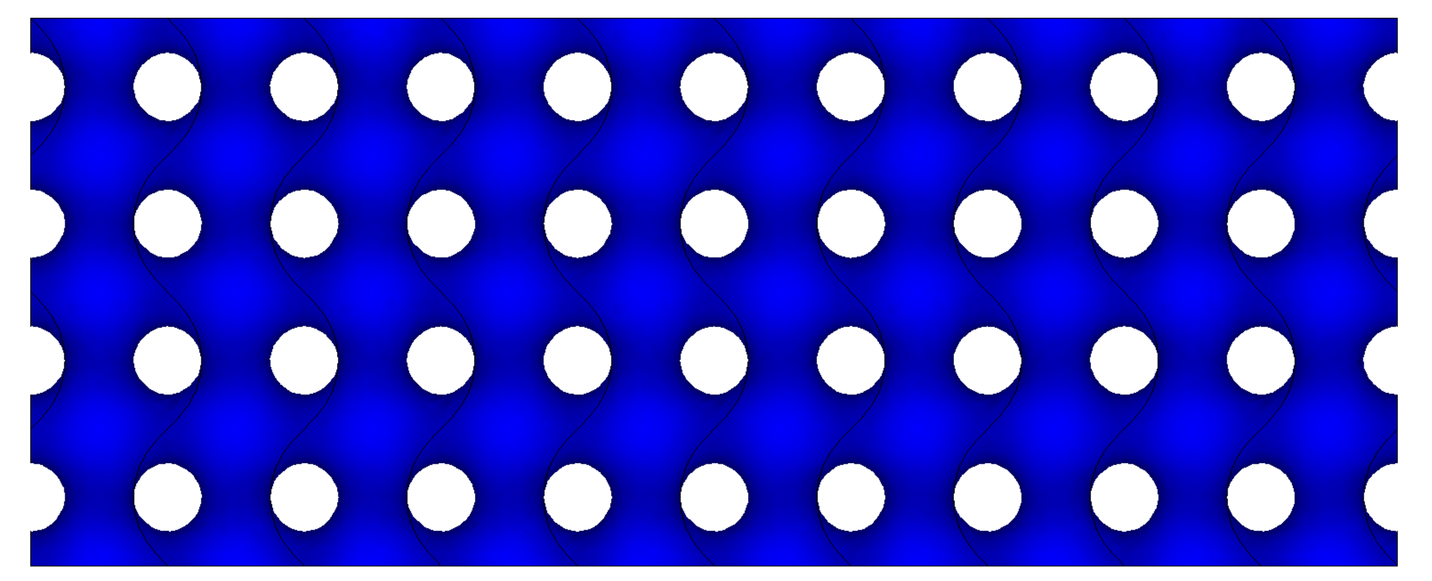
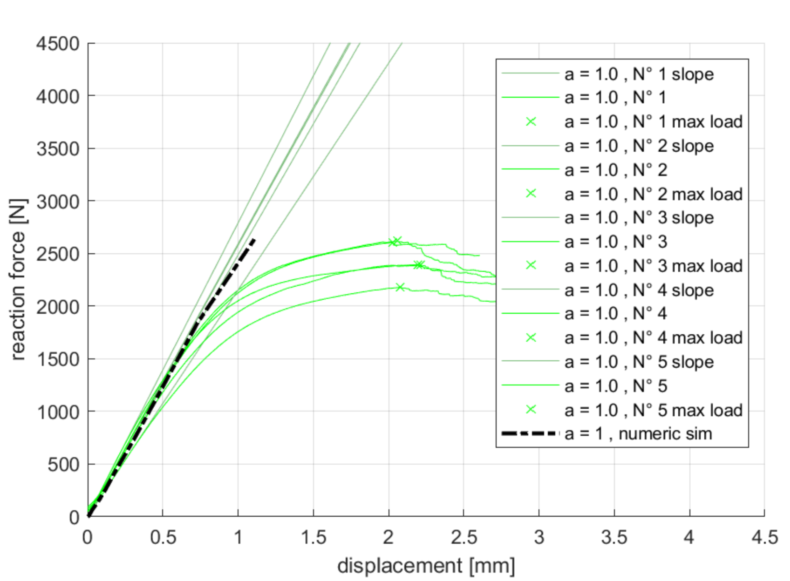
Project Status





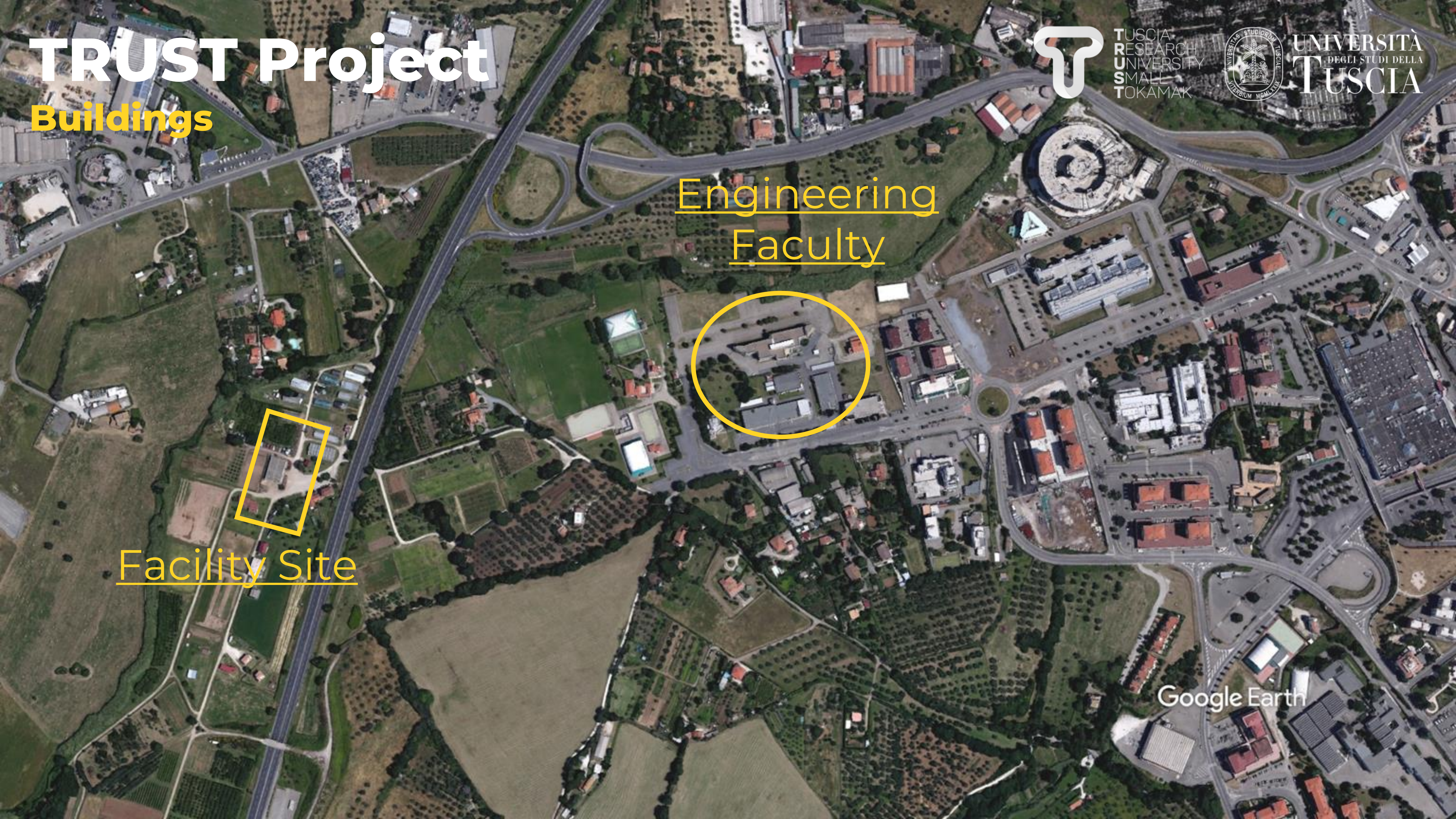


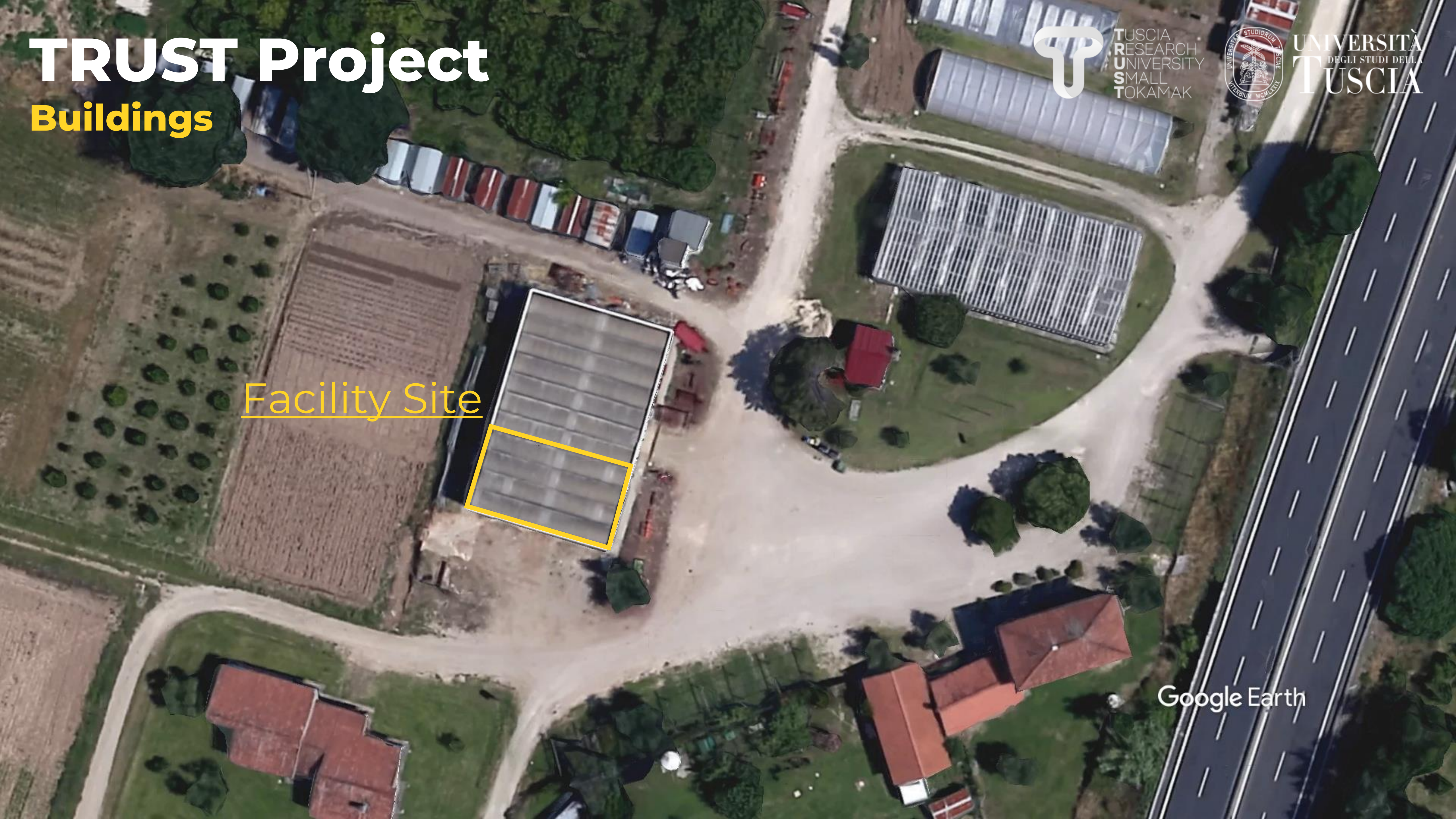




TRUST Project

Buildings




TRUST Project
Buildings
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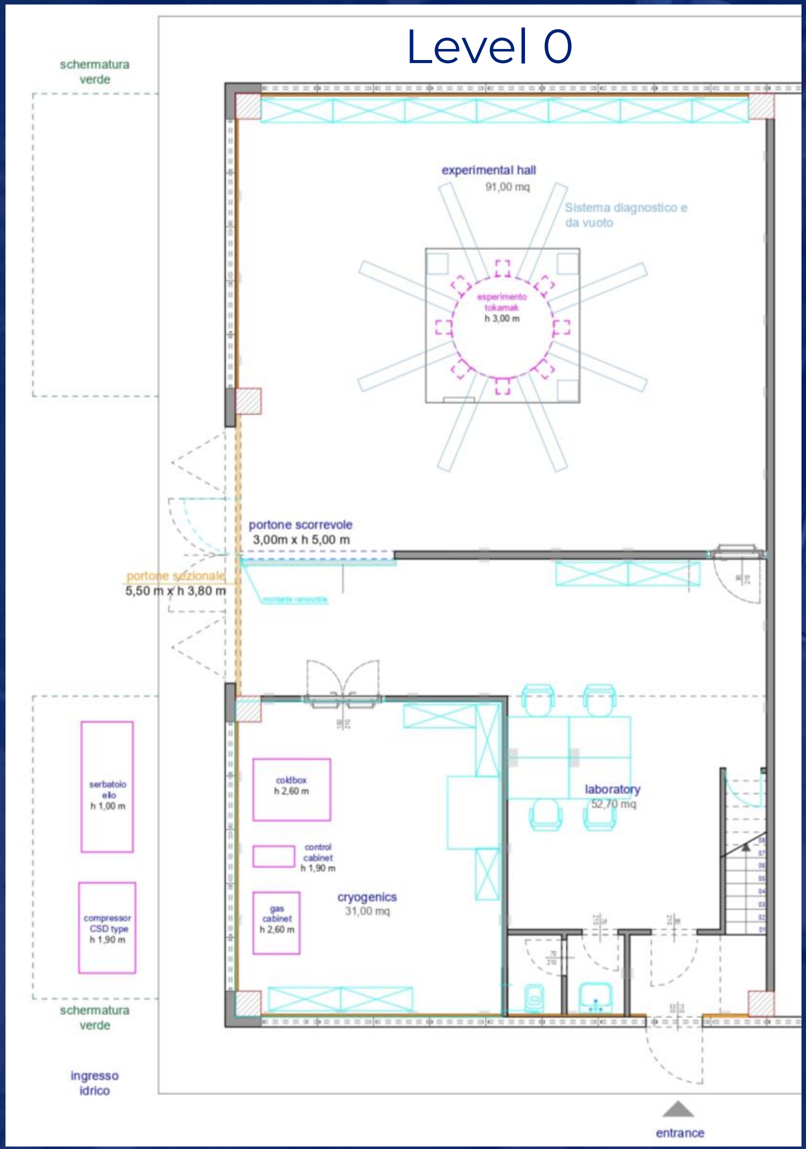
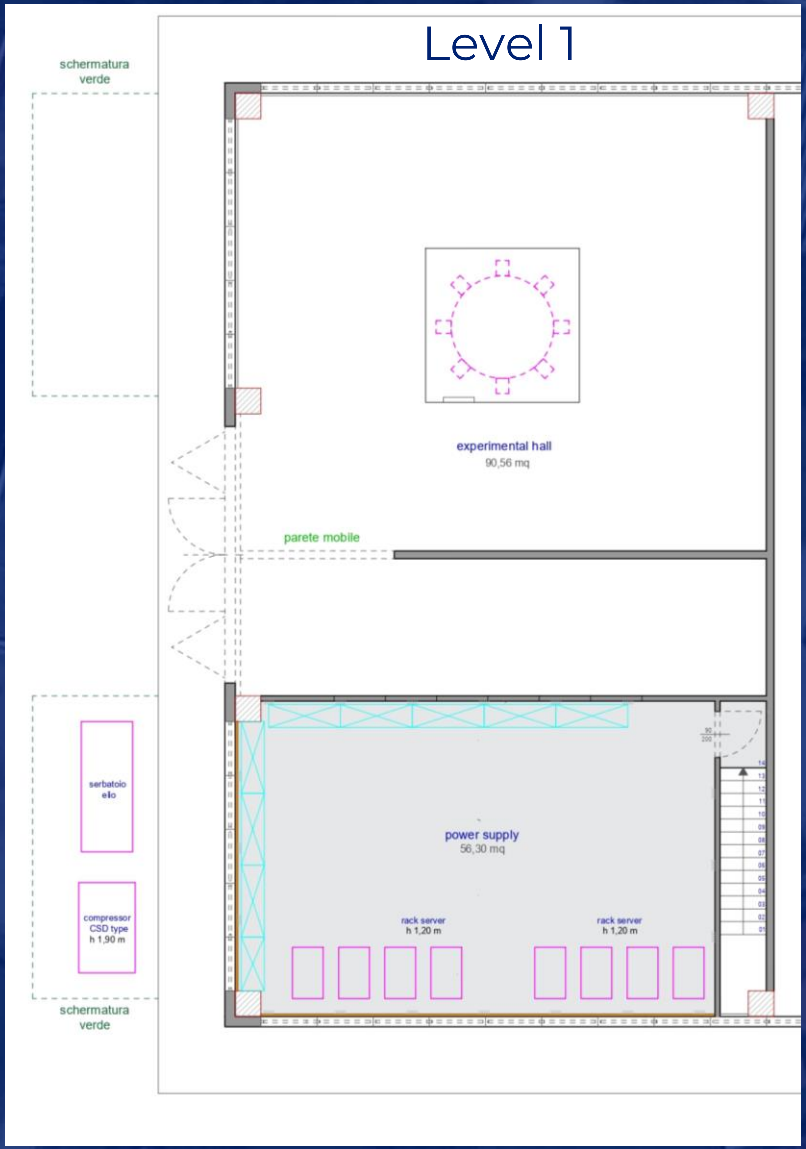
UNIVERSITÀ DEGLI STUDI DELLA TUSCIA
Facility Site
Google Earth

TRUST Project

Buildings





Approval of the preliminary project by the UNITUS Board of Directors for **€350,000.00**.

Currently the Viterbo town hall is evaluating the project to give **permission to build**.

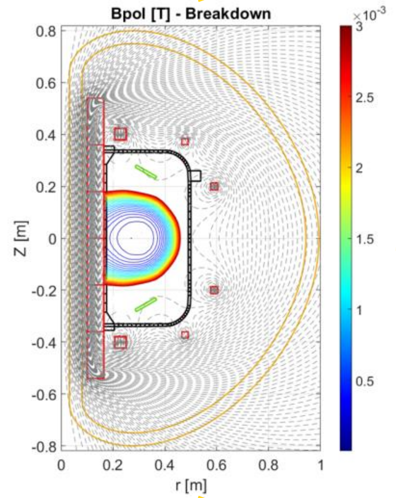
The goal is to start the works within the 2024 and **complete the facility within the summer 2025**.

TRUST Project

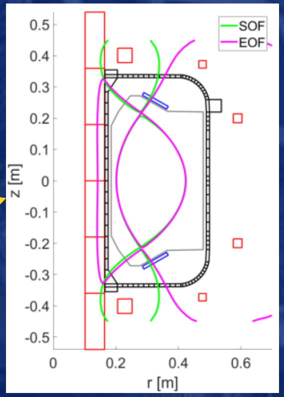
Plasma Scenario

The target SN plasma configuration was designed considering the TRUST scientific and academic goals. In fact, the target plasma scenario was achievable maintaining the economic feasibility for a university-class experiment and at the same time a scientific relevance to test meta-materials as PFC and HTS coils.

The almost up-down symmetry of the machine also allows the possibility to test and study Double Null (DN) and Upper Single Null (USN) plasma configurations

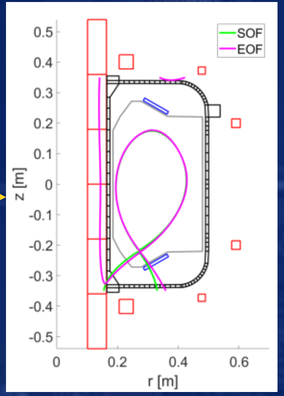


DN



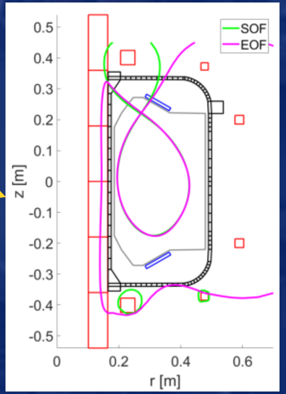
DN	@SOF	@EOF
I_{pla} [kA]	110.0	110.0
R_0 [m]	0.3	0.3
a [m]	0.11	0.11
B_T [T]	0.8	0.8
κ	~1.9	~1.9
δ_{low}	~0.3	~0.3
β_{pol}	~ 0.1	~ 0.1
li	~ 0.8	~ 0.8
q_{95}	~3.3	~3.3
Volume [m^3]	~0.125	~0.125
$\psi_{boundary}$ [Vs]	0.126	-0.190

SN



SN	@SOF	@EOF
I_{pla} [kA]	110.0	110.0
R_0 [m]	0.3	0.3
a [m]	0.12	0.12
B_T [T]	0.8	0.8
κ	~1.7	~1.7
δ_{low}	~0.3	~0.3
β_{pol}	~ 0.1	~ 0.1
li	~ 0.8	~ 0.8
q_{95}	~3.2	~3.2
Volume [m^3]	~0.125	~0.125
$\psi_{boundary}$ [Vs]	0.123	-0.193

USN

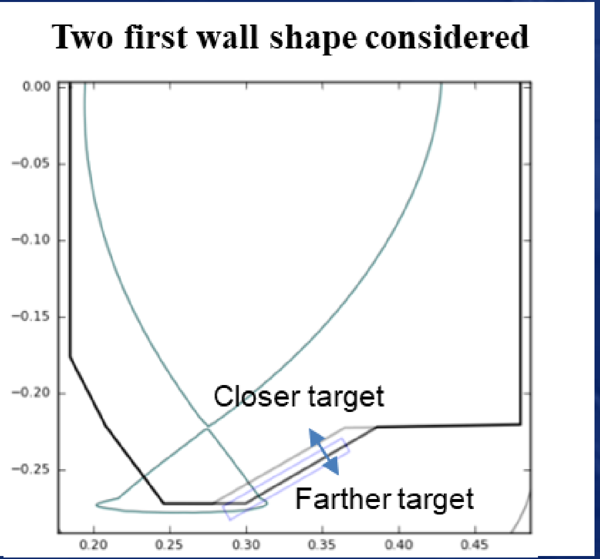


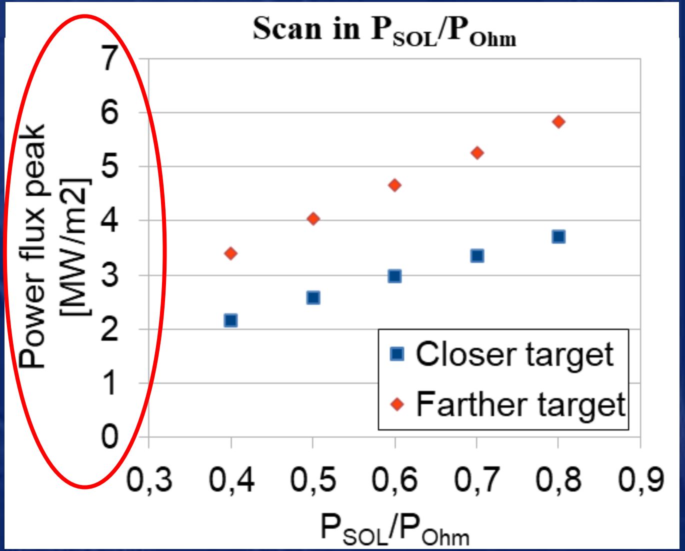
USN	@SOF	@EOF
I_{pla} [kA]	110.0	110.0
R_0 [m]	0.3	0.3
a [m]	0.12	0.12
B_T [T]	0.8	0.8
κ	~1.7	~1.7
δ_{low}	~0	~0
β_{pol}	~ 0.1	~ 0.1
li	~ 0.8	~ 0.8
q_{95}	~3.2	~3.2
Volume [m^3]	~0.125	~0.125
$\psi_{boundary}$ [Vs]	0.123	-0.193

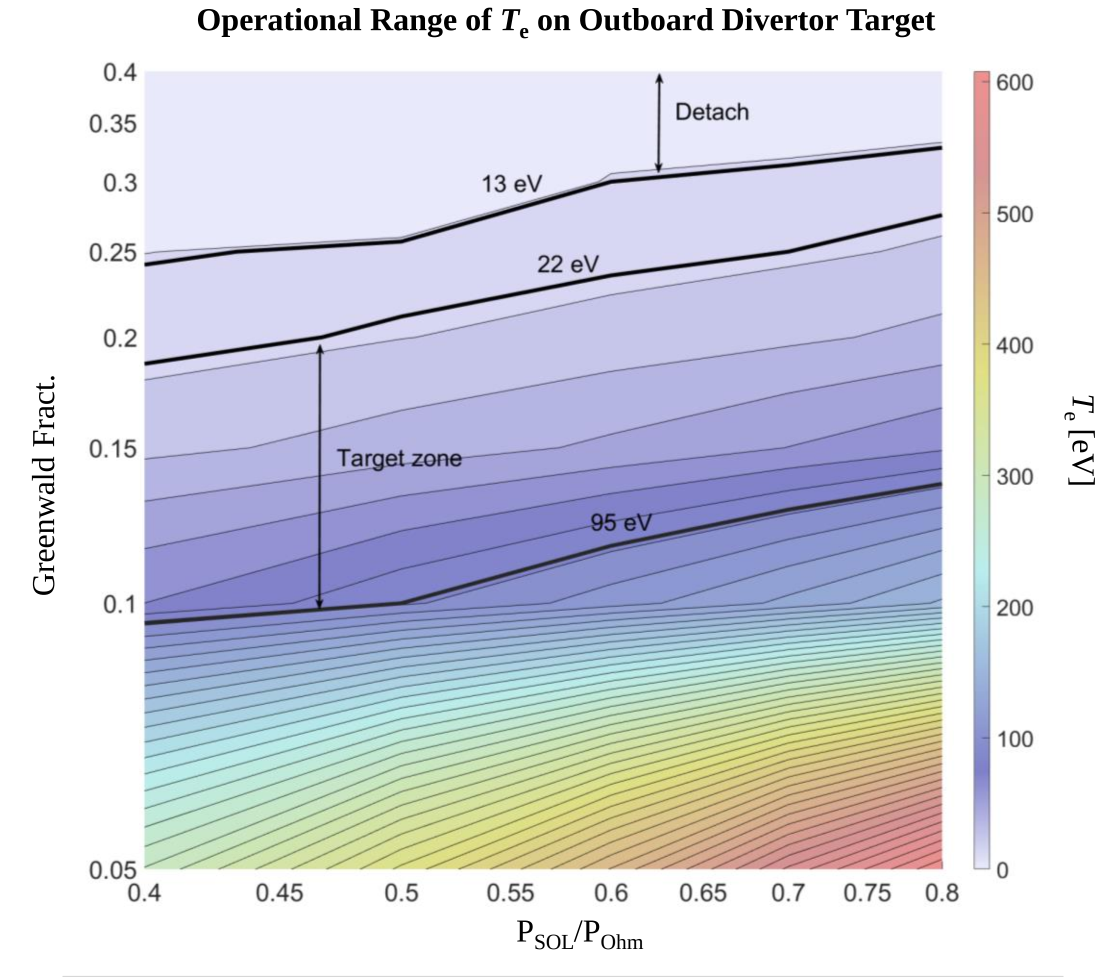
TRUST Project
Plasma Scenario

A preliminary estimation of the thermal loads and plasma temperatures at the first wall and divertor was made from SN scenario:

- A scan in P_{SOL}/P_{Ohm} was performed;
- T_e peak at the outer divertor was estimated in a density and radiated power fraction scan.

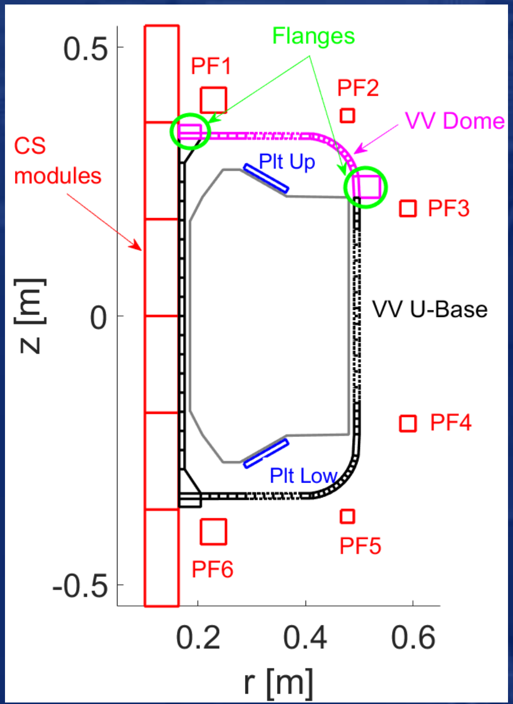


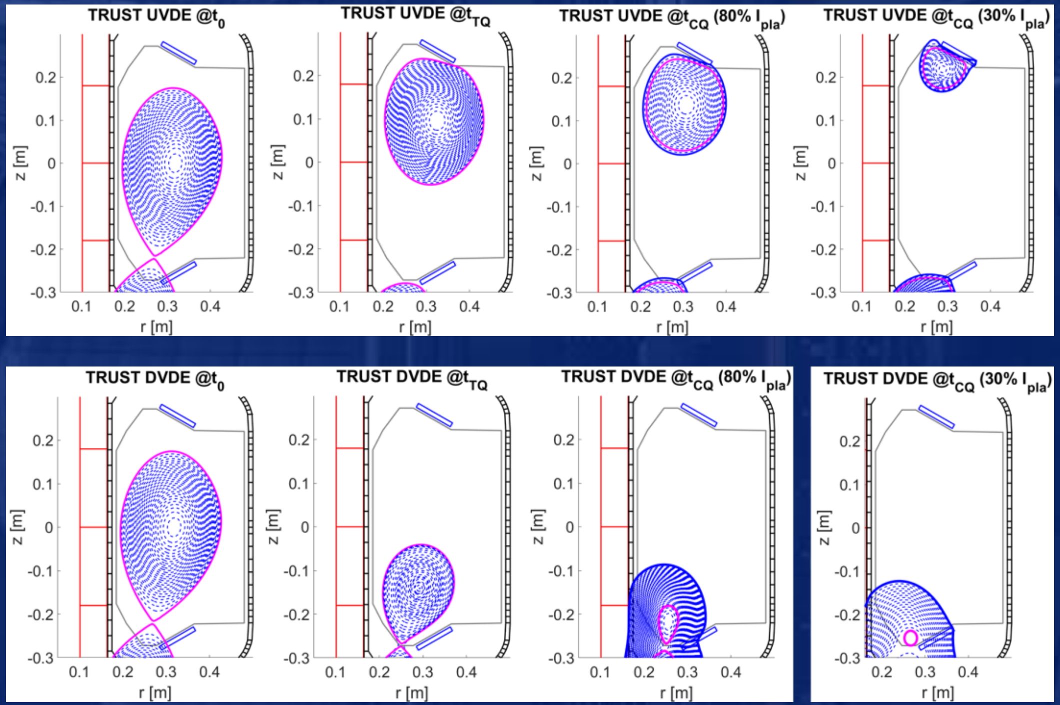




TRUST Project

Plasma Scenario





A preliminary SN plasma disruption database is under construction to evaluate the disruption specification loads for TRUST.

Including also the Electromagnetic loads acting the VV flanges, the in-vessel stabilizing plates and on the PF coils

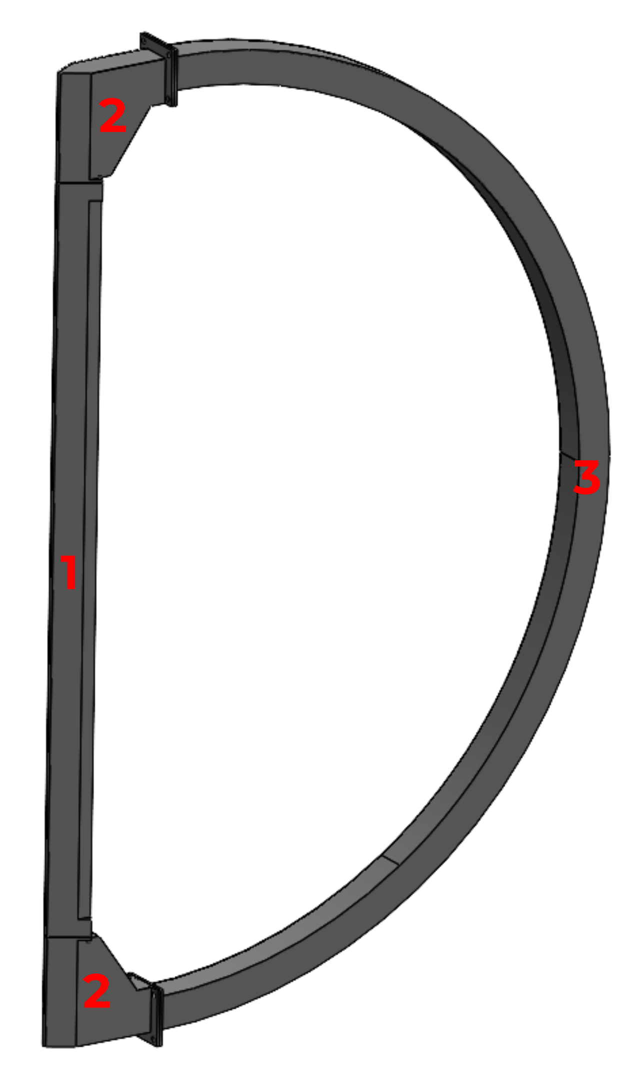
A collection of EM numerical simulations are reported, covering various plasma dynamic conditions within the operational space:

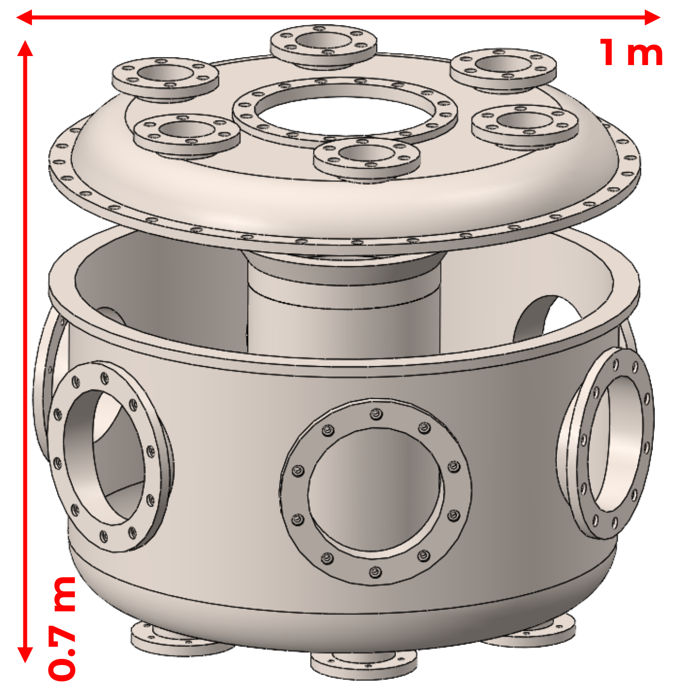
- time instant (EOF or SOF)
- plasma trajectory (UVDE or DVDE)
- CQ duration (Fast events with a CQ duration of 0.24 ms and Slow events with a CQ duration of 2.4 ms).

	SOF				EOF			
	Fast UVDE	Slow UVDE	Fast DVDE	Slow DVDE	Fast UVDE	Slow UVDE	Fast DVDE	Slow DVDE
Fz PeakTotal - Halo+Eddy [kN]	1.450	1.877	-2.236	**-6.141**	1.650	1.636	-1.376	-4.879
Fz Peak total - Eddy only [kN]	1.492	1.585	-1.942	**-4.271**	1.650	1.471	1.435	-3.928
Fz Peak Dome Supports [kN]	4.614	4.978	3.309	**2.520**	5.433	**5.537**	4.068	3.078
Fz Peak Plates [kN]	-1.818	1.876	-2.829	**-3.839**	-2.172	2.153	-2.754	-3.650

TRUST Project

Engineering Desing





The VV is under development in collaboration with Walter Tosto S.P.A. to meet their production requirements and to reduce assembly complexities (e.g., welding).

Equatorial flanges on the top decinormal shell allow an easily maintenance and assembly or disassembly procedure

The TF coils are designed to achieve the target toroidal field at the plasma magnetic axis minimizing the ripple. Their vertical extension allows to minimize the out of plane forces due to the interaction with the poloidal field.

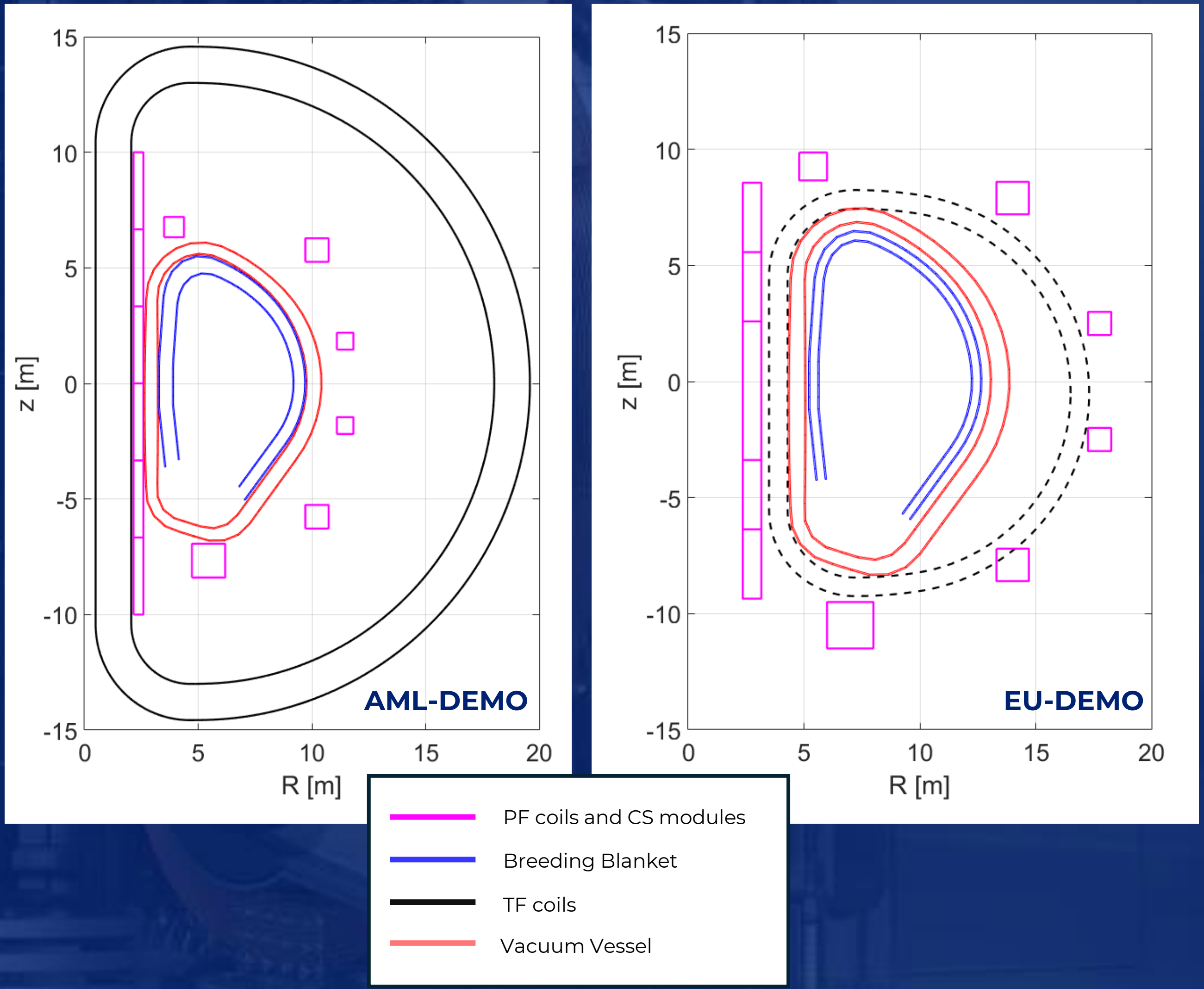
The TF coils geometry is obtained considering bending free D-shape with the addition of two electrical joint.

Alternative Magnetic Layout

DEMO scaling

The alternative magnetic layout has the Central Solenoid (CS) placed around the Toroidal Field (TF) coils central column providing a relevant reduction in the reactor size. Otherwise, the increasing in the overall dimension for the TF coils is required to sustain the increased magnetic field. In addition, to provide the required performance High Temperature Superconductor (HTS) material is foreseen for the TF coils.

The principal parameters are obtained respecting the EU-DEMO baseline main design drivers such as the Fusion Power, the Vacuum Vessel (VV) and Breeding Blanket (BB) total radial dimension (~ 1.5 m) and plasma pulse length.



Alternative Magnetic Layout

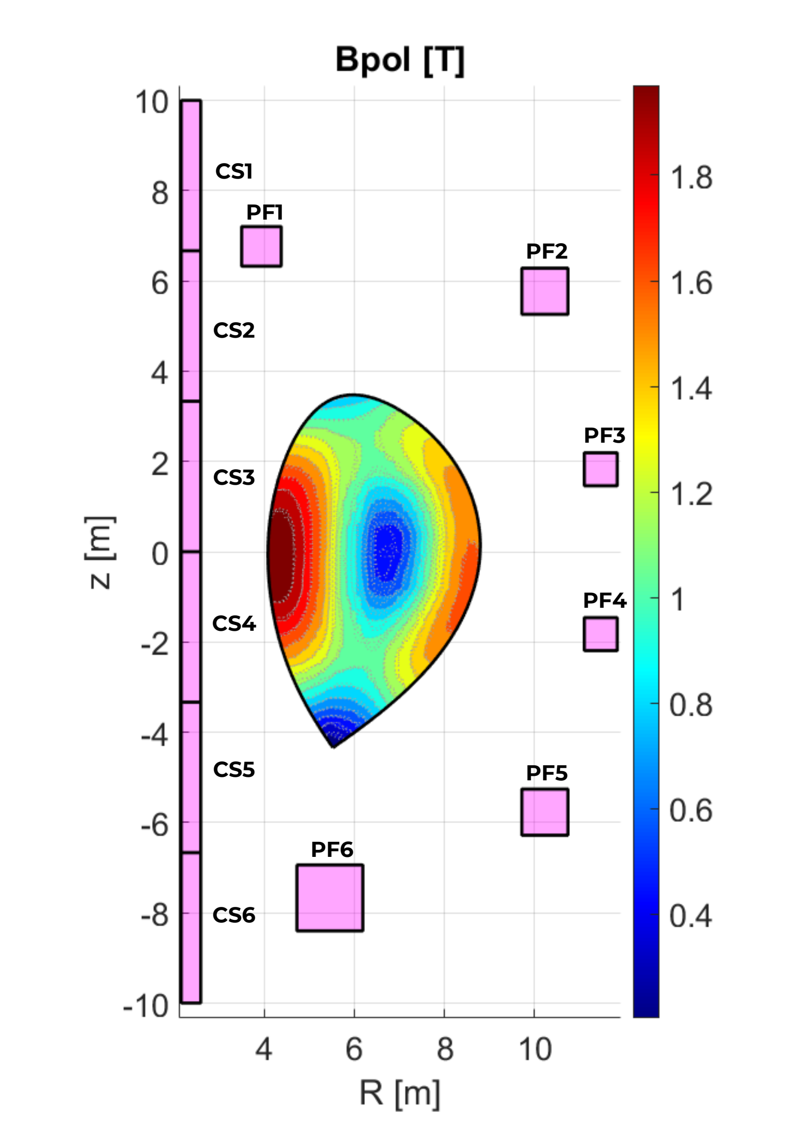
DEMO scaling

Main Parameters	AML-DEMO	EU-DEMO
R_0 [m]	6.5	9.0
A	2.71	3.1
I_{pla} [MA]	21	17.86
$B_{t,0}$ [T]	7	5.86
$B_{t,max}$ [T]	22	13
P_{fus} [MW]	1460	2000
q_{95}	3.5	3.89
Pulse length [s]	7200	7200
$\langle n \rangle / n_{GW}$	0.87	1.2
κ_{95}	1.67	1.65
δ_{95}	0.36	0.33
li	0.8	0.8
β_p	0.62	1.235
H_{98}	0.9	0.98
Volume [m^3]	1037	2579
P_{sep} [MW]	127	170.4
$P_{sep}B_{T,0}/q_{95} AR_0$ [MW T/m]	13.33	9.2
P_{add} [MW]	70	120

The PF coils and the CS modules can be placed closer to the plasma bringing a gain in plasma control, smaller diameter and increased the available CS flux. In fact, swapping the position between the TF coils and the CS in the radial building (assuming same current), the toroidal field decreases (Bt ~ 1/r) but the CS magnetic flux increases more ($\Psi cs \sim r^2$).

Alternative Magnetic Layout

Design and Scenario



Current [MA turns]	AML-DEMO	EU-DEMO
CS1	-2.247	-5.94
CS2	-43.630	-29.11
CS3	-45.123	-58.23*
CS4	-45.233	
CS5	-46.000	-29.11
CS6	-23.636	-12.44
PF1	-2.153	2.32
PF2	-9.567	-5.89
PF3	-2.672	-6.08
PF4	-3.206	-3.64
PF5	-13.035	-8.98
PF6	9.676	10.25

*EU-DEMO baseline includes 5 CS modules

Preliminary results are promising, AML offers advantages in reducing the overall reactor size while improving the assembly or maintenance phase and plasma control.

AML-DEMO → Ψ_{CS} = 295.8 Vs

EU-DEMO → Ψ_{CS} = 250.0 Vs

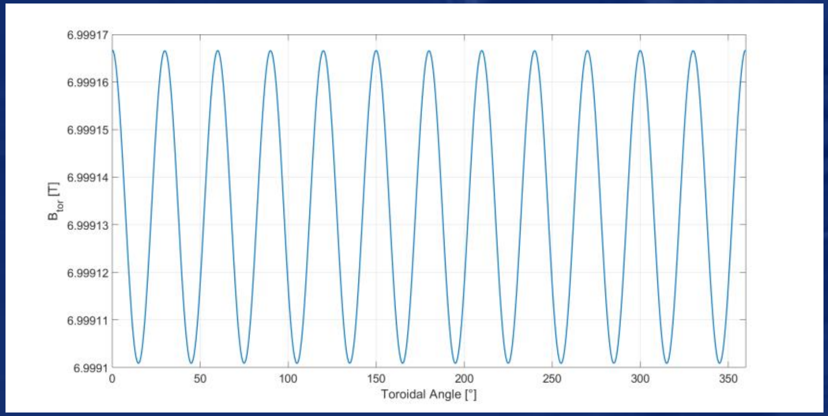
Moreover, it is possible to avoid a strong coupling between PF coils and TF coils reducing the bending effect on the latter.

Alternative Magnetic Layout

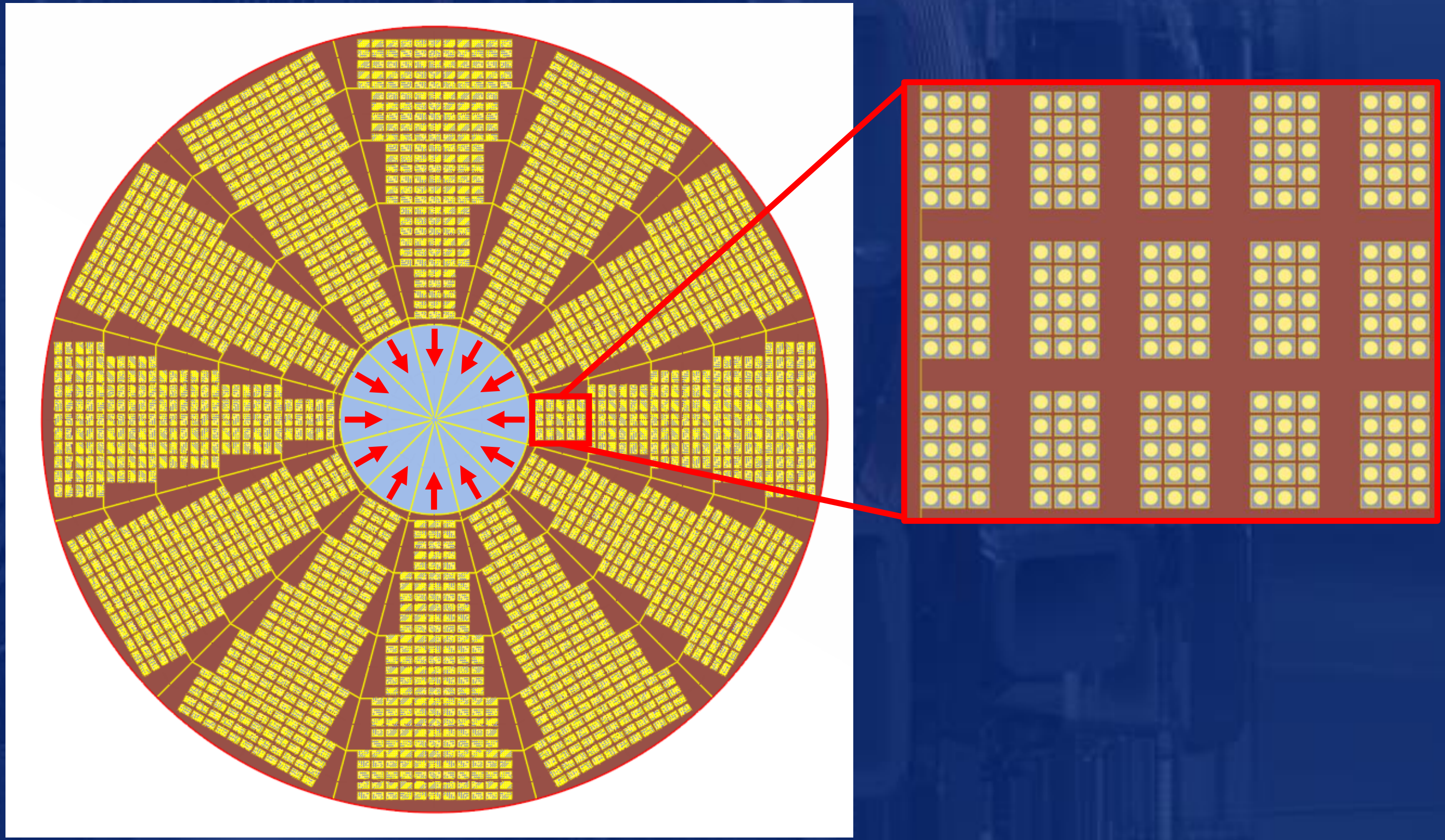
TF coils Characterization

TF coil	AML-DEMO	EU-DEMO
I_{TF} [MA]	19	14.9
$B_{t,max}$ [T]	22	13
$R_{inb,TF}$ [m]	2.07	4.3
A_{HTS} [m²]	0.527	0.69
J_{HTS} [MA/m²]	36	21
N_{TF}	12**	16
$F_{z,TF}$ [MN]	379	276
$F_{R,TF}$ [MN/m]	209	90

** The ripple is < 0.1‰ in analyzed configurations

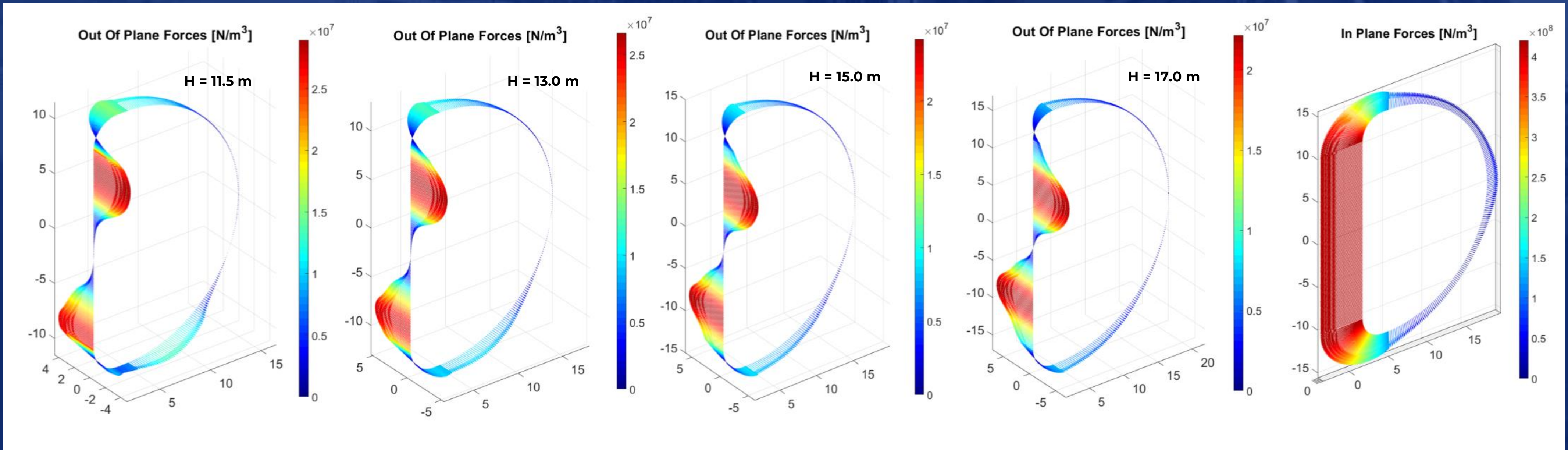


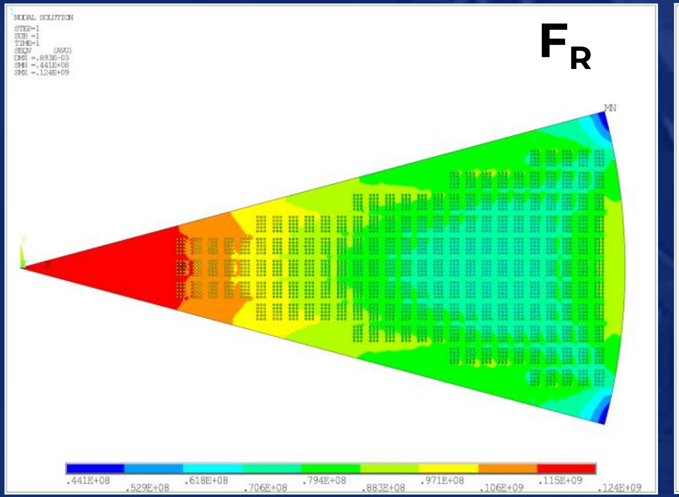
The constant tension D-Shape is used as first design for TF coils to evaluate the overall dimension and the preliminary electromagnetic loads. The radial load is sustained considering a bucked solution pushing on a steel central post.

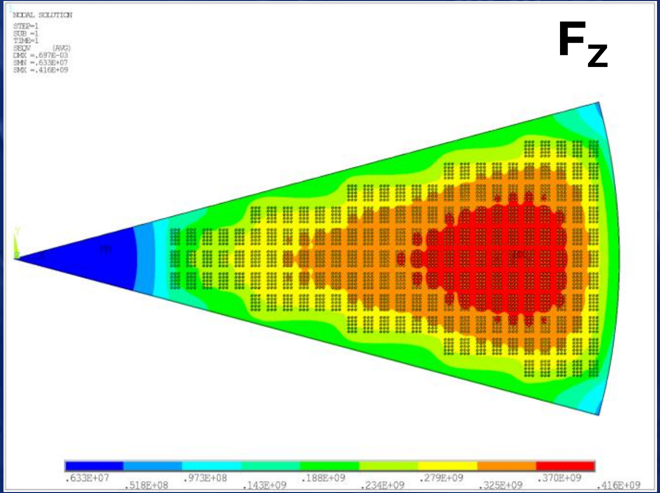


Alternative Magnetic Layout

TF coils Characterization







A parametric study is carried out varying the maximum height for the TF coil obtaining the relative Out of Plane Forces (OPF) and the In Plane Forces (IPF).

The stress state due to the IPF on the proposed layout is obtained considering a 30° sector (condition of axial-symmetry).

Conclusions

- Alternative concept for the design of tokamak radial building is proposed and studied for a DEMO class reactor
- In this framework the TRUST project has been developed as preliminary test to verify the above ideas. Consequently, the TRUST verification would be a significant step forward in the development of alternative toroidal magnetic configurations for compact tokamak reactors
- The use of high-temperature superconductors (HTS) in the TF coils is essential for sustaining high magnetic fields, and the new magnetic layout reduces coupling between the TF and poloidal field (PF) coils, enhancing mechanical stability
- The TRUST project, currently underway at the University of Tuscia, will provide a versatile and low-cost experiment for training the next generation of fusion engineers and physicists. The already operational laboratory, along with planned experiments, will help validate the technologies required for the advancement of DEMO and DTT devices

Alternative toroidal field coils conceptual design for tokamaks in the TRUST project framework

Thank you for your attention!

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