Task:DIV-IDTT.S.07-T005-D001-D002
Overview of status and program of axial symmetric in-vessel coils and stabilizing plates

Task owner: R. Ambrosino

Parners: CREATE, TUSCIA, TOR VERGATA, POLITO

WPDIV-DTT Midterm meeting

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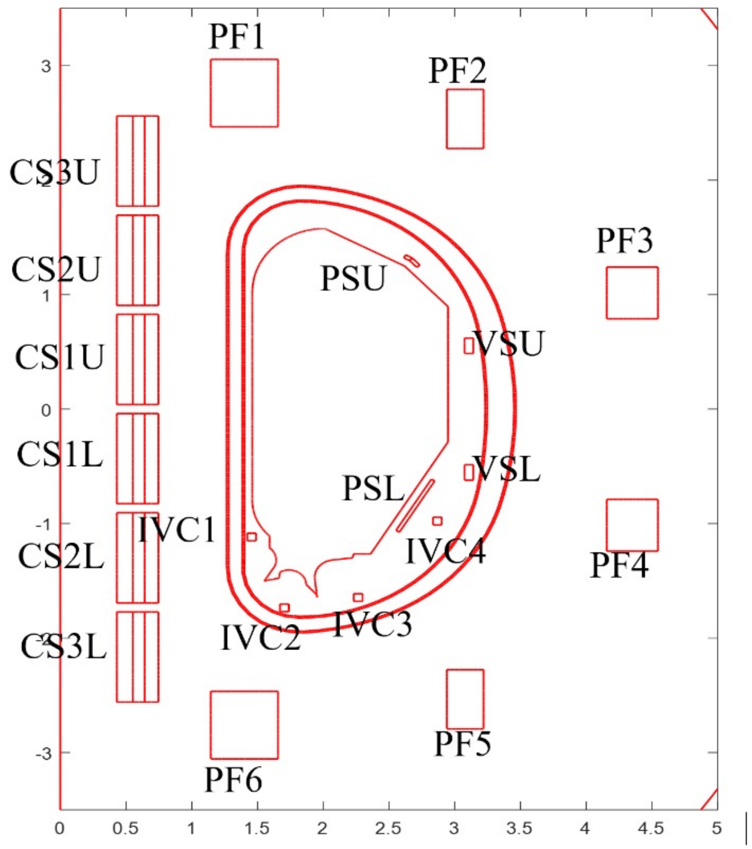
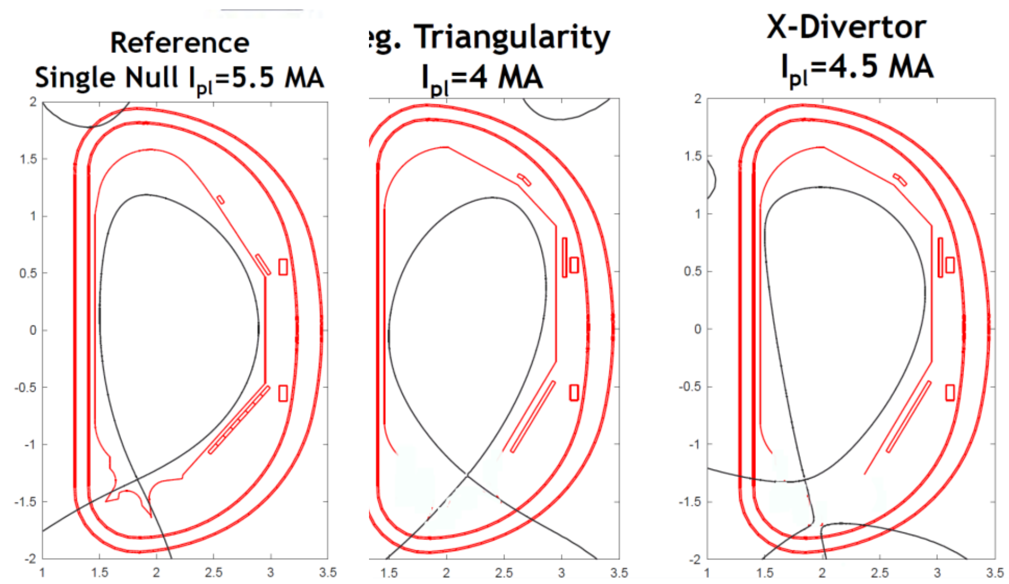
DTT geometry and scenarios



scenarios considered: obtained using only the CS/PF magnets

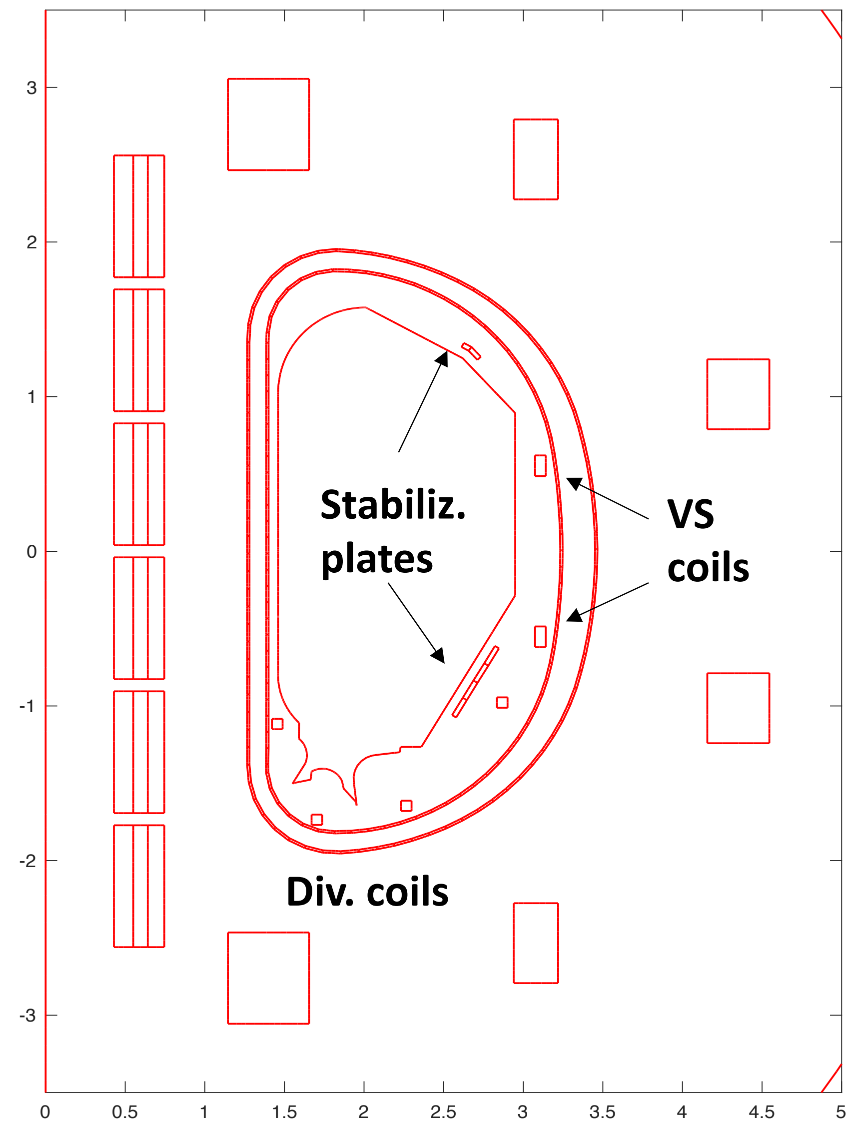
Model including:

- the 6 CS modules & the 6 PF coils
- the vacuum vessel (L/R = 48 ms)
- the in-vessel VS coils (VSU and VSL);
- the four in-vessel divertor coils (IVC1-4);
- the SS stabilizing plates in antiseries.



DTT in-vessel components

- DTT will be equipped with 6 in-vessel coils:
- **2 in-vessel equatorial coils** will be used in DTT both for vertical stabilization and fast radial control
  - Vertical stabilization connected in antiseries (radial field)
  - Radial control connected in series (vertical field)
- **4 in-vessel divertor coils** used for:
  - Local modification of the plasma divertor region
  - Sweeping control
- **Stabilizing plates** are also needed to improve the passive stability performance of the DTT scenarios



Conceptual design of the stabilizing plate

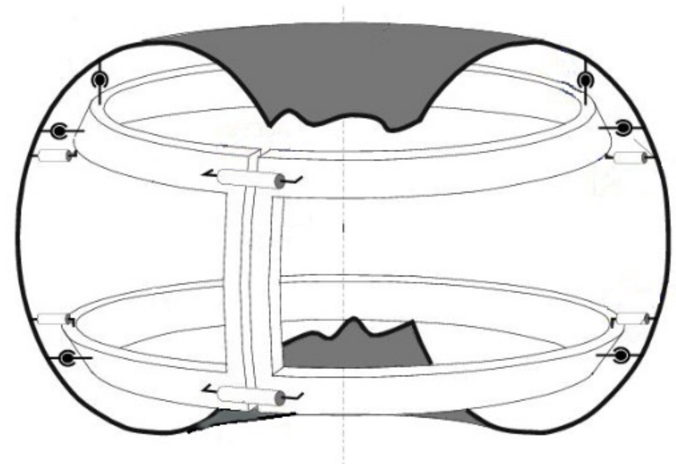
- Since the vacuum vessel, also needed for the stabilization of some instabilities, is located at a relatively large distance in DTT to allow the flexibility of the device, it is not well coupled to the plasma.

- Therefore, the USDEX-Upgrade like solution will be adopted:

a large saddle coil is installed inside the vacuum vessel. It consists of two loops made of copper on the upper and lower side of the vessel, which are connected by a bridge, so that the currents in the lower and upper part are anti-parallel and it only reacts to the net flux change of the plasma.

The advantages of this solution are:

- Robusteness wrt plasma disruptions
- Effectiveness in terms of passive vertical stabilization
- No effects on the breakdown phase



Courtesy of the ASDEX-U Group

Conceptual design of the stabilizing plate

The DTT Stainless steel (0.88 μΩm resistivity) stabilizing plates are connected in antiseries via a single poloidal connection

A preliminary VS analysis has been performed considering a thickness of 30 mm for the toroidal path and neglects the effects of the poloidal path, i.e., with a 2D axisymmetric model with the only constraint of zero net toroidal current.

R-PSU [m]	Z-PSU [m]
2.6266	1.3473
2.6752	1.3211
2.734	1.2582
2.712	1.2378
2.6566	1.2971
2.6124	1.3209
R-PSL [m]	**Z -PSL [m]**
2.848	-0.6278
2.5783	-1.0747
2.5527	-1.0591
2.8224	-0.6122

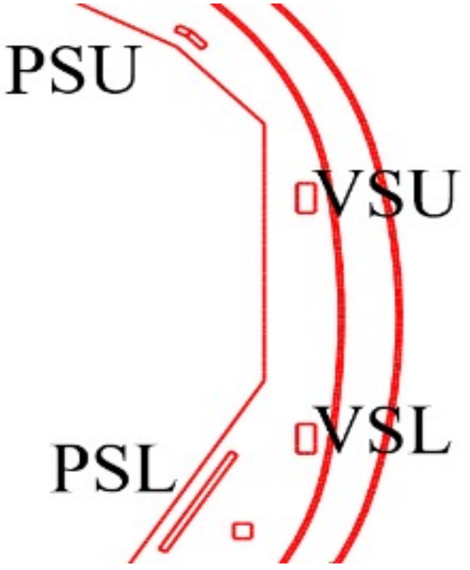
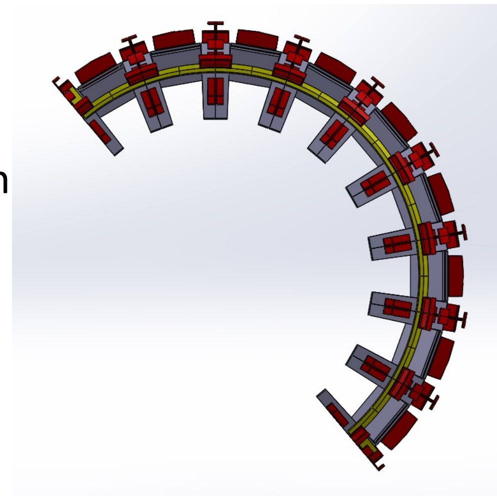


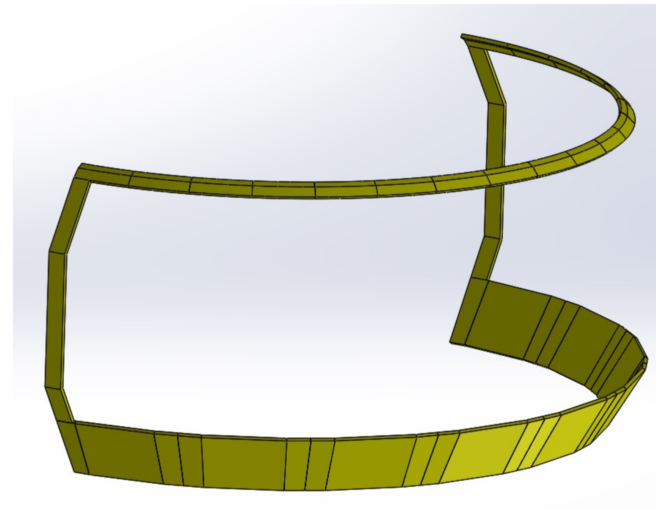
Table II. Sensitivity to the thickness of the stabilizing plates. Stability analysis for a VDE of 1 cm (worst case) with VS coils short-circuited, and in-vessel divertor coils treated as open circuits

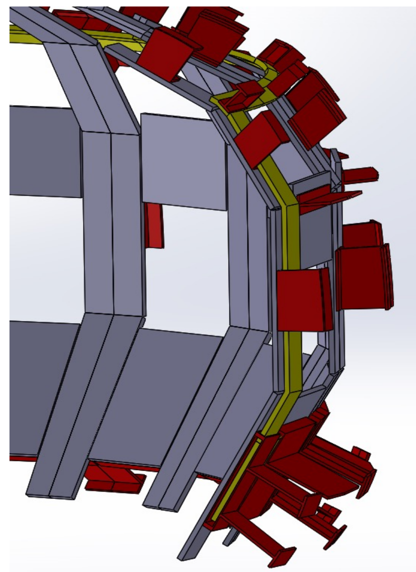
FLAT TOP WORST CASE - V=1.5V0 - TURNS=20 - VDE=1cm - NO DIV. COILS										
thickness	Ipl [MA]	betapol	li	Growth rate [s^{-1}]	Stability Margin	z0 [cm]	zmax [cm]	Voltage [kV]	currents [kA]	Power [MW]
0 (no plates)	5.5	0.1	1.2	278	0.22	1.00	1.10	-1.01	-0.41	0.42
1 cm	5.5	0.1	1.2	213	0.41	1.00	1.19	-1.02	-0.63	0.64
2 cm	5.5	0.1	1.2	194	0.41	1.00	1.19	-0.99	-0.66	0.66
3 cm (ref.)	**5.5**	**0.1**	**1.2**	**153**	**0.41**	**1.00**	**1.18**	**-0.87**	**-0.71**	**0.62**

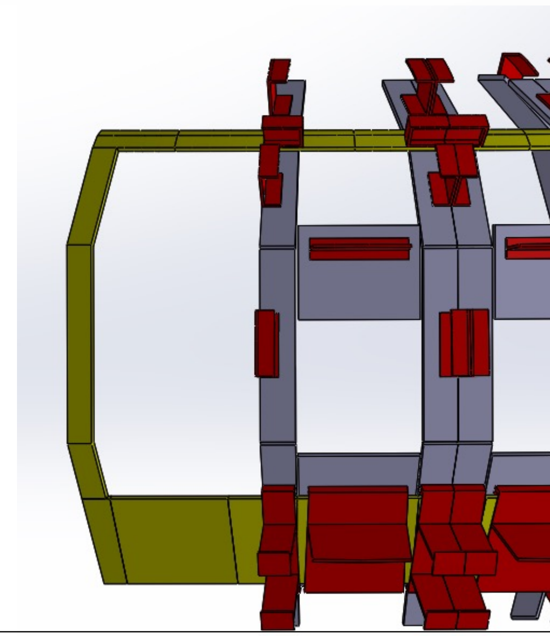
Engineering design of the stabilizing plate

- Preliminarily, the low-to-high connection is made with a thickness of 30 mm and a width equal to the top plate
- The upper plate is supported with elements (one per sector) reinforced according to the expected bending
- The 180° extension plate is assembled with the FW with position -50° to 130° in toroidal angle
- Support position, geometry and numerosity will be assessed after preliminary simulations









Design criteria for the in-vessel equatorial coils

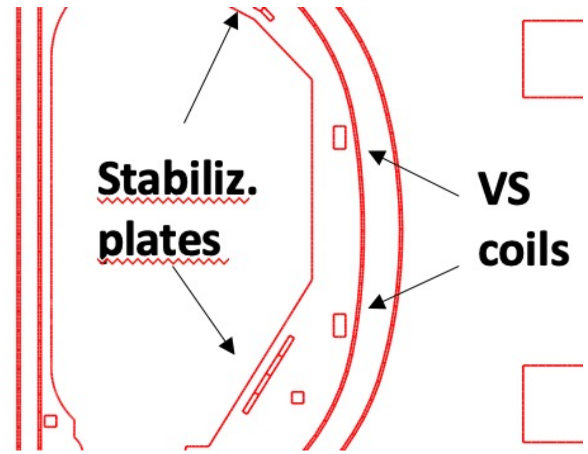
Preliminary assumption for the divertor coil

- Each coils is composed by 10 turns with a reference DC current of 5kA

Radial field for vertical stabilization

Able to stabilize VDE events (uncontrolled vertical displacement detected @ Z=Z0)

- 'reliable' operation: max(Z0)/a ≈ 5% → max(Z0) ≈ 3.5 cm
- 'robust' operation corresponds to max(Z0)/a ≈ 10% → max(Z0) ≈ 7 cm
- other disturbances, e.g., ELMs, are less demanding than the above cases in DTT



Vertical field for fast radial control

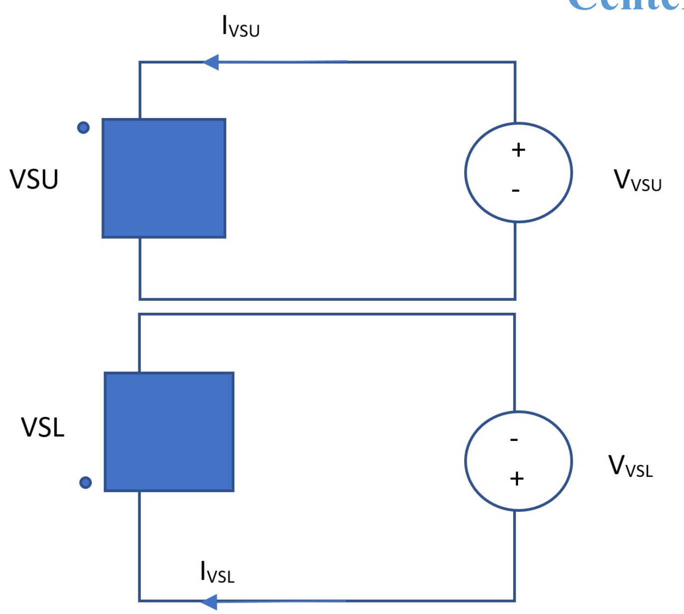
Able to provide a significant contribution to the vertical field:

- during fast H-L transitions, yielding a radial displacement of the inboard gap of ≈ 3 cm (75% of the nominal gap) in 250 ms
- in the plasma current raise during breakdown, yielding ≈ 0.12 T/s (50% of the required value of 0.23 T/s in the ohmic 0.8 V/m breakdown)

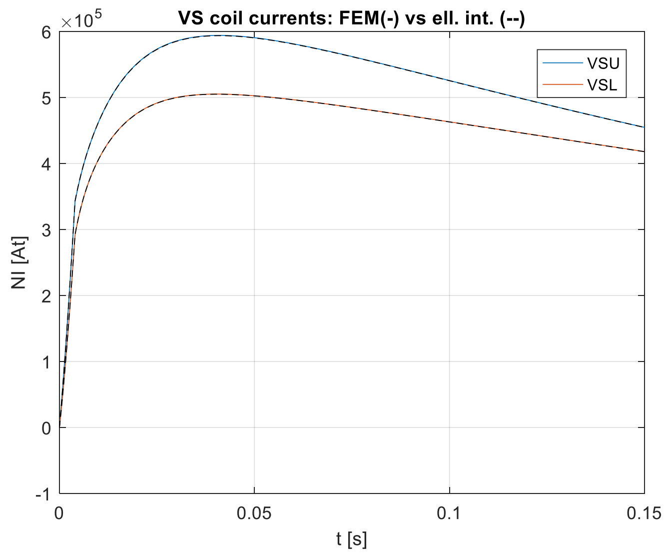
Disruption effects and protections

Without protections or mitigation, plasma disruptions induce large VS coil currents.

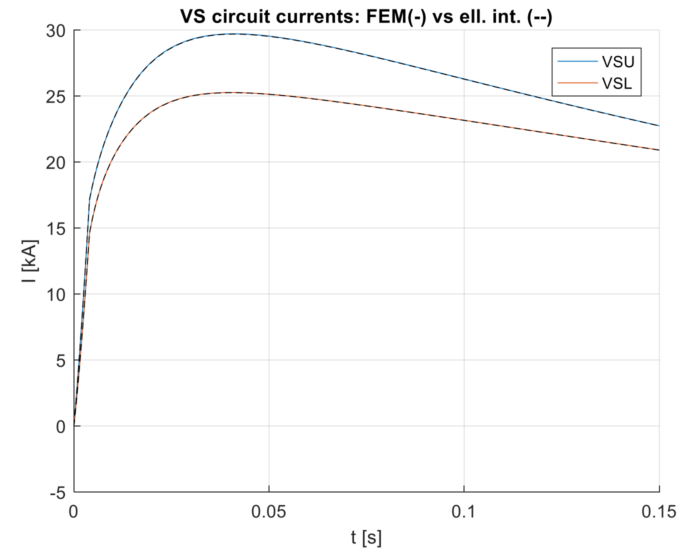
Centered 5.5 MA plasma disruption with a current quench in 4 ms



Coils (20 turns each) independently fed without protections



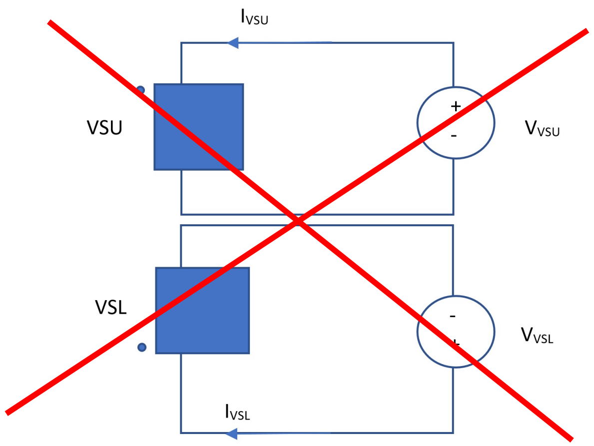
Ampereturns (up to 600 kAt)



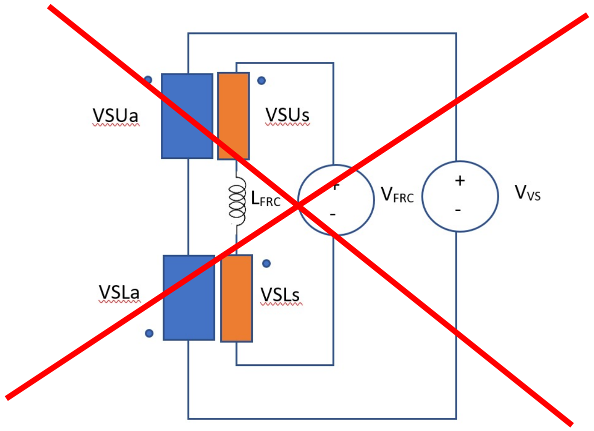
Induced currents (up to 30 kA)

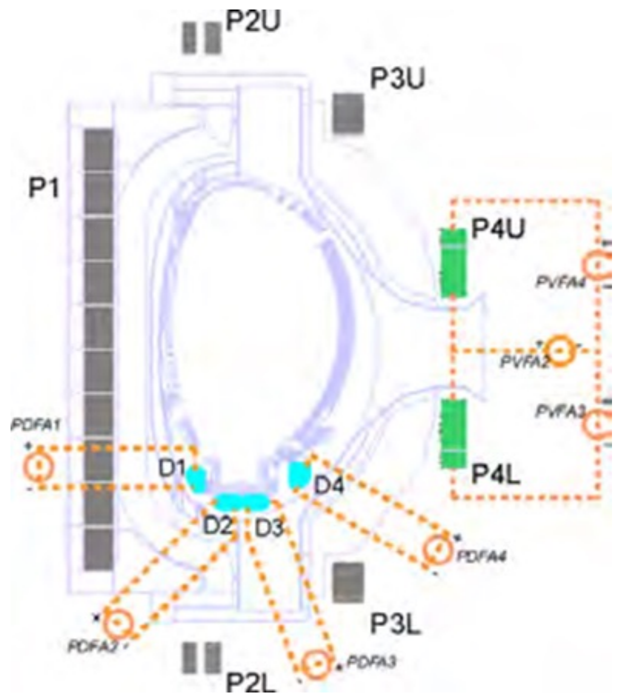
Disruption effects and protections

Coils independently fed: sensitive to disruptions

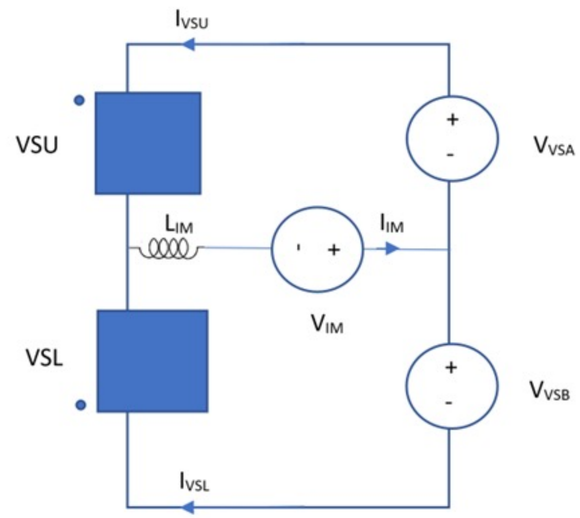


Two separate and independent circuits not fitting in the available in-vessel space





Imbalance circuit used in JET (with reversed roles of radial & vertical field)

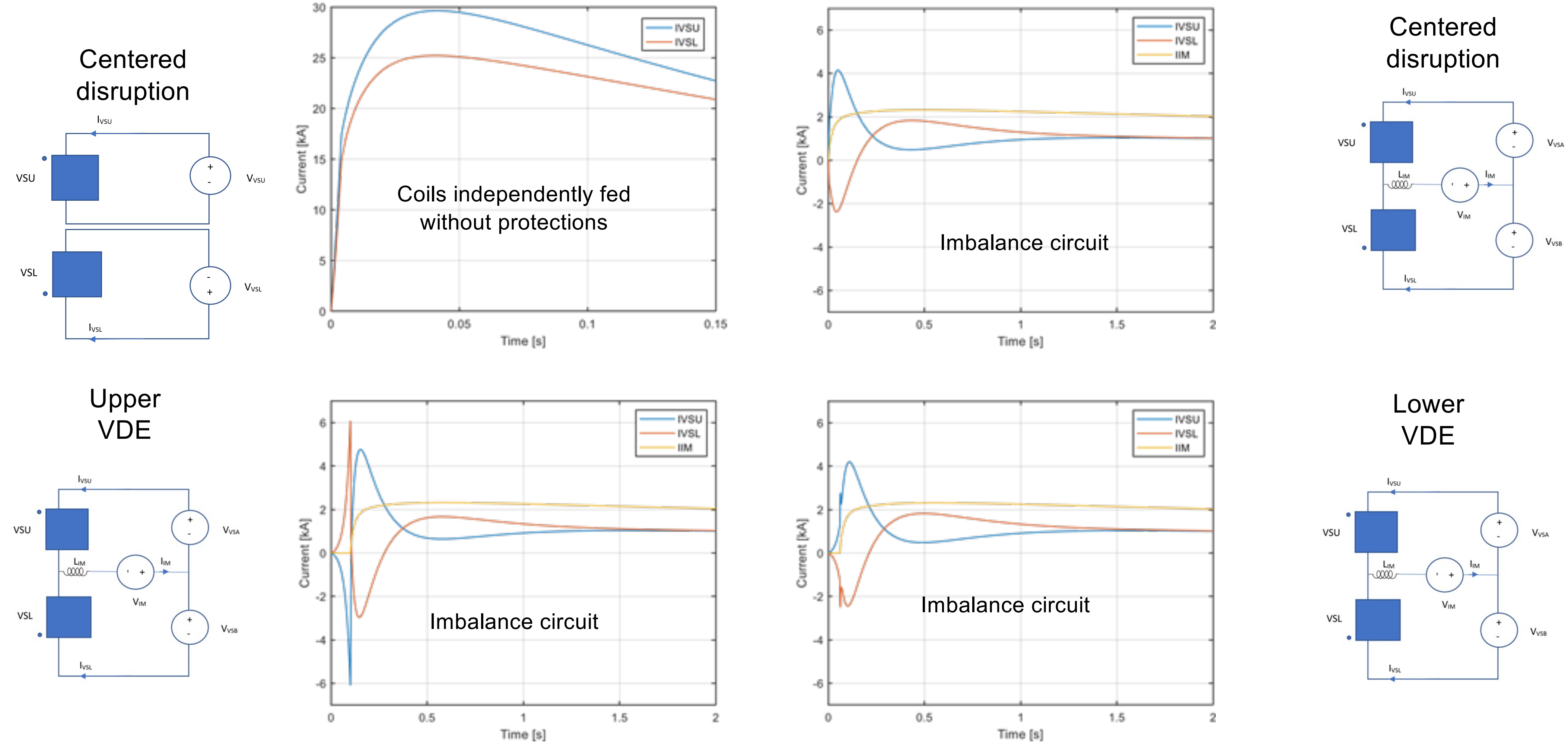


Imbalance circuit proposed for DTT VS coils (L_{IM}=100 mH)

- very fast response for vertical stabilization (radial field produced by $I_{VSL} = -I_{VSU}$)
- response slowed down for radial control and disruptions $I_{VSL} = I_{VSL}$ yielding vertical field

A Refined version has been produced under WPDIV-S08-Power supply

Design criteria for the in-vessel equatorial coils



Induced currents reduced **from 30 kA to 4 kA** in centered disruptions **and 6 kA** in VDEs

Conclusions on the equatorial coils

- VSU and VSL coils with 20 turns each, connected to the circuit with the imbalance current: the number of turns might also be changed for the optimization of the current and voltage request at fixed power;
- 4-quadrant IGBT based V_{IM} amplifier: voltage V_{IM} = 2.5 kV, current I_{IM} = 6 kA in series with an inductance of 100 mH and a fast circuit breaker acting when the current exceeds a critical value;
- 4-quadrant IGBT based V_{VSA} amplifier: voltage V_{VSA} = 2.0 kV, current I_{VSU} = 4.4 kA in series with a fast circuit breaker acting when the current exceeds a critical value;
- 4-quadrant IGBT based V_{VSB} amplifier: voltage V_{VSB} = 2.0 kV, current I_{VSL} = 4.4 kA in series with a fast circuit breaker acting when the current exceeds a critical value;
- 30 mm thick SS passive stabilizing plates in antiseries;
- same coil conductor as ASDEX-U, with an outer diameter of 26 mm, compatible with the insertion of 20 turns in a 117 mm × 117 mm square cross section and the current limits of the fast DC breakers;

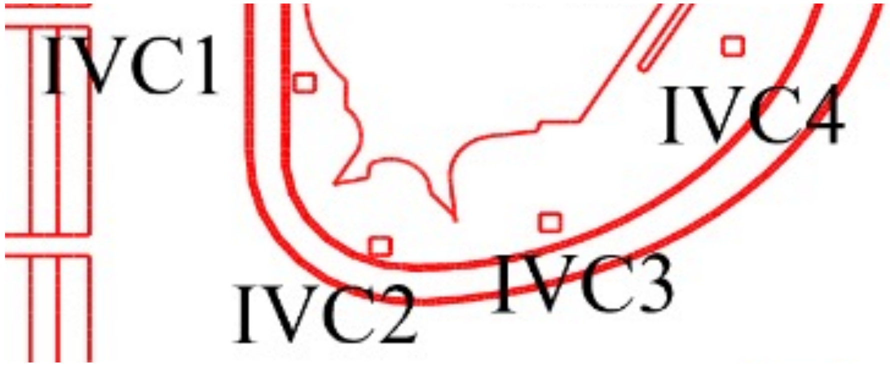
Design criteria for the in-vessel DIV coils

Preliminary assumption for the divertor coils

- 4 divertor coils compatible with the port locations have been considered (variations of the coils positions are still under analysis)
- Each coils is composed by 10 turns

Actions

- fine control of strike-pts, SOL and secondary X-point;
- Fast control during transients;
- strike-pt sweeping



Conclusions on the divertor coils

General conclusions:

- analyzed in detail the inputs for the specifications of the in-vessel divertor coils;
- shown that the in-vessel coils are well suited for their actions (fine control of strike-pts, and secondary X-point, strike-pt sweeping);
- proposed a circuit scheme, providing figures for a baseline option, deferring the optimization and assessment after the definition of the coil location.

Main features:

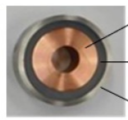
- IVC1, IVC2, IVC3, and IVC4 with 10 turns each, connected to inductors and to a "neutral" conductor: the number of turns might be changed in the final proposal;
- four 4-quadrant SCR (thyristor) power supplies with 5 kA and at least 0.5 kV;
- same coil conductor as ASDEX-U, with an outer diameter of 26 mm, compatible with the insertion of 20 turns in a 60 mm × 120 mm cross section and the current limit of 13 kA;
- currents induced in the disruptions limited by the circuit inductances to less than 9 kA;
- strike point sweeping performance: 2 cm / sinϑ @ 4 Hz;
- fine control of strike-pts and SOL possible on the time scale of 250 ms;

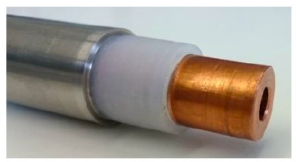
AUG Conductor

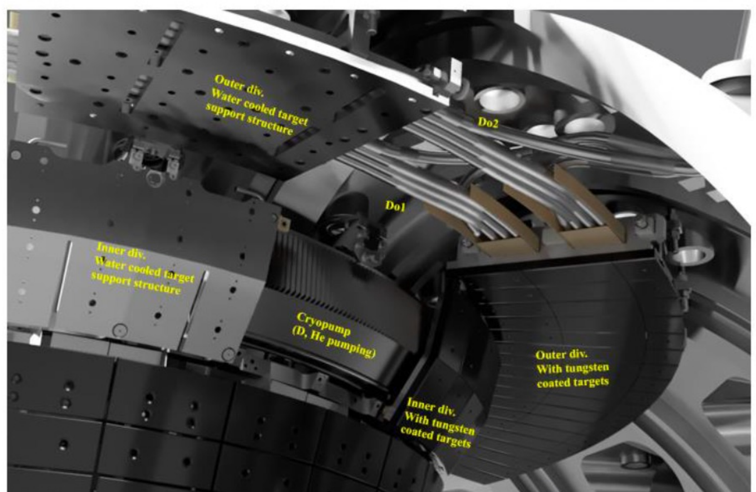
Courtesy of I. Zammuto

AUG Conductor:

- DC current up to 13 kA (per turn), 5 kV
- Tefzel insulation (2.5 mm)
- SS jacket (316L)
- Water-cooled (passively)

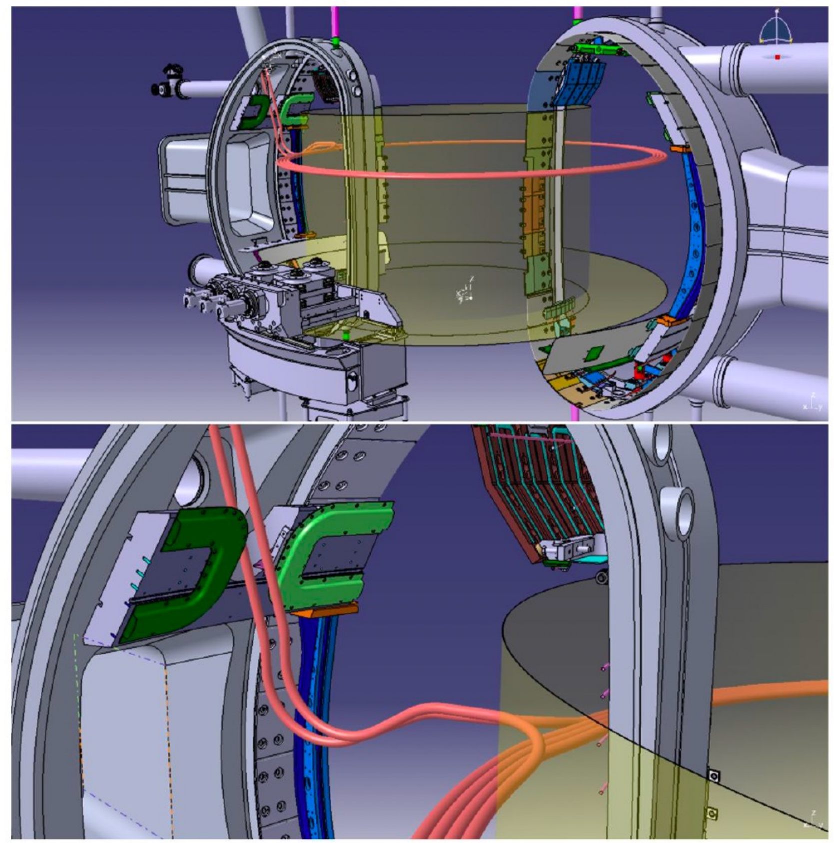






Divertor coils:

- 4 turns per coil – 2 coils for advanced divertor configurations
- w/o joints thanks to oblique port in AUG



Preliminary thermal analysis in DTT

Tefzel insulated conductor in a steel protection tube, carrying up to 13 kA, used in ASDEX-U

- The temperature increase would be $\Delta T = (\eta/\rho c S^2)\, I^2_{rms}\, \Delta t$, where I_{rms} is the rms value of the current and Δt its operation time in a pulse.
- The tolerable value of $I^2_{rms}\, \Delta t$ is given by $(\rho c S^2/\eta)\, \Delta T$, where the coefficient $(\rho c S^2/\eta)$ is 5.75 $kA^2\, s\, K^{-1}$.
- For instance, assuming a tolerable ΔT = 50 K, $I^2_{rms}\, \Delta t$ would be 288 kA^2 s, e.g., 1.7 kA for 100 s, or 2.4 kA for 50 s.
- The temperature can easily be restored by active cooling between two pulses: the water at 2.5 m/s takes about 100 s to fill the cooling channel, but the thermal time constant is less than 3 s (also other refrigerant fluids can be used)

Steakholders of the IVC -1 activities

Institution	Activity	Reference Person
Create M&C	Definition of the electromagnetic and control specification for the in-vessel coils. Disruption analysis. Sizing and positioning of the coils. Support to all the phases of the engineering design	R. Ambrosino
Create M&C	Support for the thermal analysis of the in-vessel coils	V. P. Loschiavo
Uni Tuscia	Mechanical design & EM loads specification	P. Fanelli
Tor Vergata	Static structural analyses on in-vessel coils under EM loads - Engineering design of the attachments to the VV of the divertor coils with static EM loads analysis - Engineering design of the DTT in-vessel coils feeders.	F. Vivio
PoliTo	Joining and testing of multimaterial components	M. Ferraris

Milestones of the IVC -1 activities

	Sub Task Description	Jan-22	Feb-22	Mar-22	Apr-22	May-22	Jun-22	Jul-22	Aug-22	Sep-22	Oct-22	Nov-22	Dec-22
ENGINEERING DESIGN PHASE	➢ Definition of the supports on vacuum vessel ➢ Electromagnetic and mechanical analysis of the coils ➢ Identification of the cable insulation technologies for coils (e.g. ETFE, MI, PEEK) and implications on joining of coils to feeders												
MANUFACTORING AND ASSEMBLY PROCEDURES	➢ Design for manufacturing the cable, development & R&D of the joints between coils and feeders, manufacturing-installation sequence of the system ➢ Design of supports on vacuum vessel consistent with system installation sequence												
DEFINITION OF THE TECHNICAL SPECIFICATIONS	➢ Technical specification for procurement of the cable for ICA and ICN ➢ Technical specification for the procurement of ICA												

Steakholders of the IVC -3 activities

Institution	Activity	Reference Person
Create M&C	Supporto alle specifiche tecniche, dimensionamento e posizionamento delle stabilizing plates	R. Ambrosino
Uni Tuscia	Mechanical Design	P. Fanelli
Uni Tor Vergata	Thermo-mechanical analysis of the stabilizing plates	F. Vivio

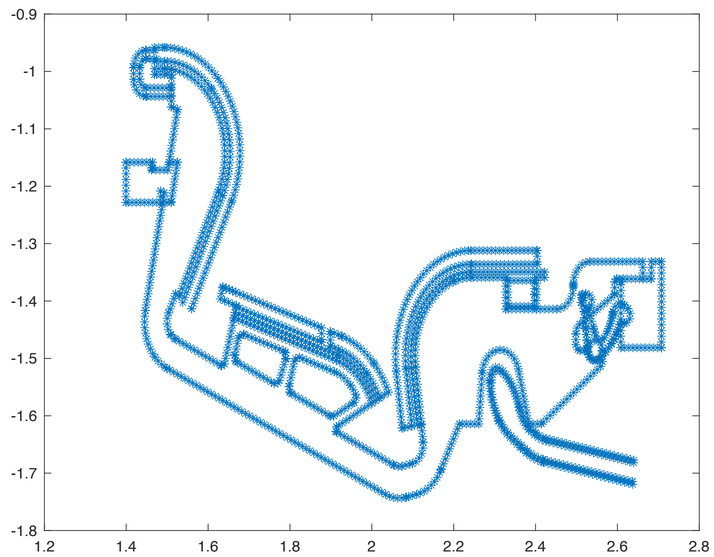
Milestones of the IVC -3 activities

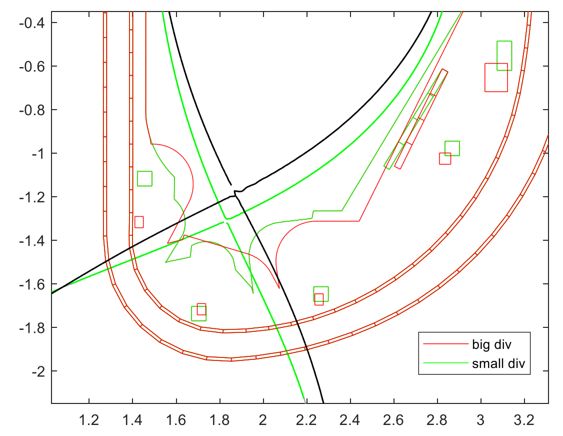
	Sub Task Description	**Jan-22**	**Feb-22**	**Mar-22**	**Apr-22**	**May-22**	**Jun-22**	**Jul-22**	**Aug-22**	**Sep-22**	**Oct-22**	**Nov-22**	**Dec-22**
ENGINEERING DESIGN PHASE	➢ Definition of the supports on vacuum vessel ➢ Electromagnetic and mechanical analysis of the SPs ➢ Identification of the materials and of the up-down connections of the plates												
MANUFACTORING AND ASSEMBLY PROCEDURES	➢ Manufacturing-installation sequence of the system ➢ Design of supports on vacuum vessel consistent with system installation sequence												
DEFINITION OF THE TECHNICAL SPECIFICATIONS	➢ Technical specification for procurement of the SPs												

Needs to revise the conceptual design…

At the beginning of 2022 two main variations of the DTT project have been implemented:

- Conceptual design of the first divertor





Vertical movement of the plasma configurations

- 10cm vertical variation of the position of the In-vessel equatorial coils

An iteration to the conceptual design phase is needed