Vincenzo Paolo Loschiavo

Tutor: Prof. Eng. Raffaele Albanese

XXIX Cycle – III year presentation

“Modelling of power exhaust in fusion plasmas”

Università degli Studi di Napoli
Federico II

Background

M.Sc. Degree in Mechanical Engineering – University of Naples Federico II

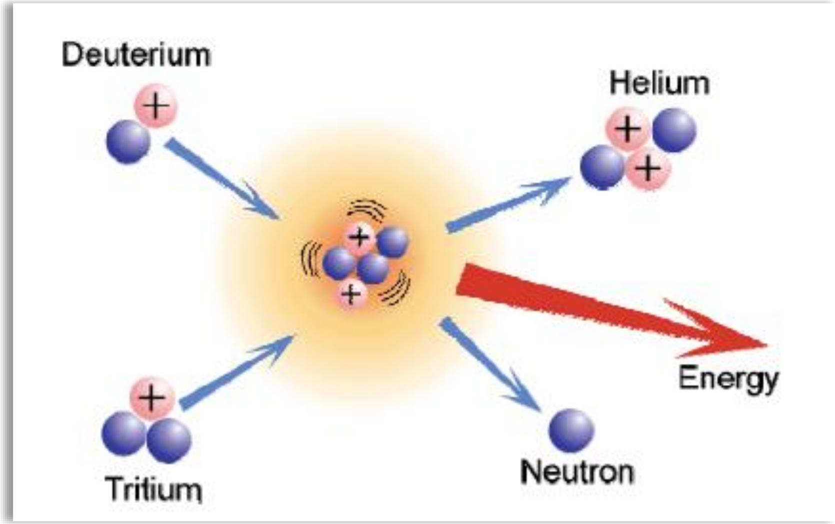
Credits summary

	Credits year 1								Credits year 2								Credits year 3									
		1	2	3	4	5	6			1	2	3	4	5	6			1	2	3	4	5	6			
	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	Summary	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	Summary	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	Summary	Total	Check
Modules	21			3		3	5	**11**	15		6		1		12	**19**								**0**	**30**	30-70
Seminars	5	0.4	0.8		1	0.2	2	**4.4**	5	0.8	0.2		0.4		0.4	**1.8**					8.4		0.6	**9**	**15**	10-30
Research	34	10	8	8	8	6	0	**40**	40	10	6	10	10	10	0	**46**		10	10	8	5	8	8	**49**	**135**	80-140
	60	10	8.8	11	9	9.2	7	**55**	60	11	12	10	11	10	12	**67**	60	10	10	8	13	8	8.6	**58**	**180**	180

Experience abroad (during the third year)

More than 4 months (1 April – 31 July 2016 and 13-19 November 2016) in the Max Planck Institut for Plasma Physics – EUROfusion (Garching – Munich)

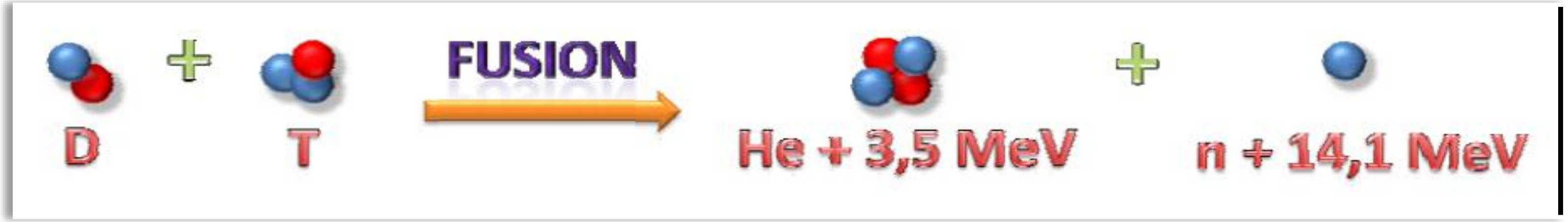
What is nuclear fusion?



Fusion is the nuclear reaction process by which two or more atoms are compressed so that the strong interaction prevails on the electromagnetic repulsion, forming one or more different atomic nuclei and subatomic particles (neutrons and/or protons)

The amount of energy released in a nuclear reaction can be expressed, according to the “theory of relativity” by Albert Einstein, by the famous expression:

$$\Delta E = \Delta M\ c^2$$



Thermonuclear fusion

Thermonuclear fusion consists in heating the fuel (Deuterium and Tritium) at extremely high temperature

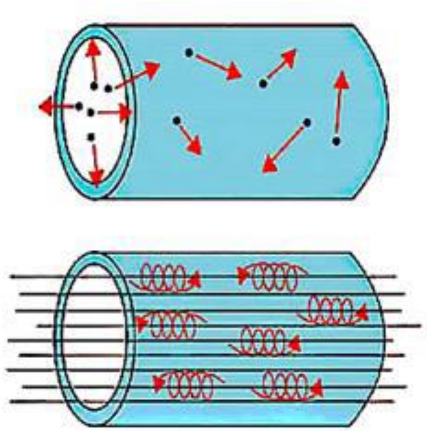
$\approx 100\ millions\ degree$

(more than 6 times the temperature in the Sun core) for a sufficiently long confinement time.

PLASMA

a gaseous mixture of negatively charged electrons and highly charged positive ions

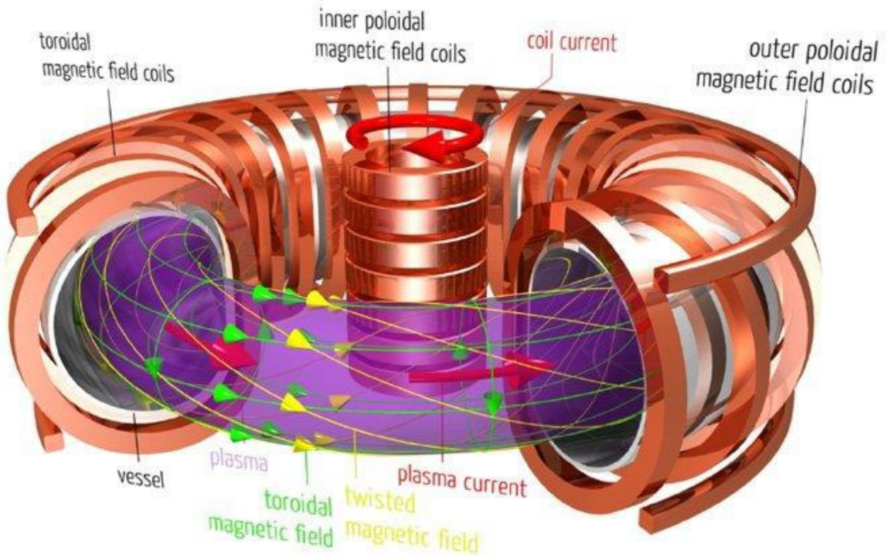
The plasma magnetic confinement (1)



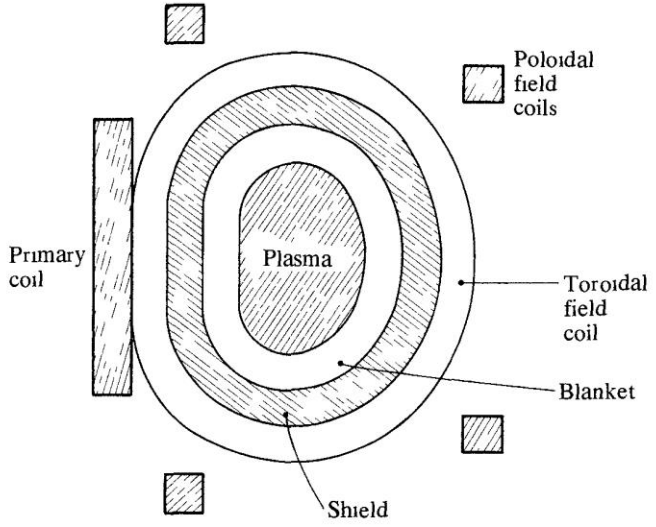
Charged particles in a magnetic field follow a helical path around the magnetic field lines according to the Larmor equation:

$$r = \frac{mv}{qB}$$

The so-called “tokamak”, a Russian acronym for TOroidalnaya kamera ee MAgnitnaya Katushka (“тороидальная камера с магнитными катушками”), which translated literally means “Toroidal Chamber with Magnetic Coils”, is nowadays the most used configuration for the plasma confinement.

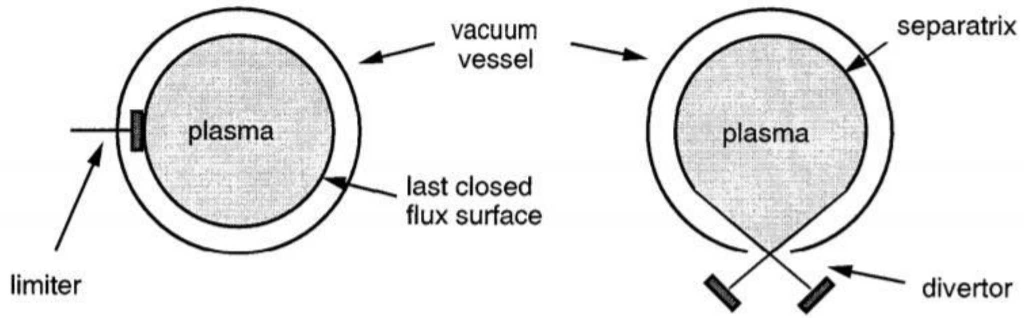


The plasma magnetic confinement (2)



The magnetic field used in an experimental fusion device is given by the superposition of magnetic fields produced with coils external to the main chamber, and the one produced by the current flowing within the plasma

In the magnetic confinement devices, the plasma is confined inside closed magnetic flux surfaces. The so-called “Last Closed Flux Surface” (LCFS) or “Separatrix” determines the plasma boundary

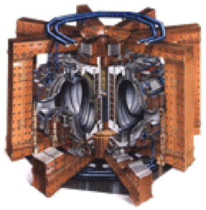


How Close Are We To Nuclear Fusion?

Fusion energy gain factor (Q), is the ratio of fusion power produced in a nuclear fusion reactor to the power required to maintain the plasma in steady state:

$$Q = \frac{P_{fusion}}{P_{external}}$$

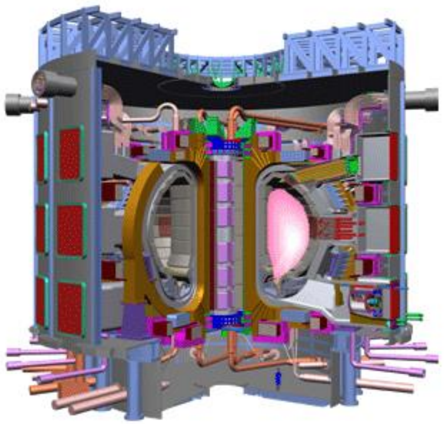
JET (to scale)



JET (Joint European Torus), operating since 1983, is currently the largest tokamak in the world. In 1997, JET produced 16 MW of fusion power from a total input power of 24 MW.

Record in 1997
$Q = 0.67$

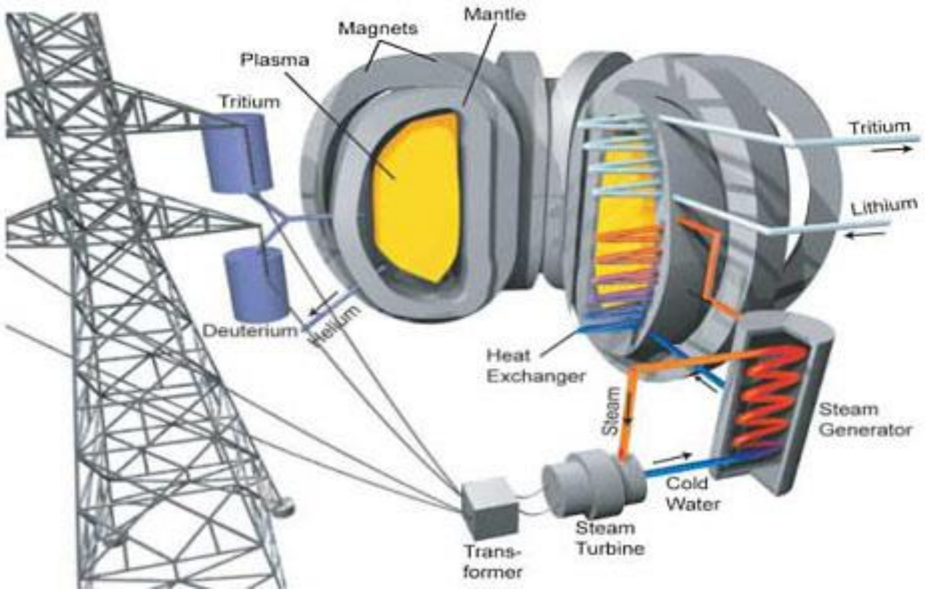
ITER



Break-even $Q = 1$

and beyond $Q = 1 \div 10$

DEMO



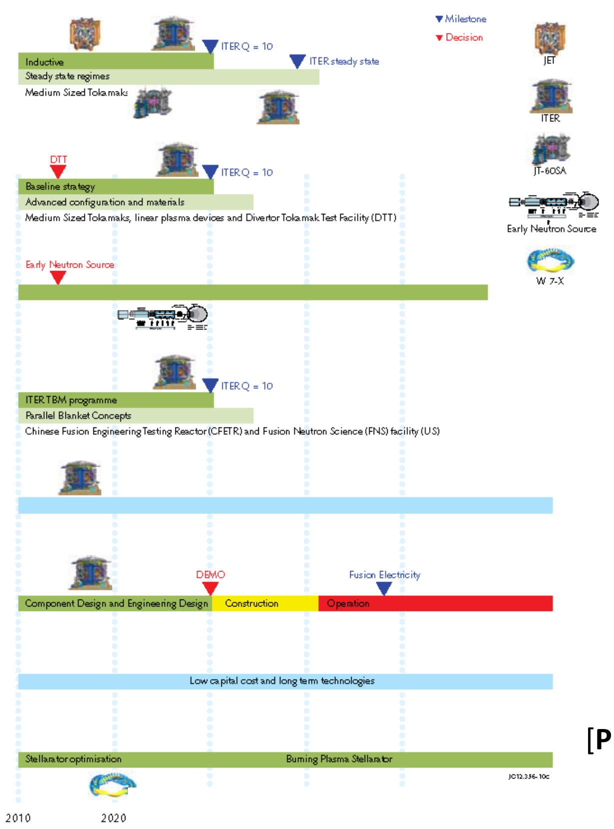
A demonstration fusion power plant

$Q \gg 1$

A roadmap to the realisation of fusion energy

1. Plasma operation
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
7. Low cost
8. Stallarator

Fusion Electricity - EFDA November 2012



The missions to the realisation of fusion

"The realisation of fusion energy has to face a number of technical challenges. For all of them candidate solutions have been developed and the goal of the programme is now to demonstrate that they will also work at the scale of a reactor. Eight different roadmap missions have been defined and assessed. They will be addressed by universities, research laboratories and industries through a goal-oriented programme […] for the Horizon 2020 period.
[…] According to the present roadmap, a demonstration fusion power plant (DEMO), producing net electricity for the grid at the level of a few hundred Megawatts is foreseen to start operation in the early 2040s. Following ITER, it will be the single step to a commercial fusion power plant."

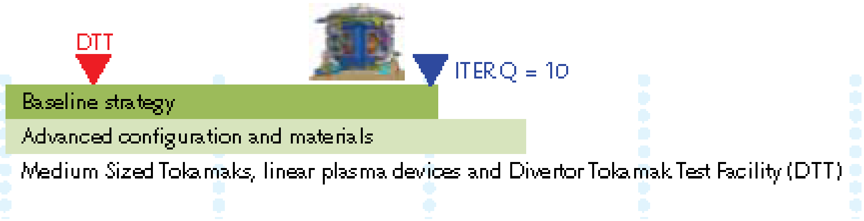
"Fusion Electricity – EFDA, November 2012"

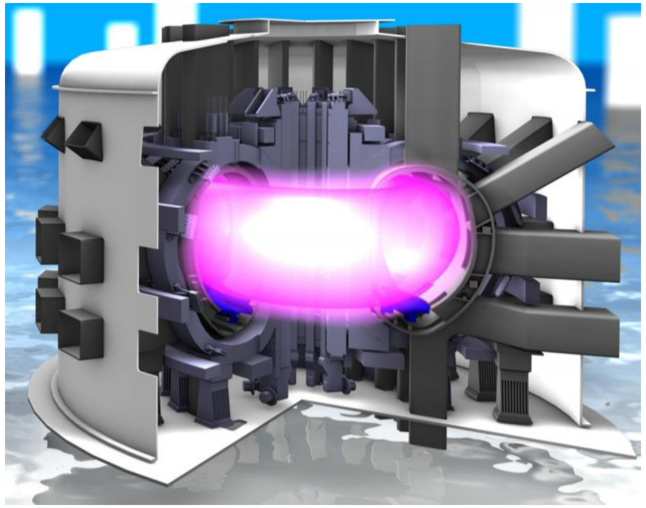
Francesco Romanelli
EFDA Leader

DTT (Divertor Test Tokamak) facility:
an Italian project proposal

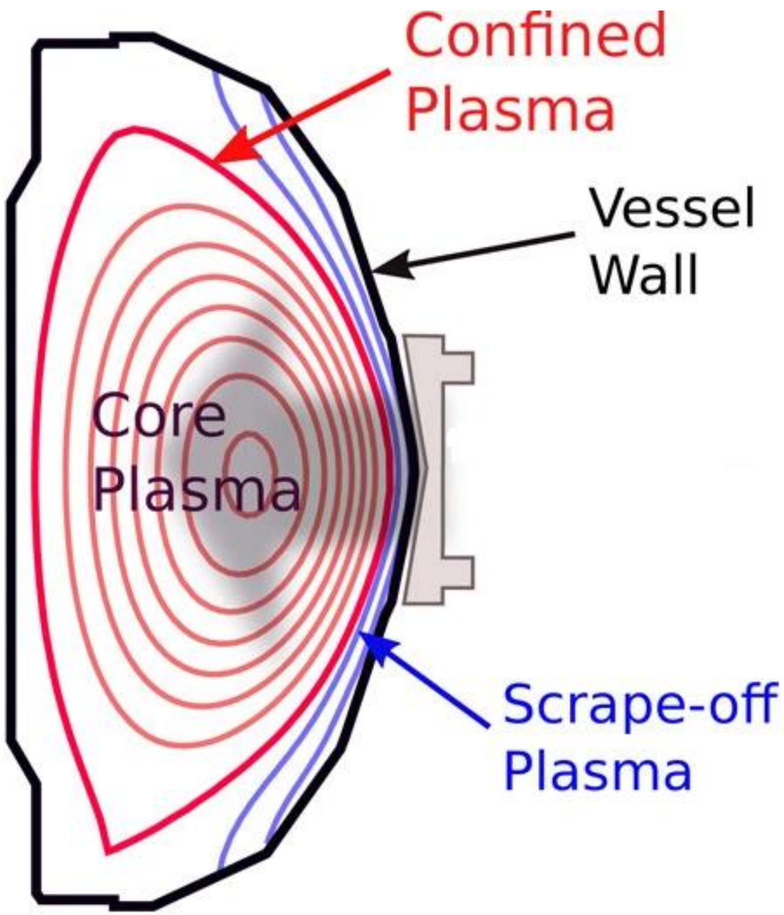
[**Prof. Raffaele Albanese** is the Project Leader for DTT II facility]

2. Heat exhaust



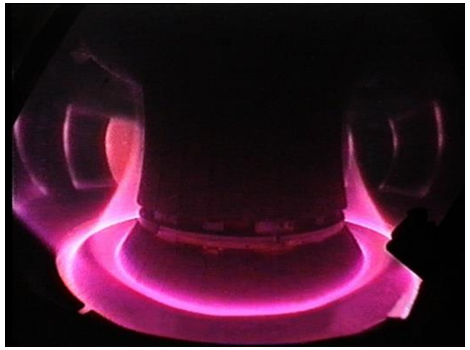


The power exhaust issue

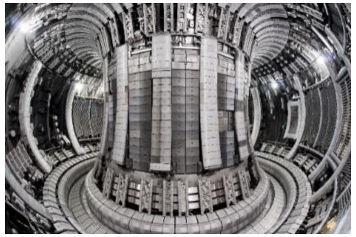


Despite the “closed nature” of the divertor plasma, a certain amount of charged particles leaves the confined plasma. Once in the so-called “scrape-off layer”, the plasma spiral down along the magnetic field and then interacts with a solid surface.

> *[…] Materials that resist heat fluxes up to 20 MW/m^2, which is of the same order as the heat load on the sun’s surface, have been produced for ITER. Alternative, backup divertor concepts are under investigation and need to be brought to sufficient maturity by 2030 through a dedicated experimental programme.”*
>
> *“Fusion Electricity – EFDA, November 2012”*



Interior of JET showing the ‘ITER-like’ wall of beryllium and tungsten.



Candidate solutions to the power exhaust

"[…] The divertor must be designed to withstand the high heat and particle fluxes from the plasma."

"[…] ***<u>Alternative, backup divertor concepts are under investigation and need to be brought to sufficient maturity by 2030 through a dedicated experimental programme</u>****."*

"Fusion Electricity – EFDA, November 2012"

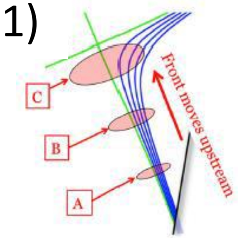
⬇

Addressing the power exhaust and particles

1) Detachment realization and control (ITER baseline)

A physical phenomenon by which the plasma materially "detaches" from the PFCs creating a neutral gas "blanket" (also called "front") in which the momentum and the energy are transferred from the plasma to the neutral gas.

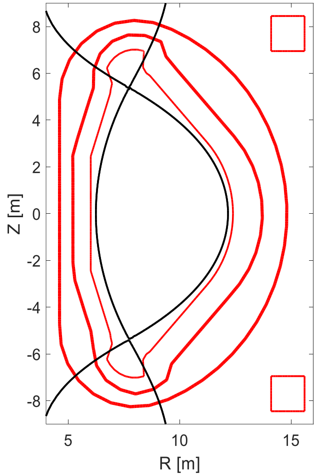
1)



2) Alternative Magnetic Configurations

The Alternative Magnetic Configurations produce magnetic fields by which the charged particles, following the field lines, spread their energy on a broader area once they reach the plasma-facing components or dissipate great part of their energy before reaching the solid surfaces.

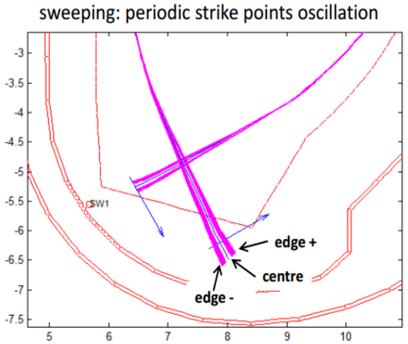
2)



3) Heat load spreading techniques

Strike-point sweeping and wobbling techniques, by which respectively part of or the whole plasma boundary is moved periodically by external coils spreading the thermal load on a wider area.

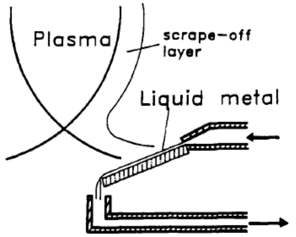
3)


sweeping: periodic strike points oscillation

4) Liquid metal divertor

Solves the problem of the melting of the divertor solid surfaces occurring at the high temperatures reached in steady-state conditions resorting to a divertor composed by liquid metals

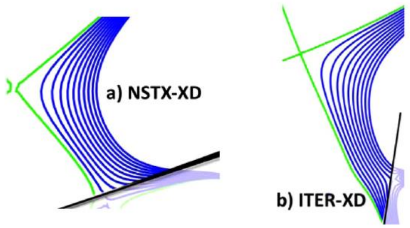
4)

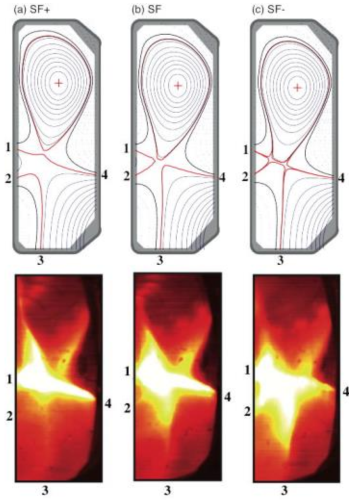


State of the art and my contribution (1)

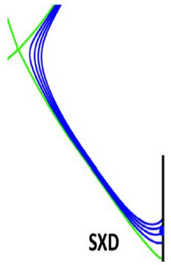
Alternative Magnetic Configurations

State of the art



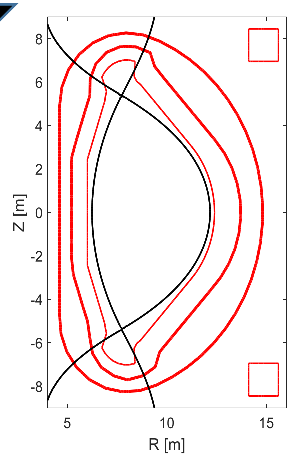


TCV SF configuration

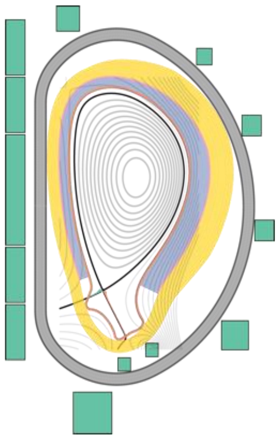


My contribution

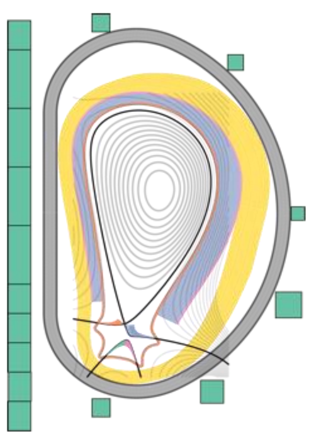
DEMO magnetic alternative configurations design and vertical stability analysis



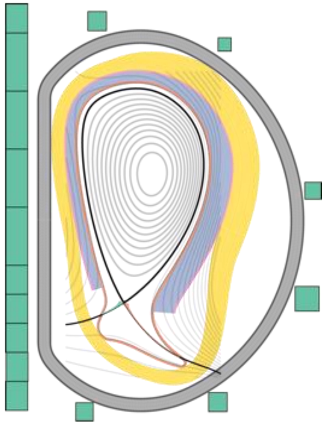
Optimized DN configuration



Optimized XD configuration



Optimized SF configuration

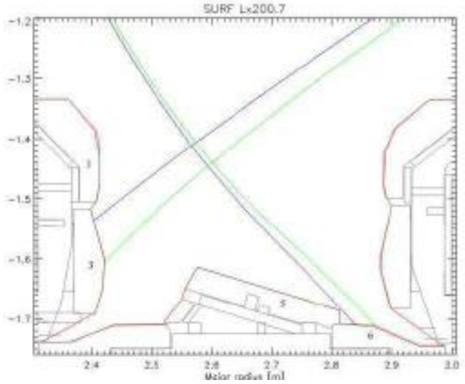


Optimized SX configuration

State of the art and my contribution (2)

Heat load spreading techniques (Strike Point Sweeping, Wobbling)

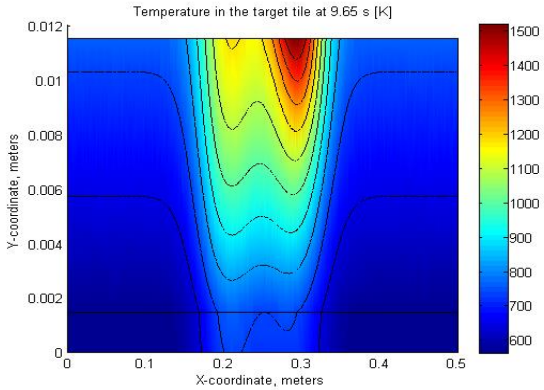
State of the art



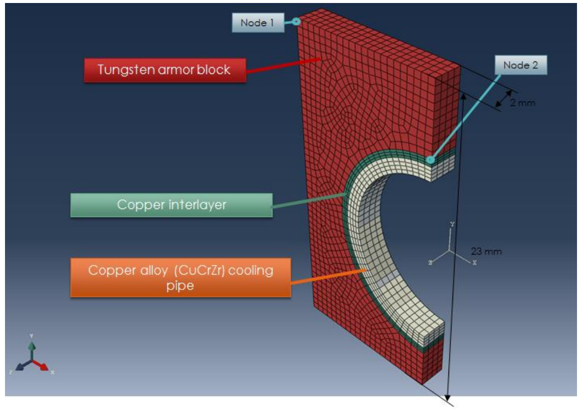
Strike-point sweeping in JET

My contribution

DEMO divertor target tiles 2D and 3D thermo-mechanical analyses in the strike-point sweeping case



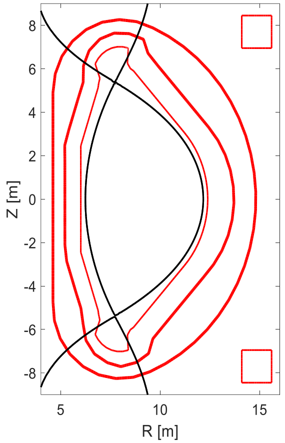
Example of a 2D FEM thermal analysis of the Divertor Target in a SP sweeping case (15 MW/m^2, Ampl. 6 cm, Freq. 1Hz)



3D FEM model of DEMO target tile

Alternative Magnetic Configurations: advantages

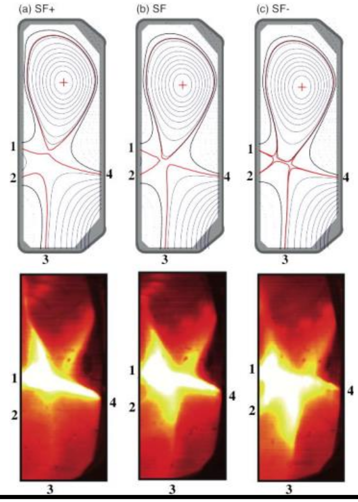
1) Double null



- Second null point in the poloidal magnetic field
- Wall interaction doubled
- Heat load reaching divertor halved

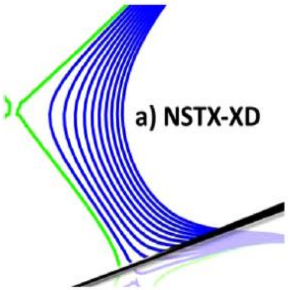
(Second divertor is needed!)

2) Snowflake



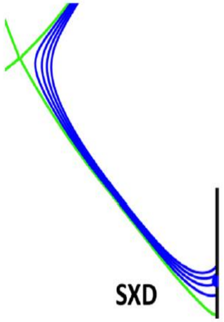
- A second order null point
- Six-fold symmetry (4 legs instead of 2)
- Increased connection length
- Increased radiation in null point region

3) X-Divertor



- A second axisymmetric X-point near divertor
- Flux expansion (Flared flux surfaces)
- Increased connection length

4) Super-X Divertor



- Superposes toroidal expansion (by placing the divertor plate at the maximum possible major radius) on the poloidal flux expansion
- Greater flux expansion

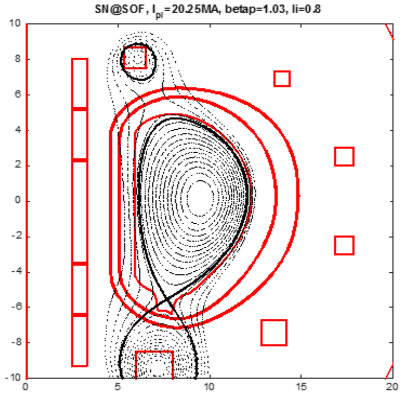
DEMO Alternative Magnetic Configurations: my contribution (1)

Design

1) Requirements

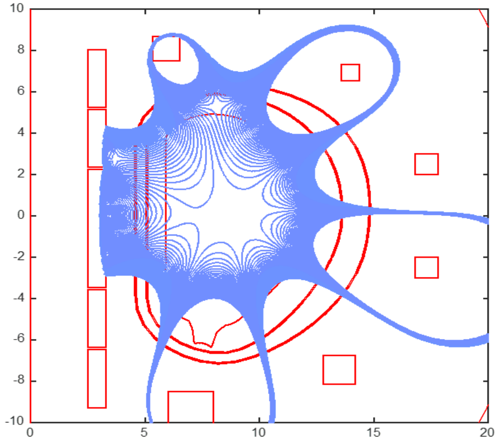
- “PROCESS” RUN -> machine and plasma parameters
- PPPT Group (Garching) -> constraints
- CCFE -> realistic design of the structures

2) PF coil system design constraints



- Current density limit on PF coils
- Maximum field at the location of the PF and CS coils
- Maximum vertical and separation forces

3) Pre-magnetization phase

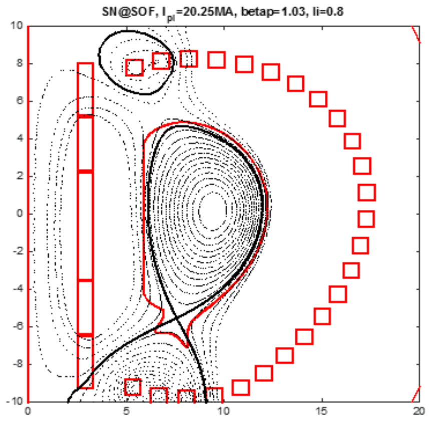


- Definition of a non-optimized set of coils: CS stack composed by 5 elements and a 6 PF coils system.
- Position and width of the CS stack are mainly related to J_{max} and B_{max} (according to constraints)
- Starting from the pre-magnetization flux, the boundary flux at Start of Flat-Top (SOF) can be computed via Ejima scaling

DEMO Alternative Magnetic Configurations: my contribution (2)

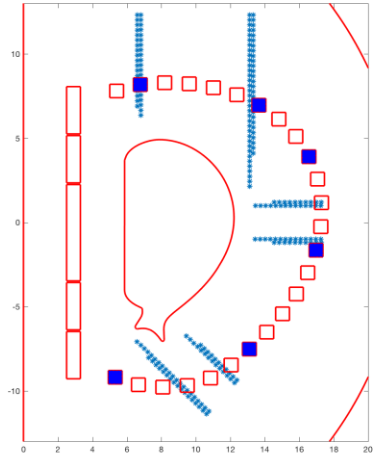
Design

4) PF coils optimization



- A redundant set of PF coils compatible with the available space - limited by the outer TF shell
- Chosen the number N constituting the PF coil set (e.g. 6 PF coils), all the possible combinations of N PF coils have to be investigated;
- Once few sets of PF coils have been identified to satisfy the constraints, an exhaustive analysis of the candidate PF coil systems is carried out in order to find SOF and EOF maximizing the flat-top flux swing.

5) The presence of the ports

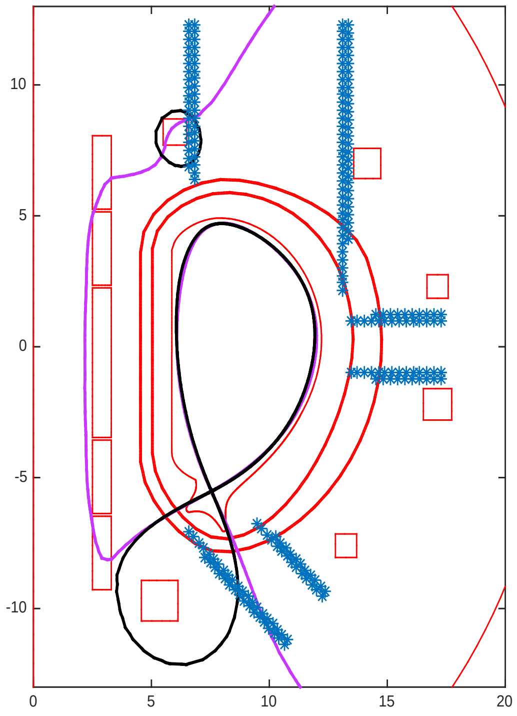


- The implementation of the optimization procedure have to take into account the presence of the ports. Typically, in a DEMO standard configuration, there are 3 ports: upper, equatorial and lower ports for maintenance and diagnostics.

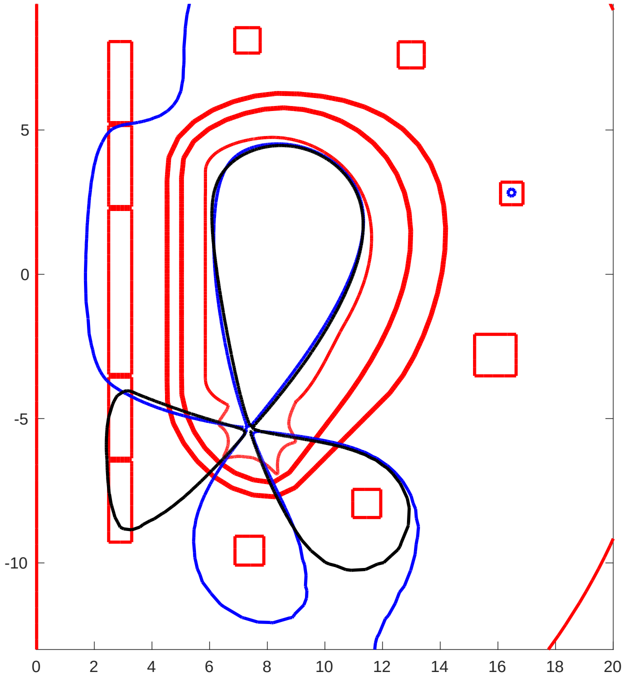
DEMO Alternative Magnetic Configurations: my contribution (3)

Design results

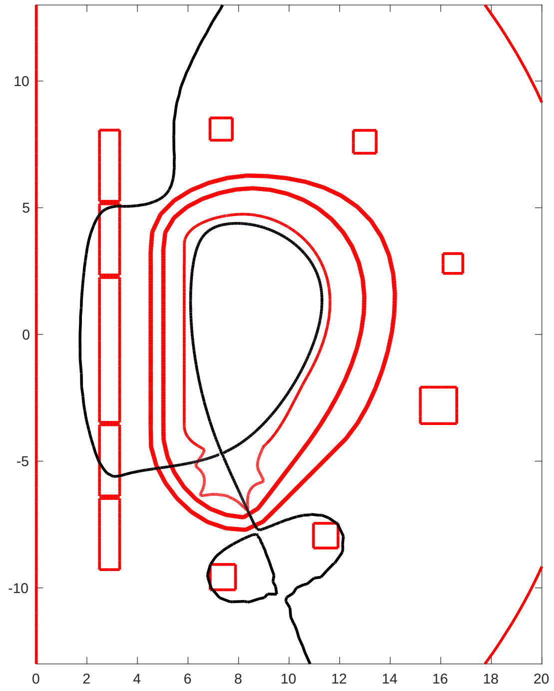
Single null



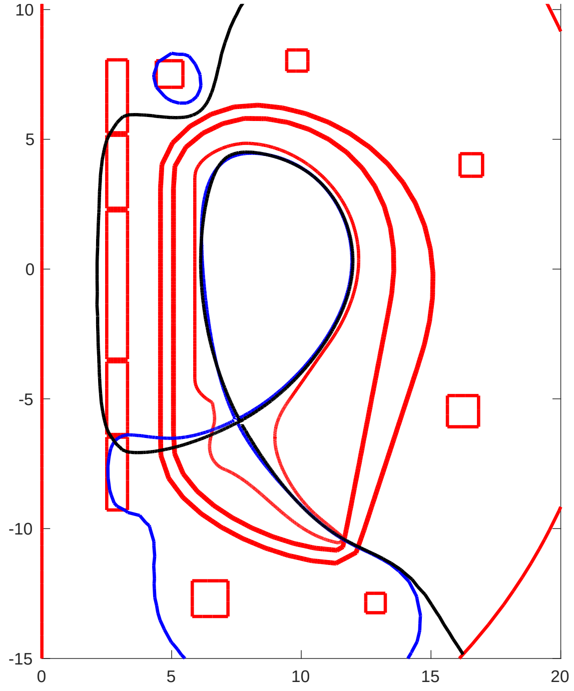
Snowflake



X Divertor



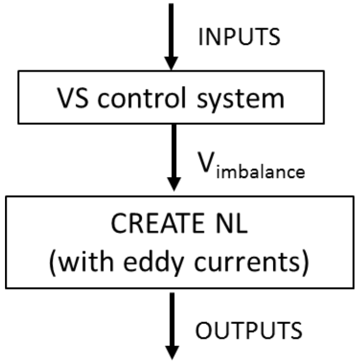
Super-X Divertor



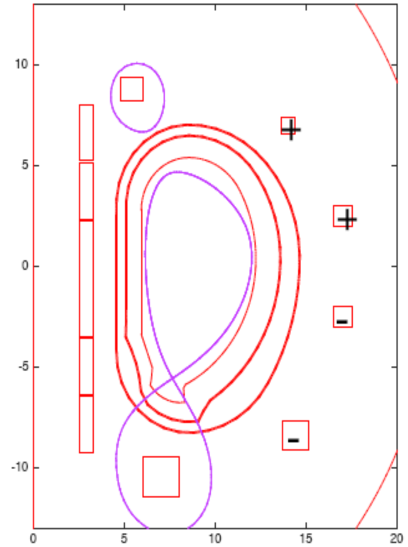
DEMO Alternative Magnetic Configurations: my contribution (4)

Vertical stability analysis

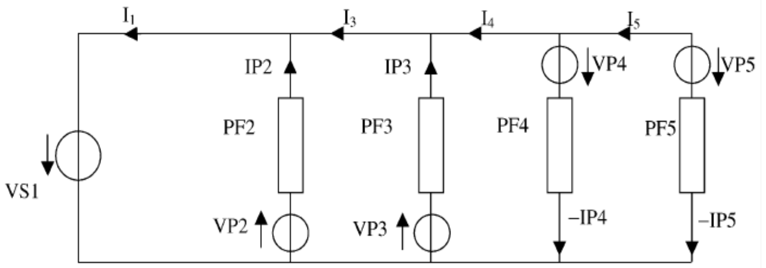
1) Open-loop non-linear dynamical simulation



AIM: assessment of the effect of critical disturbances, modelled as a variation of poloidal beta ($\Delta\beta pol$) and internal inductance (Δli), on the vertical and radial plasma displacement of DEMO standard and alternative magnetic configurations



Vertical stabilization circuit



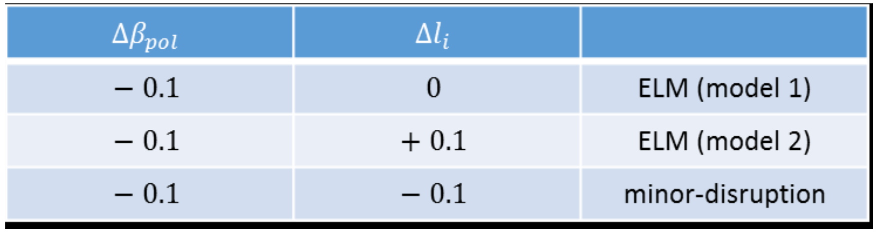
2) Main assumptions

- the eddy currents originating in the passive structures are always taken into account;
- a constant voltage on the imbalance circuit (given by the best achievable performance) is applied;
- the presence of the ports roughly has been modelled removing 1/3 of the conductive elements in correspondence of each port;
- the plasma current has been kept constant during the simulation

DEMO Alternative Magnetic Configurations: my contribution (5)

Vertical stability analysis

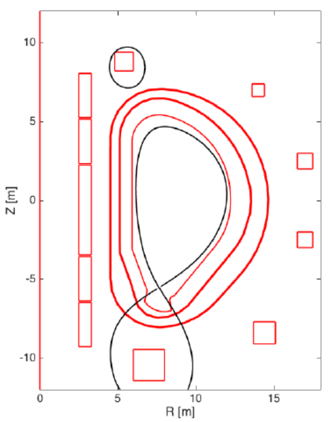
3) Perturbations considered



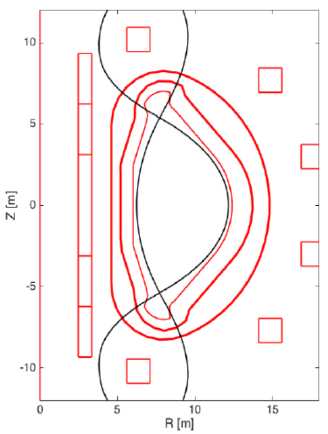
$\Delta\beta_{pol}$	Δl_i	
-0.1	0	ELM (model 1)
-0.1	$+0.1$	ELM (model 2)
-0.1	-0.1	minor-disruption

4) Configurations considered: SN vs DN (fair comparison)

SN1) $k_{95\%} = 1.59\,, \delta_{95\%} = 0.33$

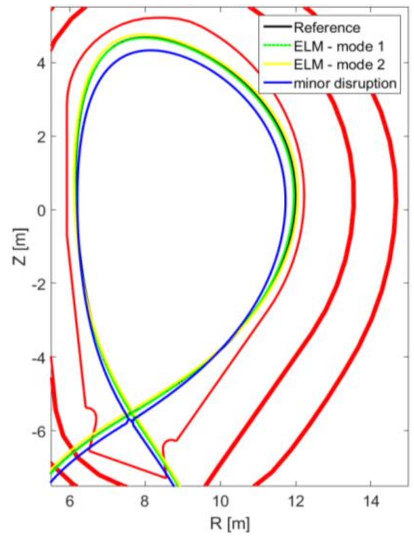


DN1) $k_{95\%} = 1.59\,, \delta_{95\%} = 0.33$

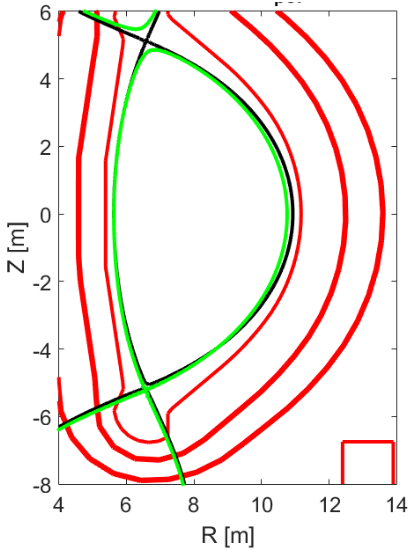


“fair” since same $k_{95\%}$ and $\delta_{95\%}$ have been considered for the SN and DN configurations

Results



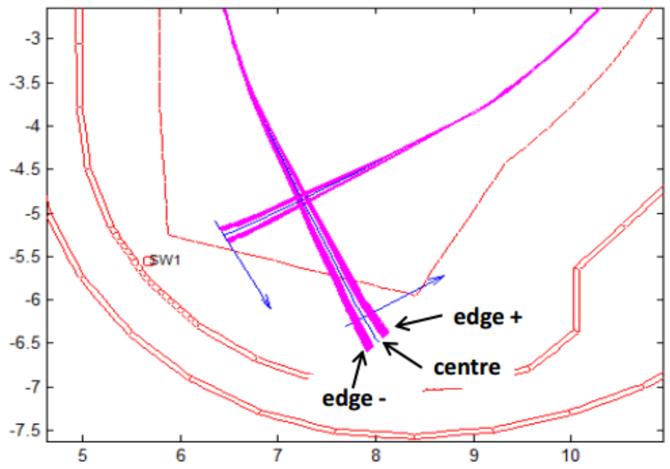
DN (minor-disruption case)

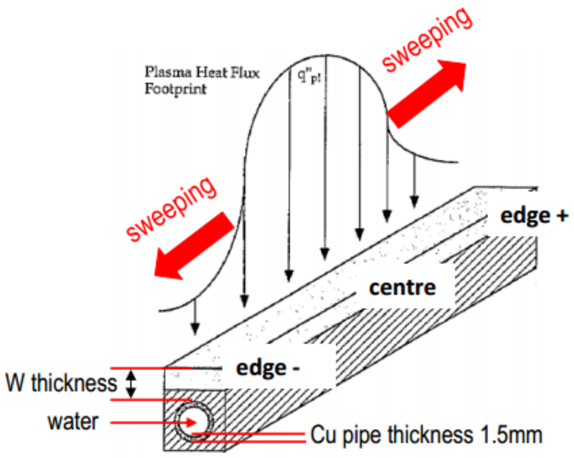


- the growth rate (γ) of the SN is always less than the DN configurations
- the total power on the imbalance circuit (P_{TOT}) for DN configurations is considerable less than in the SN case
- for the DN configuration the vertical displacement of the plasma is much lower than the SN

The strike-point sweeping technique: advantages

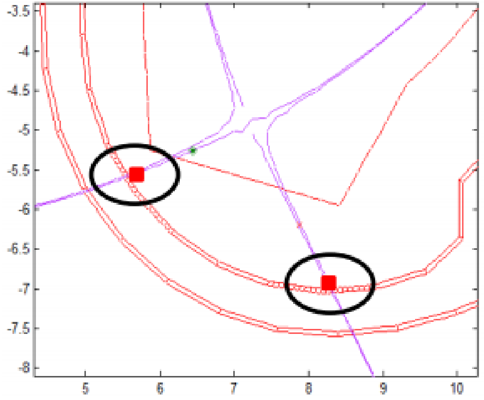
sweeping: periodic strike points oscillation





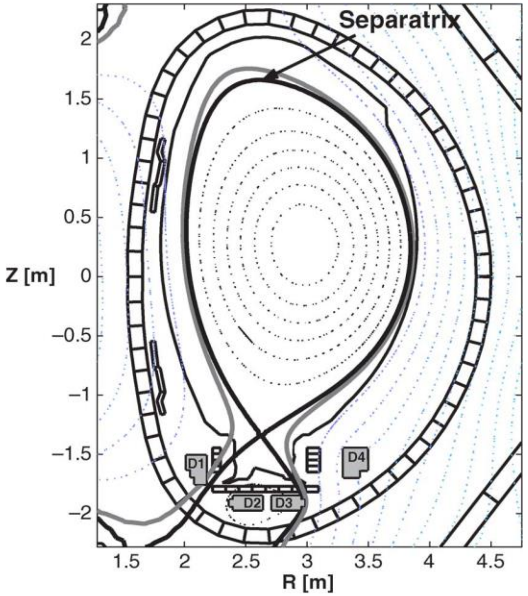
- The particles reaching the Divertor region cause a localized thermal load around the strike-points, i.e. the intersections of the separatrix with the divertor.
- To spread on a larger region this thermal load, it is convenient to resort to a periodical movement (sweeping) of the strike-points

The strike point sweeping is produced by dedicated coils connected in antiseries



Dedicated coils allowing the strike-point sweeping technique

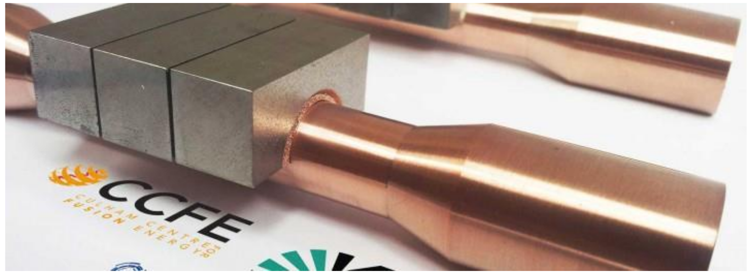
In JET different model-based algorithms for the strike-point sweeping have been presented and implemented within the JET XSC (eXtreme Shape Controller) architecture allowing to perform experimentally the strike-point sweeping



Poloidal cross-section of JET tokamak

DEMO divertor thermo-mechanical analysis: my contribution (1)

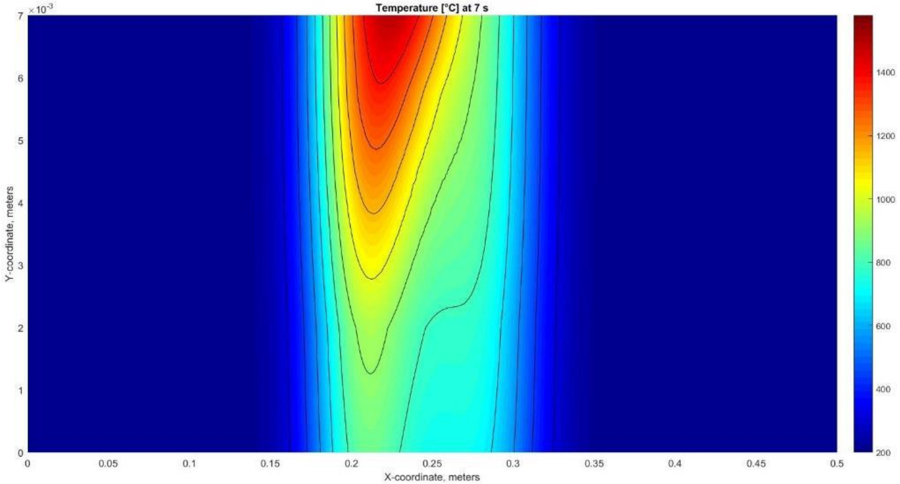
2D thermal analysis



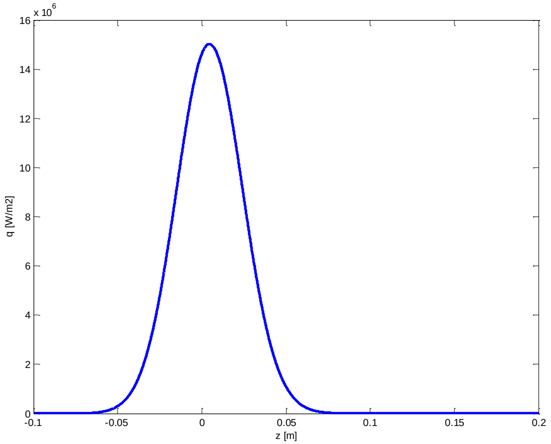
Water-cooled tungsten mock-ups produced by CCFE and KIT.

AIM: Investigate the strike points sweeping effect on the material surfaces temperature reduction depending on the main sweeping parameters: amplitude and frequency

2D FEM model implementation



A simplified 2D FEM model has been developed in MATLAB environment.

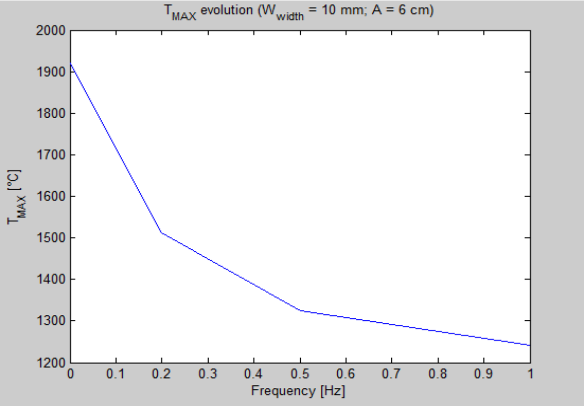


The assumed footprint of the heat flux power on the outer target

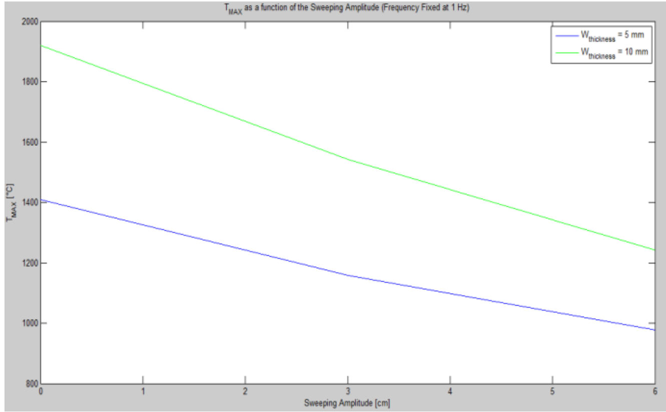
DEMO divertor thermo-mechanical analysis: my contribution (2)

2D thermal analysis

Results



$f\uparrow\Rightarrow T\downarrow$



$amplitude\uparrow\Rightarrow T\downarrow$

A decreasing of the maximum temperature in the tile is achievable:

- increasing the sweeping frequency;
- increasing the sweeping amplitude;
- reducing the tungsten thickness.

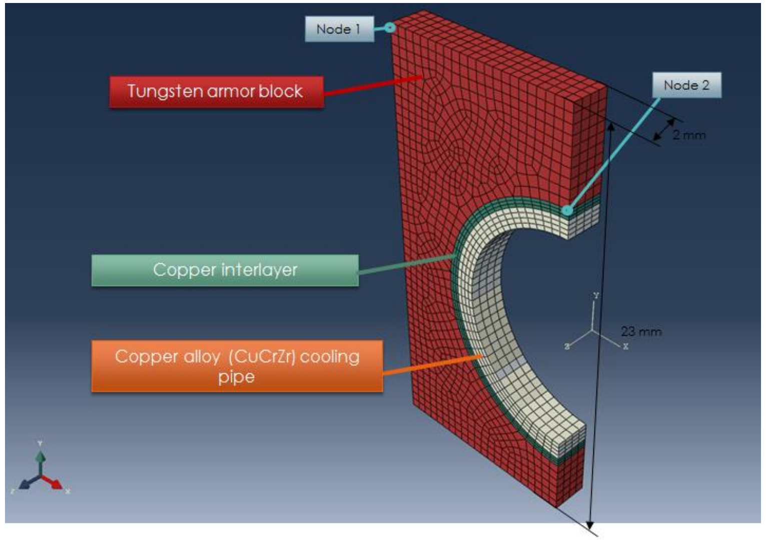
DRAWBACK ➡ A cyclical thermal loading leads to the so-called

"thermal fatigue" of the material

DEMO divertor thermo-mechanical analysis: my contribution (3)

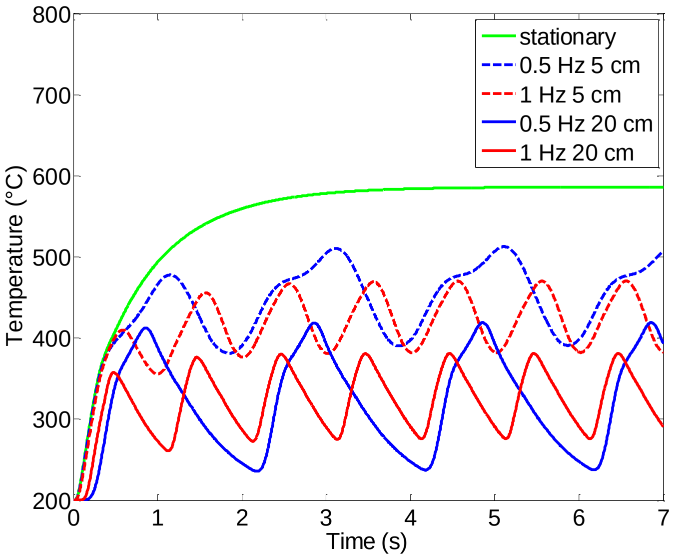
3D thermo-mechanical analysis

3D FEM model implementation



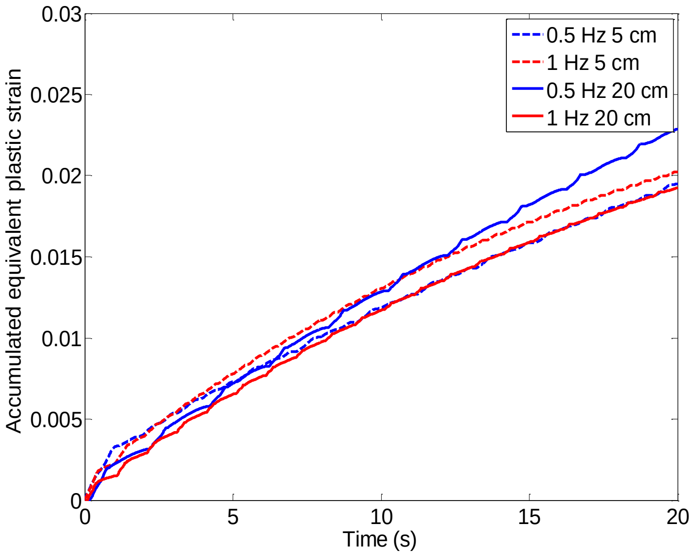
The ABAQUS 3D FE mesh of the mono-block divertor model

3D thermo-hydraulic analysis



Temperature at node 2 as a function of time

3D thermal fatigue analysis

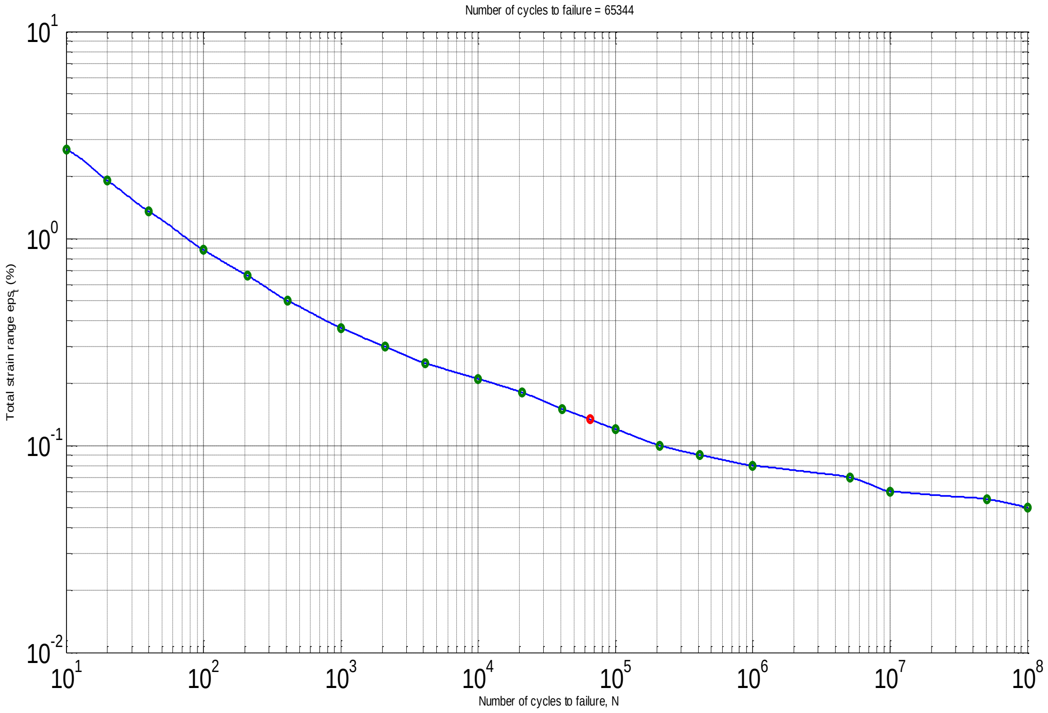


Accumulated equivalent plastic strain in the copper interlayer

DEMO divertor thermo-mechanical analysis: my contribution (4)

3D thermo-mechanical analysis results

Evaluation of the divertor fatigue lifetime

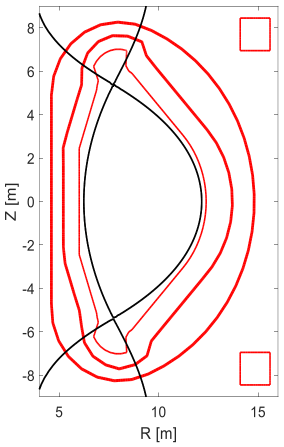


Example of the evaluation of $\Delta\varepsilon_t$ and N (15MW/m^2, 5 cm and 0.5 HZ case)

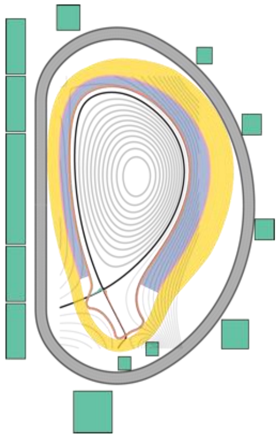
- Up to 1 Hz, the fatigue lifetime of the divertor copper interlayer seems to be the limiting factor investigating the strike point sweeping as the ultimate solution in the mitigation of the DEMO power exhaust ($\approx 100\ h$ lifetime)
- Based on the models here proposed, under less-conservative assumptions, further analyses show that increasing the sweeping frequency up to 4 Hz, with 20 cm amplitude, the predicted fatigue lifetime is 13,812 h.

Conclusions (1)

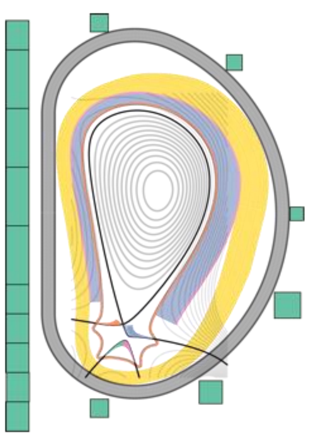
DEMO magnetic alternative configurations design and vertical stability analysis



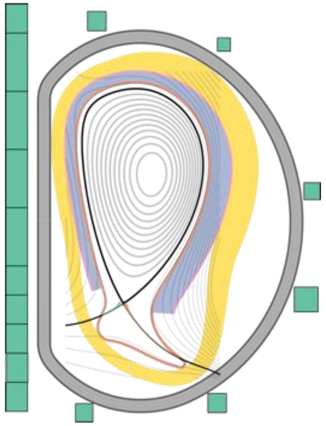
Optimized DN configuration



Optimized XD configuration



Optimized SF configuration

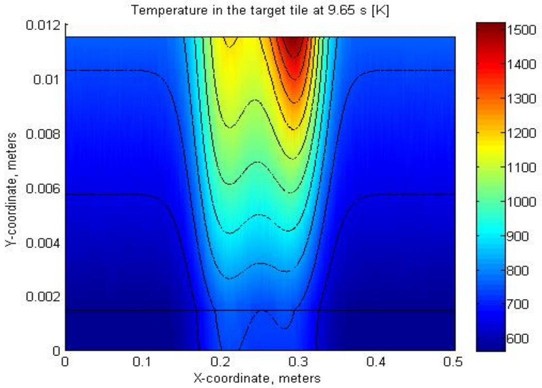


Optimized SX configuration

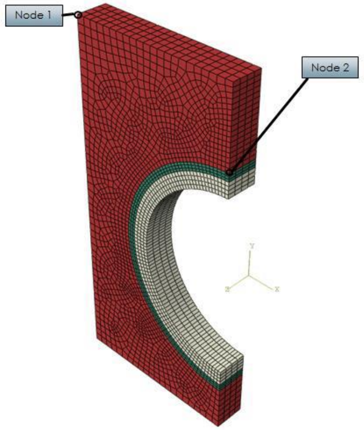
1. R. Wenninger, R. Albanese, R. Ambrosino, F. Arbeiter, J. Aubert, C. Bachmann, L. Barbato, T. Barrett, …, ***V.P. Loschiavo***, et al. "**The DEMO Wall Load Challenge**", (2016) submitted to Nuclear Fusion: NF-101339.R1
2. R. Ambrosino, ***V.P.Loschiavo*** et al. "**The DTT device: alternative configurations**", (2016) submitted to Fusion Engineering and Design: FUSENGDES-D-16-00241
3. R. Albanese, on behalf of the WPDTT2 Team1 and the DTT Project Proposal Contributors "**DTT: a divertor tokamak test facility for the study of the power exhaust issues in view of DEMO**", (2016) Nuclear Fusion, Volume 57, Number 1
4. Raffaele ALBANESE, Massimiliano DE MAGISTRIS ***Vincenzo Paolo LOSCHIAVO*** and Simone MINUCCI "**TEST OF A NOVEL TECHNIQUE FOR THE RECONSTRUCTION OF 3D MAGNETIC FIELDS IN TOKAMAKS**", (2016) submitted to IJAEM
5. Raffaele ALBANESE, Massimiliano DE MAGISTRIS ***Vincenzo Paolo LOSCHIAVO*** and Simone MINUCCI "**TEST OF A NOVEL TECHNIQUE FOR THE RECONSTRUCTION OF 3D MAGNETIC FIELDS IN TOKAMAKS**", 14thInternational Workshop on Optimization and Inverse Problems in Electromagnetism, September 13 – 15, 2016, Rome, Italy
6. F. Maviglia, G. Federici, R. Wenninger, R. Albanese, R. Ambrosino, C. Bachmann, L. Barbato, F. Cismondi, M. Firdaouss, ***V.P. Loschiavo***, C. Lowry "**Effect of engineering constraints on charged particle wall heat loads in DEMO**" SOFT, Prague 5 – 9 September, 2016
7. R. Wenninger, R. Albanese, R. Ambrosino, F. Arbeiter, J. Aubert, C. Bachmann, L. Barbato, T. Barrett, …, ***V.P.Loschiavo***, et al. "**The DEMO Wall Load Challenge**", PSI Rome, May 30 – June 3, 2016

Conclusions (2)

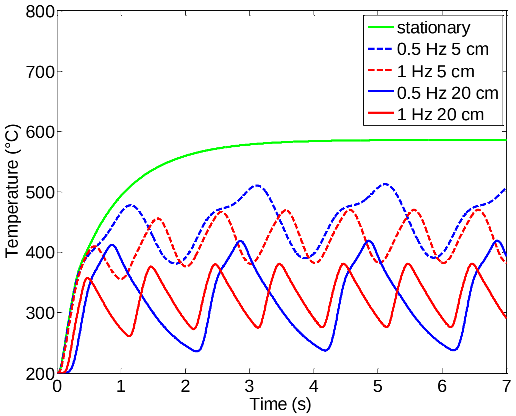
DEMO divertor target tiles 2D and 3D thermo-mechanical analyses in the strike-point sweeping case



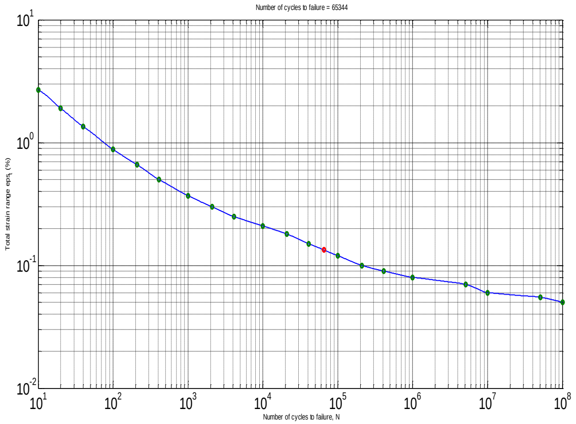
2D thermo-hydraulic analysis



3D FEM model of DEMO target tile



3D thermo-hydraulic analysis



Evaluation of the divertor fatigue lifetime

1. F. Maviglia, G. Federici, G. Strohmayer, R. Wenninger, C. Bachmann, R. Albanese, R. Ambrosino, M. Li, ***V.P. Loschiavo***, J.H. You, L. Zani "**Limitations of transient power loads on DEMO and analysis of mitigation techniques**", Fusion Engineering and Design (2016), DOI: 10.1016/j.fusengdes.2016.01.023
2. R. Albanese, on behalf of the WPDTT2 Team1 and the DTT Project Proposal Contributors "**DTT: a divertor tokamak test facility for the study of the power exhaust issues in view of DEMO**", (2016) Nuclear Fusion, Volume 57, Number 1
3. F. Maviglia, G. Federici, R. Wenninger, R. Albanese, R. Ambrosino, C. Bachmann, L. Barbato, F. Cismondi, M. Firdaouss, ***V.P. Loschiavo***, C. Lowry "**Effect of engineering constraints on charged particle wall heat loads in DEMO**" SOFT, Prague 5 – 9 September, 2016
4. F. Maviglia, G. Federici, G. Strohmayer, R. Wenninger, C. Bachmann, R. Albanese, R. Ambrosino, M. Li, ***V.P. Loschiavo***, J.H. You, L. Zani "**Limitations of transient power loads on DEMO and analysis of mitigation techniques**", 12th International Symposium on Fusion Nuclear Technology (ISFNT) 14-18 September 2015, ICC JEJU, Jeju Island Korea
5. F. Maviglia, G. Federici, G. Strohmayer, R. Wenninger, C. Bachmann, R. Albanese, R. Ambrosino, M. Li, ***V.P. Loschiavo***, J.H. You, L. Zani "**Limitations of transient power loads on DEMO and analysis of mitigation techniques**", European Fusion Programme Workshop 1 - 3 December 2014, Split, Croatia

Publications

1. R. Wenninger, R. Albanese, R. Ambrosino, F. Arbeiter, J. Aubert, C. Bachmann, L. Barbato, T. Barrett, …, ***V.P. Loschiavo***, et al.
   “**The DEMO Wall Load Challenge**”, (2016) submitted to Nuclear Fusion: NF-101339.R1
2. F. Maviglia, G. Federici, G. Strohmayer, R. Wenninger, C. Bachmann, R. Albanese, R. Ambrosino, M. Li, ***V.P. Loschiavo***, J.H. You, L. Zani
   “**Limitations of transient power loads on DEMO and analysis of mitigation techniques**”, Fusion Engineering and Design (2016), DOI: 10.1016/j.fusengdes.2016.01.023
3. R. Ambrosino, ***V.P.Loschiavo*** et al. “**The DTT device: alternative configurations**”, (2016) submitted to Fusion Engineering and Design: FUSENGDES-D-16-00241
4. R. Albanese, on behalf of the WPDTT2 Team1 and the DTT Project Proposal Contributors
   “**DTT: a divertor tokamak test facility for the study of the power exhaust issues in view of DEMO**”, (2016) Nuclear Fusion, Volume 57, Number 1
5. Raffaele ALBANESE, Massimiliano DE MAGISTRIS ***Vincenzo Paolo LOSCHIAVO*** and Simone MINUCCI
   “**TEST OF A NOVEL TECHNIQUE FOR THE RECONSTRUCTION OF 3D MAGNETIC FIELDS IN TOKAMAKS**”, (2016) submitted to IJAEM
6. Raffaele Albanese, Marco Caputano, ***Vincenzo Paolo Loschiavo*** and Robert Felton and JET EFDA Contributors,
   “**A Simplified Poloidal Beta Response Model in JET**”, Fusion Engineering and Design (2013), DOI: 10.1016/j.fusengdes.2013.01.014

Conference Presentations

1. Raffaele ALBANESE, Massimiliano DE MAGISTRIS ***Vincenzo Paolo LOSCHIAVO*** and Simone MINUCCI “**TEST OF A NOVEL TECHNIQUE FOR THE RECONSTRUCTION OF 3D MAGNETIC FIELDS IN TOKAMAKS**”, 14thInternational Workshop on Optimization and Inverse Problems in Electromagnetism, September 13 – 15, 2016, Rome, Italy
2. F. Maviglia, G. Federici, R. Wenninger, R. Albanese, R. Ambrosino, C. Bachmann, L. Barbato, F. Cismondi, M. Firdaouss, ***V.P. Loschiavo***, C. Lowry “**Effect of engineering constraints on charged particle wall heat loads in DEMO**” SOFT, Prague 5 – 9 September, 2016
3. R. Wenninger, R. Albanese, R. Ambrosino, F. Arbeiter, J. Aubert, C. Bachmann, L. Barbato, T. Barrett, …, ***V.P.Loschiavo***, et al. “**The DEMO Wall Load Challenge**”, PSI Rome, May 30 – June 3, 2016
4. F. Maviglia, G. Federici, G. Strohmayer, R. Wenninger, C. Bachmann, R. Albanese, R. Ambrosino, M. Li, ***V.P. Loschiavo***, J.H. You, L. Zani
   “**Limitations of transient power loads on DEMO and analysis of mitigation techniques**”, 12th International Symposium on Fusion Nuclear Technology (ISFNT) 14-18 September 2015, ICC JEJU, Jeju Island Korea
5. F. Maviglia, G. Federici, G. Strohmayer, R. Wenninger, C. Bachmann, R. Albanese, R. Ambrosino, M. Li, ***V.P. Loschiavo***, J.H. You, L. Zani
   “**Limitations of transient power loads on DEMO and analysis of mitigation techniques**”, European Fusion Programme Workshop 1 - 3 December 2014, Split, Croatia

Awards

EUROfusion Engineering Grant (2017)

Thank you

Vincenzo Paolo Loschiavo

vincenzopaolo.loschiavo@unina.it