EUROfusion

Fusion Activities in Greece

Presented at the FSD meeting, 14 June 2023, Heraklion, Crete

DEMOKRITOS

ARISTOTLE UNIVERSITY OF THESSALONIKI

FORTH
FOUNDATION FOR RESEARCH AND TECHNOLOGY - HELLAS

HELLENIC MEDITERRANEAN UNIVERSITY

HELLENIC REPUBLIC
National and Kapodistrian University of Athens
EST. 1837

National Technical University of Athens

Technical University of Crete

UNIVERSITY OF IOANNINA

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ
UNIVERSITY OF PATRAS

University of Thessaly

Members of the Greek Fusion Programme

Greece contributes to the European Fusion programme since 1999 and the EUROfusion programme is executed by the following Research Teams in Research Centers and Institutions of Higher Education:

- Aristotle University of Thessaloniki (**AUTH**), Department of Physics.
- Foundation for Research and Technology (**FORTH**), Institute of Electronic Structure and Laser.
- Hellenic Mediterranean University (**HMU**), Department of Electronic Engineering.
- National Center for Scientific Research "Demokritos" (**NCSRD**), Institute of Nuclear and Radiological Science and Technology, Energy and Safety, Institute of Nanoscience and Nanotechnology and Institute of Nuclear and Particle Physics.
- National and Kapodistrian University of Athens (**NKUA**), Departments of Physics and Aerospace Science & Technology.
- National Technical University of Athens (**NTUA**), Schools of Electrical & Computer Engineering and Applied Mathematics & Physical Sciences.
- Technical University of Crete (**TUC**), Department of Sciences.
- University of Ioannina (**UoI**), Department of Physics.
- University of Patras (**UoPatras**), Department of Electrical and Computer Engineering.
- University of Thessaly (**UTH**), Department of Mechanical Engineering.

Participation in EUROfusion WPs

Beneficiary:

- National Center for Science and Research “Demokritos” (**NCSRD**), *Personnel*: **17**, *Work Packages*: **PWIE, PrIO, BB, MAT, SAE, TRED, PMU, CR**

Affiliated Entities:

- Aristotle University of Thessaloniki (**AUTH**), **2**, **TE, CR**
- Foundation for Research and Technology (**FORTH**), **1**, **CR**
- Hellenic Mediterranean University (**HMU**), **11**, **ENR, TRED, CR**
- National and Kapodistrian University of Athens (**NKUA**), **11**, **W7X, ENR, HCD, TRED, PMU, CR**
- National Technical University of Athens (**NTUA**), **15**, **TE, SA, DES, HCD, TRED, PMU, CR**
- Technical University of Crete (**TUC**), **2**, **TRED, CR**
- University of Patras (**UoPatras**), **1**, **CR**
- University of Ioannina (**UoI**), **3**, **CR**
- University of Thessaly (**UTH**), **8**, **TRED, CR**

Participation in EUROfusion WPs

The detailed contribution of the Research Teams of the Hellenic Fusion Research Unit (RU) that participate in the EUROfusion Work Packages is as follows:

- **TE**: Contribution to various research topics, i.e.,
  - Development of the steady state scenario.
  - Disruption avoidance and control for ITER and DEMO.
  - ELM mitigation and suppression in ITER/DEMO relevant condition.
  - Fast–ion physics with dominant ICRF heating.
  - IBL scenarios towards low collisionality and detachment.
  - Impact of MHD activity on fast–ion losses and transport.
  - Physics and operational basis for high–beta long–pulse scenarios.
  - Physics–based machine generic systems for an integrated control of plasma discharge.
  - Physics of plasma detachment, impurity mix, heat–load patterns.
  - Physics understanding of energetics particles confinement and their interplay with thermal plasma.
  - RF–assisted breakdown and current ramp–up optimization.
  - Strategies for disruption and run–away mitigation.

Participation in EUROfusion WPs

- **SA**:
  - Building parsimonious disruption mitigation/avoidance triggers.

- **W7X**:
  - Research topics RT01 (High–performance conditions), RT02 (Heating scenarios), RT08 (Core physics studies).
  - Gyrotron development support (component design and simulation).

- **PWIE**:
  - Analysis of JET plasma facing components with μbeam NRA.
  - Analysis of samples from JET divertor tiles 0, 1, 4, 6, 7 and 8 with μbeam NRA.
  - RBS, NRA, SEM, XRD and XPS characterization of selected WEST PFUs, plasma–exposed samples, and reference coatings in support of SP E.
  - RBS, SEM, XPS, XRD and XRF characterization of selected Be reference coatings and plasma–exposed samples.
  - Surface analyses of selected WEST and GyM samples.

Participation in EUROfusion WPs

- **PrIO**:
  - ➢ Analysis of DTE2 neutron flux measurements with AFs and preparation of shutdown dose rate and streaming experiments for DTE3.
  - ➢ Analyses of TT and DT neutron flux measurements with activation foils.
  - ➢ Electro–optical methods for the characterization of ceramic materials.
  - ➢ Measurements of sample dosimetry foils and VERDI detector following DTE2.
  - ➢ Measurements on ITER material samples dosimetry foils and VERDI detectors following DTE2 and C40B campaigns.
  - ➢ PIE of insulator materials by NCSR “Demokritos”.

- **ENR (2021–2024)**:
  - ➢ Advancing shock ignition for direct–drive inertial fusion.
  - ➢ New generation of megawatt–class fusion gyrotron systems based on highly efficient operation at the second harmonic of the cyclotron frequency.

- **DES**:
  - ➢ ECRH/ECCD activities with focus on the DEMO EC system modelling for the control of radiative instability events.

Participation in EUROfusion WPs

- **BB**:
  - Neutron fluence measurements using VERDI detectors in tungsten shielding benchmark.

- **HCD**:
  - Beam–tracing evaluations of the configuration performances in an extended range of cases.
  - Beam–tracing calculations to analyze the DEMO low–AR scenario and launching angle optimization.
  - Investigations on advanced beam–tunnel structures.
  - Numerical simulations of the experimental operation of gyrotrons.
  - Studies related to parasitic wave excitation in the beam tunnel and spacer.
  - Studies with regards to possible parasitic backward–wave excitation.
  - Validation and use of the COCHLEA code for azimuthally corrugated beam tunnel.
  - Validation of the whole multi–physics model for the gyrotron cavity equipped with Raschig rings: electrodynamic part.

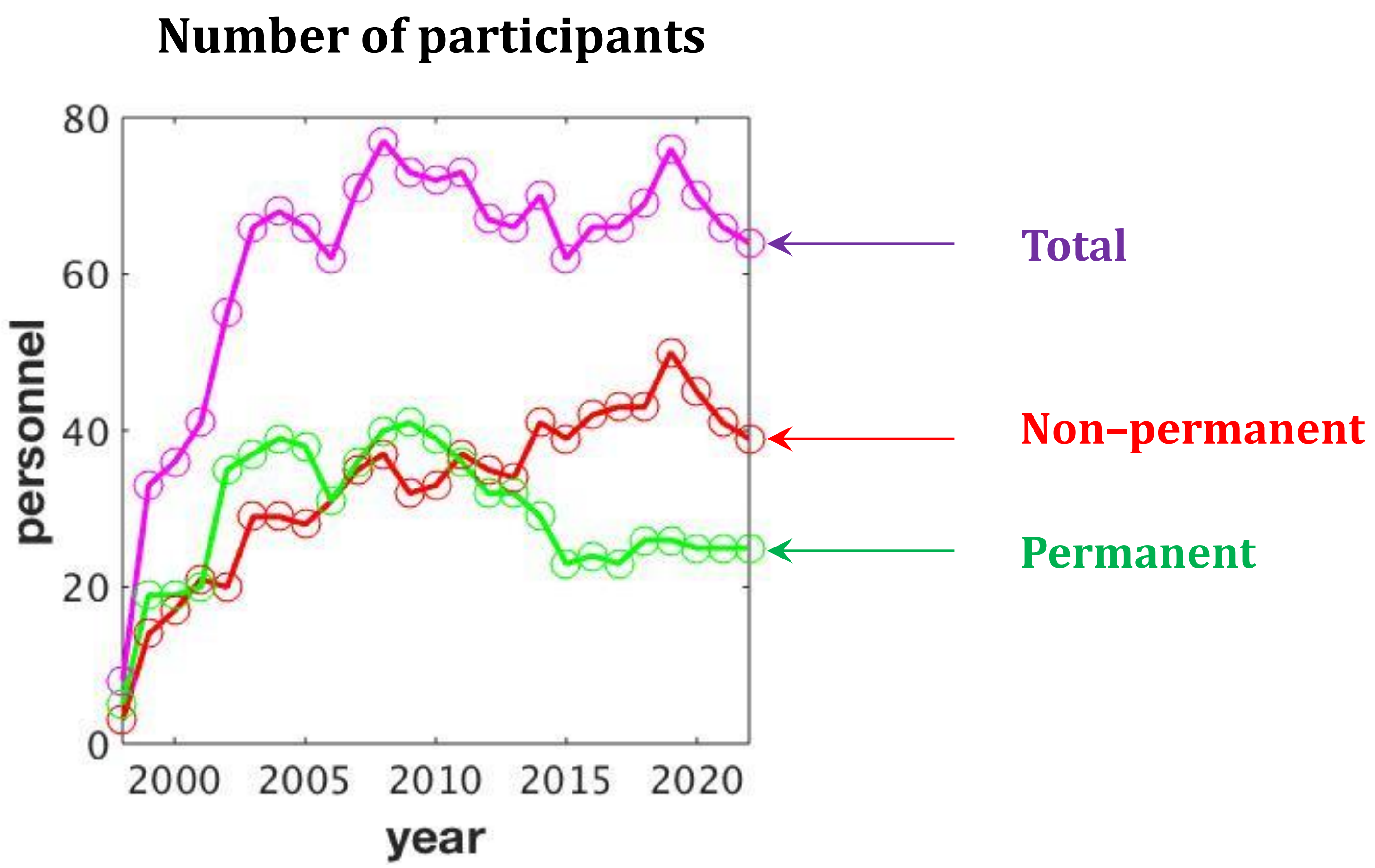
Participation in EUROfusion WPs

- **MAT/PRD**:
  - Assessment of residual stresses and dislocation density in tungsten after neutron irradiation at 800°C, 900°C and 1200°C.
  - Damage evolution in tungsten during irradiation at elevated temperature.
  - Recovery in high–dose ion irradiated Fe thin films.
  - Recovery in heavily damaged microstructures of Fe and EUROFER.

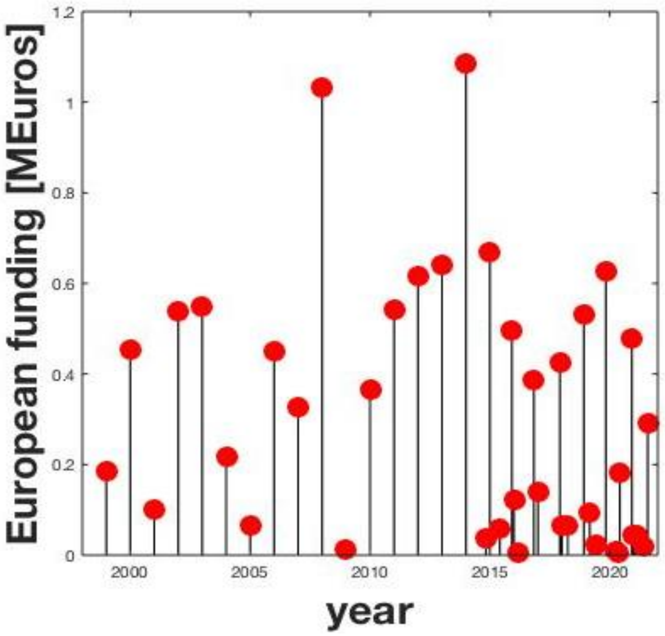
- **SAE**:
  - Occupational Radiation Exposure (ORE) analysis on DEMO divertor Primary Heat Transfer System maintenance.
  - ORE analysis on DEMO ECRH system.
  - ORE analysis on distribution between internal and external exposure for ORE.

- **TRED**:
  - 16 PhD theses (on going).

Number of scientific personnel



Funding



European funding [MEuros]
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0.2
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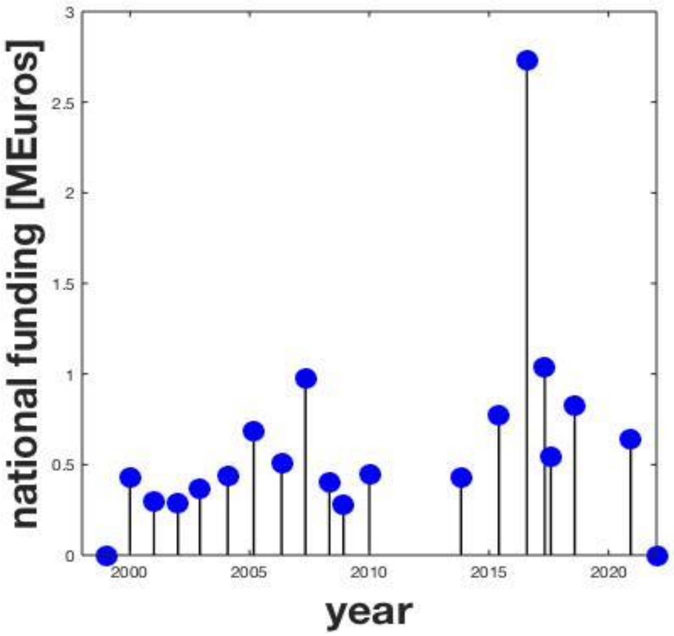
2000
2005
2010
2015
2020



national funding [MEuros]
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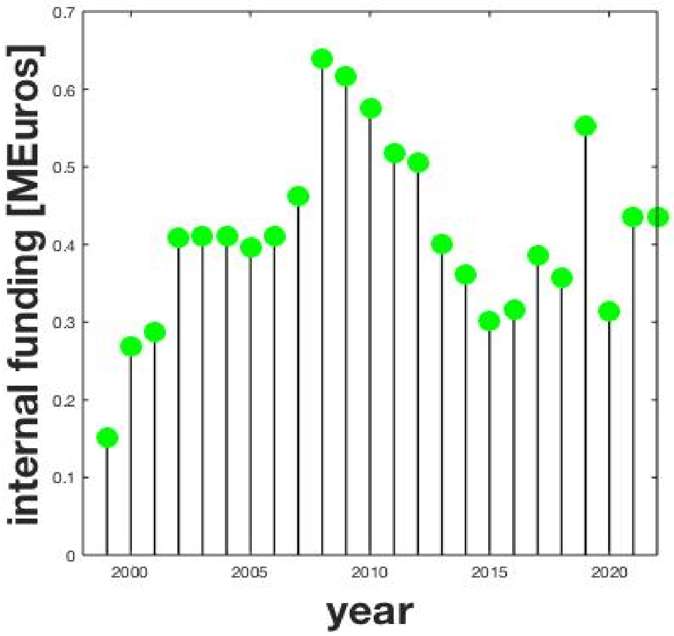
2005
2010
2015
2020



internal funding [MEuros]
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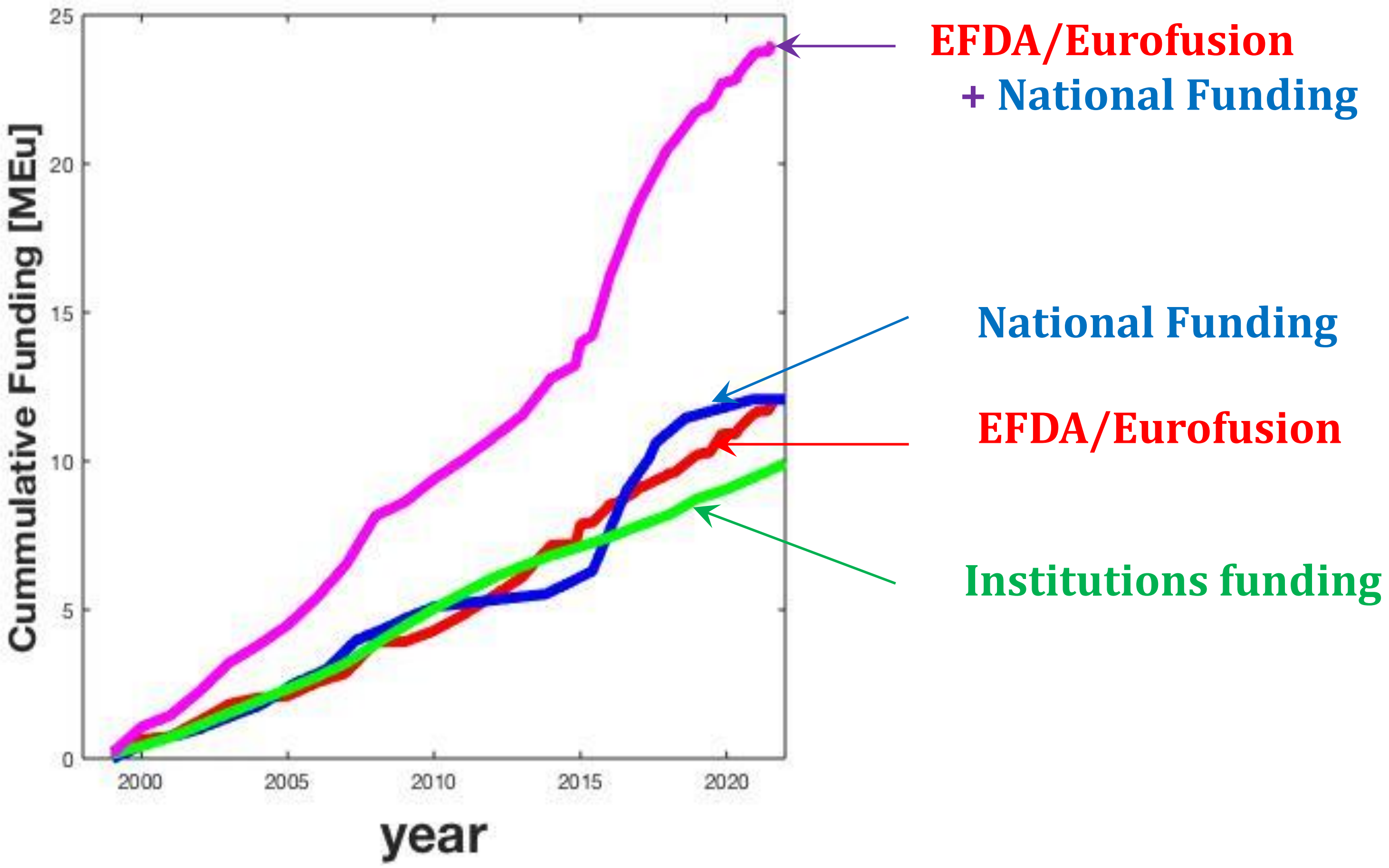
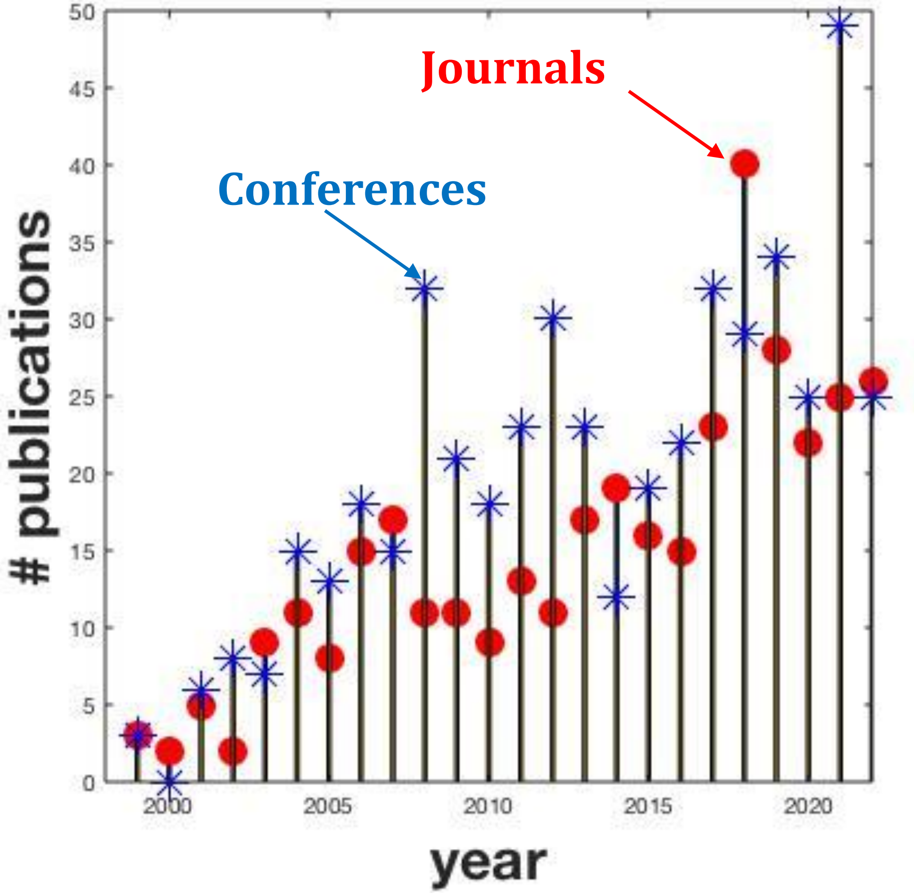
2005
2010
2015
2020

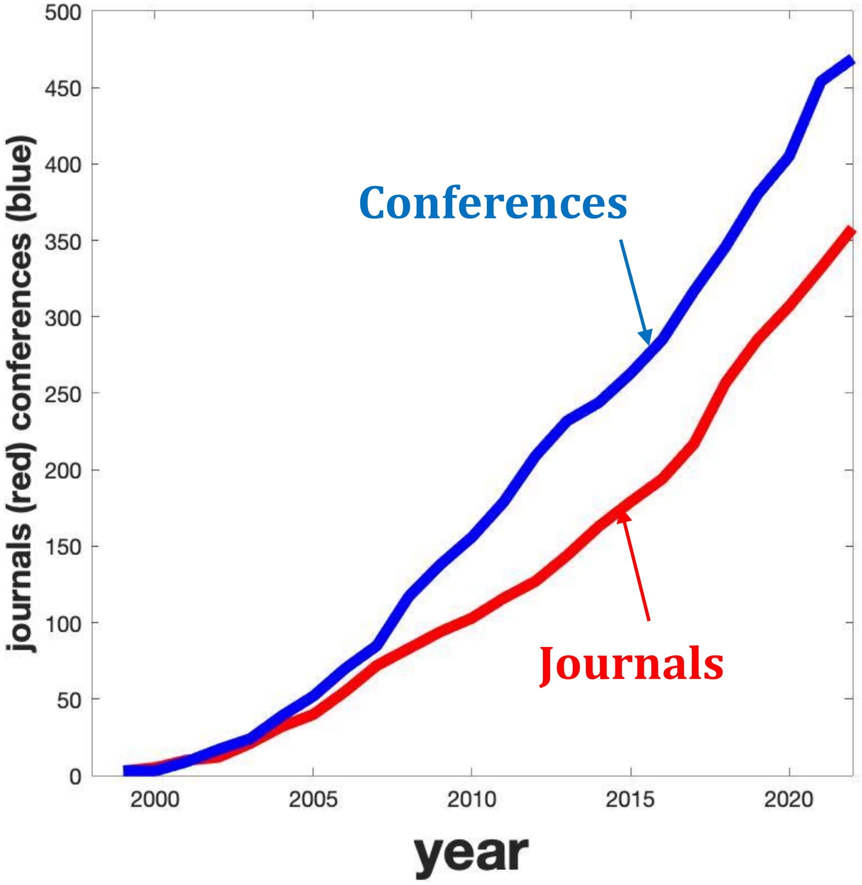
Cumulative Funding



Publications

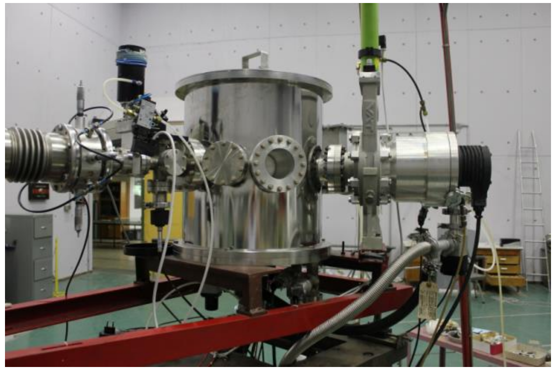
Journals – Conferences





NCSRD Facilities

- Recently upgraded TANDEM accelerator for ion irradiations of fusion materials and ion beam analysis.
- IR^2 facility for electrical recovery studies of ion irradiated materials for defect studies of fusion materials.
- Ion beam analysis (material studies):
  - Rutherford Backscattering
  - Nuclear Reaction Analysis (NRA)
  - Elastic Recoil Detection Analysis (ERDA)
  - Particle induced X–ray/Gamma–ray Emission (PIXE/PIGE)



NCSRD Facilities

Gamma Spectroscopy

- Gamma spectrometer for collimated scanning and coarse resolution imaging of radioisotope distribution in large samples.
- Compton suppression spectrometer.
- Gamma spectrometer with high activity sample analysis capabilities.

Large volume sample analysis

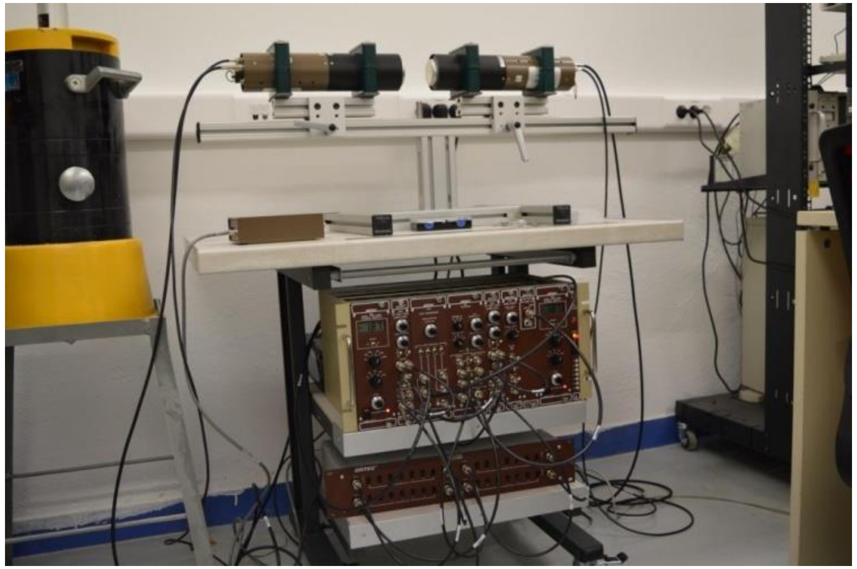
Compton suppression spectrometer

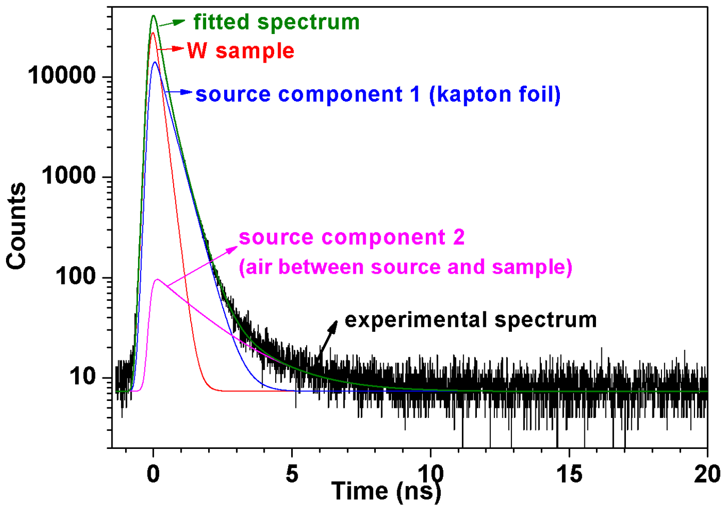
NCSRD Facilities

Defects characterization

Positron Annihilation Lifetime Spectroscopy (PALS) equipped with:

- Plastic scintillators
- Photomultipliers
- Coincidence system
- ^{22}Na source





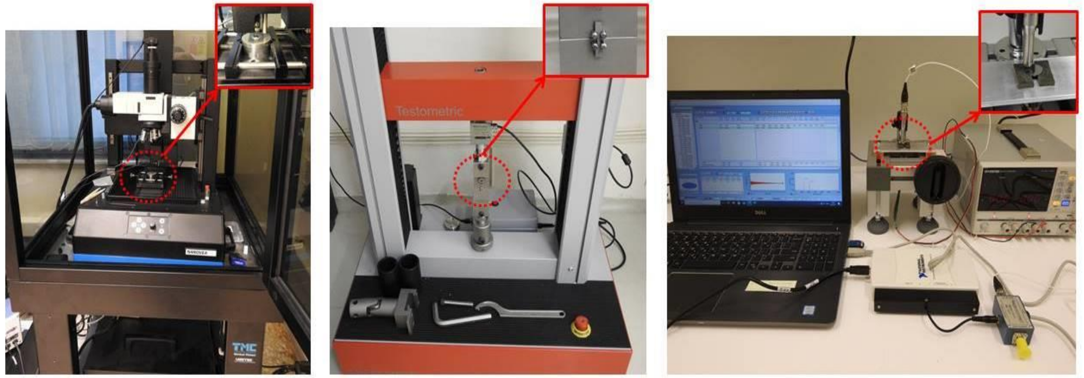
Licensed for the measurement of radioactive samples

NCSRD Facilities

Mechanical properties

- Nano/Micro – Indenter with depth sensing indentation.
  - ➢ Hardness
  - ➢ Stiffness
  - ➢ Stress–strain curves
  - ➢ Fracture toughness
  - ➢ Creep
  - ➢ Fatigue
- Universal testing machine – 50 kN with laser displacement measuring system.
- Impulse excitation apparatus.
  - ➢ Young’s modulus
  - ➢ Shear modulus
  - ➢ Poisson’s ratio
  - ➢ Internal friction coefficient

Mechanical testing apparatuses



Depth Sensing Indenter | Universal Mechanical Tester | Impulse Excitation Apparatus

Licensed for the measurement of radioactive samples

NCSRD Facilities

Structural properties

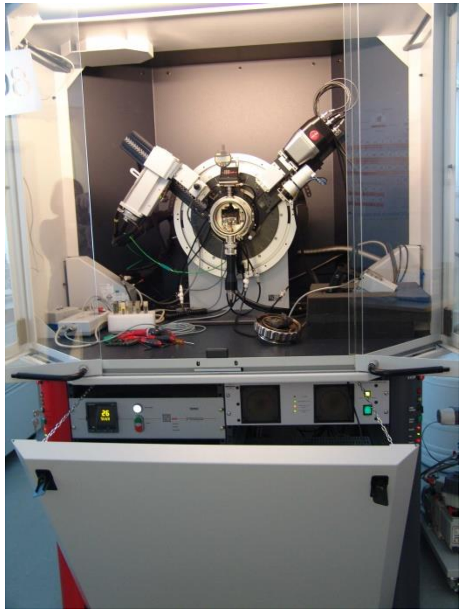
Structural characterization

- X–ray diffractometer
  - Grazing incidence diffraction
  - High and low temperature cells (–170^{o}C to 1600^{o}C)
- X–ray reflectometer (–170^{o}C to 900^{o}C) (XRR)
- Small–Angle X–ray scattering apparatus (SAXS)

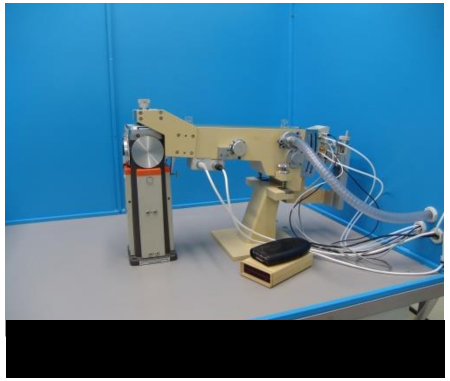
Access to Large Scale Facilities for

- Neutron tomography/radiography
- Residual stress determination
- Neutron diffraction
- Polarized Neutron Reflectivity

XRD/XRR



SAXS



Licensed for the measurement of radioactive samples

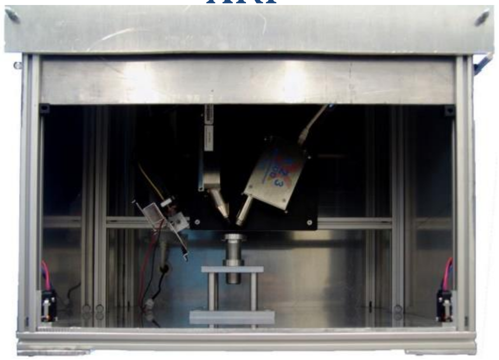
NCSRD Facilities

Material characterization infrastructure

- Vibrating sample magnetometer for magnetic properties.
- Electrical characterization apparatus of metals, semiconductors and insulators.
- Electron Microscopes:
  - SEM coupled with EDX (**for radioactive materials**)
  - TEM coupled with EELS
- Atomic Force Microscopes.
- Optical Microscopes.
- Fourier Transform Infrared spectroscopes.
- X–ray fluorescence spectrometer for stoichiometric analysis (XRF).
- Nitrogen Adsorption – Desorption Porosimetry & Surface Area Analysis (BET).
- Differential Thermal Analysis (DTA) apparatus.
- Thermogravimetric Analysis (TGA) apparatus.

FEG–SEMF

XRF



NCSRD Facilities

Coatings & Film fabrication laboratory

- Film and coatings deposition device:
  - DC and RF magnetron sputtering with in–situ substrate heating, rotation, translation and bias–voltage and deposition rate measuring device.
  - Two sputtering targets.
- Arc melting and RF melting for alloy fabrication.

NCSRD Facilities

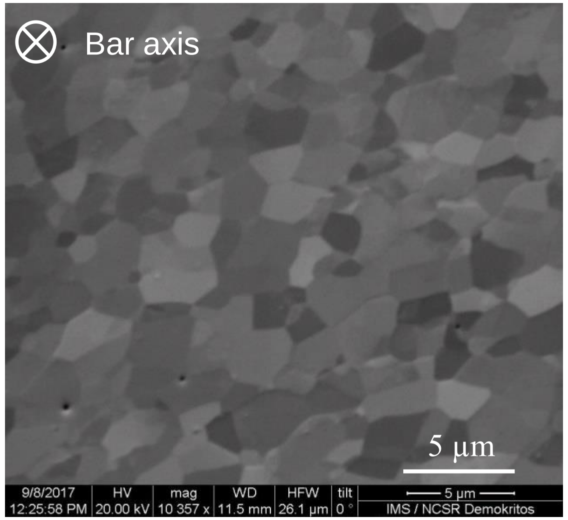
Metallographic & processing laboratory

- Struers electropolisher
- Struers & Buhler polisher automatic grinders/polishers
- Buehler IsoMet low–speed saw
- Fume hood for chemical processing of samples
- Optical microscopes

Three tubular furnaces up to 1800°C operating:

- Under vacuum (10^{-7} mbar)
- Inert gas

ITER grade W



Annealing systems

Metallography laboratory

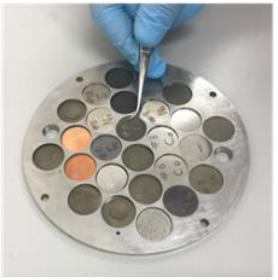
NCSRD – WPPrIO

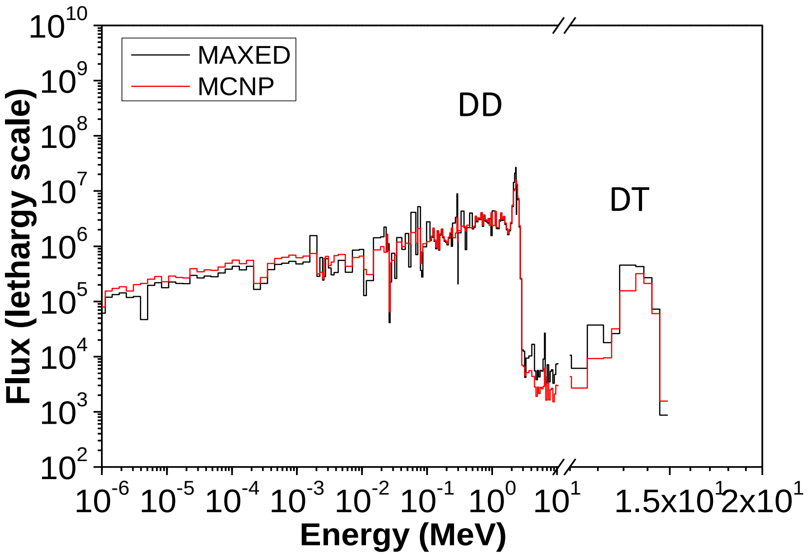
Preparation of ITER operation: Neutronics, Waste & Safety (Sub–project ACT)

Take advantage of JET operations with significant 14 MeV neutron production to improve our knowledge on the properties of materials used in the manufacturing of the main ITER in–vessel components.

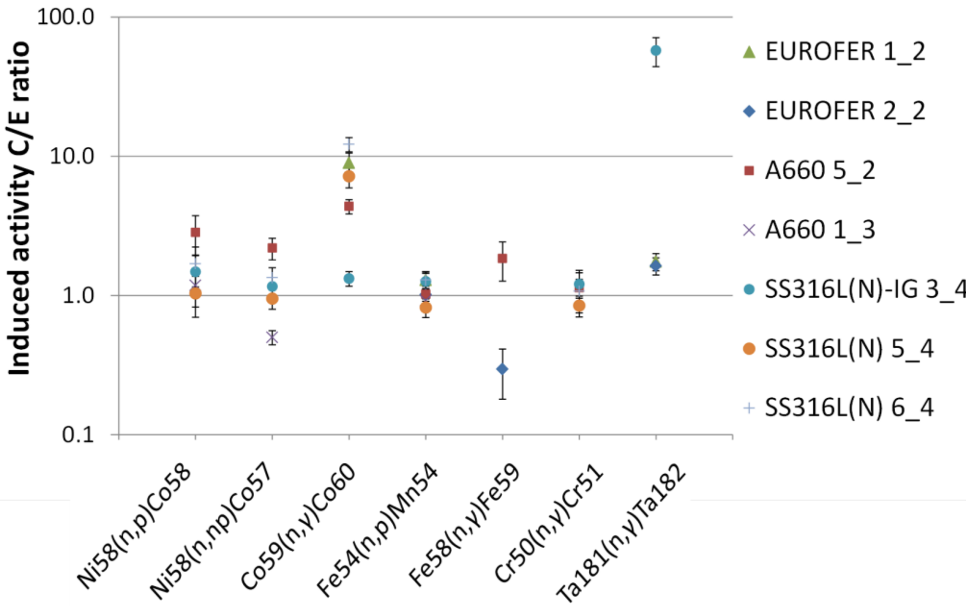
- Gamma spectroscopic analysis of ITER material samples irradiated at JET DD, TT and DT campaigns.
- Data validation using dosimetry foils and VERDI detectors.

VERDI detectors at the LTIS sample holder





VERDI derived neutron spectrum at LTIS in C38B JET DD campaign



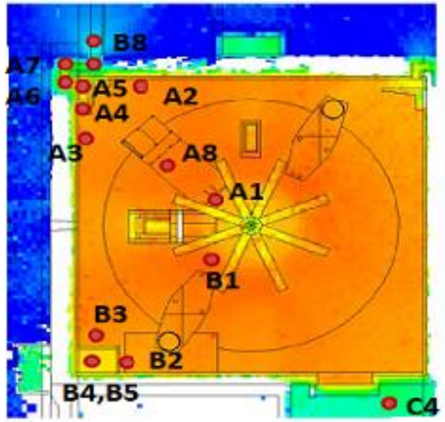
Calculated vs. Experimental activities derived for different ITER materials irradiated at JET

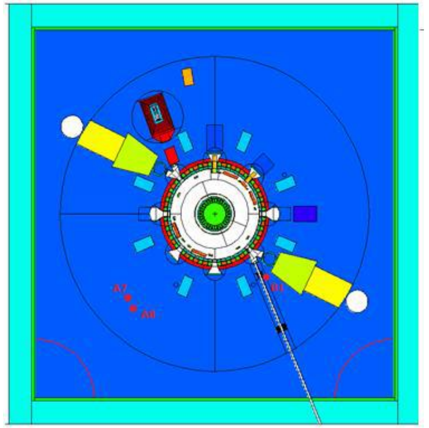
NCSRD – WPPrIO

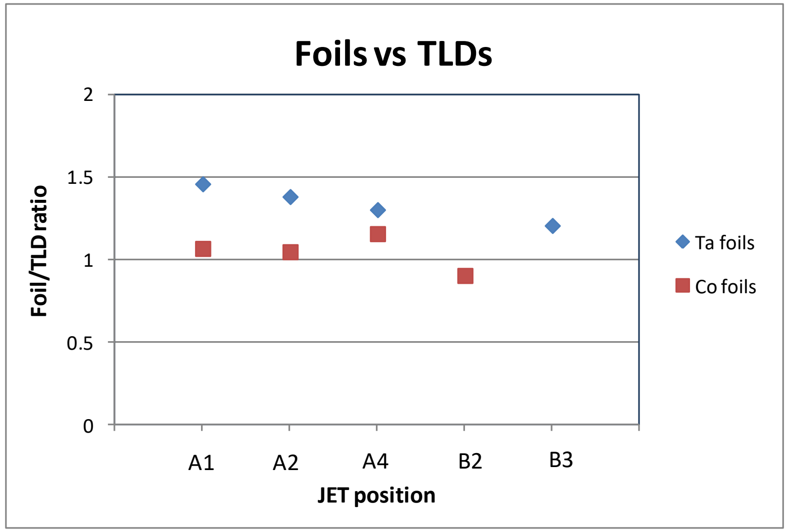
Preparation of ITER operation: Neutronics, Waste & Safety (Sub–project NEXP)

Validate numerical tools, methods and data used in ITER nuclear analysis.

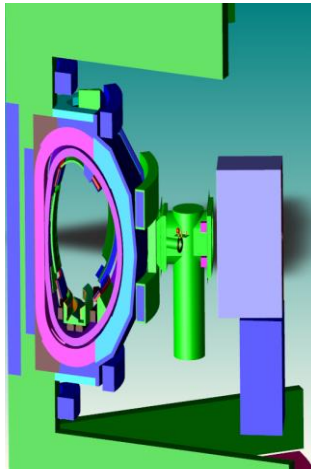
- Neutron Streaming & Shut–Down Dose–Rate experiments.
- Neutron fluence measurements using activation detectors.
- Comparison against theoretical calculations and TLD measurements.

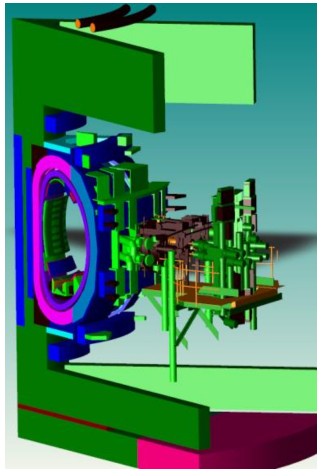


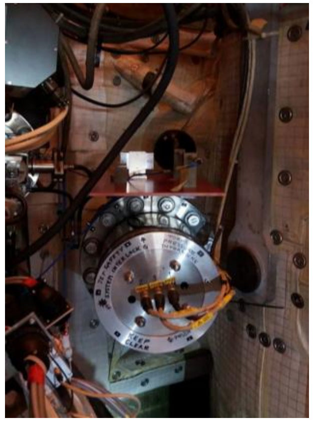




Comparison of neutron fluence results at positions within the JET Hall (DD campaign)







Octant 1

Octant 2

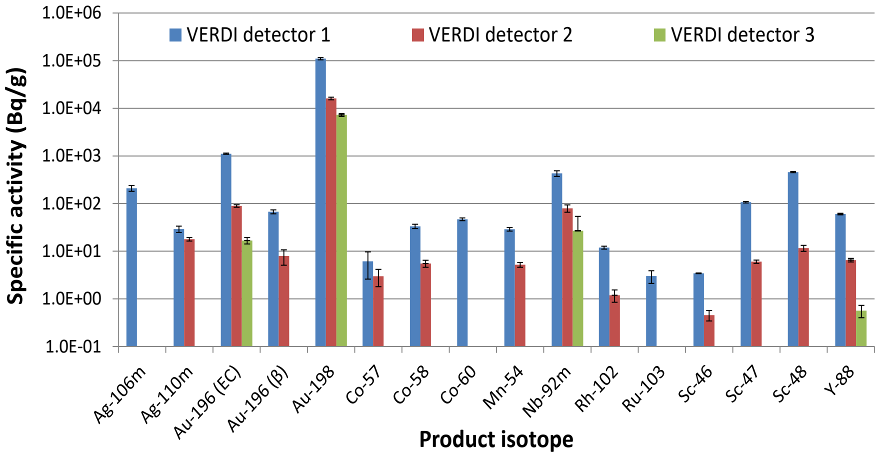
NCSRD – WPBB

Tungsten shielding benchmark experiment at ENEA–FNG

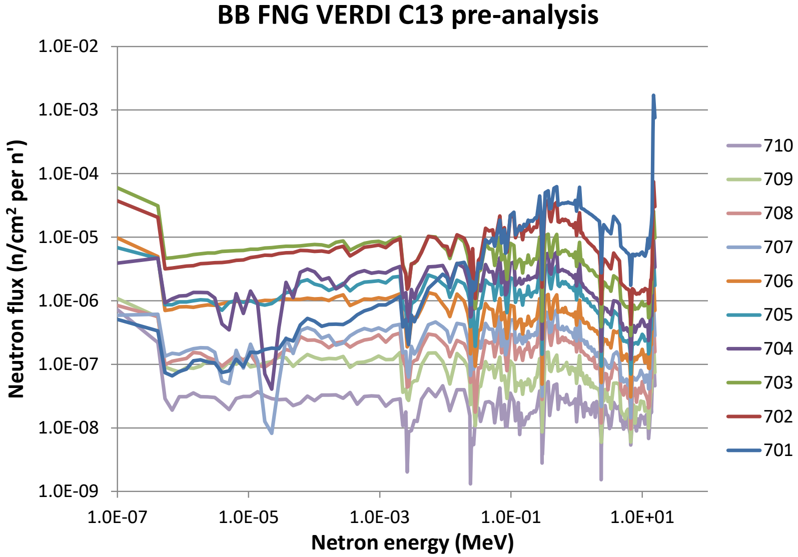
Study the neutron transport in a DEMO relevant shielding element made of tungsten (W).

- Use of VERDI detectors to derive neutron fluence and energy spectrum in the W–shield configuration.

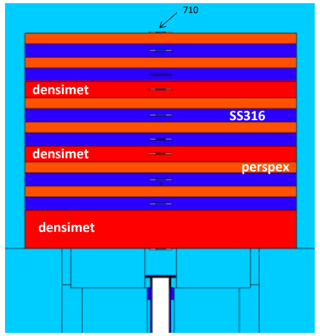
W– shield assembly at ENEA–FNG



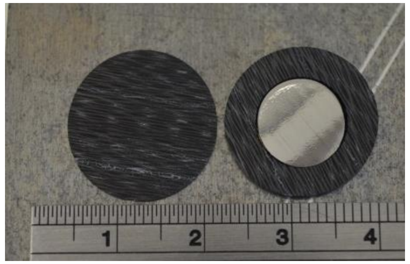
Activities induced in the VERDI detectors



Neutron energy spectrum at different positions within the W–shield assembly



W–shield assembly model



VERDI detector

***VERDI**: A novel passive neutron detector capable to determine neutron fluence and energy spectrum in the harsh conditions encountered in DEMO Breeding Blanket*

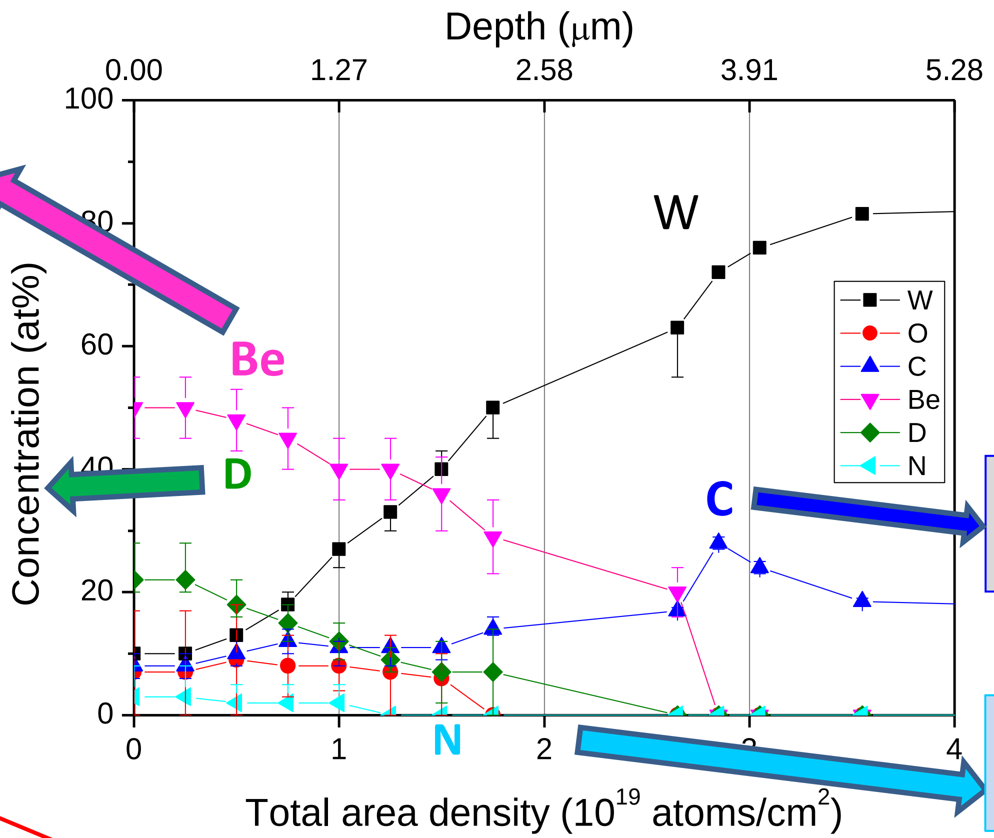
NCSRD – WPPWIE

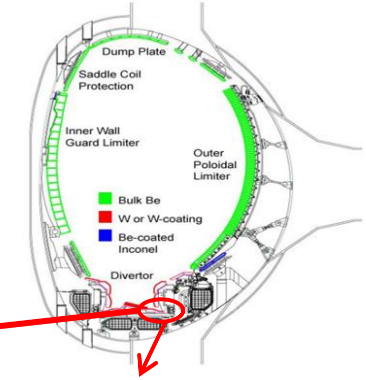
- Investigation of **fuel retention** and **material deposition/erosion** of plasma exposed materials at JET, WEST and other plasma devices.

ITER–like wall of the JET tokamak

Plasma – wall interaction at the divertor (W) of the JET tokamak

Surface erosion from main wall & material migration & deposition



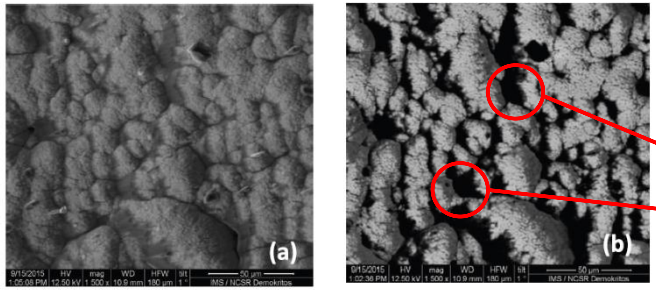


W/CFC

Fuel retention

Surface erosion & re–deposition

Nitrogen deposition

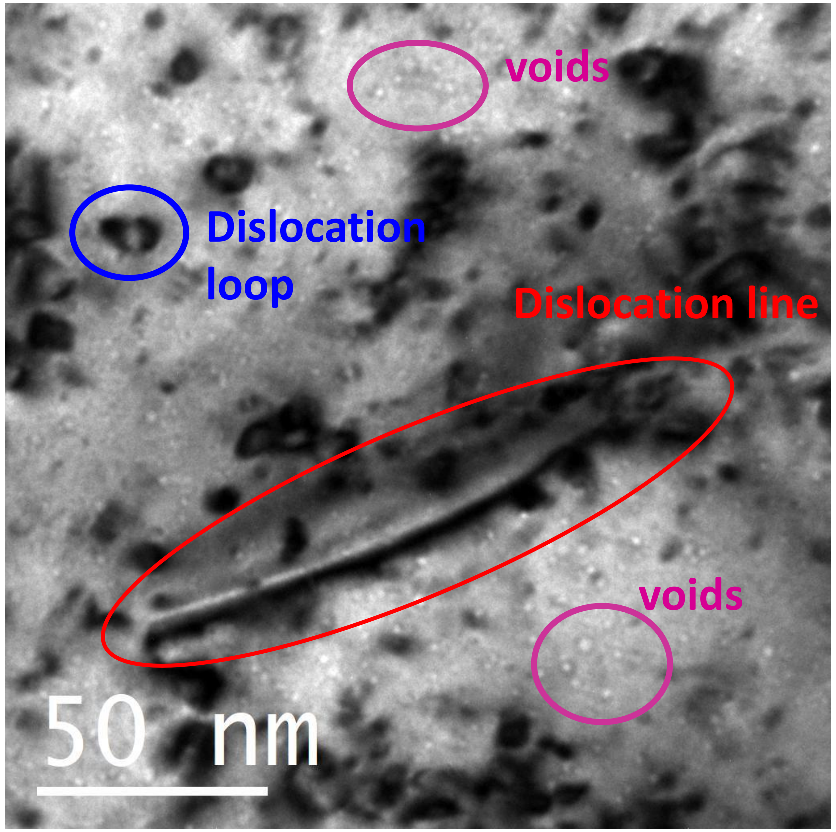


C, N, Ni, Cr, Fe, Mo (deposition)

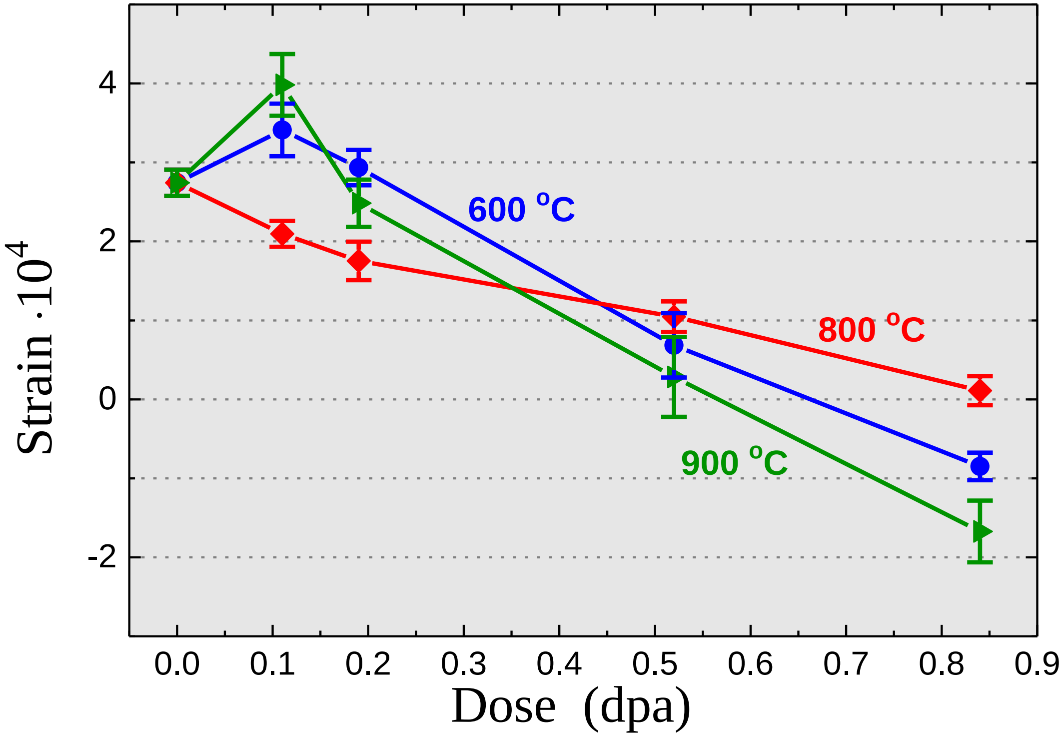
NCSRD – WPMAT –IREMEV

Neutron irradiation effects in tungsten at high temperatures

Investigation of **residual stresses** and **defect densities** in **tungsten** (ITER grade) as a function of **dose** and **irradiation temperature**.



Radiation induced defects



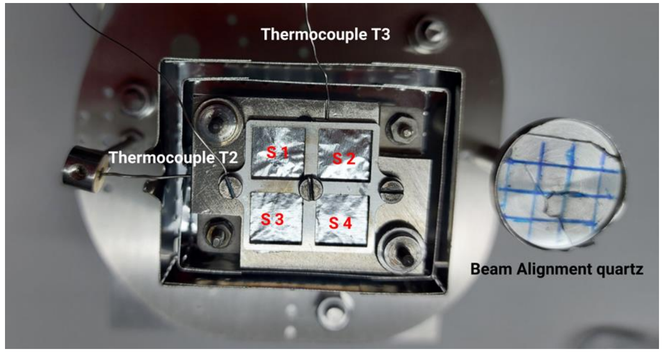
Lattice strain as a function of dose after irradiation at high temperatures

NCSRD – WPMAT –IREMEV

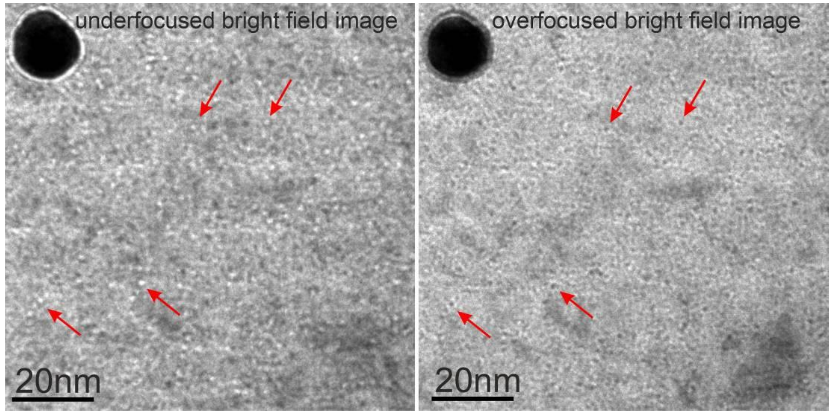
Recovery in heavily damaged microstructures of Fe & EUROFER

Experimental investigation of recovery in **heavily damaged microstructures** generated in **Fe & EUROFER** by ion irradiation **in Collaboration with RBI – Croatia and KIT – Germany.**

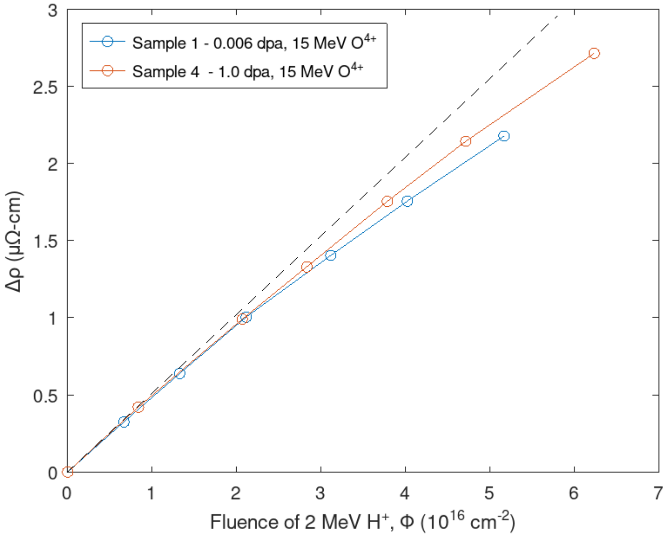
- Specimens damaged to **1 dpa** are produced by **heavy ion irradiation** at RBI accelerator and subsequently **characterized by TEM** at KIT.
- Defect recovery in the highly damaged specimens is studied by **in–situ electrical resistivity** after a 2nd, low–temperature irradiation and subsequent post–irradiation annealing.



Specimens in the DIFU irradiation chamber at RBI ion accelerator



TEM Micrographs of 15 MeV O^{4+} irradiated Fe at 1 dpa. Arrows indicate the presence of small (1–2 nm) voids



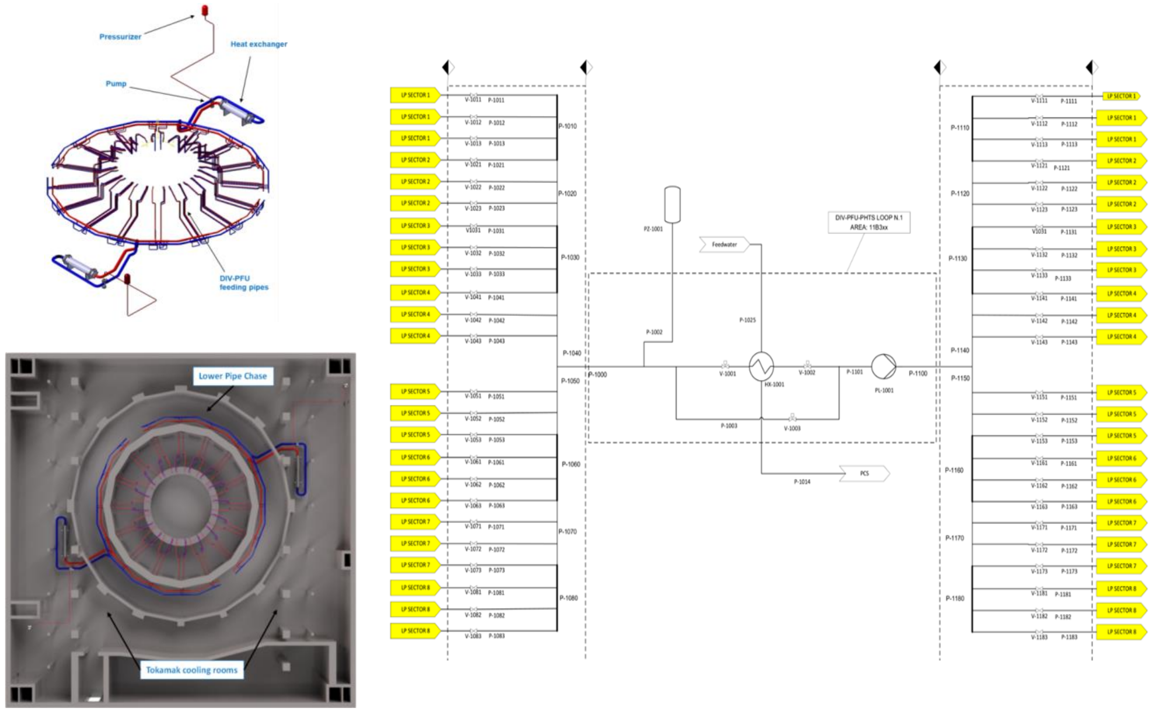
In–situ resistivity increase of damaged Fe specimens during 2 MeV H^+ irradiation at the NCSRD accelerator

NCSRD – WPSAE

Occupational Safety & Editing GSSR Vol. 4

Occupational Radiation Exposure (ORE) studies to guide DEMO design.

- To estimate ORE for the maintenance activities of the Divertor Primary Heat Transfer System (Div–PHTS) and identify the activities with the highest dose.
- To document results in Generic Site Safety Report Vol. 4.



Conceptual design of a single PHTS Plasma Facing Unit cooling loop (V. Narcisi, EFDA_D_2P9VMH, 2020)

Collective dose for maintenance operations on component i.

$$E_{c,i} = \dot{E} \times t_{e,i} \times f_y \times (1 + A) \times N_i \quad (1)$$

$\dot{E}$ is the average effective dose rate from external and internal exposure over the time period t
$t_{e,i}$ is the total work effort for maintenance on component i
f_y is the hands-on frequency;
A is the aggravating factor due to hindrance wearing personnel protective equipment in order to minimize internal contamination;
N_i is the product of the number of components per unit by the number of units in the system

Collective dose results for Div–PHTS preventive maintenance:

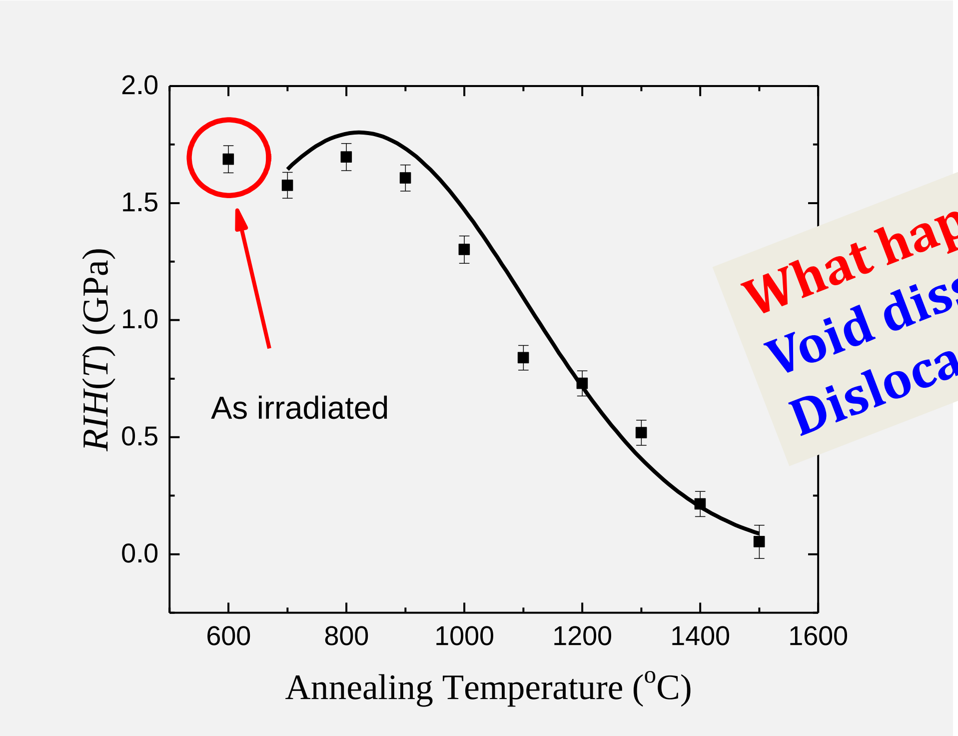
- *Plasma Facing Units loops 45700 p·μSv/y*
- *Cassettes loops 45700 p·μSv/y*
- *Auxiliary systems 15954 p·μSv/y*
- *Approximately 50% of the collective dose is received in operations within the Port Cell*

NCSRD – WPTRED

Annealing effects in neutron irradiated tungsten

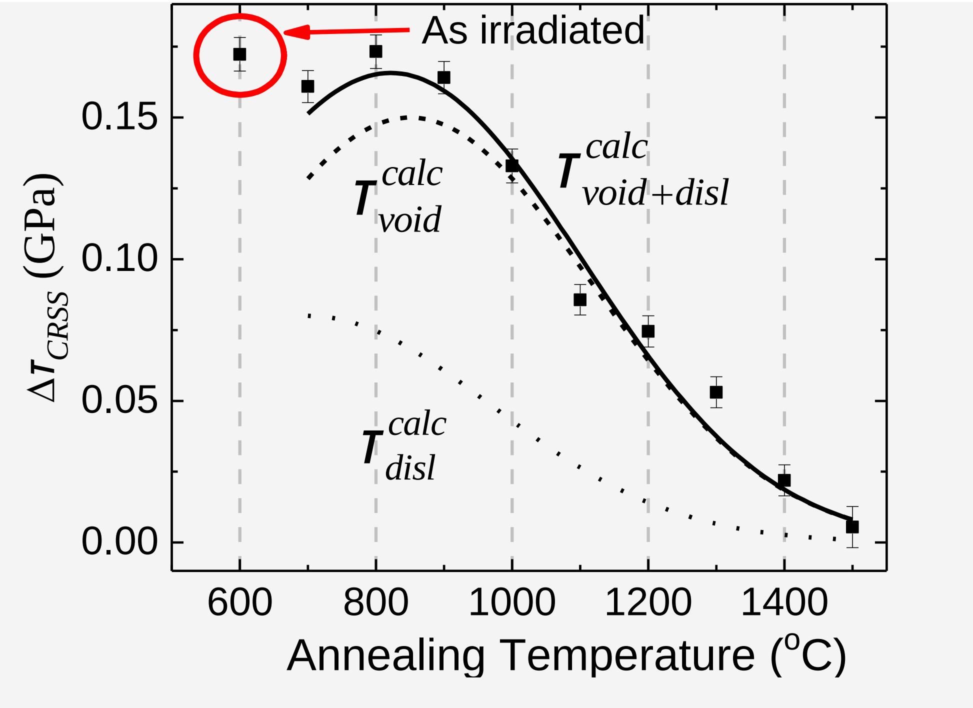
- Investigation of defect recovery mechanisms in neutron irradiated tungsten after annealing.
- Healing of neutron damage in tungsten.

Complete hardness recovery after annealing at 1500°C



Radiation induced hardness vs annealing temperature

Radiation induced critical resolved shear stress evolution

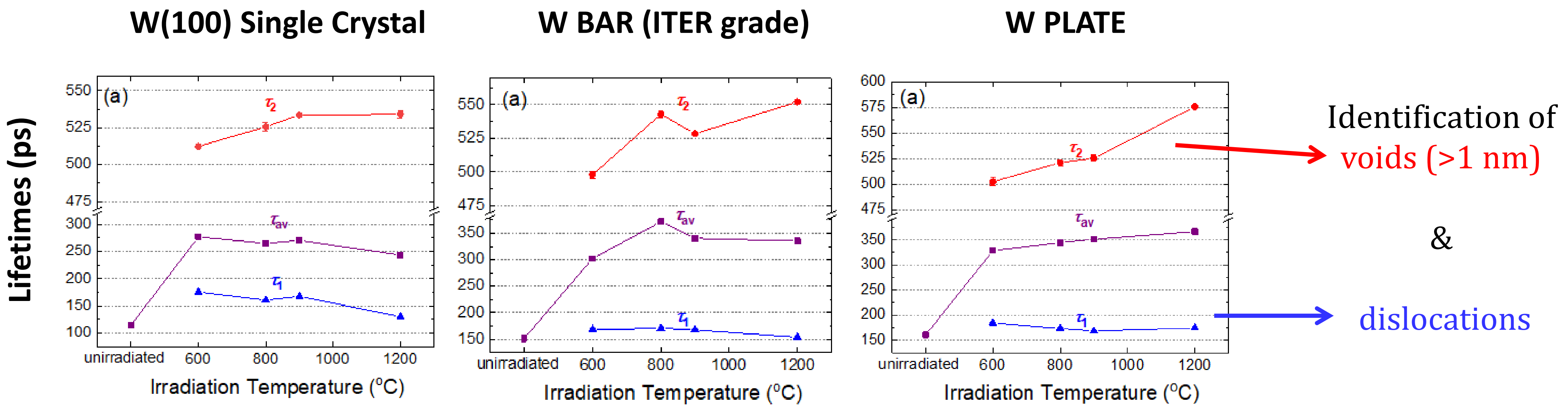


Voids & Dislocation contribution vs annealing temperature

NCSRD – WPTRED

Transmutation production and open volume defects in neutron irradiated tungsten

- Evaluation of **transmutation production** in neutron irradiated tungsten (W) and experimental validation using gamma spectroscopy.
- Investigation of the **neutron induced open volume defects** (dislocations, voids, etc.) in irradiated tungsten (W) materials as a function of the microstructure and irradiation temperature using positron lifetime annihilation spectroscopy.
- Investigation of the impact of transmutation products in the evolution of open volume defects.

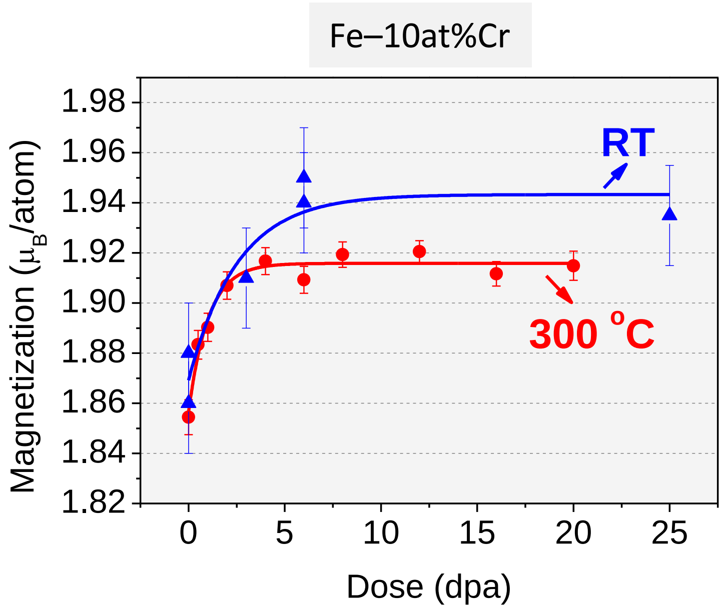


Positron lifetime as a function of irradiation temperature

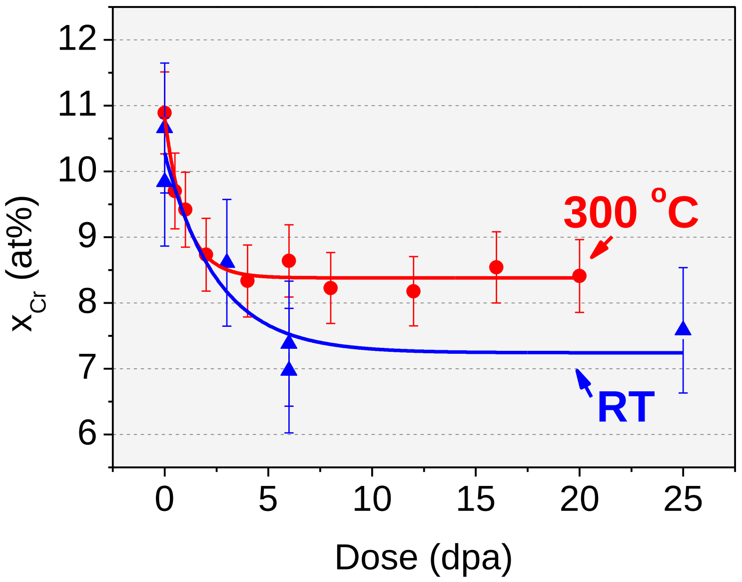
NCSRD – WPTRED

Investigation of Fe+ ion irradiation on the properties of FeCr alloys

- Explore and understand the **magnetic effects** produced by **Fe+ ion irradiation of FeCr alloys** at ambient and elevated temperatures.
- Comparison of experimental results with theoretical simulations.
- Experimental validation of modelling.



Solute Cr Content versus dose

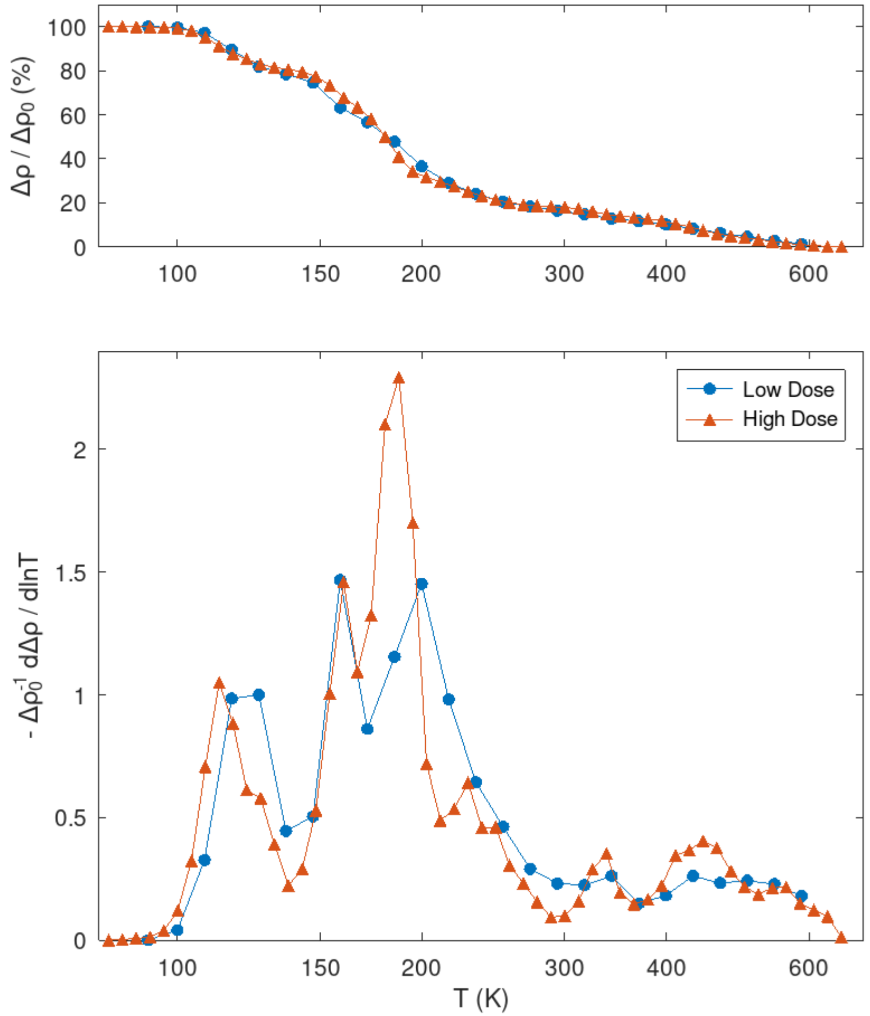


Magnetic moment enhancement as a function of irradiation dose due to Cr depletion from the FeCr matrix

NCSRD – WPTRED

Recovery in heavily irradiated fusion materials studied by in–situ electrical resistivity

- Recent experimental and theoretical radiation damage studies show that heavy irradiation of materials leads to the creation of asymptotic damage microstructures, which exhibit high thermal stability.
- Recovery of these highly damaged states is expected to be fundamentally different, and the aim of this PhD thesis is to study the relevant recovery mechanisms.
- The experimental methodology involves the generation of high damage states by ion irradiation and subsequently studying their recovery by in–situ electrical resistivity measurements.



Recovery of radiation damage in 5 MeV H+ irradiated Fe and low and high dose

AUTH – WPTE (JET)

- **Kinetic study of hot and relativistic electrons** (test–particle simulations), with emphasis on transport properties in energy space (energy distributions, transport coefficients, analysis of possible non–local fractional transport), in **MHD simulations** with the code **JOREK** of **shattered pellet injection** (SPI) for **disruption mitigation**. This work has been discussed with TSVV projects 8 and 9 and is addressing complementary questions directly related to experiments that could otherwise not be carried out.
- **JOREK MHD simulations of ELM activity and test–particle simulations of fast ions** to determine transport coefficients, to investigate particle loss mechanisms, and to identify non–Maxwellian effects in the kinetic energy distributions. This work has been discussed with and will be coordinated with TSVV project 8.

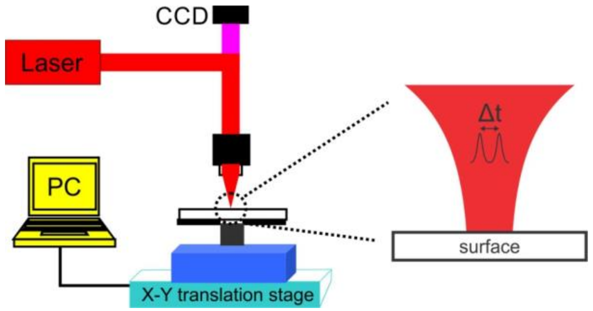
AUTH – WPCR

- Study of **magnetic reconnection and particle acceleration** in fusion plasmas with MHD simulations (codes **JOREK** and **MYDAS**).
- **Statistical analysis of turbulence**, using edge data from experiments (AUG and TCV), as well as data from gyrokinetic simulations (**GENE** code), with aim to assess the possible presence of **Self–Organized Criticality**, and to statistically analyze the dynamics of magnetic filaments.
- Modelling the **dynamics of filaments (ELMs)** in the edge region: **Test–particle simulations** in the electromagnetic fields of the MHD code **JOREK**, in order to explore phenomena of filament related particle heating and acceleration.
- **Resistive MHD simulations** (code **MYDAS**) **combined with test–particle simulations**, to study **anomalous transport phenomena in turbulent plasmas** (including reconnection phenomena), and to explore the limits of validity of the Fokker Planck model and the conditions for the appropriateness of **fractional (non–local) transport models**.
- Post–processing and in–depth **statistical analysis of gyrokinetic simulation data of turbulence** at the stellarator W7X, using the code **GENE**, for (a) **negative mirror configuration**, (b) **density profile control**, and (c) **turbulence** driven by **density gradients**.
- Post–processing and **statistical analysis of TRACER data** for **turbulent impurity transport** at the stellarator W7X triggered by TESPEL and LBO injections (based on **GENE** simulations).

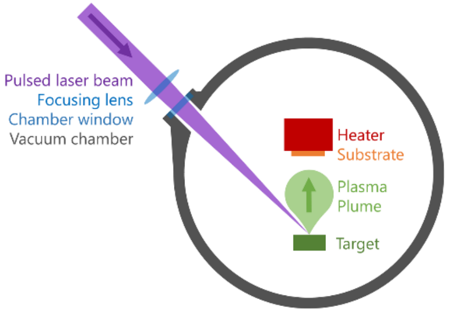
FORTH – WPCR

"Femtosecond Laser Spectroscopy in Solid State" laboratory

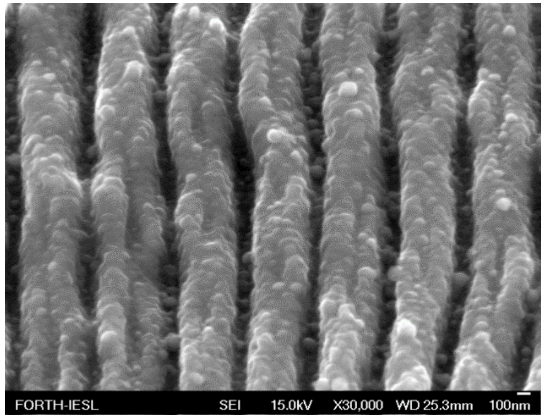
- Ultrashort laser pulses used to micro–/nano–structure solid surfaces.
- Textured solid surfaces exhibit modified radiation absorption properties.
- Pulsed Lased Deposition used to deposit Boron films on textured surfaces.
- Boron–covered textured surfaces for enhanced radiation detectors in fusion machines (collaboration with Prof. S. Moustaizis, TUC).



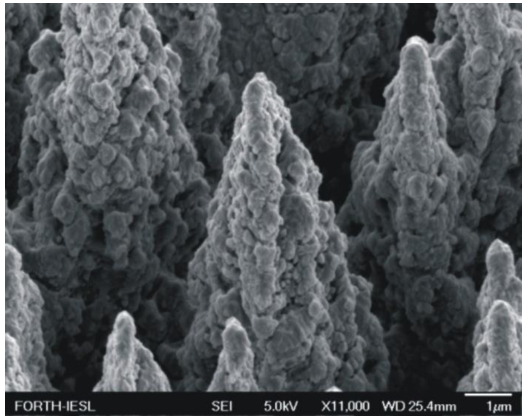
The setup for laser–texturing of solid surfaces



The Pulsed Laser Deposition Principle

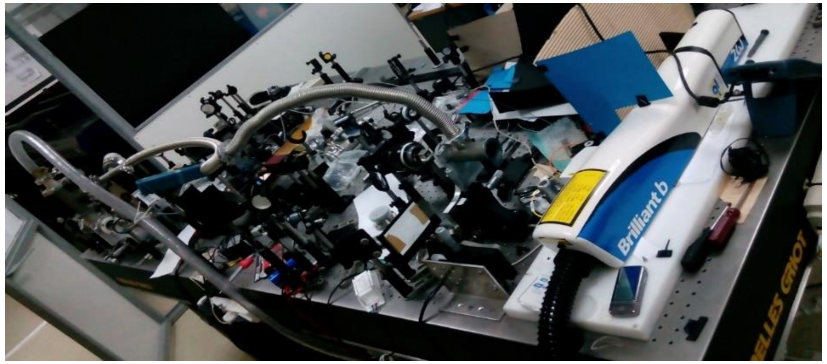


Rippled nanostructures on a Silicon surface

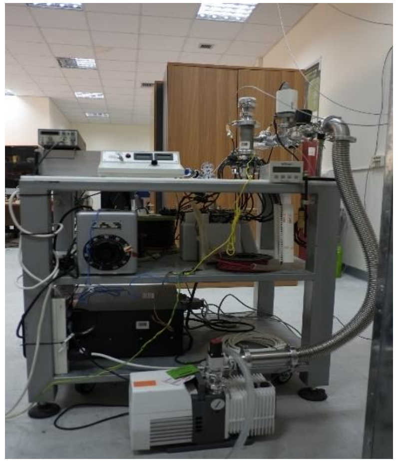


Conical microstructures on a Silicon surface

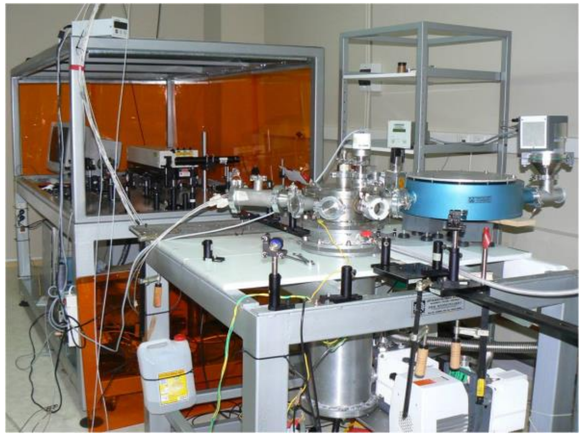
HMU Facilities



In–house developed state of the art 3D whole field spatiotemporal interferometric imaging diagnostic with nm transverse spatial resolution



Plasma focus Device Plasma Material interaction



X–pinch high–current plasma device for high–resolution X–ray radiography

Direct RE–induced damage on the FTU poloidal TZM limiter; the frozen melt pattern features explosive signatures

The 45 TW Zeus laser system

HMU – WPENR

- **CfP–FSD–AWP21–ENR–01:** Advancing shock ignition for direct drive ICF study and unlock key issues of the physics of laser direct–drive (DD) inertial fusion, and Shock Ignition (SI) in particular, complementing the NIF approach by studying the physics of potentially higher–gain DD schemes (2021–2024).

  IPPL – HMU contributes in:

  - characterization of hot electrons and hot–electron–driven SI,
  - hydrodynamic instabilities and mitigation strategies including the "imprint" mechanism,
  - parametric instabilities and cross–beam energy transfer and their mitigation using broadband lasers,
  - plasma diagnostics development for material characterization (ablators),
  - FEM modelling (ARIS supercomputer).

- **CfP–FSD–AWP24–ENR–04:** Material Damage Induced by Runaway Electron Deposition. Developing the first simulation tools capable of addressing the observed explosive phenomena, quantifying the material damage laws that characterize high–speed dust impacts in dedicated experiments and Molecular Dynamics simulations (2024–2025, *submitted*).

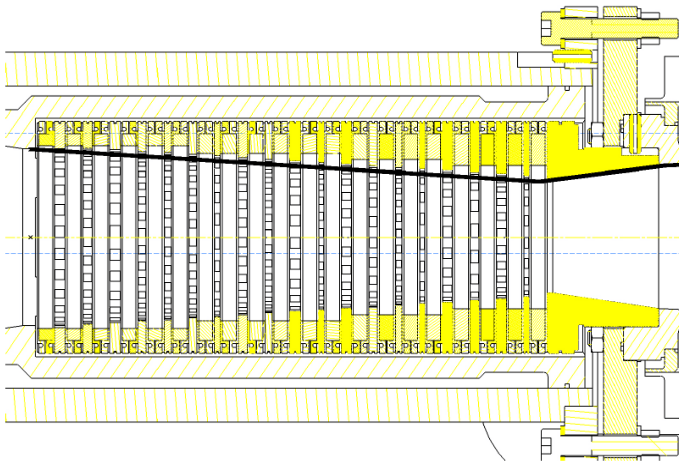
HMU – WPTRED

- **Experimental and numerical study of particle acceleration using high–intensity short laser pulses:** Study of Efficient Magnetic Vortex Acceleration by femtosecond laser interaction with long living optically shaped gas targets in the near critical density plasma regime for proton driven fast ignition & proton boron.
- **Characterisation of plasmas generated by table–top pulsed power devices & lasers.**
- **High–current generated dense plasma characterization and secondary emission studies:** Study of plasma focus and Z, X pinch magnetised plasmas for plasma and material diagnosis.

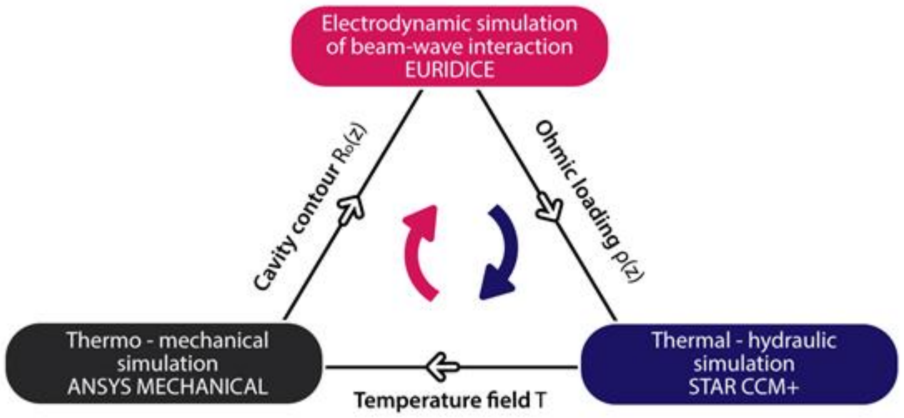
NKUA – WPW7X

Design of components for the 1.5 MW gyrotron for W7–X

- The upgrade of the ECRH system of W7–X is ongoing. In the frame of this upgrade a new 140 GHz 1.5 MW gyrotron has been developed.
- NKUA has contributed to the design and study of components (with IHM–KIT & PoliTo–ENEA).
  - ➢ Design of the beam tunnel based on self–consistent beam–wave interaction simulations (in–house code NESTOR). First use of improved ceramics for optimization of the absorption.
  - ➢ Multi–physics simulations for the numerical validation of cavity designs with improved cooling.
- A short–pulse prototype has been successfully tested at KIT.
- The first CW prototype has been manufactured by THALES and will be tested in August 2023.



The gyrotron beam tunnel

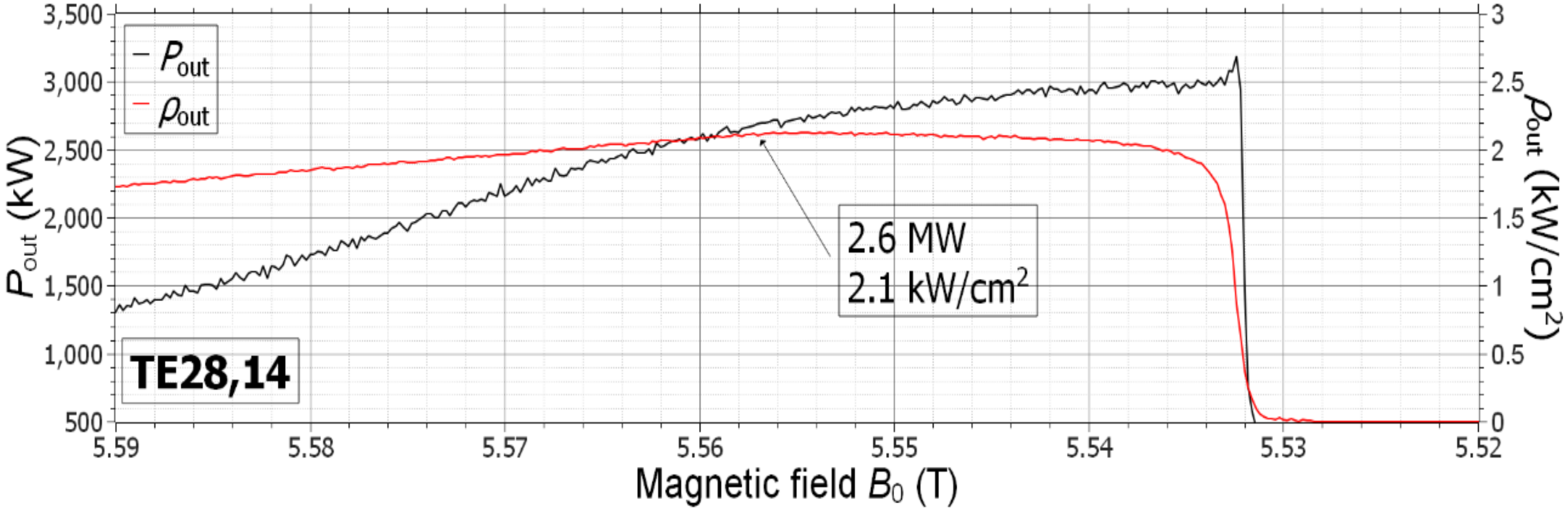


Multi–physics simulations in collaboration with PoliTo (NKUA provides the RF part)

NKUA – WPW7X

Studies and preliminary design for a future 2 MW gyrotron

- Future plans foresee the development of a new 2 MW Continuous–Wave gyrotron at 140 GHz.
- NKUA is performing studies on the design of the cavity and the beam tunnel:
  - ➢ Investigation of the different concepts (conventional or coaxial).
  - ➢ Operating mode selection for the cavity and detailed design.

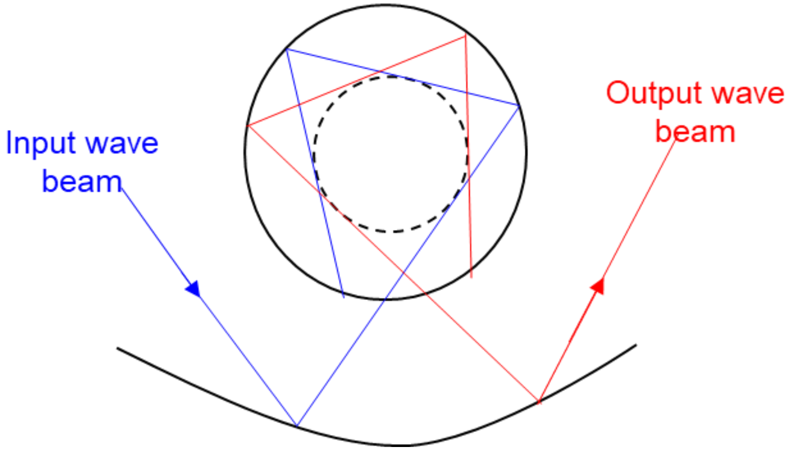


Studies towards a 2 MW gyrotron: single–mode simulation for the RF power generated in the cavity and the peak Ohmic wall loading for $TE_{28,14}$ mode.

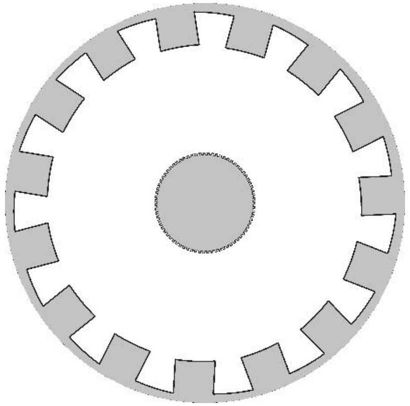
NKUA – WPENR

MW–class second–harmonic gyrotrons for DEMO and beyond

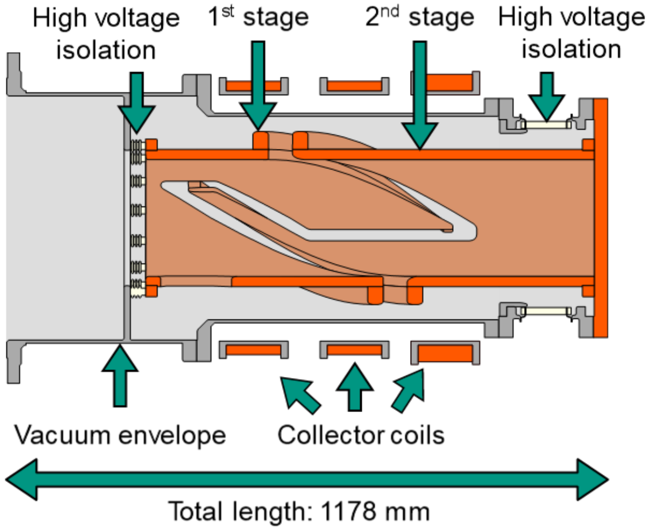
- "*New Generation of Megawatt–Class Fusion Gyrotron Systems Based on Highly Efficient Operation at the Second Harmonic of the Cyclotron Frequency*" (with IHM–KIT, 2021–2024).
- It combines the following three elements to achieve MW–class second–harmonic operation for DEMO–relevant frequencies and beyond:
  - Injection of external signal to enhance efficiency and mode selectivity.
  - Highly selective coaxial cavities with mode–converting corrugations.
  - Multi–stage depressed collectors for improved efficiency.



Launcher schematic for injecting external signal in the gyrotron cavity



Cross–section of cavity with outer corrugations for improved mode selectivity

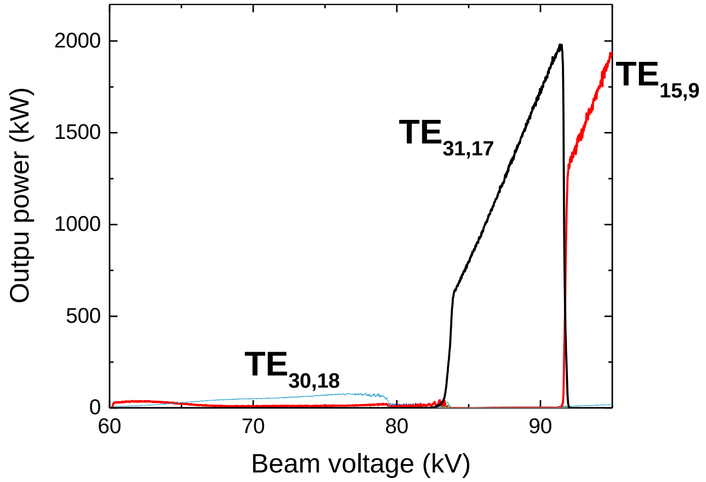


Multi–stage depressed collector (IHM–KIT)

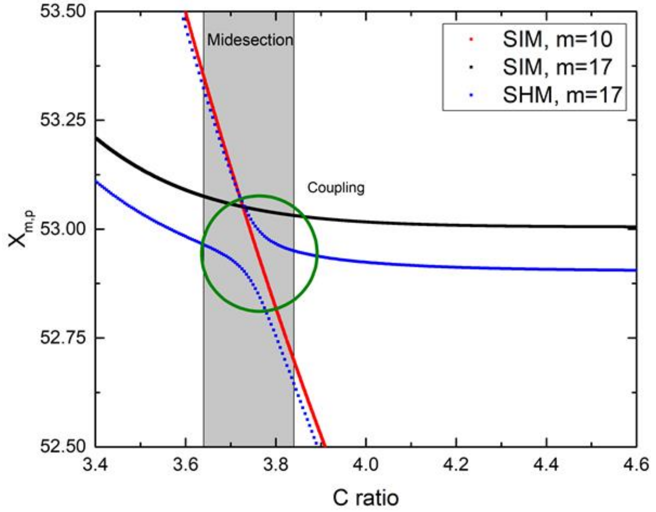
NKUA – WPENR

MW–class second–harmonic gyrotrons for DEMO and beyond

- NKUA contributes to the following topics:
  - Excitation of second–harmonic modes based on the coaxial gyrotron technology.
  - Enhancement of power/efficiency and mode selectivity by injection locking of an external signal.
  - Use of outer corrugations to enhance further mode selectivity of coaxial cavities.
  - Cavity designs for 170 GHz (heating and current drive) as well as for 280 GHz (for Collective Thomson Scattering) based on the above concepts.
  - Investigations on multi–frequency and step–tunable operation of second–harmonic modes.



Multi–mode simulation demonstrating MW–class operation of second–harmonic mode $TE_{31,17}$ against first–harmonic competitors

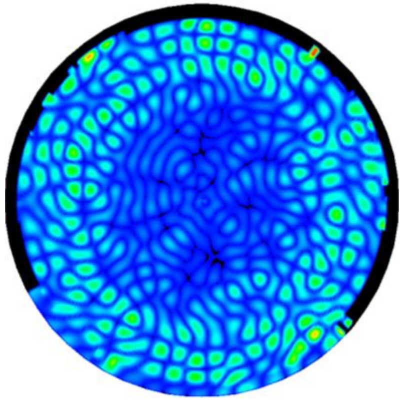


Distortion of eigenvalue curves of first–harmonic competitors by outer corrugations

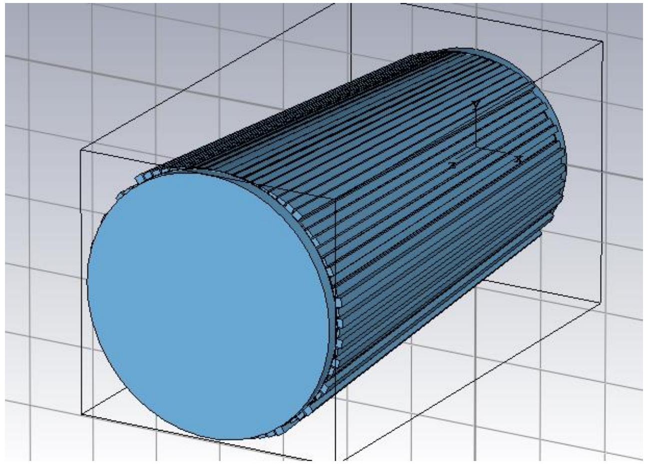
NKUA – WPHCD

Studies on cavities and advanced beam–tunnel designs

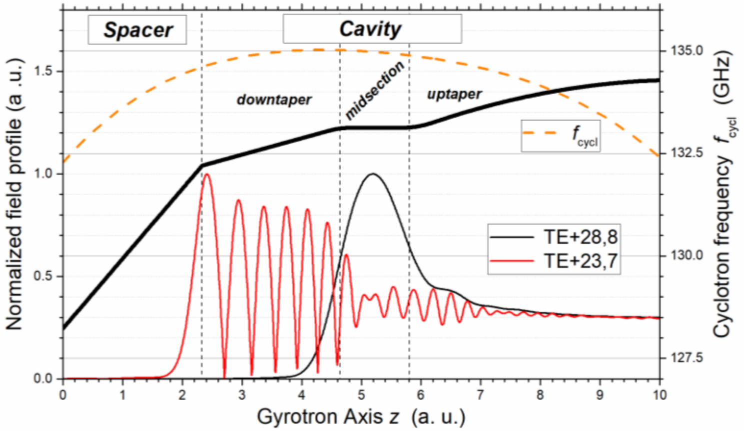
- Investigation of complex beam–tunnel designs with axial and pseudorandom azimuthal corrugations using the in–house self–consistent code COCHLEA.
- Design and simulation of full–metallic beam tunnels with diffusive surface to reduce parasitic modes using CST Studio Suite.
- In–house code–package EURIDICE for beam–wave interaction simulations and cavity design:
  - ➢ Support to gyrotron experiments (in collaboration with KIT and SPC).
    Definition of operating parameters; interpretation of experimental results.
  - ➢ Studies on parasitic oscillations.



Field profile in non–symmetric structure with pseudorandom corrugations



Model of beam tunnel with diffusive surface

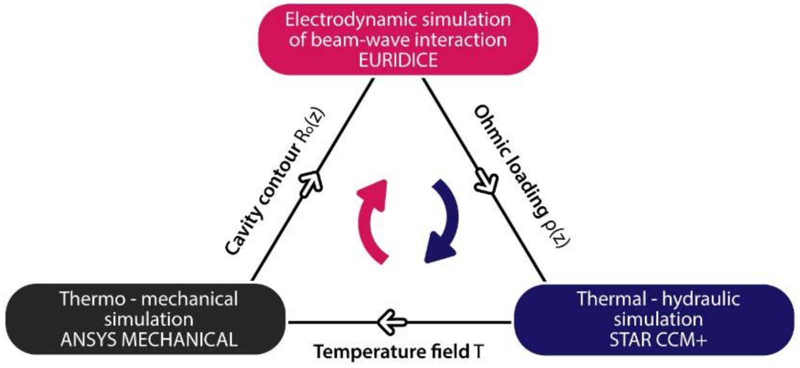


RF field amplitude, normalized to unity, of the nominal $TE_{28,8}$ mode and the parasitic $TE_{23,7}$ backward–wave mode

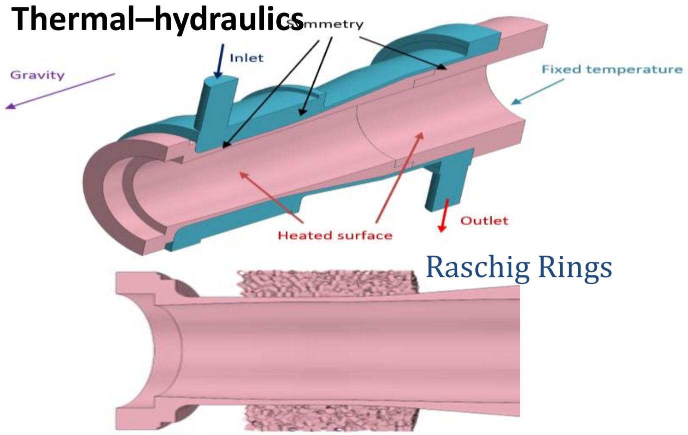
NKUA – WPHCD

Multi–physics model for the operation of the gyrotron cavity

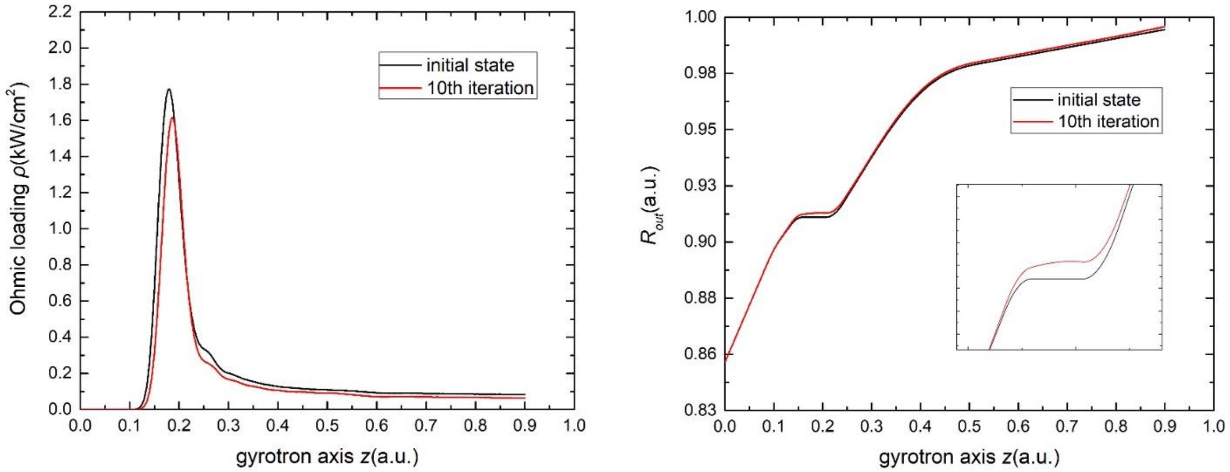
- Multi–physics simulations (in collaboration with ENEA–PoliTo) to validate the existing multi–physics model for the operation of a gyrotron cavity against available experimental results in order to study the effects of the Ohmic losses on the gyrotron's cavity operation due to thermal expansion.
- Code–package EURIDICE is used for the electrodynamic part (NKUA) and STAR–CCM+ for the thermomechanical/ thermohydraulic part (PoliTo).



Multi–physics model with the three–step simulations and the used software



Cavity structure (PoliTo)



Evolution of the Ohmic loading ρ(z) and deformation of the inner cavity contour $R_{out}(z)$ due to cavity thermal expansion

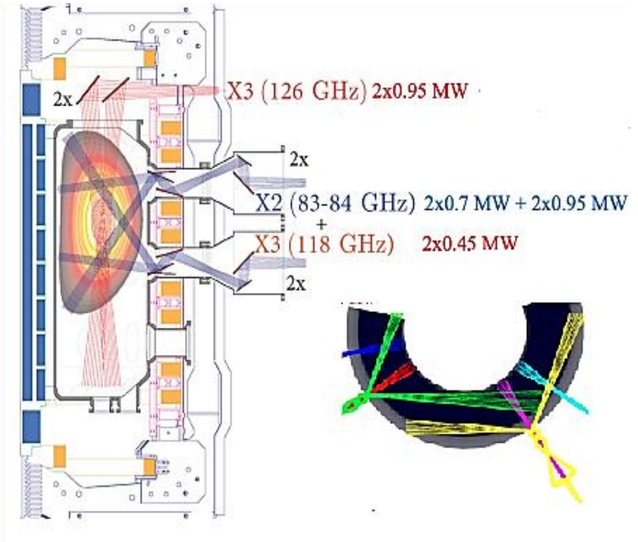
NKUA – WPTRED

- **Propagation characteristics in complex waveguide structures with applications in controlled thermonuclear fusion**: *Simulations of complex diffusers for advanced gyrotron beam tunnel designs [Relevant to WPHCD], Simulations of Ohmic losses in gyrotron cavity and corresponding studies of a new cooling system based on mini–channels for the gyrotron cavity [Relevant to WPW7X]*.
- **Theoretical and numerical studies on advanced resonant cavities with inhomogeneities for gyrotrons**: *Investigations on cavities with enhanced mode–selectivity, like cavities with corrugations and/or axial inhomogeneities, for next–generation gyrotrons targeting stable and robust operation with modes of very high order [Relevant to WPHCD]*.
- **Study and optimization of advanced high–power gyrotrons operating at the 2nd cyclotron harmonic**: *Studies on advanced MW–class 2nd harmonic gyrotrons, putting emphasis on their optimization with respect to the avoidance of parasitic modes [Relevant to WPENR]*.
- **Design and simulation of high–power gyrotron components**: *Component design (e.g., cavity, electron gun, beam tunnel) and associated numerical verification for advanced fusion gyrotrons (2–MW 140–GHz gyrotron for W7–X; gyrotrons for plasma diagnostics etc.) [Relevant to WPW7X]*.

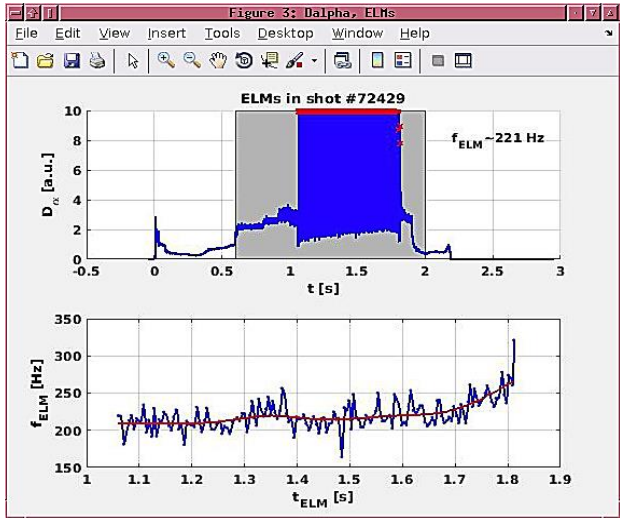
NTUA – WPTE

Investigations on ELM mitigation with edge ECRH

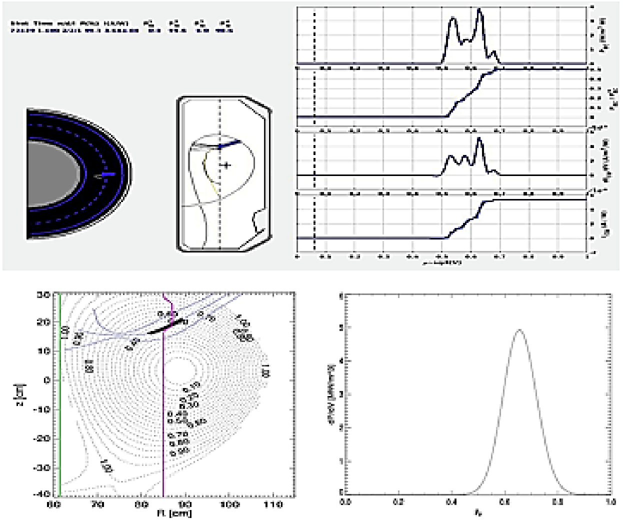
- **Mitigating effect of edge ECRH on type–I ELMs seen in TCV/AUG** (2015/2016 experiments):
  - ➢ ELM physics with respect to heat load mitigation potential is not fully assessed.
  - ➢ Study of the variation of ELM structure while varying EC deposition still required.
- **New series of experiments** performed at TCV in 2021/2022:
  - ➢ Effect demonstration in standard SND plasma and reproduction in pear–shaped plasma.
  - ➢ Modelling of ECRH deposition and edge stability in comparison to standard (type–I) ELMs.



Overview of the ECRH system (launchers X2/X3) at TCV



Results from 2022 TCV shot (ELM amplitude and frequency vs time)

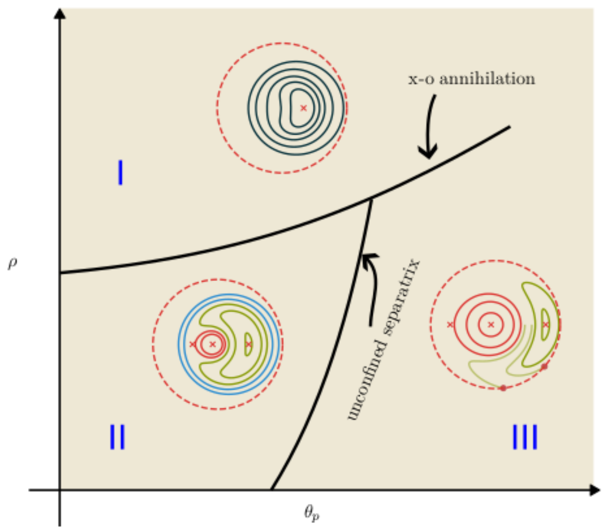


TORAY/TORBEAM simulation of ECRH during TCV shot

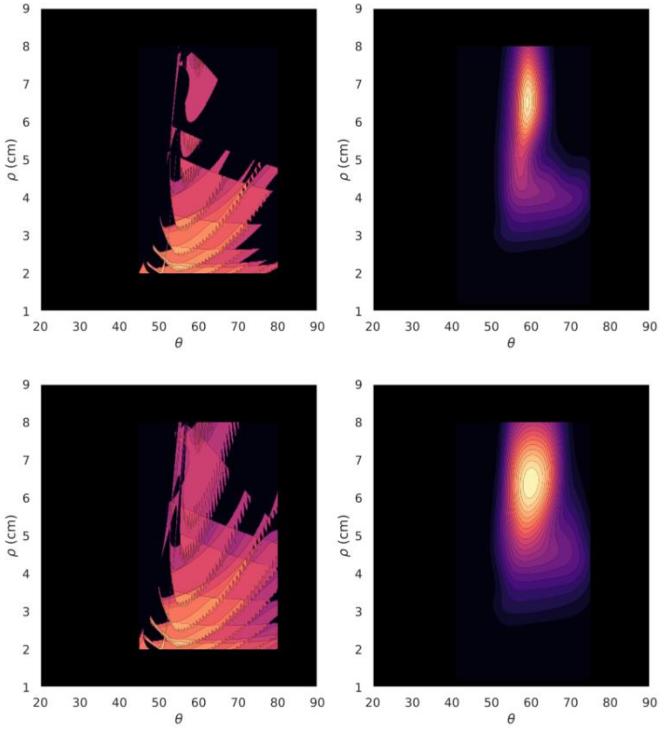
NTUA – WPTE

Study of Fast Ion losses in ASDEX upgrade

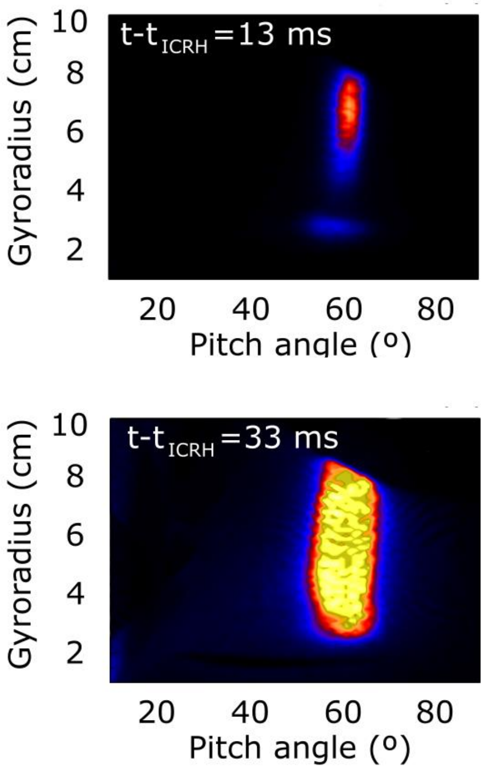
- **Estimate Fast Ion losses** by means of the distribution of unperturbed resonance orbits.
- **Resonance Index**: Measure of susceptibility to chaotic transport by means of resonance overlap.



Phase diagram of orbit topology on the FILD plane



Resonance index and synthetic FI loss signal for different snapshots

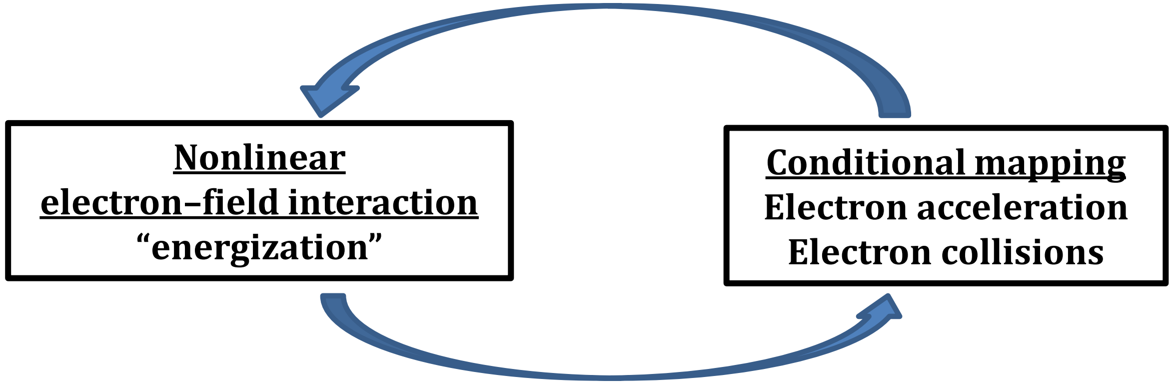


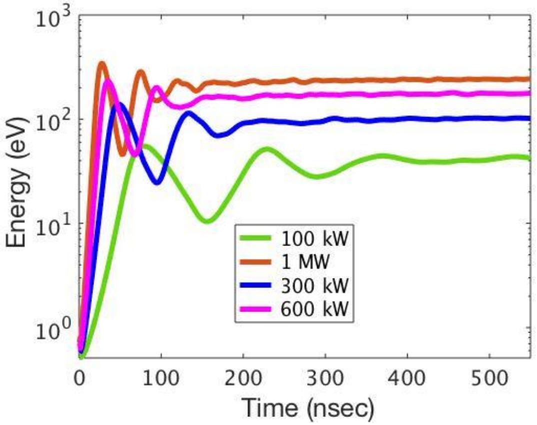
FI losses measured by FILD probe

NTUA – WPTE

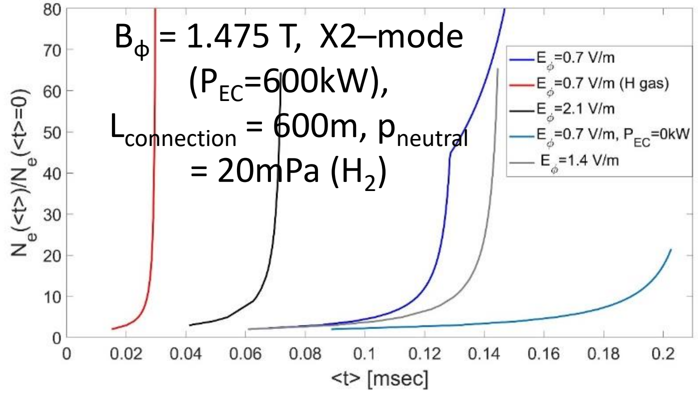
EC–assisted breakdown in tokamaks

- **Modelling breakdown/avalanche phase of start–up in the presence of**
  - ➢ B_{tor}, E_{tor}, RF Gaussian electric field (EC)
  - ➢ Impact ionization & elastic collisions
  - ➢ Loss of electrons through connection length
- **Control Parameters**
  - ➢ Power, width, polarization, inclination of EC–beam
  - ➢ Prefill pressure of neutral gas (H, H_2, D_2)
- **Outcome**
  - ➢ Electron "energization"
  - ➢ Electron population growth
  - ➢ Breakdown time estimate





Average energy gain of initial ensemble of seed electrons for various EC–beam powers (X2–mode)

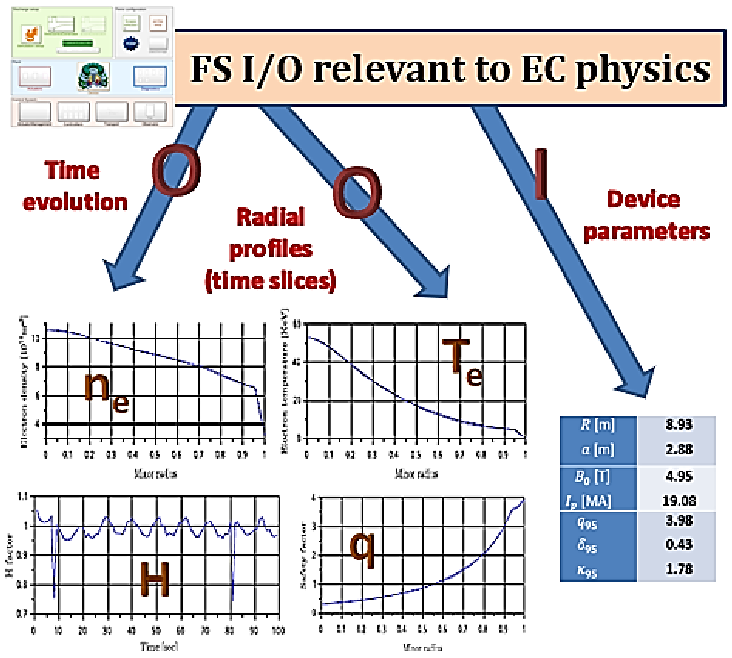


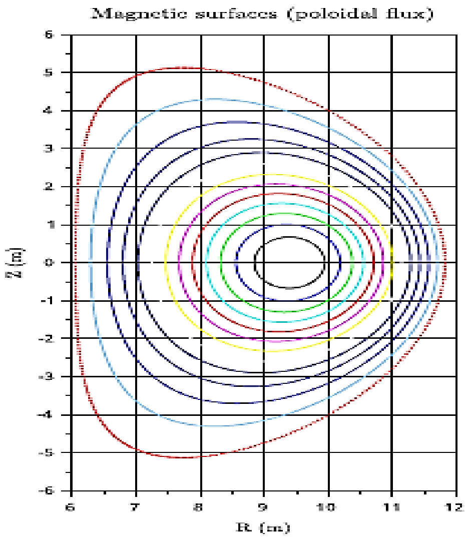
Evolution of assisted avalanche at initial stage for various loop voltages

NTUA – WPDES

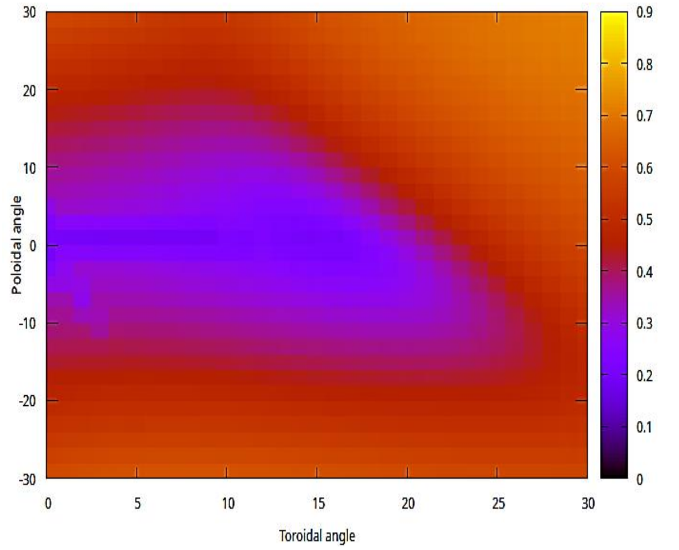
Simulations of DEMO burn control

- **Studies of plasma burn control with EC heating actuators in DEMO:**
  - ➢ Definition of (physics–based) burn control strategy.
  - ➢ Development of associated modelling tools (i.e., Tokamak Flight Simulator).
- **Set up of ECRH modelling chain, based on TORBEAM, with Tokamak Flight Simulator input:**
  - ➢ Calculation of the magnetic field components from the values of the poloidal flux.
  - ➢ Analysis of EC deposition with determination of optimal beam parameters.





Flux surfaces in the current DEMO baseline scenario

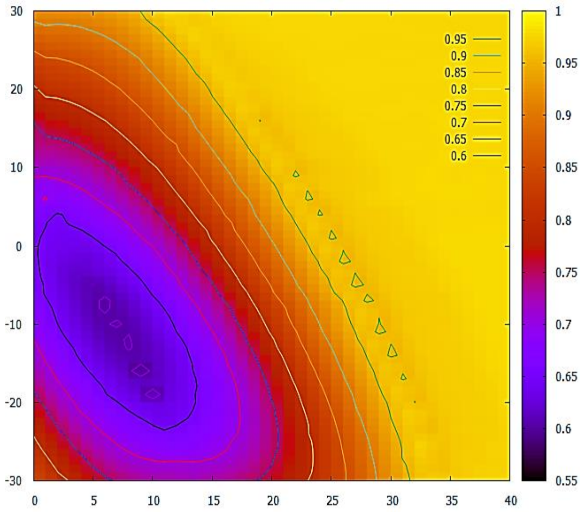


Map of deposition radius on the injection angle plane

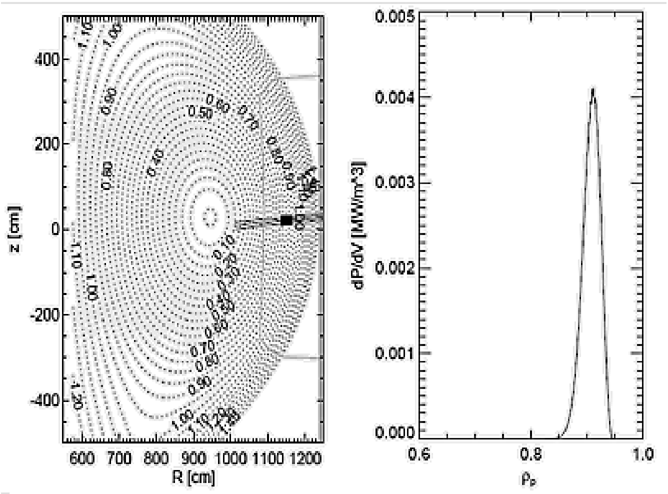
NTUA – WPDES

Analysis of DEMO–relevant Radiation Instability (RI) stabilization

- **Determination of ECRH requirements at the plasma edge for controlling radiative instabilities:**
  - ➢ Investigation on potential limitations to/of peripheral EC absorption.
  - ➢ Sustain the availability of the RI–reserved power for other functions (RU/RD, etc).
- **Improvement of TORBEAM input for ASTRA/Simulink W–event simulations:**
  - ➢ Analysis of ECRH deposition parameters for selected beam frequencies and launch points.
  - ➢ Optimization of beam absorption at the plasma edge by fine–tuning the injection angles.



Map of deposition radius on the injection angle plane



Poloidal beam projection and absorbed power density profile

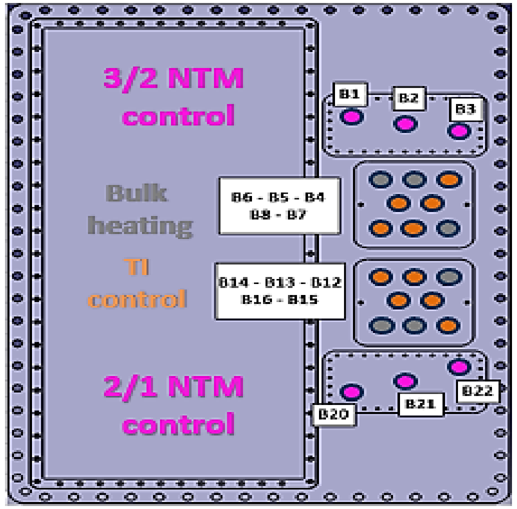
Beam	$\rho_{ABS} \pm \Delta\rho_{ABS}/2$
B4	0.8660 ± 0.0159
B7	0.8768 ± 0.0166
B8	0.9184 ± 0.0193
B10	0.8874 ± 0.0171
B11	0.9256 ± 0.0202
B13	0.8998 ± 0.0171
B14	0.9344 ± 0.0196
B15	0.8678 ± 0.0152
B16	0.9050 ± 0.0174
B17	0.8306 ± 0.0144

ECRH power deposition parameters for different beam injection positions

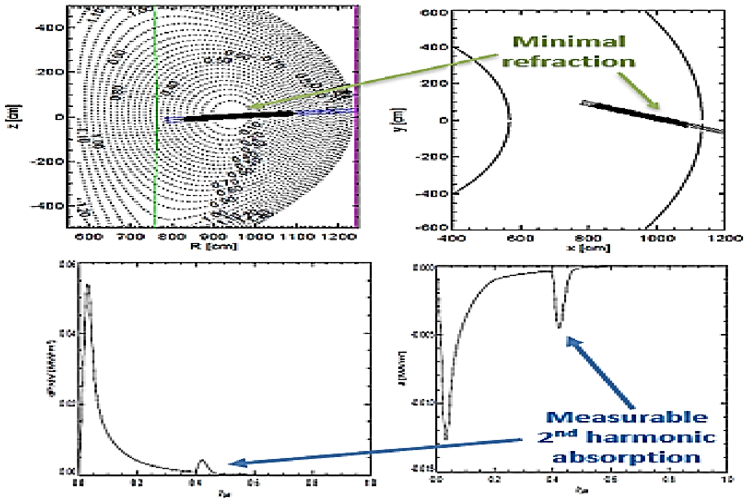
NTUA – WPHCD

Optimization of the DEMO EC launcher design

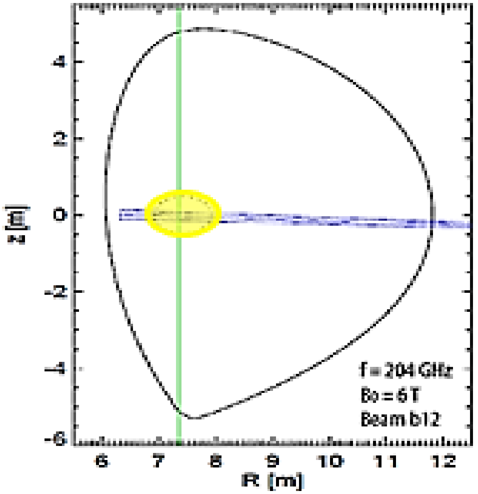
- **Beam tracing analysis of the EC launcher design and implementation for DEMO:**
  - ➢ Physics/Engineering study of RSA/MSA and OEWG beam launcher configurations.
  - ➢ Determination of the HCD efficiency in plasma start–up, core heating and NTM stabilization.
- **Simulations of the EC propagation, absorption and current drive under different conditions:**
  - ➢ Computation of the deposition radius and width, % absorption and total driven current.
  - ➢ Assessment of the fulfillment of the current SRD requirements for DEMO HCD.



Sketch of the equatorial EC port plug design



Beam projections and EC HCD profiles in core heating scenario

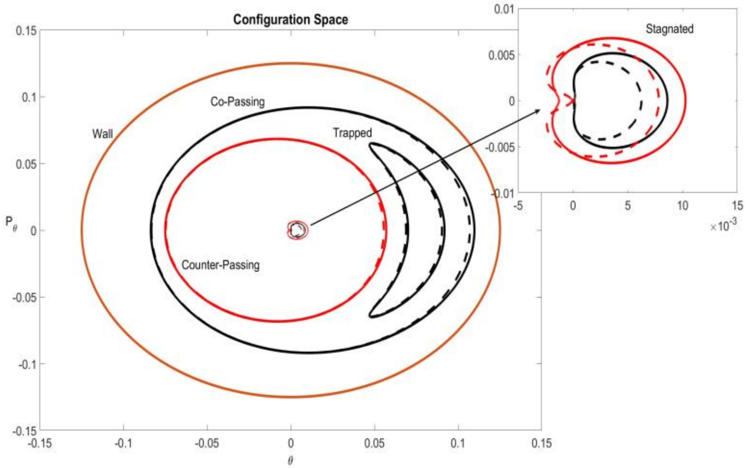


Beam setup for EC–assisted breakdown

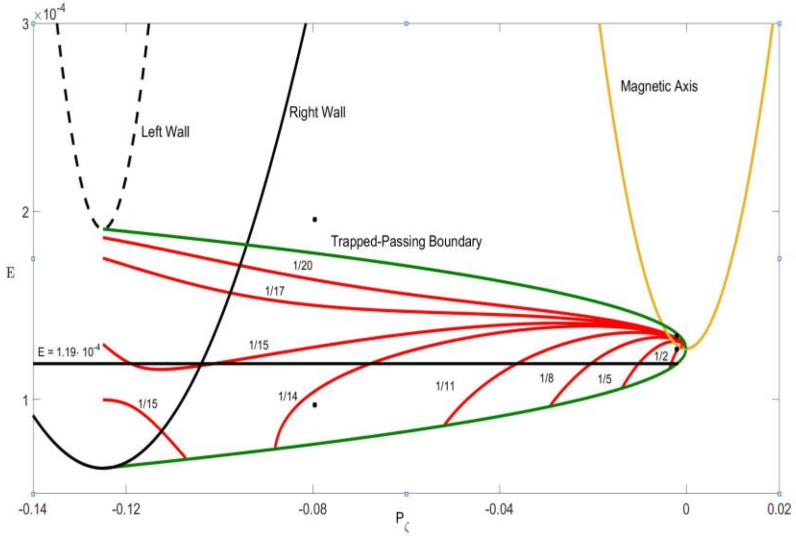
NTUA – WPTRED

Orbital spectrum analysis of GC dynamics under perturbations

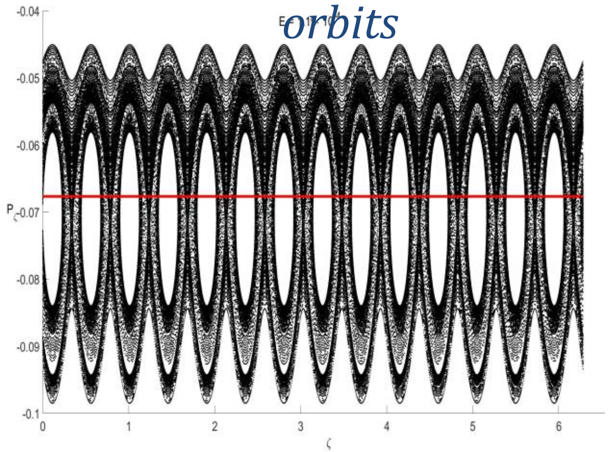
Orbital Tomography and Spectrum Analysis for Energy and Momentum Transport under Resonant Non–Axisymmetric Perturbations

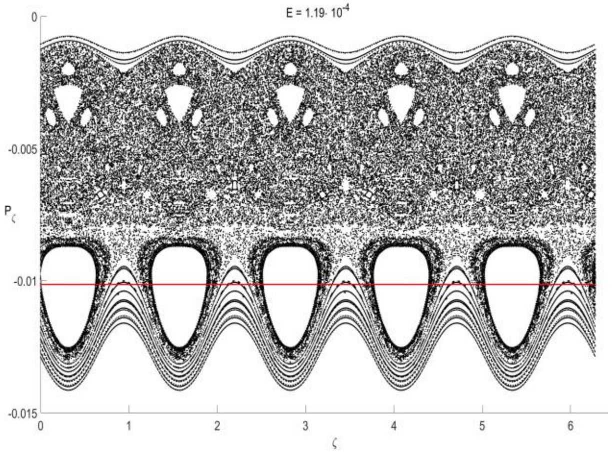


Efficient Orbital Spectrum calculation *based on judiciously selected magnetic flux surfaces of reference. Dashed lines: approximate orbits, Solid lines: exact orbits*



Resonance conditions *(red lines) on the **C**onstants **O**f the **M**otion (COM) orbit space (μ variable is fixed)*





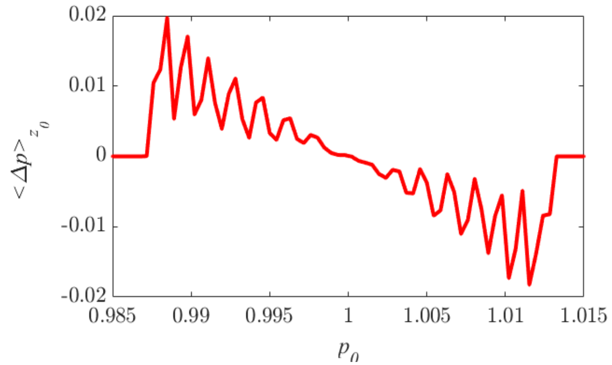
*The analytical knowledge of the full skeleton of the **resonance structure** allows to pinpoint the exact locations of resonances in the phase space*

NTUA – WPTRED

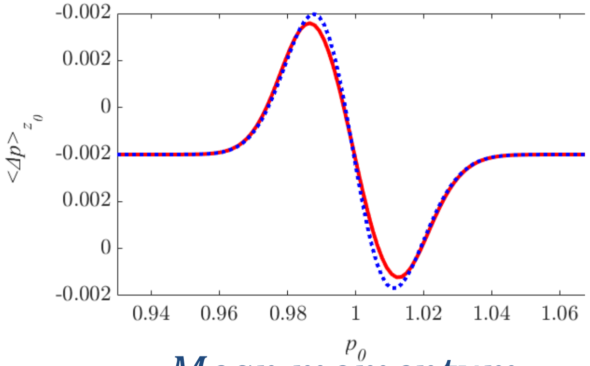
Particle momentum transport under interaction with EM waves

Study of Wave–Particle interactions and investigation of the domain of validity of analytical results in a 1–D Hamiltonian model

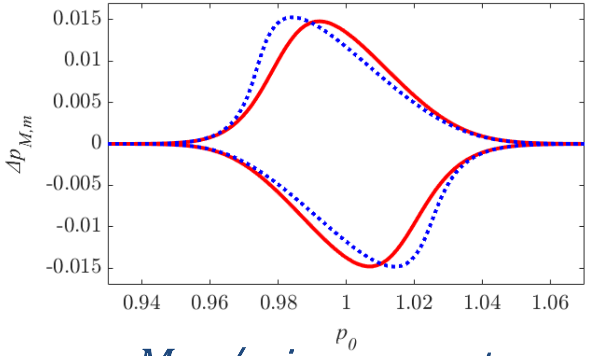
- Small–Amplitude Perturbations: Analytical results using Canonical Perturbation Theory
- Higher–Amplitude Perturbations:
  Systematic numerical investigation



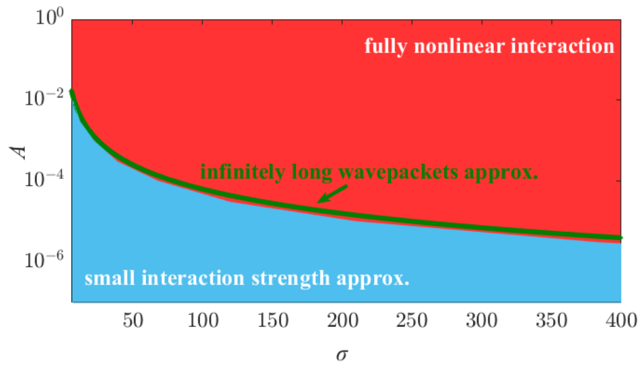
Mean momentum variation for Higher–Amplitude Perturbations



Mean momentum variation

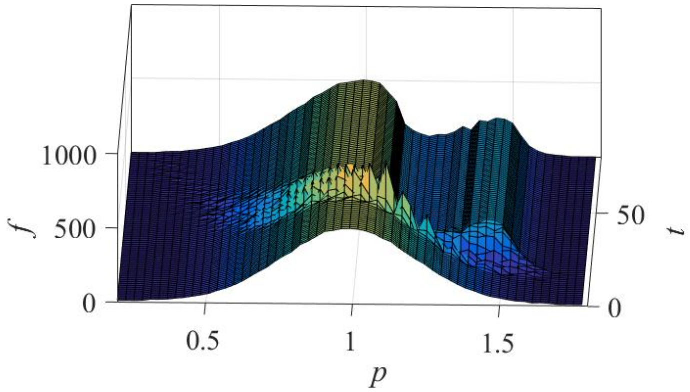


Max/min momentum variation



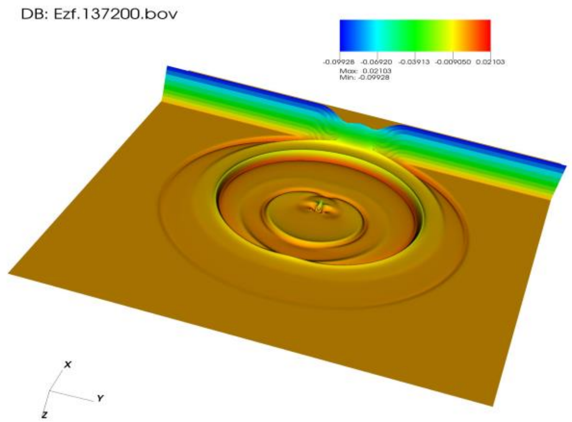
Domain of validity of analytical results

Comparison between analytical (blue) and numerical (red) results of momentum variations for Small–Amplitude Perturbations

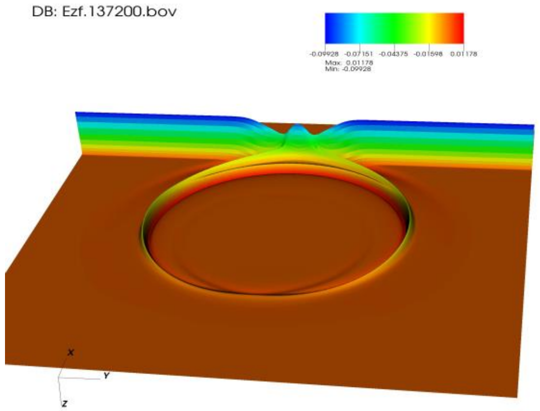


Time evolution of a Maxwellian momentum distribution function

- Construction of a Dirac–Maxwell equation for non–gyrotropic tensorial media and cold inhomogeneous plasma for quantum computing implementation: $i\frac{\partial\psi}{\partial t} = \widehat{D}\psi, \widehat{D}^{\dagger} = \widehat{D}$
    - ➢ Use of the Pseudo–Hermicity concept which has many applications in the fields of non–Hermitian quantum mechanics and optics.
    - ➢ Extending the state space according to the mathematical theory of passive media with dispersion.
- Quantum implementation of Qubit Lattice Algorithm (QLA) into quantum cirquits for simulation of propagation and scattering off tensorial dielectrics:
    - ➢ Full–wave simulations for a cylindrical and conical dielecric inhomogeneity.
- Quantum simulation of collisional magnetized plasmas using open–quantum systems theory.



Propagation and scattering of an electromagnetic pulse for cylinder

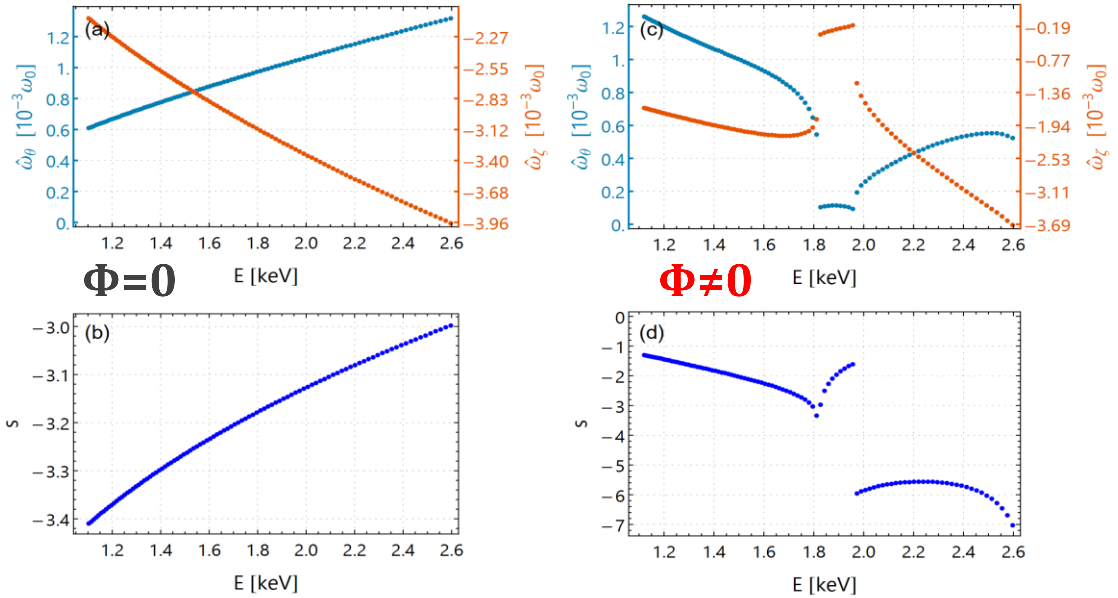


Propagation and scattering of an electromagnetic pulse for cone

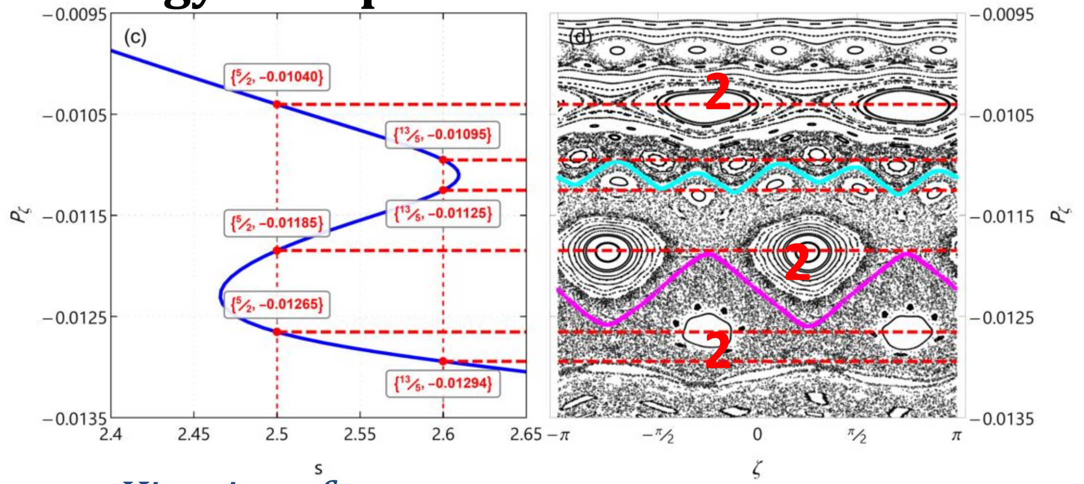
NTUA – WPCR

Role of the radial electric field in resonant mode–particle interactions

- The presence of the edge radial electric field:
  - Drastically **modifies the orbital frequencies** (bounce/transit, toroidal precession).
  - Changes **the locations of resonant interactions** with perturbative modes.
  - **Enables or prevents** resonant interactions with specific modes.
  - Enables the formation of **Transport Barriers**.
  - Drastically **modifies particle, momentum and energy transport**.



Orbital Spectrum (first row) and kinetic–q factor (s) (second row), without (left) and with (right) edge radial electric field



Kinetic–q factor (s)

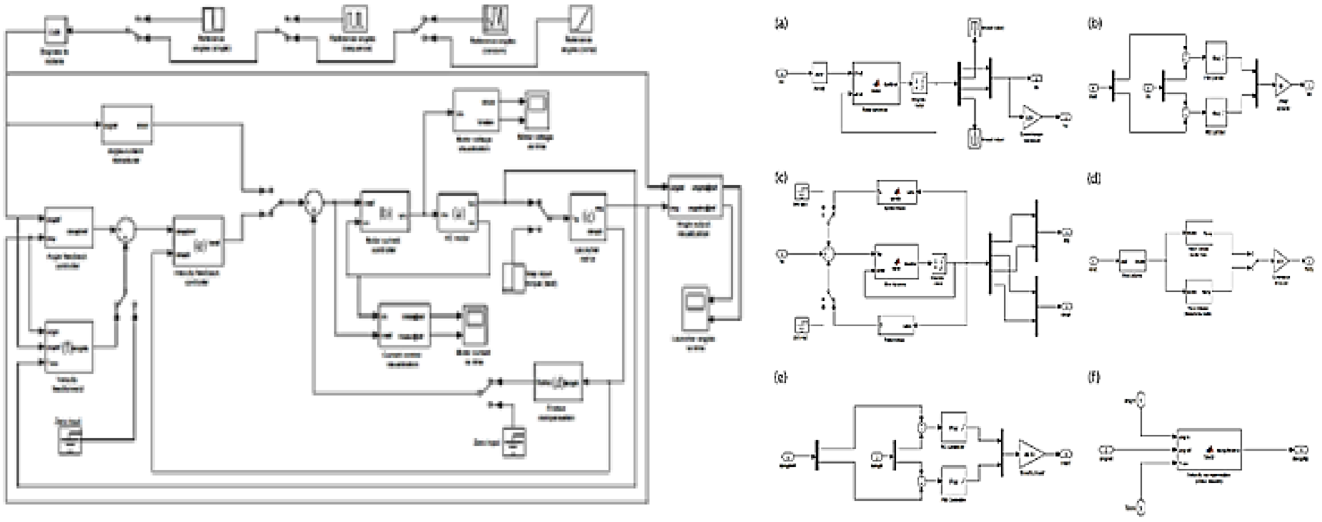
Poincaré surface of section

The kinetic–q factor (s) predicts the exact locations of the resonances; Local extrema correspond to locations of Transport Barriers

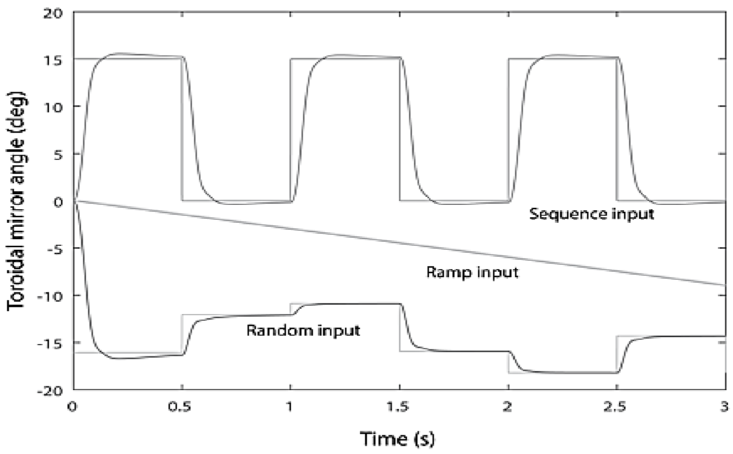
NTUA – WPCR

Control simulations of NTM stabilization

- **Control modelling of NTM stabilization with ECCD injection at the magnetic island:**
  - Physics–based models for all system components (plant, sensors and actuators).
  - Simulink model blockchain (includes functions and libraries coded in C/Fortran).
- **Control modelling sequence:**
  - EC beam injection (servomotor function, launcher mirror dynamics, nonlinear friction, etc.).
  - Wave kinetics and plasma response (EC propagation/deposition, island growth/rotation).
  - Diagnostic measurements (launcher angle/velocity, island position/rotation/width, etc).



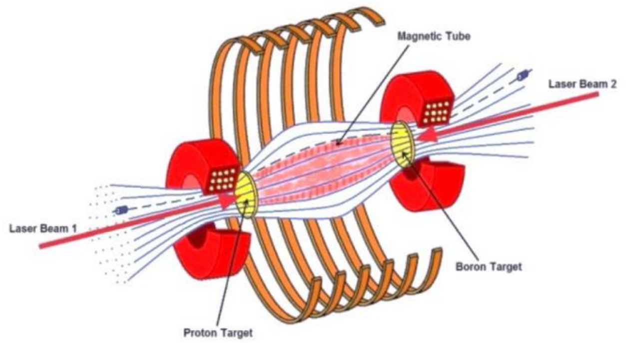
Simulink model for ECCD–based NTM control simulations



Results from controlled simulations of the EC launcher response

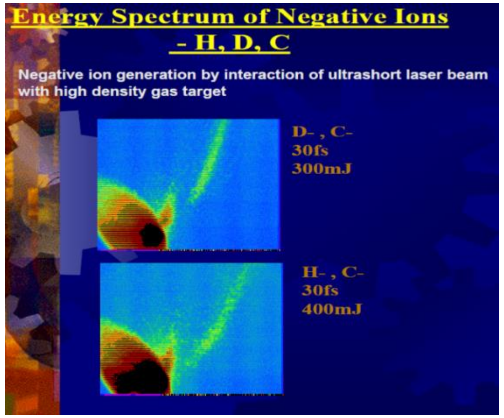
TUC – WPTRED Numerical investigation of the alpha avalanche heating effect for potential applications in Compact Magnetic Fusion devices

- p–^{11}B nuclear fusion reaction is of interest for **clean energy production**, as it produces three (3) iso–energetic alpha particles with 8.7 MeV total energy.
- Results obtained from a multi–fluid code, including collisions between all species (p, ^{11}B, e, α) and Bremsstrahlung losses, enable the investigation of the temporal evolution of the fusion species parameters (densities and temperatures, reaction rate, fusion power, radiation losses, etc.).
- The numerical results show that the alpha avalanche heating effect enhances the fusion species (p, ^{11}B) temperatures to energies corresponding to the optimum p–^{11}B fusion cross–section and leads to self–sustained ignition conditions ($Q = P_{fus}/ P_{Brems} > 1$) for initial medium temperatures **up or higher to 200 keV** and fusion species ratio $\boldsymbol{n_p / n_B = 1/10}$.
- Proposed experimental setup using laser beams for the production of the plasma species in **Compact Magnetic Fusion device**. For trapping $\sim t = 10\,\mathrm{s}$ the fusion power density is up to **0.35 MW/m^3**.

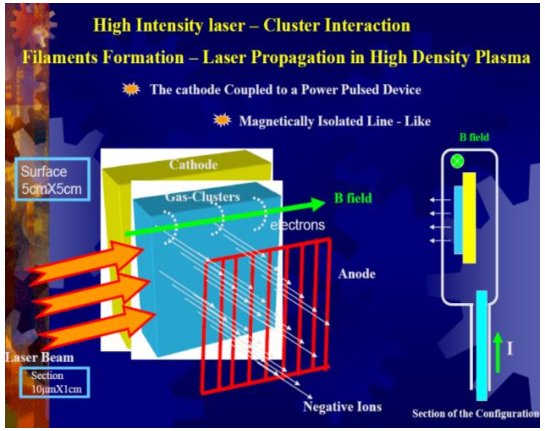


High Power Negative–Neutral Beam production

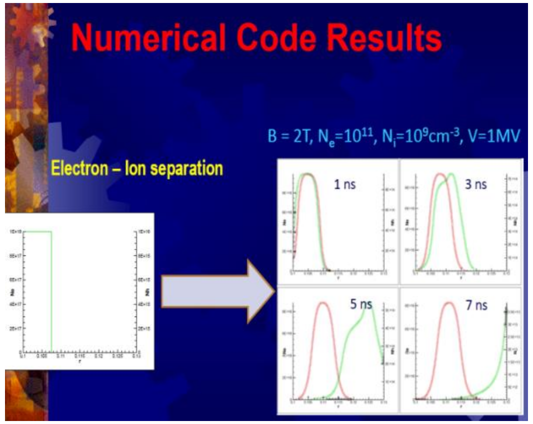
- Negative Ion H or D production from laser – cluster interaction.
- Multi–fluid simulation on geometrical and physical parameters concerning the acceleration and extraction of Negative Ions Beam from a Magnetically Insulated Diode (MID).
- High energy Neutral proton beam production by photo–Neutralization of Negative Ion Beam.
- Initiative for an experimental setup for High Power Neutral Beam production for application to Magnetic Fusion devices.



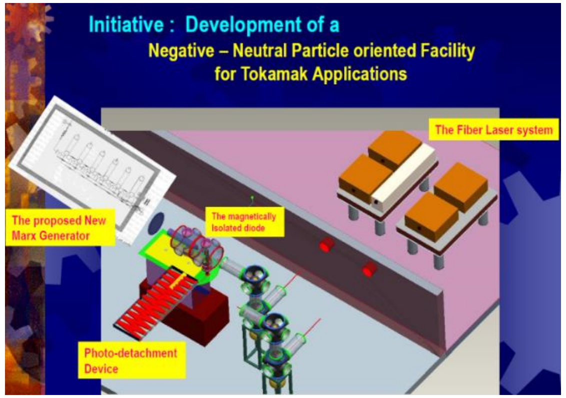
Negative Ion D and H production by laser cluster interaction



Negative ion acceleration and extraction from a Magnetically Insulated Diode



Simulation on high current extraction of Negative Ions Beam from a Magnetically Insulated Diode



Proposed experimental setup for extraction and Photo–neutralization of Negative Ion Beam Application to Tokamak

TUC – WPCR

Numerical investigation on alpha heating effect during Beam – Plasma interaction

- Negative proton production, acceleration and extraction from a Magnetically Insulated Diode.
- High–energy Neutral proton beam production by photo–Neutralization of negative beam.
- Injection of Neutral beam in mirror–like magnetic configuration.
- Interaction of a high energy beam (250 – 500 keV) with the plasma of relatively low temperature (80 keV).
- Multi–fluid numerical simulation on the temporal evolution of the alpha avalanche heating effect.
- Important temperature increase of fusion species to values corresponding to the optimum cross section.
- Collaboration with the team of FORTH on laser nanostructured materials for fusion applications.

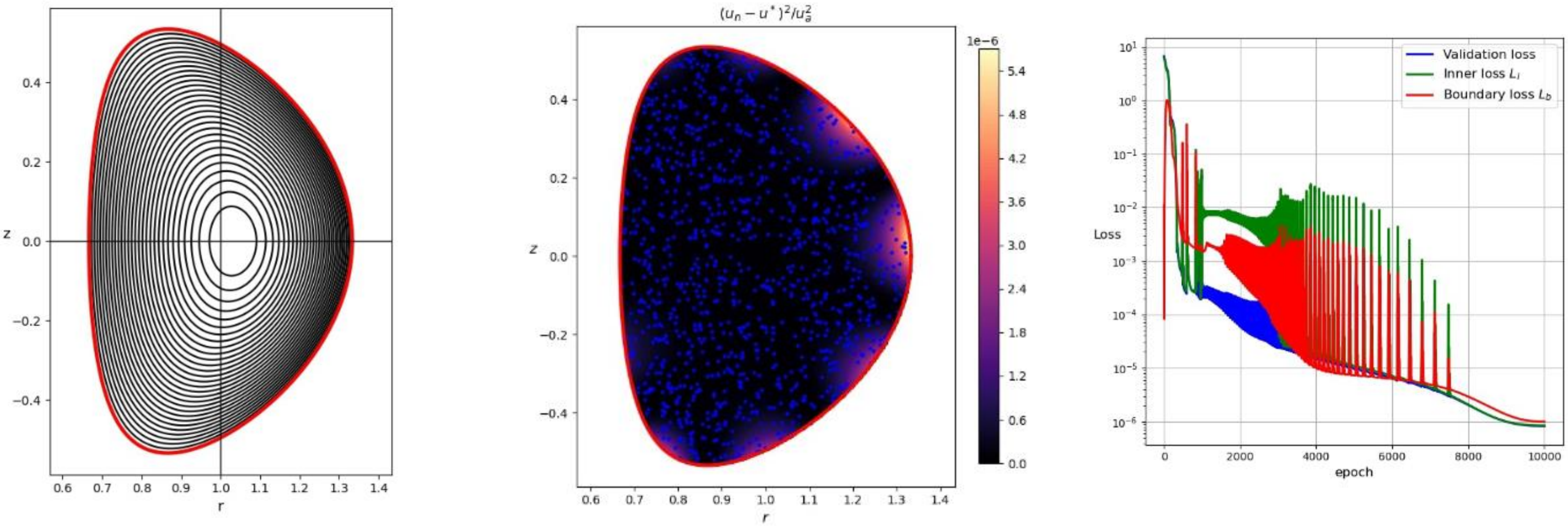
UoI – WPCR

- Two novel, generalized Hamiltonian hybrid models with fluid and kinetic ions and massless fluid electrons for the description of multicomponent plasmas with energetic particles were derived. The dynamics of the thermal component is governed by standard fluid equations in the Hall MHD limit. The generalized Ohm's law contains Hall and electron pressure terms involving a gyrotropic electron pressure tensor. The dynamics of the kinetic component is described by full–orbit Vlasov equation. [D. A. Kaltsas et al., J. Plasma Phys., 87(5), 835870502 (2021)]
- A Deep Neural Network (DNN) solver for tokamak equilibria with incompressible flows was developed. DNN tokamak equilibria were constructed solving a generalized Grad–Shafranov equation, which governs axisymmetric plasma equilibria with incompressible flows. [D. A. Kaltsas and G. N. Throumoulopoulos, Physics of Plasmas 29, 022506 (2022)]
- Classes of exact three–dimensional solutions are obtained with straight magnetic axes and closed nested pressure–surface intersections with the poloidal plane, for moderate values of the flow velocity parameters whereas these surfaces are destroyed for higher velocities. [Ap. Kuiroukidis and G. N. Throumoulopoulos, Phys. Let. A, 437 (2022)]

Future extensions: Axisymmetric formulation and construction of Tokamak equilibria with energetic particles. Stability analysis using the energy–Casimir variational principle. Kinetic extension of the energy principle. Utilization of DNNs for representing the Grad–Shafranov solution operator.

UoI – WPCR

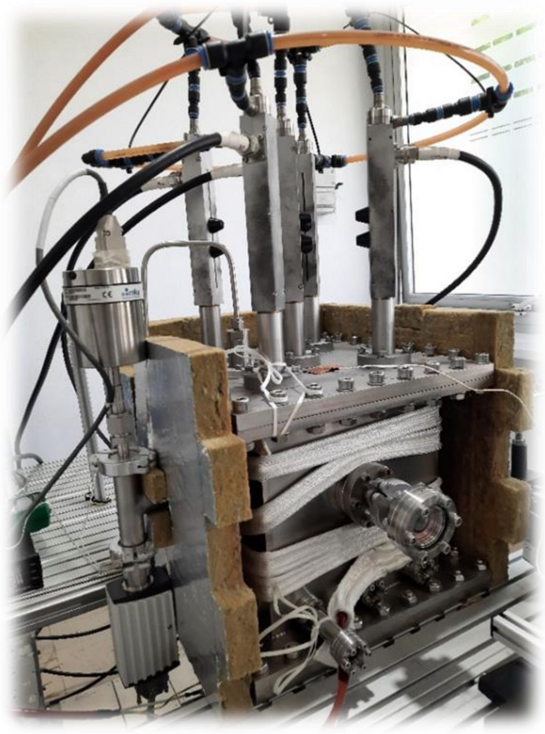
- Development of a DNN solver for tokamak equilibria with incompressible flows.
- Feed–forward, fully connected DNNs were used to approximate the Grad–Shafranov solutions with equilibrium constraints. The ADAM optimizer was used for the DNN training.



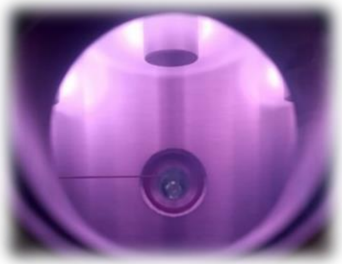
The magnetic surfaces of a linear tokamak equilibrium (left), the error of the numerical solution computed with respect to a known analytic solution (middle), and the DNN training history (right)

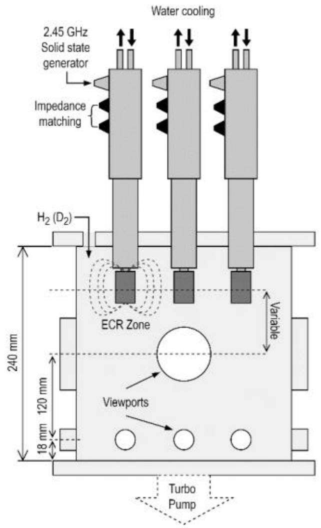
UoPatras – WPTRED

Production of H^-/D^- ions in plasmas driven by ECR modules



"Prometheus I" reactor





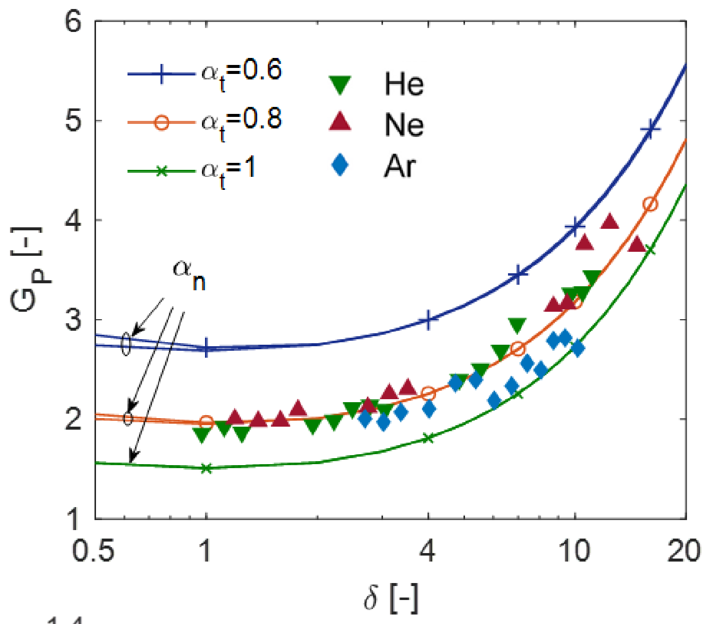
- Fundamental approach of the volume production of H^-/D^- ions in plasmas driven by dipolar ECR modules.
- Advanced diagnostics developed in–house and with close collaborators:
  - Langmuir probes.
  - Laser diagnostics: Laser–induced photodetachment (single and two–beam experiments).
  - Spectroscopic diagnostics: OES, TDLAS, VUV–FT absorption spectroscopy.
- Thorough investigation of H_2 and D_2 plasmas and the isotopic effect, e.g., on n_e, n_{H^-/D^-}, kT_{H^-/D^-}.
- Study of plasma–surface interactions (assessment of quartz, stainless steel, tungsten and tantalum surfaces).
- Exploring plasmas sustained in the pulsed mode.

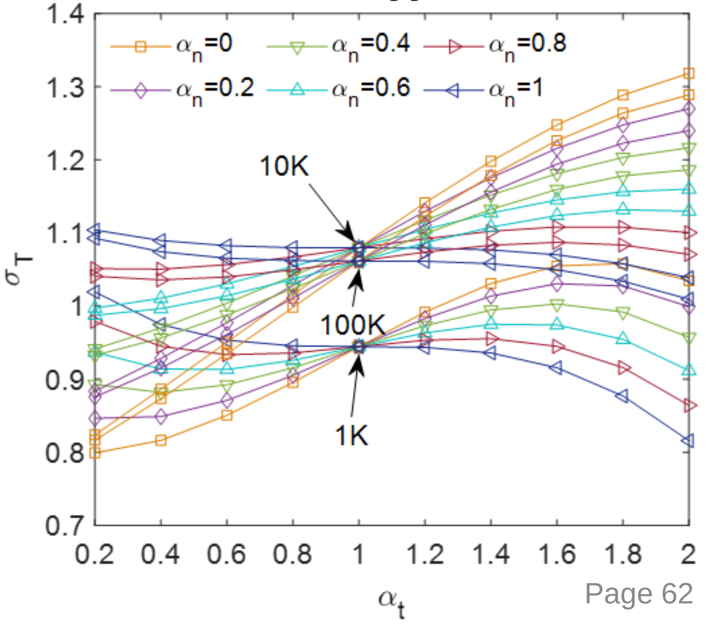
COLLABORATORS

UTH – WPTRED

Advanced boundary conditions and intermolecular potentials

- Advanced kinetic boundary conditions:
  - ➢ Numerical solution of the linearized Boltzmann equation (LBE) subject to realistic boundary conditions (RBC).
  - ➢ Pressure and temperature–driven flows.
  - ➢ Characterization of gas–surface interaction.
- Advanced intermolecular potentials:
  - ➢ Integration of ab initio (AI) potentials in kinetic modeling.
  - ➢ Quantum effects at cryogenic temperatures of light gases.
- Computation of valuable quantities in modeling of exhaust systems in fusion reactors:
  - ➢ Transport coefficients based on AI potential.
  - ➢ Velocity slip and temperature jump coefficients based on AI potential and RBC.





UTH – WPTRED

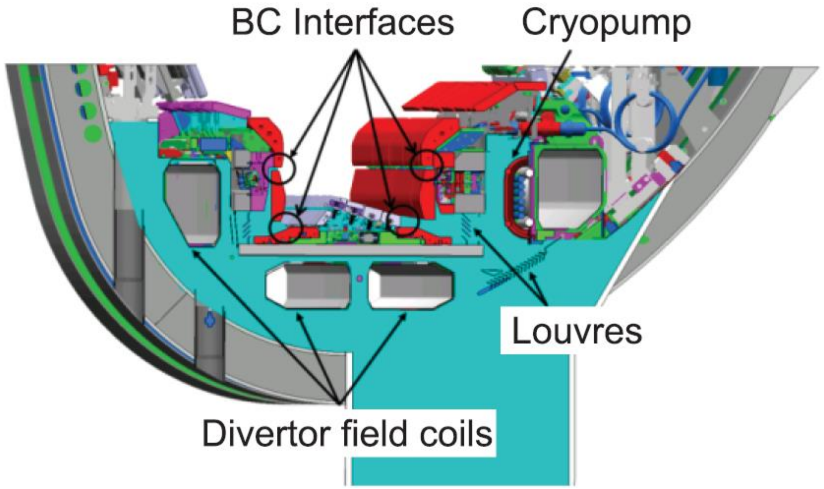
Rarefied gas pipe network analysis via kinetic theory

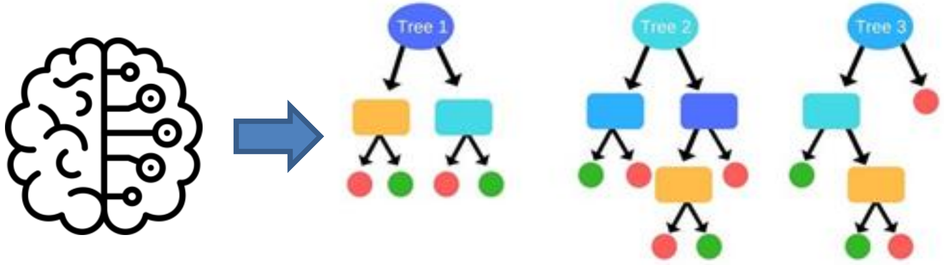
- The present work constitutes the first systematic and successful scientific effort in integrating the modeling gas flows through channels of various lengths and cross sections, under any vacuum conditions, in a unified gas pipe network solver.
- The in–house developed **A**lgorithm for **R**arefied gas flow **I**n **A**rbitrary **D**istribution **NE**tworks **(ARIADNE)** consists of the following main blocks:
  - ➢ Input of geometrical and operational data of the network through a graphical user interface.
  - ➢ Automated formulation of the governing equations describing the flow conditions of the distribution system.
  - ➢ Development and implementation of an adequate dense data base of kinetic results to be integrated into the network code.
  - ➢ Solution of the resulting system of equations.
- Several realistic fusion related networks have been simulated under various geometrical and flow configurations in order to estimate a) Gas flow paths, b) Pressure heads at the nodes, c) Flow rates/throughputs in the pipes, d) Backflow to plasma.

UTH – WPCR

Simulation of vacuum systems of JET/ITER; ML techniques

- Applicability of **ARIADNE** for simulating arbitrary large vacuum systems:
  - ➢ Simulation of the ITER divertor and lower port regions.
  - ➢ The same task is applied in JET torus pumping system, which is approximated by a network of nodes and piping elements.
- Machine learning (ML) techniques for computation of flow rates in rarefied gas flows through circular tubes:
  - ➢ Random Forest Regression (RFR).
  - ➢ Symbolic Regression (SR).
  - ➢ Drastically reduces computational effort, bypassing kinetic theory and modeling.
  - ➢ Formulation of dense kinetic database.

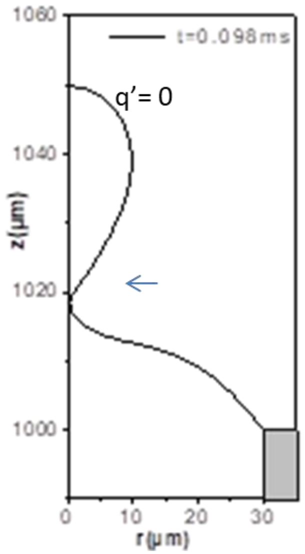


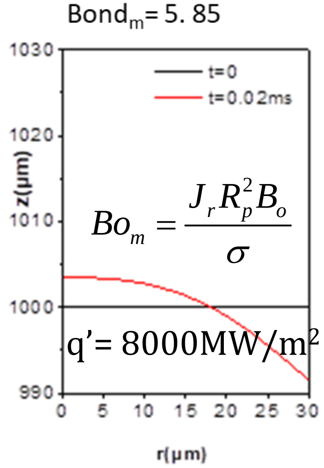


UTH – WPCR

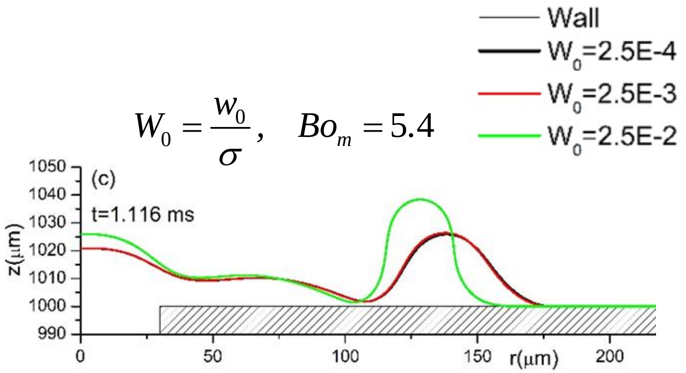
Modelling/simulation of MHD stability and spreading process on porous substrates

- Modelling of MHD stability of a liquid metal layer in a pore under high thermal/electric loading in high magnetic field environments:
  - ➢ Lorentz forces initiate drop ejection when capillarity is not strong enough to keep the liquid metal in the pore (large magnetic Bond).
  - ➢ Evaporation stabilizes the interface and prevents drop ejection as the pore region is depleted from liquid metal, especially for high thermal loads.





- Theoretical & numerical study of the spreading process of a liquid metal (e.g., lithium) on the walls of a Capillary Porous System (CPS) in the presence of adhesive and Lorentz forces:
  - ➢ A static solution with Bond magnetic Bo_m=0 is disturbed by increasing the oncoming electric current.
  - ➢ The liquid metal spreads across the wall of the CPS with a speed that increases as Bo_m increases and film steepening is exhibited.
  - ➢ As the wetting parameter W_0 increases the attractive force is more intense, spreading is decelerated and steepening is mitigated.



Contact persons for questions/cooperation

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Many thanks for your attention

Questions?