IFP in Fusion and related areas

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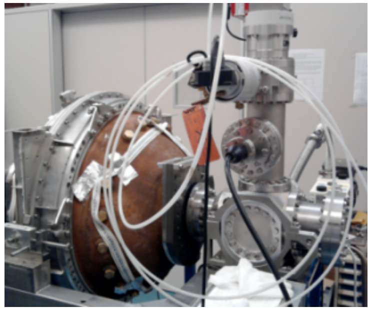
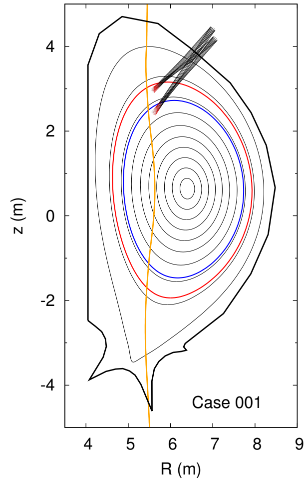
Physics & technologies for magnetic confinement fusion

(EUROfusion, F4E, ITER IO)

- ✓ Physics of EC waves (EC wave power Upper Launcher in ITER)
- ✓ Long term expertise in the design of ECRH systems
- ✓ Development of mm-wave passive components & tests
- ✓ Fusion Plasma Diagnostics: Neutron & γ-ray Spectroscopy, ECE, collective Thomson scattering, synchrotron emission analysis
- ✓ Dust in tokamaks
- ✓ Particle, energy & momentum transport studies in tokamaks
- ✓ JET, AUG, TCV, FTU exp. campaigns & data analysis
- ✓ Plasma Physics in future tokamaks: JT-60SA, DTT, ITER, DEMO

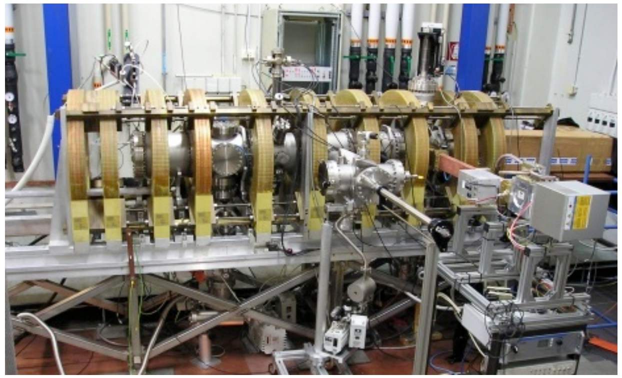




Linear plasma device GyM for plasma-material interaction studies

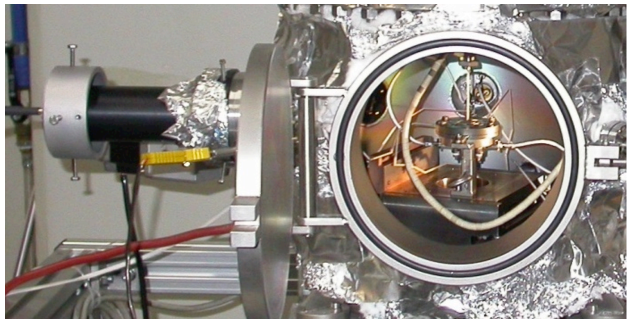
(EUROfusion)

- ✓ Surface erosion and fuel retention in plasma facing components
- ✓ Ammonia formation in N_2-seeded plasmas
- ✓ Basic plasma physics



Plasma applications to technological processes (Contracts)

- ✓ Deposition of thin films and surface modifications by PECVD and magnetron sputtering
- ✓ Deposition of diamond films by plasma micro-torch
- ✓ Surface analyses by XPS, SIMS, FT-IR, AFM
- ✓ Atmospheric plasmas for antimicrobial applications



Plasma theory and modelling

IFP is engaged in theory & modeling of fusion plasmas (FTU, TCV, AUG, ITER, DTT, DEMO)

- **Propagation of RF Gaussian beams** at electron cyclotron frequencies (30-170 GHz) in high temperature tokamak plasmas (1-30 keV)

- <u>Goal:</u> plasma heating and **non-inductive current generation**
- <u>Framework:</u> WKB propagation, wave dispersion in anisotropic medium, quasilinear plasma response

- **Magnetohydrodynamic (MHD) instability** analysis in tokamak plasmas

- <u>Goal:</u> plasma instability control
- <u>Framework:</u> MHD theory, 0D analysis with physics stabilizing actuators

- **Heat, particle & momentum transport** in fusion plasmas

- <u>Goal:</u> effect of «electron» instabilities on energy confinement & associated **plasma potential fluctuations**
- <u>Framework:</u> gyro-kinetic simulations (HPC)

- **RF assisted plasma breakdown**

- <u>Goal:</u> simulation of plasma startup
- <u>Framework:</u> 0D fluid plasma model, ionization processes

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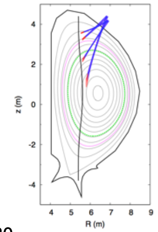

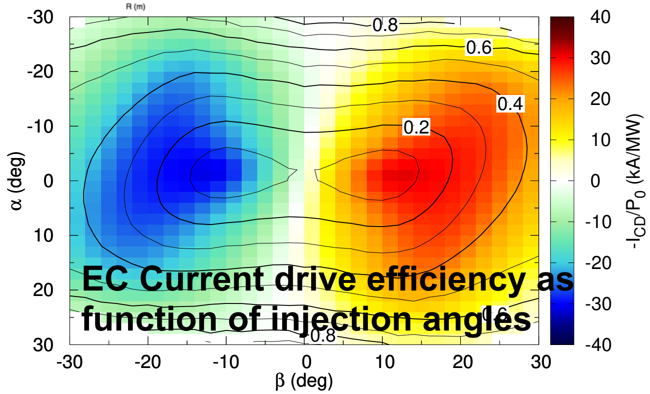

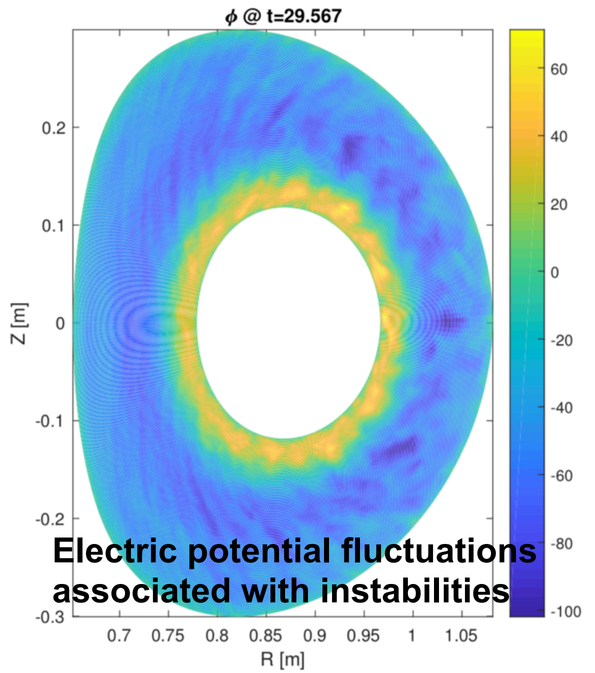

JET experiments & data analysis

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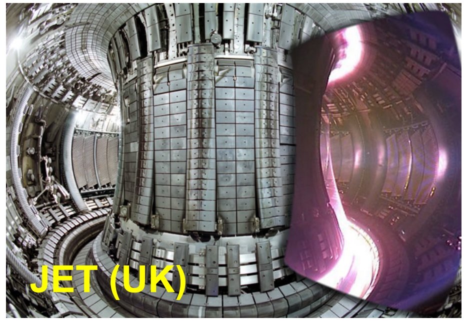
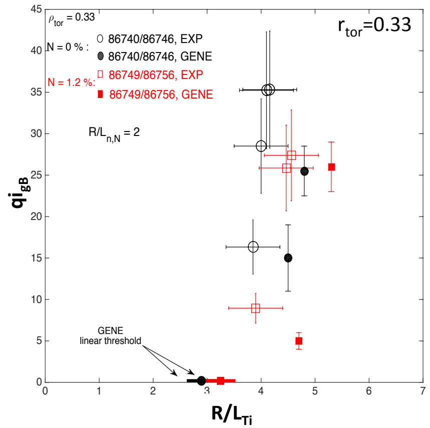
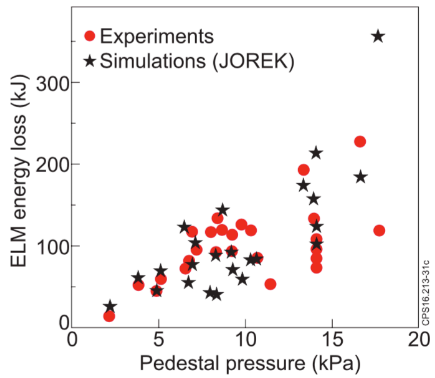
IFP is deeply involved into the preparation, execution and data analysis of experimental campaigns in **JET**:

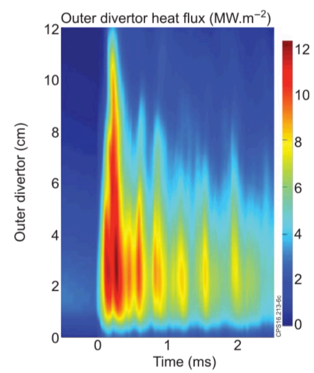


- Data analysis and modeling by means of advanced transport codes (ASTRA, JETTO, CRONOS) and empirical and first-principle based models (GLF23, TGLF, QLK)
- Gyro-kinetics flux-tube simulations (GENE, GKW): linear and non-linear, single-scale and multi-scale
- The analyses cover the electron and ion heat transport, bulk plasma and impurity density transport, and plasma momentum transport
- Neo-Tearing Mode analysis in JET discharges in H-mode with NBI and ICRH heating. Transport in presence of magnetic islands.
- MHD modeling of Edge Localized Modes
- Disruption and runaway electron modeling



Ion heat flux vs T_i gradient





Medium Size Tokamak experiments

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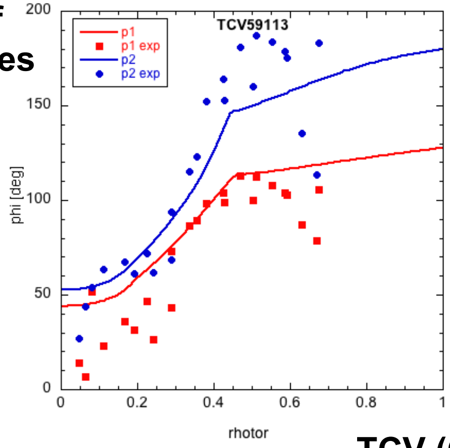
IFP is deeply involved into the MST-1 European programme, with proposals for experiments and participation to the experimental campaigns in AUG, TCV and WEST tokamak devices in the following subjects:

- **Transport related activities**
  - **Confinement scenarios and transport studies**
  - Dimensionless ρ* and β scaling of confinement and turbulence in standard and improved regimes
  - Bulk ion heating with ^{3}He heating

Exp. vs numerical simul. of electron temperature profiles

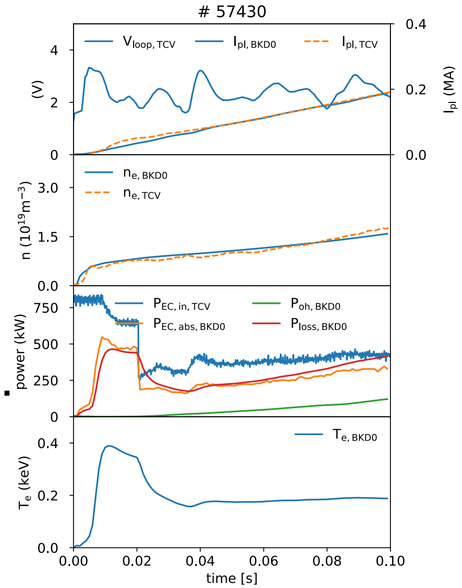


TCV (CH)

- **ECRH related activities**
  - Magneto hydrodynamic instabilities (NTM) onset mechanisms
  - NTM control using Electron Cyclotron waves injection
  - Disruption Avoidance techniques development
  - **Plasma start-up with Electron Cyclotron waves assistance**
  - Wall Cleaning experiments using Electron Cyclotron waves

- **Fast ions related activities**
  - Off-axis neutral beam current drive
  - Effects of plasma instabilities on fast ions

Exp. vs numerical simul. of EC assisted start-up



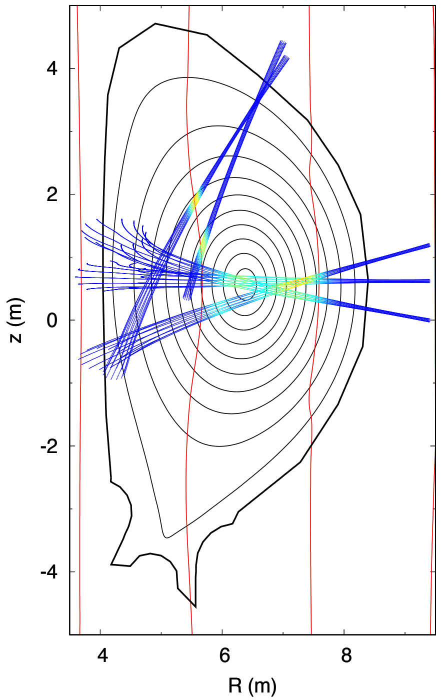
EC waves physics and technology

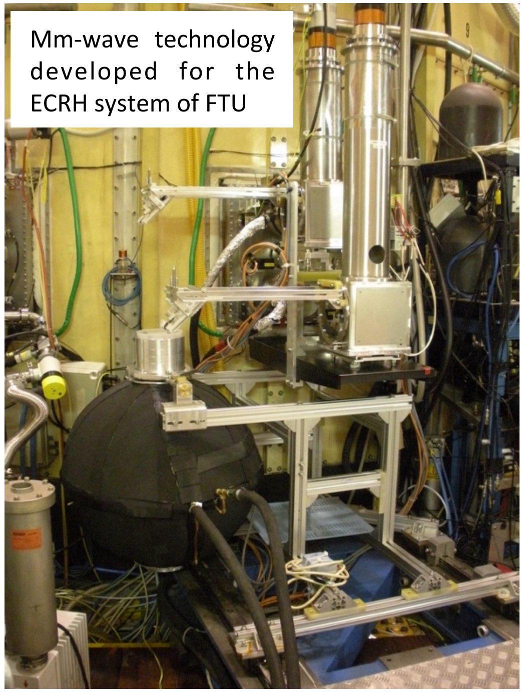
Electron Cyclotron (EC) waves give energy to electrons when electron oscillation and microwave frequency matches.

IFP has wide experience on basic theory and numerical modeling of EC waves in magnetized plasmas: heating, current drive, plasma control and stabilization, EC-wave based diagnostics

To inject high power (~ MW) EC wave several studies and components are required, and this broad spectrum of IFP expertise is certified

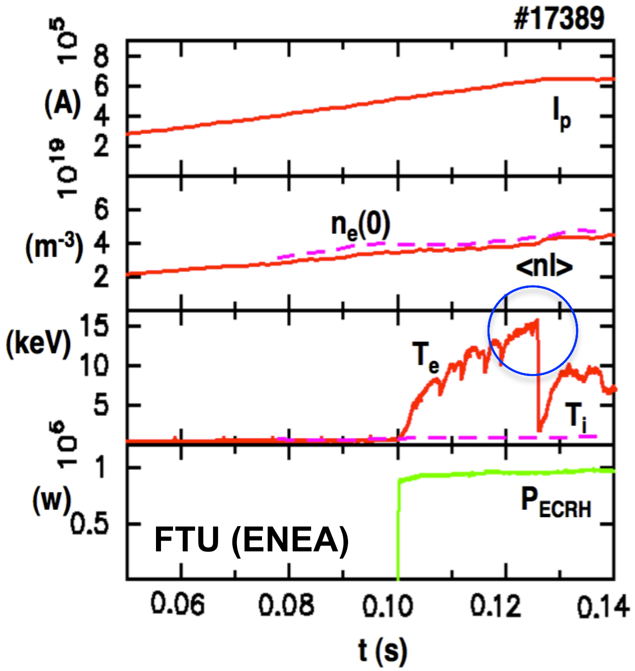
Codes and tools for EC waves propagation studies





Mm-wave technology developed for the ECRH system of FTU

Large variety of experiments performed for plasma heating



ECRH systems

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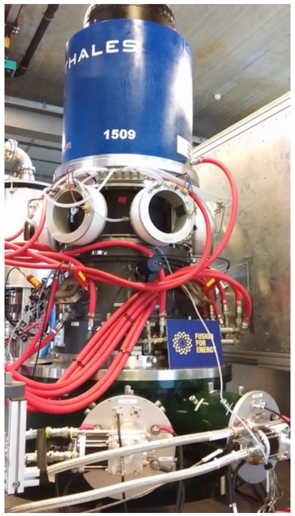
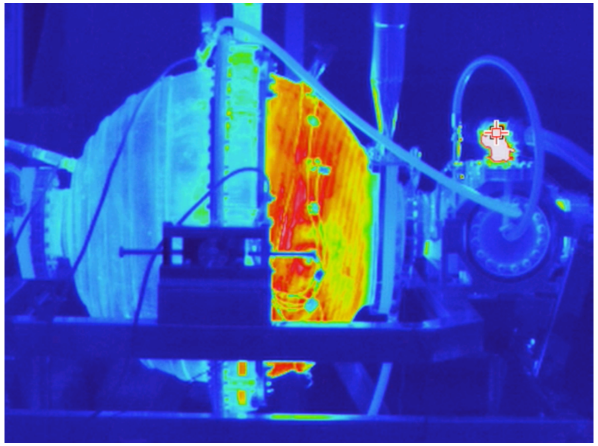
IFP participates in the exploitation and in the design of multi-MW ECRH systems for present (FTU, TCV) and future devices (ITER, DEMO, JT60-SA, DTT) covering all the related mm-wave aspects and components. Standard and innovative solutions are pursued.

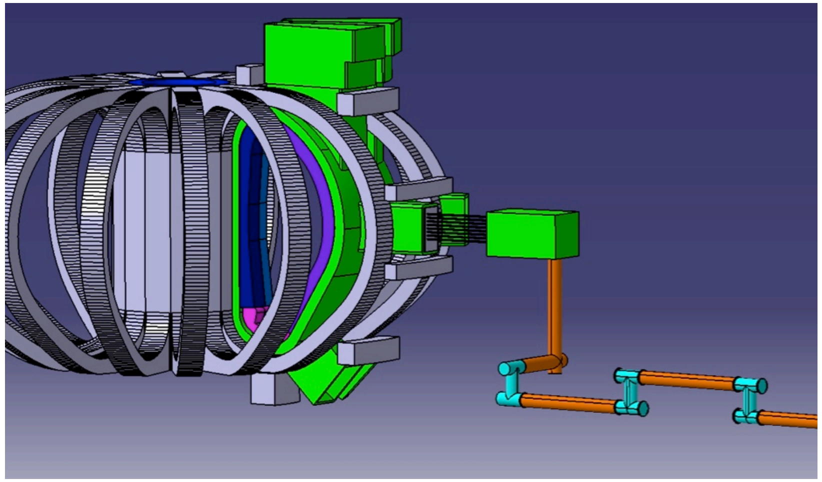
Electron Cyclotron Resonance Heating System components: power source (gyrotron), transmission lines, launcher, control systems:



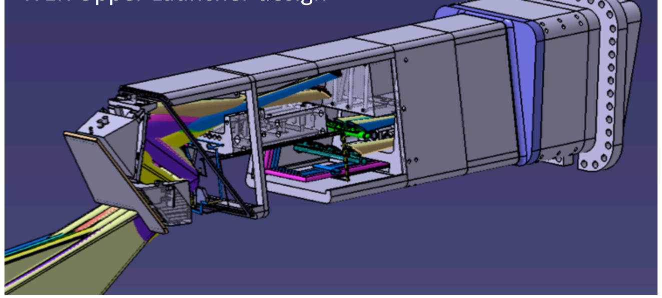
Testing prototype components and concepts for ITER (gyrotron and dummy load for high power operations)



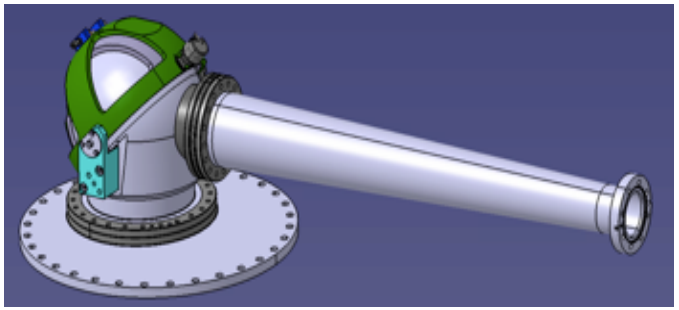
Conceptual design for DEMO reactor transmission line

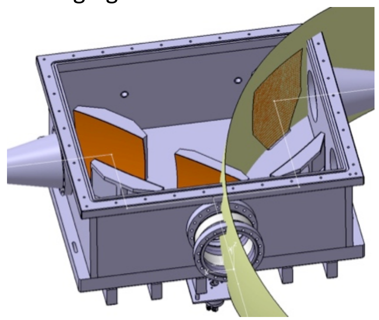


ITER Upper Launcher design



Launcher and matching optics components desging for TCV tokamak





GyM: for plasma turbulence studies

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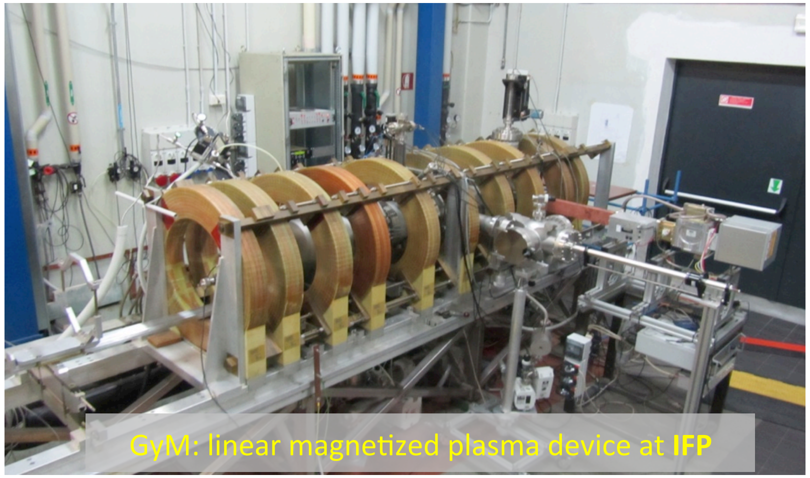
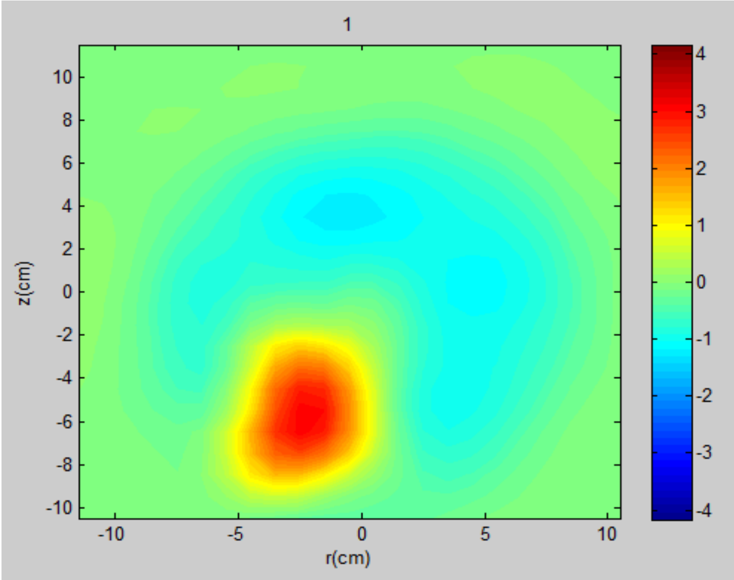


Vacuum chamber	length 211 cm
	radius 25 cm
Plasma production	Magnetron, ECRH in OM
	2.45 GHz, 3 kW-CW
Plasma parameters	Column length/diam: 200/3.4-20 cm
	B peak value on-axis: 0.13 T
	Plasma species: H_2, He, Ar
	Electron temperature (T_e): 2-5 eV
	Electron density (n_e): $10^{16} – 10^{17}$ m^{-3}



Fast Camera + Image Intensifier (× 10000) shared between Torpex (Swiss Plasma Center, CRPP-Lausanne) and GyM (IFP):

- **resolution: 1024 × 1024 pixel, up to 3000 fps**
- **pixel dimensions: 17×17µm**
- **max recording speed: 250,000 fps**
- **6 seconds of recording at 1000 fps**

Sample exposure to Gym plasma

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RESULTS

Sample FeW/Si - exposure to GYM D plasma:

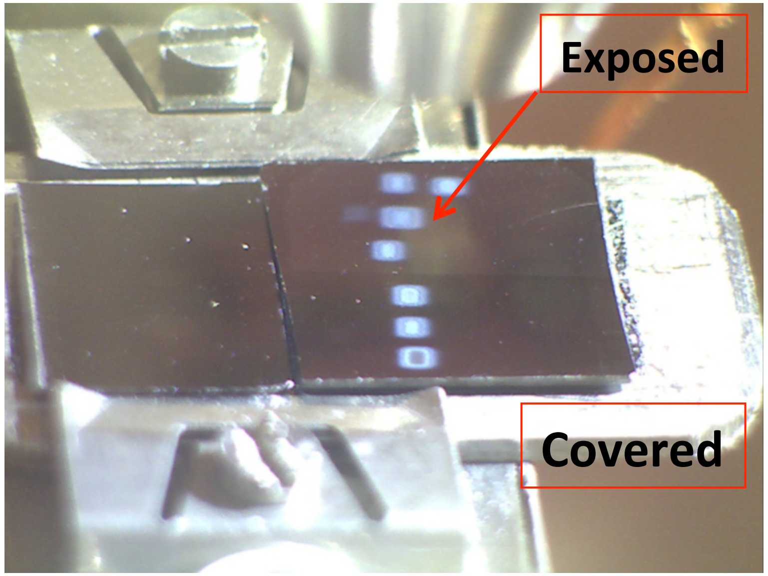
Flux: 3.0 E 20

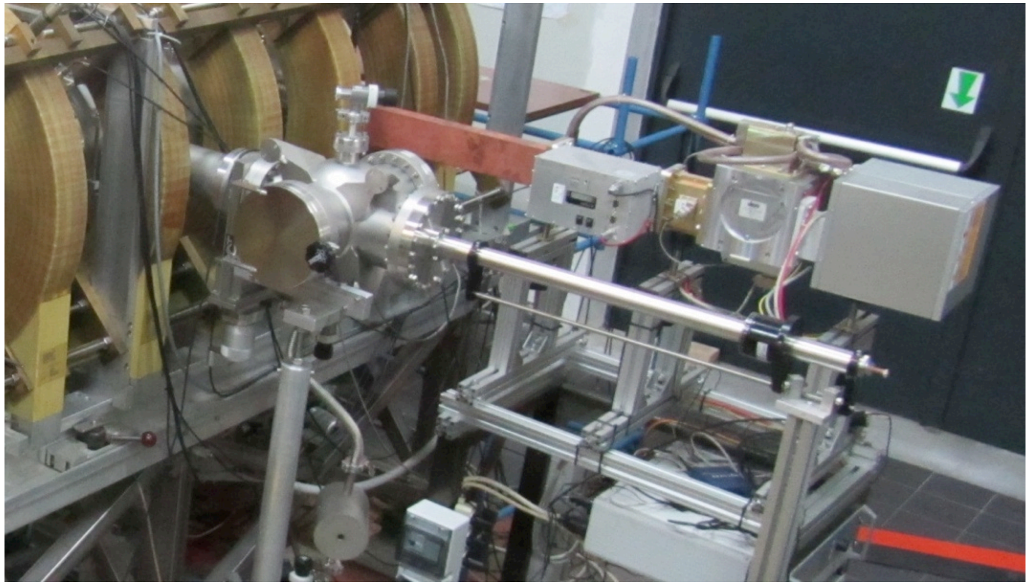
Expos. Time: 90 min

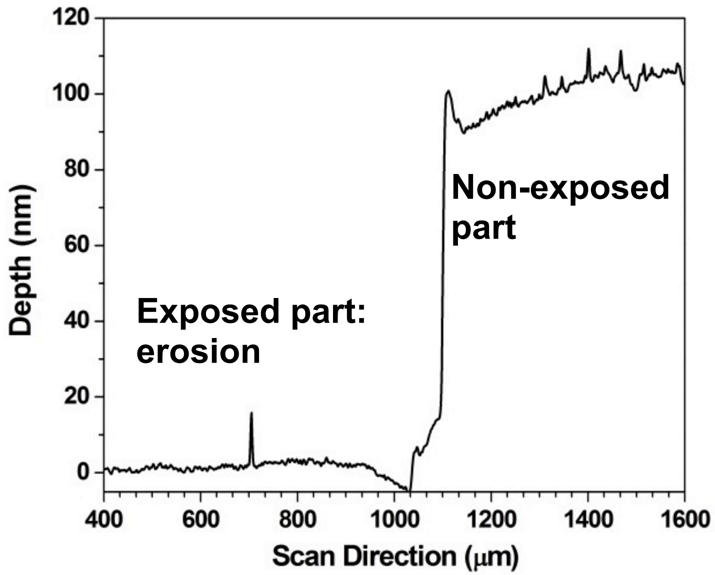
D flux: 22 sccm

$T_{substrate}$ = 200 °C

$V_{substrate}$ = 300 V







IFP contribution to JT-60SA

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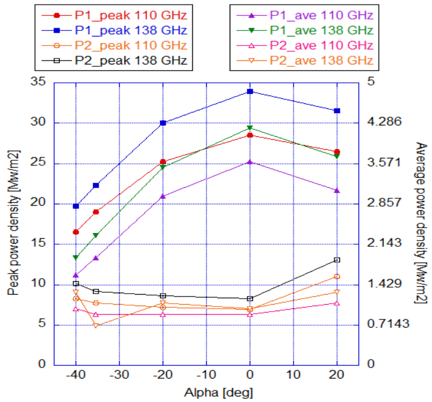
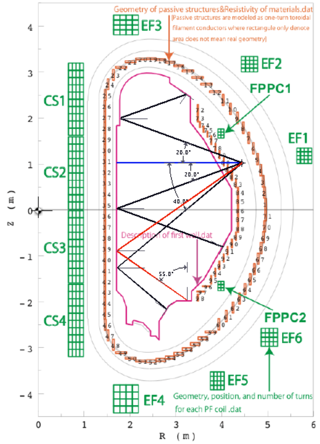
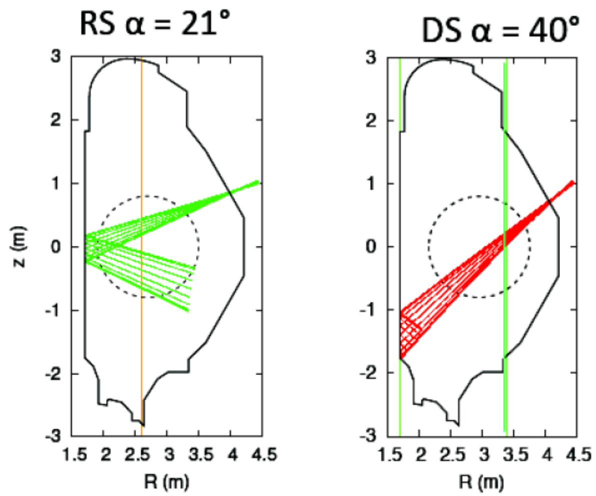
IFP contributes to the implementation of a few sub-systems for the Japanese ITER-satellite tokamak JT-60SA:



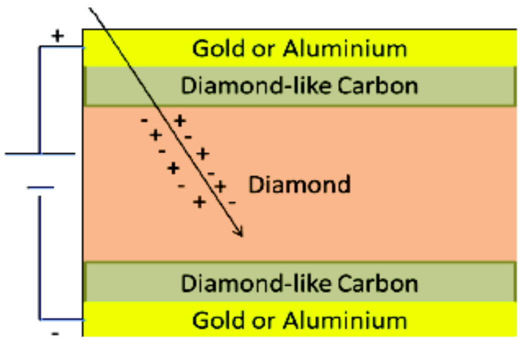


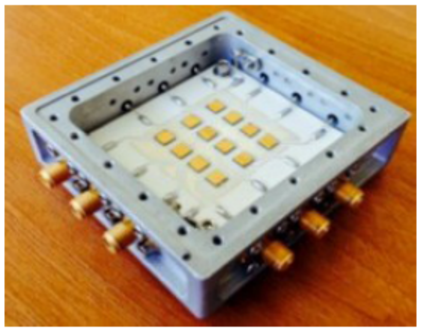
- **ECRF stray system for machine protection**
  Evaluation of stray level in low absorption scenarios and wall loads → special kinds of experiments/ operation: EC assisted breakdown and EC wall conditioning



- **Design of ECRF antenna**
  Electromagnetic calculations of mm-wave beams from source to reflectors for power absorption and driven current computations → NTM control and EC-assisted breakdown

- **Development of Fast Ion Losses Detector**
  Analysis in time and velocity-space of non-confined fast ions





Also:

- **Procurement of bolometric loads**
  → see next slide

Bolometric loads for ECRH systems

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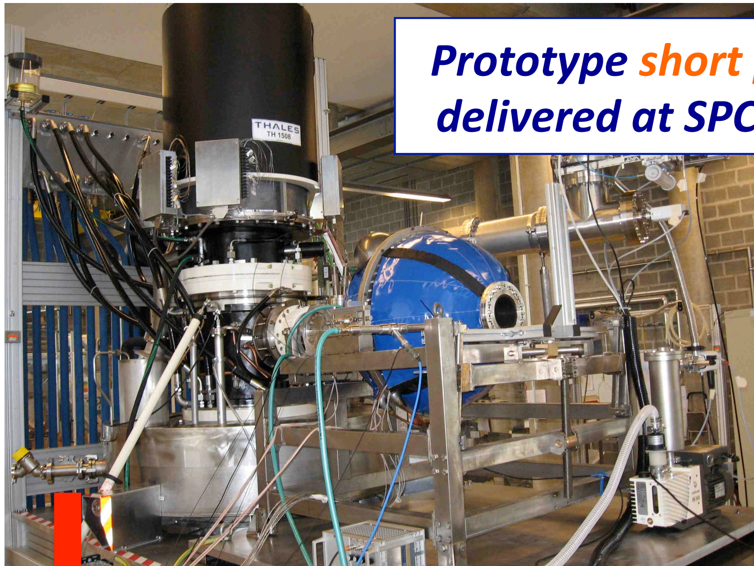
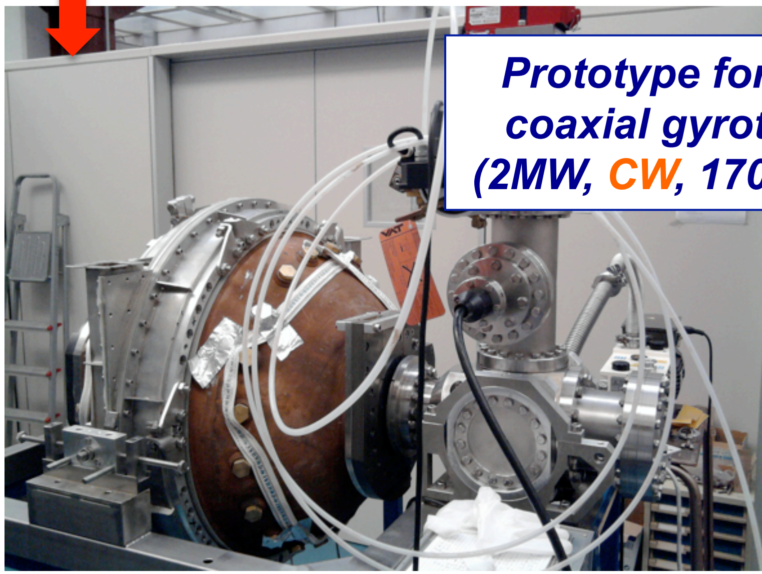
IFP is member of the EU Consortium EGYC holder of the F4E *Grant* for the development of the ITER gyrotron

Prototype short pulse delivered at IPP-Garching



Prototype short pulse delivered at SPC (CH)



Prototype for EU coaxial gyrotron (2MW, CW, 170GHz)

- 15 years of R&D on loads
- installed in FTU (ENEA), AUG (IPP-Garching), JT-60SA (QST-Naka)
- load for the EU gyrotron test-bed (SPC)
- ambitious goal: procurement of the loads for the ITER ECRH system

Micro-plasma jet

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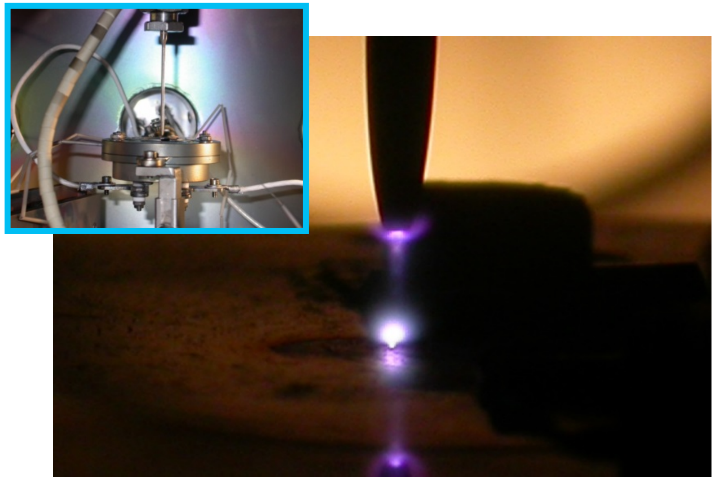
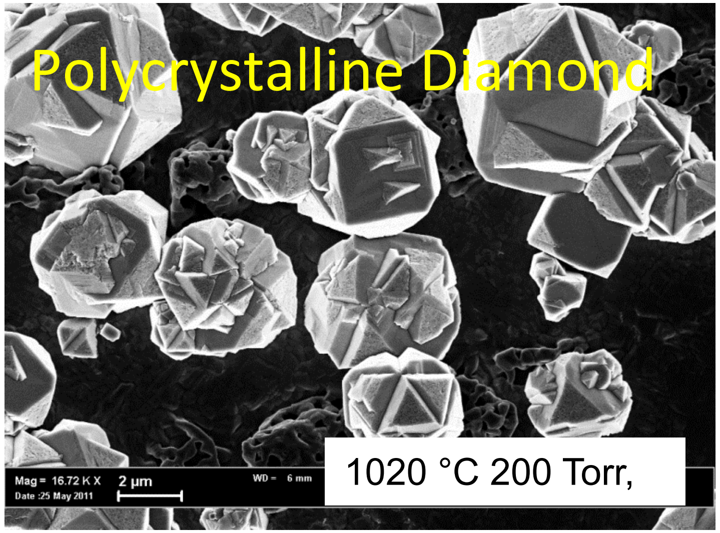
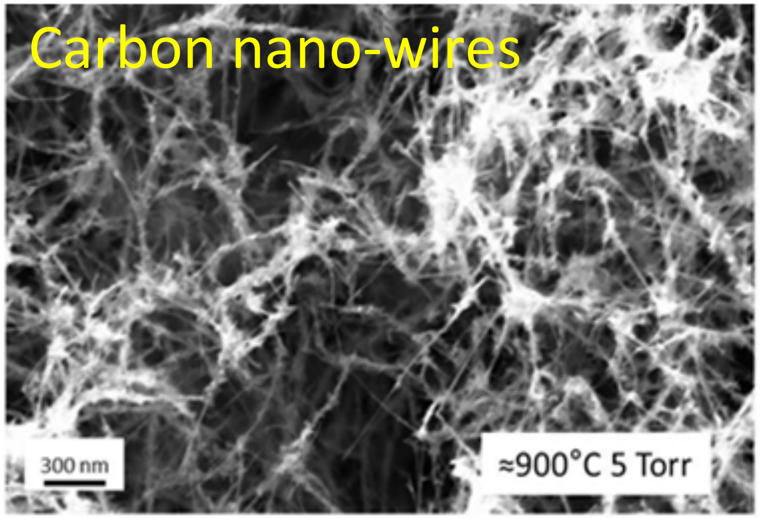
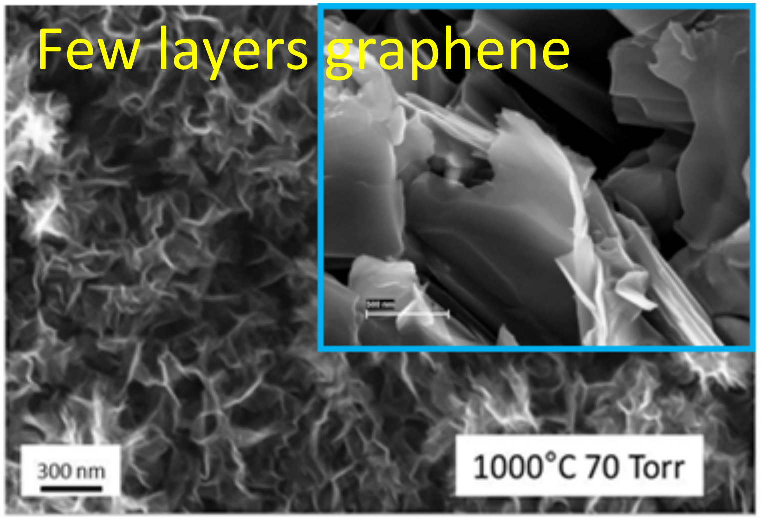


Microhollow cathode plasma discharge
Gas: H_2, CH_4

IFP







Thin layer deposition of *diamond-like* C to develop neutron detectors

Plasma diagnostics

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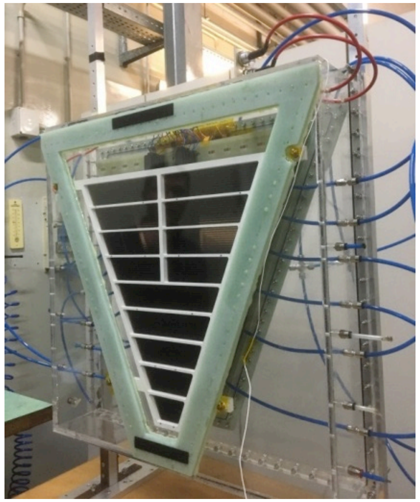
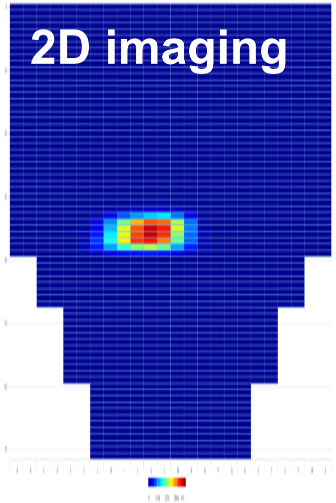
Soft X-Ray imaging with GEM detectors



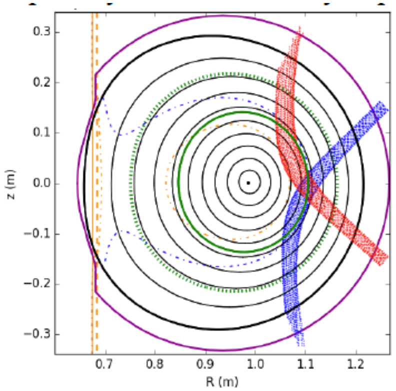


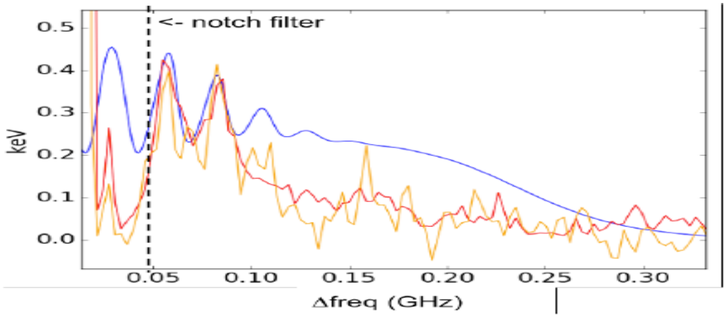
Detection of neutrons and gamma-rays escaping the plasma.

Applications:

- Monitoring
- Real Time Control
- Physics studies

Collective Thomson Scattering

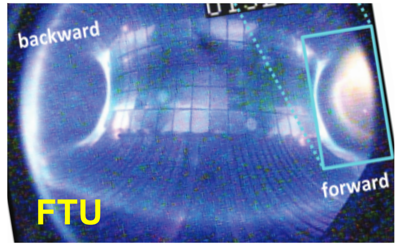


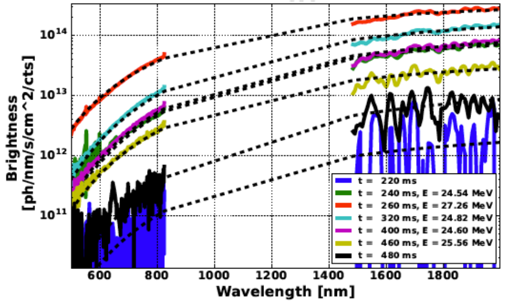


Detection of scattered GHz-frequency electromagnetic waves

Applications: Physics studies

Runaway Electrons Imaging and Spectral analysis





Detection of runaway electron beam images & synchrotron emission spectra

Applications:

- Monitoring
- Real Time Control
- Physics studies

Plasma diagnostics

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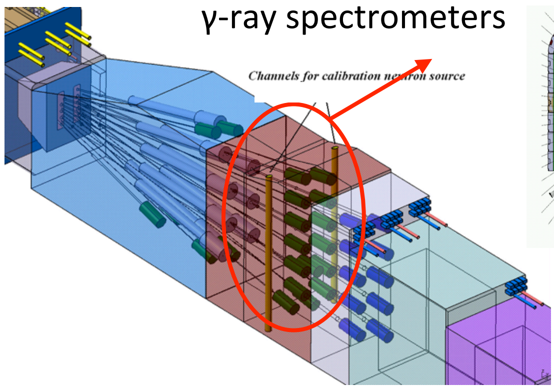
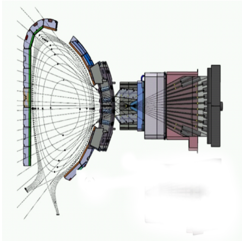
Neutron & γ-ray spectroscopy for JET & ITER



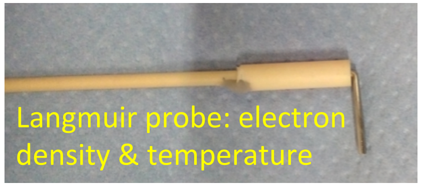


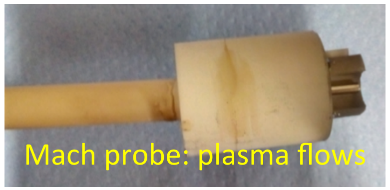
Detection of neutrons and gamma-rays escaping the plasma.
Applications:

- Monitoring
- Real Time Control
- Physics studies

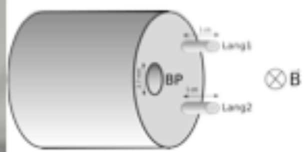
ITER Radial Neutron Camera with gamma ray spectrometers

Electrostatic probes for laboratory plasmas





Ball pen probe: plasma potential

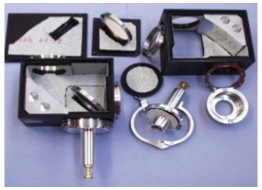


Measurements of electron density, temperature, plasma flows & potential. **Applications:** Physics studies

µ-wave diagnostics

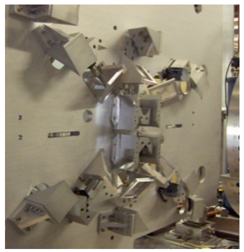
Reflectometry to determine (ITER) plasma position, electron cyclotron radiation (ECE) to determine electron distribution function, measure of CMB in Planck
Applications:

- Monitoring
- Real Time Control
- Physics studies



test of Low-Frequency Instrument

designed and built



Plasma-materials interaction

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IFP carries out activities on the interaction between plasmas and material surfaces (metal, liquid metals, biological substances, various elements):

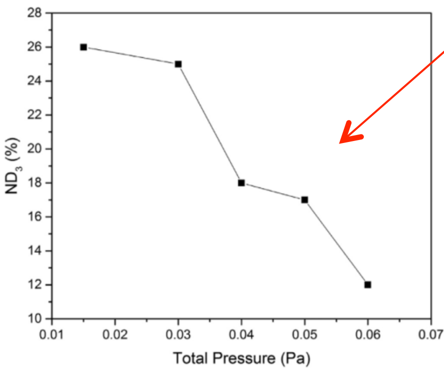
Liquid metal layer protects fusion reactor wall against high heat loads

Due to the high heat loads, solid PFCs in fusion devices will be subject to damages.
Liquid Metals (LMs) are known to be a viable alternative to solid PFCs in laboratory experiments.
However retention properties of LMs need to be clarified.
Samples of liquid Sn have been exposed to D_2 plasma to a 10^{24} m^{-2} fluence in GyM device. D retention, studied with Nuclear Reaction Analysis and Elastic Recoil Detection Analysis, turns out to be negligible. D content in the samples expressed as retained fraction ($D_{retained}/D_{incident}$) is of the order of 10^{-5}

Free liquid Sn exposed to plasma

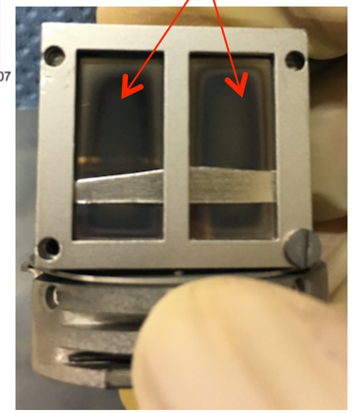
Mitigation of power loads on the divertor plates by N_2 seeding

N_2 used to reduce the power load onto the divertor plates has the drawback of ammonia (NH_3) formation. In a reactor NT_3 could appear.
A study of the production of ND_3 as a function of the electron temperature and neutral pressure in a N_2/D_2 plasma mixture in the linear plasma device Gym was studied.
The ND_3 produced during experiments has been quantified by an in-line LN_2 trap, Liquid Ion Chromatography and Optical Emission Spectroscopy.
ND_3 was formed only during plasma phase. He addition to the N_2-seeded D plasma reduces ammonia by 80%, without modifying plasma parameters.



Ammonia conversion as a function of the total neutral pressure of D-N plasma.

Exposed Eurofer-97 samples



Study of the erosion of Eurofer-97 steels with the linear plasma machine GyM

In future nuclear fusion power plants, bare reduced activation ferritic martensitic (RAFM) steels, like Eurofer-97, are possible candidate for the highly eroded recessed elements of the first wall.
An experimental study of the erosion of Eurofer-97 steel samples exposed to the deuterium plasma of GyM at different temperatures and ion fluences is carried out.
After exposure, the samples are deeply characterized by profilometry, RBS, XPS, LEIS, AFM, SEM and PIXE.

Plasma-materials interaction

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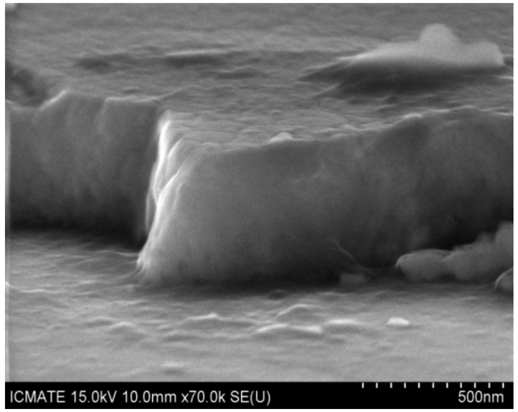
Nanomaterials for energy applications

Development of advanced semiconductor materials (thin films, textured coatings) for low power electronics with a focus on renewable energy (*I-ZEB project).*

Bismuth vanadate coatings ($BiVO_4$) are produced by plasma sputtering deposition technology using a Ar/ O_2 mixture with bismuth oxide and vanadium targets.

Coatings composed mainly of monoclinic phase are obtained by optimizing the power density supplied to targets.

Energy Dispersive X-ray Spectrometry measurements show an atomic % for Bi, V and O of 16.9, 16.7 and 66.3, respectively (≈1:1:4). Coatings show a dense, uniform, and smooth structure (at Scanning Electron Microscopy) with a band gap of the order of 2.4 eV.

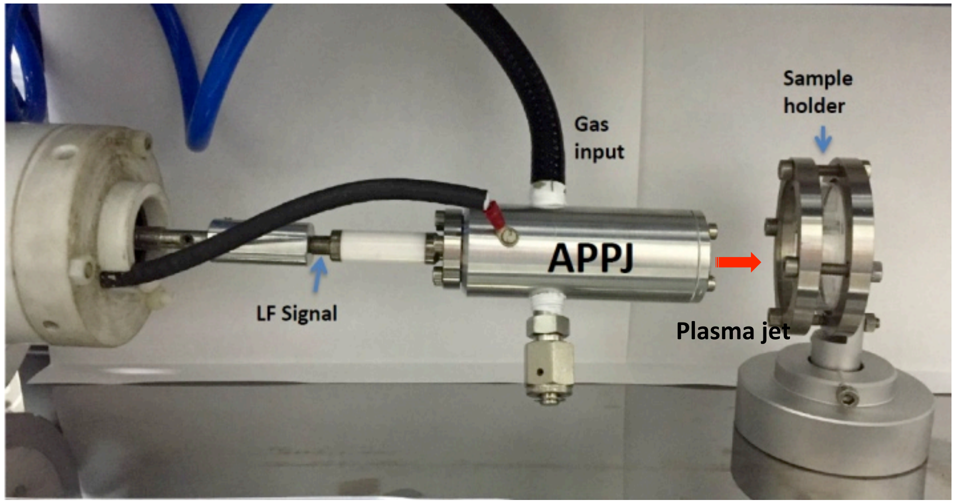


SEM image (ICMATE Milano Lab)

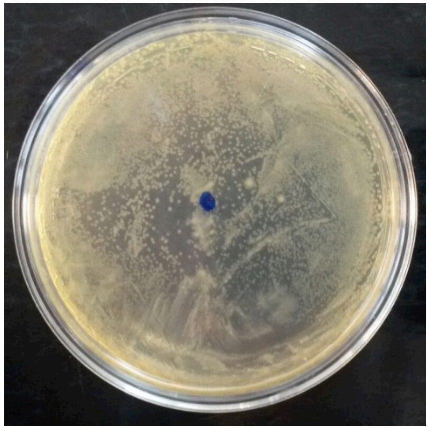
Sterilization/decontamination of materials by plasma methods

The plasma can be used as an effective tool to sterilize and decontaminate surfaces without damaging them, or can be used to produce surfaces with bactericidal activity.

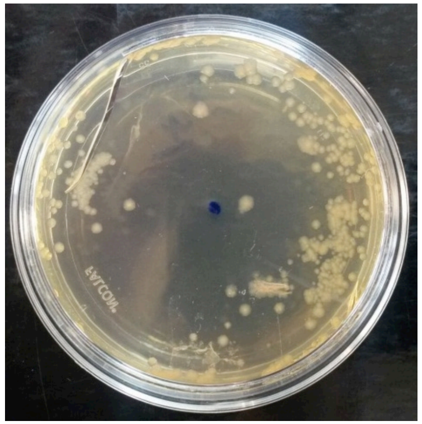
A significant microbial reduction of *E. Coli* was achieved within 60 s of air plasma treatment. This result was related to the presence in the plasma volume of reactive species, in particular O radicals (*Kenosistec project*).



Bacteria inactivation by Atmospheric Pressure Plasma Jet (APPJ) treatment



Bacterium E. Coli 5.000.000 CFU/5µl before plasma treatment



After 30 sec of plasma treatment

Education & Training

Consiglio Nazionale delle Ricerche
Engineering, ICT and Technologies for Energy and Trasportation Department

Every year **IFP** is committed in the following E&T initatives:
- Lectures and Courses in Undergraduate/PhD/Master Programs, ~ 120 students
- 2 OPEN DAYS (lectures and visit to laboratories) for university and high-schools: ~ approx. 150 students
- School-job turnover for high school student: two weeeks in our labs (10 students)
- Participation to FUSENET programme (http://www.fusenet.eu/)

IFP presently employs 15 young researchers and post-docs under fixed-term contracts for training in the priority areas of fusion programme


OPEN DAY at IFP


Educational home-made experimental device for plasma generation and testing has been assembled


Work-linked training project at IFP

Dissemination

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IFP participates successfully to the *MeetMeTonight festival* (the Milan edition of the *European Researcher's Night*)
in a central location hosting many groups from Universities and Research Centers.

IFP delivers lectures in Secondary Schools on Energy and Fusion:
~ 100 students per year

IFP appears in Social Media
https://it-it.facebook.com/IFPCNR/