Italian National Agency for New Technologies, Energy and Sustainable Economic Development

External collaborations

RF group - Lab. SDL

WIP, 07/02/2022

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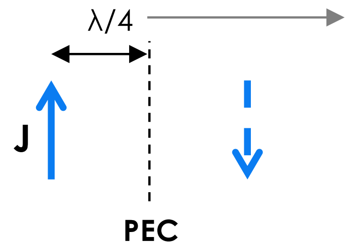
Outline

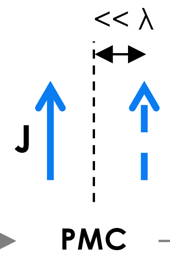
- Ion Cyclotron Resonance Heating (ICRH)
- Lower Hybrid & Current Drive (LHCD)
- Electron cyclotron resonance heating (ECRH)

ICRH antenna with high impedance surface

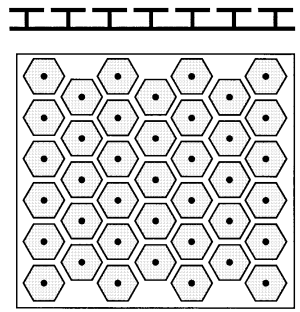
- Basics of antenna theory:



impossible in tokamaks if λ ≈ 5 m, need of a high impedance surface (HIS), i.e. of a perfect magnetic conductor

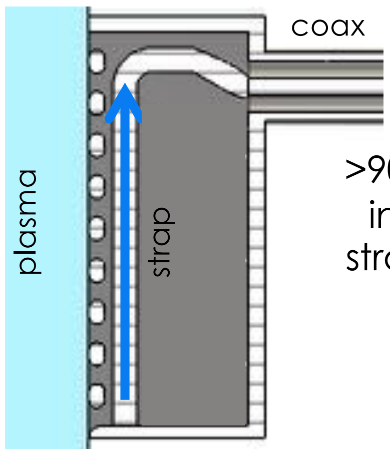


e.g.

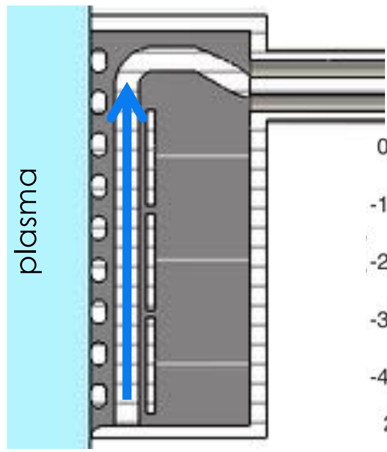


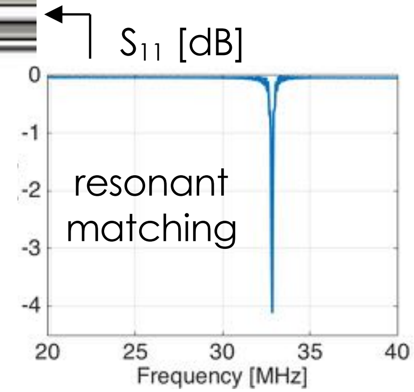
Sievenpiper et al., IEEE T-MTT 47-11 (1999), 2059

- ICRH antennas:



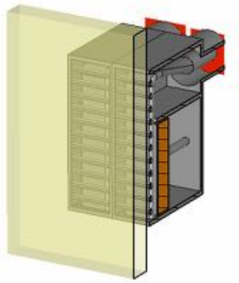
>90% reflection in traditional strap antennas

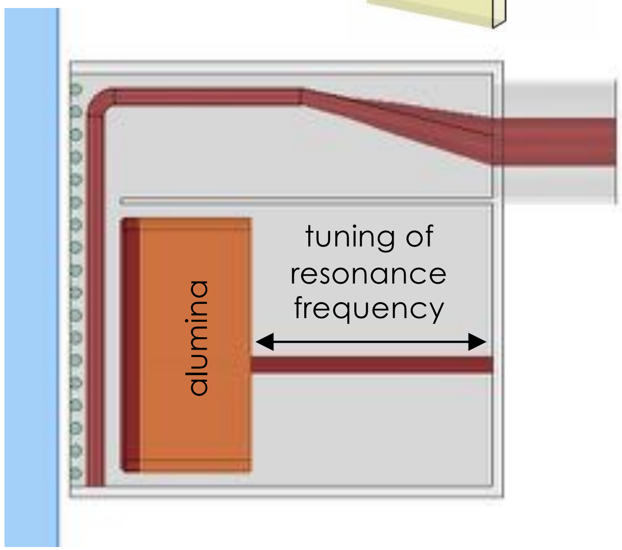




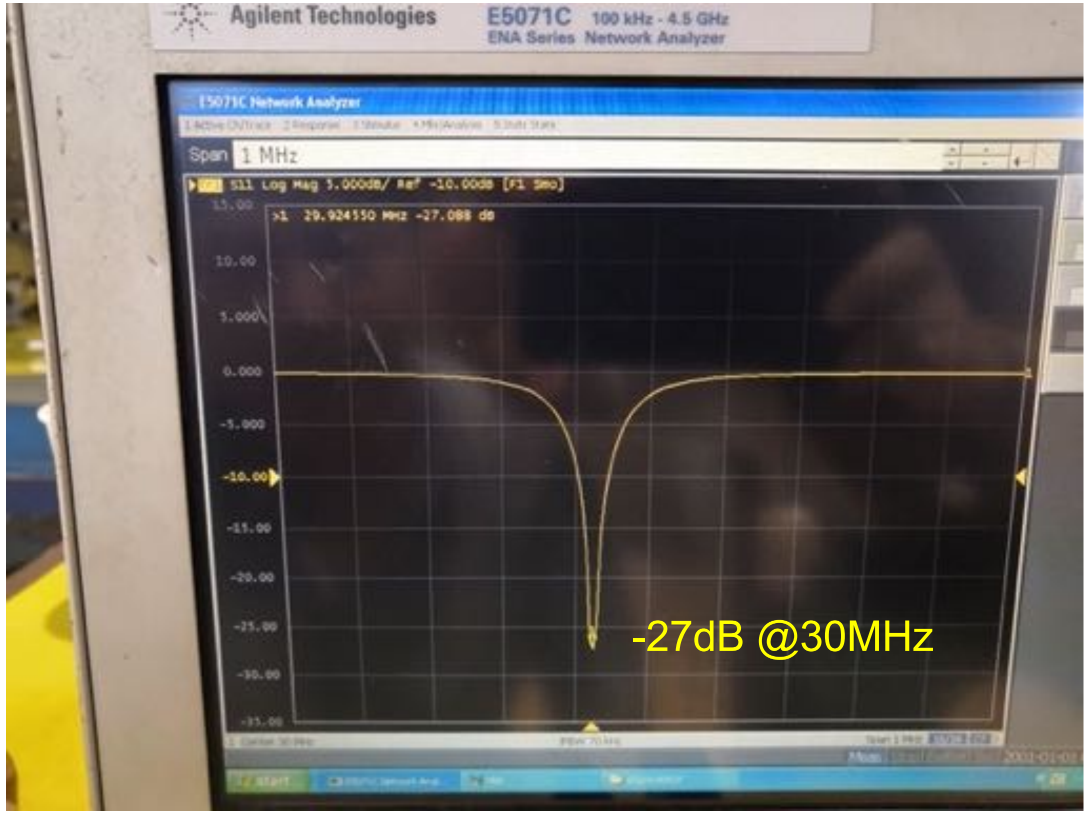
HIS antenna in collaboration with Polito and ASIPP

- EAST mockup:





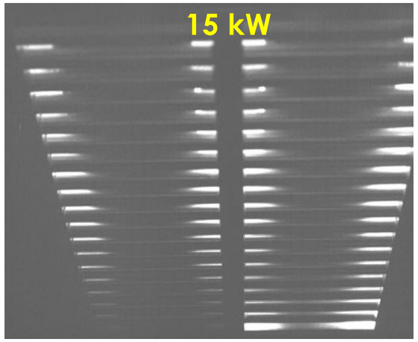
- Low power tests (Sept. 2018):

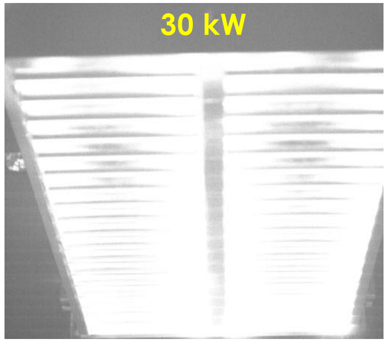


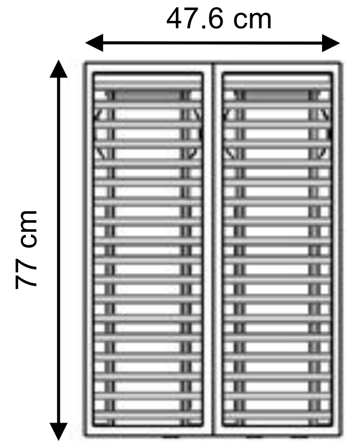
High power tests

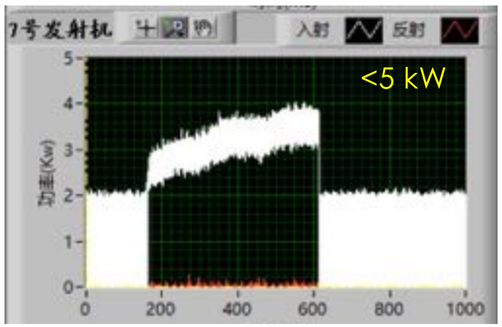
- High power tests (Nov. 2018):

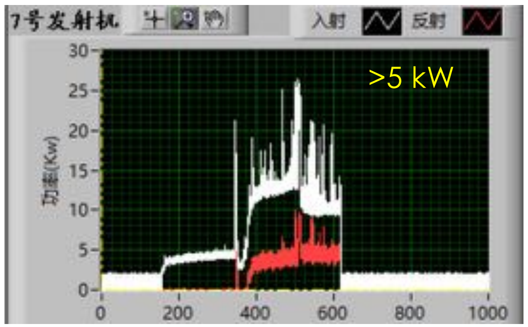
visible fast camera looking at antenna front

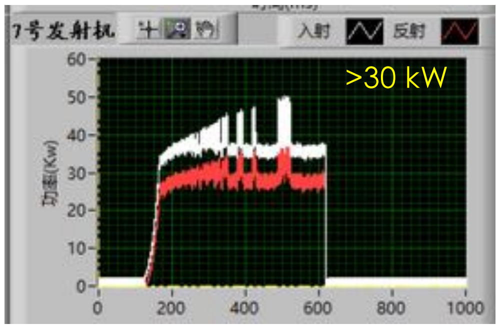










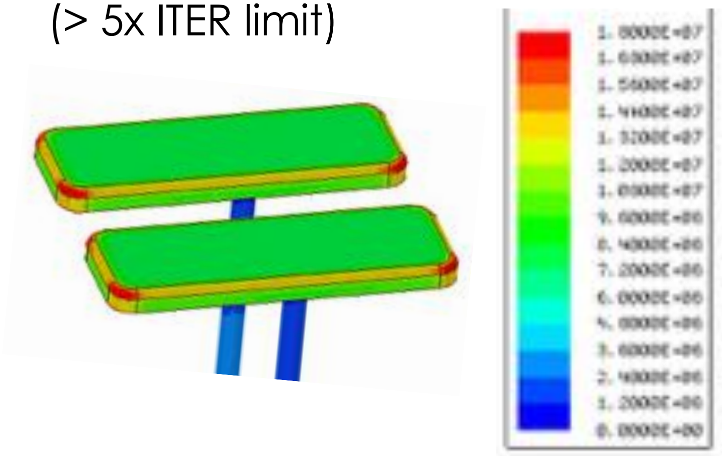


white = forward power

red = reflected power

Traces of electrical arcing

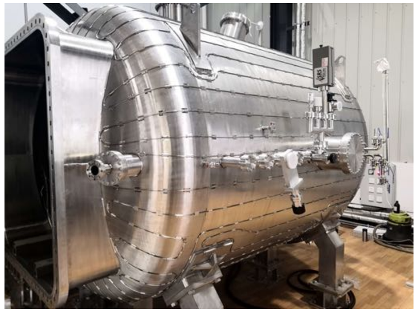
- Predicted E-fields are indeed high (> 5x ITER limit)



But also testing conditions were not optimal (no baking, cleaning of vacuum chamber, …) and arcing position suggests the presence of volume with trapped air at contact surfaces of alumina parts.

Design improvements

- Two antennas have been manufactured and tested respectively in May 2019 and Nov. 2019 with the following improvements:
  - baking of vacuum chamber and antennas:



  - better vacuum pumping (in coaxial feeders and on the rear part of the antenna;
  - single alumina block instead of three;
  - one traditional and one HIS strap on the same antenna to compare their behaviour;
  - thinner metal cap of the high impedance surface, made by copper coating in the second antenna improvement:

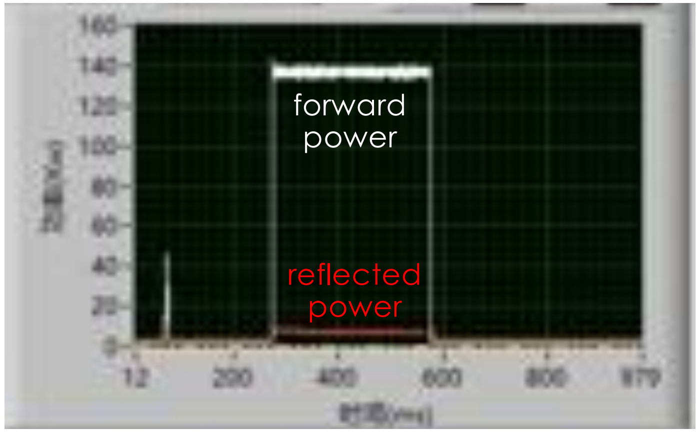
HIS of May 2019

HIS of Nov. 2019

Last tests

- Traditional strap with matching network works as expected:

40kW @39.74MHz, 500ms pulse length



- HIS strap still presented arcing:

Best shot: 39.775 MHz, 35 kW, 100 ms. with no sparking and almost zero reflection at generators.

After increasing the pulse length to 200 ms, arcing occurred again with no chance to have good performance again => damages

- No further progress on this topic.
- Polito proposed a HIS antenna without alumina for DTT

Design of oversized microwave components

SPECIFIC TOPICS OF COOPERATION

Between

IPR, GANDHINAGAR, INDIA

And

ENEA, FRASCATI, ITALY

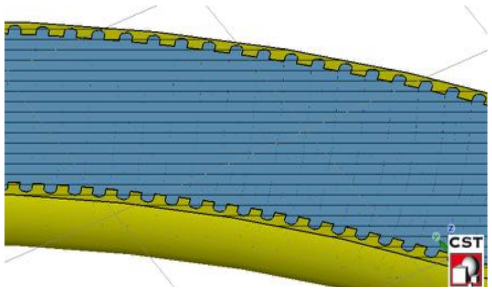
For

THE DEVELOPMENT OF OVERSIZED COMPONENTS FOR TRANSMISSION LINES OF A REACTOR RELEVANT LHCD SYSTEM

YEAR 2015

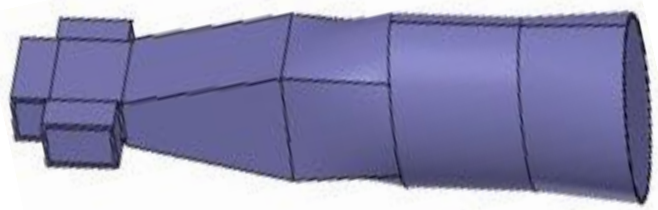
RF design	Fabrication of Corrugated Bend + 2 convertors	Providing Testbed (excluding cost of klystron operation)
< 1k€	50k€ (Al) or 60k€ (ETP Cu)	15 k€
ENEA	**IPR**	**CEA**

corrugated bend in circular waveguide for the TE_{01} mode



designed by S. Ceccuzzi

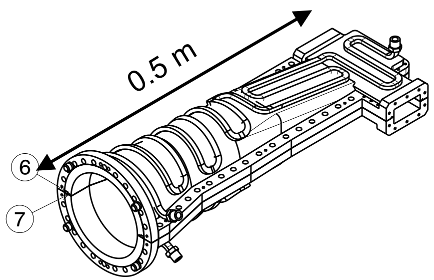
mode converter from TE_{10} mode in rectangular waveguide to TE01 mode in circular waveguide

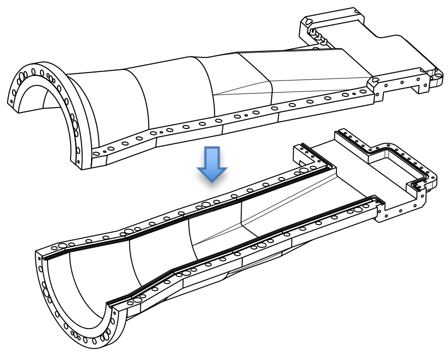


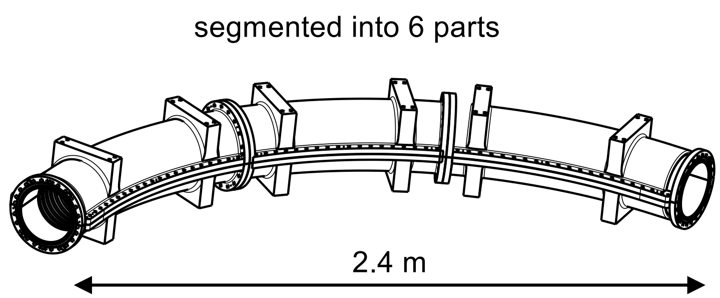
designed by G.L. Ravera

Progress of collaboration activities

- scaled mockup from 5 GHz (ITER frequency) to 3.7 GHz to allow high-power test
- long collaboration due to slow progress of IPR activities:
  - June 2015: the specific topic of cooperation (STC) IPR-ENEA is signed;
  - June 2015: ENEA sends the CAD files of the components (RF design) to IPR;
  - January 2016: final executive mechanical designs are approved;
  - August 2016: IPR places the order for the components, expected delivery within 9 months;
  - October 2017: order is cancelled because the manufacturer cannot satisfied required tolerances;
  - October 2018: a new order has been issued with expected delivery within 8 months;
  - October 2020: the components are delivered to IPR and low power tests are carried out.



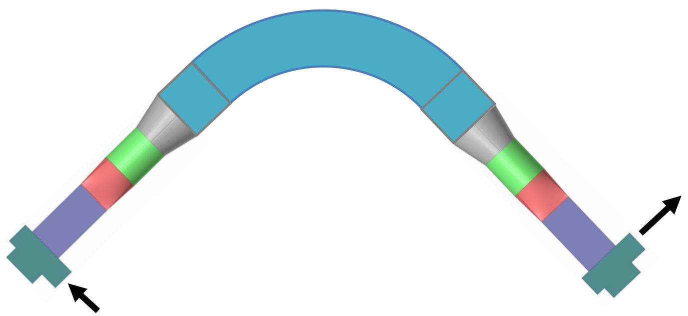


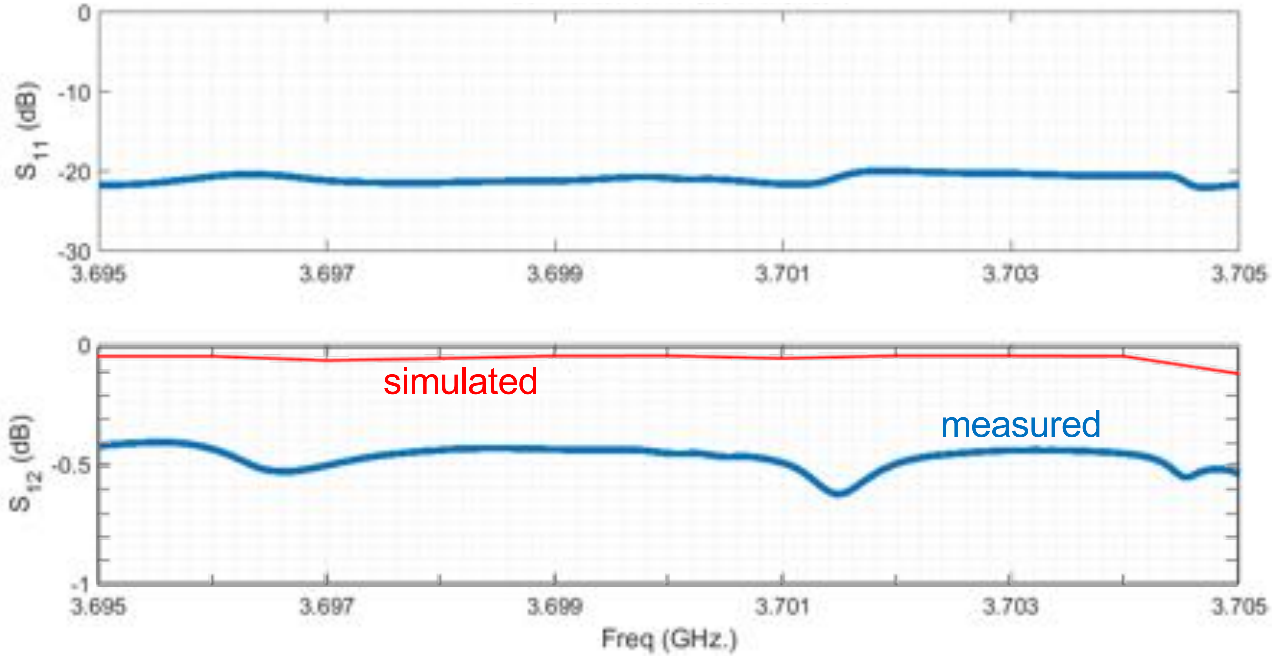


Low-power tests

- Transmission efficiency @3.7 GHz
  - simulated: 99%,
  - measured: 90%

- Reflection coefficient @3.7 GHz
  - simulated: -38 dB,
  - measured: -22 dB

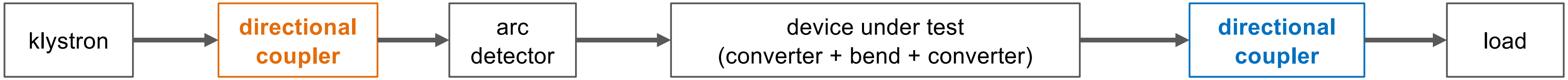


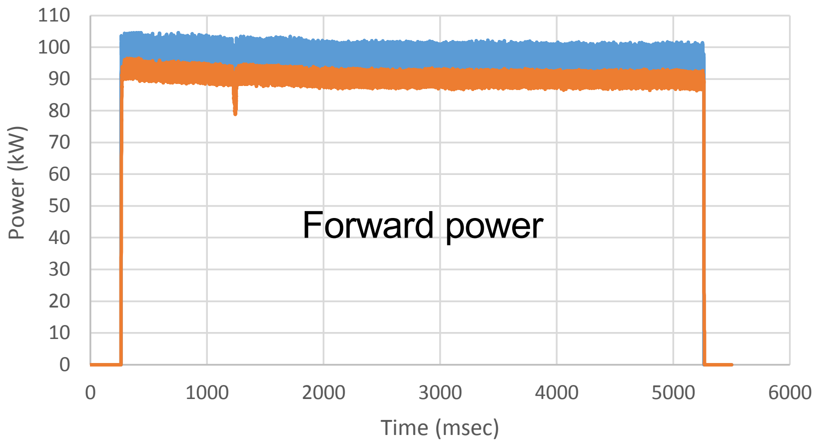


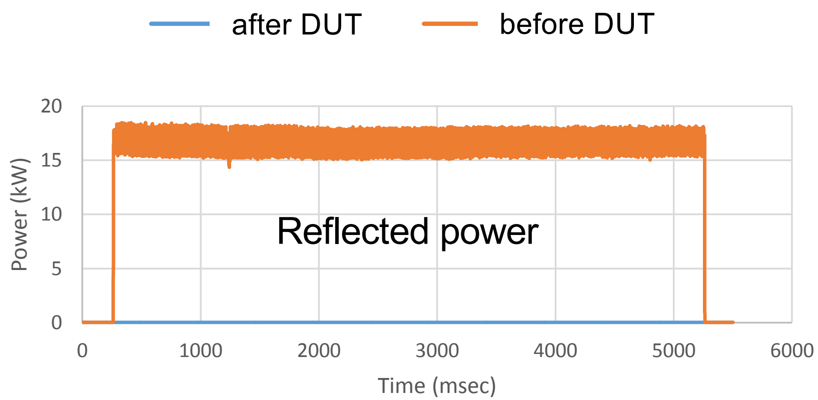
Satisfactory results considering the mechanical design (segmentation and tolerances of CNC in India).

High-power tests – Sept. 2021

- Due to pandemic situation, high-power tests are carried out in India:







measurement accuracy = +/- 10%, no arc detected, interlock due to high reflection, then disabled.

ENEA suggested to check visual deformation on the components, swap directional coupler and/or repeat low-power measurements.

Collaboration ENEA-CEA-DTT

- Collaboration agreed on October 26, 2021, on several topics:

Topics	Contact persons	
	CEA	ENEA-DTT
Collaboration coordination	G. Giruzzi	M.Ciotti - F. Crisanti
WEST experiments	E. Tsitrone	F. Bombarda
WEST operation: plasma control	Ph. Moreau	L. Boncagni
WEST operation: heating systems	J.M. Bernard	S. Ceccuzzi
Divertor technologies for DTT	M. Missirlian	S. Roccella
PFCs instrumentation and monitoring for DTT	M. Houry	M. Iafrati
Physics programme	G. Giruzzi	F. Crisanti

- The topic on heating systems regards ion-cyclotron resonance heating (ICRH) and electron cyclotron resonance heating (ECRH)

Collaboration ENEA-CEA-DTT on ICRH

- ICRH is a topic with high priority; two groups of collaboration subjects have been identified:

clear interest => quantitative proposal for resource

Topics matching DTT and CEA interests, i.e.

- training of ENEA staff in control room and plant activities + diagnostics, protections, experiments.
- CEA participation to the expertise and milestones of the DTT ICRH system.

Proposed ppm

	ENEA-DTT		CEA/IRFM	
Year	**@home**	**@WEST**	**@home**	**@DTT**
2021	1		0.5	
2022	2	2.5	1	
2023	1.5	2	1	
2024	1	1.5	0.5	1
2025	1	1	0.5	1
2026	1	1.5	0.5	1
2027	1	1.5	0.5	
2028	1.5	2	0.5	2
Total	**10**	**12**	**5**	**5**

potential interest => qualitative list of topics

Activities for which a binding commitment is premature at this stage due to uncertainties on DTT needs and difficult quantification of the resources needed for their execution. Detailed provisions to be deeply assessed and agreed in due time:

- Use of TITAN facility to test antenna prototypes and/or RF contacts,
- Direct involvement of CEA in the procurement of diagnostics, in particular
  - arc detection systems like SHAD, optical techniques, (IR cameras);
  - voltage probes & phase measurements.

Collaboration ENEA-CEA-DTT on ECRH

ECRH-relevant subjects may be included at some point during the collaboration (WEST ECRH system to be deployed from 2023):

- Participation of ENEA-DTT staff to
  - gyrotron and ECRH plant commissioning,
  - antenna commissioning,
  - ECRH system commissioning and ECRH first experiments.

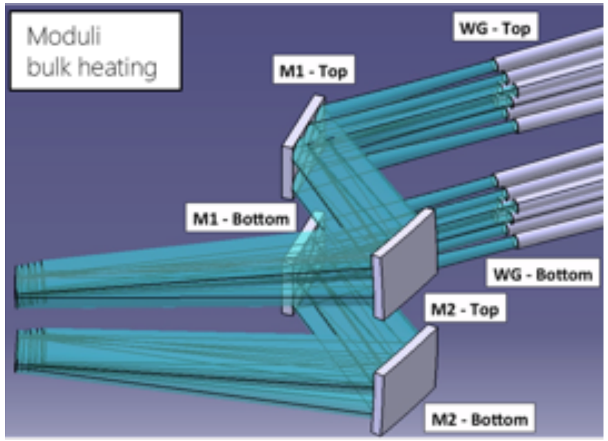
- Participation of CEA/IRFM staff to
  - design of elements of the TL and launchers,
  - ex-vessel and/or in-vessel diagnostics,
  - ECRH control system design and development.

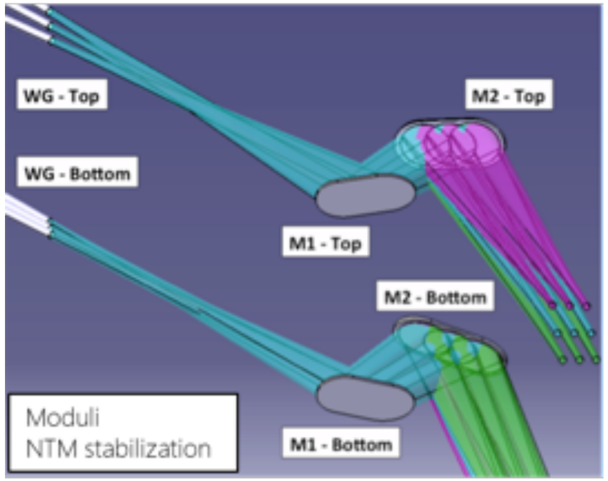
Design of DEMO ECRH antenna

Task in collaboration with ISTP-CNR, part of the WP HCD

General description

- The system is located in the equatorial port and consists of four modules:
    - Two modules, each dedicate to 3 beams, on the upper and lower region of the port for NTM stabilization (170 or 204 GHz);
    - Two modules, each dedicated to 8 beams, in the central region for plasma heating (170 or 204 GHz) and power deposition at the pedestal for the stabilization of thermal instabilities (136 or 170 GHz).
- Each module includes a pair of mirrors, the first fixed and flat, the second focusing and, for NTM only, steerable in the poloidal direction.

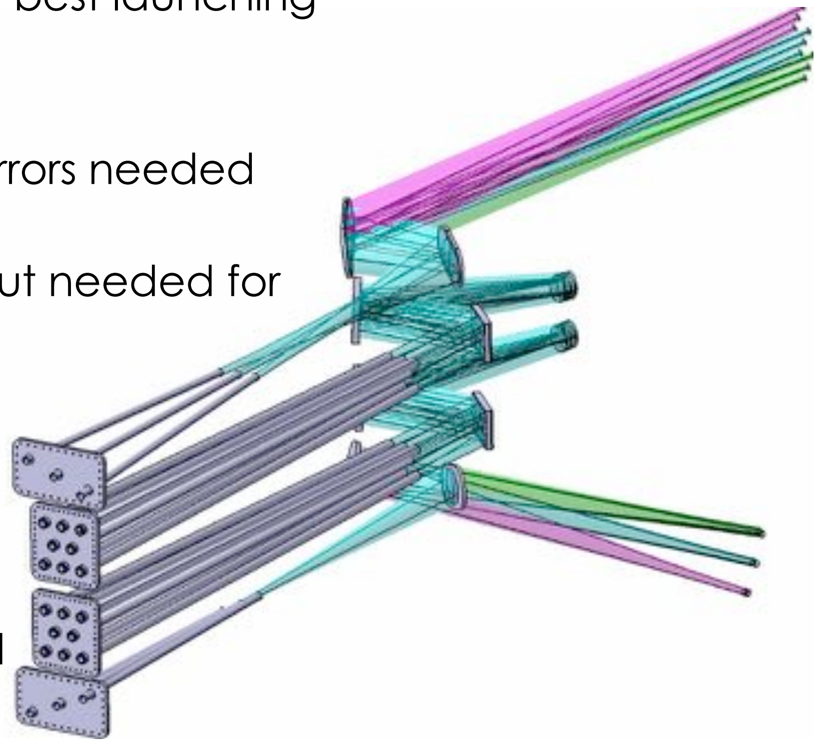




Design of DEMO ECRH antenna

Objectives of the task

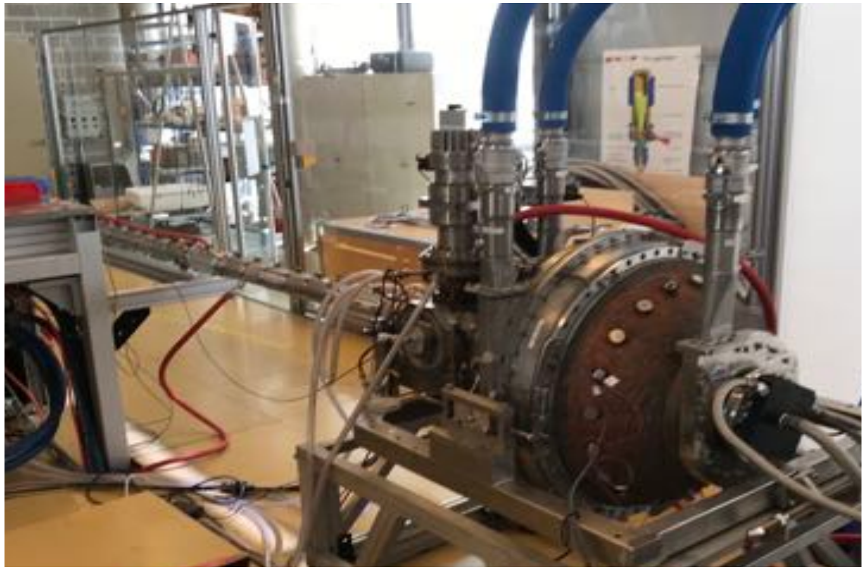
- Definition of position, orientation, optical surface, size and contour of the mirrors after optimization process by physics (i.e., identify the best launching direction depending on the task).
- Definition of waveguides direction inside the port;
- Evaluation of the microwave thermal load distribution on mirrors needed for the design of the cooling system.
- Definition of the minimum size of the breeding blanket cut-out needed for the passage of the microwave beams.



Tools developed for the task (used also for DTT antennas)

- Parametric CATIA model (e.g., optical parameters of the beams, geometrical data for mirrors) with publication between different parts → easing the update of the model;
- Matlab code for QO design and generation of thermal load maps.

Calorimetric loads for the commissioning of gyrotrons



Task in collaboration with ISTP-CNR

Objective of the task

- Participation to call for tender for the procurement of high power, high frequency calorimetric loads for the commissioning of gyrotrons.
- A design phase is required to demonstrate the compliance with the requirements provided by the Contractor.

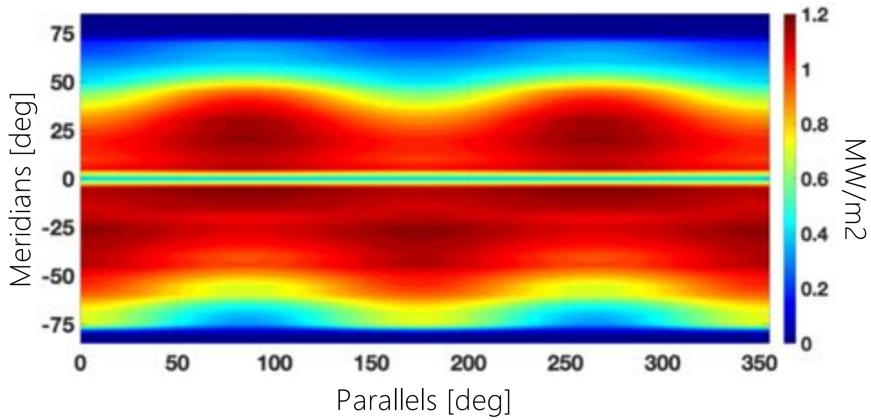
Tools developed for the task

Ray-tracing Matlab code based on geometrical optics. The input data of the code are:

- Input Gaussian beam, modelled as ideal beam (part of the code) or using the field calculated with the commercial code GRASP (provided by ISTP-CNR);
- Profile of the spreading mirror, designed to have a well-defined primary illumination inside the loads (provided by ISTP-CNR);
- Absorbing coating thickness profile (provided by ISTP-CNR).

Calorimetric loads for the commissioning of gyrotrons

- The beam is discretized in a bundle of many rays, each with its direction and carried power.
- The geometry of the loads and its components (preload and mirror) is implemented in the code using analytical formulation (with minor approx.).
- At each bounce, the incidence point and incidence angle are calculated.
- The fraction of power absorbed is calculated considering the local thickness of the coating, the incidence angle and the polarization of the ray → local absorption coefficient.
- The propagation continues until:
    - the power content of the ray decrease below a value set to stop the simulation (e.g. 50 mW);
    - the ray escapes back into the waveguide (provide fraction of back-reflection, usually ~0.5% of the total power).
- The code can be used with different geometries, absorbing materials and with a different input beam mode mix (input from GRASP required).



Example of absorbed power density distribution on the absorbing portion of the spherical load in the nominal case of input HE11 mode.

Thank you for the attention