ECRIS 2018

23rd International Workshop on ECR ion sources

Plasma Heating and Innovative Microwave Launching in ECRIS: Models and Experiments

G. Torrisi[1], D. Mascali[1], A. Galatà[2], L. Celona[1], G. Sorbello[1,3]
G. Castro[1], G. Mauro[1], M. Mazzaglia[1], E. Naselli[1,4], S. Gammino[1]

1) INFN - Laboratori Nazionali del Sud, Catania, Italy
2) INFN- Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy
3) Università degli Studi di Catania, DIIEI, Catania, Italy
4) Università degli Studi di Catania, DFA, Catania, Italy

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

Outline

- **INTRODUCTION**

  Microwave-to-plasma coupling "Cavity-dominated" VS "**Launching-dominated**"

- **NUMERICAL MODELING**

  EM wave propagation in the anisotropic magnetized plasmas of ion sources

Outline

- **INTRODUCTION**

  Microwave-to-plasma coupling "Cavity-dominated" VS "**Launching-dominated**"

- **NUMERICAL MODELING**

  EM wave propagation in the anisotropic magnetized plasmas of ion sources

- **IMPLEMENTATION AND EXPERIMENTAL BENCHMARKS**

  1. **B-minimum device (Electron Cyclotron Resonance (ECR) Ion Sources @**ATOMKI **)**
  2. **ECR-based Charge Breeder (**PHOENIX Charge Breeder @LPSC)
  3. **Simple-mirror axis-symmetric linear device (Flexible Plasma Trap @INFN-LNS)**

Outline

- **INTRODUCTION**

  Microwave-to-plasma coupling "Cavity-dominated" VS **"Launching-dominated"**

- **NUMERICAL MODELING**

  EM wave propagation in the anisotropic magnetized plasmas of ion sources

- **IMPLEMENTATION AND EXPERIMENTAL BENCHMARKS**

  1. **B-minimum device (Electron Cyclotron Resonance (ECR) Ion Sources @**ATOMKI **)**
  2. **ECR-based Charge Breeder (**PHOENIX Charge Breeder @LPSC)
  3. **Simple-mirror axis-symmetric linear device (Flexible Plasma Trap @INFN-LNS)**

- **PERSPECTIVES**

  1. **short term (2 years): Reshaping plasma chambers with non-conventional features;**
  2. **short/mid-term (3 years): Innovative RF launcher and quasi-optical approach;**
  3. **Long Term (5 years): futuristic all-dielectric mm-waves launching structures.**

Overcoming the actual limit of ECRIS

$\omega_p^2 < \omega^2$ → $n_e < \frac{\epsilon_0 m_e}{e^2}\omega^2 = n_{cutoff}$ → ***INTRINSIC Density limitation***

ECRIS STD MODEL. Frequency scaling

$I \propto n_e$ $\langle \boldsymbol{q} \rangle \propto \boldsymbol{n}_e$ $n_e \propto \omega_{RF}^2$ →

1. **High Frequency Generators**
2. **High Magnetic Fields to make longer the ions confining time;**

$B_{ECR}\,[\mathrm{T}] = f_{RF}\,[\mathrm{GHz}]/28$

$B_{rad}/B_{ECR} = 2$

$B_{ext} \approx 0.9 B_{rad}$

$B_{min} \approx 0.4 B_{rad}$

$B_{inj}/B_{ECR} = 4$

Brute force cannot be anymore used because of technological reasons (magnets forces, hot electrons generations, plasma overheating, cooling, ...)

Overcoming the "brute force" empirical approach based on **Geller's scaling laws** $I \propto f_{RF}^2$ $q \propto \log B^{3/2}$

towards a "**Microwave Absorption Optimization-oriented**" design in order to Develop **the next generation Ion Sources**

ECRIS NUMERICAL MODEL: STATE OF THE ART

Up to now several studies make various approximations by:

- **assuming "zero-dimensional" up to 2D-simulation** model for calculating the charge state distribution in a parametric way;
- **considering a simplified magnetostatic scenario** with **an axial symmetry** (only simple mirror configuration instead of minimum-B);
- considering the **medium as an equivalent dielectric load**
- solving the wave equation in **Wentzel Kramers Brillouin (WKB) approximation** (Fusion plasma)

- ❑ *T. Ropponen et al., Nuclear Instruments and Methods in Physics Research A 587, 115-124 (2008).*
- ❑ *B. P. Clugghish and J. S. Kim, Nuclear Instruments and methods in Physics Research A 664, 84-97 (2012).*
- ❑ *E.G. Evstatiev, V.A. Svidzinsky, J.A. Spencer, J.S. Kim, Rev. Sci. Instrum. 85, 02A503 (2014)*
- ❑ *T. Thuillier, T. Lamy, L. Latrasse, I.V. Izotov, A.V. Sidorov, V.A. Skalyga, V.G. Zorin, M. Marie-Jeanne, Rev. Sci. Instrum. 79, 02A314 (2008)*
- ❑ *V. Mironov, S. Bogomolov, A. Bondarchenko, A. Efremov, V. Loginov, Phys. Rev. ST Accel. Beams 18, 123401 (2015)*
- ❑ *G D Shirkov 1993 Plasma Sources Sci. Technol. 2 250*
- ❑ *J. Vamosi, S. Biri, Comput. Phys. Commun. 98, 215 (1996)*
- ❑ *G.D. Shirkov, C. Muhle, G. Musiol, G. Zschornack, Nucl. Instrum. Meth. A 302, 1 13.*
- ❑ *A. Girard, C. Pernot, G. Melin, C. Lecot, Phys. Rev. E 62, 1182 (2000)*
- ❑ *K. Crombe et al., AIP Conf. Proc. 1406, 97 (2011).*
- ❑ *M. El Khaldi et al., AIP Conf. Proc. 1187, 273 (2009).*

"Cavity vs "Launching" Microwave-plasma coupling

TYPICAL WAVELENGTHS AND SIZES OF COMPACT ION SOURCES		
λ_{RF} Launching [mm]	λ_{RF} Diagnostics [mm]	$L_c[mm]$
10-120	7-15	250

microwave-to-plasma coupling

"Launching-dominated"

$$L_n = \left|\frac{n_e}{\nabla n_e}\right| \quad L_T = \left|\frac{T}{\nabla T}\right| \quad L_B = \left|\frac{B}{\nabla B}\right|$$

"Cavity-dominated"

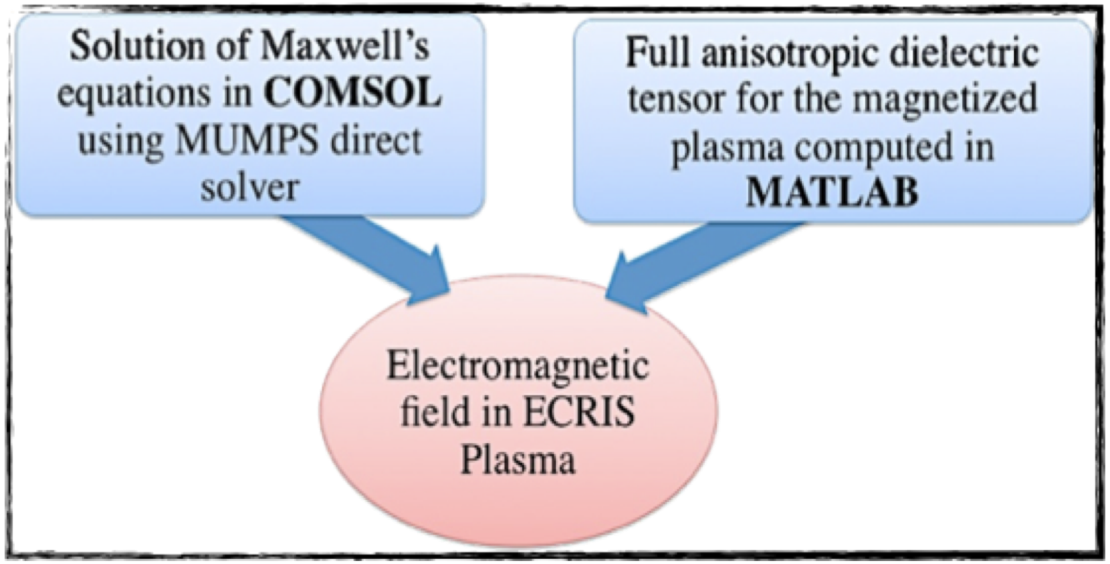
$$L_B, L_T, L_n >> \lambda$$

In large-size fusion reactor ray-tracing calculations can be performed

$$L_B, L_T, L_n \approx \lambda$$

in the ECRIS, ray-tracing approximation is not applicable, and the full-wave calculations have to be applied to simulate the wave behaviour in the plasma

Modeling of wave propagation in Anisotropic plasma of ECRIS



$$\nabla \times \nabla \times \boldsymbol{E} - \frac{\omega^2}{c^2}\overline{\overline{\epsilon_r}} \cdot \boldsymbol{E} = 0$$

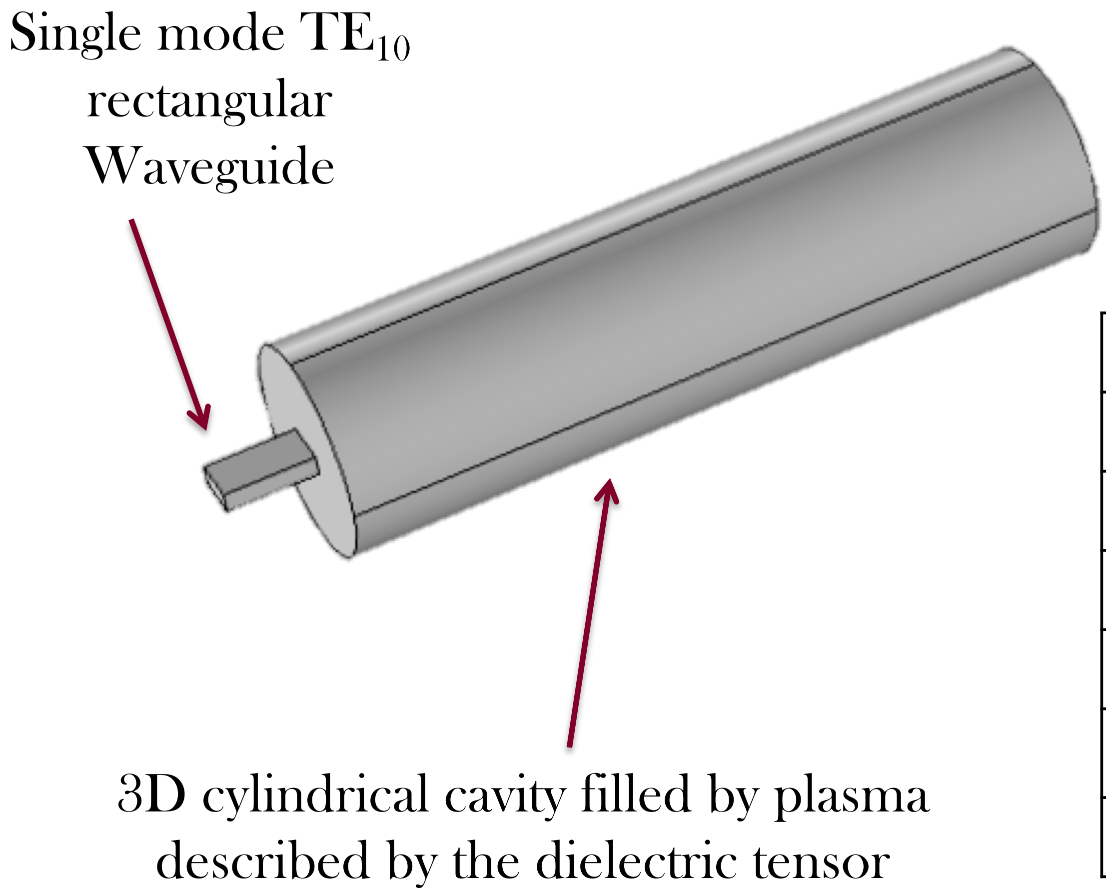
Wave equation with tensorial permittivity

$$\overline{\overline{\epsilon}} = \epsilon_0 \overline{\overline{\epsilon}}_r = \epsilon_0\left(\overline{\overline{\epsilon'}} - i\overline{\overline{\epsilon''}}\right) = \epsilon_0\left(\overline{\overline{I}} - \frac{i\overline{\overline{\sigma}}}{\omega\epsilon_0}\right)$$

$$= \epsilon_0 \begin{bmatrix} 1 + i\frac{\omega_p^2}{\omega}\frac{a_x}{\Delta} & i\frac{\omega_p^2}{\omega}\frac{c_z + d_{xy}}{\Delta} & i\frac{\omega_p^2}{\omega}\frac{-c_y + d_{xz}}{\Delta} \\ i\frac{\omega_p^2}{\omega}\frac{-c_z + d_{xy}}{\Delta} & 1 + \frac{i\omega_p^2}{\omega}\frac{a_y}{\Delta} & i\frac{\omega_p^2}{\omega}\frac{c_x + d_{yz}}{\Delta} \\ i\frac{\omega_p^2}{\omega}\frac{c_y + d_{xz}}{\Delta} & i\frac{\omega_p^2}{\omega}\frac{-c_x + d_{zy}}{\Delta} & 1 + i\frac{\omega_p^2}{\omega}\frac{a_z}{\Delta} \end{bmatrix}$$

Full-3D non homogeneous dielectric permittivity Tensor depends on local electron density and magnetic field B

Simulation Setup in COMSOL



Simulation parameter

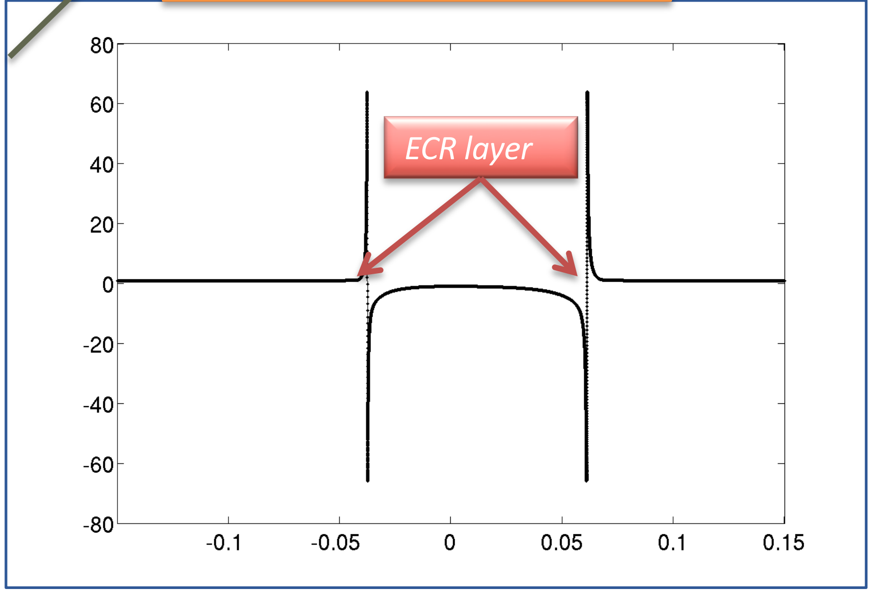
PARAMETER	VALUE
Cavity length	450 mm
Cavity radius	65 mm
Frequency	8 GHz
Waveguide width	28.5 mm
Waveguide height	12.6 mm
RF Power	100 W

FEM "Full Wave" solution approach

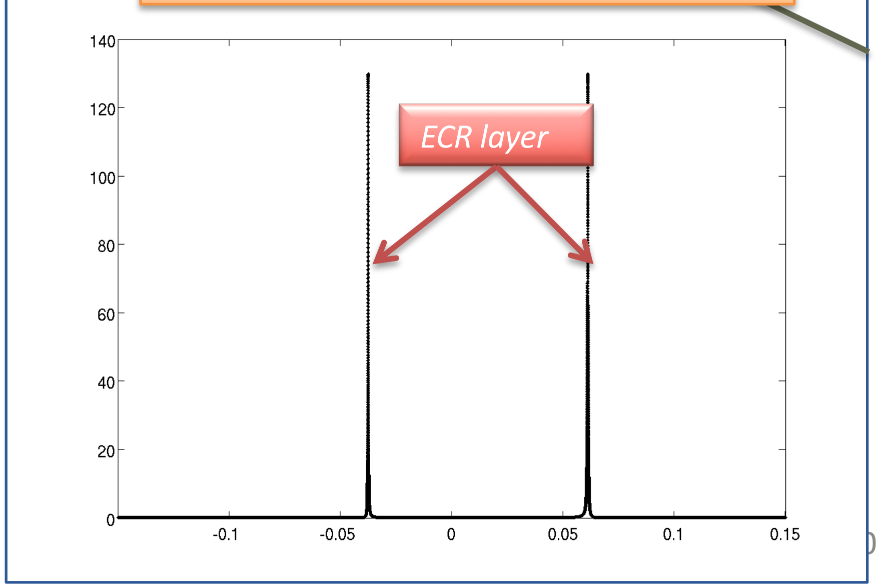
$$\omega_{eff} = \omega_{RF} / 10^3$$

$$\frac{\bar{\bar{\varepsilon}}}{\varepsilon_0} = \begin{bmatrix} 1 + j\frac{\omega_p^2}{\omega}\frac{A_x}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{C_z + D_{xy}}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{-C_y + D_{xz}}{\Delta} \\ j\frac{\omega_p^2}{\omega}\frac{-C_z + D_{xy}}{\Delta} & 1 + j\frac{\omega_p^2}{\omega}\frac{A_y}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{C_x + D_{yz}}{\Delta} \\ j\frac{\omega_p^2}{\omega}\frac{C_y + D_{xz}}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{-C_x + D_{zy}}{\Delta} & 1 + j\frac{\omega_p^2}{\omega}\frac{A_z}{\Delta} \end{bmatrix}$$

Real part of ε_{r11}

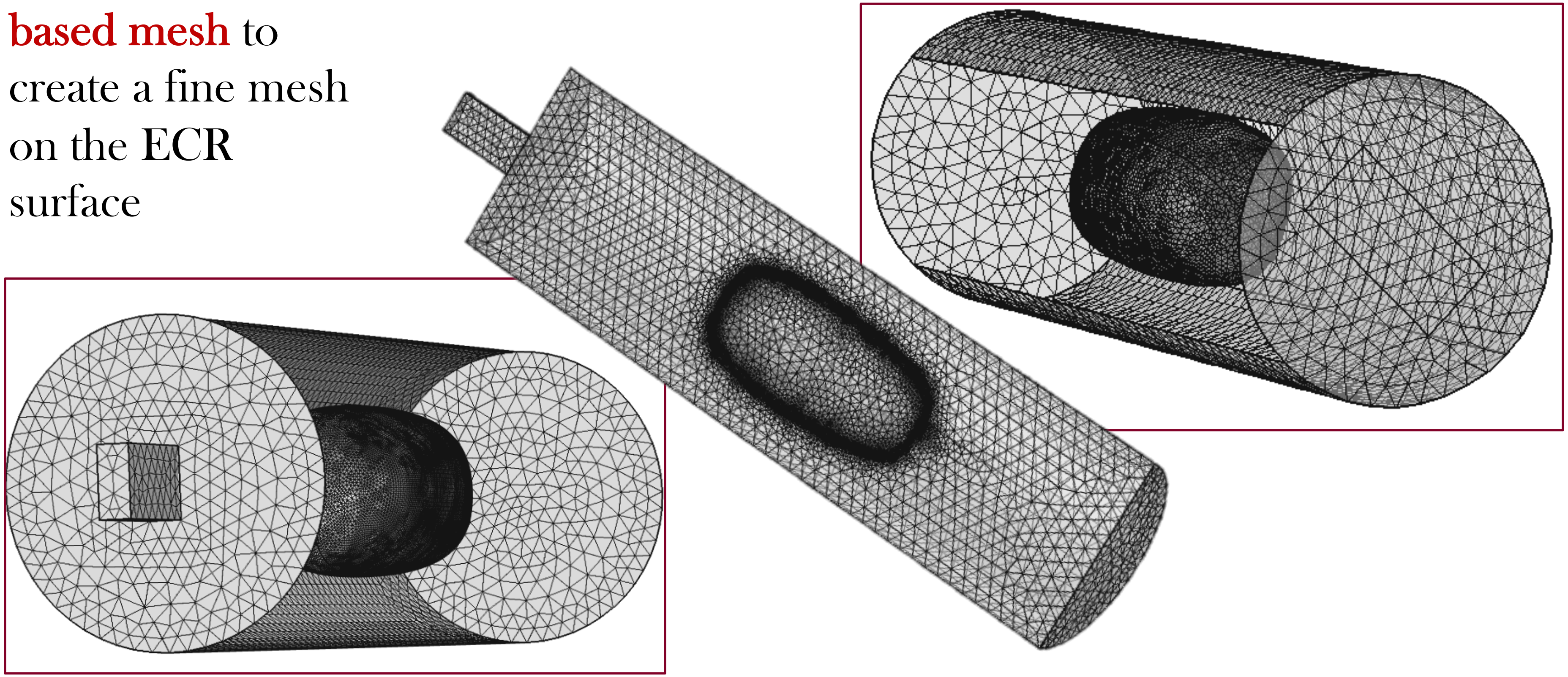


Imaginary part of ε_{r11}



Mesh procedure

ECR-surface-based mesh to create a fine mesh on the ECR surface

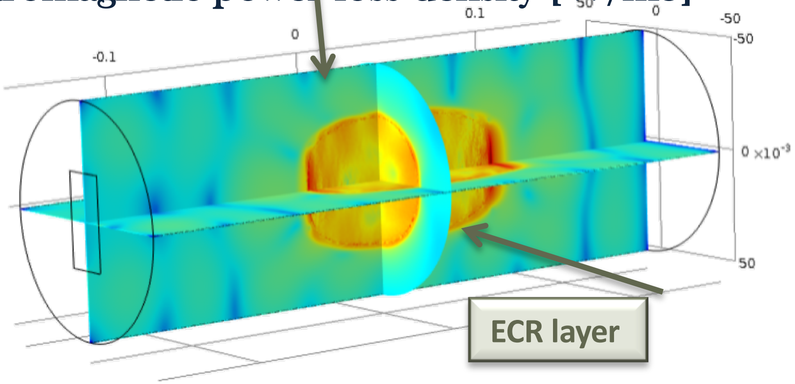


The mesh is very fine on the ECR surface and relatively coarser away from the resonance zone.

Numerical results: Snapshots of the Electric field ams Power loss density on a slice

The largest fraction of energy is absorbed at the ECR

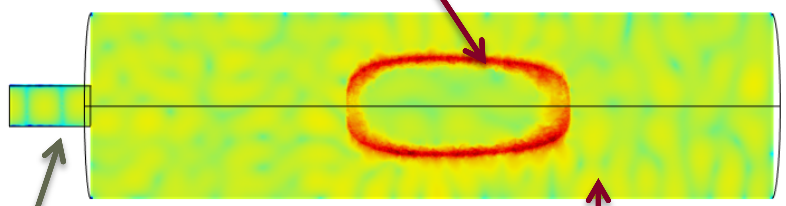
Electromagnetic power loss density [W/m3]



$$P_{diss} = \vec{J} \cdot \vec{E} = \left(\bar{\bar{\sigma}} \cdot \vec{E} \right) \cdot \vec{E}$$

Power deposition : the 55 % of the total input Power is absorbed by the plasma

Intensification of the e.m. field in the near resonance zone

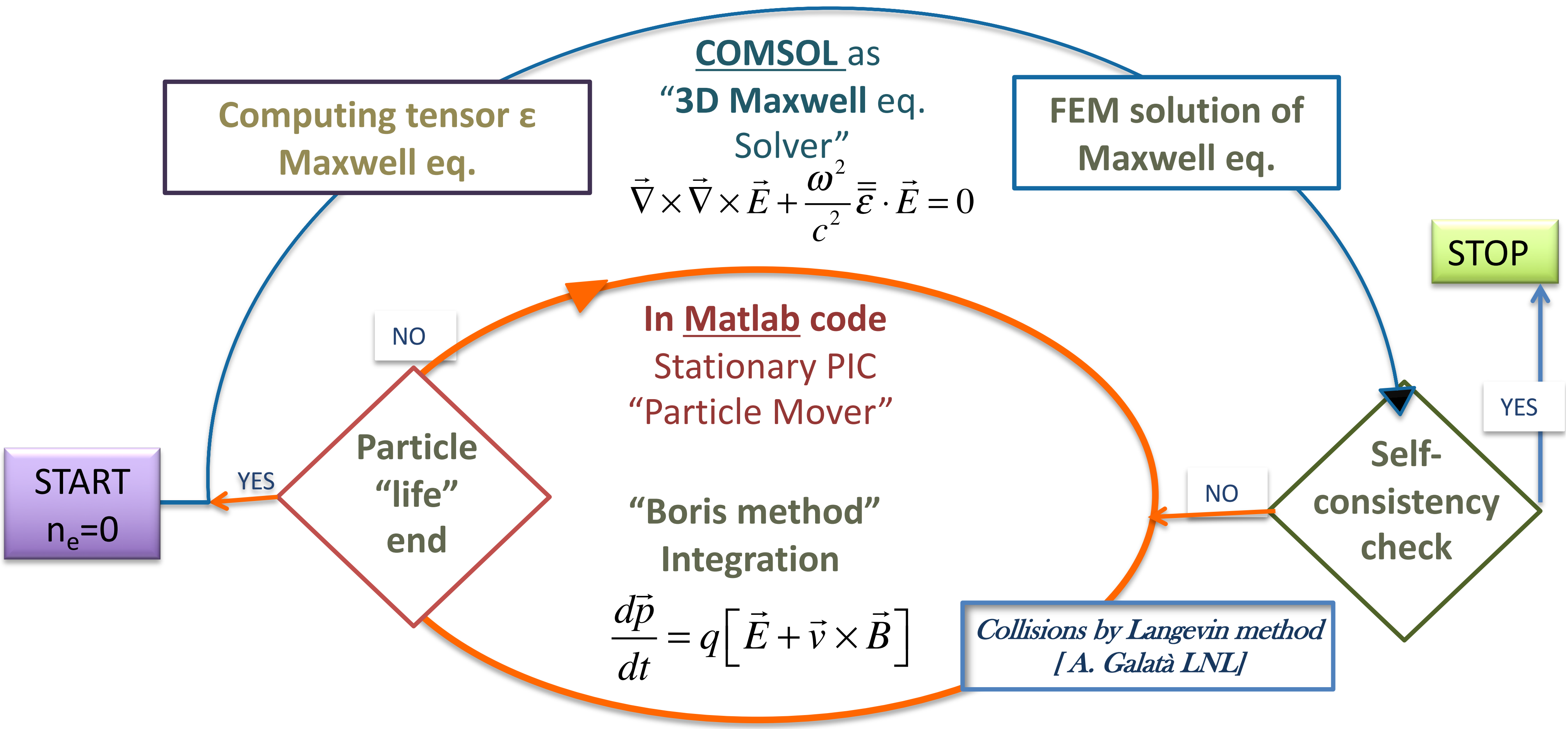


TE_{10} mode in vacuum WR

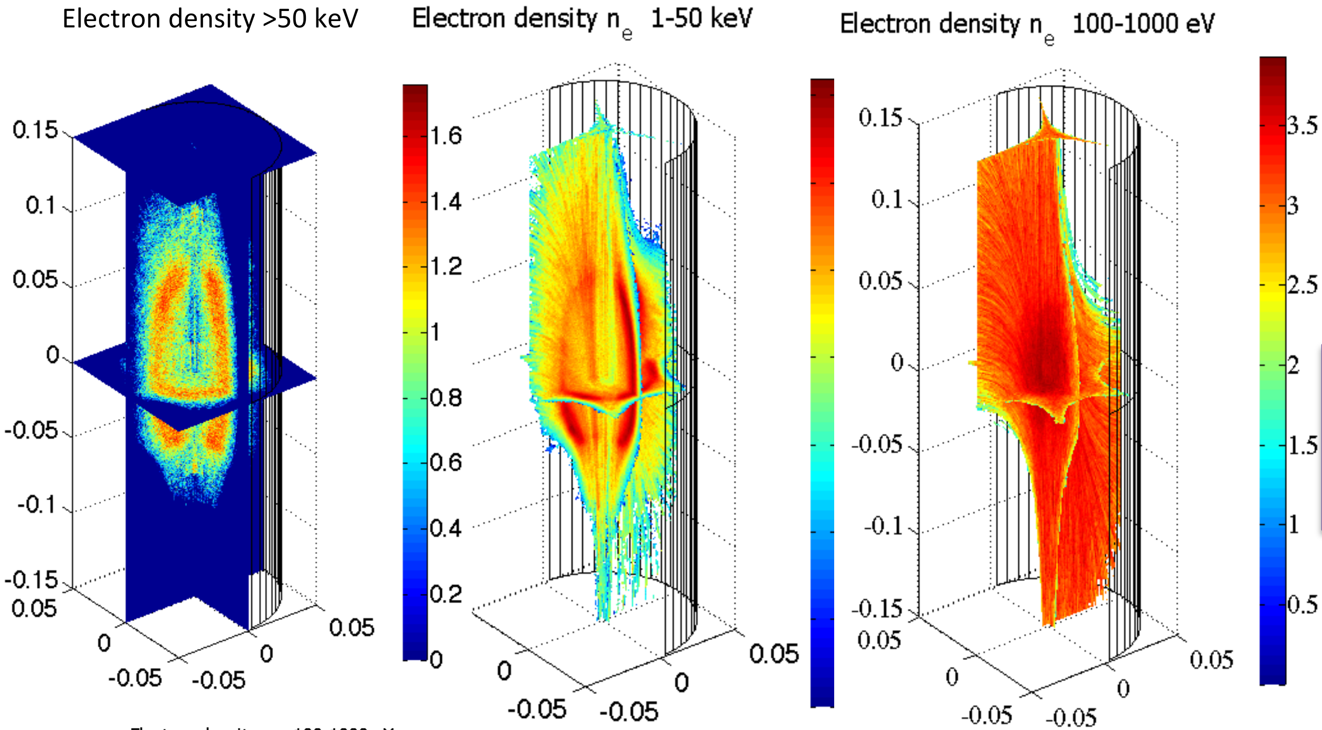
Cold Plasma

2÷3 orders of magnitude Difference between Electric field of ECR zone and outer ones

Iterative "Stationary" PIC strategy Diagram

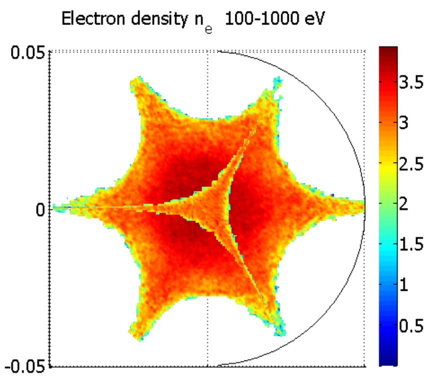


Self-consistent simulations

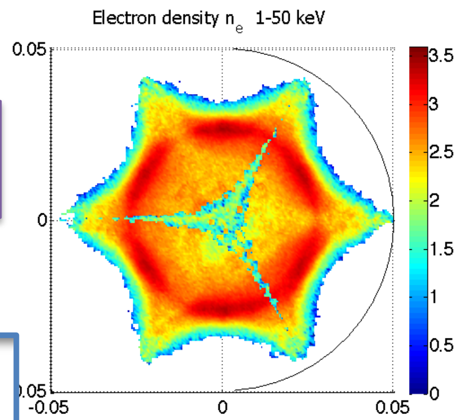


Simulated electron density distribution at different Energy ranges

Different space distribution*:*
cold electrons in the core, hot ones in near ECR regions



the plasma concentrate mostly **in near resonance region:**
a ***dens****e* ***plasmoid*** is surrounded by a ***rarefied halo***

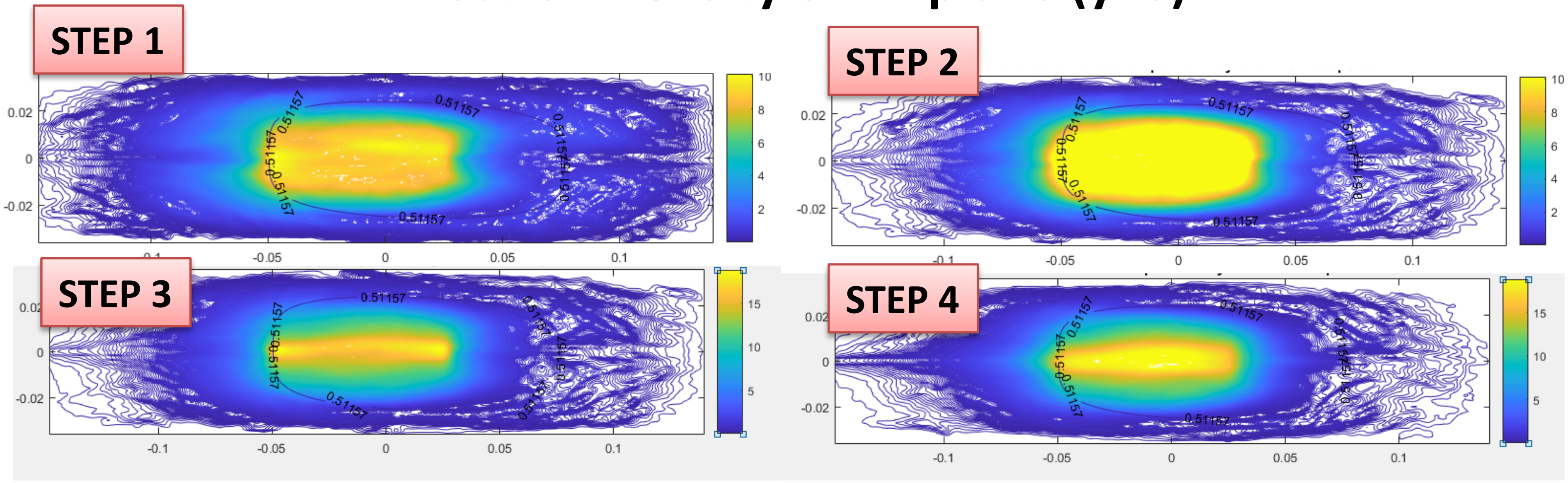


[D. Mascali, G. Torrisi, L. Neri , G. Sorbello, G. Castro, L. Celona, and S. Gammino. *European Physical Journal – D*]

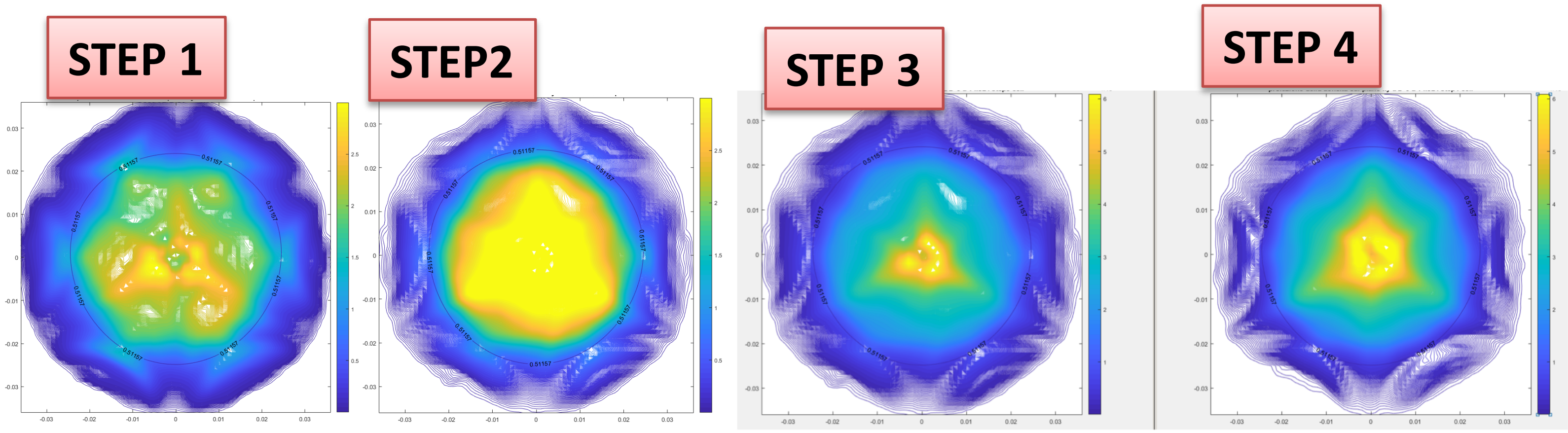
Road Towards Self Consistency…

exit from the loop

Electron Density on xz plane (y=0)



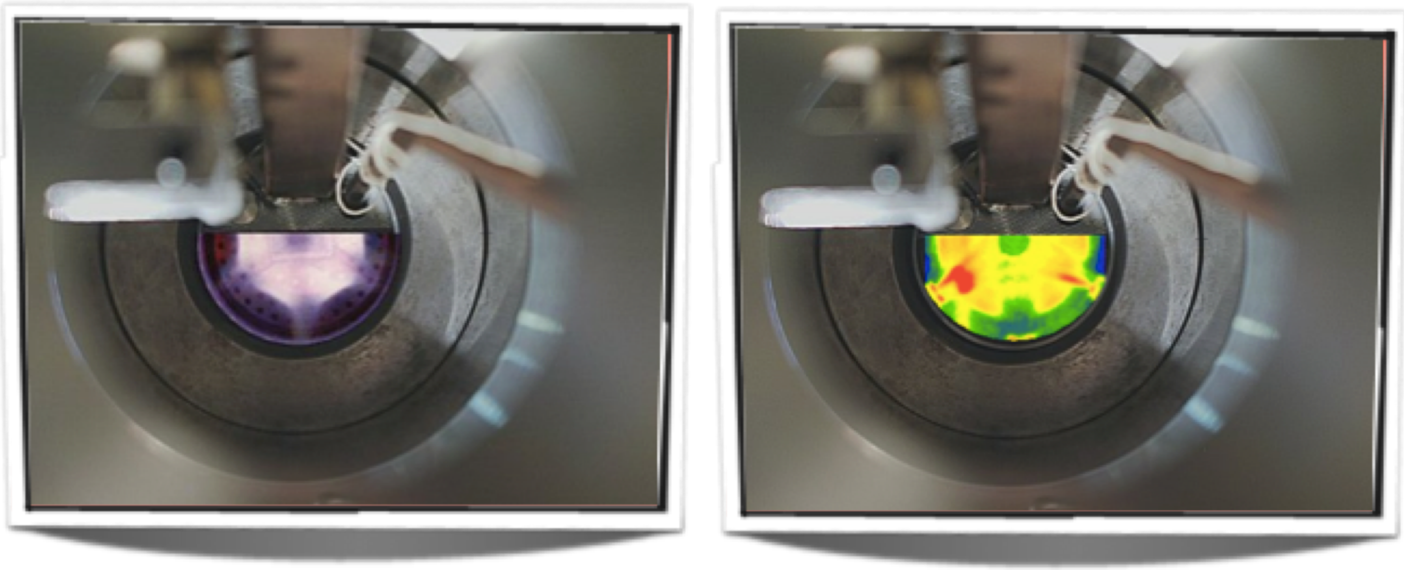
Electron Density on xy plane (z=0)



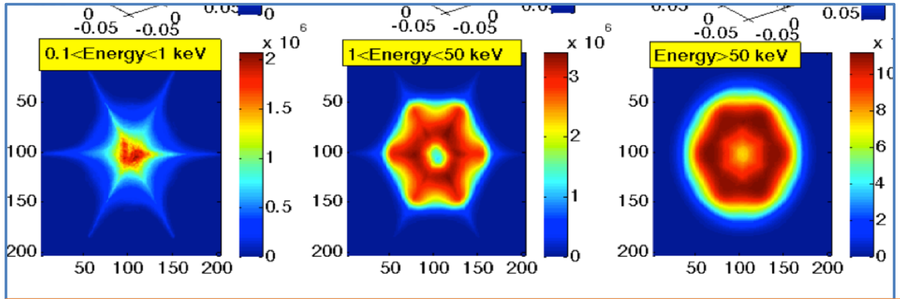
- **IMPLEMENTATION AND EXPERIMENTAL BENCHMARKS**

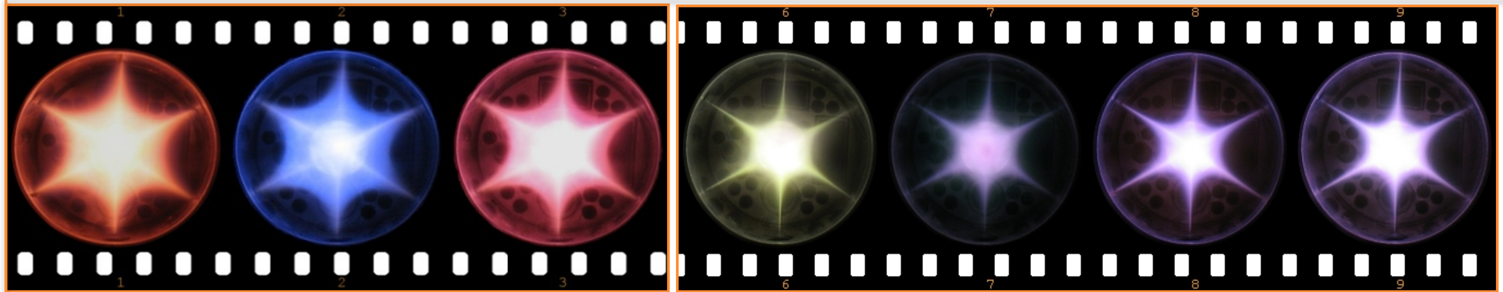
1. B-minimum device ***(Electron Cyclotron Resonance (ECR) Ion Sources @ATOMKI)***

Exploring plasma structure:
first time X-ray imaging experiment
in Atomki-Debrecen



Exploring plasma structure in Atomki-Debrecen

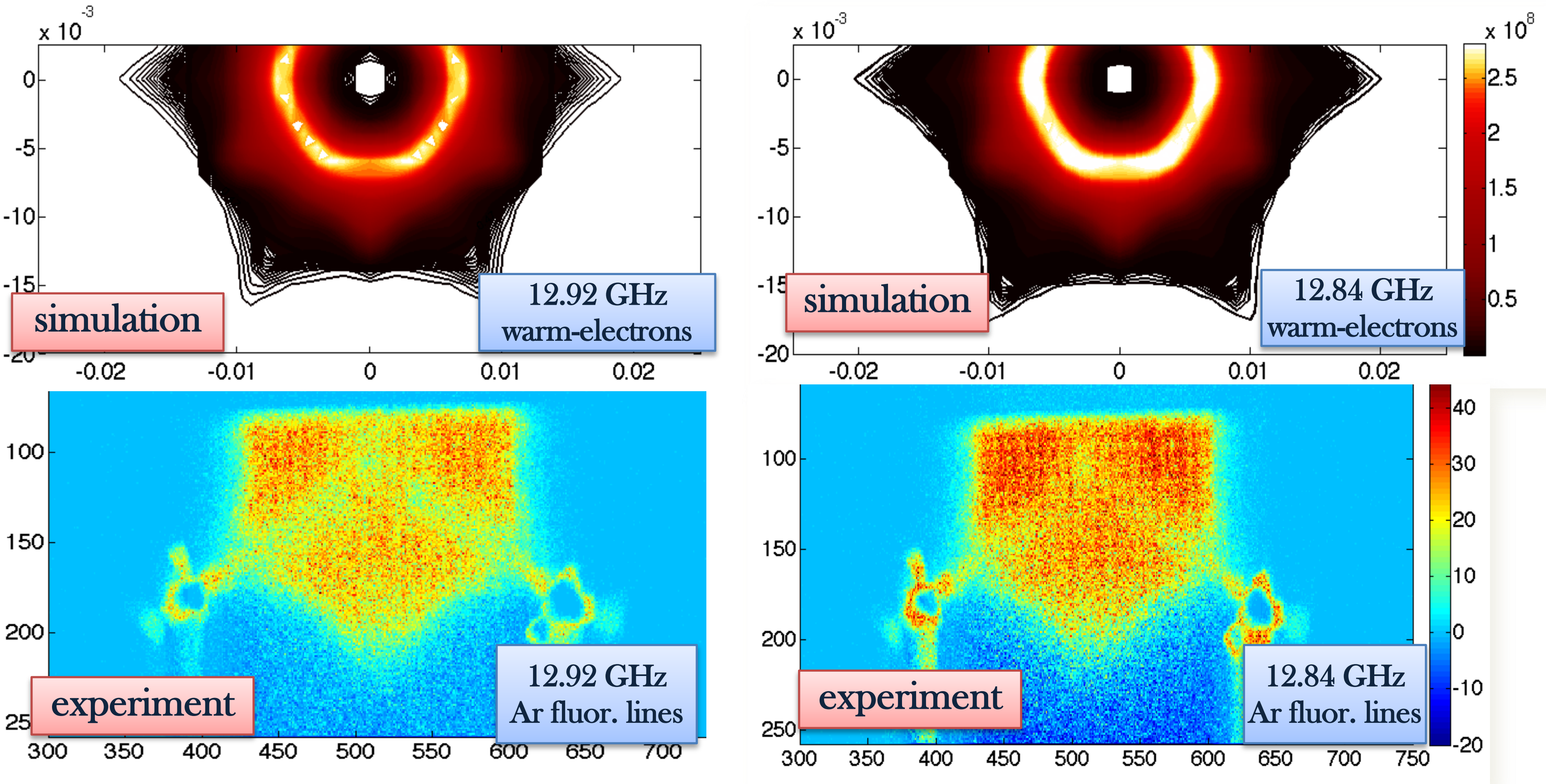




[S. Biri , R. Rácz, J. Pálinkás "Studies of the ECR plasma in the visible light range" talk @ECRIS '08"]

"Visible light (VL) photos transform information mainly on the cold electron component of the plasma. ***Cold electrons are confined in the central plasma part.*** *X-ray (XR) photos show the spatial distribution of ions. These ions and* ***the warm electrons are well confined by the magnetic field lines structure*** *showing strong asymuthal and radial inhomogenity"*

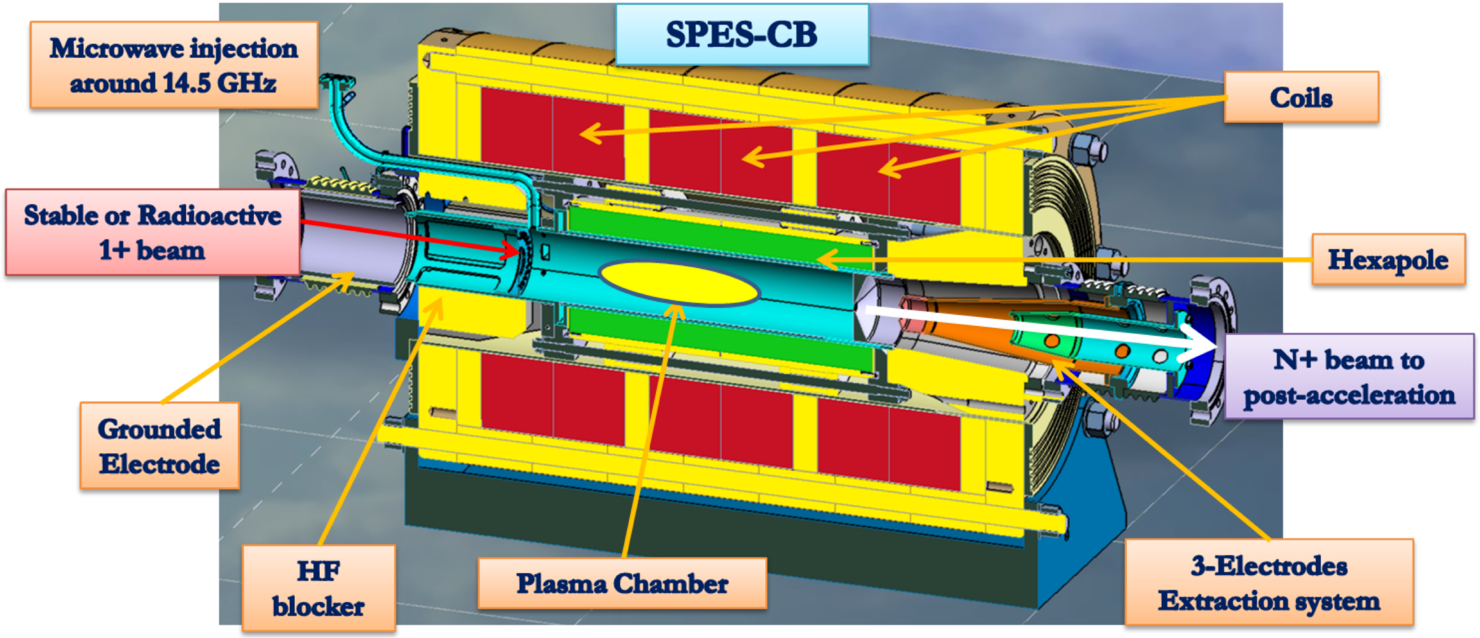
Comparison to self-consistent simulations
12.84 or 12.92 GHz



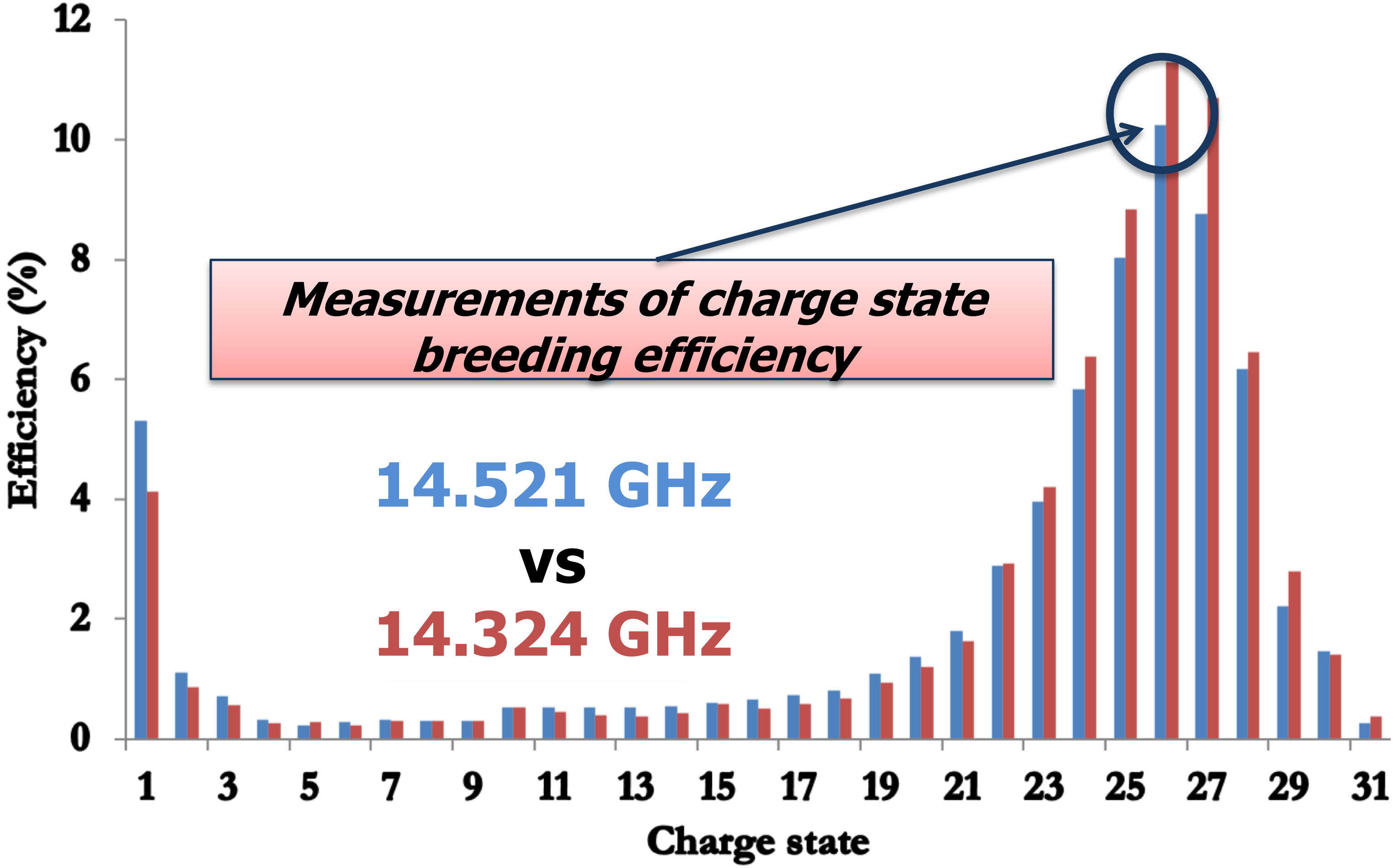
2D plasma imaging @ 12.92 GHz **2D plasma imaging @ 12.84 GHz**

▪ IMPLEMENTATION AND EXPERIMENTAL BENCHMARKS

2. ECR-based Charge Breeder (PHOENIX Charge Breeder @LPSC)

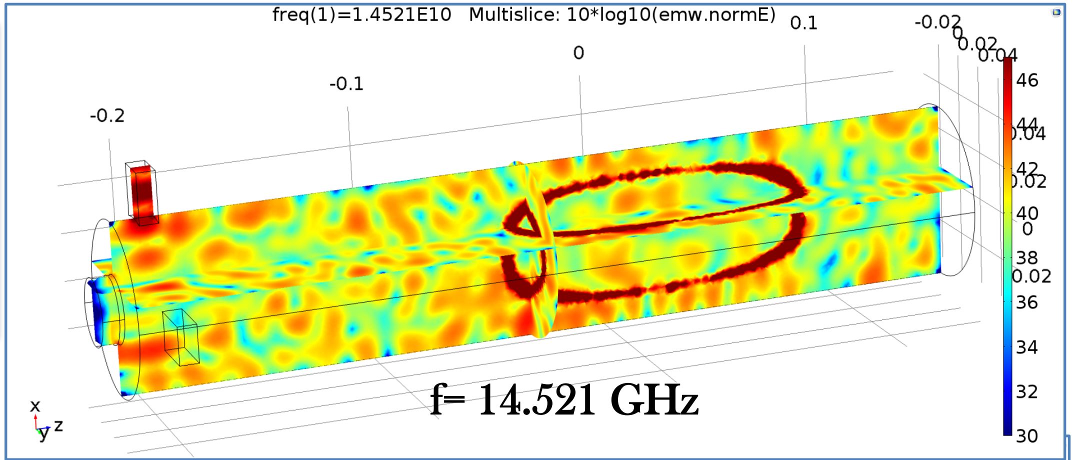


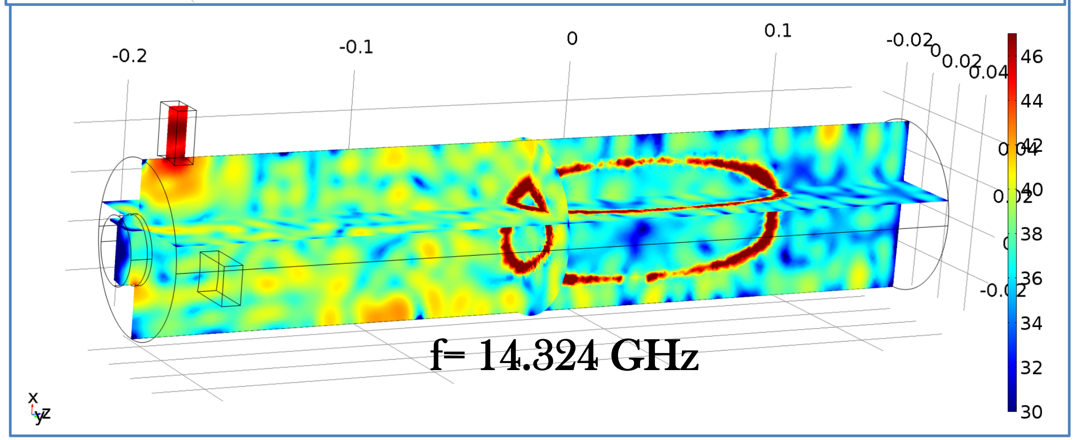
SPES charge breeder
Acceptance test



Simulation results

Frequency [GHz]	14.52	14.32
Input Power [W]	100	100
Absorbed Power [W]	24.4	80.4



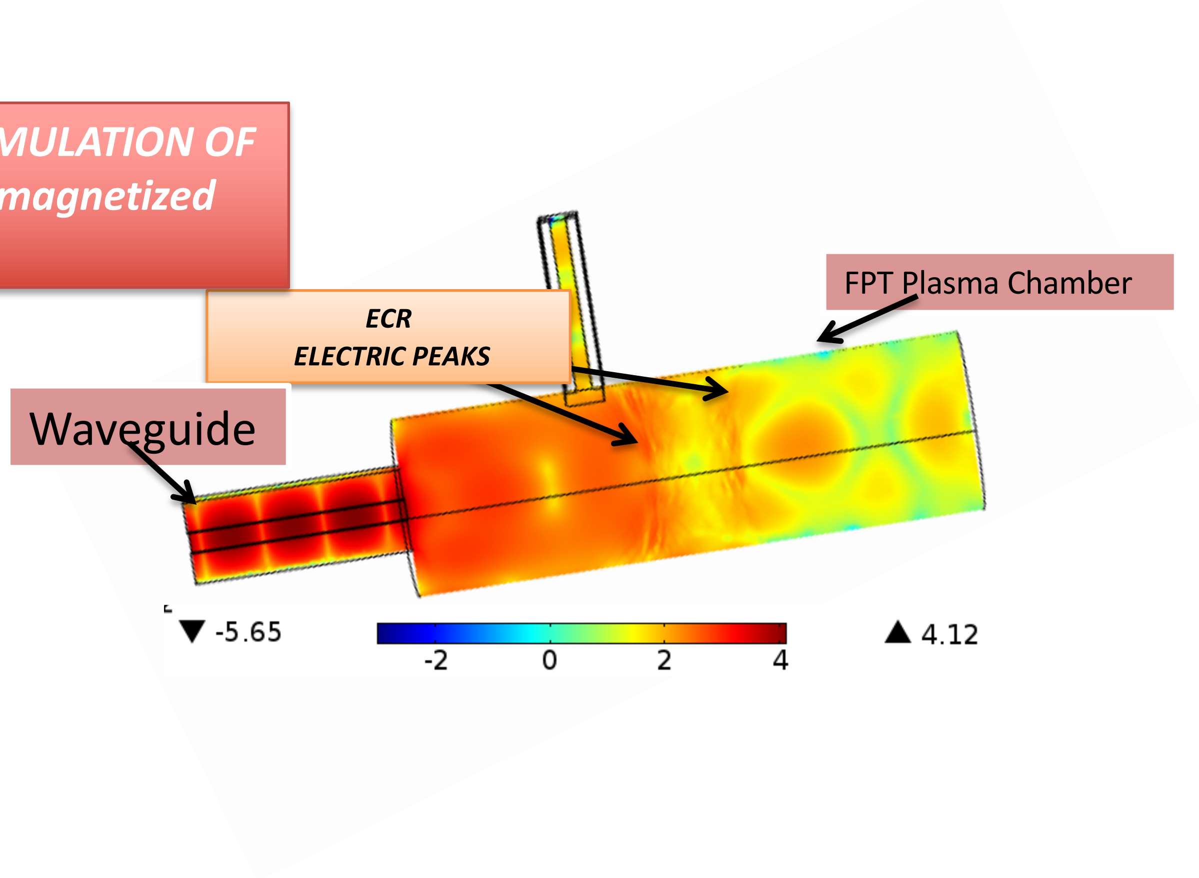


NUMERICAL EVIDENCE OF THE FREQUENCY TUNING EFFECT !

▪ IMPLEMENTATION AND EXPERIMENTAL BENCHMARKS

3. Simple-mirror axis-symmetric linear device (Flexible Plasma Trap @INFN-LNS)

FULL-WAVE SIMULATION OF WAVES in FPT magnetized plasma

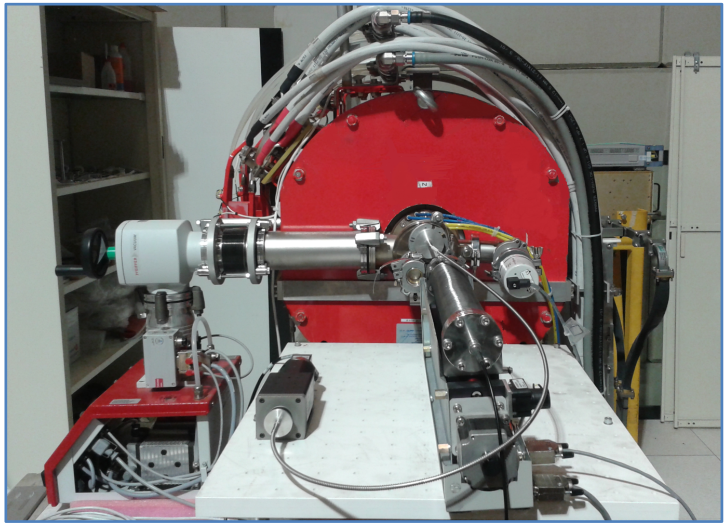


Flexible Plasma Trap (FPT) Setup @INFN-LNS

INFN

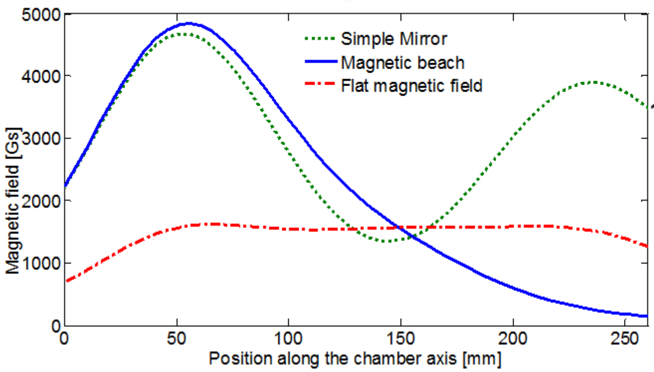
Flexible magnetic field

- Flexible magnetic field generated by three solenoids generator;
- Different magnetic field profiles: ***Simple Mirror & Magnetic Beach***

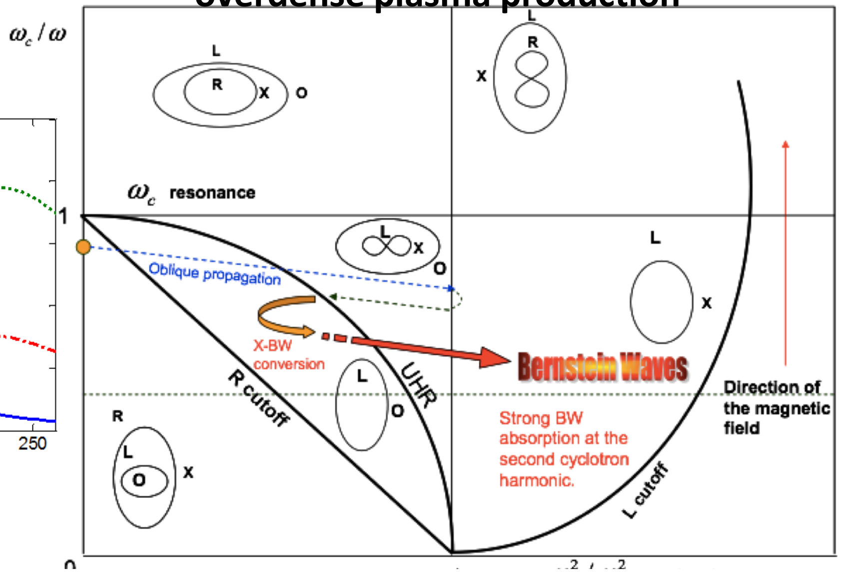


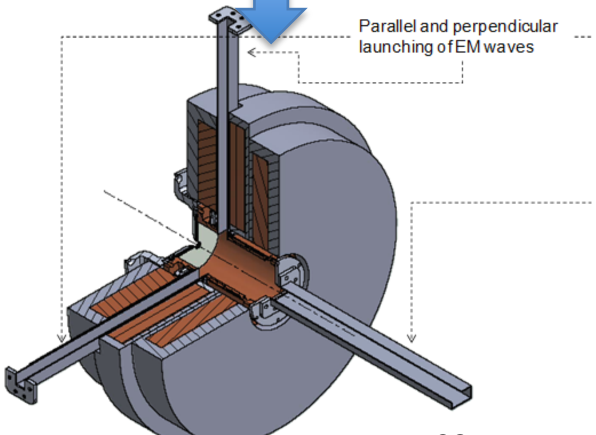
Flexible RF injection

- Three microwaves inputs: *1 axial* and 2 radial;
- Microwave frequency in the range **4-7 GHz**



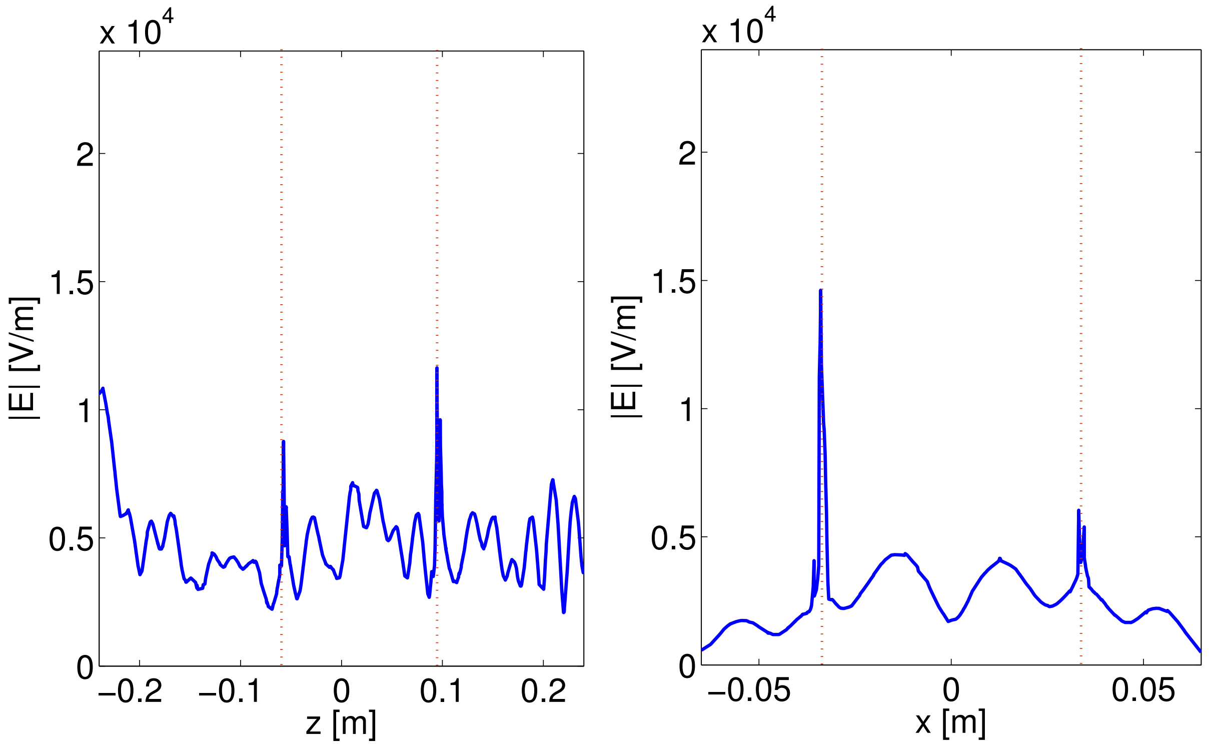
Modal Conversion for overdense plasma production





Measurements of wave in plasma: Special probes development

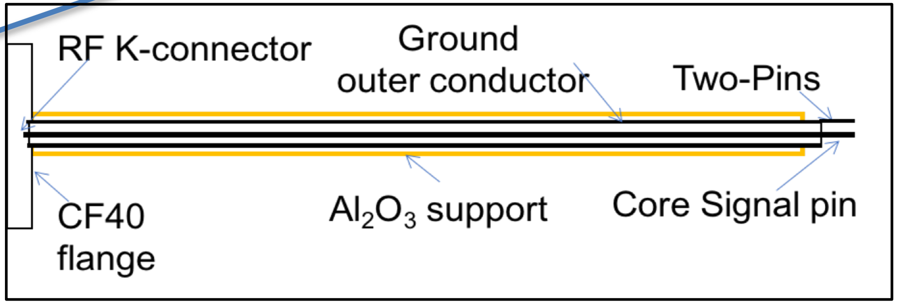
- ***sensitive to the short wavelength*** of longitudinal waves near the resonance layer
- ***polarization sensitive, the electrostatic radial component***
- **small enough to have the desired spatial resolution**



Simulated Electric filed profile along longitudinal z-axis and transversal x-axis of FPT

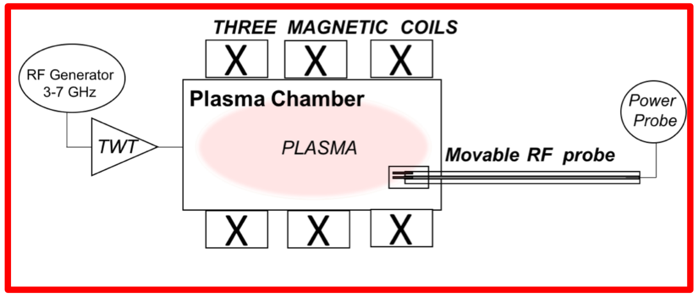
Measurements of waves in plasma SETUP: HF probes

Al_2O_3 support



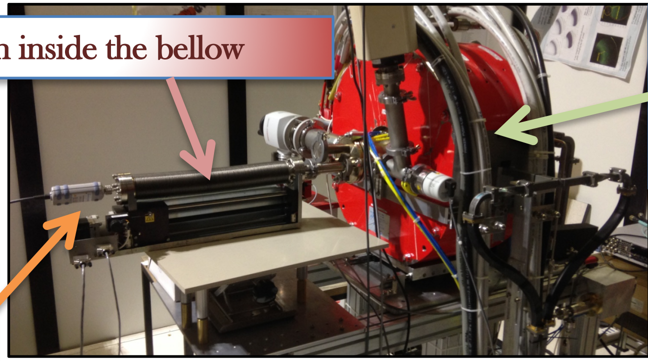
Two-Pins
length of 3.5 mm
a distance of 2 mm

"Customized" Microwave coaxial Cable "Sucoflex 102" DC/40 GHz enclosed in Alumina tube



Schematic of the FPT experimental setup at INFN-LNS

Installation inside the bellow

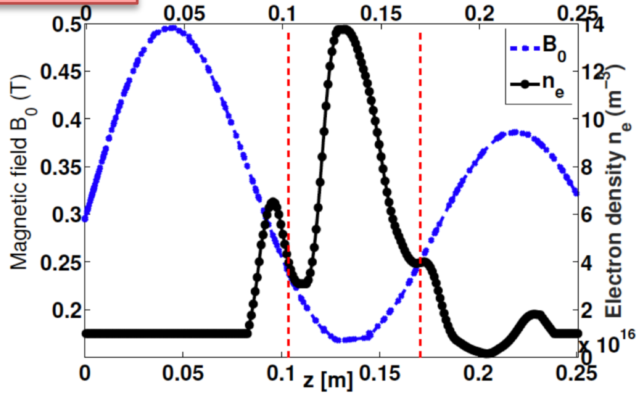


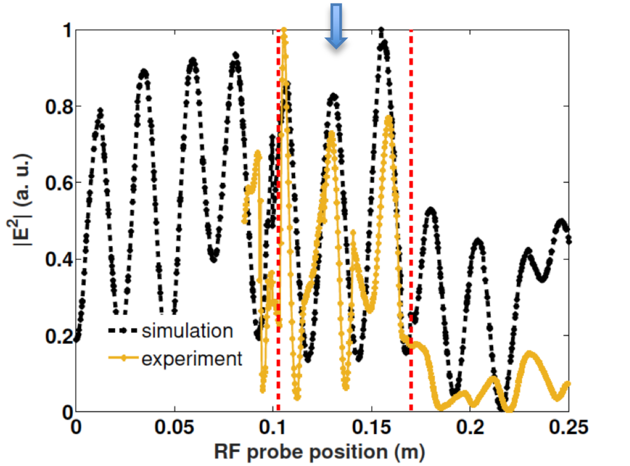
FPT magnet sorrounding Plasma chamber

Power probe

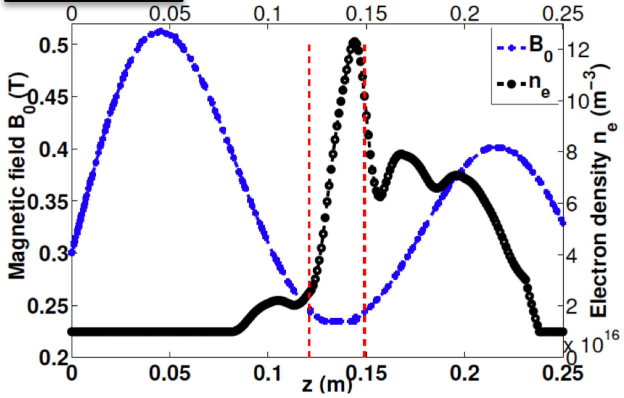
EXPERIMENTAL RESULTS

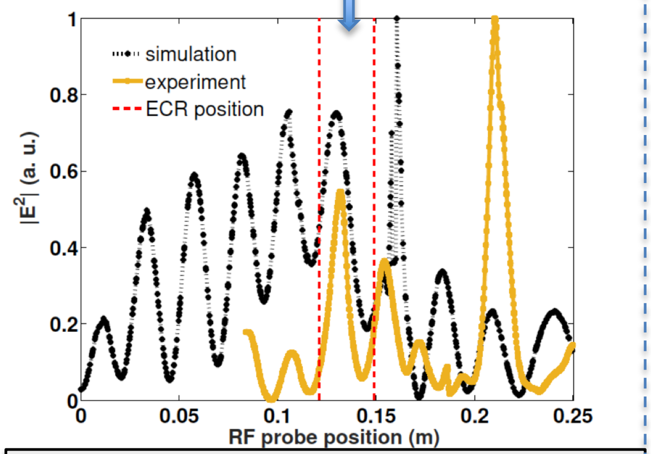
Case 1



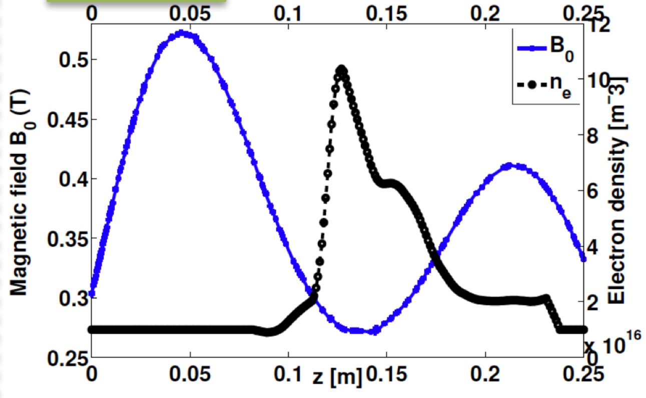


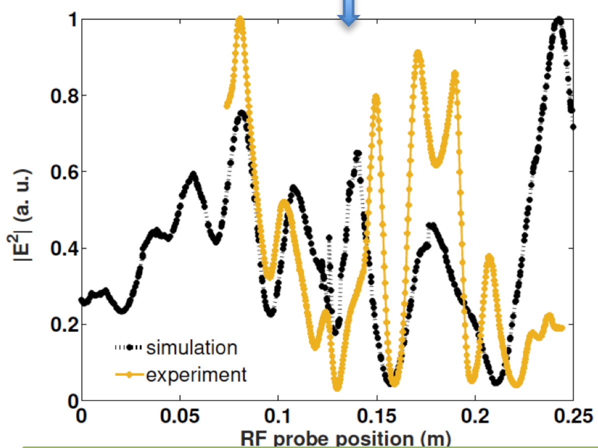
Case 2





Case 3





Case 1: w_{ECR}= 70 mm.
The largest plasma volume enclosed by the ECR layers.
There is an **excellent agreement between simulated and measured RF field distribution**

Case 2: w_{ECR}= 30 mm. The plasma volume is smaller.
The agreement between simulated and measured RF field distribution is still evident.

Case 3: $w_{ECR} \rightarrow 0$.
This represents a critical configuration.
General agreement even if locally the two plots deviate somewhere

- **The excellent agreement between model predictions and experimental data are very promising** for the study and design of future launchers or "exotic" shapes of the plasma chambers in compact machines, such as ECR Ion Sources and other similar devices

["ECR ION SOURCES - PAST, PRESENT AND FUTURE", *Columbia University, Claude Lyneis LBNL*]:

Questions:

– How strong is the RF coupling/damping in an ECR plasma chamber?

– What limits the plasma density?

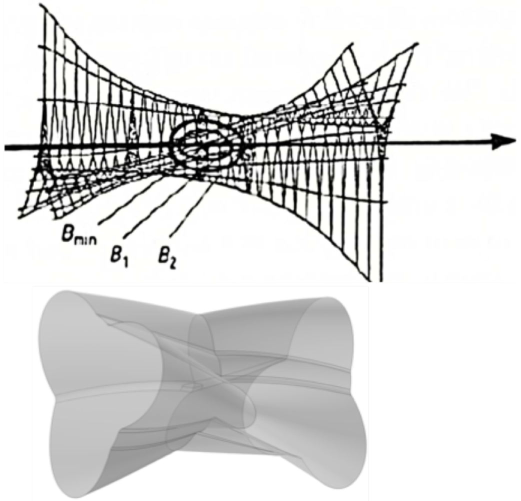
– How can we get a handle on these questions?

PERSPECTIVES

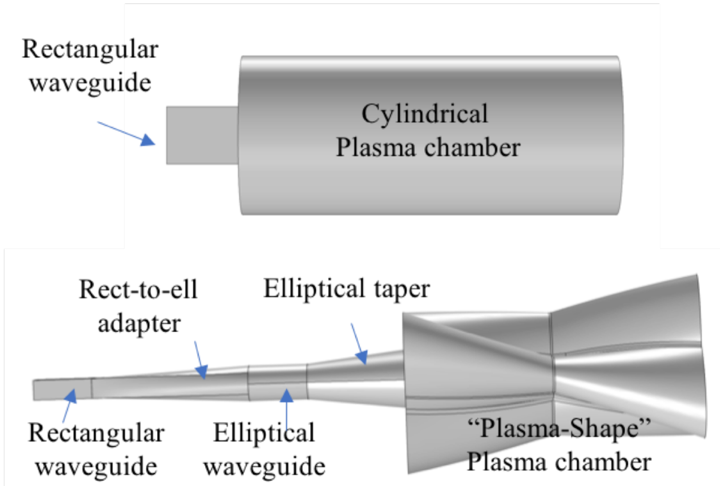
- **short term (2 years)** Reshaping plasma chambers with non-conventional features;
- **short/mid-term (3 years):** new launchers based on waveguide arrays,, especially for new schemes of ECR-Heating such as Bernstein Waves, and for ECRIS still fulfilling frequency scaling laws above 28 GHz (quasi-optical approach);
- **Long Term (2-5 years):** futuristic all-dielectric mm-waves launching structures.

Reshaping plasma chambers with non-conventional features

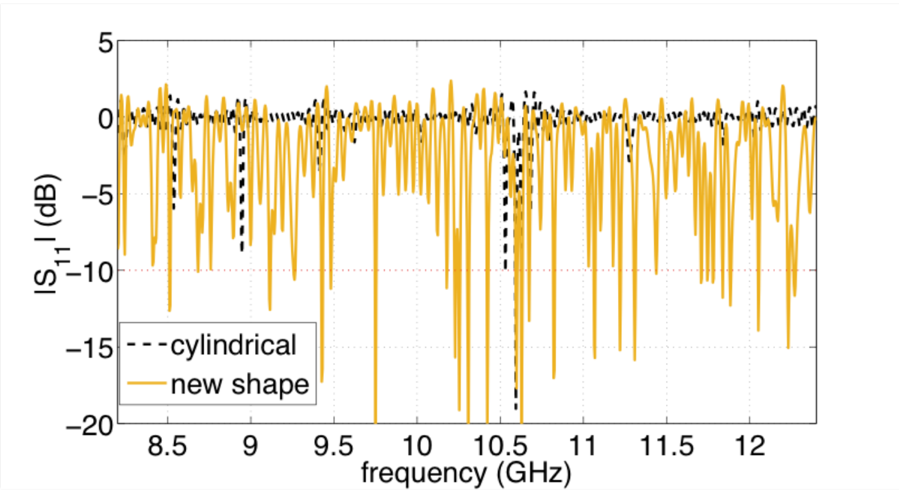
short term (2 years)



Sext-in-Sol magnetic field structure



new-shaped" plasma chamber



CST simulated Reflection coefficient

Cylindrical symmetry is **broken,**

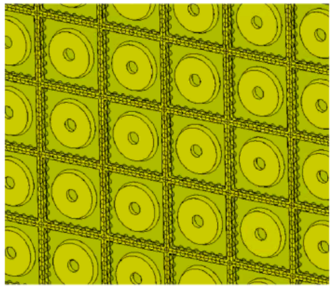
RF matching is dramatically improved

short/mid-term (3 years):

Phased Array

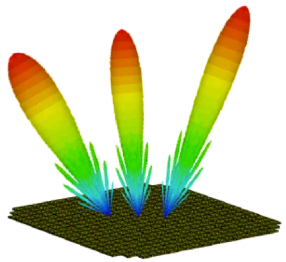
What are they?

Many radiators in close proximity



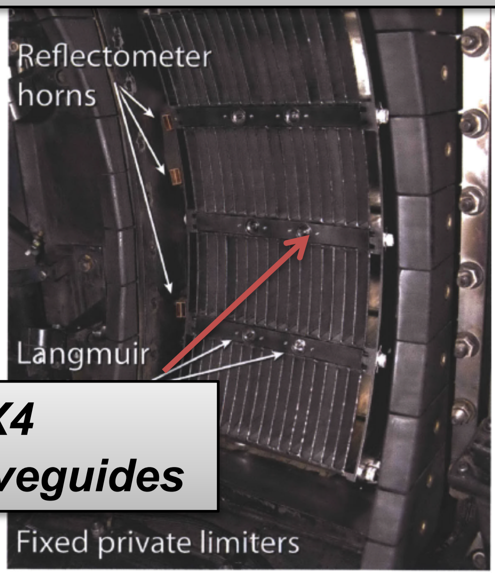
Why are they used?

Beam control with fixed geometry



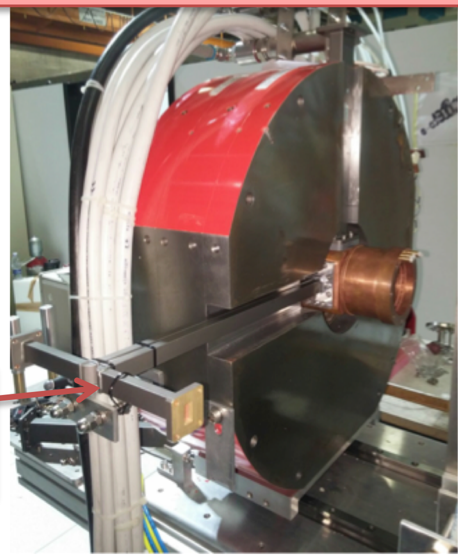
Alternative Microwave-plasma heating

Phased Array on a fusion reactor: waveguide "grill"



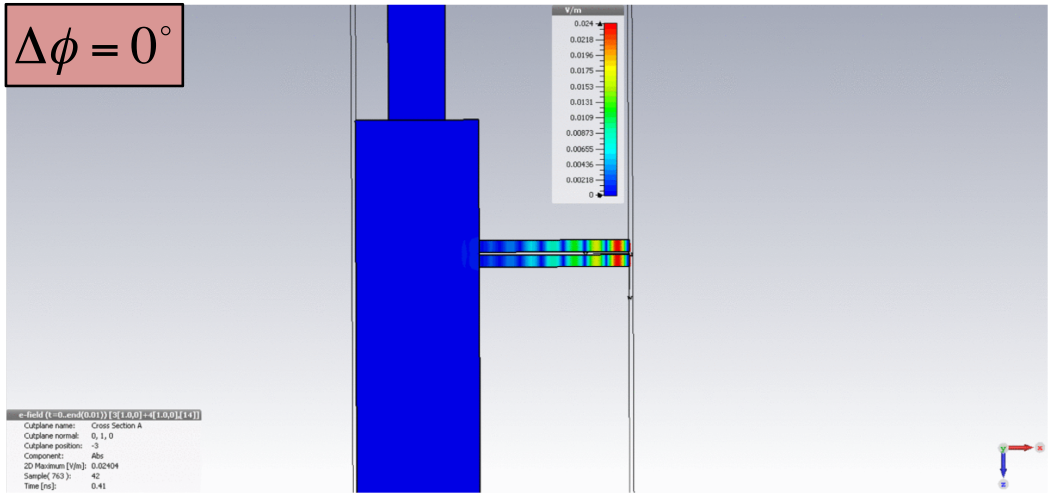
16X4 waveguides

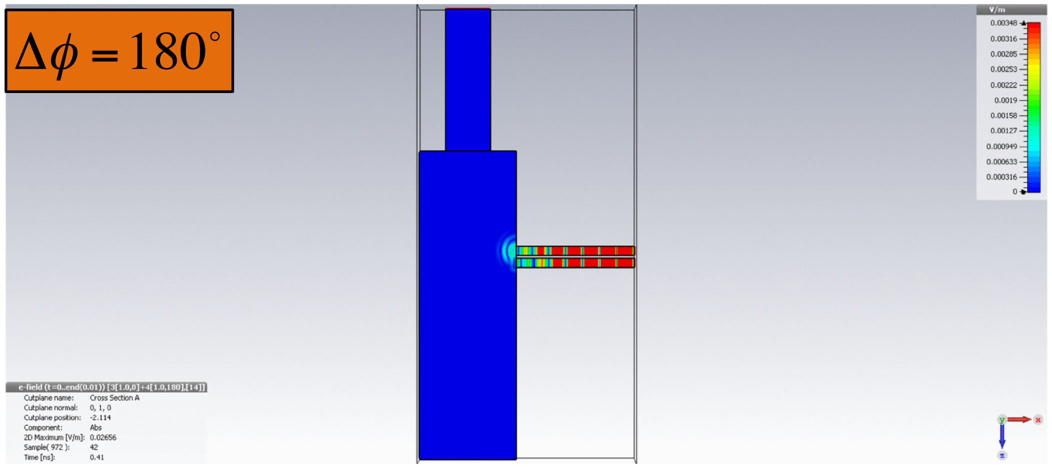
Phased Array on a Ion source plasma reactor: two waveguide array



2X1 waveguides

Phased waveguide array of two elements: FIT FDTD Simulation

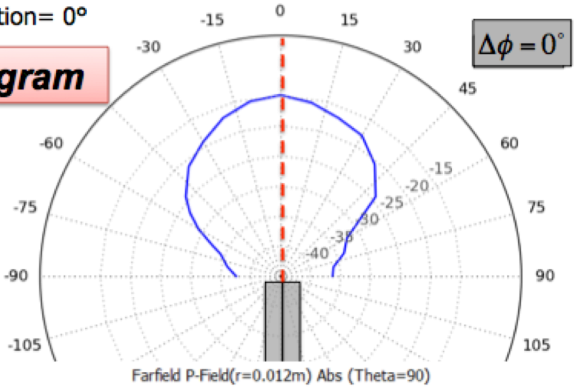




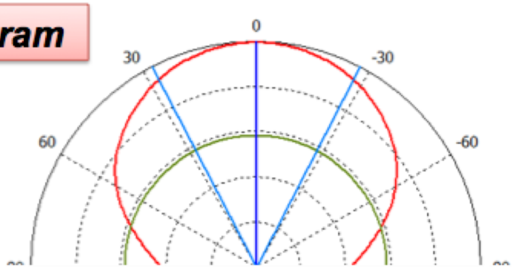
Radiation Diagrams @ 14 GHz

Main lobe direction= 0°

Measured diagram

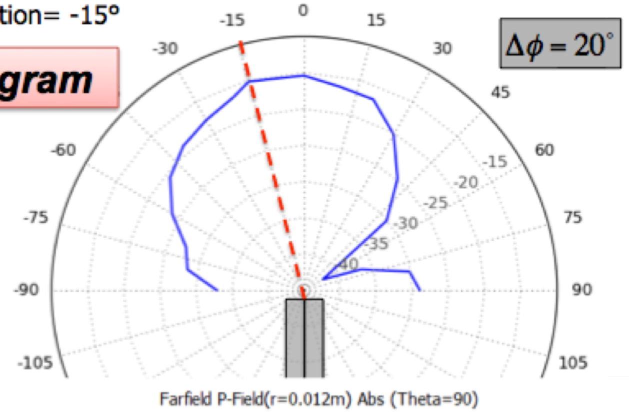


Simulated diagram

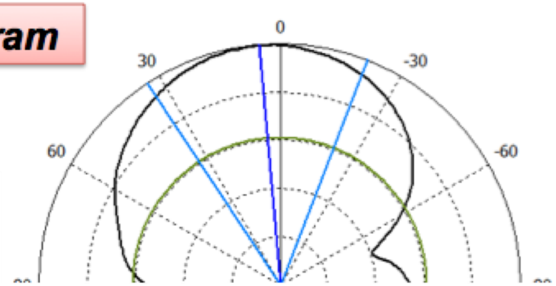


Main lobe direction= -15°

Measured diagram

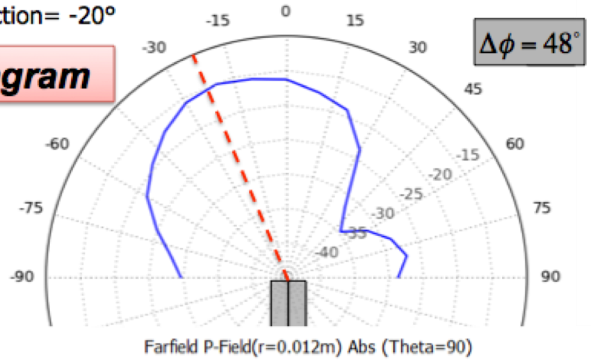


Simulated diagram

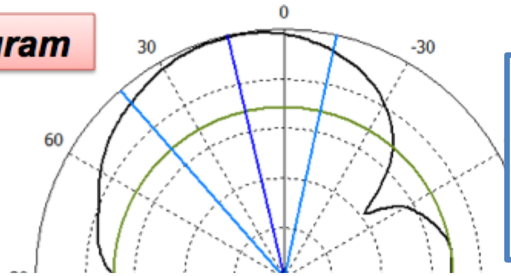


Main lobe direction= -20°

Measured diagram

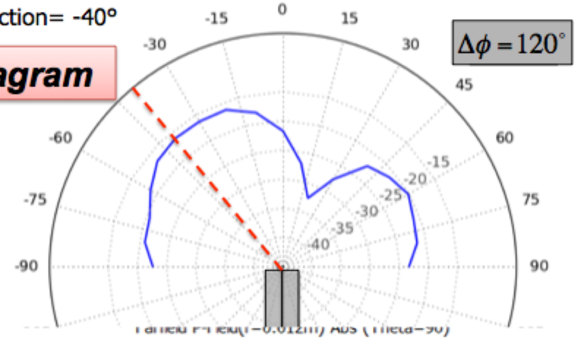


Simulated diagram

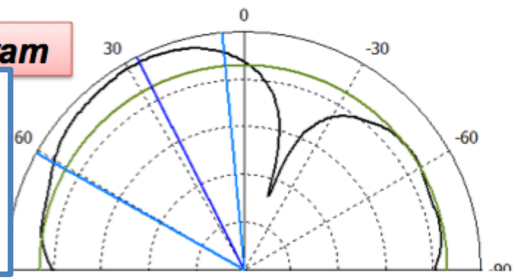


Main lobe direction= -40°

Measured diagram



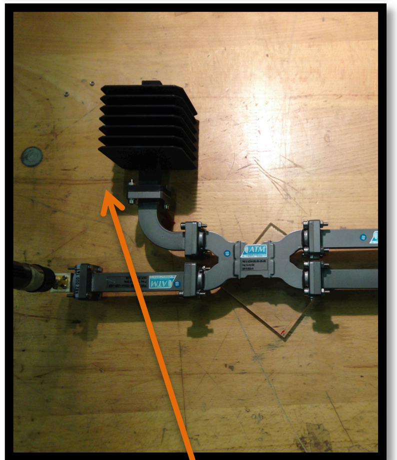
Simulated diagram



- **G. Torrisi, G. Sorbello, O. Leonardi, D. Mascali, L. Celona, and S. Gammino, *A new launching scheme for ECR plasma based on two-waveguides-array*,** Microw. Opt. Technol. Lett., 58: 2629–2634. doi:10.1002/mop.30117

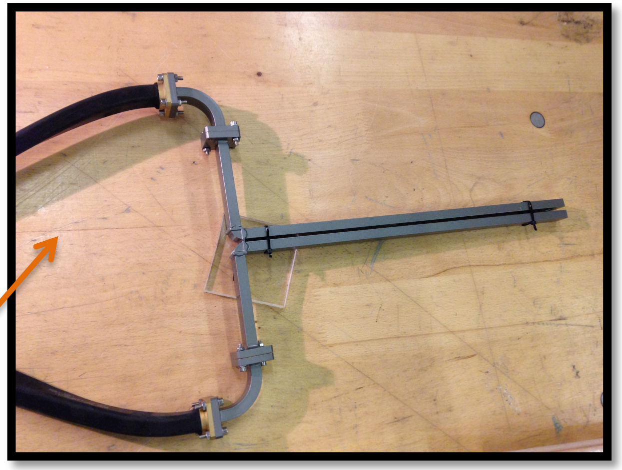
Microwave launcher Antenna assembly

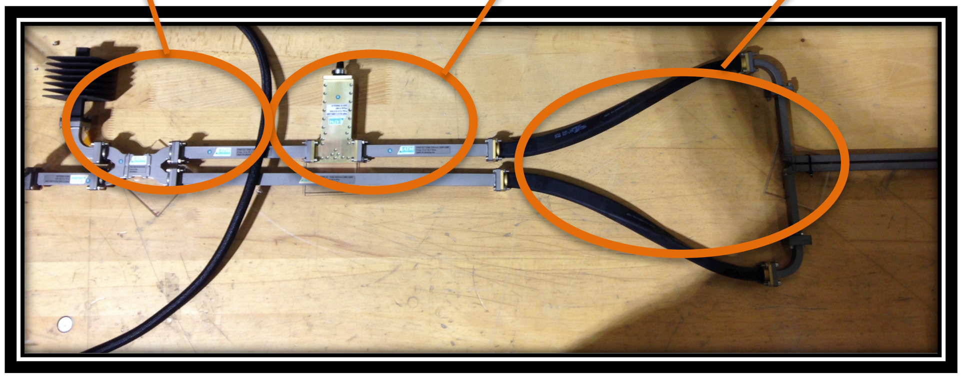
Power divider



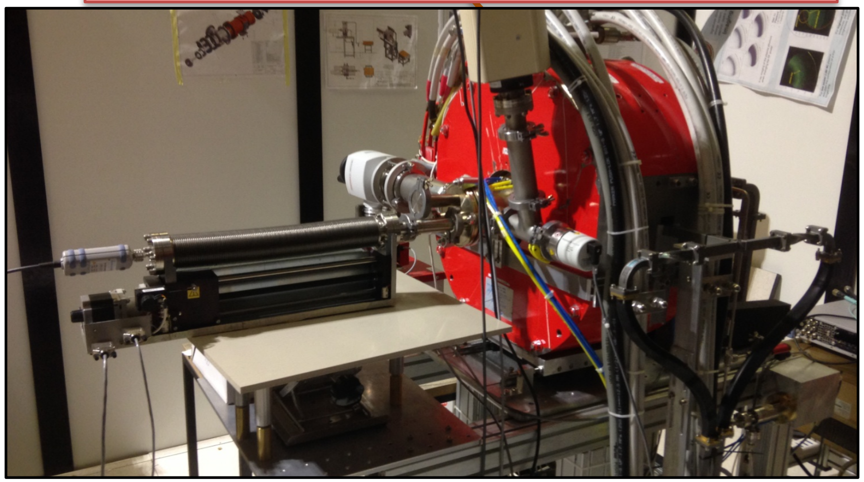
Phase shifter

Two **Cut Waveguides Array** as **antenna**





Microwave launcher Antenna assembly

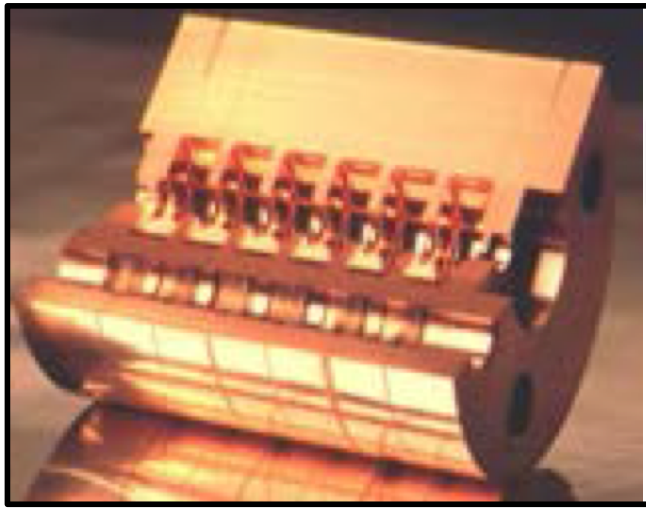


["ECR ION SOURCES - PAST, PRESENT AND FUTURE ", Columbia University, Claude Lyneis LBNL]:

«Frequency scaling is roughly correct from 6 to 28 GHz and is expected to work for 4th generation ECR's at ~50 GHz

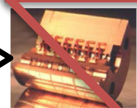
«The technical challenges at 50 GHz make it attractive to look for new approaches»

Conventional RF technology scaled down?



$\lambda \sim$[cm]

Conventional RF technology scaled down?



$\lambda \sim$ [sub-mm]

- Metal absorbs at higher frequency
- Difficult to fabricate

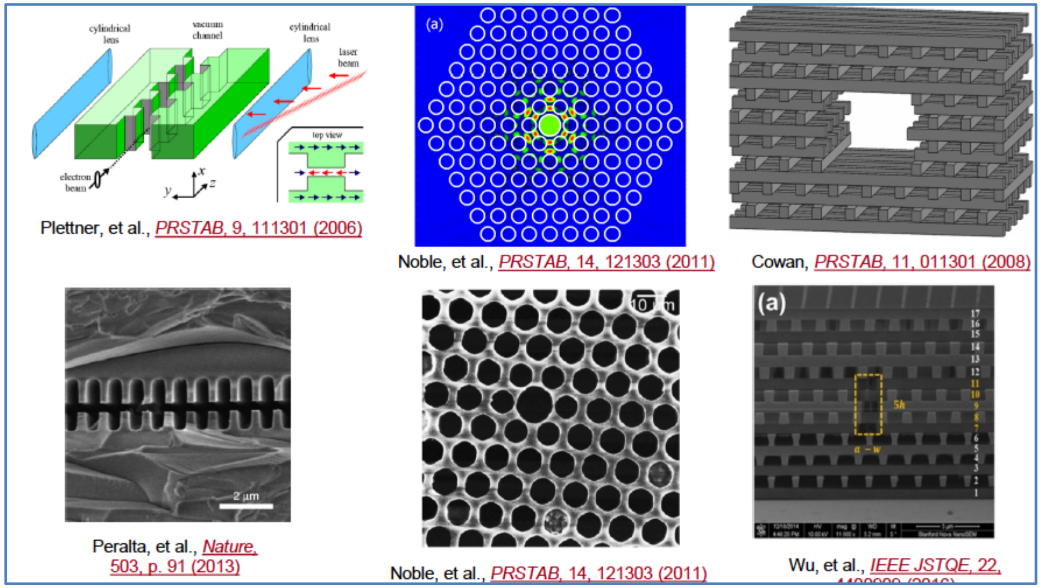
Dielectric accelerator structures

Types:

- Dielectric wall acceleration
- Dielectric wakefield acceleration
- Dielectric laser acceleration
- Dielectric assisted waveguide
- Dielectric loaded waveguides

Advantages:

- High breakdown threshold (1-5 GV/m)
- High frequency operation
- Can reduce wakefields (photonic crystals)
- Mature fabrication technologies available



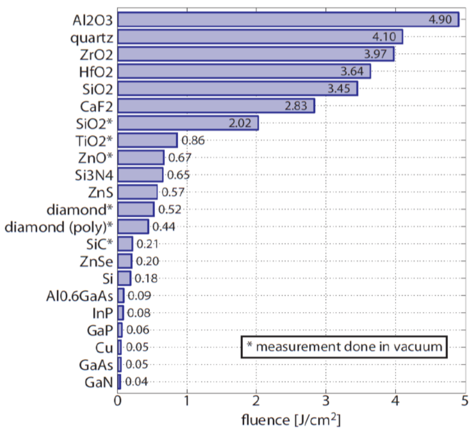
Plettner, et al., PRSTAB, 9, 111301 (2006)
Noble, et al., PRSTAB, 14, 121303 (2011)
Cowan, PRSTAB, 11, 011301 (2008)
Peralta, et al., Nature, 503, p. 91 (2013)
Noble, et al., PRSTAB, 14, 121303 (2011)
Wu, et al., IEEE JSTQE, 22,

Structure proposed

A range of proposals:

- ❑ Lin (2001),Mizrahi and Schachter (2004)
- ❑ Cowan (2008), Naranjo et al. (2012)
- ❑ First demonstration - Peralta et al. (2013)

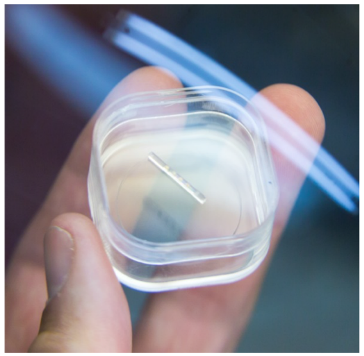
Dielectric High Damage threshold



High gradients enable compact linear accelerators

Accelerator on a Chip International Program (ACHIP)

Stanford , UCLA, EPFL, TU Darmstadt , Tech-X



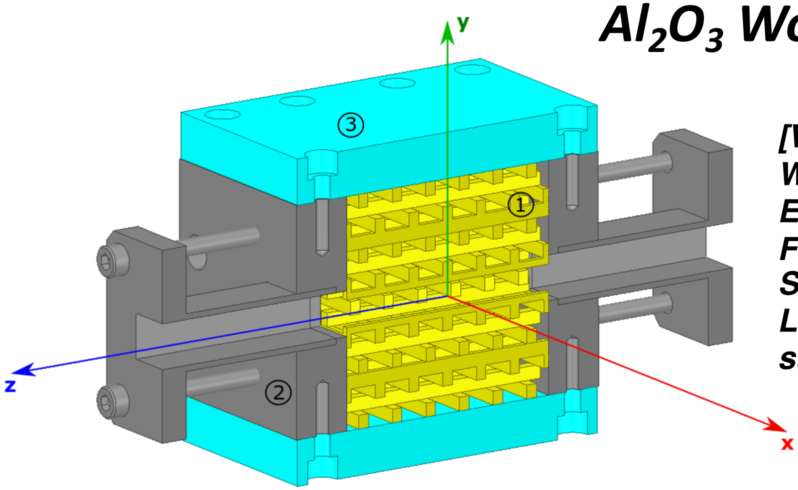
[Wootton, SLAC – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017 7]

Long Term
(2-5 years)

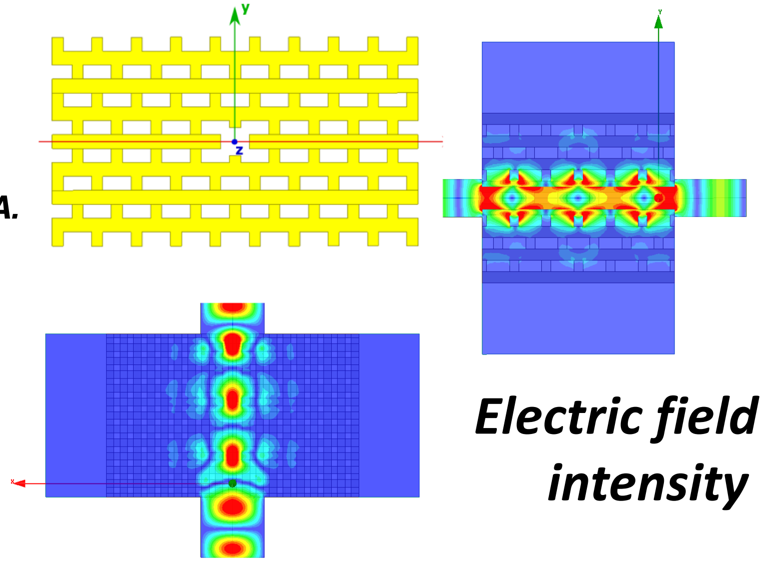
All-dielectric structures

Proof-of-concept experiments are taking place @LNS

Al_2O_3 Woodpile structure as a DC-BREAK

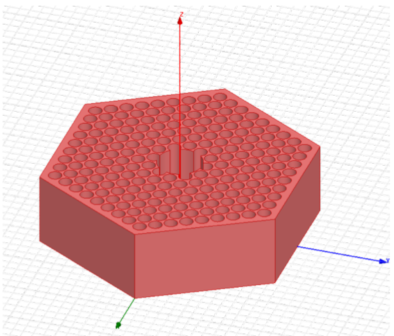


[WOODPILE EBG WAVEGUIDE AS A DC ELECTRICAL BREAK FOR MICROWAVE ION SOURCES, G. S. Mauro, A. Locatelli, G. Torrisi et al; submitted on MOTL]

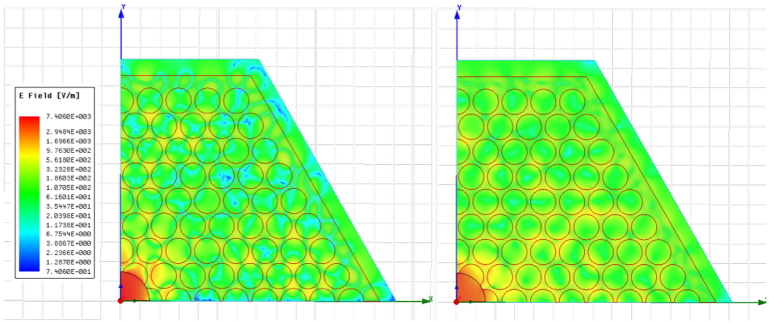


Electric field intensity

DC break including: (1) Al_2O_3 woodpile structure, (2) metallic waveguides flanges, (3) top and bottom PMMA covers.



Dielectric waveguide



electromagnetic field

[Leonardi, Torrisi et al., «Hollow-core Electromagnetic Band Gap Waveguide as DC-break for Ion Sources», PIERS 2017]
[Locatelli, Sorbello, Torrisi et al., Photonic Crystal Waveguides for Particle Acceleration; 2017]

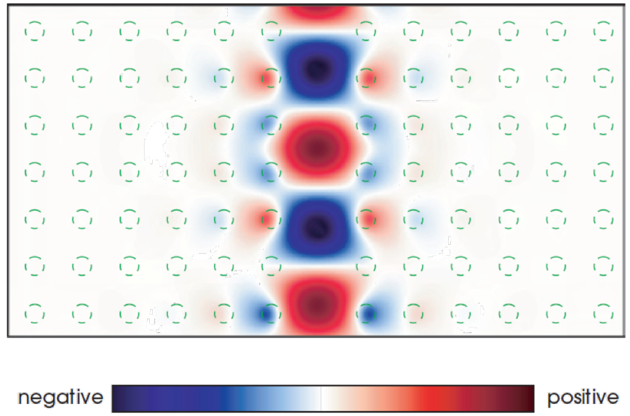
All-dielectric mm-waves launching structures

Long Term (2-5 years)

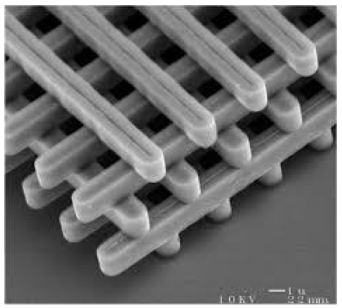
Emerging electromagnetic concepts

- Photonic Crystal (PhC) technology
- Metamaterials
- Engineering of the geometry of the structure allows for creation of "artificial materials" for unusual EM responses
- Scalability
- Potentially low cost TM01 mode

Dielectric EBG waveguide

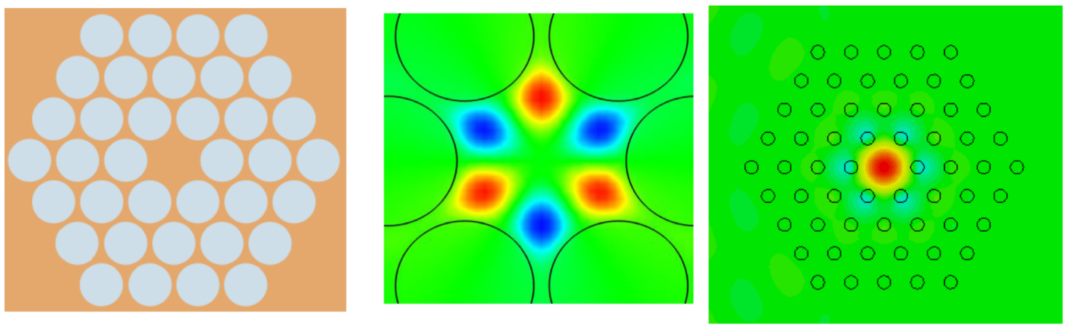


periodic dielectric structures allows Manipulation of the electromagnetic properties of materials



Reinvent resonant structures using dielectric

dielectric cavity



Conclusion

- The **wave propagation in plasmas has been modelled** with **a full wave numerical** approach under **"cold" plasma approximation**.

- For the first time, **the electric field amplitude has been measured by mean of a two-pins RF probe** in a compact plasma trap in conditions resembling very closely the features of a **common simple-mirror-configuration ECR ion source.**

- **The excellent agreement between model predictions and experimental data are very promising** for the study and design of future launchers or "exotic" shapes of the plasma chambers in compact machines, such as ECR Ion Sources and other similar devices

- **Further steps forward are going to be done as concerning the improvement of the model, including the "hot" plasma tensor**: this will perspectively allow to master additional mechanisms such as modal conversion at the hybrid resonance.

The authors wish to thank the 5th Nat. Comm. of INFN, under the Grant PANDORA for the financial support.
We wish to acknowledge the support of A. Caruso, Alberto Longhitano, S. Passarello, and of the INFN-LNS mechanical workshop for the design and manufacture of several items.

Thank You!

G. Torrisi[1], D. Mascali[1], A. Galatà[2], L. Celona[1], G. Sorbello[1,3]
G. Castro[1], G. Mauro[1], M. Mazzaglia[1], E. Naselli[1,4], S. Gammino[1]

1) *INFN - Laboratori Nazionali del Sud, Catania, Italy*
2) *INFN- Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy*
3) *Università degli Studi di Catania, DIIEI, Catania, Italy*
4) *Università degli Studi di Catania, DFA, Catania, Italy*