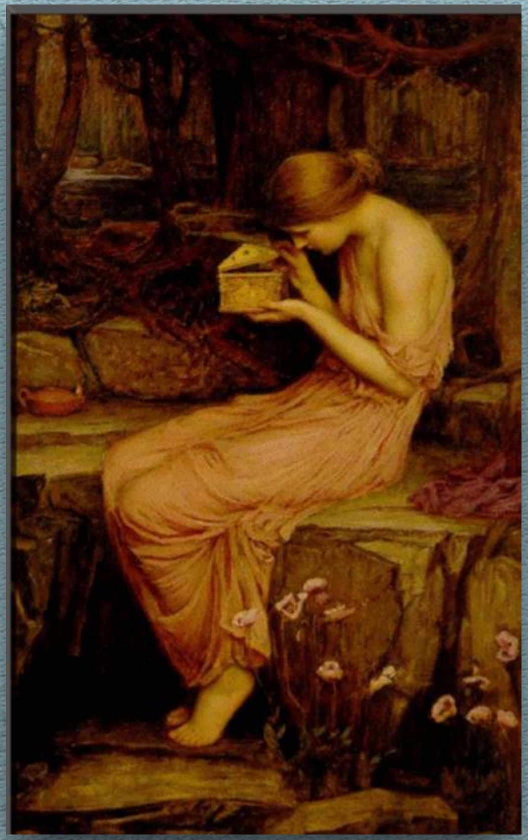
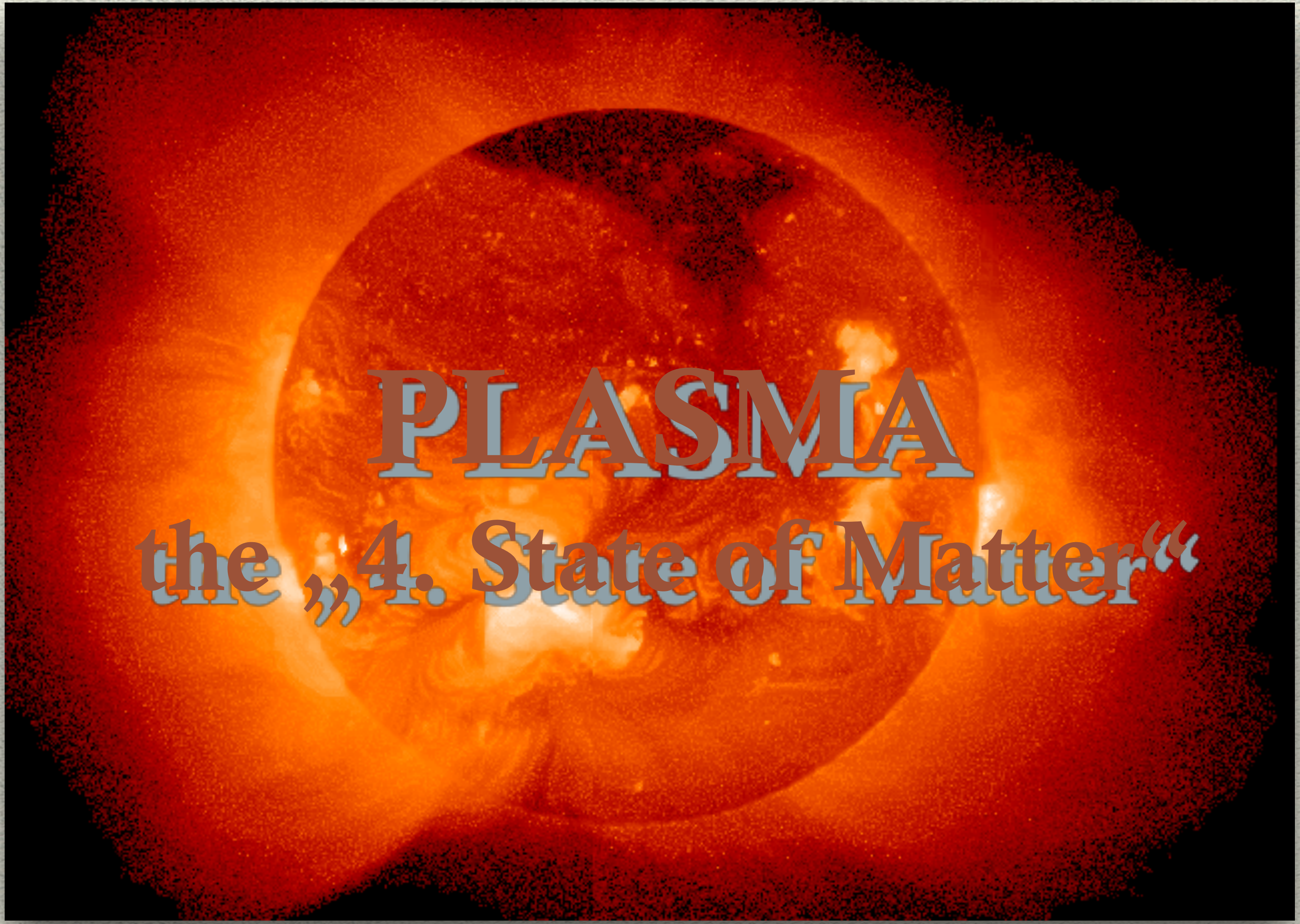



**P**lasmas for
**A**strophysics,
**N**uclear
**D**ecays
**O**bservation and
**R**adiation for
**A**rchaeometry

David Mascali, INFN
Laboratori Nazionali del Sud - 18 Feb. 2019

# Physics and Technology of magnetized plasmas

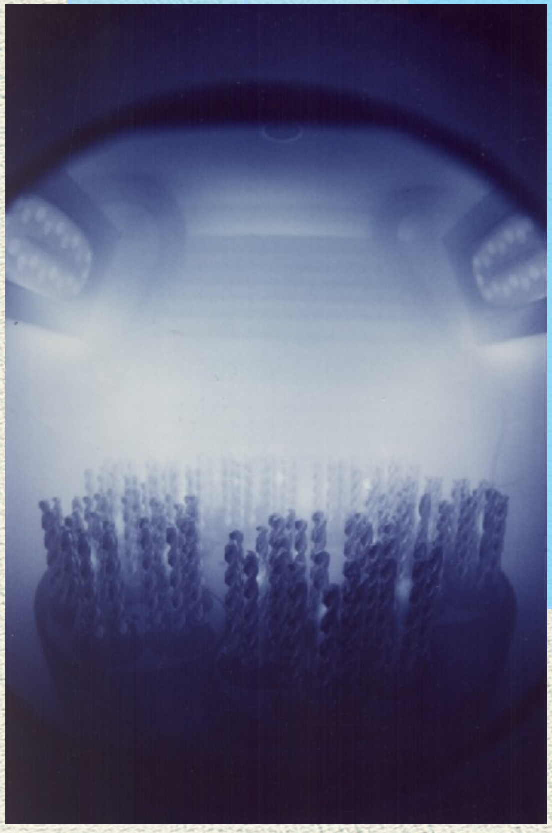

PLASMA
the „4. State of Matter“

# *Some Applications*

Light

(see lamps und projector)

Surface Hardening



Plasma Monitor (Television)

large, well resolving, flat

cold plasma

Surface Refinement

Plasma treated roof of the cathedral „Christ the Saviour“ in Moscow. Steel tiles covered with films of Titanium Nitride and diamond-like carbon

# Main Plasma Constituents

- positively charged ions
- electrons
- neutrals

# Key Plasma Properties

- quasineutrality
- collective behavior

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# *Electron Temperature and Distribution Functions*

Weakly ionized plasma is a mixture of different gases:

neutral gas, ion gas and electron gas.

Under the action of electromagnetic fields electrons gain much more energy from the EM-field than ions. Their mean energy exceeds by far the mean energy of the ions and the neutrals. Thus

$$T_e >> T_+, \mathrm{T}_n$$

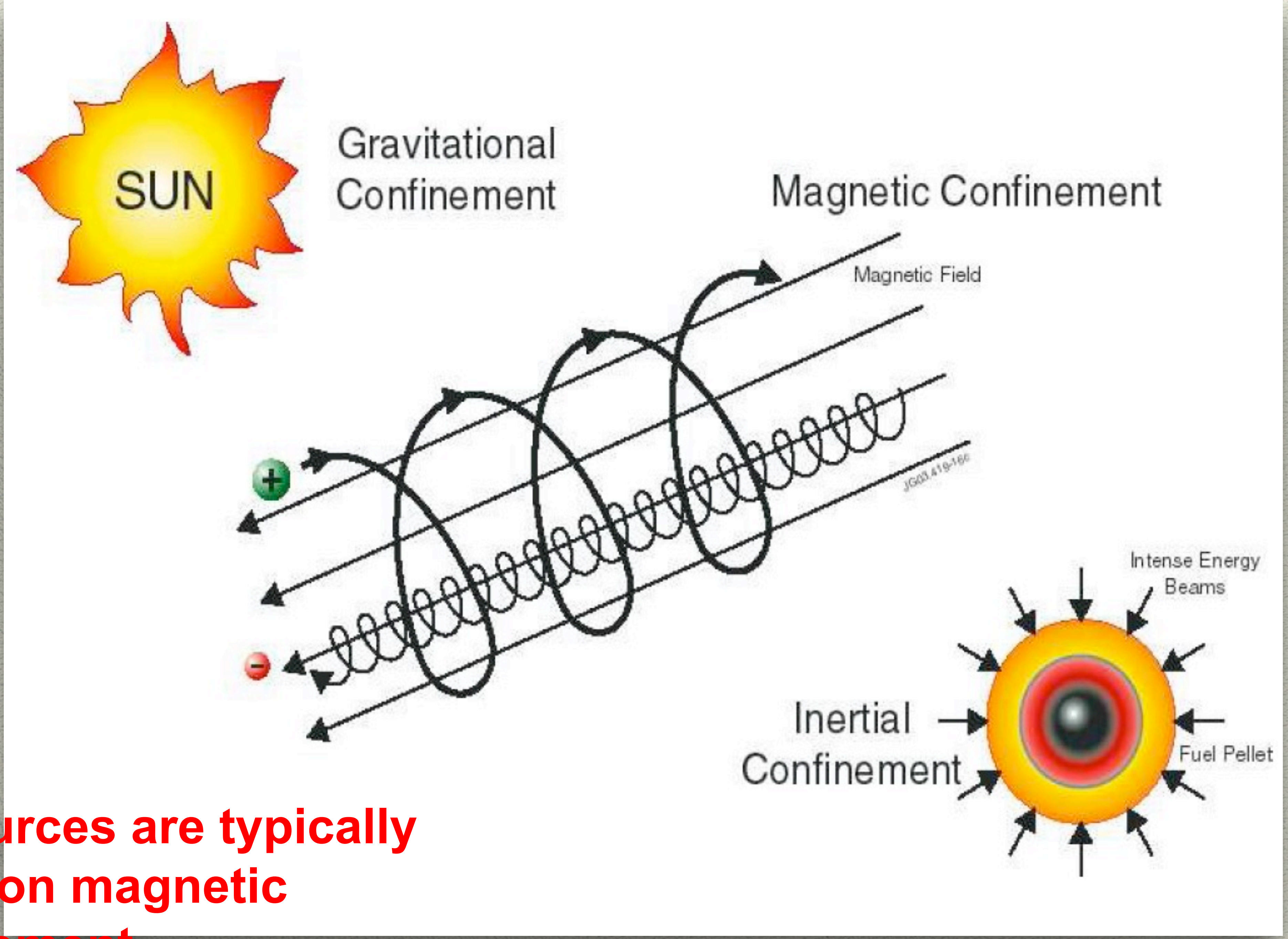
In plasma temperatures are measured in eV:

$kT$ = 1eV corresponds to $T$ = 11600 K

Typical values: $kT_e = 1 \ldots 10^4$ eV for electrons (i.e. $10^4 - 10^8$ °K !!)

$kT_+ = 0.03 \ldots 1$eV for *ions*

# How do plasmas can be confined?



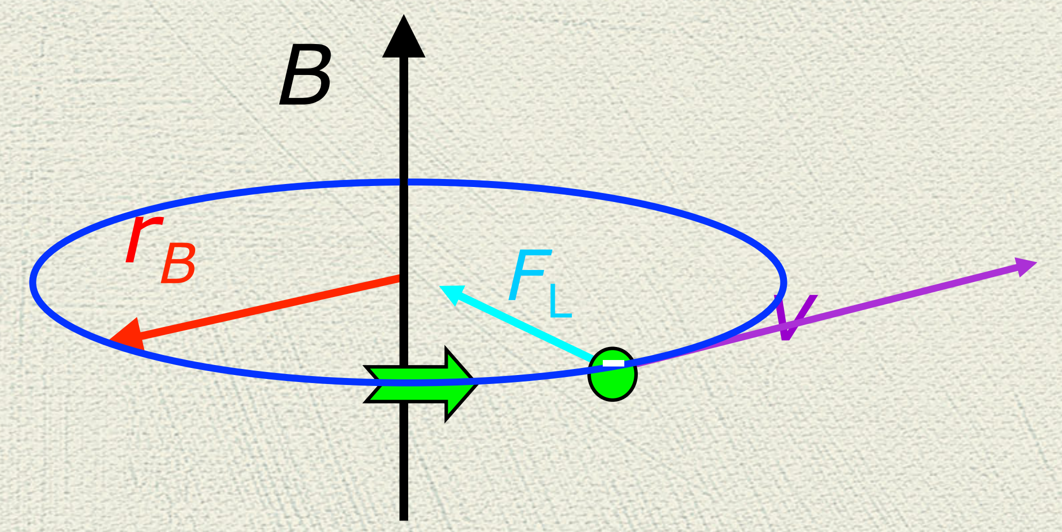

**Ion sources are typically based on magnetic confinement**

# Gyration of ions and electrons under the action of a static magnetic field

❖The Lorentz force $\boldsymbol{F}_{\mathrm{L}}$ exerted by a static magnetic field of induction $B$ on particles of mass $m$ bearing an elementary charge $e$ causes a circular motion.

❖The radius (cyclotron radius) $r_{\mathrm{B}}$ of the circular trajectory is given by $r_{\mathrm{B}}=mv/eB$

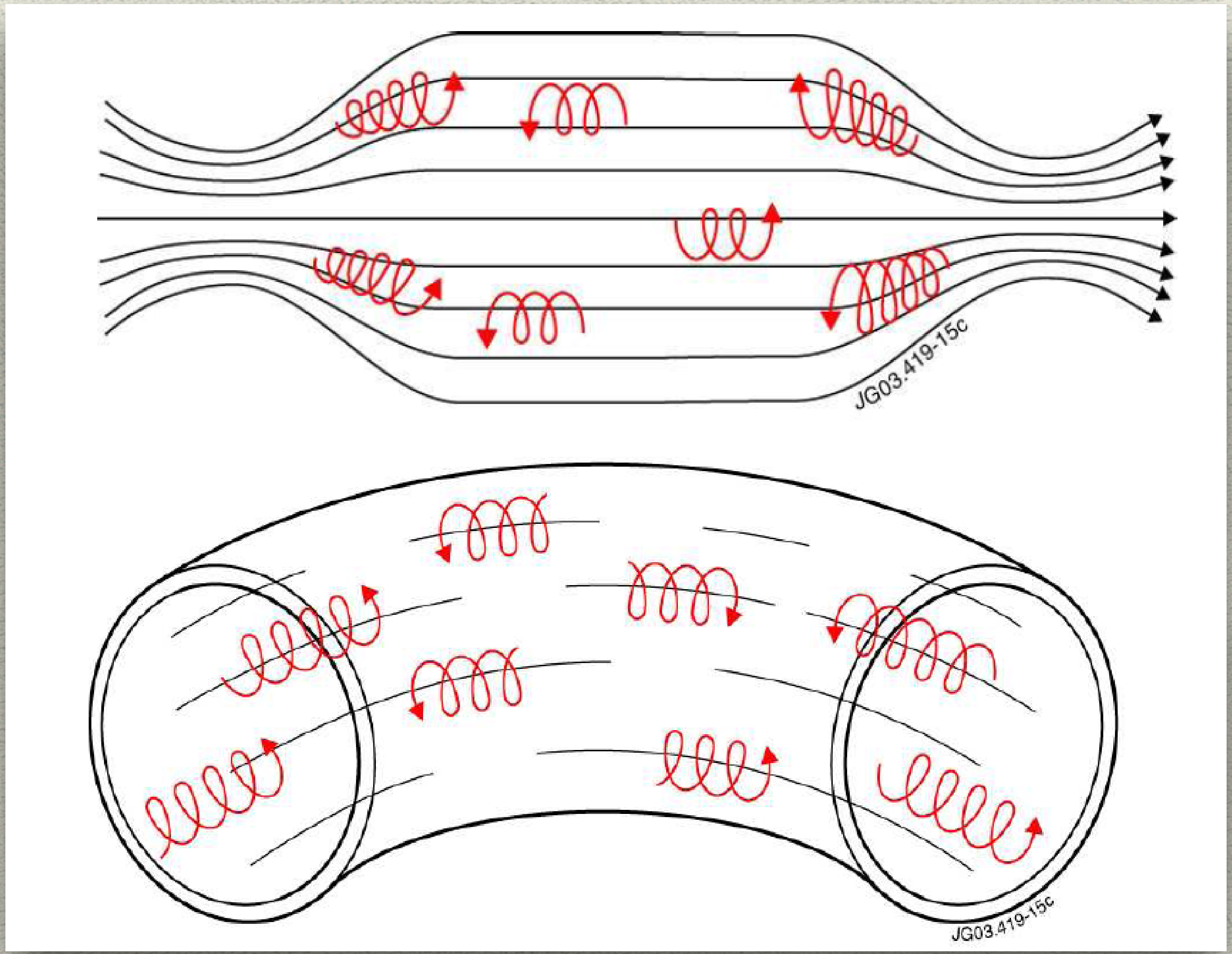
❖The corresponding cyclotron frequency $\omega_{\mathrm{B}}$ does not depend on the particle velocity $v$: $\omega_{\mathrm{B}}=eB/m$




$$F_{\mathrm{L}} = qv \times B$$

# Magnetic Confinement

Magnetic fields intrinsically force charged particles to reduce freedom degrees: electrons spiralyze around the field lines and can be trapped for several ms in mirror machines or toroidal structures.




**MIRROR STRUCTURES** have axial symmetry and can be produced by sequences of room temperature or SC coils. They are commonly used in ion sources field

**TOROIDAL CONFINEMENT** is typical of Fusion Machines like TOKAMAKS or STELLARATORS

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# The ideal confinement requires some stringent conditions on plasma equilibrium and stability

Plasma can also be viewed as fluids. Therefore the confinement and its equilibrium and stability can be investigated by looking to the equilibrium between the plasma kinetic pressure and the magnetic (confining) field pressure.

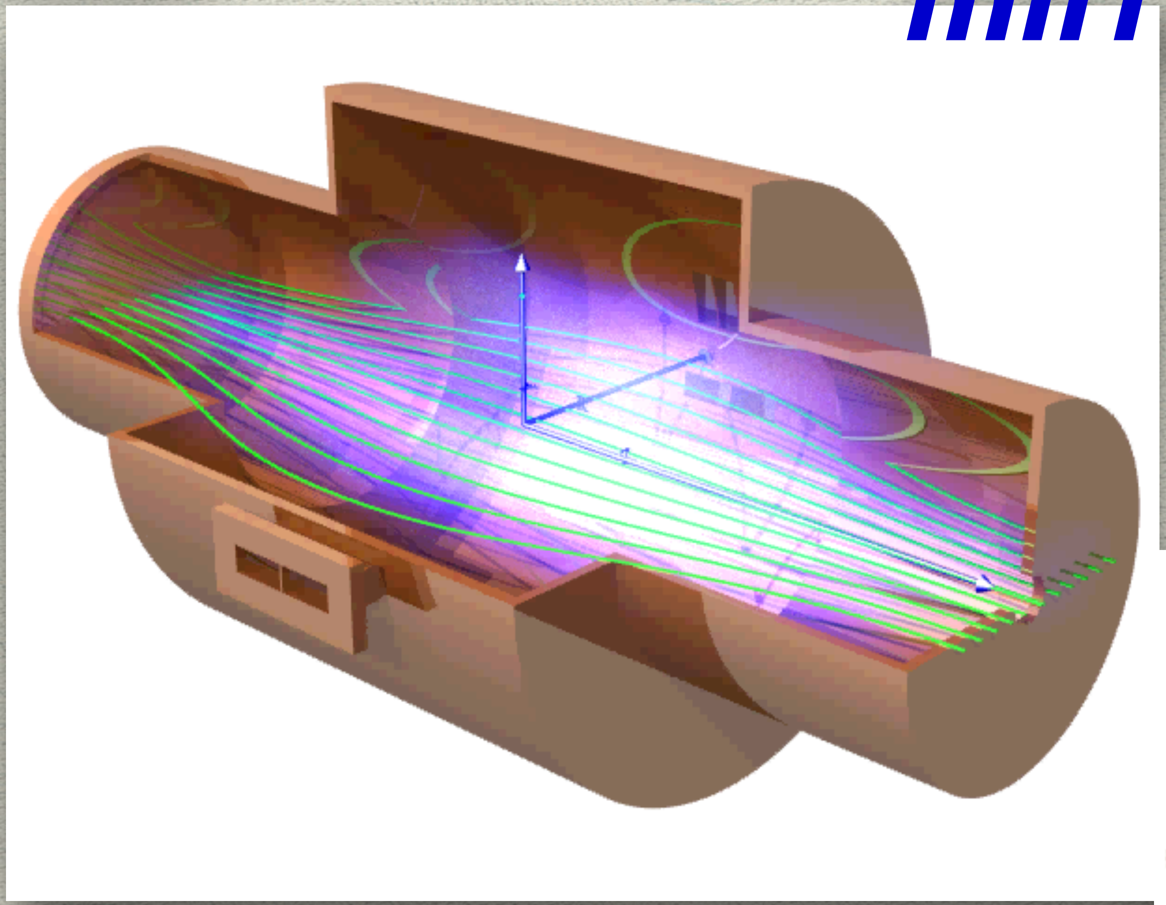
$$\boxed{p + \frac{B^2}{2\mu_0} = costante}$$

The stability of the confinement can be studied as a function of the β parameter, which is the ratio between the kinetic and magnetic pressures.

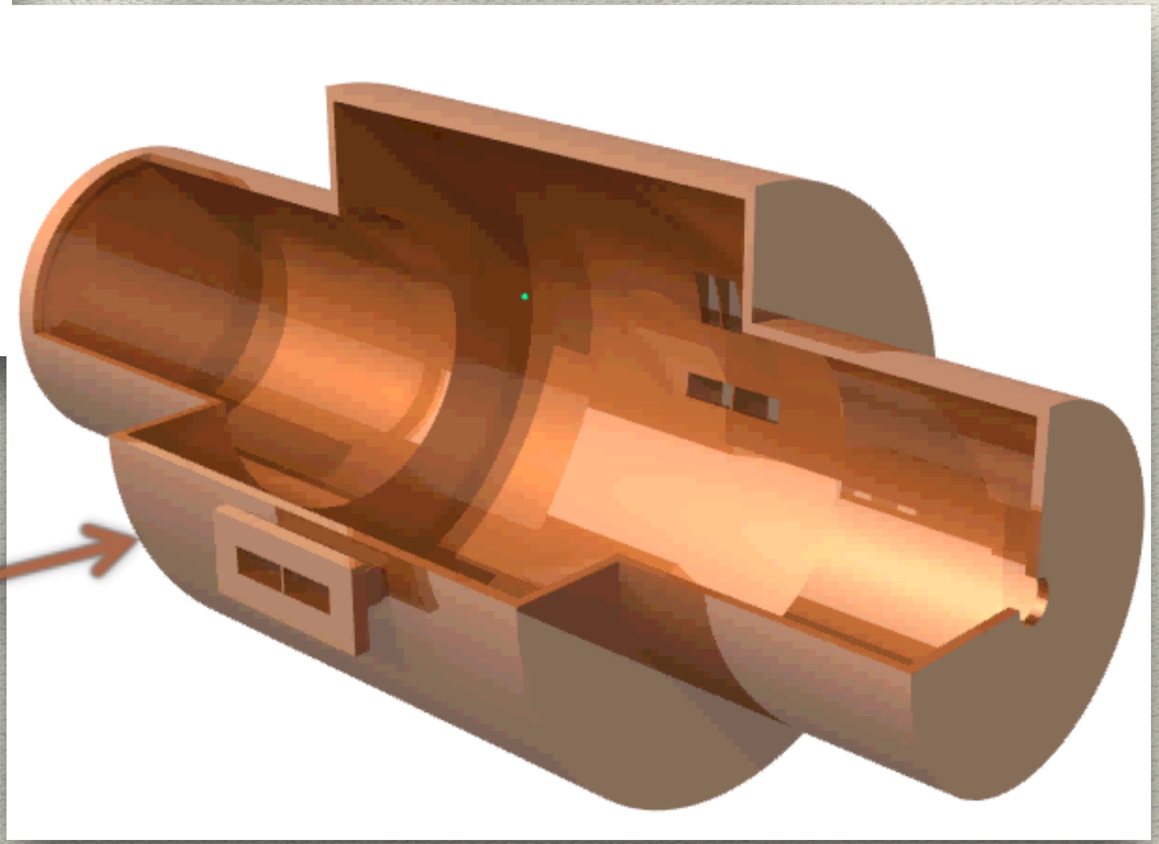
$$\boxed{\beta \equiv \frac{\sum nkT}{\frac{B^2}{2\mu_0}}}$$

The condition for a magnetically stable plasma is that $\beta << 1$

# Principles of magnetic mirrors



Particles trajectories in plasmas are affected by several drifts, due to spontaneous or induced E fields, B lines curvature, B gradient, gravity, etc…



Particles rebounce inside the trap and are contemporaneously affected by the "phi" drift around the magnetic axis, due to the B curvature and axial gradient

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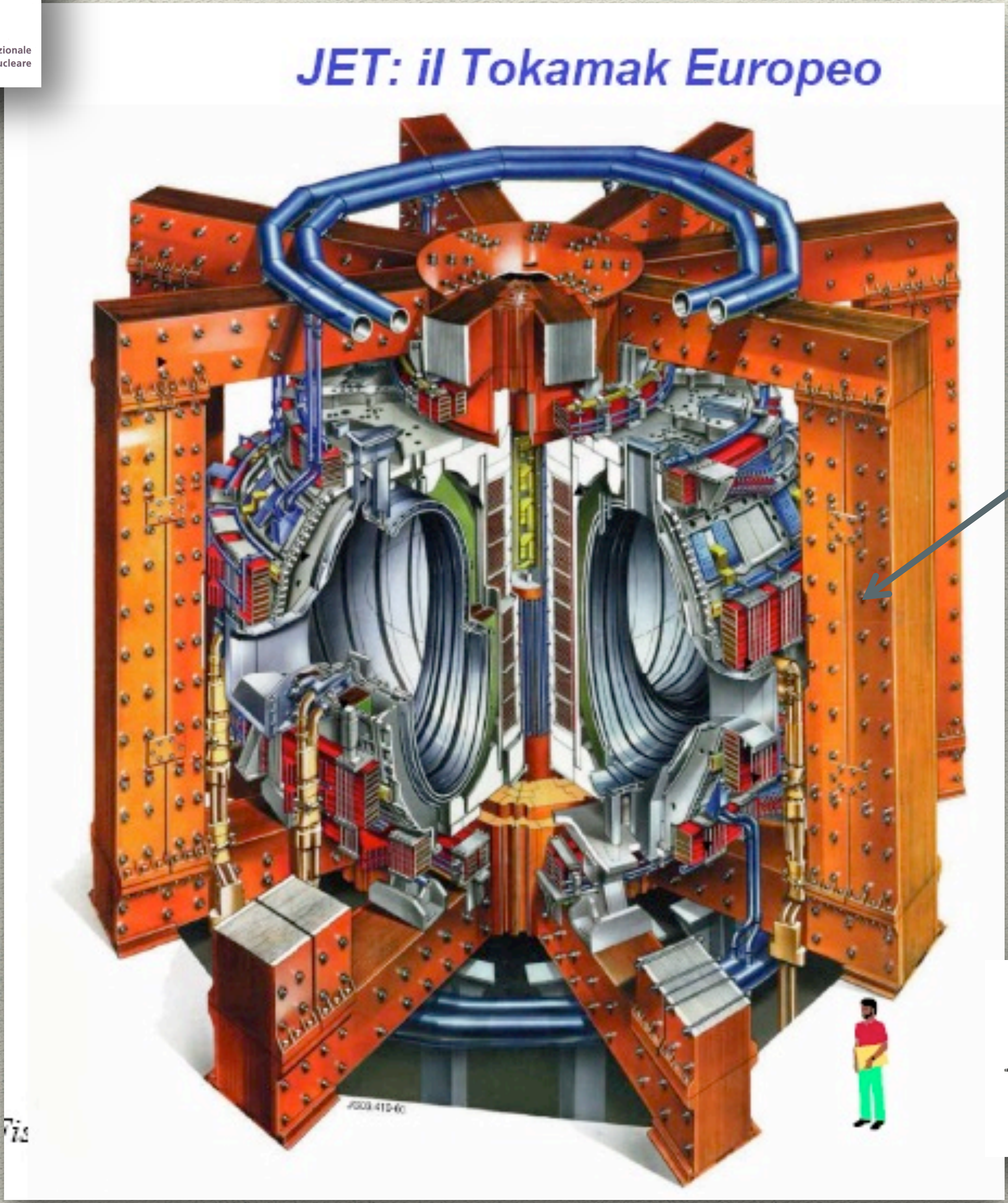
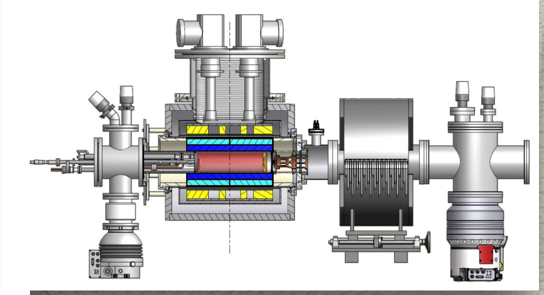
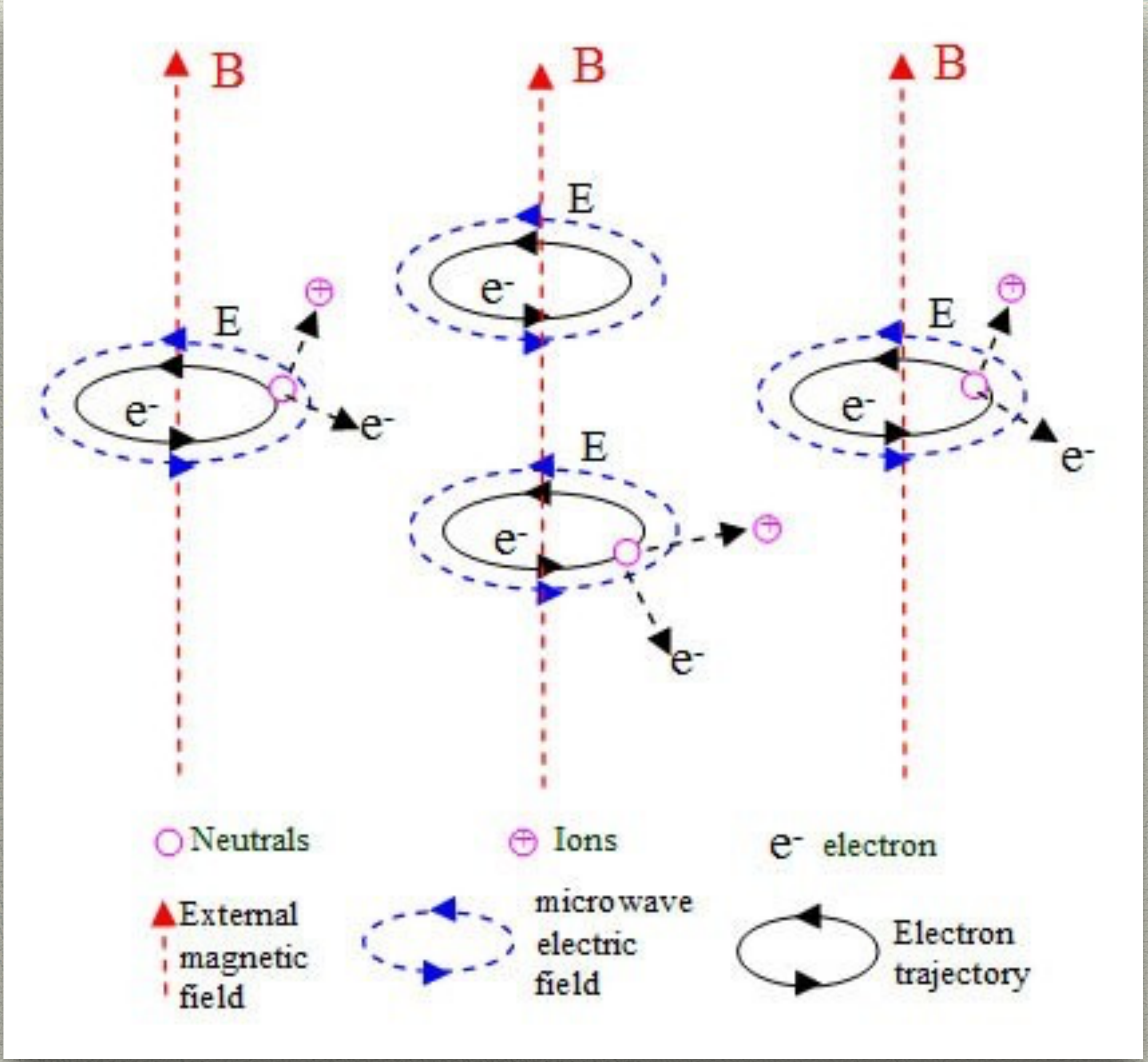



JET Tokamak for nuclear fusion (energy production)

**AISHA: an extremely compact plasma machine**



# The plasma heating via Electron Cyclotron Resonance



# LNS plasma team topics

**Fundamental plasma investigation**

- Wavelet-Analysis
- RF probes
- Advanced Sensors R&D
- High-Resolution X-ray Spectroscopy
- Ultra Compact Proton Source & negative noble-gas ions injector
- Optical Emission Spectroscopy
- RF Polarimetry

**Ion Beams Production**

**P**lasmas for
**A**strophysics,
**N**uclear
**D**ecays
**O**bservation and
**R**adiation for
**A**rchaeometry

# INFN-LNS plasma-based machines

| Name | Type | Trap | Species | $I$ | $n_e$ - $T_e$ |
|---|---|---|---|---|---|
| *SERSE*<br>CS Injector | ECR | B-min<br>S.C. | from H to Pb | $O^{6+} \sim 500\,\mu A$<br>$Ar^{16+} \sim 20\,\mu A$ | $n_e \sim 10^{13}\,cm^{-3}$<br>$T_e^{warm} \sim 1 \div 10\,keV$<br>$T_e^{hot} \sim 100\,keV$ |
| *CAESAR*<br>CS Injector | ECR | B-min<br>N.C. | Ne, Ar | H, O, N,<br>$O^{6+} \sim 80\,\mu A$<br>$Ar^{14+} \sim 20\,\mu A$ | $n_e \sim 10^{12}\,cm^{-3}$<br>$T_e^{warm} \sim 0.5 \div 5\,keV$<br>$T_e^{hot} \sim 50\,keV$ |
| *PS-ESS* | MDIS | B-flat<br>N.C. | Protons,<br>also $H^{2+}$, D | $\sim 100\,mA$ | $n_e \sim 10^{12}\,cm^{-3}$<br>$T_e \sim 15 \div 25\,eV$ |
| *FPT*<br>Test-bench | Trap | Bottle<br>B-flat<br>Beach | gaseous<br>elements | | $n_e \sim 10^{12} \div 10^{13}\,cm^{-3}$<br>$T_e \sim 15 \div 25\,eV$ |
| *AISHa*<br>Hadrontherapy machine | ECR | B-min<br>S.C. | C, Li, O, Ar | $C^{4+} \sim 800\,\mu A$<br>$O^{6+} \sim 800\,\mu A$ | $n_e \sim 10^{12} \div 10^{13}\,cm^{-3}$<br>$T_e \sim 15 \div 25\,eV$ |
| *VIS* | MDIS | B-flat<br>S.C. | H, $H^{2+}$, D, He | $H^{+} \sim 60\,mA$<br>$He^{+} \sim 40\,mA$ | $n_e \sim 10^{12} \div 10^{13}\,cm^{-3}$<br>$T_e \sim 15 \div 25\,eV$ |

# Catania: a fertile network of "plasma-users"


100 m

# High power proton accelerator for spallation

## ESS accelerator

**Design Drivers:**

High Average Beam Power
5 MW
High Peak Beam Power
125 MW
High Availability
> 95%

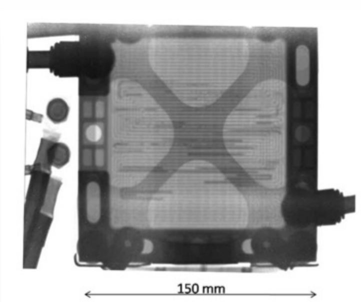
**Key parameters:**

**-2.86 ms pulses**
**-2 GeV**
**-62.5 mA**
**-14 Hz**
**-Protons (H+)**
-Low losses
-Low heat loss cryostats for minimum energy consumption
-Flexible design for future upgrades

LABORATORI NAZIONALI DEL SUD

## Boosting neutron science for fundamental physics and applications

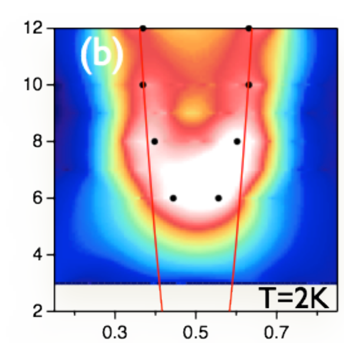
**Charge neutral**
deeply penetrating




Li motion in fuel cells

Help build electric cars

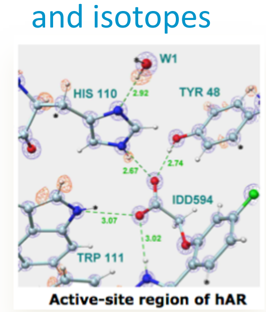
**S=1/2 spin**
probe directly magnetism



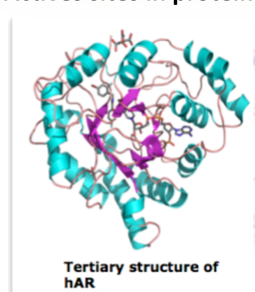

Solve the puzzle of High-Tc superconductivity

Efficient high speed trains

**Nuclear scattering**
sensitive to light elements and isotopes




Actives sites in proteins

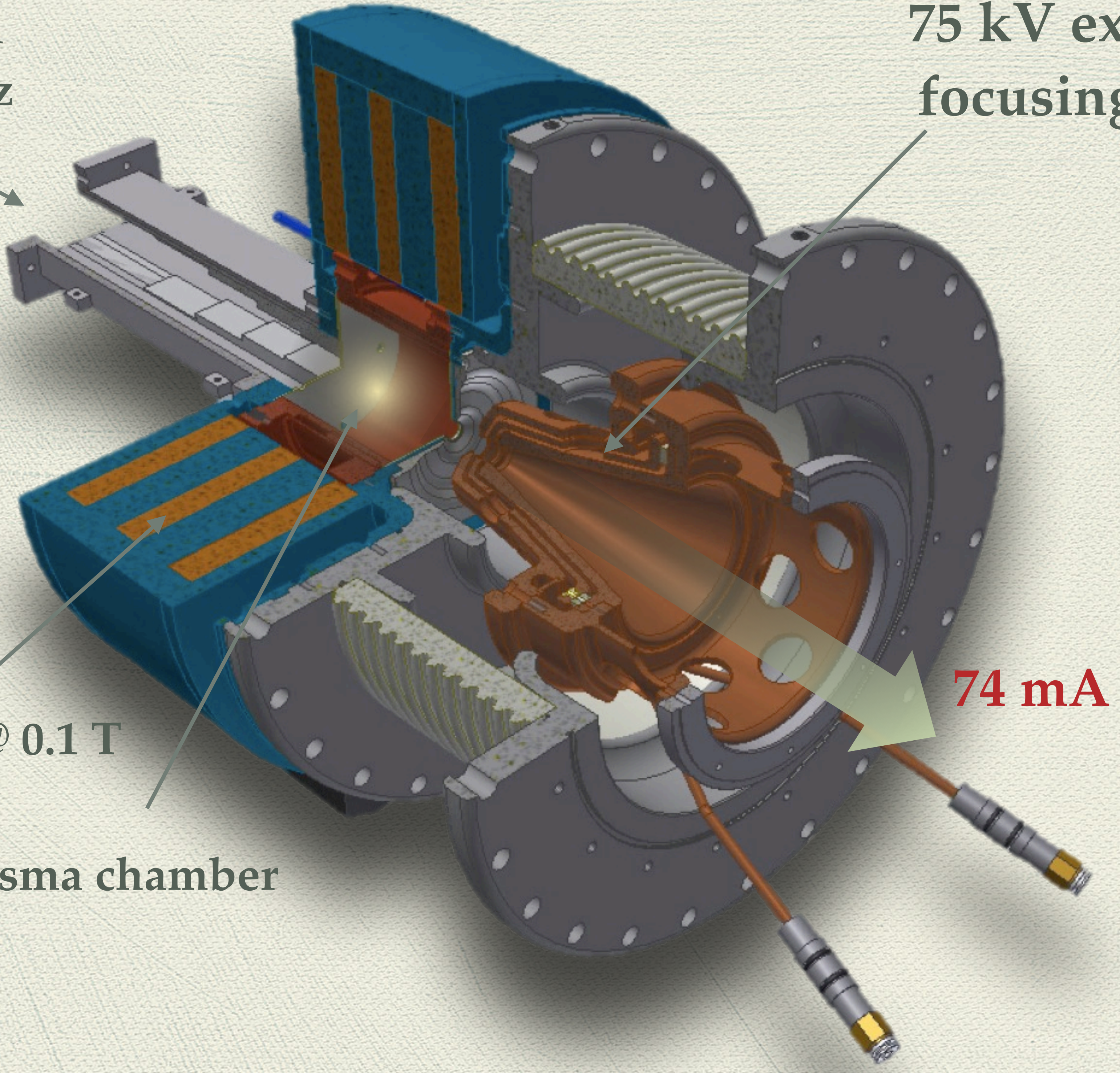



Better drugs

EUROPEAN SPALLATION SOURCE

LABORATORI NAZIONALI DEL SUD

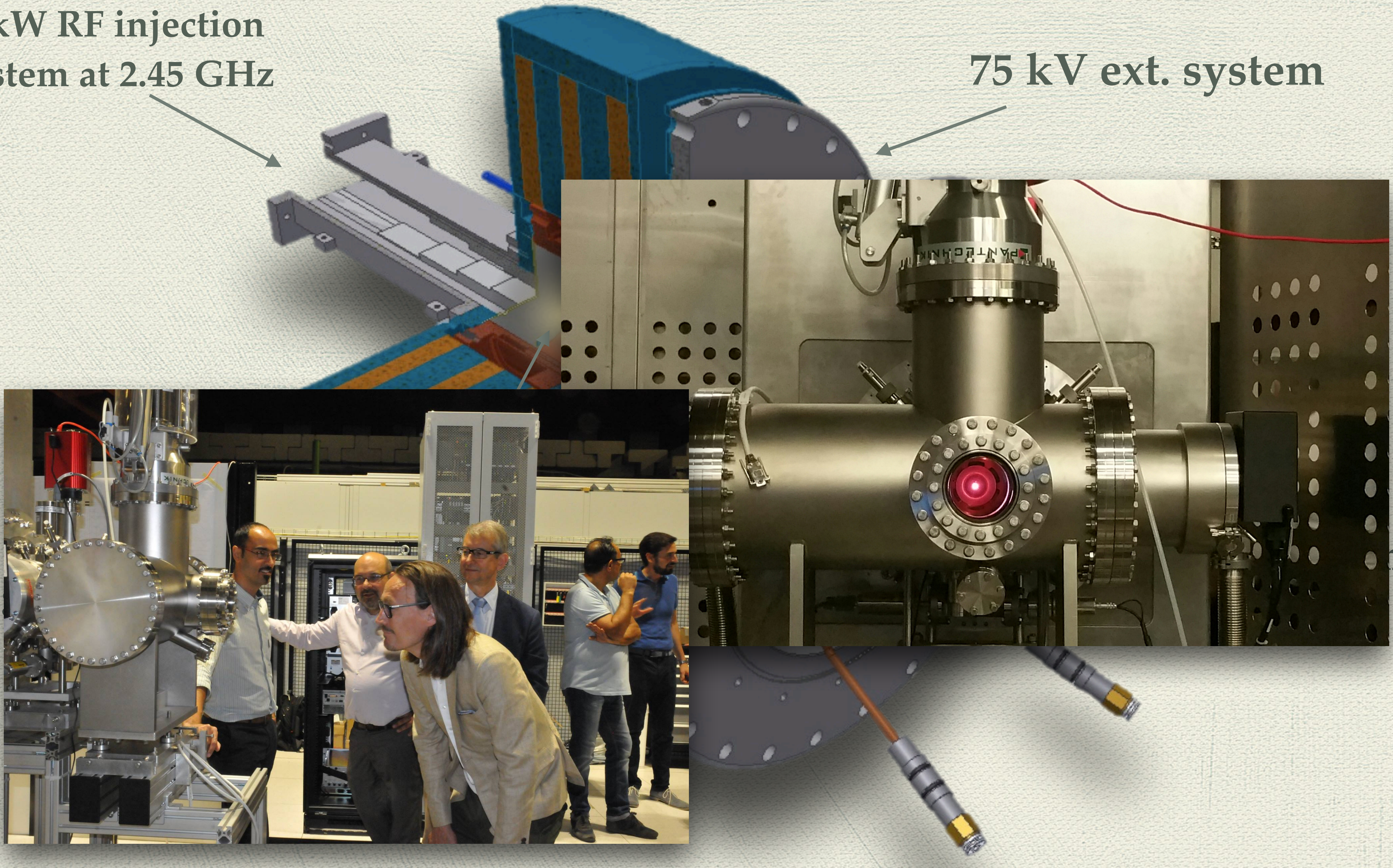
# The proton source for ESS accelerator



# The proton source for ESS accelerator

1 kW RF injection system at 2.45 GHz

75 kV ext. system



Ma

m

**100 mA proton curr. - 0.2 pi mm mrad reached!!**

AISHa

# POR – U.E. funds for regional development

UNIONE EUROPEA

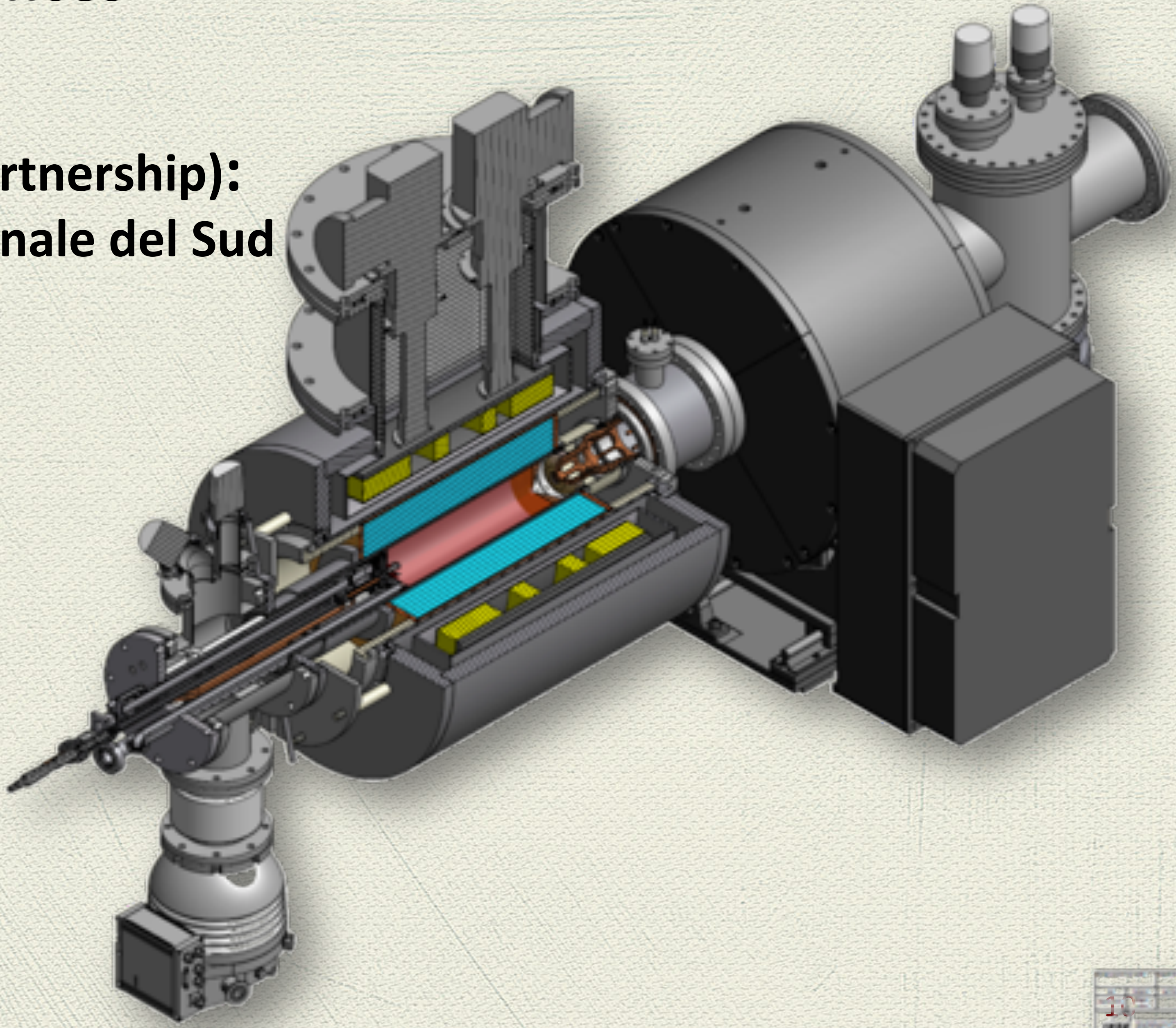
Regione Siciliana

PO FESR Sicilia 2007/2013

## Topics: Health and Life Sciences

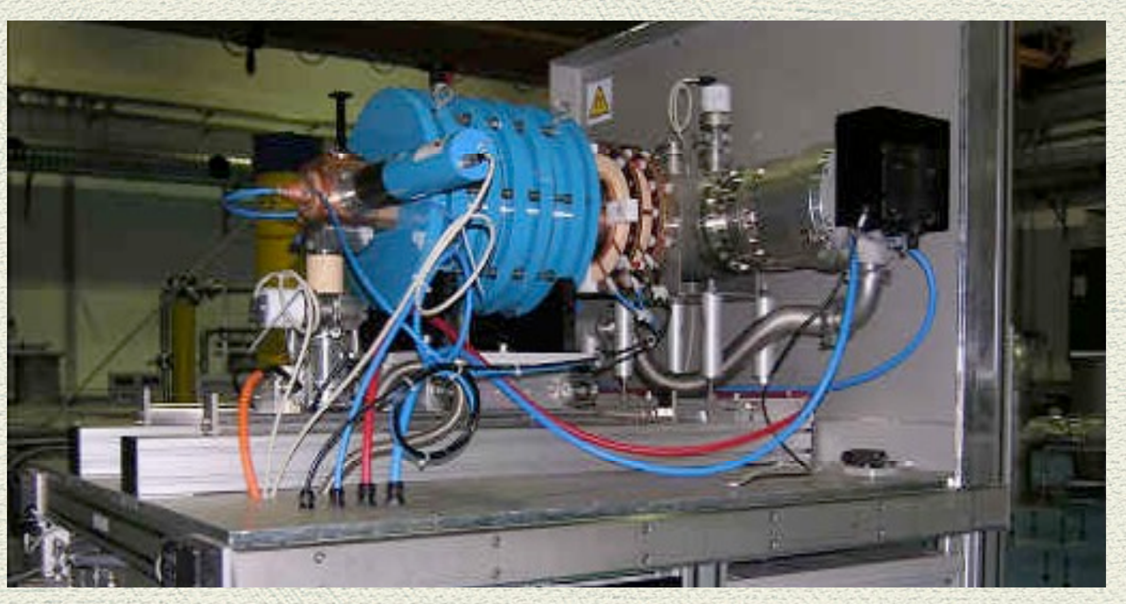
## Proponents (public-private partnership):

- INFN-Laboratori Nazionale del Sud
- Hitec2000 srl
- C3SL srl
- Unico srl



*AISHa*

# The GOAL: make a step forward w.r.t. PK-SUPERNANOGAN for CNAO and other hadron therapy facilities



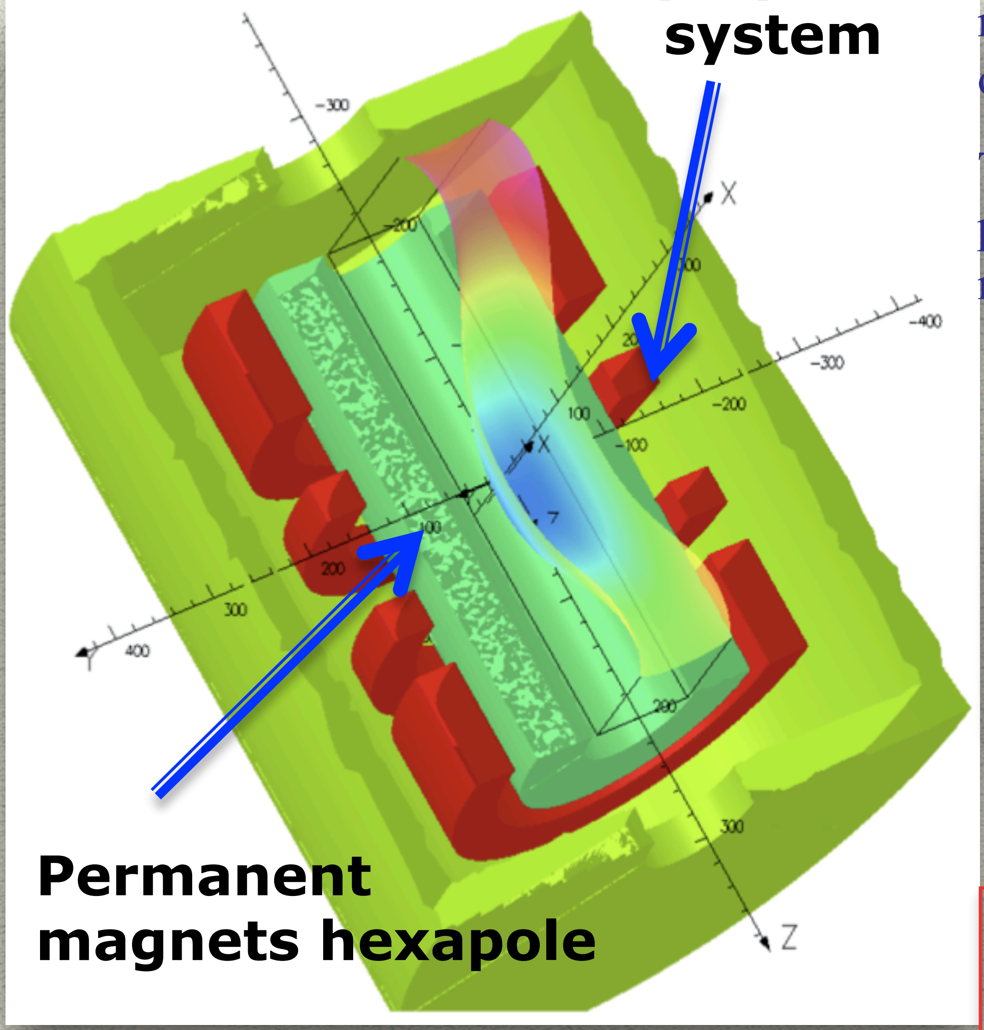
## Measured performances

| Ions | Current (request) [μA] | Current (avail.) [μA] | After improvements by INFN-LNS [μA] | Emittance (request) π mm.mrad | Emittance (new extractor) π mm.mrad | Stability [99,8%] |
|---|---|---|---|---|---|---|
| $C^{4+}$ | 200 | 200 | 250 | 0.75 | 0.56 | 36 h |
| $H_2^+$ | 1000 | 1000 | | 0.75 | 0.42 | 2 h |
| $H_3^+$ | 700 | 600 | 1000 | 0.75 | 0.67 | 8 h |
| $He^+$ | 500 | 500 | | 0.75 | 0.60 | 2 h |


**Significant improvements have been provided by INFN-LNS: frequency tuning effect, gas control, extractor reliability, etc. but further improvements are not possible and different set of requirements are done for the treatments by therapy experts.**

*AISHa*

# AISHA
## Advanced Ion Source for HAdrontherapy

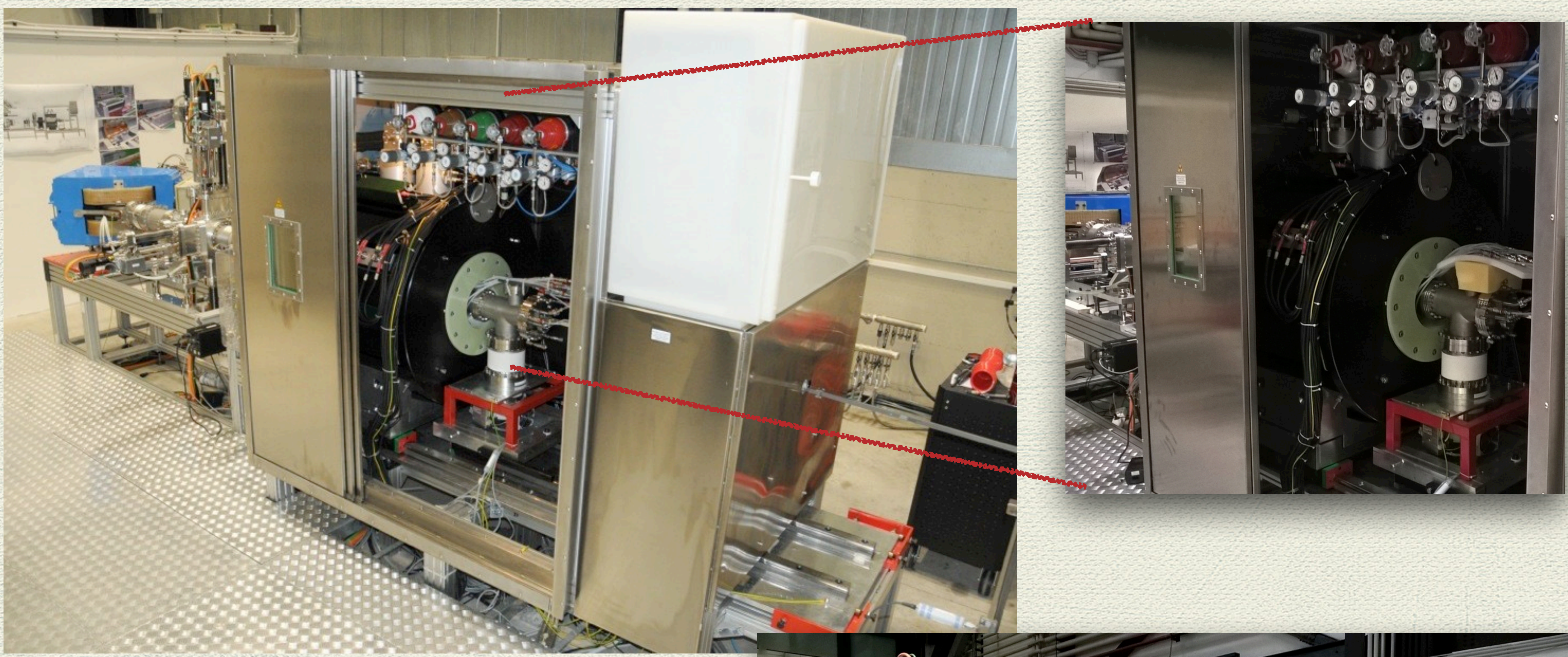


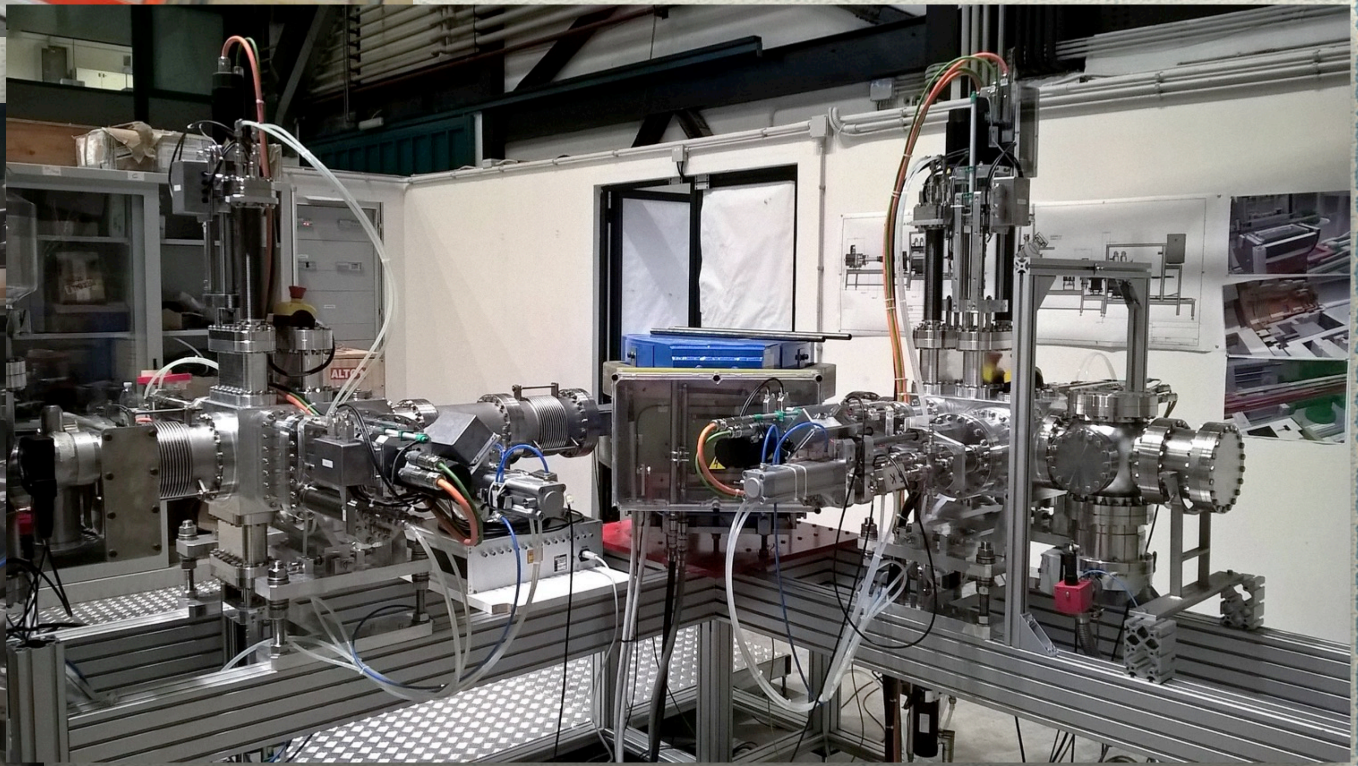

AISHA is a hybrid ECRIS: the radial confining field is obtained by means of a permanent magnet hexapole, while the axial field is obtained with a **Helium-free superconducting system.**

The **operating frequency of 18 GHz will permit** to maximize the plasma density by employing commercial microwave tubes meeting the **needs of the installation in hospital** environments.

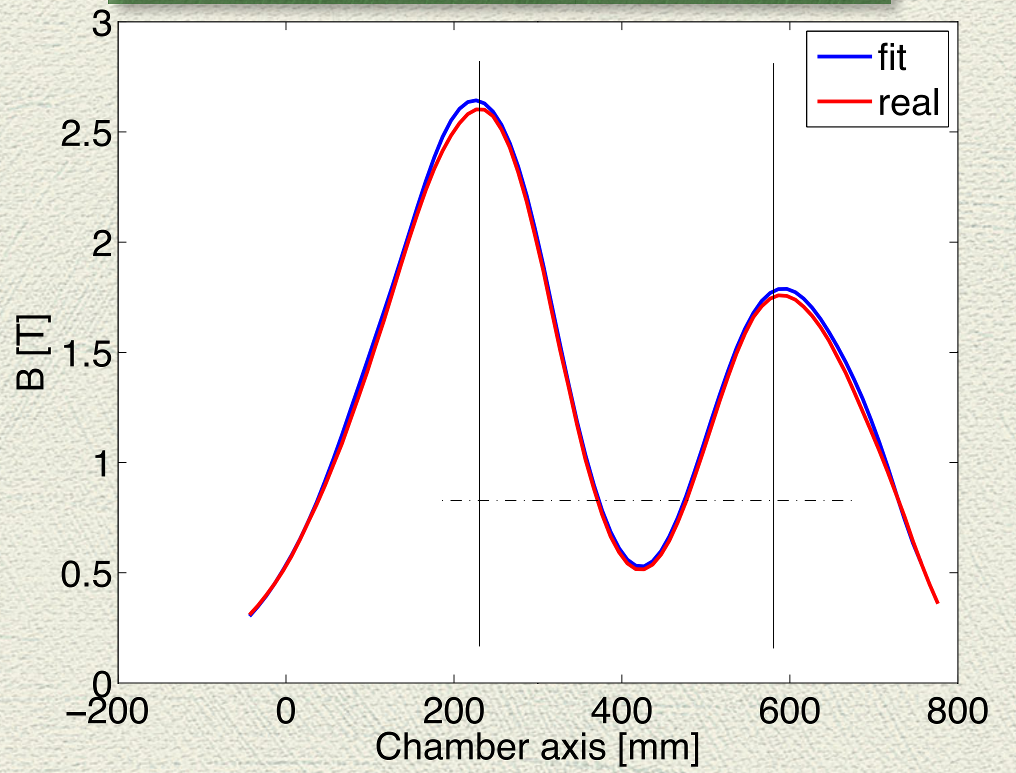
| | |
|---|---|
| Radial field | 1.3 T |
| Axial field | 2.7 T - 0.4 T - 1.6 T |
| Operating frequencies | 17.3 GHz – 21.5 GHz |
| Operating power | 1.5 + 1.5 kW (max) |
| Extraction voltage | 40 kV (max) |
| Chamber diameter / length | Ø 92 mm / 360 mm |
| LHe | Free |
| Warm bore diameter | 274 mm |
| Source weight | 1400 kg |

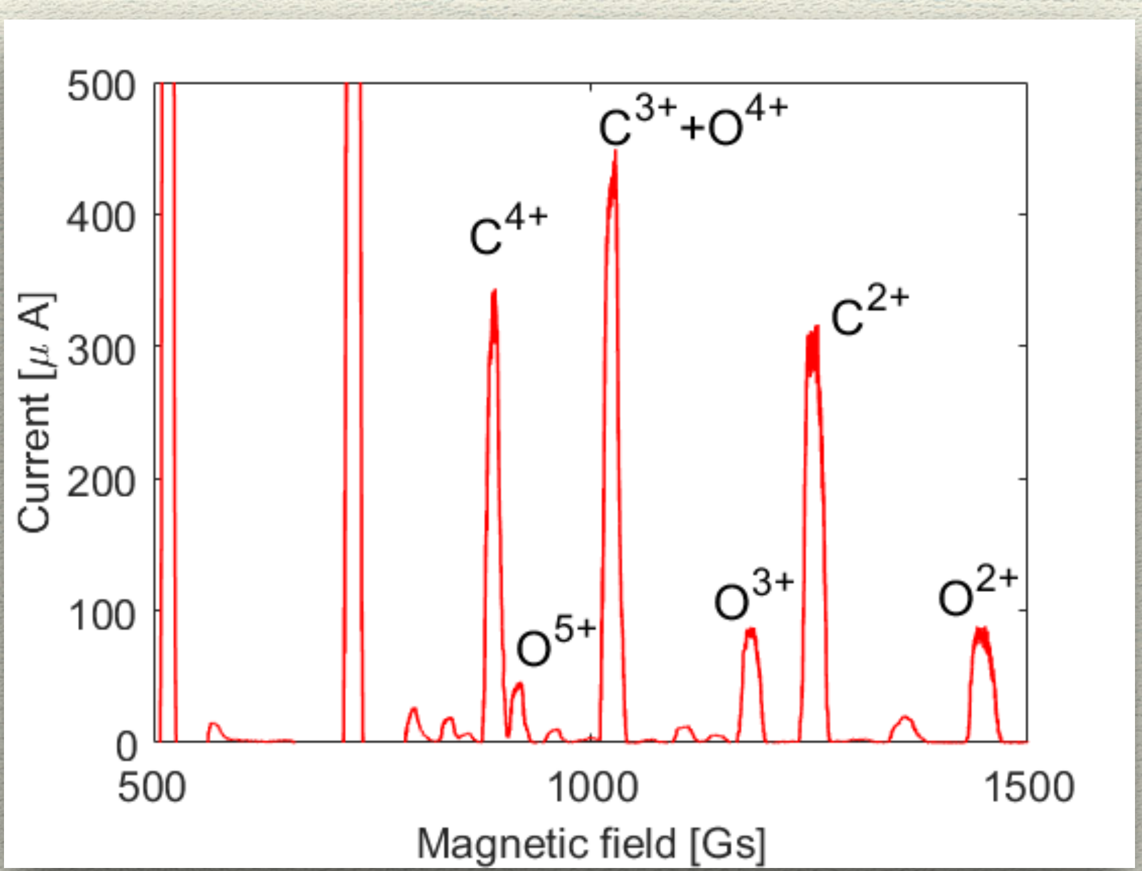
*AISHa*

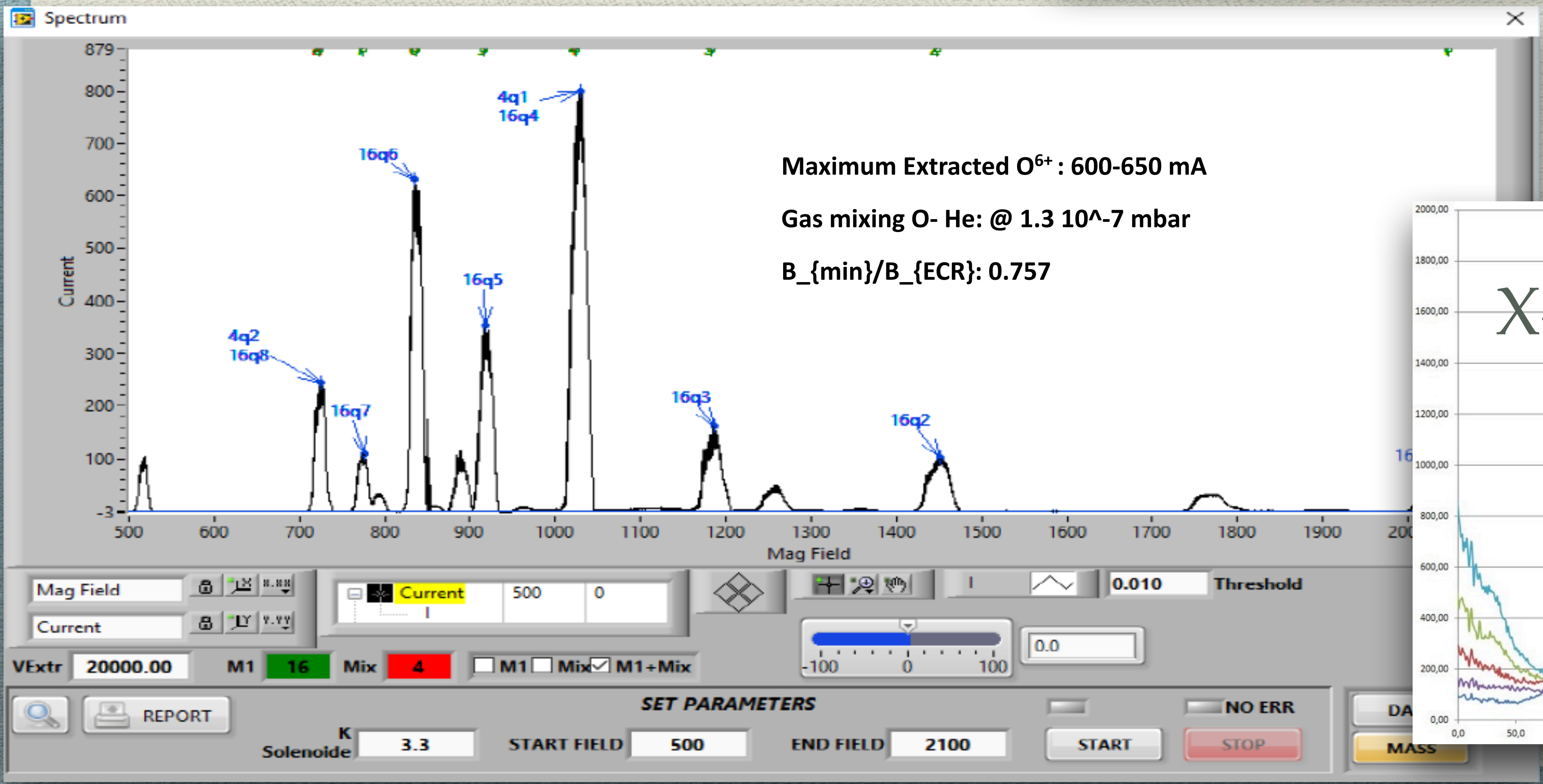


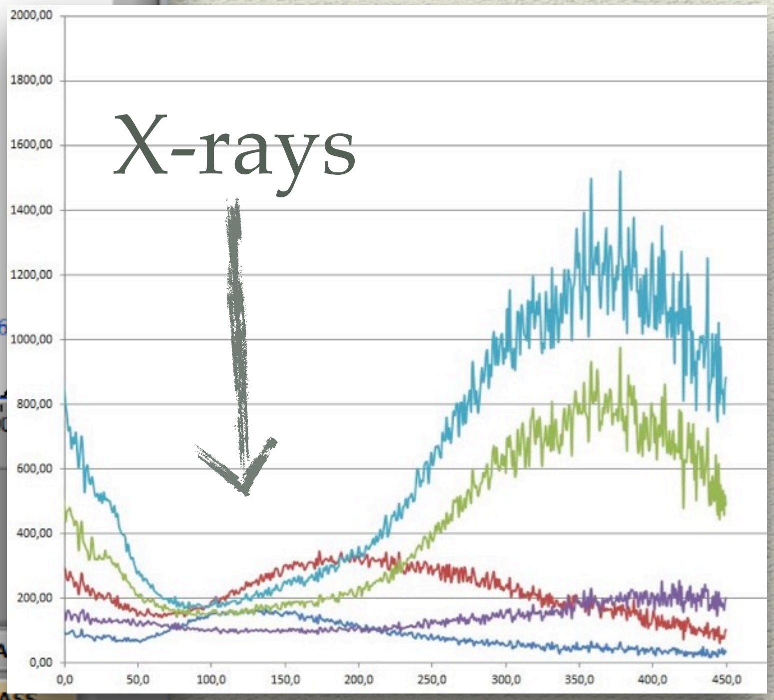


# First Spectra



# LNS plasma team topics

**Fundamental plasma investigation**

*Wavelet-Analysis*

*RF probes*

*Advanced Sensors R&D*

**Ion Beams Production**

*High-Resolution X-ray Spectroscopy*

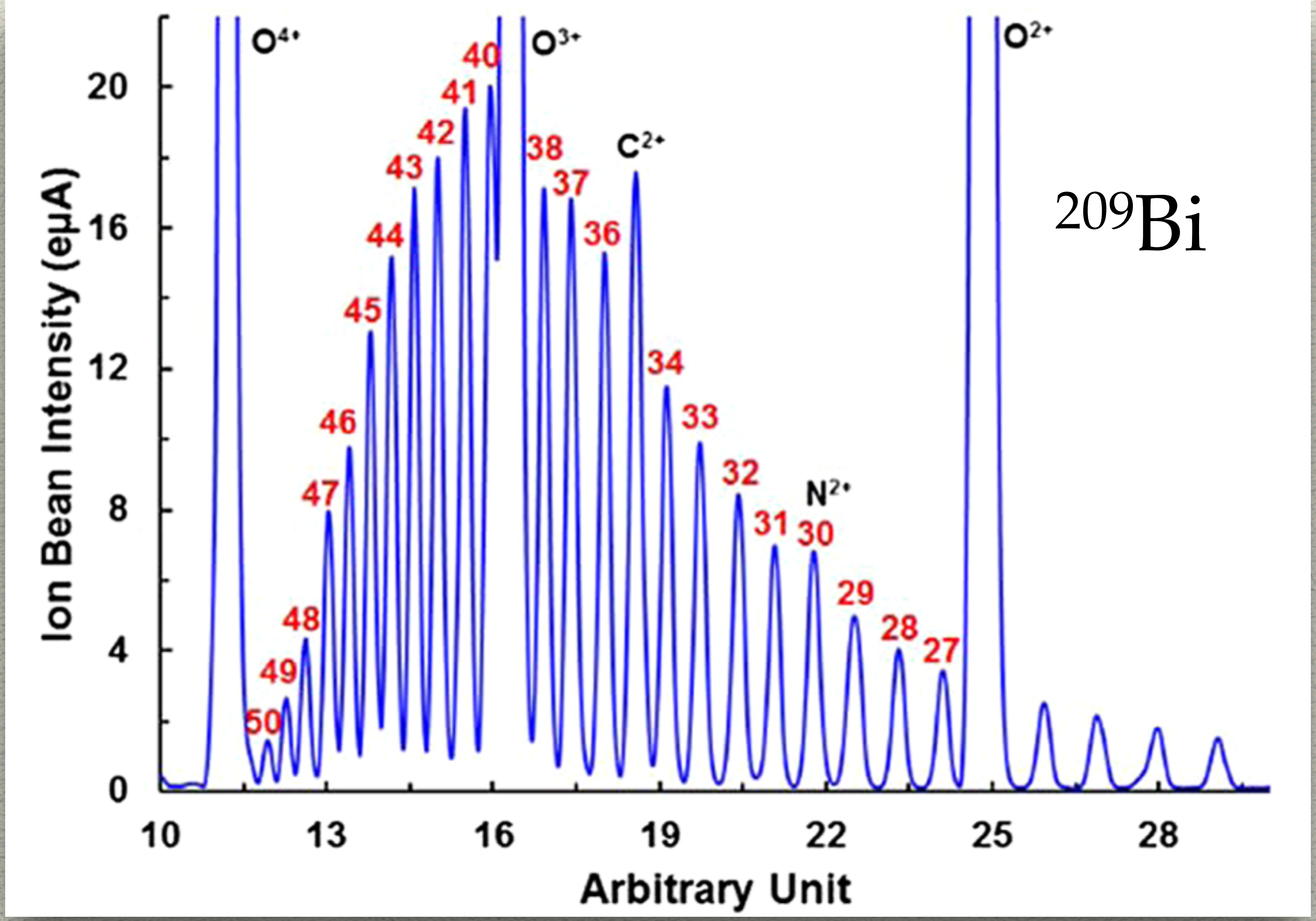
*Ultra Compact Proton Source & negative noble-gas ions injector*

*RF Polarimetry*

*Optical Emission Spectroscopy*

**P**lasmas for
**A**strophysics,
**N**uclear
**D**ecays
**O**bservation and
**R**adiation for
**A**rchaeometry

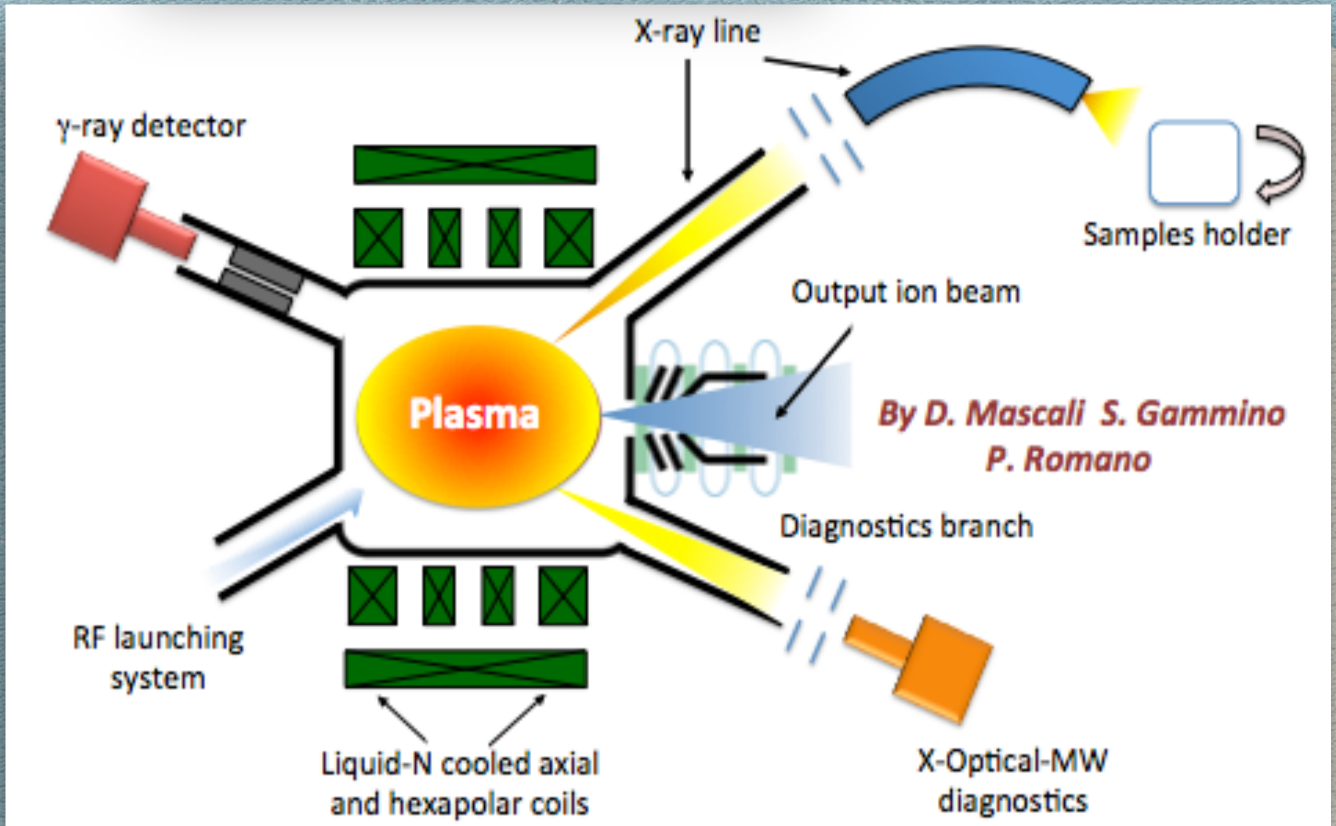
# Confinement of highly charged ions in a magnetoplasma

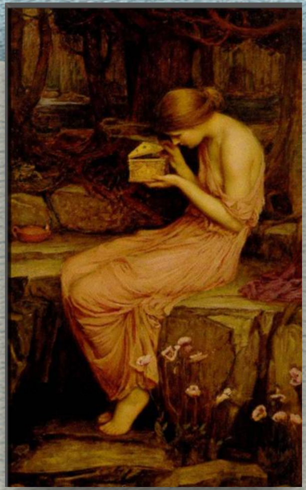



SECRAL source at IMP - Lanzhou, China

**According to the plasma density, temperature and confinement time, a given charge state distribution can be mainteined in a dynamical equilibrium for hours or even days!!**

1. **Plasma can be obtained by (almost) any element, including rare isotopes**
2. **The Charge State Distribution can be modulated according to the plasma density and temperature**
3. **The decay-products can be tagged by γ-rays or by XRF on accumulation targets**



**P**lasmas for
**A**strophysics,
**N**uclear
**D**ecays
**O**bservation and
**R**adiation for
**A**rchaeometry

*S-process*

$^{85}$**Kr** [$T_{1/2}$ = 10.76 y, ***s-process***, γ@514 keV]

$^{176}$**Lu** [$T_{1/2}$ = 38 Gy, (***CosmoChronometers***) γ @ 202.88 & 307 keV]

$^{187}$**Re** [$T_{1/2}$ = 50 Gy, (***CosmoChronometers***), no γ —> $^{187}$Os.]

$^{87}$**Rb** [$T_{1/2}$ = 48 Gy, (***CosmoChronometers***), no γ —> $^{87}$Sr.]

$^{7}$**Be** [$T_{1/2}$ = 53 d, (***BBN, solar neutrino***) γ @477.6 keV.]

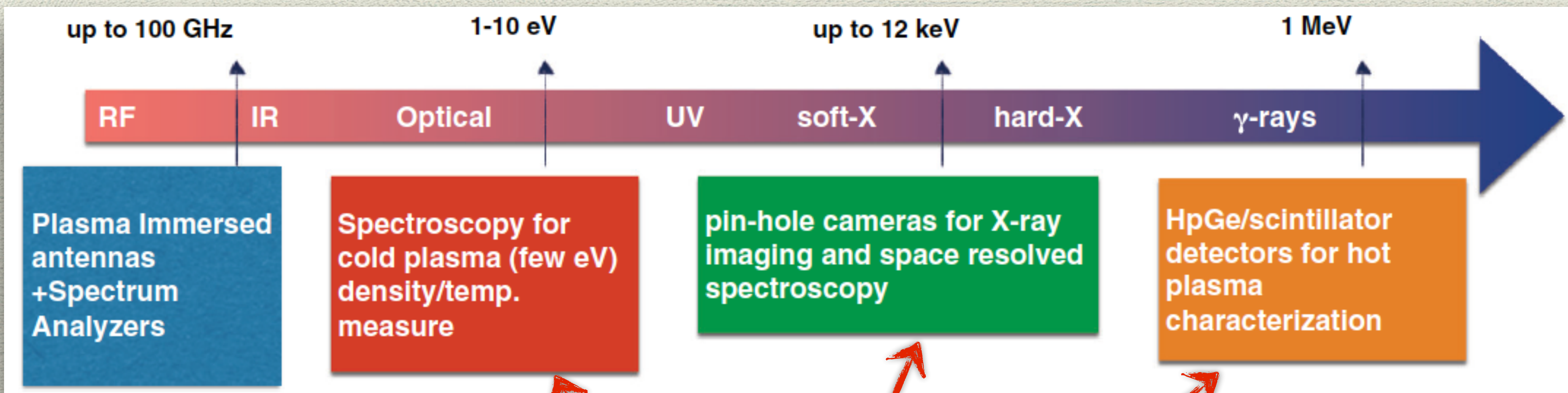
*CosmoChronometers*

**Magnetoplasmas in laboratory**

*Opacities for MM physics*

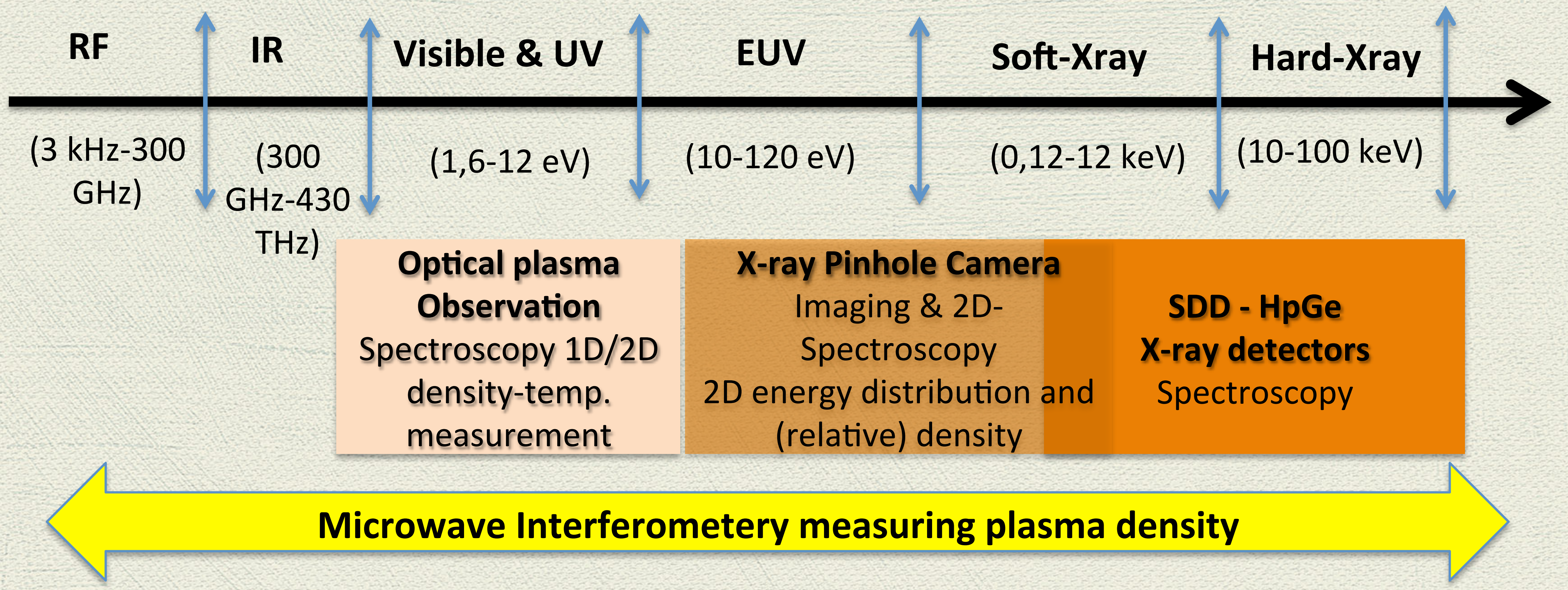
**Let's trap beta-decaying radionuclides in magnetoplasma, thus studying if and how the lifetime is affected by the atomic charge state and by the "environment"**

# Non-intrusive plasma diagnostics methods




Measuring the plasma density in different energy regimes: density, temperature and plasma structure evaluation under different operative parameters

# Non-intrusive plasma diagnostics methods

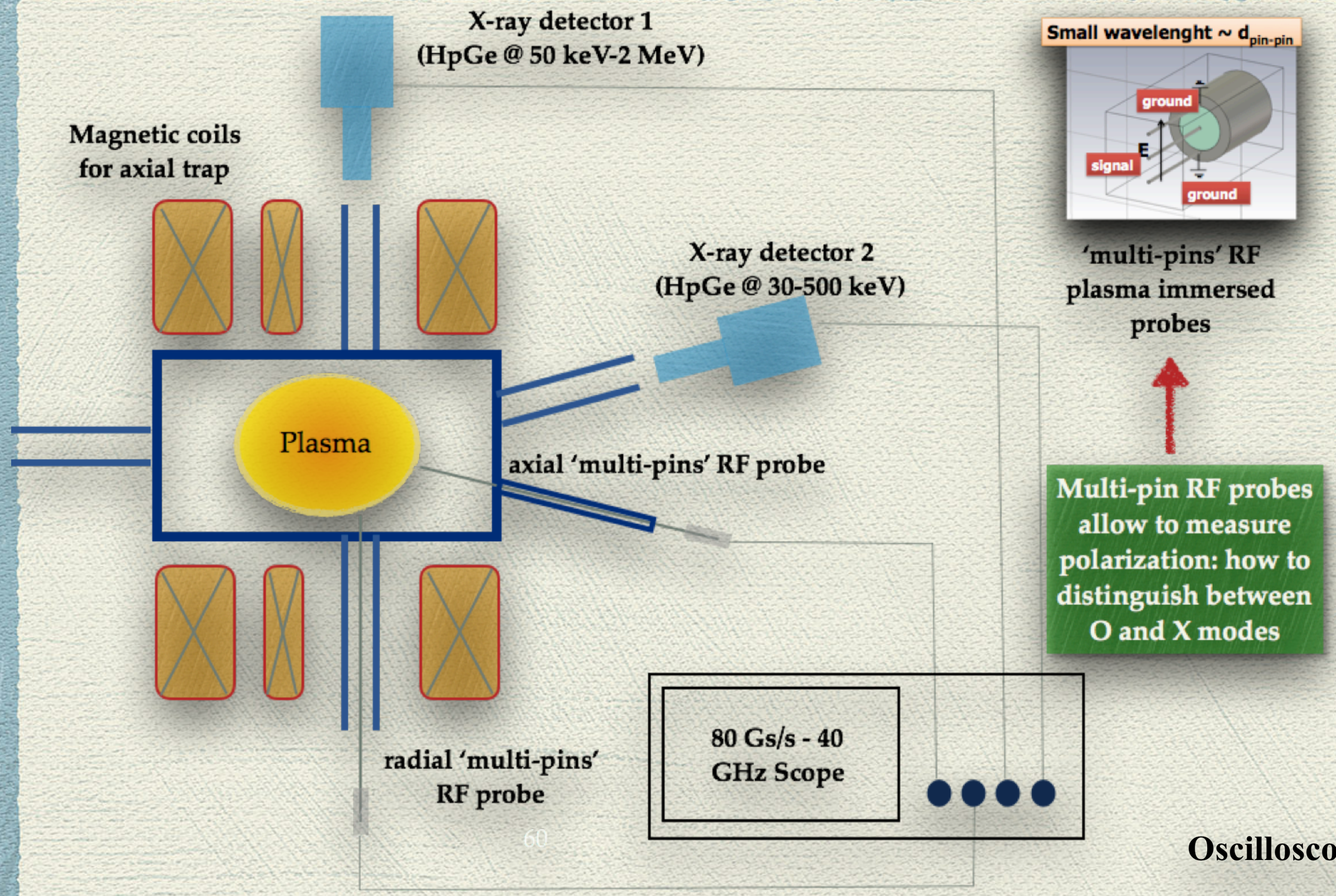


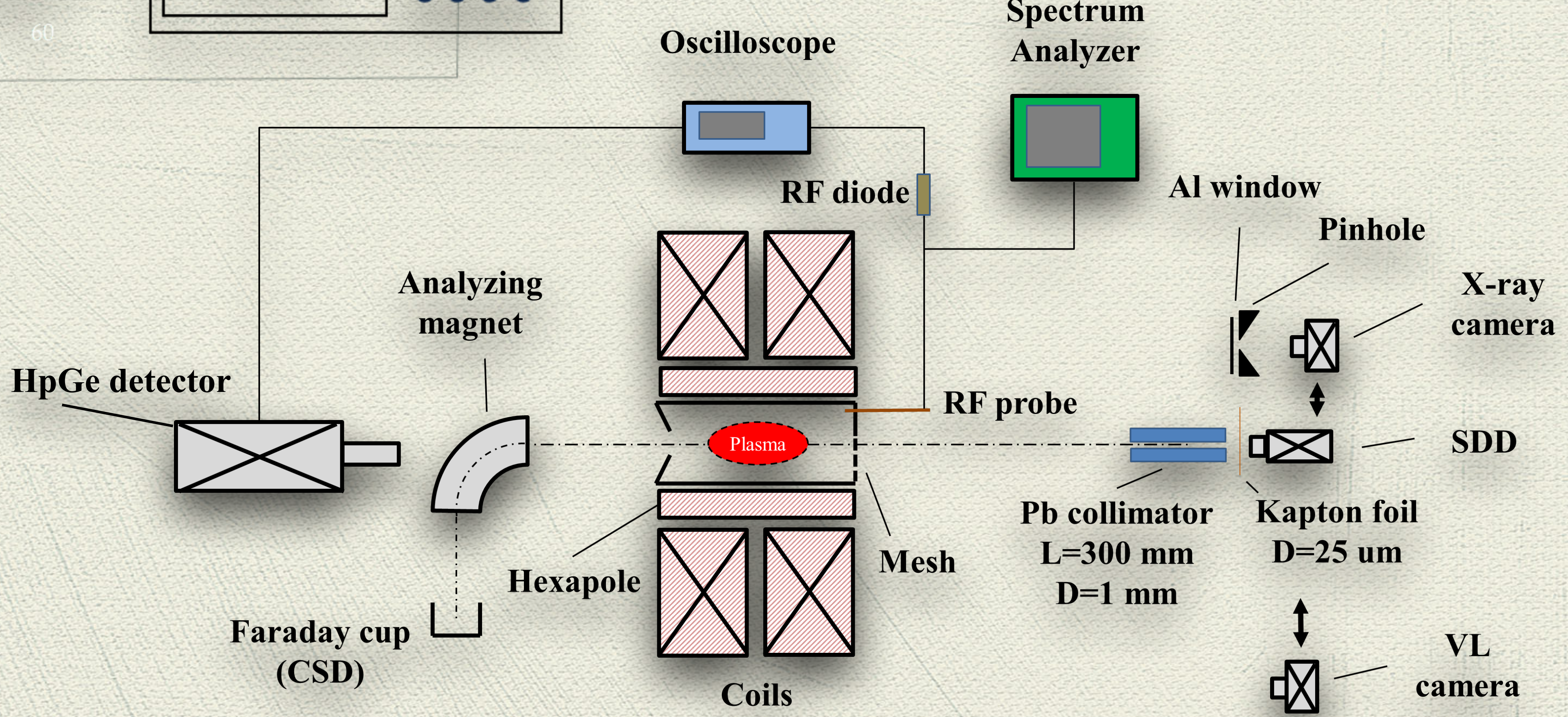

We need a tool able to measure density of electrons with an externally injected "probing" radiation (no perturbation since $P_{probing}/P_{exciting}<1\%$)

→ Density measurement technique no-longer based on plasma emission but on "response-on-transmission" of microwaves through the plasma

**MICROWAVE INTERFEROMETRY**

# Experimental setups for SPACE and TIME-resolved characterization of magnetoplasmas in compact traps, including kinetic turbulences




[see also E. Naselli et al. poster presentation, this conf.]

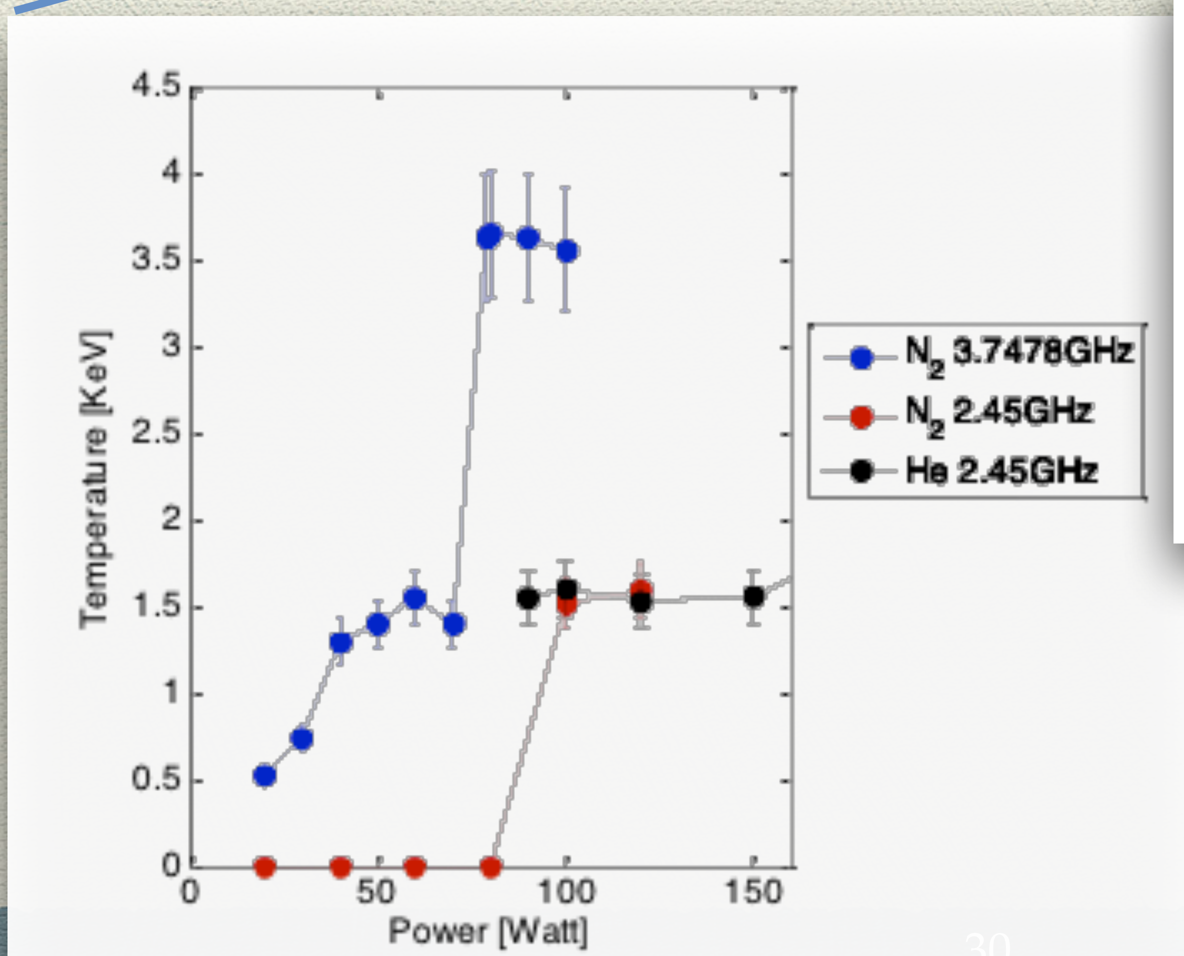
# Non-intrusive plasma diagnostics methods

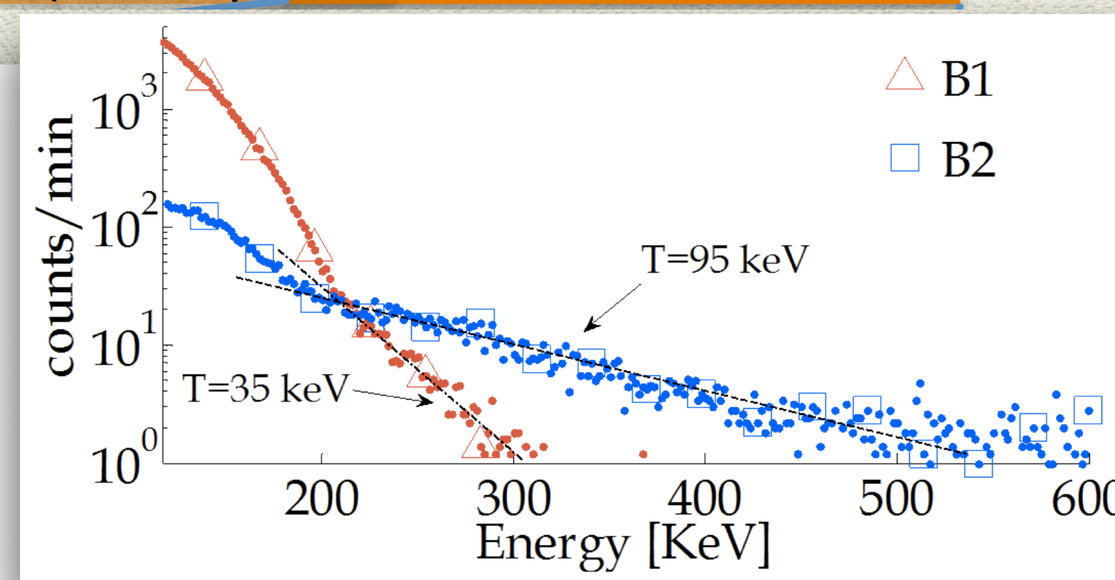
| RF | IR | Visible & UV | EUV | Soft-Xray | Hard-Xray |
|---|---|---|---|---|---|
| (3 kHz-300 GHz) | (300 GHz-430 THz) | (1,6-12 eV) | (10-120 eV) | (0,12-12 keV) | (10-100 keV) |

**Optical plasma Observation**
Spectroscopy 1D/2D
density-temp. measurement

**X-ray Pinhole Camera**
Imaging & 2D-Spectroscopy
2D energy distribution and (relative) density

**SDD - HpGe X-ray detectors**
Spectroscopy



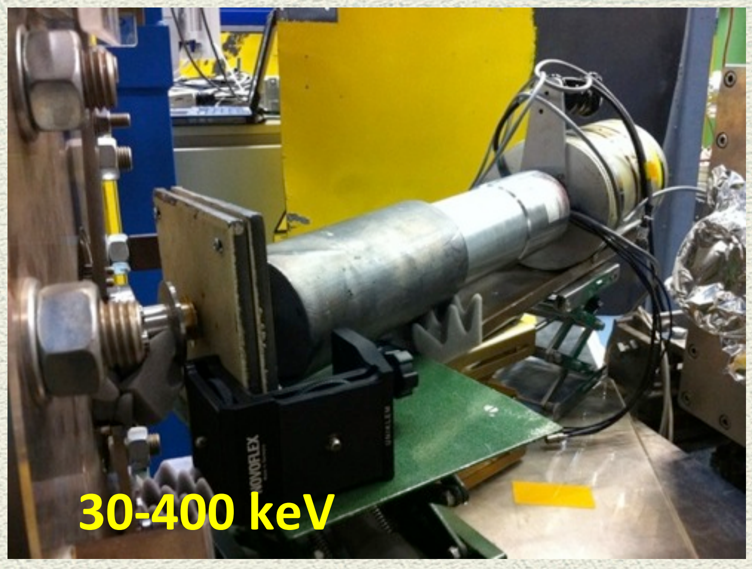



# Correlating X-ray fluxes, plasma density and <q>: volumetric measurements

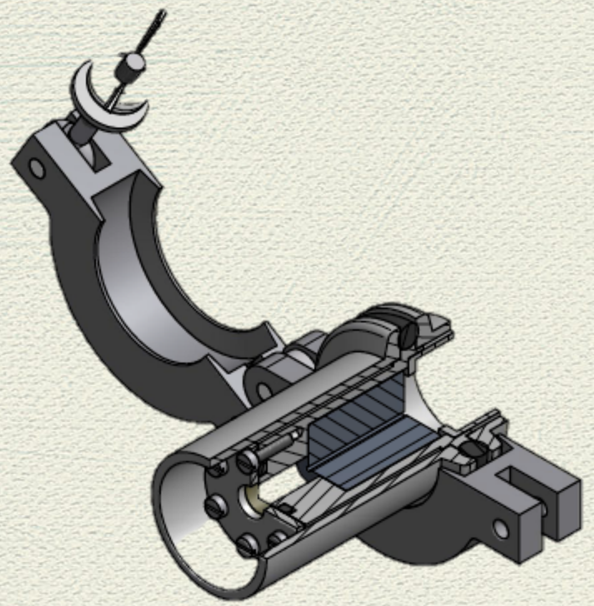
## Measurements at GSI (March 2013):

***impact of the pumping wave frequency on the X-ray spectra for either intermediate and high energy levels***

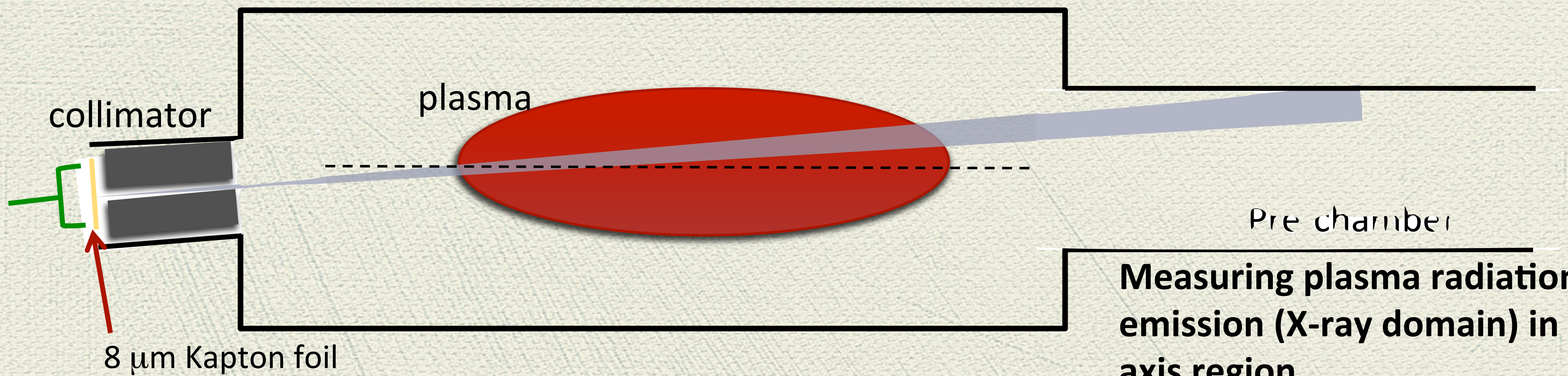

***SDD detector*** *for warm electron component*




***HpGe detector*** *for hot electron component*

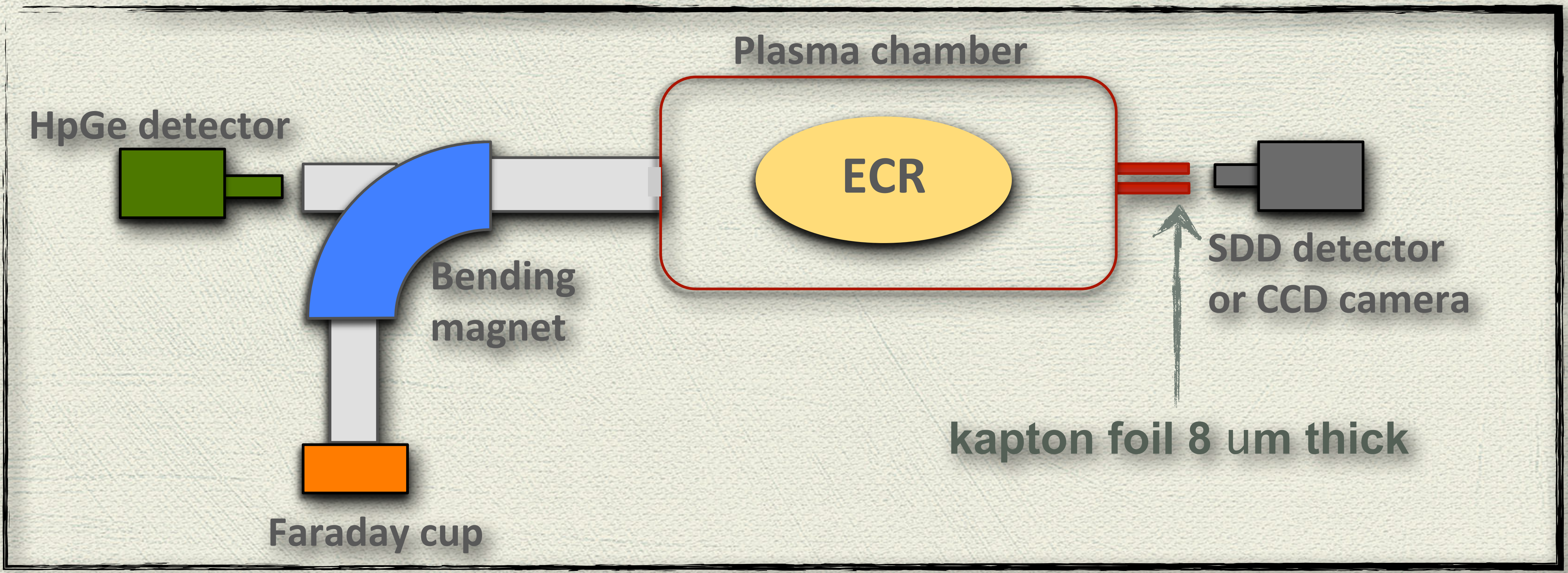


***Collimation system*** *for the detection of the plasma-core (only) X-radiation.*



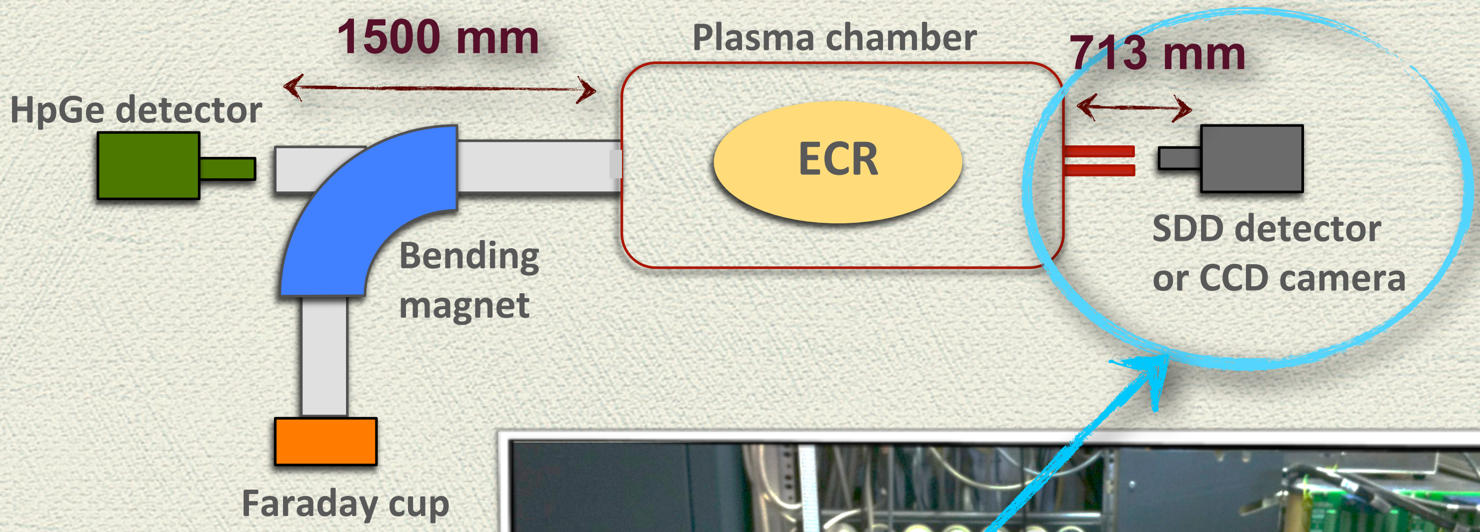

**Measuring plasma radiation emission (X-ray domain) in near axis region.**

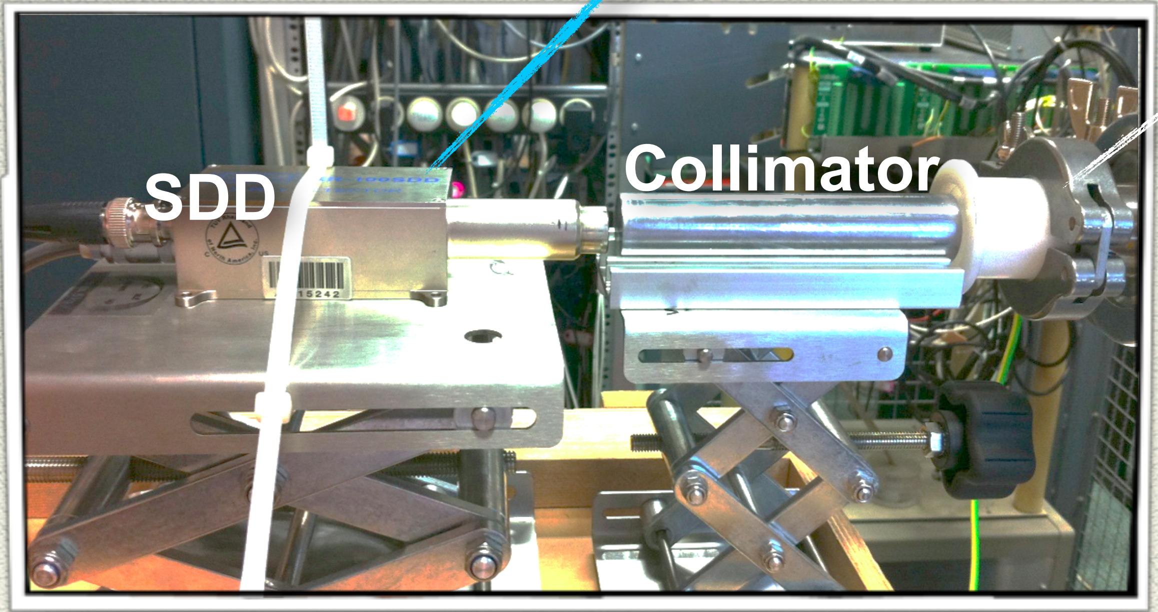
# Experimental setup for simultaneous measurement of density, temperature and CSD

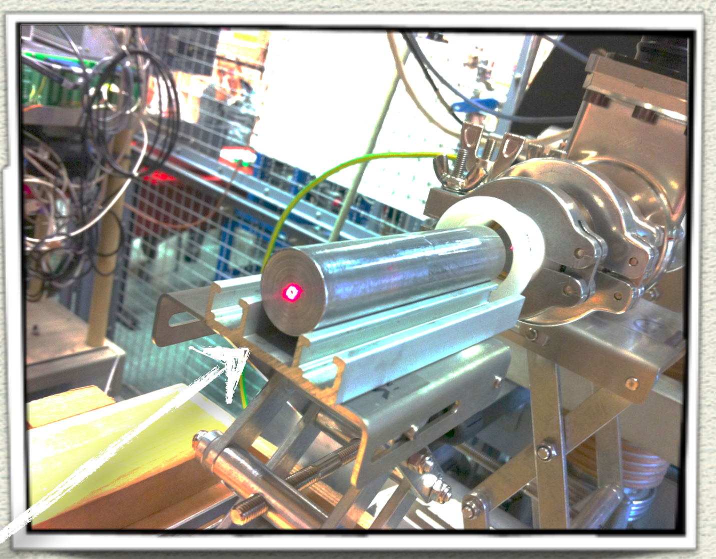



- Three detectors were used for a broad characterization of the EEDF:
  - HpGe for "hot electrons" E>30 keV
  - SDD for "warm electrons" 2<E<30 keV
  - CCD camera for imaging and 2D resolved spectroscopy 1<E<10kEV

# SDD – Setup @ ATOMKI Hungarian Acc. of Sciences

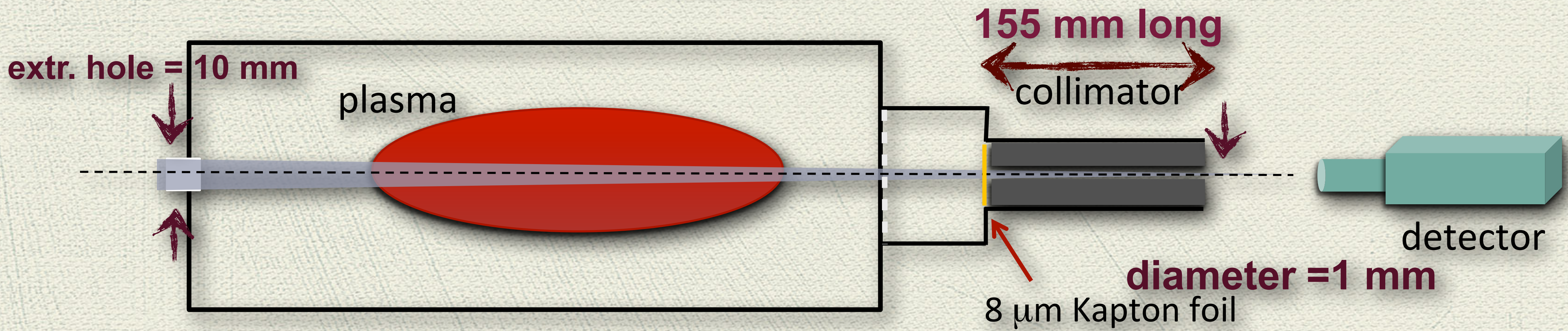


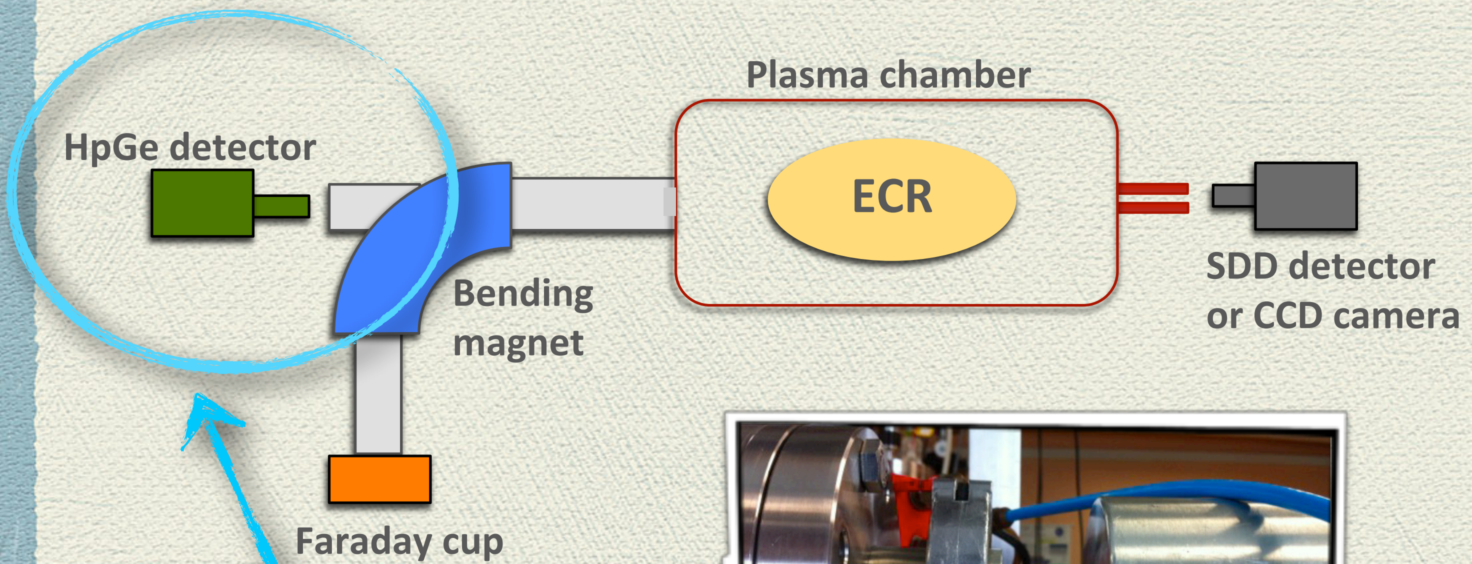
Collimator alignement

Bulk lead 155 mm long drilled collimator for near axis inspection

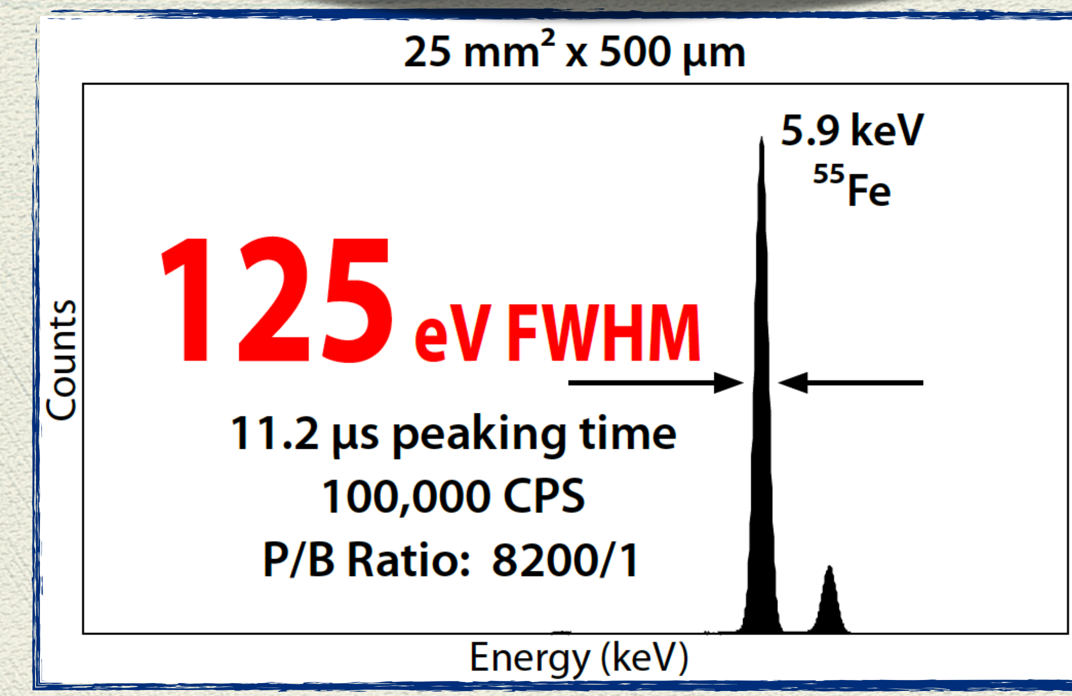


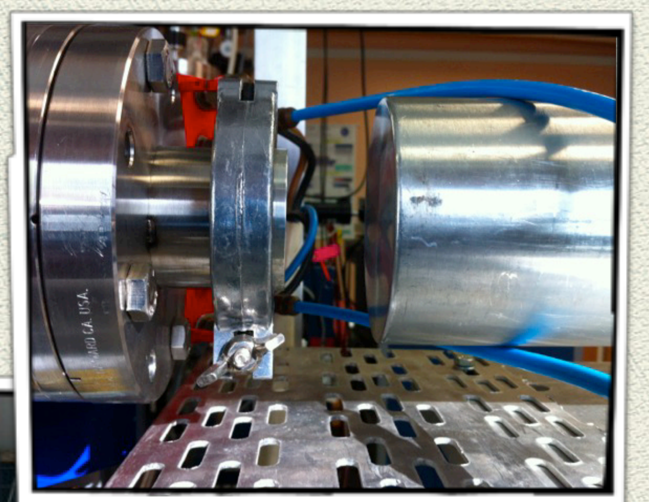

“LONG” collimator

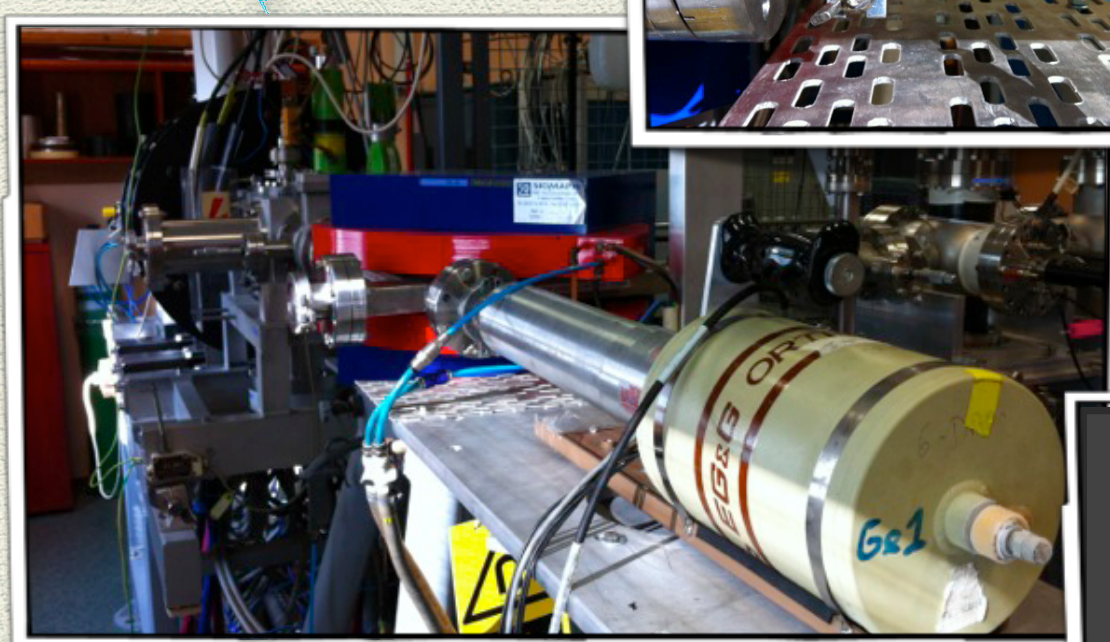
# SDD and HpGe Set-up




**SDD -** Silicon Drift Detector (SDD - 80 mm$^2$ active area) for measuring **warm X-rays** in the 2.5-30 keV domain.

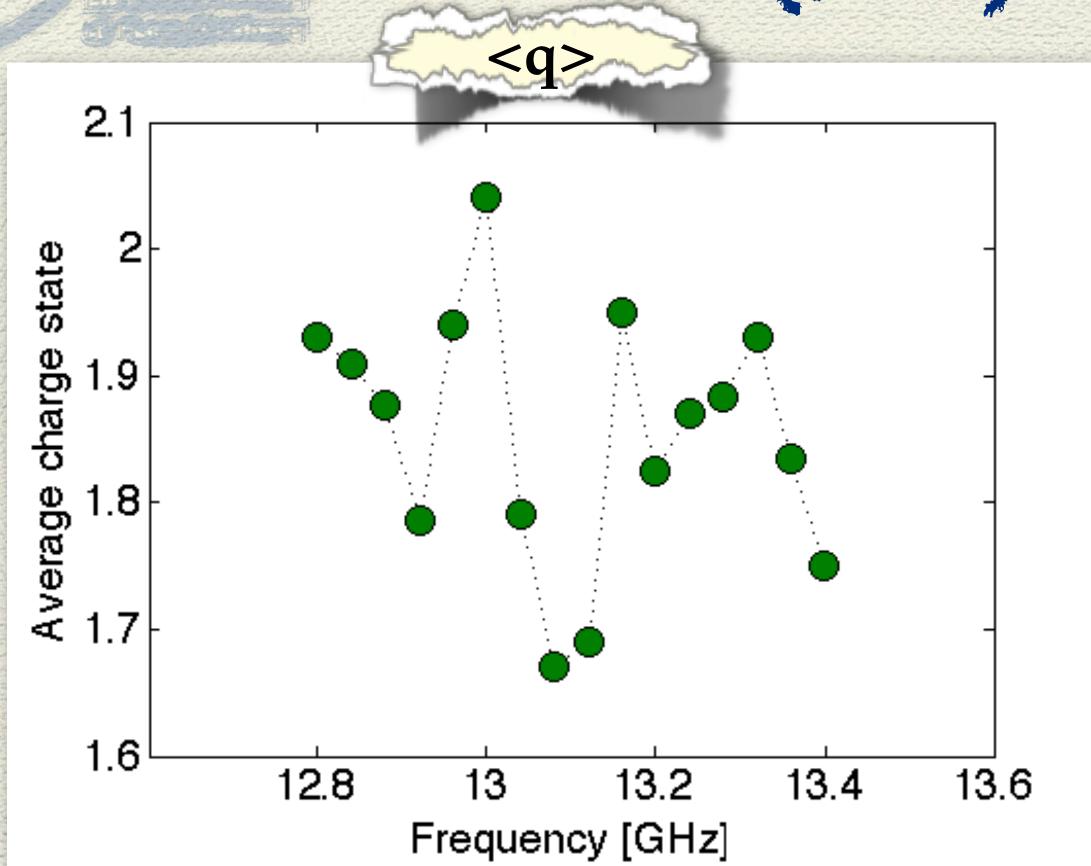


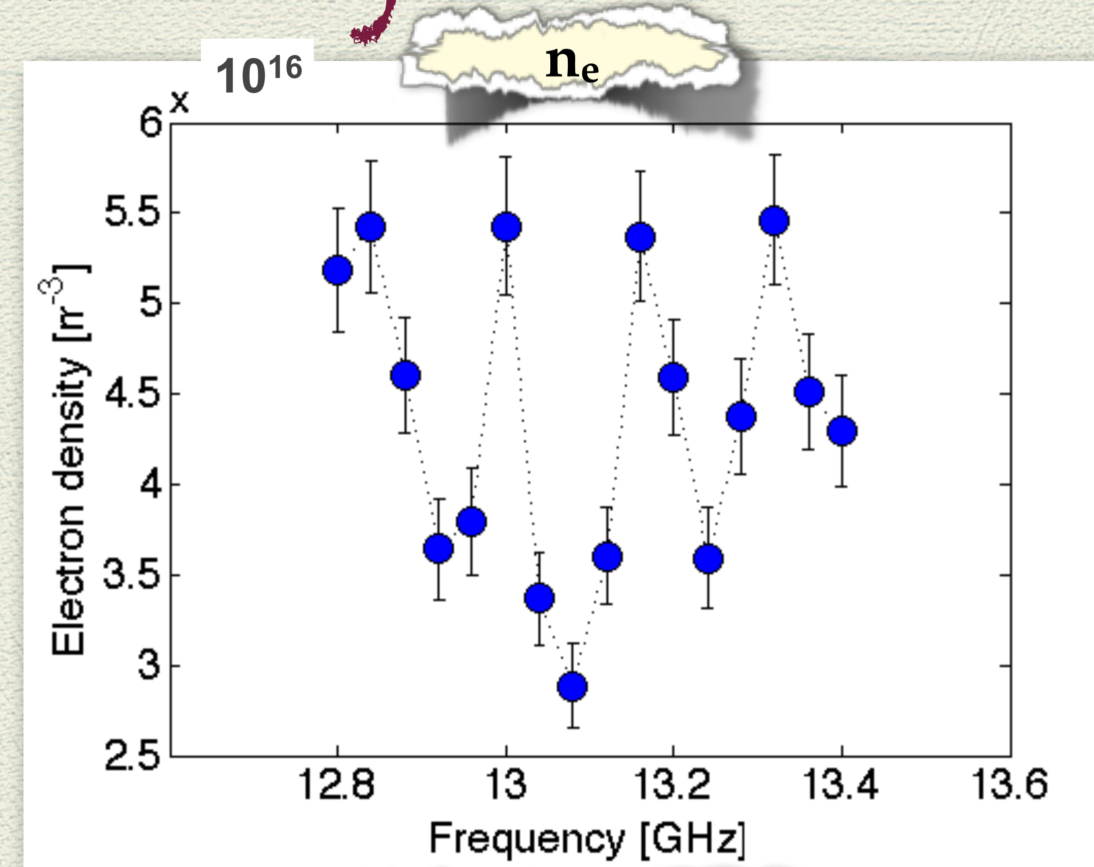



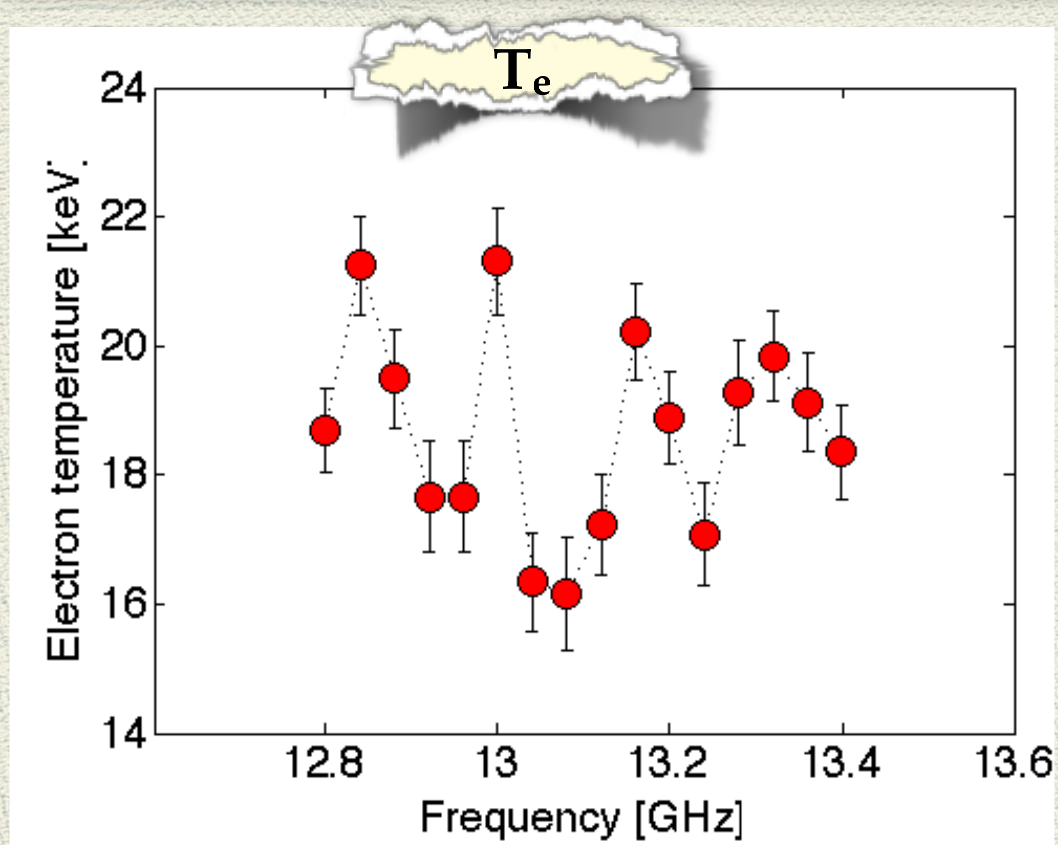


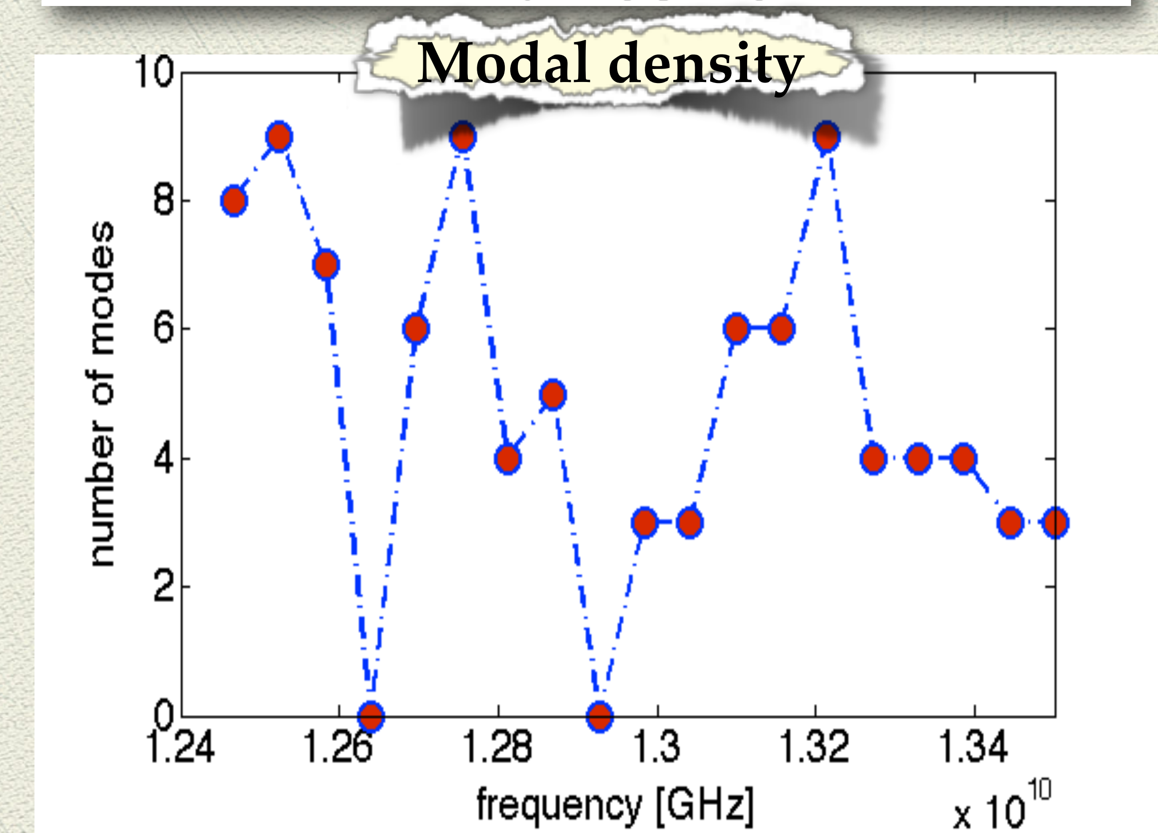
**HpGe -** HeGe Detector (3000 mm$^2$) active area for measuring **hot X-rays** in the energy domain 30-400 keV

# (SDD) F.T.E. study






*Mascali et al., Review of Scientific Instruments* ***87****, 02A510 (2016);*

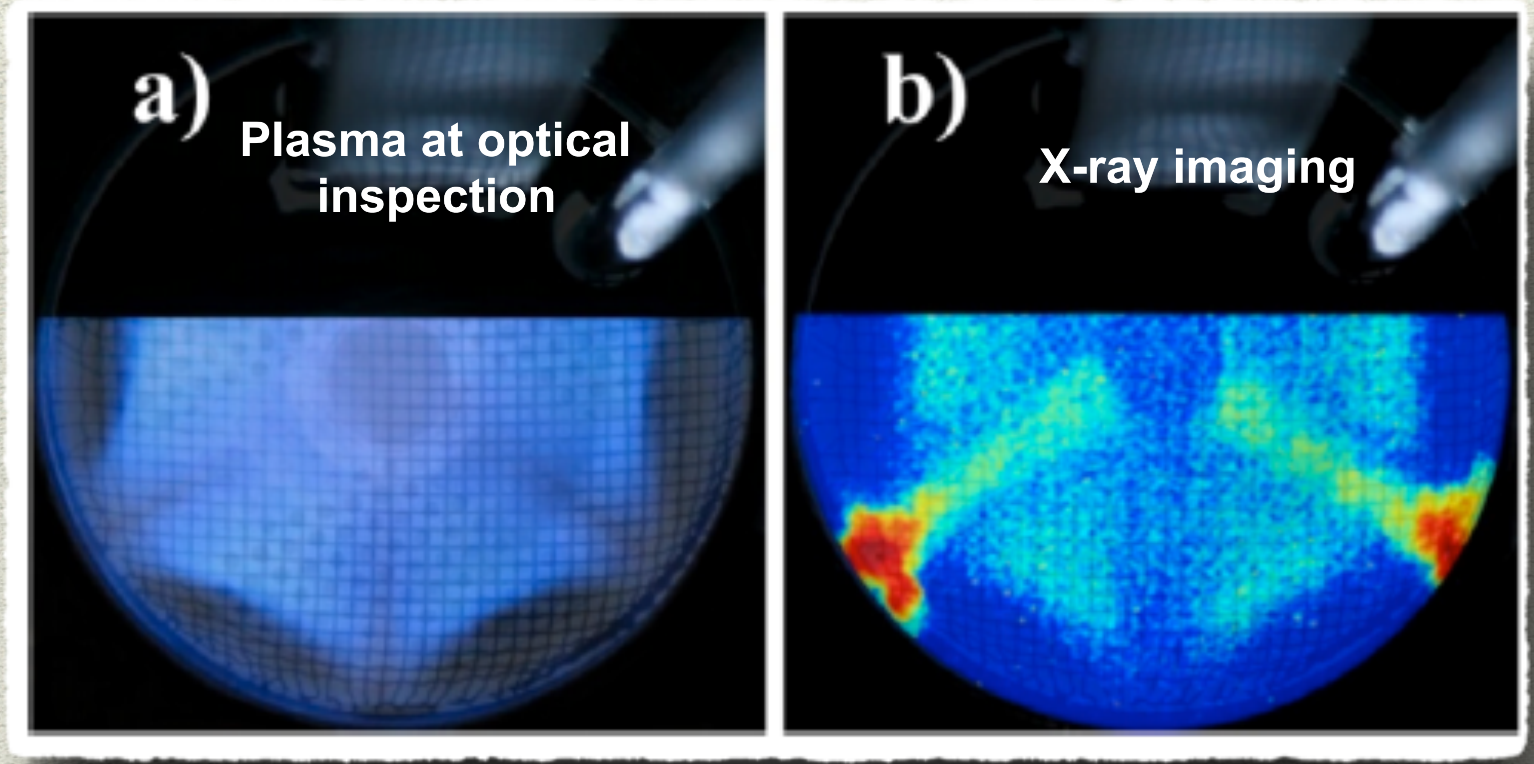
# Non-intrusive plasma diagnostics methods

| RF | IR | Visible & UV | EUV | Soft-Xray | Hard-Xray |
|---|---|---|---|---|---|
| (3 kHz-300 GHz) | (300 GHz-430 THz) | (1,6-12 eV) | (10-120 eV) | (0,12-12 keV) | (10-100 keV) |

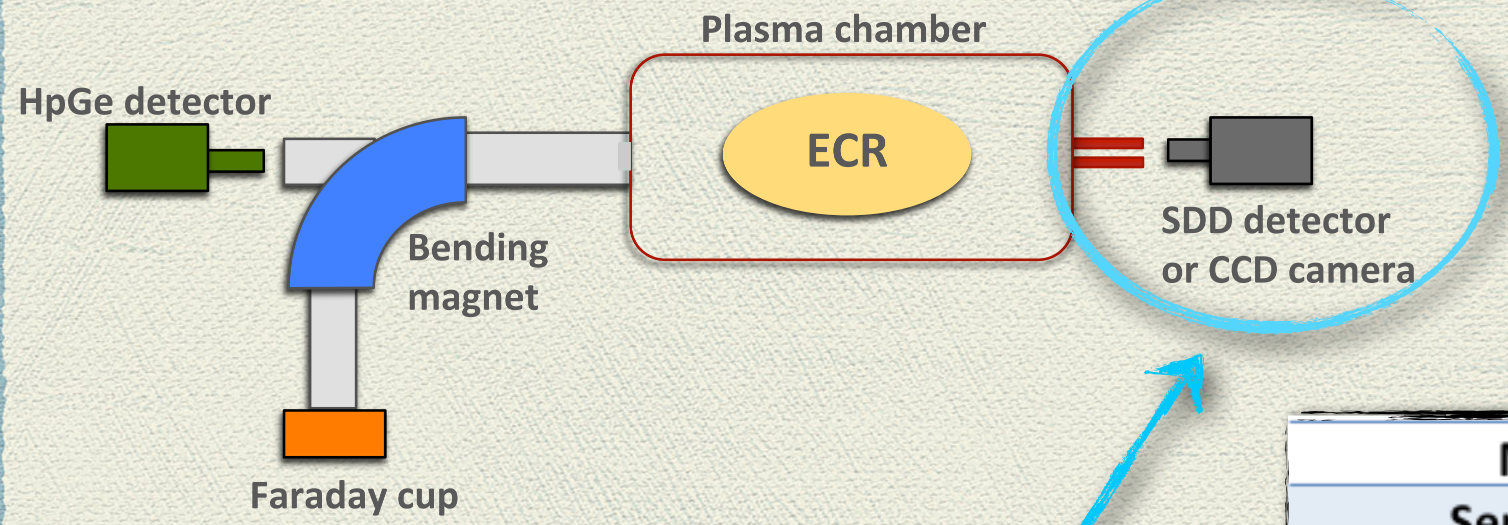
**Optical plasma Observation**
Spectroscopy 1D/2D
density-temp. measurement

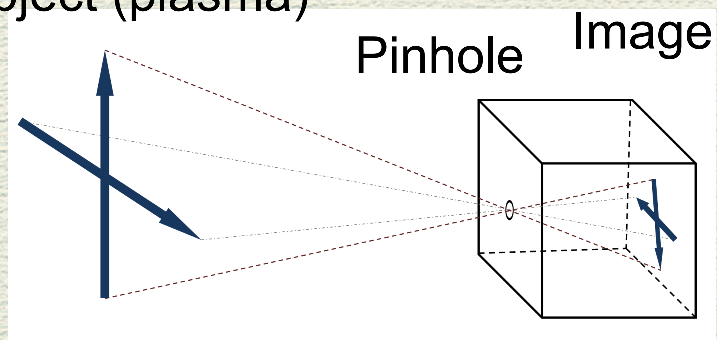
**X-ray Pinhole Camera**
Imaging & 2D-Spectroscopy
2D energy distribution and (relative) density

**SDD - HpGe X-ray detectors**
Spectroscopy

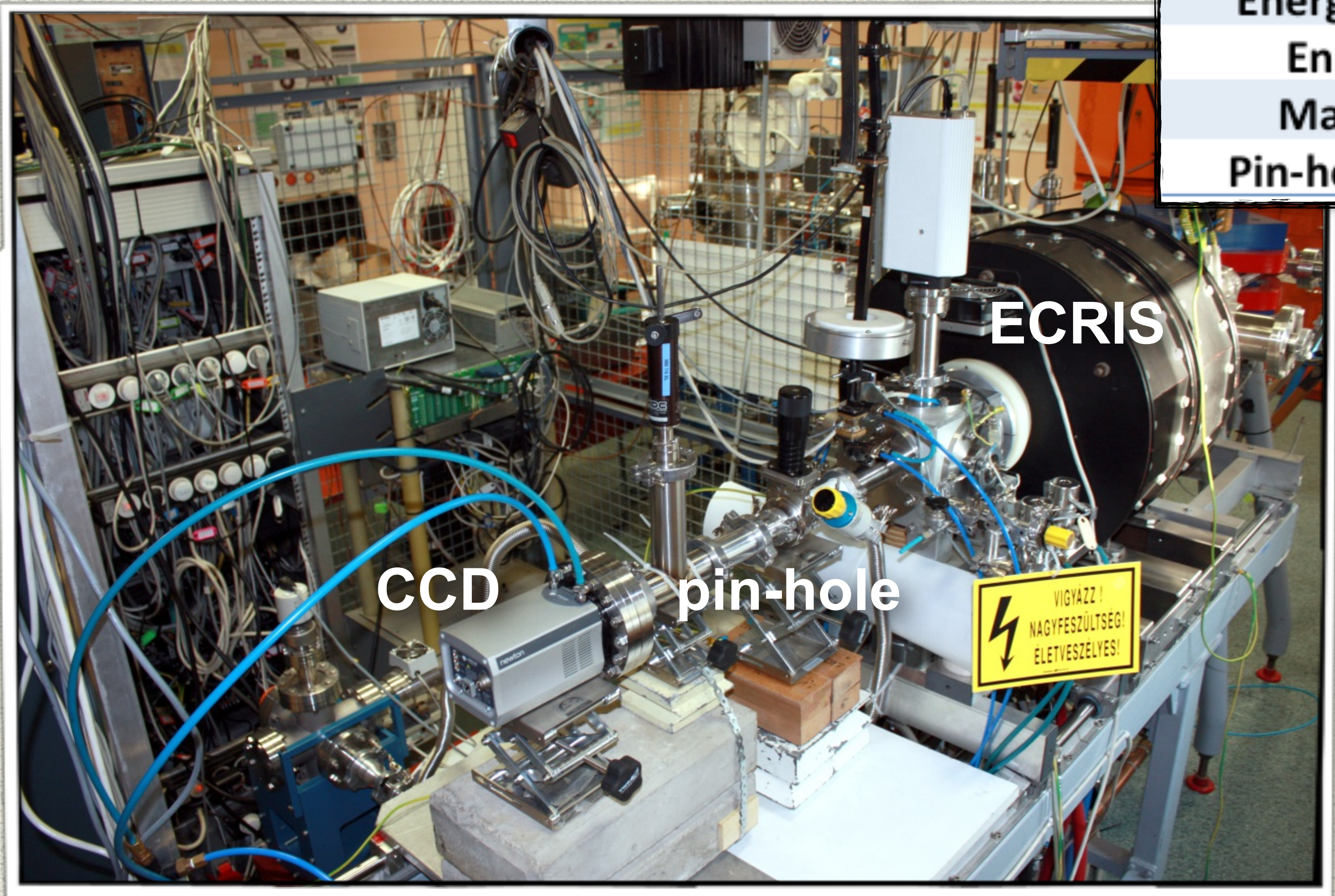


# CCD camera Set-up

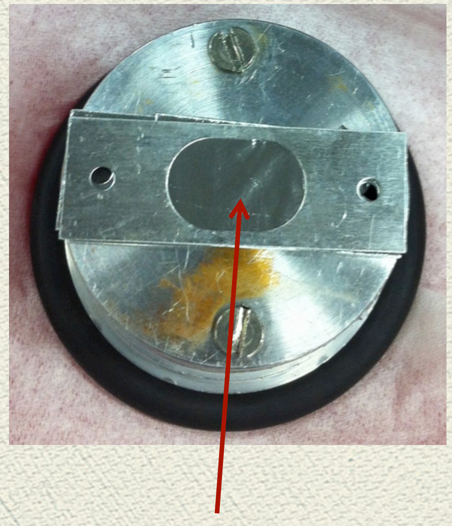



| Model | Andor Technology - Newton |
|---|---|
| Sensor size | 27.6 mm x 6.9 mm |
| Pixels | 1024 x 255 (0.3 MP) |
| Energy Resolution | 150 eV |
| Energy range | 1-10 keV |
| Magnification | 0.082-0.124-0.158 |
| Pin-hole diameters | 75 um and 100 um (W and Pb) |



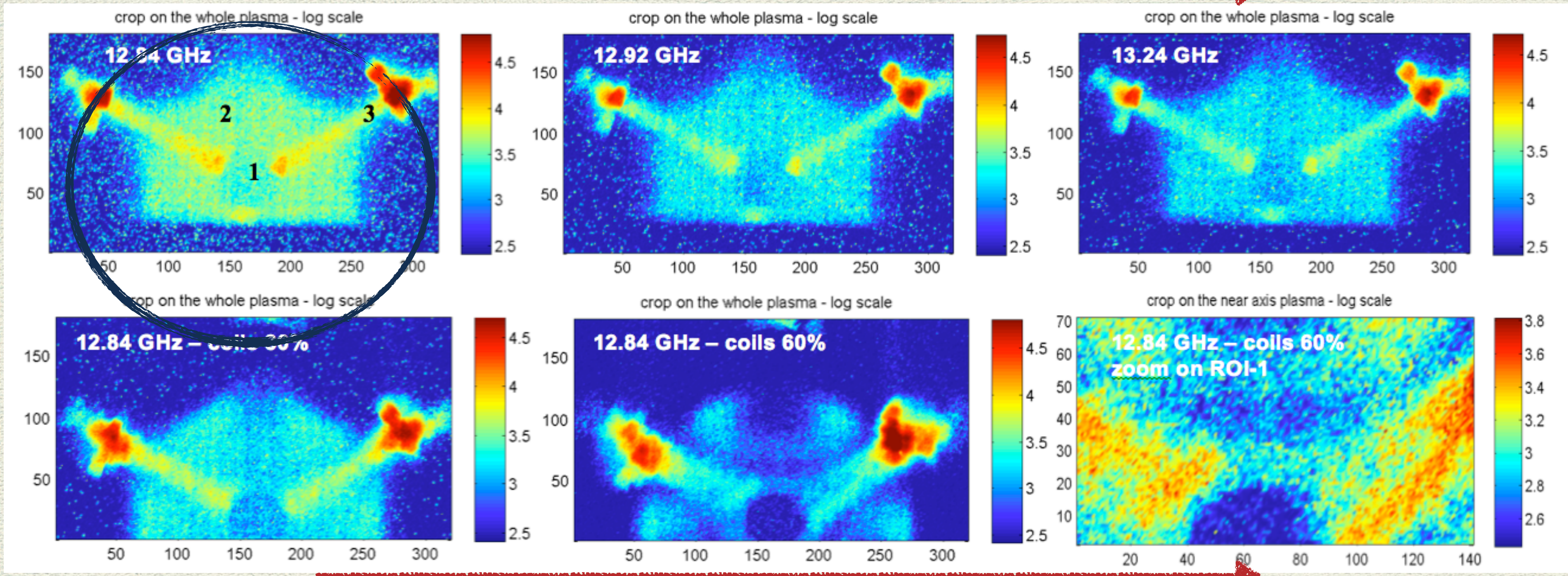

Pin-hole holder



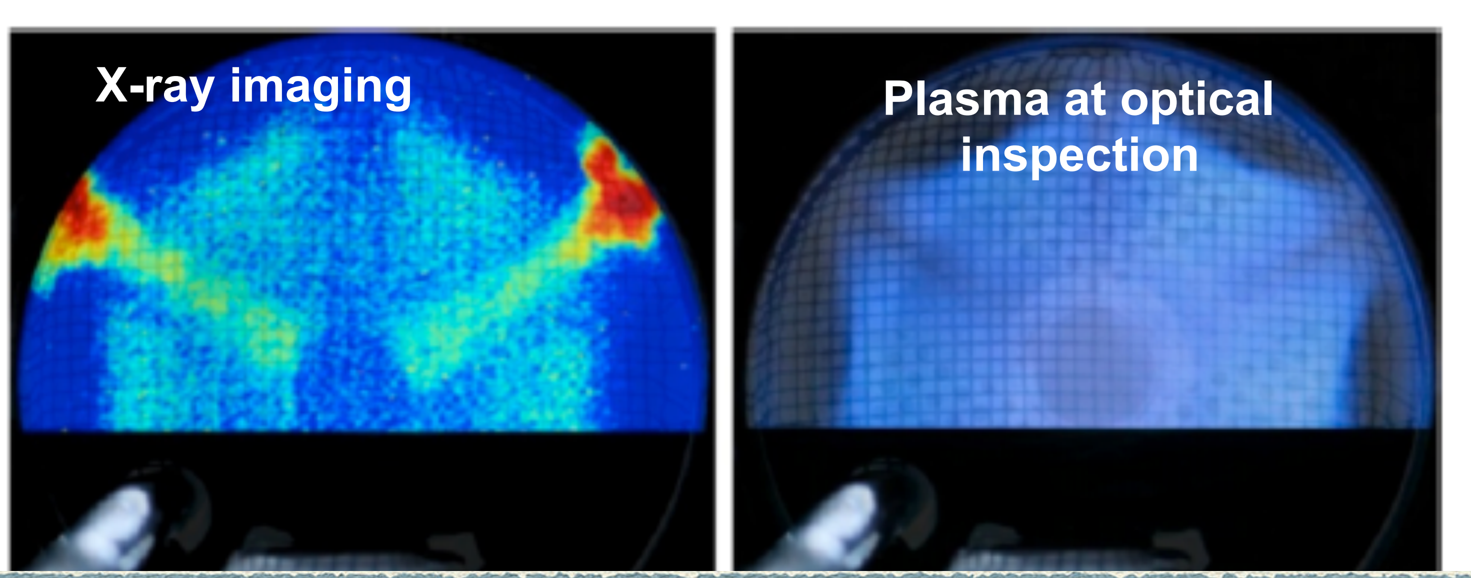
Aluminum Window

# X-ray imaging

## Varying the pumping wave frequency (F.T.E.)



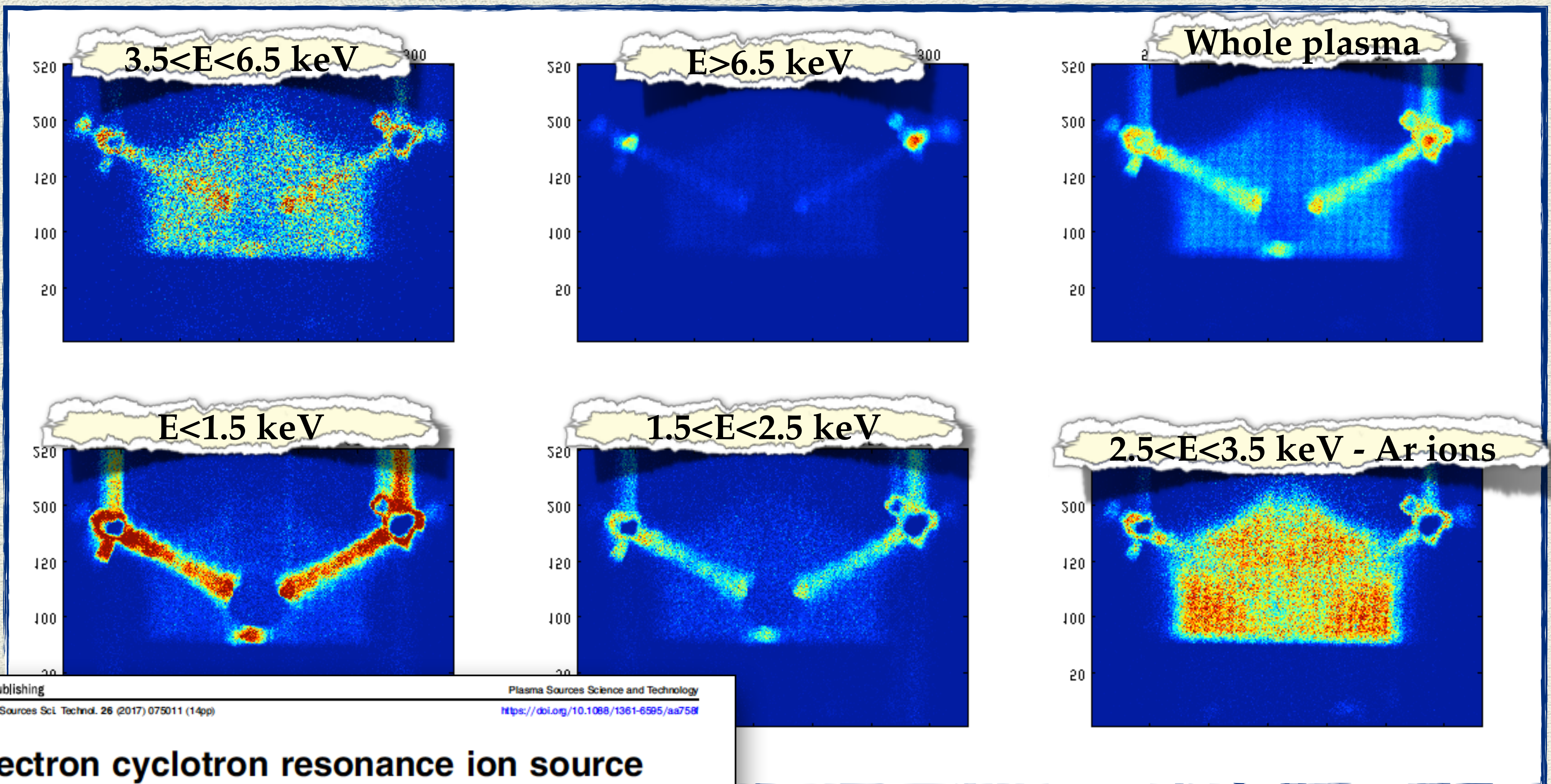

## Varying the magnetic field strength

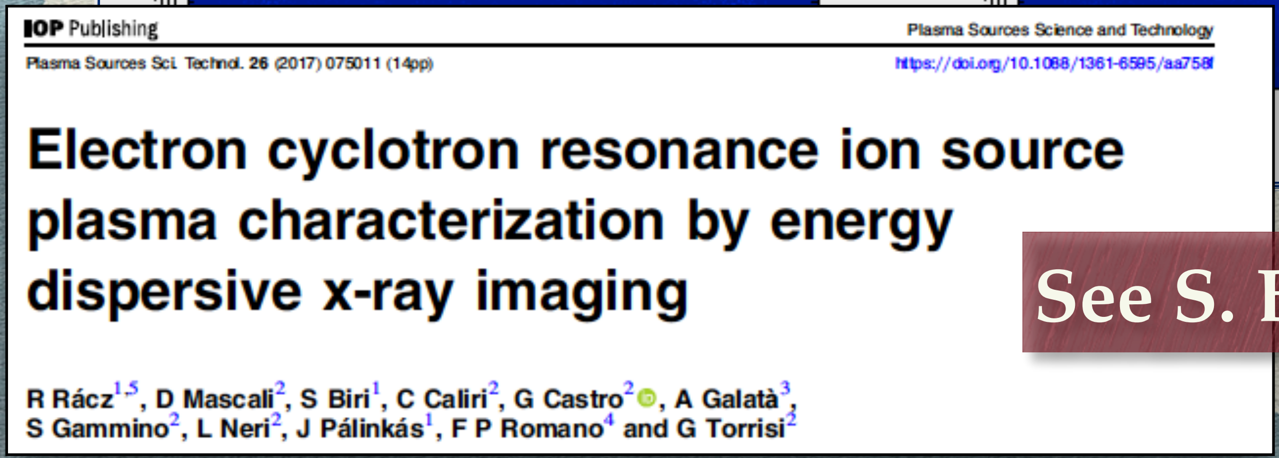


# Plasma inspection after energy filtering

## 13.24 GHz - distribution at different energies

(equalized pseudocolor maps)



IOP Publishing Plasma Sources Science and Technology
Plasma Sources Sci. Technol. 26 (2017) 075011 (14pp) https://doi.org/10.1088/1361-6595/aa758f


**Electron cyclotron resonance ion source plasma characterization by energy dispersive x-ray imaging**


R Rácz[1,5], D Mascali[2], S Biri[1], C Caliri[2], G Castro[2], A Galatà[3], S Gammino[2], L Neri[2], J Pálinkás[1], F P Romano[4] and G Torrisi[2]

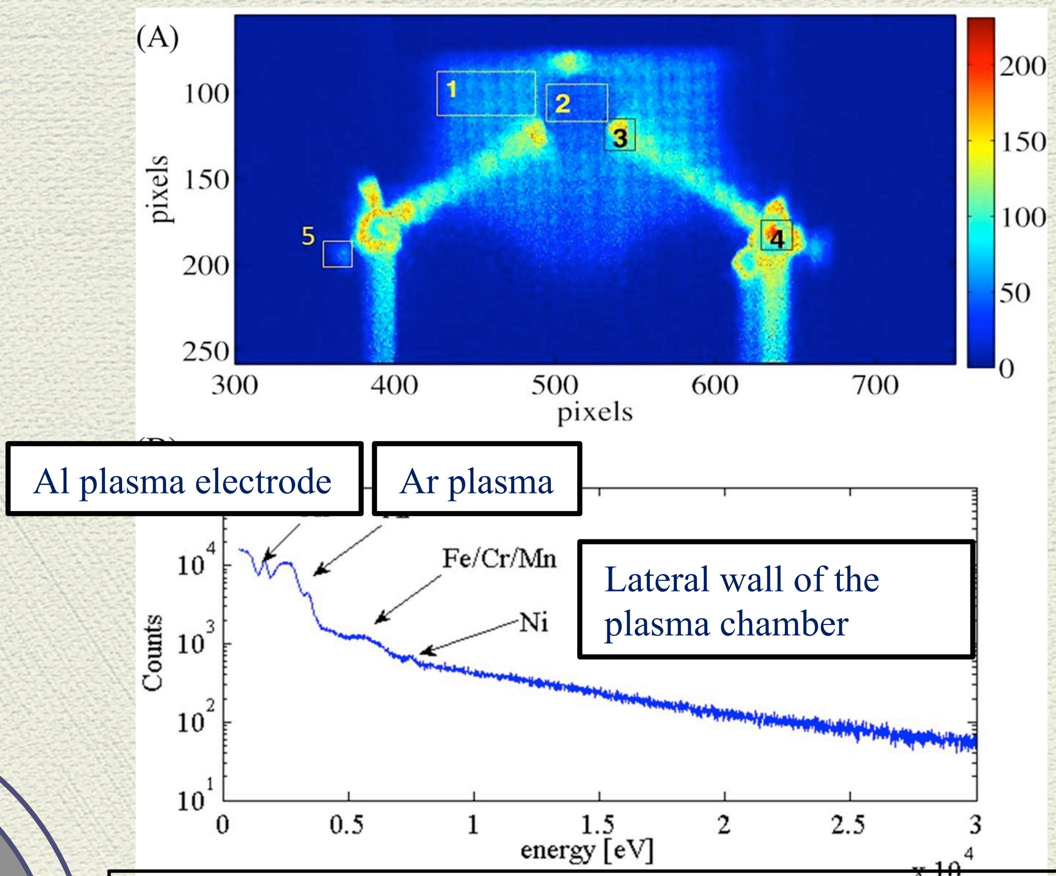

See S. Biri's talk for last news and experiments!!

# Advanced design of the plasma chamber walls oriented to spatially-resolved X-ray spectroscopy

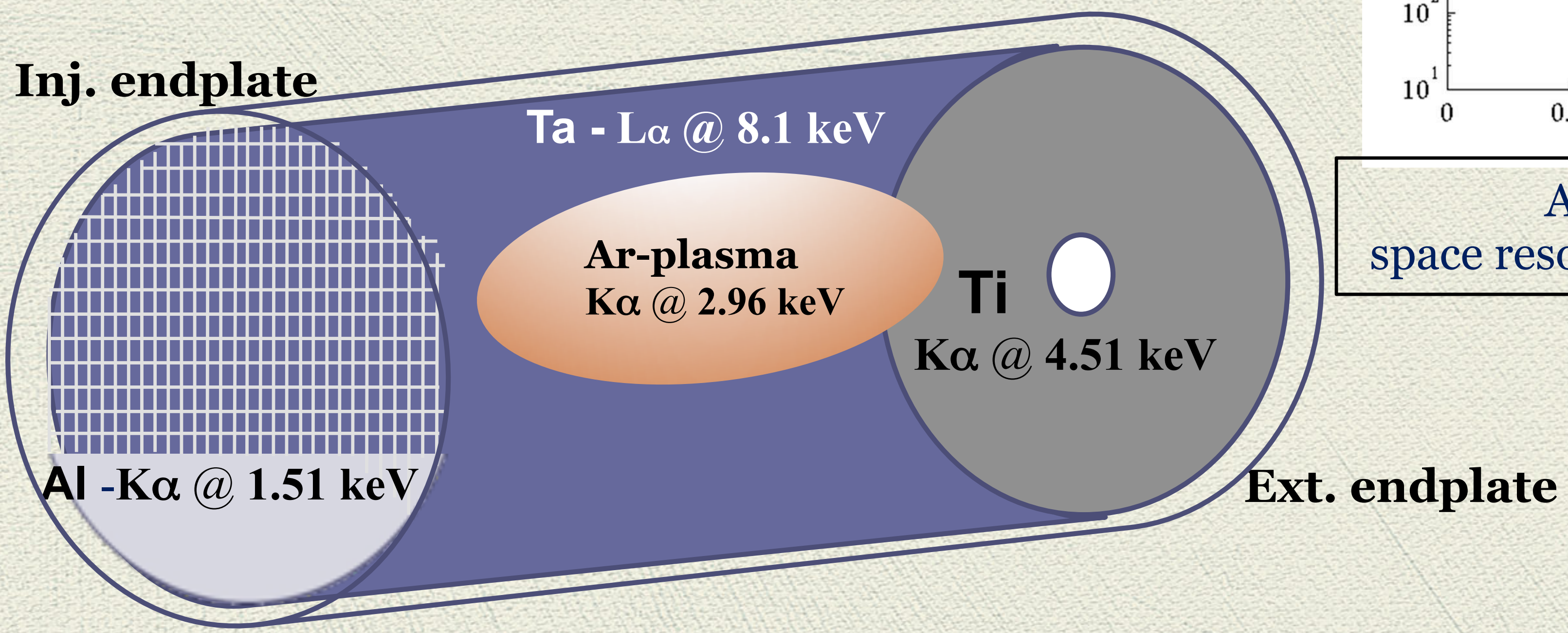
Measurements in 2014 show that fluorescence lines can be used to get info about where the electrons collide on the chamber walls!

**Now, in order to have well separated component of the emitted X-ray:**
**→ special design of plasma chamber for studying confinement dynamics**
(plasma vs. losses X-radiation emission)

X-ray image from 2014 experiment




Already in 2014 PhC X-ray space resolved-spectroscopy was performed

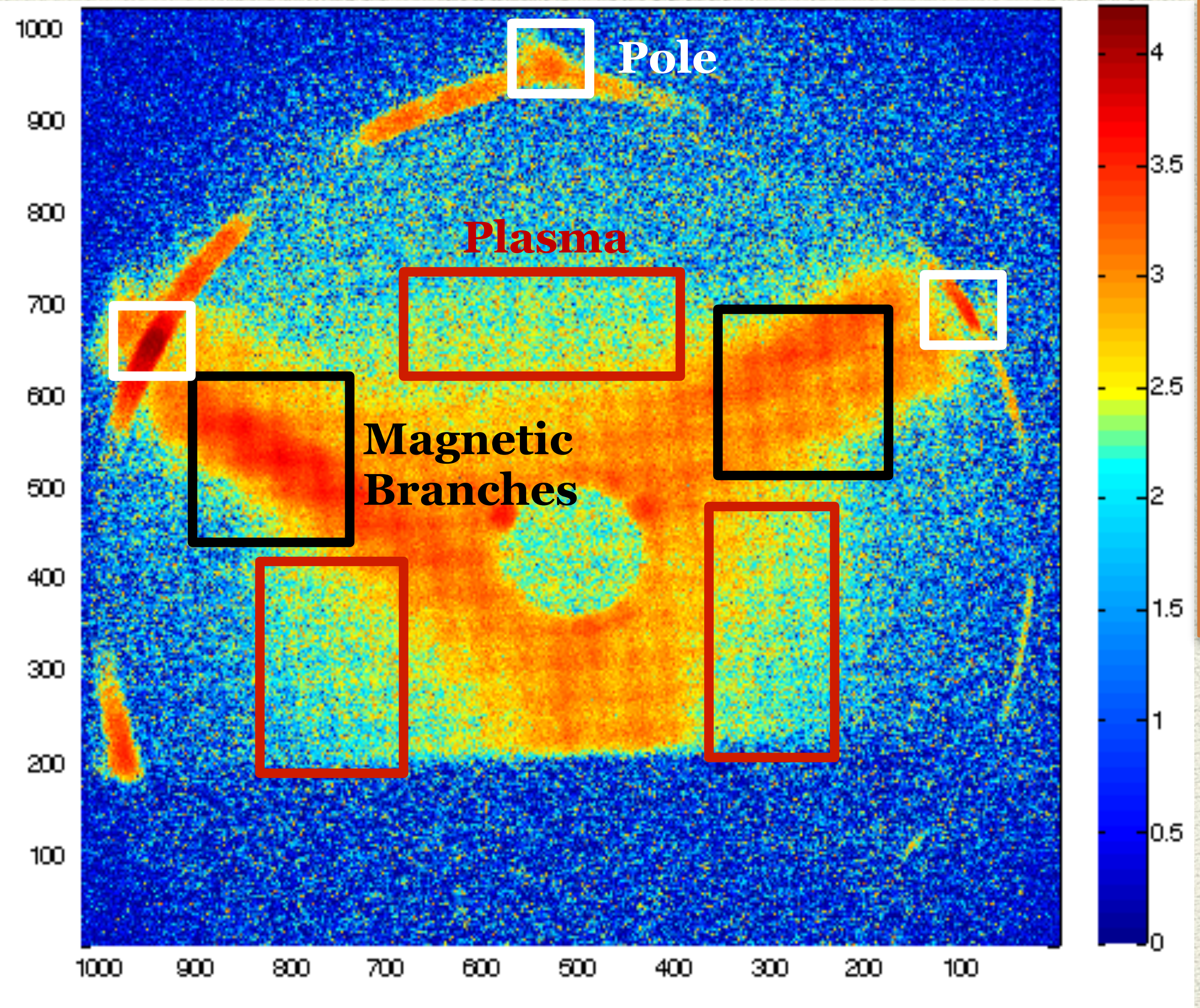



*R. Racz et al. Plasma Sources Science and Technology, Vol. 26, No. 7*
*D. Mascali et al., Review of Scientific Instruments **87**, 02A510 (2016)*

# Advanced design of the plasma chamber walls oriented to spatially-resolved X-ray spectroscopy

High-spatial resolution, time integrated images with an **exposure time of 50 sec**

→ **Counts estimated in each ROI rely to n·E, i.e. including both photon flux and energy content**




**X-rays coming from magnetic branches consist of mostly fluorescence from Ti**

**X-rays coming from plasma are mostly due to ionized Kα Argon lines**

**X-rays coming from poles are mostly due to radial losses impinging on the Ta liner**

Flux in Branches+Poles=**LOSSES**
Flux in red rectangles: **PLASMA**

Decoupling of n vs E will possible only after the spectral analysis (already acquired but not yet elaborated)

# Comparison with self-consistent simulations

*Solving the **time-dependent Vlasov equation**, including single particle collisions*

$$\frac{\partial f_\alpha}{\partial t} + \vec{v}\cdot\vec{\nabla} f_\alpha + \frac{q_\alpha}{m_\alpha}\left(\vec{E} + \frac{\vec{v}\times\vec{B}}{c}\right)\cdot\vec{\nabla}_{\vec{v}} f_\alpha = 0$$

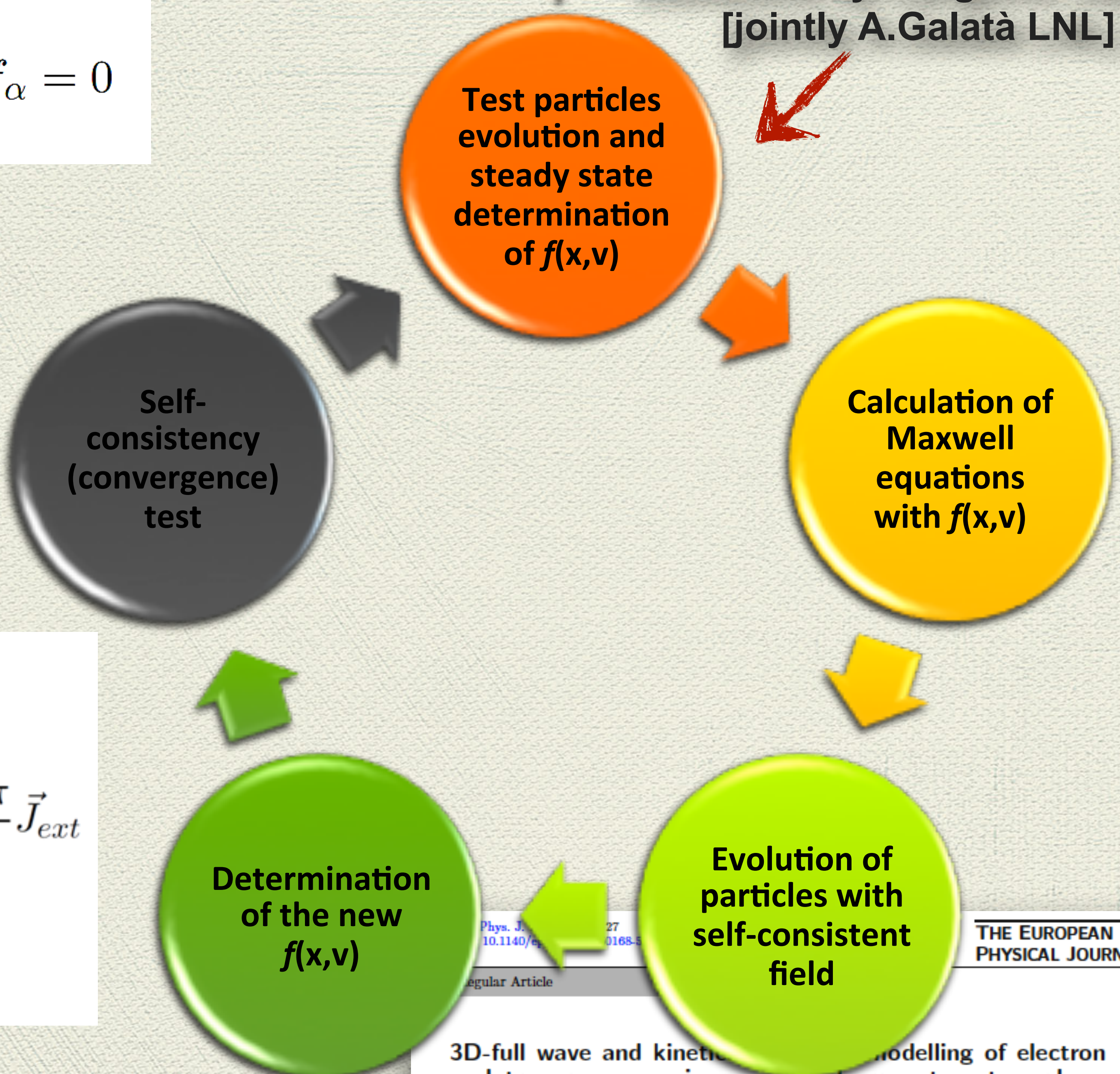
$$\frac{d\vec{v}}{dt} = \frac{q}{m_0\gamma}\left[\vec{E} + \vec{v}\times B - \frac{\vec{v}\cdot\vec{E}}{c^2}\vec{v}\right]$$

**Collisions by Langevin method [jointly A.Galatà LNL]**

**Step-by-step current**

**Step-by-step plasma density**

$$\begin{aligned}
\vec{\nabla}\cdot\vec{E} &= 4\pi\sum_\alpha \overline{n}_\alpha q_\alpha \boxed{\int f_\alpha d\vec{v}} + 4\pi\rho_{ext} \\
\vec{\nabla}\times\vec{B} &= \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c}\sum_\alpha \overline{n}_\alpha q_\alpha \boxed{\int \vec{v} f_\alpha d\vec{v}} + \frac{4\pi}{c}\vec{J}_{ext} \\
\vec{\nabla}\times\vec{E} &= -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}
\end{aligned}$$




THE EUROPEAN PHYSICAL JOURNAL D
Regular Article

**3D-full wave and kineti... modelling of electron cyclotron resonance ion sources plasma: steps towards self-consistency***

David Mascali[1], Giuseppe Torrisi[1,2,a], Lorenzo Neri[1], Gino Sorbello[1,3], Giuseppe Castro[1], Luigi Celona[1], and Santo Gammino[1]

# Comparison with self-consistent simulations

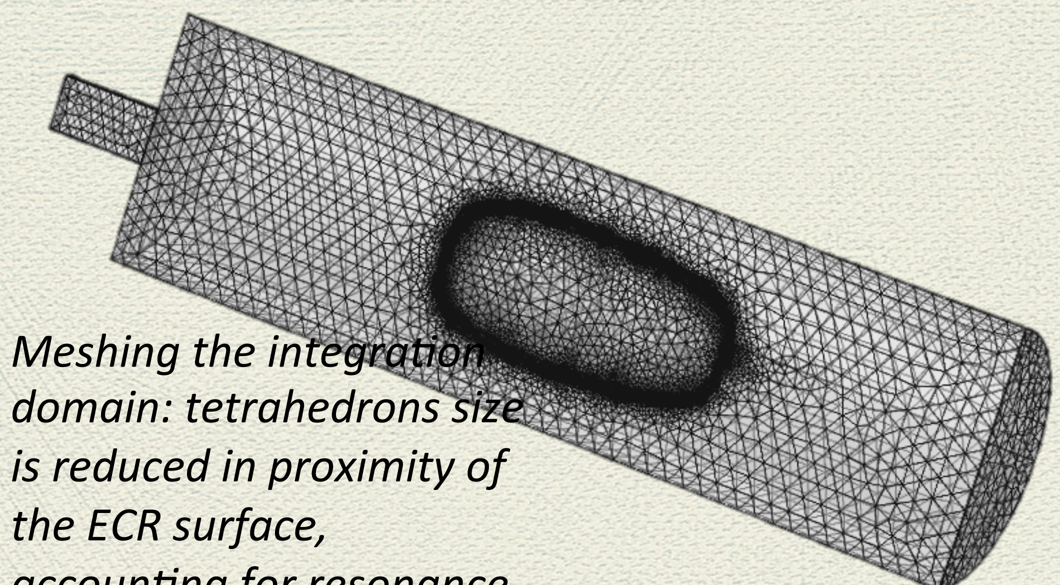
Solution of Maxwell's equations in **COMSOL** using MUMPS direct solver

Full anisotropic dielectric tensor for the magnetized plasma computed in **MATLAB**

Electromagnetic field in ECRIS Plasma

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

**Wave equation with tensorial permittivity**



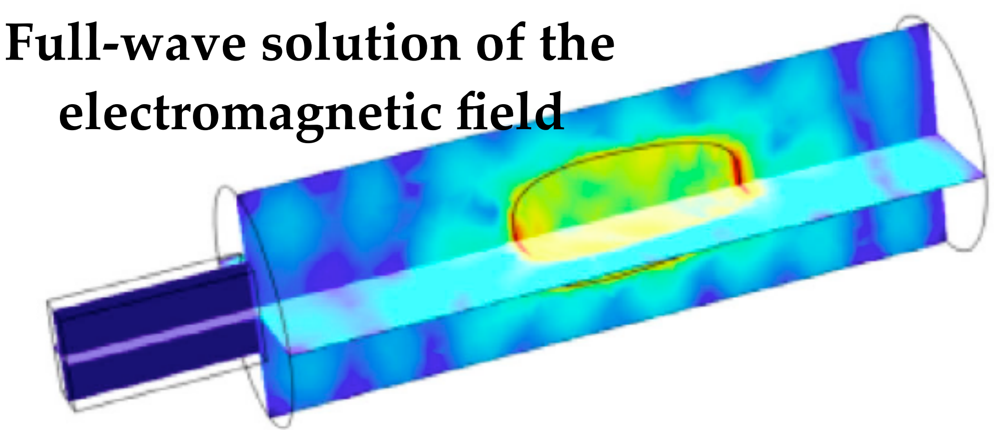
*Meshing the integration domain: tetrahedrons size is reduced in proximity of the ECR surface, accounting for resonance.*

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

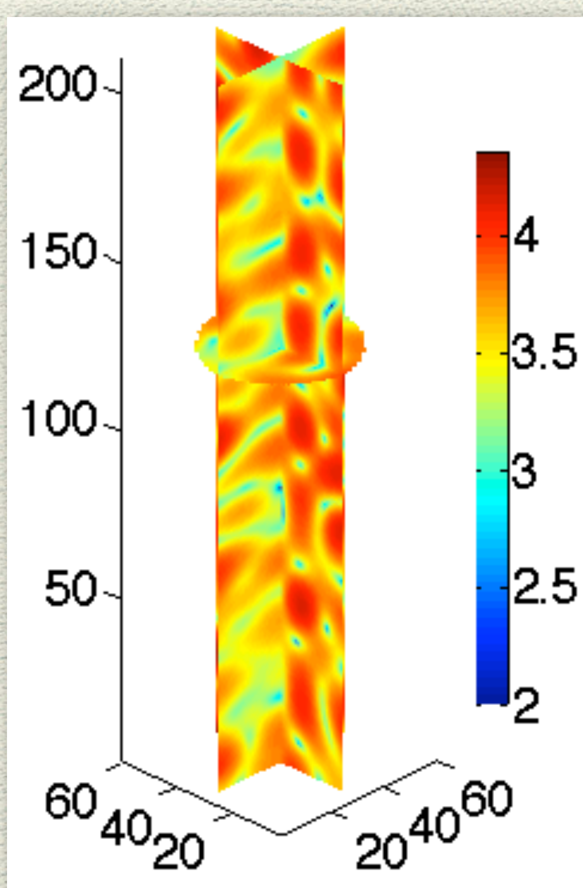
$$= \epsilon_0 \begin{bmatrix} 1 + i\frac{\omega_p^2}{\omega}\frac{a_x}{\Delta} & i\frac{\omega_p^2}{\omega}\frac{c_z + d_{xy}}{\Delta} & i\frac{\omega_p^2}{\omega}\frac{-c_y + d_{xz}}{\Delta} \\ i\frac{\omega_p^2}{\omega}\frac{-c_z + d_{xy}}{\Delta} & 1 + \frac{i\omega_p^2}{\omega}\frac{a_y}{\Delta}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

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

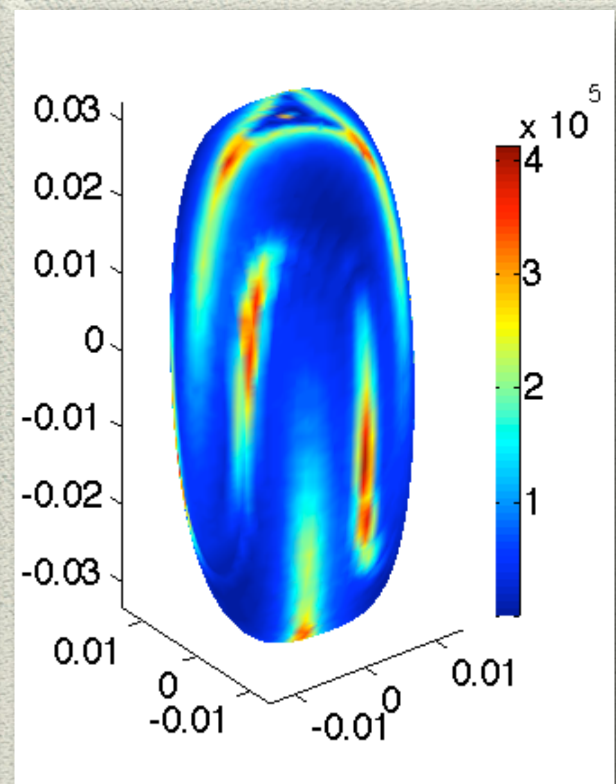
**Full-wave solution of the electromagnetic field**



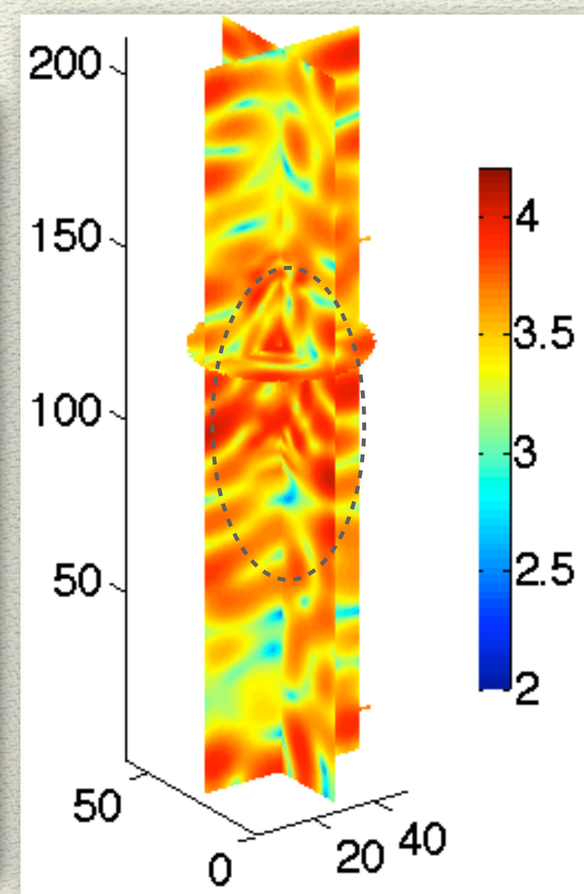
# Searching self-consistency



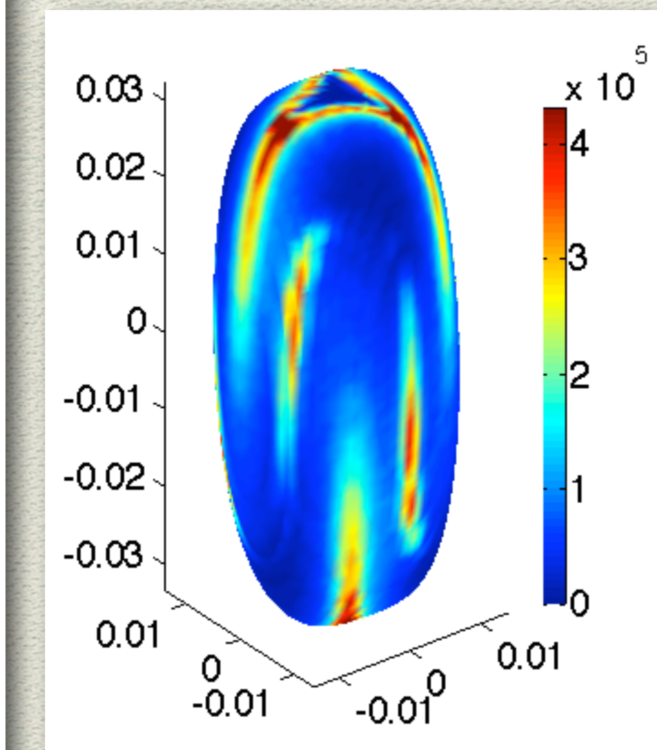

Freq. dom. solution
step 0
(vacuum cavity)




Particle Tracking
step 1
(vacuum field+plasmoid-halo initial density distr.)

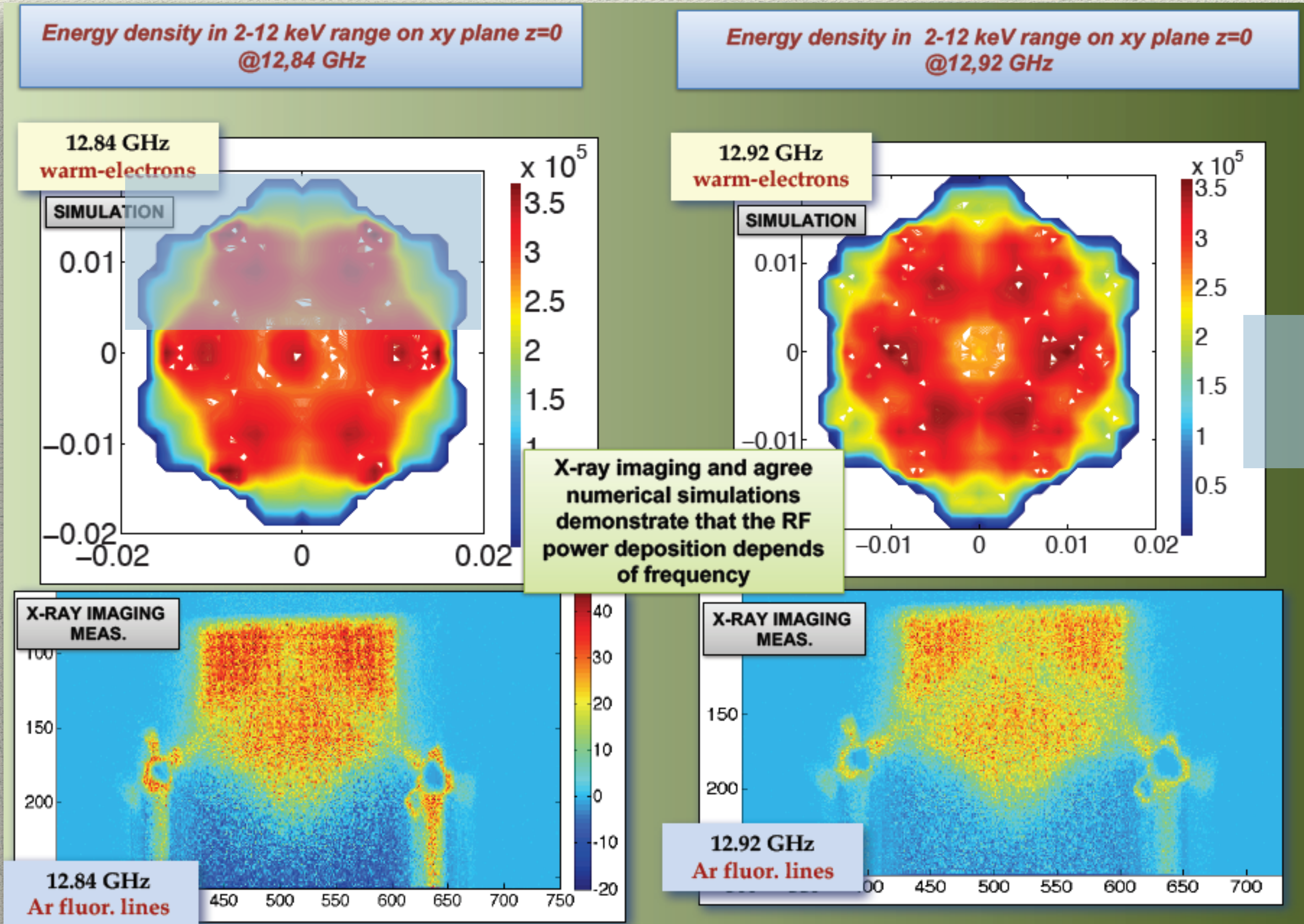



Freq. dom. solution
step 1
(70% density from plasmoid halo model+30% step-1 density structure)




Particle Tracking
step 2
(70% vacuum field + 30% step-1 full-wave calculated field)

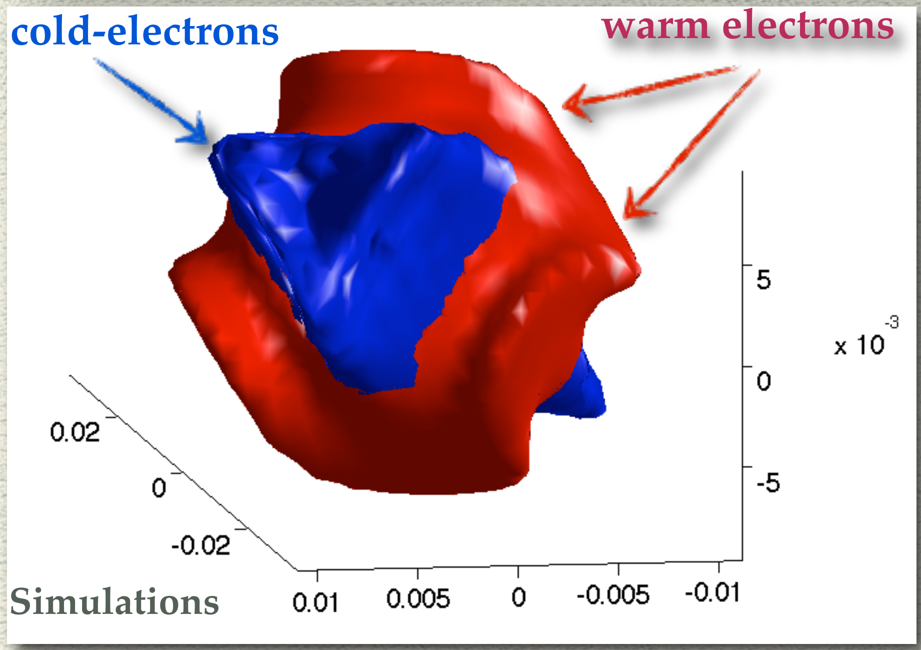
# Comparison to self-consistent simulations
## 12.84 and 12.92 GHz



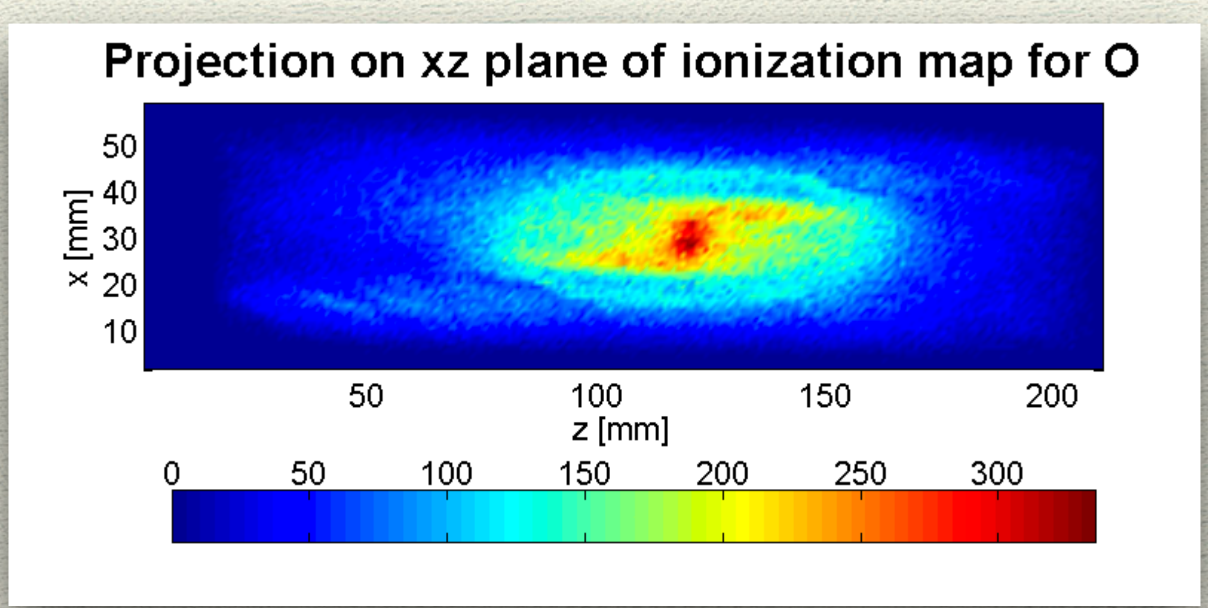
# Including ionization

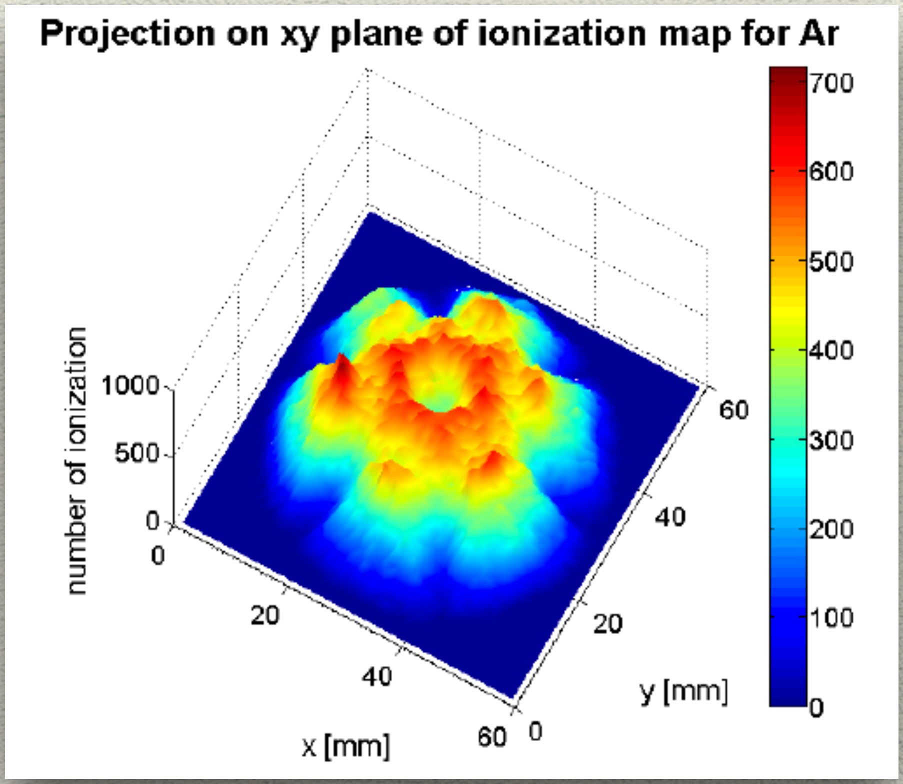
$$\frac{\nu_{ion\, i\to i+1}}{n_e} = \sum_{j=1}^{N} \frac{a_{ij} q_{ij}}{T_e^{3/2}} \left\{ \frac{1}{P_{ij}/T_e} E_1(P_{ij}/T_e) - \frac{b_{ij} e^{c_{ij}}}{P_{ij}/T_e + c_{ij}} E_1(P_{ij}/T_e + c_{ij}) \right\}$$

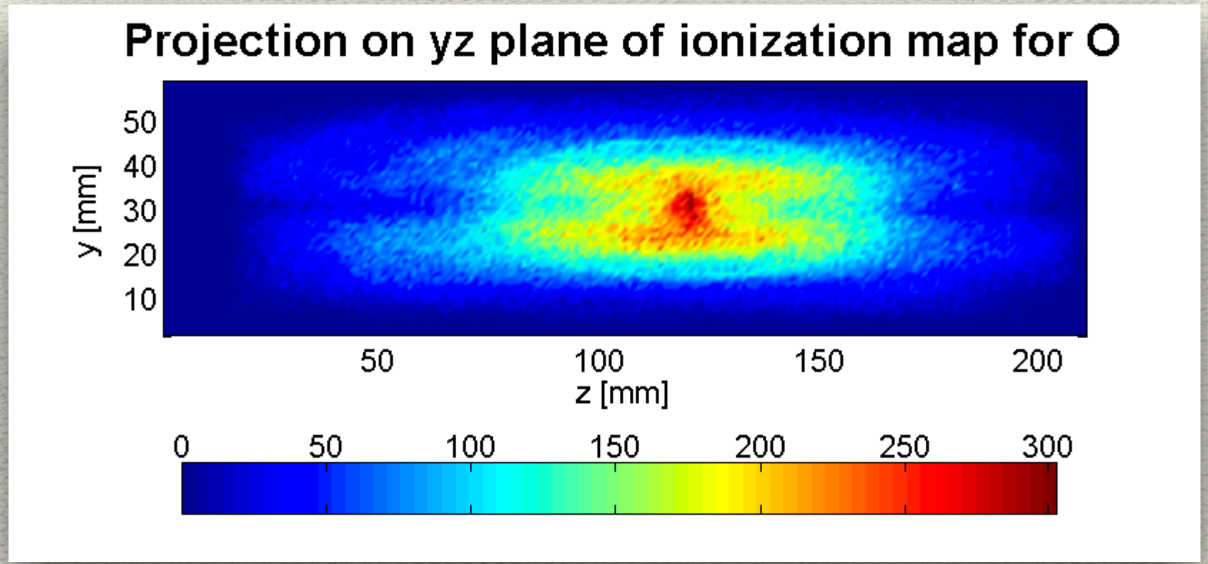
Lotz formula for multi-step ionisation



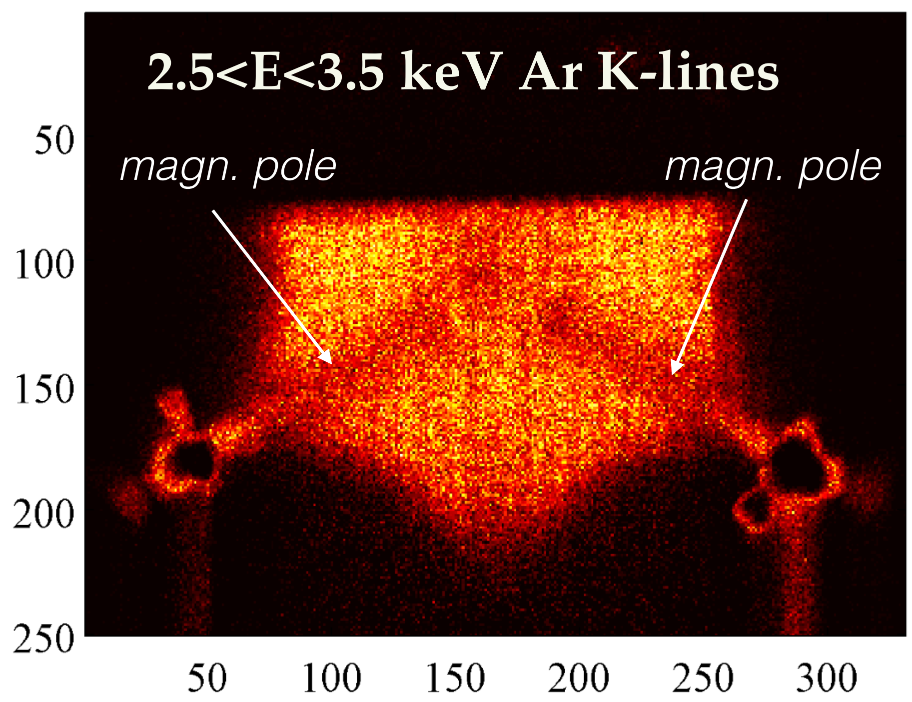

Starting from 3D distribution of electrons in the plasma, maps of ions distribution can be obtained



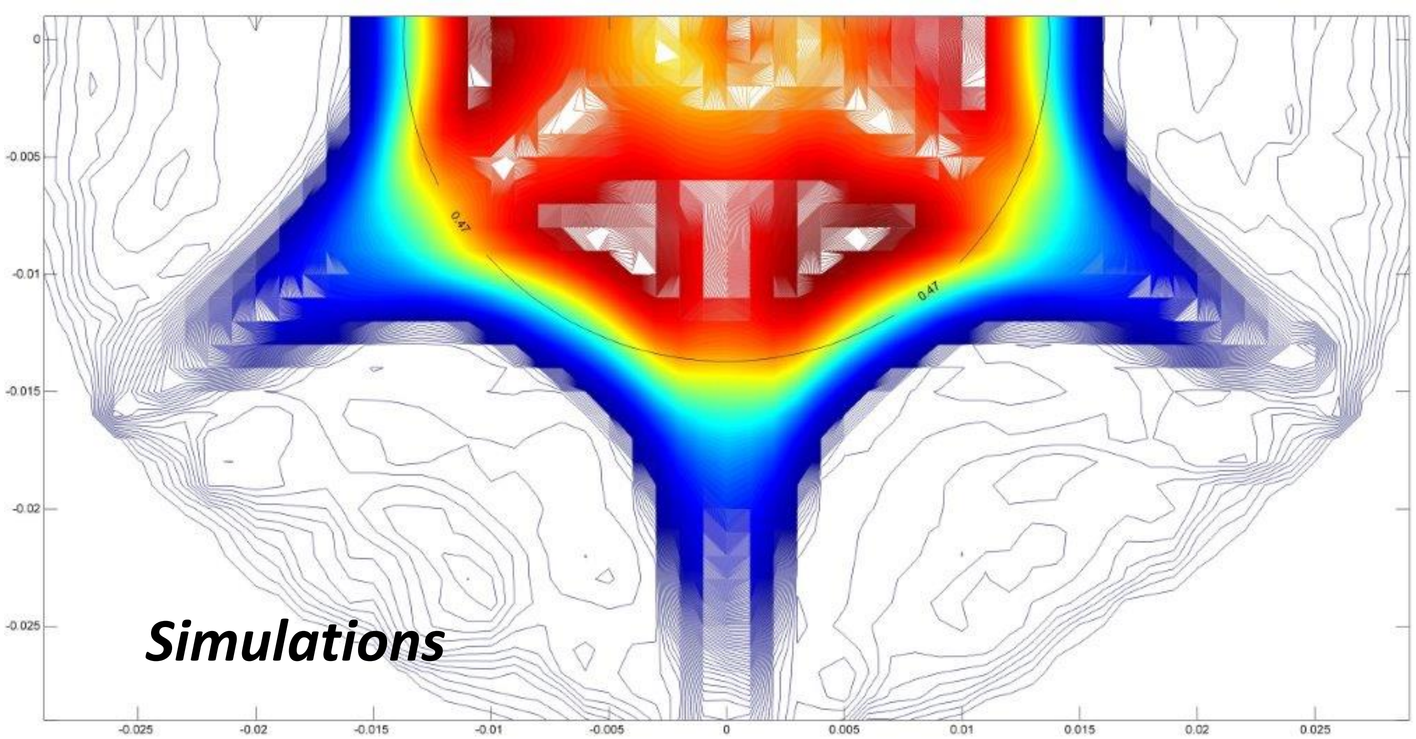



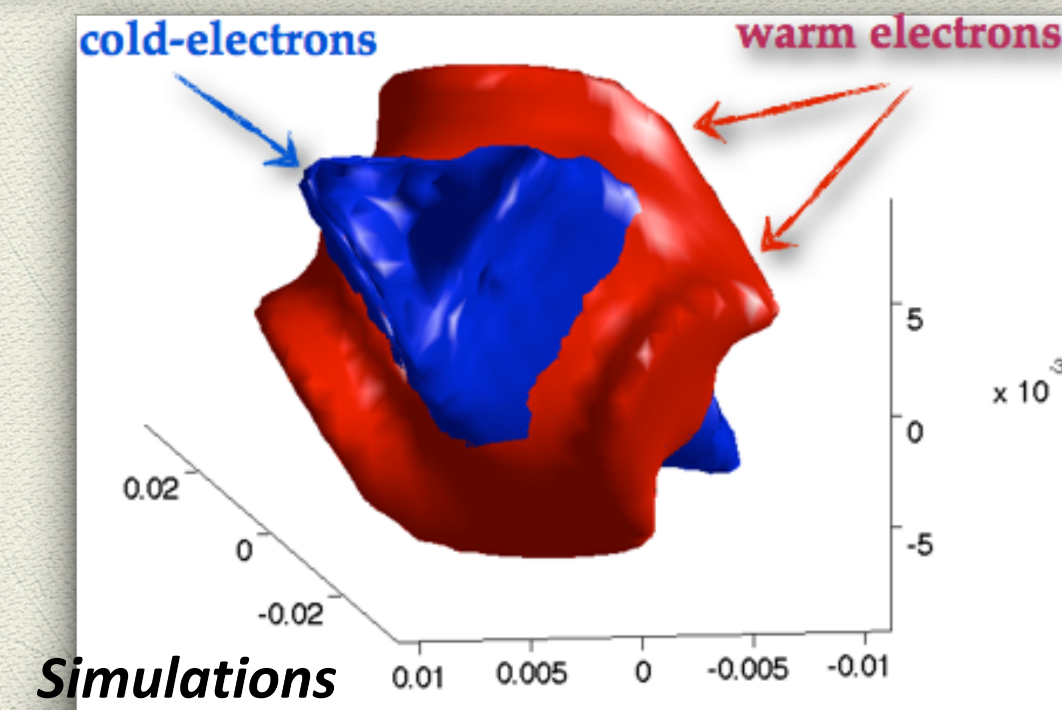
# *X-ray imaging and 3D plasma modelling*




**X-ray fluorescence from Ar ions in the plasma**




3D self-consistent simulations very well reproduce energy content distribution of the plasma, which in turn fits with experimental detected displacement of Argon ions

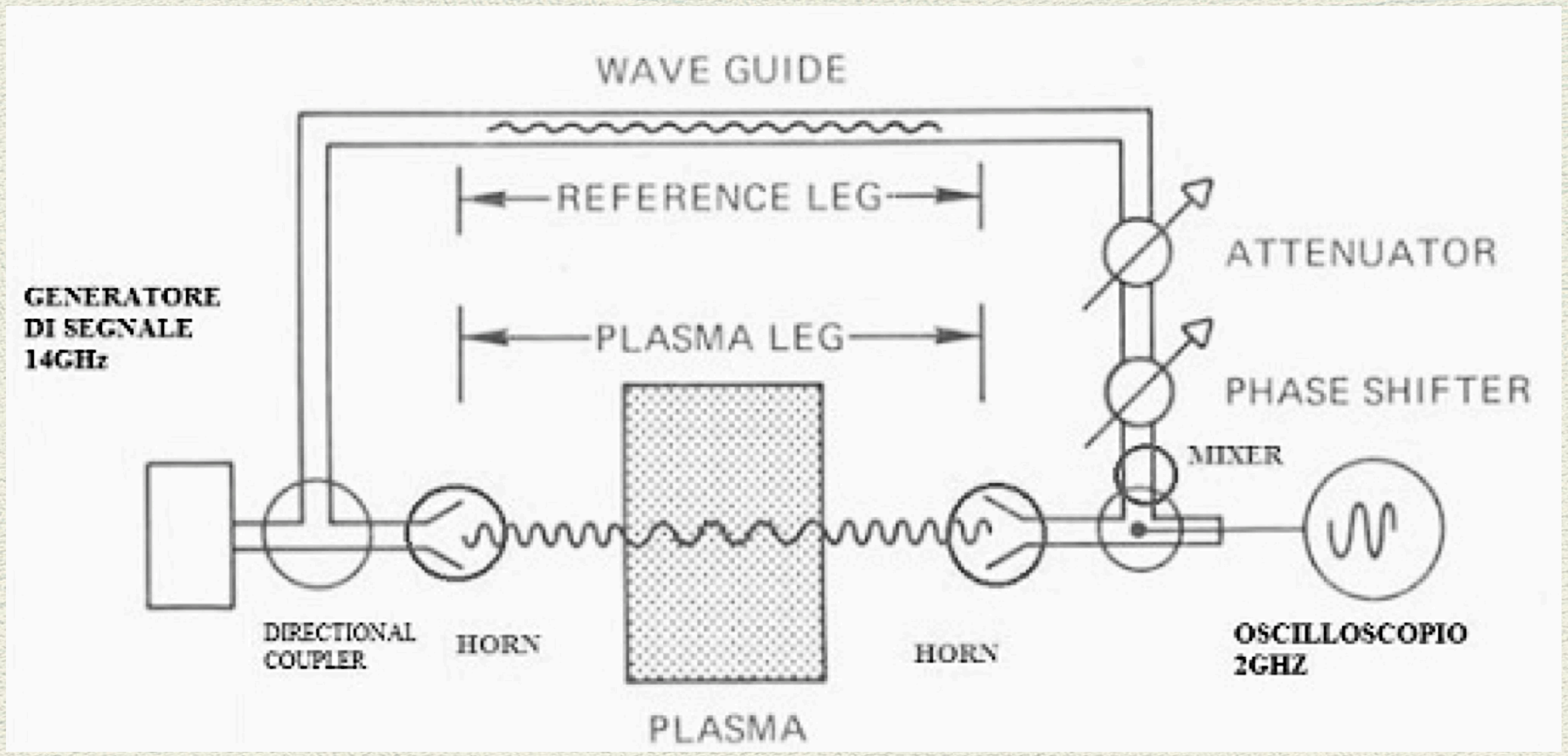


# Probing the plasma density in all the energy domains

## VESPRI

VEry Sensitive evaluation of Plasma density by micRowave Interferometry

# Probing the plasma density in all the energy domains




Classical Scheme of Interferometer

How to calculate the density n of the plasma

$$\Delta\varphi = \frac{\omega}{c}\left[1-\left(1-\frac{{\omega_p}^2}{\omega^2}\right)^{\frac{1}{2}}\right]L \quad \rightarrow \quad {\omega_p}^2 = \frac{4\pi n e^2}{m\varepsilon_0} \quad \rightarrow$$

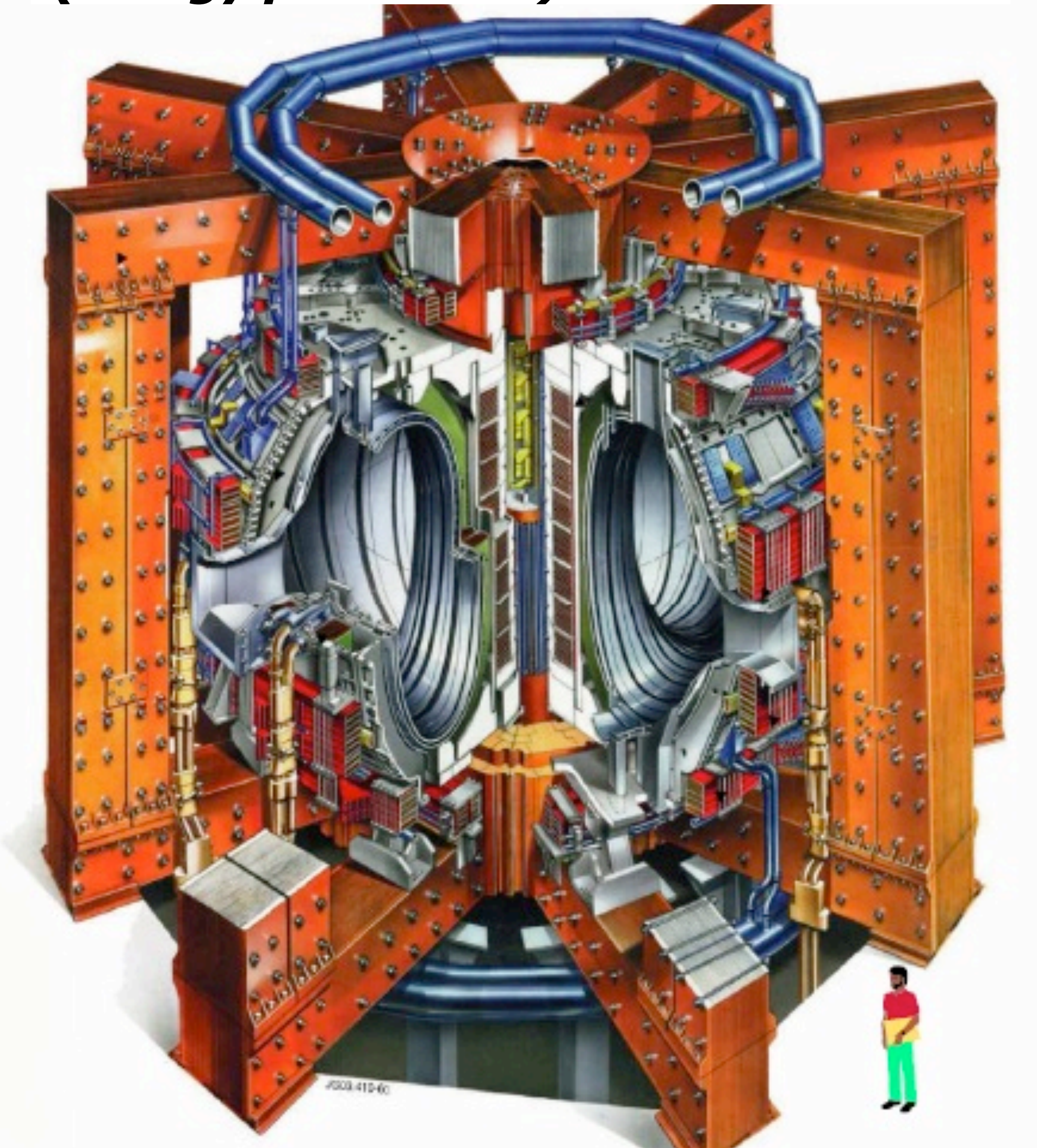
Microwave interferometry measures plasma density through a measurement of phase shift.

In plasmas the phase variation depends on the “ natural plasma frequency”

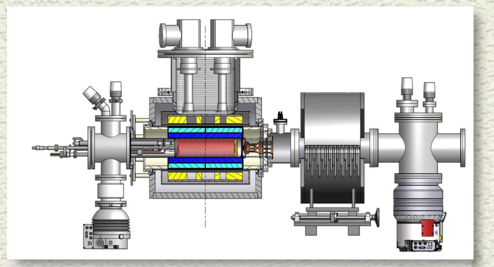
The plasma frequency depends on the density

# The main challange: "downsizing"

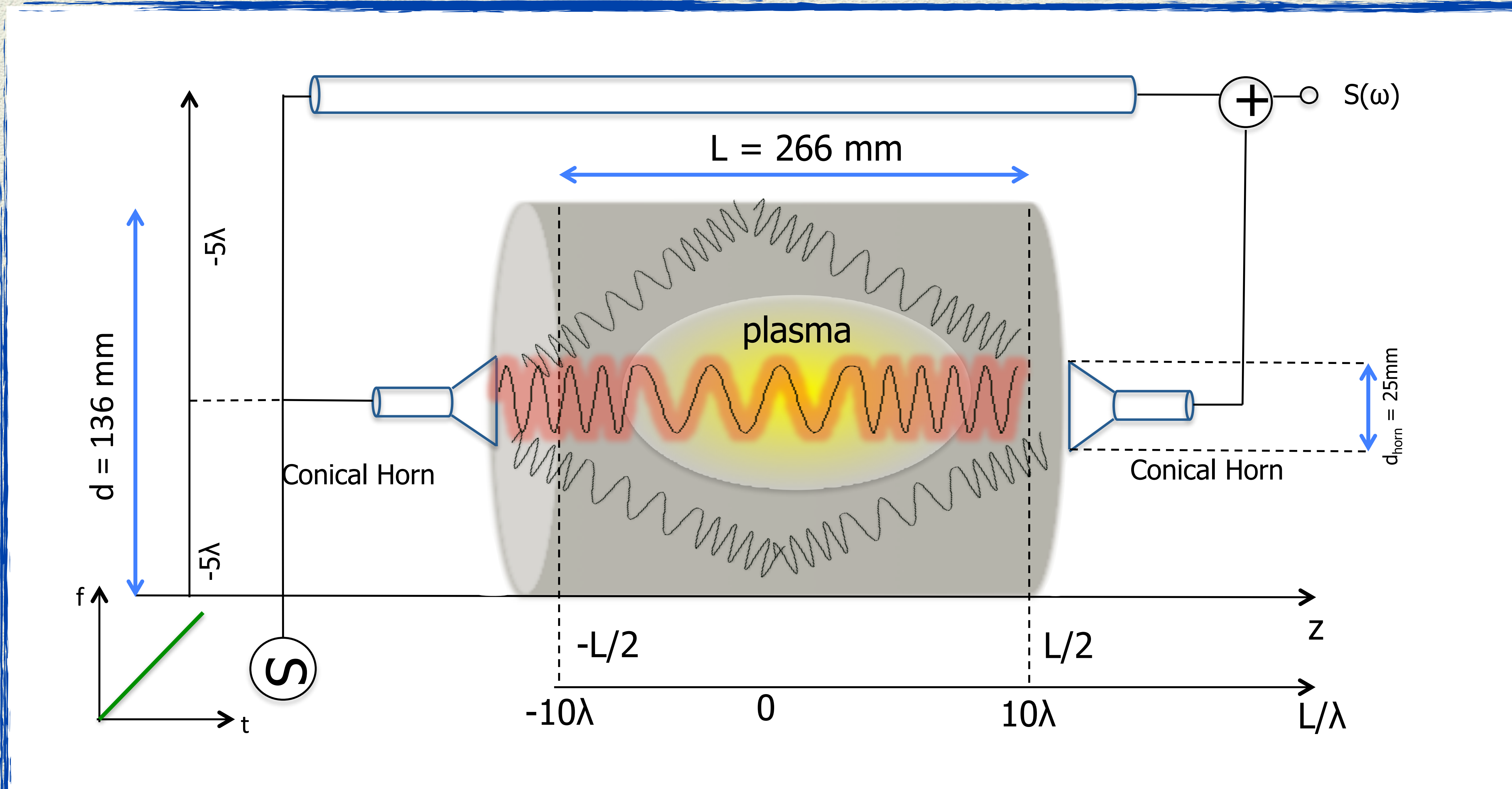
***JET Tokamak for nuclear fusion (energy production)***



***ECR ION Source: extremely compact plasma machine***



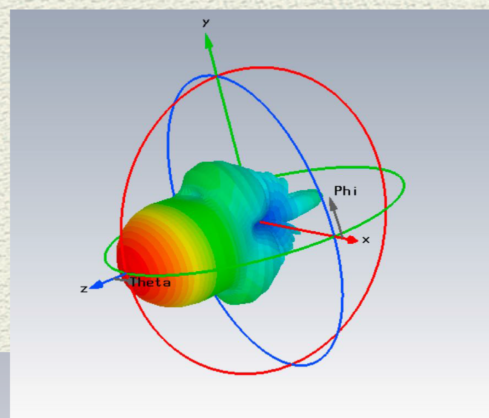
# Probing the plasma density in all the energy domains



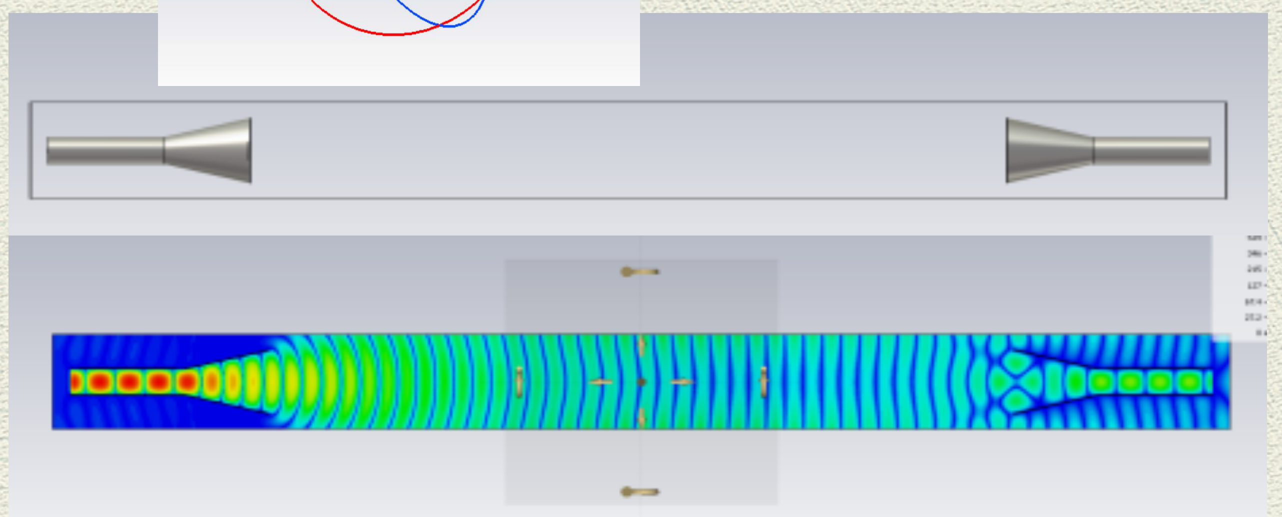

**Drawbecks** →

- **Limited ECRIS access probing port**
- **Multi-paths introduce spurious signals**

# Interferometry in ECRIS: simulations

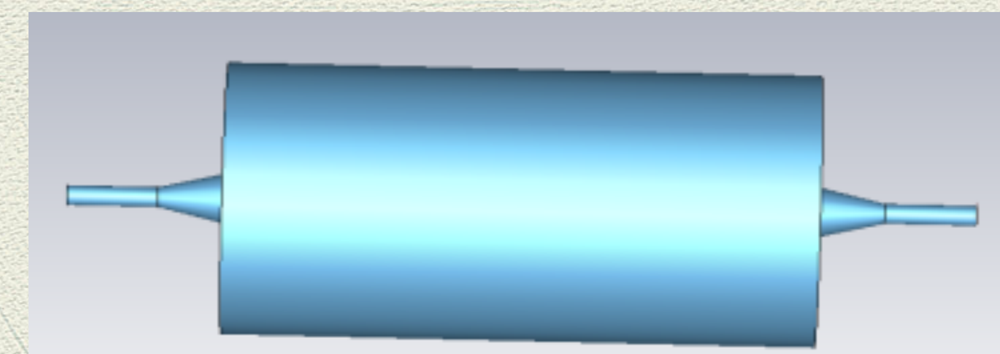



•Antenna directivity

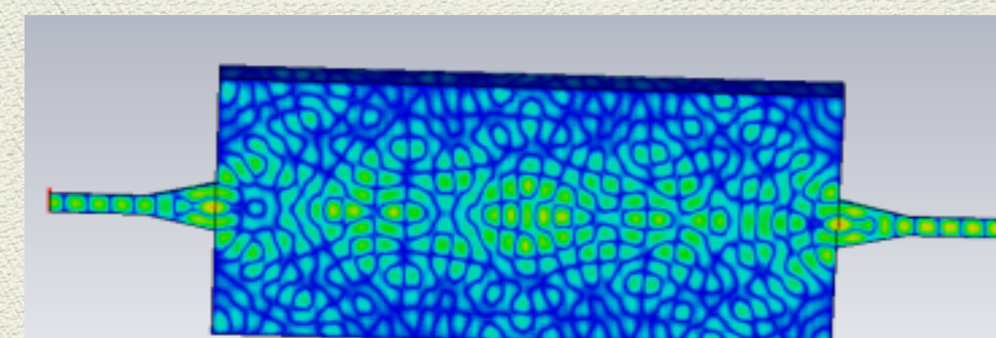


Horn-to-horn transmission for antennas facing each other in vacuum

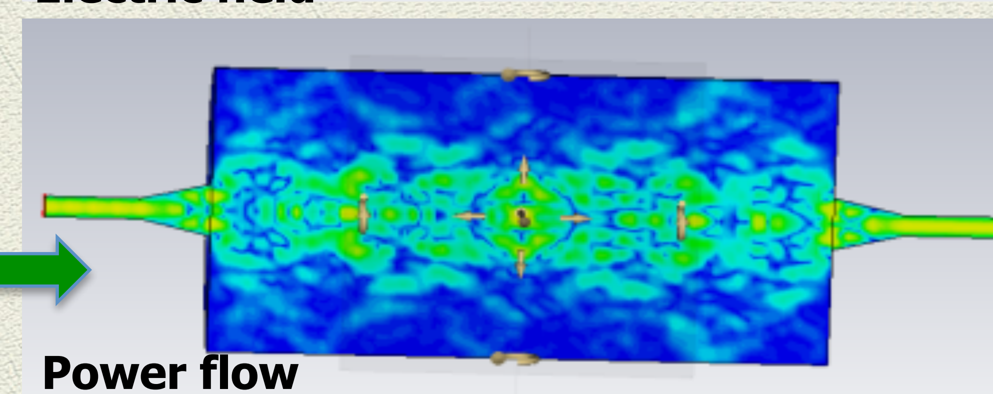
Numerical simulations (COMSOL+CST) put in evidence cavity walls effects



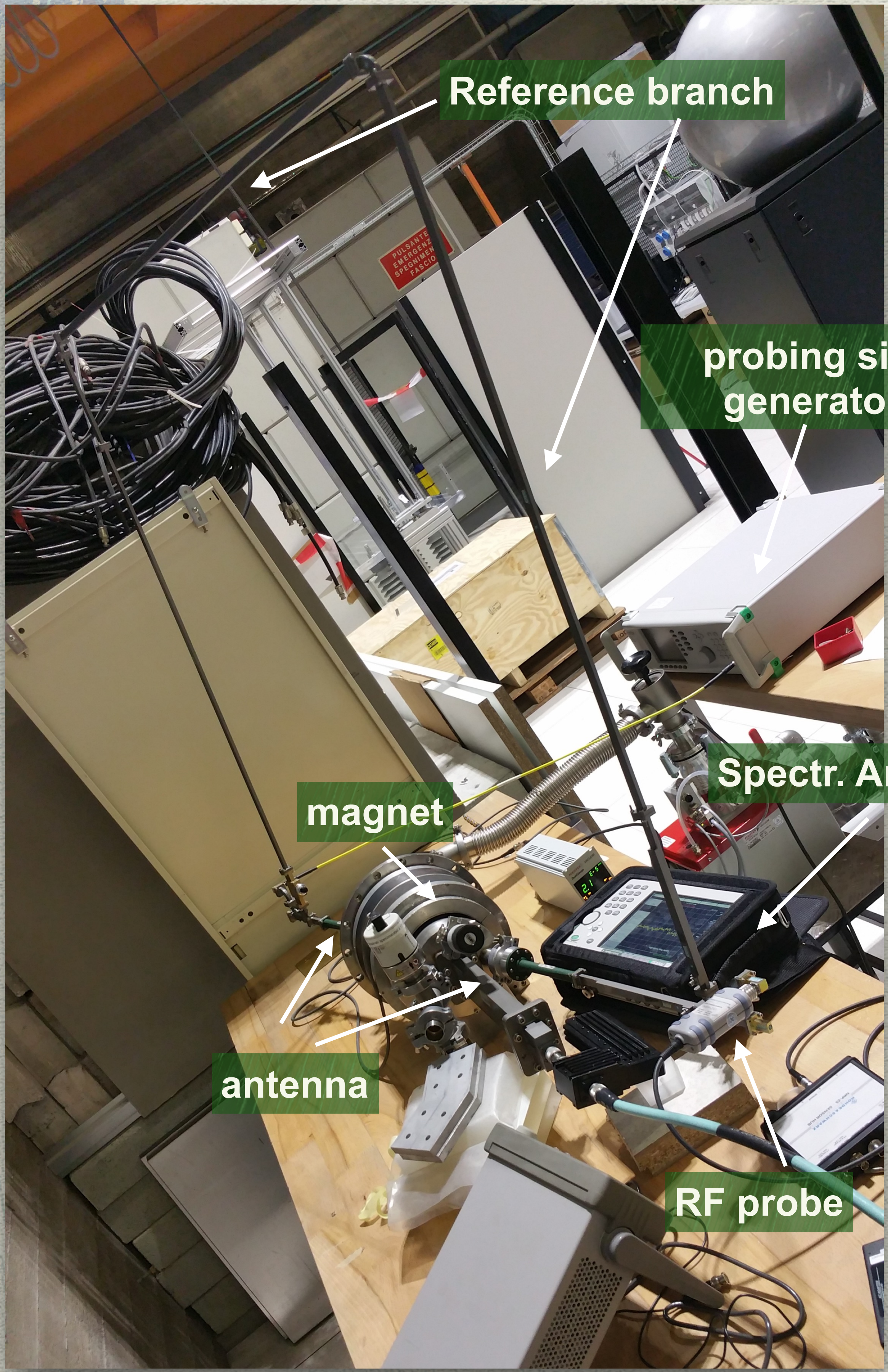
**Horn connected to the plasma cavity**

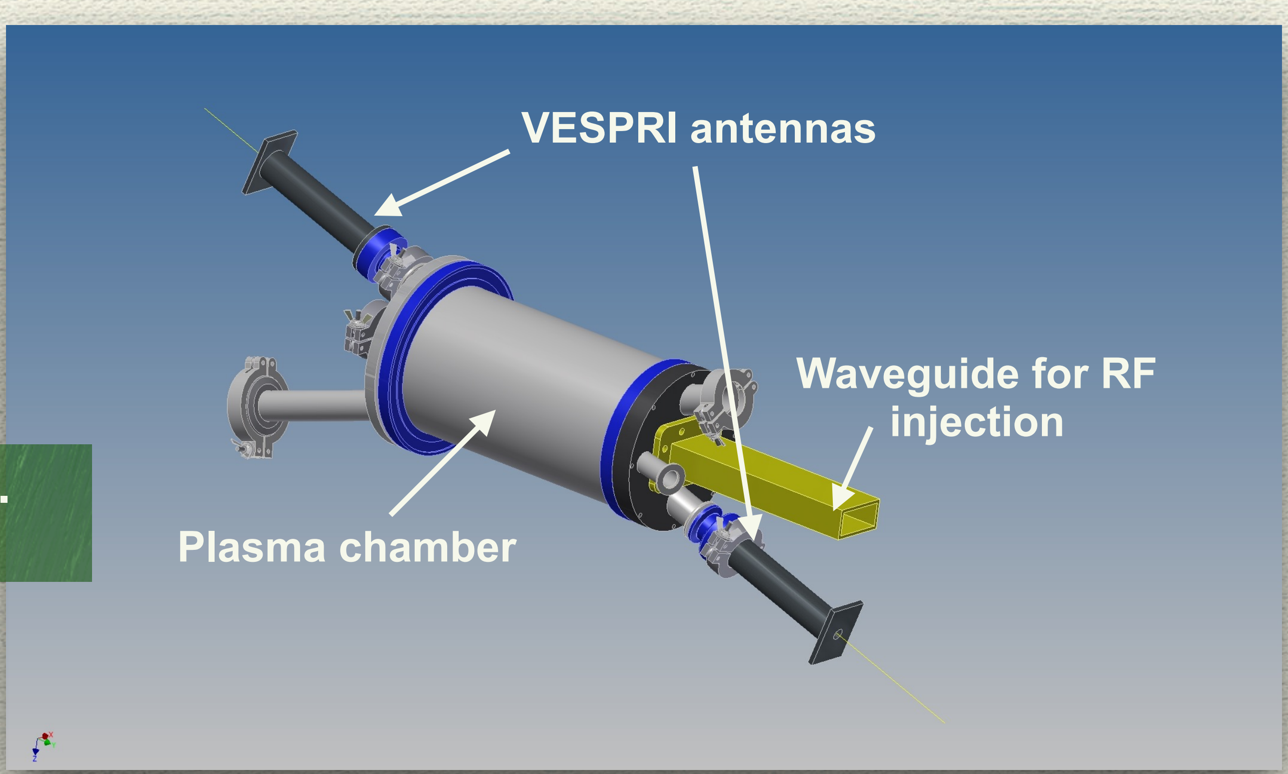


**Electric field**



**Power flow**



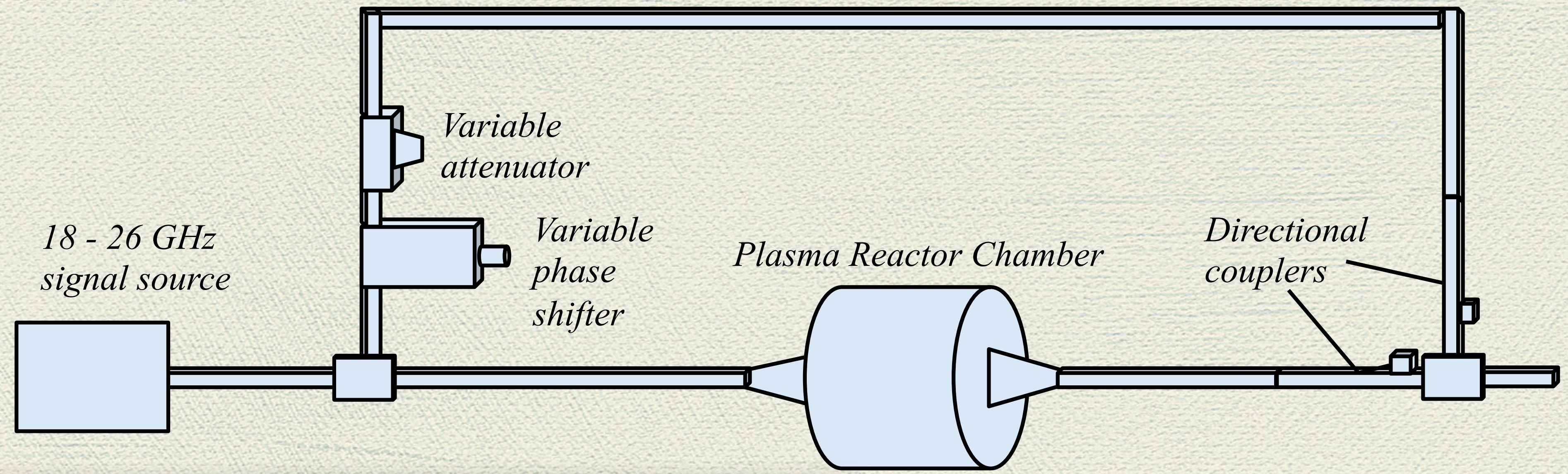



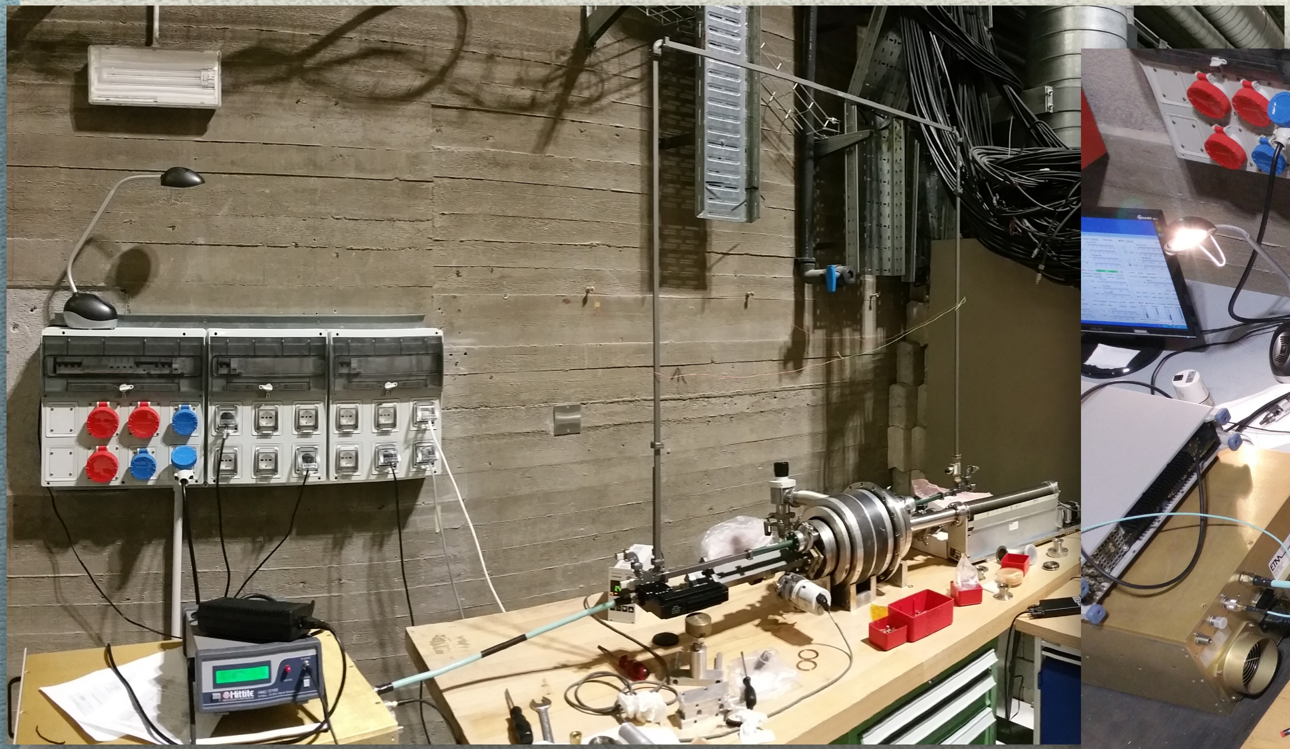

# Interferometry in ECRIS:

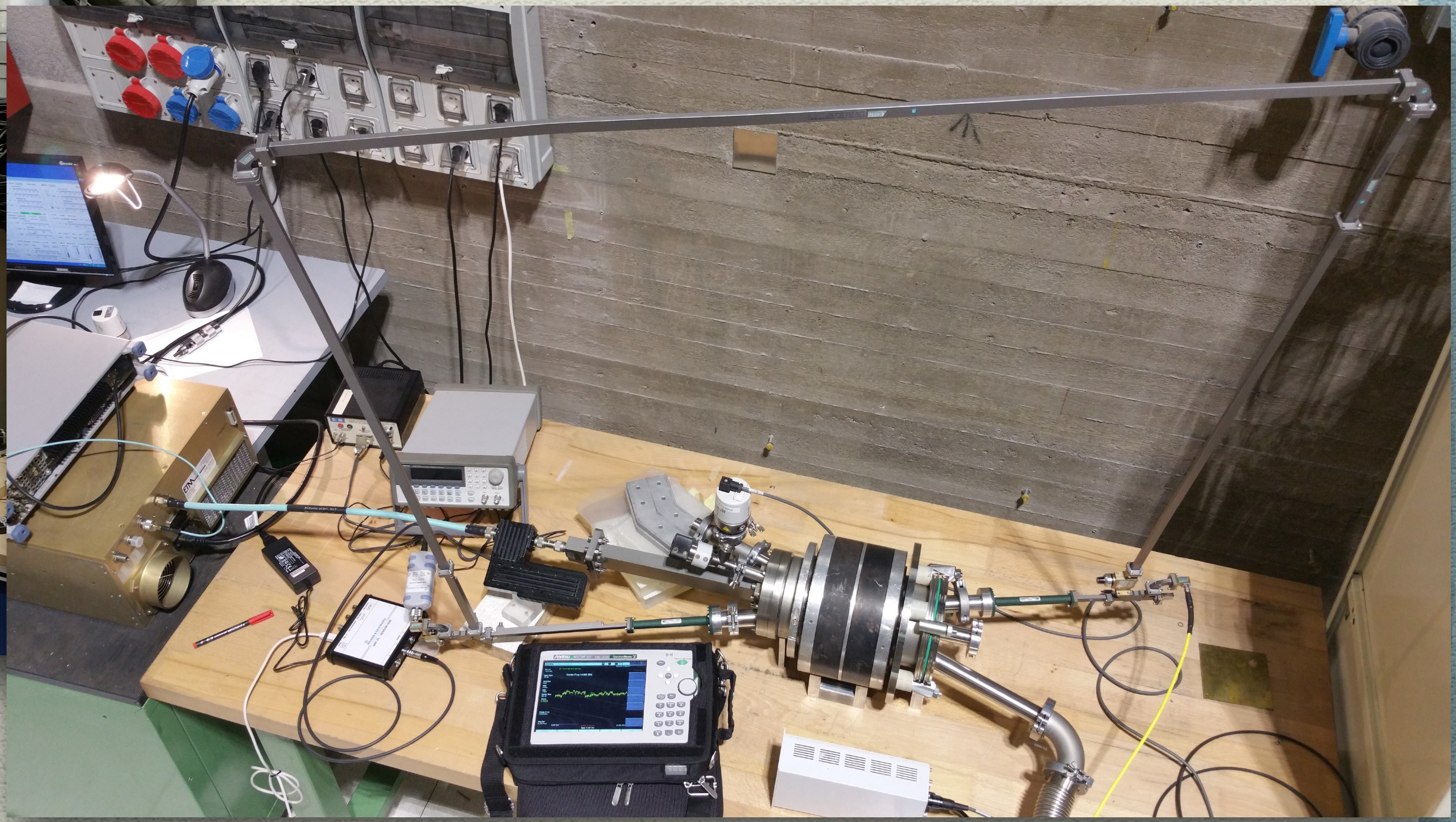
## measuring of plasma density inside the cavity of the LNS plasma reactor

*G. Torrisi et al., Review of Scientific Instrumentsl 87, p. 02B909 (2016).*

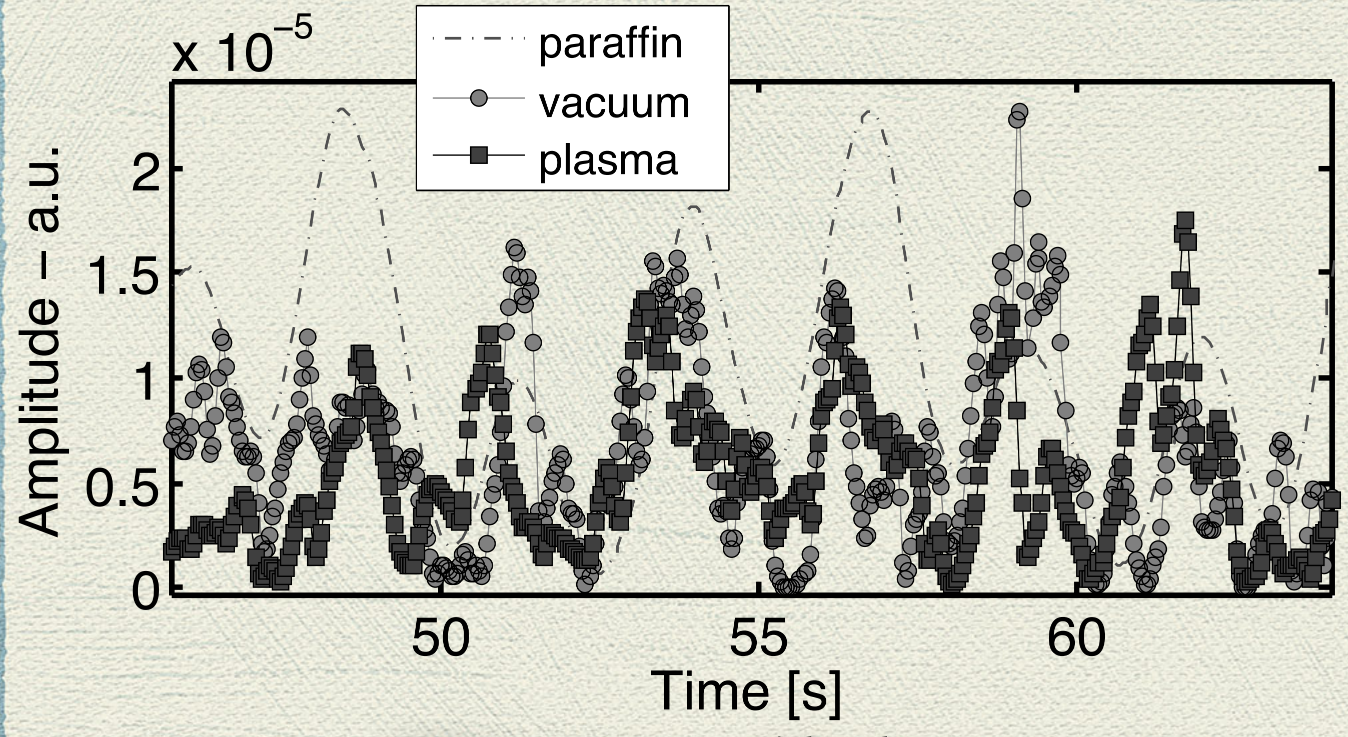
# Interferometry in ECRIS:
## the frequency sweep method

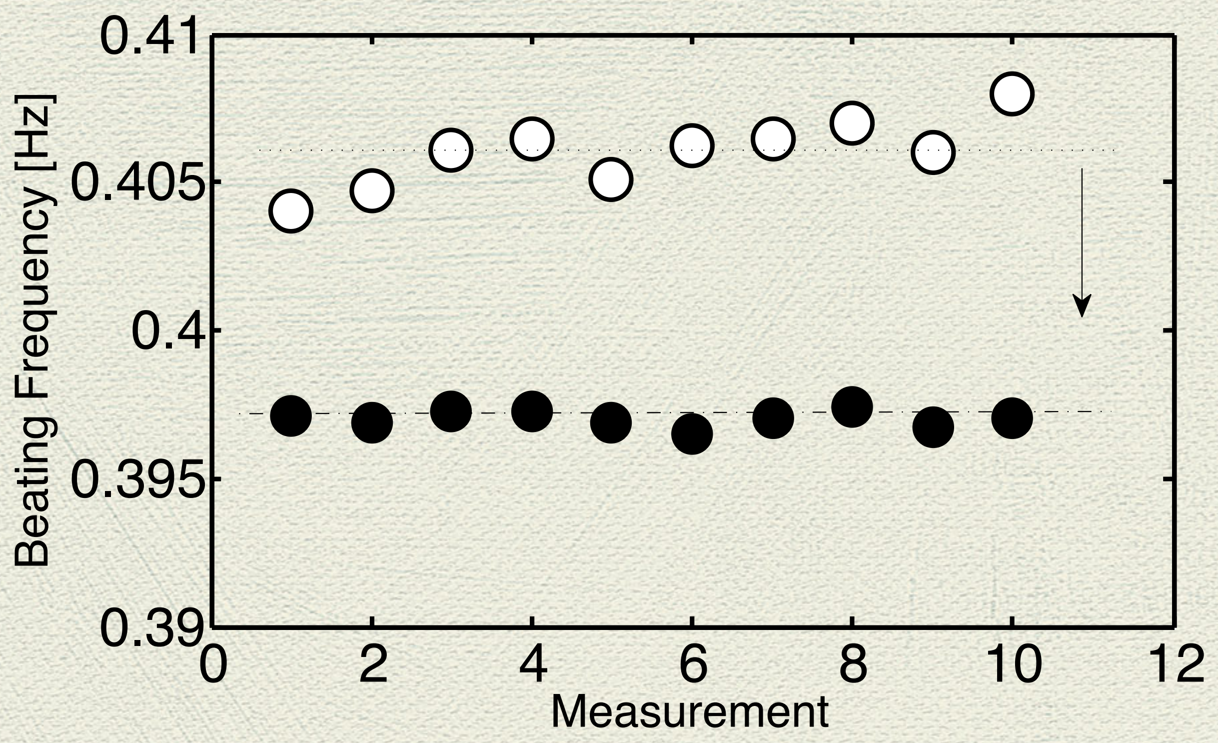


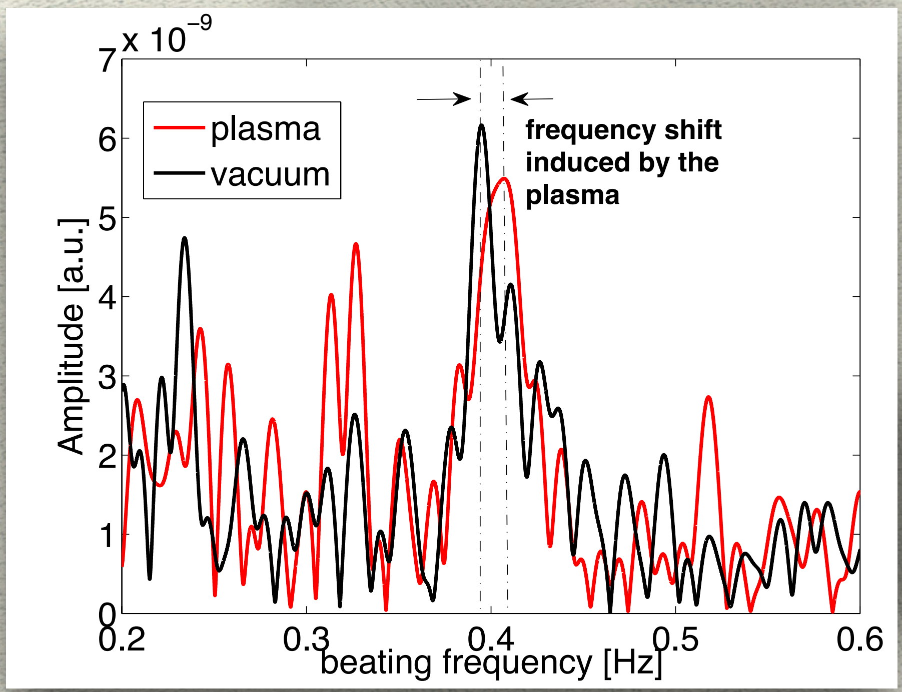


# Interferometry in ECRIS:
## the measurements in plasma

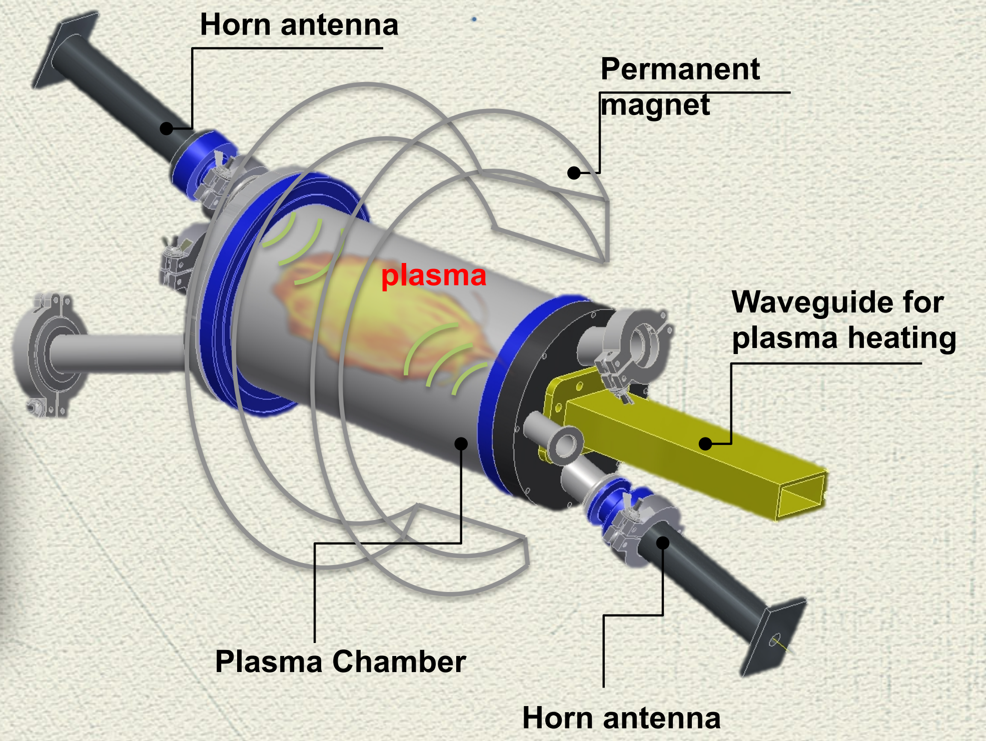



**FFT spectrum with plasma vs vacuum**

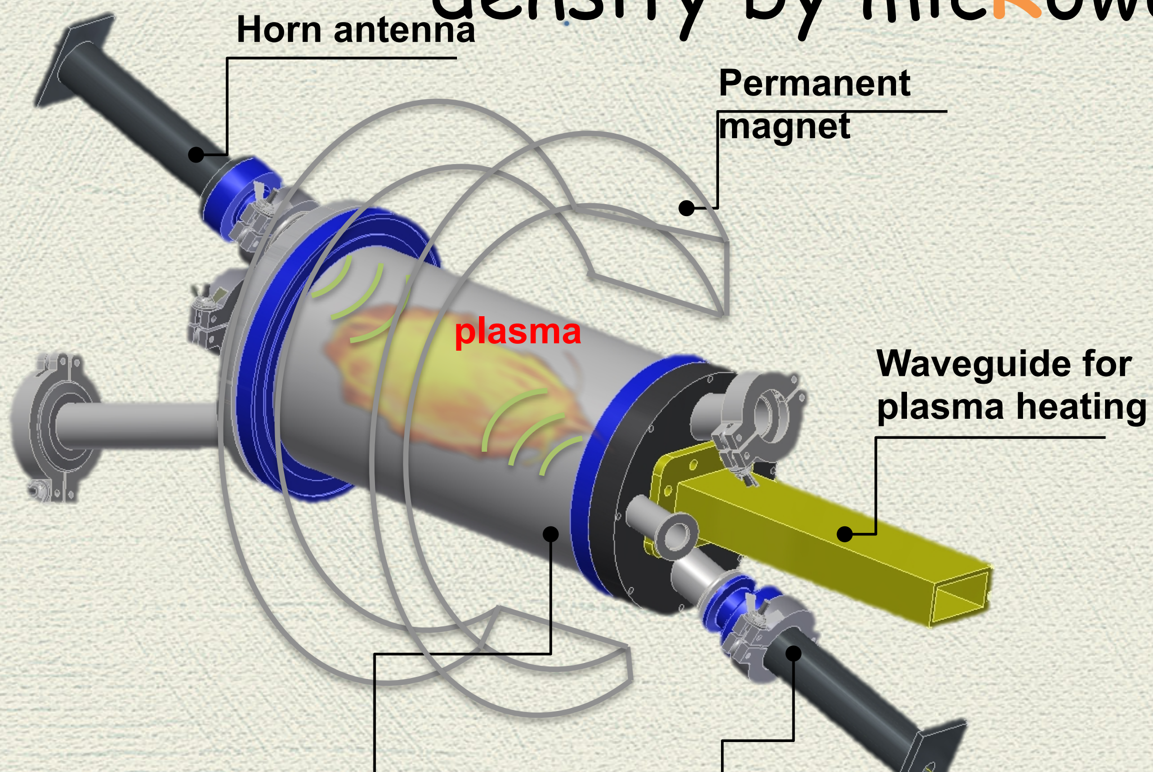


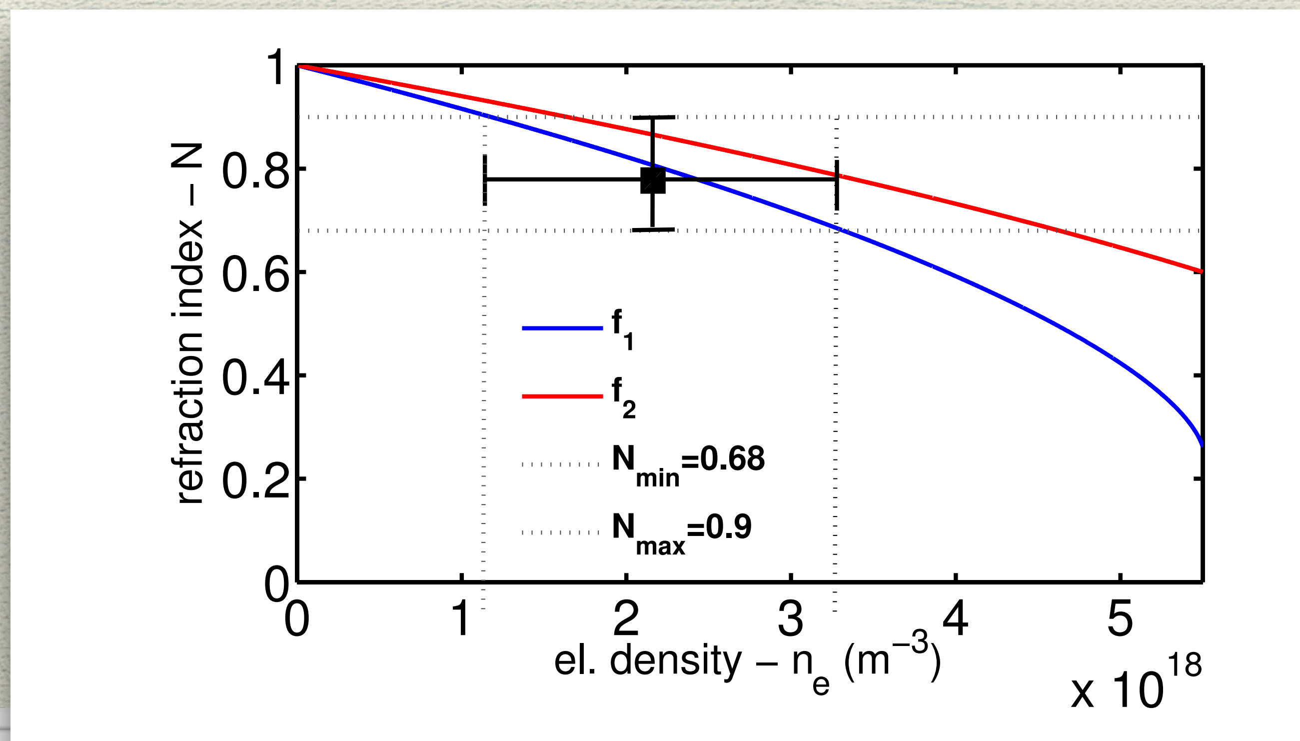

*[G. Torrisi et al.* ***"A Novel Microwave Frequency Sweep Interferometer for ECR Plasma Electron Density Measurements"****, accepted for oral presentation at EuMW2016 and publication on IEEE Xplore]*



# VESPRI

## VEry Sensitive evaluation of Plasma density by micRowave Interferometry





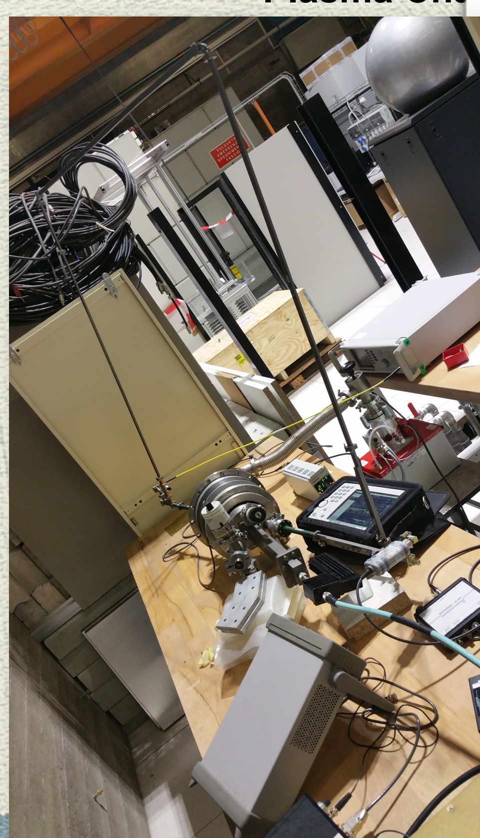
REVIEW OF SCIENTIFIC INSTRUMENTS 87, 000000 (2016)


### The first measurement of plasma density in an ECRIS-like device by means of a frequency-sweep microwave interferometer


D. Mascali,[1,a)] G. Torrisi,[1] O. Leonardi,[1] G. Sorbello,[1,2] G. Castro,[1] L. G. Celona,[1] R. Miracoli,[3] R. Agnello,[1] and S. Gammino[1]
[1]INFN - Laboratori Nazionali del Sud, 95123 Catania, Italy
[2]Universitá di Catania, Dipartimento di Ingegneria Elettrica Elettronica e Informatica, 95125 Catania, Italy
[3]ESS Bilbao, 48170 Zamudio, Spain



(Received 29 June 2016; accepted 15 September 2016; publis

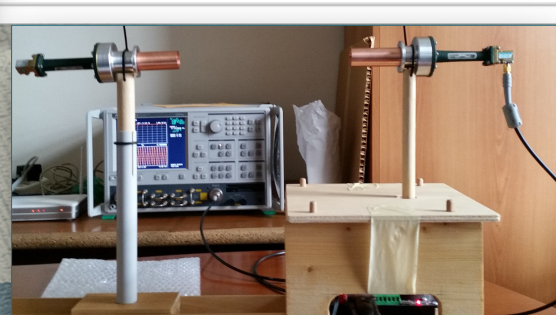


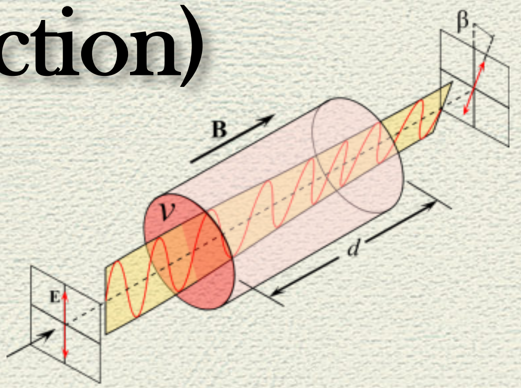
TABLE I. Horn-to-horn signal beating frequencies and corresponding indexes of refraction. Comparison among the three cases: empty, paraffin, plasma filled cavity.

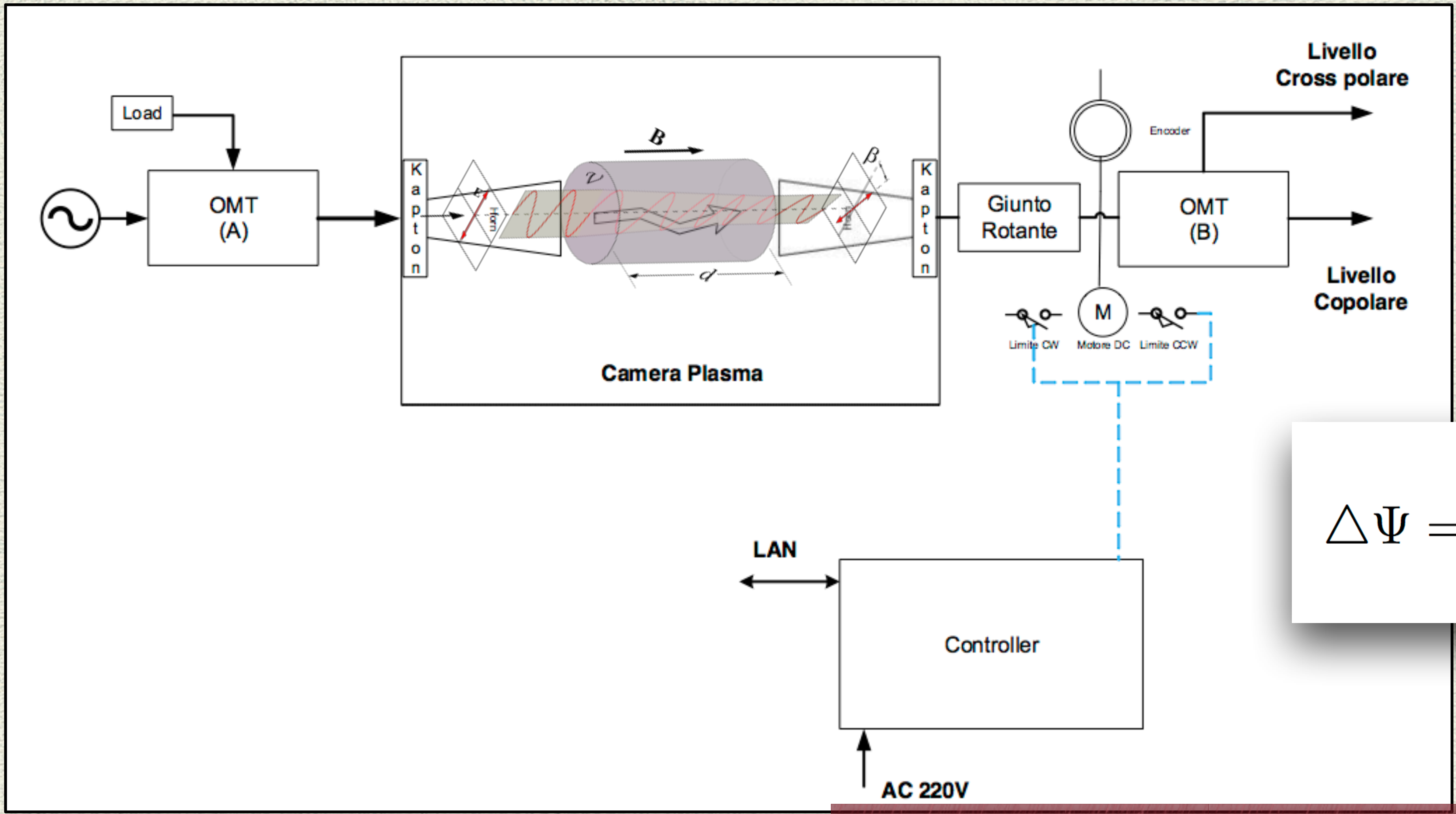
| Medium | $P_{RF}$[W] | $\omega_{beat}$[rad/sec] | refr. index N |
|---|---|---|---|
| Empty Cavity | 0 | $2\pi * 0.397$ | $1^a$ |
| Bulk Paraffin | 0 | $2\pi * 0.380$ | $1.43^b$ |
| **Plasma** | 150 | $2\pi * 0.407$ | $\mathbf{0.79 \pm 0.11}^c$ |

[a] assumed by definition for the absolute calibration.
[b] in agreement with the literature value $N_{20GHz} \simeq 1.45$.
[c] Error evaluation in a series of ten measurements.

# Faraday rotation measurements

## Next step Polarimetry (Faraday rotation detection)





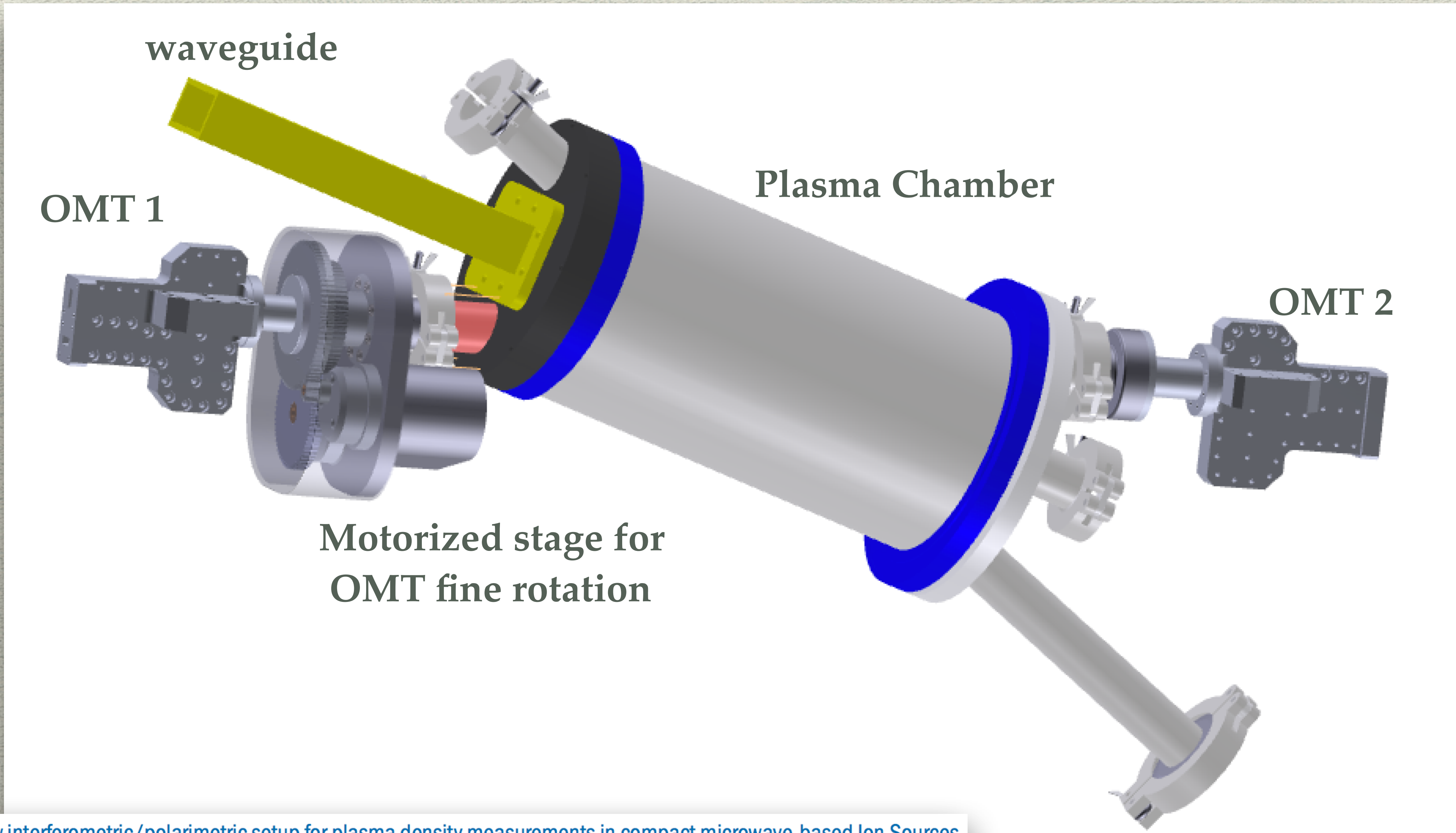

*Setup Block Diagram*

$$\triangle\Psi = \frac{e^3\lambda^2}{2\pi m_e^2 c^4}\int_0^L n_e(l)B_{\|}(l).dl$$

**The polarimetric system has been designed jointly with SICIL-Sat s.r.l. (satellite communications)**

# Faraday rotation measurements

## Final Design of the OMT-based system



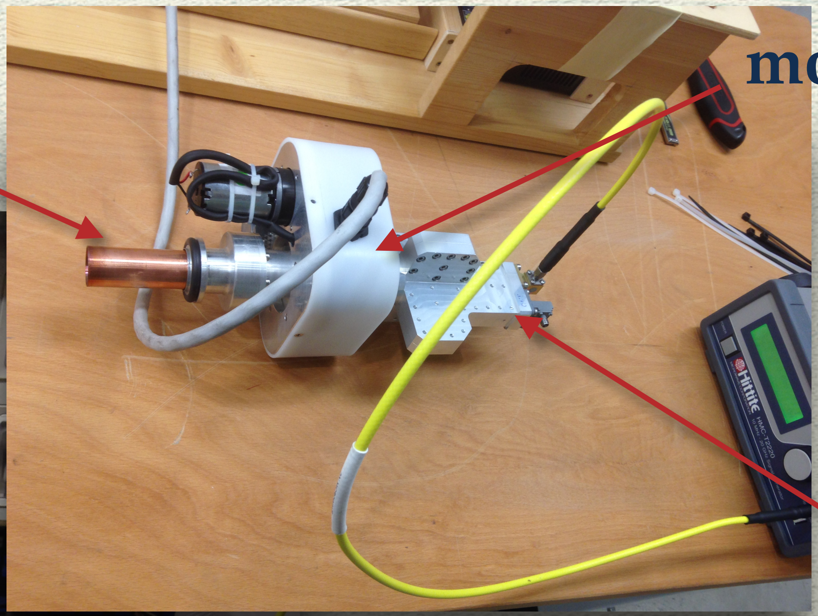

A new interferometric/polarimetric setup for plasma density measurements in compact microwave-based Ion Sources
G. Torrisi, E. Naselli, D. Mascali, G. Castro, L. Celona, G. Sorbello and S. Gammino
2017 *J. Inst.* **12** C10003 https://doi.org/10.1088/1748-0221/12/10/C10003

# Faraday rotation measurements

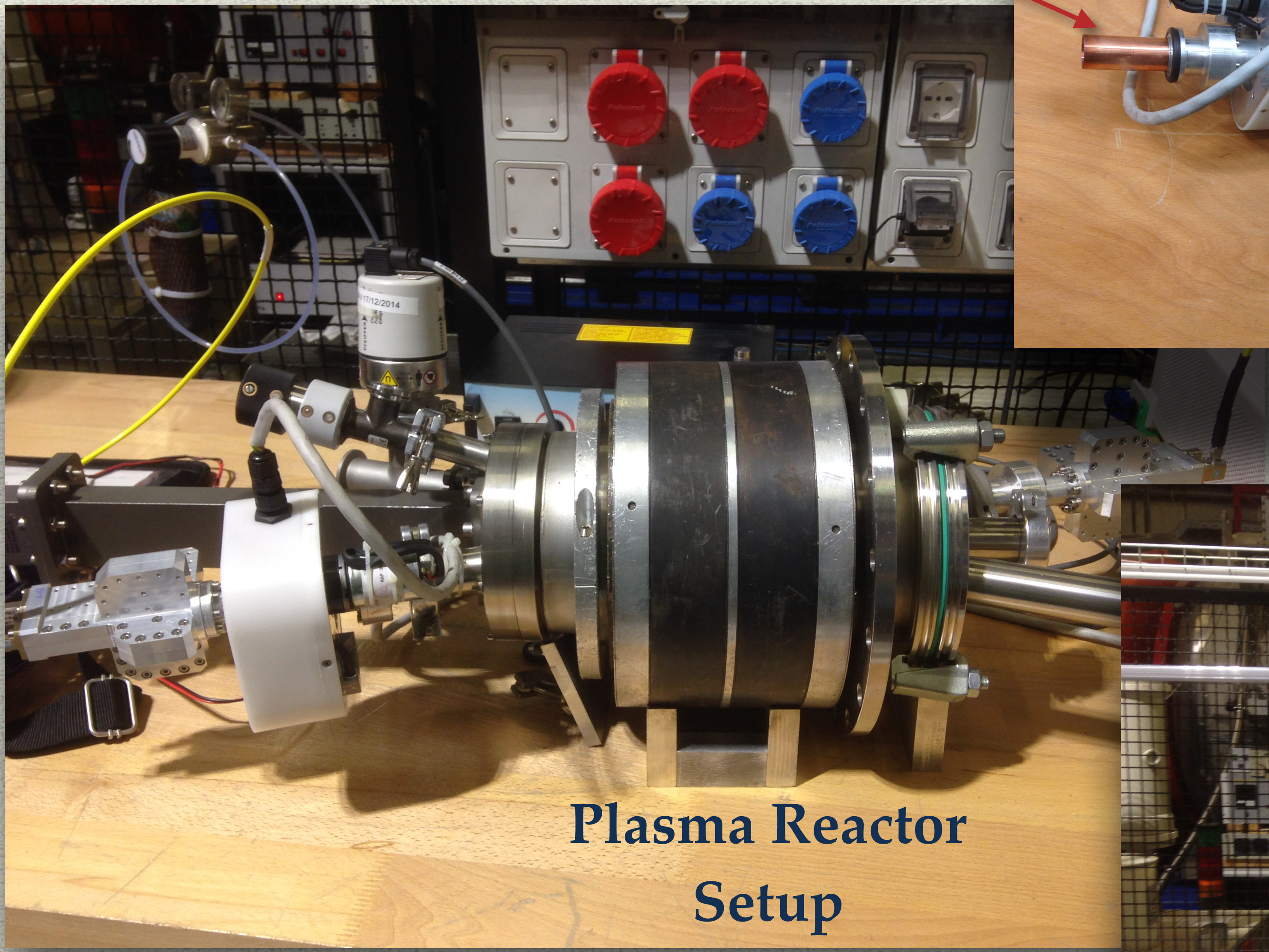
## Installation of the OMT-based system

Antenna

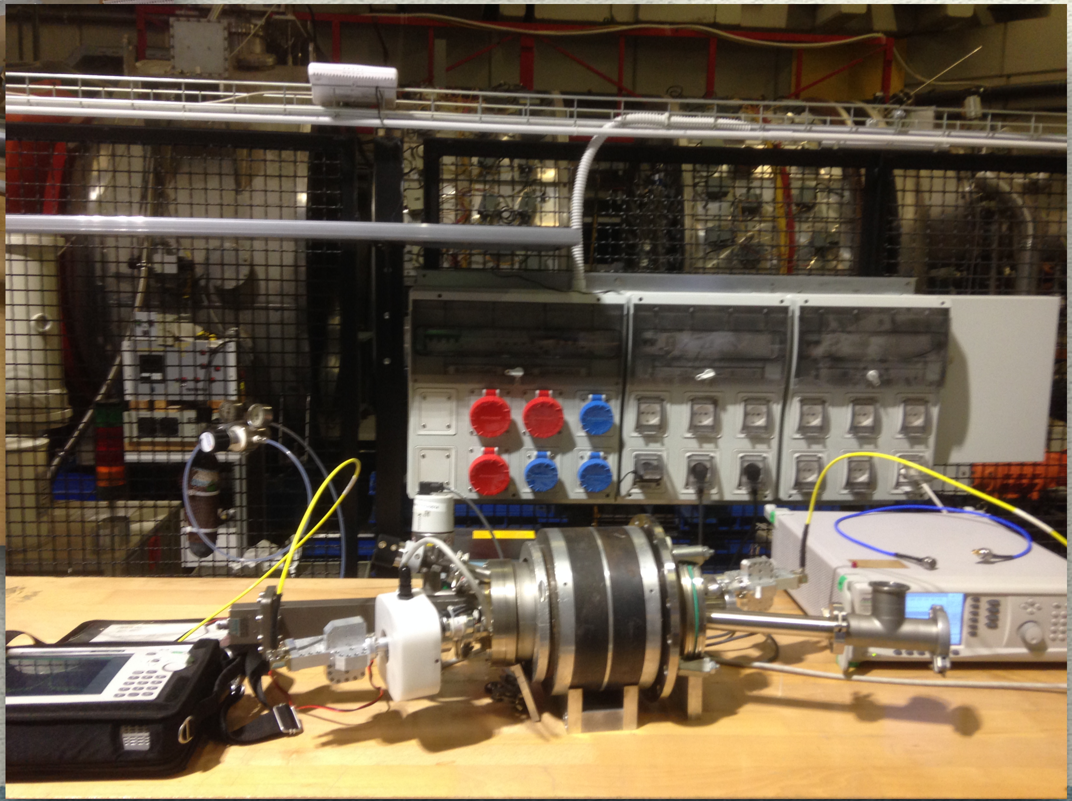
motorized stage



OMT

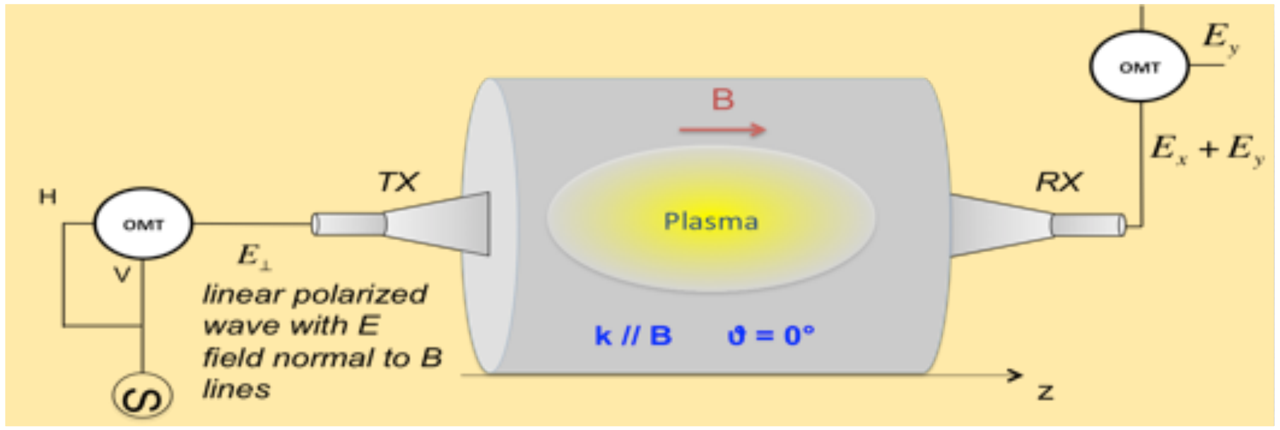


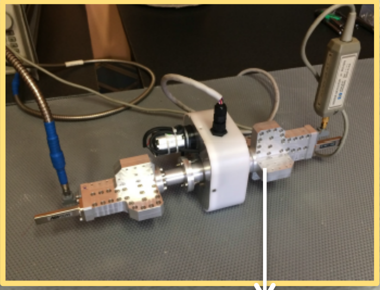
Plasma Reactor
Setup



# Faraday rotation measurements

## Original Analysis method development



OrthoMode Trasducer (OMT)

$$\beta = \frac{q_e^3}{8\pi^2 c^3 m_e^2 \varepsilon_0} B d\, n_e \lambda^2$$

- Microwave range 18 GHz ÷ 26.5 GHz
- Test-bench: Plasma Reactor

L=26.6 cm
d=13.6 cm
B≈0.1 T

→ ~~$\lambda/L << 1$~~ → Undesired plasma chamber/Cavity effects

→ Spurious components rejection: Malus law-based selection

$$P = P_0 \cos^2\vartheta + b$$

- Free-space
- Empty cavity

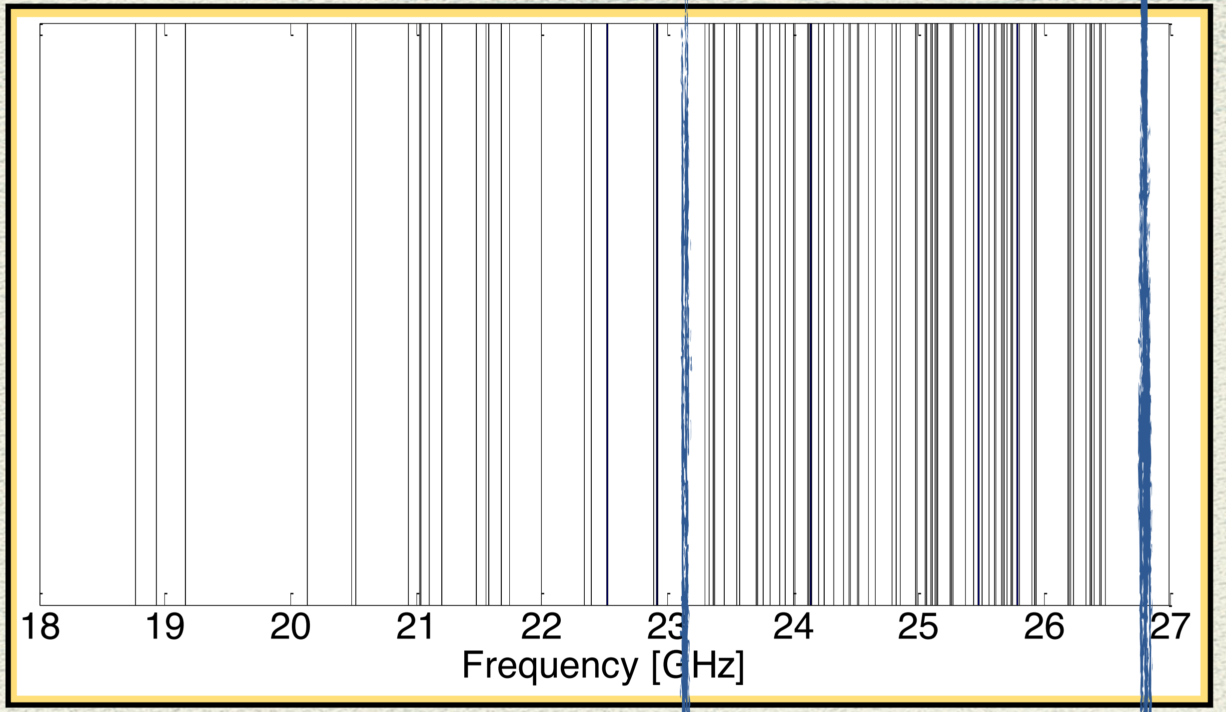
$\vartheta_{P_{max}} = 0°$
$\vartheta_{P_{min}} = 90°$

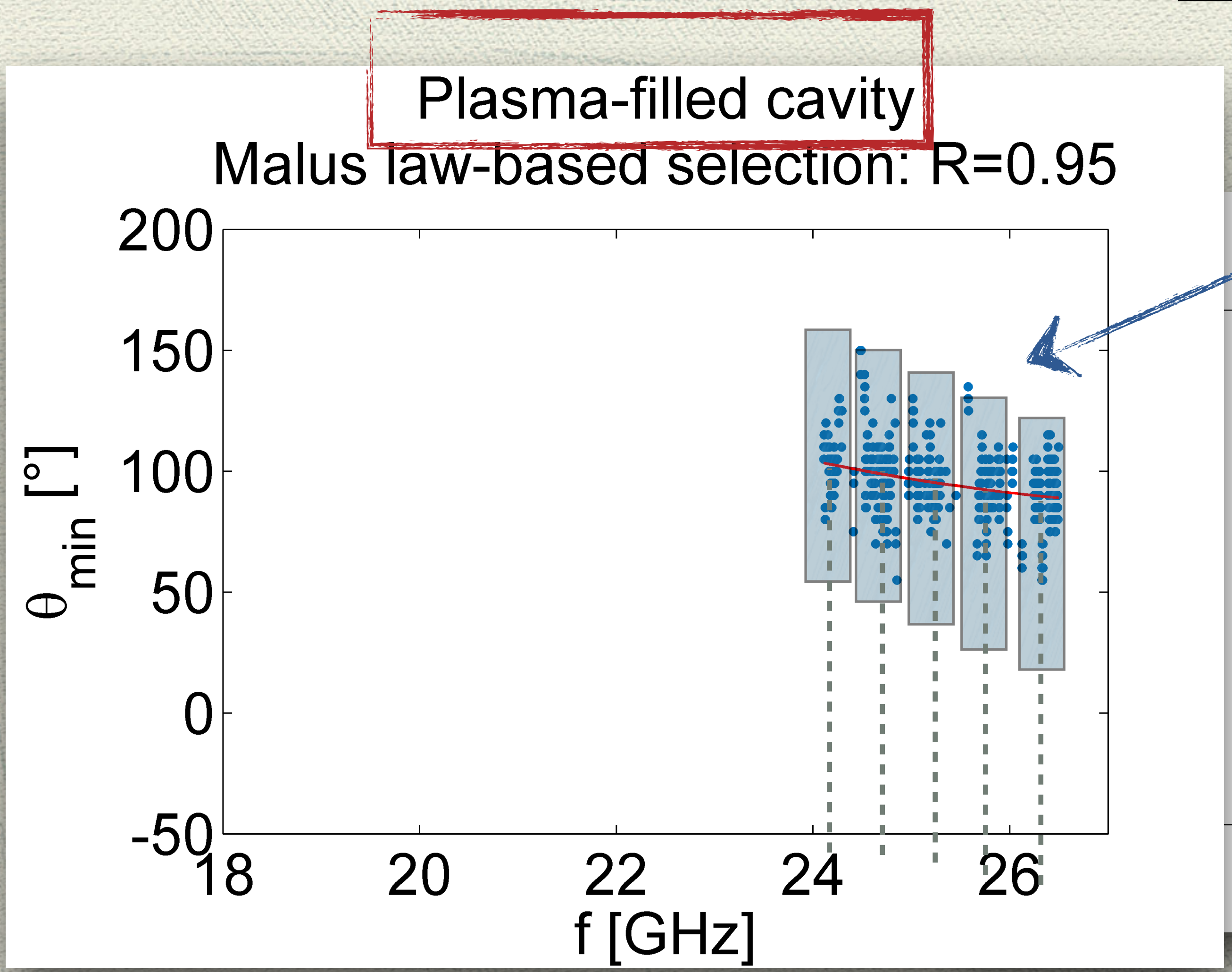
- Plasma-filled cavity

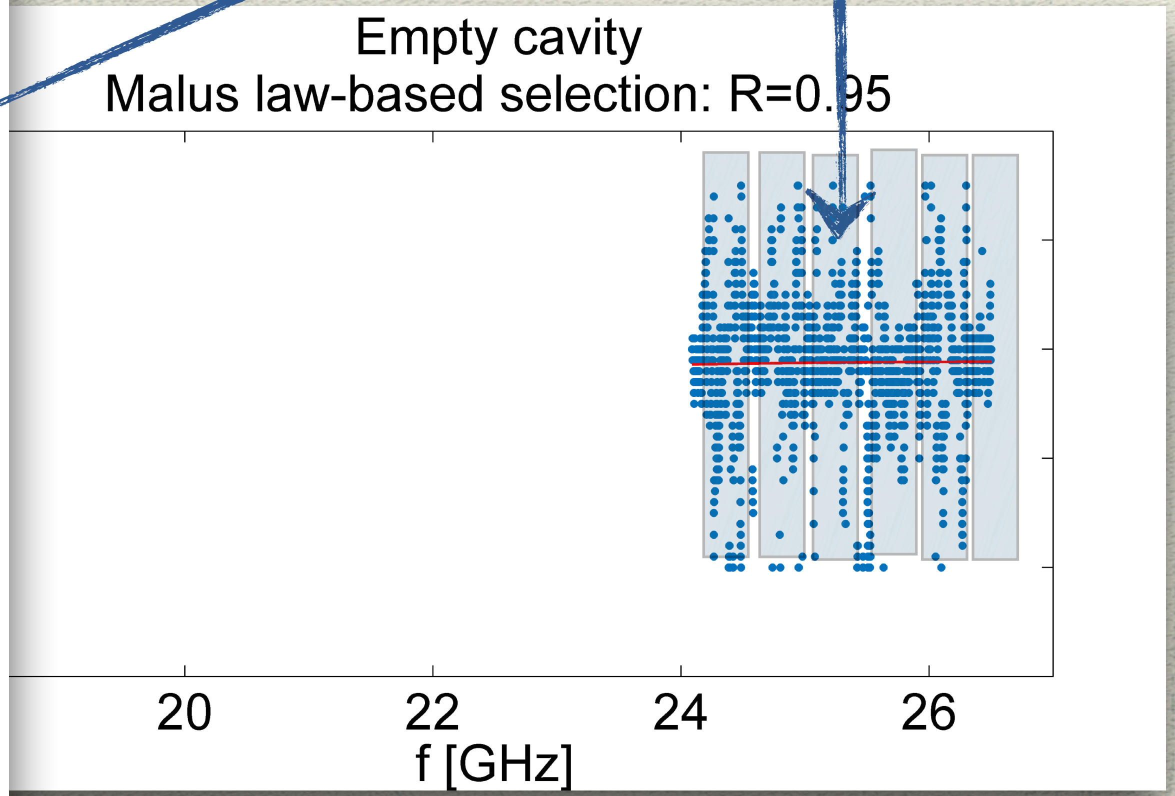
$\vartheta_{P_{max}} = \beta_{Faraday}$
$\vartheta_{P_{min}} = 90° + \beta_{Faraday}$

Faraday rotation measurements

CUT on the frequencies unaffected by the cavity

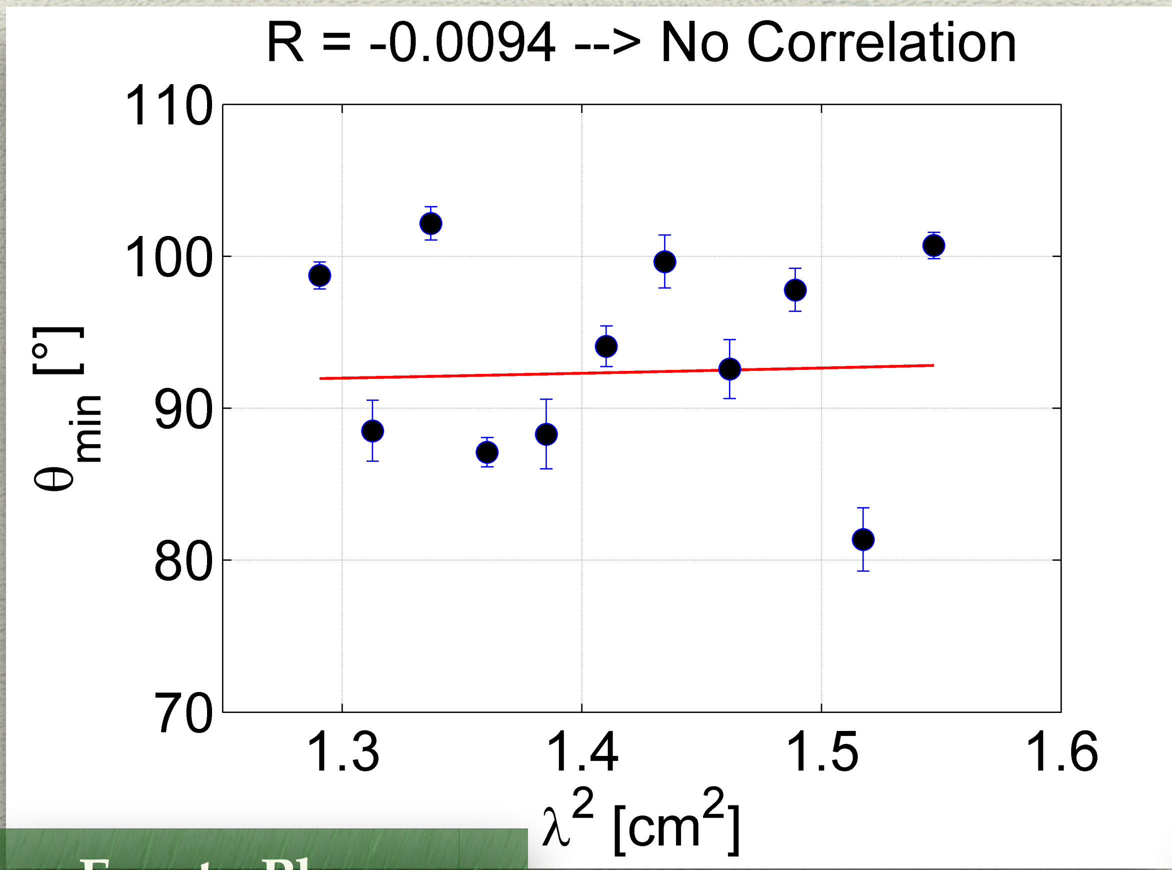


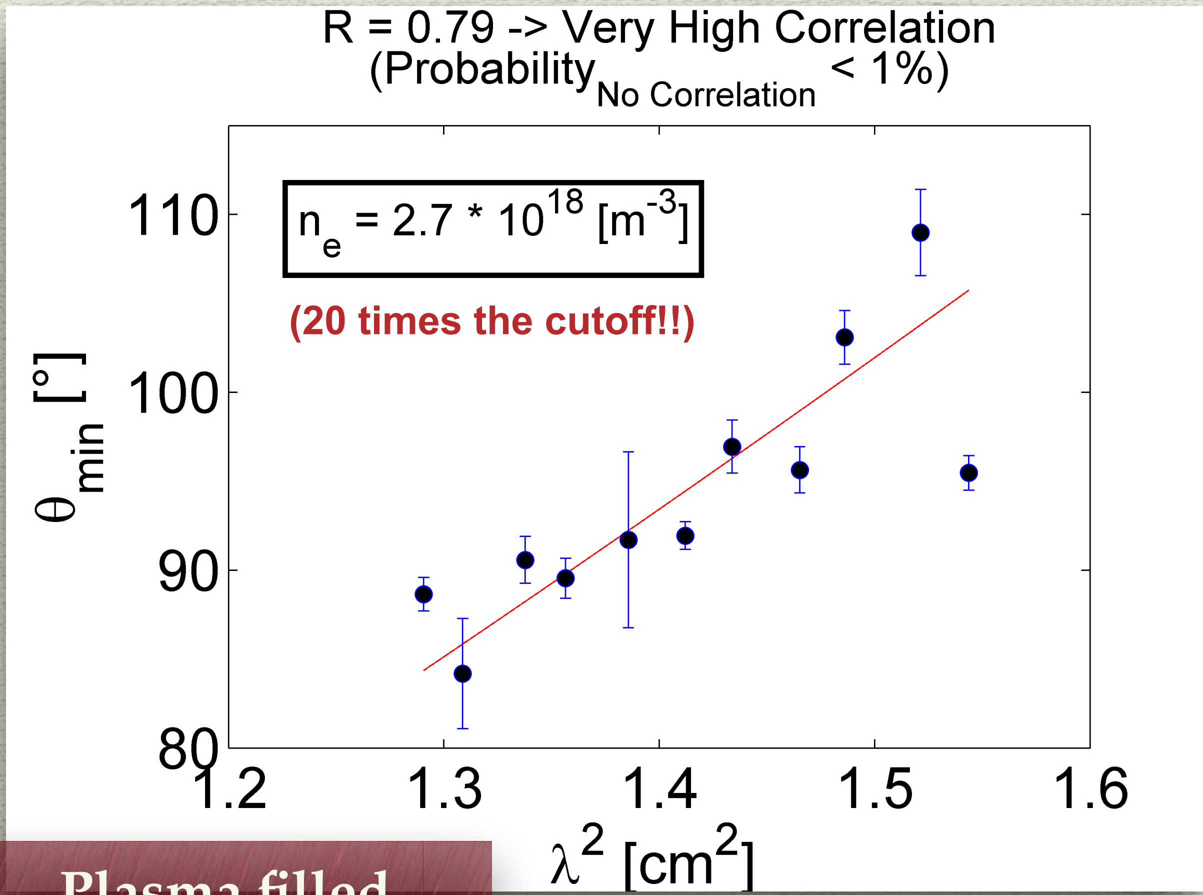



# Faraday rotation measurements

## Fitting procedure




**Empty Plasma Chamber**




**Plasma filled Chamber**

Experimental data have been **fitted** with statistical consistence **by a $\lambda^2$ law, in agreement with Faraday rotation** dependence on the probing wave-length

*wavelength*

$$\theta = \frac{q_e^3}{8\pi^2 c^3 m_e^2 \varepsilon_0} Bd\ n_e \lambda^2$$

*Magnetic field*

*plasma density*

E. Naselli et al., *The first measurement of plasma density by means of an interfero-polarimetric setup in a compact ECR-plasma trap* **Oral Presentation at the 28th Symposium on Plasma Physics and Technology** June 18–21, 2018 Czech Technical University in Prague

READY for Multidiagnostics operations!!

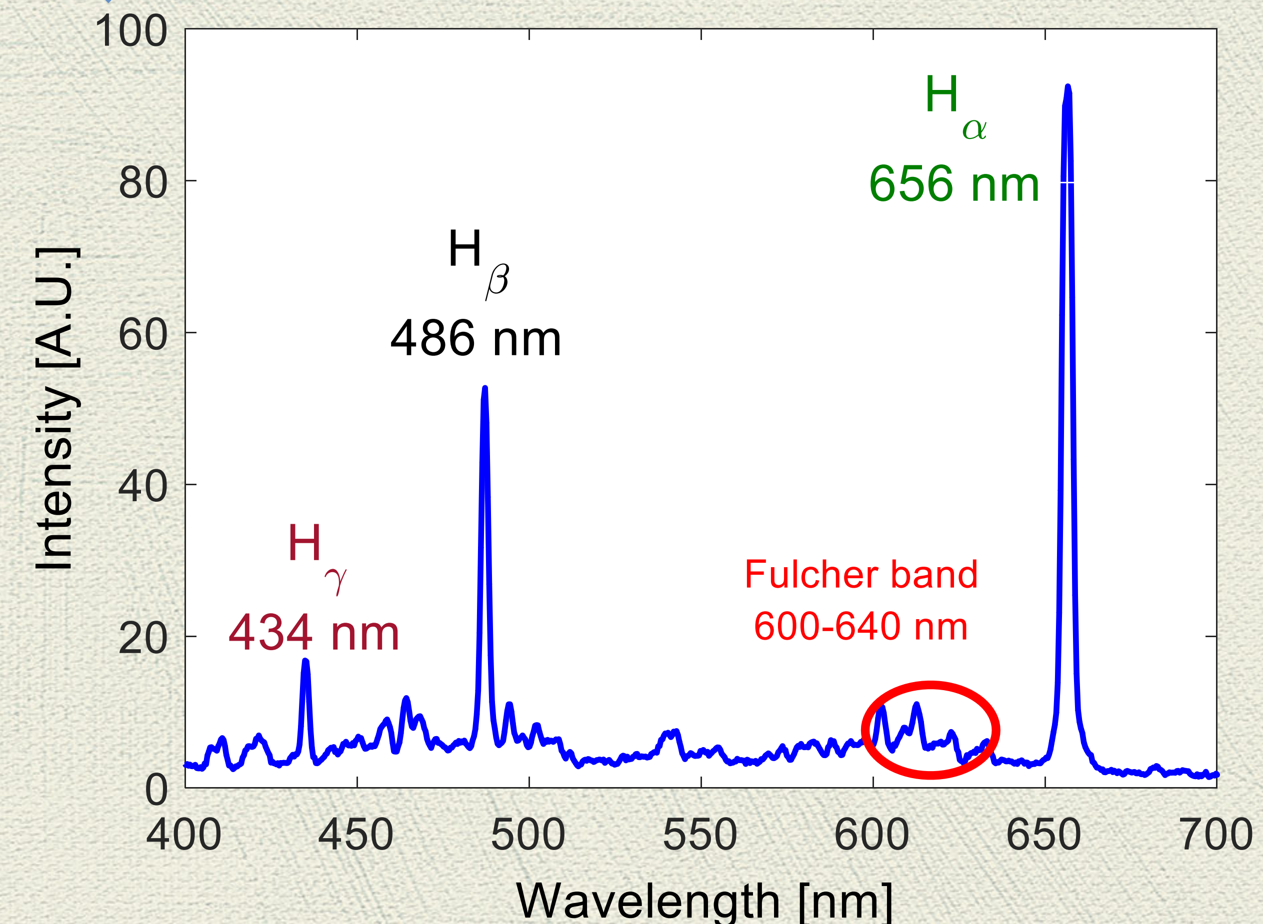
# Non-intrusive plasma diagnostics methods

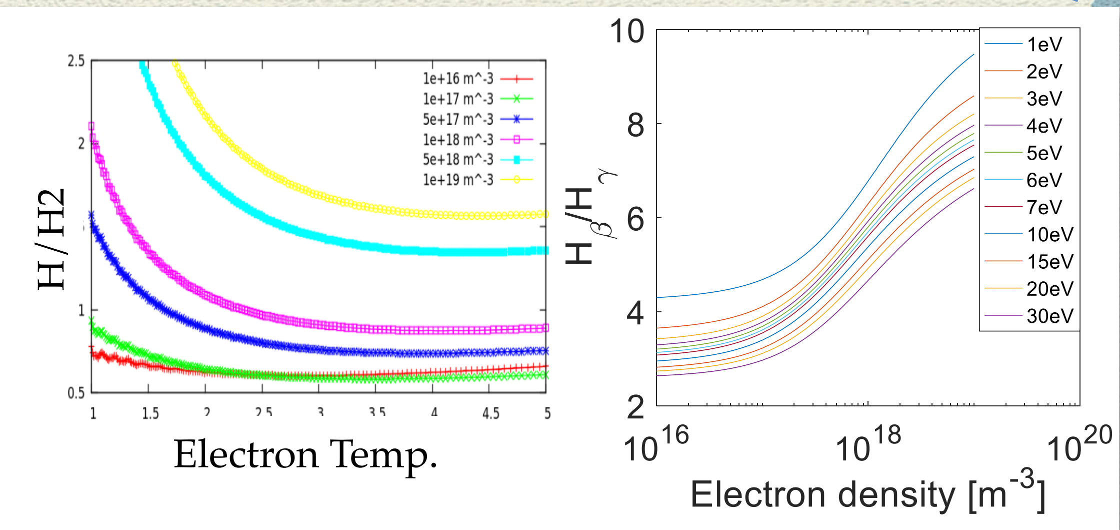
| RF | IR | Visible & UV | EUV | Soft-Xray | Hard-Xray |
|---|---|---|---|---|---|
| (3 kHz-300 GHz) | (300 GHz-430 THz) | (1,6-12 eV) | (10-120 eV) | (0,12-12 keV) | (10-100 keV) |

**Optical plasma Observation**
Spectroscopy 1D/2D
density-temp.
measurement

**X-ray Pinhole Camera**
Imaging & 2D-Spectroscopy
2D energy distribution and (relative) density

**SDD - HpGe**
**X-ray detectors**
Spectroscopy

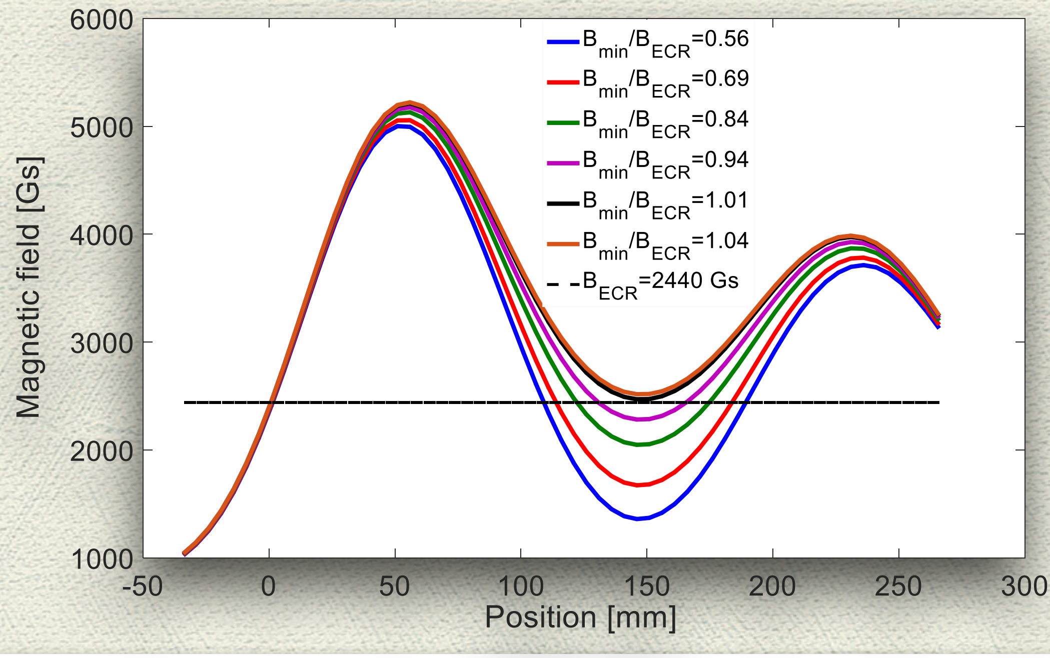


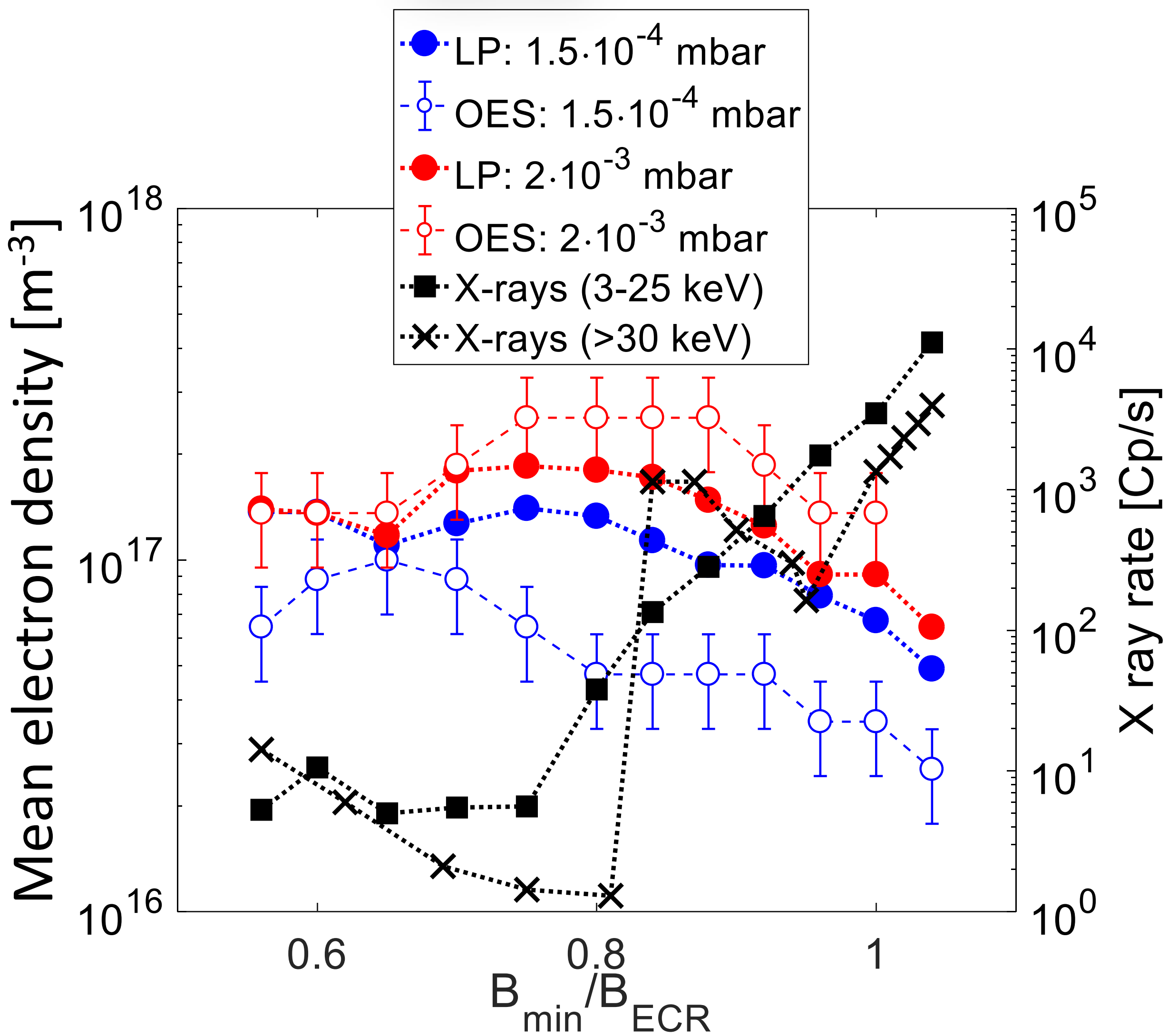

*U. Fantz, Plasma Sources Sci. Technol. 15, p. S137 (2006).*

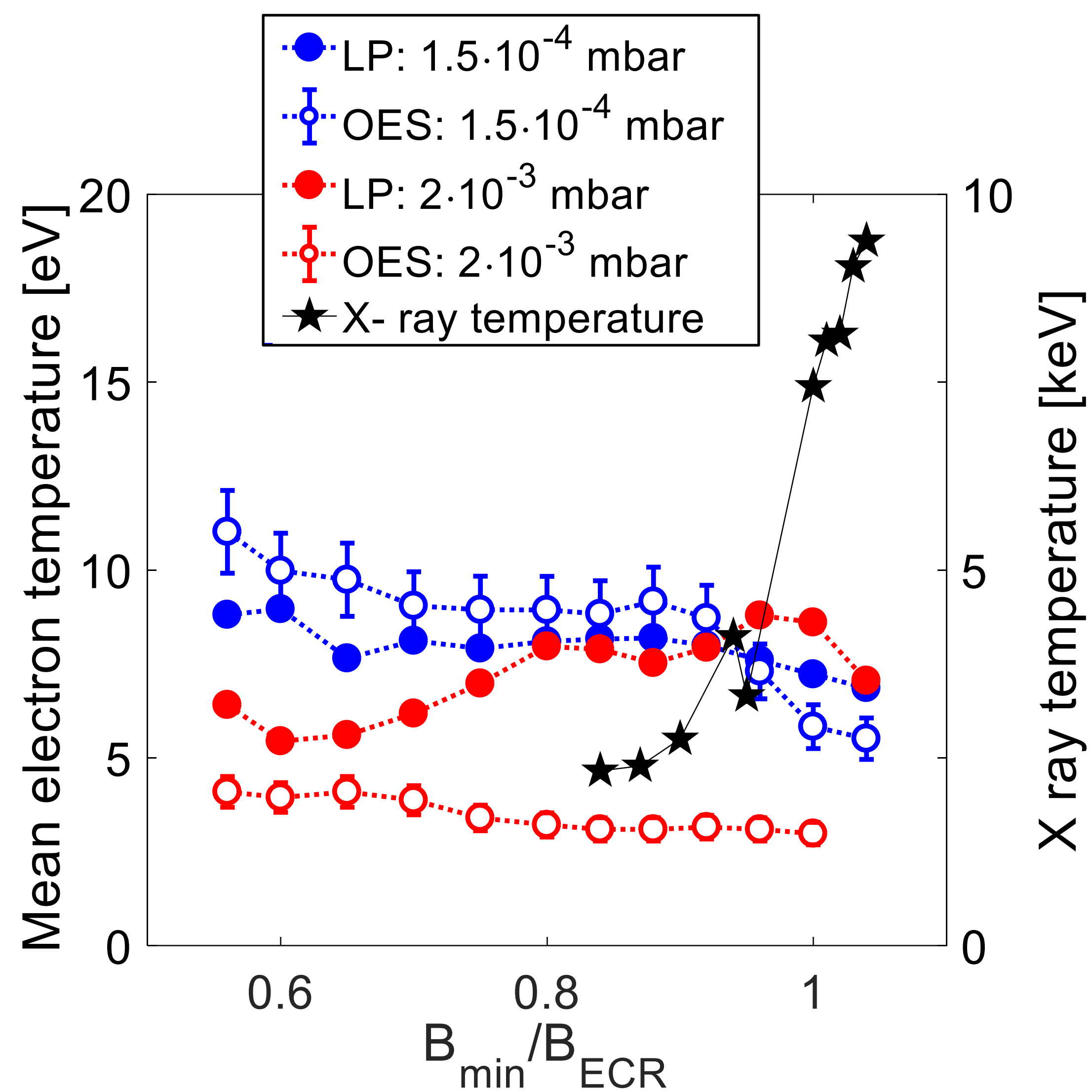
# Multidiagnostics including OES

recently presented at ICIS17-Geneva




Data seem to say temperature and abundances of warm/ hot electrons depend mostly from axial gradients

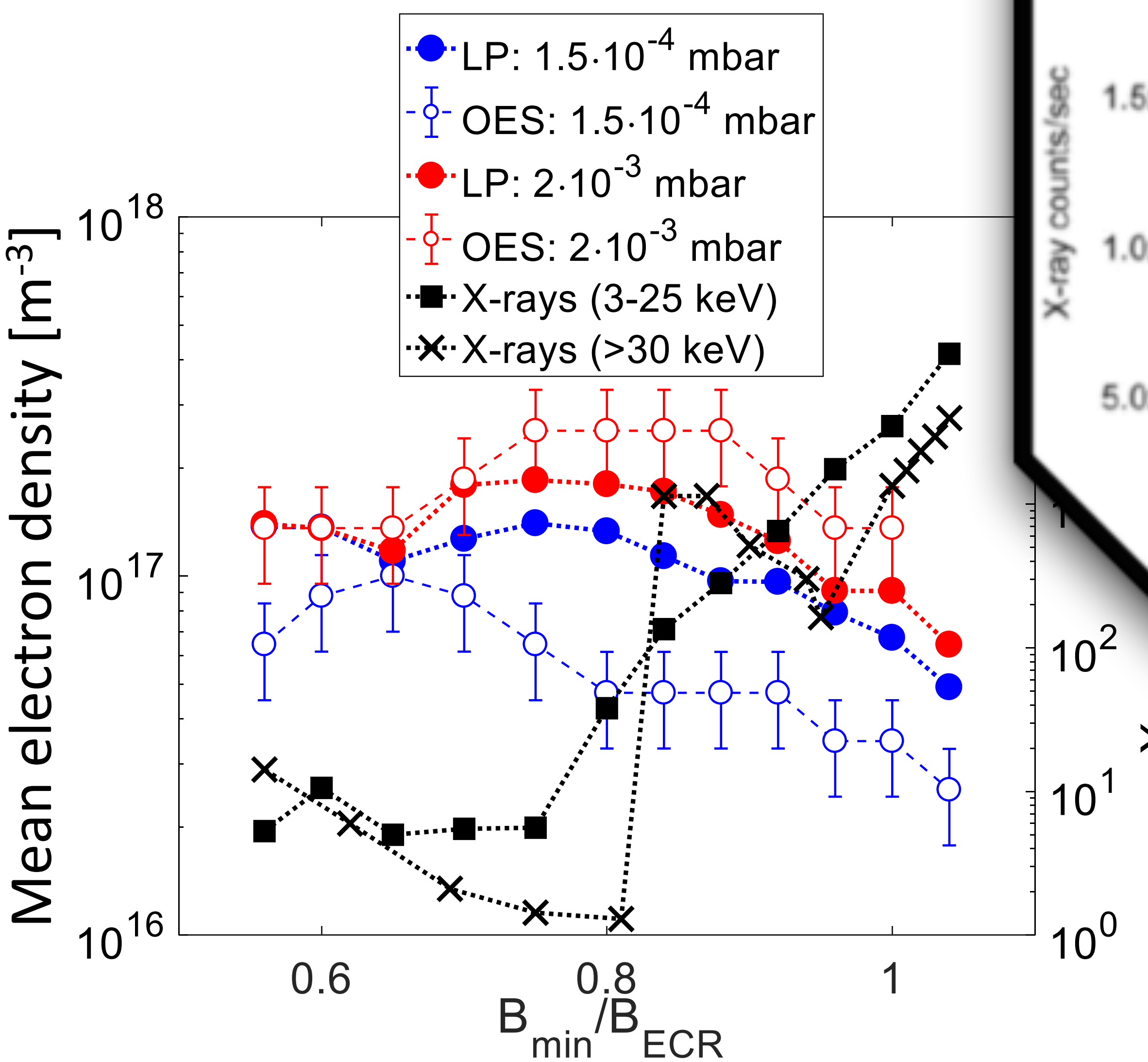


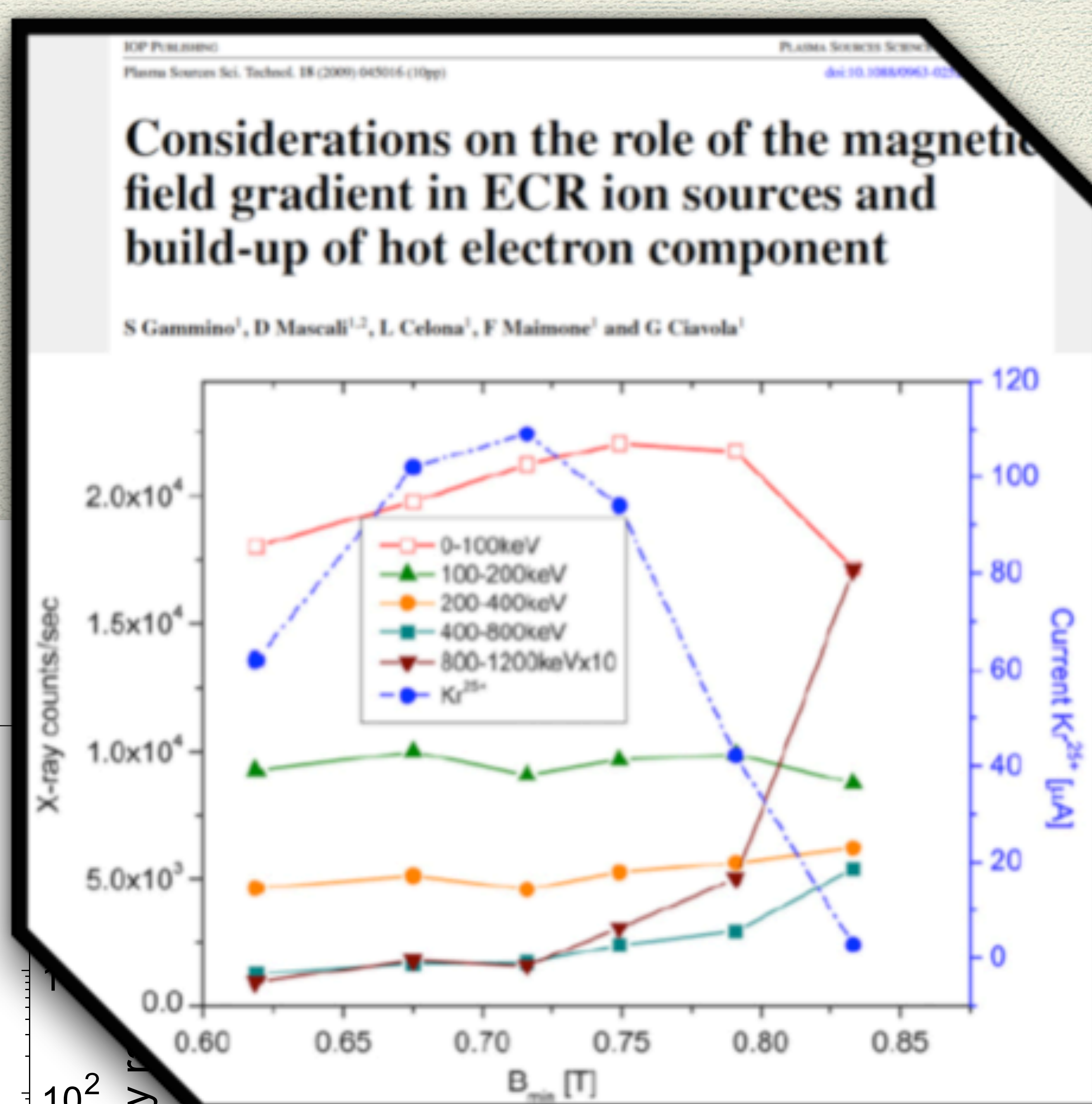




*In collaboration with Max Plank Institute – Institute of Plasma Physics (Germany)*

# Multidiagnostics including OES

It helps to explain the scaling laws and rule of thumbs of existing ECR.



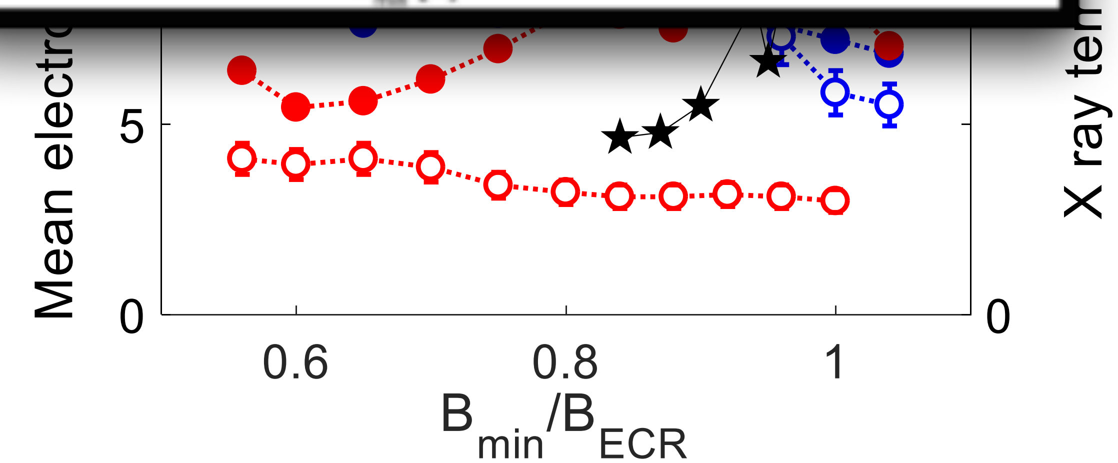
IOP Publishing

Plasma Sources Sci. Technol. 18 (2009) 045016 (10pp)

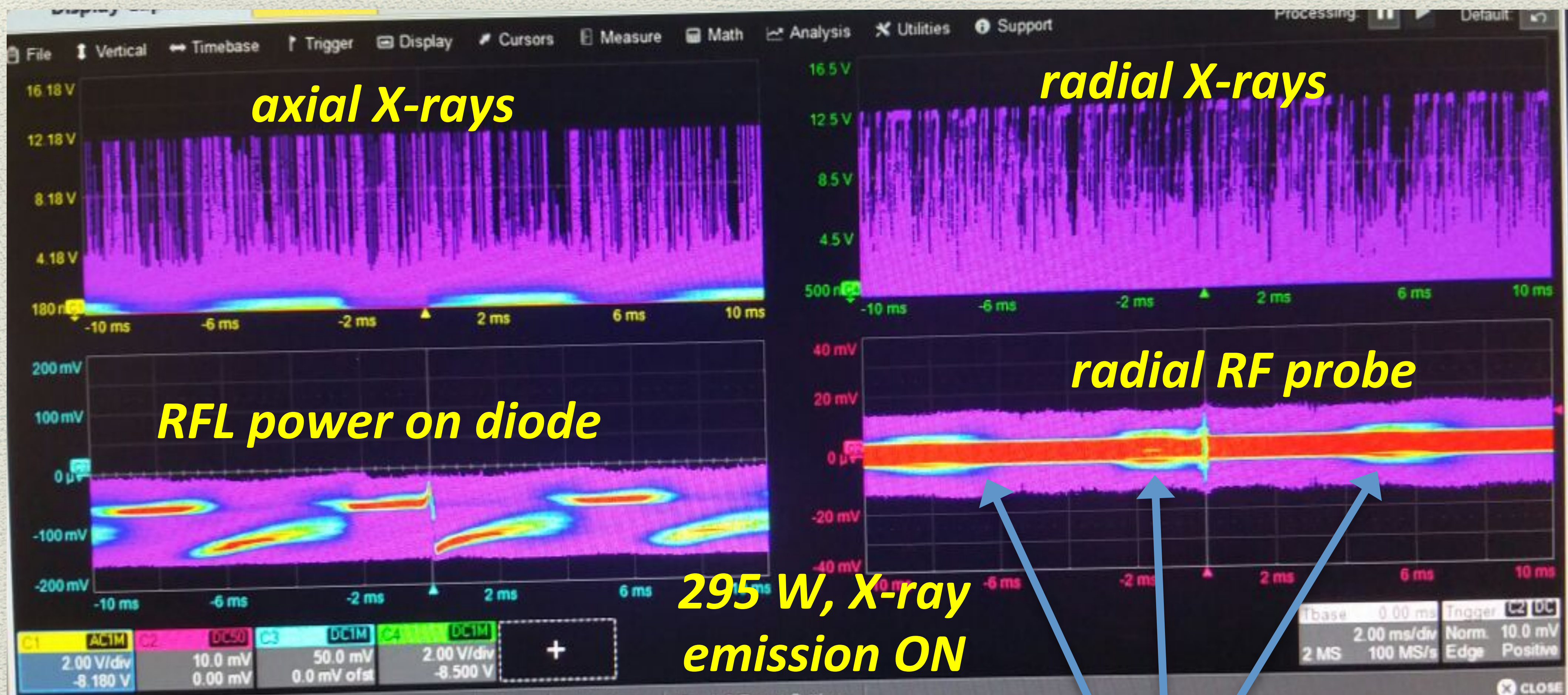
**Considerations on the role of the magnetic field gradient in ECR ion sources and build-up of hot electron component**

S Gammino[1], D Mascali[1,2], L Celona[1], F Maimone[1] and G Ciavola[1]





# Probing turbulent plasma regimes (CYCLOTRON MASER INST.) in a Time-Resolved way




Radio-Bursts

**Kinetic instabilities in a mirror-confined plasma sustained by high-power microwave radiation**

A. G. Shalashov, M. E. Viktorov, D. A. Mansfeld, and S. V. Golubev

Citation: Physics of Plasmas **24**, 032111 (2017);

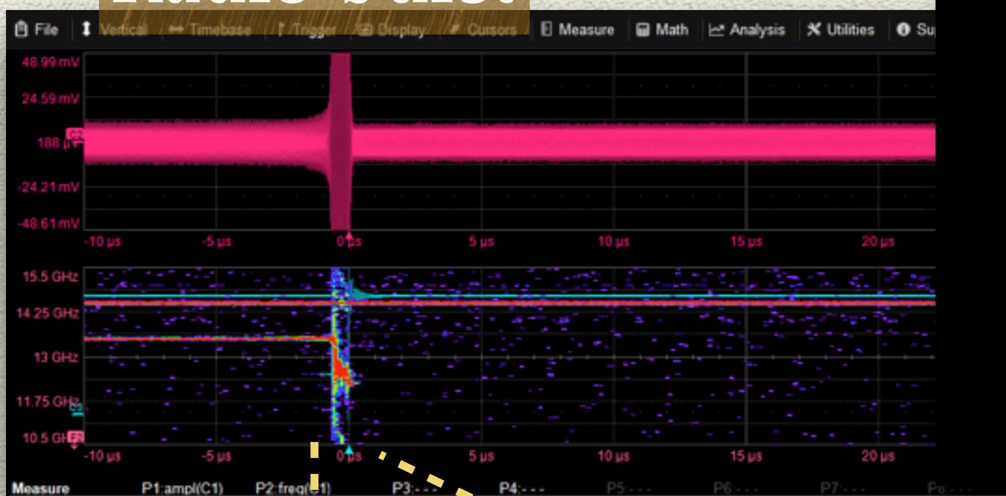
IOP Publishing
Plasma Sources Science and Technology
Plasma Sources Sci. Technol. **23** (2014) 025020 (8pp)
doi:10.1088/0963-0252/23/2/025020

**Beam current oscillations driven by cyclotron instabilities in a minimum-*B* electron cyclotron resonance ion source plasma**

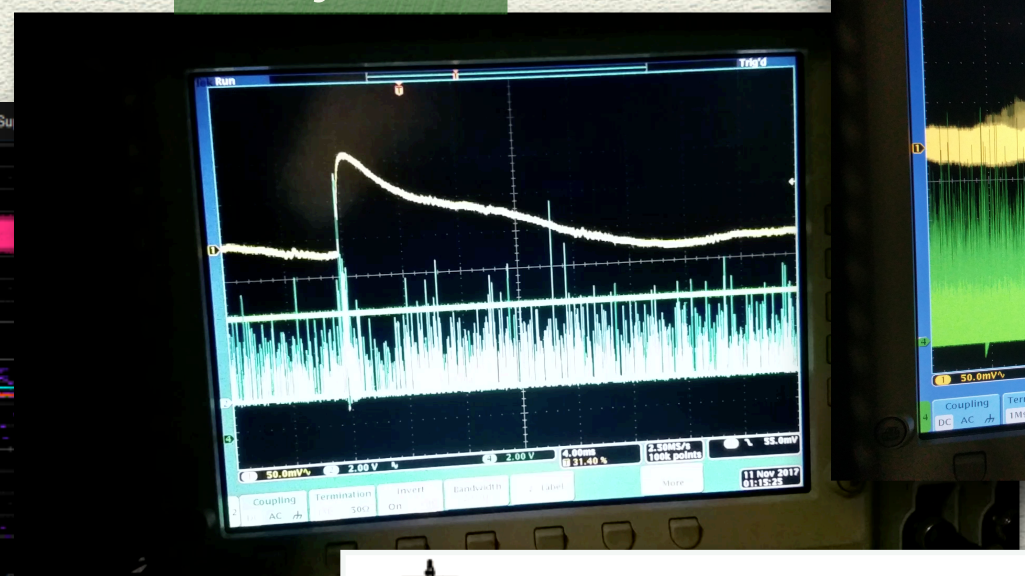
O Tarvainen[1], I Izotov[2], D Mansfeld[2], V Skalyga[2,3], S Golubev[2,3], T Kalvas[1], H Koivisto[1], J Komppula[1], R Kronholm[1], J Laulainen[1] and V Toivanen[4]

# Time Resolved Characterization at the LPSC Charge Breeder

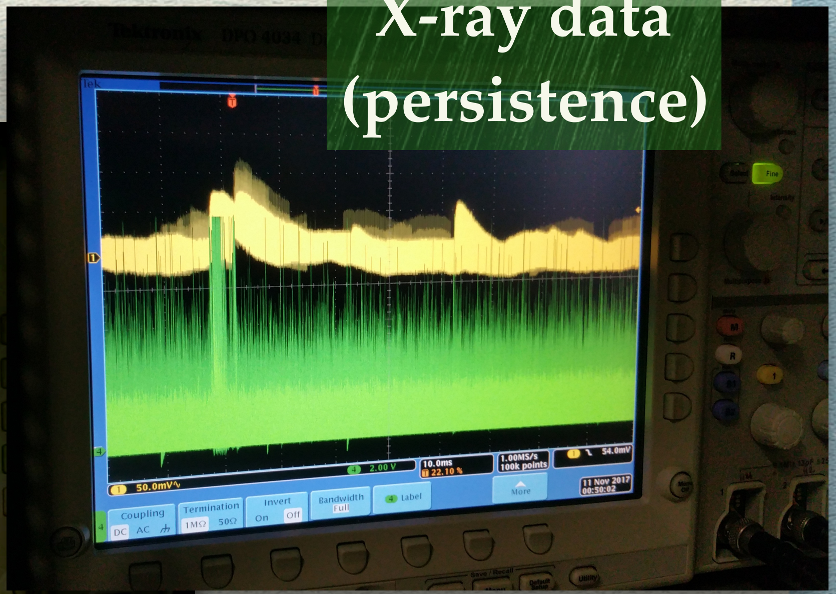
Radio-burst

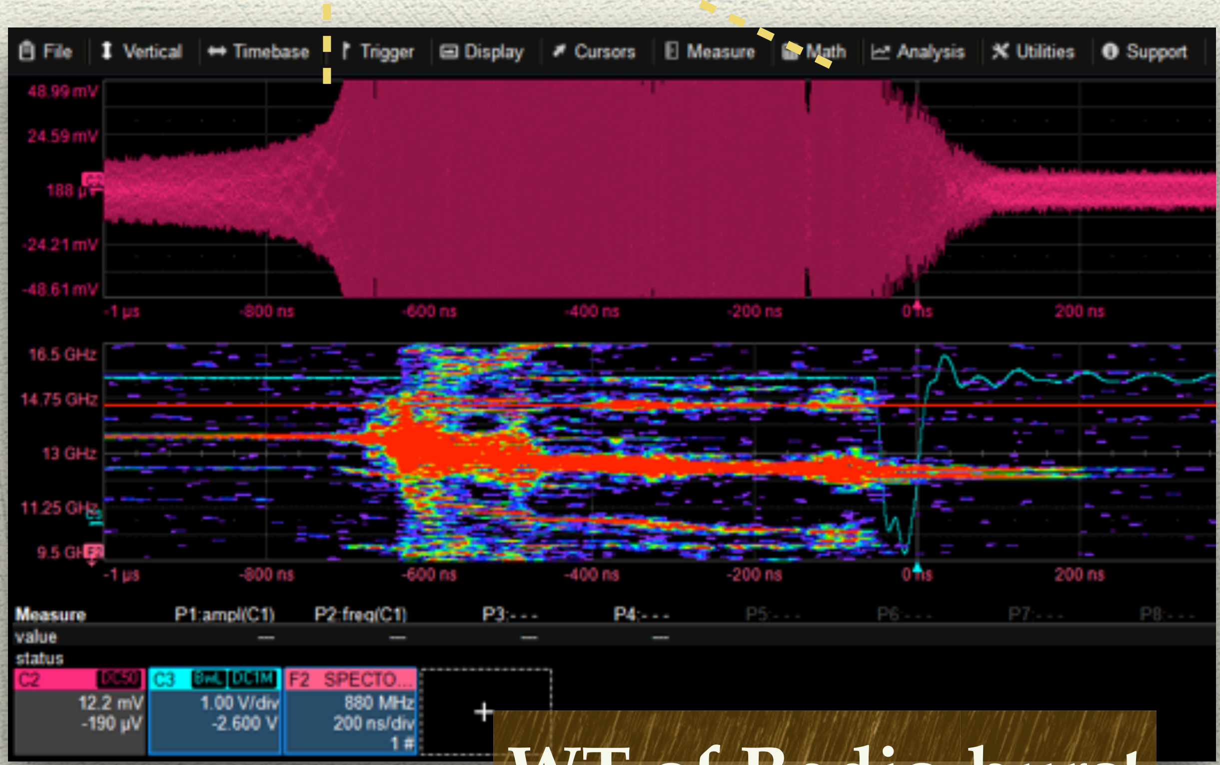


X-ray data

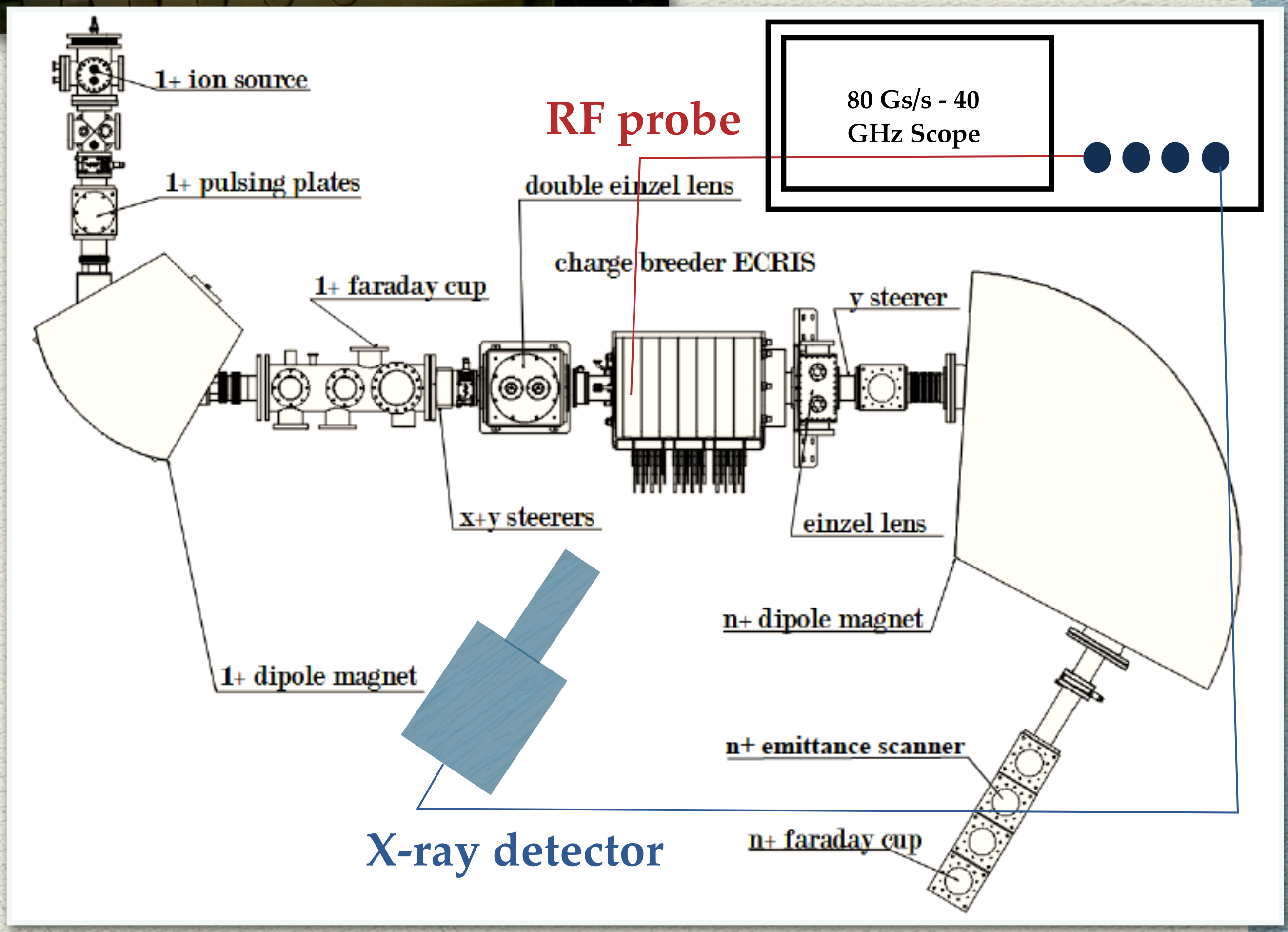


X-ray data (persistence)

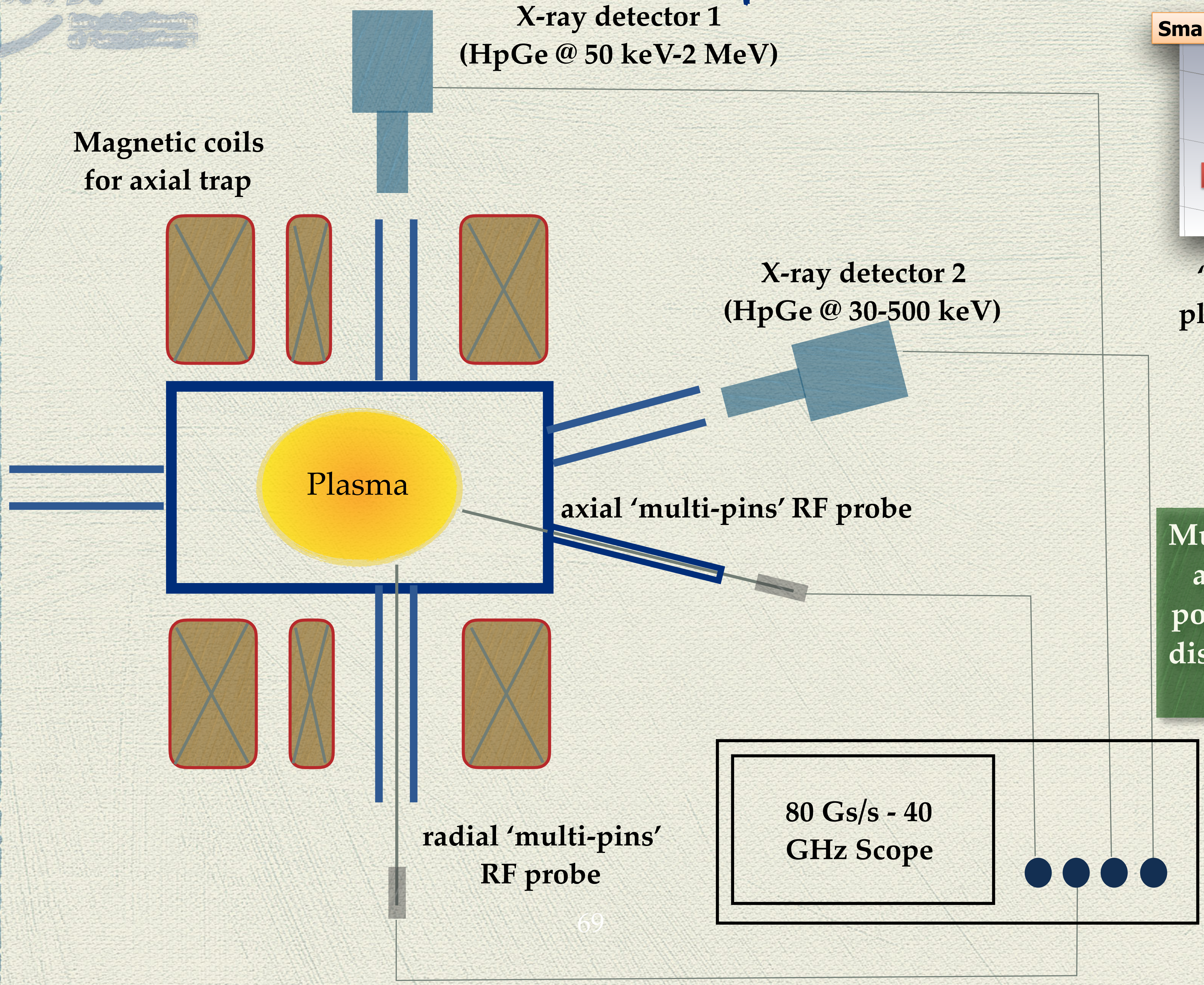


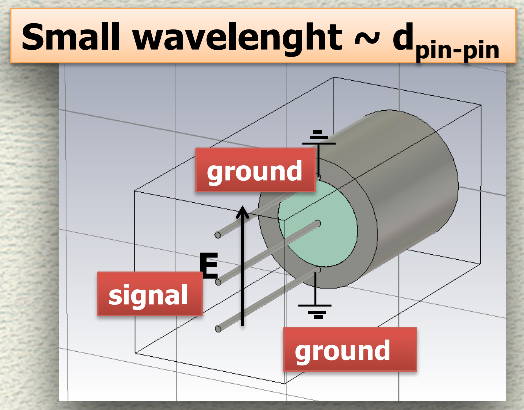


WT of Radio-burst



# Experimental setup @ LNS



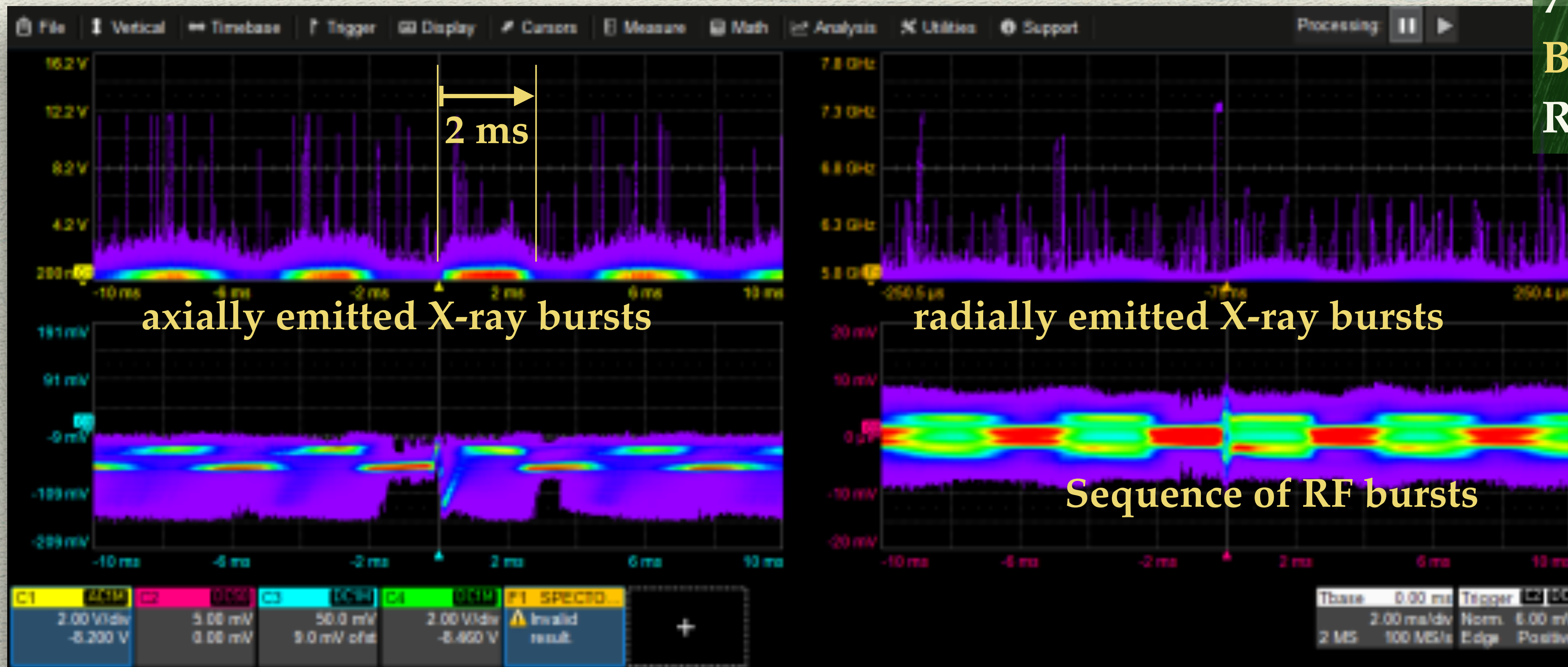




'multi-pins' RF plasma immersed probes

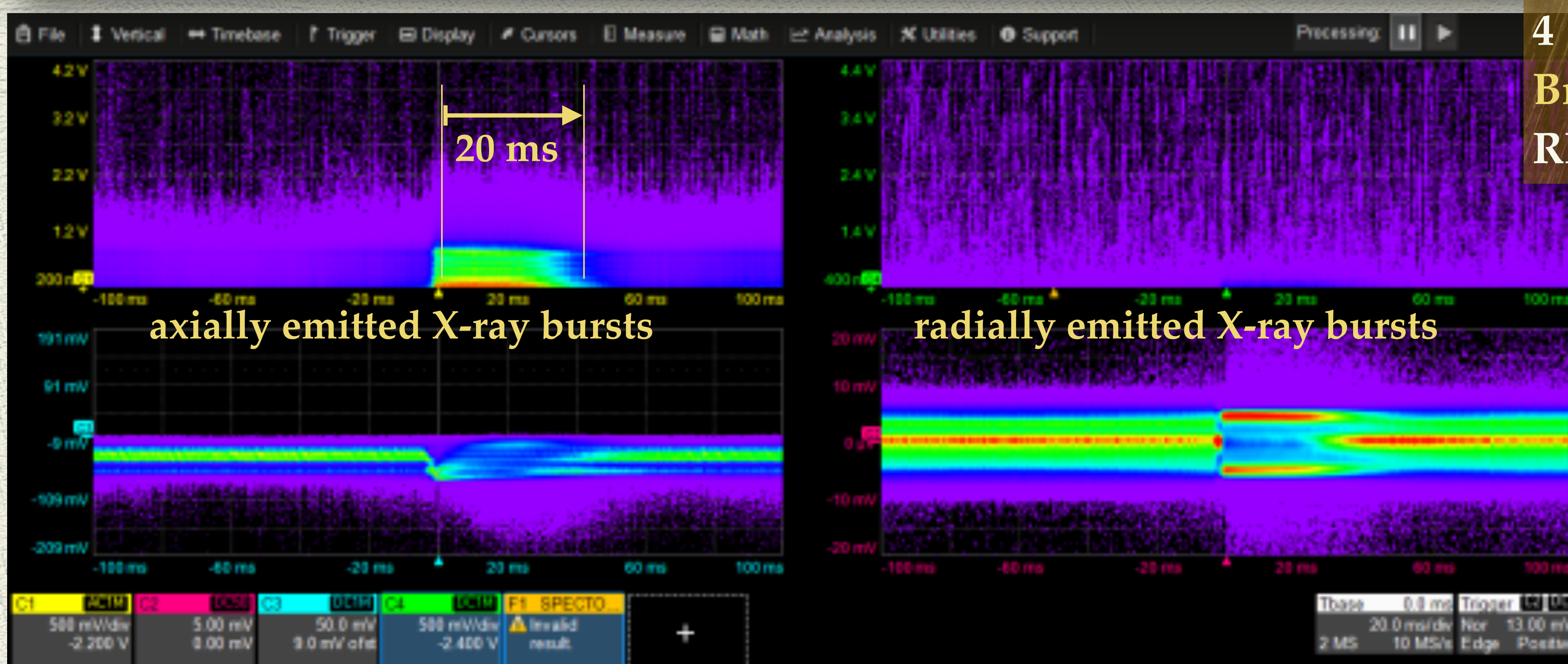
Multi-pin RF probes allow to measure polarization: how to distinguish between O and X modes

# INSTABILITY ONSET DEPENDS FROM THE AXIAL TRAP'S SCALE-LENGTH ONLY!! (*L parameter*)

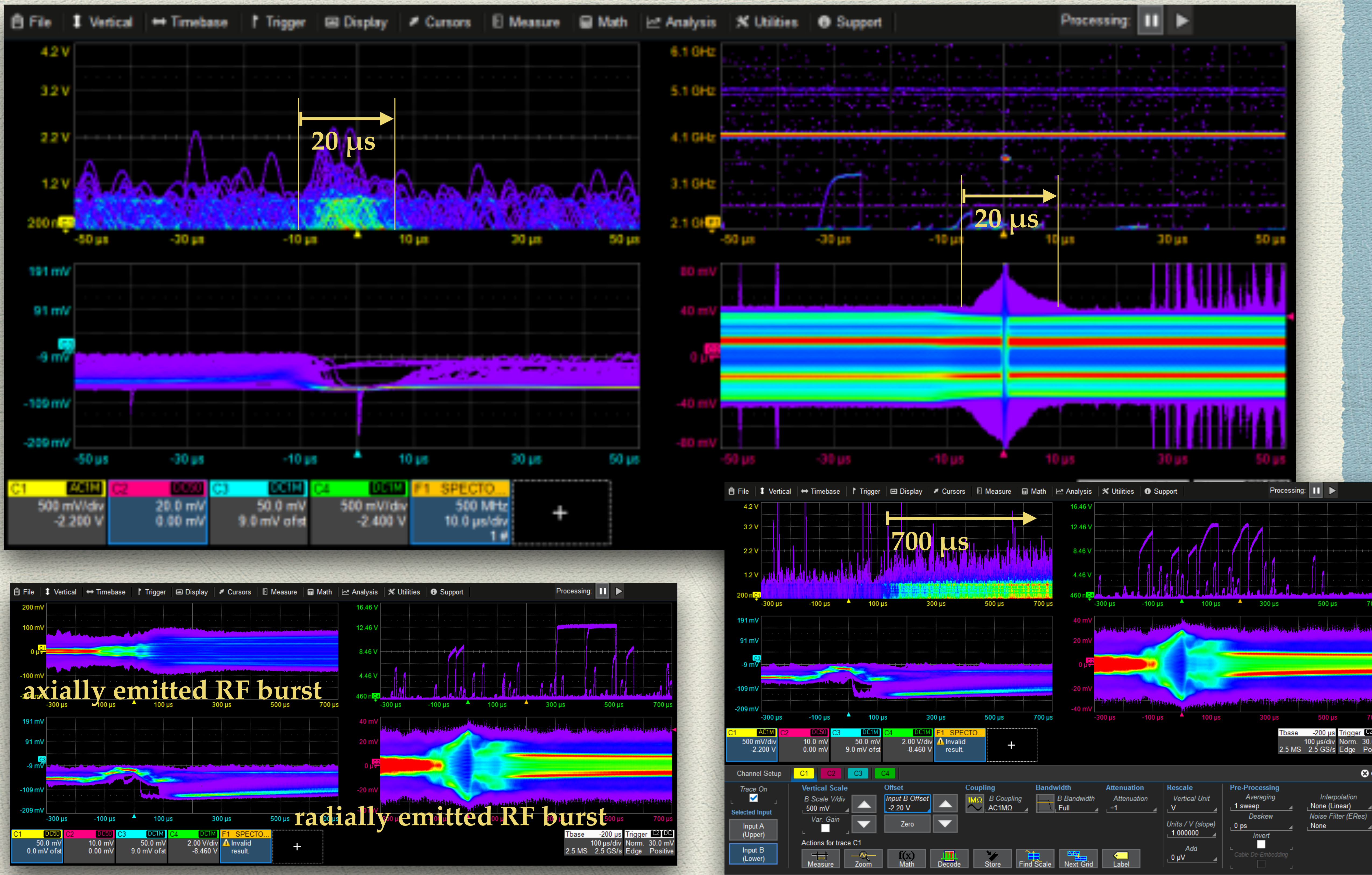
7 GHz
Bmin/Becr=0.8
RF power= 250 W




4 GHz
Bmin/Becr=0.95
RF power= 250 W



# IN ADDITION TO THE "DELAYED" EMISSION OF X-RAY BURSTS, NORMALLY RELATED TO "PRECIPITAION" OF ELECTRONS FROM THE TRAP, SIMULTANEOUS EMISSION OF X-RAYS HAS BEEN OBSERVED IN THE RF BURST TIMESCALE

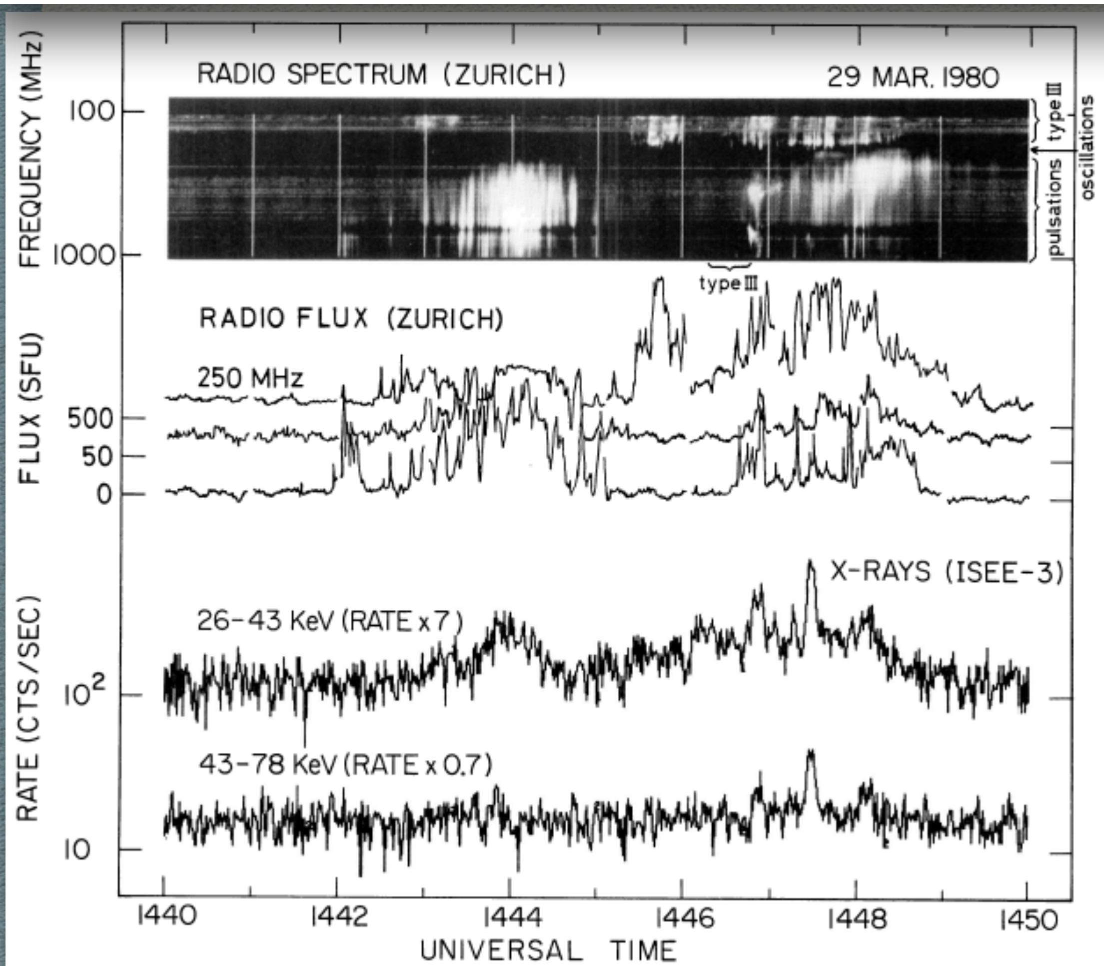


Astron. Astrophys. 229, 206–215 (1990)

ASTRONOMY AND ASTROPHYSICS

# Correlation of solar radio pulsations with hard X-ray emission

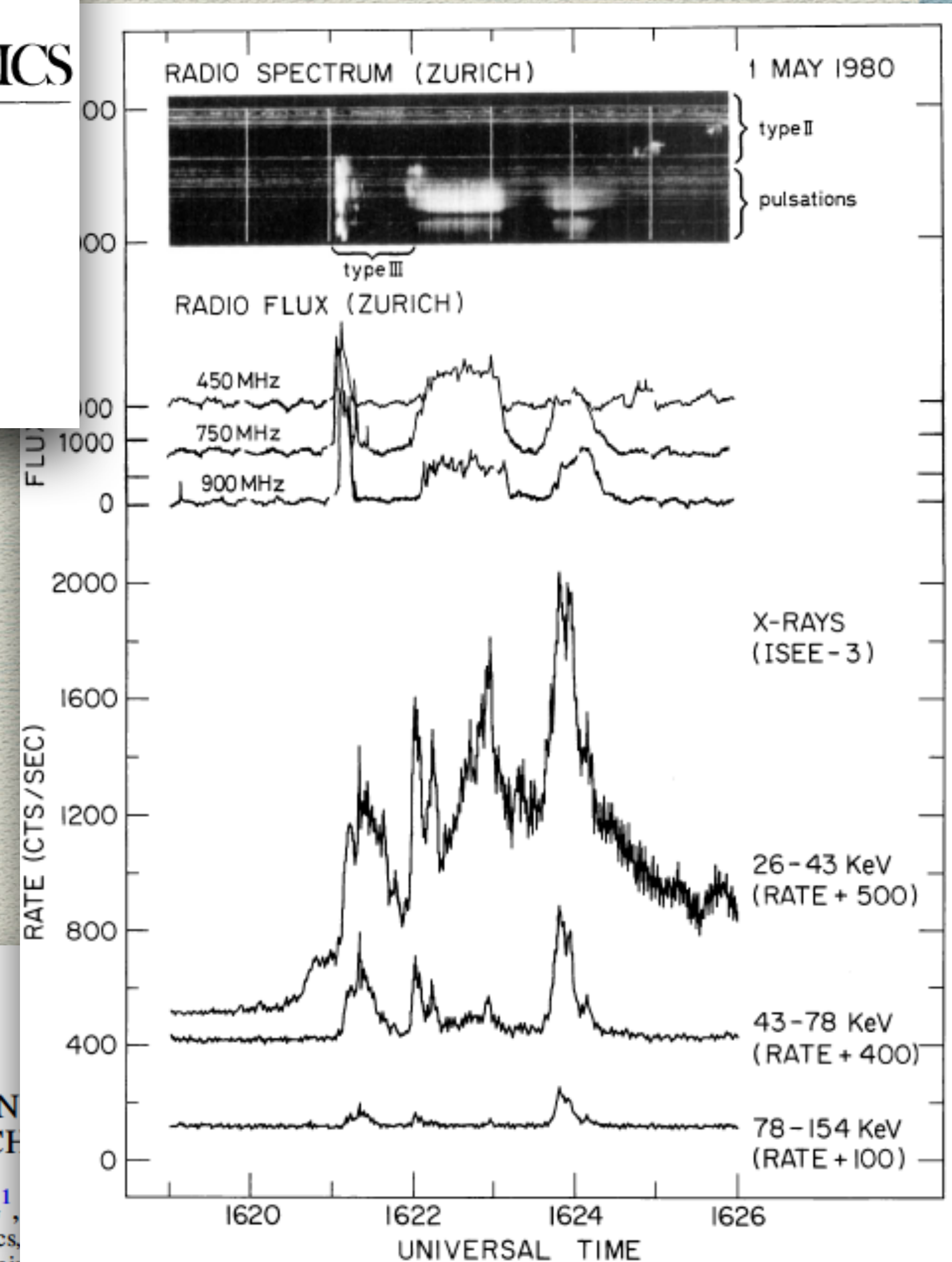
M.J. Aschwanden*, A.O. Benz[1], and S.R. Kane[2]




...TROPHYSICAL JOURNAL, 822:58 (8pp), 2016 May 10


CYCLOTRON MASER EMISSION ...
PITC...

G. Q. Zhao[1], H. Q. Feng[1], ...
[1] Institute of Space Physics, ...
[2] Purple Mountai...
[3] Xinjiang Astronomical Observatory, CAS, Urumqi 830011, China
Received 2016 January 25; accepted 2016 March 6; published 2016 May 5




A&A 370, 1000–1003 (2001)
DOI: 10.1051/0004-6361:20010290

Astronomy & Astrophysics

# Coherent cyclotron maser radiation from UV Ceti

R. Bingham[1,2,3], R. A. Cairns[3], and B. J. Kellett[1]

# Fertile network of collaborations

INFN
Istituto Nazionale
di Fisica Nucleare

INFN-LNS
Plasma studies

INFN-LNL
Beam-plasma studies

INFN-LNS
Nucl. Exp. aspects

INFN-Pg
Theory

INFN-other section
interested (Bo, Ts, Ge)

University of Michigan
University of Cambridge

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

## Collaborations

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Official declaration of interest

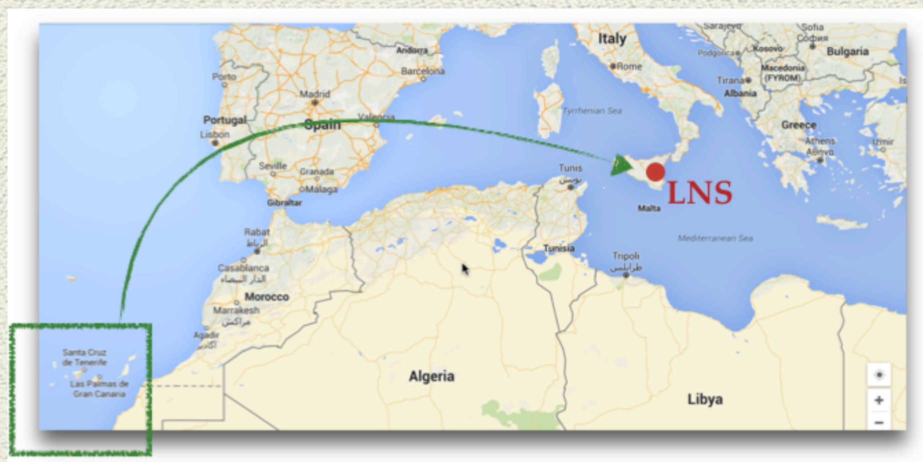
MTA atomki DEBRECEN

GANIL GRAND ACCELERATEUR NATIONAL D'IONS LOURDS

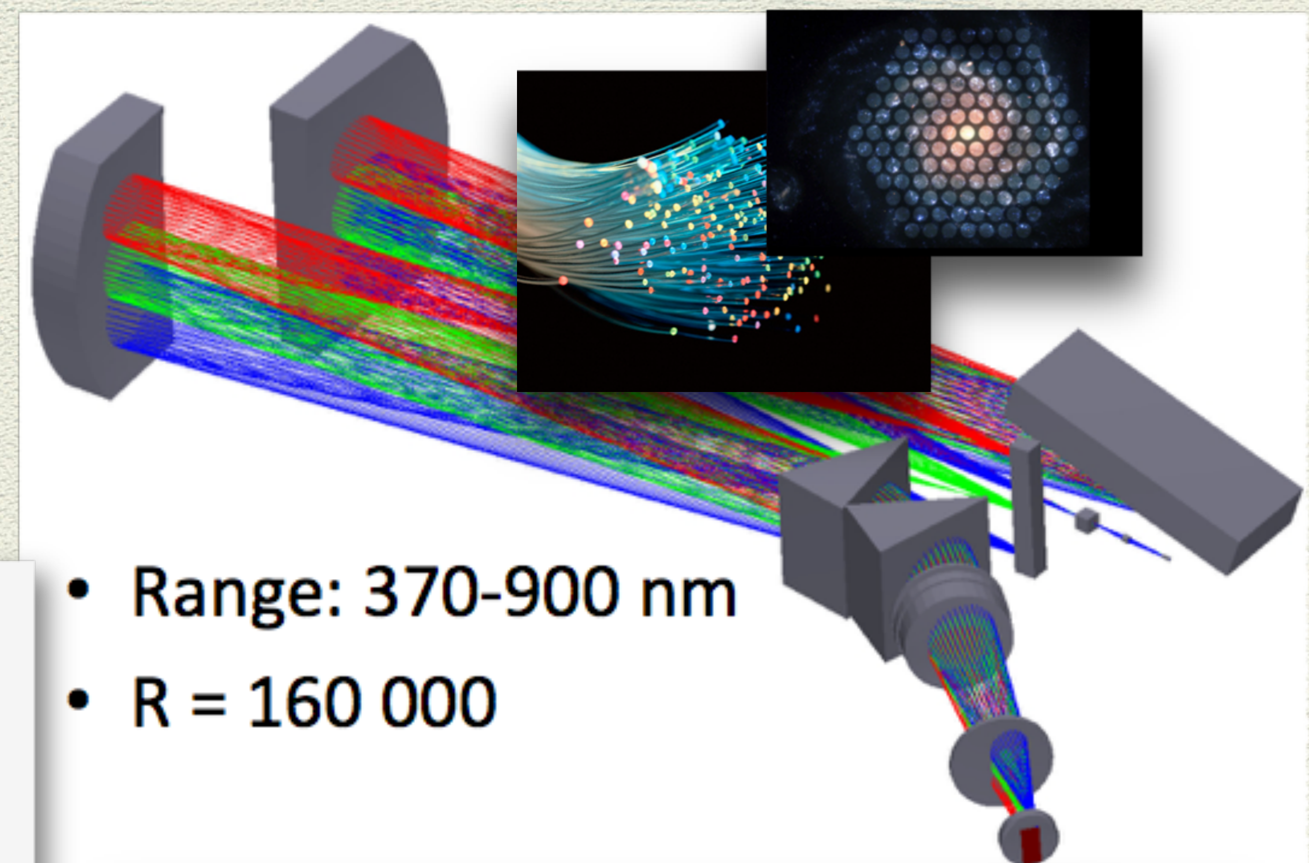
LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

PAUL SCHERRER INSTITUT PSI

# *SpectroPolarimetry for C.S.D. on-line measure*




## Spettrografo Alta Risoluzione Galileo



- Range: 370-900 nm
- R = 160 000

***PANDORA@Work***

INFN-INAF *MoU*
in progress

the first *MoU* to
be signed by the two institutions

CSN III and V

INAF

INFN
Istituto Nazionale di Fisica Nucleare

MEMORANDUM OF UNDERSTANDING

*TRA*

ISTITUTO NAZIONALE DI ASTROFISICA,
OSSERVATORIO ASTRONOMICO DI CATANIA

*E*

ISTITUTO NAZIONALE DI FISICA NUCLEARE,
LABORATORI NAZIONALI DEL SUD

*RIGUARDANTE*

*Un'intensa sinergia su obiettivi comuni della ricerca scientifica al fine di incentivare le attività interdisciplinari basate sulla fisica dei plasmi ad alta densità e temperatura, di interesse per la produzione di fasci ionici, l'astrofisica nucleare e l'astrofisica osservativa, e segnatamente nel campo della propagazione a microonde in plasmi magnetizzati, della spettroscopia ottica/UV, della spettropolarimetria, e dell'analisi dell'emissione di raggi X.*

**Starting a new synergy with Astronomy/Astrophysics!!!**

**SARG has been transfered to LNS from T.N.G. in La Palma, Canary Islands**


SARG@TNG, Canary Islands, has been one of the most powerful spectropolarimetry for the observation of magnetized stars' atmospheres

# SARG@LNS, February 2018 --> Now in the installation phase


# SpectroPolarimetry for C.S.D. on-line measurements

Optical Emission Spectroscopy is already widely used worldwide to measure plasma density and temperature...

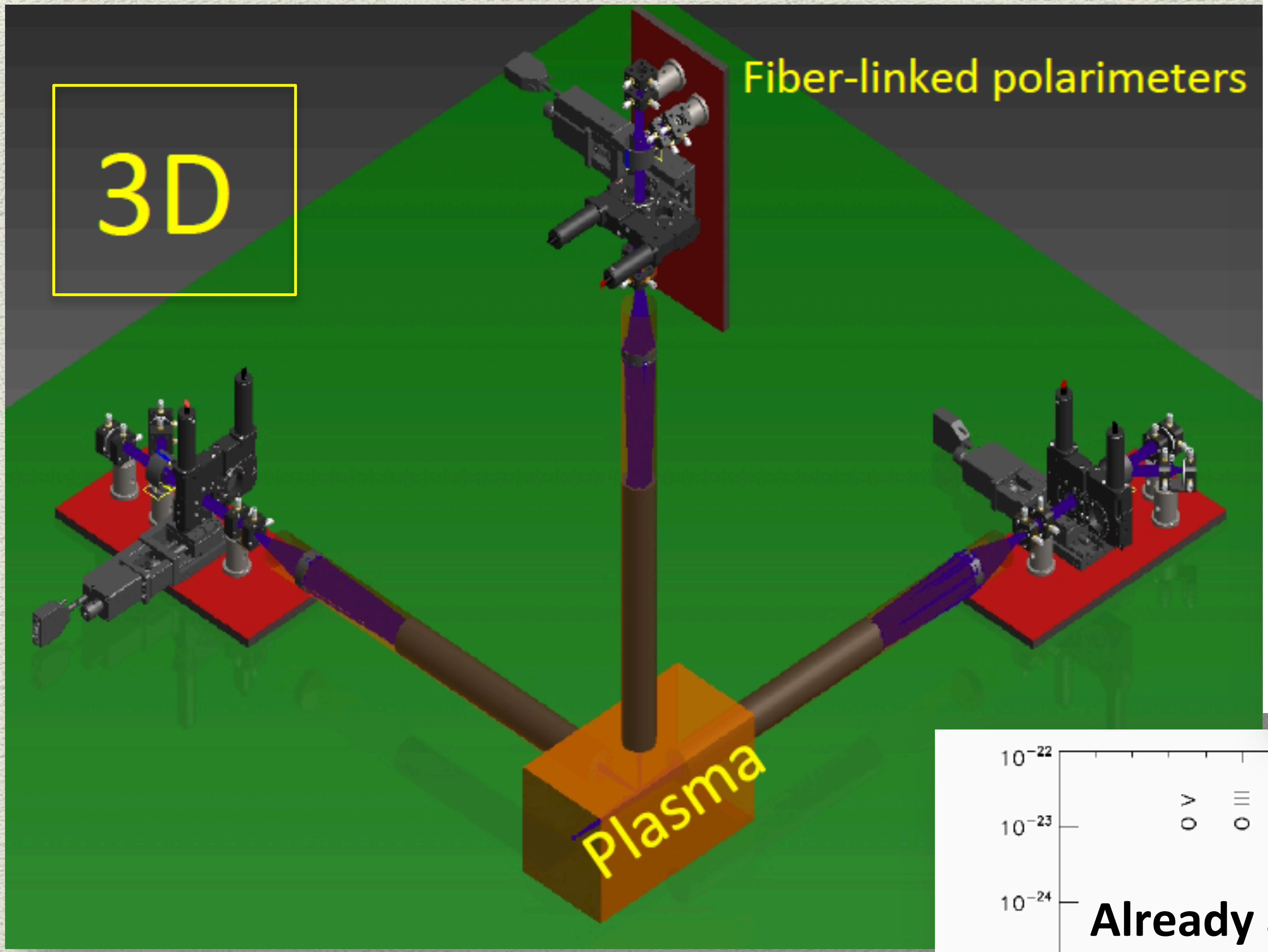
BUT...

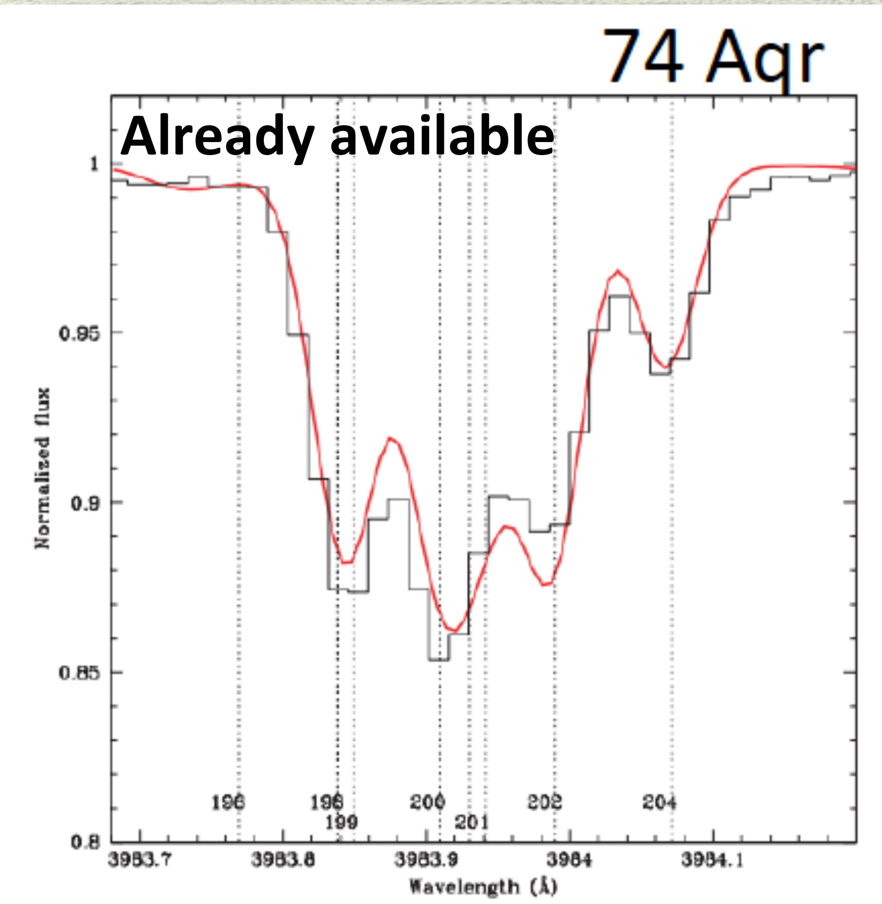
The effect of the magnetic field is rarely taken into account. It may affect in a relevant way line-ratios, etc.

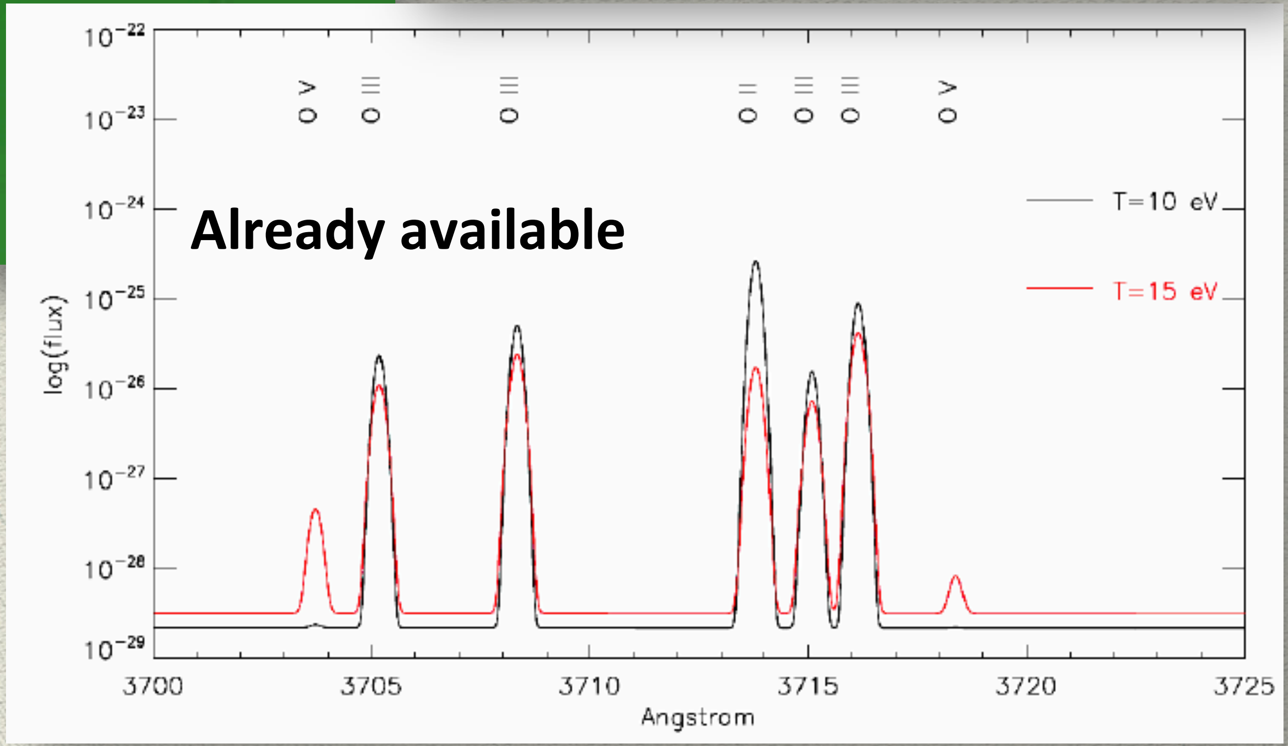
⟶ SPECTROPOLARIMETRY is needed!

Collaboration with Cambridge Univ. and University of Michigan started to integrate astrophysical databases to ECR plasmas

# SpectroPolarimetry for C.S.D. on-line measurements

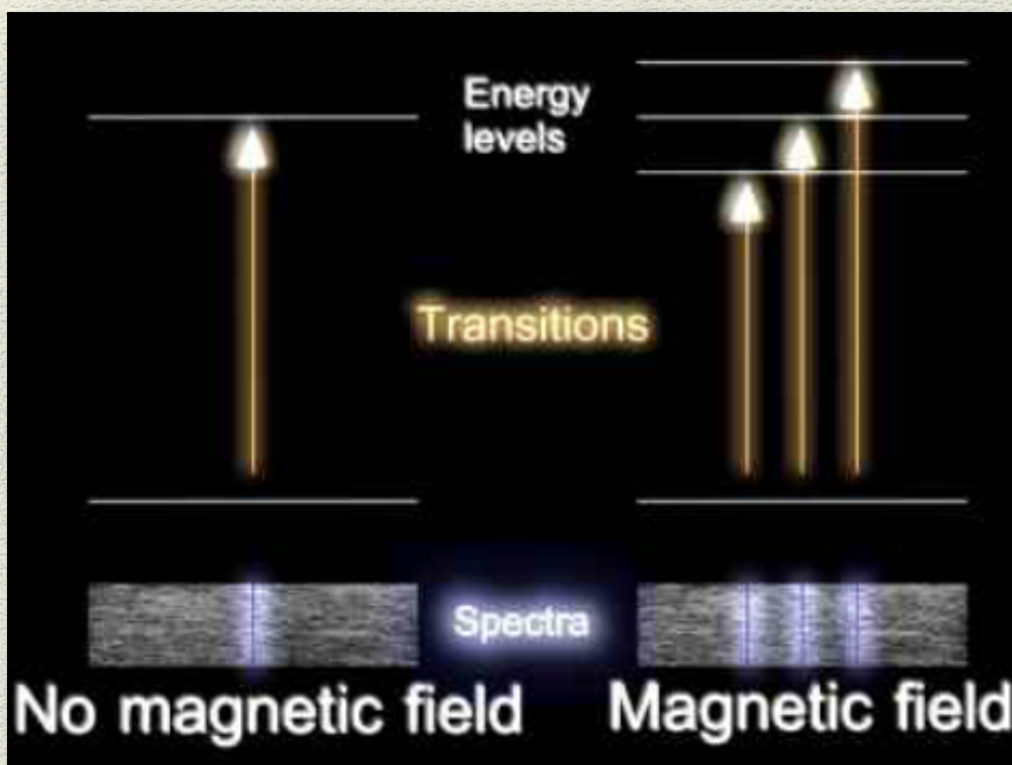


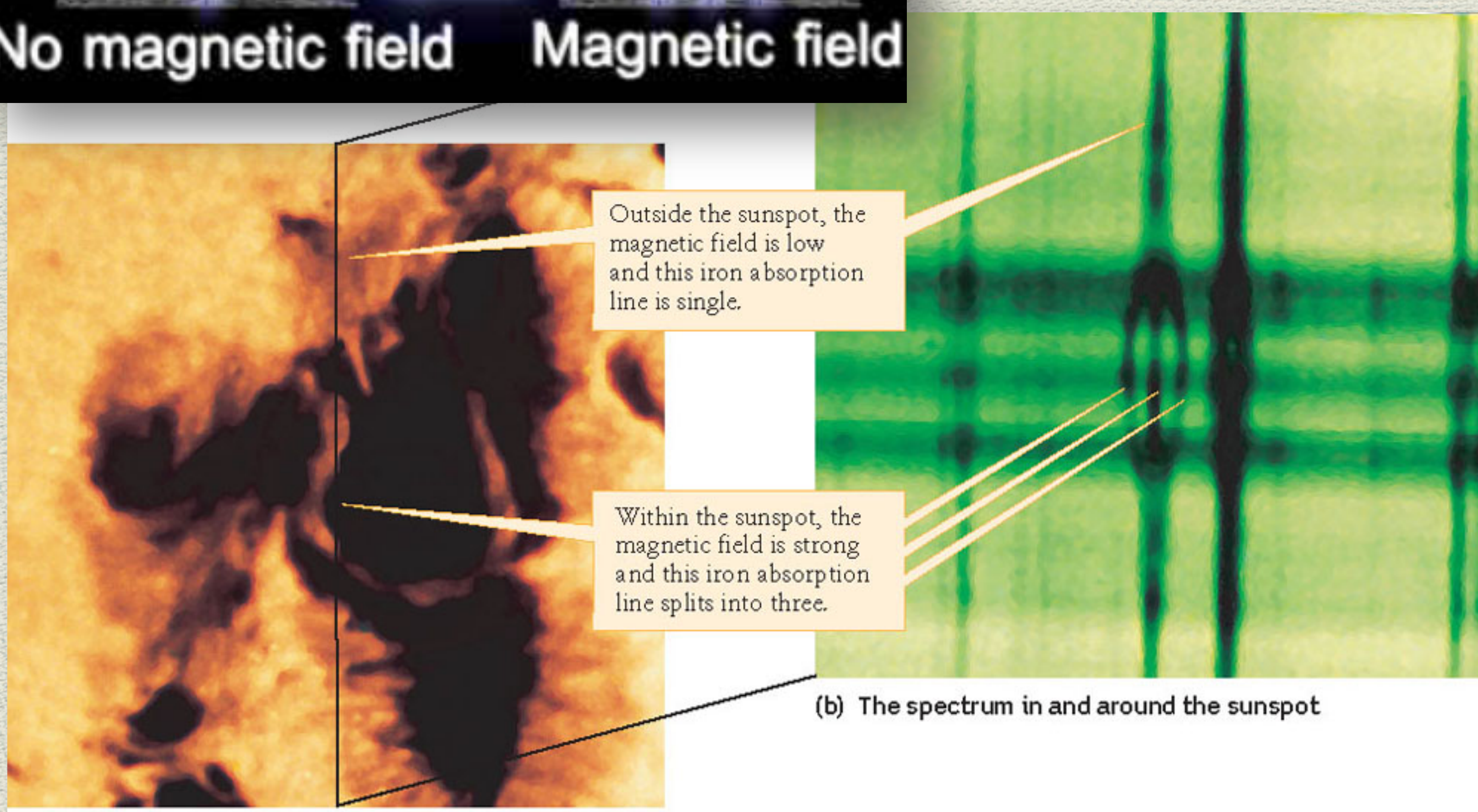




**UPGRADE of SARG for allowing 3D plasma tomography is needed!!**

# *PANDORA's fall-out for Cosmic Magnetic Fields*



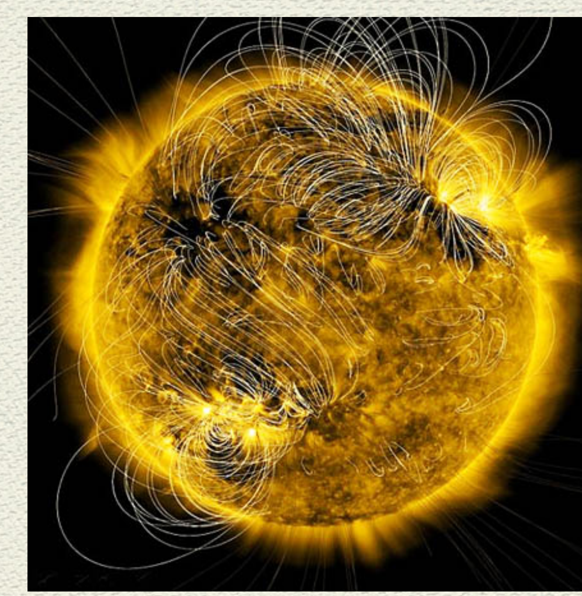

*Since George Ellery Hale (1908) we measure* *LS-coupling* *magnetic fields*



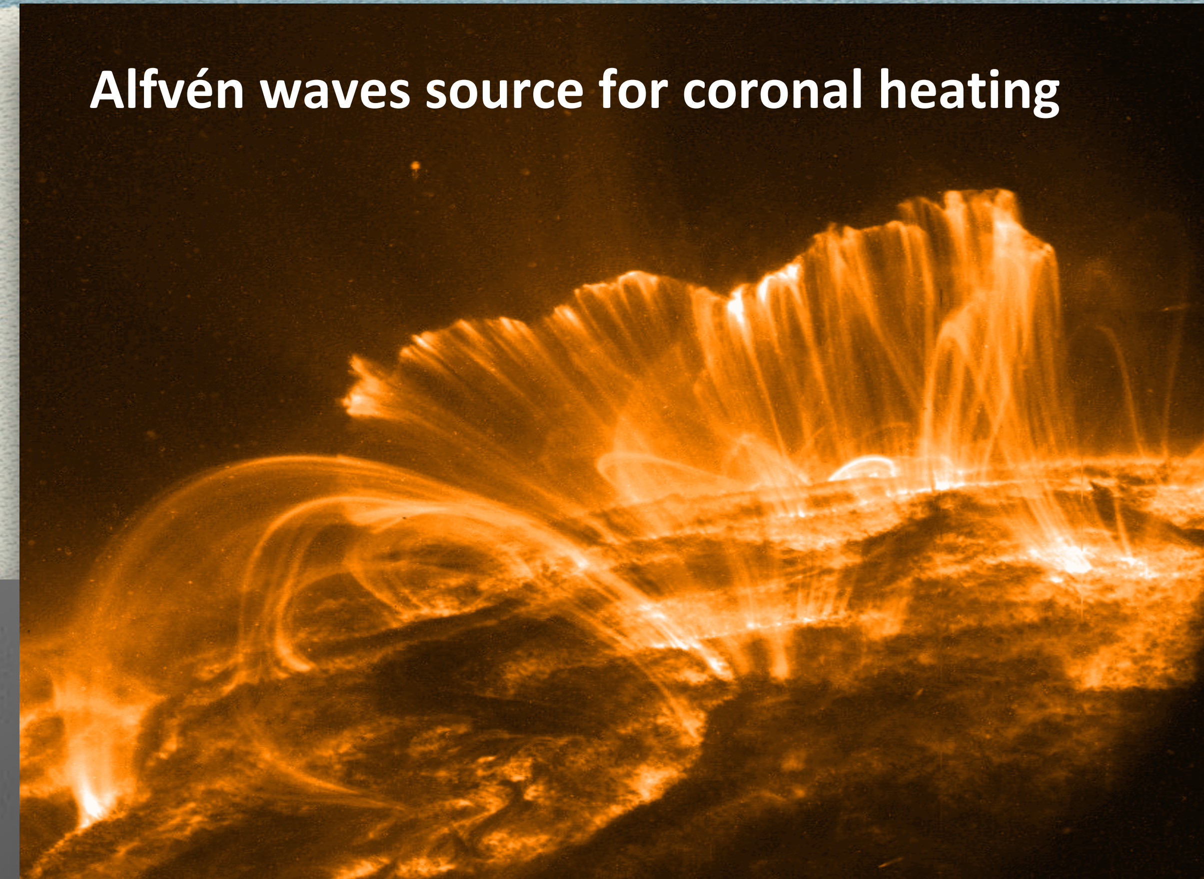

(a) A sunspot

(b) The spectrum in and around the sunspot

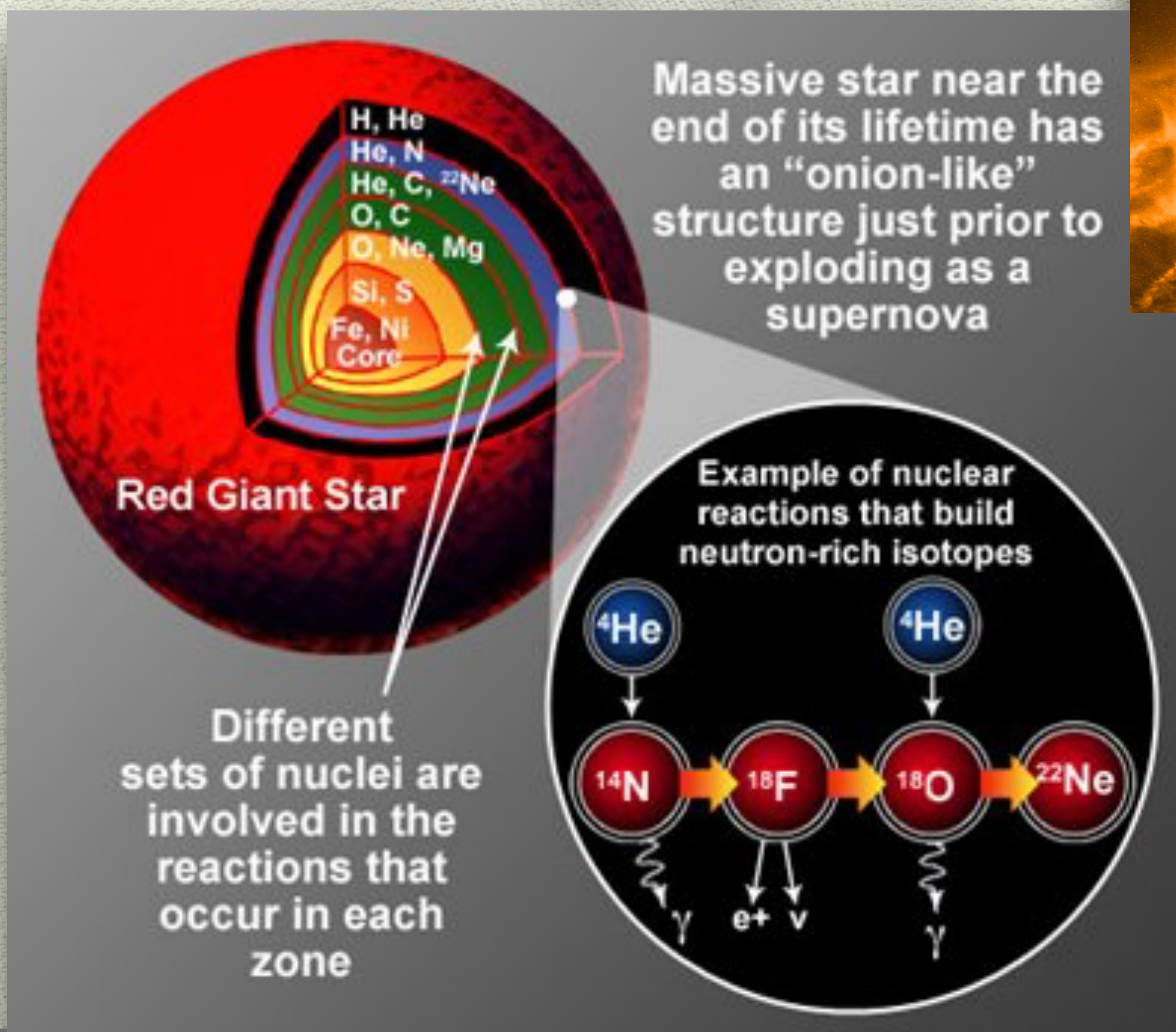
**Building In-laboratory DATABASE of Landé factors**



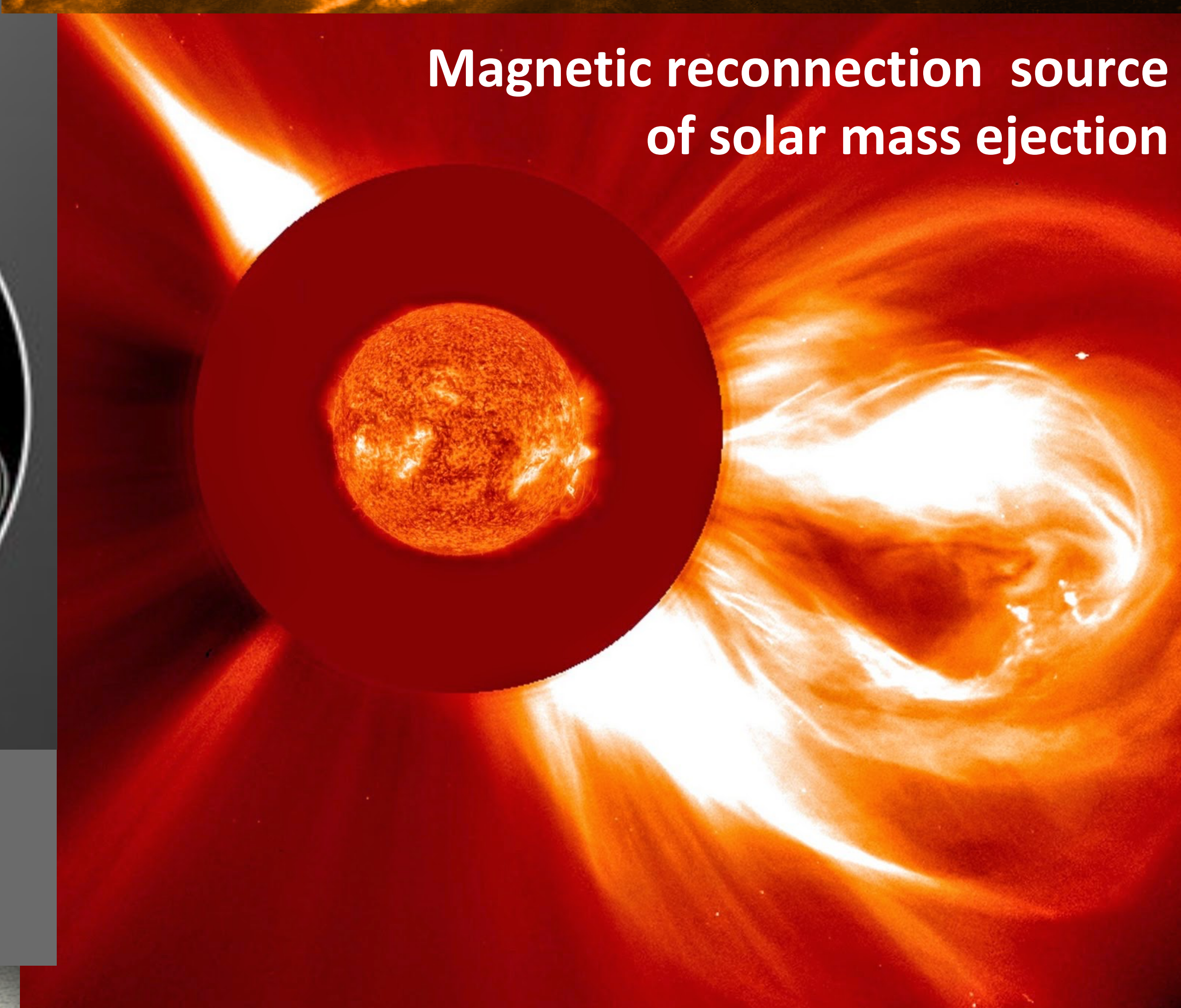
# First-light PANDORA Astrophysics



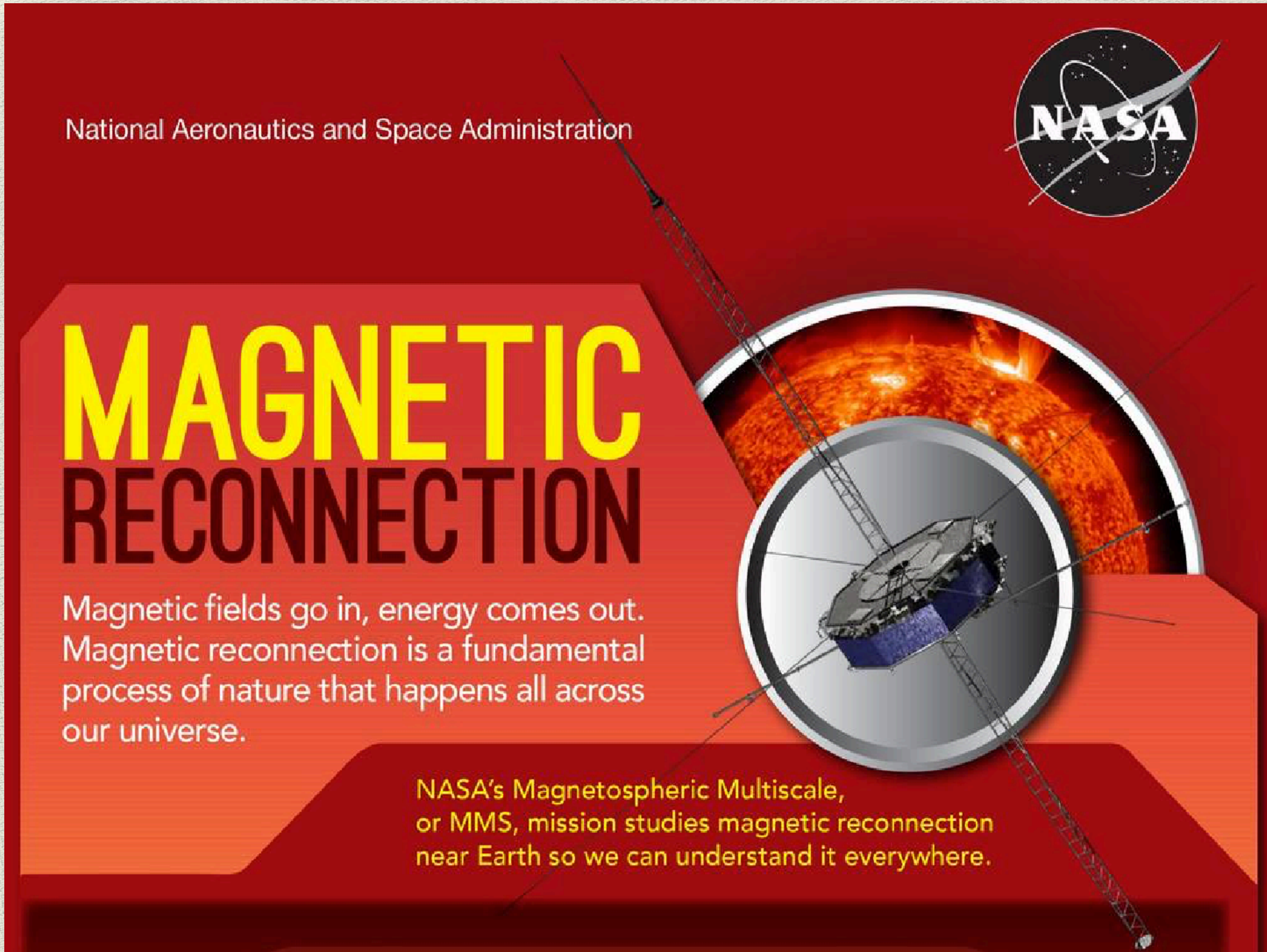
Alfvén waves source for coronal heating




Nuclear reactions for Stellar Structure and Chemical evolution



Magnetic reconnection source of solar mass ejection

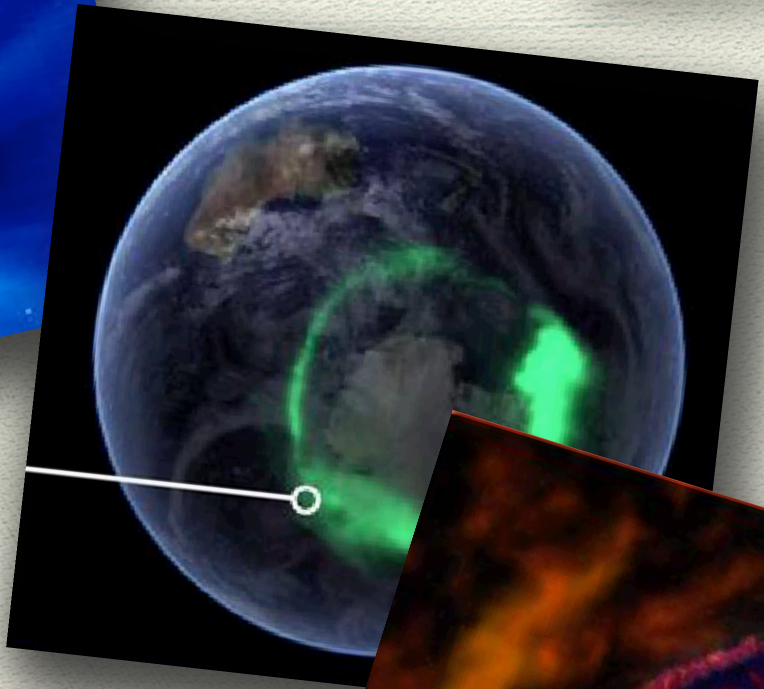

National Aeronautics and Space Administration
NASA
MAGNETIC
RECONNECTION
Magnetic fields go in, energy comes out. Magnetic reconnection is a fundamental process of nature that happens all across our universe.
NASA's Magnetospheric Multiscale, or MMS, mission studies magnetic reconnection near Earth so we can understand it everywhere.

## *Magnetic Reconnection occurrence in the Universe*

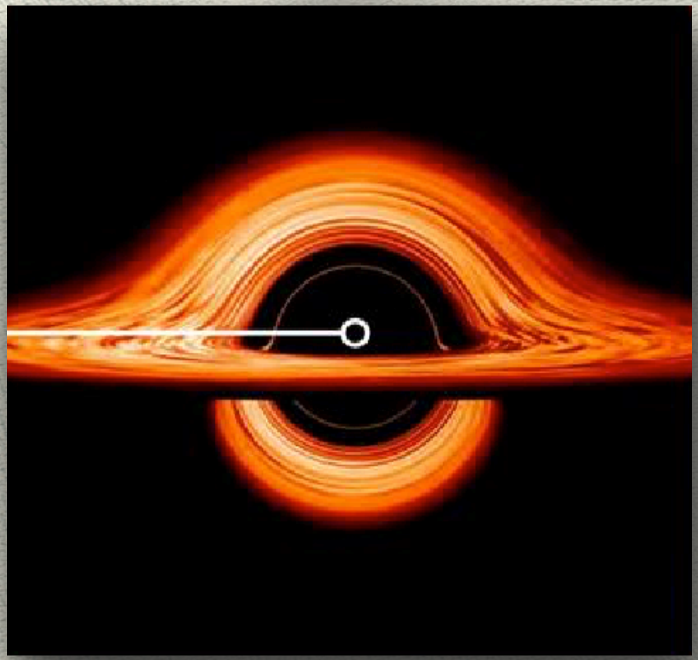
## *PANDORA's fall-out for Observative Astrophysics*

*Coronal mass ejection*

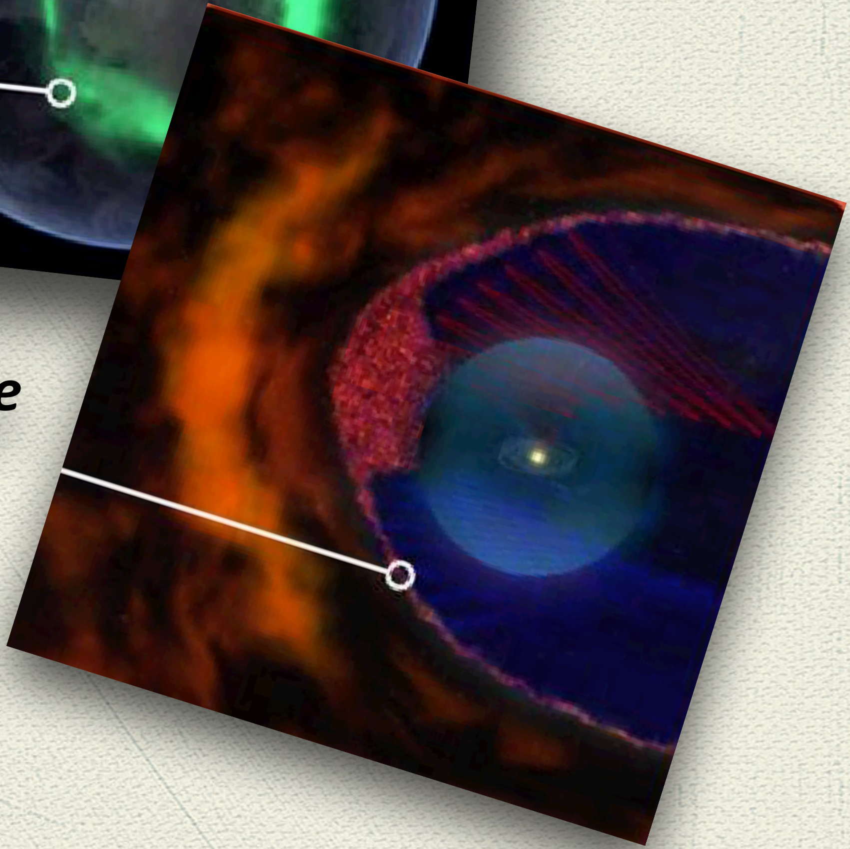
*Auroras*



*Black holes*



*Heliopause*



# LETTER

doi:10.1038/nature24298

## Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger

E. Pian[1], P. D'Avanzo[2], S. Benetti[3], M. Branchesi[4,5], E. Brocato[6], S. Campana[2], E. Cappellaro[3], S. Covino[2], V. D'Elia[6,7], J. P. U. Fynbo[8], F. Getman[9], G. Ghirlanda[2], G. Ghisellini[2], A. Grado[9], G. Greco[10,11], J. Hjorth[8], C. Kouveliotou[12], A. Levan[13], L. Limatola[9], D. Malesani[8], P. A. Mazzali[14,15], A. Melandri[2], P. Møller[16], L. Nicastro[1], E. Palazzi[1], S. Piranomonte[6], A. Rossi[1],

"Stars in Jar" –> The issue of astrophyiscal plasma opacities

The Astrophysical Journal, 774:25 (13pp), 2013 September 1 doi:10.1088/0004-637X/774/1/25



## OPACITIES AND SPECTRA OF THE *r*-PROCESS EJECTA FROM NEUTRON STAR MERGERS

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[3] Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK

*Received 2013 March 5; accepted 2013 June 24; published 2013 August 12*

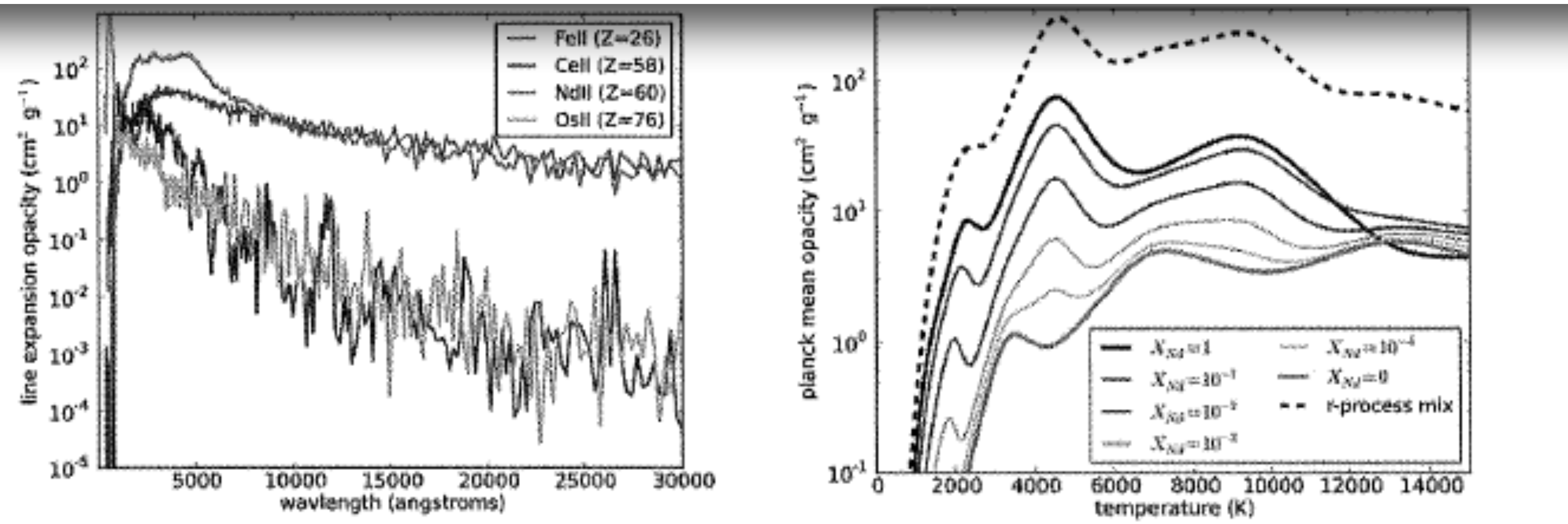
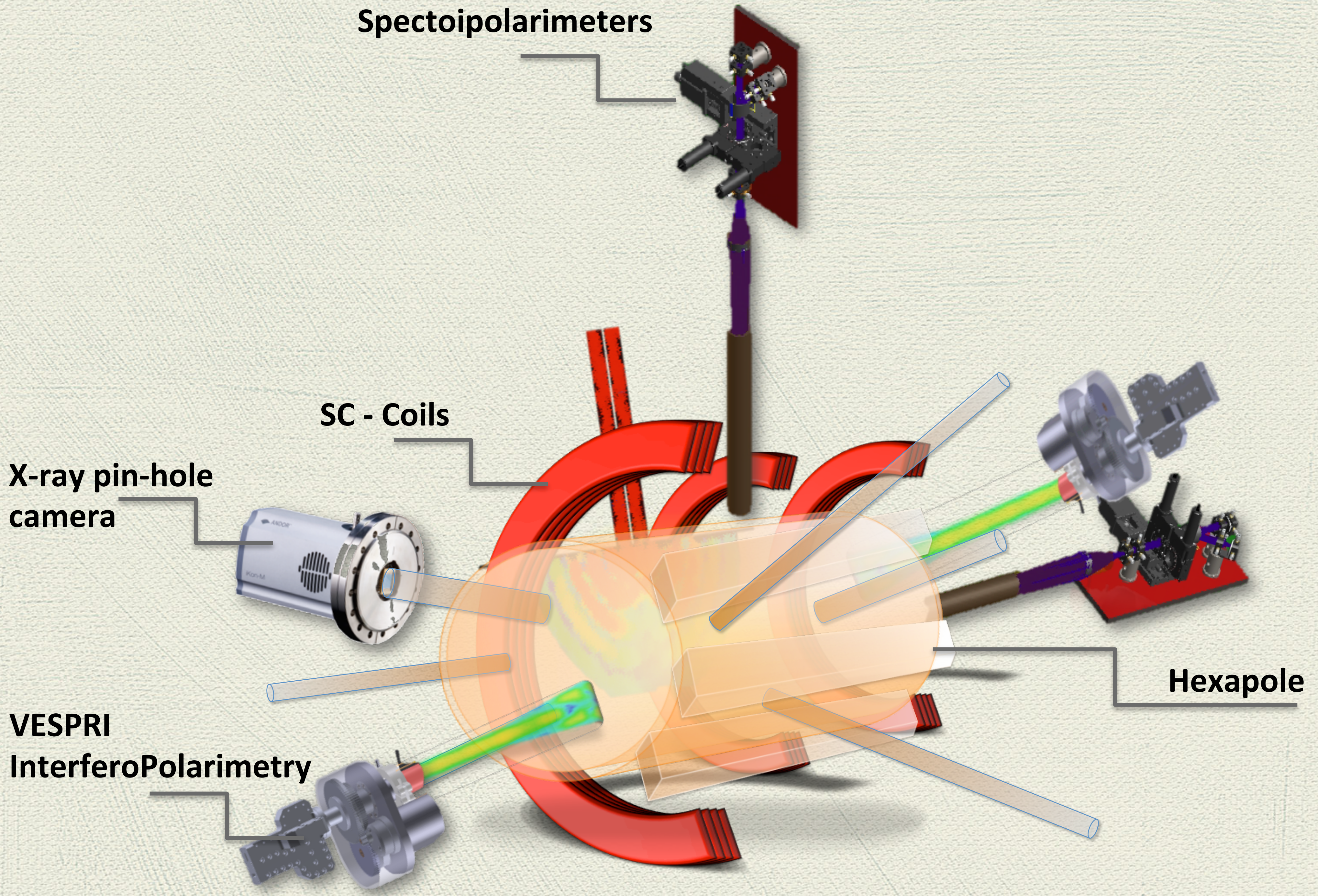
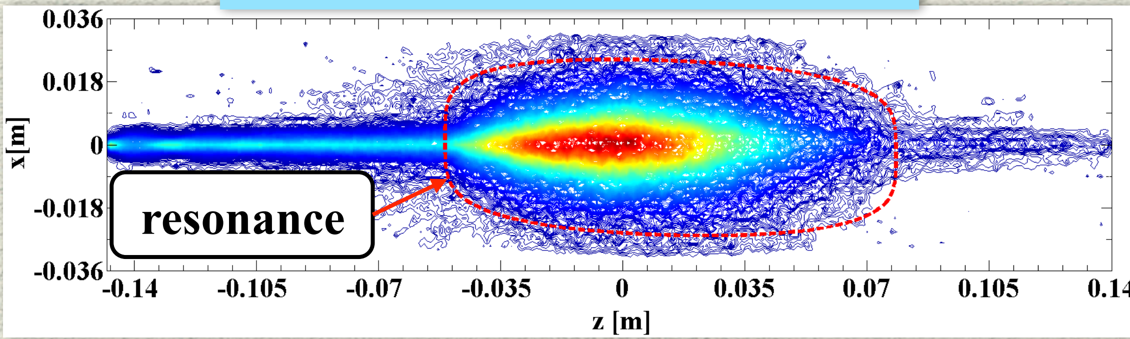



Figure 2: **Left:** Line opacity as a function of wavelength, comparing elements with d-shell valence shell electrons (iron, cerium) to lanthanides with f-shell electrons (e.g. Nd, Os). **Right:** Planck mean opacities, $\kappa_{\rm Pl} = \frac{\int_0^\infty \kappa_\nu B_\nu(T) d\nu}{\int_0^\infty B_\nu(T) d\nu}$, for ejecta containing different mass fractions of lanthanides $X_{\rm Nd}$, the remainder being non-lanthanides $X_{\rm Fe} = 1 - X_{\rm Nd}$. From Kasen et al. (2013).

# PANDORA Multi-Diagnostics approach

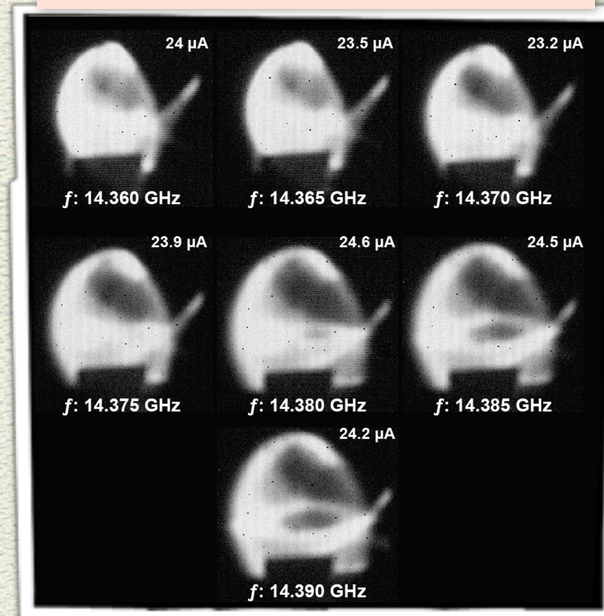


## Charge breeding process



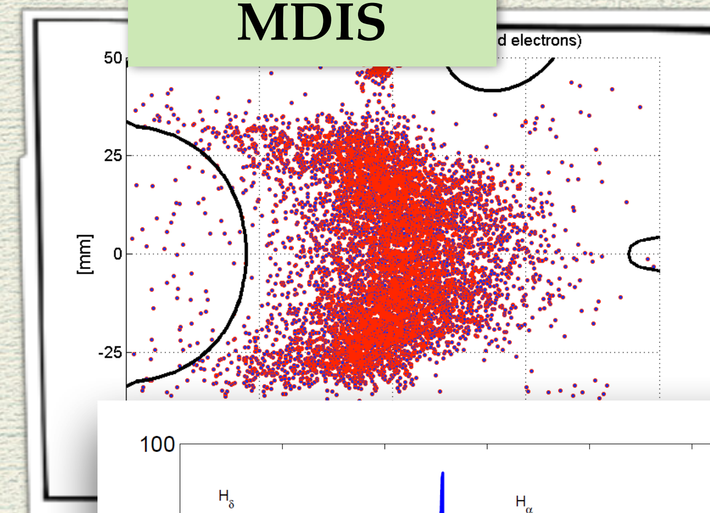

jointly with LNL (A. Galatà)

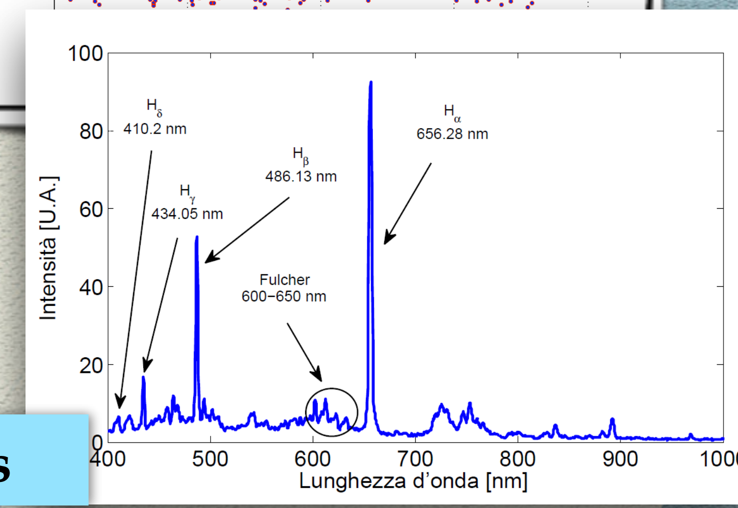
## Beam diagnostics




D. Nicolosi, R. Crispino, A. Mazzaglia

## OES and operations of MDIS



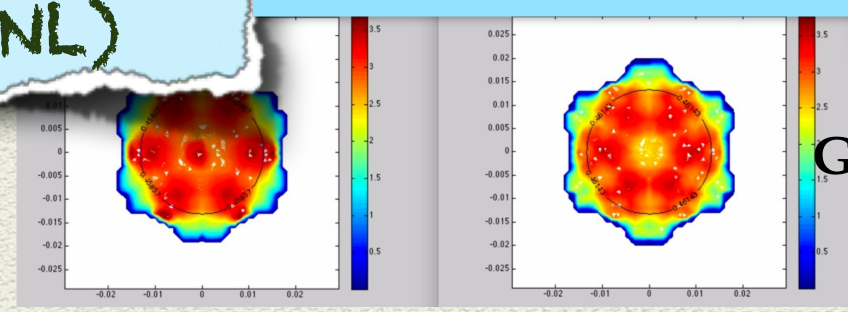



G. Castro, M. Mazzaglia, L. Neri

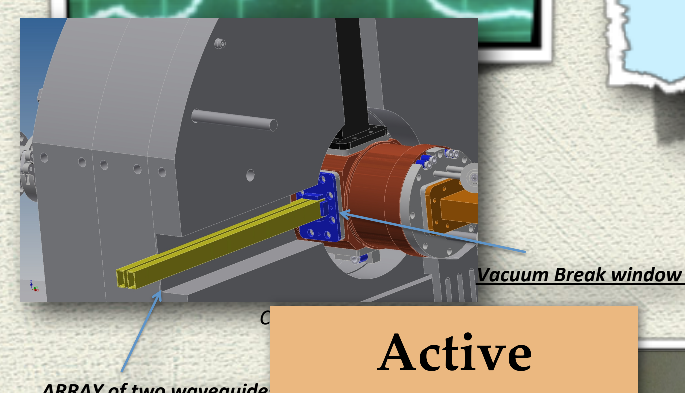
## wave-plasma interaction


PLASMA team@LNS (and LNL)

## self-consistent models



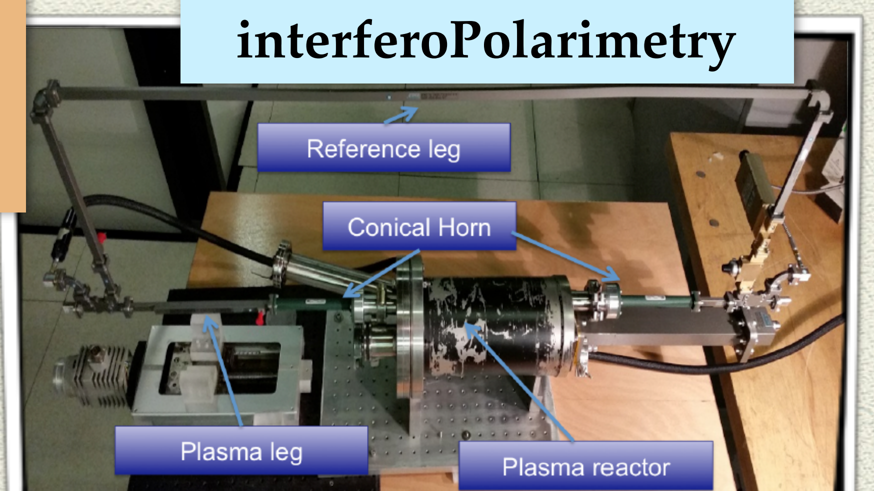
G. Torrisi, A. Galatà




## Active microWaves launching

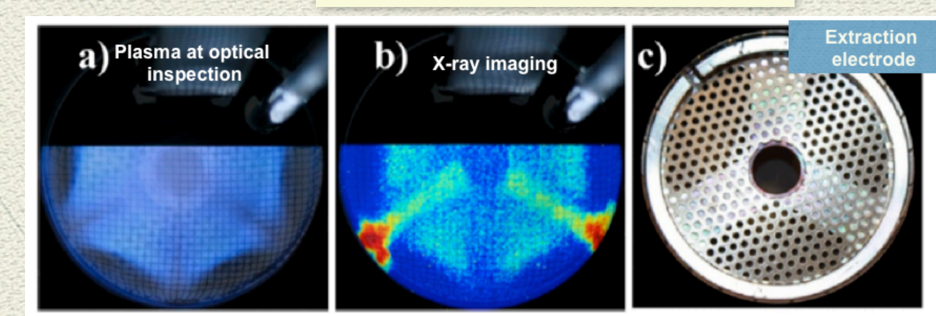
G. Castro, G. Torrisi

## interferoPolarimetry




G. Torrisi, E Naselli, M. Roccasalva

## X-ray imaging and spectroscopy




R. Rach, C. Caliri, C. Altana

# Many thanks to the LNS plasma & ion source group

The presentation is the results of a collective effort by senior and young colleagues!

Many thanks to Santo Gammino, Luigi Celona, Alessio Galatà, Giuseppe Torrisi, Giuseppe Castro, Lorenzo Neri, Eugenia Naselli, Maria Mazzaglia, Marina Giarrusso, Franco Leone, Carlo Sportato, Tommaso Podestà, Gianluigi Cosentino, Mario Musumeci, Sara Palmerini, Cristian Massimi, Vincenza Bonanno

**Thank you for your attention!!**

# Achievements and Perspectives

- We are now able to see what happens into the plasma and to model through numerical simulations how it could be happen differently (and in a better way)

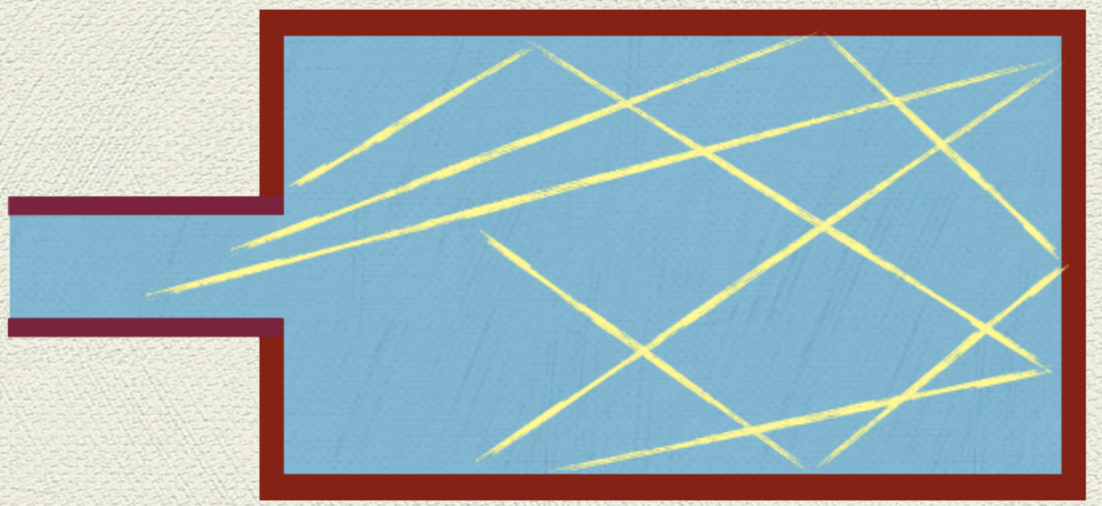
- Microwave absorption oriented design is needed: Power deposition into the plasma must be done in a highly controlled way → **Single pass absorption**

**Some ideas**

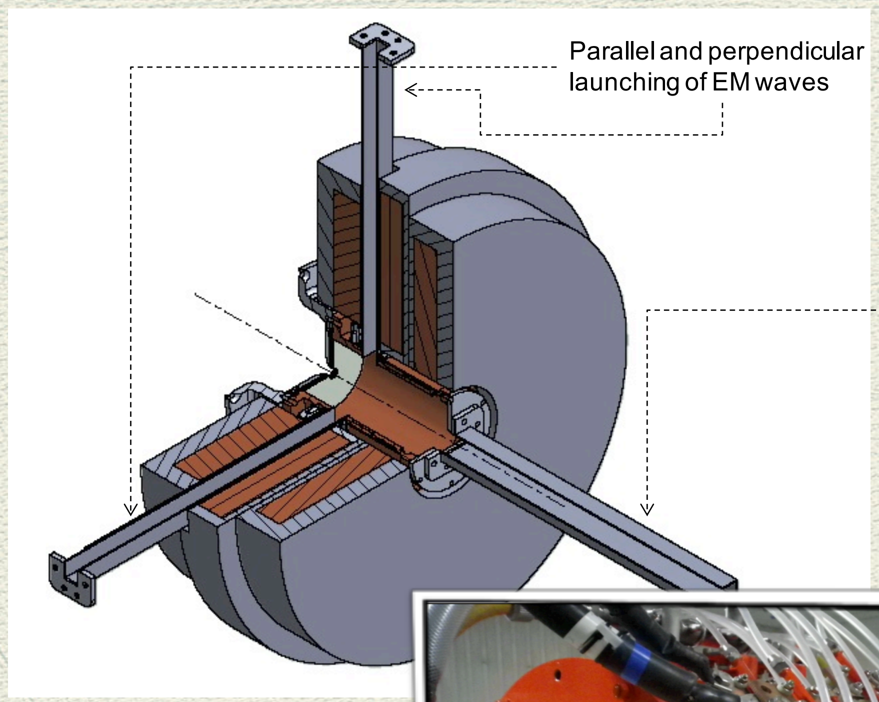
- STILL IN ECR-heating paradigm: are cylindrical shapes of the plasma chamber still mandatory?

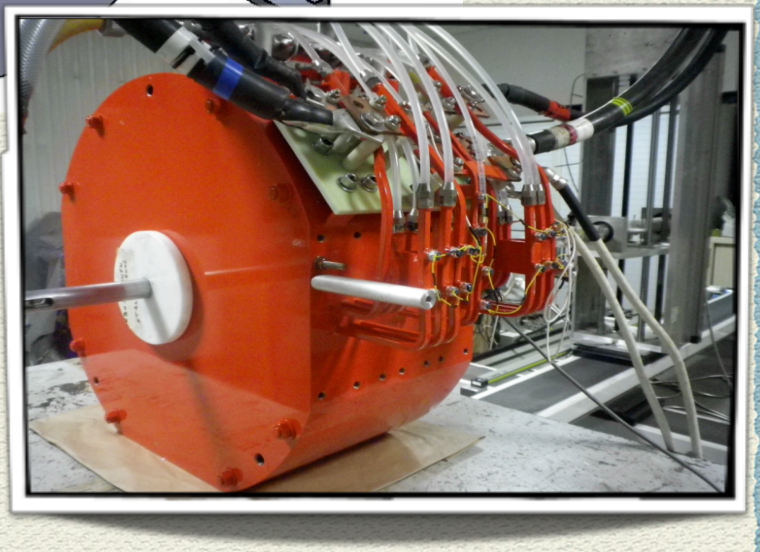
- OVERCOMING ECR-heating paradigm: on-purpose design of launchers

# "Microwave-absorption-oriented" design

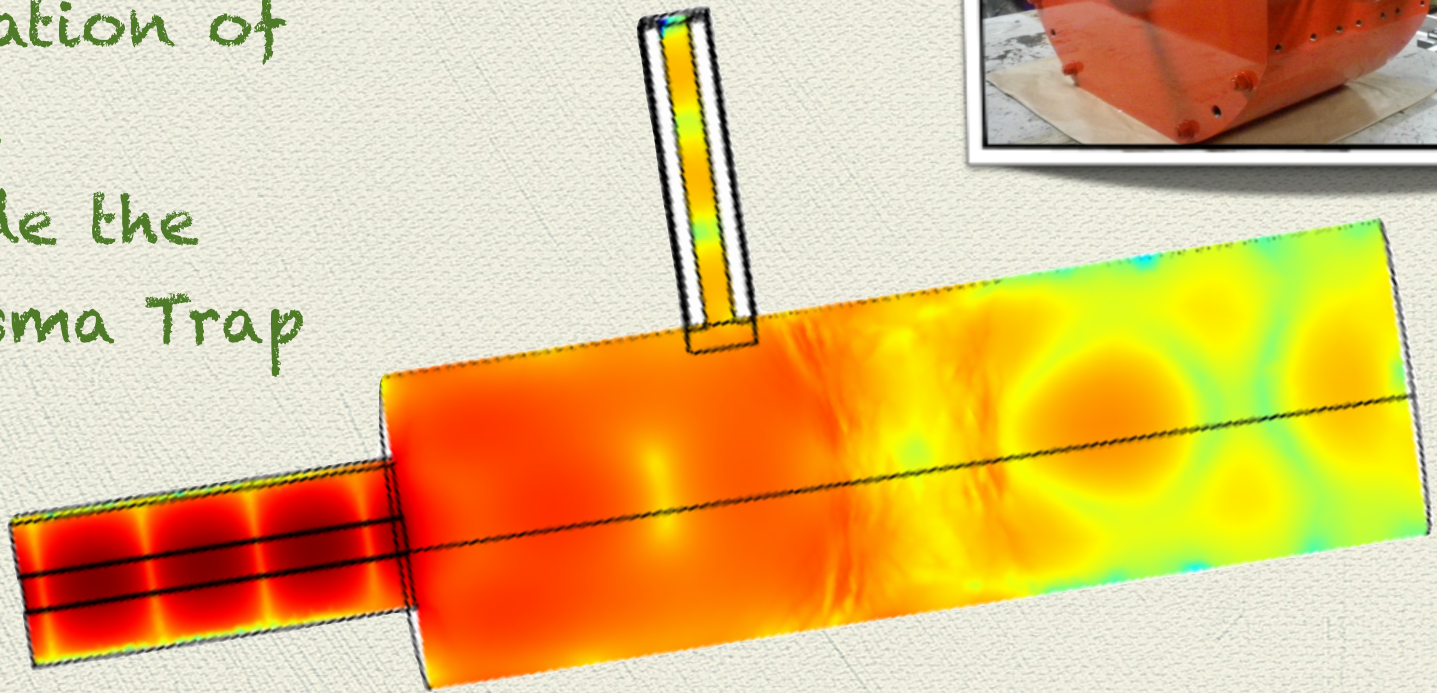


M.A. + guiding + resonator scheme

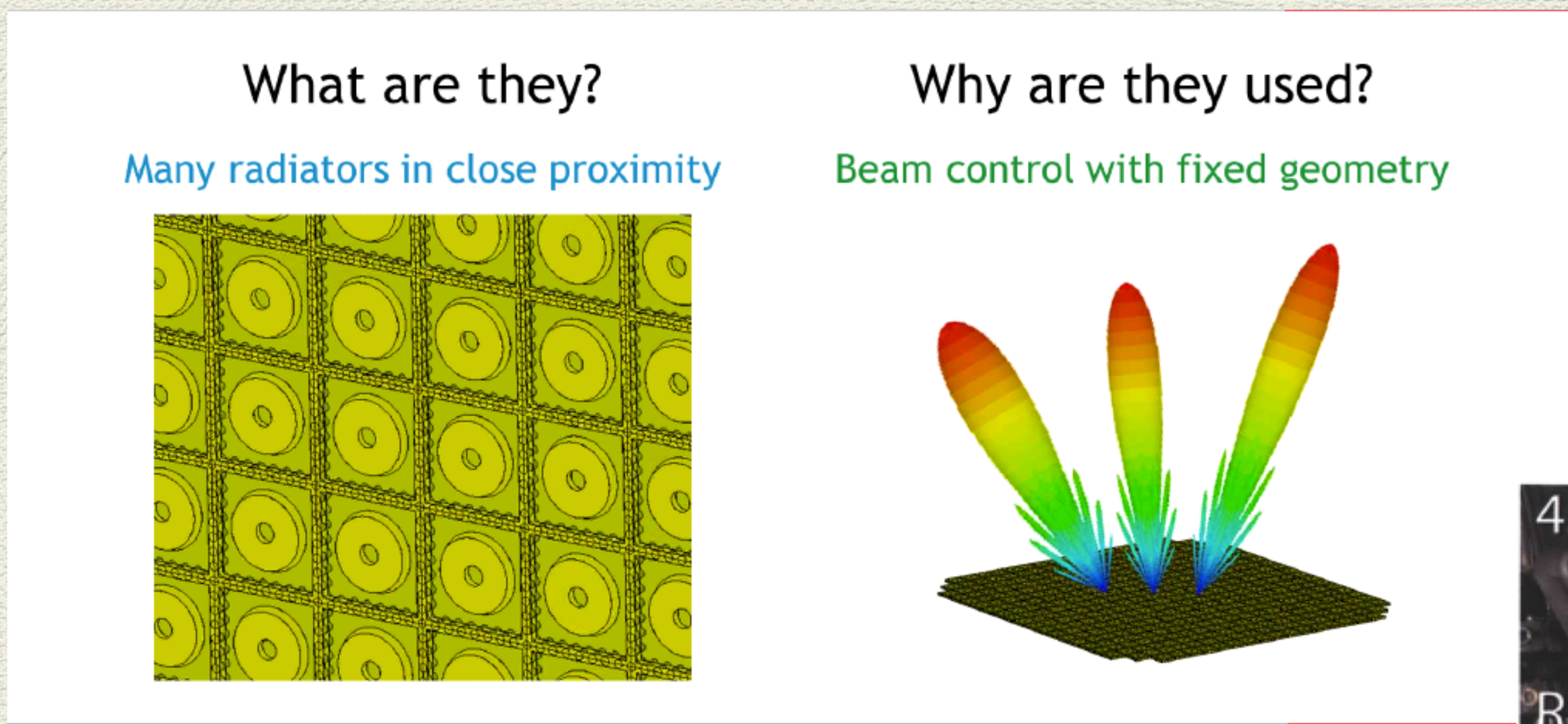


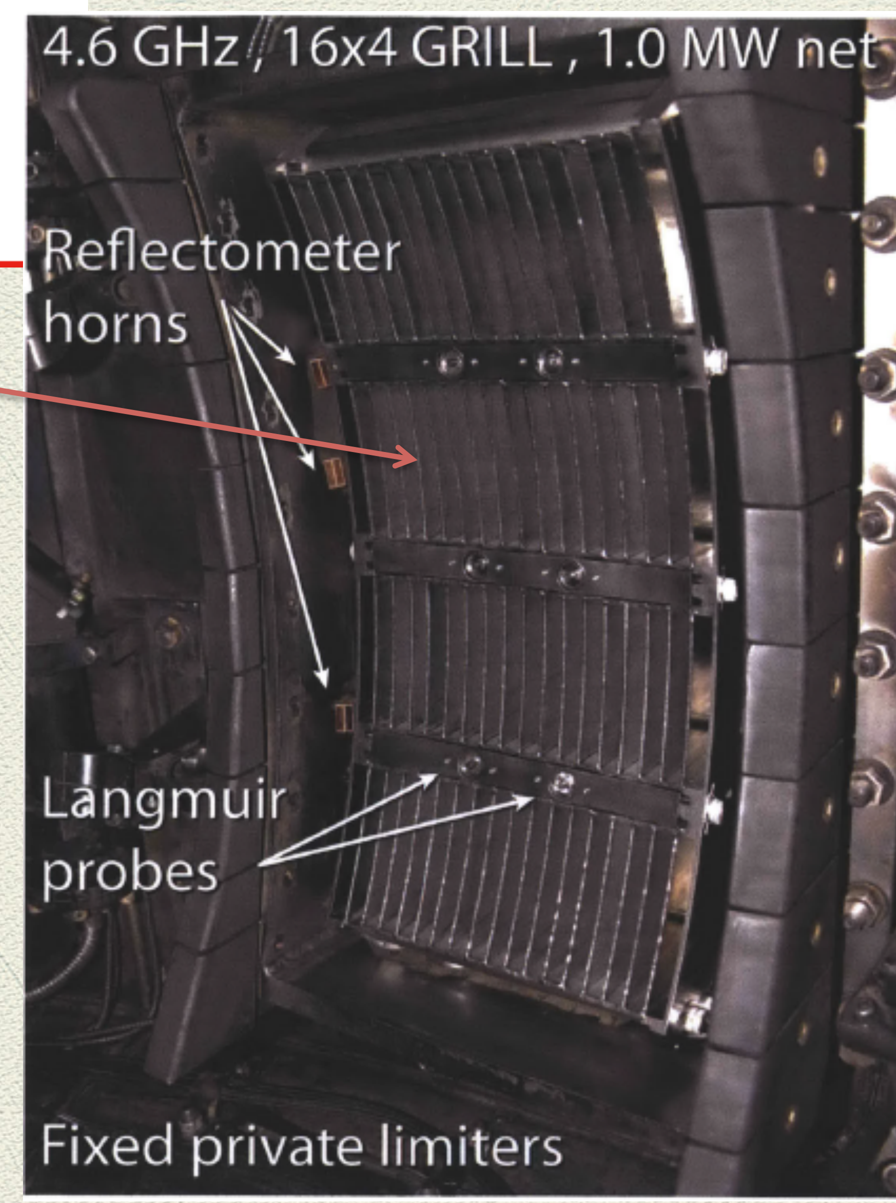



Full-wave calculation of the electric field distribution inside the new Flexible Plasma Trap at INFN-LNS

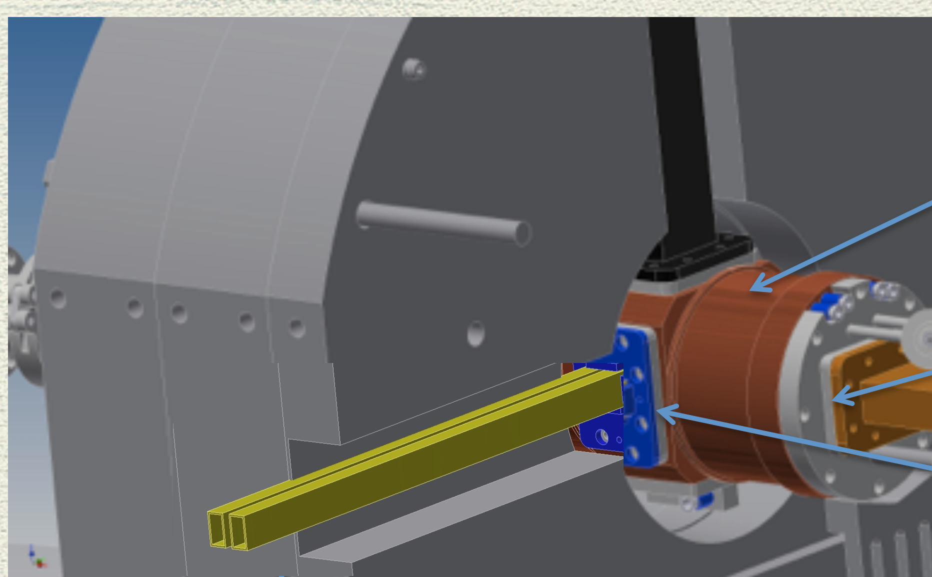


# "Microwave-absorption-oriented" design




**16 X 4 waveguides**



**Plasma chamber**

**Plasma heating @ 7 GHz**

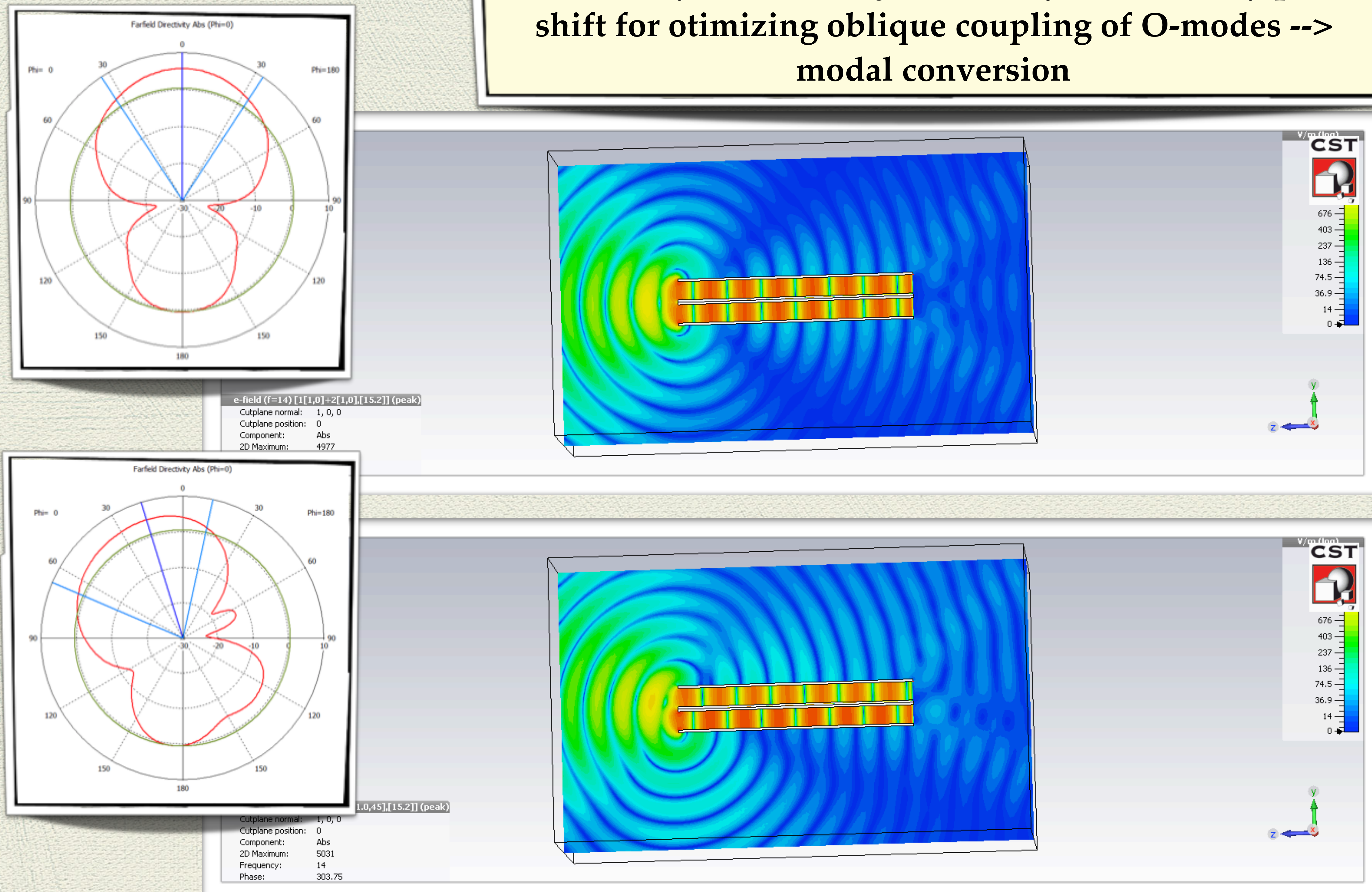
**Vacuum Break window**

***Courtesy of S. Passarello***

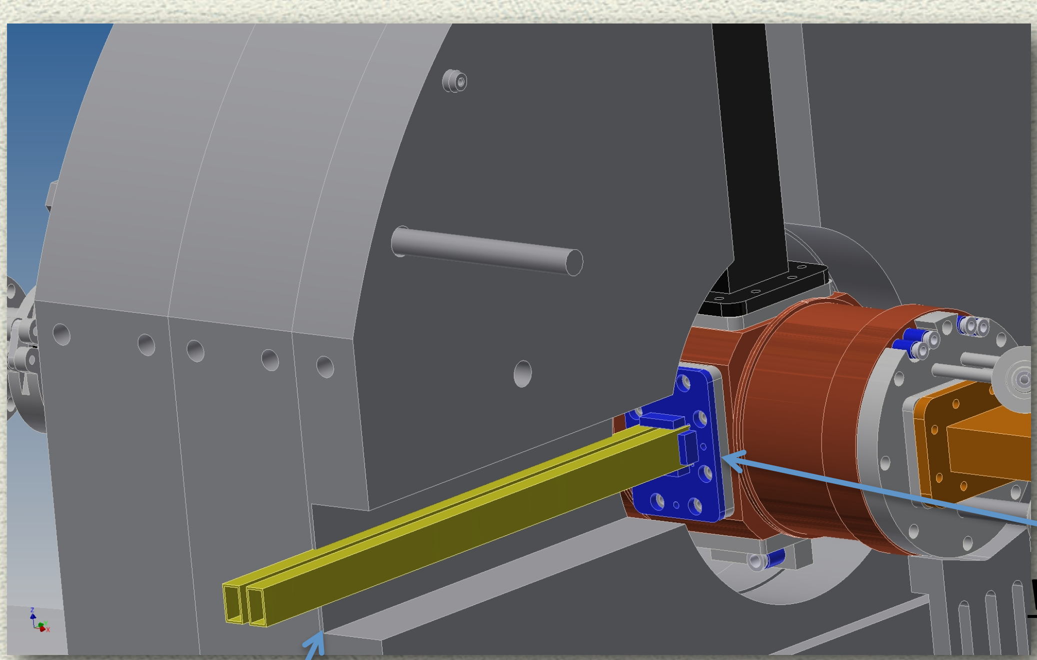
**ARRAY of two waveguides as Alternative plasma heating @ 14 GHz**

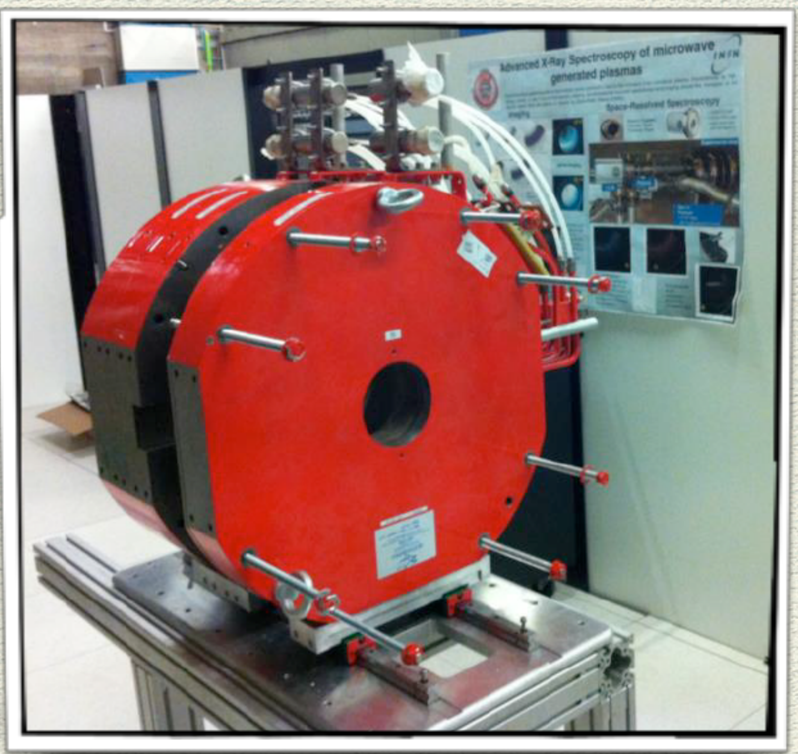
# "Microwave-absorption-oriented" design

**Launcher by "two-waveguides-array": lobe tilt by phase shift for otimizing oblique coupling of O-modes --> modal conversion**



# Mechanical Implementation at LNS





***Vacuum Break window***

*Courtesy of S. Passarello*

***ARRAY of two waveguides***

**A new setup developed at LNS for fundamental studies: RF launcher construction is ongoing**