PHYSICS AND TECHNOLOGY OF COMPACT PLASMA TRAPS

David Mascali on behalf of INFN-LNS R&D on Ion Sources and Plasma Physics Group and for the PANDORA collaboration

International Conference on Cyclotrons and their Applications (CYC2019) Cape Town

INFN
LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

Laboratory magnetoplasmas in compact traps: historically used for ion beams

High-Resolution X-ray Spectroscopy (Space and Time-Resolved)

RF probes

Advanced Sensors R&D

Fundamental plasma investigation

Ultra Compact Proton Source & negative noble-gas ions injector

Optical Emission Spectroscopy

RF Interferometry

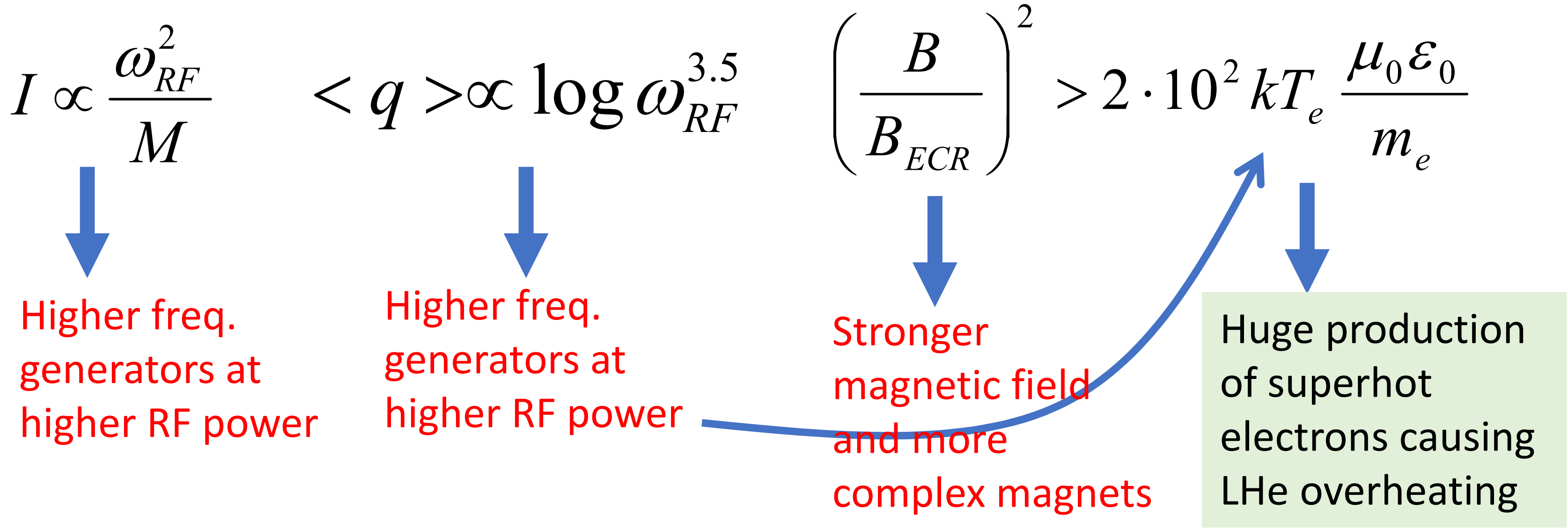
Ion Beams Production

R&D on plasma traps for:

- **Broadening Ion Beam availability**
- **Increasing beam current and charge states**
- **Figuring out new «LIFES» for ECR traps**

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

QUESTION 1: is the path to new generation ECRIS based on scaling laws only? Let’s try to answer…



Scaling laws:

$I \propto \frac{\omega_{RF}^{2}}{M}$

$< q > \propto \log \omega_{RF}^{3.5}$

$\left(\frac{B}{B_{ECR}}\right)^{2} > 2 \cdot 10^{2} kT_{e} \frac{\mu_{0}\varepsilon_{0}}{m_{e}}$

Issues:

Higher freq. generators at higher RF power

Higher freq. generators at higher RF power

Stronger magnetic field and more complex magnets

Huge production of superhot electrons causing LHe overheating

- **MAYBE WE CAN LOOK AT “SIDE” SOLUTIONS?**
  - New designs of magnetic field
  - Exotic solutions for RF coupling (different shapes of plasma chamber?!)
  - Different coupling of RF power (multiple-frequency heating by innovative solutions)
  - A lot of diagnostics and modelling are needed

QUESTION 2: How can a better knowledge of Plasma Physics (via Diagnostics and Modelling) help R&D on Ion Sources?

More stable Beams: role of turbulence

- Study of transient phenomena such as **kinetic instability**
- **Time-resolved diagnostics** are needed
- **X-ray and RF burst measurements** simultaneously to ion beam properties

More knowledge about B-field role

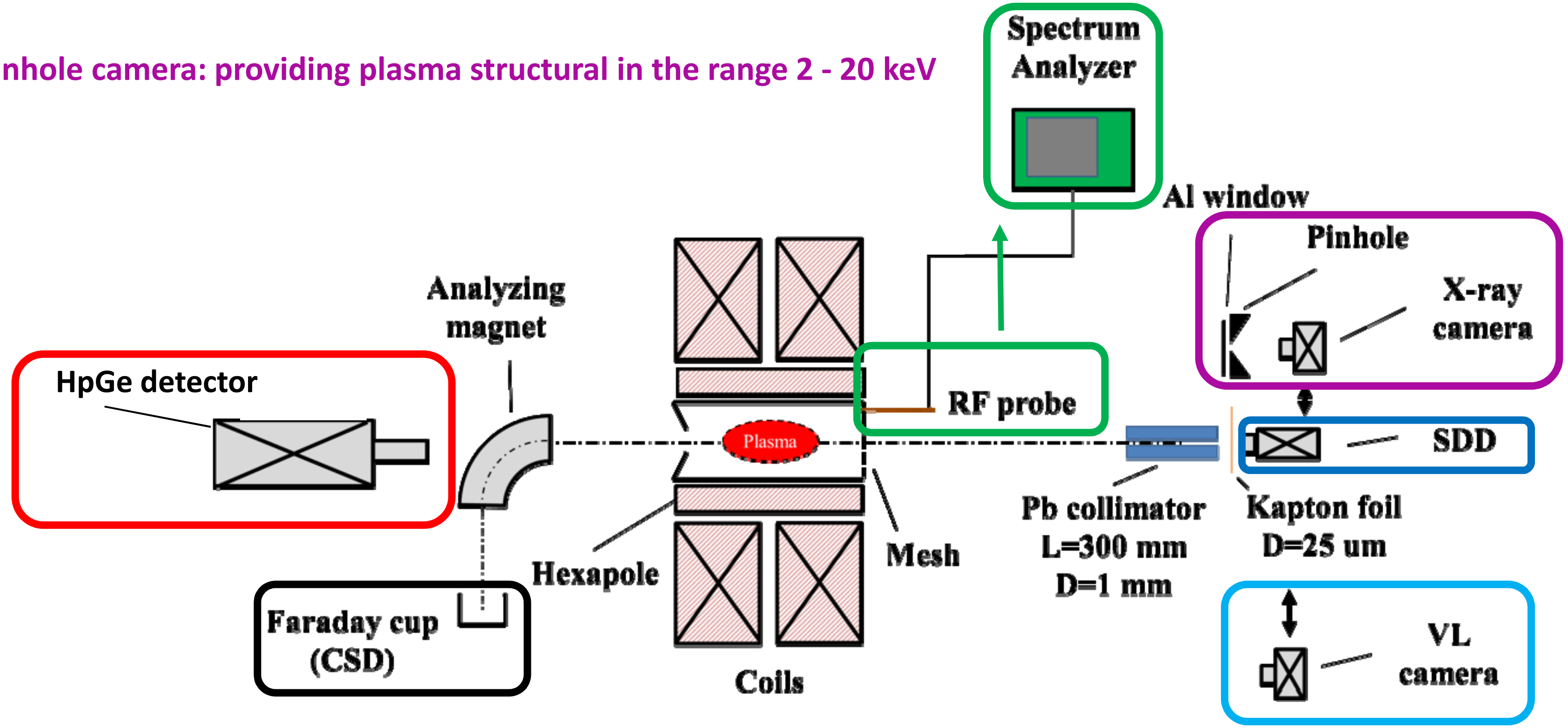
- Study of **axial vs. radial B-field** components roles
- **Explain fundamentals of scaling laws**
- **Design more reliable ECRIS** with a proper magnetic trap for **more stable beams**

Better RF Coupling and launching

- **Direct, space-resolved inspection of the plasma** to find where RF power is deposited
- **Explain fundamentals of scaling laws**
- **Design more reliable ECRIS** with a proper magnetic trap for **more stable beams**

PROBING ECR PLASMAS: a multi-diagnostics setup for simultaneous measurements of plasma properties in space-time resolved way

- Mass spectrometry: evaluation of CSD
- SDD: probing volumetric soft X-radiation in the 2 – 20 keV domain
- HPGe: providing time integrated X-ray spectra in the 30 - 300 keV domain
- VL camera: probing volumetric optical radiation in the 1 – 12 eV domain
- Pinhole camera: providin
- Pinhole camera: providing plasma structural in the range 2 - 20 keV
- RF probe + Spectrum analyzer: plasma radio-emission analysis



PROBING ECR PLASMAS: a multi-diagnostics setup for simultaneous measurements of plasma properties in space-time resolved way

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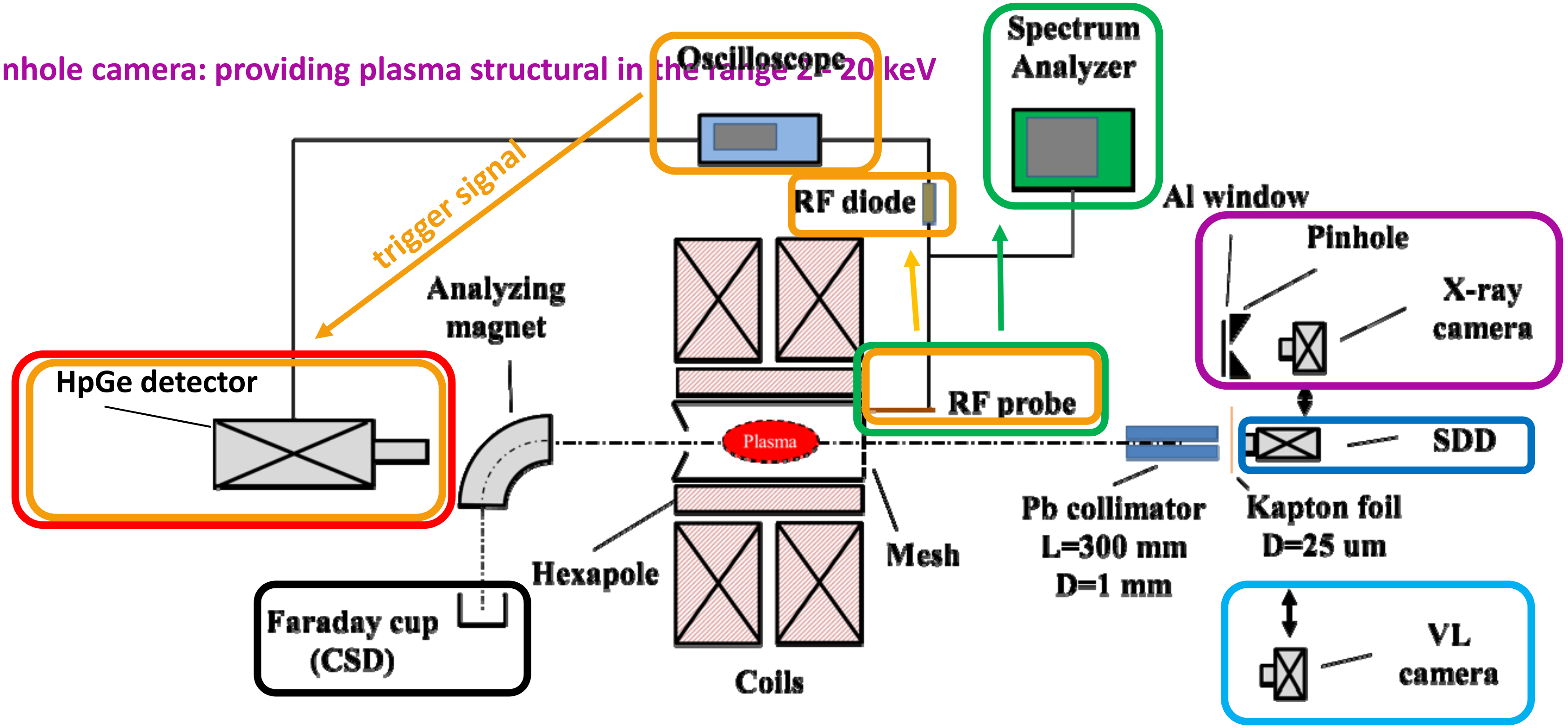
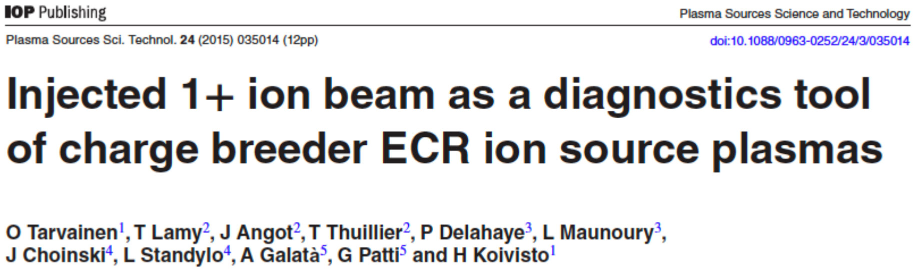
- Mass spectrometry: evaluation of CSD
- SDD: probing volumetric soft X-radiation in the 2 – 20 keV domain
- HPGe: providing time integrated X-ray spectra in the 30 - 300 keV domain
- VL camera: probing volumetric optical radiation in the 1 – 12 eV domain
- Pinhole camera: providing plasma structural in the range 2 - 20 keV

- RF probe + Spectrum analyzer: plasma radio-emission analysis
- Time resolved X-ray spectra with 6 ms resolution if triggered by RF probe (useful for instabilities)

- Pinhole camera: providing plasma structural in the range 2 - 20 keV



WORLDWIDE EFFORTS: An Increasing number of papers reporting on plasma diagnostics and related measurements of plasma parameters



IOP Publishing Plasma Sources Science and Technology

Plasma Sources Sci. Technol. **24** (2015) 035014 (12pp) doi:10.1088/0963-0252/24/3/035014

Injected 1+ ion beam as a diagnostics tool of charge breeder ECR ion source plasmas

O Tarvainen[1], T Lamy[2], J Angot[2], T Thuillier[2], P Delahaye[3], L Maunoury[3],
J Choinski[4], L Standylo[4], A Galatà[5], G Patti[5] and H Koivisto[1]

Splitting axial from radial field, separate measurements show the role played by the two field components in a B-min trap

REVIEW OF SCIENTIFIC INSTRUMENTS **89**, 125112 (2018)

Plasma characterization of a microwave discharge ion source with mirror magnetic field configuration

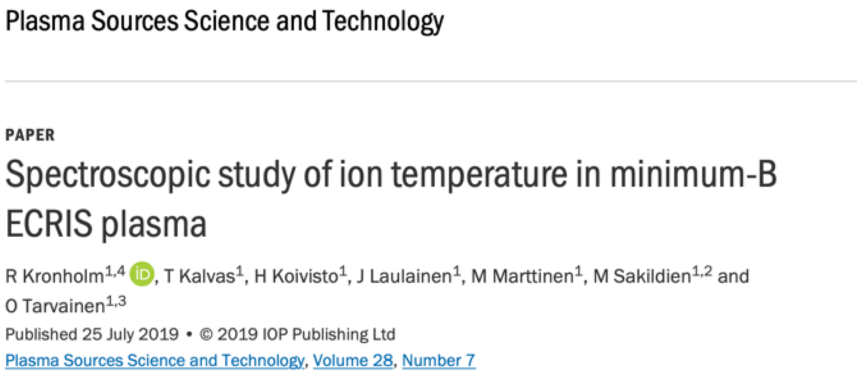
C. Mallick,[1,2,a)] M. Bandyopadhyay,[1,2,a)] and R. Kumar[1,2]
[1]*Institute for Plasma Research (IPR), Gandhinagar, Gujarat 382 428, India*
[2]*Homi Bhabha National Institute (HBNI), Mumbai, Maharastra, India*

Free . Published Online: 21 September 2018

First results on radial and azimuthal dependence of plasma parameters in a hexapole-trapped ECR discharge

AIP Conference Proceedings **2011**, 020010 (2018); https://doi.org/10.1063/1.5053252

R. Rácz[a)], S. Biri, Z. Perduk, *and* J. Pálinkás



Plasma Sources Science and Technology

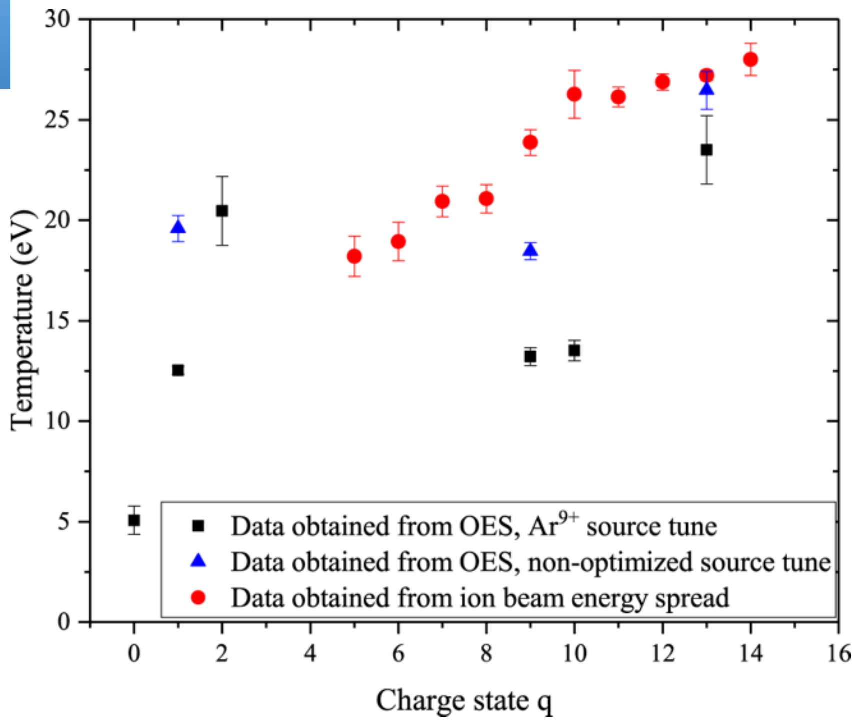
PAPER

Spectroscopic study of ion temperature in minimum-B ECRIS plasma

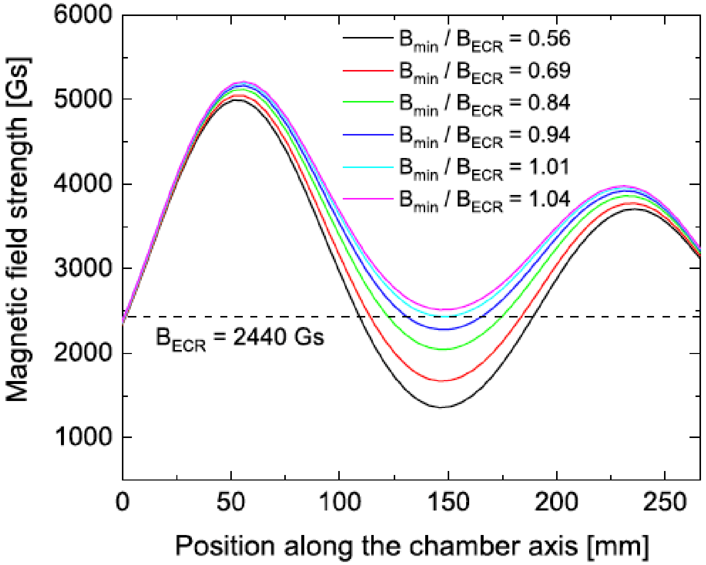
R Kronholm[1,4], T Kalvas[1], H Koivisto[1], J Laulainen[1], M Marttinen[1], M Sakildien[1,2] and O Tarvainen[1,3]

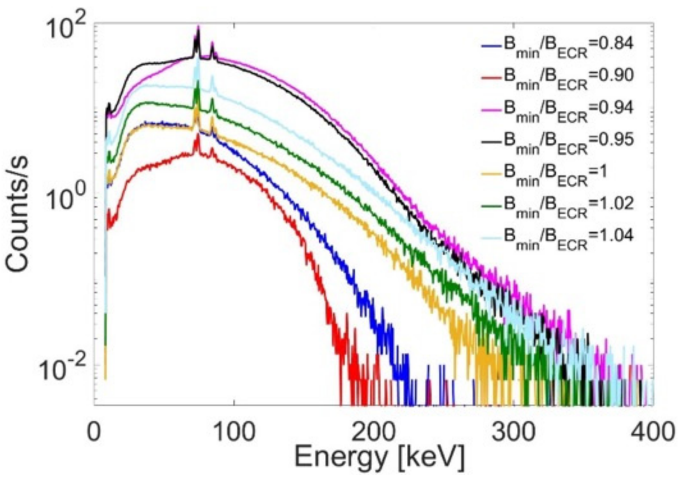
Published 25 July 2019 • © 2019 IOP Publishing Ltd

Plasma Sources Science and Technology, Volume 28, Number 7



IMPACT OF MAGNETIC FIELD PROFILE: impact on X-ray production of the variation of the longitudinal trap (independently from the radial one)

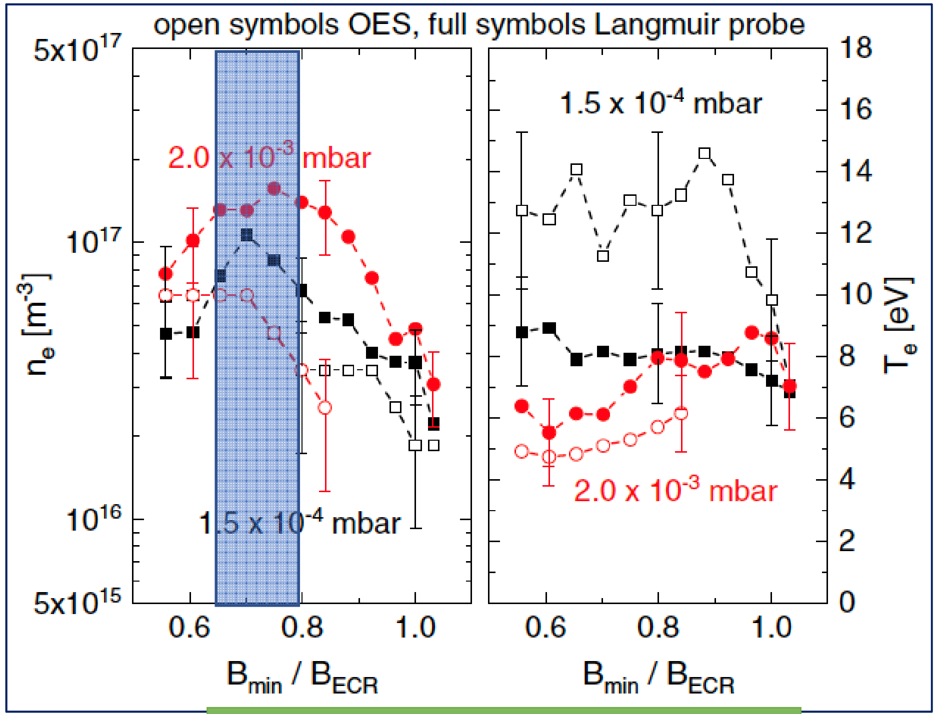




Impact of the ratio $\frac{B_{min}}{B_{ECR}}$

on the X-ray spectra and plasma density:

BASIS of SCALING LAWS

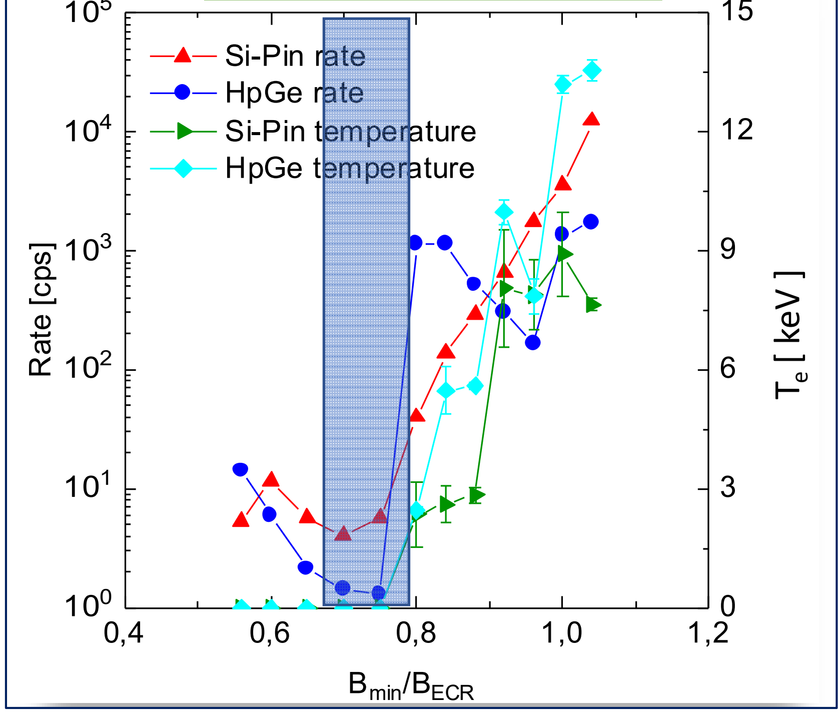


Density of cold electrons

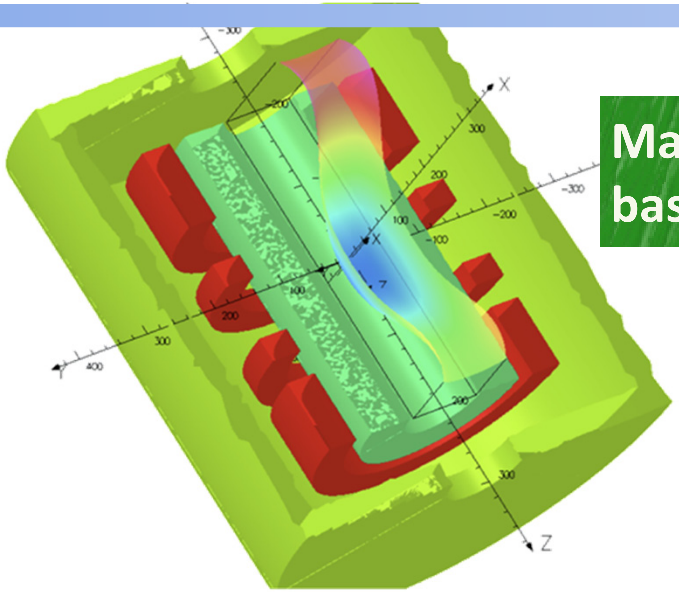
Both Si-Pin and HpGe show a strong increase of electron temperature and X-ray emission rate when

$B_{min}/B_{ECR} > 0.76$

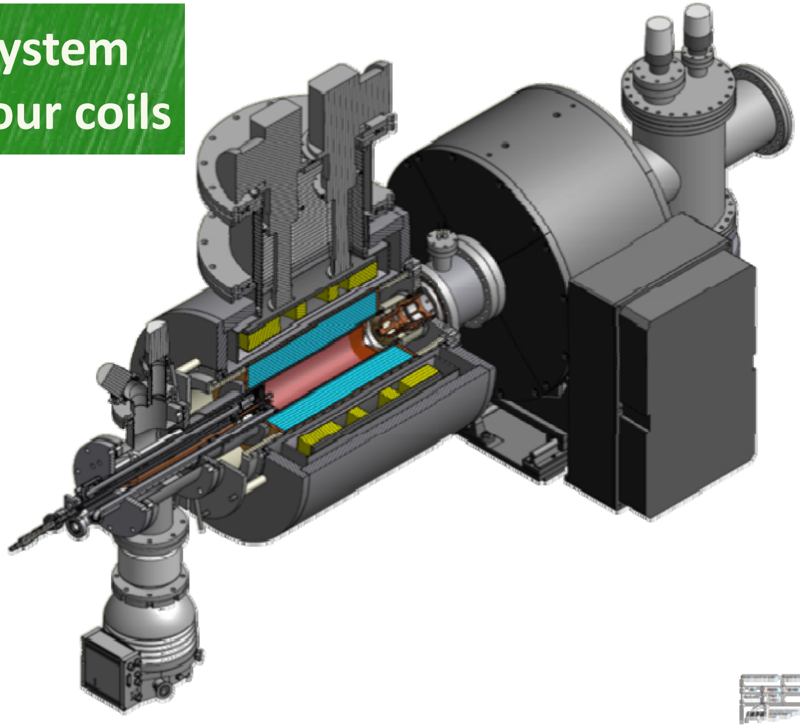
High energy X-rays

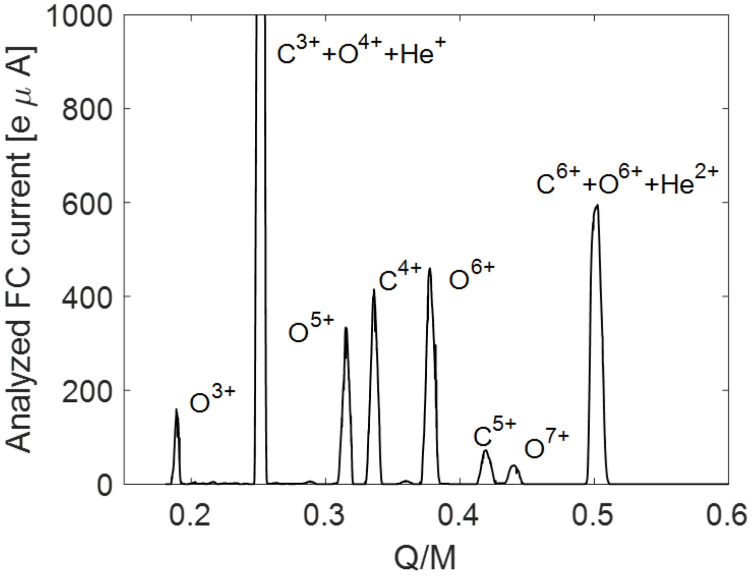


The AISHa Source: an hybrid (4 SC coils + PM hexapole) producing intense ion beams for hadrontherapy --> *Now Commissioning...*

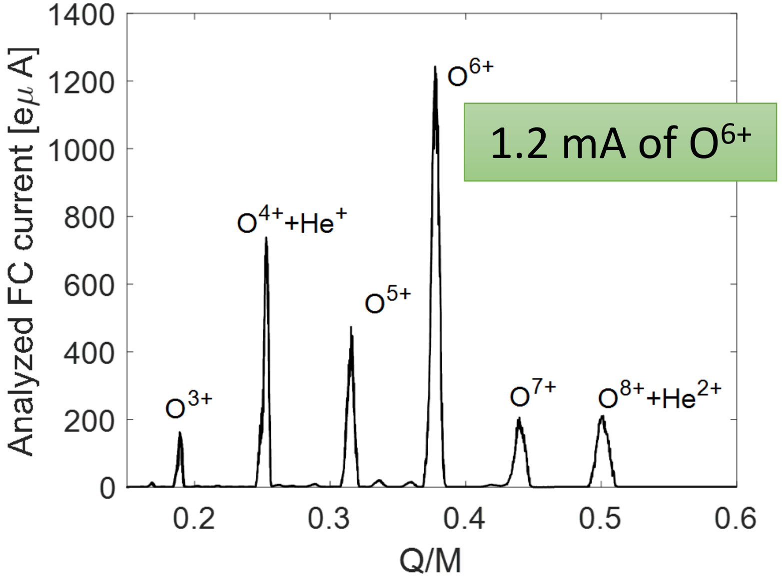


Magnetic system based on four coils



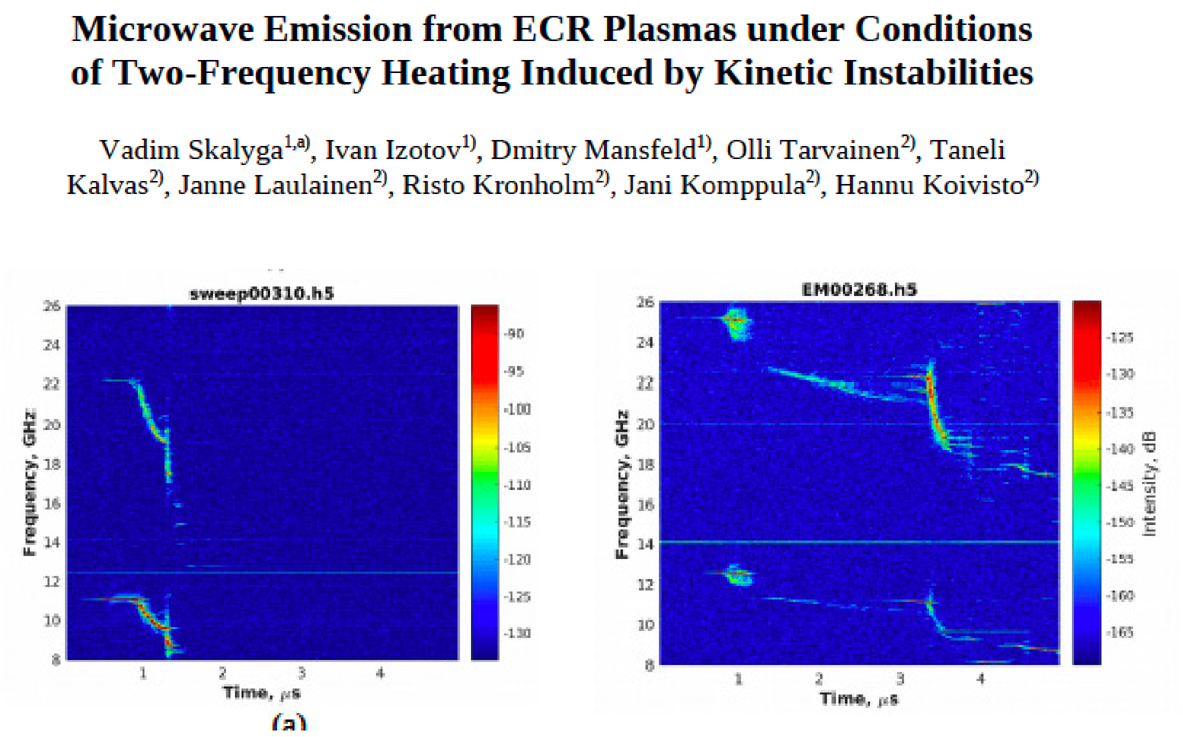


- ✓ ***high stability***
- ✓ ***high reproducibility***
- ✓ ***low maintenance time***
- ✓ ***Compact setup***
- ✓ ***highly charged ion beams***



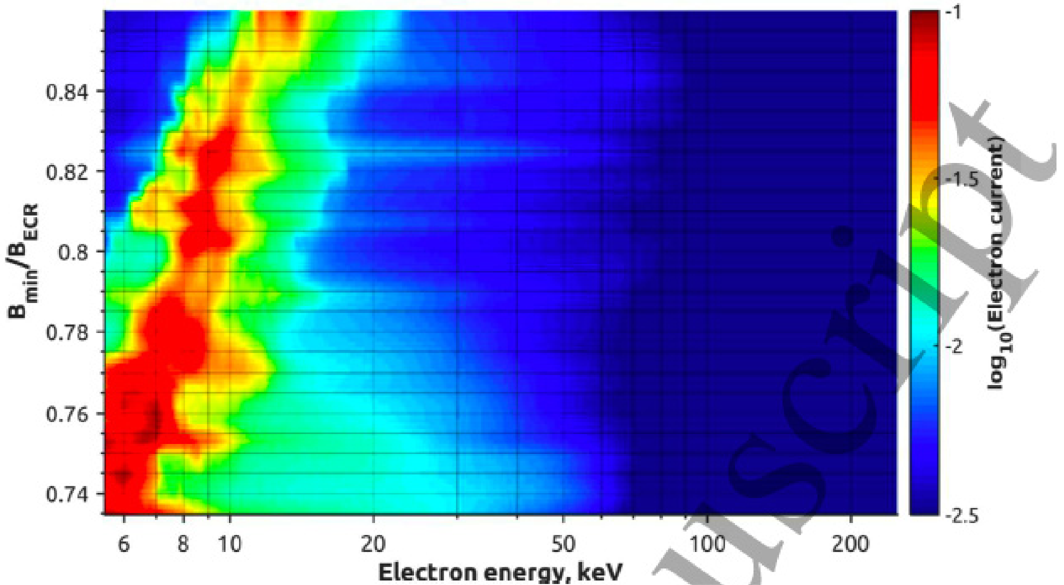
1.2 mA of O^{6+}

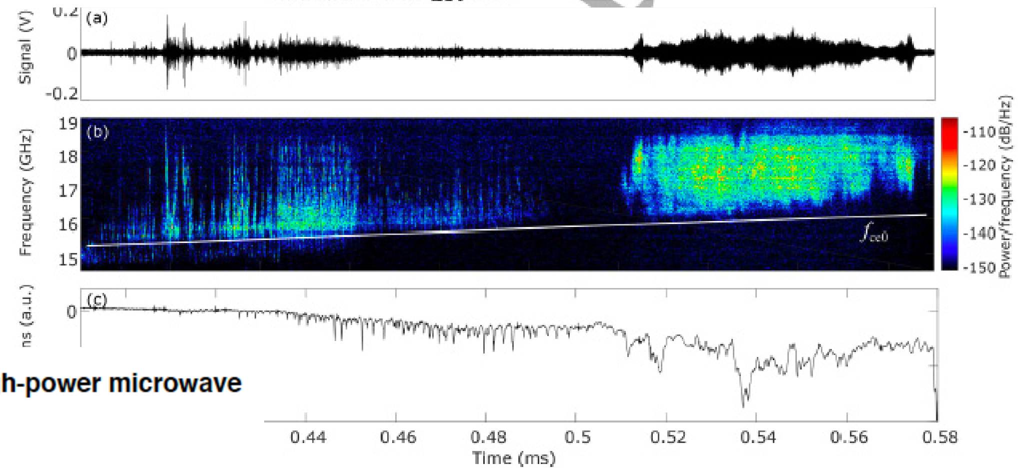
INTERPLAY BETWEEN MAGNETIC FIELD AND RF POWER: few groups are working since 2015 on kinetic turbulences overall ECRIS stability



Microwave Emission from ECR Plasmas under Conditions of Two-Frequency Heating Induced by Kinetic Instabilities

Vadim Skalyga[1,a)], Ivan Izotov[1)], Dmitry Mansfeld[1)], Olli Tarvainen[2)], Taneli Kalvas[2)], Janne Laulainen[2)], Risto Kronholm[2)], Jani Komppula[2)], Hannu Koivisto[2)]





Measurement of the energy distribution of electrons escaping minimum-B ECR plasmas

Article in Plasma Sources Science and Technology · January 2018
DOI: 10.1088/1361-6595/aaac14

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);

INTERPLAY BETWEEN MAGNETIC FIELD AND RF POWER: few groups are working since 2015 on kinetic turbulences overall ECRIS stability

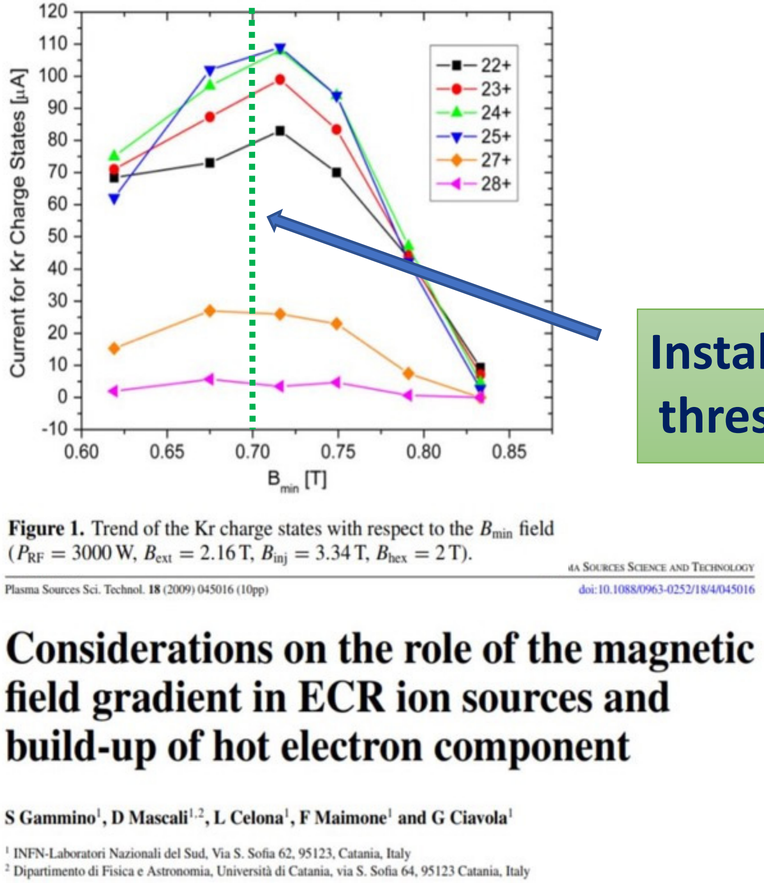


Figure 1. Trend of the Kr charge states with respect to the B_{min} field ($P_{RF} = 3000$ W, $B_{ext} = 2.16$ T, $B_{inj} = 3.34$ T, $B_{hex} = 2$ T).

MA SOURCES SCIENCE AND TECHNOLOGY

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

doi:10.1088/0963-0252/18/4/045016

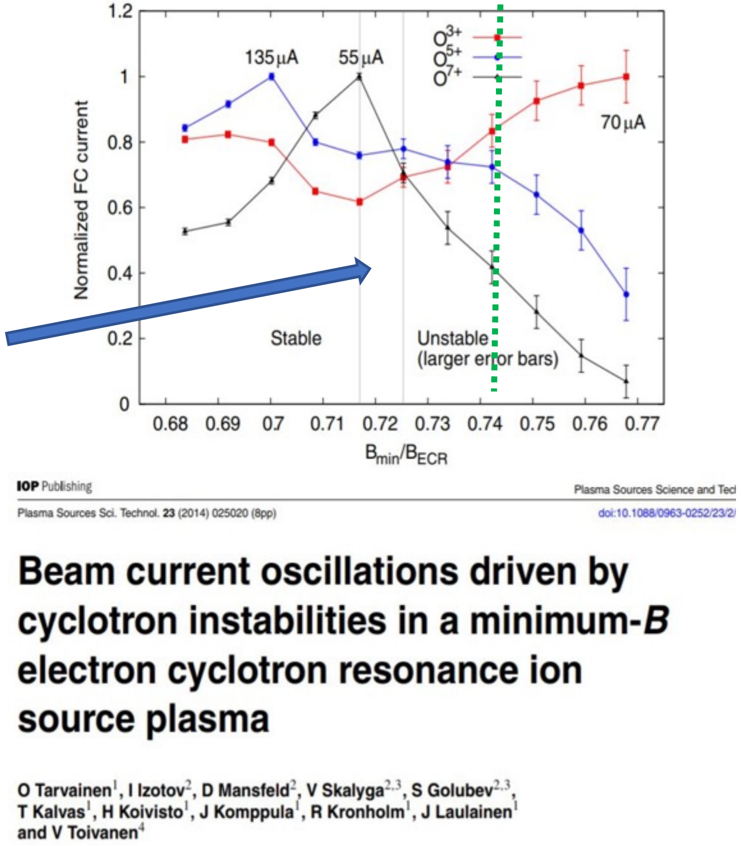
Considerations on the role of the magnetic field gradient in ECR ion sources and build-up of hot electron component

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

[1] INFN-Laboratori Nazionali del Sud, Via S. Sofia 62, 95123, Catania, Italy

[2] Dipartimento di Fisica e Astronomia, Università di Catania, via S. Sofia 64, 95123 Catania, Italy

Instability threshold



IOP Publishing

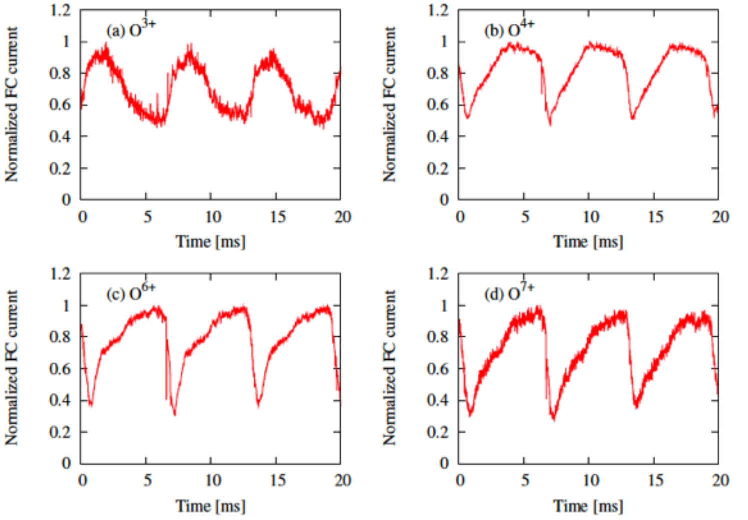
Plasma Sources Science and Tec

Plasma Sources Sci. Technol. **23** (2014) 025020 (8pp)

doi:10.1088/0963-0252/23/2/

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]



- *Beam oscillations occur in a ms timescale.*
- *Same observation in charge breeders, triggered by beam injection*

Turbulent regimes of plasmas produce **intense X-ray/RF bursts**, causing in ECR ion sources **performance deterioration** in term of:

- ***Decrease of high charge state production***
- ***Beam ripple***

TIME RES. MEASUREMENTS @ INFN-LNS: Simultaneous spectral analysis in RF and X-ray ranges by 80 Gs/s Scope and HpGe detectors

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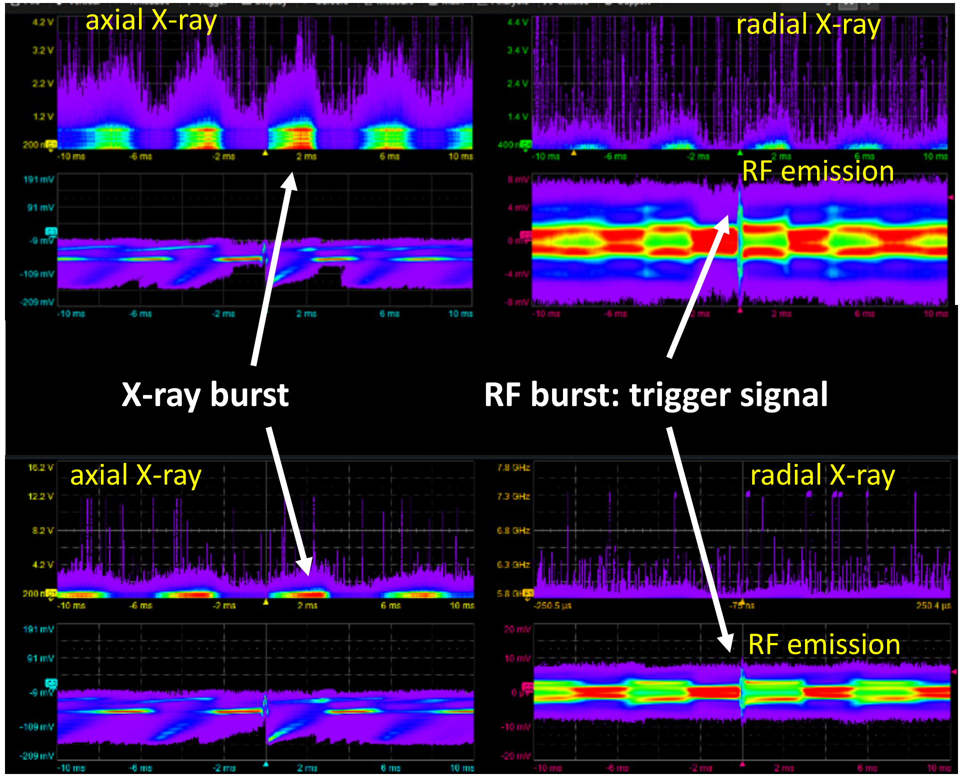
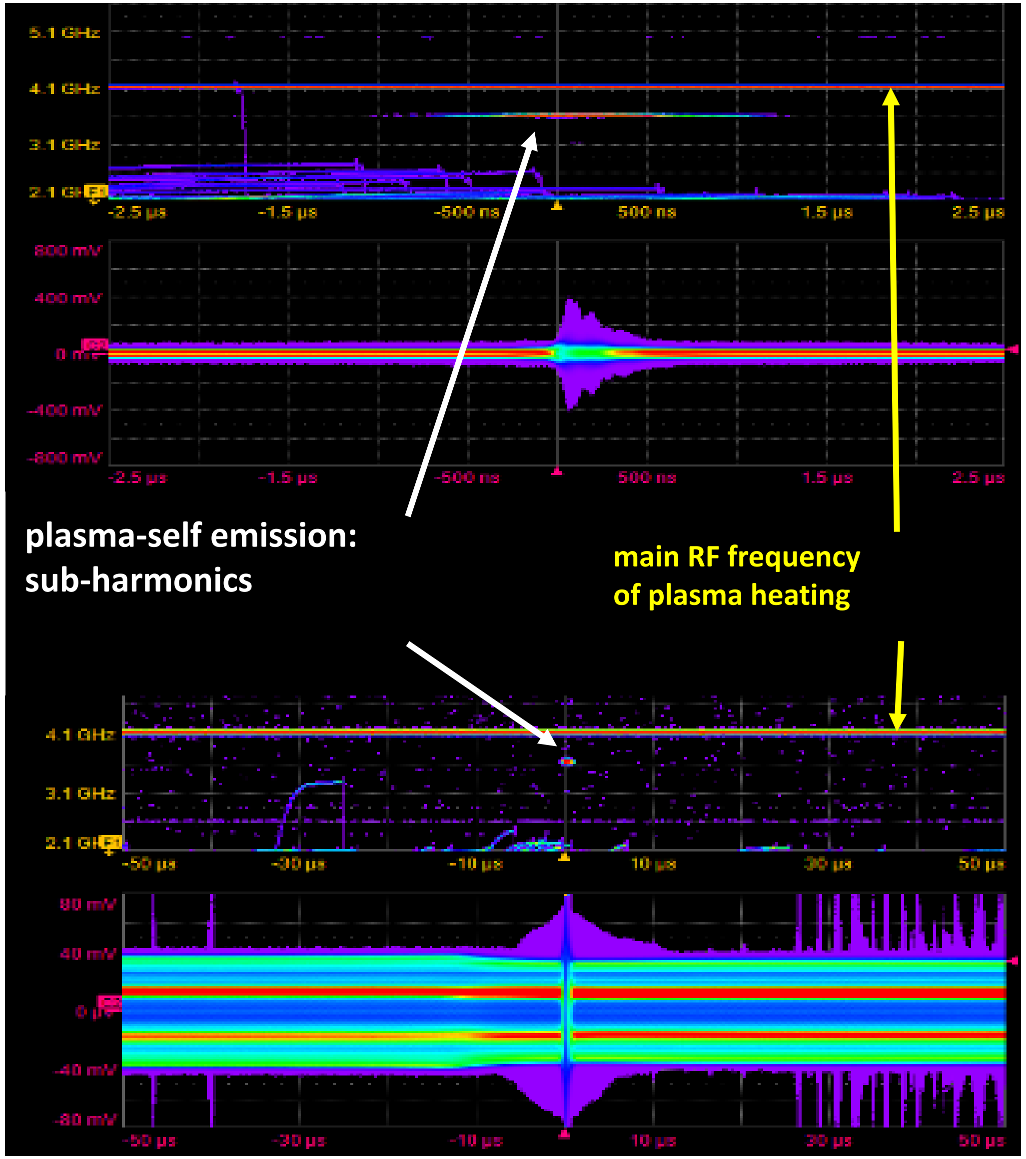
- **RF burst** → trigger signal
  - axial and radial X-ray measurements → **X-ray burst**
  - Spectrogram → **microwave plasma-self emission**

→ Instabilities depend from the axial magnetic field profile in term of:

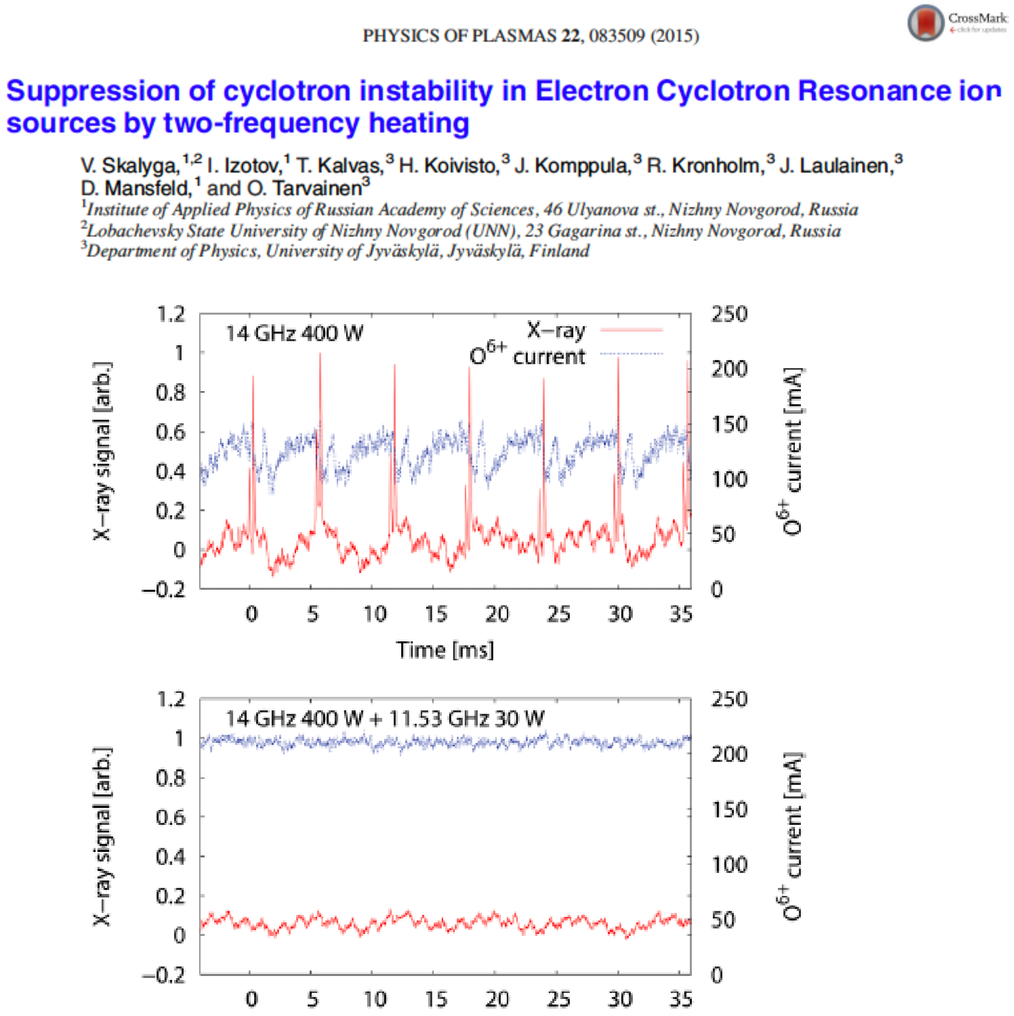
- Time Duration of X-ray burst ~ msec
- Intensity of X-ray burst
- Time repetition of X-ray and RF bursts ~ some msec





QUESTION 3: Is there any way to damp instabilities?

Answer: YES!!



PHYSICS OF PLASMAS **22**, 083509 (2015)

CrossMark

Suppression of cyclotron instability in Electron Cyclotron Resonance ion sources by two-frequency heating

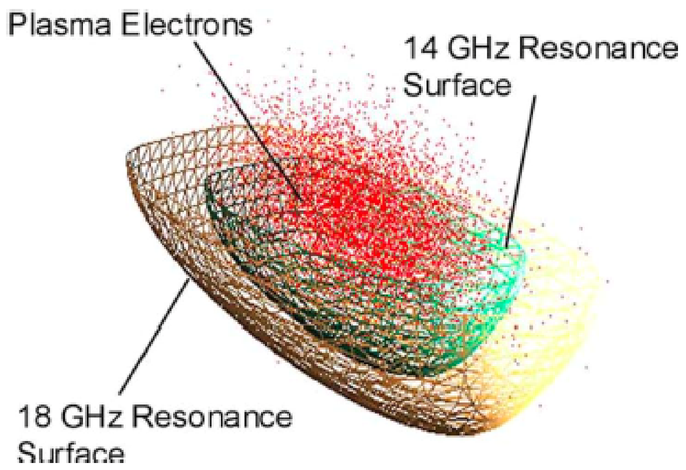
V. Skalyga,[1,2] I. Izotov,[1] T. Kalvas,[3] H. Koivisto,[3] J. Komppula,[3] R. Kronholm,[3] J. Laulainen,[3] D. Mansfeld,[1] and O. Tarvainen[3]

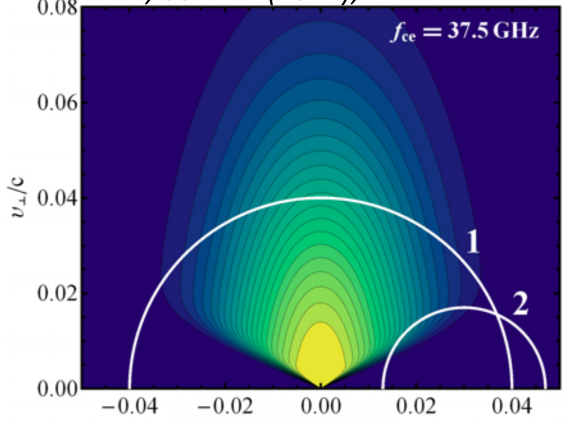
[1]*Institute of Applied Physics of Russian Academy of Sciences, 46 Ulyanova st., Nizhny Novgorod, Russia*
[2]*Lobachevsky State University of Nizhny Novgorod (UNN), 23 Gagarina st., Nizhny Novgorod, Russia*
[3]*Department of Physics, University of Jyväskylä, Jyväskylä, Finland*

MULTIPLE FREQUENCY HEATING IS A WAY!!

Two frequency heating (far frequencies)

A.G. Shalashov et al. Physics of Plasmas 24, 032111 (2017);





A Novel Approach: Two Close frequency heating (near frequencies)

$$\frac{\delta\omega}{\omega} \leqslant \frac{Y}{M^{\frac{5}{12}}} \longrightarrow M = \frac{\pi R_1^{\frac{1}{2}} \omega_1 L \rho}{2\left(Ai(0)\frac{4\pi e}{m}\right)^{\frac{3}{5}}\left(\mathcal{E}_1^2 + \mathcal{E}_2^2\frac{B_1}{B_2}\right)^{\frac{3}{10}}\left(\frac{2B_1}{(\mathrm{d}B\,/\,\mathrm{d}z)_1\omega_1^{\frac{1}{2}}}\right)^{\frac{2}{5}}}$$

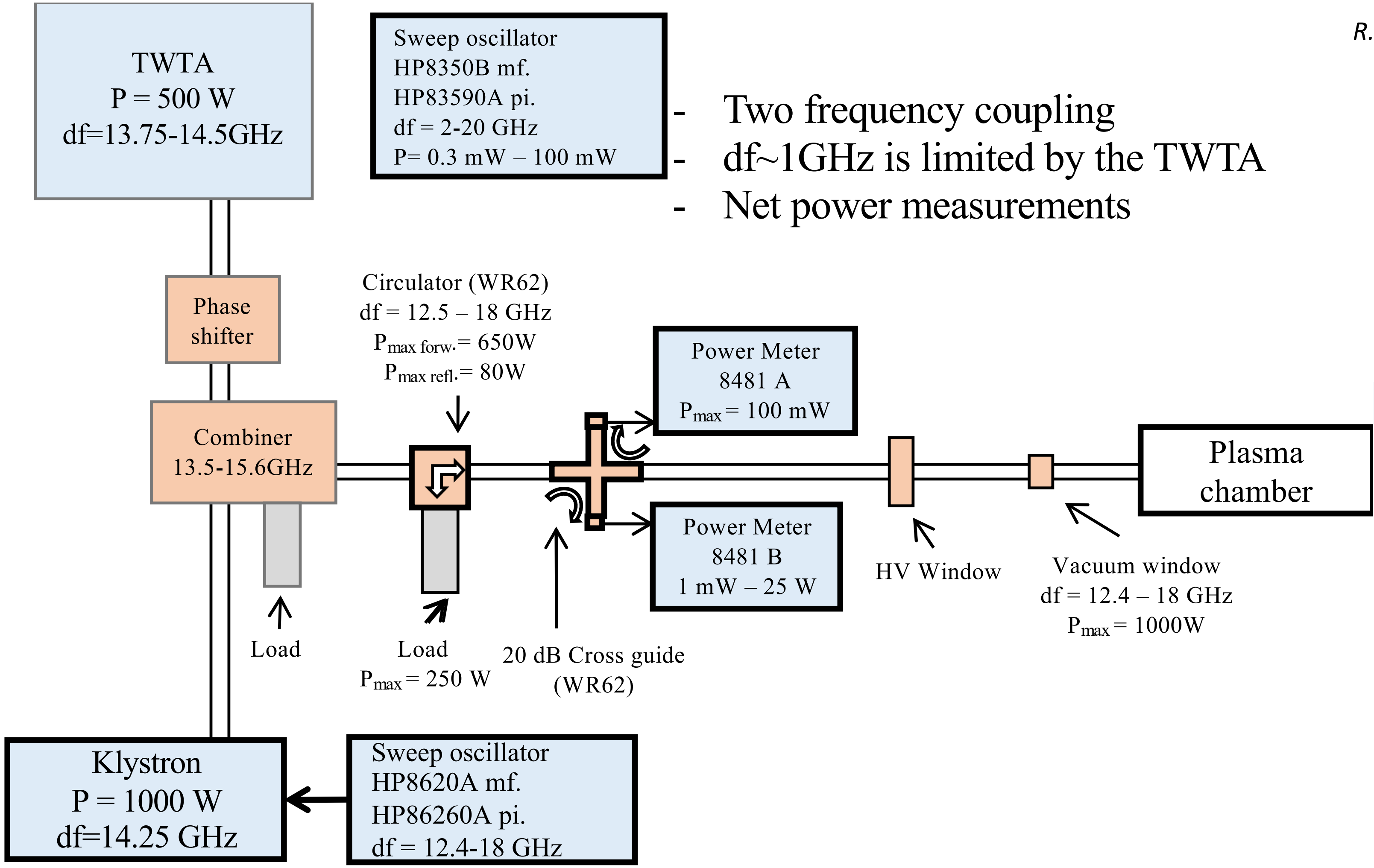
$$\Downarrow$$

$$\boxed{\pm 0.45\ \text{GHz}}$$

Electric field amplitude
of the two waves

Under this assumption, Wave-to-plasma interaction improves, leading to a stronger and more efficient heating, partially restoring isotropy in velocity distribution into the phase space

First experiment in 2018: Probing two-close-freq.-heating at ATOMKI-Hungarian Accademy of Sciences



TWTA
P = 500 W
df=13.75-14.5GHz

Sweep oscillator
HP8350B mf.
HP83590A pi.
df = 2-20 GHz
P= 0.3 mW – 100 mW

- Two frequency coupling
- df~1GHz is limited by the TWTA
- Net power measurements

Phase shifter

Combiner
13.5-15.6GHz

Circulator (WR62)
df = 12.5 – 18 GHz
$P_{max\ forw.}$= 650W
$P_{max\ refl.}$= 80W

Power Meter
8481 A
P_{max} = 100 mW

Power Meter
8481 B
1 mW – 25 W

Plasma chamber

Load

Load
P_{max} = 250 W

20 dB Cross guide
(WR62)

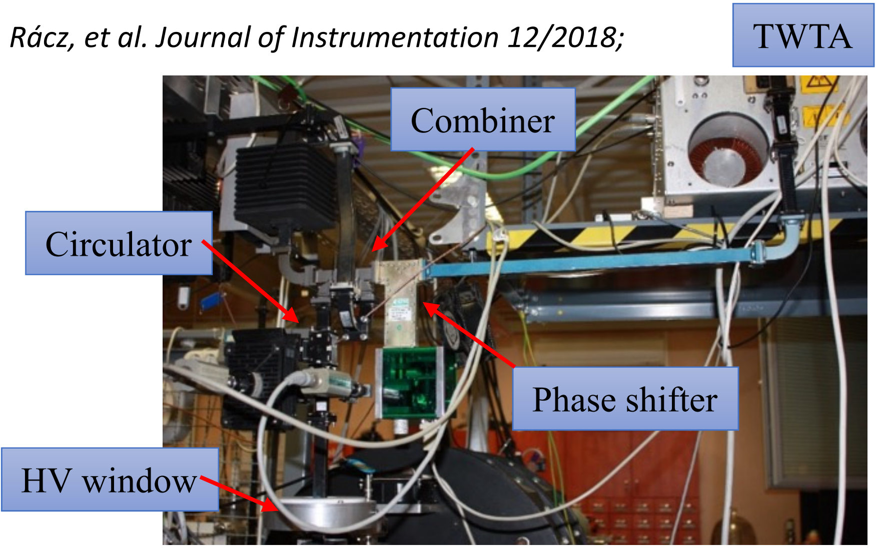
HV Window

Vacuum window
df = 12.4 – 18 GHz
P_{max} = 1000W

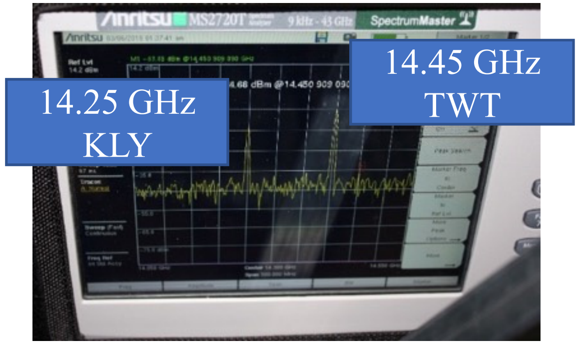
Klystron
P = 1000 W
df=14.25 GHz

Sweep oscillator
HP8620A mf.
HP86260A pi.
df = 12.4-18 GHz

R. Rácz, et al. Journal of Instrumentation 12/2018;

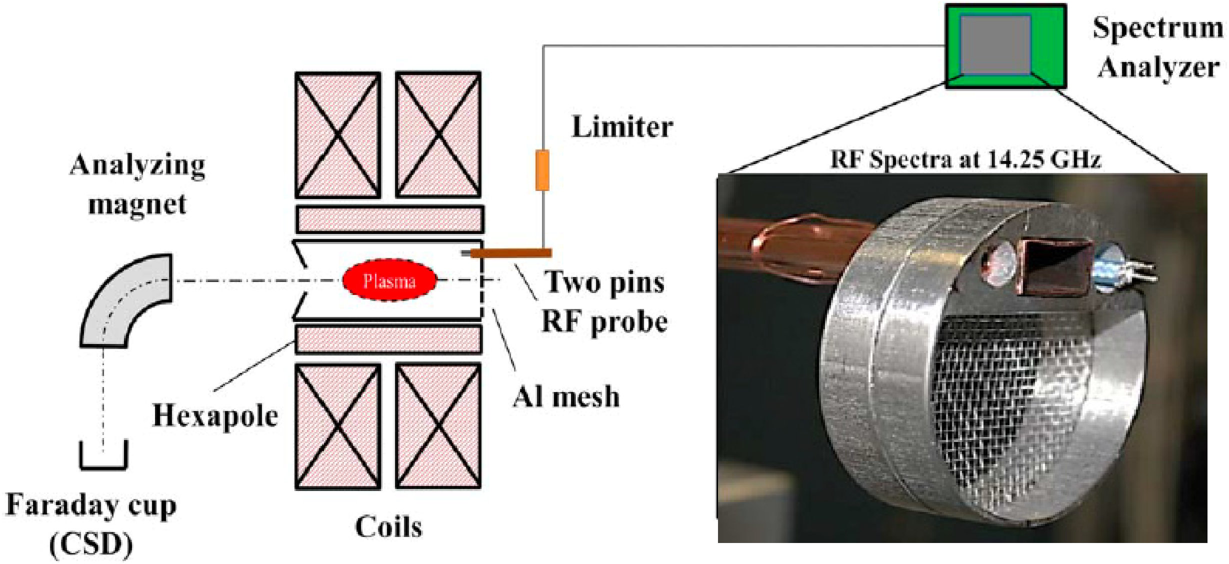


Direct frq. measurements
by Spectrum Analyzer

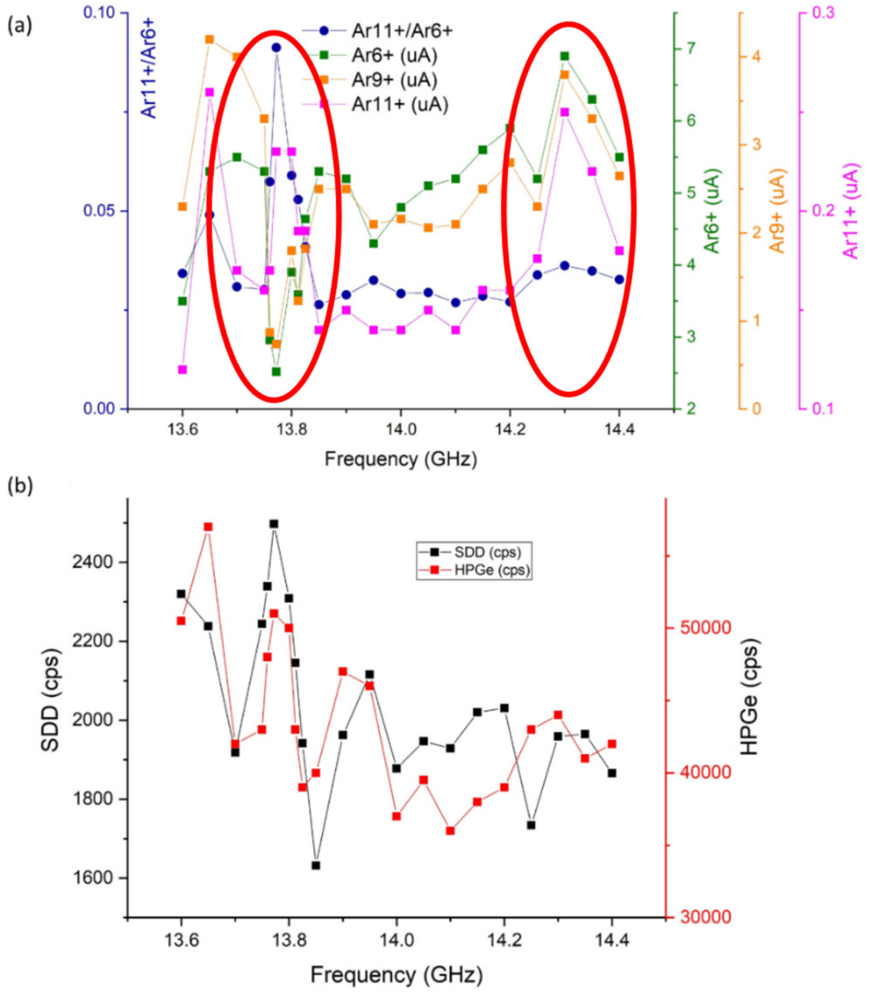


Microwave coupling for 2CFH, allowing phase control

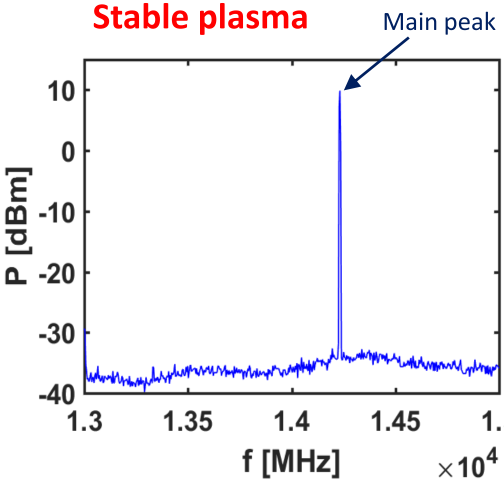
First experiment in 2018: how to measure the instability and the effect of 2CFH on the output beams currents



Two-pin probes have been designed and realized at INFN-LNS on purpose



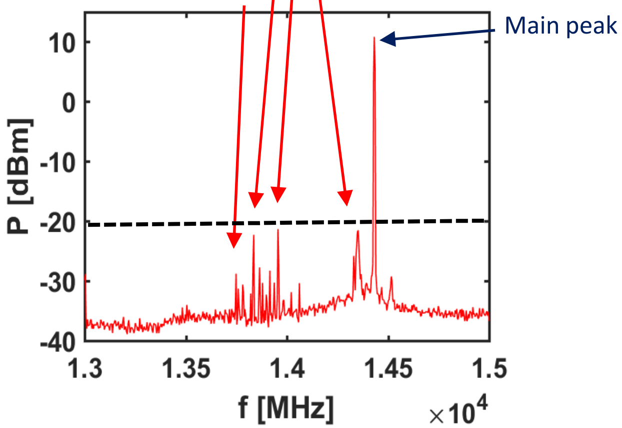
Stable plasma



Unstable plasma

→ high number of sub-harmonics

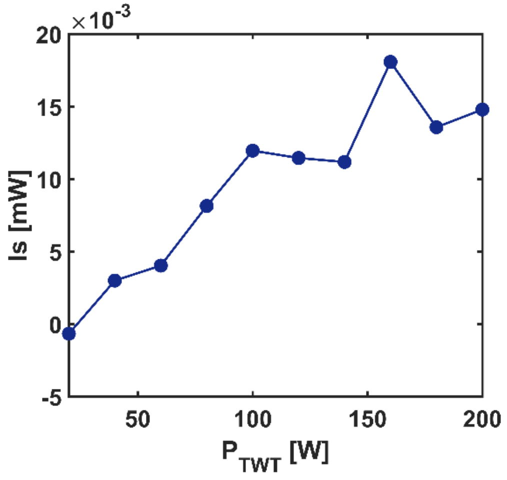
→ low power plasma-self emitted for each



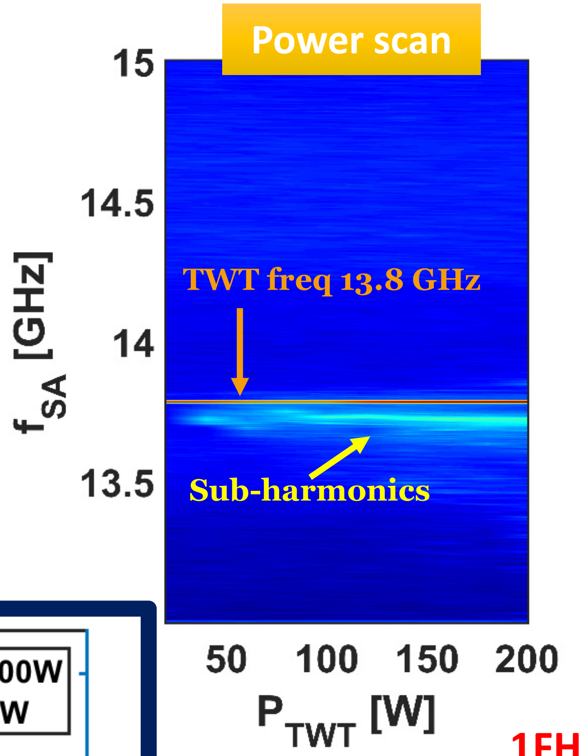
A quantitative parameter to evaluate if and how the plasma is unstable

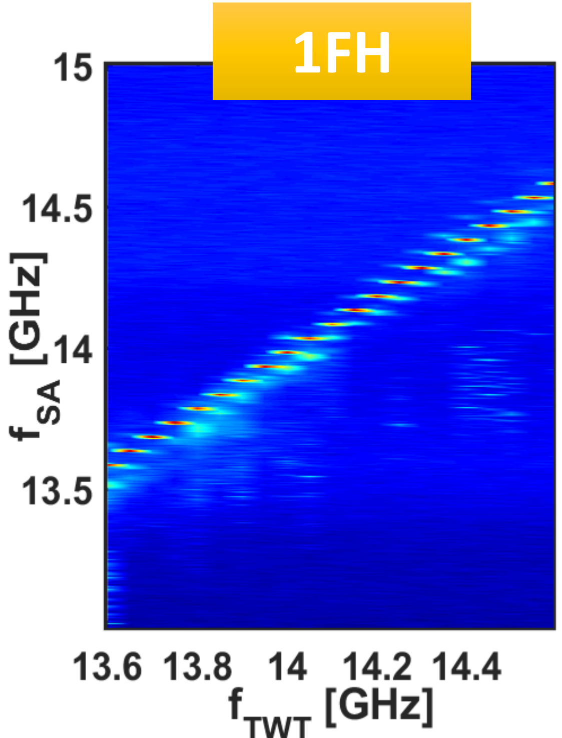
$$Is = \left(\int_{13GHz}^{15GHz} P(f)df - \int P(f)_{main\ peak}\, df\right)\cdot\left(1 + w(N_{peaks} - 1)\right)$$

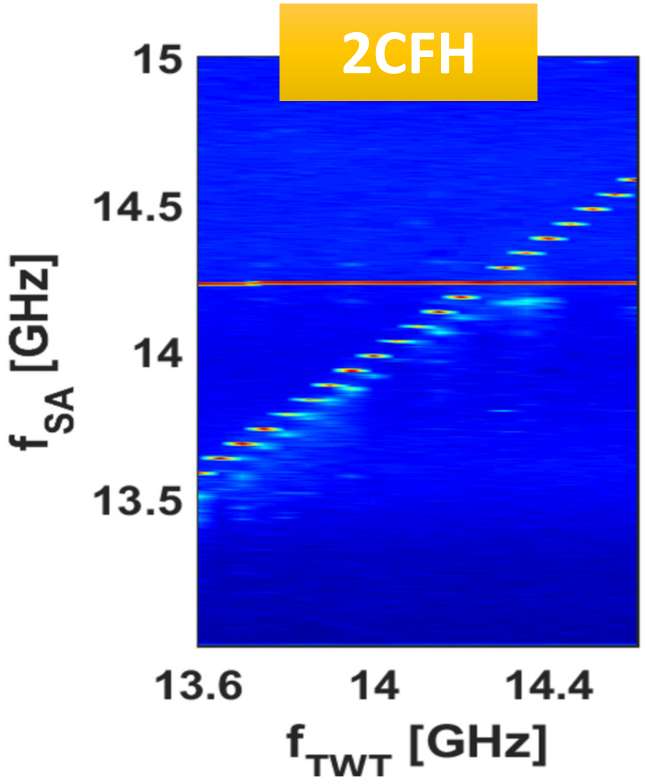
First experiment in 2018: measurement of instability level vs. RF power and in single vs. double frequency heating



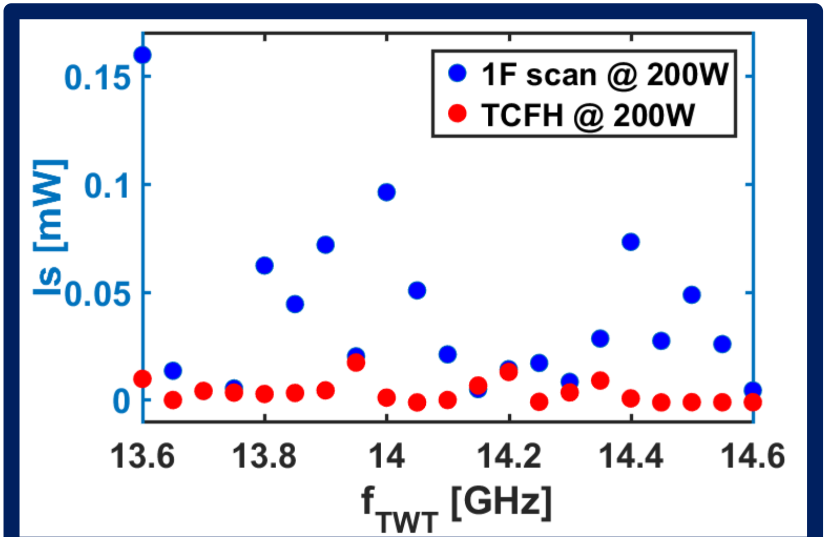
1FH: TWT power scan at **13.8 GHz**







1FH: Frequency scan by TWT;
13.6 GHz – 14.6 GHz, δf = 50 MHz, $P_{net} = 200W$

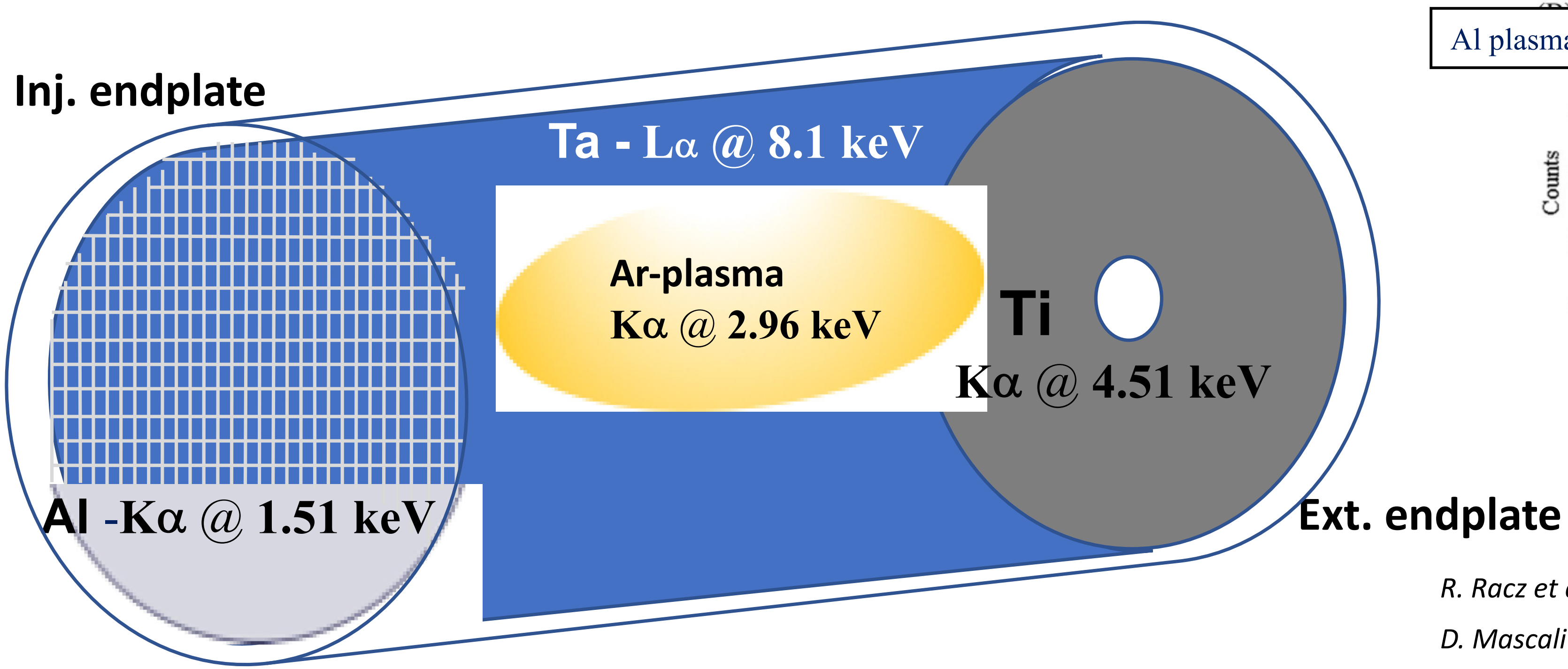


IS in 2CFH is one order of magnitude lower than IS in 1FH
Histograms demonstrate that Instability is damped by 2CFH
2CFH at 200W is much more stable than the single frequency at 120W (~ half power)

First experiment in 2018: a new plasma chamber setup for measuring X-rays coming from plasma and from plasma losses fluxes

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)



Inj. endplate

Ta - Lα @ 8.1 keV

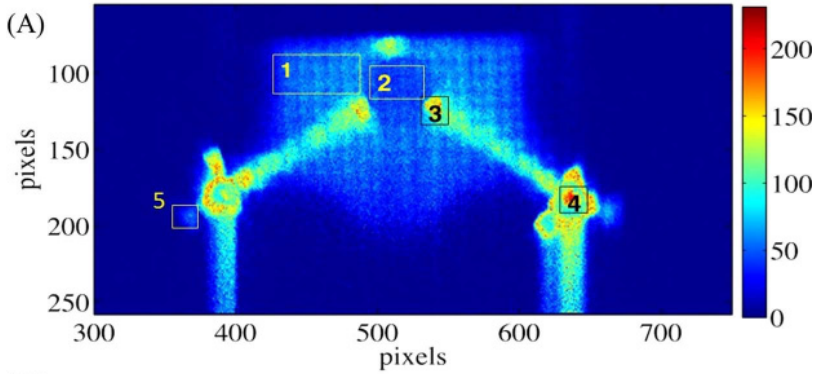
Ar-plasma
Kα @ 2.96 keV

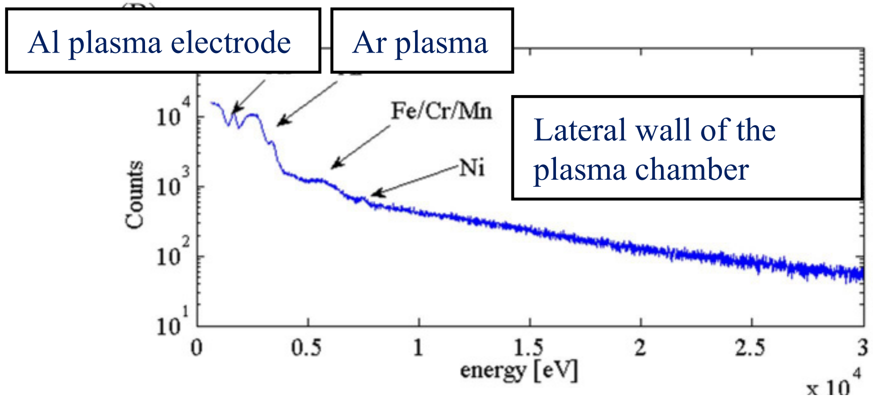
Ti
Kα @ 4.51 keV

Al -Kα @ 1.51 keV

Ext. endplate

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)*

First experiment in 2018: a new plasma chamber setup for measuring X-rays coming from plasma and from plasma losses fluxes

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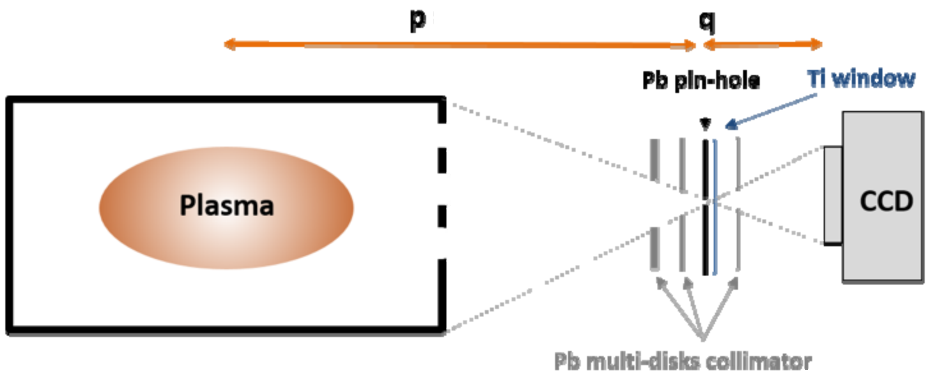
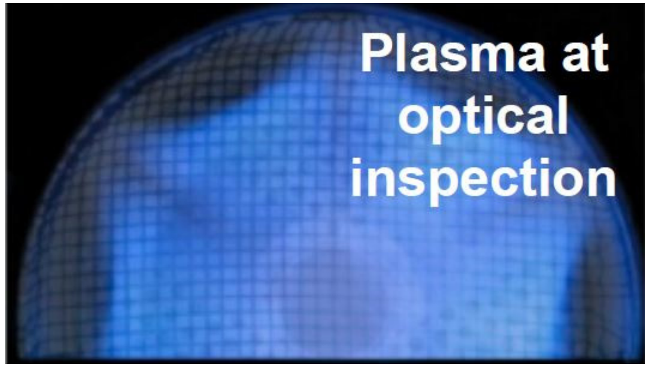
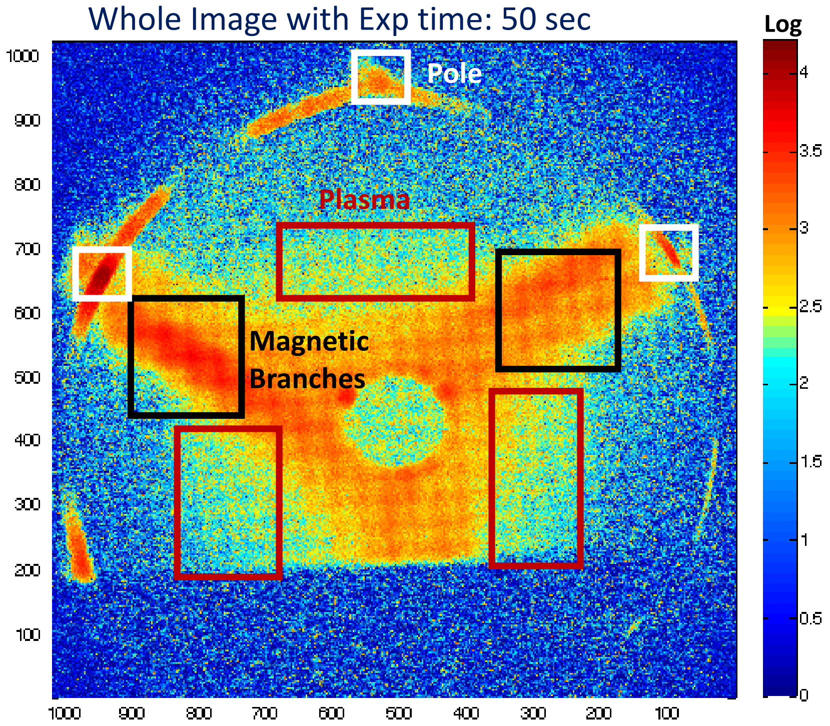
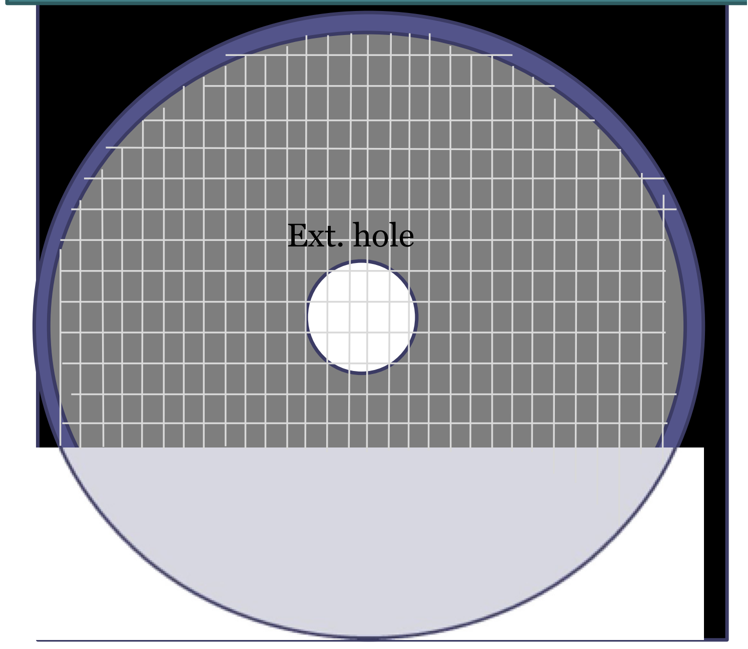






Flux in Branches + Poles = **LOSSES**
Flux in red rectangles: **PLASMA**

Perspective front-view of the plasma chamber in the FULL-FIELD X-ray pin-hole camera setup



⬜ Al inj endplate and mesh

⬛ Ti ext. endplate

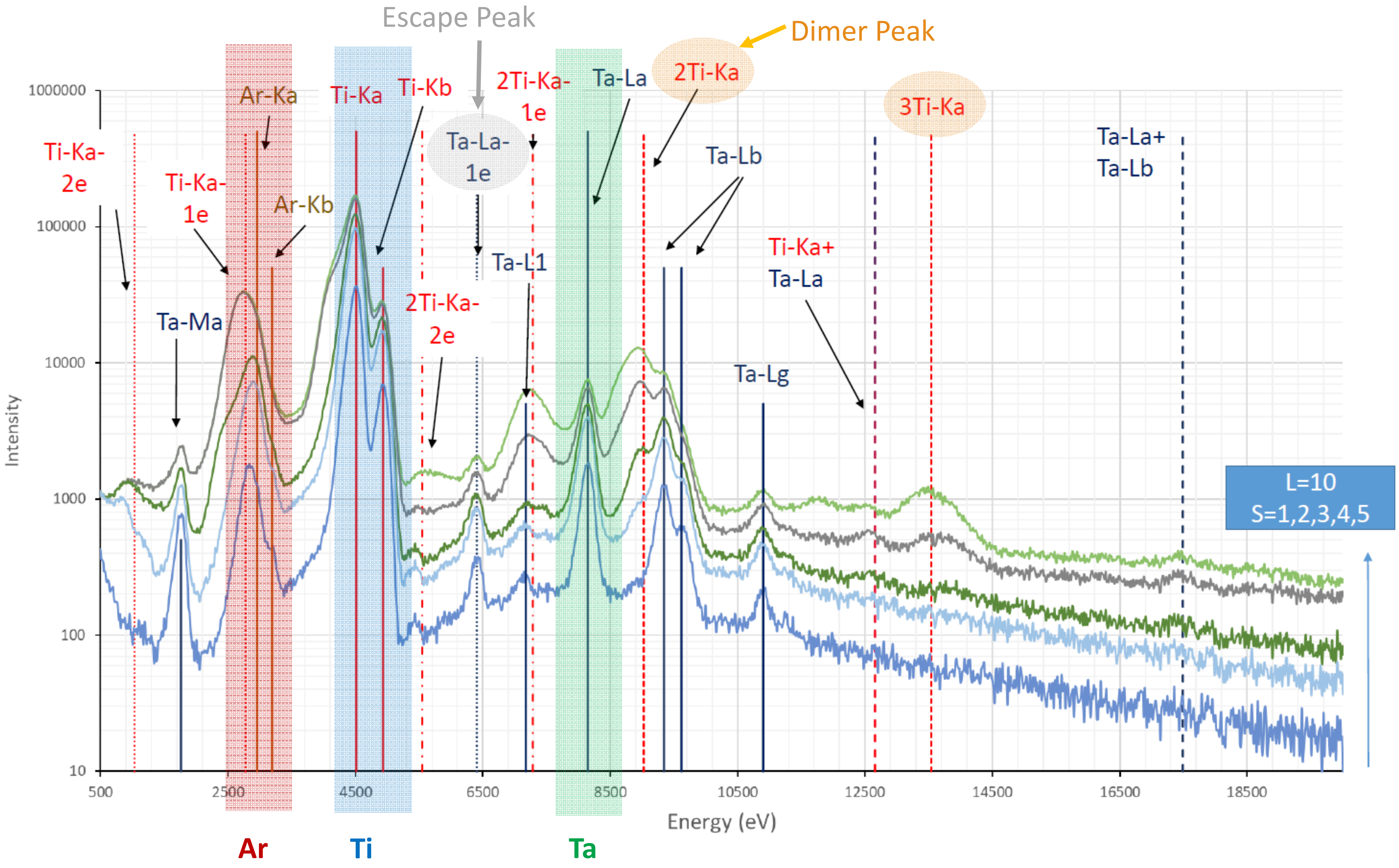
🟦 Tantalum

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

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

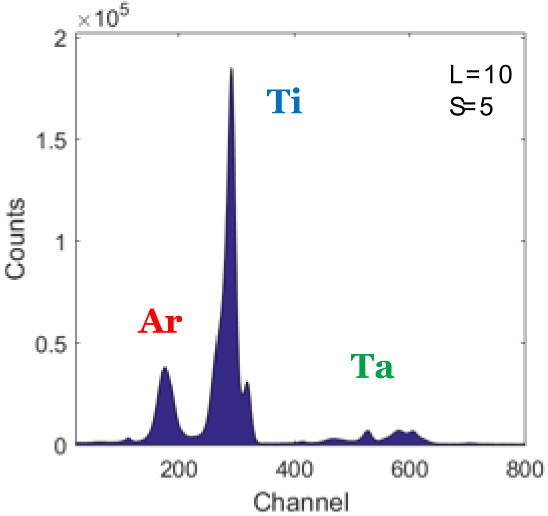
X-rays coming from **poles** are mostly due to radial losses impinging on the **Ta liner**

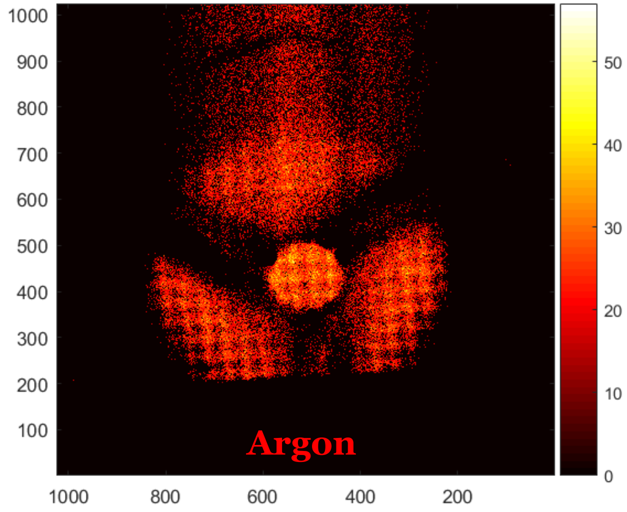
Very high spatial resolution: Al mesh with wire diameter ~ 0.4 mm



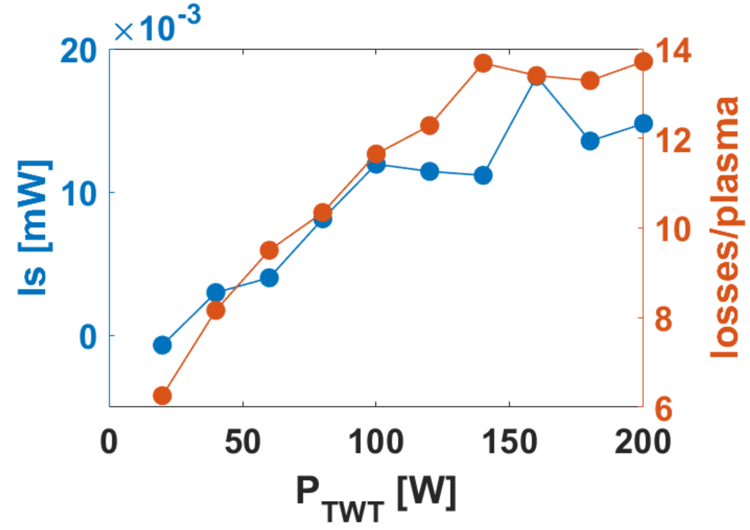
Energy Resolution ~ 230 eV at 8.1 keV (Ta-Lα fluorescence line)

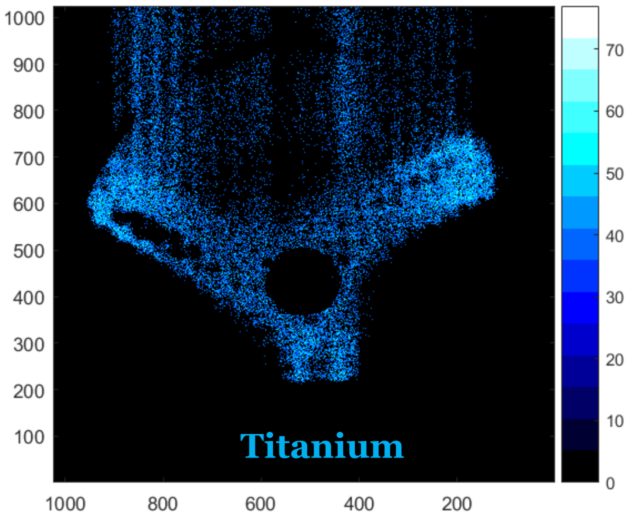
SPACE RESOLVED SPECTROSCOPY allows plasma and plasma losses unprecentedly inspection





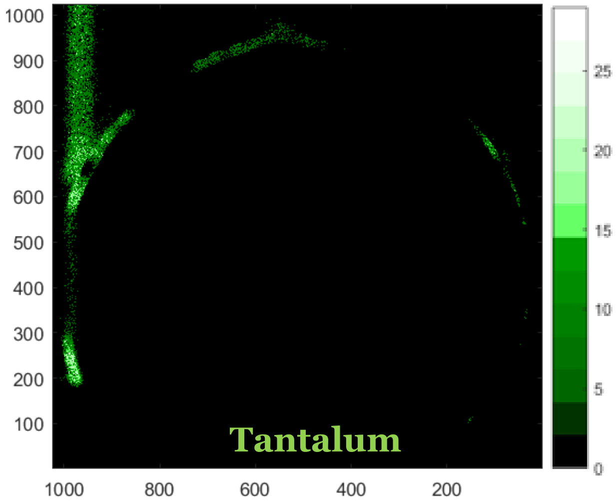
Plasma vs. plasma losses dynamics



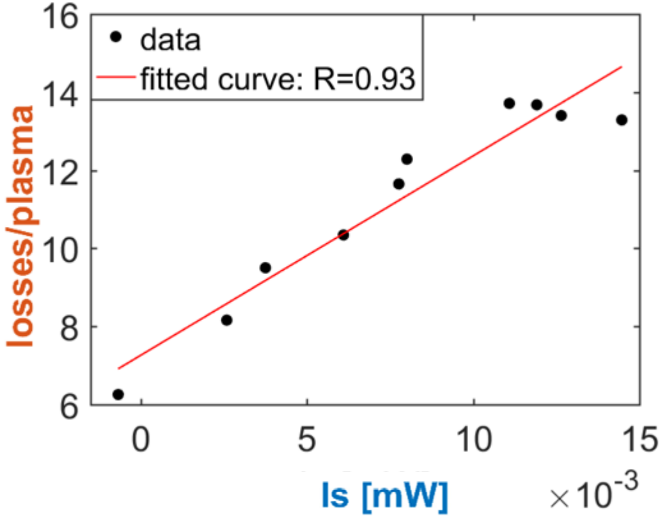


Titanium

Tantalum



Correlation plot



Benchmarks from theory and simulations: how to self-consistently model wave-plasma interaction and first converging results

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

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

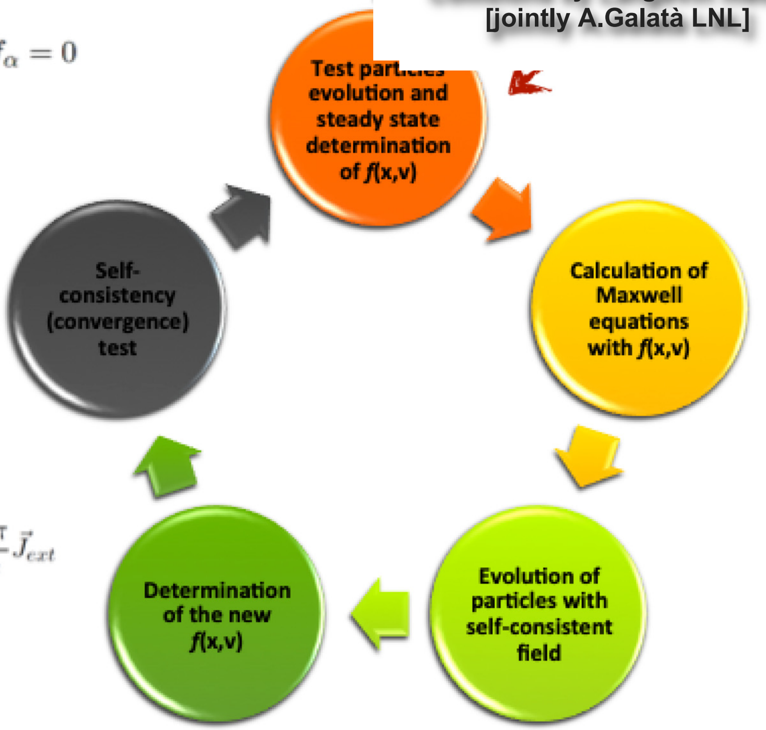
Step-by-step current

Step-by-step plasma density

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

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

Collisions by Langevin method [jointly A.Galatà LNL]



Test particles evolution and steady state determination of *f*(x,v)

Calculation of Maxwell equations with *f*(x,v)

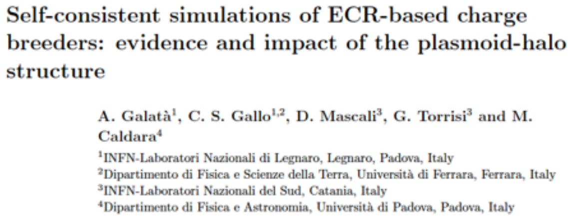
Evolution of particles with self-consistent field

Determination of the new *f*(x,v)

Self-consistency (convergence) test

self-consistency*

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

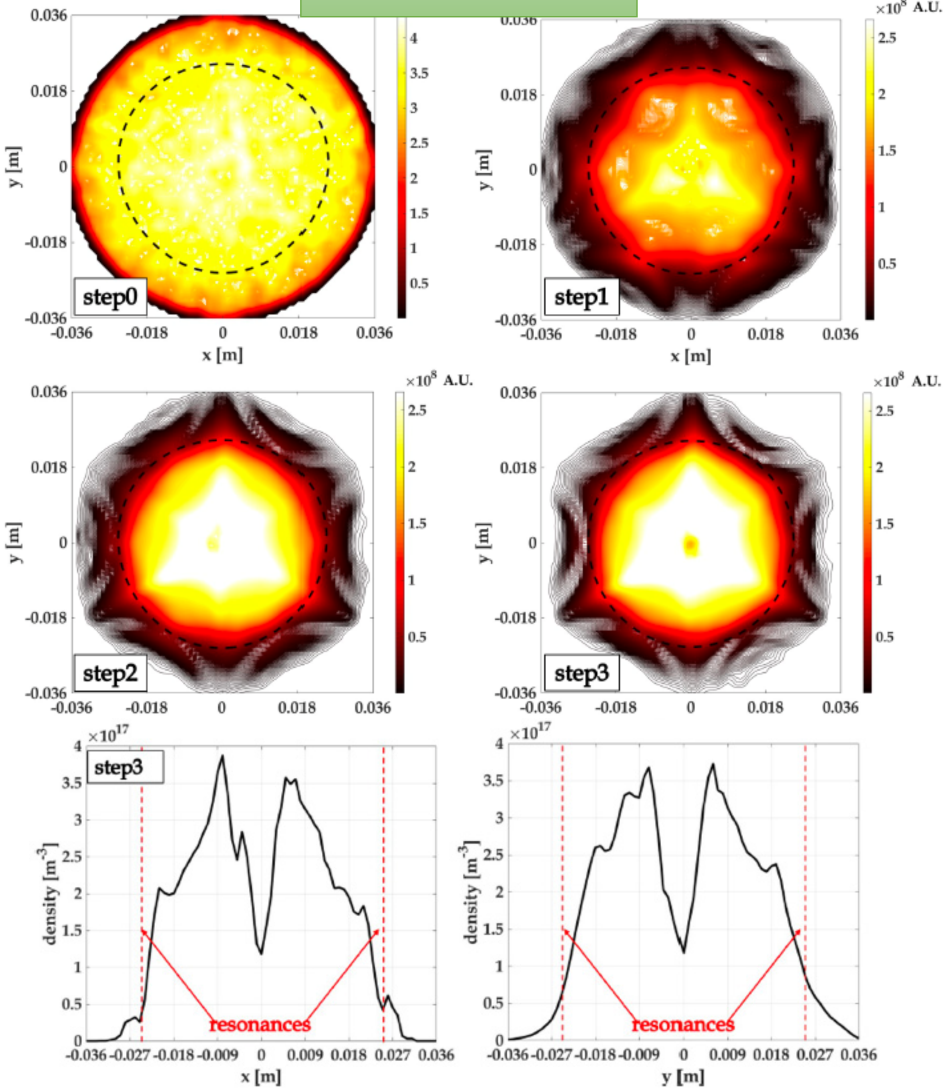


Self-consistent simulations of ECR-based charge breeders: evidence and impact of the plasmoid-halo structure

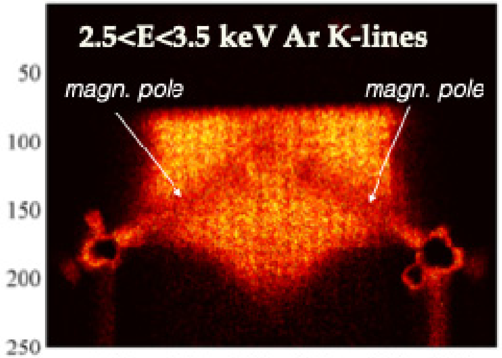
A. Galatà[1], C. S. Gallo[1,2], D. Mascali[3], G. Torrisi[3] and M. Caldara[4]

[1]INFN-Laboratori Nazionali di Legnaro, Legnaro, Padova, Italy
[2]Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Ferrara, Italy
[3]INFN-Laboratori Nazionali del Sud, Catania, Italy
[4]Dipartimento di Fisica e Astronomia, Università di Padova, Padova, Italy

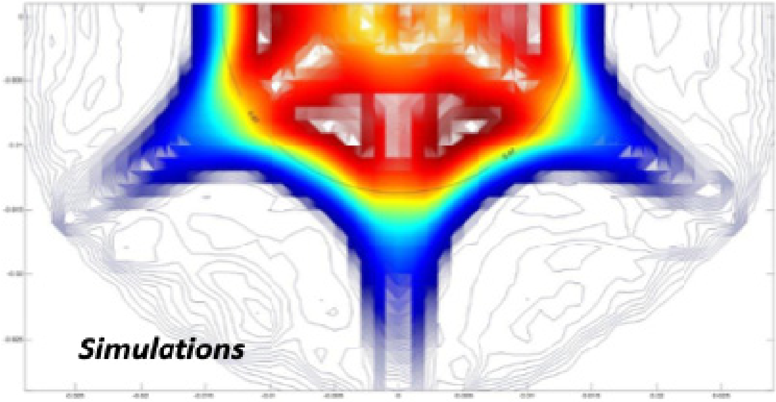
RESULTS



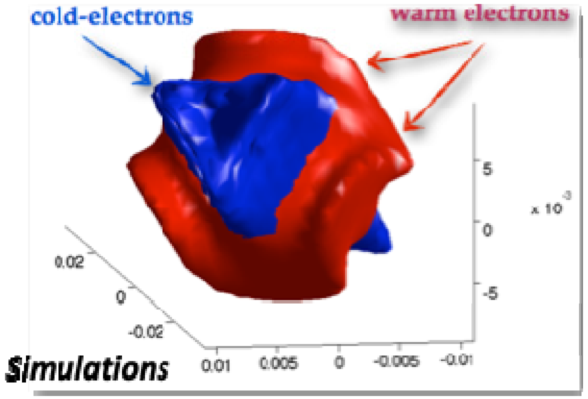
Benchmarks from theory and simulations: how to self-consistently model wave-plasma interaction and first converging results



X-ray fluorescence from Ar ions in the plasma



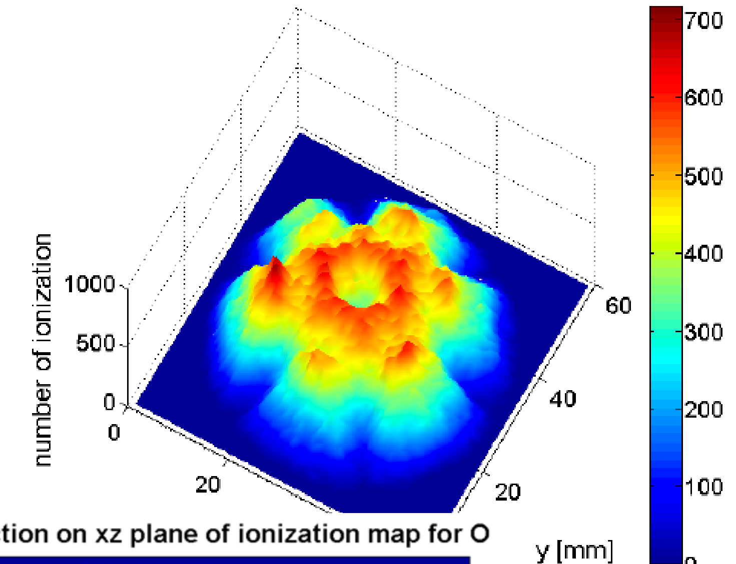
3D self-consistent simulations very well reproduce energy content distribution of the plasma, which in turn fits with experimental detected displacement of Argon ions



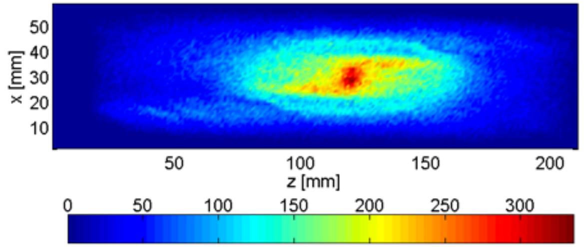
Starting from 3D distribution of electrons in the plasma, maps of ions distribution can be obtained

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

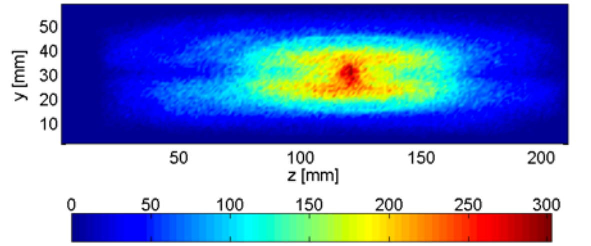
Projection on xy plane of ionization map for Ar



Projection on xz plane of ionization map for O



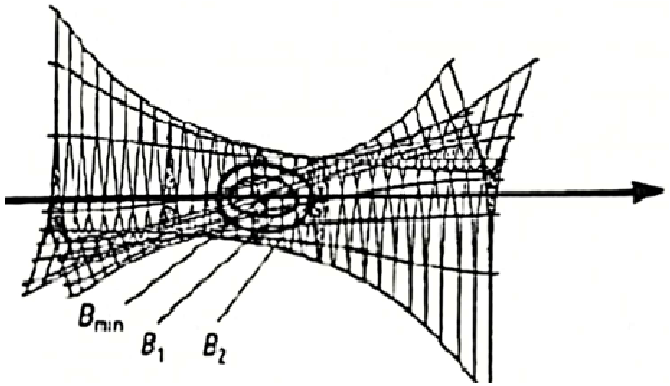
Projection on yz plane of ionization map for O

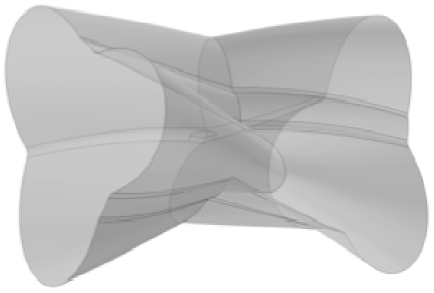


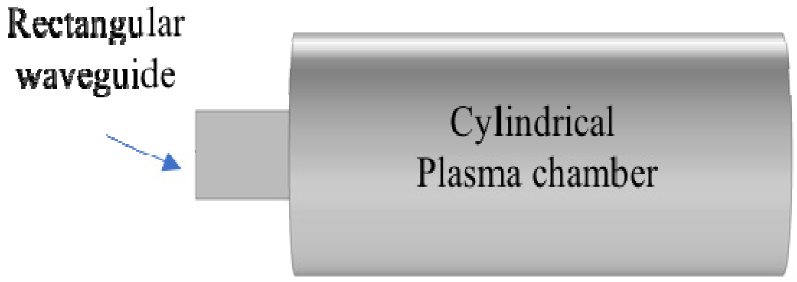
QUESTION 4: Can the shape of the plasma chamber be changed?

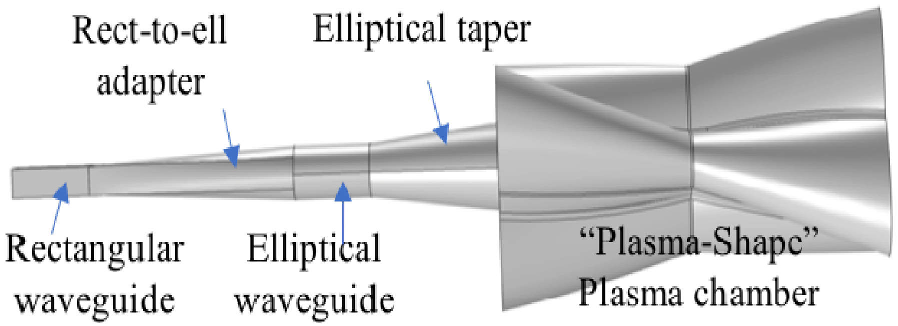
New chambers for a radical improvement of RF coupling

The underlying idea to **IRIS-like shapes** of the plasma chamber is that we have to break the cylindrical symmetry in order to increase the intensity of the electromagnetic field in the near-axial region.

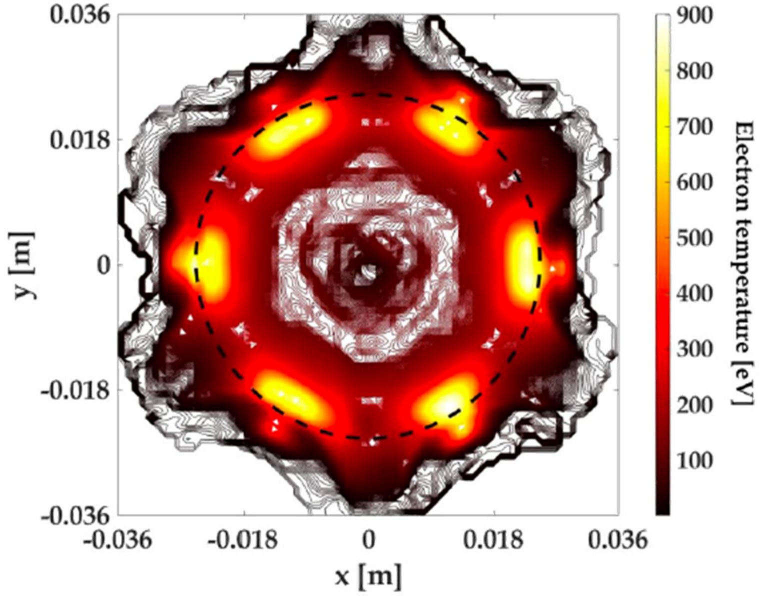








Energy content of the plasma that is common in a cylindrical shaped camera



As for Stellarator thermonuclear reactors, **"shape matching"** between plasma (determined by the magnetostatic structure) and plasma-chamber should be reached.

QUESTION 4: Can the shape of the plasma chamber be changed?

YES! The phase space (S11 parameter) is hugely broadened

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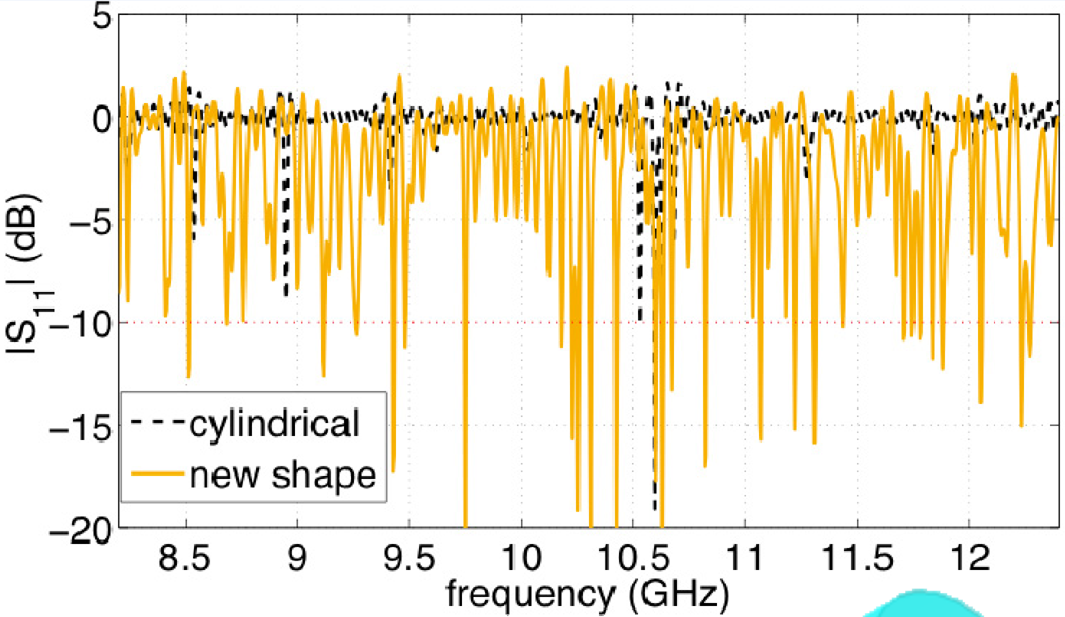
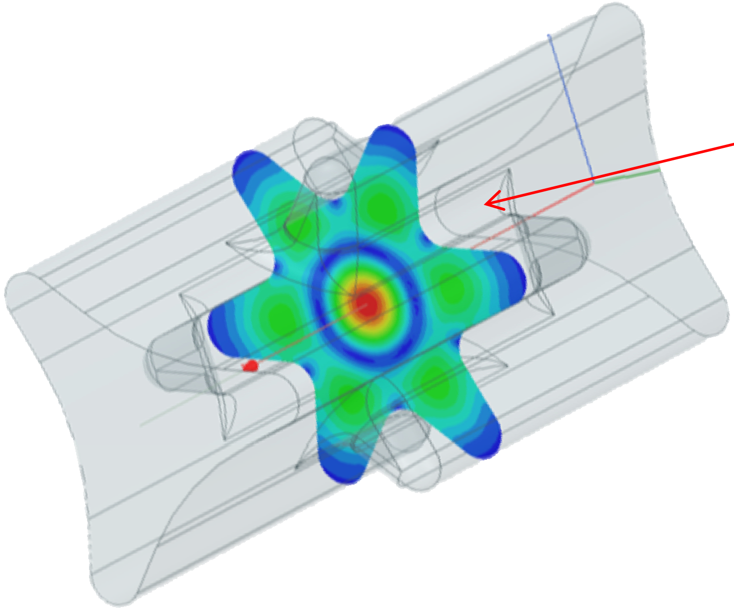
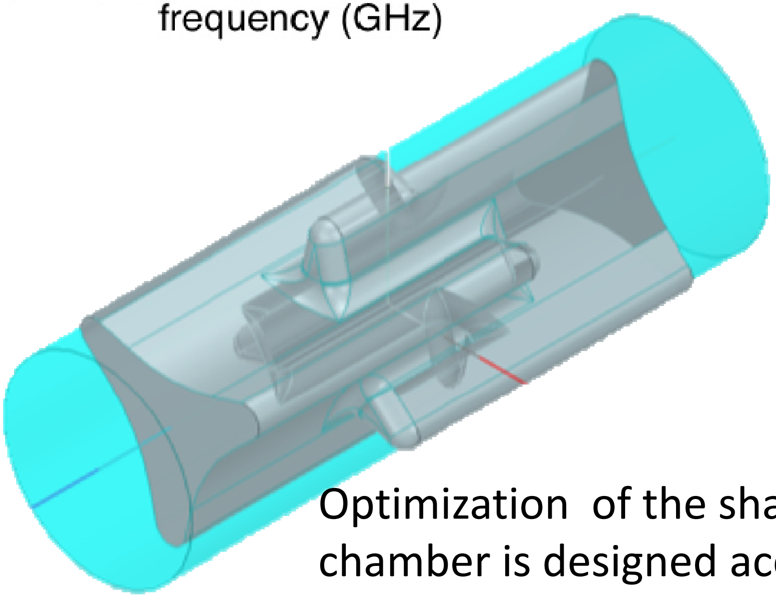


The electromagnetic analysis of the IRIS-shape shows the S11 parameter space can be drastically broaden!! (→ the system is much less sensitive to the frequency)



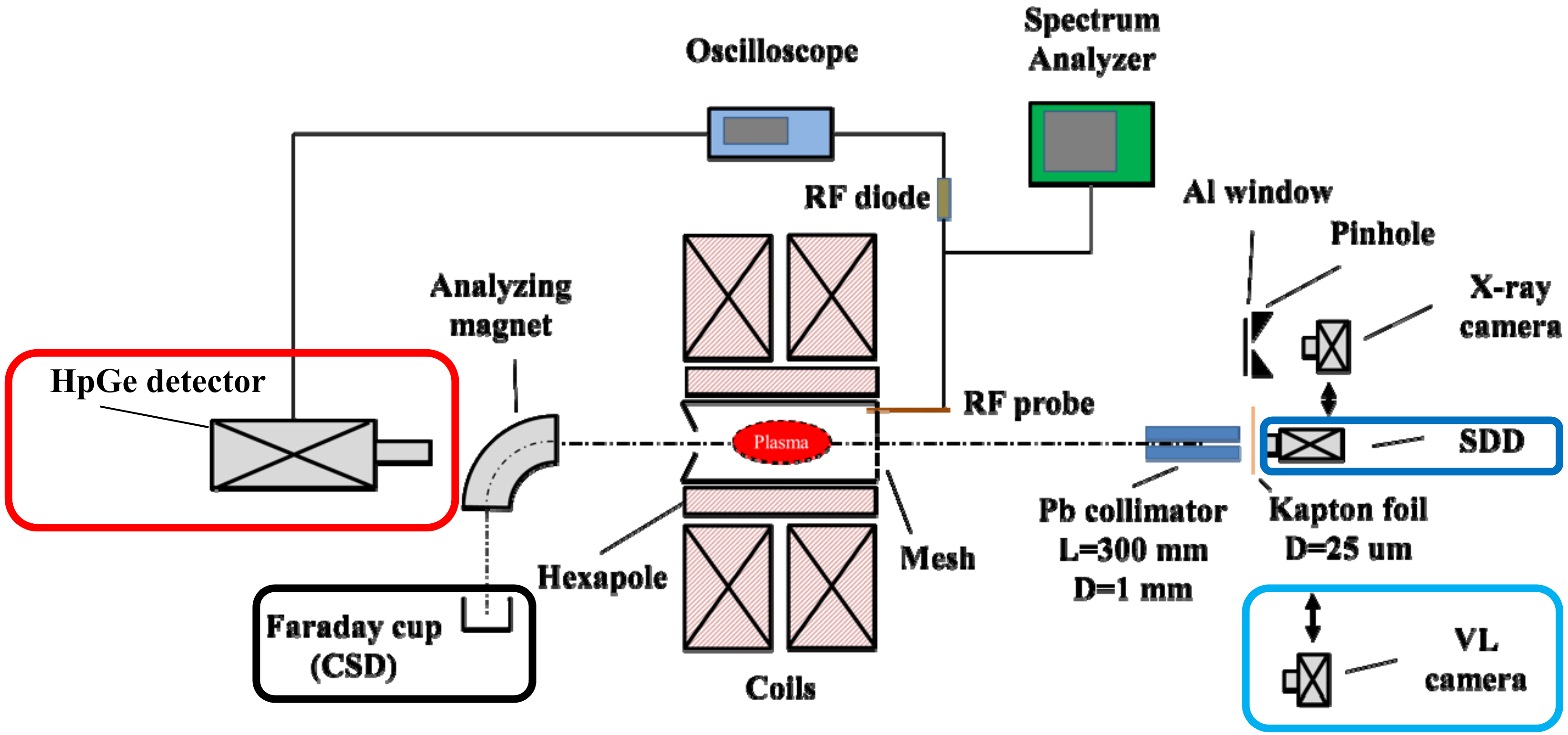
Maximal em-field occurs at the axis for most of the feeding freqs



Optimization of the shape is ongoing: the structure of the chamber is designed according to the electron density distribution

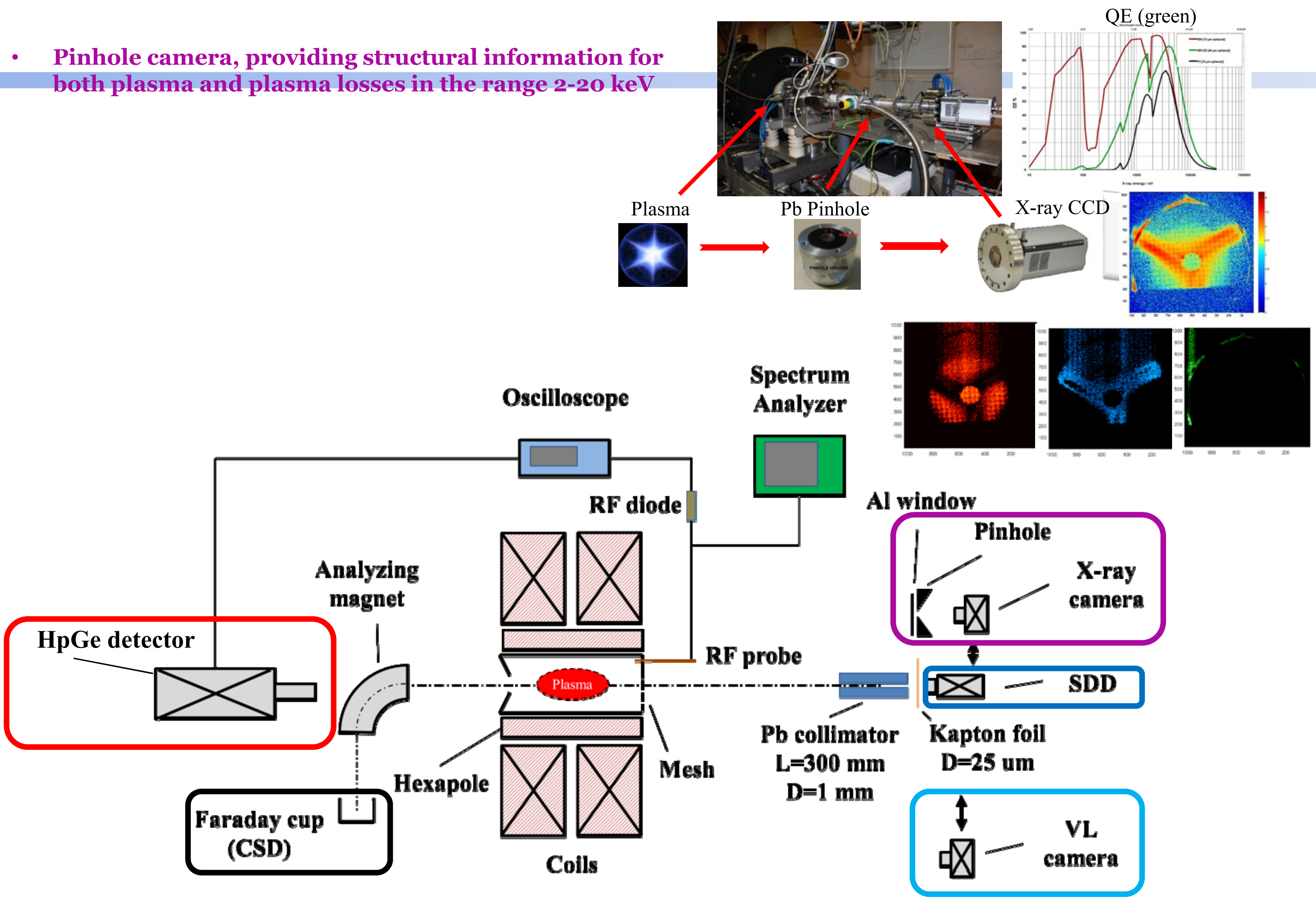
Summary about the Diagnostics "Arsenal"

- SDD (Silicon Drift Detector): probing volumetric soft X-radiation in the 2 – 20 keV domain
- HPGe (High Purity Germanium Detector) providing:
  - time integrated X-ray spectra in the 30-300 keV;
- Mass spectrometry: simultaneous evaluation of CSD
- VL camera, probing volumetric optical radiation in the 1 – 12 eV domain



Summary about the Diagnostics “Arsenal”

- **Pinhole camera, providing structural information for both plasma and plasma losses in the range 2-20 keV**

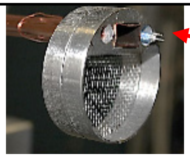


Summary about the Diagnostics “Arsenal”

- **RF probe + Spectrum analyzer: plasma radio-emission analysis**

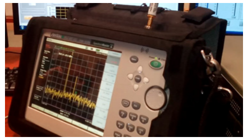
Plasma → RF probe — Attenuators — Limiter — Spectrum Analyzer

Mounted to the injection plate

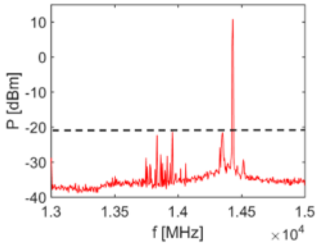


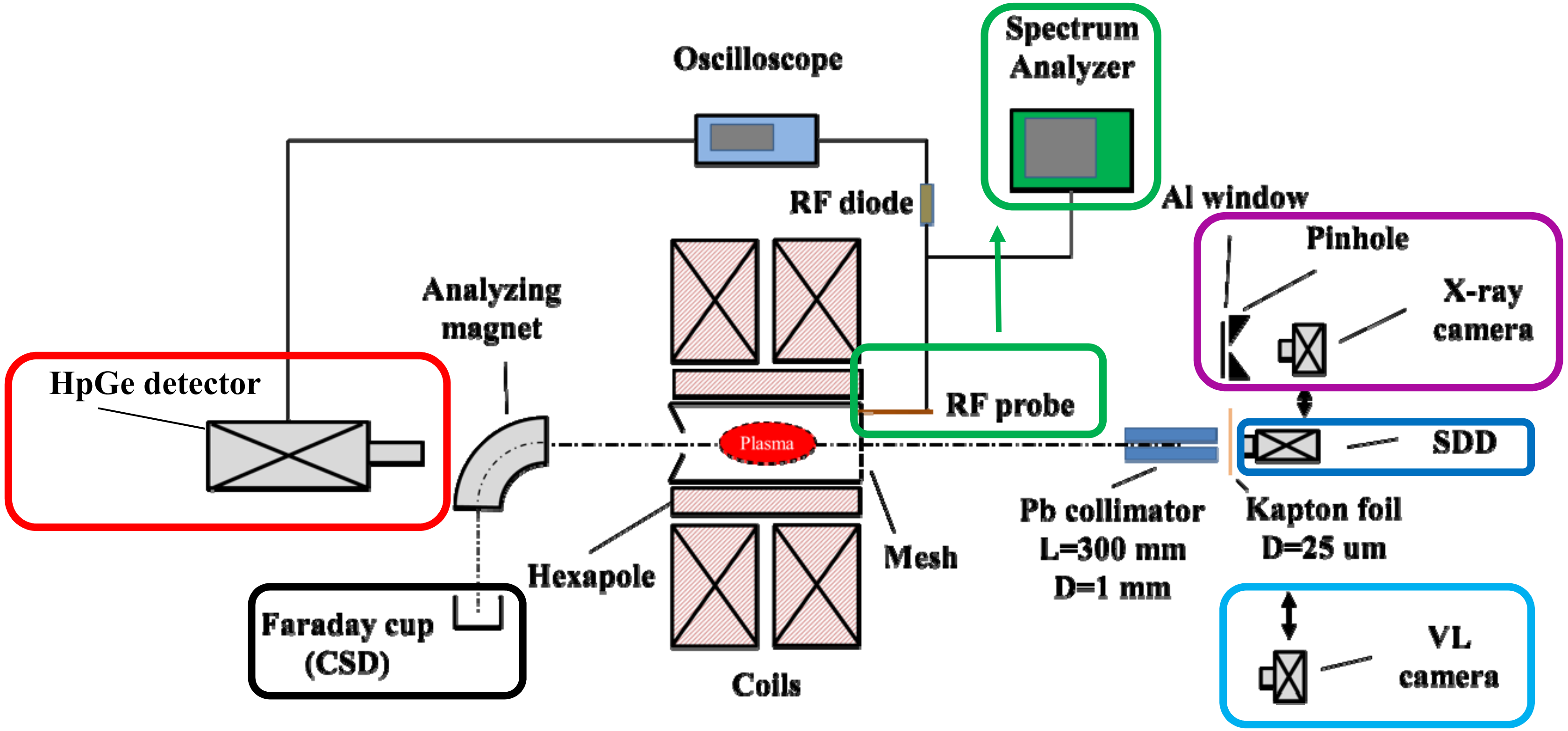
RF probe

Plasma EMW detection in GHz ranges



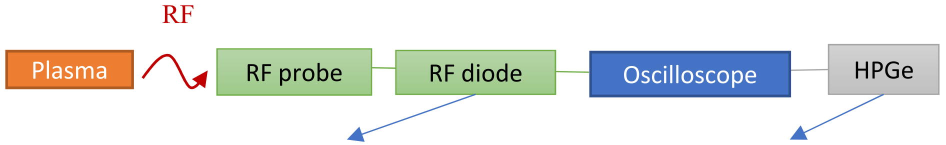
Frequency scan from 13.6-14.6 GHz



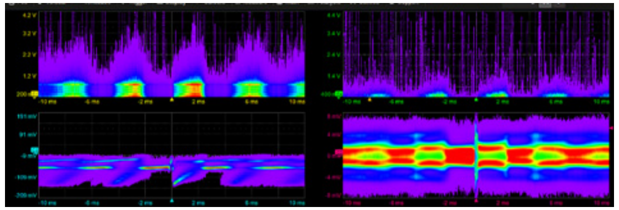


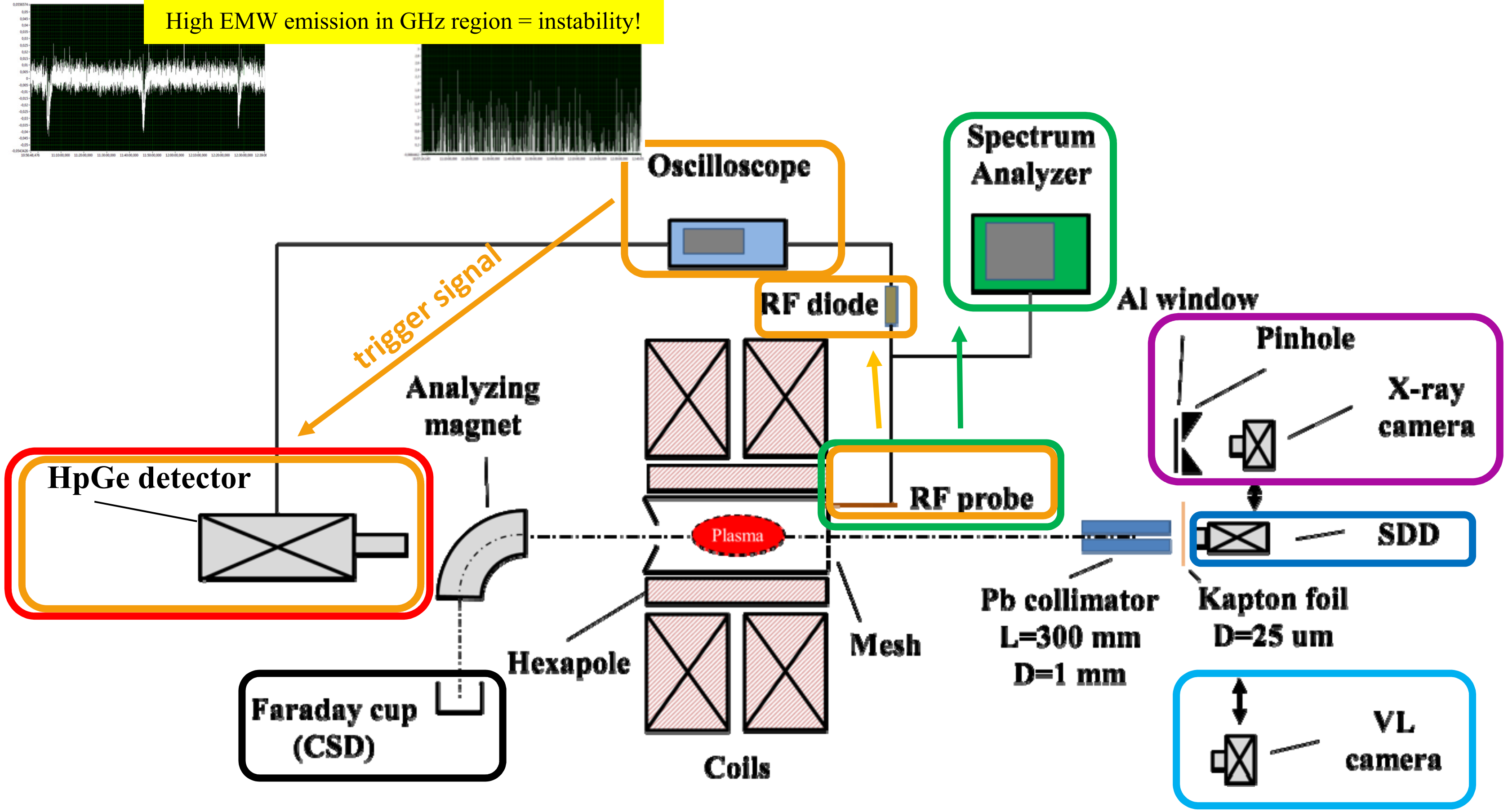
Summary about the Diagnostics “Arsenal”

- **RF probe + Spectrum analyzer: plasma radio-emission analysis**
- **Time resolved spectra with 6 μs resolution if triggered by RF probe (useful for instabilities!!)**



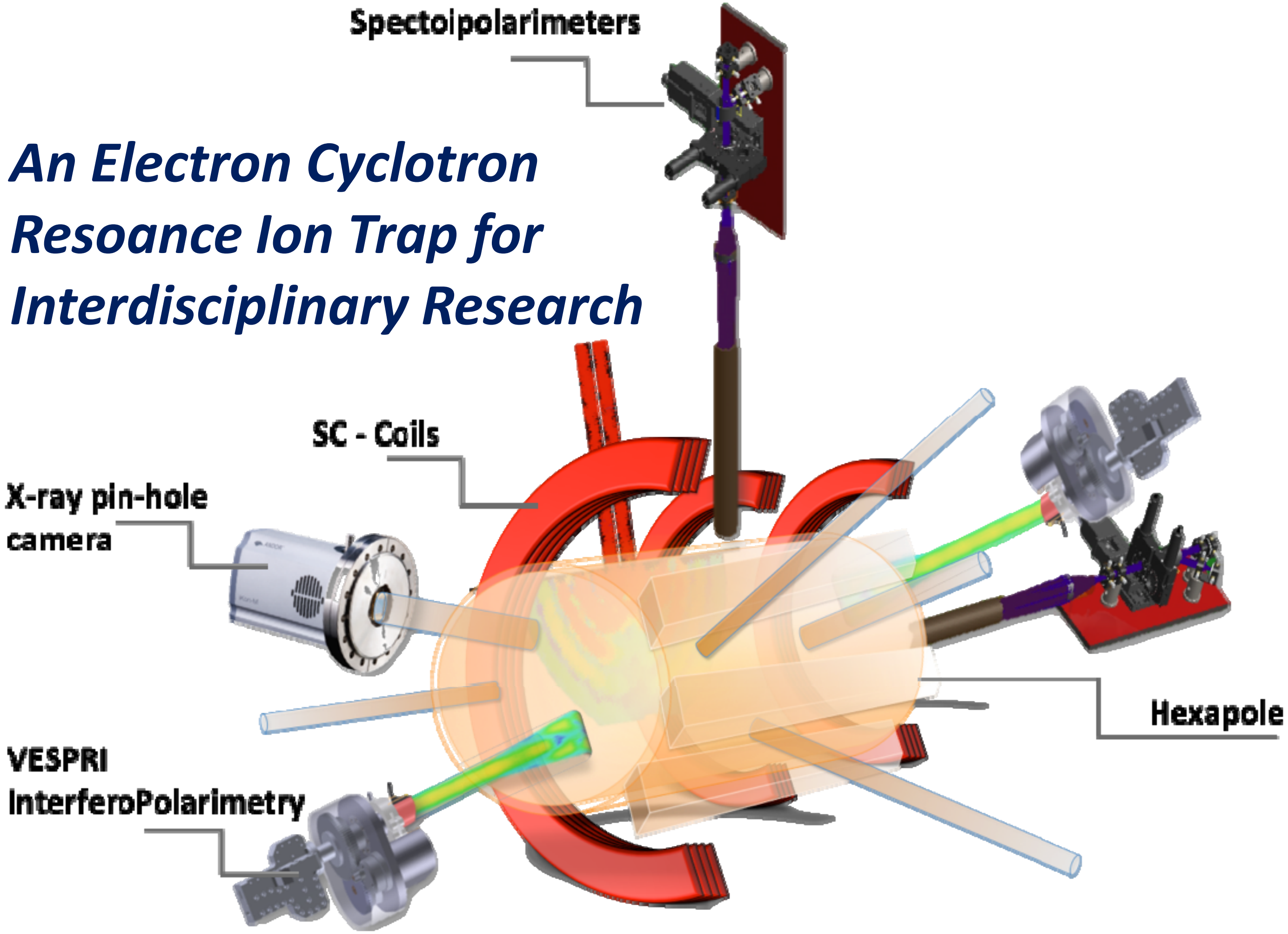
Time resolved emw emission (amplitude in reverse) → Measurement of HPGe signal in coincidence of the sudden emw emission of the plasma

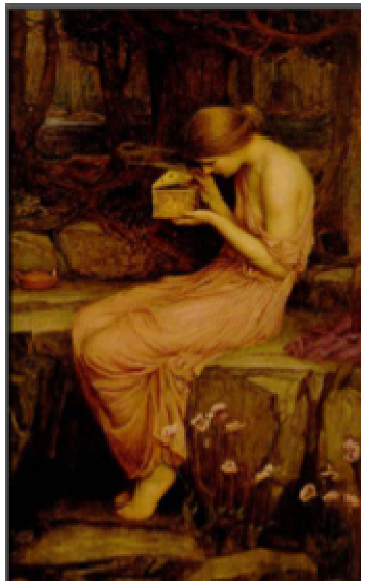



High EMW emission in GHz region = instability!

PANDORA: Plasmas for Astrophysics, Nuclear Decays Observation and Radiation for Archaeometry → A New Life for ECRIS(T)

An Electron Cyclotron Resoance Ion Trap for Interdisciplinary Research





Plasmas for
Astrophysics,
Nuclear
Decays
Observation and
Radiation for
Archaeometry

Isotope	$T_{1/2}$ (yr)	Eγ (keV)
^{1} Lu	3.78x1 ^{10}	8 400
^{1} Cs	2.06	>600
Nb	2.03x1 ^{4}	>700

PANDORA: Exploring β-decays for stellar nucleosynthesis → A New Life for ECRIS(T), playing a role in s-processes in stars

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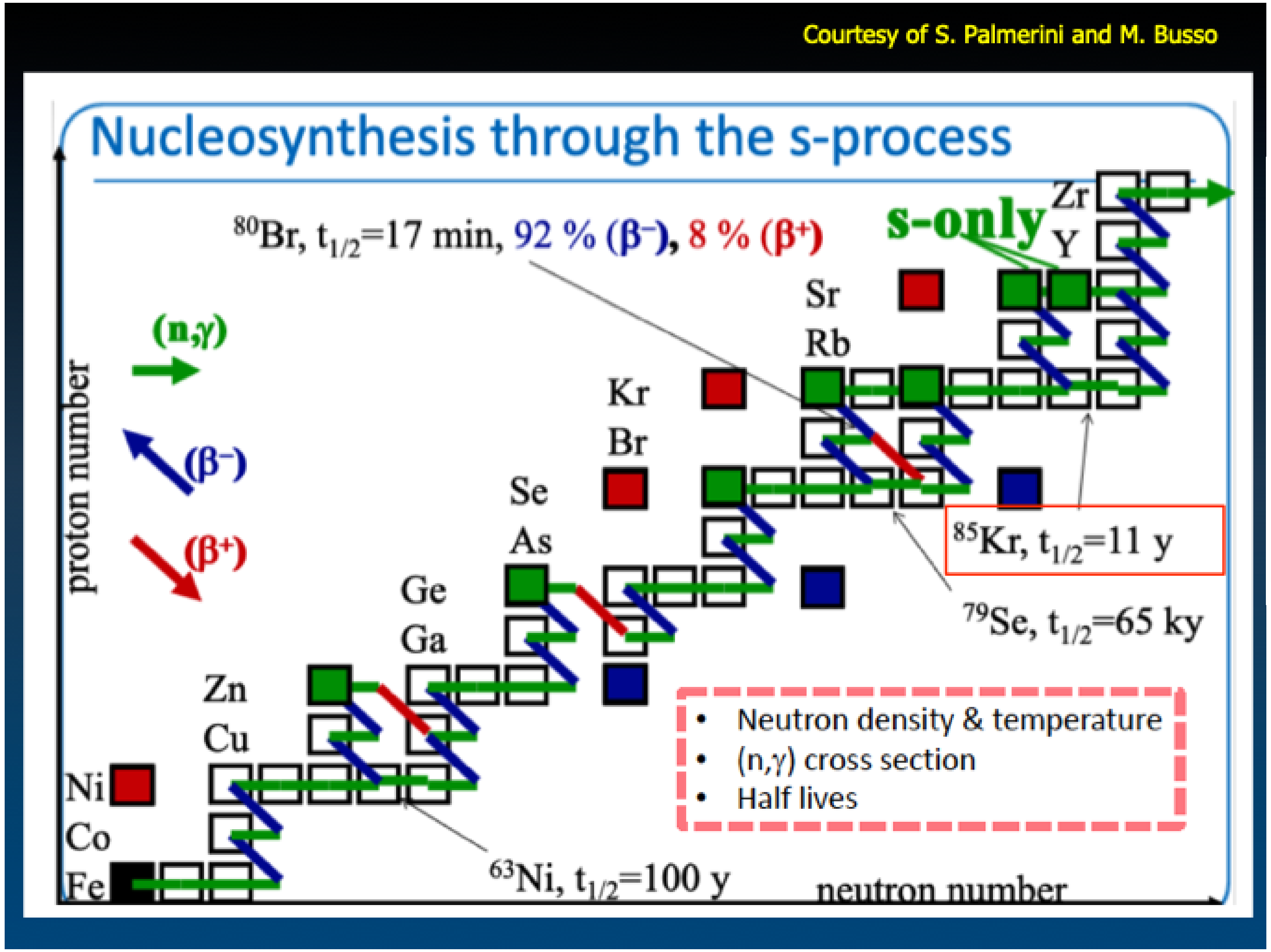
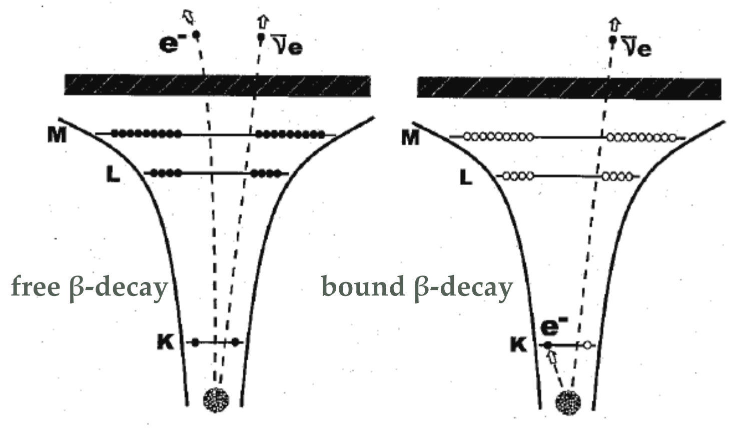


Courtesy of S. Palmerini and M. Busso

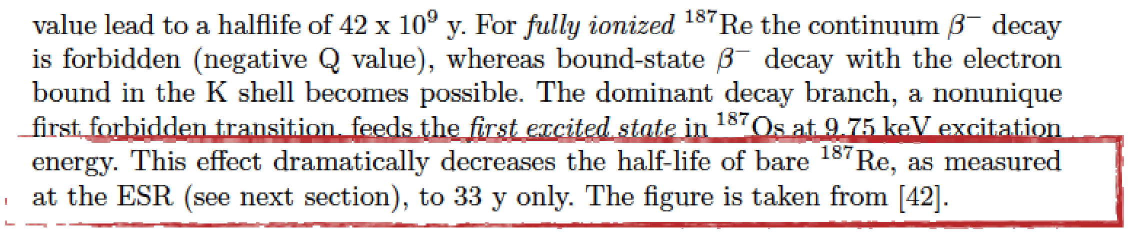
Nucleosynthesis through the s-process

- Neutron density & temperature
- (n,γ) cross section
- Half lives

The idea is to measure nuclear β-decays in an Electron Cyclotron Resonance Ion Trap

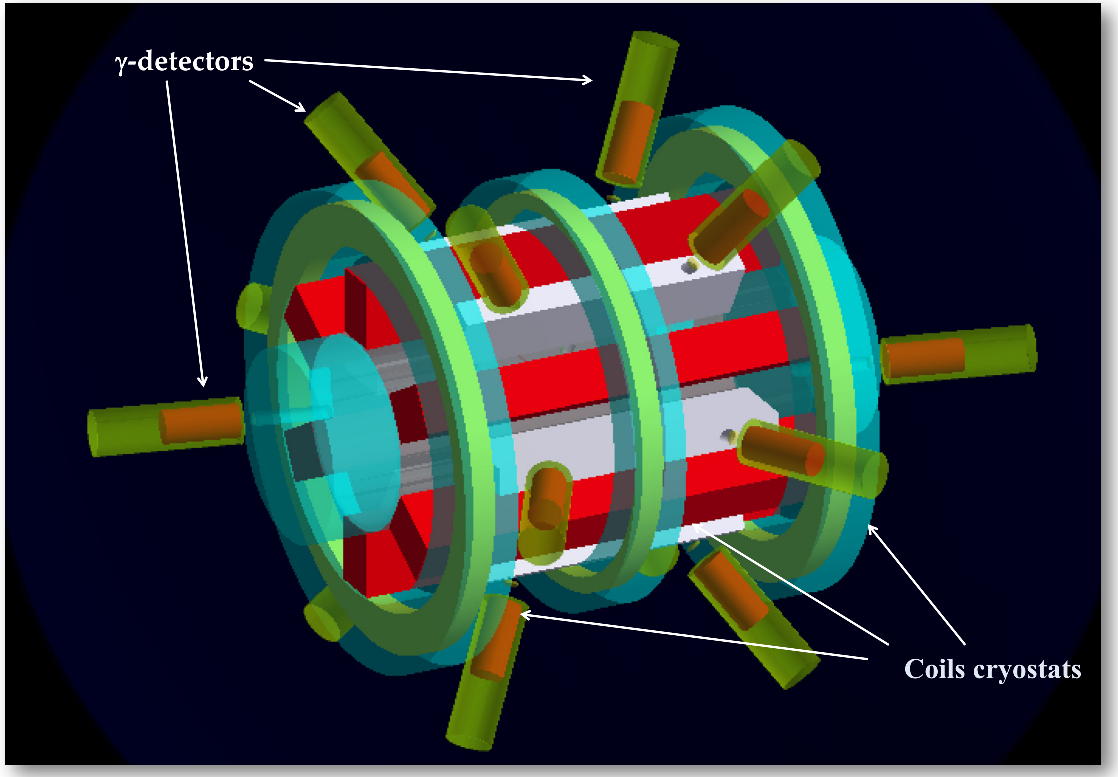


For ^{187}Re a lifetime variation of 9 orders of magnitude (!!) was observed in Storage Rings



value lead to a halflife of 42 x 10^9 y. For *fully ionized* ^{187}Re the continuum β^- decay is forbidden (negative Q value), whereas bound-state β^- decay with the electron bound in the K shell becomes possible. The dominant decay branch, a nonunique first forbidden transition, feeds the *first excited state* in ^{187}Os at 9.75 keV excitation energy. This effect dramatically decreases the half-life of bare ^{187}Re, as measured at the ESR (see next section), to 33 y only. The figure is taken from [42].

PANDORA: the overall setutp as modelled and simulated by GEANT-4 code: a big trap surrounded by a detectors array

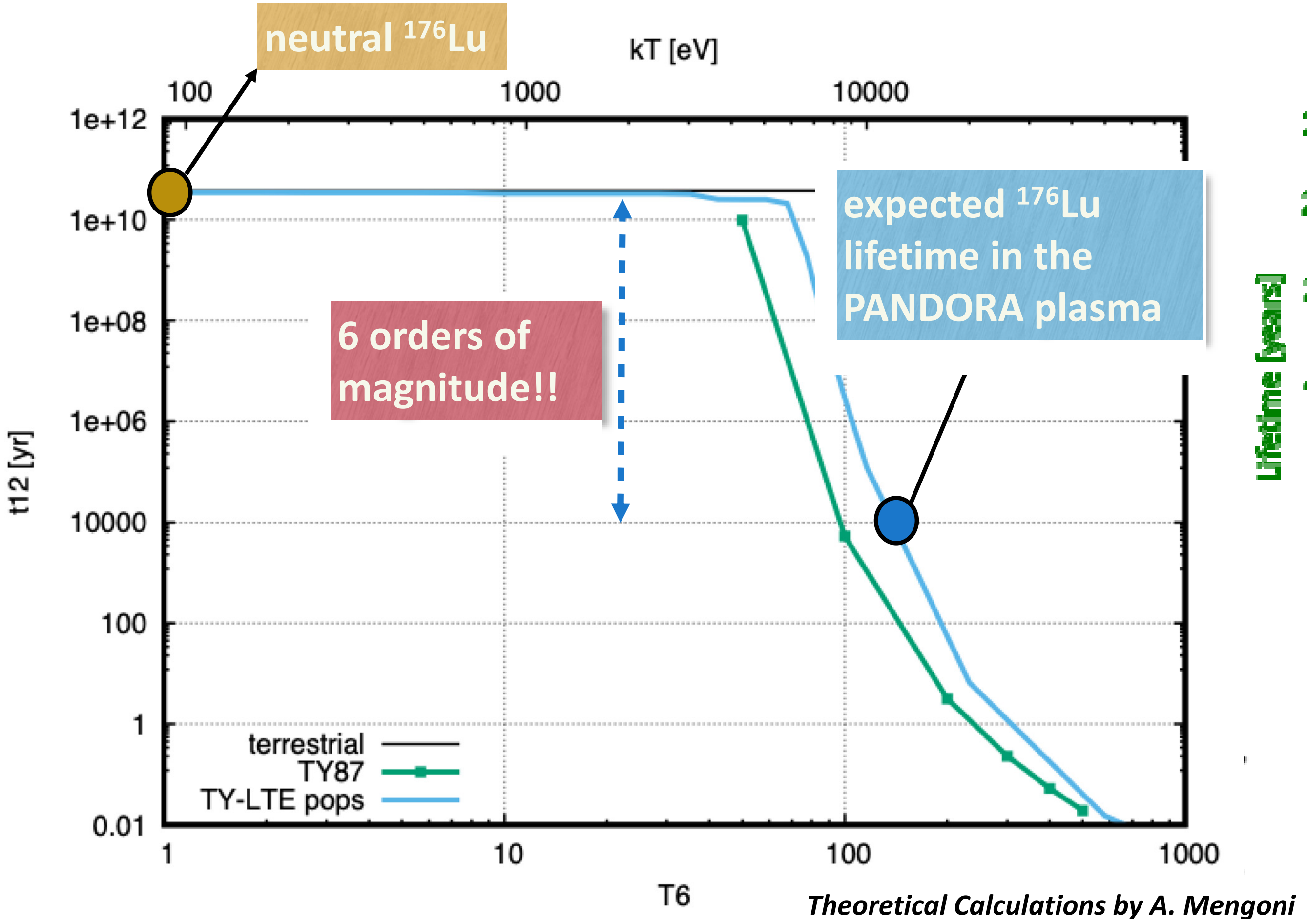


- A "buffer plasma" is created by He, O or Ar up to densities of 10^{13} cm^{-3}
- The isotope is then directly fluxed (if gaseuous) or vaporized by appropriate ovens and then fluxed inside the chamber to be turned into plasma-state
- **Relative abundances of buffer vs. isotope densities range from 100:1 (if the isotope is in metal state) to 3:1 (in case of gaseous elements)**

- **3 SC coils and a Cu monocoil hexapole are used as magnetic trap**
- **14 HpGe detectors are used for tagging β-decays by the γ-rays emitted from the decay-products in their excited states**

The plasma is maintained in dynamical equilibrium by equalizing input fluxes of particles to losses from the magnetic confinement

PANDORA’s challenges: “Collapse” of ^{176}Lu lifetime

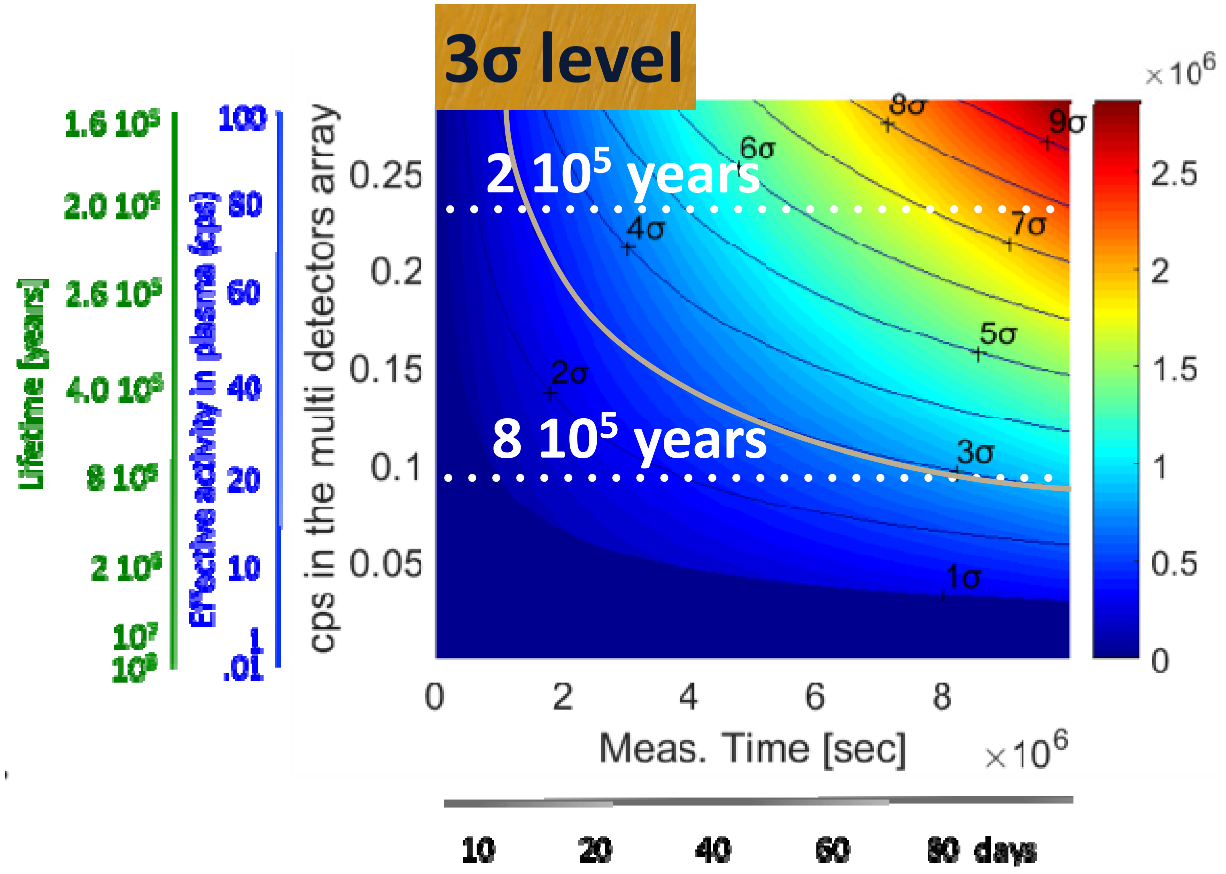


neutral ^{176}Lu

6 orders of magnitude!!

expected ^{176}Lu lifetime in the PANDORA plasma

Theoretical Calculations by A. Mengoni



3σ level

2 10^5 years

8 10^5 years

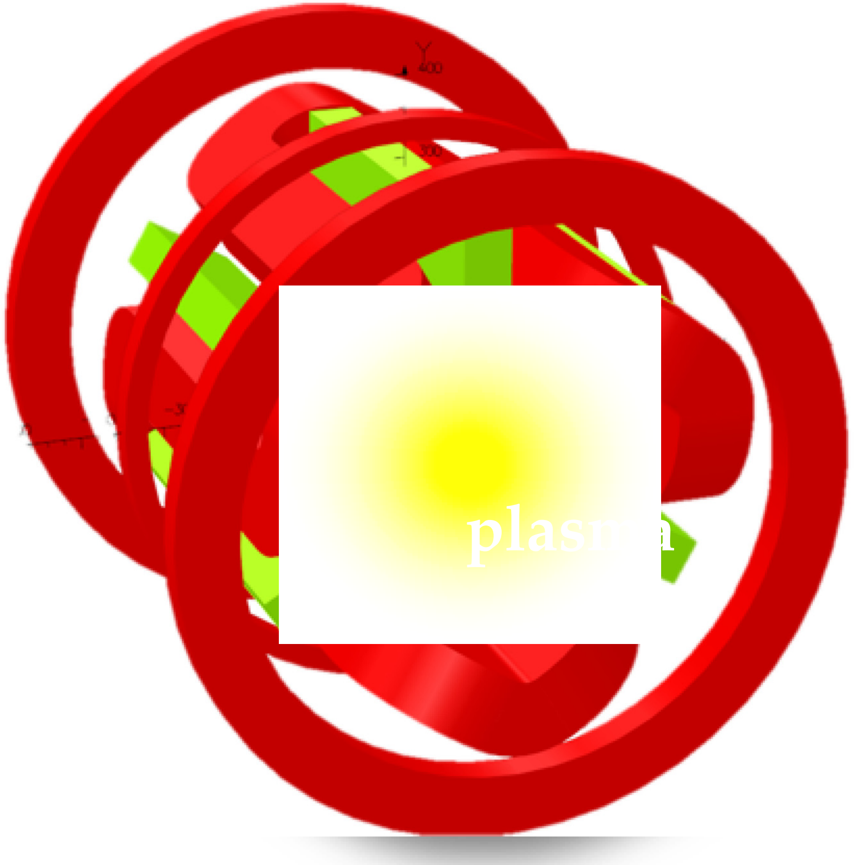
Estimation of lifetime variation as a function of plasma temperature

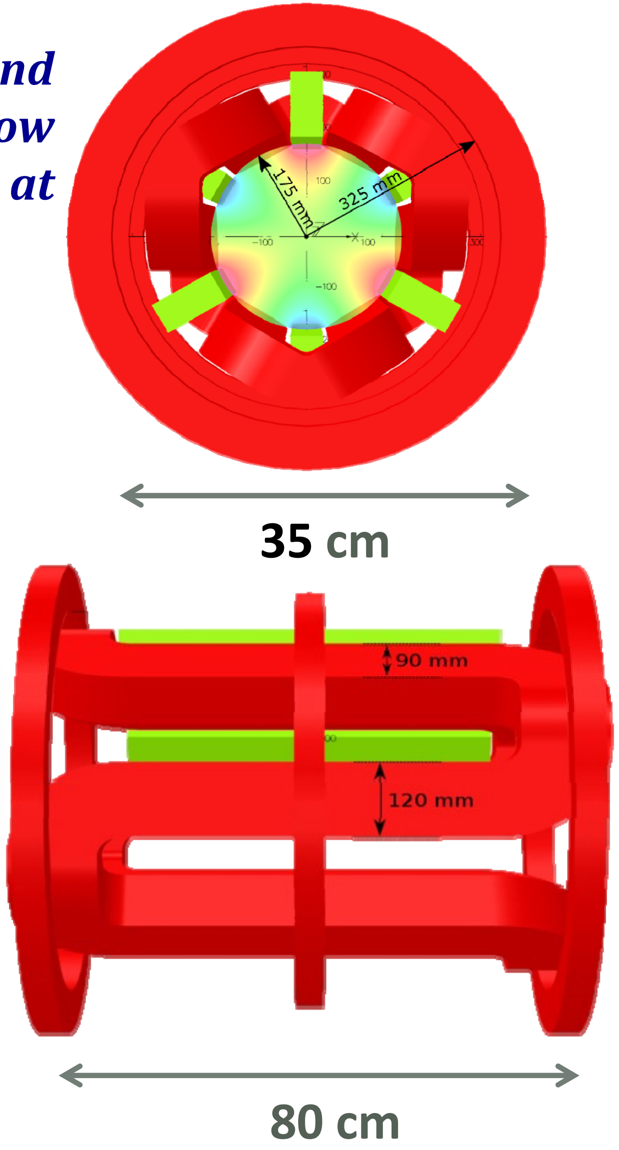
“Measurability” of ^{176}Lu lifetime from GEANT-4 simulations (by an array of 14 HpGe-detectors)

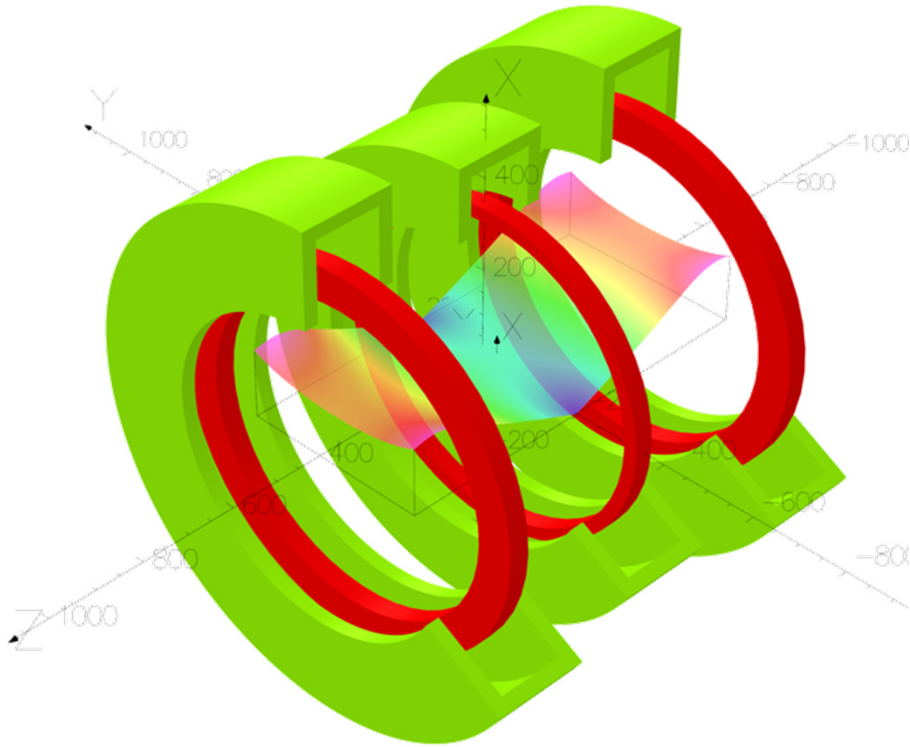
PANDORA: Plasma Trap design in order to have long plasma lifetime and sufficient flexibility and accessibility

The maximum fields of 2.1 T on the axis and 1.2 T on the radial direction will allow stable plasma generation by an RF field at 18 GHz via Electron Cyclotron Resonance.

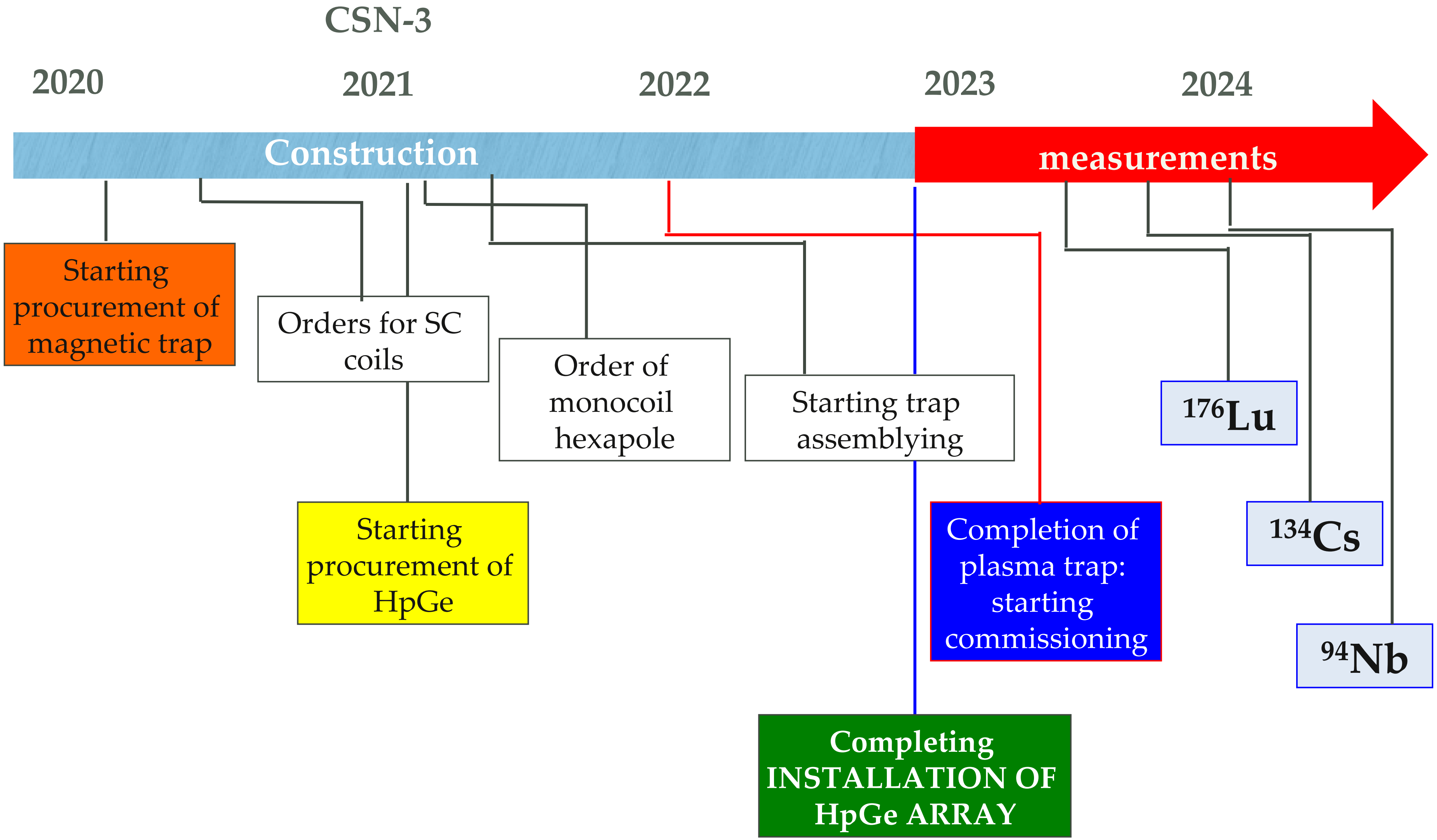
It is the largest magnetic trap never design in a B-min scheme, having a length of 80 cm and a diameter of 35 cm







PANDORA: timescale and deliverables in the next years



CSN-3

2020

2021

2022

2023

2024

Construction

measurements

Starting procurement of magnetic trap

Orders for SC coils

Starting procurement of HpGe

Order of monocoil hexapole

Starting trap assemblying

Completion of plasma trap: starting commissioning

Completing INSTALLATION OF HpGe ARRAY

^{176}Lu

^{134}Cs

^{94}Nb

Conclusions: trying answering to the former question…

- **MAYBE WE CAN LOOK AT “SIDE” SOLUTIONS?**
  - New designs of magnetic field
  - Exotic solutions for rf coupling (different shapes of plasma chamber?!)
  - Different coupling of rf power (multiple-frequency heating by innovative solutions)
  - A lot of diagnostics and modelling are needed

⬇

Answer seems to be: YES

✓ Now an “arsenal” of diagnostics tools is available
✓ numerical methods are now more complete and reliable
✓ several groups are looking to smart/exotic solutions for bypassing a pure frequency-magnetic field scalings