Multi-diagnostics setup as a tool to overcome the limits of ion sources

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Developments

Very detailed characterization of kinetic turbulence in radio emission and electrons precipitation from the B-min trap

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

Vadim Skalyga, Ivan Izotov, Dmitry Mansfeld, Olli Tarvainen, Taneli Kalvas, Janne Laulainen, Risto Kronholm, Jani Komppula, Hannu Koivistoinen

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

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

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

Splitting axial from radial field, separate measurements show the role played by the two field components in a B-min trap
Plasma diagnostics for Highly Charged Ion Sources

• A Multi-Diagnostics set-up for investigation of plasma parameters: density, temperature, CSD
• Time-Res Meas. for Cyclotron Maser Instability Characterization
• Investigation of plasma in multiple-Frequency Heating regimes (Plasma Turbolences damping)
• X-rays Space-Resolved Analysis for studying Plasma structure

Innovative and advanced Multidiagnostic Setup becomes necessary!

Plasma diagnostics for High Intensity Ion Sources

• Advantages of OES in compact sources;
• OES as a monitor of proton source performances:
  Online evaluation of species fraction and extracted current;
• Perspectives of OES in compact sources;
Laboratory magnetoplasmas in compact traps are historically used for ion beams production. Laboratory magnetoplasmas are suitable and interesting for other researches.
Laboratory-Magnetoplasmas can become ENVIRONMENT for multidisciplinary research

- **Laboratory-Plasmas for Nuclear Physics and Nuclear Astrophysics**: To measure plasma properties (density, temperature, ionisation states) and correlate them to lifetimes. The idea is to trap beta-decaying radionuclides in magnetoplasma, thus studying if and how the lifetimes is affected by the atomic charge state and by the «Environment».

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}$ (yr)</th>
<th>$E_\gamma$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{176}$Lu</td>
<td>$3.78 \times 10^{10}$</td>
<td>88-400</td>
</tr>
<tr>
<td>$^{134}$Cs</td>
<td>2.06</td>
<td>&gt;600</td>
</tr>
<tr>
<td>$^{94}$Nb</td>
<td>$2.03 \times 10^4$</td>
<td>&gt;700</td>
</tr>
</tbody>
</table>

Experiments in S.R. and theory say $\beta$-decays lifetimes are modified by the atomic charge state.

EC-lifetime variation already observed in Storage Rings.

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*D. Mascali et al., European Physical Journal A 53(7), 2017*
1. The decay-products can be tagged by $\gamma$-rays coming out from the «radio-product» with typical energies between 300 keV and 1800 keV.

2. We are carrying out numerical simulation by GEANT4 according to a certain plasma model.

- ECR Plasma Trap
- Chamber Length: 80 cm
- Chamber Diameter: 40 cm

- 3 Coils for Axial Magnetic field:
  \[ B_{\text{max}} = 2 \, \text{T} \quad B_{\text{min}} = 0.3 \, \text{T} \]

- Exapolar solution for Radial Magnetic field: \( B_{\text{max}} = 1.6 \, \text{T} \)

- Plasma density: \( 10^{11} - 10^{13} \, \text{cm}^{-3} \)
- Hot plasma temperature: 1 - 150 keV
- Operative frequency: 18 GHz
- Maximum RF Power: 6 kW
Multi-diagnostics Setup

- 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 spectra with 6 ms resolution if triggered by RF probe

Plasma Emitted Radiation

**Volume-Integrated Spectroscopy**

Measuring the plasma parameters in different energy regimes: density and temperature evaluation

- Soft and hard X-ray measurements: SDD and HPGe detectors
- Optical emission spectroscopy
- RF plasma emitted radiation measurements: Plasma immersed antennas
- Interfero-polarimetry plasma density measurements

**SPACE-Resolved Soft X ray Spectroscopy**

Plasma structure evaluation and confinement studies

- Soft X-ray Pin-hole Camera

**TIME-Resolved RF +Soft/Hard X ray Spectroscopy**

Probing turbulent plasma regimes (Cyclotron Maser Instability characterization)

- RF plasma immersed antenna + Spectrum Analyzer and HPGe detector
Cause in ECR ion sources performance deterioration:

- Beam ripple
- Decrease of high charge state production

To find a method for damping the instability:

- RF Probe + Spectrum Analyzer
  RF plasma emitted radiation measurements

Plasma for Astrophysical Research:

- RF Probe + Scope + HpGe
  X-ray/RF Time-resolved Spectroscopy

Multidiagnostic Setup for MASTERING turbulent regimes of plasma:

- Pin-hole Camera
  High resolution X-ray Space-resolved Spectroscopy

Impact of instabilities on plasma structure and confinement

Understanding of physical mechanisms about electrons precipitation
We estimated the Instability Strength (IS) in a quantitative way.

Instabilities detection via RF spectra

Impact of the ratio $\frac{B_{\text{min}}}{B_{\text{ECR}}}$ on X-ray spectra

Sketch of the LNS Experimental Setup on FPT
For characterization of Maser instabilities
Looking to the scaling laws in a different way...
Langmuir probe / X ray characterization
Probing turbulent plasma regimes (Cyclotron Maser Instability characterization) at $B_{\text{min}}/B_{\text{ECR}} = 0.93$
TIME-Resolved RF + Soft/Hard X ray Spectroscopy
RF plasma immersed antenna + Spectrum Analyzer and HPGe detector

Probing turbulent plasma regimes
(Cyclotron Maser Instability characterization)

Preliminary analysis

Paper in preparation

18th International Conference on Ion Source – Lanzhou 1-6 September 2019
Interfero-Polarimetry plasma density measurements

K-band (18 ÷ 26.5 GHz) microwave Interferometer

18 ÷ 26.5 GHz OMT-based Polarimetric system

Reference branch
probing sig. generator
antenna
Spectr. Analyzer
RF probe

Plasma Immersed Antennas + Spectrum Analyzer
Non-linear wave-plasma interaction

Optical plasma Observation
Spectroscopy for cold plasma (few eV) density/temperature measure

X-ray Pinhole Camera
X-ray Imaging and space-resolved spectroscopy 2D energy distribution and (relative) density

SDD - HpGe X-ray detectors
Spectroscopy (for warm and hot plasma characterization)

Microwave Interferometry and Polarimetry measuring plasma density

Plasma heating Waveguide
L=26 cm

OMT
Plasma chamber
OMT
antenna
Rotating-OMT
OMT
Plasma Reactor
Interferometer: the density determination is based on the phase - shift induced by the plasma refractive index

Polarimetry: based on the evaluation of the Faraday rotation angle of the polarization plane of an electromagnetic wave that passes through the magnetoplasma.

\[ \theta_{\text{Far}} = \int_0^\lambda \frac{q^2}{8\pi^2 c^2 \mu_0} B(z) n_e(z) \lambda^2 dz \]
Evaluation of the integrated plasma density

Polarimetric $(2.93 \pm 0.80) \cdot 10^{18} \text{m}^{-3}$ and Interferometric $(2.1 \pm 1.0) \cdot 10^{18} \text{m}^{-3}$ estimation of the plasma density are statistically coherent each other.

Conclusions and perspectives #1

✓ On-line evaluation of plasma **density** and **temperature** in any spectral domain

✓ **Time-resolved** spectroscopy → **Plasma for Astrophysical research**

✓ **Space-resolved** spectroscopy → **Suppression** of plasma turbulence  
   **Improvement** of plasma confinement

**CSD on-line measurements** → **SpectroPolarimetry**  
**SARG** (**Spettrografo Alta Risoluzione Galileo**)

**EFFORTS** needed to still improve multi diagnostics setup for the new **plasma trap for nuclear β-decays measurements**
Advantages of OES in high intensity sources

OES is a **non-invasive diagnostics** that does **not affect the plasma** and is **not affected by the plasma**

**High voltage and mechanical constraints** limit the use of plasma diagnostics during ECRIS normal operation

OES needs just access to plasma light!

OES permits to monitor on-line:

- Electron density;
- Electron temperature;
- Ion temperature;
- Ion drift velocity;
- Local magnetic field (via Zeeman effect)
- Charged ion density

**Catania set-up for OES diagnostics on the PS-ESS proton source**

**Access to plasma light**
OES as a monitor of proton source performances: Online evaluation of species fraction and Extracted Current

A very cost-effectiveness instrument (few k€) can be used for check of source performances during normal operation.

ImSpector-V8E Spectrometer
Spectral range: 400-1000 nm
Spectral resolution: 2nm
Theoretical and experimental approach

Collisional Radiative (CR) model
rate equations for each state of the particle together with
the coupling to other particles
CR models from Yacora developed by Max Plank institute (https://www.yacora.de)

The comparison between theoretical and experimental line ratio permits to evaluate
plasma parameters

\[ \frac{H_\alpha}{H_\beta}, \frac{H_\beta}{H_\gamma}, \frac{H_\gamma}{\int f \cdot \text{band}} \]
\[ T_e, n_e, \frac{N(H)}{N(H_2)} \]
Density saturates at $0.9 \times 10^{18}$ m$^{-3}$ - 10 times overdense plasma generated;

- Evidences of heating mechanisms different from usual ECR: Electrostatic wave heating? What else?
- Temperature slightly decreases with power down to 6 eV. Trend confirmed by several authors
semiempirical 0-dimensional model

Solution of balance equations

\[
\frac{dn(H^+)}{dt} = n(H_2)n_e<\sigma v>_3 + n(H_2)n_e<\sigma v>_4 + 2n(H_2^+)n_e<\sigma v>_5 + n(H)n_e<\sigma v>_6 + n(H_2^s)n_e<\sigma v>_9 + n(H_3^+)n_e<\sigma v>_{12} - n(H^+)/\tau(H^+)=0
\]

\[
\frac{dn(H_2^+)}{dt} = n(H_2)n_e<\sigma v>_2 - n(H_2^+)n_e<\sigma v>_4 - n(H_2^+)n_e<\sigma v>_5 - n(H_2^+)^2n_e<\sigma v>_{10} - n(H_2^+)N(H_2)<\sigma v>_{11} - n(H_2^+)/\tau(H_2^+)=0
\]

\[
\frac{dn(H_3^+)}{dt} = n(H_2^+)N(H_2)<\sigma v>_{11} - n(H_3^+)N(H_2)<\sigma v>_{12} - n(H_3^+)N(H_2)<\sigma v>_{13} - n(H_3^+)/\tau(H_3^+)=0
\]

\[n(H^+) + n(H_2^+) + n(H_3^+) = n_e\]

Input parameters
\[n_e, T_e, n(H)/n(H_2)\]

Unknowns:
\[n(H^+), n(H_2^+), n(H_3^+), \tau\]

Hypothesis:
Free parameters:
\[T_i: 1 \text{ eV} \quad T_n: 0.25 \text{ eV}\]

Electron induced reaction:
\[t_e \gg T_i, T_n\]

Ion induced reaction:
\[T_i \gg T_n\]

OES Plasma Parameter Parameters: \[n_e, T_e, n(H)/n(H_2)\]

Semiempirical 0-dimensional model

In plasma Ion abundances:
\[n_{pl}(H^+), n_{pl}(H_2^+), n_{pl}(H_3^+)\]

Child-Langmuir hypothesis @ extraction
Dependence on \(1/\sqrt{m}\)

Beam parameters:
Species fraction, \(I_{exr}\)

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Main cross sections in a hydrogen plasma

\[ \sigma_1: H_2 + e \rightarrow H + H + e \]
\[ \sigma_2: H_2 + e \rightarrow H_2^+ + 2e \]
\[ \sigma_3: H_2 + e \rightarrow H^+ + H + 2e \]
\[ \sigma_4: H_2 + e \rightarrow H^+ + H + 2e \]
\[ \sigma_5: H_2^+ + e \rightarrow H^+ + H^+ + 2e \]
\[ \sigma_6: H + e \rightarrow H^+ + 2e \]
\[ \sigma_7: H + e \rightarrow H^2+ + e \]
\[ \sigma_8: H + e \rightarrow H^{2s} + e \]
\[ \sigma_9: H^{2s} + e \rightarrow H^+ + e \]
\[ \sigma_{10}: H_2^+ + e \rightarrow H + H \]
\[ \sigma_{11}: H_2^+ + H_2 \rightarrow H_3^+ + H \]
\[ \sigma_{12}: H_3^+ + e \rightarrow H^+ + 2H \]
\[ \sigma_{13}: H_3^+ + e \rightarrow 3H \]

*Janev et al., Collision Processes in Low-Temperature Hydrogen Plasmas*
Evaluation of species fraction: results

- The model gives a prediction of the species fraction, especially at higher power;
- $H^+$ fraction is predicted with satisfactory precision;
- Constant $T_i$, $T_{\text{neutral}}$ assumed.
- Further measurements needed to validate the model in continuous wave!

$T_i$: 1 eV
$T_{\text{neutral}}$: 0.25 eV

An option to monitor species ratio just by looking at plasma light!

Huge room for improvements!

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Evaluation of extracted current

1. Ions moves along a flux tube parallel to the magnetic field \((D_\parallel \gg D_\perp)\) having radius equal to the extraction hole \(r\);
2. All ions who reach plasma meniscus are extracted;
3. Ions enter the extraction region with Bohm velocity \(V_B\): \(\sqrt{\frac{kT_e}{M}}\)
4. \(\int f(+v_z) = \int f(-v_z)\) just 1/2 of the ions move towards the extraction hole;

\[
J_{\text{extr.}} \sim \frac{1}{2} qn_eV_B \quad \Rightarrow \quad I_{\text{extr.}} \sim \frac{1}{2} \pi r^2 \sqrt{\frac{kT_e}{M}} n_e
\]
Evaluation of extracted current: results

- The semiempirical model is able to give a rough prediction of the extracted current measured by ACCT:
  \[ I_{\text{extr.}} \approx \frac{1}{2} \pi r^2 \frac{kT_e}{M} n_e \]

- Also in this case, OES could be used as a monitor of proton source performances;

- Further measurements are needed to validate the model in CW and in HV conditions.

![Graph showing calculated extracted current vs. ACCT measured current with microwave power on the x-axis and current on the y-axis.]
Conclusions and perspectives #2

- OES has allowed the investigation of plasma parameters of the PS-ESS proton source:
  - Strongly overdense plasma revealed: $1 \times 10^{18} \text{ m}^{-3} \sim 10 \text{ times cut-off density}$ at 2.45 GHz
  - Slightly decreasing electron temperature in the range 15 - 5 eV
  - Atomic to molecular neutral ratio $N(H)/N(H_2)$ in the range 0.5 - 2

- OES can be used for monitoring (or estimate) beam parameters by looking at the plasma light
  - Good agreement between experimental results and calculation obtained by semiempirical 0-dimensional model
  - Species fractions and extracted current estimated by OES plasma parameters
  - A lot of room for further improvements!

- Two different new high resolution spectrometers soon in operation:
  - A Monocromator $\Delta \lambda \sim 15 \text{ pm}$
  - High resolution spectropolarimeter SARG $\Delta \lambda \sim 3 \text{ pm}$

  $T_{\text{rot.}}$, splitting Zeeman, $T_n$, high charge state line, etc.
THANKS FOR YOUR ATTENTION AND FOR YOUR WARM WELCOME IN LANZHOU !!!