JRA01-ARES

(Advanced Research on Ecr ion Sources)

INFN - GSI - GANIL - JYFL - KVI
ATOMKI- IFIN HH – IKF

Coordinator: *G. Ciavola (INFN-LNS)*

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JRA01-ARES Structure

TASK 1-Plasma heating, Wave-plasma interaction

Task Leader: **INFN** - Participants: INFN, JYFL, GSI, ATOMKI, IFIN-HH, IKF

TASK 2- Ion beam formation and transport

Task Leader: **GSI**- Participants: GSI, JYFL, INFN, KVI, ATOMKI, IKF

TASK 3- Production of metal ion beams

Task Leader: **JYFL**- Participants: JYFL, GANIL, GSI, INFN, KVI

The Joint Research Activity has been carried out according to the programme and a smooth path towards the completion is expected.
The support of EU through ENSAR contract has been an important opportunity for three excellent young researchers, that has contributed significantly to the progress of this JRA: Olli Tarvain (JYFL), winner of the Geller prize in 2010 (Grenoble), Fabio Maimone (GSI), David Mascali (INFN-LNS), winner of the Geller prize in 2012 (Sydney).

ARES Milestones and Deliverables

Milestones	**Milestone name**	**Involved**	**Expected date**
M-JRA01-1.1.1	*Correlation of X-rays emission measurements and electron heating study and relationship between the data obtained and the charge state distributions.*	*JRA01*	*27*
M-JRA01-1.2.1	*3D-simulations of ion beam extraction and transport.*	*JRA01*	*30*
M-JRA01-1.2.2	*Experimental beam analysis.*	*JRA01*	*42*
M-JRA01-1.3.1	*Ionization efficiency measurements with different mixing gas parameters.*	*JRA01*	*36*

Deliverables

Task 1

D-JRA01-1.1: Report on experimental results of microwave to plasma coupling and description of the ion sources improvements obtained in the frame of the JRA (month 48)
D-JRA01-1.2: Report on simulations and experiments on extraction and beam transport (month 48)
D-JRA01-1.3: Report on experimental results for metal ion beam (month 42).

ARES collaboration meetings

➡ Several informal phone-web meetings, one general meeting per year, a few meetings per tasks

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➡ Informal meeting, but with the participation of almost all the partners, during the ECRIS 2012 Workshop, Sidney 25th September, 2012

➡ Last general formal meeting two weeks ago, organized by JYFL in Jyvaskyla

ARES goals

➨ Improve the performances of ECR ion sources adopted in Nuclear Physics laboratories, especially of the ones involved in ENSAR.

➨ Improve the beam extraction process and the coupling of the ion source with the Accelerator.

➨ Improve the knowledge of the underlying physics to address the construction of future ion sources.

➨ Improve the diagnostics of plasmas and beams.

JRA01-ARES

(Advanced Research on Ecr ion Sources)

TASK 1

Plasma heating, Wave-plasma interaction

Task Leader: **INFN**

Participants: INFN, JYFL, GSI, ATOMKI, IFIN-HH, IKF

AIM: Overcoming the current limits of ECRIS

Activities Task 1 up to date

INFN Experiment at LNS with the plasma reactor devoted to investigate the creation of over-dense plasmas by means of electrostatic waves;
Measurements of resonant frequencies; New X-ray diagnostics;
Correlation of X-rays emission measurements and electron heating study;
Relationship between the X-rays emission data and the charge state distributions

GSI Theoretical analysis and consideration of microwave injection; Sweeping frequency over a wide range at different power levels; Multiple frequency heating;
Measurements of resonant frequencies

ATOMKI Simulation studies of the plasma: non-lost and lost electrons

IFIN-HH IKF Increase the ionization efficiencies by higher ion confinement times and higher electron densities (MD-method);
Study of plasma wall interactions and influences of the variation of source parameters on the high energetic electron population in the plasma;

JYFL Study of the resonance properties of a plasma filled electron cyclotron resonance ion source (ECRIS) plasma chamber.

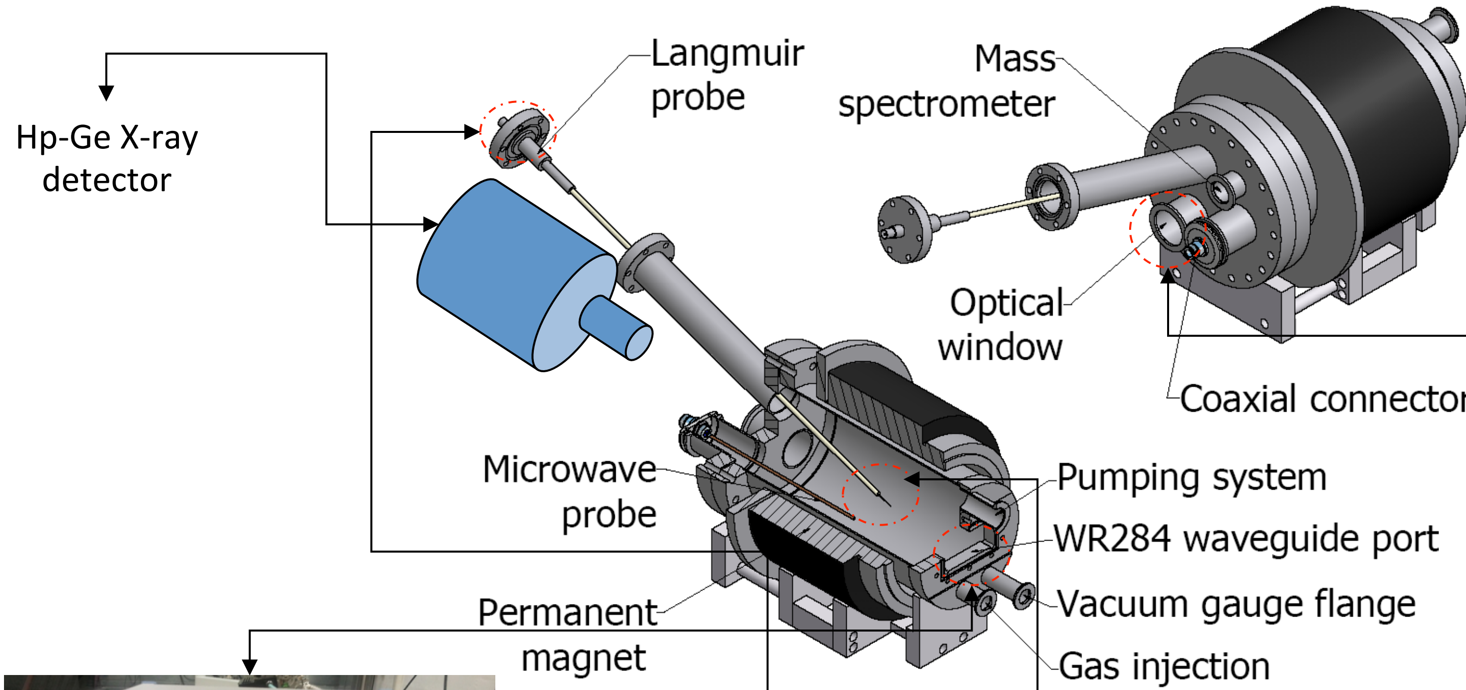
Plasma density can be hugely increased!!

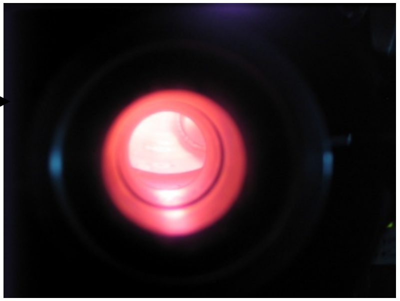
Non-linear plasma heating and hard X-rays production

Stimulated production of plasma waves

If stimulated in simplified magnetostatic field strucures, EBW can trigger overdense plasma formation producing intense fluxes of X-rays in low/medium energy range (0.1-30 keV)

Experimental apparatus for mode conversion detection@INFN-LNS

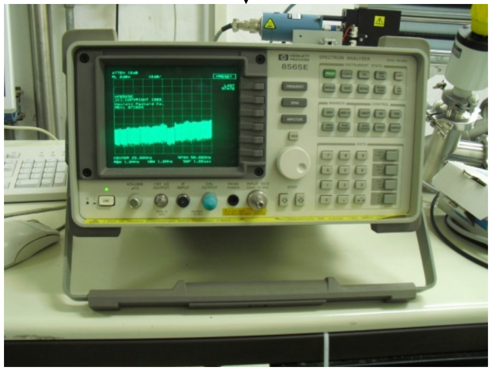




Optical window for direct observation of plasma

Travelling Wave Tube (TWT) able to erogate microwaves from 2.3 to 4.9 GHz

Tungsten probe tip: 4 mm length, 0.15 mm diameter



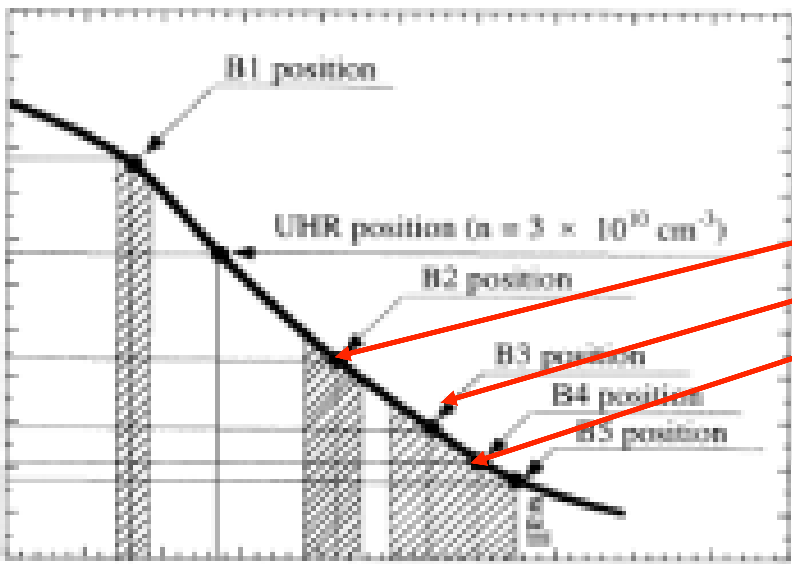
Spectrum analyzer for inner plasma electromagnetic waves detection

Theory of EM to ES mode conversion: from X to Bernstein Waves

Mode conversion takes place when the incident EM-X wave encouters the UHR layer, where it is in spatial and temporal resonance with the nascent EB mode.

Dispersion relation for EBW

$$1+\left(\frac{k_B v_{th}}{\omega_p}\right)^2 = e^{-k_B^2 r_L^2 I_0\left(k^2 r_L^2\right)} - 2\left(\frac{\omega}{\omega_c}\right)^2 \sum_q e^{-k_B^2 r_L^2} \frac{I_q\left(k_B^2 r_L^2\right)}{q^2 - \left(\frac{\omega^2}{\omega_c^2}\right)}$$

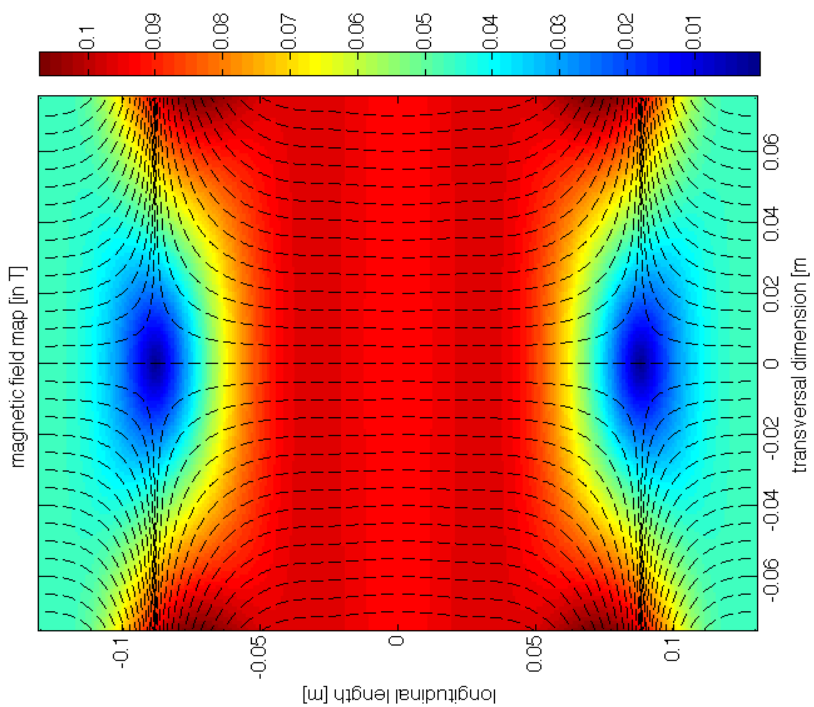


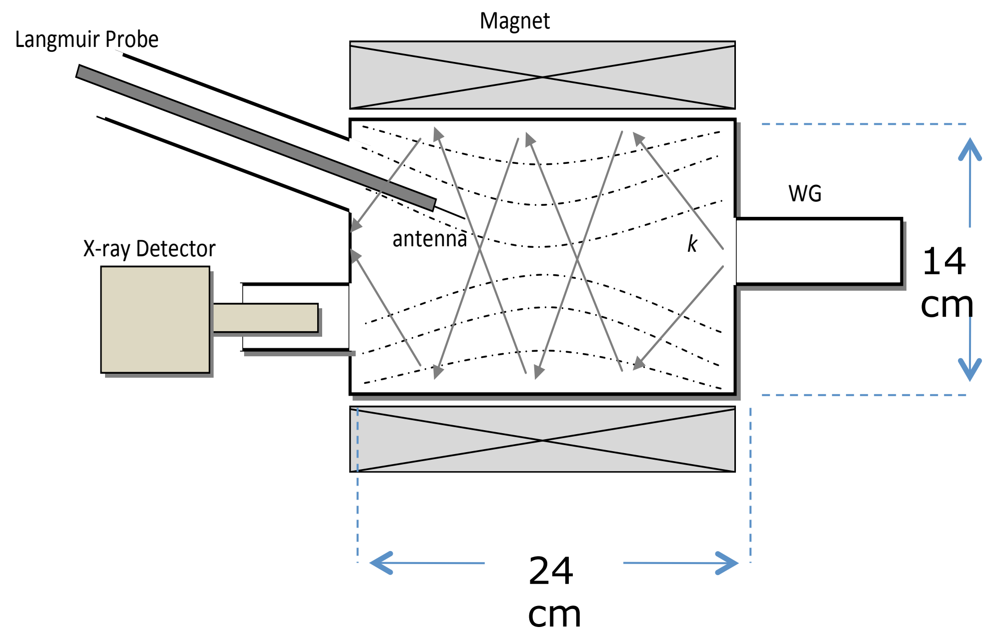
When: $B = \frac{1}{q}\frac{m}{e}\omega_{RF}$ **q=1,2,…,n**

(cyclotron harmonics) this term approaches zero and electron Bernstein waves can be absorbed by the plasma

Plasma density can be hugely increased!!

Non-linear plasma heating and hard X-rays production



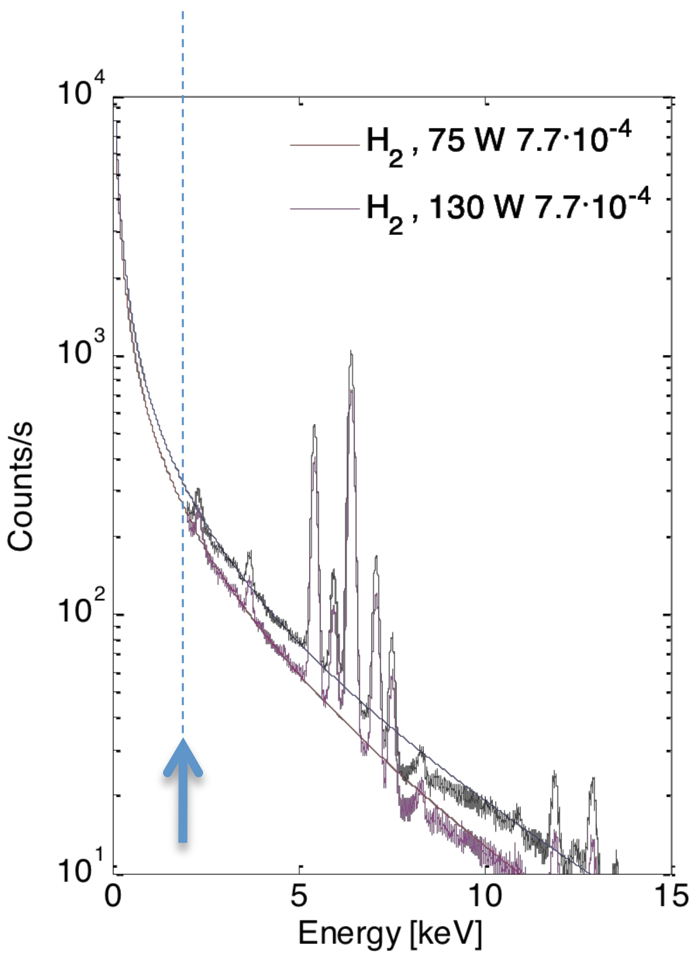


Overdense plasma production

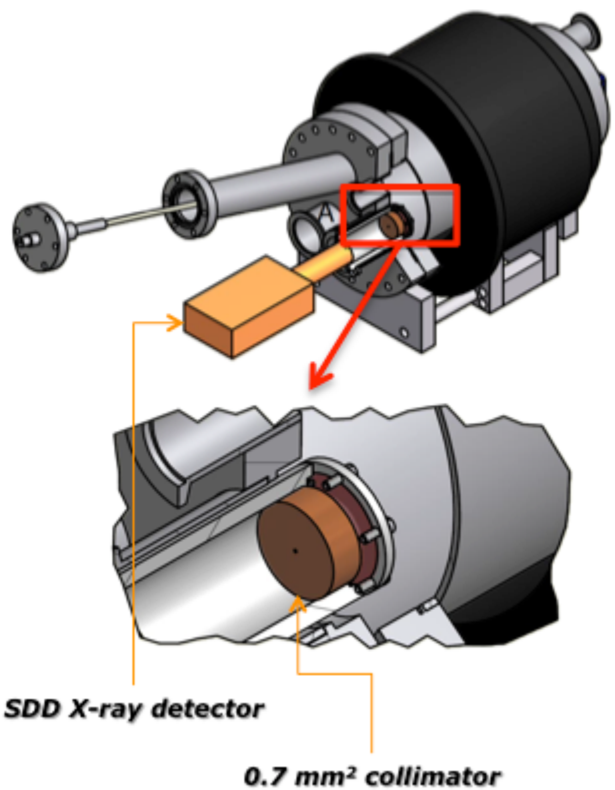
Estimation of plasma temperature and total emission

$$J_{M-K}(h\nu) = n^2 (Z\hbar)^2 \left(\frac{4\alpha}{\sqrt{6m_e}}\right)^3 \left(\frac{\pi}{kT_{Mw}}\right)^{1/2} e^{\left(-\frac{h\nu}{kT_{Mw}}\right)}$$

X-ray emissivity of an equilibrium (Maxwellian) plasma

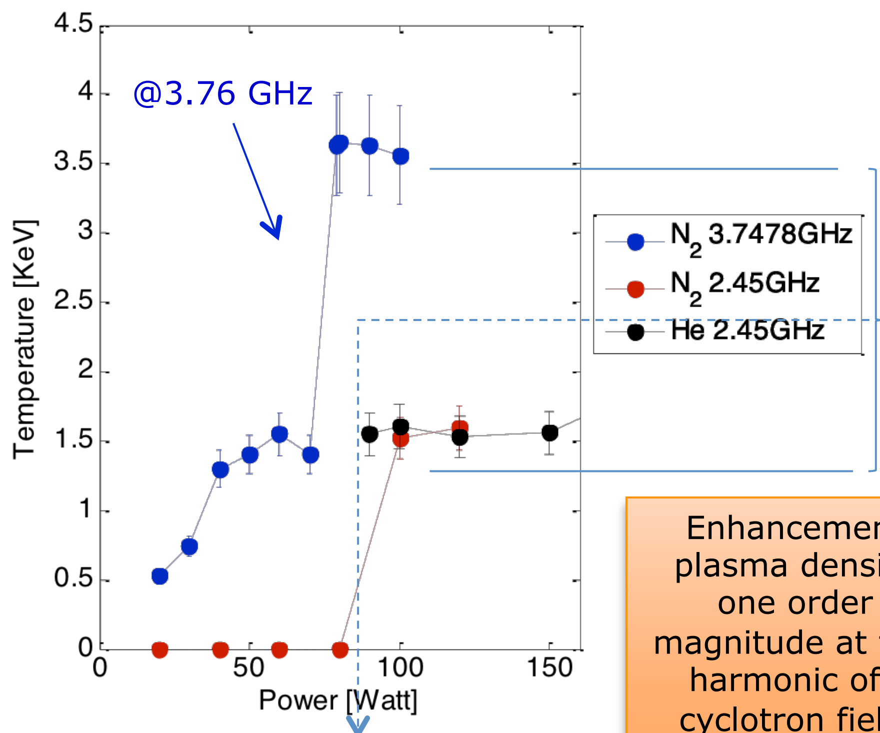


Low efficiency threshold

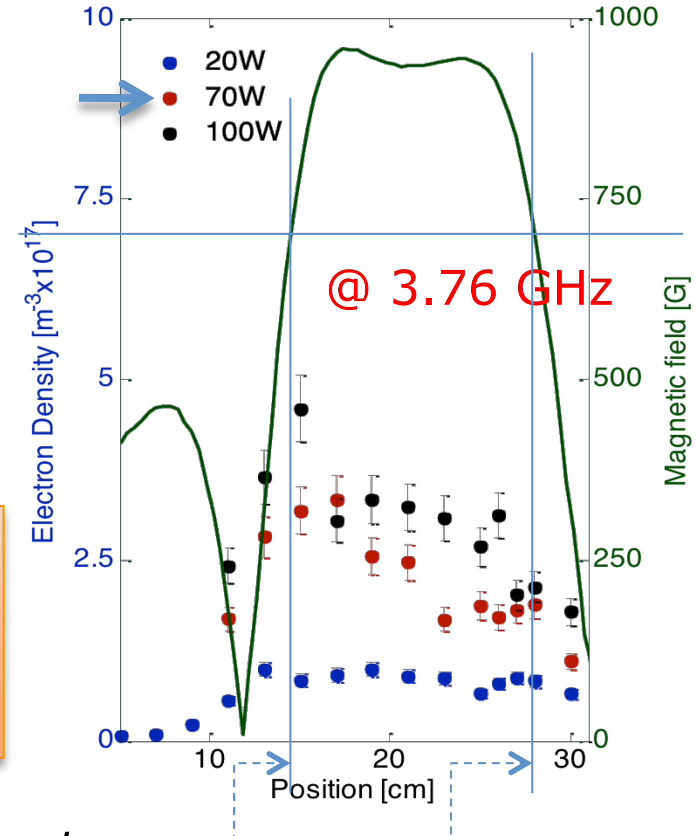


Overdense plasma production

1. Plasma density @ 2.45 and 3.76 GHz measured by electrostatic probe



Enhancement of plasma density of one order of magnitude at the 1° harmonic of the cyclotron field !!!



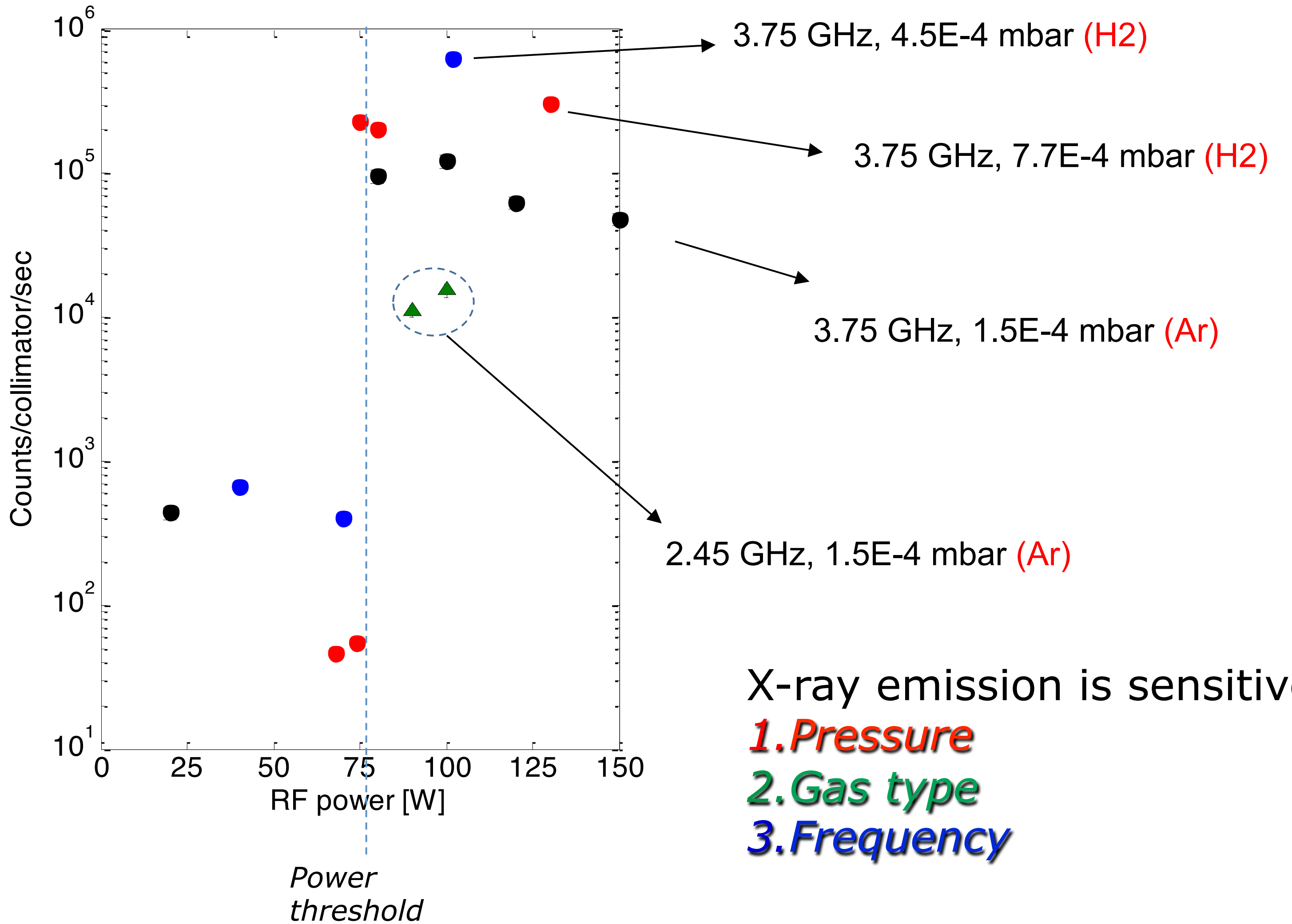
Evidence of strong non linear heating above a critical threshold

First harmonic

Experimental observation shows a non-linear growing of plasma temperature and density, with a JUMP above a certain threshold of the RF power.

Overdense plasma production

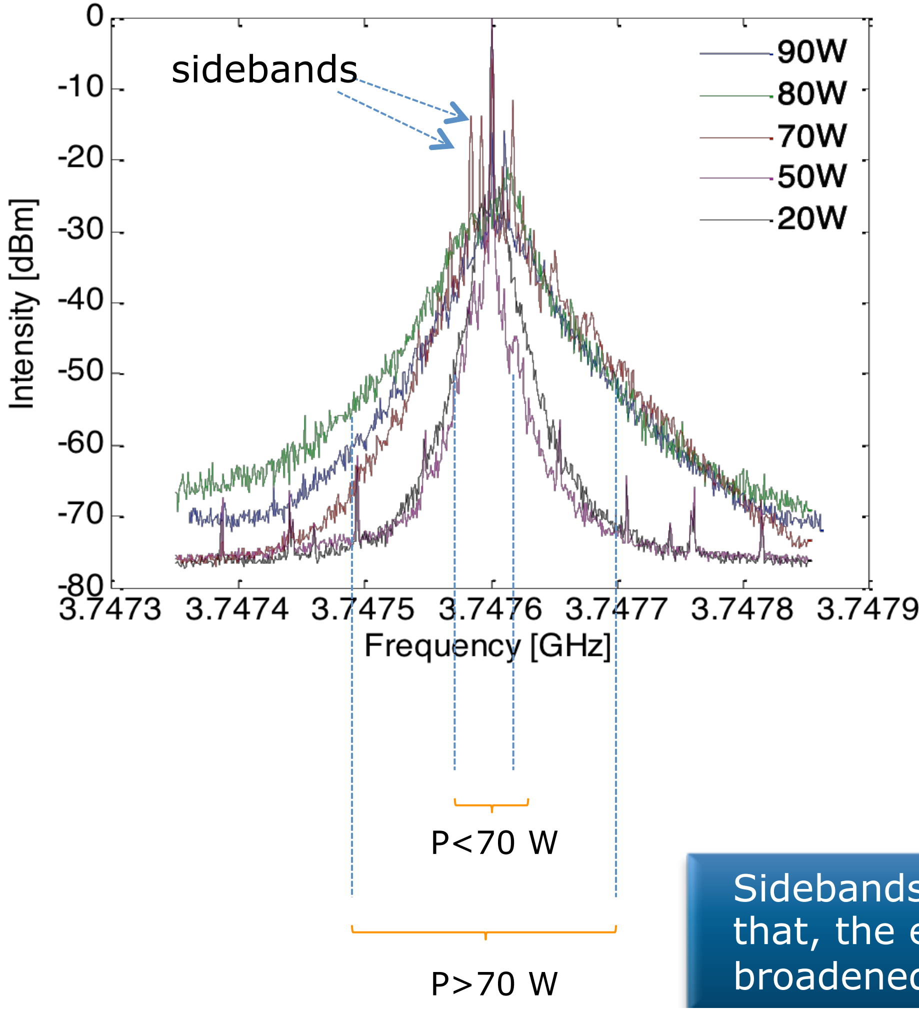
2. Preliminary studies on X-ray emission maximization

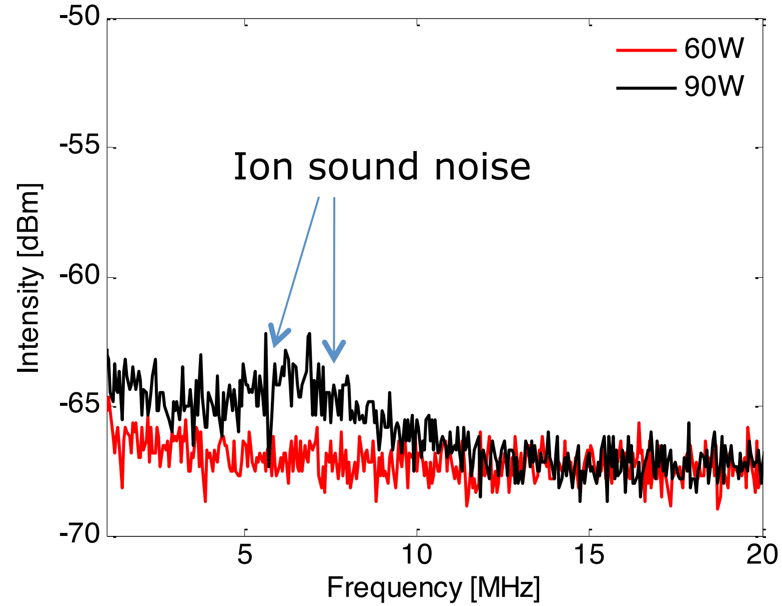


X-ray emission is sensitive to:

1. *Pressure*
2. *Gas type*
3. *Frequency*

3. Non-linear broadening of the spectrum of the pumping electromagnetic wave



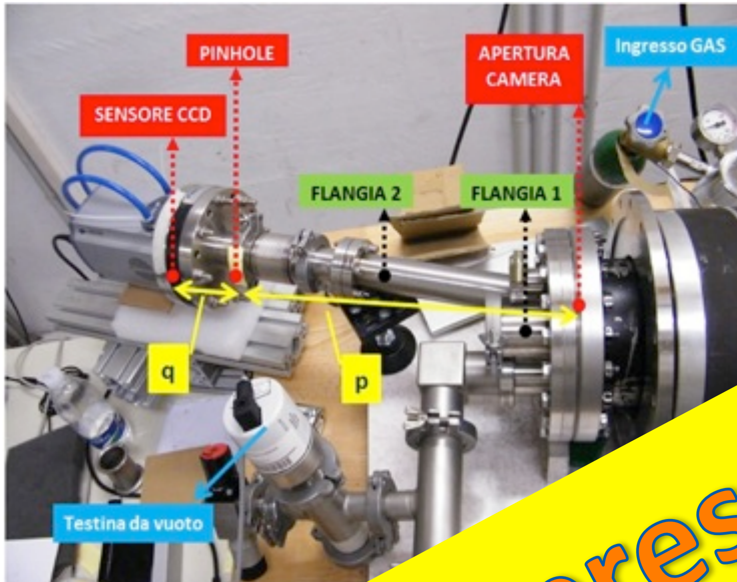


The spectral broadening of the pumping wave is accompanied by the ancillary generation of ion acoustic waves (IAW) in the MHz range

Sidebands appeared at the threshold (70 W). After that, the electromagnetic spectrum was completely broadened by the plasma turbulence.

Advanced techniques of plasma diagnostics have been already implemented the:

X-ray pin-hole camera

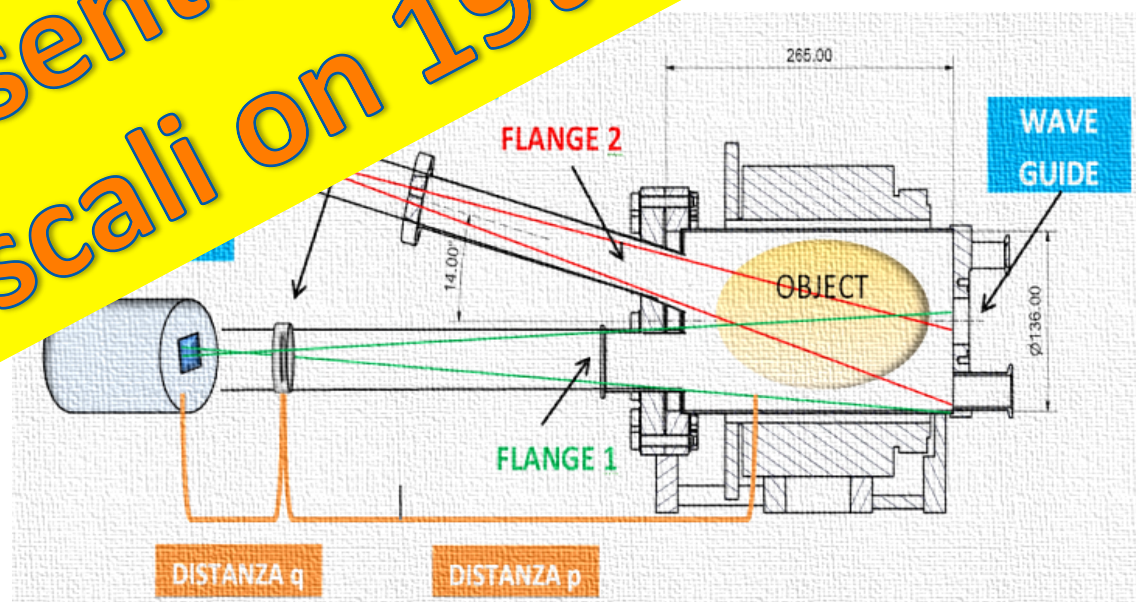


X-ray imaging can be perfo… hole camera technique

The pin-h… nd a X-r… 024

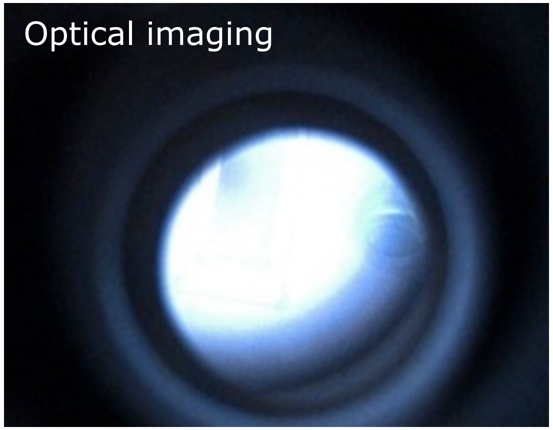
To be presented by David Mascali on 19th

X-ray se… CCD - camera



First direct observation of a HOT ELECTRON LAYER in the X-ray energies domai

To be presented by David Mascali on 19th

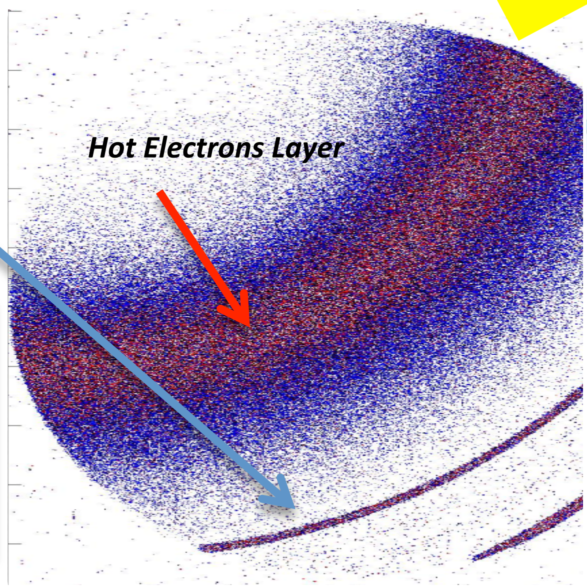


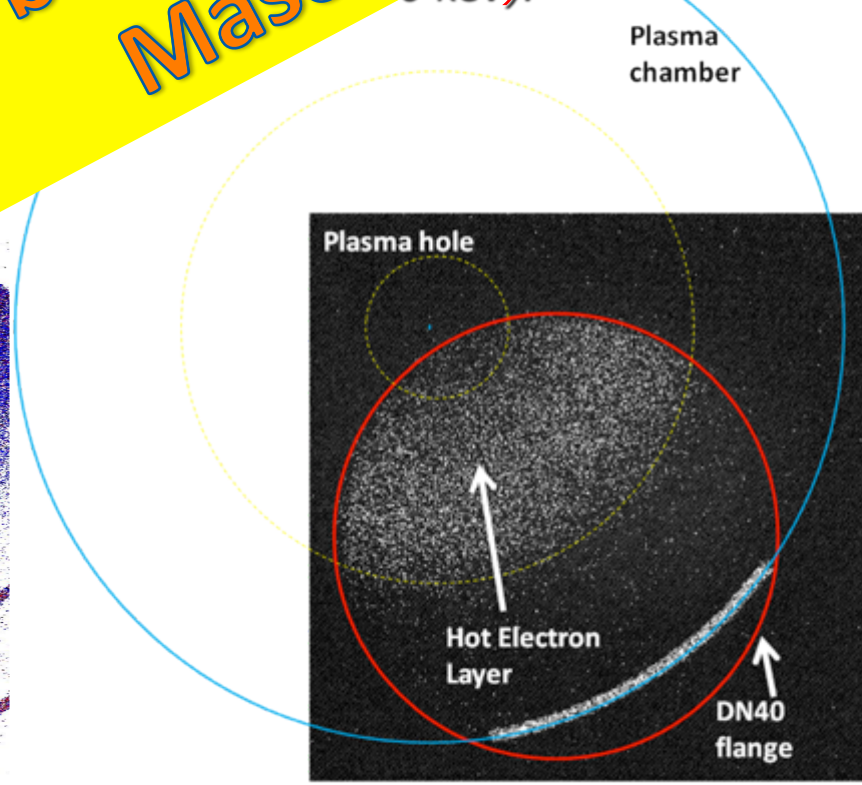
Images in the optical window, taken ... DN40 flange, evidence the gen... annulus surrounding a dar...

...ction of ...ure in X-ray ...keV).

X-ray imag... that the ... is deposi... annulus, w... energetic e... generated

A high brightness strip appears due to electrons impinging on the chamber walls (bremsstrahlung through the stainless steel walls)





gas:Argon
pressure:3*10-4 mbar
RF power:100W
1000 frames - 1sec exposure for each one

Overdense plasma production

What we understand up to now:

1- All the physical requirements for mode conversion are satisfied in our plasma;

2- It has been demonstrated, for the first time, that standing waves formed in resonant cavities facilitate the mode conversion;

3- therefore the X-wave launching system is not strictly required;

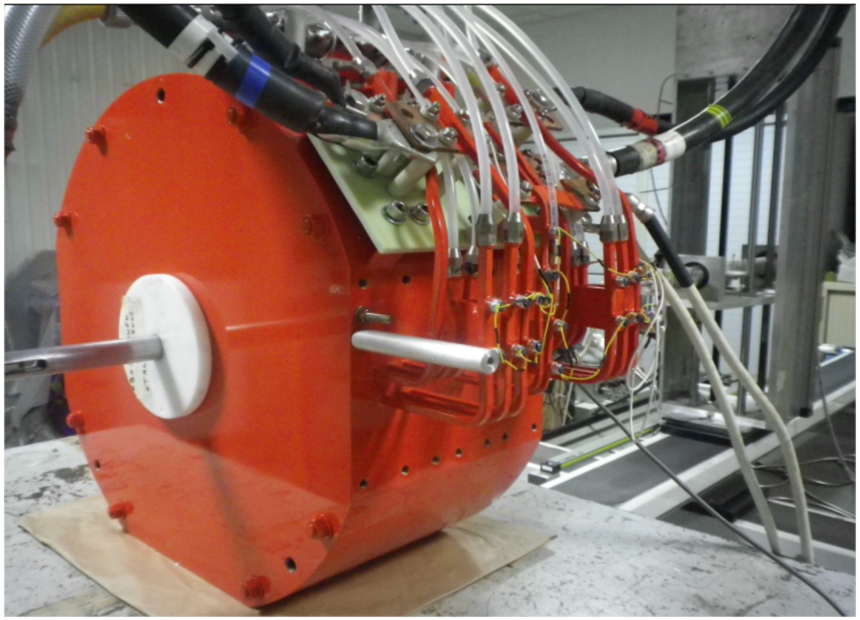
4- it may be generated conversion somewhere (conditions could be fulfilled only by certain profiles of the magnetic field);

5- The new plasma trap will help to evaluate the conversion efficiency with parallel launching (in this case the tuning of the frequency is needed, to find the proper angle of k), or with pure perpendicular launching;

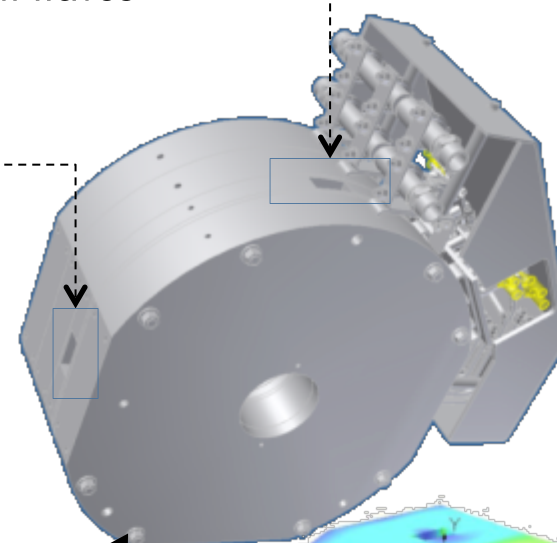
6-The new plasma trap with variable magnetic field is essential to study the phenomenon at different frequencies.

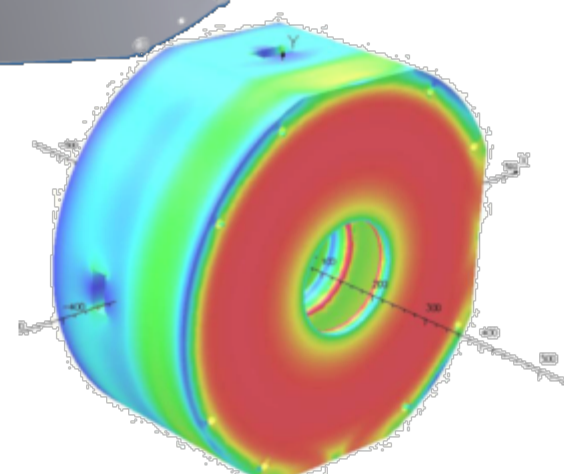
To be done: similar tests with PLASMA TRAP with versatile B-field

Investigation of EBW-heating under different magnetic field configurations



Parallel and perpendicular launching of EM waves





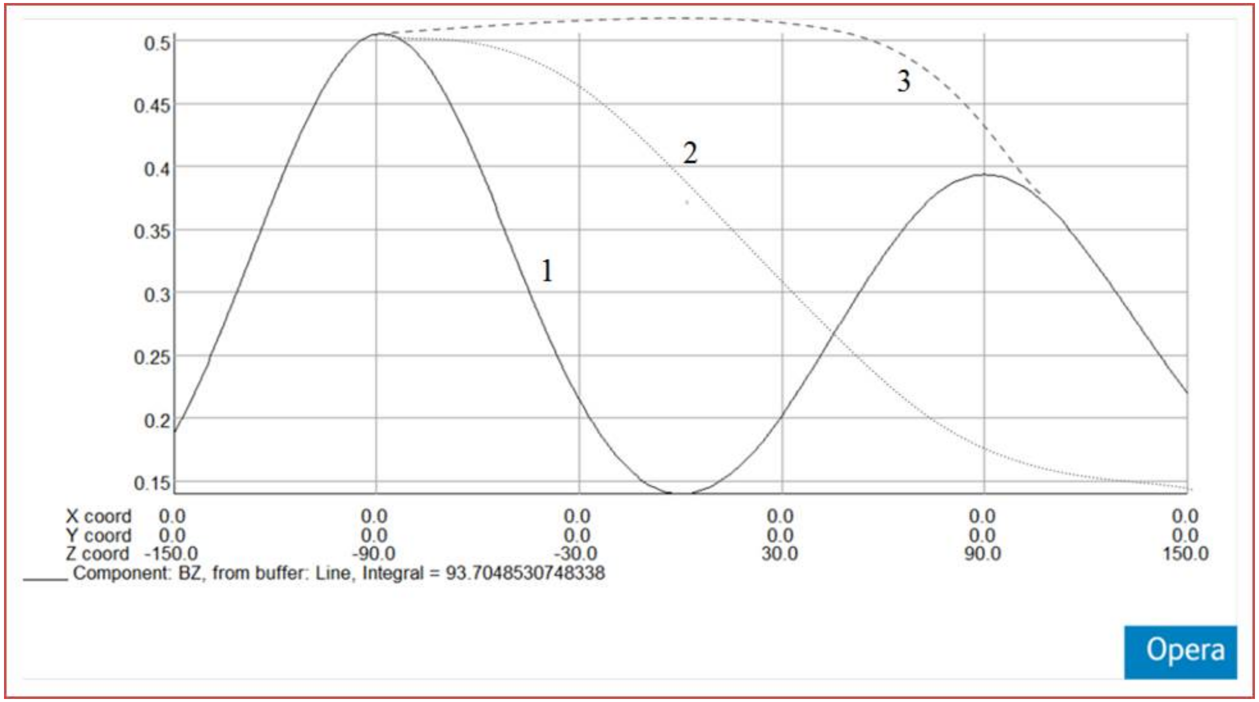
B-field magnets and structure

The new plasma trap has been designed as test-bench for plasma diagnostics and EBW-heating at 5-10 GHz:

X-ray imaging
LP measurements
RF diagnostics (spectral analysis)

PLASMA TRAP with versatile B-field

Investigation of EBW-heating under different magnetic configurations



The plasma trap is made of three solenoids which allow the tuning of the magnetic field profile. They will be studied with plasma and RF diagnostics placed parallely and perpendicularly to the B axis.

1. "Simple mirror" for multiply charged ions production;
2. "Magnetic Beach" for exploiting mode conversion at UHR and EBW absorption in higher harmonics;
3. "Off-Resonance configuration" for studies on plasma dynamics in case of parrallel/perpendicular launcing in a B field configuration like that of MDIS;

TASK 1- Some facts

1. An electromagnetic structure is preserved into the chamber even in presence of plasma. Resonant modes are excited inside the cavity and the plasma dynamics **depends on their structure;**

2. Different modes take to different **heating rates**;

3. Density non-uniformity can make shorter the **ion lifetime τ_i and the plasma energy content is depressed**.

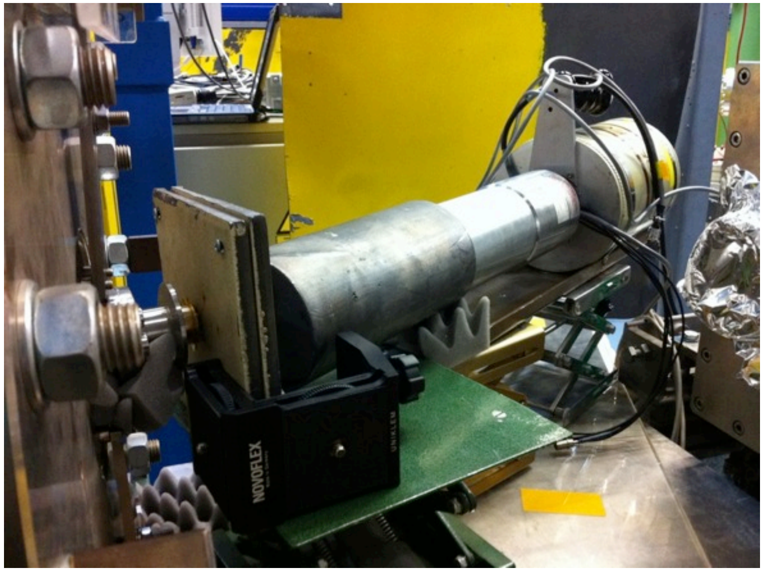
4. The hollow beam typically extracted from ECRIS reflects the high order modes which are usually excited in ECRIS.

Under investigation: Tuning of frequency may restore conditions of good axial confinement, removing the hollow shape of extracted beam, and positively affecting the **heating rapidity, the ion confinement time and the emittance**.

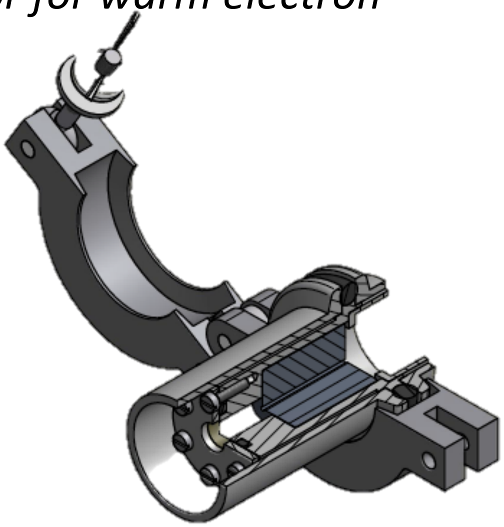
Measurements at EIS testbench (GSI):

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

SDD detector for warm electron component



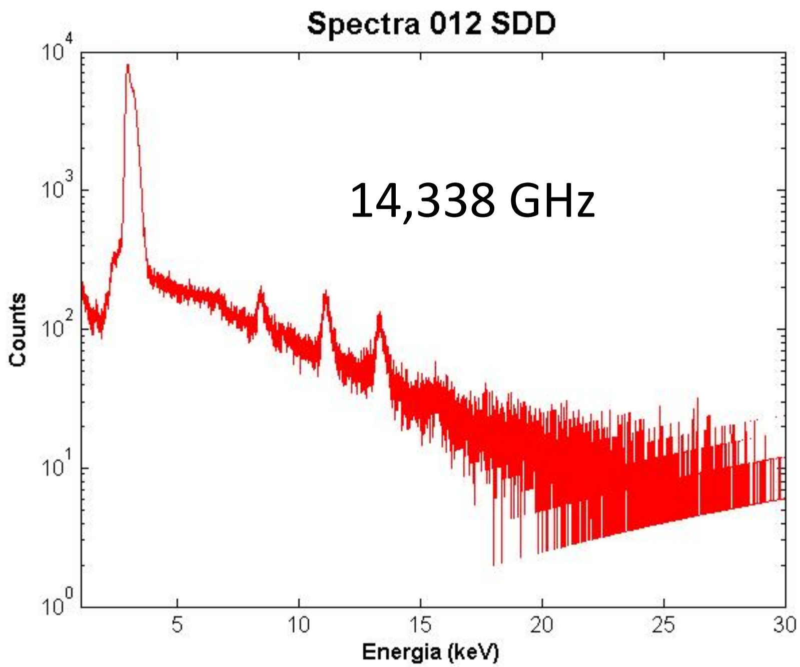
HpGe detector for hot electron component



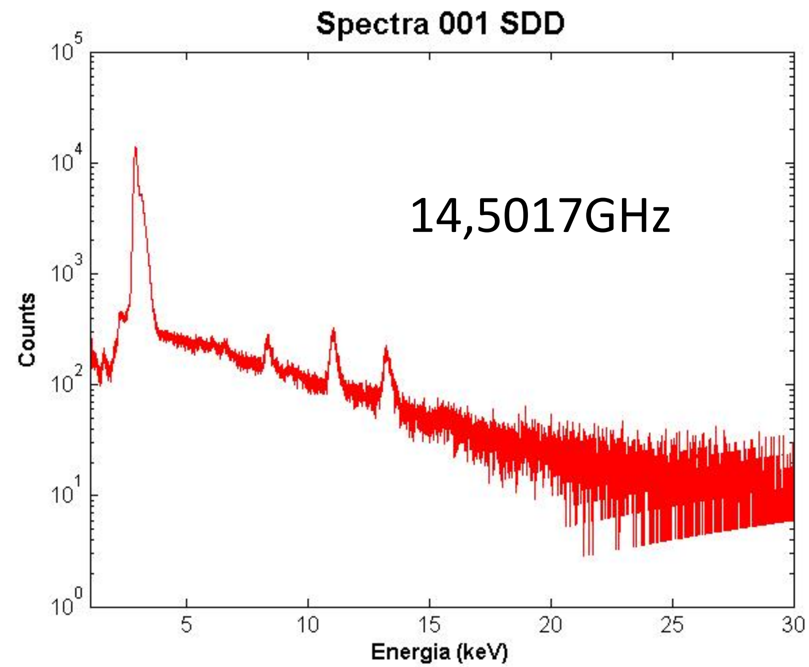
Collimation system for the detection of the plasma-core (only) X-radiation.

Measurements at EIS testbench (GSI):

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



T=6,5617 keV ± 0,56833622



T=8,5279 keV ± 0,341697613

The fine tuning of the frequency produced strong changes in the energy spectrum, reflecting on the warm plasma temperature.

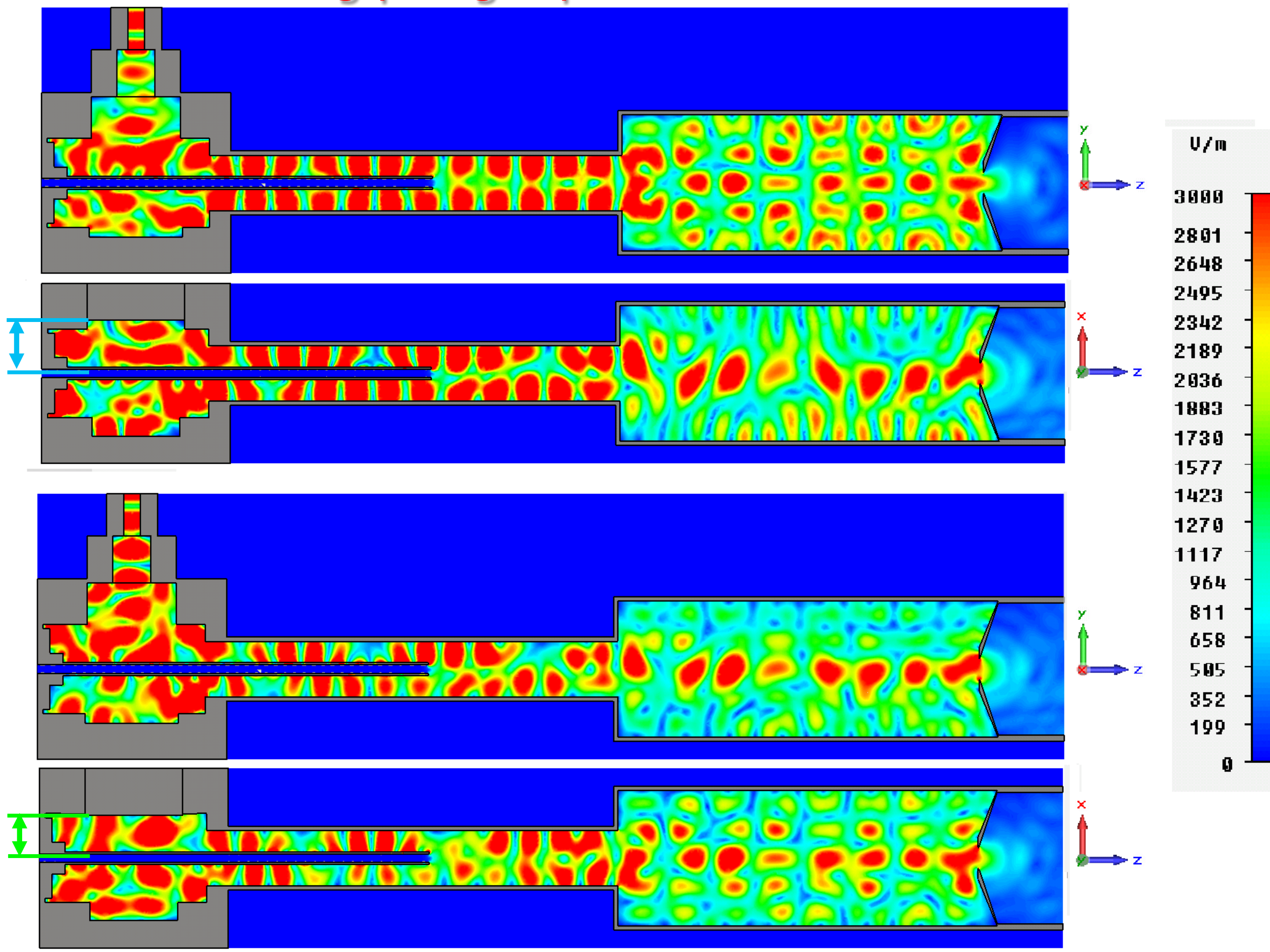
PISTON TUNING SIMULATIONS RESULTS

Effect of the tuning of the matching plunger position on the electric field

- Electric field amplitude at 14.5 GHz, in the yz and zx planes.

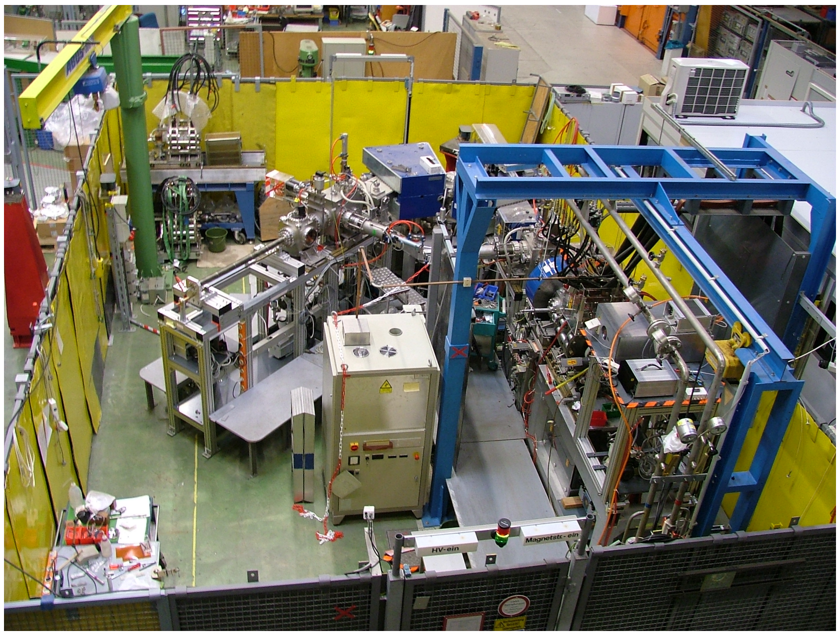
- Two settings of the plunger: 25.05 mm and 20.05 mm of distance with respect to the plasma chamber axis

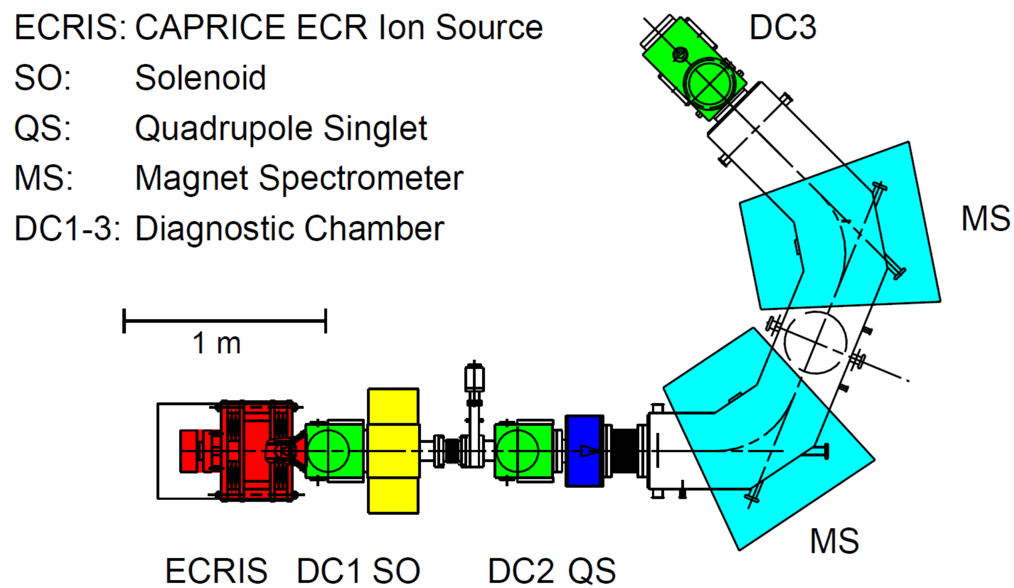
- Different electromagnetic field patterns for the two settings



CAPRICE ECRIS AND TEST BENCH DESCRIPTION

ECR INJECTION SET-UP BEAM LINE

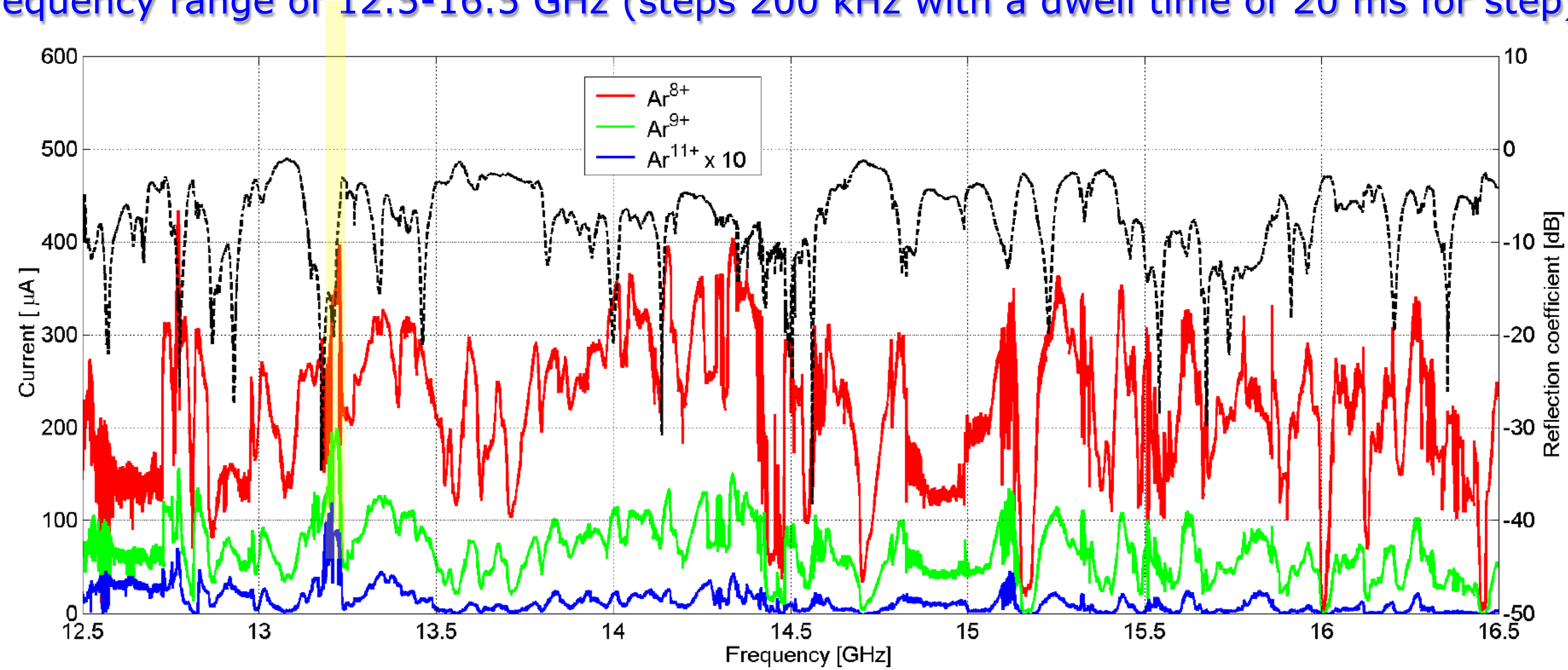




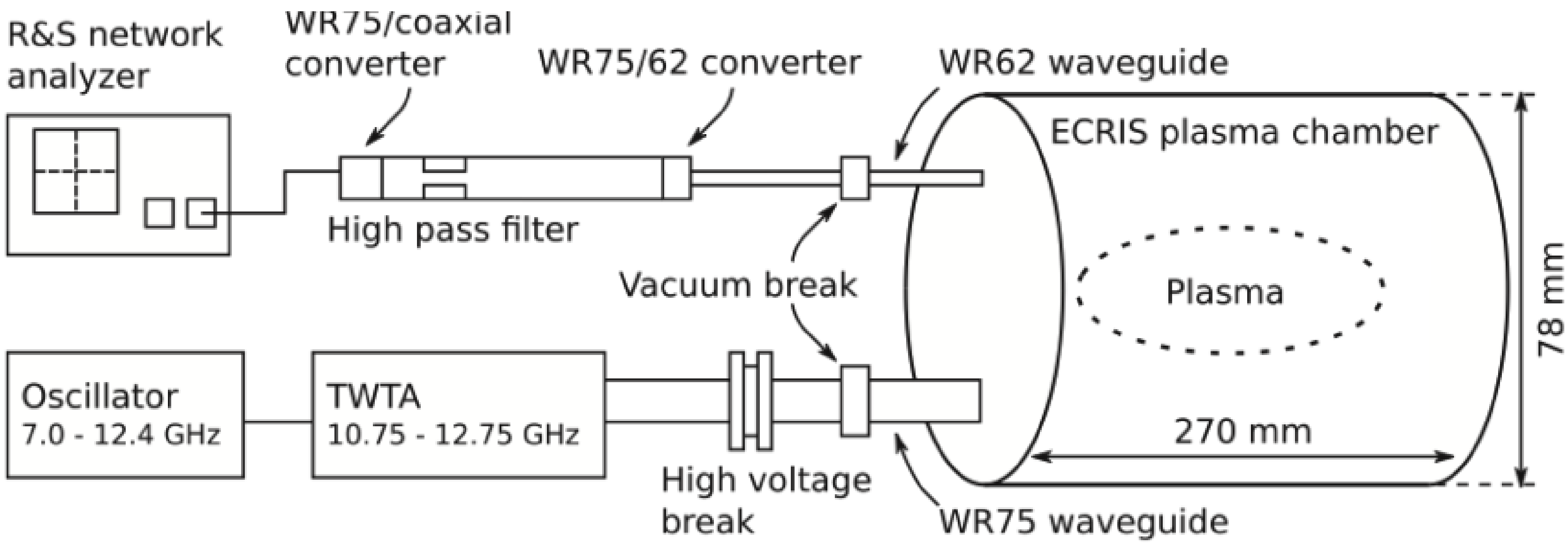
FREQUENCY TUNING: EFFECT ON THE HIGHER CHARGE STATES 1/2

- The CAPRICE source parameters were set in order to maximize the production of the Ar^{11+} ion current. Then the frequency sweeps were performed while the Ar^{8+}, Ar^{9+} and Ar^{11+} beam currents were measured
- For some frequencies, like 13.221 GHz, the higher charge states current enhances with respect to the case of 14.5 GHz

The electromagnetic waves, amplified by a TWTA up to 550 W, sweep in the frequency range of 12.5-16.5 GHz (steps 200 kHz with a dwell time of 20 ms for step)

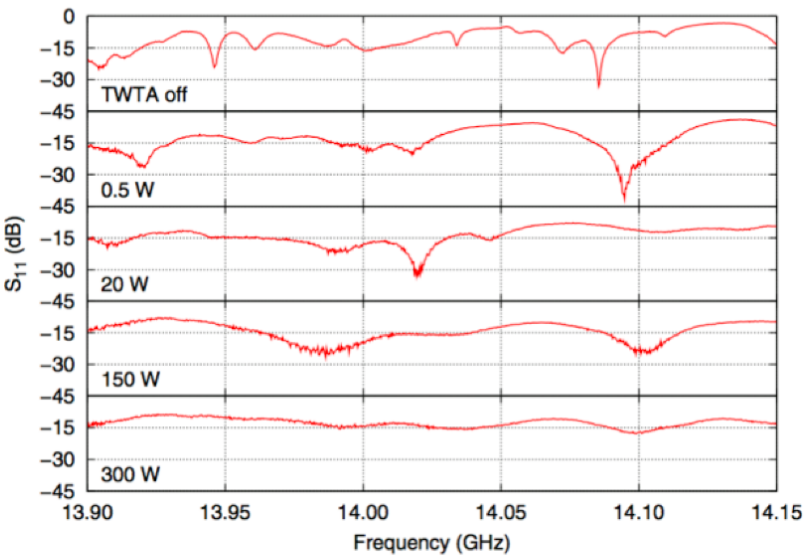


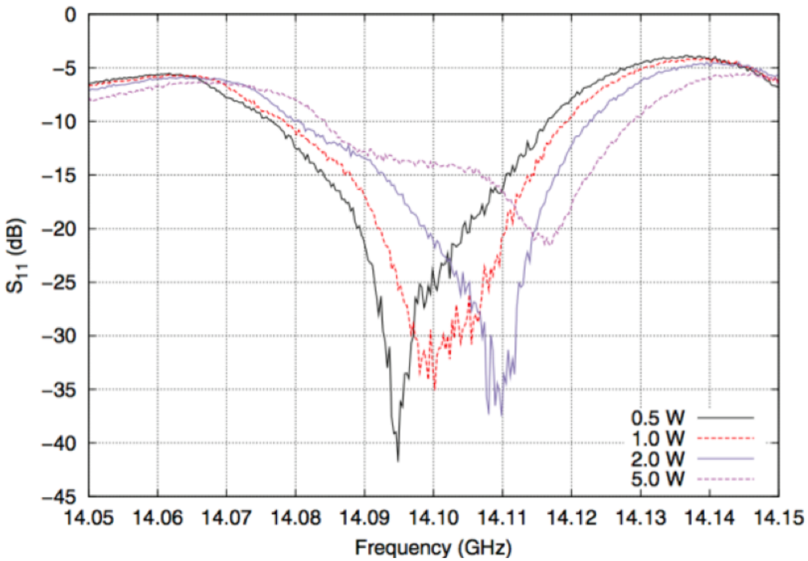
ECRIS studies with Network Analyzer @ JYFL



Dual port measurement setup for probing the coupling properties of plasma loaded cavity.

ECRIS studies with Network Analyzer @ JYFL



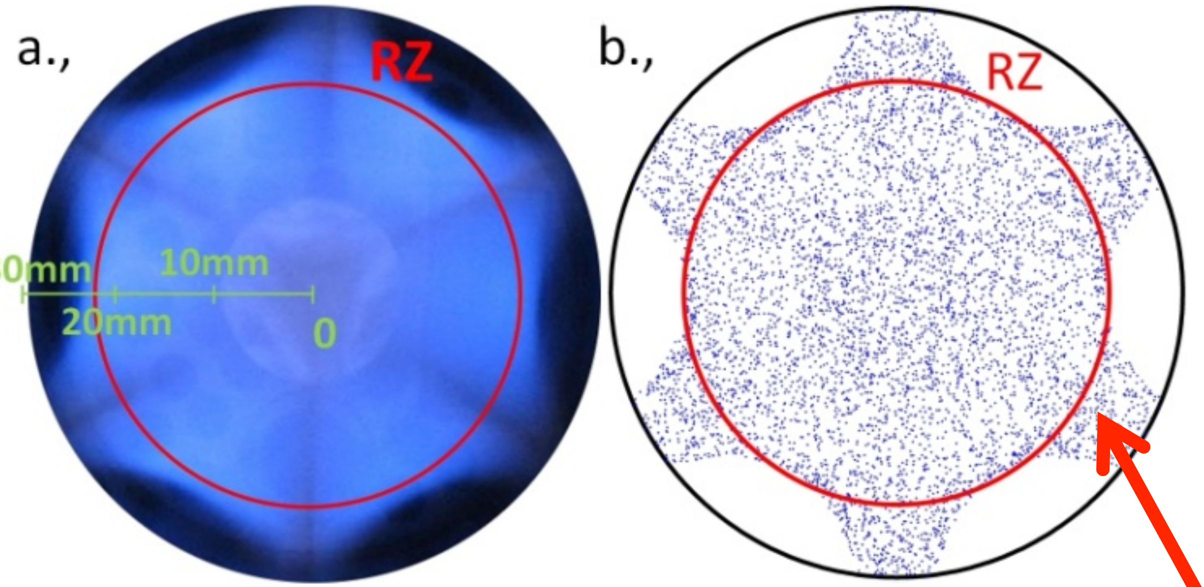


The presence of plasma changes the cavity resonance properties significantly, damping the mode behavior

Controversial results obtained from this and the two previous activities.

Item to be discussed to understand the reason of such discrepancy!!!

Comparison: VL-photo and electron simulation @ Atomki



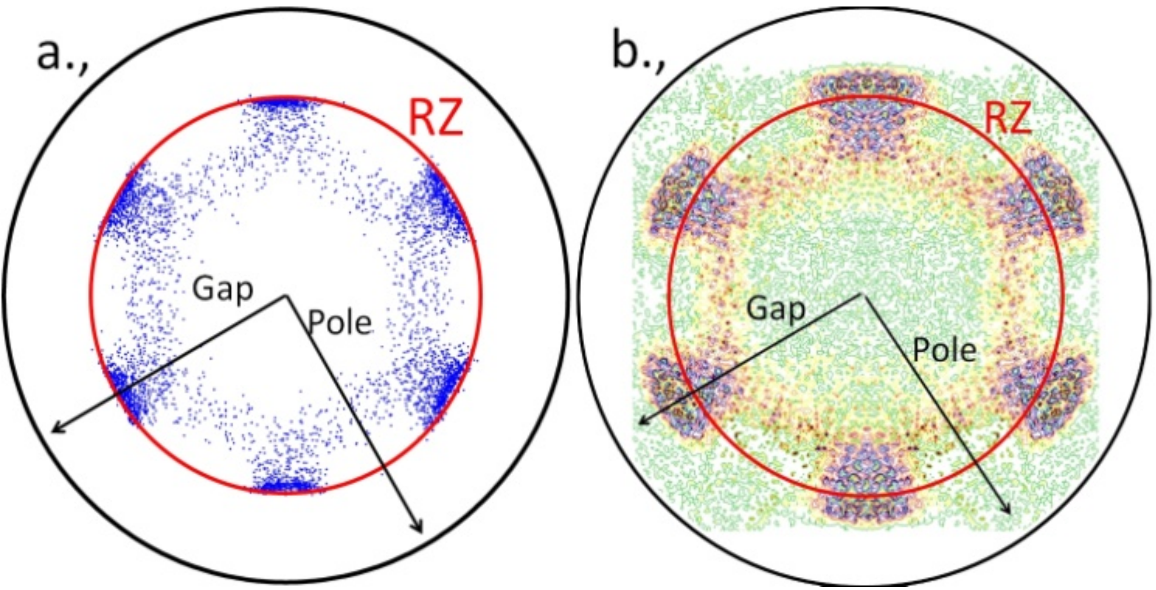
Typical argon plasma. Photons from excited atoms and ions. 14 GHz, 50 W

TrapCAD simulation, 14 GHz, electrons

- $5*10^5$ starting particle
- start from resonance zone
- start energy: 1-100 eV
- random direction
- ECR heating ON
- Calculation time: enough statistics for lost and non-lost electrons
- filtered energy: 1-200 eV
- 5000 electrons left

- Good agreement between the photons and electrons.
- Cold electrons are not so well bounded: the plasma is not empty.
- In contrast to high energy electrons, cold electrons are very effective in exciting visible light.
- VL-photographs show the plasma region with cold electrons confined almost equally inside the RZ.

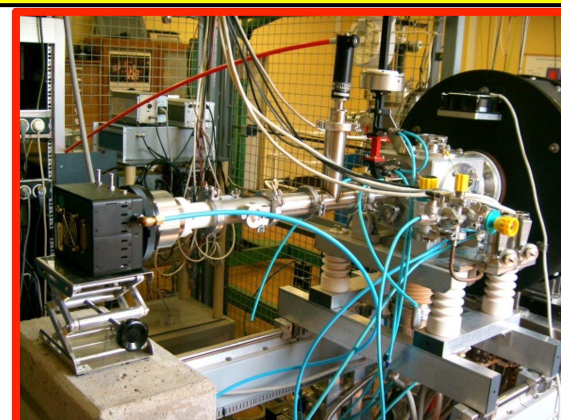
Comparison: electron simulation and X-ray-photo @ Atomki



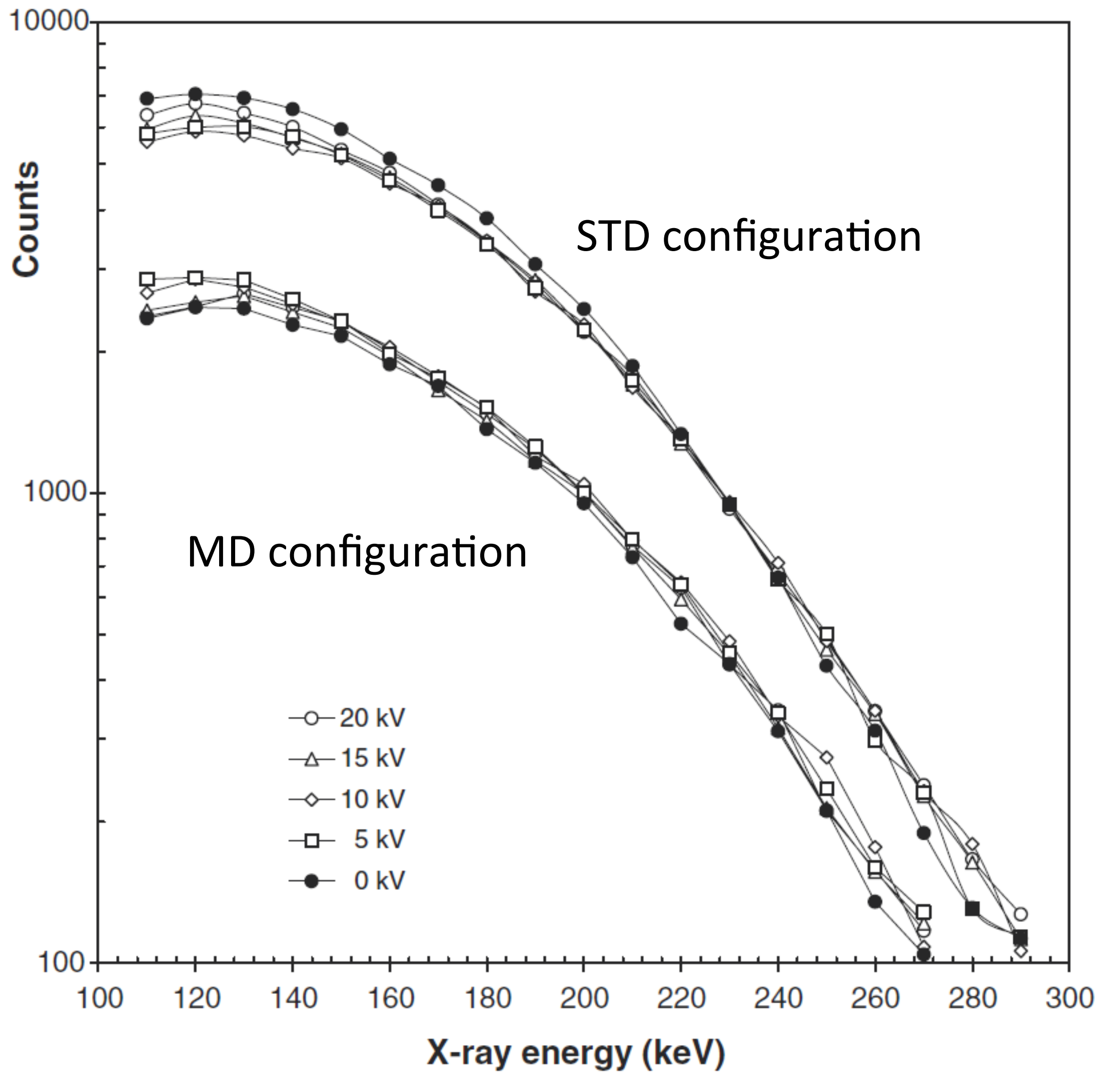
- Good agreement between simulation and XR-photo.
- Warm electrons are trapped at magnetic **gap**.
- Argon ions locate at the **same** positions.
- Strong azimuthal and radial inhomogenity.

TrapCAD simulation, 14 GHz, warm electrons. The same output file was used as for cold electrons. Filtering here: 3-10 keV

X-ray photo, argon Kα radiation (cca 3 keV) *14 GHz, 50 W*



Investigation on the influence of the extraction voltage on energetic electron population in ECRIS plasma @ IKF.



An influence of the extraction voltage on the high-energy slope of Bremsstrahlung-radiation spectra has been reported in ECRIS experiments and was interpreted as an indication of a change of the EEDF.

Drastic reduction of the x-radiation level by using MD-structures is obvious. Within statistical accuracy (error bars are smaller than the symbol sizes), ***there are no drastic changes with extraction voltage for the two configurations****. Interestingly, the x-ray spectra for the standard configuration at 0V extraction voltage are highest while they are lowest for the MD configuration. This can be understood by the fact that at suppressed ion extraction more compensating plasma currents are redirected to the walls. The presence of the Ta-MD structure minimizes this effect*

Task 2

Ion beam formation and transport

2a) Simulations with KOBRA3D with trajectories starting inside the plasma

2c) Space charge compensation of the ion beam and its effect on ion beam quality and beam line transmission

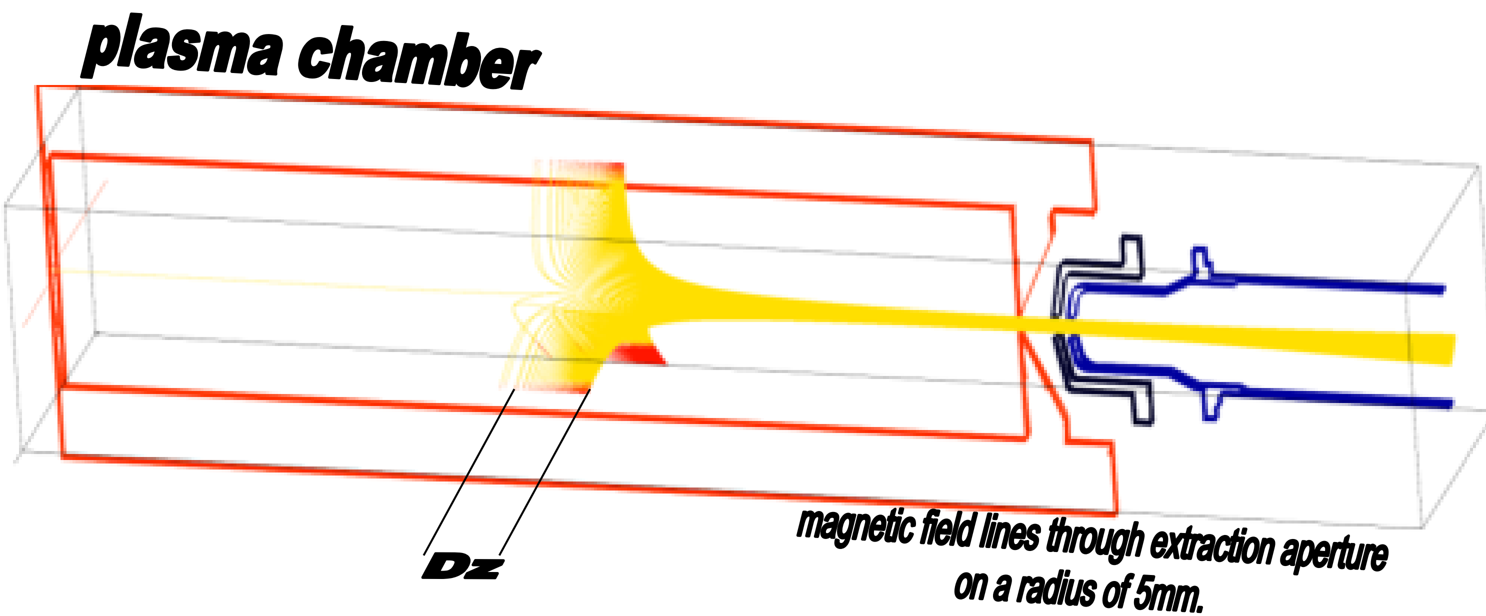
2d) Beam transmission in connection with investigations of task 1

2e) Beam analysis using pepper pot device and viewing targets

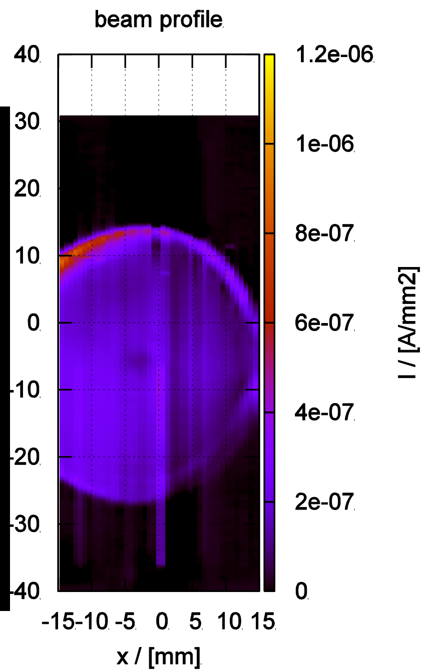
2g) Comparison of simulation results (LNS code, KOBRA3-INP, KVI code) and experimental data at different test benches

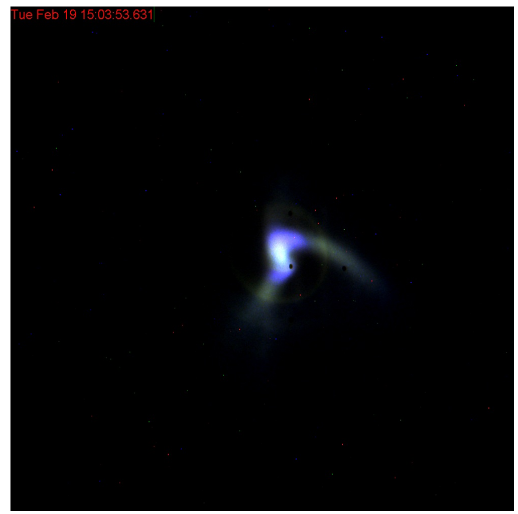
Ion beam formation and transport

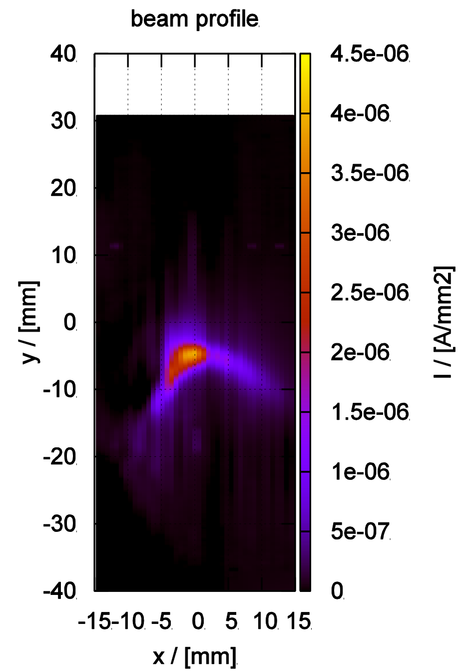
- Assuming that electrons and ions are magnetized within the ion source plasma:
    - Ions do follow magnetic field lines.
    - Because field lines with different azimuthally positions at the plane of extraction originate from different longitudinal positions, they do have a different B at the initial position. See Fig. 5 in [6].
    - Simulations with KOBRA3D satisfy this model with trajectories starting inside the plasma.



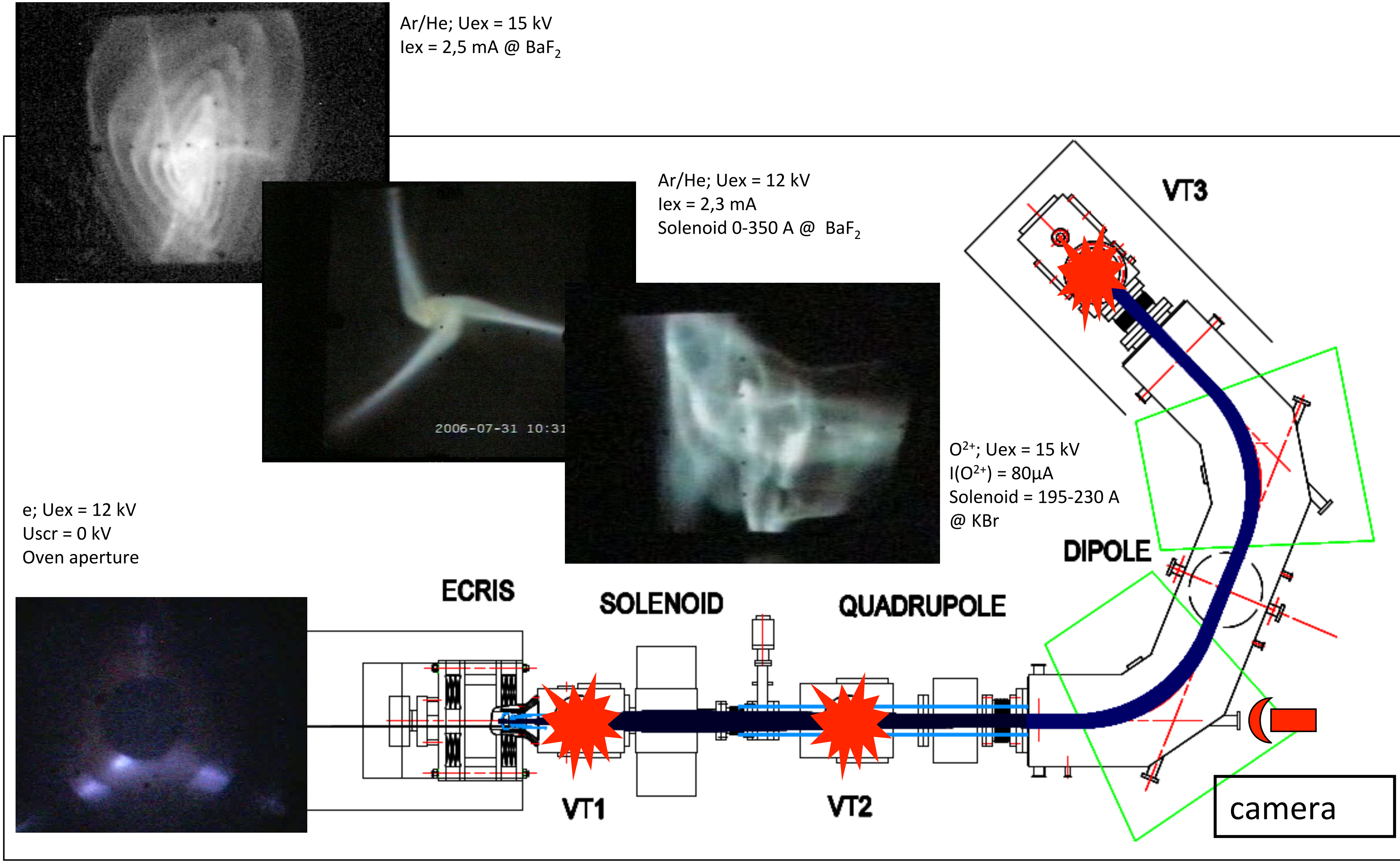
Confirmation of obtained profiles using viewing targets by multi FC array measurements!





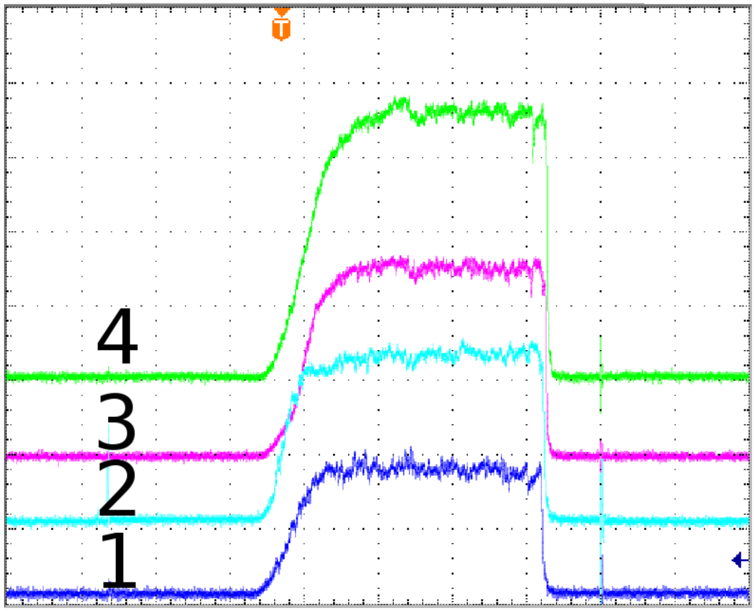


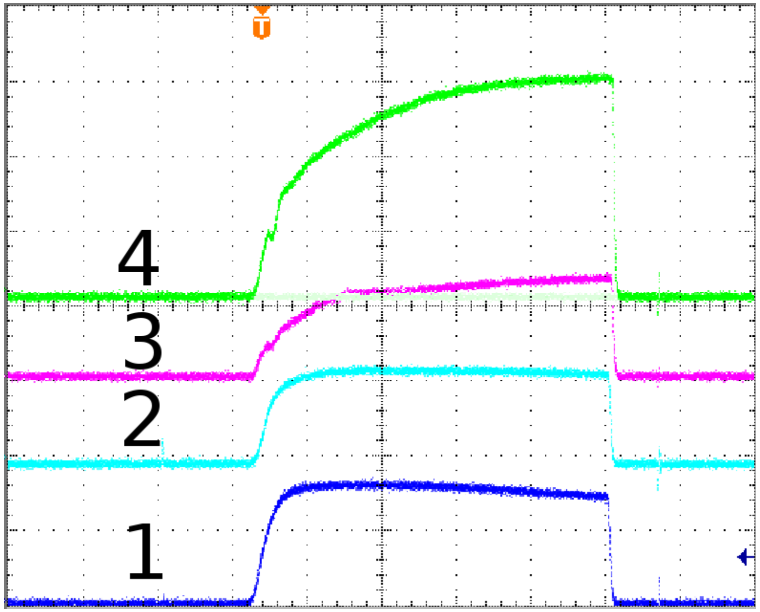
Viewing screens at the EIS-GSI test bench



Measurement of degree of space charge compensation

- Pulsed beams (if plasma rise time < SCC rise time)

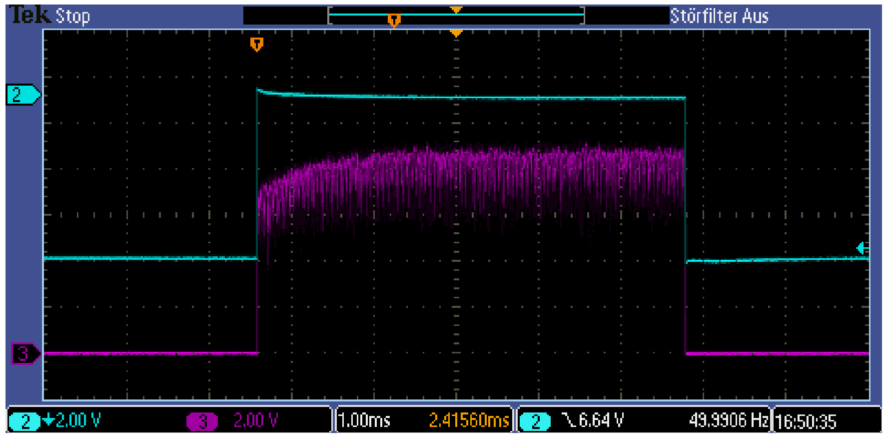




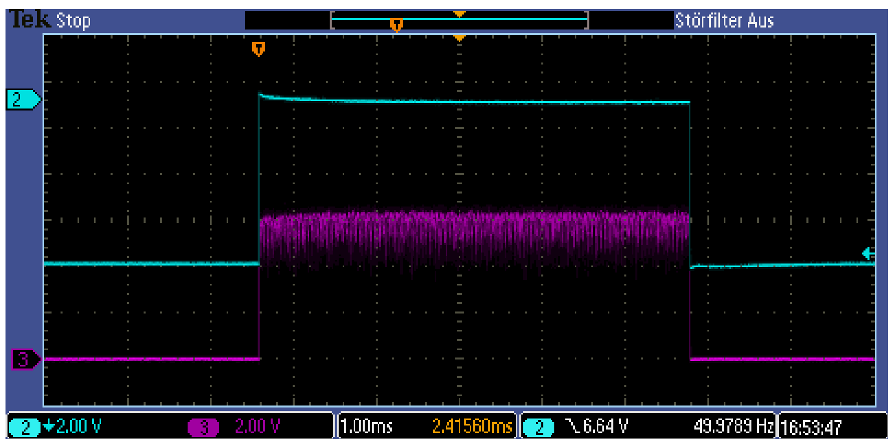
Beam transformer signals (1-4) along the beam line from a MEVVA-IS (Ni^{2+}) and a MUCIS (N^{2+}) [4].

The beam transformer measurement gives the possibility to compare signals of the <u>same</u> macro pulse.

10keV He$^+$ Beam (800µA without grid, 600µA with grid)



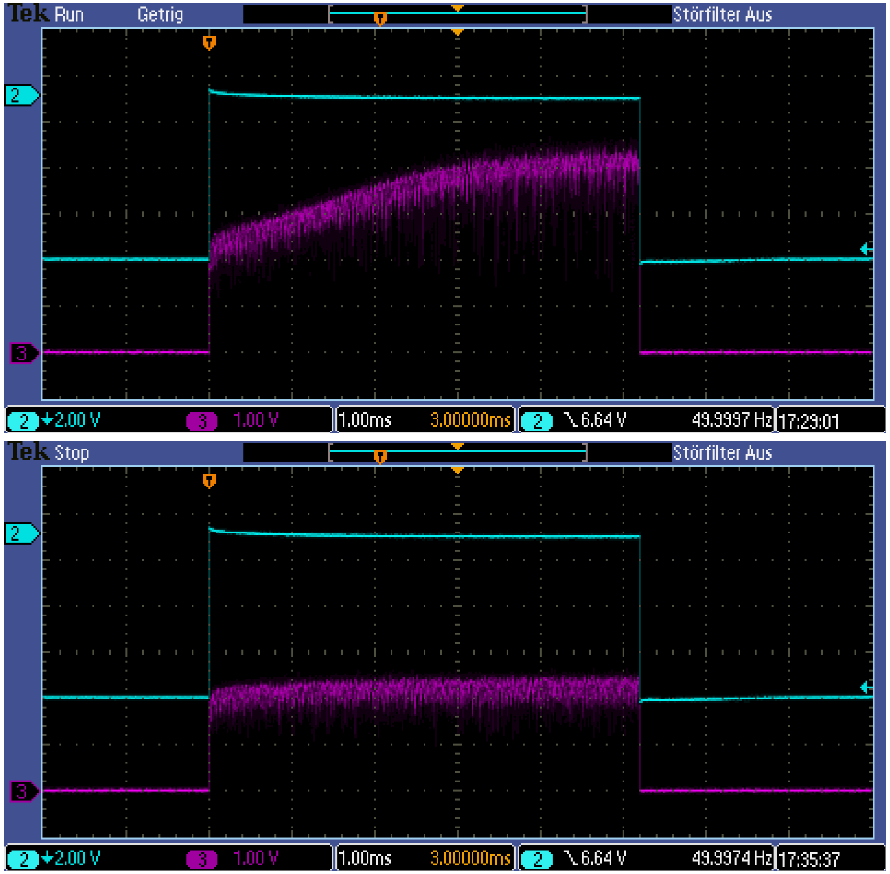
Grid out



Grid in

1ms build-up time in residual gas only, 0 with additional grid

5keV He$^+$ beam (400µA without grid, 250µA with grid)



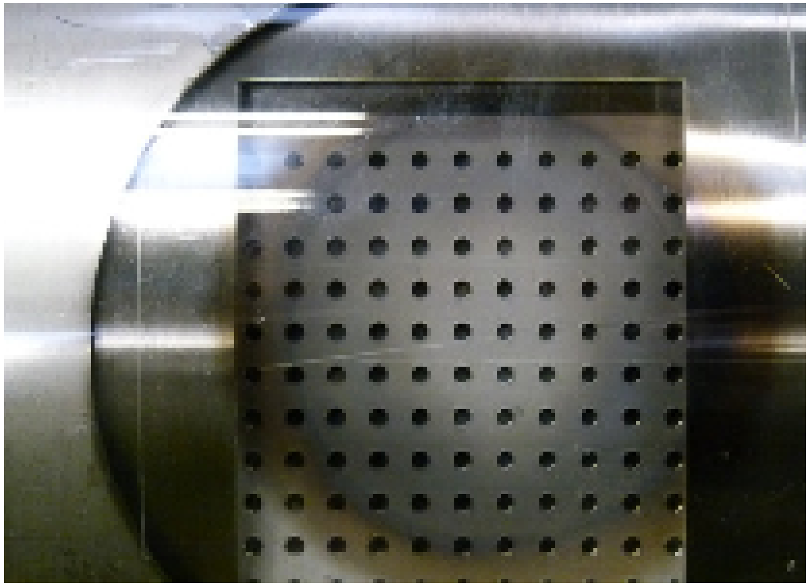
Grid out

Grid in

3.5 ms build-up time in residual gas only, 0 with additional grid

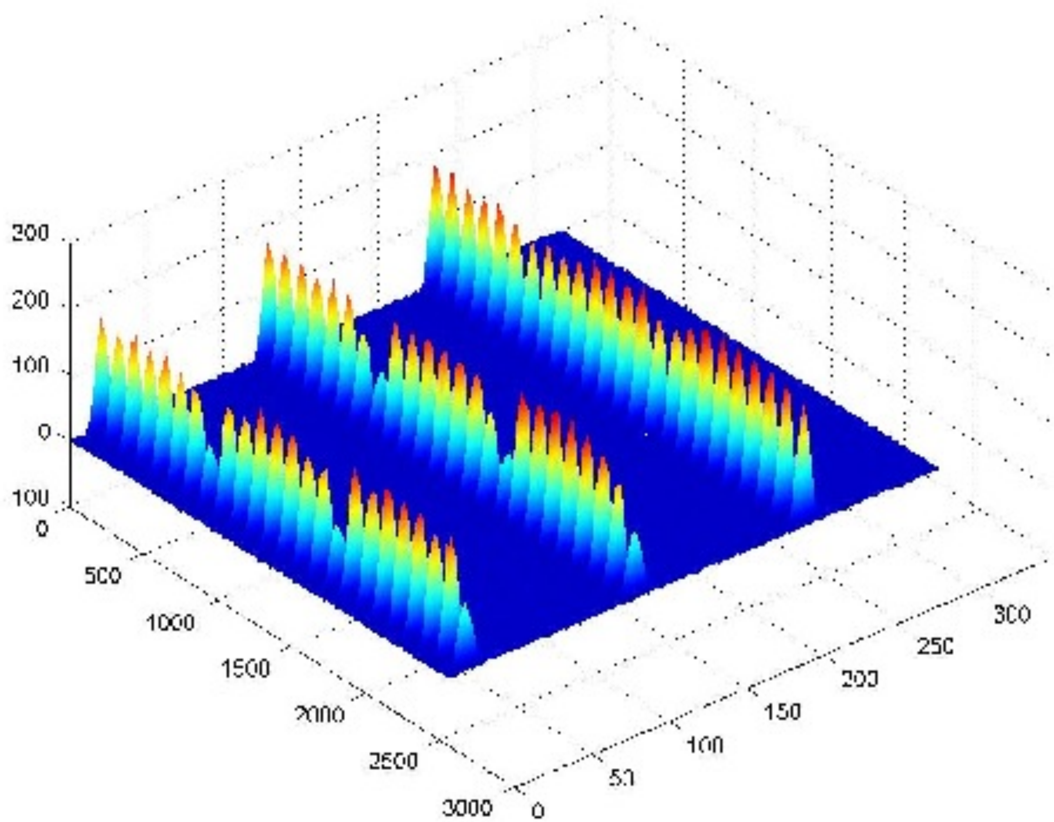
Commissioning of both versions of the pepper pot

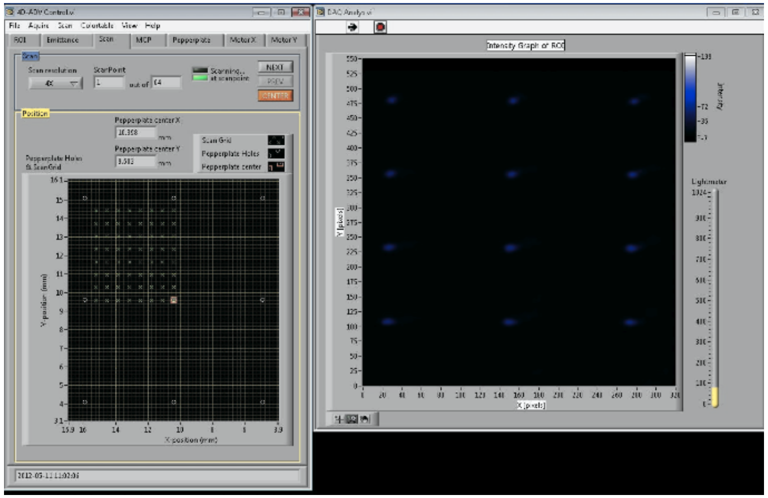
- Software update of the pepper pot behind the dipole. Both devices have now an improved software (process control and data analysis).
- Investigation about MCP lifetime (shutter required?) (ongoing).
- Absolute alignment between pepper pot and MCP required (ongoing).
- Adapted data presentation required (ongoing).

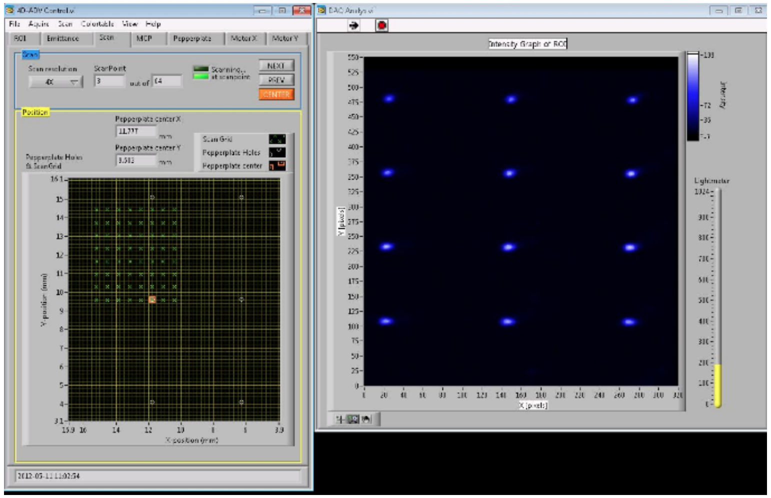


KVI designed and constructed both devices [8]

Pepper pot





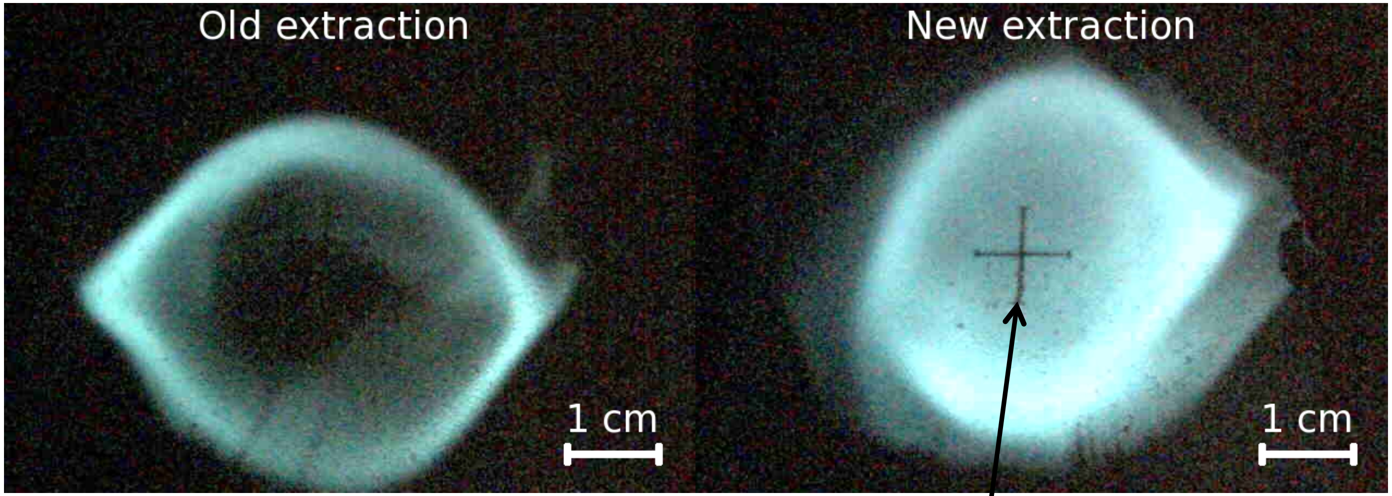


Measured pattern: always the same MCP position shows a lower intensity.

Future prospects for Task 2 (JYFL)

A remarkable improvement on the beam transport has been obtained with the new extraction. Still further improvement is required!

New vs. old extraction – beam profiles



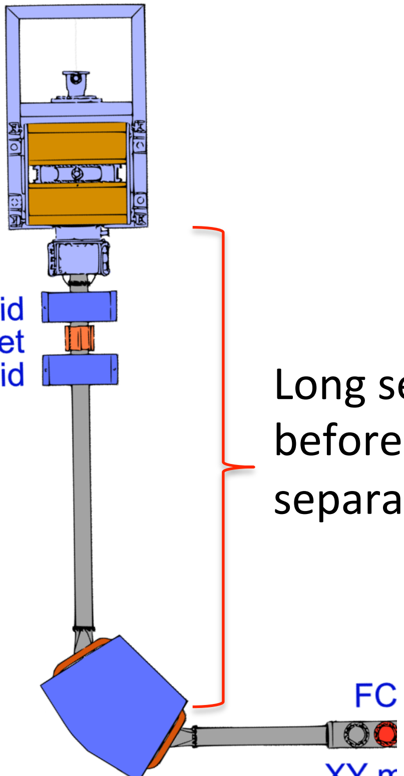
~130 μA of $^{40}Ar^{8+}$
~1 mA of total extracted current

Still some hollowness caused by the space charge

European Nuclear Science and Applications Research

Future plans:

Beam transport: Minimize the space charge effect



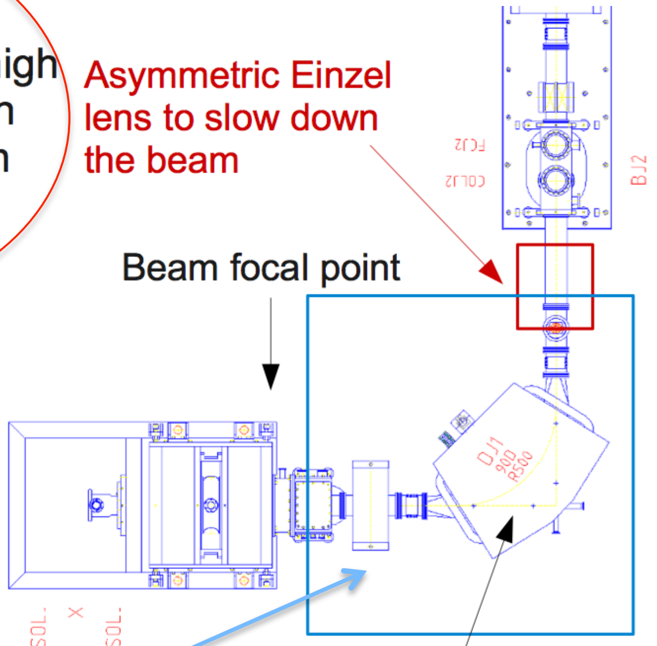
Long section before mass separation

Minimization of the high space charge section and HV biased beam line

ECRIS on rails in order to be able to open the extraction

Asymmetric Einzel lens to slow down the beam

Beam focal point



New analyzing magnet

High voltage beam line section (≈ 5 kV)

Velocity of beam increases
→ space charge effect decreases
→ beam quality improves (more beam can be transported)

This work will be done during 1st half of 2014

Space charge compensation??

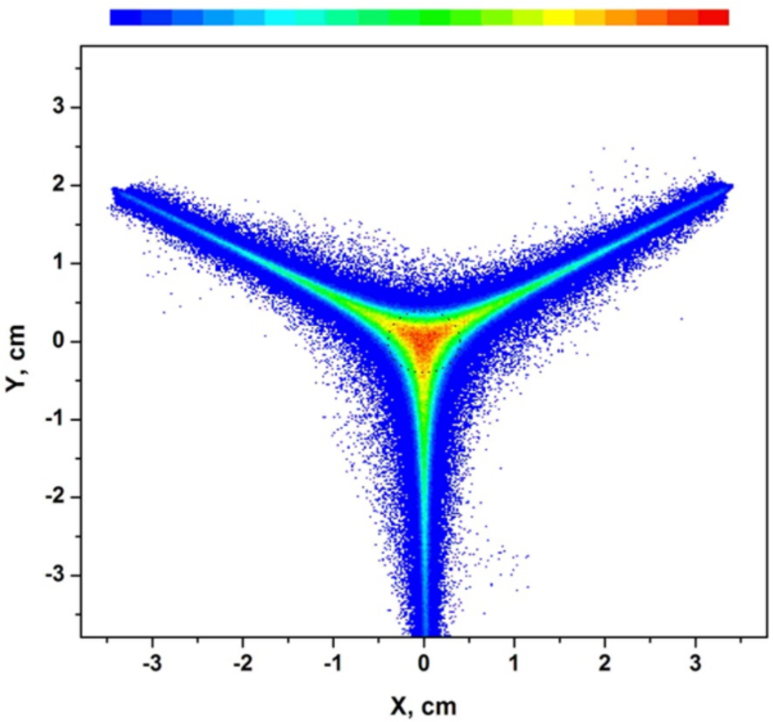
Simulations

Particle-in-Cell Monte-Carlo Collisions Code (PIC-MCC)

- 3D simulations of ion motion in ECRIS magnetic field
- Ion-ion collisions are treated using an energy/momentum conserving algorithm
- Electron density is calculated by requiring charge-neutrality
- Ionization and electron-ion heating <- electron temperature of 1-10 keV
- Charge-exchange and ion elastic scattering in the ion-neutral collisions
- Neutralization of ions in collisions with the surface and subsequent thermalization of the scattered fast atoms
- Ion confinement by the potential dip inside ECR zone

Simulations

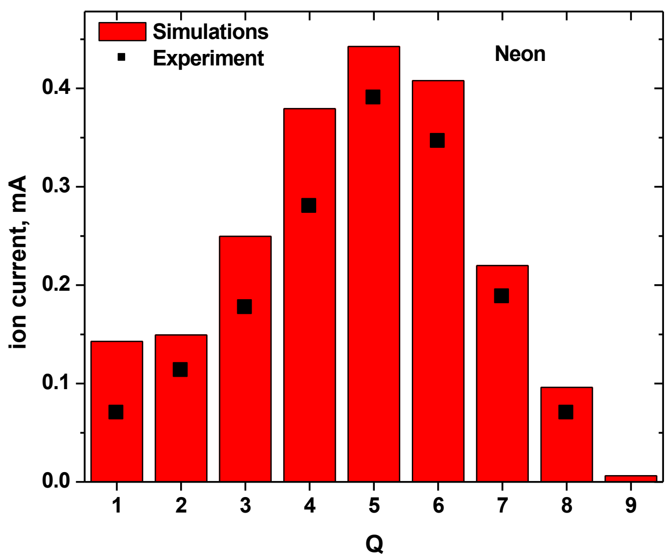
Spatial distribution of ions at the extraction electrode

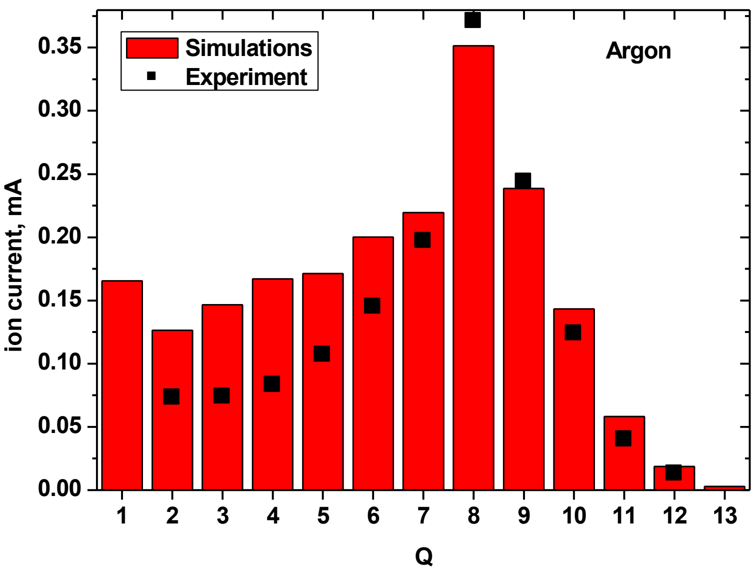


Output can be used for the low energy beam line simulations. Highest charge states are located closer to the center.

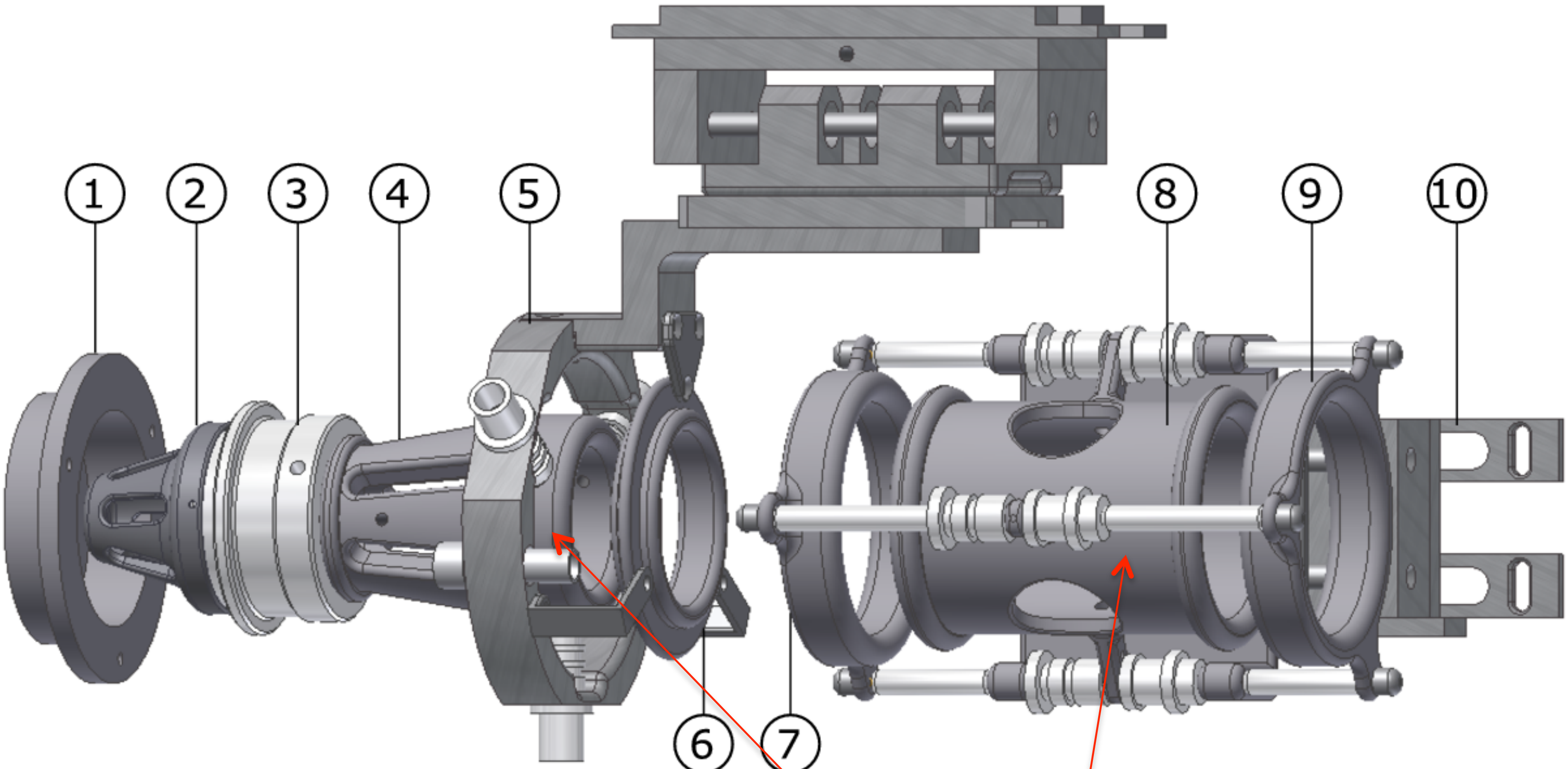
Simulations

Charge-state-distributions of the extracted ions





New extraction – mechanical design @ JYFL



Acceleration voltage ≈ 10 kV → Einzel1/Einzel2: 15/10 kV

Measured Ar transmission
New vs. old extraction

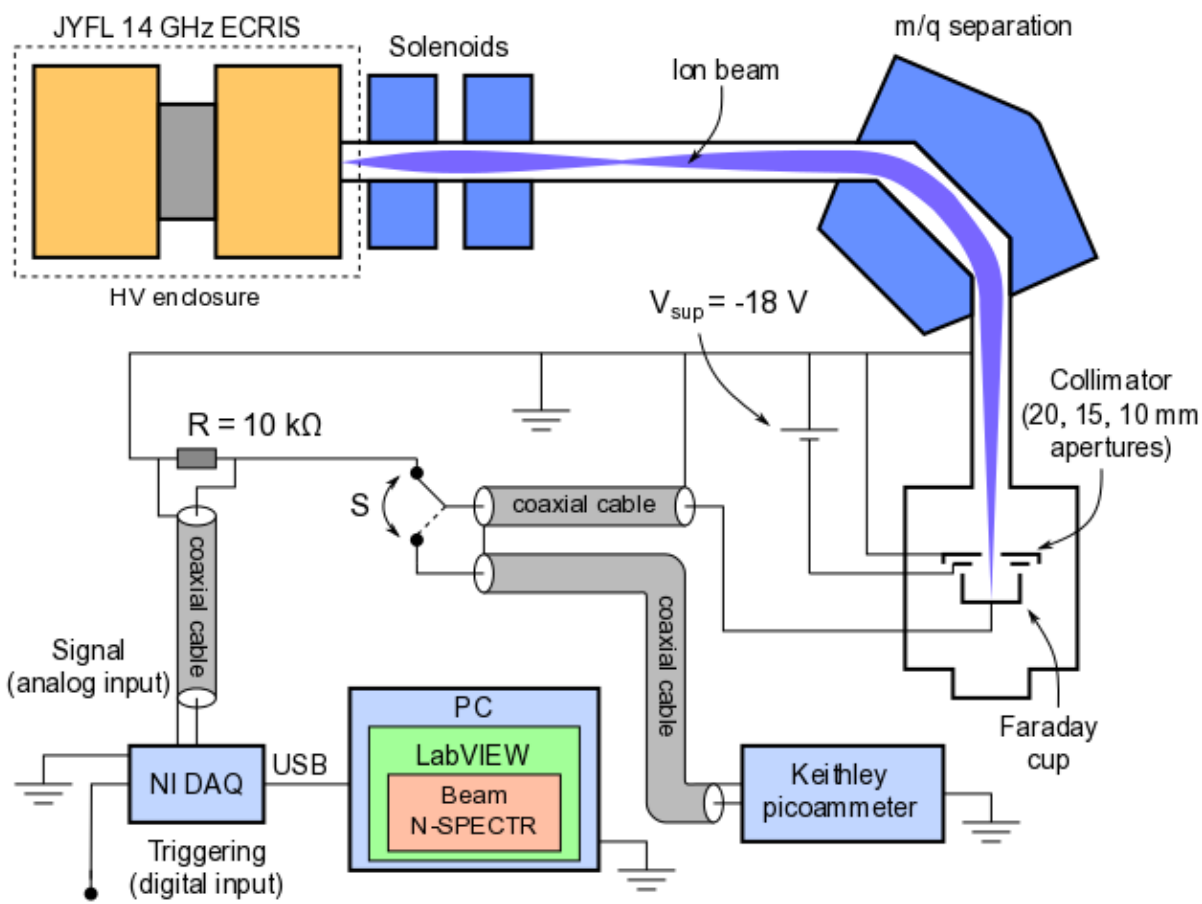
Beam	Extraction	I_{ECR} (μA)	I_{ACC} (μA)	T (%)
$^{40}Ar^{8+}$	Old	90	2.3	2.6
$^{40}Ar^{8+}$	Old	138	3.1	2.3
$^{40}Ar^{8+}$	Old	170	3.6	2.1
$^{40}Ar^{8+}$	New	84	3.7	4.4
$^{40}Ar^{8+}$	New	105	5.2	5.0
$^{40}Ar^{8+}$	New	132	6.0	4.6
$^{40}Ar^{8+}$	New	187	7.4	4.0

Accelerated beam intensities

Transmission efficiency has improved even by a factor of 2!

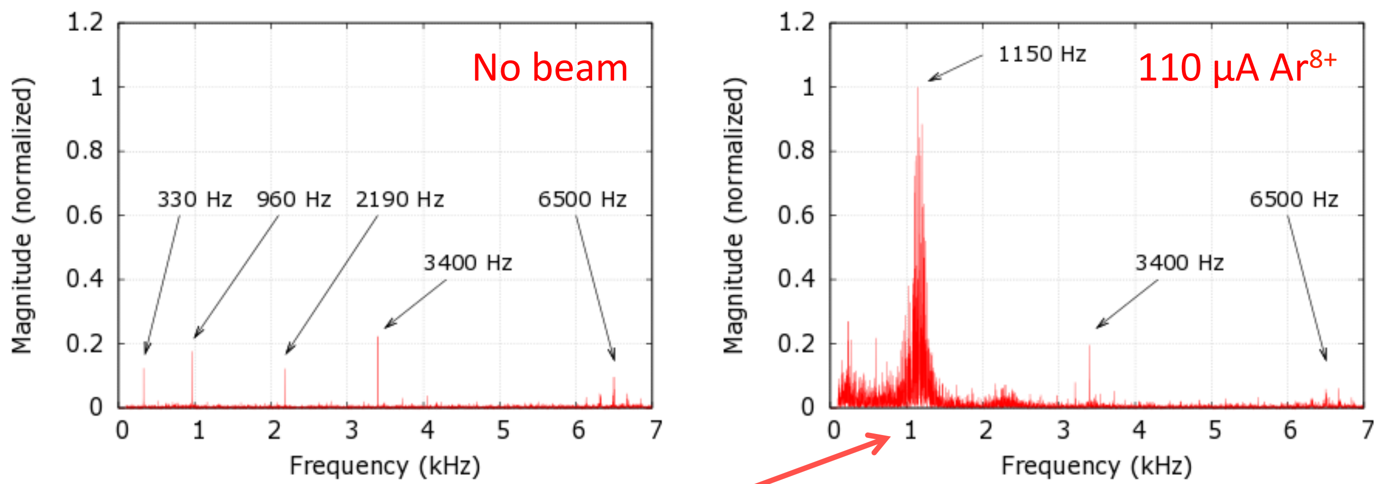
Beam oscillation experiments
Measurement setup

V. Toivanen, O. Tarvainen, J. Komppula and H. Koivisto,
Journal of Instrumentation (IOP Science), Vol. 8, (2013), T02005.



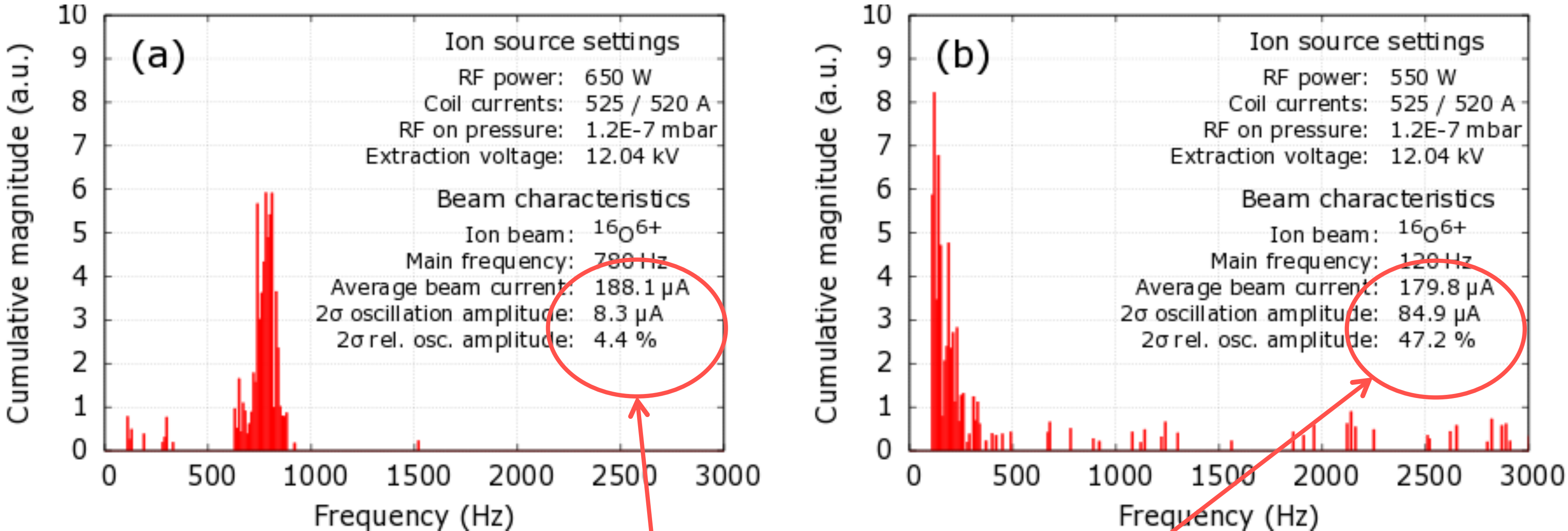
Current oscillation characteristics

- Properties vary significantly with ion source tuning
  - Occur at frequencies 100 – 1500 Hz
  - Amplitudes vary between 1 – 65% of average beam current



Bean induces clear peak,
location varies with ECRIS settings

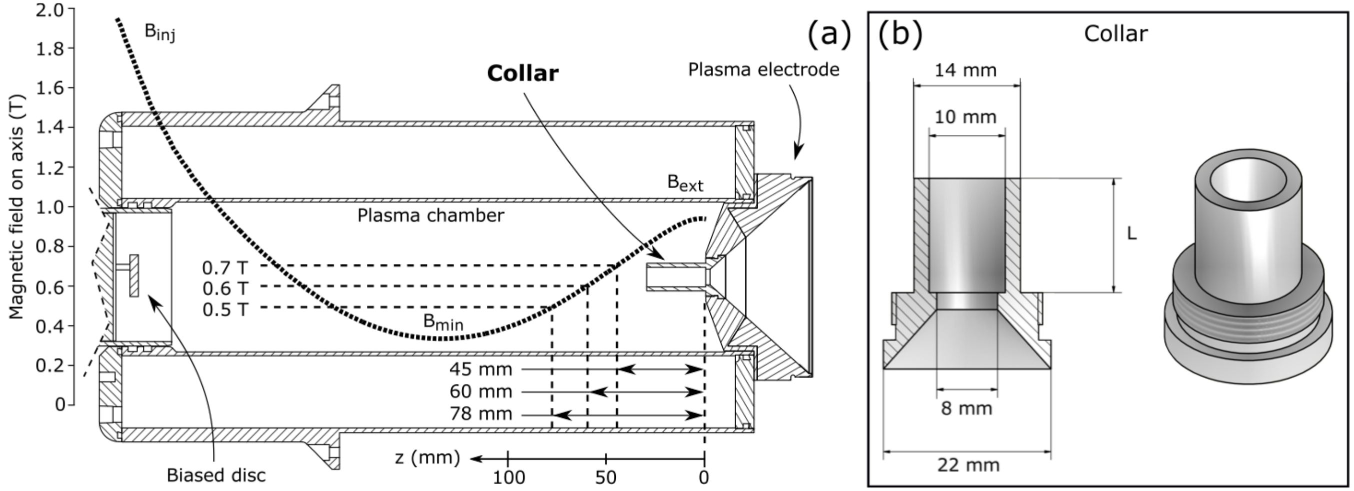
Oscillations vary with ECRIS tuning



Practically same average beam current but dramatically different oscillation properties!

Experiments with the collar @ JYFL (first tested at KVI)

V. Toivanen, O. Tarvainen, J. Komppula and H. Koivisto, accepted for publication in Nucl. Instrum. Meth. A (2013).



Not a strong effect – but seems to improve the intensities up to 30 % and also seems to decrease the emittance. Main finding: the length of the collar can be even 30 mm without negatively affecting the performance of ECRIS! Do we have extra space available for some tricks still to be invited?

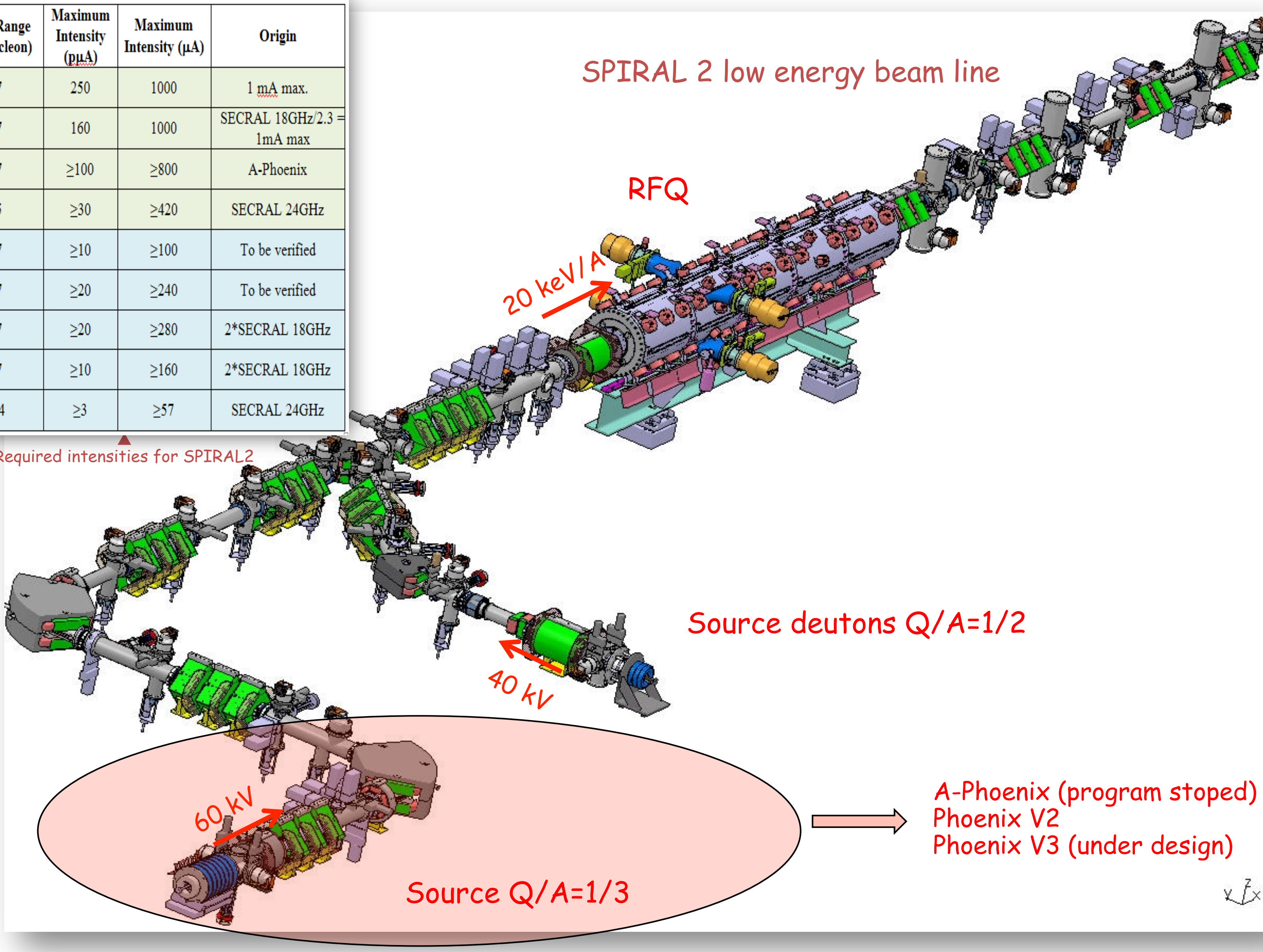
TASK 2 summary

- Good results obtained up to date
- New insights are expected in the last period with new experiments
- Plasma diagnostics and simulation codes have permitted these improvements, but there is still a lot of work to be done by improving these tools

TASK 3 - Oven development @ GANIL

Ion(s)	Energy Range (MeV/nucleon)	Maximum Intensity (pµA)	Maximum Intensity (µA)	Origin
$^{12}C^{4+}$	5-7	250	1000	1 mA max.
$^{18}O^{6+}$	5-7	160	1000	SECRAL 18GHz/2.3 = 1mA max
$^{22}Ne^{8+}$	5-7	≥100	≥800	A-Phoenix
$^{40}Ar^{14+}$	4-5	≥30	≥420	SECRAL 24GHz
$^{28-30}Si^{10+}$	5-7	≥10	≥100	To be verified
40Ca14+	5-7	≥20	≥240	To be verified
48Ca16+	5-7	≥20	≥280	2*SECRAL 18GHz
58Ni19+	5-7	≥10	≥160	2*SECRAL 18GHz
$^{58}Ni^{19+}$	4-14	≥3	≥57	SECRAL 24GHz

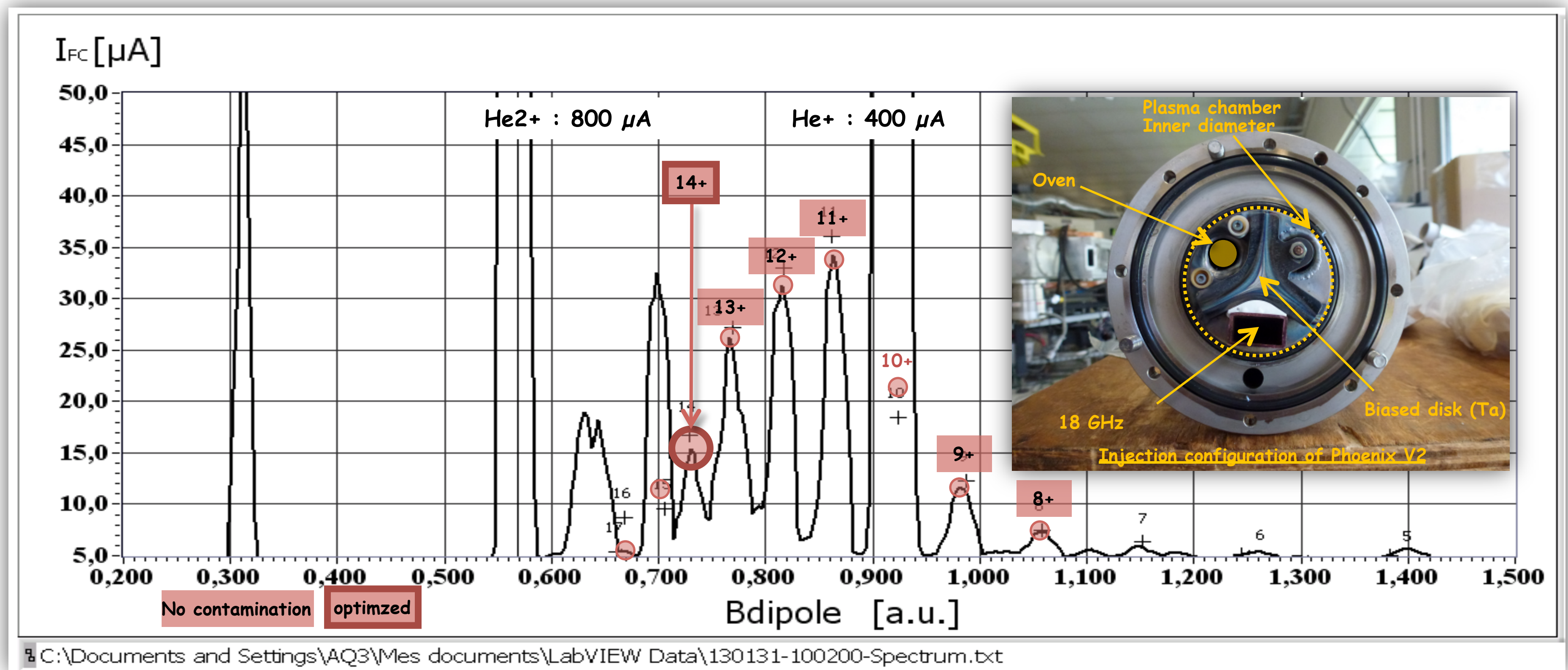
Required intensities for SPIRAL2



A-Phoenix (program stoped)
Phoenix V2
Phoenix V3 (under design)

Oven development @ GANIL

Ca + He (January 31th, 2013)



RF: 700W, 115W | **Bias**: -25V, 0.1 mA | **Oven**: – 5 mm, < 1 W (< 100°C ⇔ vp Ca < E-9 mbar) | **HV**: 40 kV,1.5 mA | **p_inj**: 1.3E-3 mbar, **p_ext**: 1.1E-7 mbar.

Best intensities obtained :

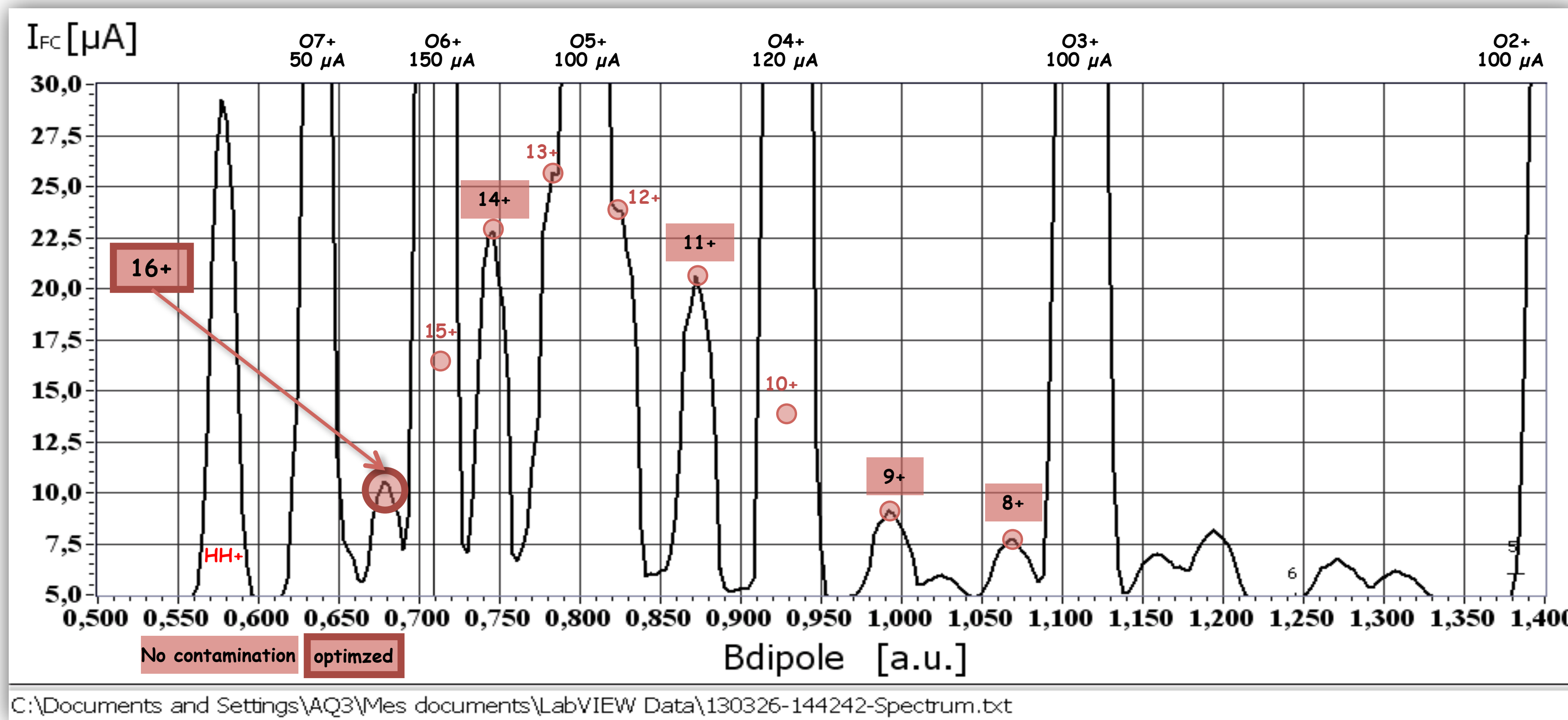
40Ca14+ : 10 µA

40Ca16+ < 1 µA

(same performance as those obtained in october 2010).

Oven development @ GANIL

40Ca + O2 (March 26th, 2013)



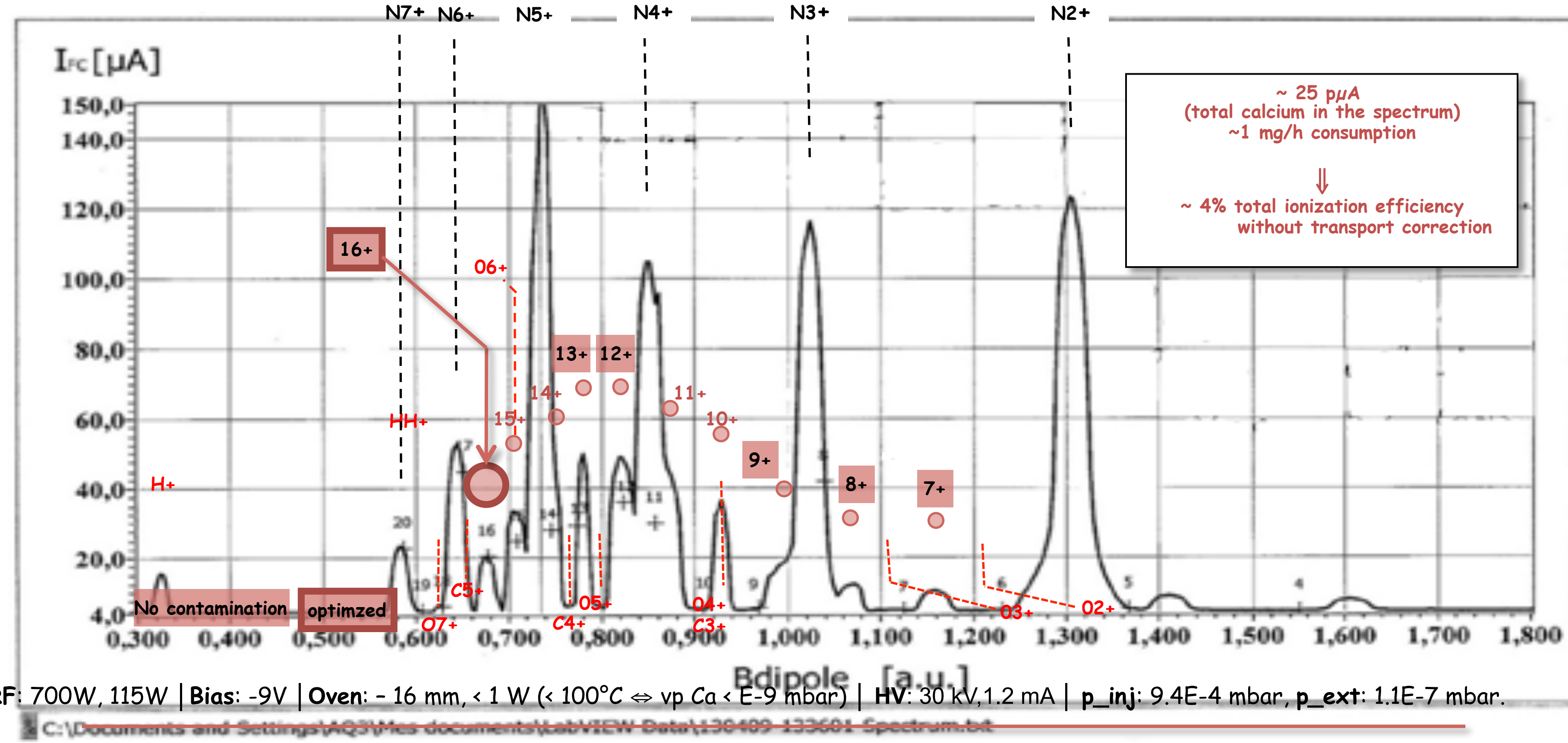
RF: 700W, 115W | **Bias**: -25V, 0.1 mA | **Oven**: – 16 mm, < 1 W (< 100°C ⇔ vp Ca < E-9 mbar) | **HV**: 40 kV,1.5 mA | **p_inj**: 1.3E-3 mbar, **p_ext**: 1.1E-7 mbar.

Best intensities obtained :

40Ca14+ : 20-30 µA (X2 compared to He)
40Ca16+ : 6 µA (X6 compared to He)

Oven development @ GANIL

40Ca + N2 (April 9h, 2013)



RF: 700W, 115W | **Bias**: -9V | **Oven**: – 16 mm, < 1 W (< 100°C ⇔ vp Ca < E-9 mbar) | **HV**: 30 kV,1.2 mA | **p_inj**: 9.4E-4 mbar, **p_ext**: 1.1E-7 mbar.

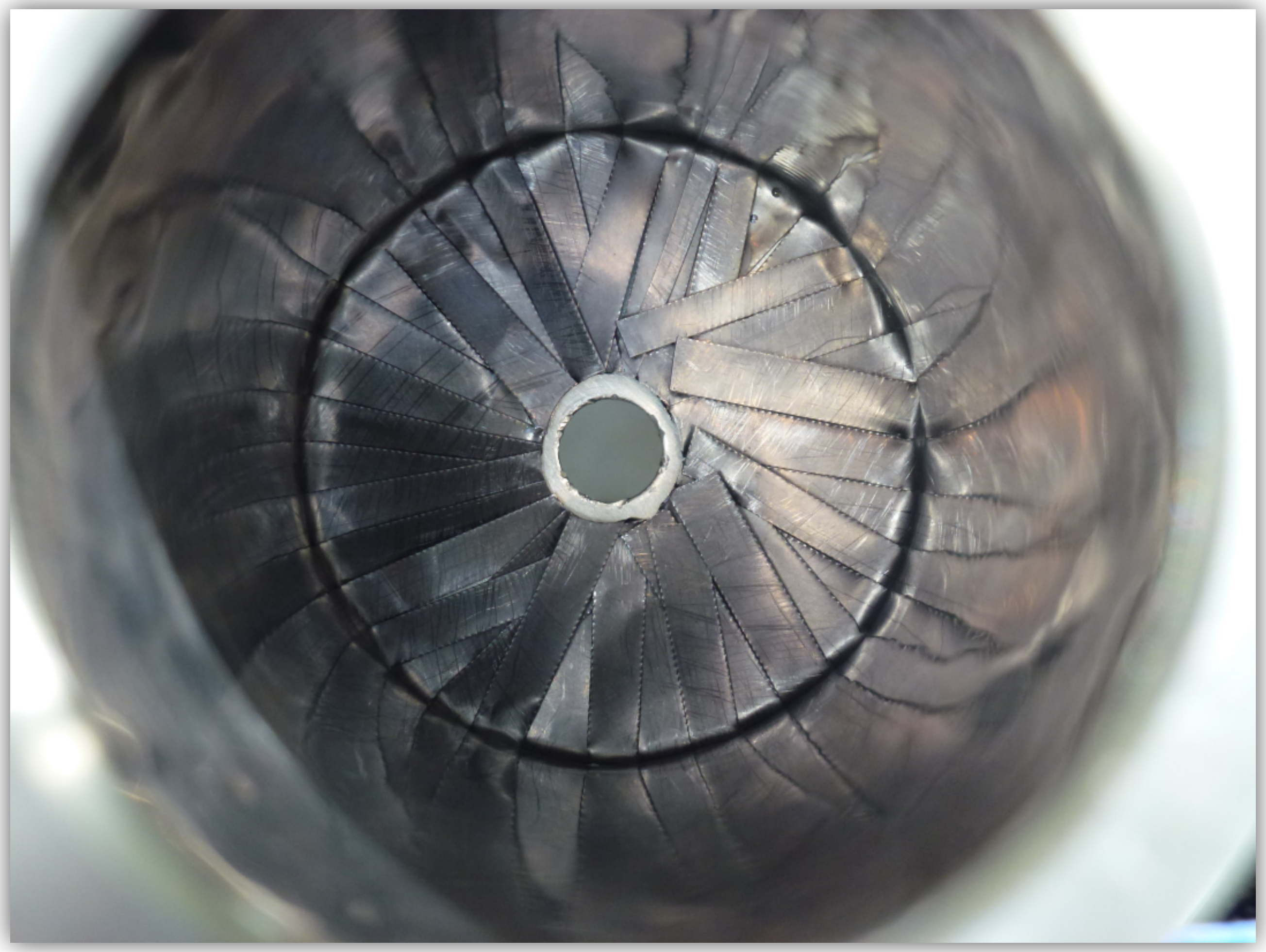
Best intensities obtained :

40Ca14+ : 35 µA (x1.7 compared to O2)
40Ca16+ : 16 µA (x2.7 compared to O2)

PHF 830 W / 128 W, biased disk -25 V / 0.1 mA, oven position – 5 mm, oven power 1 W (~ 100°C),
B : 1095 A / 898 A / 1250 A, 40 kV / 2.0 mA, p_ext : 1.1E-7 mbar

Oven development @ GANIL

Hot Tantalum wall



View from injection of the Ta cylinder inside the plasma chamber. (April 10th, 2013)

Oven development @ GANIL Summary

	He support gas		O_2 support gaz		N_2 mixing gas	
	I (μA)	Stability	I (μA)	Stability	I (μA)	Stability
40Ca14+	10	Stable with a fine tuning of He	20	Not stable	35*	stable
40Ca16+	1		6		16	

- Increase of CSD with RF power :

The increase of the RF power improves the charge state distribution. No saturation observed.

- Increase of Ca evaporation with RF power :

For a constant support gaz flow and oven power, the increase of the RF power increases the calcium evaporation. For a RF power greater than 800 W (oven < 100°C off line), the calcium evaporation is too high, and it leads to a worse charge state distribution (no gain in intensity anymore for 40Ca16+). For an oven position closer to the plasma this RF power limit is lower.

- Increase of Ca evaporation with support gaz flow :

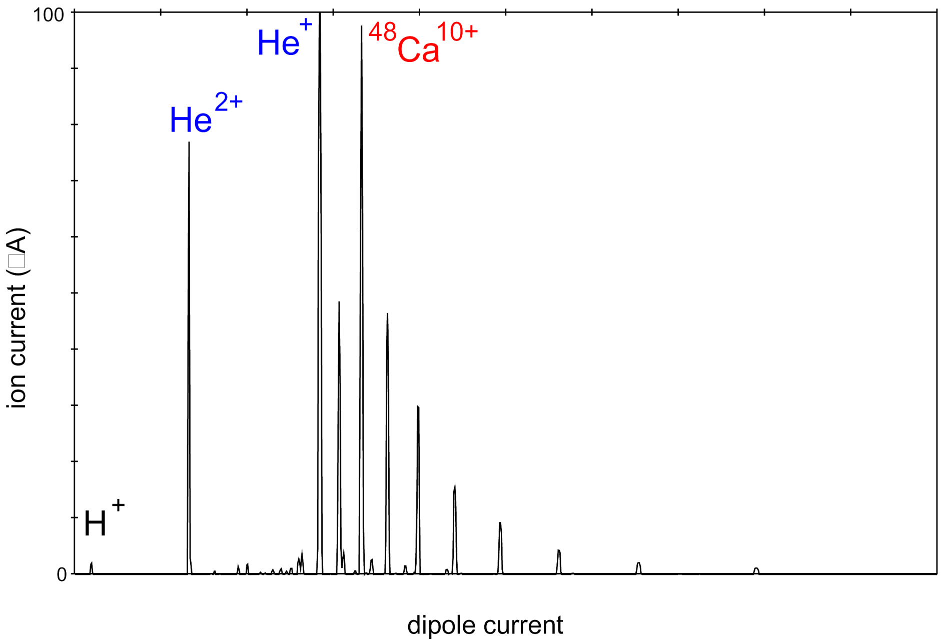
The same effect as above has been seen a very strong observed when the gaz flow is increased while keeping all source parameters constants.

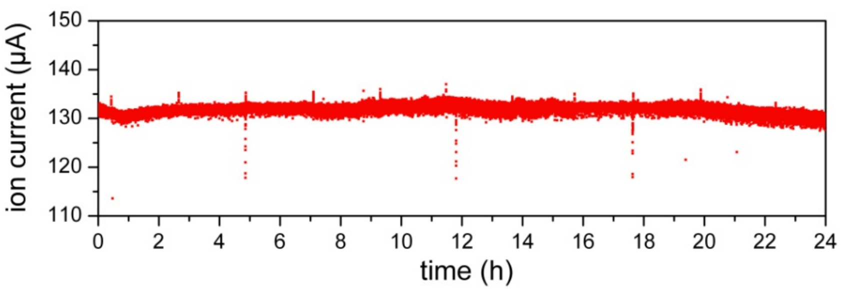
- Chemical getter effect :

When using O2 as support gaz, we have seen a very strong chemical getter effect. When the calcium evaporation is increased, while keeping constant gaz flow, the amount of oxygen decreases. A too high calcium evaporation may cause the disappearance of the O2 support gaz. We have not seen this effect with He and N2, or at least no measurable.

Oven development @ GANIL

Hot liner experiments with ^{48}Ca

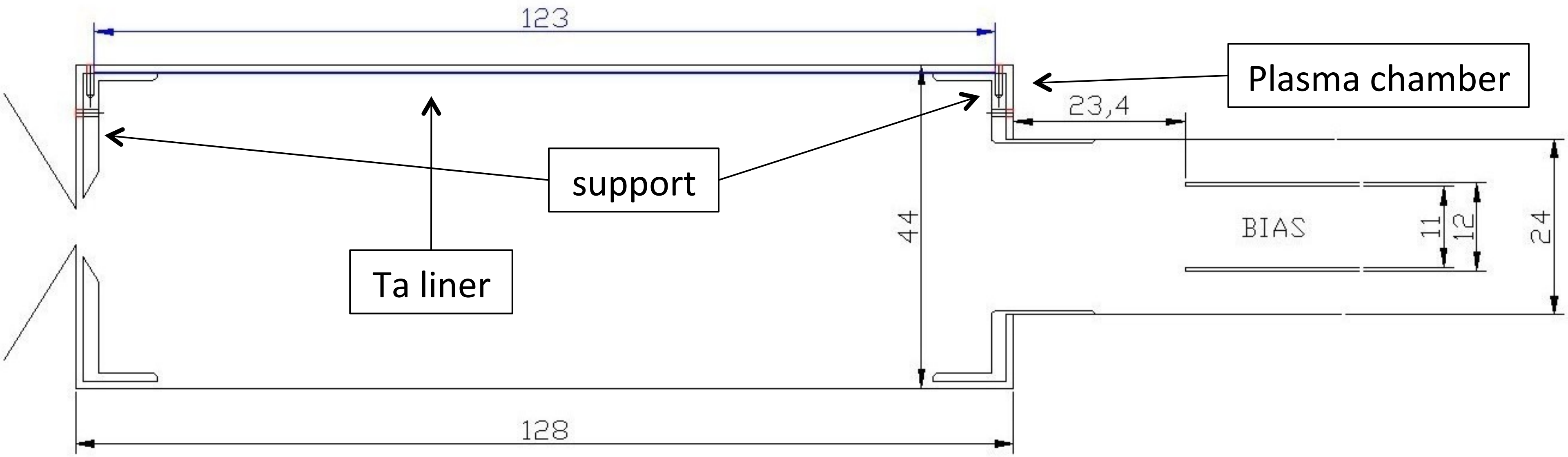


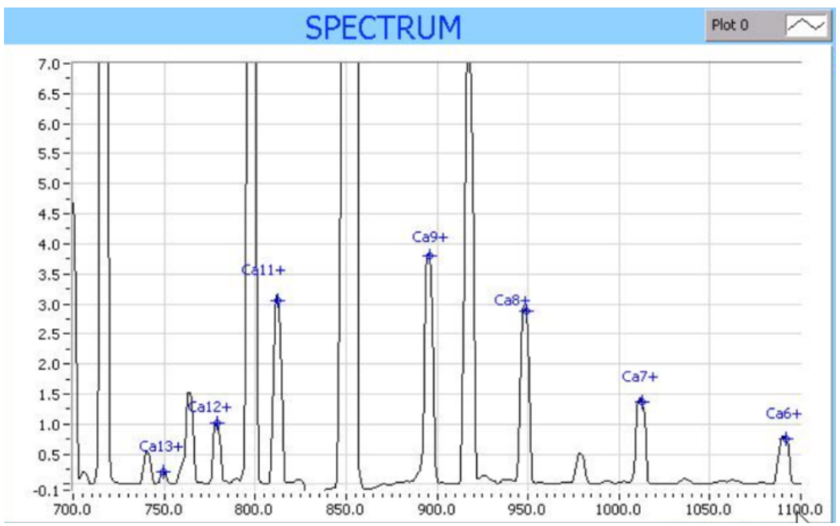


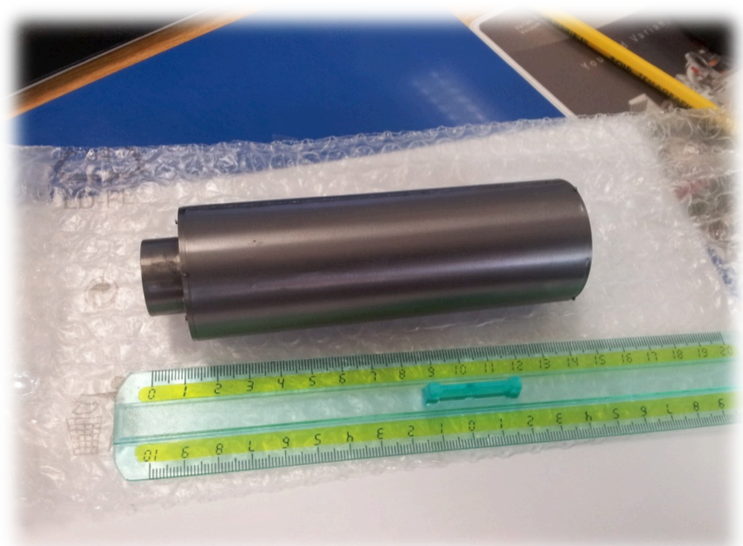
With a hot liner, inserted into the plasma chamber, it was noticed:

- intensive $^{48}Ca^{10+}$ ion beam (100-140 μA) can be produced
- Efficiency has been imroved (consumption rate as low as 0.2 mg/h)
- Global efficiency as high as > 40 %
- Very good long-term stability (He as a mixing gas)

Oven development @ INFN-LNL



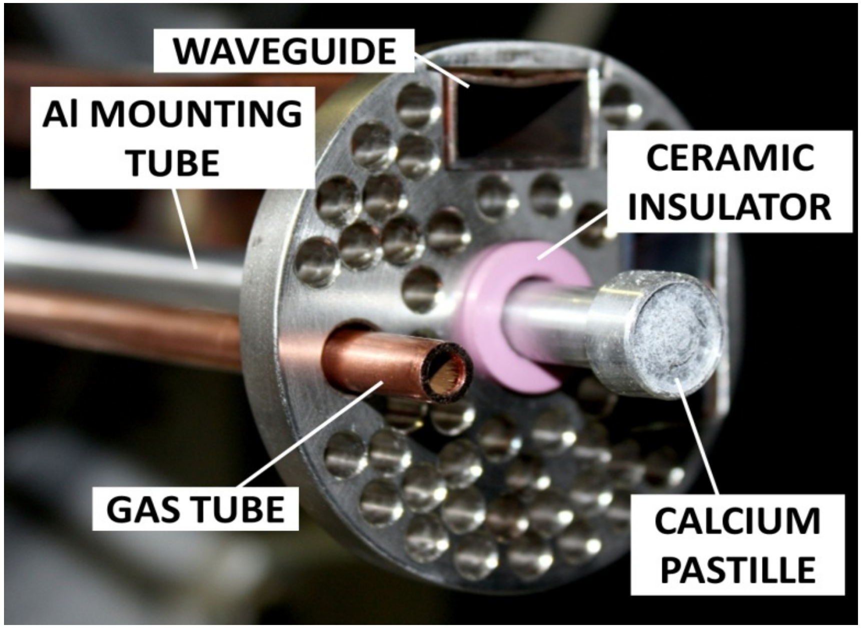




Double intensity, same consumption compared to earlier

Metallic ion production @ Atomki

Sputtering experiments



More axial sputtering experiments were performed at ATOMKI:

Results: Au^{20+}: 1 μA (very stable, O_2 buffer)
Ca^{8+}: 2 μA
Si^{5+}: 2 μA

The work will be continued to obtain higher beam intensities.

S. Biri, R. Rácz, Z. Perduk, I. Vajda and J. Pálinkás : Recent developments and electron density simulations at the ATOMKI 14.5 GHz ECRIS, Int. Workshop on ECR Ion Sources, Sidney, Australia, 25-28 September 2012. Proceedings on the JACOW.

Operation of the CAPRICE electron cyclotron resonance ion source applying frequency tuning and double frequency heating; F. Maimone, K. Tinschert, L. Celona, R. Lang, J. Mäder, J. Roßbach, and P. Spädtke; Rev. Sci. Instrum. 83, 02A304 (2012).

Investigations on the structure of the extracted ion beam from an ECRIS; P. Spädtke, R. Lang, J. Mäder, F. Maimone, J. Roßbach, and K. Tinschert, Rev. Sci. Instrum. 83(2), 02B720 (2012).

F. Maimone, PhD Thesis, University of Catania, 2012

Metal ion beam production with improved evaporation ovens; K. Tinschert, R. Lang, J. Mäder, F. Maimone, J. Roßbach, GSI, Darmstadt, Germany; Proc. of the 20th Workshop on ECR Ion Sources, Sydney, Australia, 25-28 Sept 2012.

Ion beam extraction from magnetized plasma; P. Spädtke, R. Lang, J. Mäder, F. Maimone, J. Roßbach, K. Tinschert, GSI Darmstadt; Proc. of the 20th Workshop on ECR Ion Sources, Sydney, Australia, 25-28 Sept 2012.

- K.E. Stiebing, L. Schachter and S. Dobrescu, The influence of the extracted voltage on the energetic electron population of an electron cyclotron resonance ion source plasma.
  Rev. of Sci. Instrum., 83, 2, 02A 331, 2012

- L. Schachter, K.E. Stiebing and S. Dobrescu, The impact of plasma-wall interaction on the gas mixing efficiency in electron cyclotron resonance ion source. Rev. of Sci.Instrum., 83, 2, 02A348, 2012

- K.E. Stiebing, L. Schachter and S. Dobrescu, Secondary electron enhanced plasma as an alternative to double/variable frequency heating in ECRIS. ECRIS Workshop, September 25-29, Sydney, Australia

- K. Tinschert, R. Lang, J. Mäder, J. Roßbach, P. Spädtke, P. Komorowski, M. Meyer-Reumers, D. Krischel, B. Fischer, G. Ciavola, S. Gammino, L. Celona, Design and Investigations of the Superconducting Magnet System for the Multipurpose Superconducting ECR Ion Source (MS-ECRIS), Rev. Sci. Instrum. 83, 02A319 (2012)

- G. Castro, D. Mascali, P. Romano, L. Celona, S. Gammino, R. Di Giugno, D. Lanaia, R. Miracoli, T. Serafino and G. Ciavola, Comparison between off-resonance and E.B.W. heating regime in a Microwave Discharge Ion Source, Rev. Sci. Instrum. 83, 02B501 (2012)

- L. Neri, D. Mascali, L. Celona, S. Gammino, G. Ciavola, A 3D MonteCarlo code for the modelling of plasma dynamics and beam formation mechanism in ECRIS, Rev. Sci. Instrum. 83, 02A330 (2012)

- D. Mascali, S. Gammino, L. Celona, G. Castro, D. Lanaia, R. Miracoli, P. Romano, T. Serafino and G. Ciavola, Towards a better comprehension of plasma formation and heating in high performance ECRIS, Rev. Sci. Instrum. 83, 02A336 (2012)

26/09/2012 – **International "Richard Geller Prize"**, awarded biennially to recognize outstanding work of young researchers in the field of ECR ion sources and is named in honor of the inventor of the ECR source, Dr. Richard Geller.

D. Mascali 20th ECRIS Workshop, Australia, Sydney, September 26th 2012, **invited talk** at the "Geller Prize Ceremony". The presentation was entitled: *"A "simple" model of ECRIS plasma"*.

D. Mascali, European Conference on X-ray Spectroscopy (EXRS-2012), 18-22 June 2012, Vienna; oral presentation *"Preliminary investigation of X-ray emission from an innovative trap based on Bernstein waves heating"*.
L. Celona et al., ECRIS workshop (2012), Sidney, *Design of the AISHA ion source for hadron therapy*, JACOW

PAPERS

- D. Mascali, L. Celona, S. Gammino, G. Castro, R. Miracoli, L. Malferrari, F. Odorici, G. P. Veronese , R. Rizzoli, T. Serafino, *Generation mechanism and new damping of method of suprathermal electrons in a multi-mirror ECR machine*, **submitted to Plasma Sources Science and Technology**.
- G. Castro et al., *Ion acceleration in non-equilibrium plasmas driven by fast drifting electron*, **Appl. Surf. Science D-11-04119R1 (2013)**

- D. Mascali et al. *Non-linear heating of plasma in off-resonance mode*, **in preparation for Physical Review Letters**
- C. Caliri et al. *X-ray imaging of a plasma heated by off-resonance discharge,* **in preparation for Plasma Sources Science and Technology**
- G. Castro et al. Characterization of an overdense plasma through Langmuir probe and small-wire antenna in EBW-heating regime, in preparation for **Plasma Sources Science and Technology**
- D. Mascali et al. *A new X-ray source based on a stationary magnetized plasma,* **in preparation for Journal of X-ray Spectroscopy**

CONFERENCES IN 2013

Partecipation to the 2013 International Conference on Ion Sources is foreseen for next September (Chiba, Japan).
A contribution on wave-plasma interaction (modeling and simulations) will be also presented at the20th Topical Conference on RF power in Plasmas, that will be held in Sorrento, Italy, on next June.

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This is (not) the end !

Forthcoming months

- ✓ **Task 1: exploitation of new Flexible Plasma Trap at INFN-LNS, X-ray measurements at GSI, plasma physics studies**

- ✓ **Task 2: minimization of space charge effects, further optimization of coupling to accelerators, simulation code continuous update**

- ✓ **Task 3: improvements of techniques yet developed for metal ion beams production, with particular care to efficiency and stability versus time**