What is the improvement to ECRIS discipline coming from 4 years of ENSAR-ARES activity?

Not equal improvements per each task/per each institution (key actions were considered in Task 1 according to initial programme):

- *Different manpower availability*
- *Different equipment availability*
- *Different difficulties and site constraints*
- *Different perspectives*

We should not determine bad workers/good workers, but we should propose a list of real improvements that may be used a short-list for ENSAR managers to show the progress in our field.

In fact the so called "untangible assets" are the most difficult to be recognized in Economics and this is even more evident for our field.
It is well known that any breakthrough in Physics is based on a series of small results, often not recognized until the breakthrough occurs.
The ENSAR/ARES results seem to enter in this historical case.

We have not

- new ECR ion sources built under ARES
- new "standard" theories
- breakthrough in HCI beam production or "astonishing results"

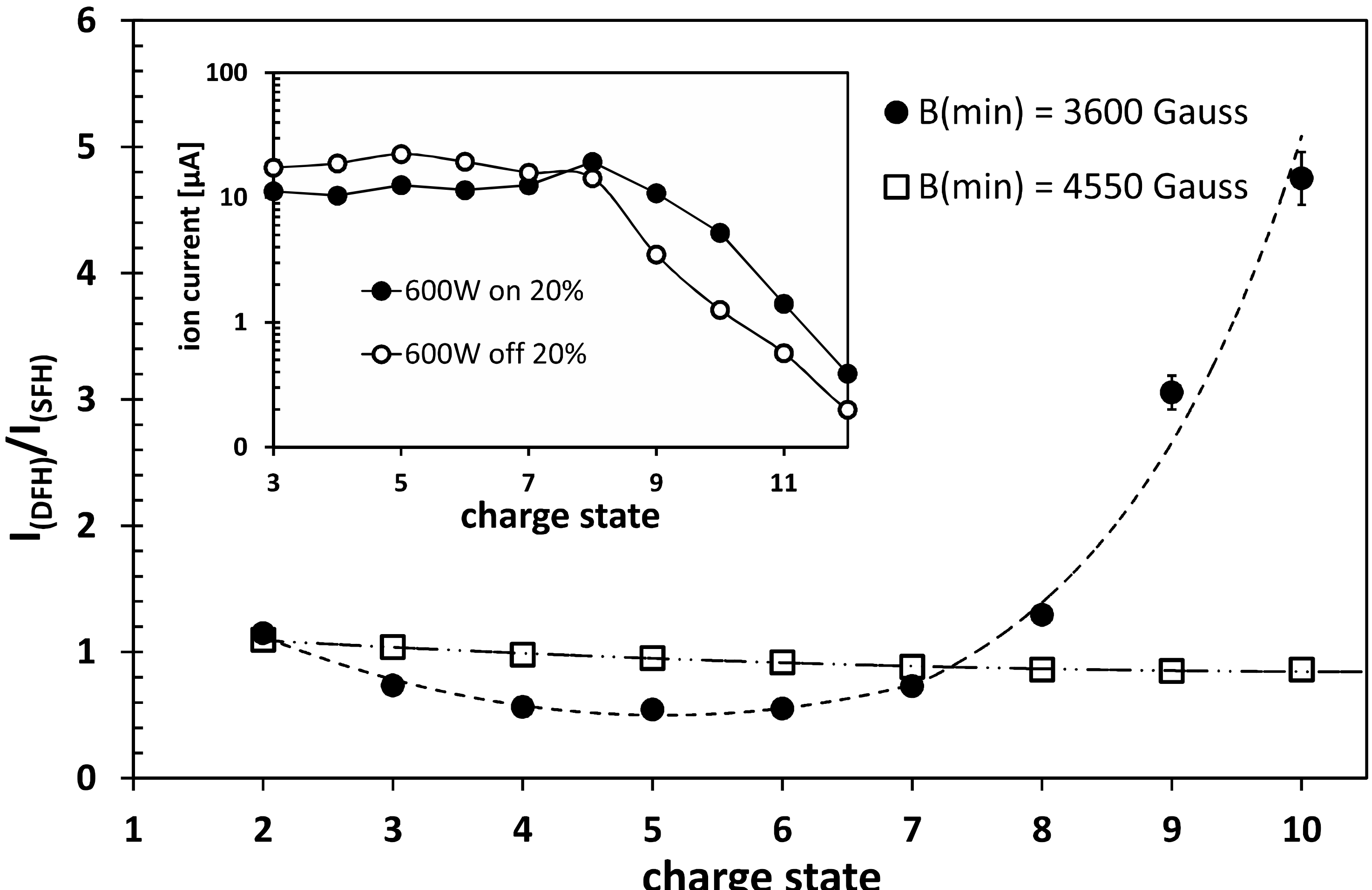
but….

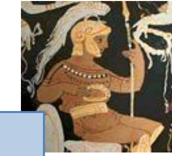
ENSAR

We gained .....

- *largely improved diagnostics*
- ***simulations more and more adherent to real world***
- *Improved RF matching to plasma*
- *A different view to beam formation and space charge effects minimization (2009 statement @Review on high-current proton sources: "beam formation and LEBT transport cannot be studied separately", now is a common statement)*
- *A different view to the metallic species production thanks to systematics done under ARES*

It is mandatory to understand the relationship between macroscopic parameters (RF field, B) and EEDF, as well as the role of EEDF in HCI production: there were some evidences and recent experiment of IKF-IFIN confirmed that fine tuning with DFH helps a lot





A paradox:

The ECRIS scenario is not depending on Electron Cyclotron Resonance only (we should study carefully the theoretical and experimental works from Golovanivsky and Dougar-Jabon ¼ century ago: back to the future)

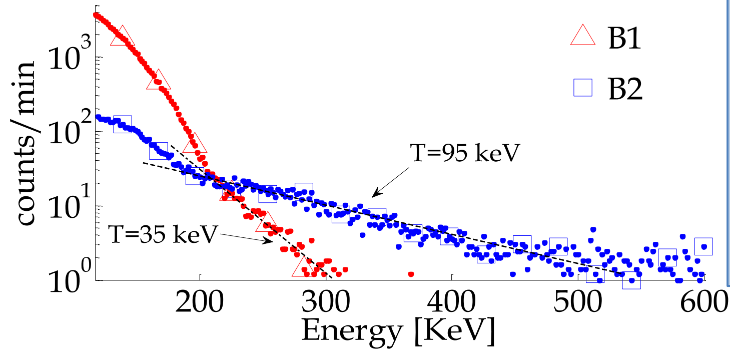


Figure 1 – X-ray Spectra coming out from the CAESAR source for two different L-parameters (B1 → L=60 mm, B2 → L=64 mm)

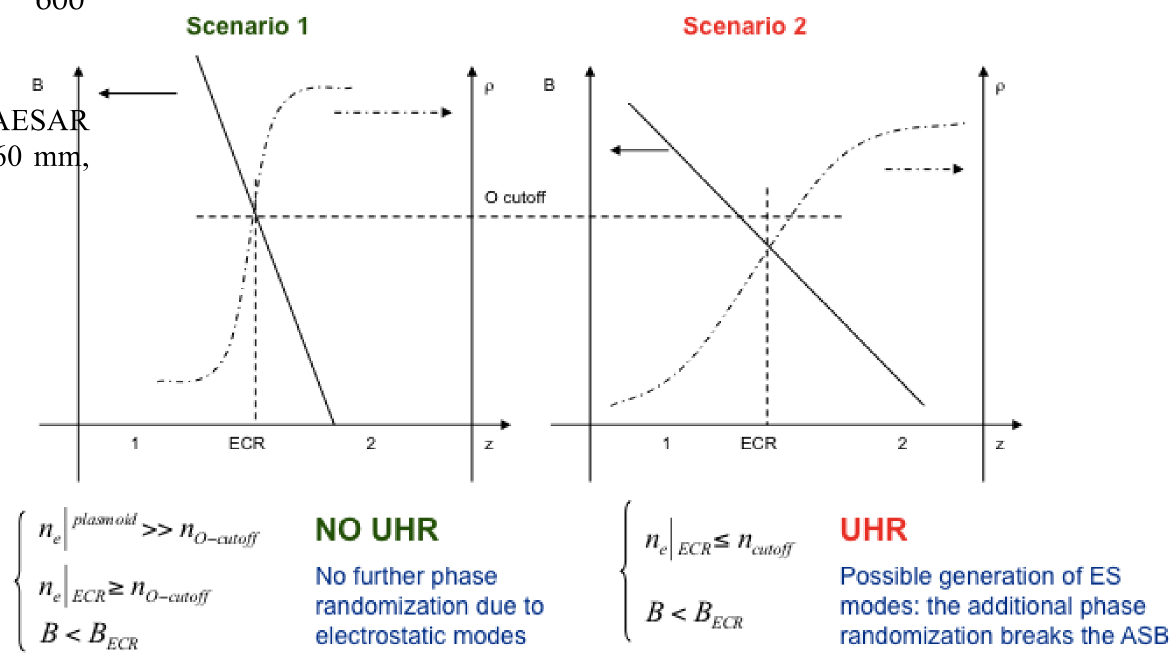
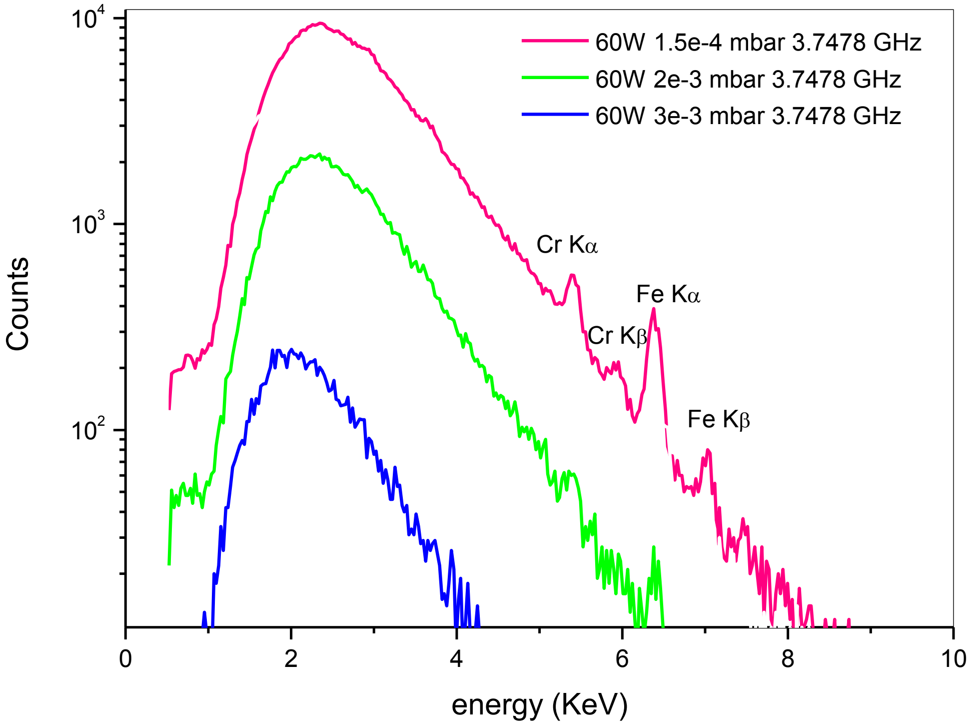
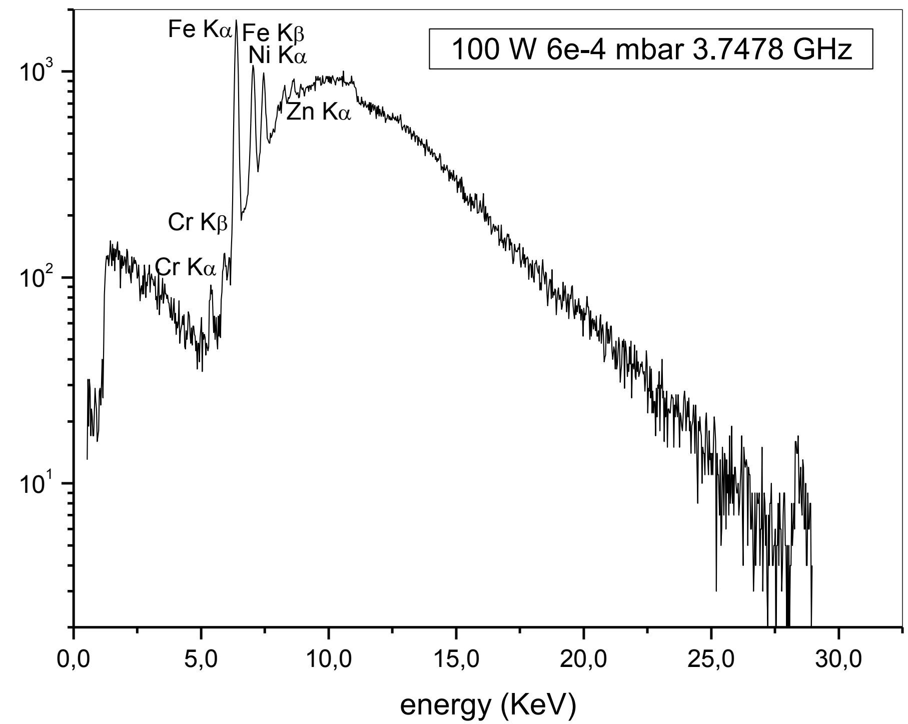


Figure – 7 Scenarios arguable when considering the impact of magnetic field profile on the ECRIS plasma heating. The heating regimes are regulated by the establishment of UHR inside the chamber.

Our advantage: order of magnitudes improvements for computer simulations, remarkable jump in diagnostics capability

X-ray spectra during EM-ES conversion





1. **Boost of X-ray energy** for low pressures;
2. The plasma exhibits a **threshold-like behavior**: at 1.5E-4 mbar **hot electrons are generated for P_{rf}>80 W;**
3. In the same RF power domain, a **plasma hole appears** and it is observable in the visible range.

1. **Understanding the origin of the threshold behaviour**
2. **Defining the parameters that determine the EEDF**
3. **Exporting this mode of operation to highly charged ion sources (is it possible?)**

Improvements for Diagnostics

Diagnostics Available :

-Langmuir Probe for plasma density and temperature measurements in low temperature regimes; (the LP typically hosts the RF antenna for spectral analysis);

-Amptek X-rays detector @ E<100 keV;

-Spectrum Analyzer for electromagnetic spectrum characterization;

-Network Analyzer for resonant cavities characterization;

-**Pin-hole camera for X-rays Imaging and spectroscopy**: a proper CCD camera was purchased for X-ray imaging in the energy domain E<50 keV.

- **A Scintillator** detector was coupled to the CCD to extend the detection range of the pin-hole camera up to 1 MeV (in this way X-ray imaging could be carried out on SERSE and on other ECRISs).

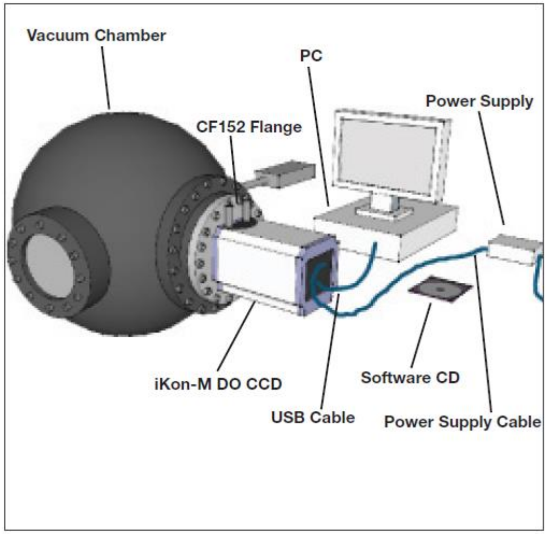
- **optical spectrometers**;

- **CCDs** used for optical imaging of the Plasma Trap;

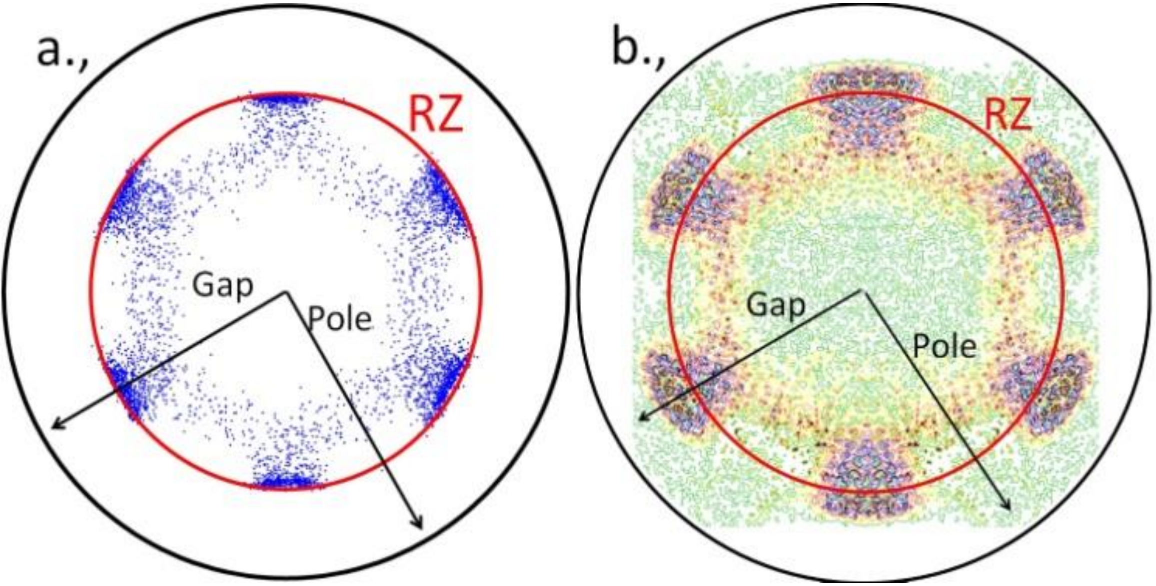
-**RF antennas** should be designed to "intra-plasma" electromagnetic spectrum characterization;

- **Microwave interferometer**;

- **A broadband and high frequency oscilloscope** to investigate wave's propagation, conversion and absorption in the transient regime.



Comparison: electron simulation and X-ray-photo

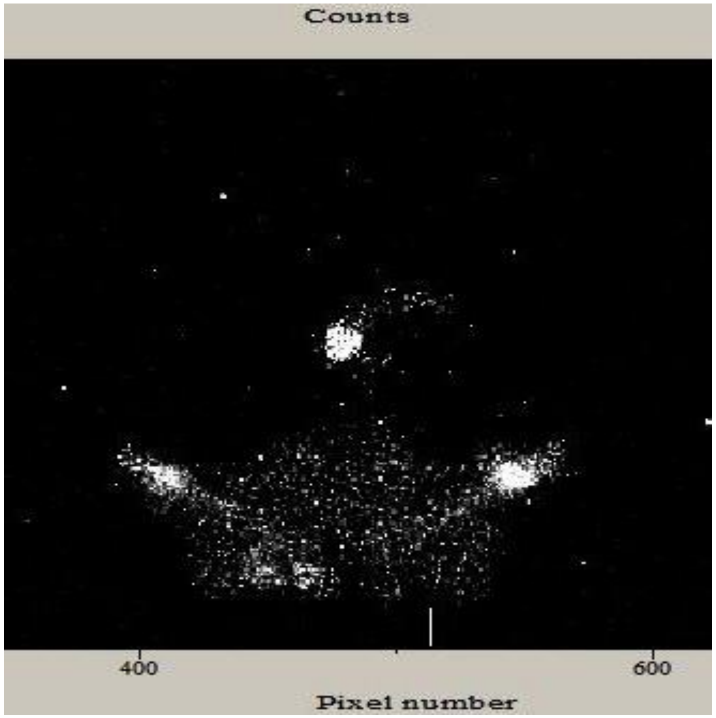


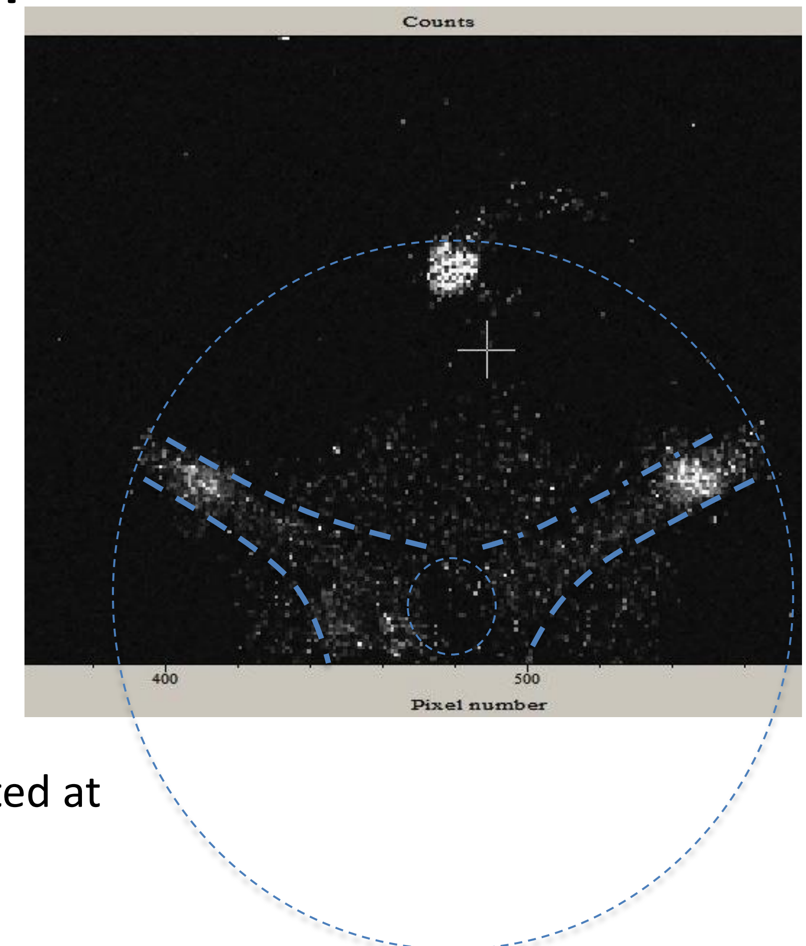
- Good agreement between simulation and XR-photo.
- Warm electrons are trapped at magnetic **gap**.
- Argon ions locate at the **same** positions.
- Strong azimuthal and radial inhomogenity.

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*

INFN-LNS & ATOMKI Experiment





Preliminary results from a 30 W argon plasma, excited at 3.5E-6 mbar, B_{inj}=1.2/B_{min}=0.33/B_{ext}=0.9/B_{hex}=0.9 T.

Just imaging (not yet SRS – Space Resolved Spectroscopy) after 1 second time exposure by 256x1024 (pixels of 26.6x26.6 μm^2) CCD camera in pin-hole mode.

Simulations and modeling

MonteCarlo simulations

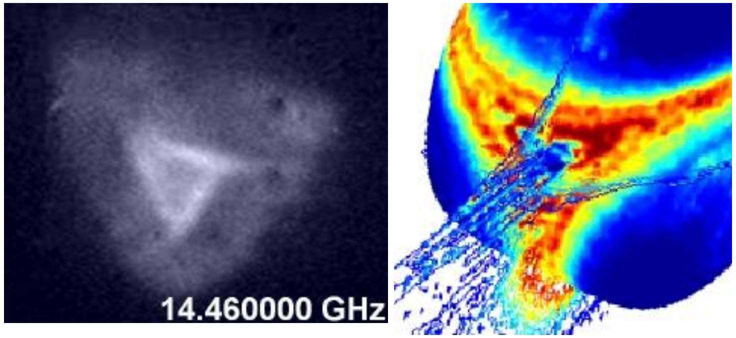
-3D MonteCarlo simulations have successfully explained the hollow beam formation in high frequency ECRIS; The efforts will continue to extend the applicability of the model to MDIS, matching our code to codes able to simulate beam transport (in the framework of ESS program).

-In particular the possibility to use the output of our code as input of TRACEWIN is envisaged.

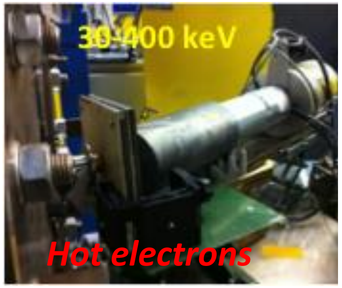
-The simulations will be improved through the introduction of self-consistency;

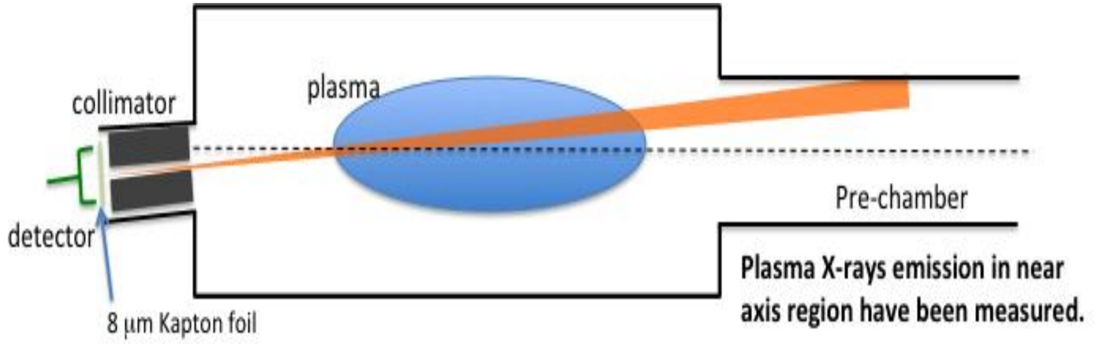
-On this purpose, **approximated "ray tracing" calculations** on the basis of Appleton-Hartree relation will be developed, in order to self-consistently determine the propagation direction of pumping waves;

-1D PIC code will be developed to investigate electron and ion dynamics coupling at the plasmoid edge



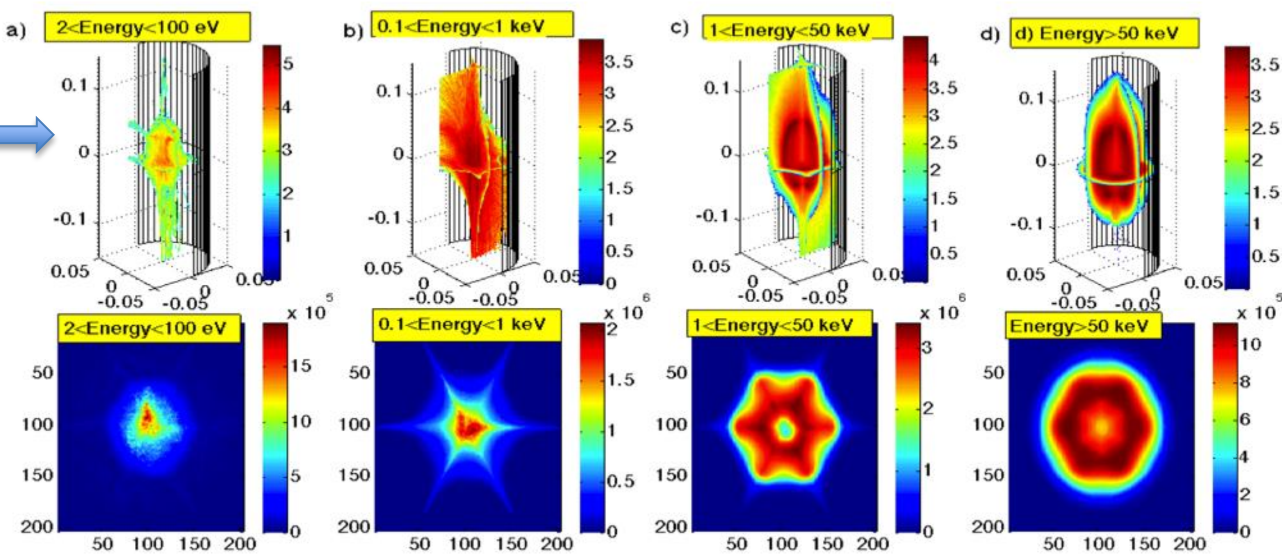
Impact of the inner plasma density structure on the output beam as correctly explained by MC calculations



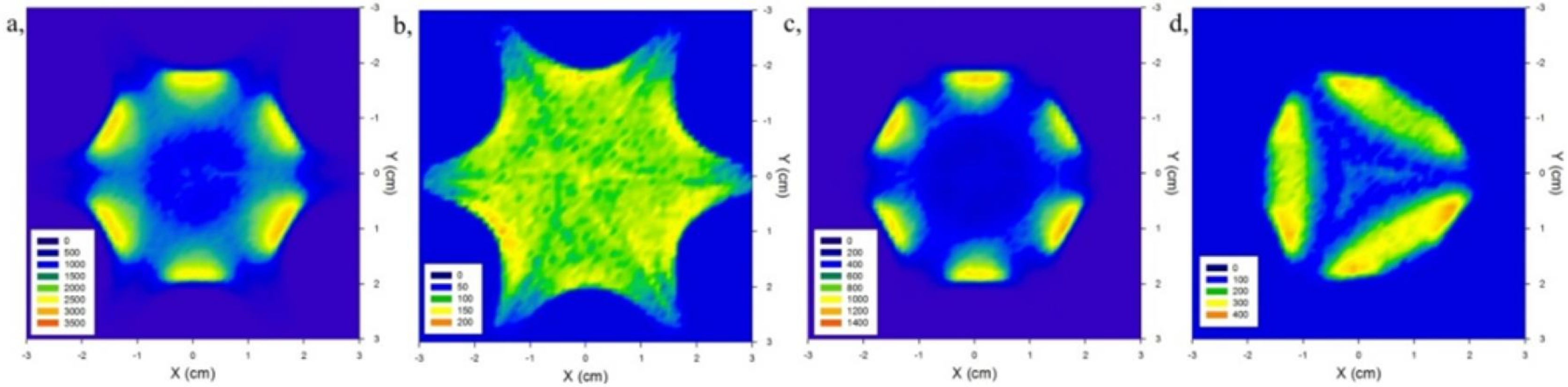


***Collimation system** for X-rays detection from the plasma-core*

Self-consistent simulation of Plasma density structure in different energy domains: in qualitative agreement with optical and X-ray imaging (dense plasmoid formation + depletion in the near axis region)



- D. Mascali et al., *Rev. Sci. Instrum.* 85 , 02A956 (2014) ;
- G. Torrisi et al.; *The Journal of Electromagnetic Waves and Applications* (in press);
- D. Mascali et al.. *Submitted to European Physical Journal – D.*

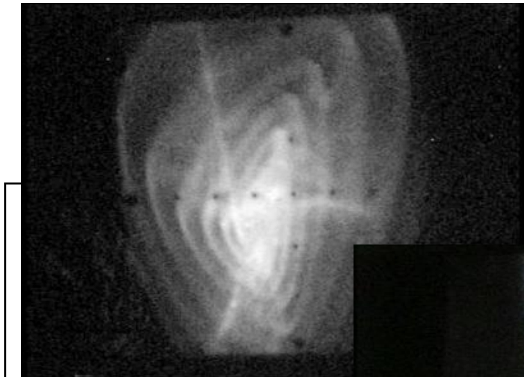


Axial projection of all the non-lost (a), of the cold (b), of the warm (c) and of the energy and spatially filtered coordinates (d) electrons in the GSI CAPRICE source (output from TrapCAD).

Availability of better and better plasma diagnostics will permit in the future to check the results of simulation and then to predict the beam formation process in a realistic way: this was our dream 5 years ago, it is almost reached.

Finally beam users are interested to the value of "beam on target", then the improvement of beam emittance and matching to accelerator may be even more important than a large increase in extracted current from ECRIS

Viewing screens at the EIS test bench

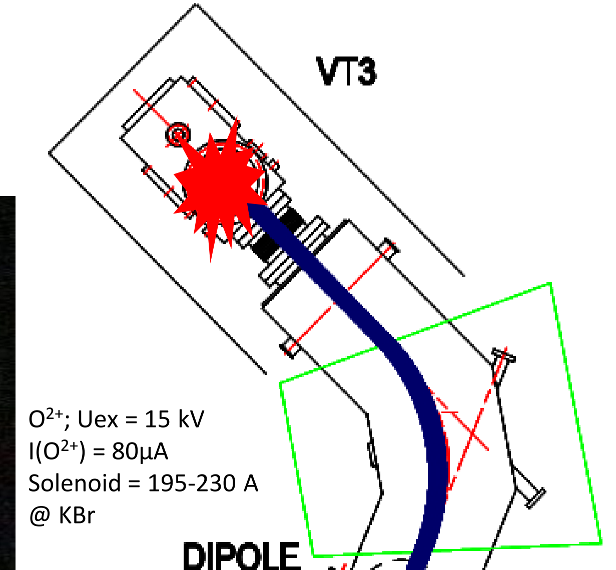


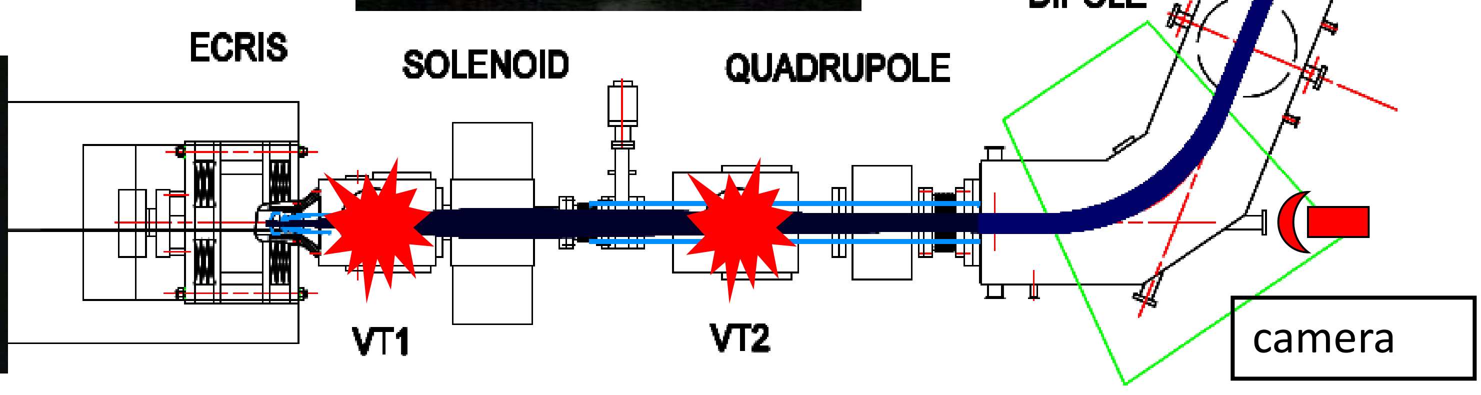
Ar/He; Uex = 15 kV
Iex = 2,5 mA @ BaF_2

Ar/He; Uex = 12 kV
Iex = 2,3 mA
Solenoid 0-350 A @ BaF_2

O^{2+}; Uex = 15 kV
$I(O^{2+})$ = 80μA
Solenoid = 195-230 A
@ KBr

e; Uex = 12 kV
Uscr = 0 kV
Oven aperture





FREQUENCY TUNING: EFFECT ON THE HIGHER CHARGE STATES

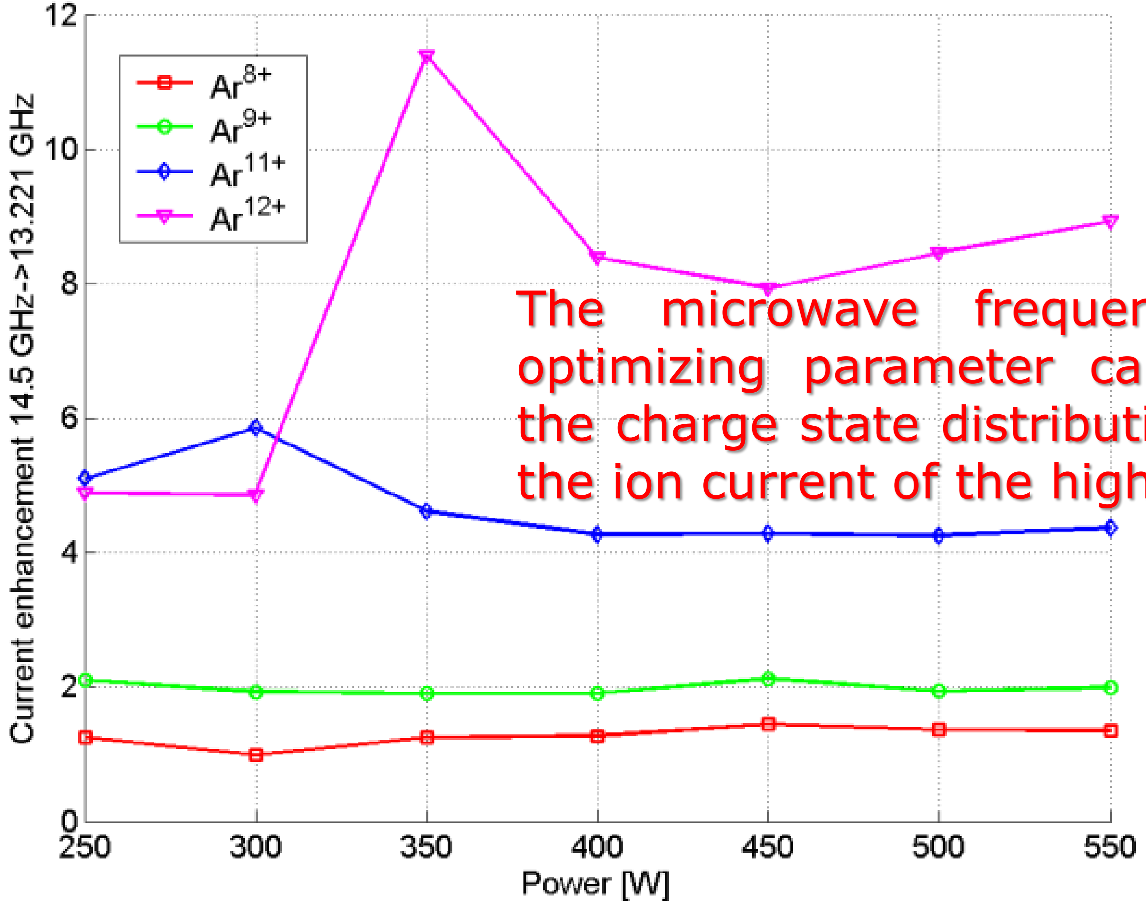
- The charge state distributions were measured at 13.221 GHz and 14.5 GHz for microwave powers ramping from 250 W to 550 W in steps of 50 W (the other source settings were not varied)
- The measured current values reveal how the increase of power is effective only for the higher charge states (i.e. above the Ar^{8+})
- The ratio of the two current values, at 14.5 GHz and at 13.221 GHz, (for the last four rows of the table) demonstrates how effective is the choice of the frequency for the high charge state ion production

Currents of Argon beams expressed in μA for different power levels at two microwave frequencies

	MICROWAVE POWER [W]													
	250		300		350		400		450		500		550	
	14.5 GHz	13.221 GHz	14.5 GHz	13.221 GHz	14.5 GHz	13.221 GHz	14.5 GHz	13.221 GHz	14.5 GHz	13.221 GHz	14.5 GHz	13.221 GHz	14.5 GHz	13.221 GHz
Ar^{3+}	34.5	56.4	30.9	56.8	29.2	46.3	27.9	53.9	26.5	39.2	25.7	35.7	26.6	36.5
Ar^{4+}	65.2	71.7	60.7	64.5	58.9	66.7	57.2	71.3	55.1	68	54.3	66.4	54.7	64.7
Ar^{5+}	116.2	99.4	112.1	87.8	110.3	98	111.2	109.5	105.9	105.9	109.3	103.5	106.8	103.9
Ar^{6+}	180.4	144.5	186.2	101.2	185	160.8	184.2	173.5	185.4	182.8	187.9	174.7	180.9	166
Ar^{7+}	219.3	175.9	232	147.8	244.3	230.1	252.4	259.6	259.5	297.3	262.3	280.8	265.3	267.6
Ar^{8+}	226.9	283.7	270.2	267.4	290.5	361.6	295.9	377.2	310.5	449	327.1	445	310.9	421
Ar^{9+}	60.6	127.1	72.9	140.5	85.3	162.5	92.3	175.4	96.4	204.6	104.2	202.1	104.1	207.8
Ar^{11+}	0.78	4	1	5.85	1.3	6	1.5	6.4	1.8	7.7	2.0	8.5	2.2	9.6
Ar^{12+}	0.04	0.21	0.06	0.28	0.08	0.9	0.1	0.85	0.13	1	0.13	1.1	0.14	1.2

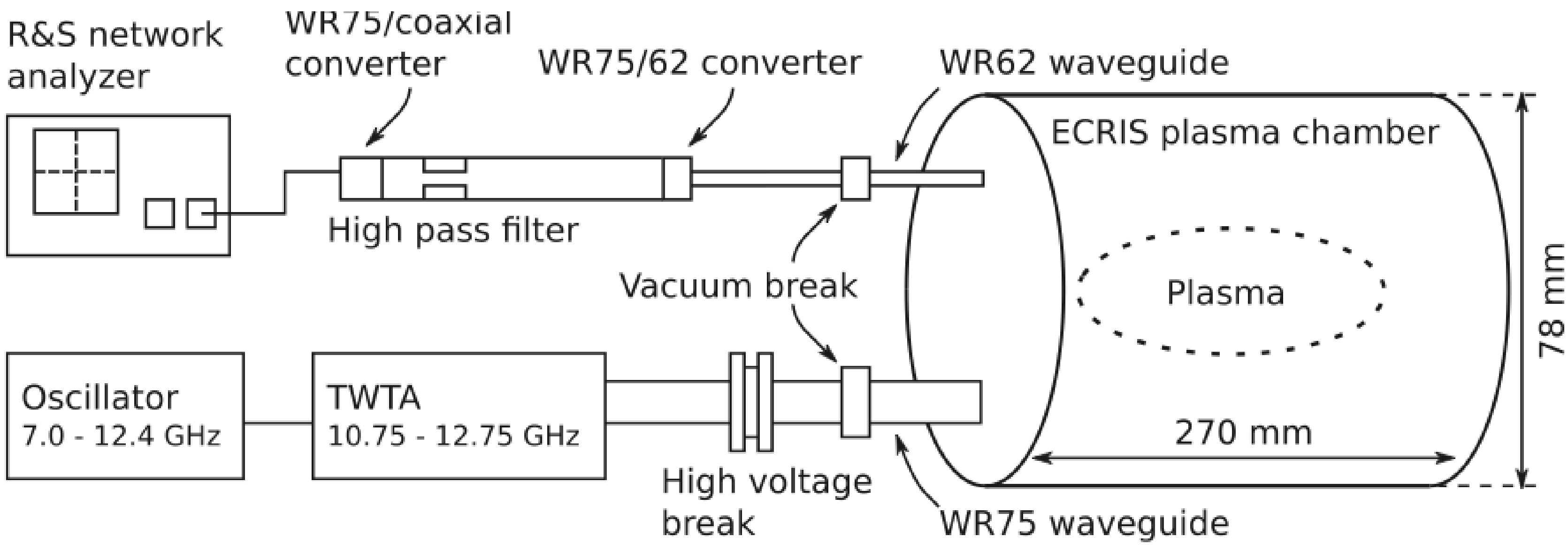
FREQUENCY TUNING: EFFECT ON THE HIGHER CHARGE STATES

Ratio of the two current levels measured at 13.221 GHz and 14.5 GHz for different microwave powers



The microwave frequency used as an optimizing parameter can strongly modify the charge state distribution thus increasing the ion current of the higher charge states.

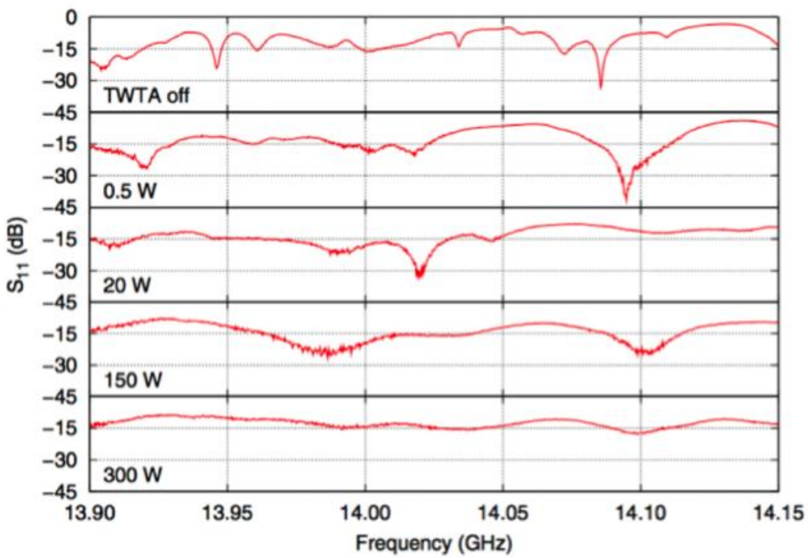
ECRIS studies with Network Analyzer @ JYFL

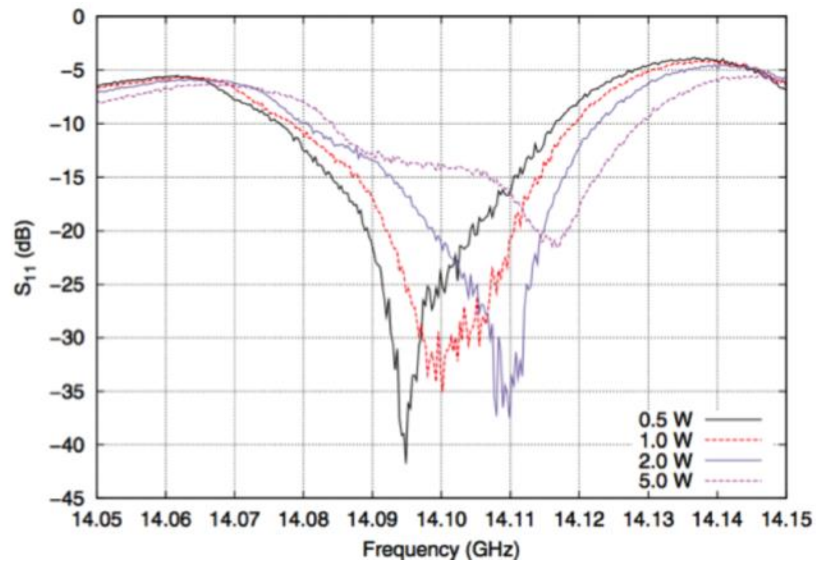


Dual port measurement setup for probing the coupling properties of plasma loaded cavity.

ECRIS studies with Network Analyzer @ JYFL

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ





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

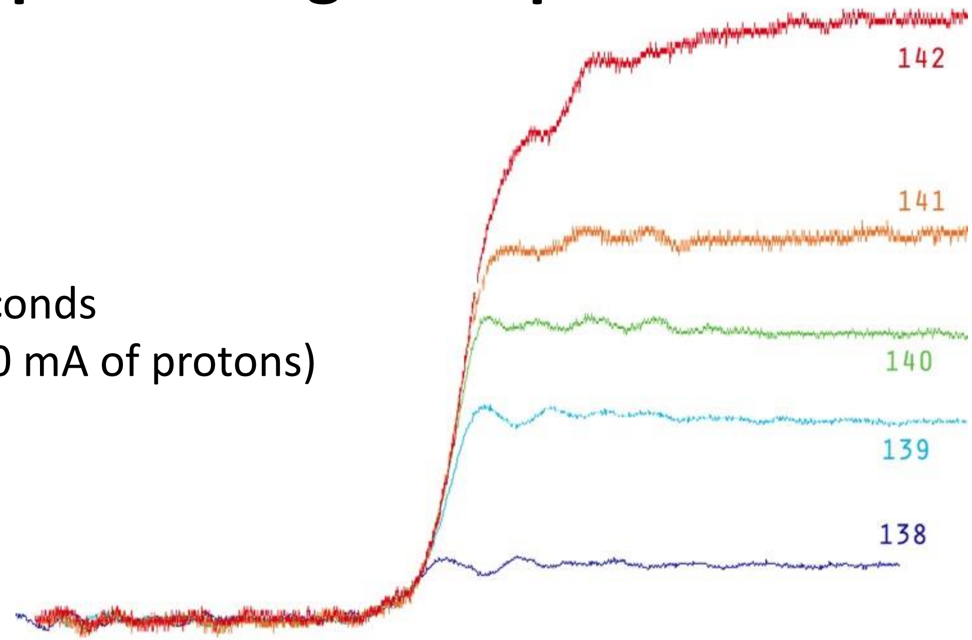
The investigation of the influence of the “frequency tuning” technique exhibited a considerable influence on ion beam intensity and transmission through the LEBT.→ this is a particularly remarkable result as it confirmed with systematics what before ARES has been just a series of observation → it is to be understood if the ripple of the extracted beam plays a major role in the determination of the emittance because of a poor space charge compensation

The typical internal structures of ion beam profiles coming from ECRIS have been verified (GSI)

The results of the simulations have been compared with measurements of both beam profiles and of effective emittances. The results show that the beam is fully space-charge compensated for the beam currents that have been used (450 μA). @KVI

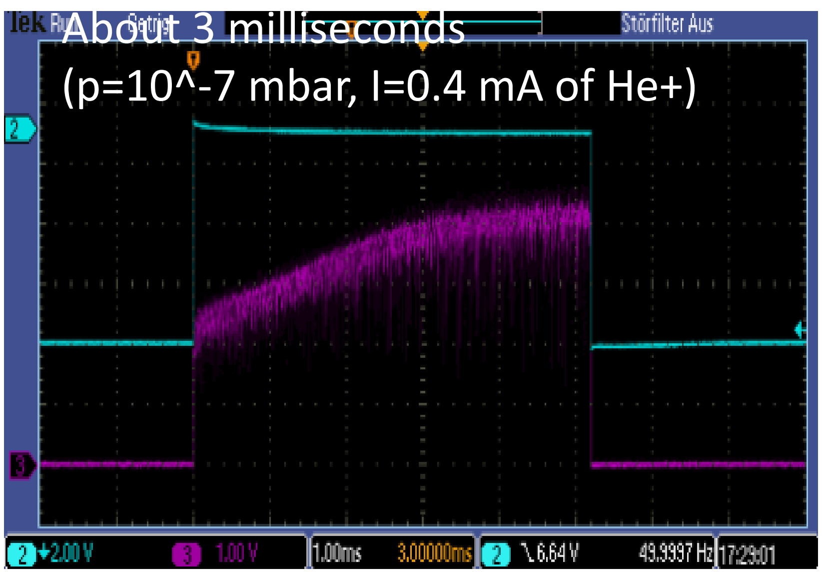
A new extraction system has been designed for the JYFL 14 GHz ECRIS with IBSimu code → it is not the only evidence of technical progresses driven by simulation, and this ability to predict ECRIS improvement and to test it can be proposed as a major improvement coming after ENSAR/ARES.

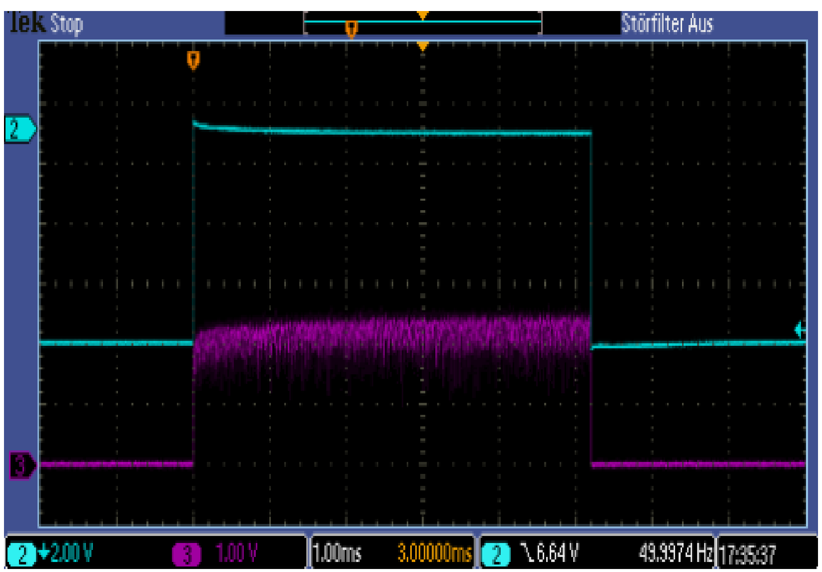
Space charge compensation



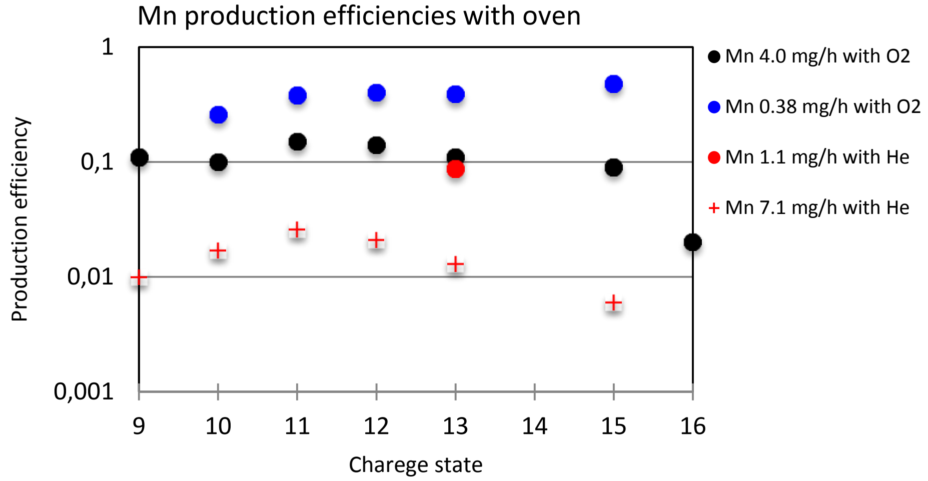
Some hundred microseconds
(p=3*10^-5 mbar, I=5-40 mA of protons)

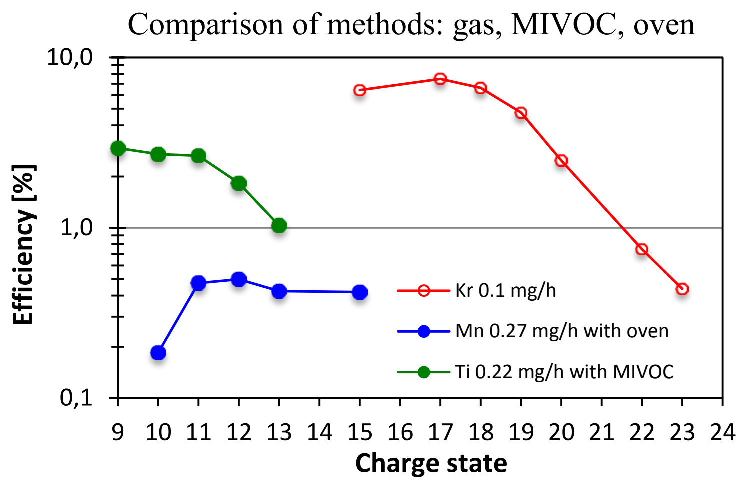
About 3 milliseconds
(p=10^-7 mbar, I=0.4 mA of He+)





Ionisation efficiency measurements with different mixing gas parameters: Milestone MS84 -JRA01-ARES

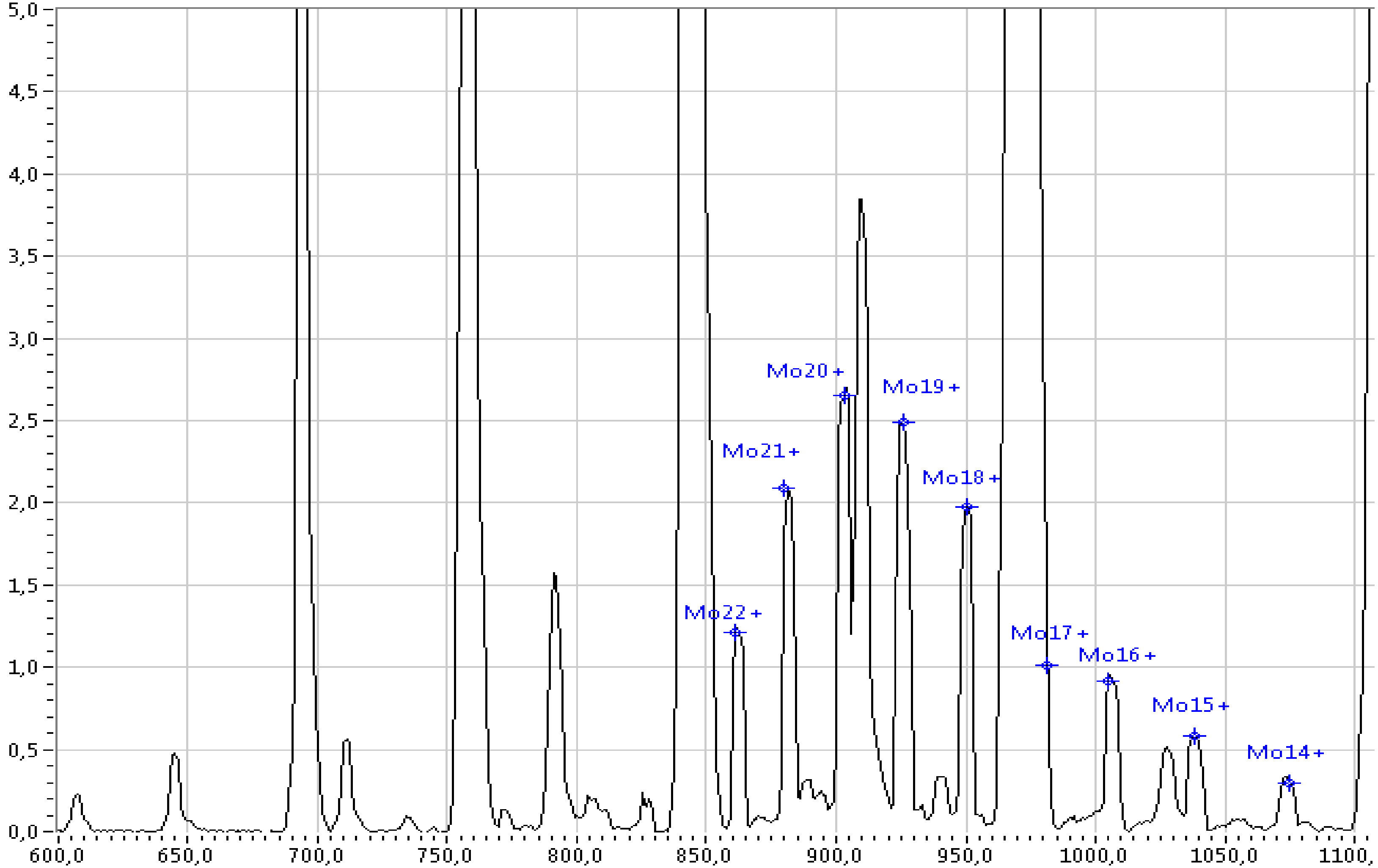




Main findings:

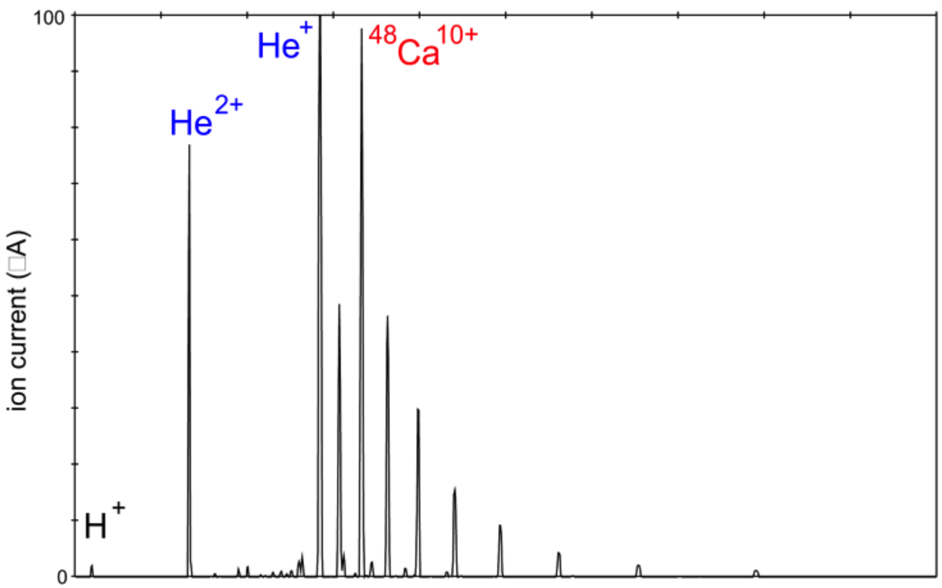
- as a mixing gas oxygen is superior compared to helium (left-hand-side graph)
- MIVOC method is very efficient when compared to oven method (right-hand-side graph)
- →oven method has space for further improvements in terms of production efficiency (oven geometry, location, means to guide the evaporated elements into the plasma,…)

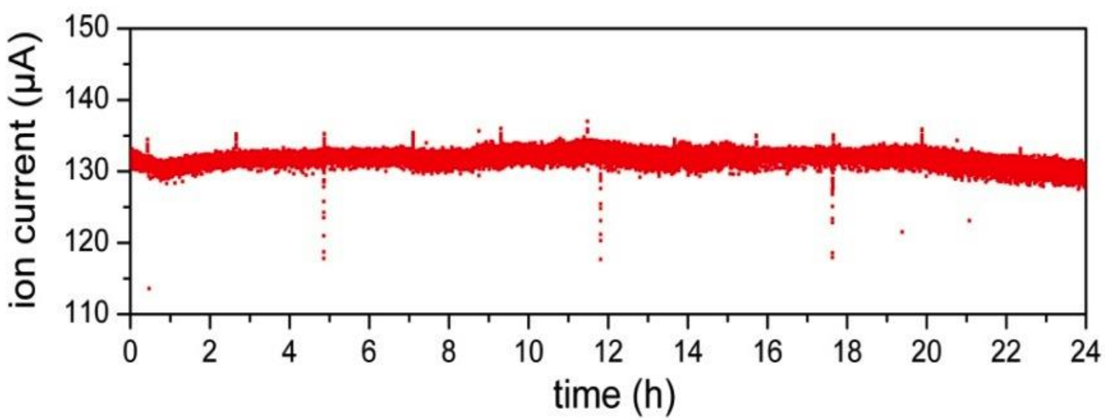
The oven geometry should be designed such a way that the evaporated metal atom has a very limited possibility to enter the cold plasma chamber wall.
In addition, the method to guide the evaporated elements directly into the plasma should be considered.



Mo22+
Mo21+
Mo20+
Mo19+
Mo18+
Mo17+
Mo16+
Mo15+
Mo14+
5,0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
600,0
650,0
700,0
750,0
800,0
850,0
900,0
950,0
1000,0
1050,0
1100,

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 improved (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)

This is a partial view of the work done in 4+ years.
But it’s enough to show that the results of ARES, though “intangible”, are “assets” for the European Research Infrastructures.

Something that deserves to be underlined is that ECRIS community in Europe has been working in the frame of European Research Area (ERA) long before this concept was proposed in official documents, and that many of us are collaborating according to ERA since mid’90s: this is not negligible and it has permitted remarkable results in presence of minor investments.

Therefore, to a colleague who during a meeting claimed that ARES has not obtained recognizable results, it was easy to demonstrate that he was wrong.

But *we cannot feel that this is a success story* until the time that the world beyond the ECRIS Standard Model is disclosed. I dream since long about a MCI source without hexapole or a trap producing high brightness beams without reaching a level of unaffordable investments. There is a lot to do, starting from ARES results.

In a few words, to synthesize the “net gain” for EU coming from ENSAR/ARES investment, I’d say:

- **A different basis for the design of 3° generation ECRIS, that could make reasonable the cost and reliability of a 4° generation ECRIS (56-70 GHz)**
- A better exploitation of microwaves, even with a more complex LLRF setup (mechanics and/or magnetic field outside the standard?) → refusal of “brute force” approach coming from a straight application of ECRIS Standard Model
- ***This way of looking to the future in a proactive approach is the only way to manage the future requests of accelerator facility: it is clear that the ECRIS of ‘20s will manage tens of mA total current to produce multi-mA HCI beams***
- *It is also clear that a simple scaling will entail investments above the scale of 10 M€, i.e. the cost of injectors becomes not negligible even for large Research Infrastructures → this makes the ECRIS Standard Model poorly applicable in the long term*
- **The generation of hard X-rays may be a showstopper for 4° generation ECRIS, making unreliable the magnetic trap and complex the safety as well as the HV insulation**

European Nuclear Science and Applications Research
ENSAR

(continue)

- The evidence of the role of different paths to electron heating makes more and more important to understand better which kind of plasma physics is involved in ECRIS plasma formation: the picture is complex and mistakes can be done, but hopefully the ARES-generated information may pave our road.
- It may be that we will continue to call our source "ECRIS" just for historical reasons, but the role of "ECR" may be only a partial one.
- ***Last but not the least, the EU cooperation team has played an unique role in training for young researchers, that is a main benefit for EU Research Institutions, and (not to be neglected) it worked as a "gymnasiòn" for elder scientists.***