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ECR Plasma Physics and Production of Highly Charged Heavy Ion from MS-ECRIS

S. Gammino for the ISIBHI collaboration

INFN - GSI - GANIL - CEA - JYFL - KVI - TSL - CERN - NIPNE - IKF

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Outline

1. The ECR laws and their limits: experimental evidences.
2. The 3rd generation ECRISs and the status of the MS-ECRIS source.
3. Possible future steps with MS-ECRIS and beyond.
4. Warning: usually invited speakers give answers, I will often pose questions…

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Intense beams of highly charged heavy ions

- Intense beams: study of rare processes (RIBs, SHE).
- Highly charged ions -->> higher energy for cyclotron beams.
- Heavy ions (particularly metals) are needed.
- These requests may be fulfilled by 3rd generation ECRIS (f > 24 GHz, B > 3 T).

ECRIS generations

(presented at HIAT'98)

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How to increase highly charged ion production?

- Up to recent times, the continuous improvements of magnet technology and RF generators technology have guided the steps towards the use of higher magnetic field and higher microwave frequency to heat the electrons via the ECR heating.
- A simple scaling of frequency and magnetic field according to the Geller's scaling laws cannot be continued 'ad libitum' as we are near the limit of magnets' technology.
- Additional limitation: ECR plasma physics is not completely understood.

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Scaling laws, High B mode, Golovanivsky plot

a) the radial magnetic field value at the plasma chamber wall must be B_{rad} ^{3} $2 B_{ECR}$;

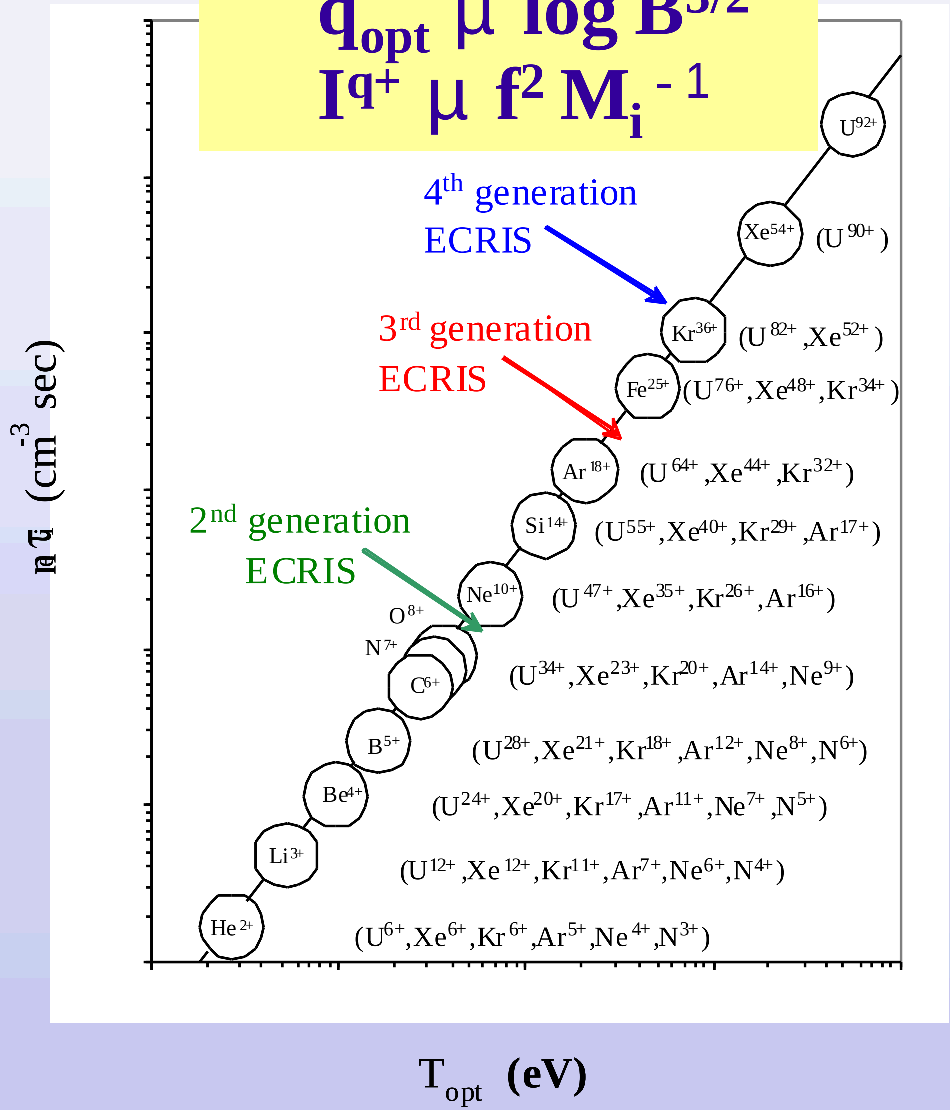
b) the axial magnetic field value at injection must be about B_{inj} » $3B_{ECR}$ or more;

c) the axial magnetic field value at extraction must be about B_{ext} » B_{rad} ;

d) the axial magnetic field value at the minimum must be in the range $0.30 < B_{min}/B_{rad} < 0.45$.

$q_{opt}\ \mu\ \log B^{3/2}$

$I^{q+}\ \mu\ f^2 M_i^{-1}$



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Scaling to 3rd and 4th generation ECRIS

If we consider a simple scaling law for the magnetic field and frequency, we obtain 3-5 T for the 3rd generation ECRIS and 28-37 GHz operational frequency; 6-8 T for the 4th generation and 56-75 GHz frequency.

The former case is still within the existing technology of magnets and RF generators.

The latter case it is not for the magnets, as these field can be obtained only with Nb_3Sn magnets, but maybe it will be in the next decade (progresses are ongoing).

Microwave power

It is not also for microwave generators, as a generator of the right frequency (40 to 60 GHz) and power (in the range of tens of kW), working in cw mode, has to be built 'ad hoc'.

Power is a major issue, in fact following a simple scaling laws

$$P = V\, E_e\, n_e/t_e$$

for a 4th generation ECRIS we would need more than 50 kW !

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For MS-ECRIS and for the next generation of ECR sources it will be necessary to master critical issues of plasma physics to fully exploit their characteristics.

Even if relevant technological achievement may provide higher confining field and higher power/frequency microwave generators, they will be not useful without the competent ***understanding of non-linear effects*** arising in the ECRIS plasma.

These considerations are reinforced by experimental results:

Some experimental 'strange' data

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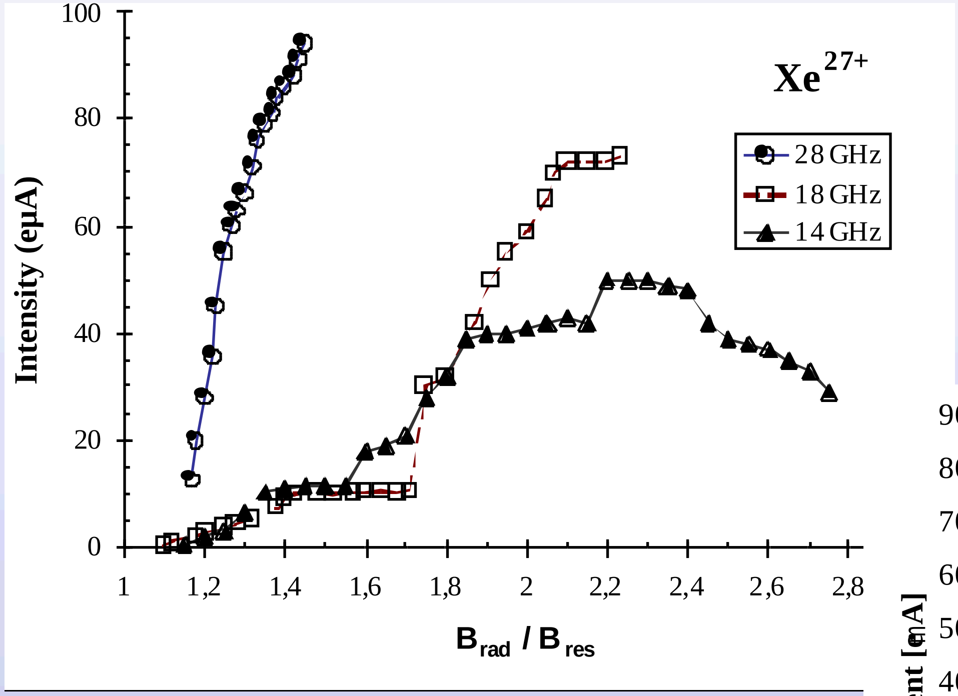
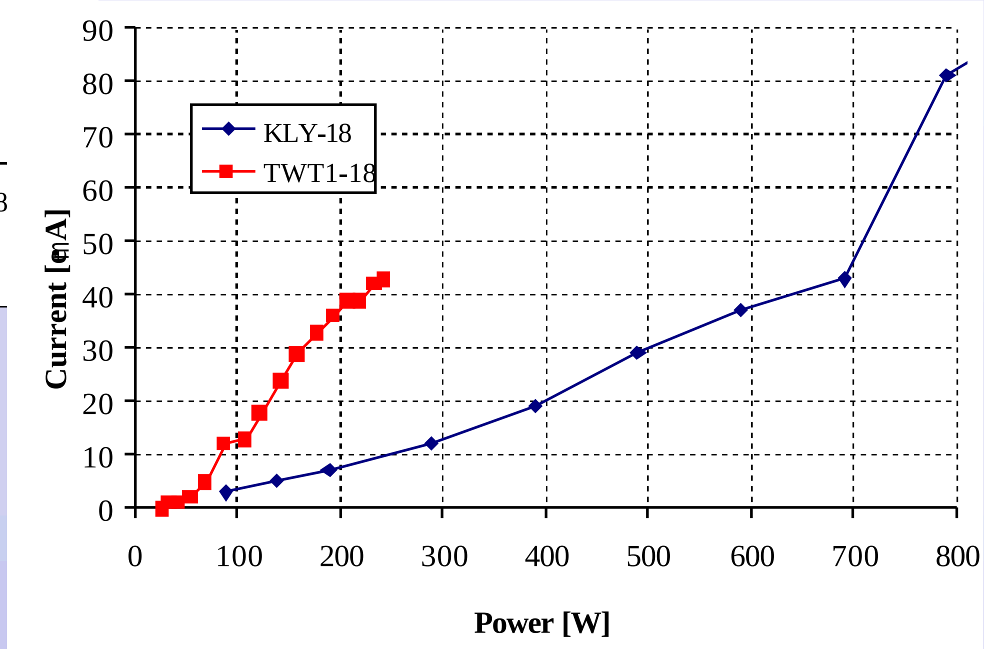


SERSE
Aug-Sept. 2000

SERSE
Oct. 2001-summer 2002



There is something except HBM and scaling laws

- The explanation was found in the assumption that microwaves injection and coupling to the plasma as well as ECR heating is not a simple matter of ‘brute force’ but the way that microwaves are injected is important.
- L. Celona proposed different schemes of microwaves injection at ECRIS’04 workshop at LBNL.

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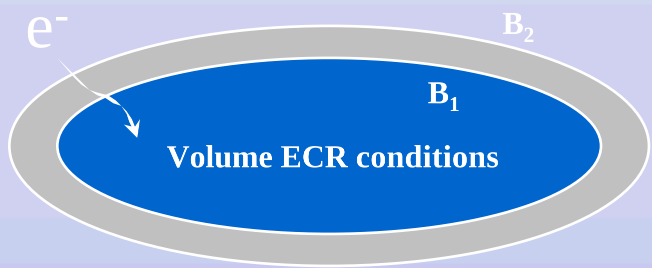
Broadband generators and ECR condition

$$B = B_{ECR} = \frac{2\pi\, m_e}{|q_e|}\nu_{EM}$$

When TWT is used VOLUME EFFECT takes place?

$$\begin{cases} B_1 = \dfrac{2\pi m_e}{|q_e|}(\nu_{EM} - \Delta\nu) \\ B_2 = \dfrac{2\pi m_e}{|q_e|}(\nu_{EM} + \Delta\nu) \end{cases}$$



From the talk given by L.Celona
at ECRIS'04

- SERSE test with broad frequency spectrum (continuous and discrete)
- White noise generator
- Test with a passband filter (able to withstand the full power of the microwave generator) to select exactly the needed bandwidth.
- Accurate modelling of the phenomena.
- Development of broadband microwave generator (e.g. GyroTWT) is requested.

Broader resonance or something else?

The explanation in terms of a broader resonance related to the broad bandwidth of the amplifier was not fully convincing: it does not explain the different results when different sources operate in Two Frequency Heating mode.

An experiment with White Noise Generator, was successfully carried out by a JYFL-ORNL collaboration in 2005 (Y. Kawai et al, Rev.Sci.Instr. 77,03A331).

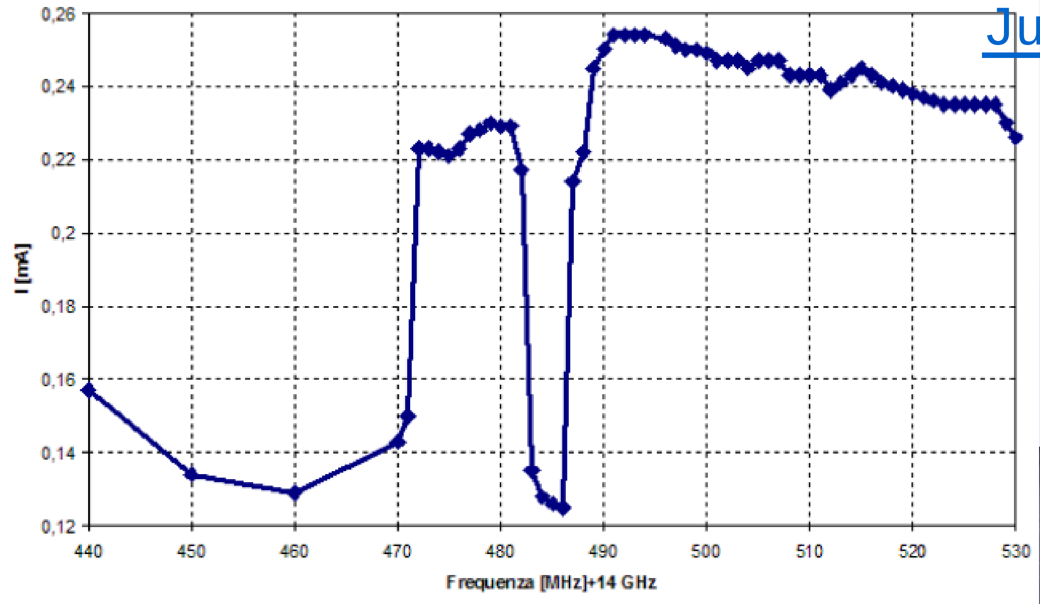
An improvement of a factor 2-3 was obtained for the current of the highest charge states produced by a old 6.4 GHz ECRIS (the amount of power was only about 200 W).

Frequency tuning effect

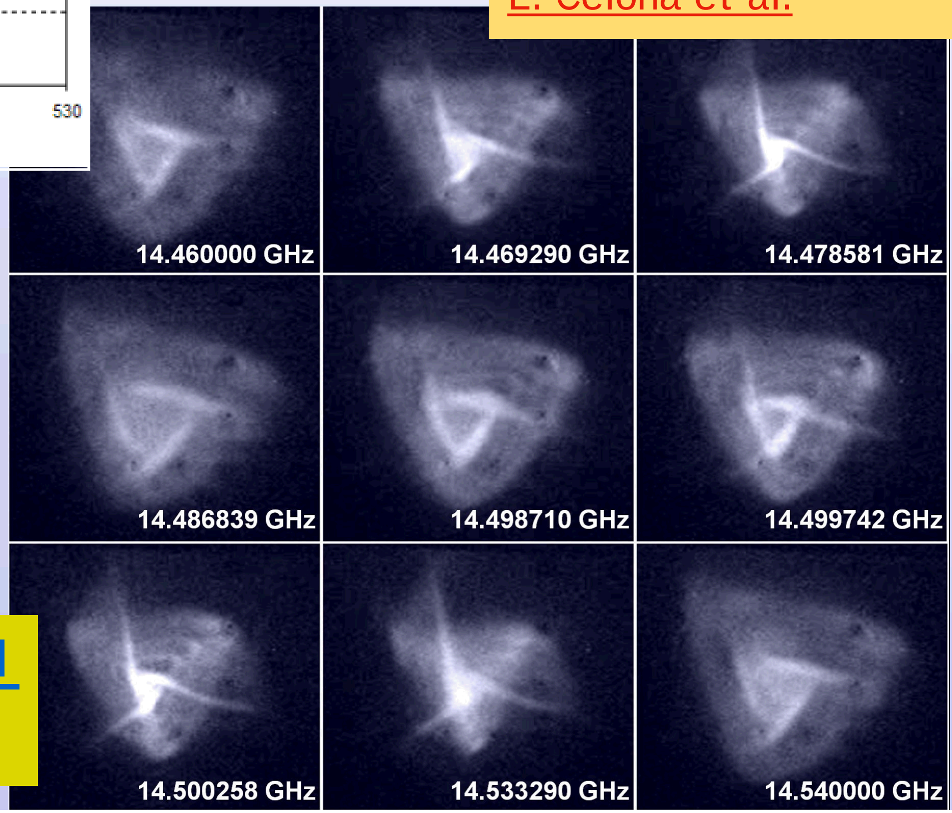
In the meantime the need to define the ideal position of the waveguide ports in MS-ECRIS made necessary to study the shape of modes excited inside the plasma chamber; a parallel study about the effectiveness of the ECR heating in the case of the SERSE source made clear that the important figure is not the maximum field in the plasma chamber but the maximum value that the field reaches on the resonant surface.

Some experimental results made this picture more convincing, showing that minor changes of frequency may be relevant on the performance as they rapidly and completely change the maximum of the field.

SUPERNANOGAN - CNAO
July 2005



L. Celona et al.



CAPRICE -GSI
fall 2006

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Are we able to apply these results to existing ECRIS?

- Different sources use TWT generator and already operate the frequency tuning.
- 14 and 18 GHz Klystron generators may be also tuned within few tens of MHz.
- Gyrotrons cannot, but microwave launching and modes excitation in the plasma chamber may be optimized (latest point is still to be studied).
- Minor investment may take to relevant performance increase (multi-frequency heating is still not fully exploited).

Simulations' Results for Single Frequency Heating

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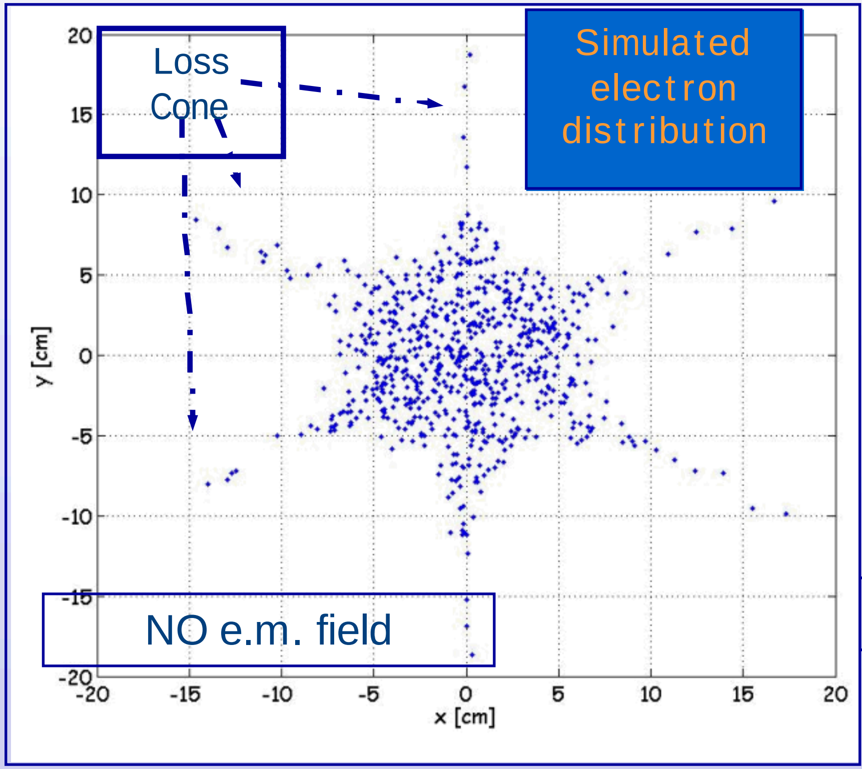
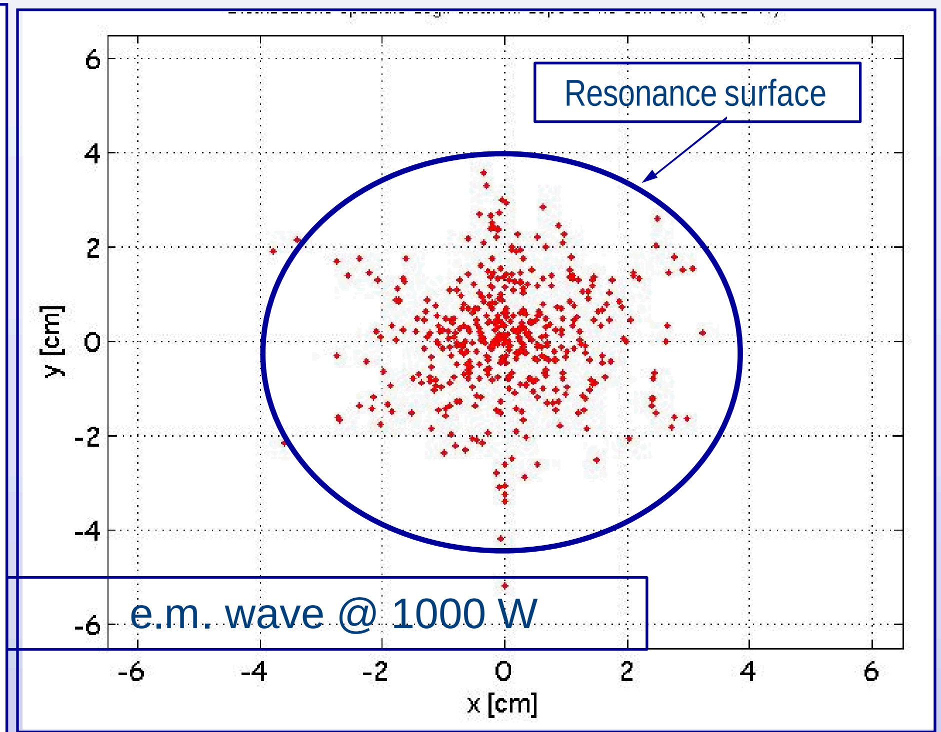




The e.m. field allows to confine up to

60% of electrons that otherwise go away from the plasma.

Improvement of the electron heating

by means of Two Frequency Heating - TFH

Strong ECR plug effect and plug-in

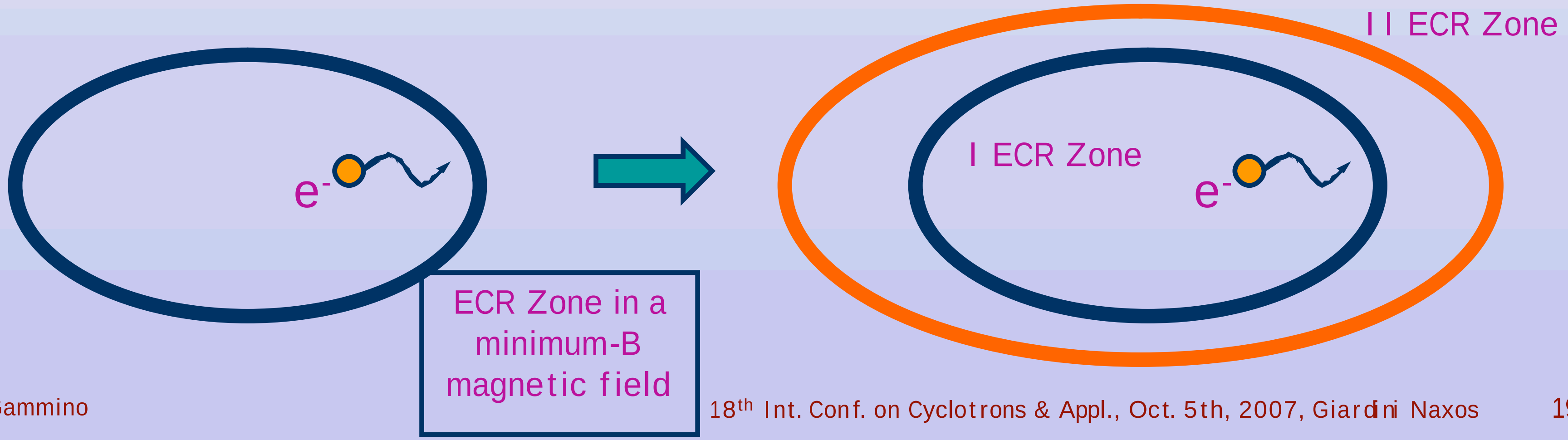
Energy Saturation at higher powers

↓

plasma heating with two electromagnetic waves instead of one, by using two lower power values

↓

possibility to optimize the plasma heating by efficient transfer of the electromagnetic energy



ECR Heating dependence on the electromagnetic field shape

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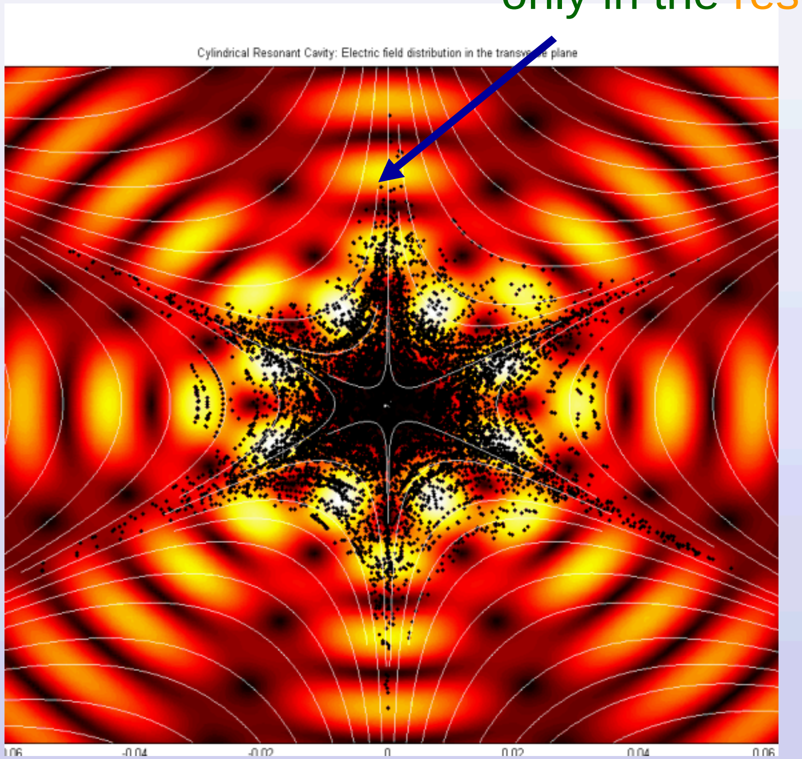
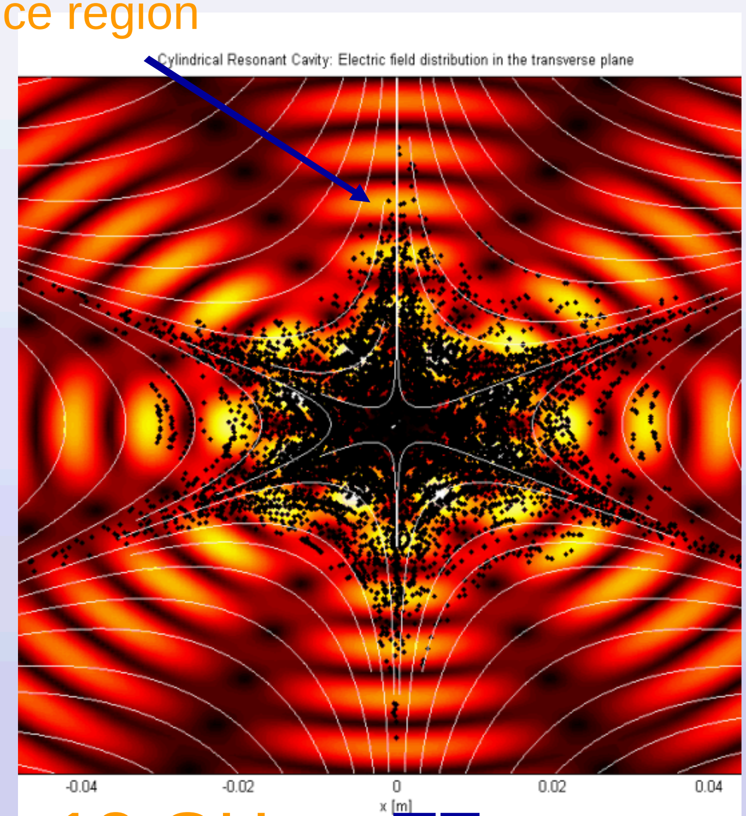
The electron heating occurs only in the resonance region

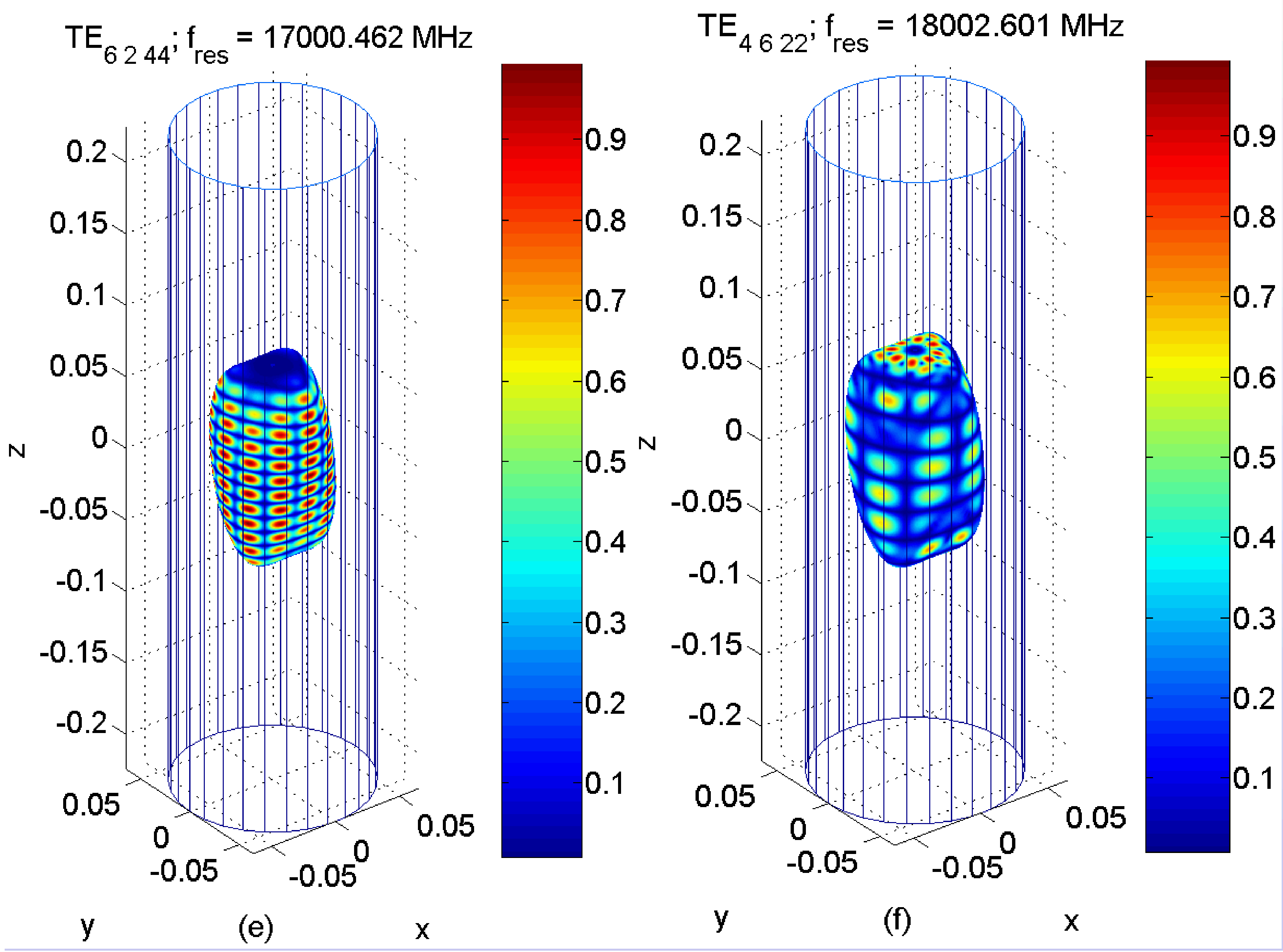


14 GHz – $TE_{4,4,23}$ mode



18 GHz – $TE_{4,6,22}$ mode

For TE4,4,23 the electric field is five times higher than TE4,6,22 at the resonance



TE6 2 44; fres = 17000.462 MHz
TE4 6 22; fres = 18002.601 MHz
z
y
x
(e)
(f)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

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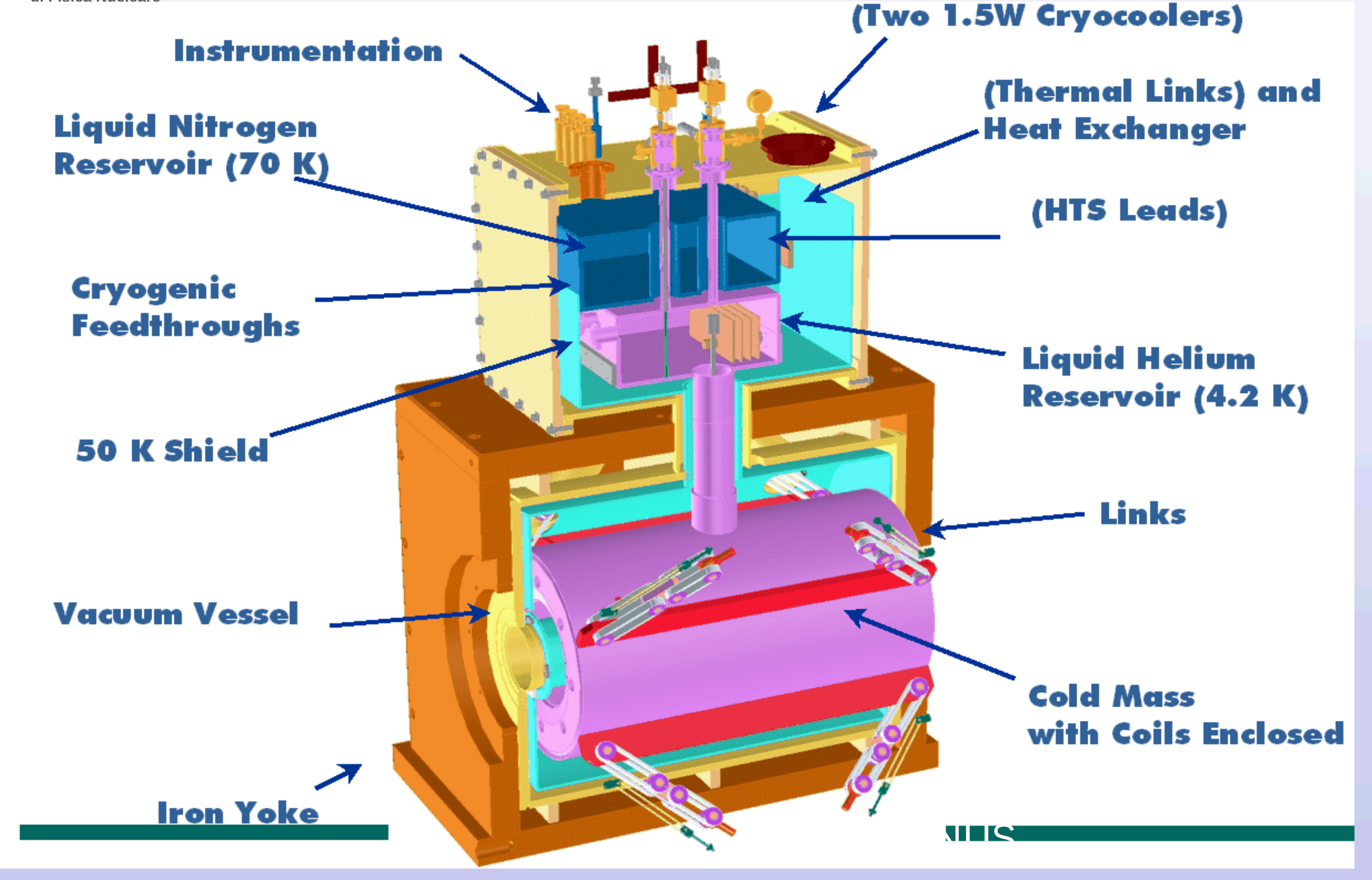
How to apply these results to 3rd generation ECRIS?

- Microwave launching and modes excitation in the plasma chamber may be optimized.
- The magnetic field parameters are to be adapted to the microwave field distribution.
- For TFH a TWT generator should be used in order to operate the frequency tuning.
- Broadband high frequency generator should be built (above 28 GHz), not necessarily above 10 kW.
- Further insights in the ECR plasma physics is mandatory to fully exploit 3rd generation ECRISs.

II part

- State of the art of 3rd generation ECRIS
- The MS-ECRIS source

VENUS @ LBNL



(Two 1.5W Cryocoolers)
Instrumentation
(Thermal Links) and
Heat Exchanger
Liquid Nitrogen
Reservoir (70 K)
(HTS Leads)
Cryogenic
Feedthroughs
Liquid Helium
Reservoir (4.2 K)
50 K Shield
Links
Vacuum Vessel
Cold Mass
with Coils Enclosed
Iron Yoke

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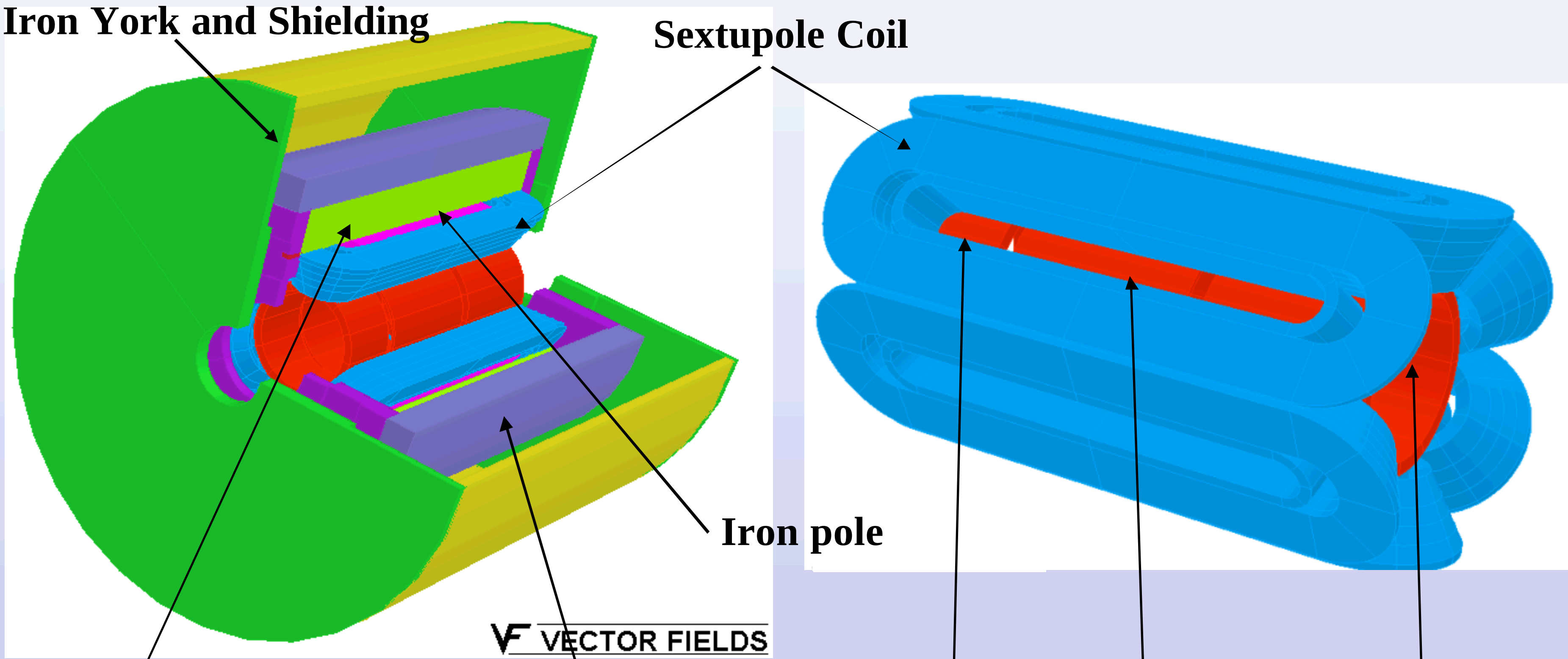
SECRAL
(IMP, Lanzhou, China)



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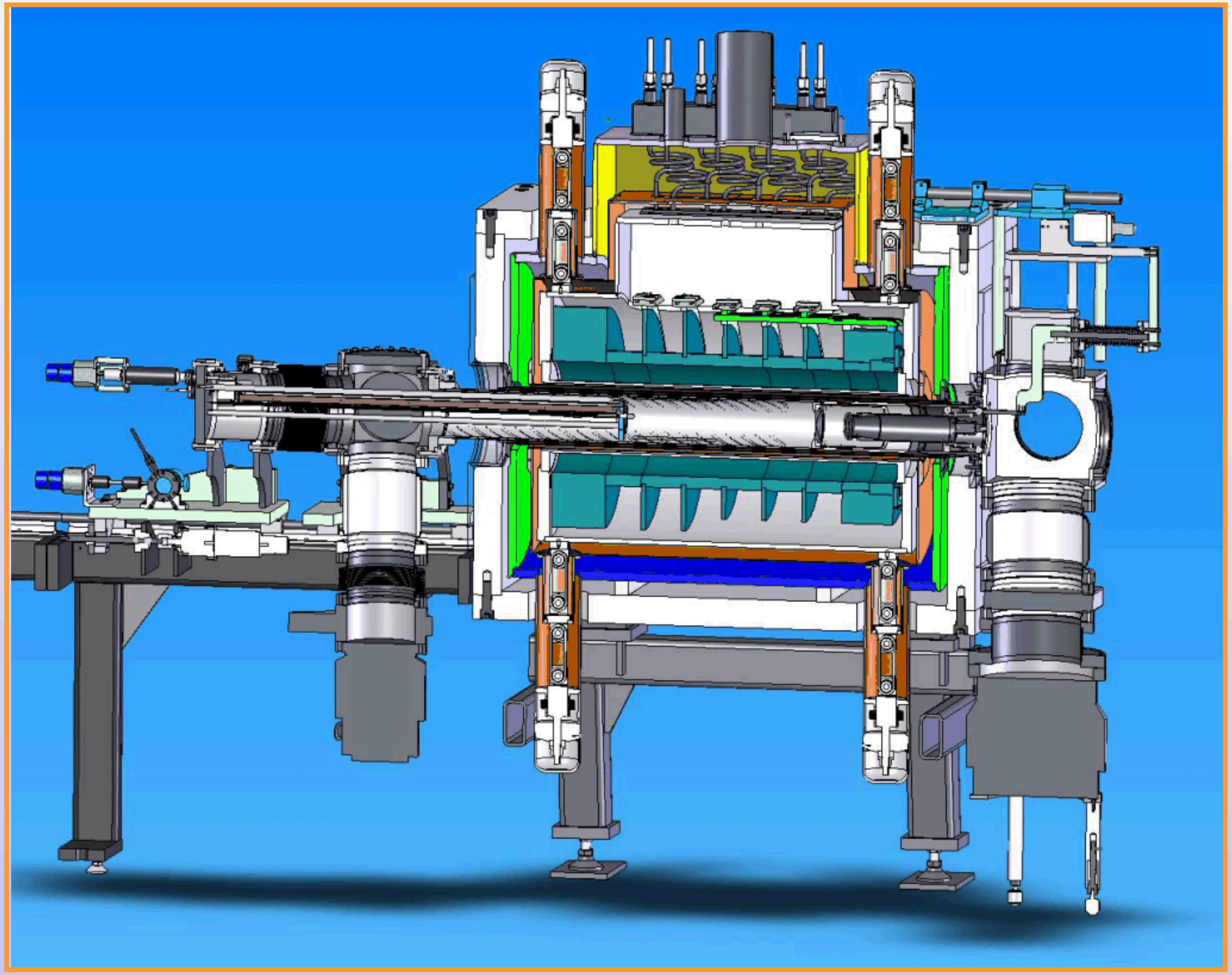
SuSI @ NSCL
Superconducting Source for Ions



A-PHOENIX
a hybrid ECR Ion Source

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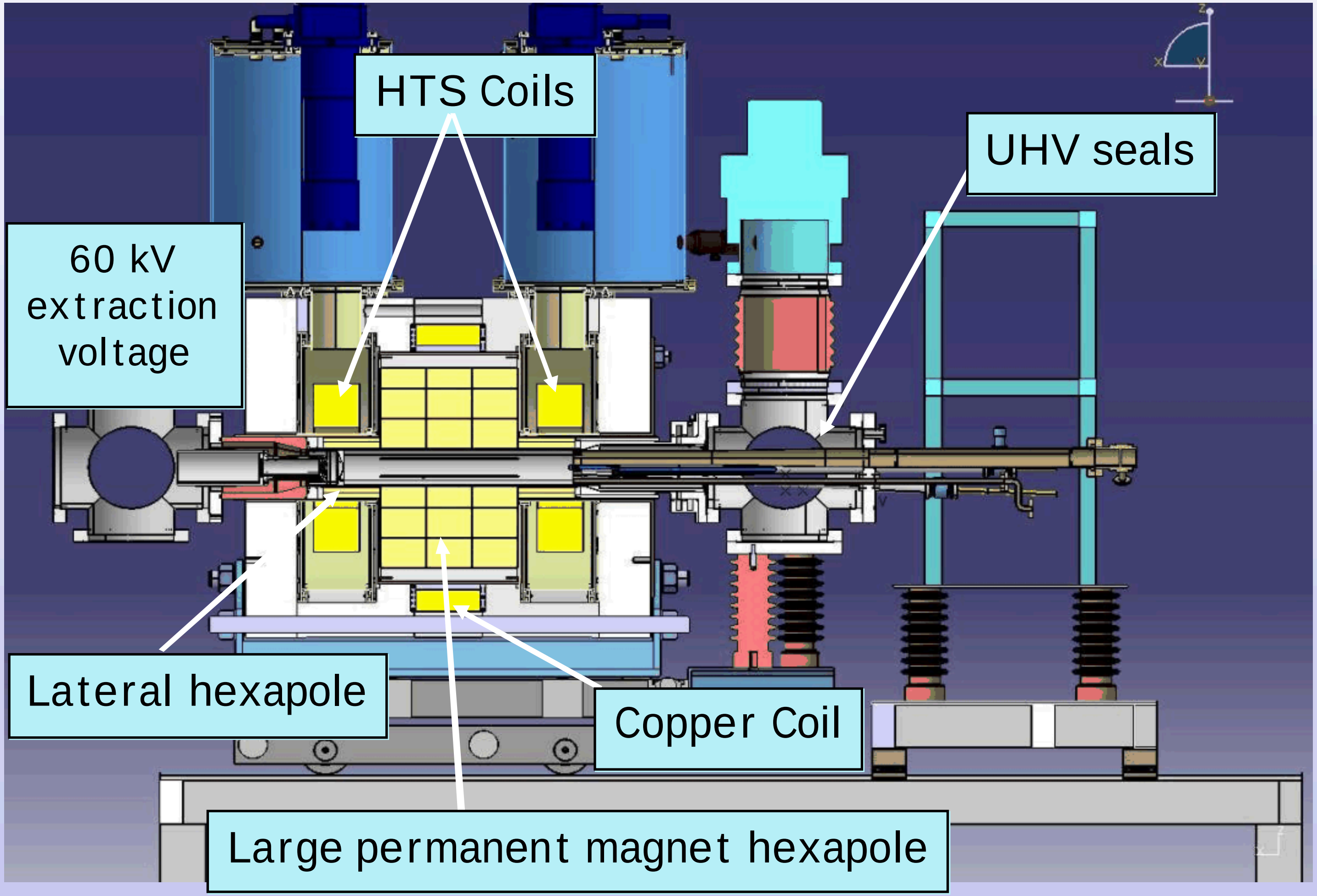
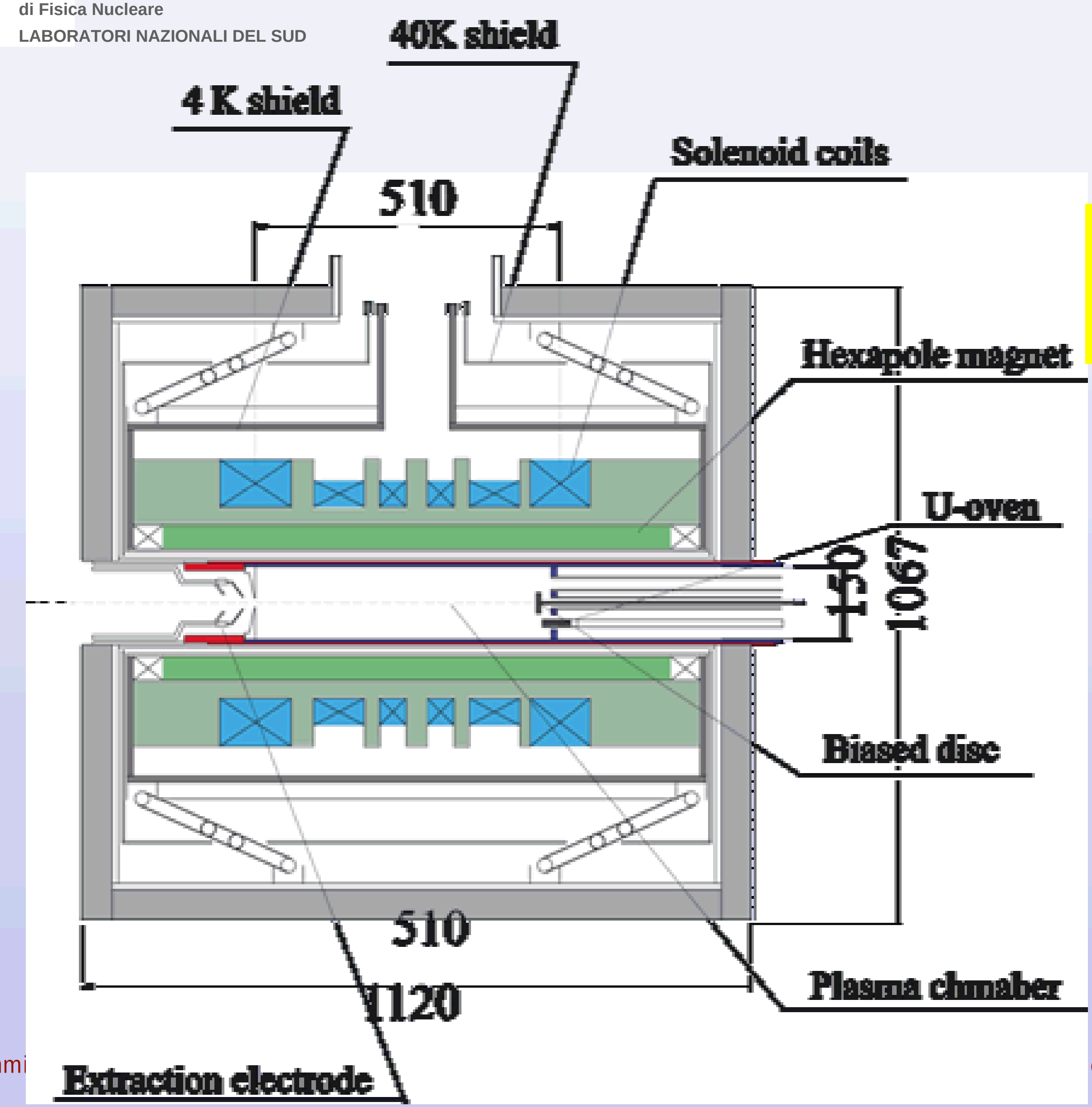


RIKEN SC-ECRIS(28GHz)



Goal for RIBF
15 pμA of U^{35+}

	VENUS	SECRAL	A-PHOENIX	SuSI	MS-ECRIS	RIKEN
B_{radial}	2.1 T	2 T	1.7-2.2 T	2.0 T	2.7 T	2 T
B_{axial}	4.0 T	3.6 T	3 T	3.6 T	4.5 T	4 T
V_{ext}	20 kV	20-30 kV	60 kV	60 kV	40-60 kV	---
$f_{chamber}$	150 mm	126 mm	70 mm	100 mm	180 mm	150 mm

Multipurpose Fully Superconducting Magnets ECRIS (MS-ECRIS)

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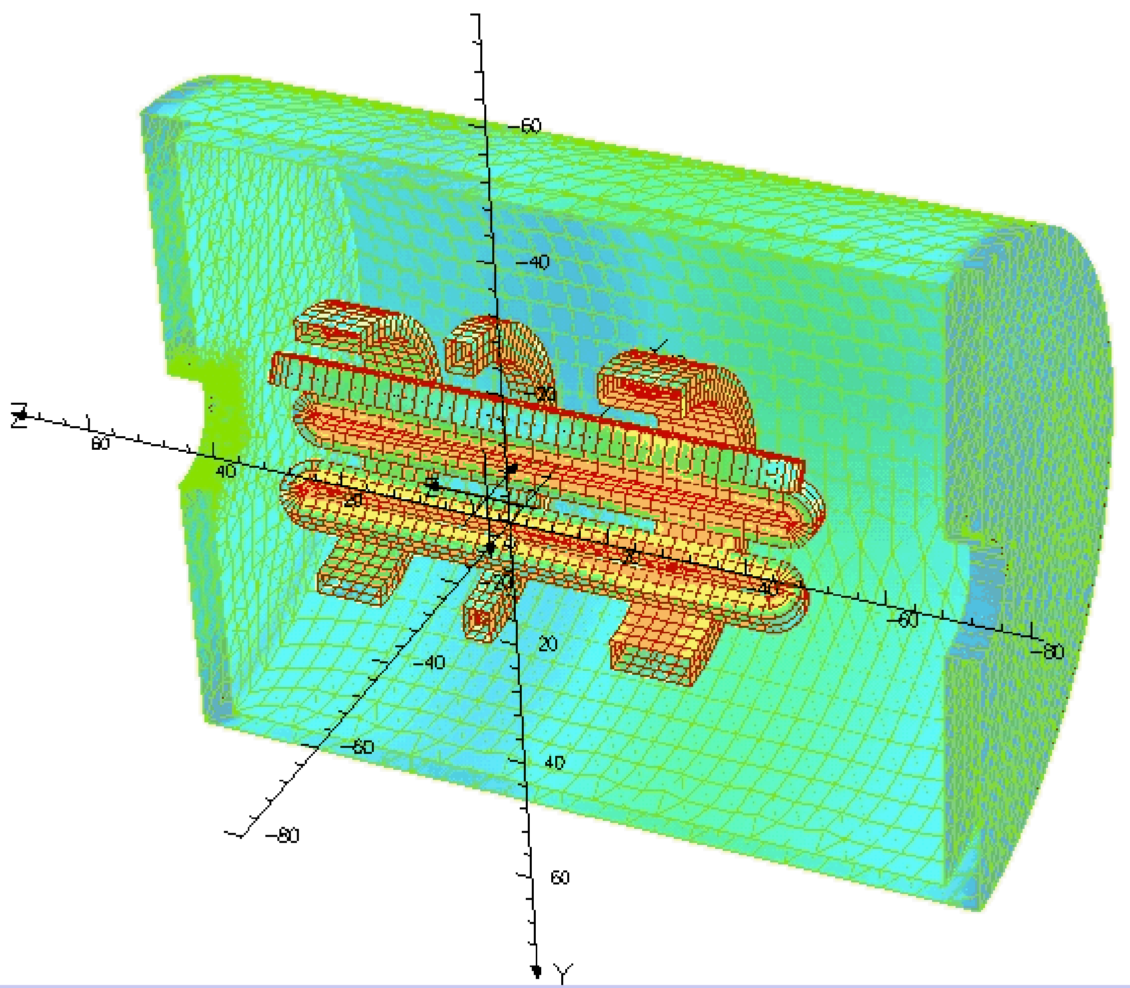

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ISIBHI collaboration

- EU has partially funded the MS-ECRIS construction through the FP7 EURONS/ISIBHI programme (FY 2005-2008).
- MS-ECRIS has been built in about two years with a contribution of 9 institutions.
- Its design has been based on the GyroSERSE project of INFN-LNS.
- It will upgrade GSI facilities, but it may be useful also for SPIRAL2, LHC, INFN-LNS (to revive Nuclear Physics,LBNL88"-like) and other accelerators facility.
- The commissioning was scheduled for the 1st half 2007.
- Non critical delay due to delayed delivery of some mechanical parts.
- Critical delay due to the delivery of magnets and cryostat.
- Gyrotron availability also delayed (not critical because of magnets' delay).

MS-ECRIS assembly

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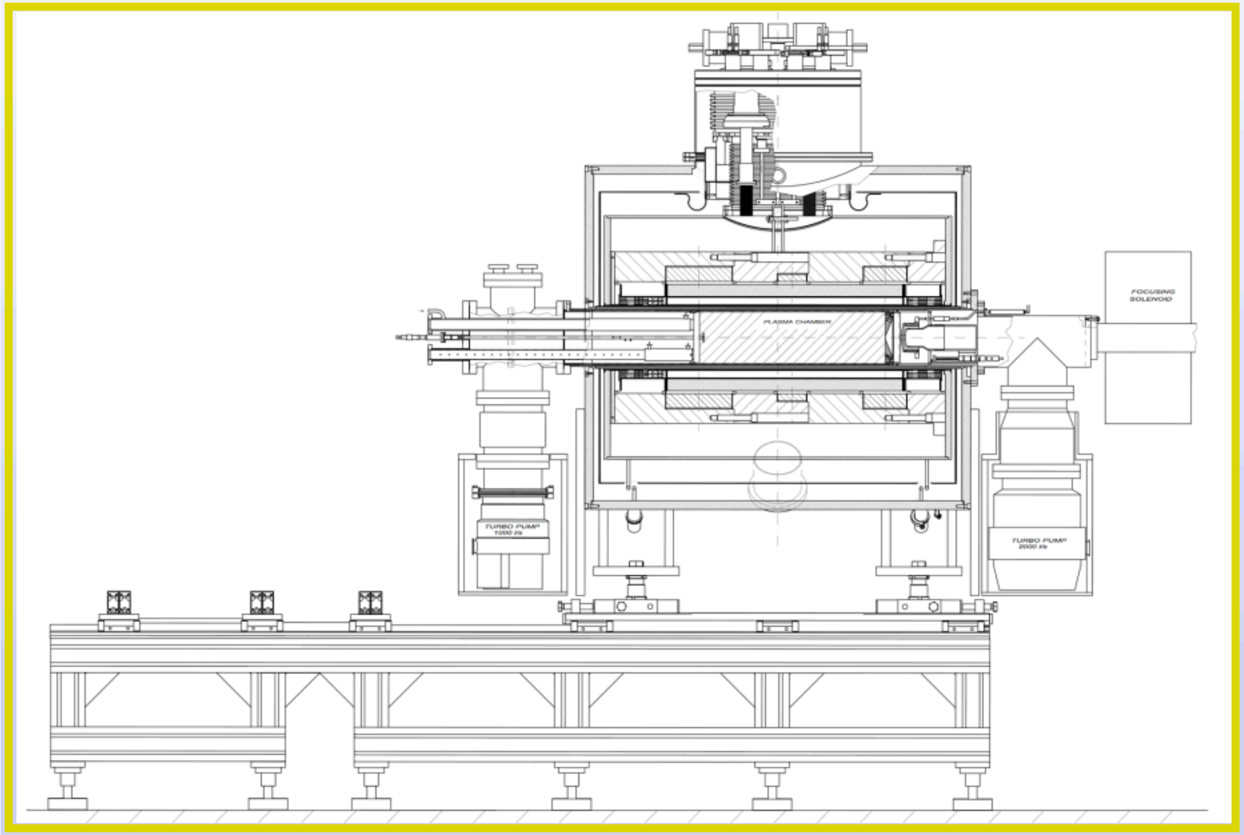

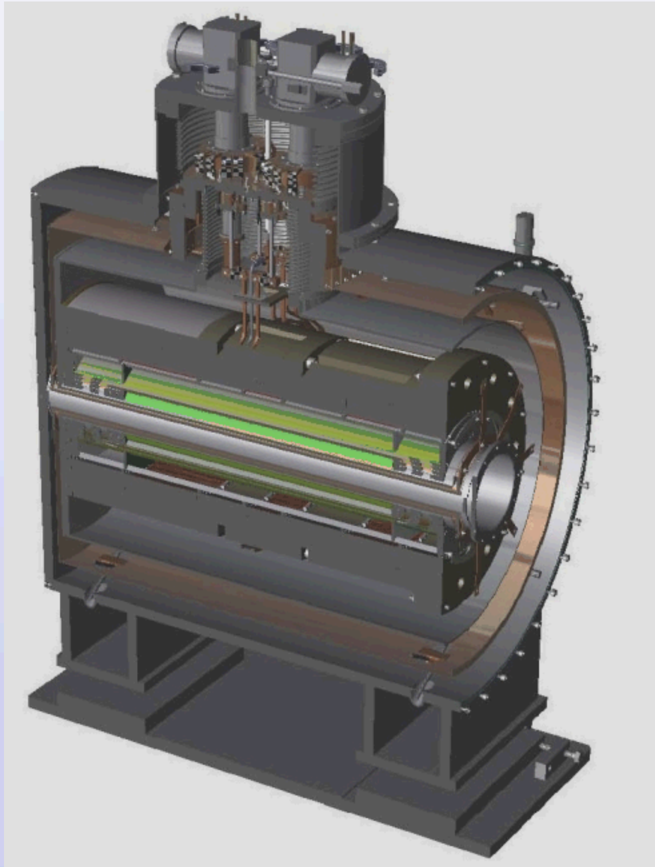

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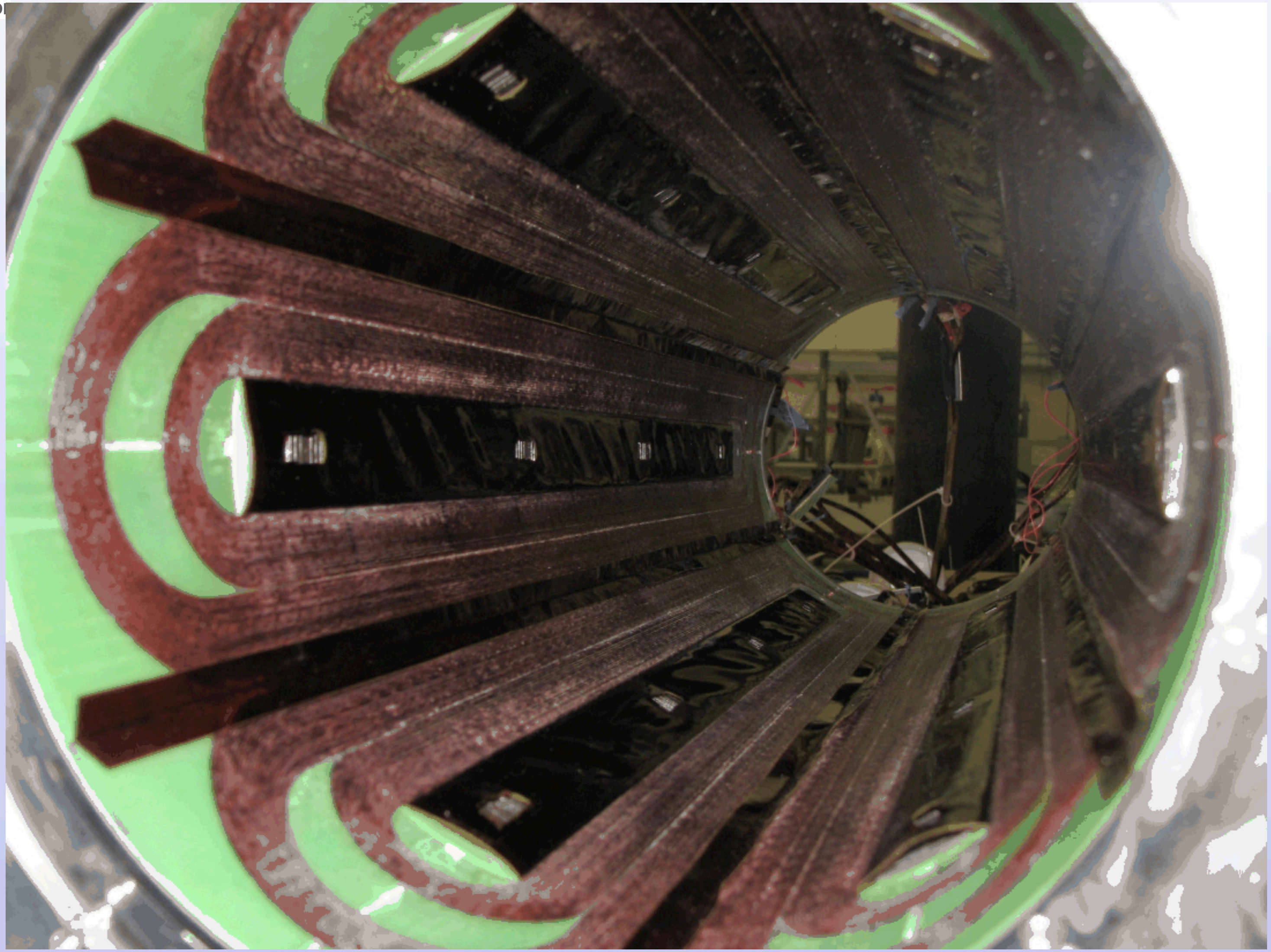
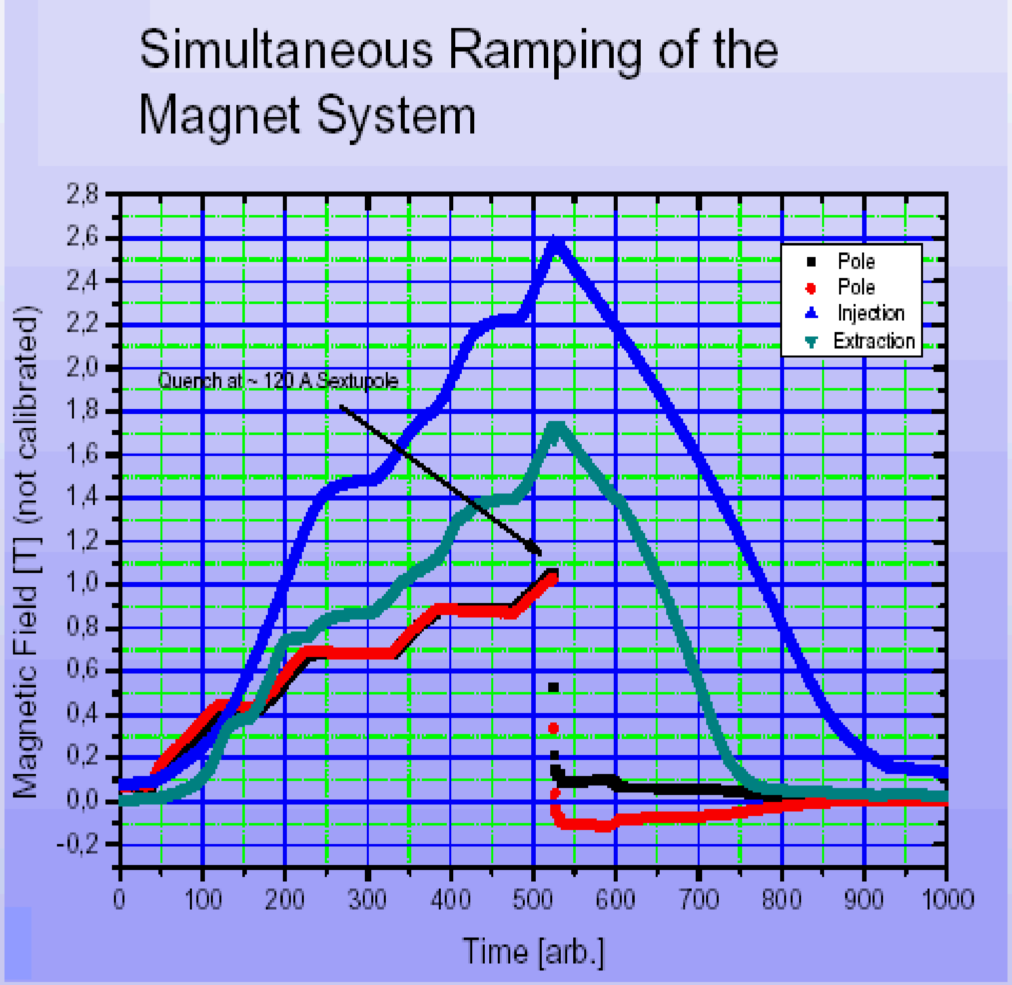
Hexapole after collar pressing



Cold mass tests

The tests of the cold mass were successful: hexapole field reached 78% of the nominal field after two quenches and full system quenched at about 40%.



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Additional safety and related delay

The analysis of the cold mass test results took to add additional safety keys to guarantee the magnetic system safety under non-typical conditions (e.g. injection solenoid energized, the other two not energized), in which case forces up to 30 tons are generated.

This problem and short circuits one added up a total delay of the project of 8 months.

- Factory tests are scheduled for mid-October
- Final tests at GSI will come one month later.
- All the other components ready to be assembled

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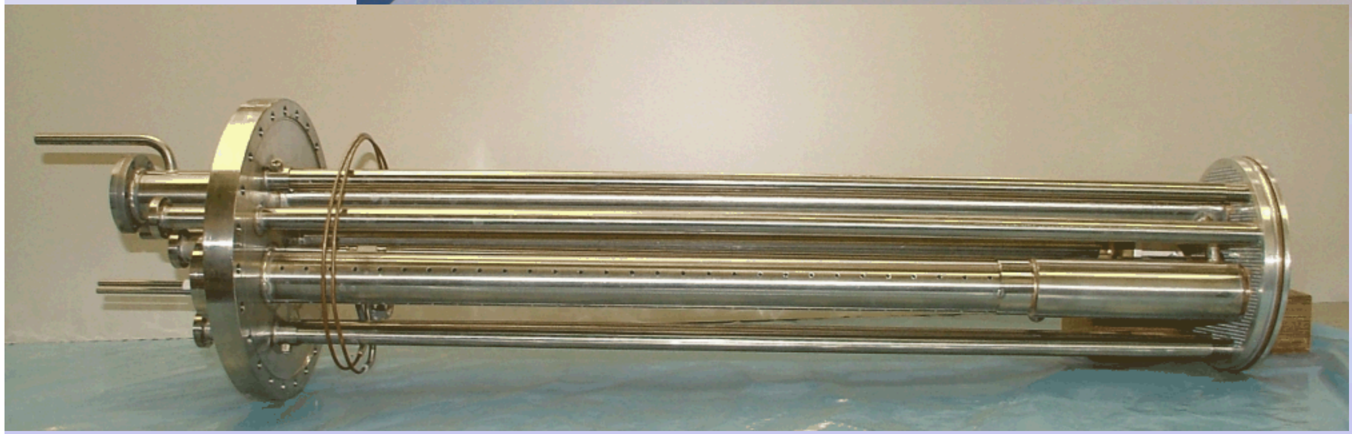
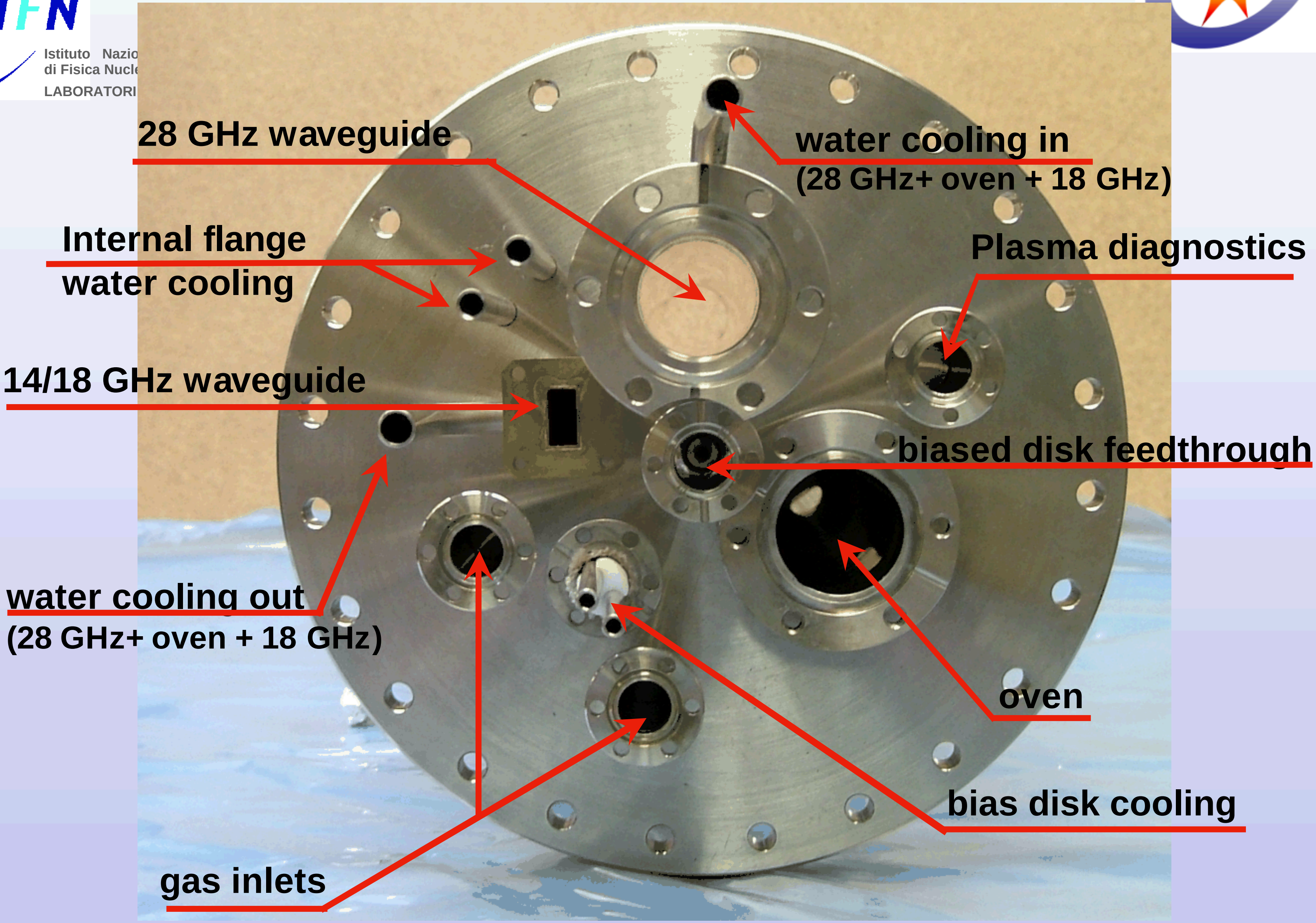
Plasma chamber and injection plug



Injection flange



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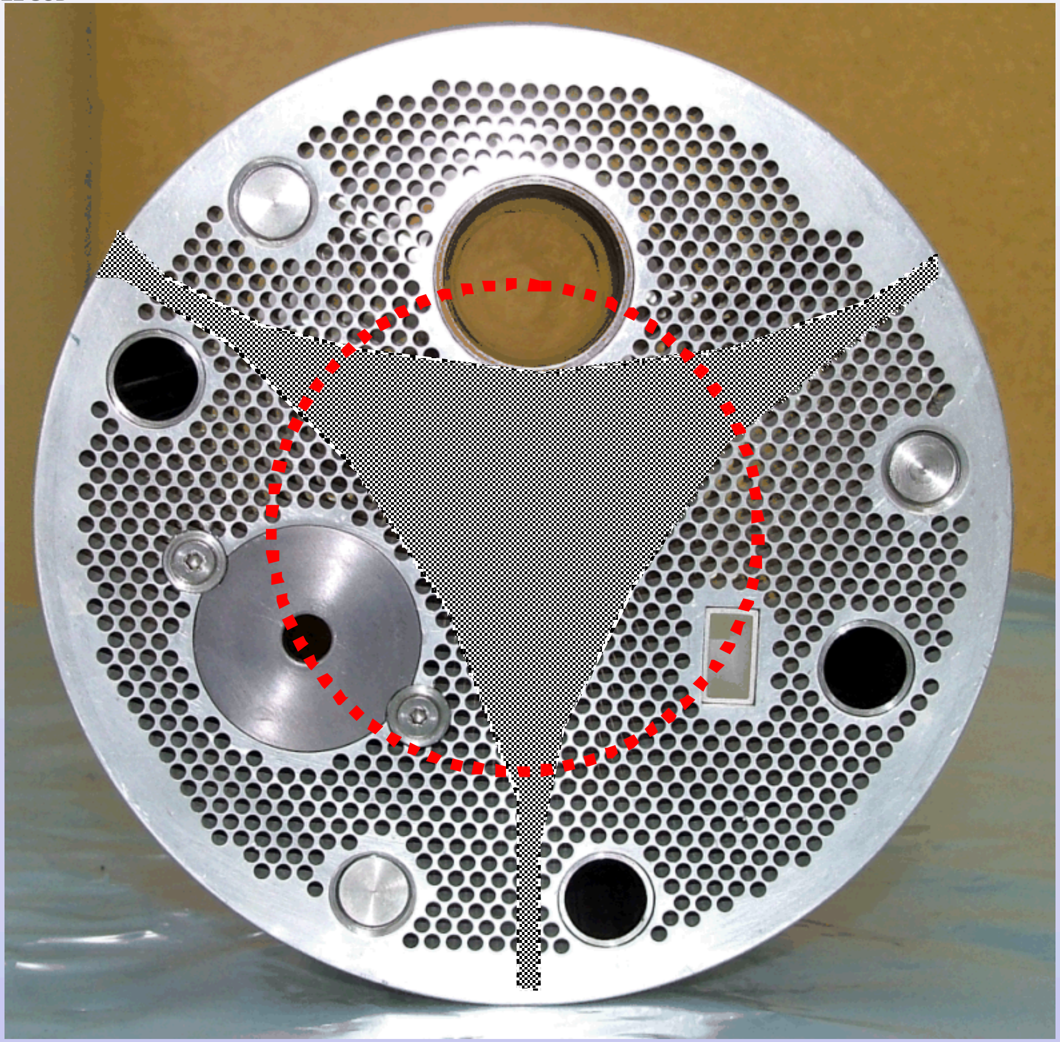
Injection flange



Positioning of waveguides

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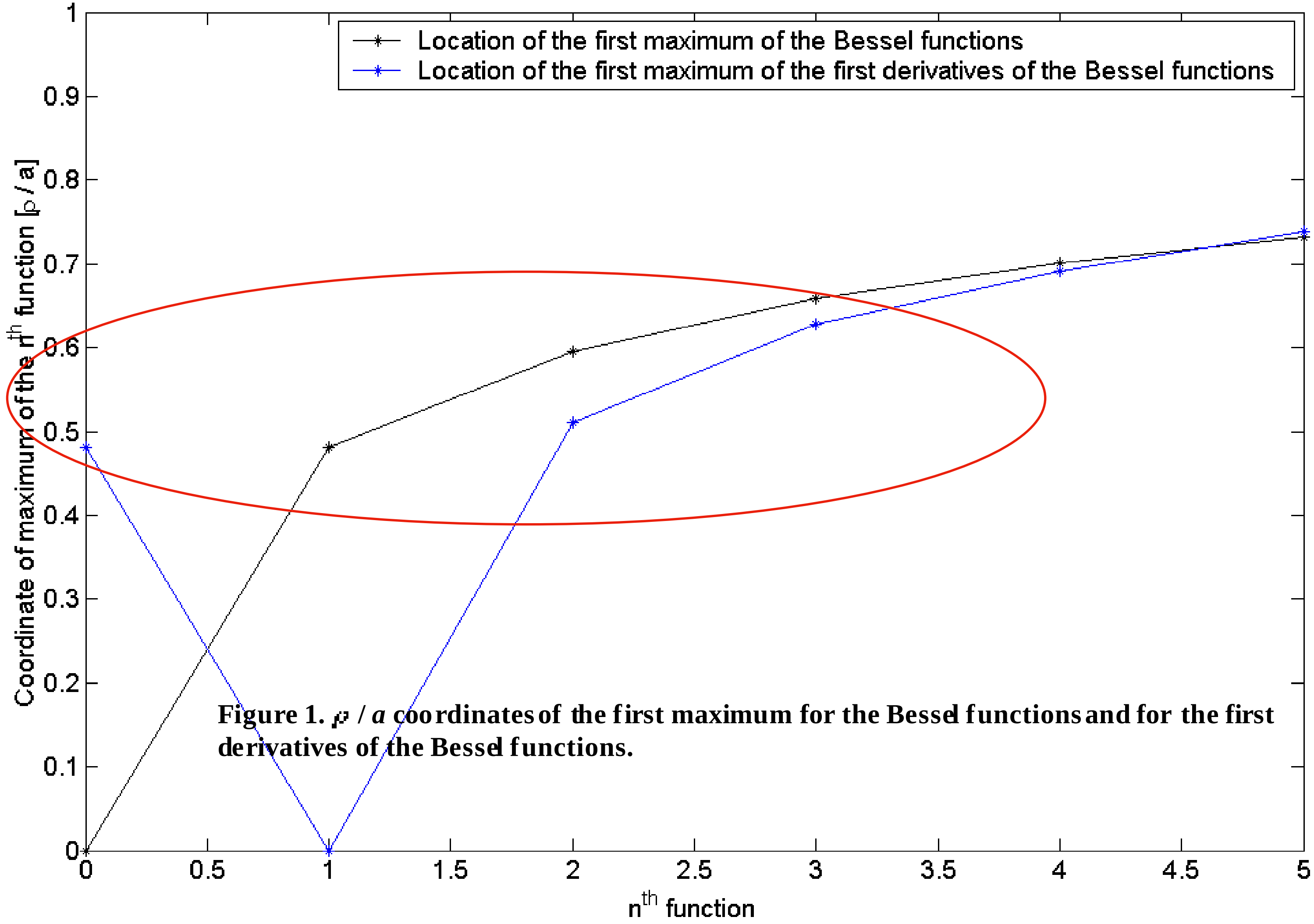

Figure 1. *ρ / a* **coordinates of the first maximum for the Bessel functions and for the first derivatives of the Bessel functions.**

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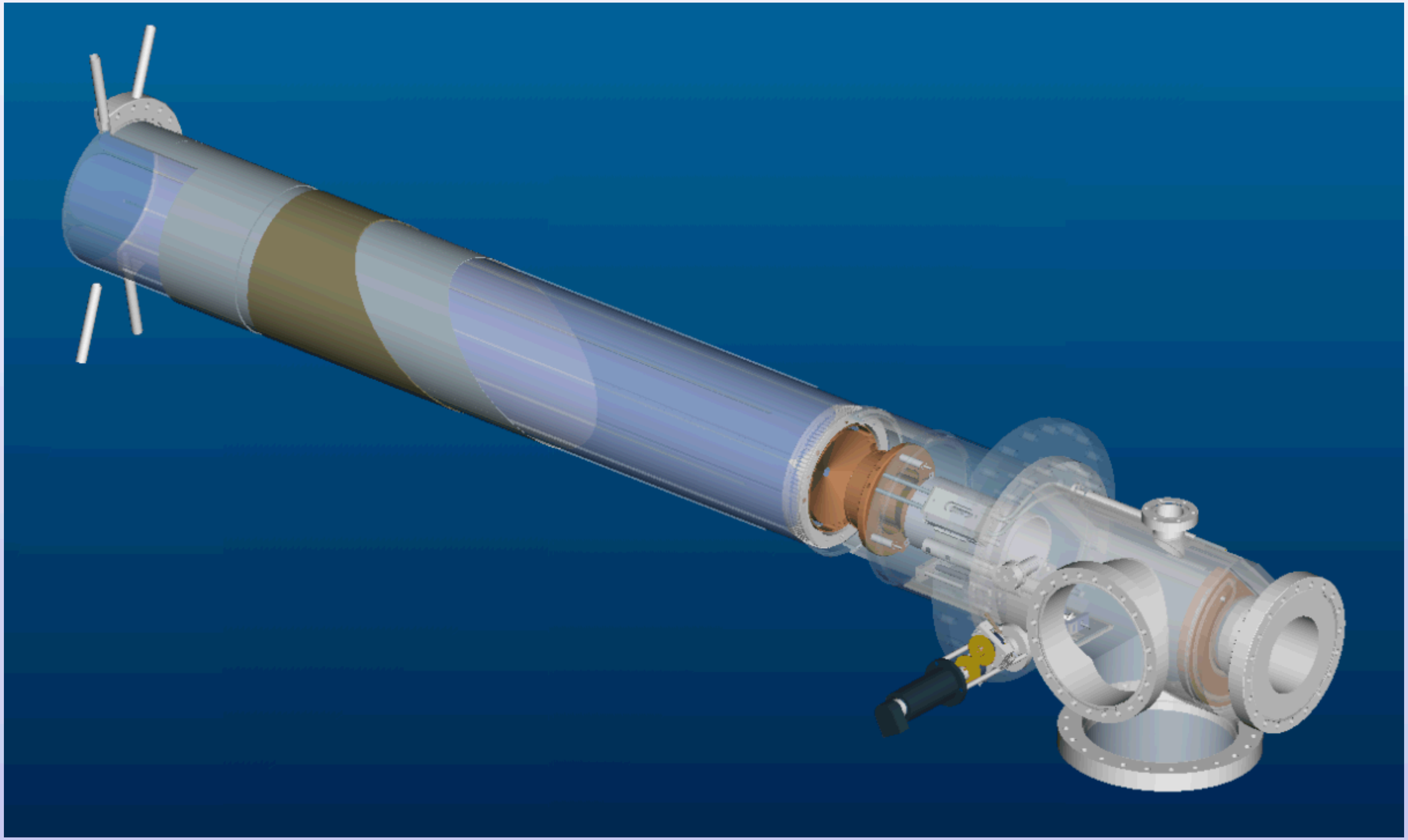
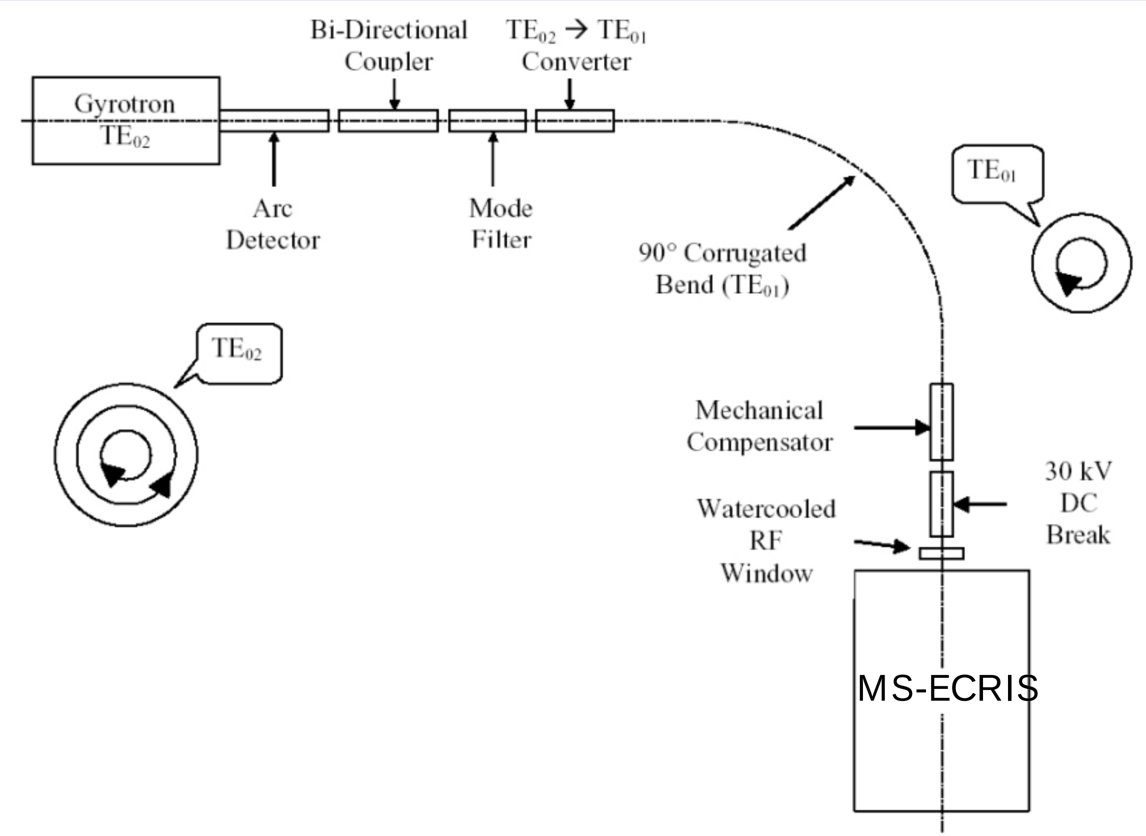
Plasma chamber and extraction vacuum chamber



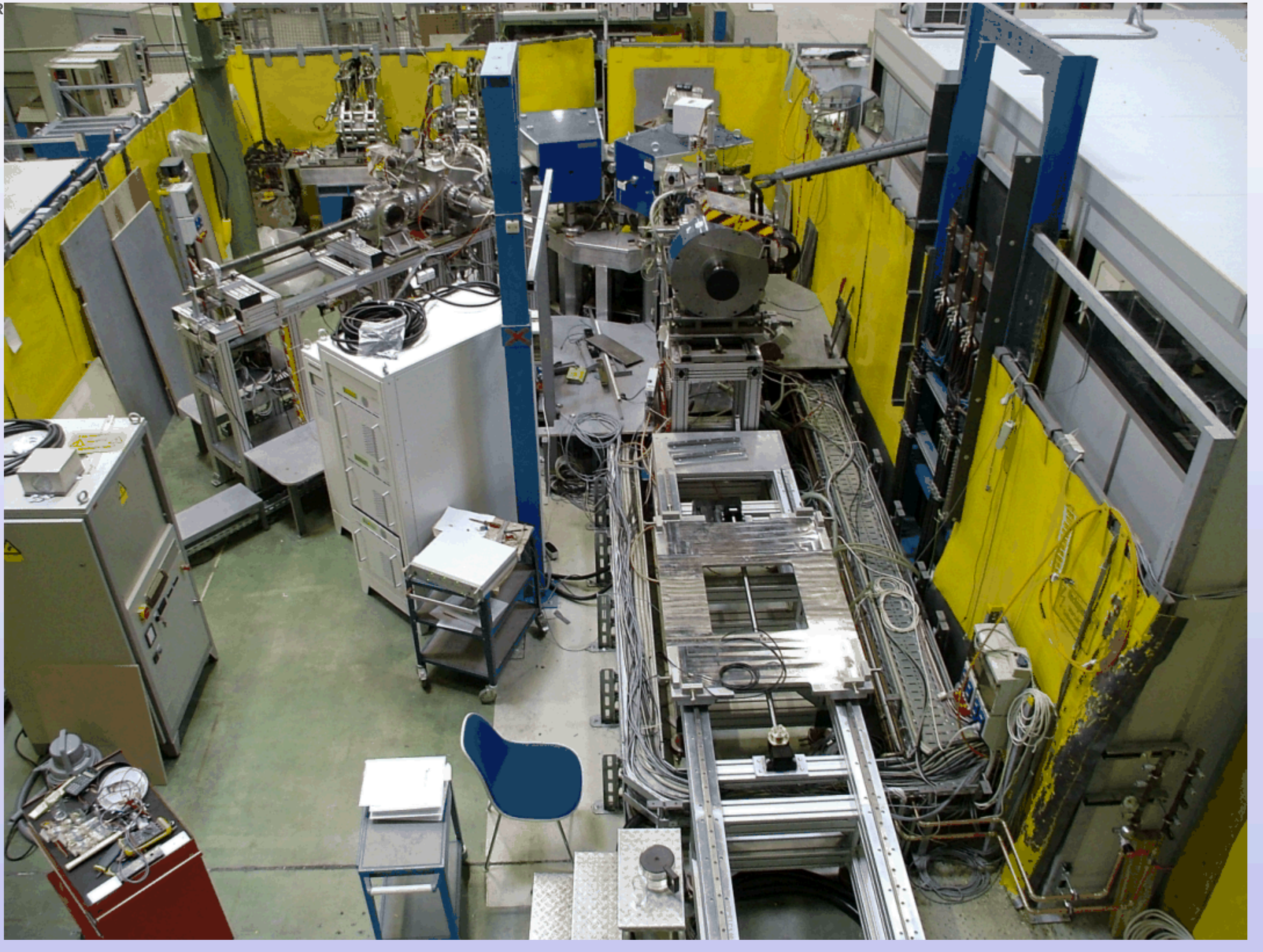
28 GHz Gyrotron

The 28 GHz-10 kW gyrotron tube used for the tests with SERSE in 2000 have been updated with a new HV power supply and control system.



The tube has been recently tested at the CPI factory and the whole generator was tested at 11 kW in France in August. It will be moved at GSI this month.

EIS modification



Perspectives

- Assembly of the source will be completed in November.
- First tests will begin in Dec. '07 in cw mode, with gas.
- Optimization of beamline, optimum position of biased disk and of extraction electrode (+ tests of different materials and dimensions).
- Optimization of cw beams with different magnetic field profile, tests of scaling of B_{inj}, B_{ext}, B_{rad}, B_{min}.
- Plasma Diagnostics: X, RF, optical.
- Beam Diagnostics.

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Perspectives

- Emittance Measurements.
- Maximum power
- Two Frequency Heating.
- Metal ion beams in cw mode.
- Ion beams from gas and metals in pulsed and afterglow mode.

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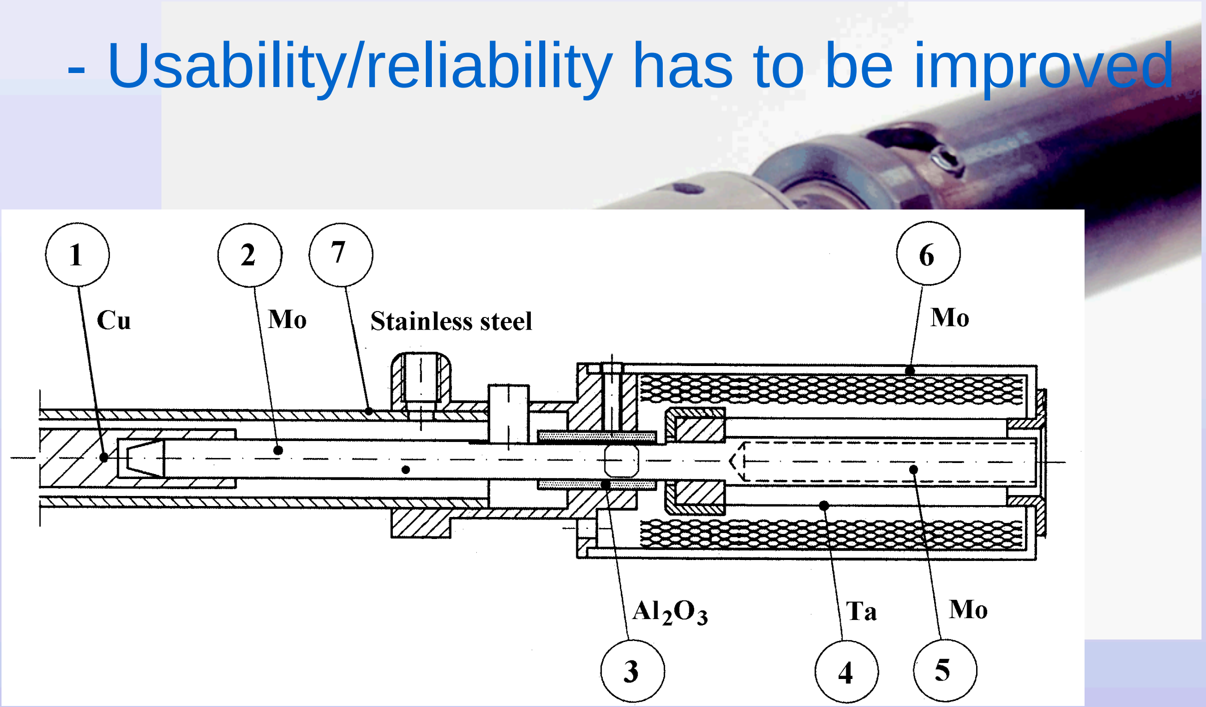
Metal ion production

1. Resistively heated foil oven
2. Inductively heated oven

- Above 2000ÚC

- Usability/reliability has to be improved



2009 and beyond

- Further tests with MS-ECRIS are under consideration (electron density increase, plasma diagnostics, etc.).
- The ISIBHI partners + ATOMKI + IKF-JWG + IAP are preparing an application for the 7th FP of EU (the Joint Research Activity COMPLECS)
- If the application will be successful, a completely new experimental and theoretical activity will be pursued with different sources, including MS-ECRIS as major tool, at least for a few months per year.

Q. - What are the perspective experiments that may guide towards better understanding of ECR plasma physics and higher currents/charge states beams ?

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I have a dream: less RF power, more beam!

•Qualitative explanations of ECR-Heating has been given by the study of the shape of the electromagnetic field generated in the plasma chamber by the injection of microwaves.

•We‘re able to explain many experimental results obtained so far, but qualitative description is not enough, a quantitative evaluation may permit precise prediction for future ECRIS.

•The minimization of the microwave power suggested by our simulations of TFH will improve ECRIS reliability and stability (lower power used for the same beam production decrease the technological criticalities).

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MS-ECRIS' future

- § Not only operation at f > 35 GHz.
- § Extensive use of diagnostics for the understanding of the processes that occur in the plasma in order to maximize the amount of 'useful' electrons for ionization (warm population) and to minimize the amount of unwanted' electrons (hot population).
- §Increase of the plasma density (overdense plasma, OXB transition).
- §Study and optimization of beam formation in presence of space charge forces, in connection with beam emittance measurements and beam transport study.
- §Design, construction and coupling with MS-ECRIS of a broadband generator at a frequency above 35 GHz (GyroTWT?)

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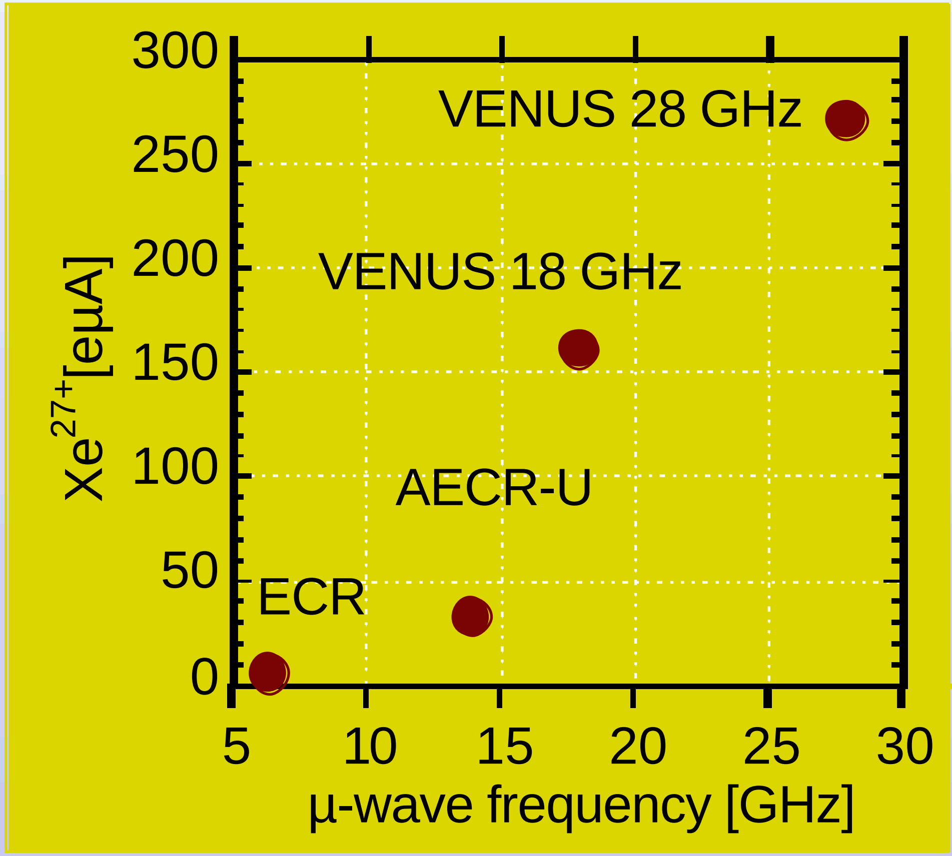
MS-ECRIS 56 GHz
(out of this scale)



56 GHz

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Last consideration:

For any kind of ion species, ECRIS have increased the current with a rate close to one order of magnitude per decade

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Last question:

I wonder if we can maintain this trend for many decades....

The answer will be given at 28th ICCA !!!