Beam current, charge state and ion species: possible upgrades of LNS ion sources

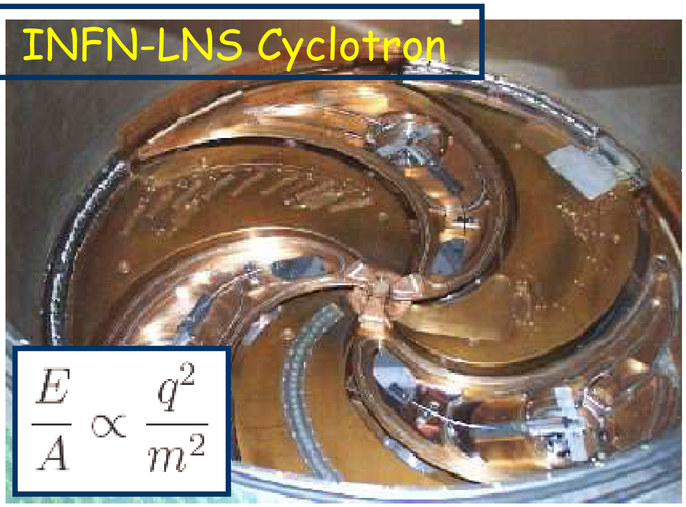
Santo Gammino, Luigi Celona and Giovanni Ciavola

MOTIVATIONS

ION SOURCES:

The R&D carried out in 1997-2001 has permitted to achieve the accelerator performances used up to now

INFN-LNS Cyclotron



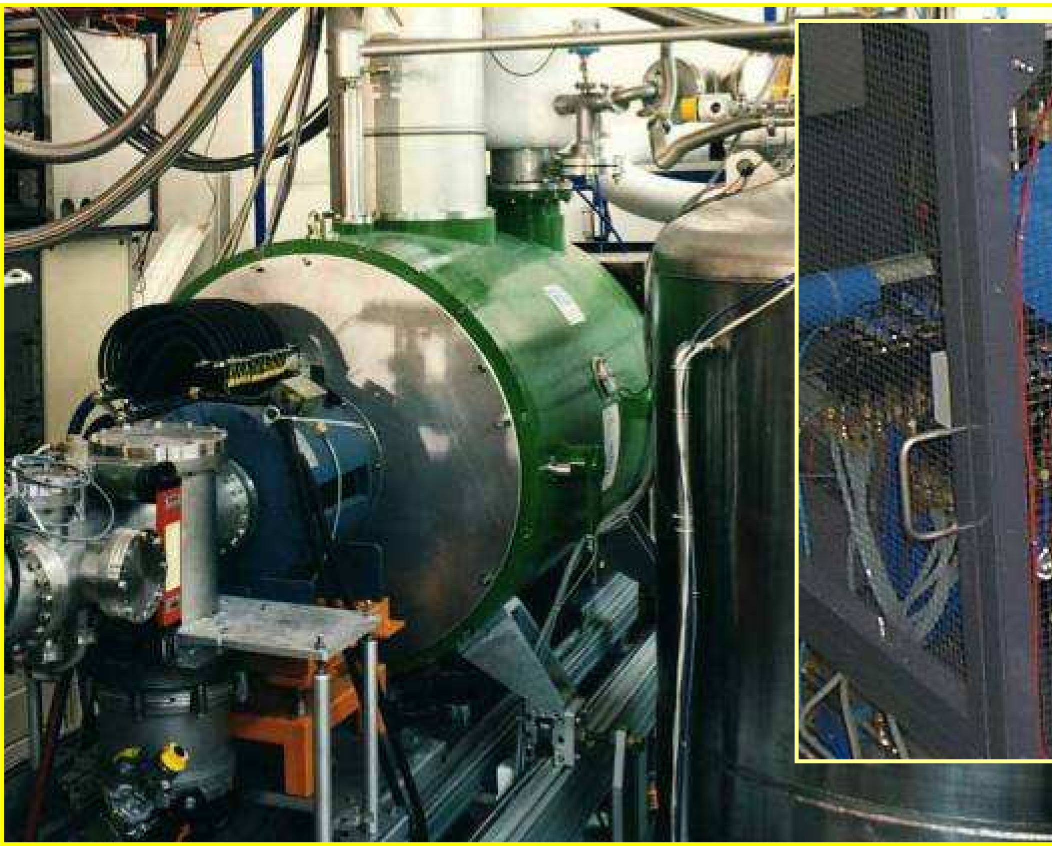
$$\frac{E}{A} \propto \frac{q^2}{m^2}$$

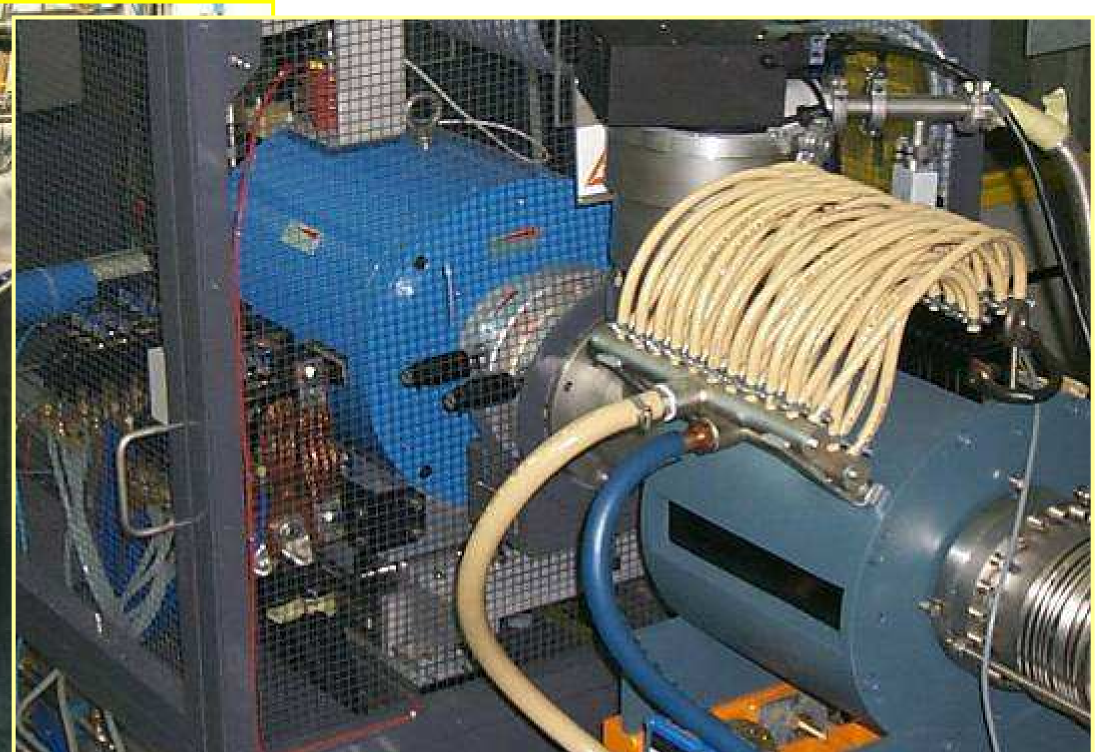
Increase of Ion Charge States → Higher energies attainable by Accelerators

Increase of Ion Current → Decrease of acquisition times for rare events

Increase of ECRIS performances allows to enhance the Accelerators' ones without any hardware modification (e.g. LBNL).

NOT EXPENSIVE, NOT RISKFUL, NOT LARGELY AFFECTING BEAM DELIVERY TO USERS!

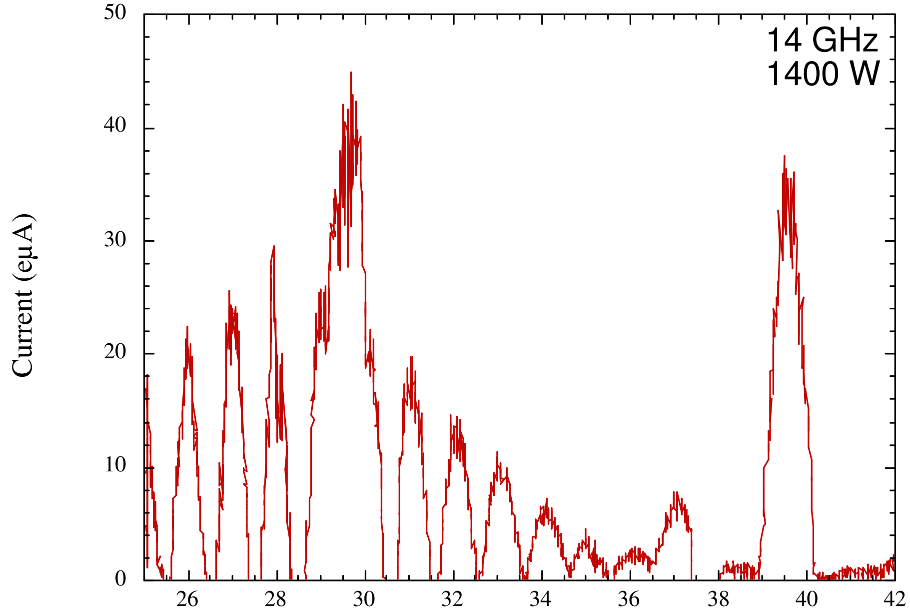


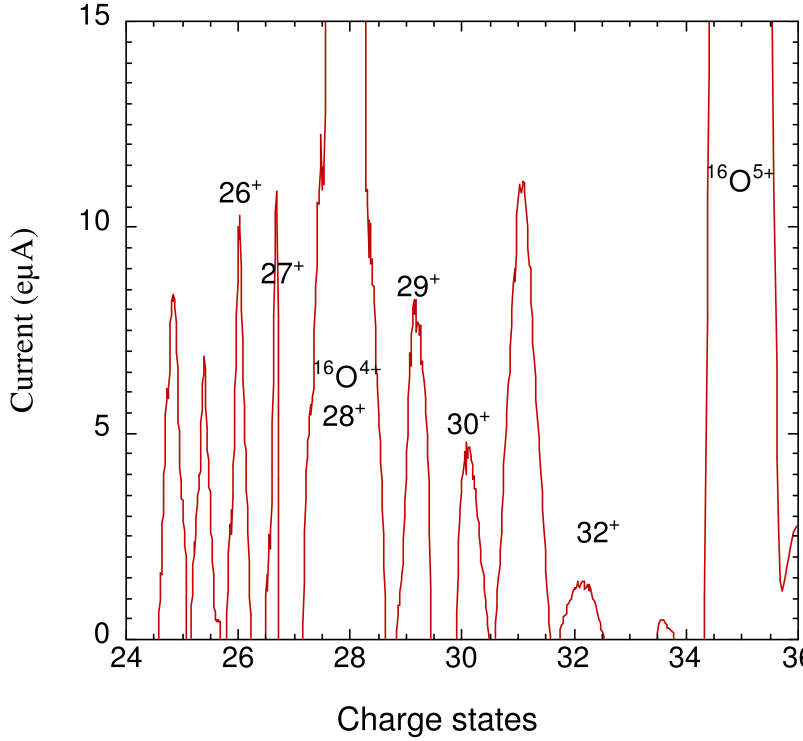


CAESAR (1999)

SERSE (1998)

INFN-LNS





Serse highly charged beams

O^{6+}	540	Kr^{22+}	66	Au^{30+}	20
O^{7+}	208	Kr^{25+}	35	Au^{31+}	17
O^{8+}	62	Kr^{27+}	7.8	Au^{32+}	14
Ar^{12+}	200	Kr^{29+}	1.4	Au^{33+}	12
Ar^{14+}	84	Kr^{31+}	0.2	Au^{34+}	8
Ar^{16+}	21	Xe^{27+}	78	Au^{35+}	5.5
Ar^{17+}	2.6	Xe^{30+}	38.5	Au^{36+}	2.5
Ar^{18+}	0.4	Xe^{31+}	23.5	Au^{38+}	1.1
Kr^{17+}	160	Xe^{33+}	9.1	Au^{39+}	0.7
Kr^{18+}	137	Xe^{34+}	5.2	Au^{40+}	0.5
Kr^{19+}	107	Xe^{36+}	2	Au^{41+}	0.35
Kr^{20+}	74	Xe^{38+}	0.9	Au^{42+}	0.03

Caesar highly charged beams

Ion	LNS-ECR2
N^{5+}	515
N^{6+}	160
$^{15}N^{7+}$	25
O^{6+}	720
O^{7+}	105
Ne^{7+}	230
Ne^{8+}	170
Ne^{9+}	14
Ar^{11+}	120
Ar^{14+}	10
Ar^{16+}	2
Ca^{12+}	52
Ca^{14+}	6
Ni^{17+}	18
Kr^{22+}	10
Kr^{28+}	1
Ta^{26+}	10
Ta^{27+}	10

H_2^+
H_3^+
$^2D^+$
^4He
He-H
^9Be
^{12}C
^{13}C
^{14}N
^{16}O
^{18}O
^{19}F
^{20}Ne
^{27}Al
^{32}S
^{35}Cl
^{36}Ar
^{40}Ar
^{40}Ca
^{48}Ca
^{58}Ni
^{62}Ni
^{64}Ni
^{86}Kr
^{93}Nb
^{107}Ag
^{112}Sn
^{116}Sn
^{120}Sn
^{124}Sn
^{129}Xe
^{197}Au

No difficult beams have been developed in last 7 years (only He-H, D, Be, F, Cl).

A number of improvements can be expected, in terms of:

- ***Larger Beam Currents***
- ***Higher Charge States***
- ***Ion species variety***

with an adequate R&D of Ion Sources

Four different approaches

- **Low-cost/easy to do**: utilization of existing equipment, minor modifications to hardware, implementation of a new high temperature oven (already offered by Tinschert of GSI, some years ago) and of an inductively heated oven (available from Jyvaskyla in the frame of EURONS/ISIBHI collaboration, or can be asked to MSU-NSCL group), application of the results of the work of Ion Source R&D Team in these years and applied elsewhere.

- **Low cost/complex/manpower needed**: design of a new plasma chamber, higher voltage upgrade (I proportional to $V^{3/2}$) for SERSE, redesign of CAESAR injector adapted to larger microwave power (originally was 1200 W, now only 350 W), upgrade to 18 GHz for CAESAR (generator available), Aluminum chambers, Alumina inserts (as used for TRIPS).

- **Expensive/easy to do**: purchase of a higher frequency generator (24 GHz) for HBM operations of SERSE (not complex as the scaling studies were completed in 2000 and interpolation is possible)

- **Expensive/complex**: to transform SERSE cryostat in a LHe-free one to improve its reliability; to build a new III generation ECRIS to operate at 28 GHz (JUMP of performances, JUMP of costs).

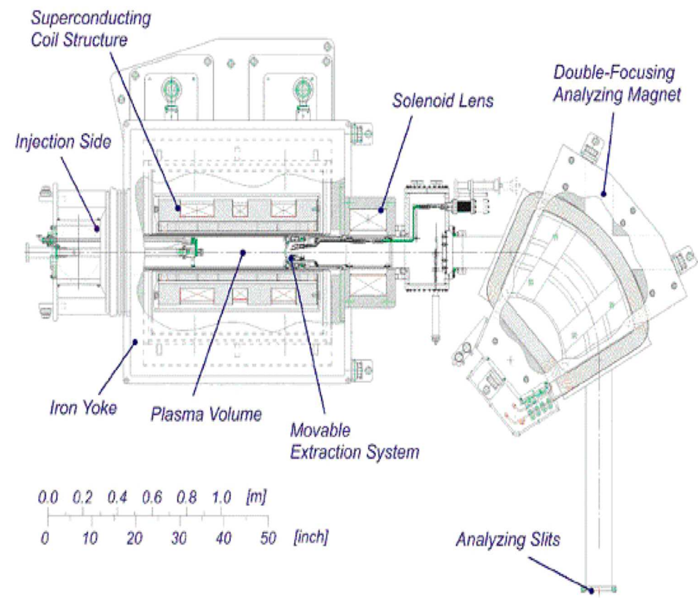
- Not to be said, I have always suggested the last approach, proposed by our team 15 years ago and verified nine years ago; now it was implemented by **LBNL**, Lanzhou, RIKEN and MSU.

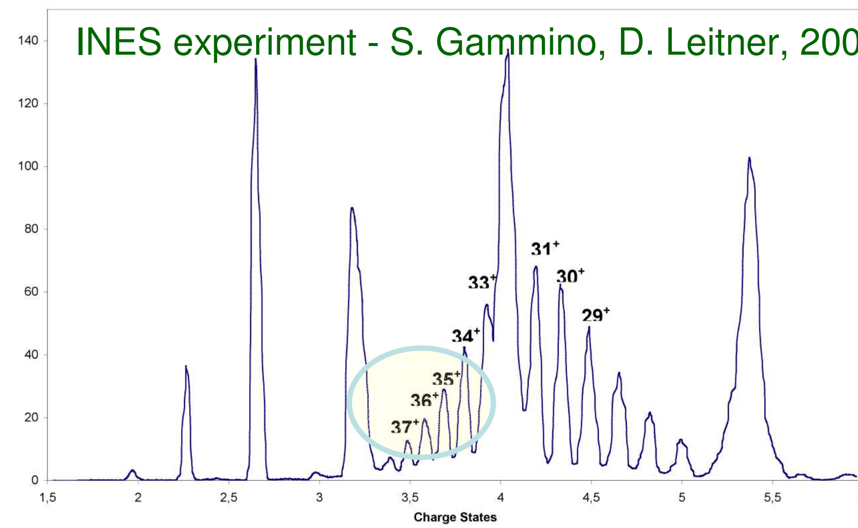
- 1.5 M€ is a relevant investment, but the advantages are clear (a factor 4 to 20 in current).

- If still not possible for budgetary reasons, a number of new initiatives are possible.

- It is evident that the **improvement of beams available for users is not a DREAM!**

Kr	I [μA]	Xe	I [μA
24^+	192	30^+	98
25^+	223	31^+	80
27^+	88	33^+	61
28^+	25	34^+	42
29^+	5	35^+	28
		36^+	19
		37^+	12
		38^+	7





Overcoming the current limits of ECRIS

Roadmap indicated by the ECRIS

Standard Model:

- High Frequency Generators;
- High Magnetic Fields;

Investigations about RF energy transfer to the electrons may allow to overcome the limits

$$\langle q \rangle \sim n_e T_i$$

$$I \sim n_e / T_i$$

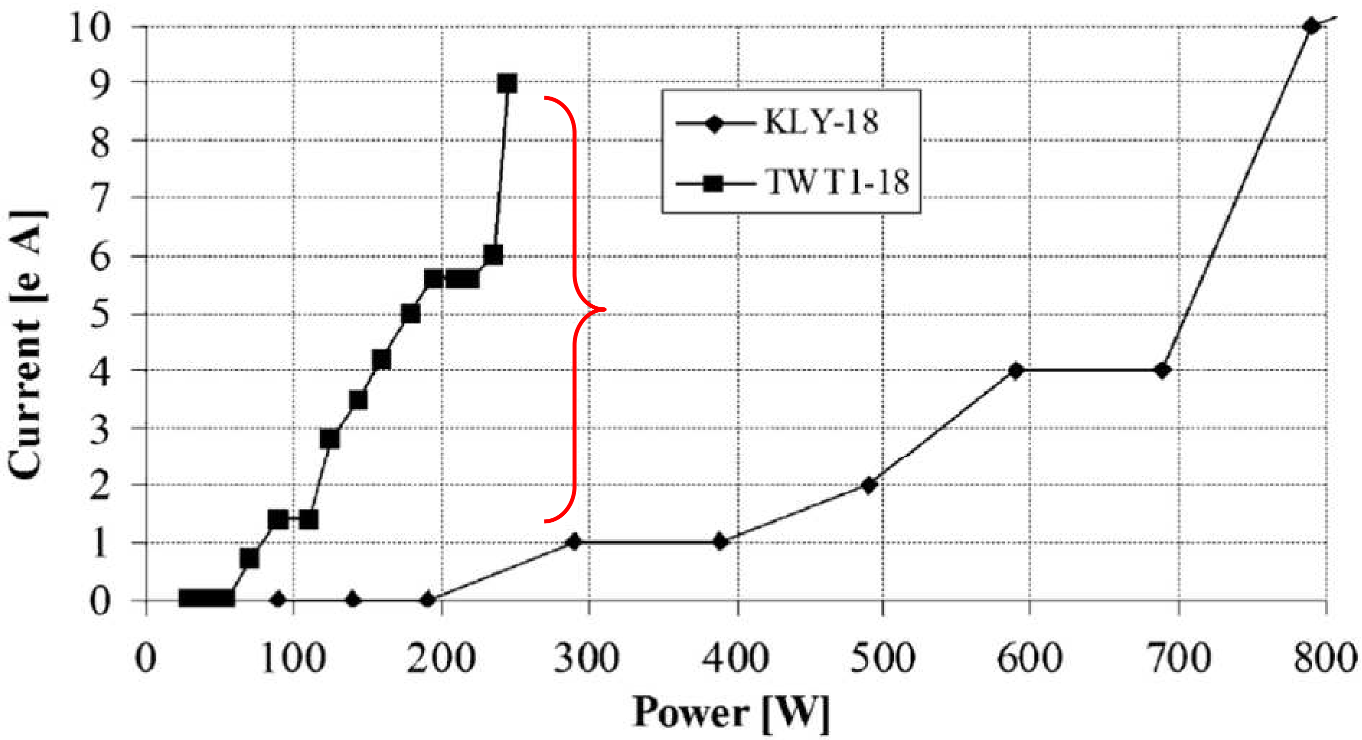
By quickly replacing the loss hot electrons we can increase the Electron Density and the heating rapidity

The optimization of the wave-electron energy transfer allow to slightly relax the confinement conditions

Alternative mechanisms of plasma heating

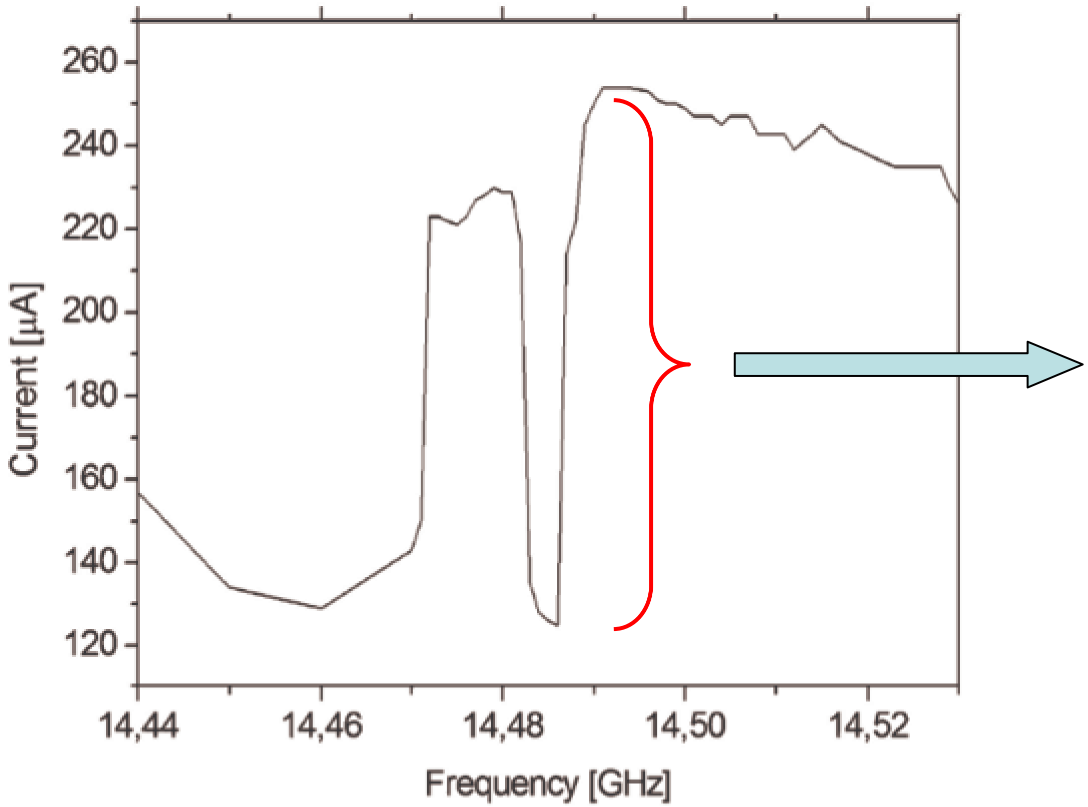
1. Frequency tuning
2. Two Frequency Heating
3. Two Closed Frequency Heating
4. ~~“Flat B Field” heating~~
5. ~~“Broadband” heating~~

Signals about the importance of the frequency tuning effect came already in 2004 from one of the few experiments carried out on SERSE during last seven years [A. Galatà, Tesi di Laurea]



Comparison between trends of O^{8+} at 18 *GHz* for klystron (up to 800 W) and TWT1 operating in the same range of frequency.

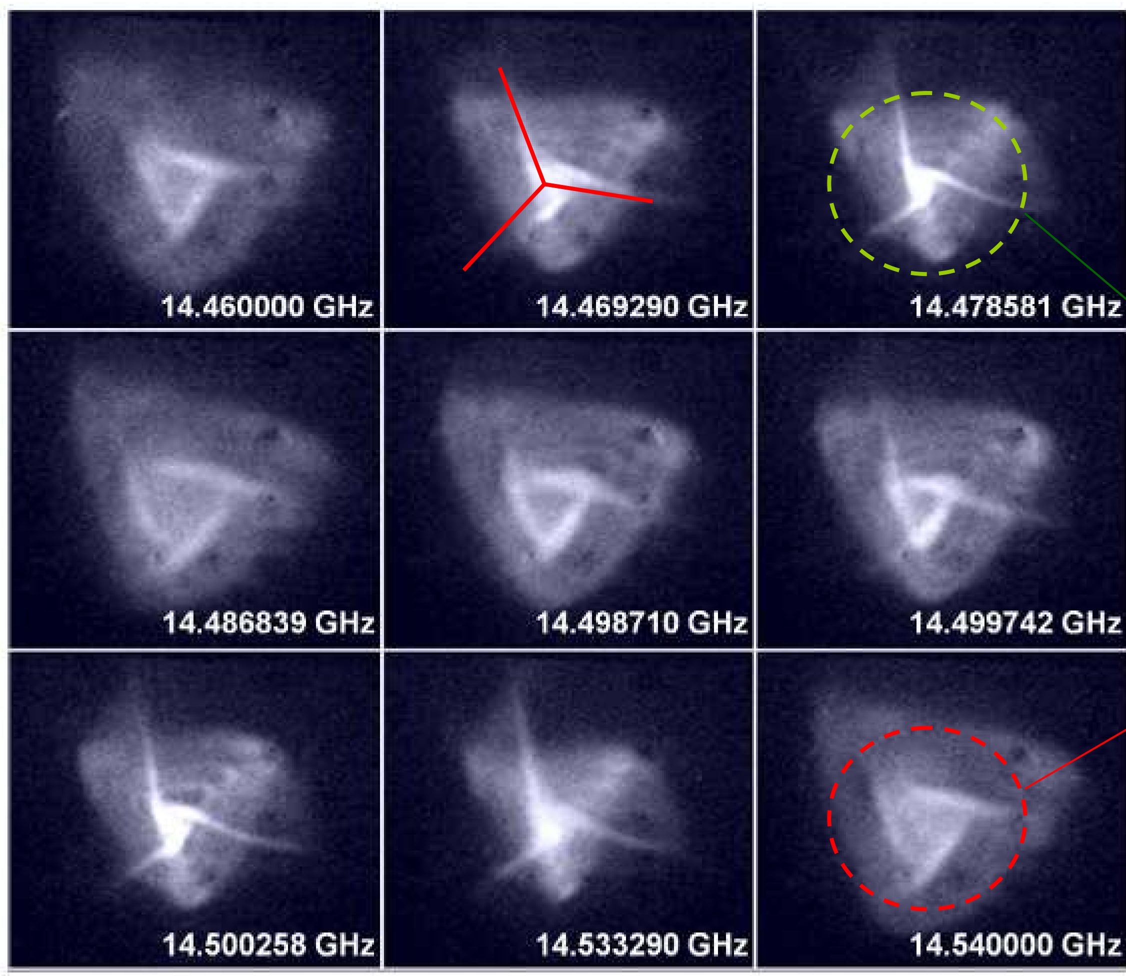
Evidence of Frequency Tuning Effect (FTE) on the SUPERNANOGAN source of Heidelberg HIT (2005)



The extracted current is doubled after a frequency shift of 5 MHz

Frequency tuning on the CAPRICE source at GSI

[L. Celona, et al. Observations of the frequency tuning effect in the 14 GHz CAPRICE ion source. *Rev. Sci. Instrum.*, Feb. 2008. vol. 79, no. 2, p. 023 305.]



Frames of the extracted beam for different frequencies

“three cusp” shape of the extracted beam according to the magnetic structure

Well focused and high brightness beam

Broadened, low brightness beam

The Frequency Tuning strongly affects also the beam shape and brightness

Similar results have been obtained with CNAO ion sources in 2006-08.
A campaign of measurements with different ECRIS is scheduled in the coming months to check our simulations' results and to verify the relationship between the electron dynamics in the ECR minimum-B trap and the ion dynamics which finally affects the emittance of the beam injected in the accelerator.

The first experiment is scheduled at Jyvaskyla accelerator chain (April 20-26) and the preparation is almost finished.

The second experiment is scheduled at CNAO, Pavia, including the transmission in the RFQ (end of May-beginning of June, to be confirmed).

The third experiment will be carried out at IMP- Lanzhou with the high performance ECRIS named SECRAL in October or November.

Contacts ongoing with MSU-NSCL to make further tests with SUSI.

Some of these experimental activities may be carried out at LNS according to the SYFTE proposal, pending since fall '08.
An evident advantage to make such experimental activity here is that the Cyclotron's users may immediately get better beams, after years of status quo.

The TWO Frequency Heating effect: a long history

1994 – First evidence of the TFH at LNBL, California

[Z. Q. Xie and C. M. Lyneis. Improvements on the LBL AECR Source. *in Proc. 12th Int. Workshop ECR Ion Sources, Tokyo, Japan*, 1995.]

CSD peak from 33+ to 36+ for ^{238}U*, current increased by a factor 2-4 for CS>35+*

2001 – TFH on the SERSE source at INFN-LNS; first evidence of the importance of TWT also in case of TFH

[S.Gammino, G. Ciavola, L. Celona, D. Hitz, A. Girard, and G. Melin. Operation of the SERSE superconducting electron cyclotron resonance ion source at 28 GHz. *Rev. Sci. Instr.* 72, pp. 4090-4097.]

3 eμA of Sn^{29+} were produced with two KLY (1.4 +1.0 *kW) @ 14.5 and 18 GHz. The same current with TWT 8-18 GHz @ 200 W*

2002 – Observation of TFH at ORNL, Argonne, together with FTE

[R. C. Vondrasek, R. H. Scott, R. C. Pardo, and H. Koivisto. Operational improvements of the Argonne ECR sources. *in Proc. 15th Int. Workshop ECR Ion Sources, Jyvaskyla, Finland*, Jun. 12-14, 2002. p. 174.]

TWT (*60 W*) + Kly (*400 W*)
I = 66 eμA
Kly (*400 W*)
I = 39 eμA

neither the relationship between the two frequencies nor the respective power was univocally determined.

Improvement of the electron heating

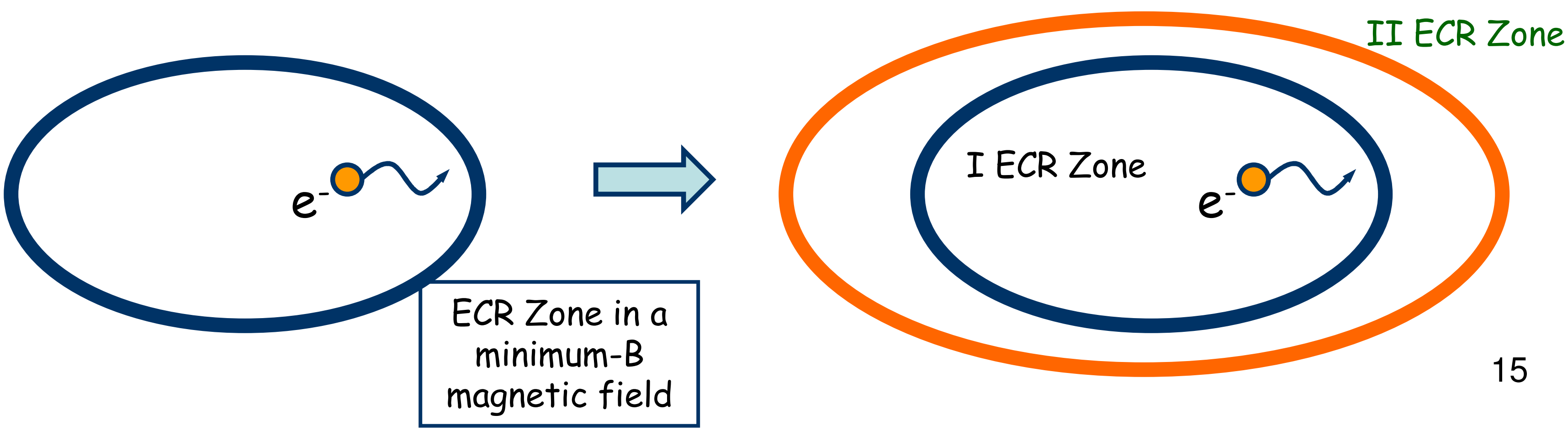
The possibility of Two Frequency Heating - TFH

Strong ECR plug effect and plug-in

Energy and "recovering mechanism" saturation with the RF power

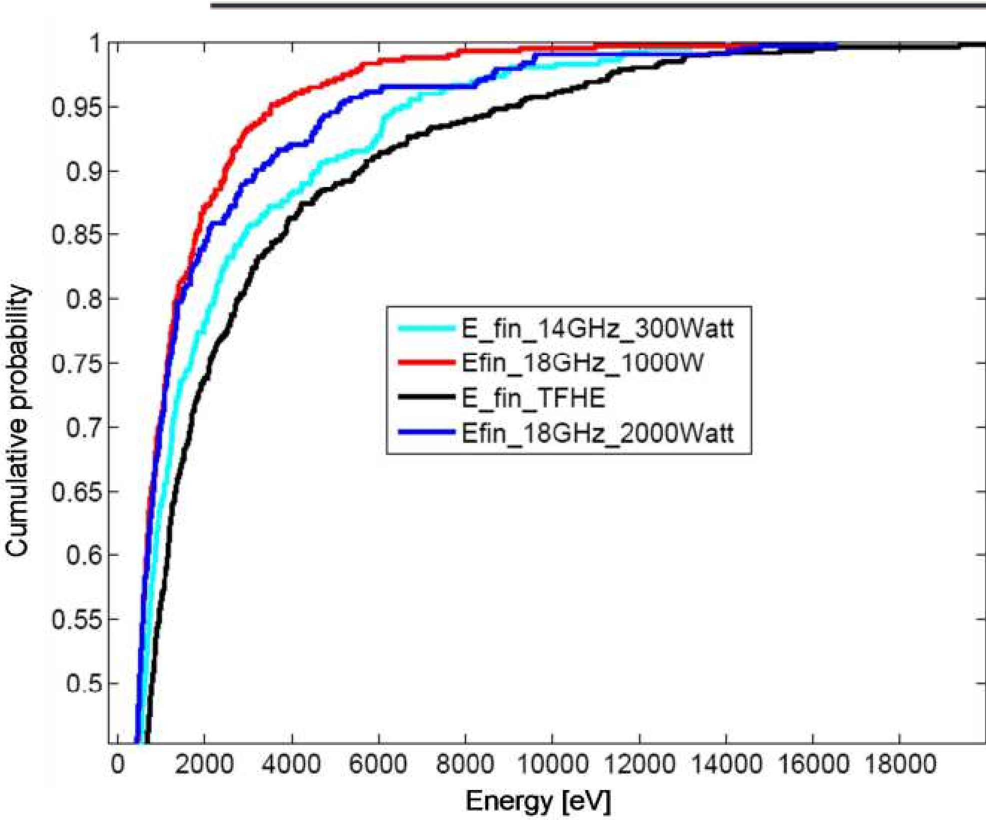
plasma heating with two electromagnetic waves instead of one, by using two medium or low powers

possibility to optimize the plasma heating by efficiently transferring the electromagnetic energy



Simulations of the Two Frequency Heating

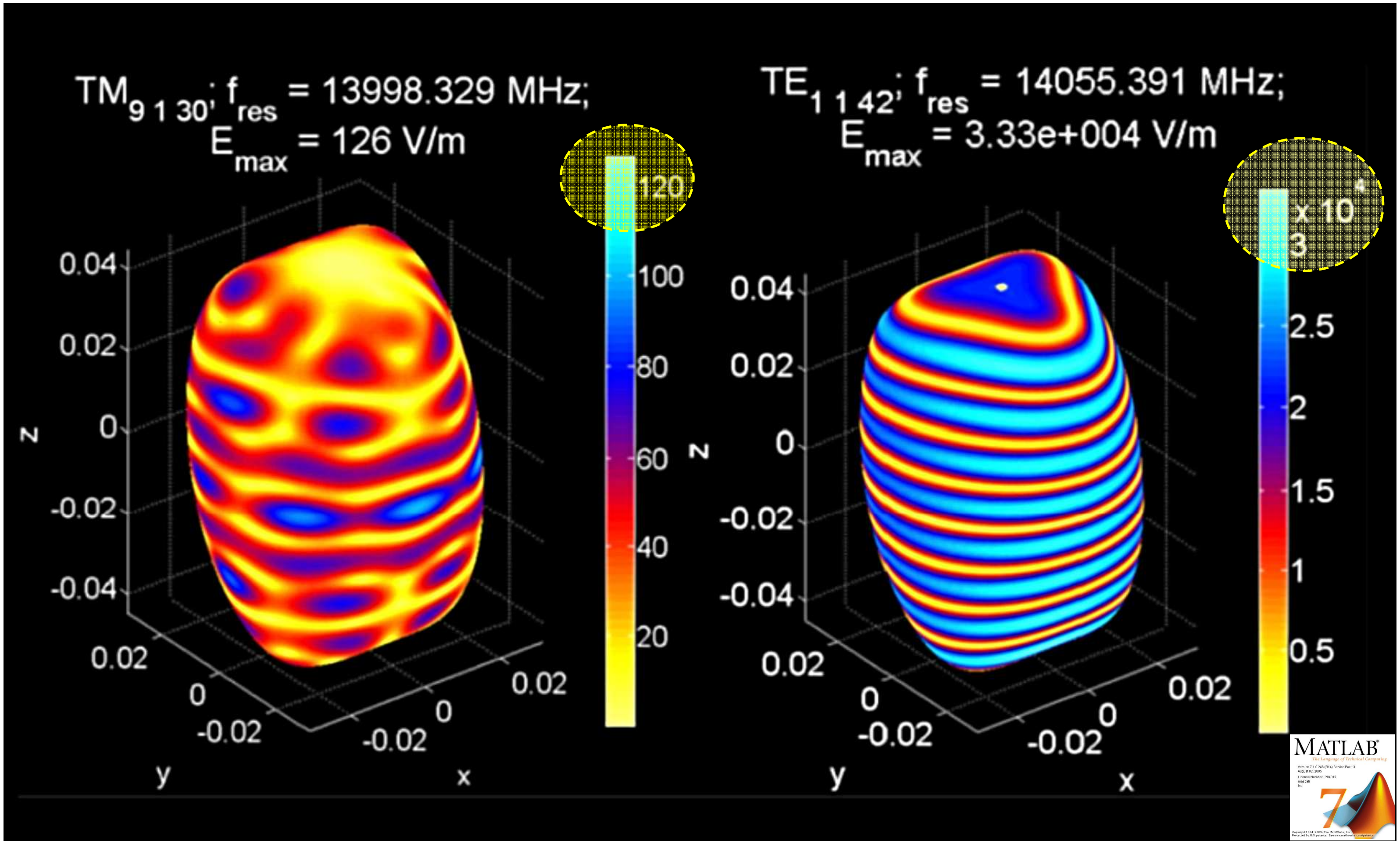
	$(14+18)GHz$, $(1000+300)W$	$18\ GHz$, $2000\ W$	$18\ GHz$, $1000\ W$	$14\ GHz$, $300\ W$
Recovered electrons [%]	38.2	35.2	19.2	12.9
Energy (keV)	1.9589	1.2612	1.0141	1.5509



1. Strong increase of the confined fraction in the case of TFH;
2. Strong increase of the mean electron energy;
3. TFH @ 1300 W more efficient than Single Frequency Heating (SFH) @ 2000W;
4. Electron Energy for @ 300 W – 14GHz higher than @ 2000 W – 18 GHz.

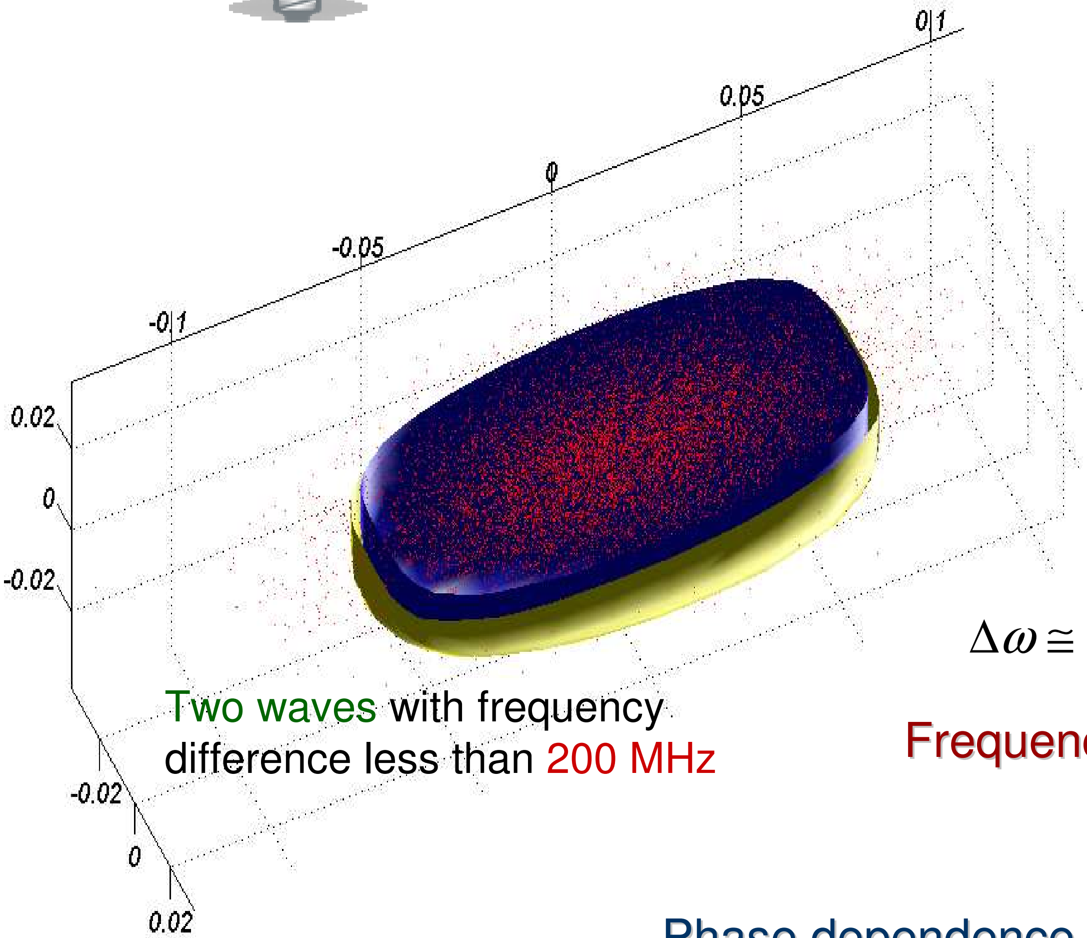
[D. Mascali et al. *Enhancement of the electron confinement and temperature by means of the two frequency heating in ECR ion sources plasmas*. in Proc. Eur. Phys. Soc. Conf. Plasma Phys., Warsaw, Poland, 2007. vol. 31F, p. *O*2.013.]

Explanation of frequency tuning effect



But even slight variation of the exciting frequency produce strong changes in the electric field distribution over the resonance surface.

A "new idea" : the Two Close Frequency Heating Effect



Two waves with frequency difference less than 200 MHz

Two contiguous resonance surfaces ensure a sort of "electron surfing" on the two heating frequencies if the phase relationship is proper

Frequency correlation

$$\Delta\omega \cong 1.4z\left(\frac{2k_2q}{m}\right)\left(\frac{c}{\omega}\right)\left[\frac{\left(\frac{eE}{mc\omega}\right)^2}{\left(\frac{c}{\omega}\right)\left(\frac{\Delta B}{\Delta z}\right)\left(\frac{1}{B_{ECR}}\right)^3}\right]^{1/5}$$

Phase dependence on microwaves power

$$\Delta\vartheta \equiv \left(\frac{\pi}{2} - const\cdot\frac{\overline{\omega}}{P}\right)$$

S. Gammino, G. Ciavola, L. G. Celona, D. Mascali, and F. Maimone. *Numerical Simulations of the ECR Heating With Waves of DIfferent Frequency in Electron Cyclotron Resonance Ion Sources*. **Review paper on IEEE Transaction on Plasma Science**, 2008. vol.36, no.4.

Low cost activities

Implementation of frequency tuning, TCFH, phase correlation and plug-in effect : all necessary equipment have been already purchased by Ion Source R&D Team in the past years with the support of 5° National Committee, under the EDIPO, INES, HELIOS experiments): only the availability of SERSE is needed, existing personnel is sufficient (INISOR technicians + Celona and Gammino).

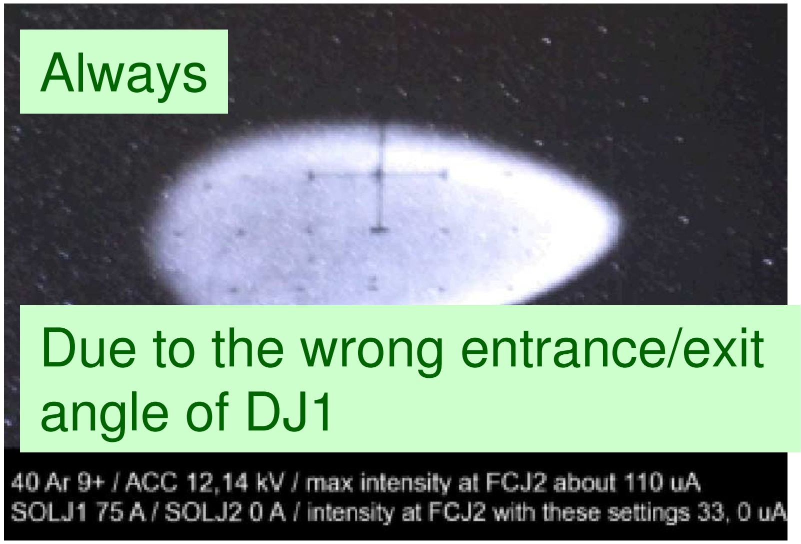
Beam transmission systematics, throughout the inflector and after the cyclotron, to be correlated with emittance measurements and ion source parameters (SERSE and CAESAR needed, additional skilled manpower).

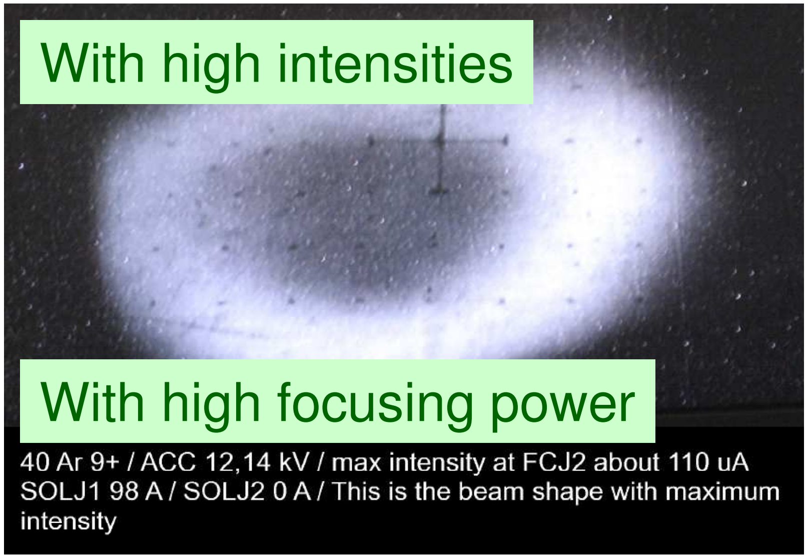
Use of KBr viewers may help in this case.

Beam profiles

Beam profile has been studied by KBr-viewers

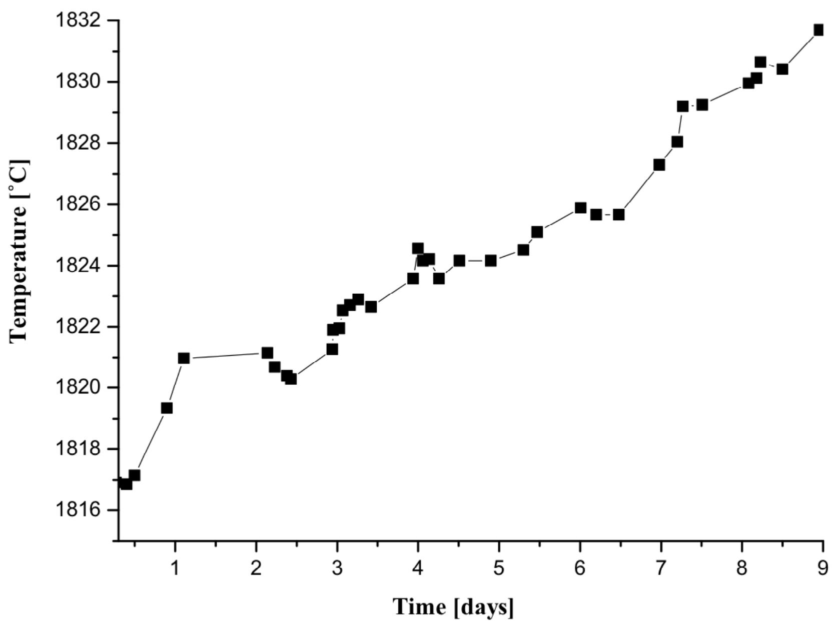
Two problems were found:

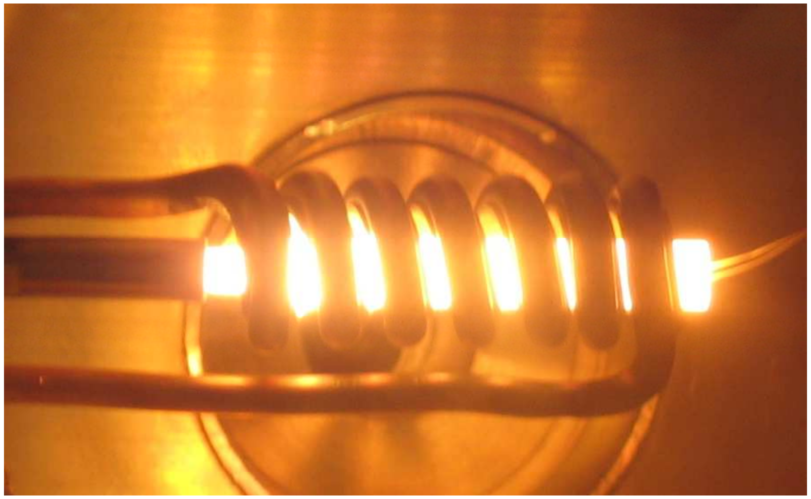




Inductively heated oven

The latest version of inductively heated oven developed in the frame of EURONS/ISIBHI seems to be reliable in operation





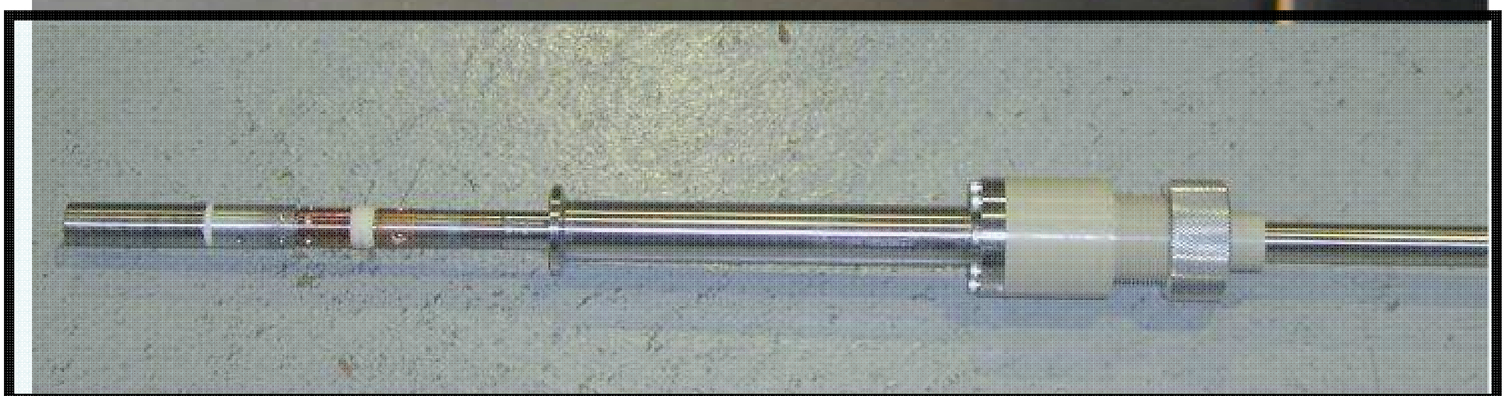
High temperature oven

- The GSI oven may be adapted to our mechanics.
- GSI offered to help us some years ago, but no formal step was done by LNS.
- If may be useful for some beams, we may revive the discussion

Ovens for ECRIS

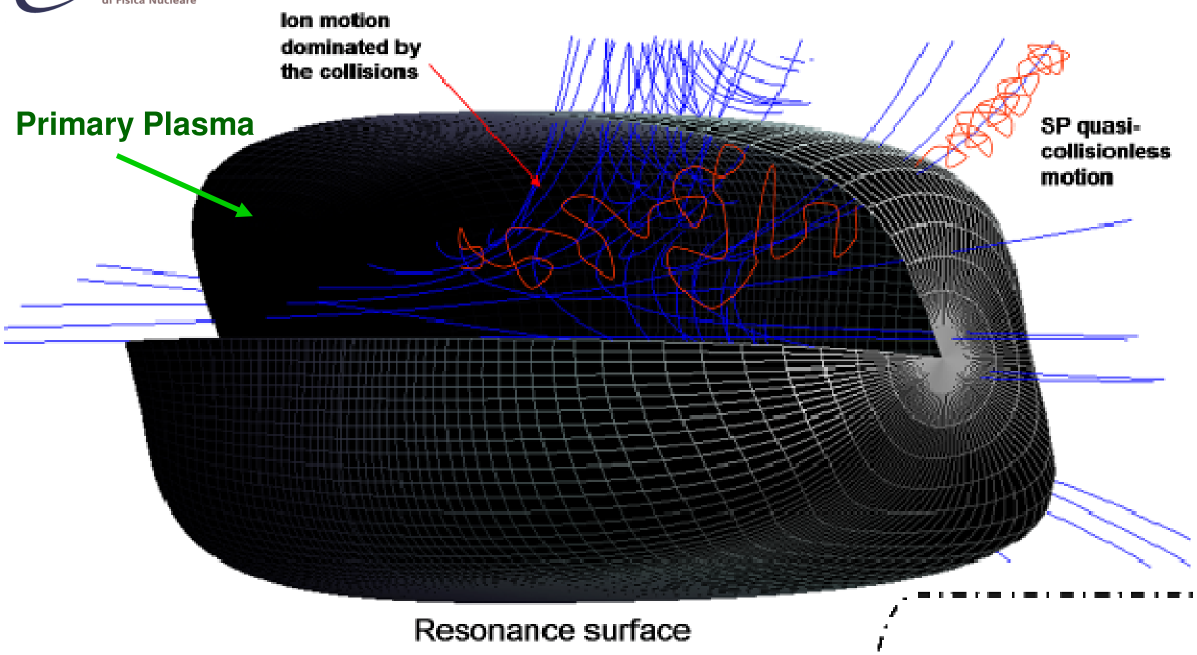
STO

HTO



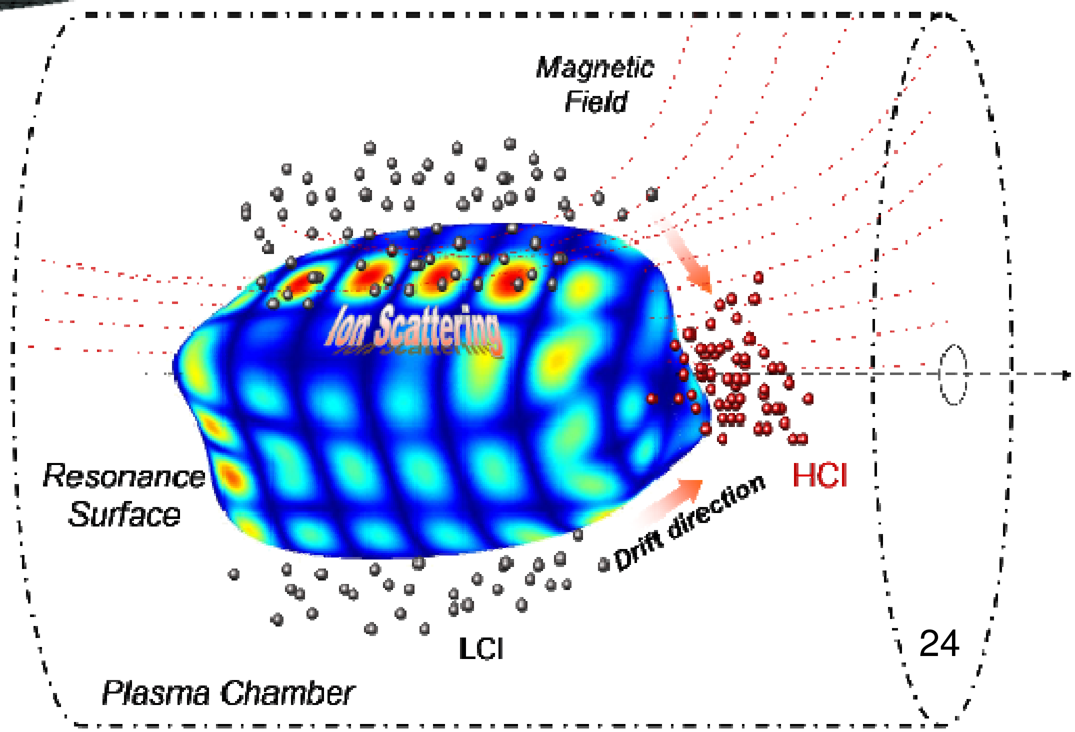
HTO

Ion Dynamics and Beam Formation



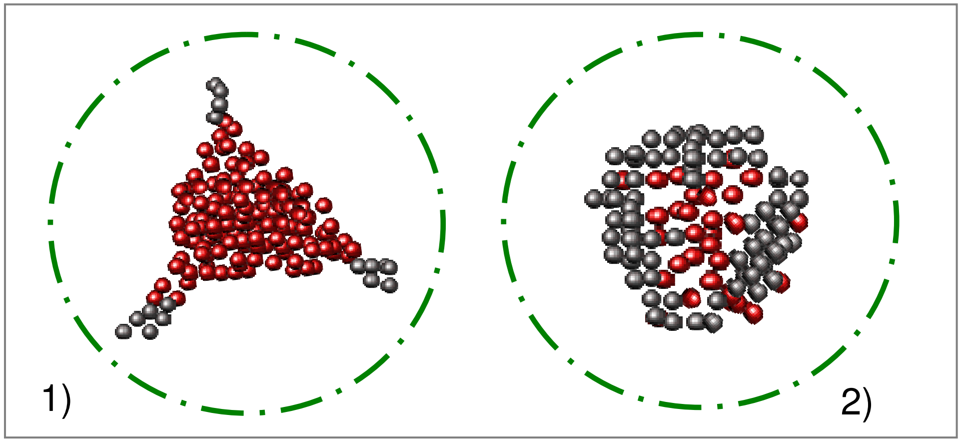
The Plasma can be divided into two regions: PRIMARY (inside the ECR volume) & SECONDARY plasma

The e.m. field pattern influences the PP potential distribution, which in turn affect the ion dynamics

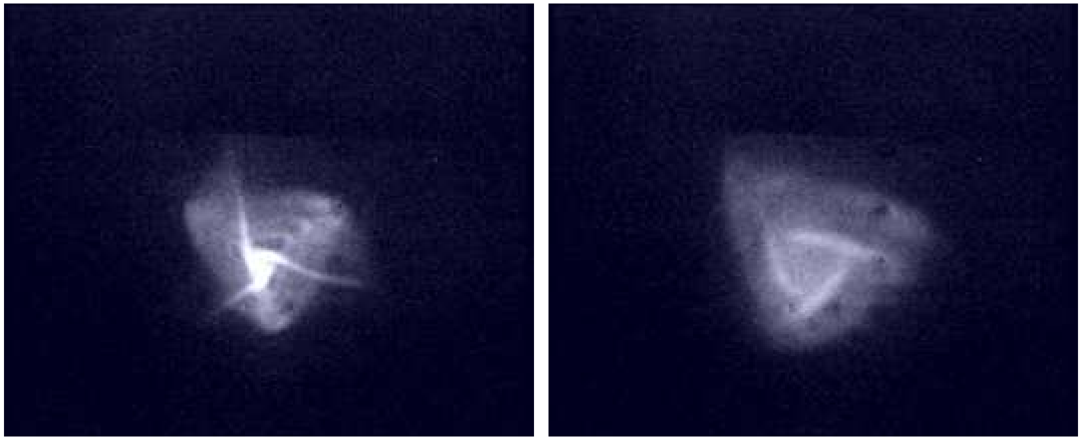


Ion Dynamics and Beam Formation

Modeling of beam formation and experimental measurements



1) Optimal Source performances: Higly Charged ions concentrated in the center of the extracted beam
2) Bad Source performances: ion scattering injects lowly charged ions in the loss cone. The beam periphery is populated by LCI



Also Ion Dynamics may take advantage from Frequency Tuning

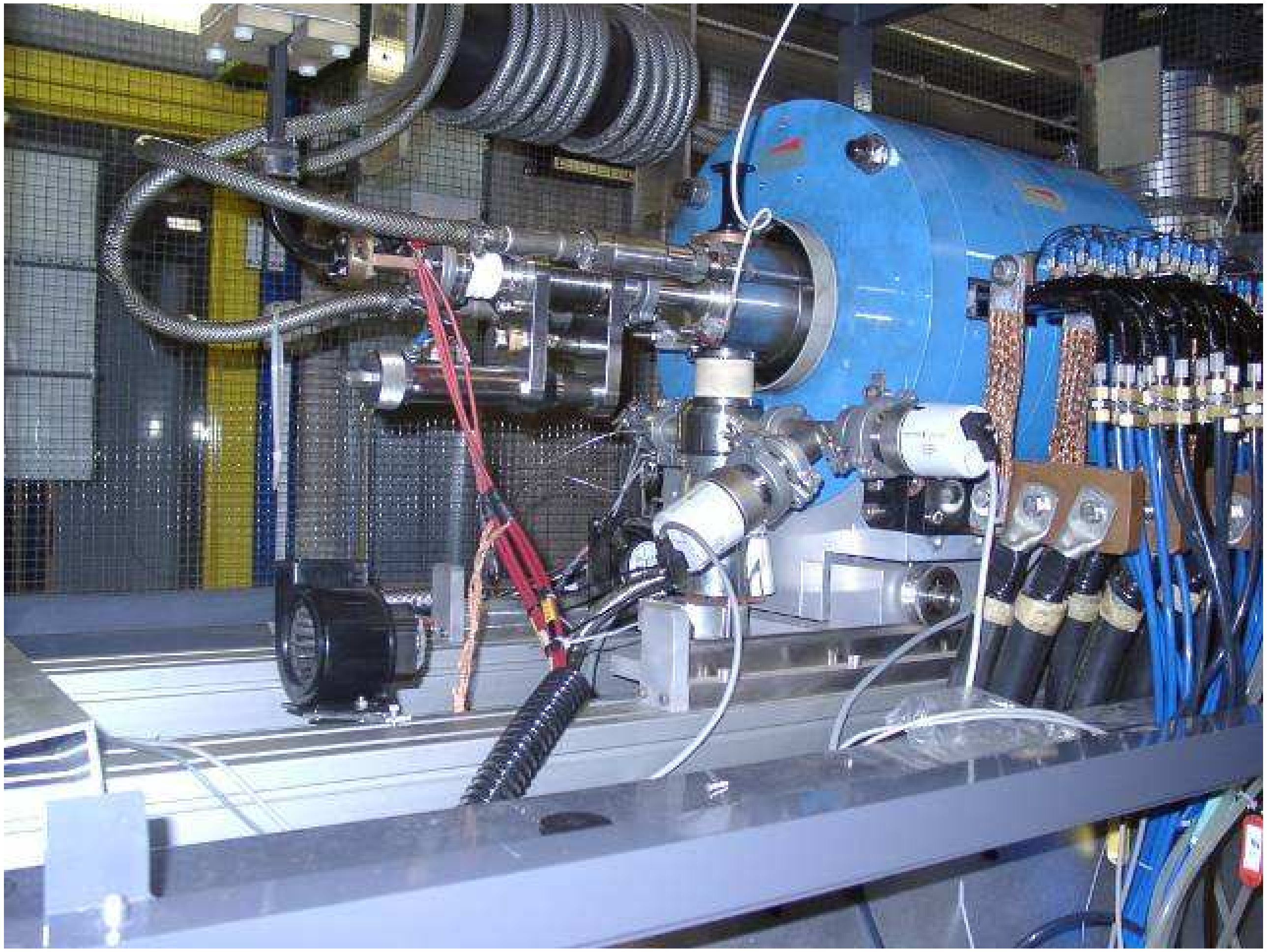
More expensive initiatives

- Low cost/complex/manpower needed: design of a new plasma chamber, higher voltage upgrade (I proportional to $V^{3/2}$) for SERSE, redesign of CAESAR injector adapted to larger microwave power (originally was 1200 W, now only 350 W), upgrade to 18 GHz for CAESAR (generator available)
- Expensive/easy to do: purchase of a higher frequency generator (24 GHz) for HBM operations of SERSE (not complex as the scaling studies were completed in 2000 and interpolation is possible)
- Expensive/complex: to transform SERSE cryostat in a LHe-free one to improve its reliability; to build a new III generation ECRIS to operate at 28 GHz (JUMP of performances, JUMP of costs).

MSECRIS-like plasma chamber for SERSE (design prepared by LNS technical staff)

Microwave injection channel: water cooling to be implemented in order to operate at 1200 W as in 1999, instead of 300-400 W, used since the redesign in 2003.
Upgrade to 18 GHz: the source was designed for 18 GHz operation and two frequency heating (a mixer is available), but the upgrading was not possible at the beginning for the unavailability of a second 18 GHz generator.

CAESAR



24 GHz upgrading for SERSE (> 100k€)

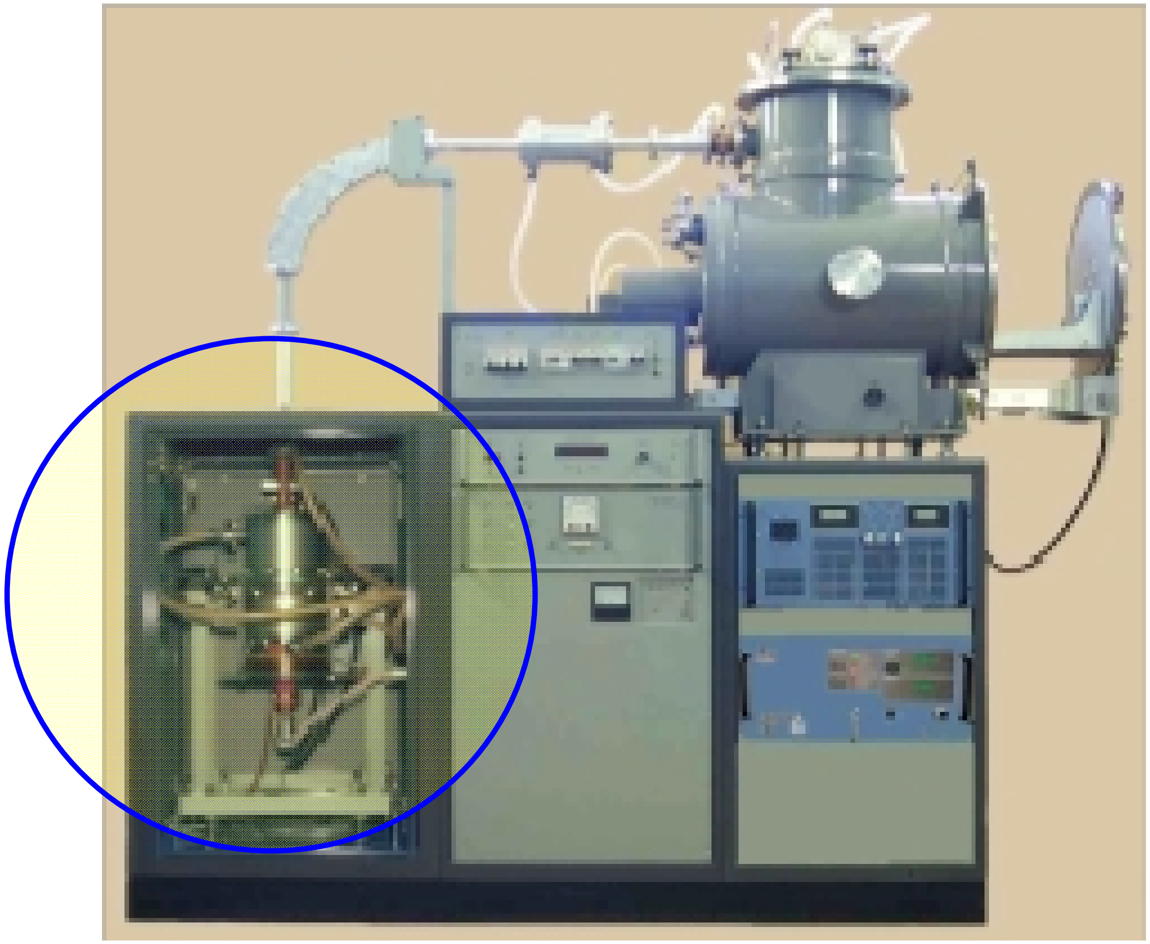
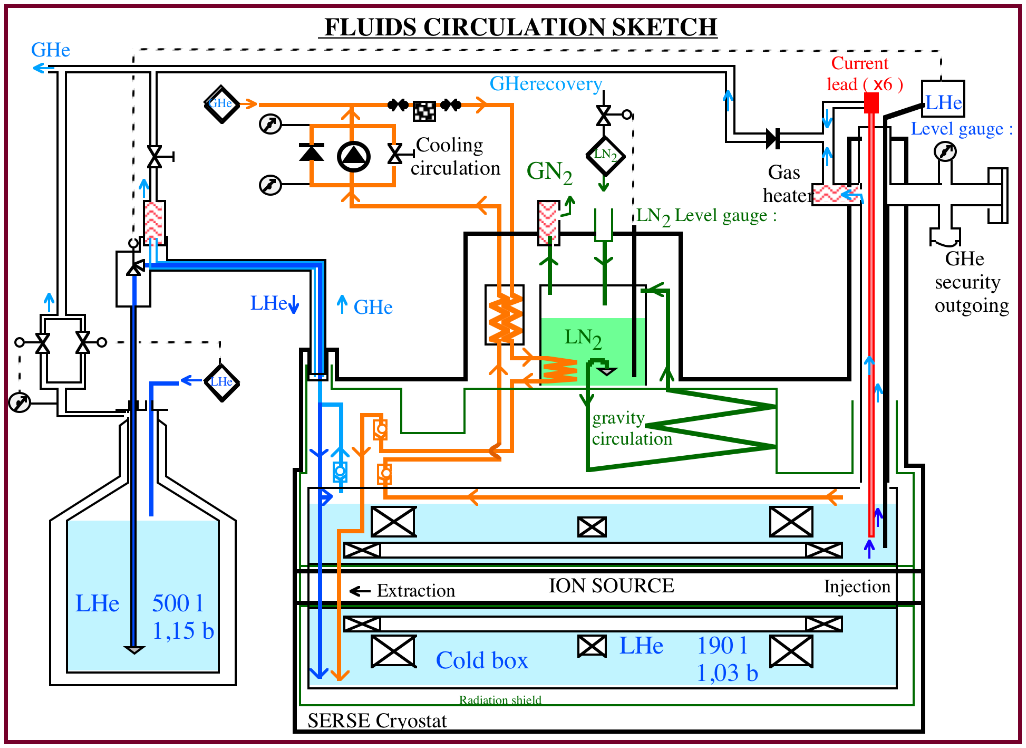


Figure 2: 3kW 24 GHz gyrotron system.

LHe-free modification



Proposed by CEA Grenoble in 2001

HTS current leads purchased in 2002 with EU funding (5° FP), never used for SERSE.

LHe free option is already available in similar sources, following this proposal.

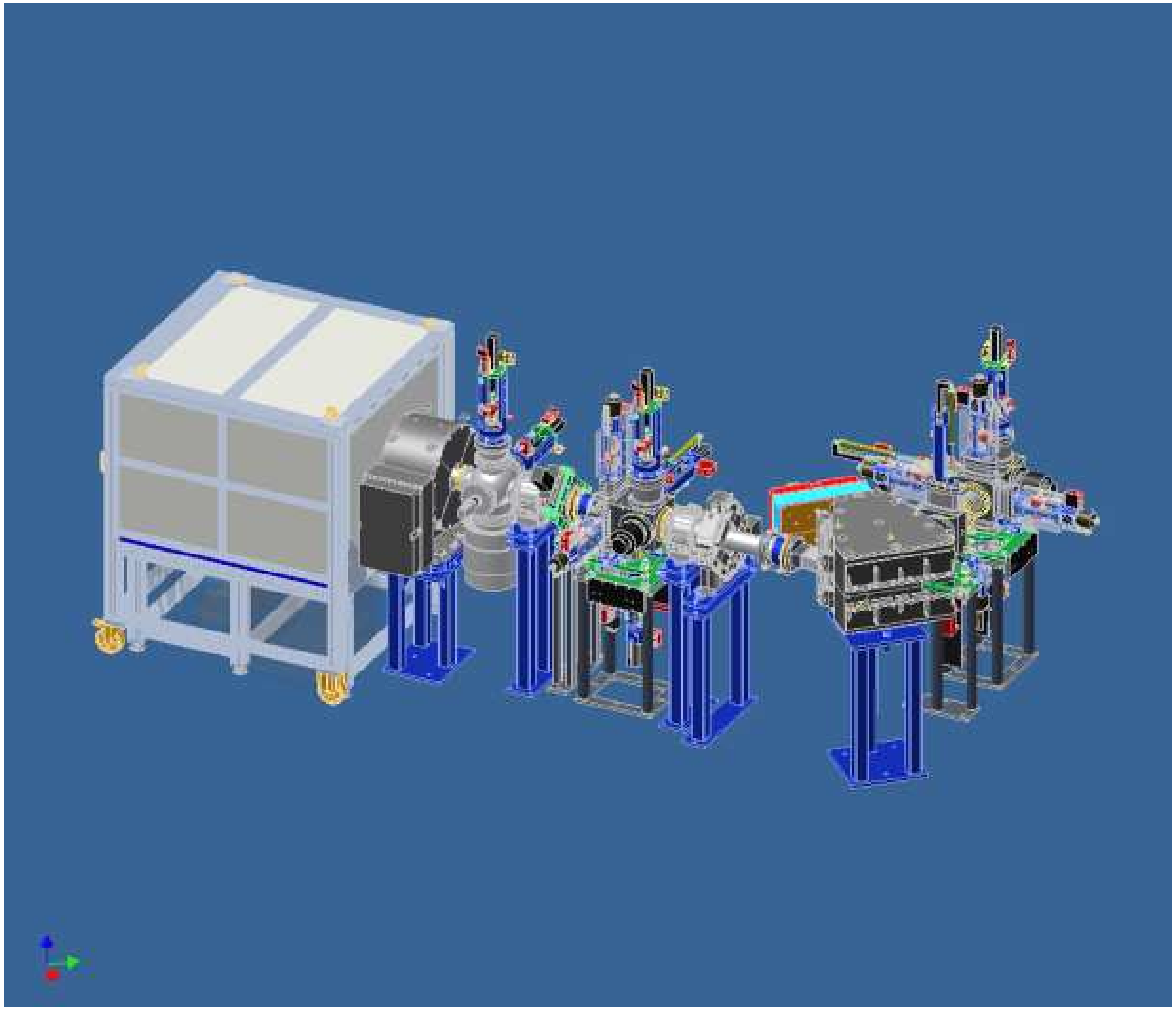
Remaining cost : about 120-150k€.

Different possible design for a new high performance source

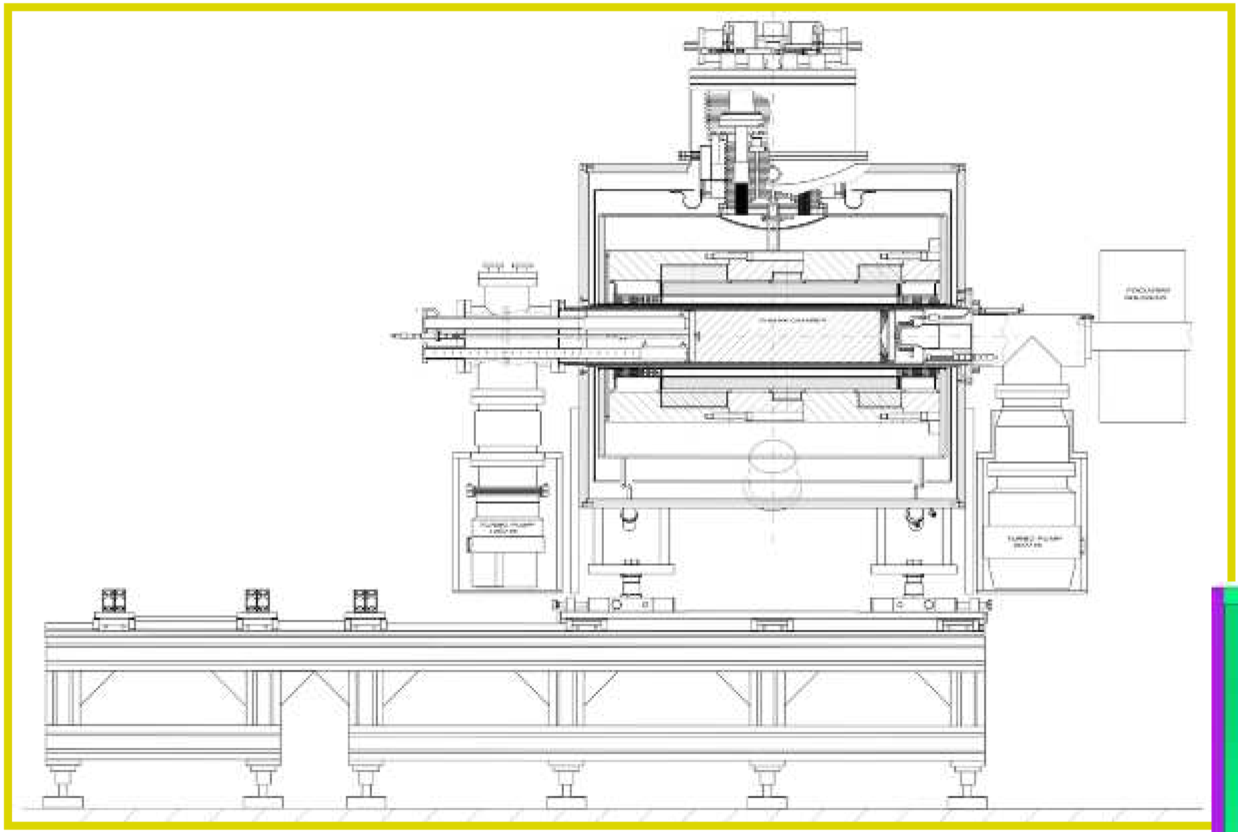
- VENUS
- SUSI-RIKEN
- MS-ECRIS
- SECRAL
- MISHA

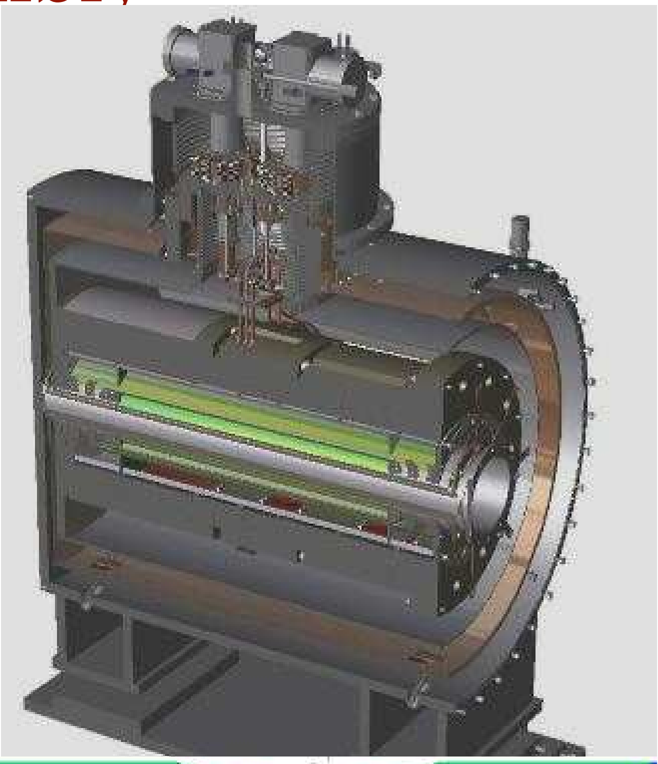
- Costs in the order of 1.5 to 2 M€, including the LEBT, slightly lower for the last one.

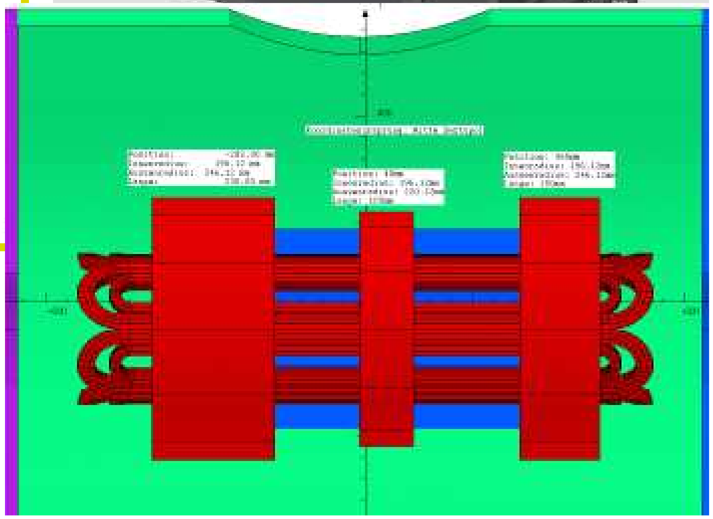
MISHA @ CNAO



MS-ECRIS assembly







What about the need of FRIBS?

- Some of the ion species that are requested have not been produced yet with the ECRIS@LNS, but they have been nicely produced elsewhere (Mg at IMP, Si at MSU, Al and Fe at many labs), in particular in laboratories strictly linked with our lab.

Oggetto: Re: magnesium
Da: "赵红卫" <zhaohw@impcas.ac.cn>
Data: Sat, 14 Mar 2009 22:14:06 +0800 (CST)
A: "santo" <gammino@lns.infn.it>

Dear Santo,

We ever provided 26Mg beam for four times to our cyclotron. What is the most importan for us during running 26Mg beam is comprimise between beam intensity and 26Mg consumption because 26Mg is expensive. The beam charge state that we delivered is 8+. The mixing gas is oxygen. We produced the beam with our small oven. The typical temperature of the oven is about 400 degree C. I think 26Mg and 24Mg should be similar. It is not difficult to produce Mg beam with oven. It is better for source runing if you apply some currents to the oven for outgasing in a vacuum chamber before you install the oven into the source. It is better to fill the oven with Mg grain, and in the very begining you have to raise the oven temperature very slowly, it may take 2-3 hours for the source conditioning and the oven outgasing. As soon as you see some Mg beams, it is better to make spectrum from time to time. You can know whether you need increase the oven temperature or decrease the oven temperature from the yields of the high charge state and low charge state beams in the spectrum. PLease rember, do not increase the oven temperature too high, otherwise, most of Mg would come out from the oven.

Best regards
Hongwei

What about the need of FRIBS?

- Some of the ion species that are requested have not been produced yet with the ECRIS@LNS, but they have been nicely produced elsewhere (Mg at IMP, Si at MSU, Al, Ni and Fe at IMP and other labs, Zn^{16+} at RIKEN), in particular in laboratories strictly linked with our lab. Rod, induction oven, sputtering are used, seldom MIVOC.
- Some other species (Ne, C, ^{18}O) are within the experiences of Accelerator Division, but an increase of current is required.
- In conclusion, with minor costs and with the support of the technical staff a remarkable improvement is possible and (once that some conditions are fulfilled) an important increase of current and energy is REALISTIC, not an idealization.
- Relevant but not huge investments, in the range of hundred k€, may give further improvements.

- Additional and large improvements are still possible, but relevant investments are needed, above 1 M€, as well as adequate resources in terms of room and manpower.

- Obviously, not only FRIBS but all the experiments may gain from any upgrade (e.g. the ones related to CHIMERA and MAGNEX).

- The appeal of a research facility depends on the ability to fulfill the request of users. Clearly, we have to work harder, but we can do it.

S'io avessi, lettor, più lungo spazio….

Let me conclude with some words from Dante's Comoedia:

Io ritornai da la santissima onda
rifatto sì come piante novelle
rinnovellate di novella fronda,
puro e disposto a salire alle stelle.

(Purgatorio, XXXIII,142-145)