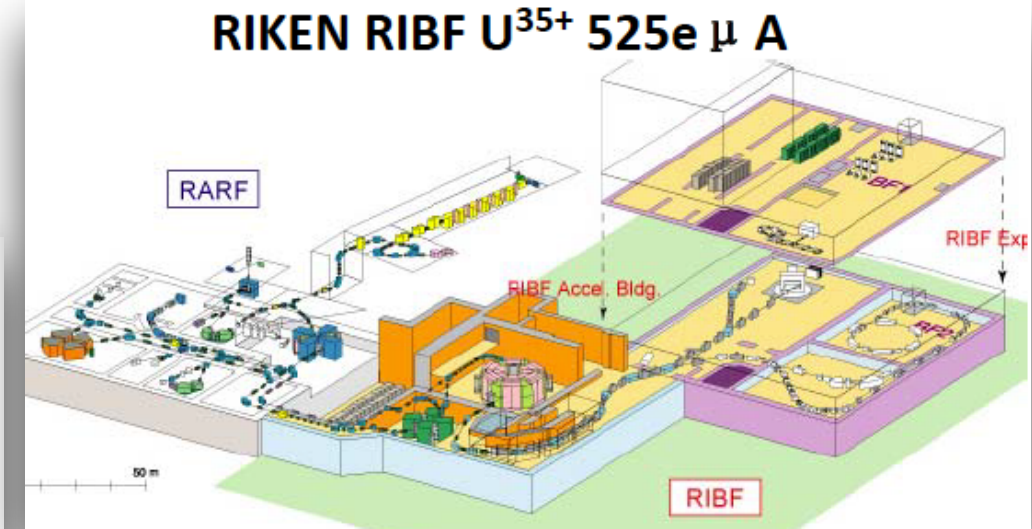
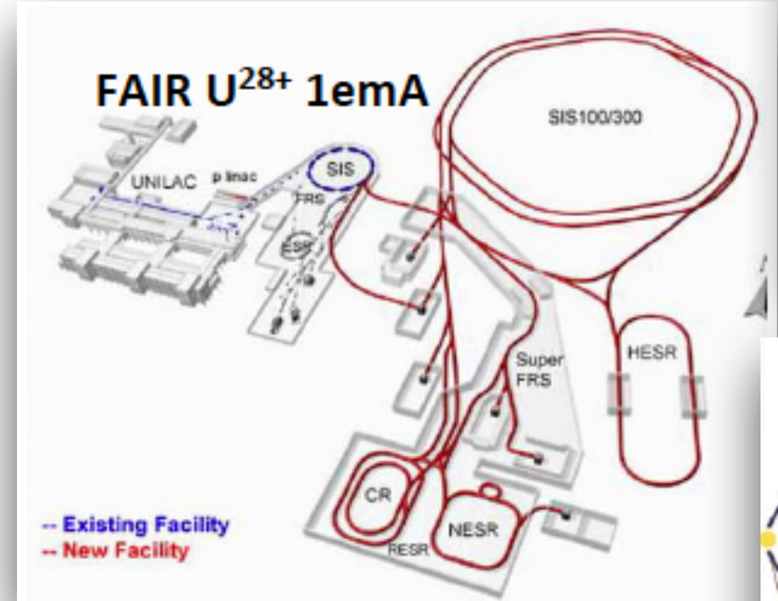
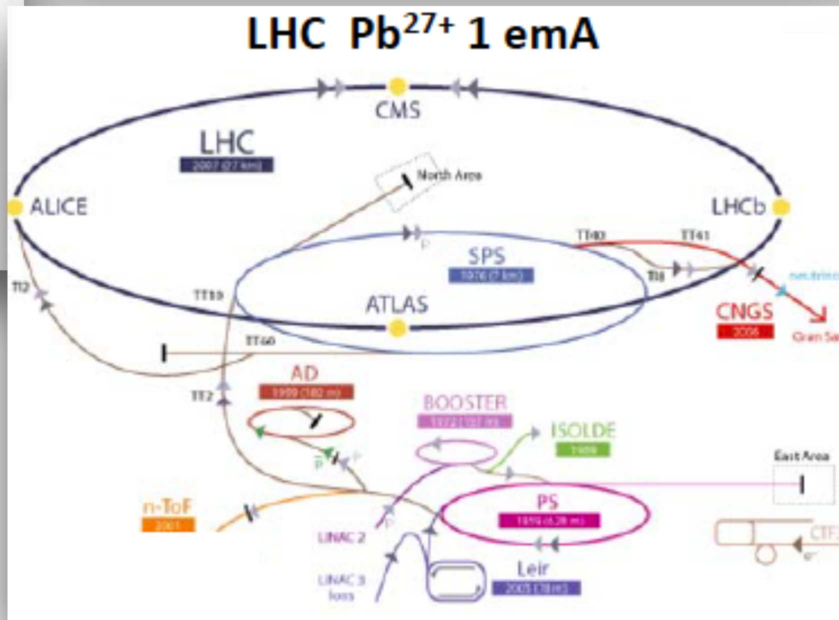
Sorgenti ioniche di nuova generazione per acceleratori ad alta intensità

Santo Gammino
Laboratori Nazionali del Sud, CATANIA

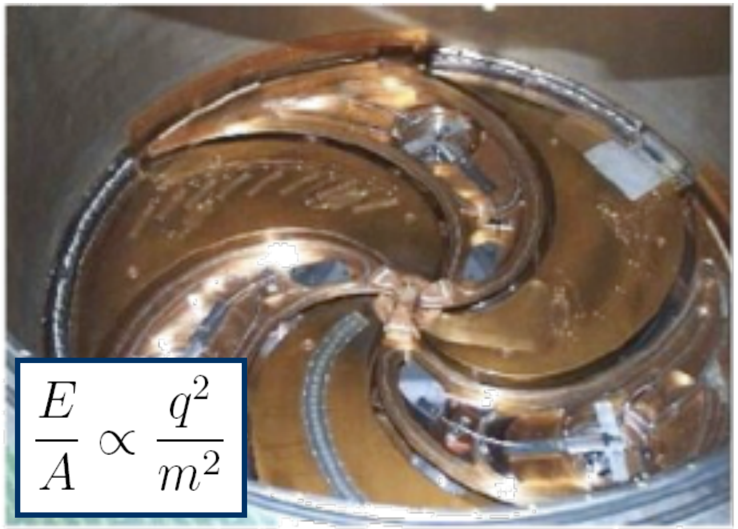
Big Facilities over the world require intense beams of multiply charged ions







Boosting Accelerators performances: production of intense beams of highly charged ions



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

INFN-LNS Cyclotron

Increase of Ion Charge States

↓

Higher energies attainable by Accelerators

Increase of Ion Current

↓

Decrease of acquisition times for rare events

Increase of Accelerators' performances without hardware modifications

High power proton accelerators require 100 mA of monocharged ions or more

ESS accelerator

Design Drivers:

- High Average Beam Power
  - 5 MW
- High Peak Beam Power
  - 125 MW
- High Availability
  - > 95%

Key parameters:

-2.86 ms pulses
-2 GeV
-62.5 mA
-14 Hz
-Protons (H+)
-Low losses
-Low heat loss cryostats for minimum energy consumption
-Flexible design for future upgrades

Strategy

High charge states (ECRIS):

high electron density, high plasma confinement time → high frequency, high magnetic field

High current (MDIS):

high electron density (overdense plasmas), low plasma confinement time → 2.45 GHz frequency, low magnetic field

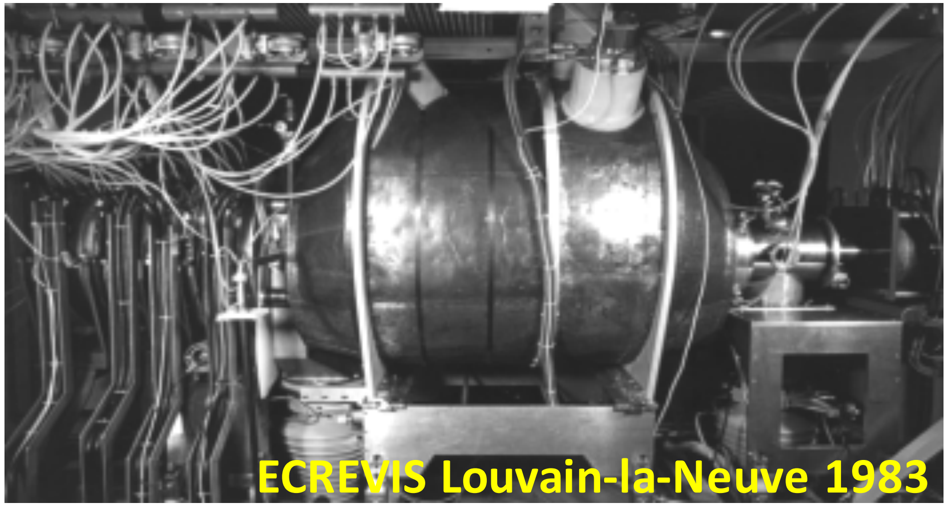
High current ion sources: achievements & challenges

Since the end of ‘80s INFN has supported a relevant investment in high current ion sources, along three main directions:

- **Electron Cyclotron Resonance (ECR) ion sources for multiply charged heavy ion beam** production (with the corollary of charge breeders for radioactive beams);
- **Microwave discharge ion sources (MDIS) for high power proton accelerators (HPPA)**;
- **Laser ion sources**;

→ Laboratori Nazionali del Sud, Catania (important achievements in modeling within a collaboration LNS-LNL, additional collaborations with Universities)

In the last two decades most of results have been made possible by the availability of more powerful magnetic system and microwave generators, but this is not an “ad libitum” process and the better comprehension of the behavior of the plasmas is mandatory, with increased emphasis w.r.t. what was done in the past, that is not negligible.
Let’s start from historical information.



The Electron Cyclotron Resonance heating

During the plasma start-up an exiguous number of free electrons exist

→ Magnetic Field

Electrons turn around the magnetic field lines with the frequency:

$\omega_g = qB/m$

↓

A circulary polarized electromagnetic wave transfer energy to the electrons by means of the ECR :

$\omega_{RF} = \omega_g$

←

The energetic electrons ionize the gas atoms and create a plasma.

The ionization up to high charge state is a step by step process which requires long ion confinement times and large electron densities

Microwave discharge & ECR ion sources scheme

High currents of 1+ ions (mA- level)

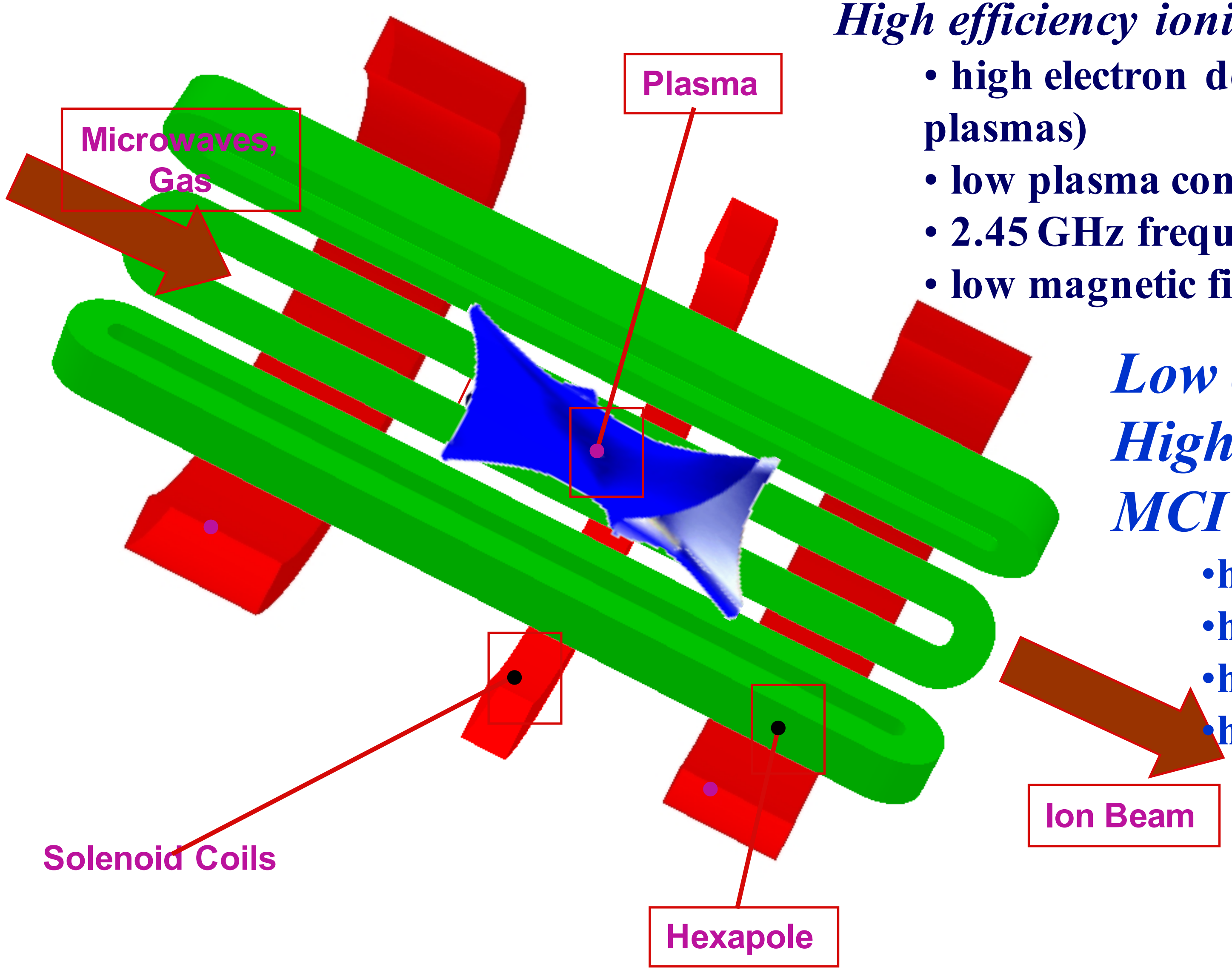
High efficiency ionisation of 1+ ions:

- **high electron density (overdense plasmas)**
- **low plasma confinement time**
- **2.45 GHz frequency**
- **low magnetic field**

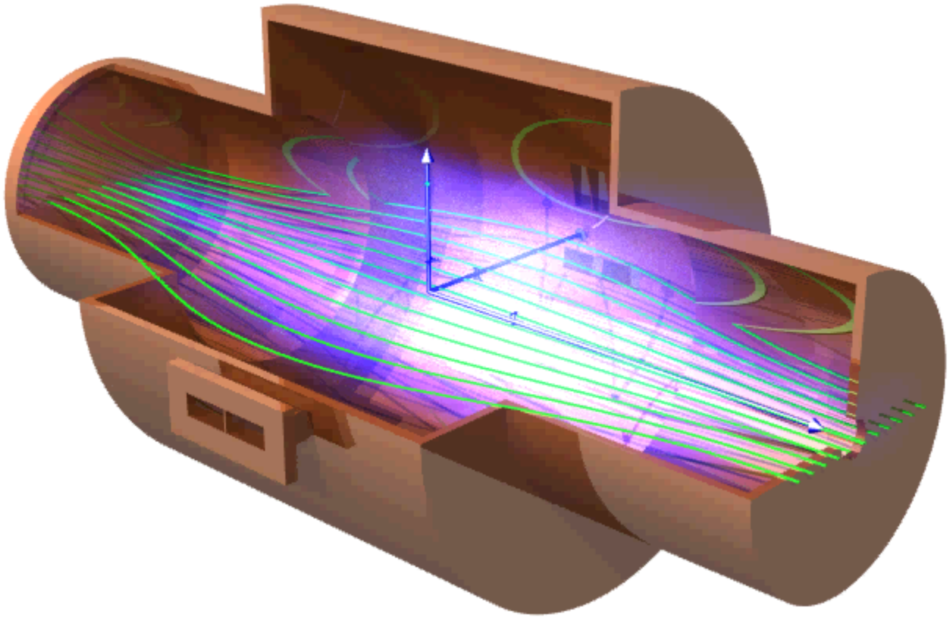
Low current of HCI

High current of LCI and MCI

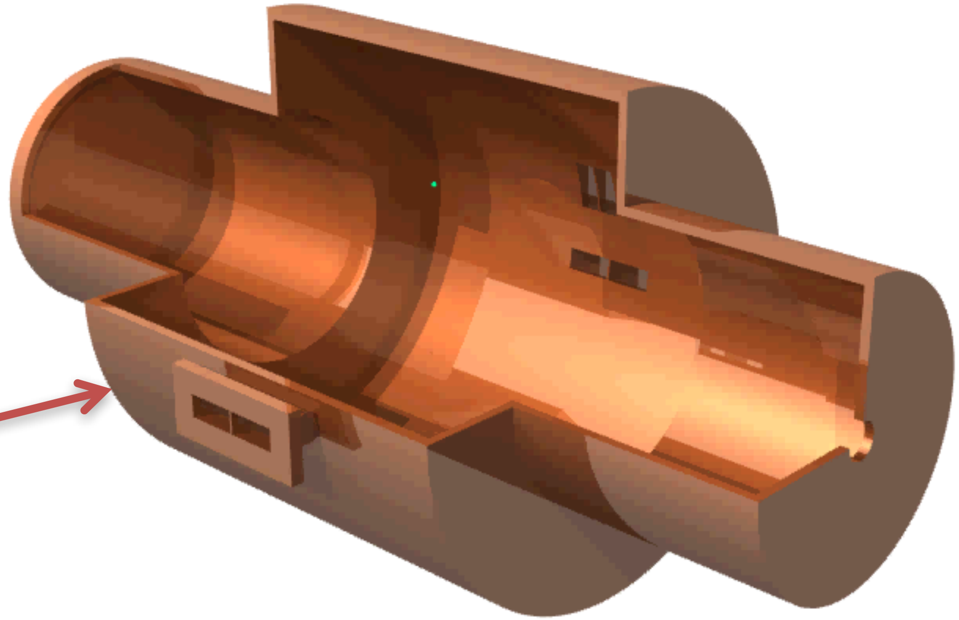
- **high electron density**
- **high plasma confinement tim**
- **high frequency**
- **high magnetic field**



Plasma Confinement in compact traps



Particles trajectories in plasmas are affected by several drifts, due to spontaneous or induced E fields, B lines curvature, B gradient, gravity, etc…



Particles rebounce inside the trap and are contemporaneously affected by the “phi” drift around the magnetic axis, due to the B curvature and axial gradient

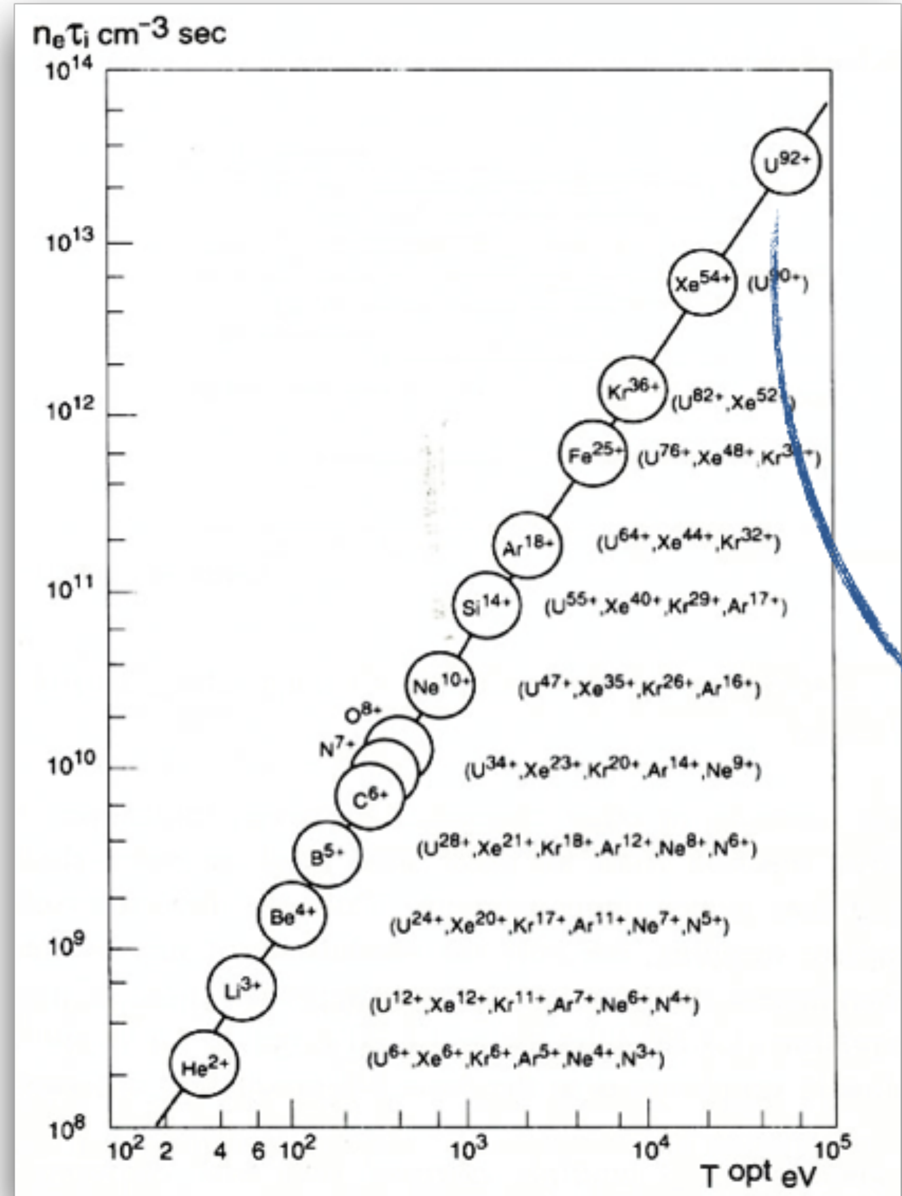
High density – long lifetime required for fusion

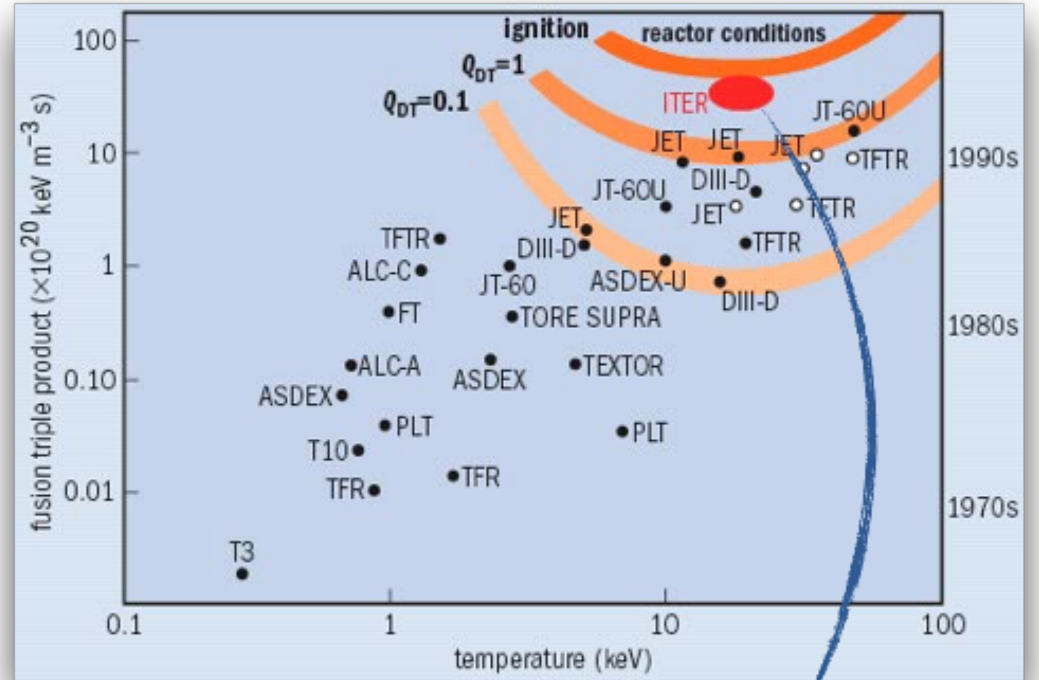
Approximately the same requirements are valid for ion source plasmas

$$I_{ext} \propto \frac{n_e}{\tau_i} \; ; \qquad < q > \propto n_e{}^{*}\tau_i$$

Plasmas at high electron density and characterized by long ion lifetimes are specifically required. They can be produced by high intensity electron beams and/or sustained by microwaves

A challenge similar to the "fusion dream"...





The triple product of density, lifetime and electron temperature for obtaining fully stripped heavy ions is not far from the value of "Ignition"

The main goal of ion sources is the production of high quality ion beams to be injected into particle accelerators, minimizing beam losses and maximizing the overall reliability

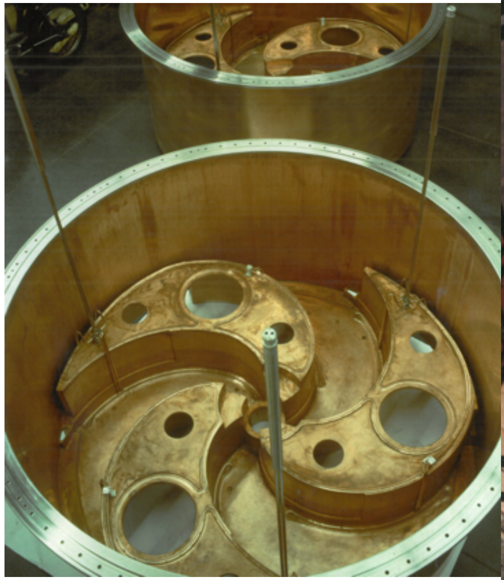
The requirements of Ion sources employed for accelerators like LINACS or Cyclotrons are:

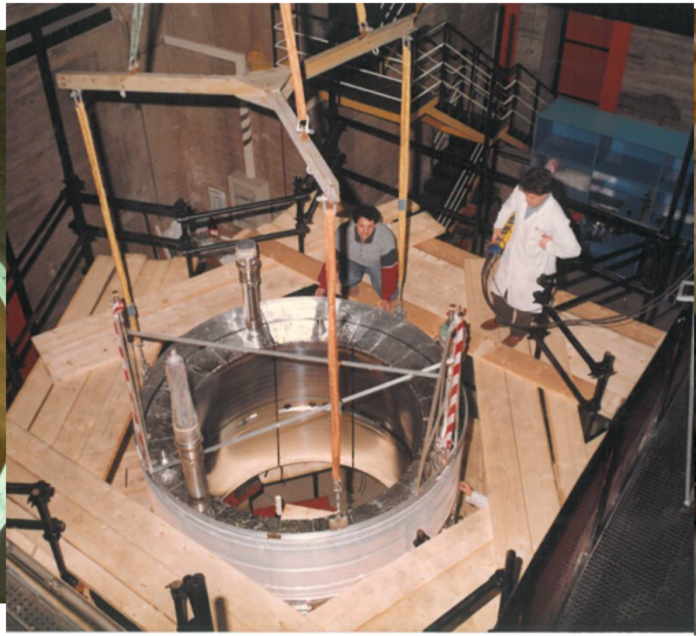
- ❑ **Production of intense beams of highly charged ions**
- ❑ **Low emittance.**
- ❑ **High stability and long-time operations without significant maintenance**

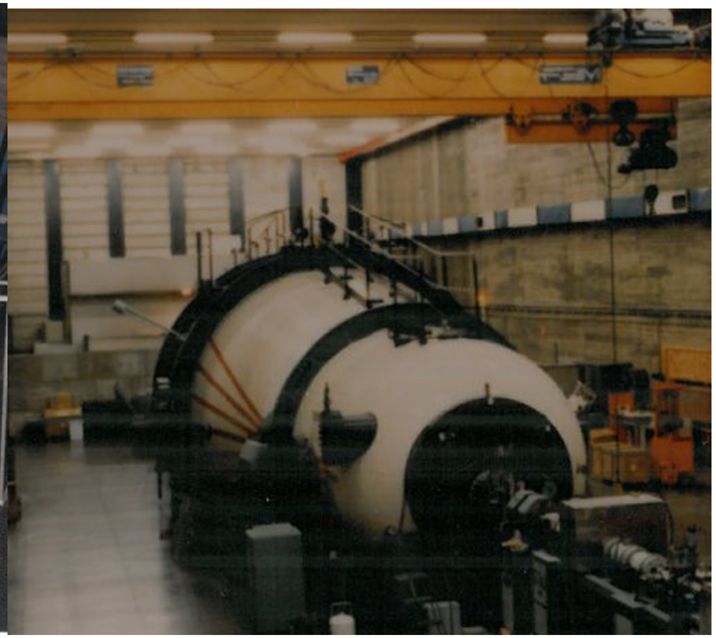
Time machine - I

1987-90

1. LNS future machine, K-800 Superconducting Cyclotron (CS), is under construction.
2. The project is based on the radial injection of the beam accelerated by the Tandem and matched to the CS after a stripping and bunching process. Axial injection is considered but not designed.
3. The current from the Tandem is limited because of the two stripping process.
4. The maximum energy is limited by the maximum charge states obtained.







Time machine - II

1987-90

1. An additional scheme is viable, through the installation of an inflector and of a central region allowing to inject highly charged ions, but….
2. The best ion sources are the Electron Cyclotron Resonance Ion Sources ; unfortunately the best available ones at that moment (GANIL, Julich, LBL) are not sufficient for LNS needs
3. The LNS management starts a R&D program to answer to the question: how to design an ECR able to replace the Tandem ?

Scaling laws

R. Geller (Grenoble, 1987,1990) has inferred from the experimental data some useful relations:

1) $\tau_i \propto L^2_{plasma}\ B^{1.5}_{ECR}$

2) $B \propto \omega$

3) $n_e \propto \omega^2$

4) $T_e \propto P_{rf} \propto \bar{q}^2$

5) $P_{rf} \propto \sqrt{\omega} \cdot \bar{q}^3\ V$

→ 6) $I_{q+} \propto \omega^2\ M^{-\beta}$ $\beta = 0.5 \div 1$

→ 7) $\bar{q} \propto log(B_{max})$

Microscopic parameters $n_e, T_e, \tau_i, \bar{q}$

Macroscopic parameters $V, L_{plasma}, B, \omega, P_{RF}, M$

Studies of plasma physics

\+

Accidental situations

History: accidents force humans to new ideas...

Sometime in Sixties

Prof. Richard Geller, during an experimental night shift, worked to maintainance of a PIG source and a small accident happened, resulting in a leg injury.

Result: he said himself that a new type of ion source was absolutely necessary, which does not need daily maintainance.

1965: the main ideas that led to the Electron Cyclotron Resonance Ion Source design are set by Geller (he used to be a "FTP" or "**maquis**" and during the war he knew Frederic Joliot-Curie, founder of CEA)

1974: Geller's scaling laws are mentioned for the first time (technical R&D in'80s).

Time machine - III

1989

1. Luciano Calabretta and Giovanni Ciavola ask Prof. Migneco to arrange a period of stage at GANIL or KVI, where ECRIS developments are ongoing, for the newcomer of Accelerator Division
2. GANIL is not interested to host an external guest in this field.
3. KVI accepts to host the INFN guest (**accident#1**)
4. The research about ECRIS is carried out by Dr. Arne Drentje, who is counselor of the Director for the accelerators and has not much time for development of same ideas to improve the existing 10 GHz source and for the commissioning of the new 14 GHz source. Good to host a good-will junior scientist, said Arne (especially if paid by INFN !!!)
5. Dr. Drentje appreciates the ability of the young guest to operate AUTONOMOUSLY the two sources with the help of the technician Jans Sijbring and ask to follow the programme of development on his behalf, but…

History: accidents pushed us to new ideas…

1989-90

…but… the 14 GHz source, in spite of the fulfillment of the Geller's scaling laws does not work properly in terms of high charge states production, and the amount of X-rays is awful and restricts the R&D. (**accident#2**)

Discussion Gammino-Drentje: evidently the Geller's laws are not complete. What's wrong? Why this time they do not work (September 1989)? Phone/message discussions with Ciavola at LNS: no solutions.

About the same period: somebody at KVI (maybe Ronnie Hoekstra) has shown Nd-Fe-B magnets →I risked my finger to be injuried (**accident#3**)

November 1989: Two months of full immersion in plasma physics' world (access to Russian and US textbooks at RUG Groningen) takes to the **formulation of High B mode** (in the meantime back to LNS → days of discussions with Giovanni Ciavola → improvement of the concept → key question of Giovanni "**is the magnet the right one?**", answer of Santo "no, it isn't, *a 20% larger hexapole would be the right one*, new type? " → Drentje purchases a hexapole based on a new VACODYM-type (Nd-Fe-B)

March-April 1990 : replacement of the hexapole → excellent results, no X-rays up to 300-400 W ! Current records of KVI cancelled in a week.

History: accidents pushed us to new ideas…

1990

First report which describes the High B mode concept, first proposal to Prof. Geller to prepare a MoU for the construction of a source based on HBM

1991

Presentation to the Ion Source community, positive (4th ICIS, Bensheim, Germany): at the same time the paper on "Biased Disk" is presented. Negotiation between Ciavola and Geller, preparation of the TDR.

$\frac{B^2}{2\mu_0} \gg n_e k T_e \Longrightarrow$ for a fixed f the effective n_e is dependent from the confining field

In the case of SC-ECRIS the electron density improved by rising the field.

Therefore if B is too low, it is not useful to increase the frequency

High frequency with low fields means plasma instability and finally bad source behaviour!

If $\beta = \frac{n_e k T_e}{B^2/2\mu_0} \simeq 0.01 \div 0.02$ the frequency increase may result in a higher charge states buildup

"High B mode" concept (HBM)

$$\beta = p_{particle}/p_{magnetic} = n_e\, kT_e/(B^2/2\mu_0) < 0.01 \quad (1)$$

if $kT_e \gg kT_i$

$$n_e = n_{cutoff} = (m_e/e^2)\varepsilon_0\, \omega^2_{RF} = (\varepsilon_0/m_e)\, B^2_{ECR} \quad (2)$$

$\omega_{RF} = e\, B_{ECR} / m_e$

$$(\varepsilon_0/m_e)\, B^2_{ECR}\ kT_e < 0.01 B^2/2\mu_0 \quad (3)$$

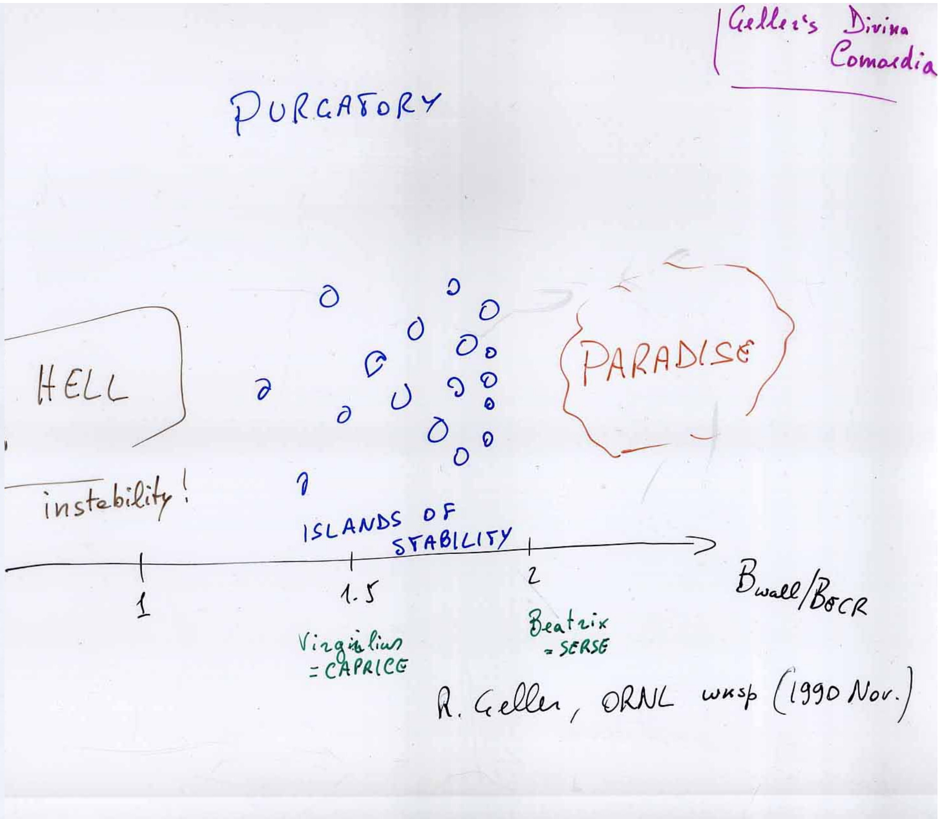
$$(B/B_{ECR})^2 > 100 * kT_e * 2\mu_0\, \varepsilon_0 / m_e \quad (4)$$

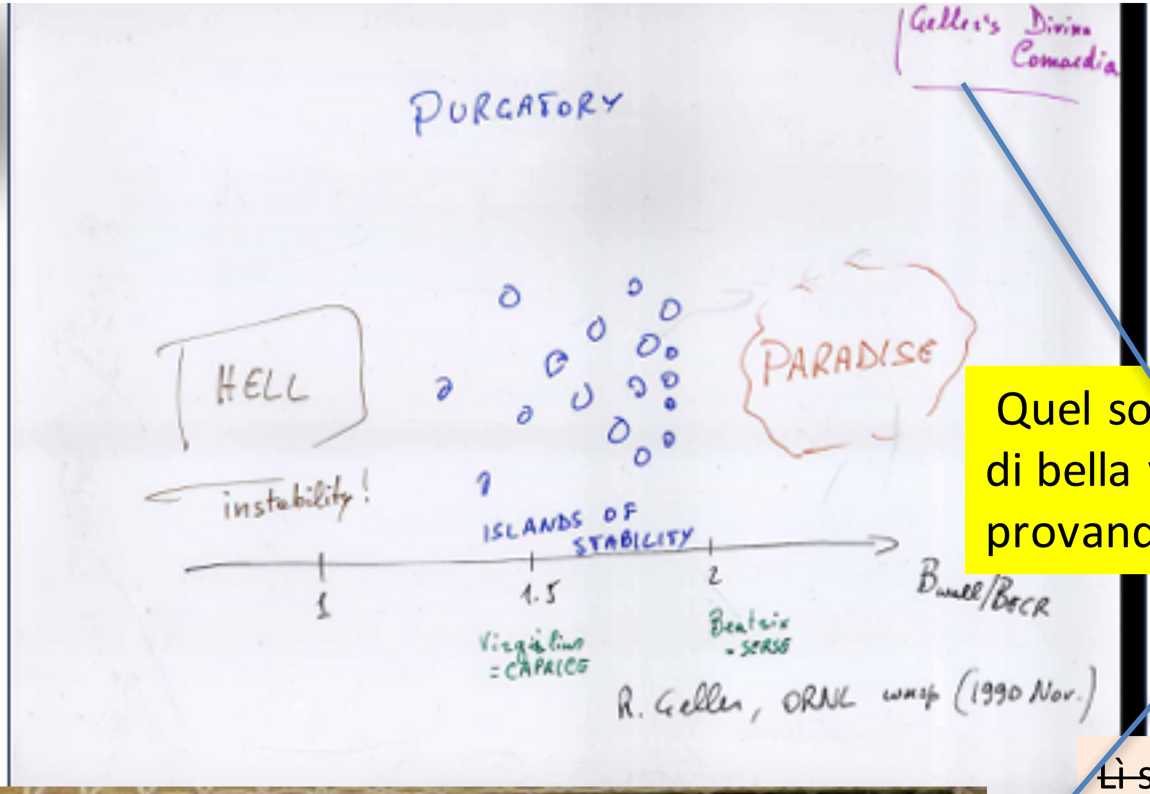
$\mu_0\, \varepsilon_0 = 1/c^2$ and $m_e c^2 = 511$ keV

$$(B/B_{ECR})^2 > (200\ kT_e) / (511 \text{ keV}) \quad (5)$$

for $kT_e = 10$ keV

$$(B/B_{ECR}) > 2.$$





Quel sol che pria d'amor mi scaldò'l petto
di bella verità m'avea scoverto,
provando e riprovando, il dolce aspetto;

~~Lì si vedrà ciò che tenem per fede,~~
~~non dimostrato, ma fia per sé noto~~
~~a guisa del ver primo che l'uom crede.~~

~~O voi che siete in piccioletta barca,~~
~~desiderosi d'ascoltar, seguiti~~
~~dietro al mio legno che cantando varca,~~
~~tornate a riveder li vostri liti:~~
~~non vi mettete in pelago, ché forse,~~
~~perdendo me, rimarreste smarriti.~~

Provando e riprovando,
mettemmo la piccioletta barca
in pelago...

A superconducting electron cyclotron resonance source for the L.N.S.

G. Ciavola and S. Gammino
I.N.F.N.-Laboratorio Nazionale del Sud, Vl. A. Doria (ang. V. S. Sofia), 95123 Catania, Italy

(Presented on 3 October 1991)

At the "Laboratorio Nazionale del Sud" (L.N.S.) the K-800 Superconducting Cyclotron (C.S.) is under construction and by the end of 1992 it will be completed in order to work as a booster for the 15-MV Tandem. With this facility fully stripped light ions will reach 100 MeV/amu, while the heaviest ions are foreseen to get 16 MeV/amu. In order to increase both charge states and intensities, mostly for the heaviest ions, of the beams injected into the C.S. a project for a superconducting electron cyclotron resonance (ECR) ion source has been developed and it will be carried out as a joint venture between the L.N.S. and the C.E.N. of Grenoble. This source will be the first superconducting ECR source to be coupled to a superconducting cyclotron in Europe, and it is particularly suited to exploit the capabilities of our K-800 superconducting cyclotron. The source will be working at 14.5 GHz and the confinement will be performed by superconducting magnets able to give 1.3 T on the plasma chamber wall, permitting attainment of a very good confinement. The design is at a preliminary level, but the main characteristics of the source have been established. The construction is scheduled to begin in 1992 and the source is expected to be working in 1995.

Experiment with a biased disk at the K.V.I. ECRIS

S. Gammino,[a] J. Sijbring, and A. G. Drentje
Kernfysisch Versneller Instituut, 9747 AA-Groningen, The Netherlands

(Presented on 3 October 1991)

Some measurements have been done on the source ECRIS 1 at K.V.I., showing the beneficial effect to the output currents when a biased disk is positioned in the first stage, as reported by the Grenoble ECRIS group. The increase is in the order of 40% and it can be explained by the enrichment of the electron density in the plasma. Different saturation voltages for different charge states tend to confirm this explanation, suggesting new experiments, as, for example, the substitution of the first stage by an electron gun.

1992

Approval by LNS Director and proposal for funding, positively evaluated by the INFN Executive Board

1993

Positive accidents (**accident#4**): while at MSU Rad. Ion Beam Conf., we propose the operation of SC-ECRIS in High B mode → all records exceeded by far in 2 days and one night (bad coffee, impossible to do more) → unscheduled invited talk because the HBM behavior is promising for charge breeders and paper by Antaya, Gammino, Ciavola, Loiselet ***Selective enhancement of highly charged ions extracted from the SCECR ion source***, Proc. 3rd Int. Conf. on Radioactive Nuclear Beams → **first relevant paper for charge breeding**

MSU SC ECR 1993

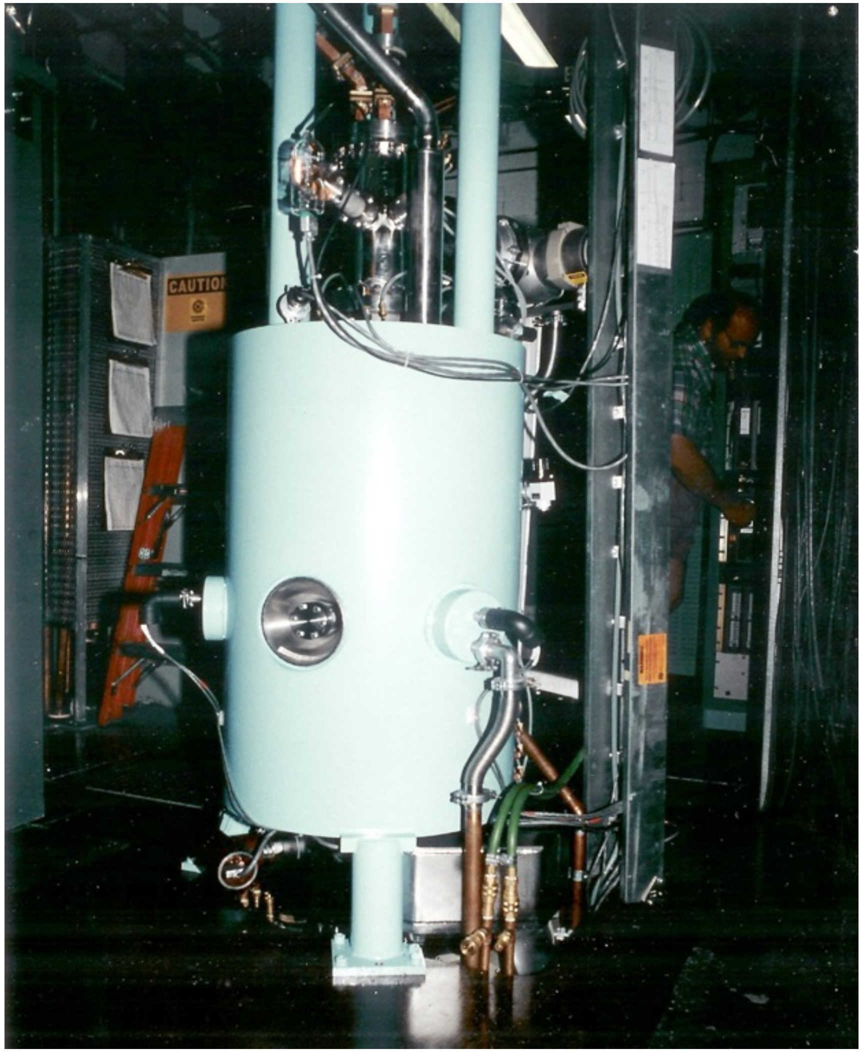
First vertical superconducting ECR

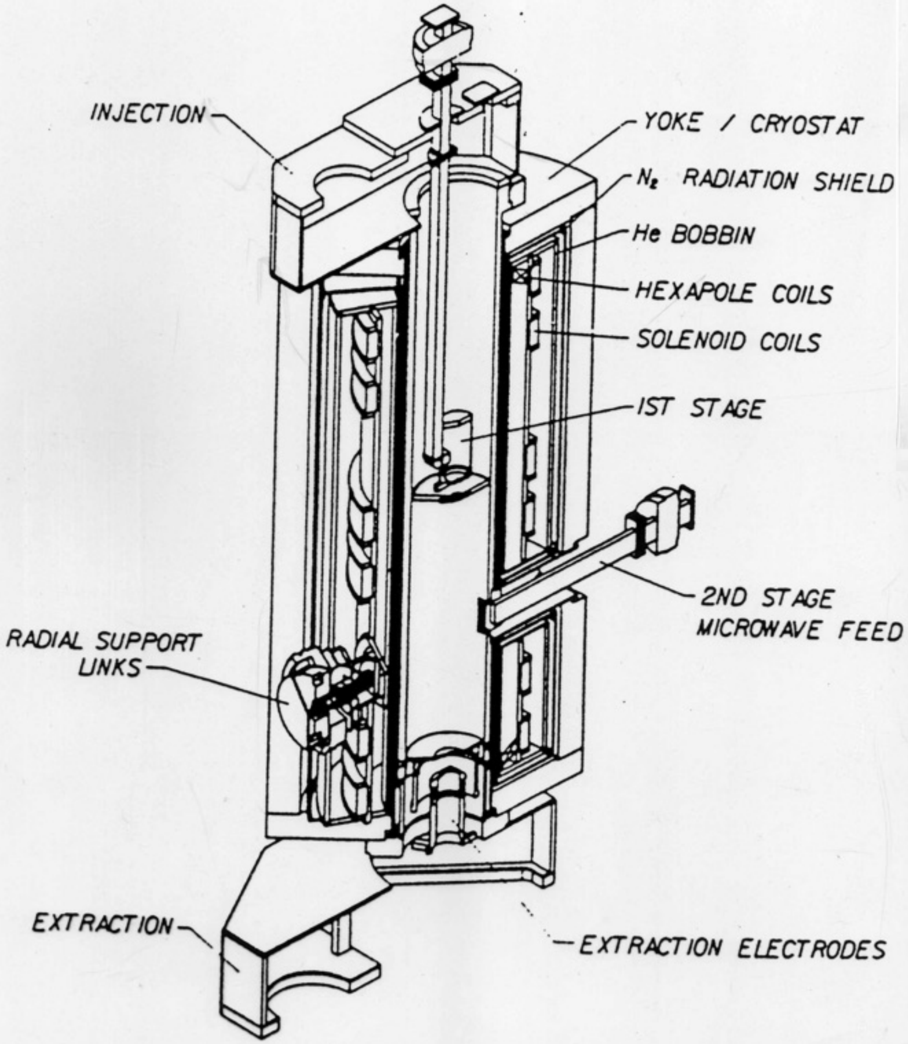
Most years in operation

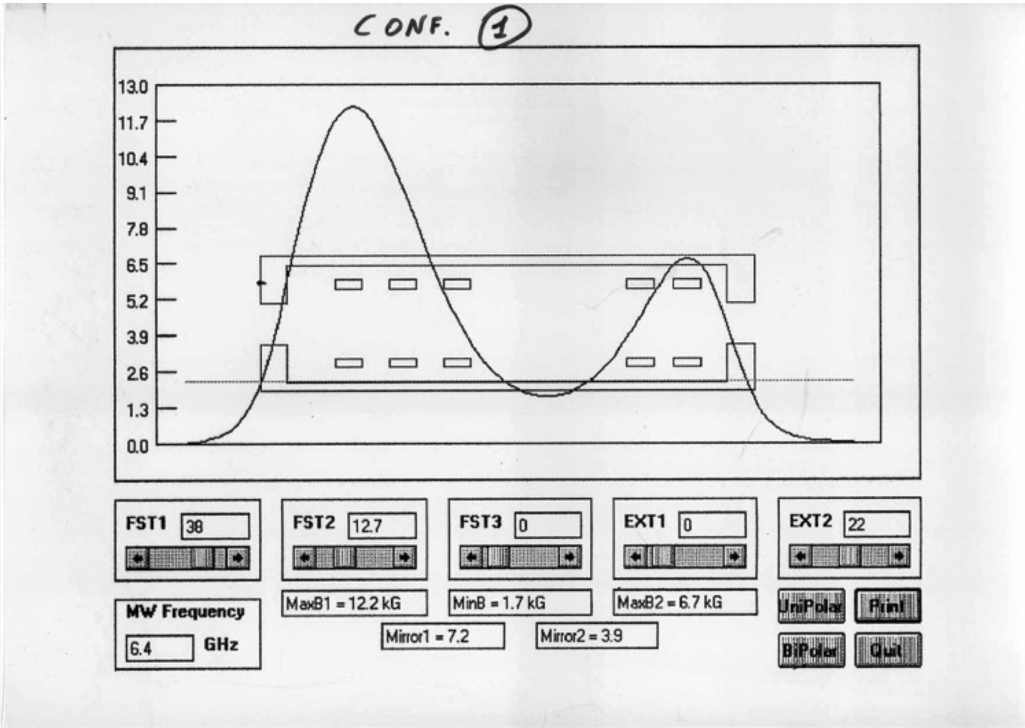
Designed for 6 and 14 GHz

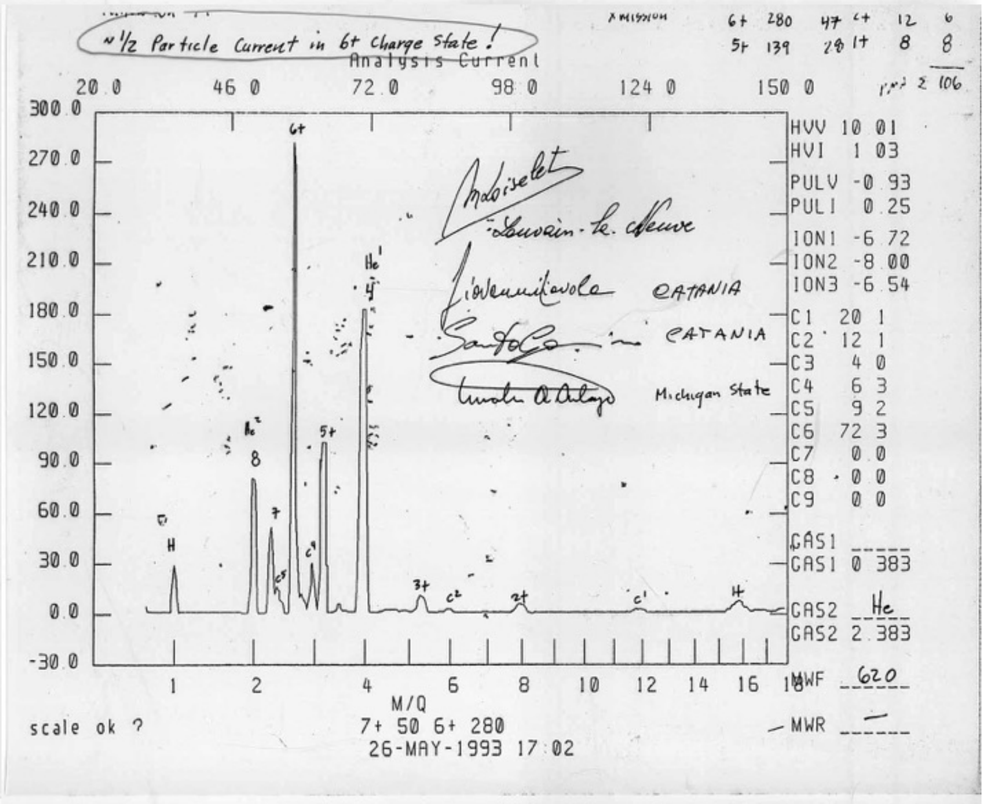
High B-mode demonstration at 6.4 GHz
(Gammino, Ciavola, Antaya, Loiselet)

Sextupole field too low for 14 GHz
(Quenching)




INJECTION
YOKE / CRYOSTAT
N_2 RADIATION SHIELD
He BOBBIN
HEXAPOLE COILS
SOLENOID COILS
1ST STAGE
2ND STAGE
MICROWAVE FEED
RADIAL SUPPORT
LINKS
EXTRACTION
EXTRACTION ELECTRODES


CONF. 1
13.0
11.7
10.4
9.1
7.8
6.5
5.2
3.9
2.6
1.3
0.0
FST1 38
FST2 12.7
FST3 0
EXT1 0
EXT2 22
MW Frequency
6.4 GHz
MaxB1 = 12.2 kG
MinB = 1.7 kG
MaxB2 = 6.7 kG
Mirror1 = 7.2
Mirror2 = 3.9
UniPolar
Print
BiPolar
Quit


~1/2 Particle Current in 6+ Charge State!
Analysis Current
6+ 280
5+ 139
20.0
46.0
72.0
98.0
124.0
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300.0
270.0
240.0
210.0
180.0
150.0
120.0
90.0
60.0
30.0
00.0
-30.0
HVV 10.01
HVI 1.03
PULV -0.93
PULI 0.25
ION1 -6.72
ION2 -8.00
ION3 -6.54
C1 20.1
C2 12.1
C3 4.0
C4 6.3
C5 9.2
C6 72.3
C7 0.0
C8 0.0
C9 0.0
GAS1
GAS1 0.383
GAS2 He
GAS2 2.383
MWF 620
MWR
Louvain-la-Neuve
CATANIA
CATANIA
Michigan State
1
2
4
6
8
10
12
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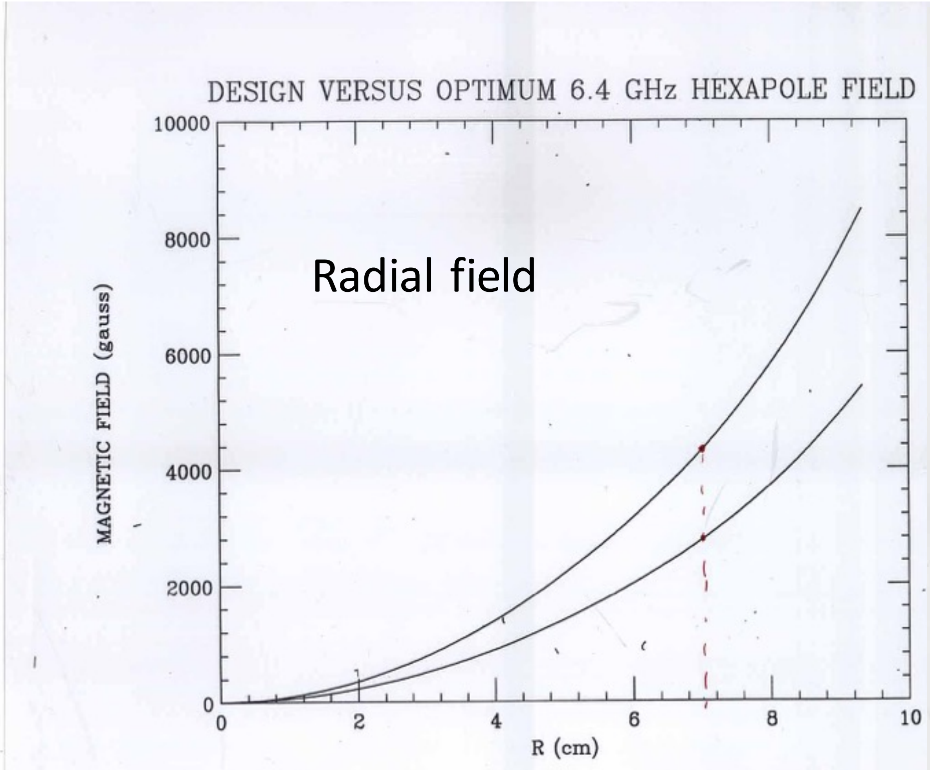
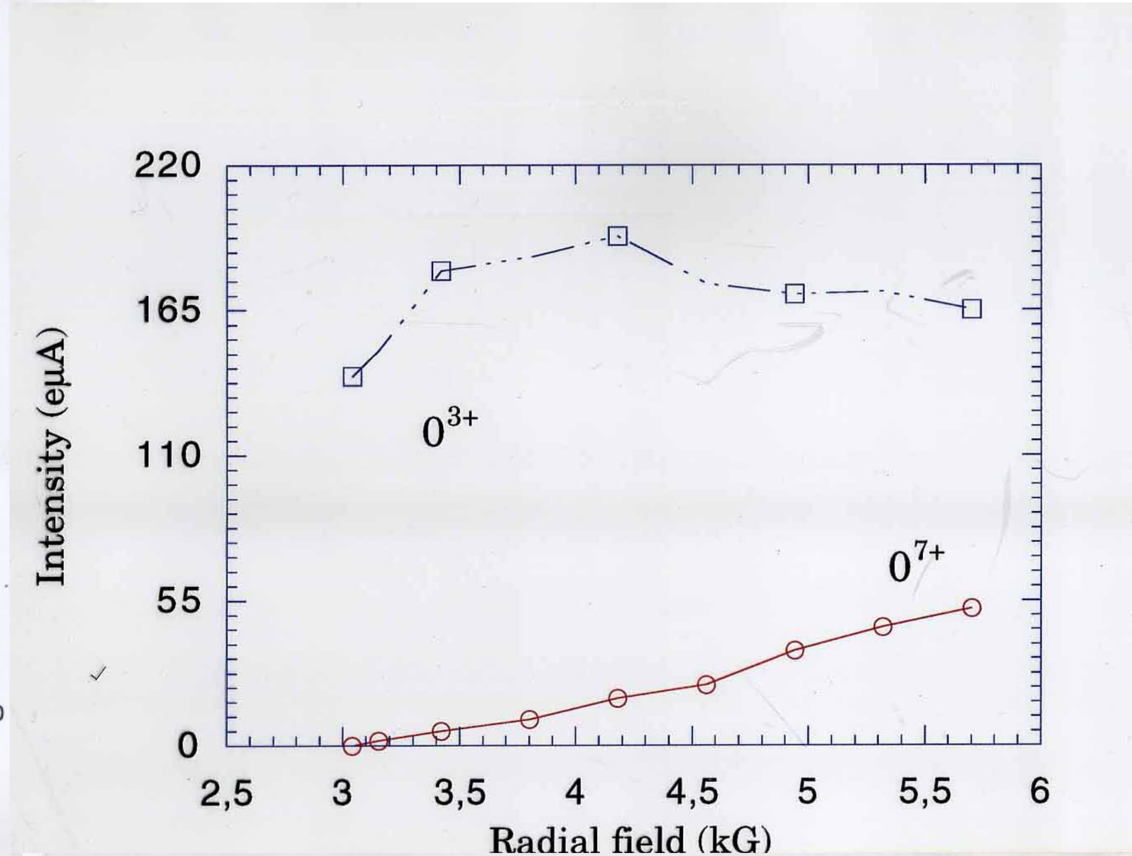
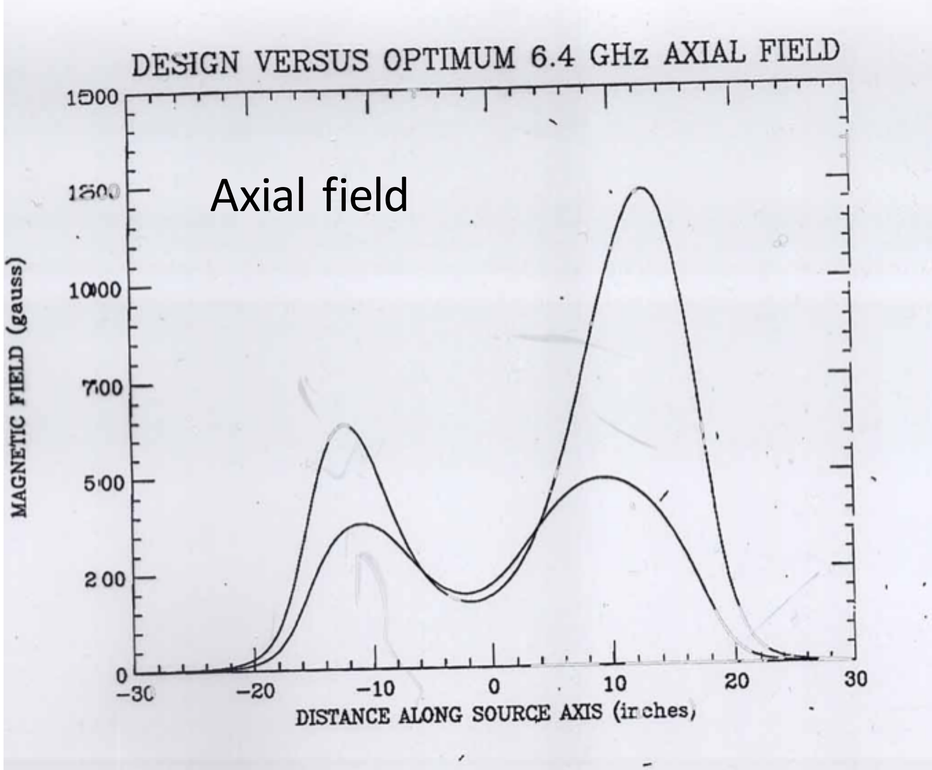
16
18
M/Q
scale ok ?
7+ 50 6+ 280
26-MAY-1993 17:02







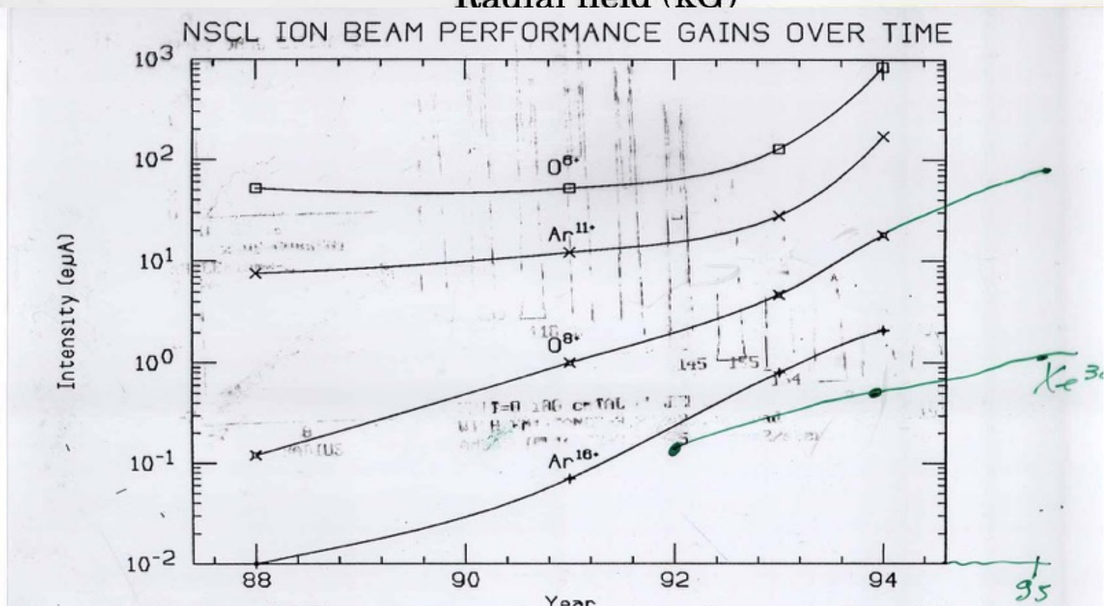
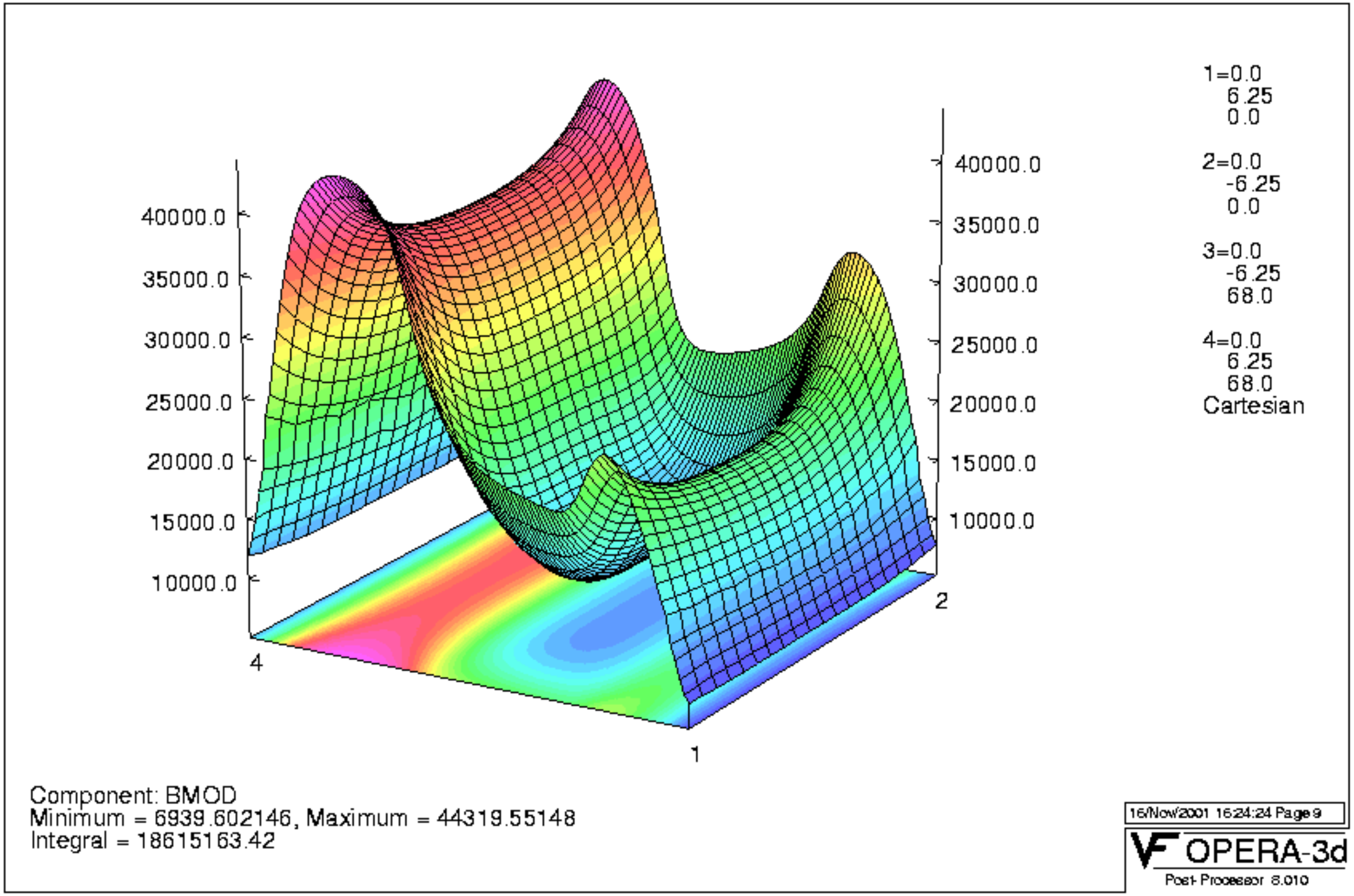


Figure 1.2: The best NSCL performance for several ions from a number of developments tracked for several years.

ECRIS magnetic structure

The necessity of the minimum B structure



Proceedings of the 14th International Conference on Cyclotrons and their Applications, Cape Town, South Afric

ECR ION SOURCES AND SCALING LAWS

S. GAMMINO, G. CIAVOLA

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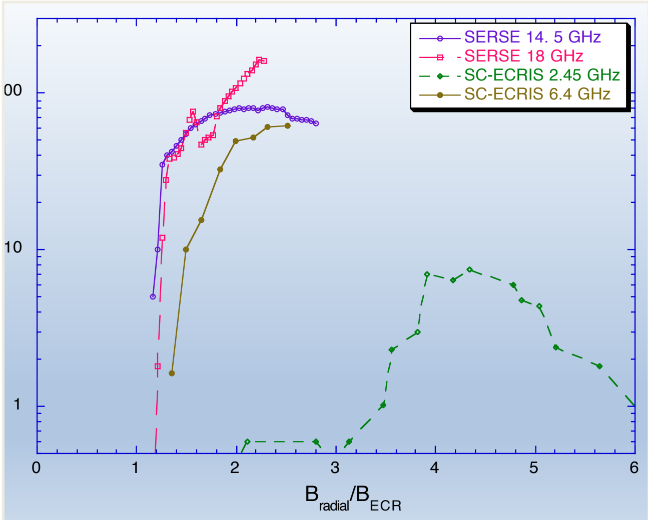
The development of Electron Cyclotron Resonance (ECR) ion sources has been continuous during twenty years but the knowledge of the laws which determine their behaviour is not yet complete. In 1987 a list of tentative scaling laws was proposed by Geller and coworkers[1] and for a few years these semiempirical laws have been the guidelines for the design of new ECR sources and the improvement of the existing ones.
In order to prove or to reformulate these laws, we have made some systematic tests on the superconducting source SC-ECRIS at the National Superconducting Cyclotron Laboratory of the Michigan State University, devoted to the definition of the role of different parametres which determine the performance of ECR sources.
The results of such tests and the conclusions which we have drawn will be outlined, with particular attention on the role of the confining magnetic field.
A fundamental parameter appears to be the ratio of particle pressure to magnetic pressure, $\beta = n_e k T_e / (B^2/2\mu_0)$, which has been decreased in order to obtain a stable plasma, by increasing the confining field in each direction.



The superconducting electron cyclotron resonance 6.4 GHz high-*B* mode and frequency scaling in electron cyclotron resonance ion sources[a)]

T. A. Antaya
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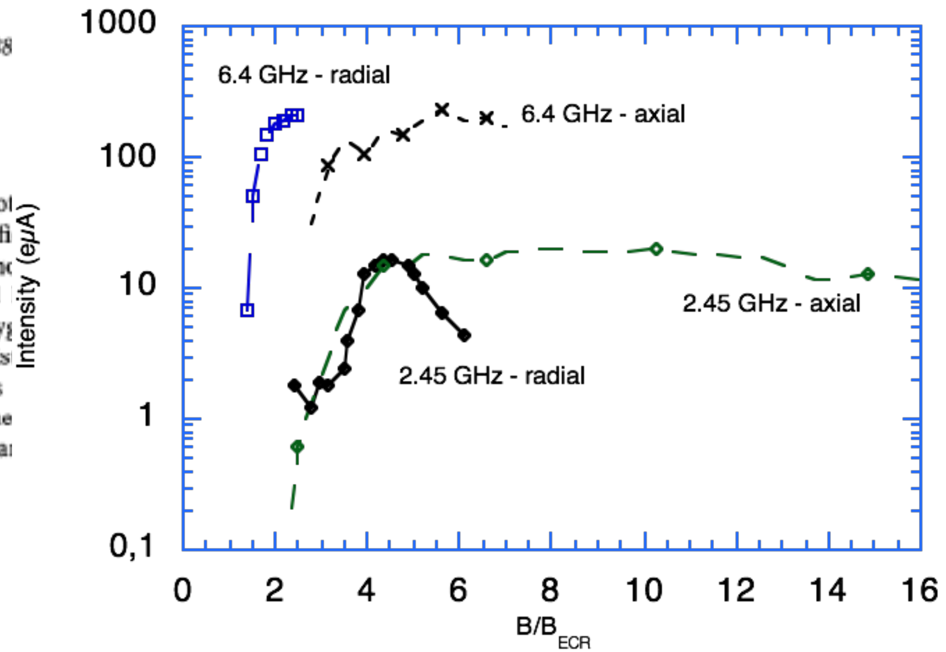
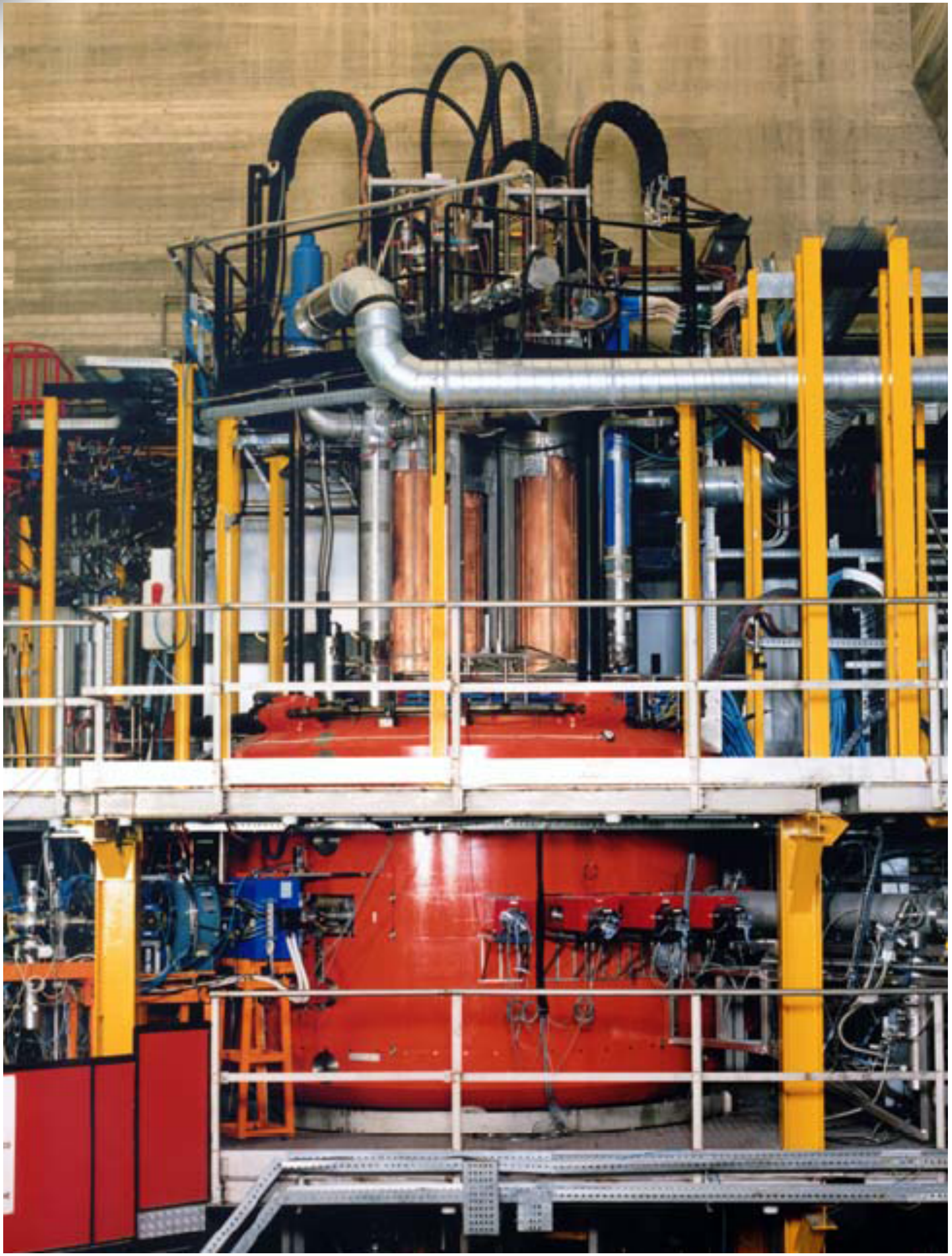
(Received 31 August 1993; accepted for publication 30 September 1993)

We would like to present the initial results and description of the superconducting electron cyclot resonance ion source (SCECR) operating in the high-*B* mode—a new high magnetic fi low-frequency mode of operation. First, we describe the operating characteristics of this mc which include very high mirror confinement in all directions, yet having a minimum field enough for electron cyclotron resonance heating of 6.4 GHz. The source performance for oxy neon, argon, krypton, and xenon is presented and comparisons are made with several exis high-performance ECR sources. In this high-*B* mode the SCECR matches or exceeds performance of all existing ECR sources. These results perhaps invalidate the classical freque squared source performance scaling law, and suggest the new possibility of high-performa low-frequency (and hence low cost) sources as will be discussed.





LNS Superconducting Cyclotron	
Bending limit	K=800
Focusing limit	Kfoc=200
Pole radius	90 cm
Yoke outer radius	190.3 cm
Yoke full height	286 cm
Total weight	176 tons
Min-Max field	2.2-4.8 Tesla
Main coil At	$6.5\ 10^6$
Sectors	3
Min. hill gap	8.6 cm
Max valley gap	91.6 cm
Trim coils	20
Dees	3
RF range	15-48 MHz
Oper. Harmonics	1,2,3,4
Peak dee voltage	100 KV

SERSE installation at LNS

1994

Contract with Ansaldo for the B-min trap superconducting magnet

1995-96

Poor performance of the Ansaldo magnetic system, new order to ACCEL; construction of the other components of the source.

1997

Successful operation on the CEA testbench

1998

March: end of developments at the testbench, preparation to transfer

May 11th, boxes on the truck, I declare to CEA colleagues that we will install at LNS in one month: smiles and laugh…

May 14th SERSE arrives at LNS

June 13th - St. Anthony day - SERSE first plasma (miracle of LNS technical staff)

SERSE @ LNS

SERSE typical currents at 18GHz (1997-2000)

O6+	540	Kr22+	66	Au30+	20
O7+	208	Kr25+	35	Au31+	17
O8+	62	Kr27+	7.8	Au32+	14
Ar12+	200	Kr29+	1.4	Au33+	12
Ar14+	84	Kr31+	0.2	Au34+	8
Ar16+	21	Xe27+	78	Au35+	5.5
Ar17+	2.6	Xe30+	38.5	Au36+	2.5
Ar18+	0.4	Xe31+	23.5	Au38+	1.1
Kr17+	160	Xe33+	9.1	Au39+	0.7
Kr18+	137	Xe34+	5.2	Au40+	0.5
Kr19+	107	Xe36+	2	Au41+	0.35
Kr20+	74	Xe38+	0.9	Au42+	0.03

28 GHz operations 1 μA Xe42+, 8 μA Xe38+, 100 μA Xe30+

CAESAR installation at LNS

1997

SERSE is on the good track, but CS needs another ECRIS, as a working horse → commercial one (Hypernanogan) but with many improvements

1998

Call for tender and construction

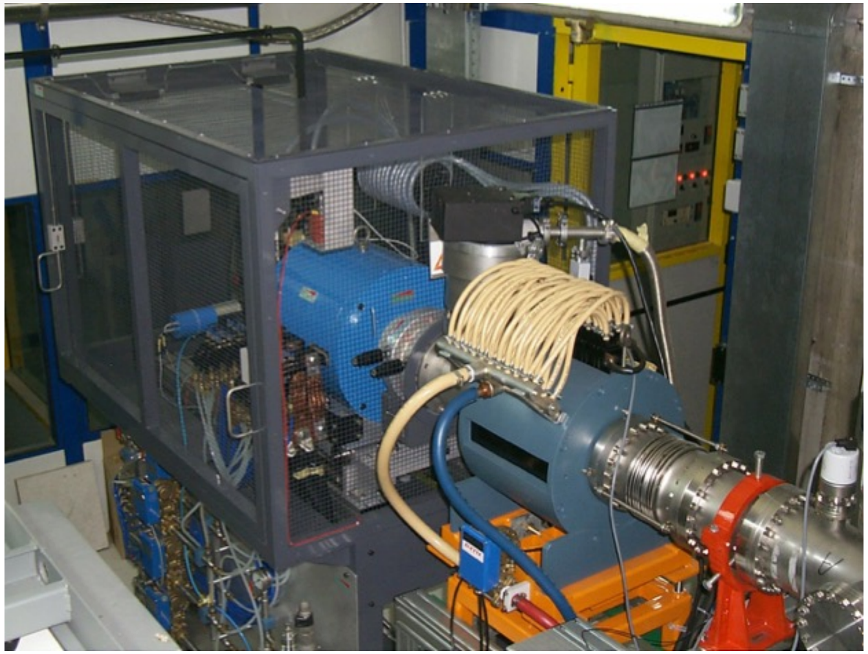
1999

CAESAR in operation at LNS

2000

CAESAR (and SERSE) coupled to the CS

CAESAR for EXCYT



N5+	515	Ne7+	230	Ar16+	2
N6+	160	Ne8+	170	Ca12+	52
15N7+	25	Ne9+	14	Ni17+	18
O6+	720	Ar11+	120	Kr28+	1
O7+	105	Ar14+	10	Ta27+	10

Operating frequency	14 and 18 GHz
Maximum radial field on the wall	1.1 T
Maximum axial field (injection)	1.58 T
Maximum axial field (extraction)	1.35 T
Minimum axial field	0.4 T
Hexapole	NdFeB made 1.1 T
Extraction system	Accel-decel, 30 kV/12 kV max
Plasma chamber	St. steel or Al made

Catana: eye tumours protontherapy facility required beam current stability, high reliability and reproducibility

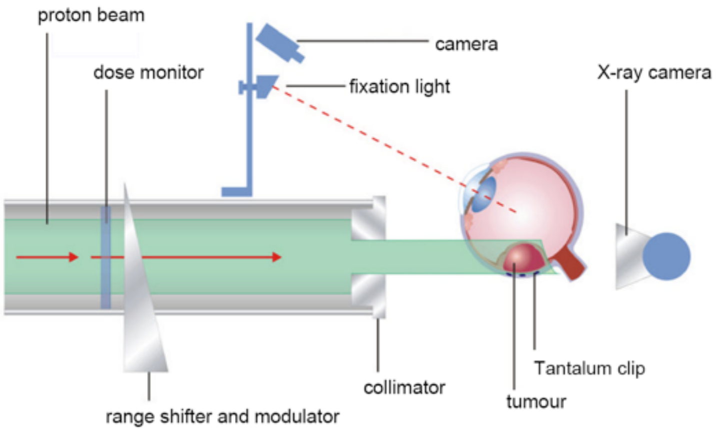
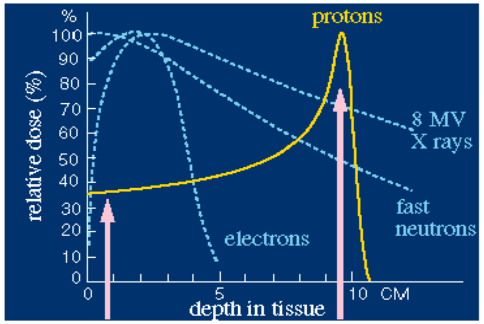
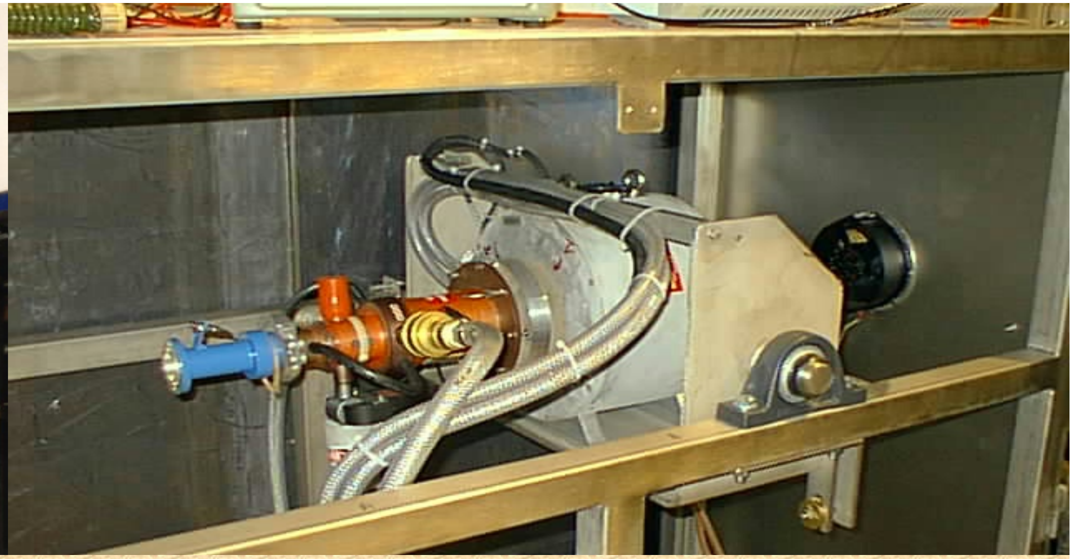


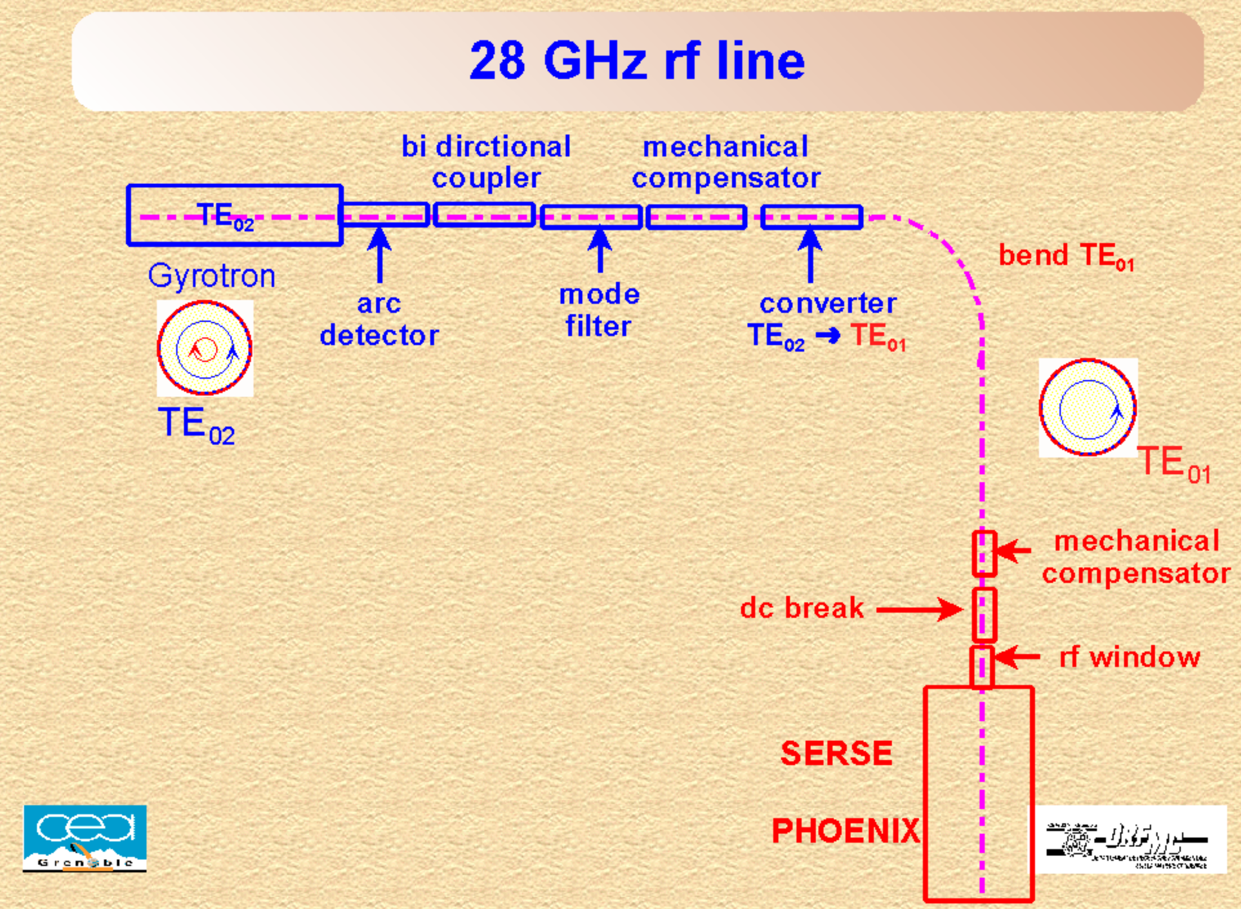
Figure 6: Principle of the irradiation The range shifter and the modulator wheel are represented by the range modulator.



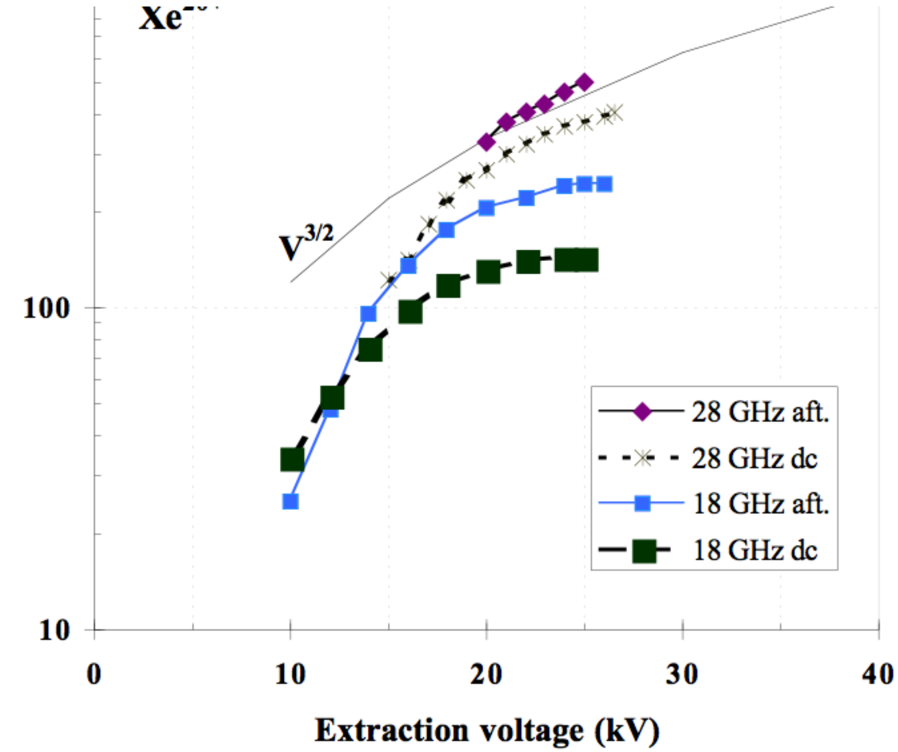
- **>350 patients treated (since Feb. 2002)**
- **uveal melanomas**
- **conjunctival melanoma**
- **other malignancies (orbital RMS, non-Hodgkin Lymphoma, various metastases)**
- **Follow-up: 95% of success**

5 sessions on average per year

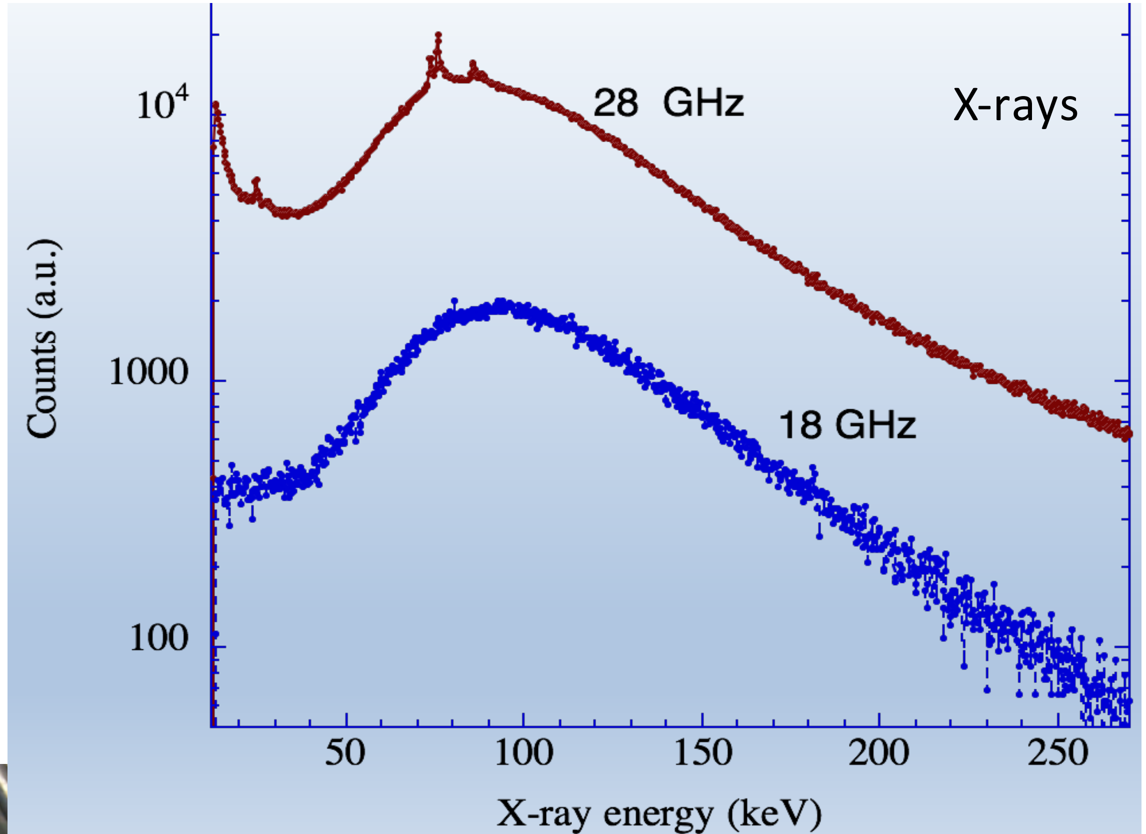




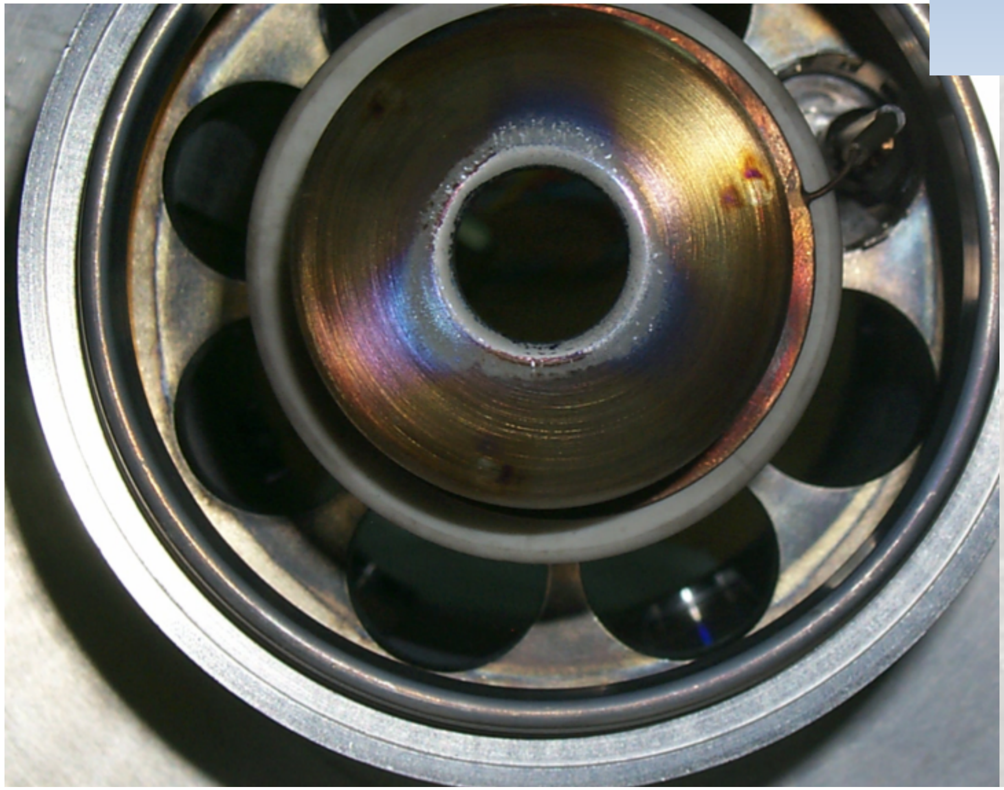
INFN-CEA experiment
(5th Framework Programme)

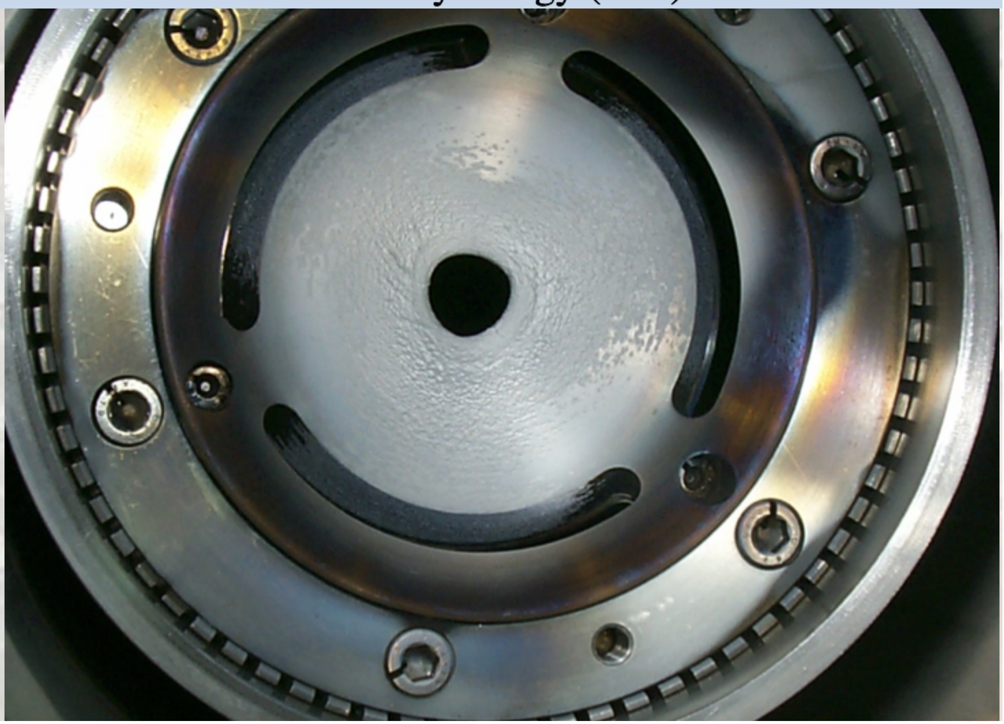


Xe
V3/2
100
10
0
10
20
30
40
Extraction voltage (kV)
28 GHz aft.
28 GHz dc
18 GHz aft.
18 GHz dc

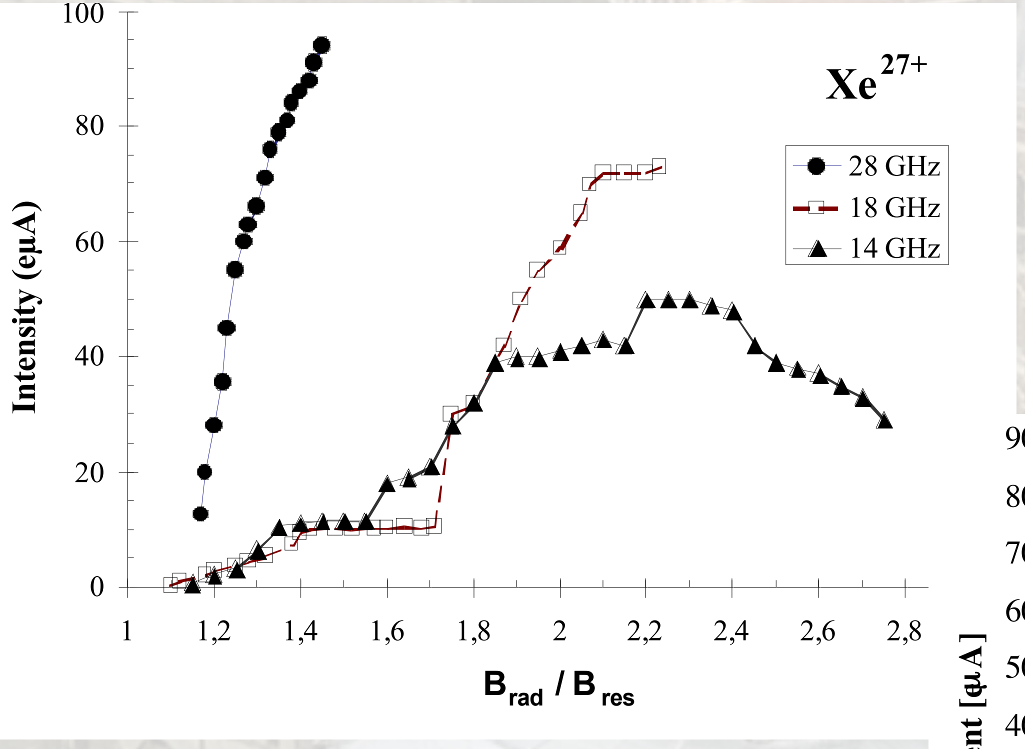


10^4
1000
100
Counts (a.u.)
28 GHz
X-rays
18 GHz
50
100
150
200
250
X-ray energy (keV)





Some experimental 'strange' data

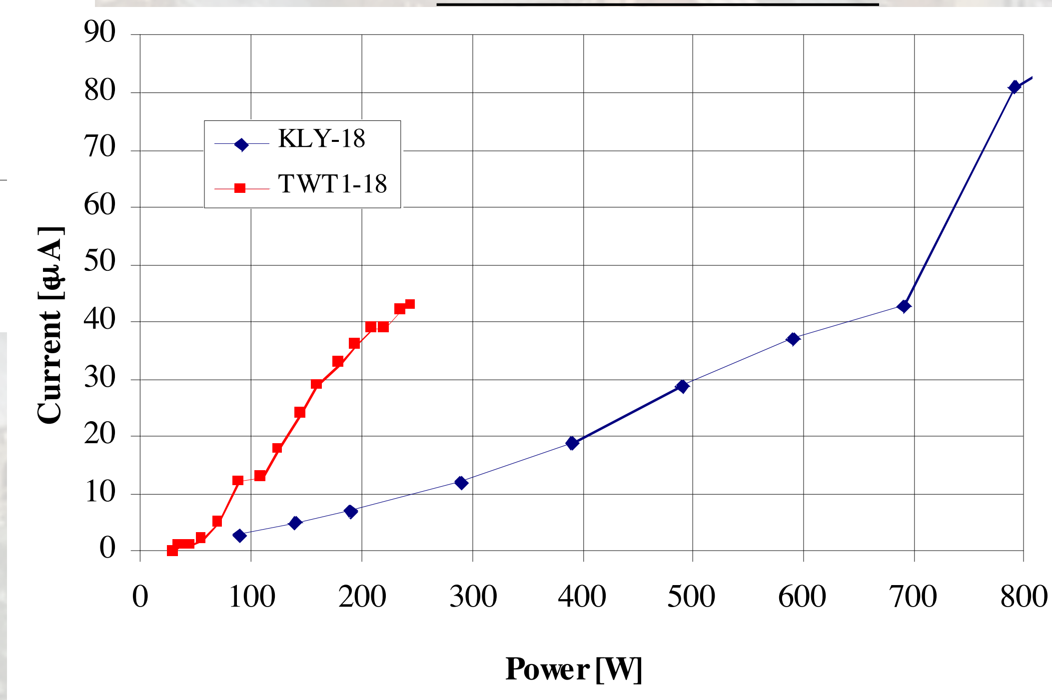


SERSE

Aug-Sept. 2000

SERSE

2001 & 2003



A. Galatà, MSc. Thesis (Oct. 2003)

Overcoming the current limits of ECRIS

Roadmap indicated by the ECR Standard Model:

- High Frequency Generators;
- High Magnetic Fields;

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

By quickly replacing the hot electrons lost for insufficient confinement we can increase the Electron Density, the heating rapidity and finally the main part of the energy content, i.e. $n_e kT_e$

$$\langle q \rangle \sim n_e \tau_i$$

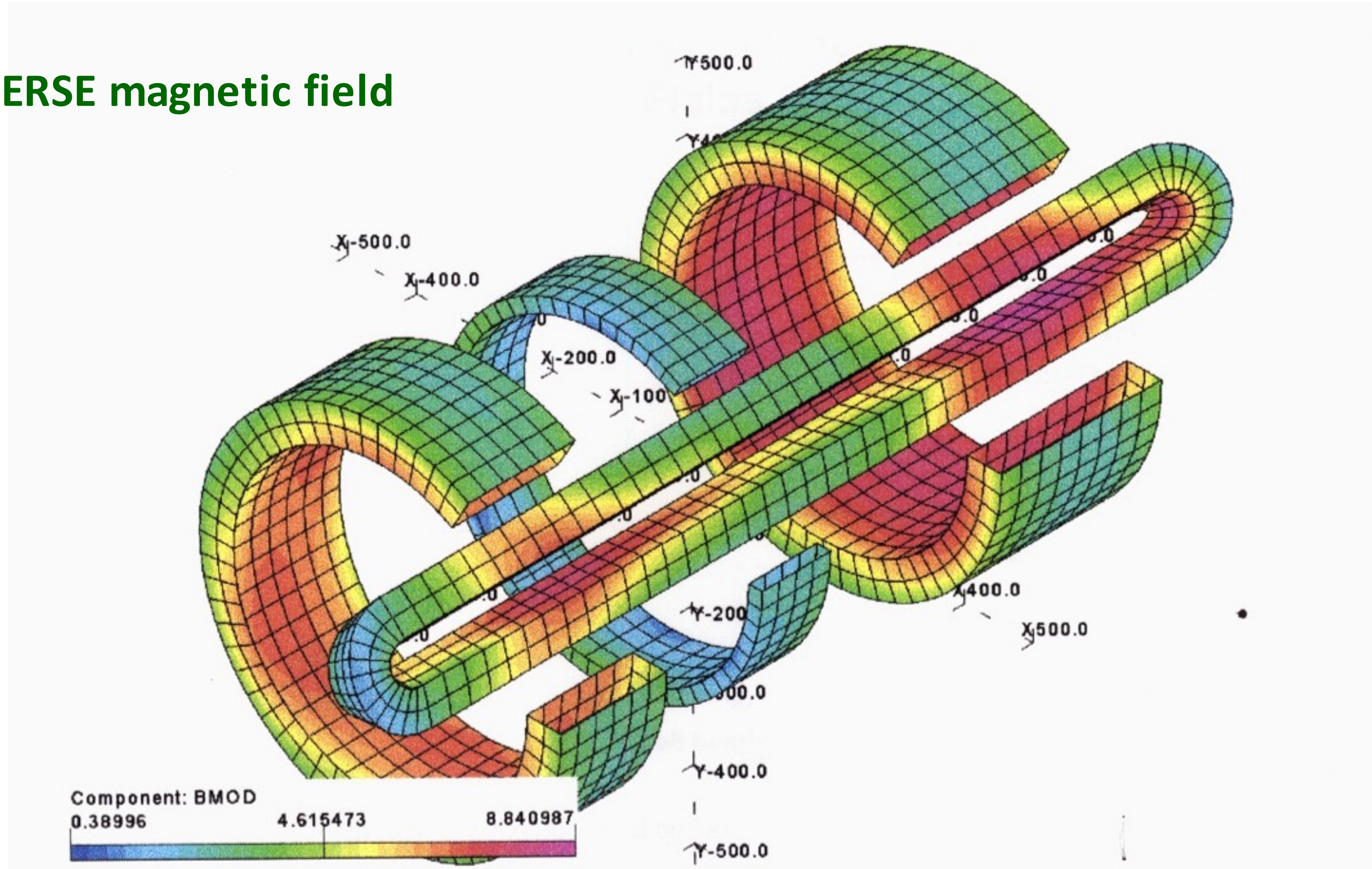
$$I \sim n_e / \tau_i$$

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

1994 Eur. Cycl. Prog. Meet., Dubna:

scaled version of SERSE for 28 GHz was presented ("gyroSERSE") but scaling laws for magnetic field and frequency were still questionable.

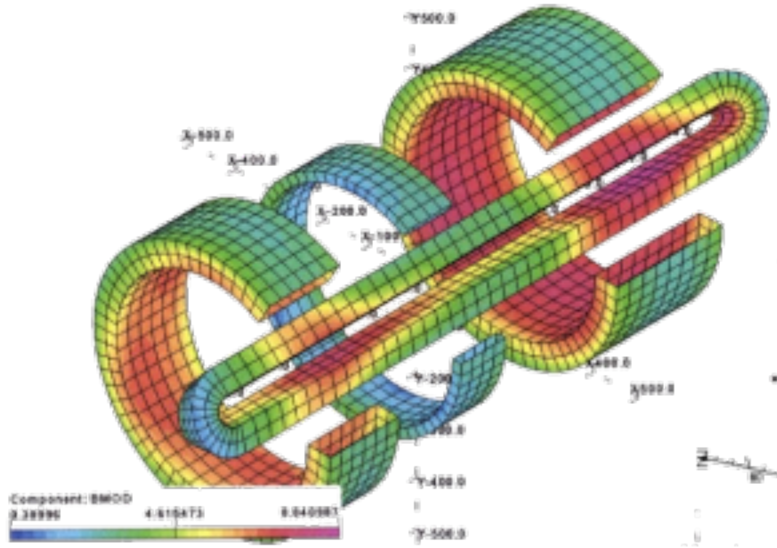
GyroSERSE magnetic field

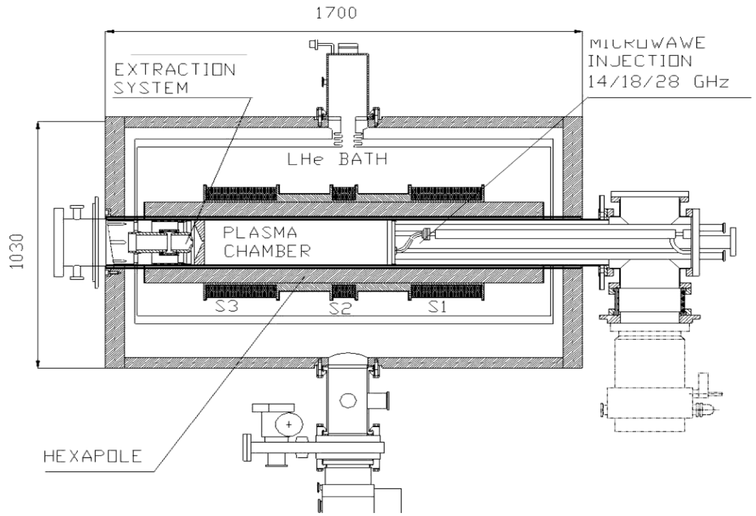


Assembled coil arrangement (constant perimeter with coil heigh 60 mm). The conductor surfaces are coloured according to the absolute value of the flux density. Five sextupole coils are omitted for a better view.

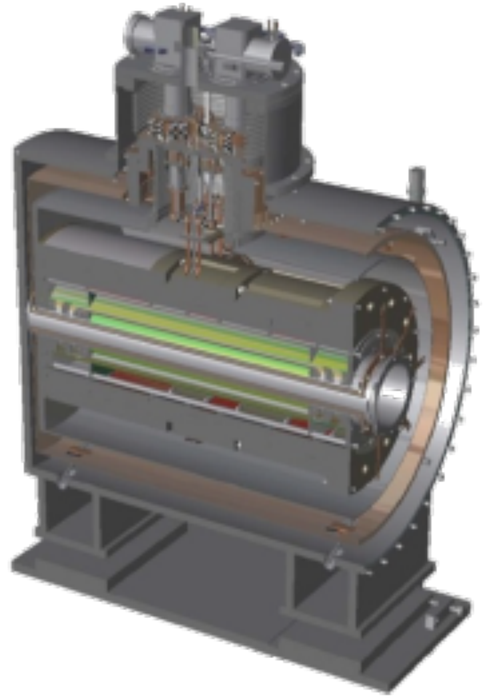
Steps towards III generation sources

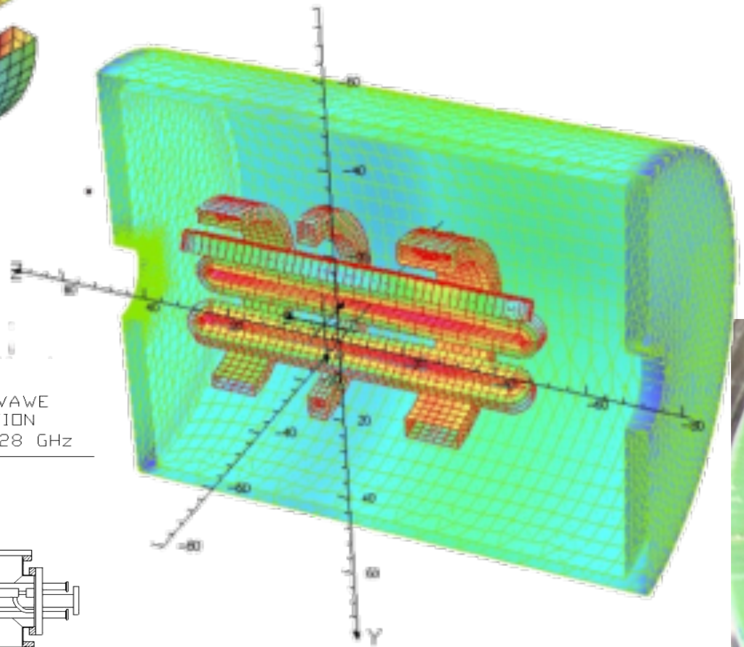
From Gyro-SERSE (bridging Scaling Laws to 28GHz operations)…

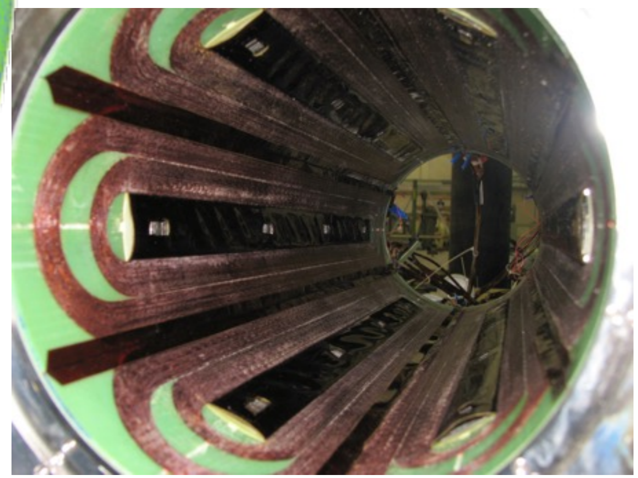




…to MS-ECRIS (2005): the first attempt of a B-min trap suitable for 28 GHz. No mature technology for SC magnets at that time: end of the story ?







Evidences

- *LUCKY ACCIDENTS + TECHNOLOGICAL IMPROVEMENTS + STUDY OF PLASMA PHYSICS*
- *→ now something more is necessary and plasma diagnostics to check numerical simulation is a key element for the next progress.*

- The microwave coupling to plasma cannot be managed in terms of 'brute force'.
- The position of the waveguide and the matching give different results either in terms of available beam current and (more important) in terms of beam emittance.
- To have bright beams, we need to optimize the microwave coupling, not to increase the power.
- To improve ECRIS performance, we need to know better how they work.

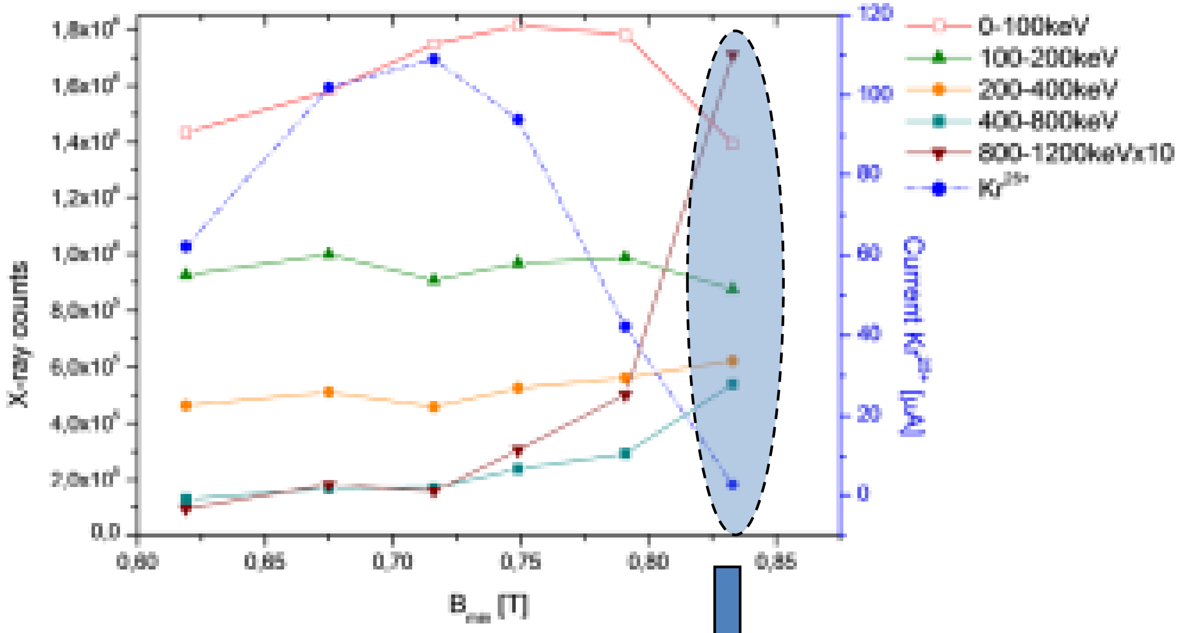
The "prophecy" of Richard Geller

Already in 1990 Geller, who was the "father" of ECRIS, underlined the importance of plasma physics for future improvements of the source performances:

> *We want to show that without a minimum of plasma science no progress is possible in ECRIS and probably also in other source development.*
>
> *R. Geller*

Experimental Results on magnetic scaling on VENUS

Analysis of CSD for Krypton (left) and counts integrals of emitted X-rays at different energy intervals (right)

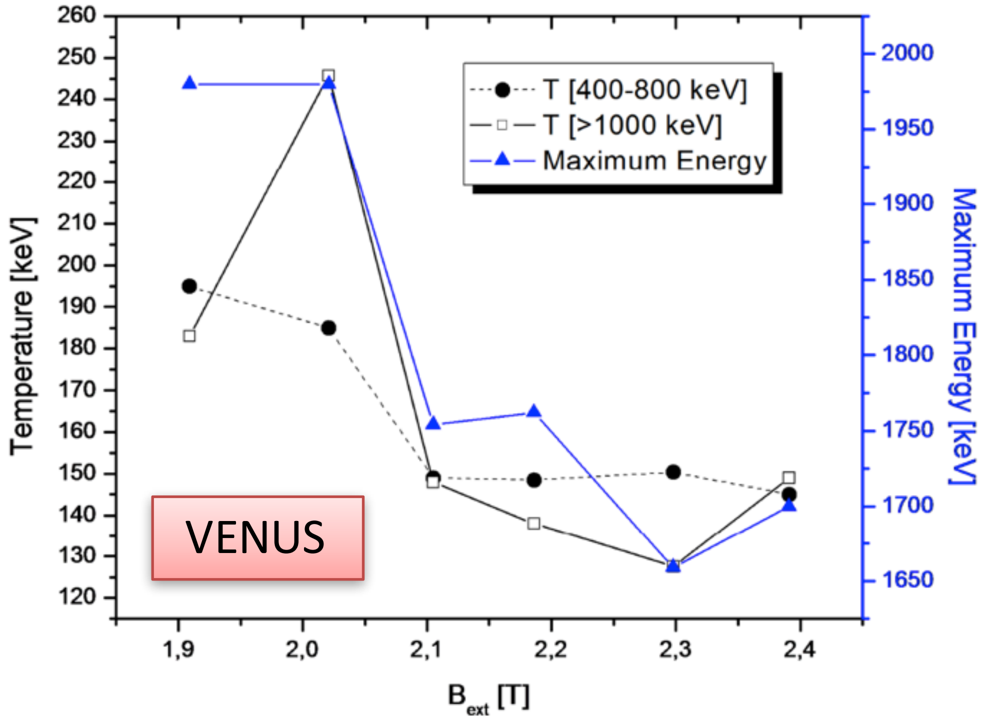


The number of X-rays above 400 *keV* strongly increases with B_{min} (i.e. reducing the mirror ratio).

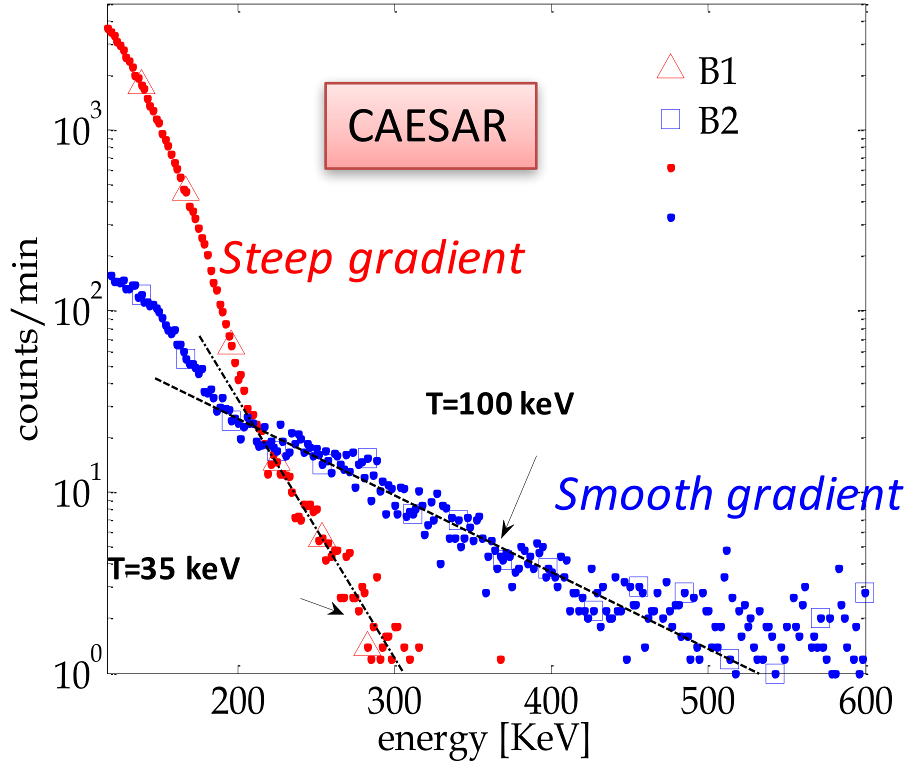
The CSD trend and the production of high energy electrons are strictly connected

Magnetic field impact on plasma temperature

Slight variations of B are critical for hard-X rays generation
(exp. with VENUS@Berkeley, and CAESAR@INFN-LNS)



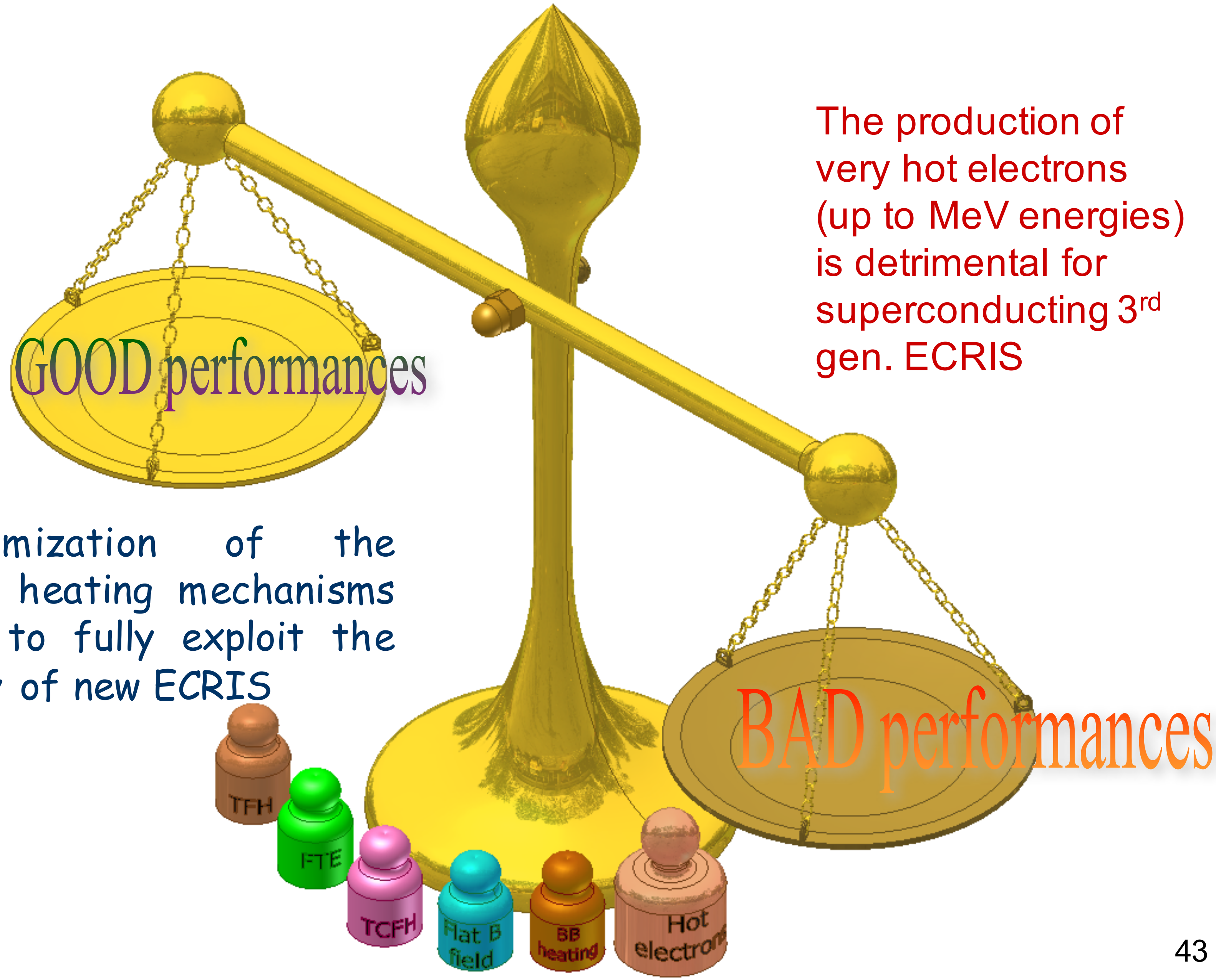
Hot tail electron temperature jump for different Bext values



Hot tail electron temperature jump for different gradients (for few % of changes) of the magnetic field

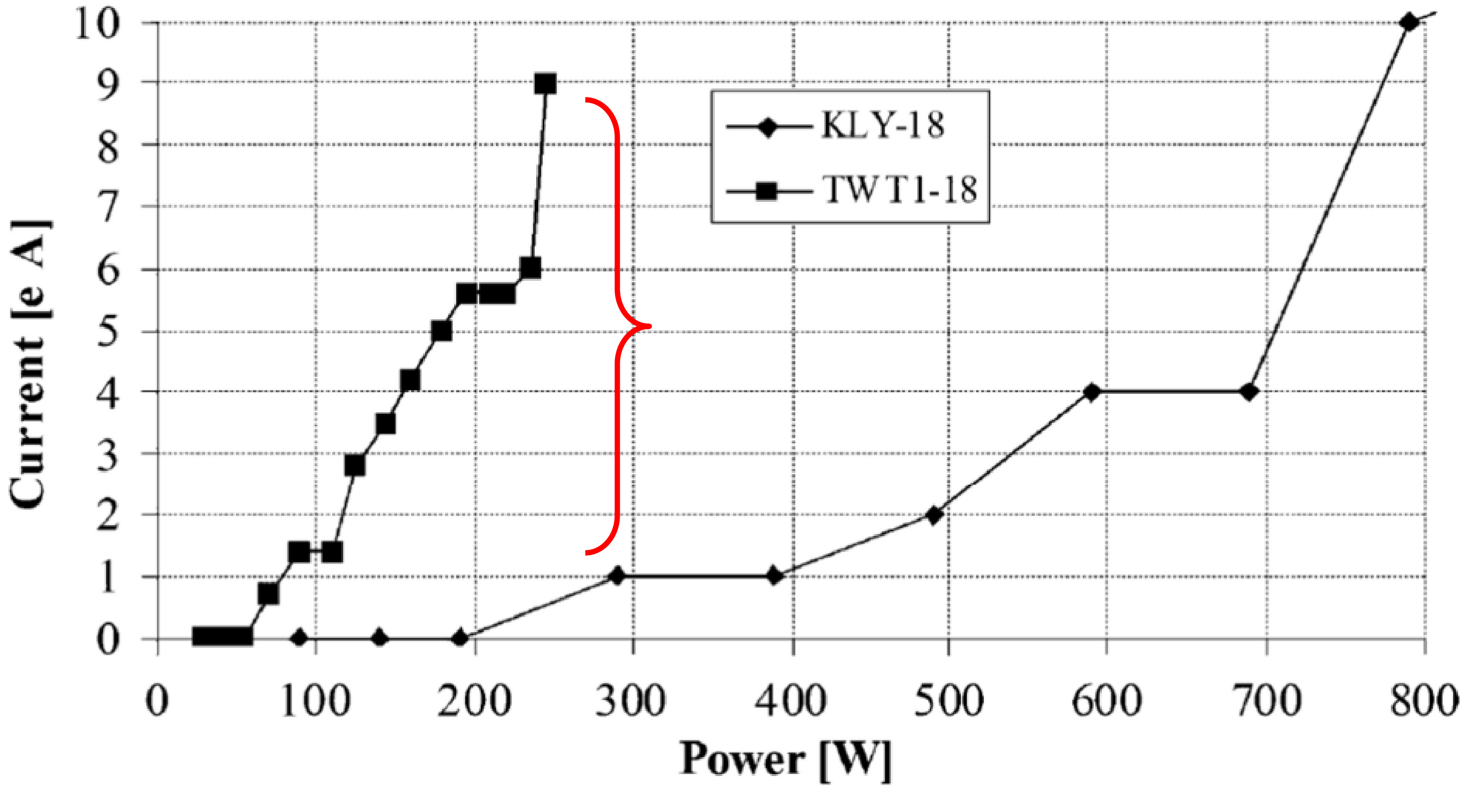
What we learn from the experiments at INFN- LNS and Berkeley ? Which tile is lacking to complete the mosaic?

The production of very hot electrons (up to MeV energies) is detrimental for superconducting 3rd gen. ECRIS



The optimization of the alternative heating mechanisms may allow to fully exploit the potentiality of new ECRIS

Signs about the importance of the frequency tuning effect came already in 2001-2004 from an experiment carried out on SERSE [L. Celona et al., ECRIS04]

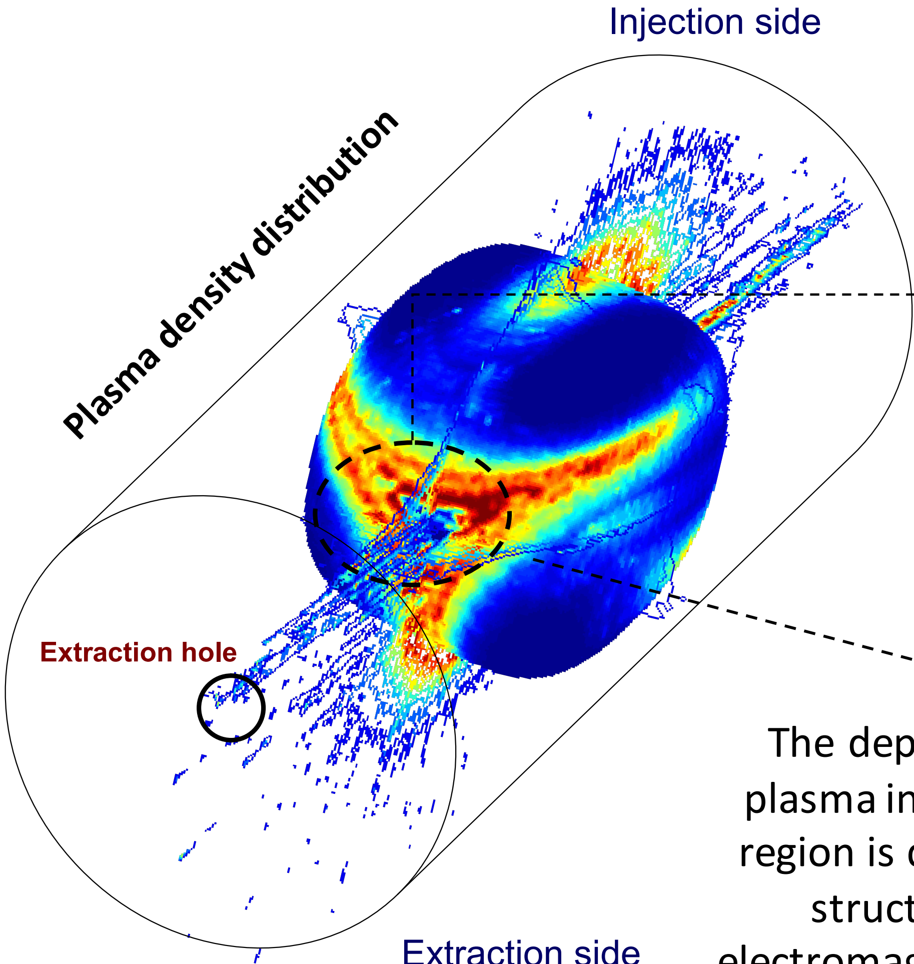


Comparison between trends of O^{8+} at 18 *GHz* for klystron (up to 800 W) and TWT1 operating in the same range of frequency.

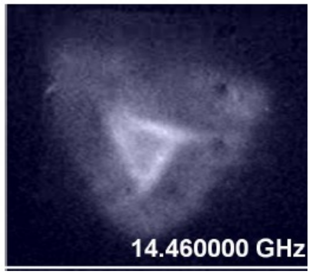
TWT worked better than klystron: why?

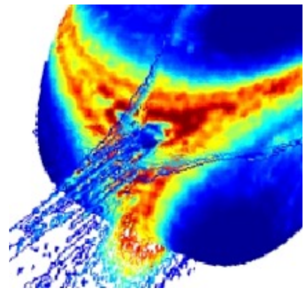
Explanation of Frequency Tuning Effect

impact on the ion beam structure

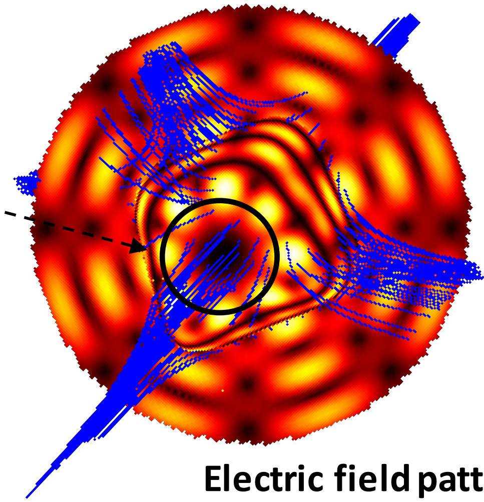


The density distribution explains why for some frequencies the beams appear hollow





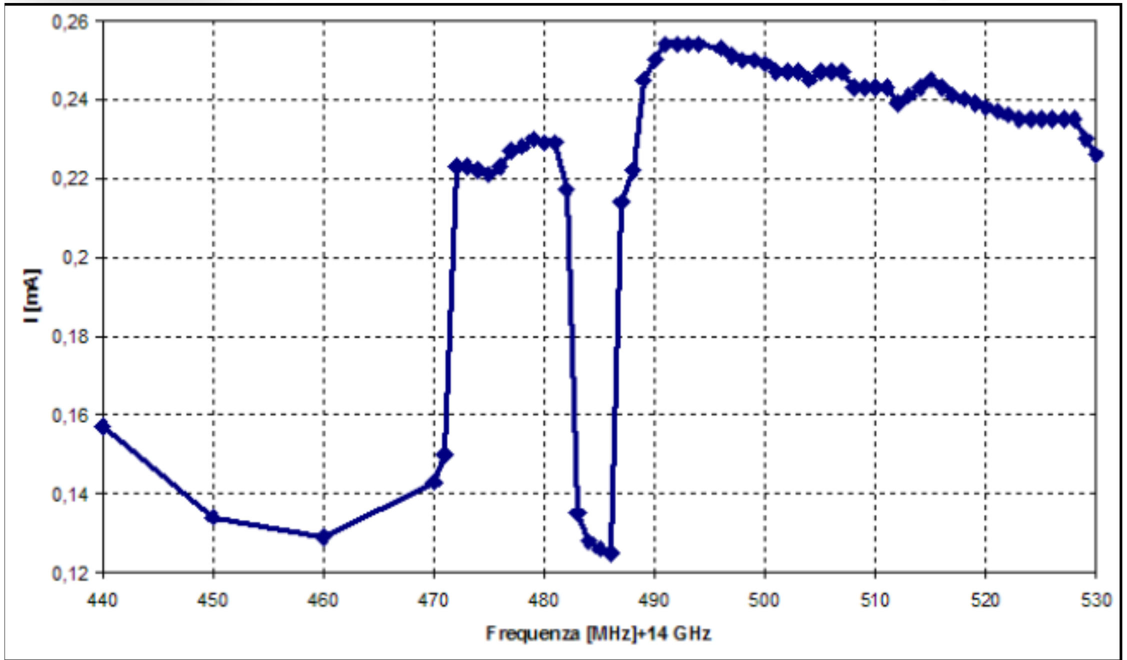
The depletion of plasma in near axis region is due to the structure of electromagnetic field.



Electric field pattern

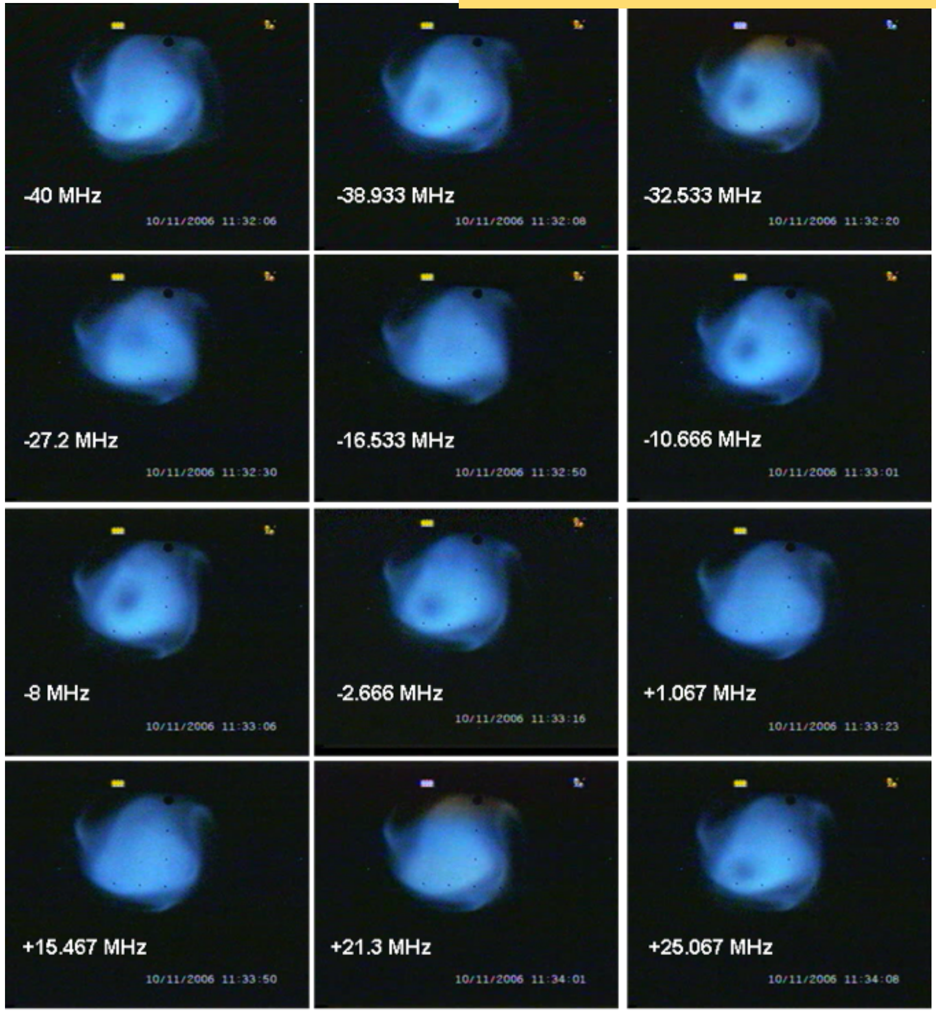
Frequency Tuning Effect

SUPERNANOGAN - CNAO
S. Gammino - July 2005



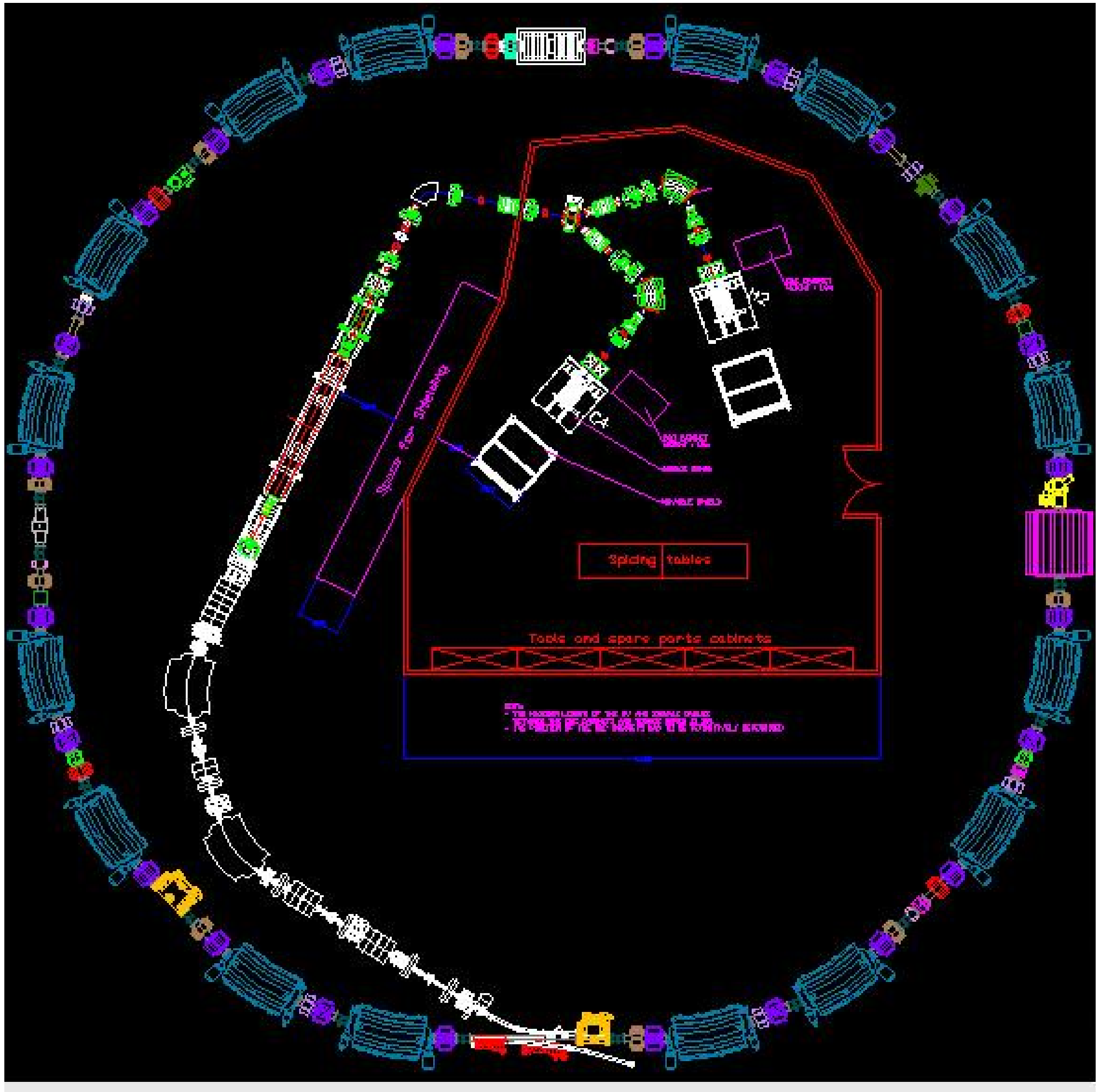
CAPRICE -GSI
fall 2006

L. Celona et al.



The Frequency Tuning strongly affects the beam shape and brightness

Frequency Tuning Effect was crucial for the achievement of CNAO request



CNAO layout

Modified SUPERNANOGAN

Contribution to CNAO: Centro Nazionale di Adroterapia Oncologica

ECRIS MAIN PARAMETERS

OPERATING FREQUENCY:

14.5 GHz (TWTA output: 400 W max.)

MAGNETIC FIELD GENERATED BY PERMANENT MAGNETS

- B_{inj} =1.2 T
- B_{ext} =1.1 T
- B_{rad} =1.2 T
- B_{min}=0.37 T

MAXIMUM EXTRACTION VOLTAGE:

30 kV (24 kV operating value)

ECR Ion Sources for CNAO

Ions	Current (requested) [μA]	Current (available) [μA]	After improvements by INFN-LNS [μA]	Emittance (requested) π mm.mrad	Emittance (new extractor) π mm.mrad	Stability [99,8%]
C^{4+}	200	200	250	0.75	0.56	36 h
H_2^+	1000	1000		0.75	0.42	2 h
H_3^+	700	600	1000	0.75	0.67	8 h
He^+	500	500		0.75	0.60	2 h

Major improvements

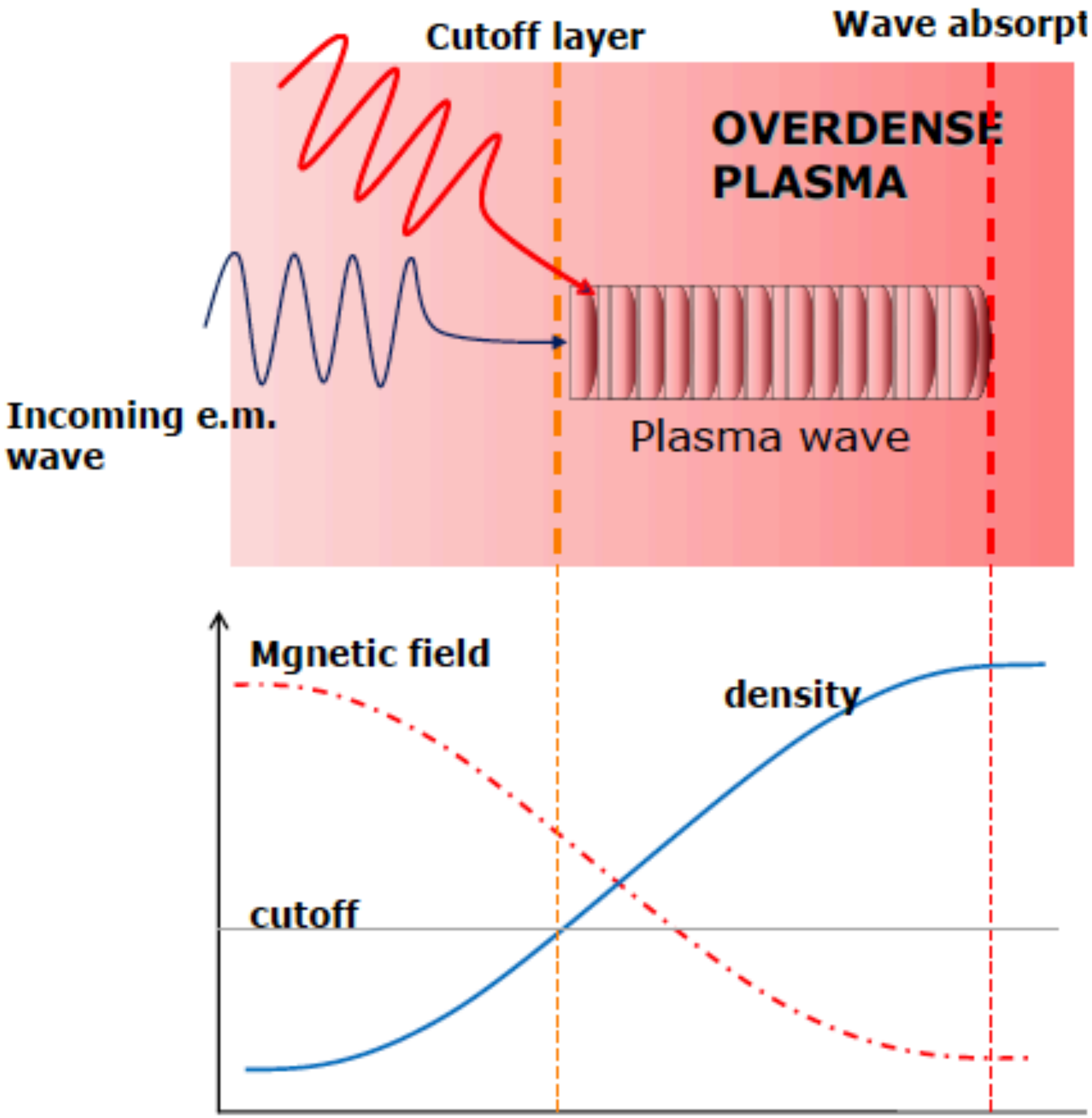
1) **Frequency tuning for the microwave injection: improvement to beam intensity and emittance (tested for the 1st time with HIT sources in July 2005)**
2) **New extraction system: improvement to beam emittance and stability**
3) **Changes to gas input system: much better stability**

Tuning of frequency allows plasma density optimization

critical limitation still remains: the cutoff density, limiting also nuclear fusion rate in Tokamaks and Stellarators

Towards a radically different plasma heating mechanism: Synergies and cross-fertilization with Fusion Research come again onto the scene

Generation of extremely overdense @3.76 GHz plasmas through EBW-heating in flat-B-field devices

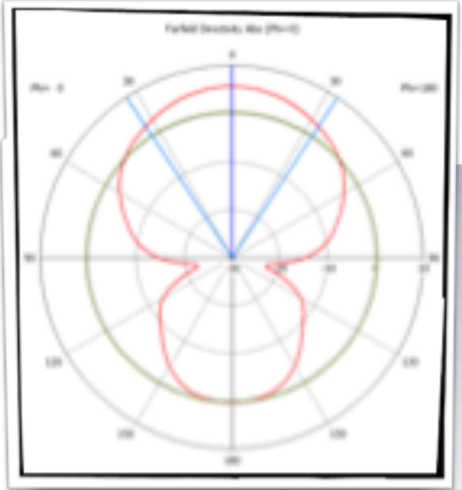


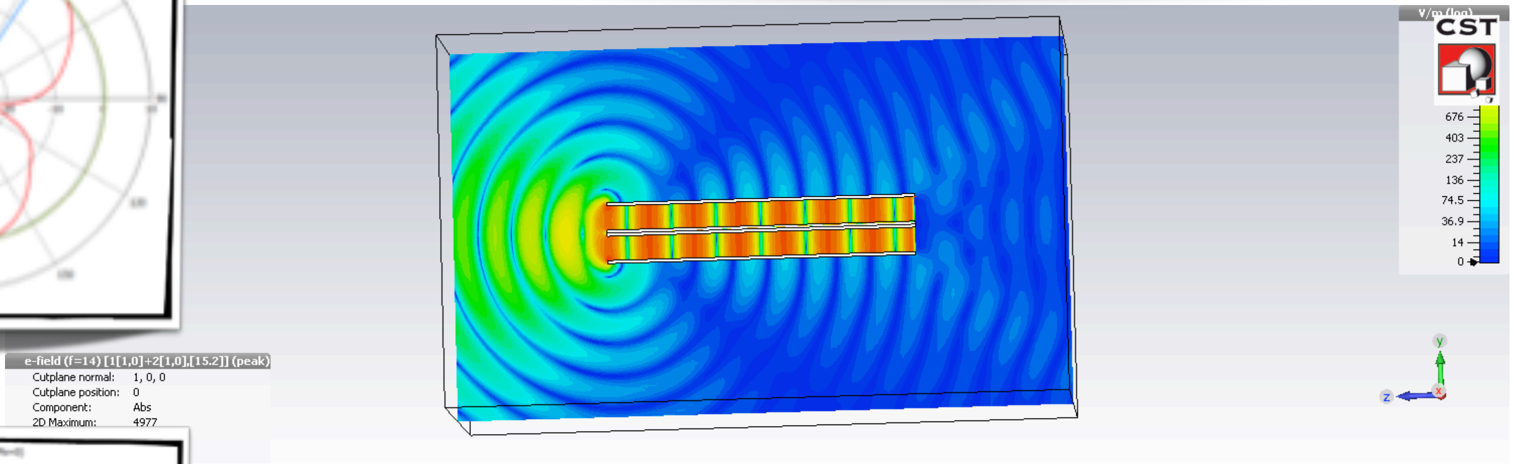
The overdense plasma is accessible only to plasma waves, that can be excited by pumping electromagnetic waves under proper injection properties

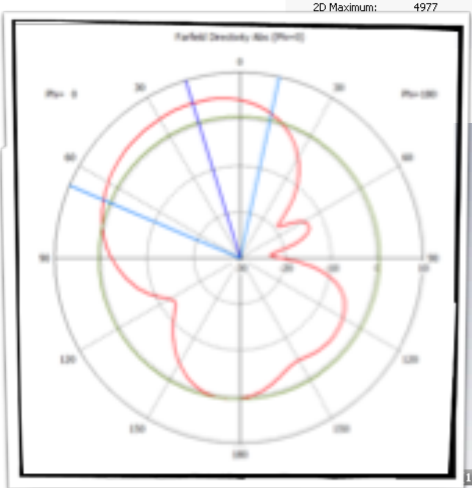
A new heating method has been attempted, modifying the magnetic field profile (double-beach structure) and providing an off-resonance discharge.

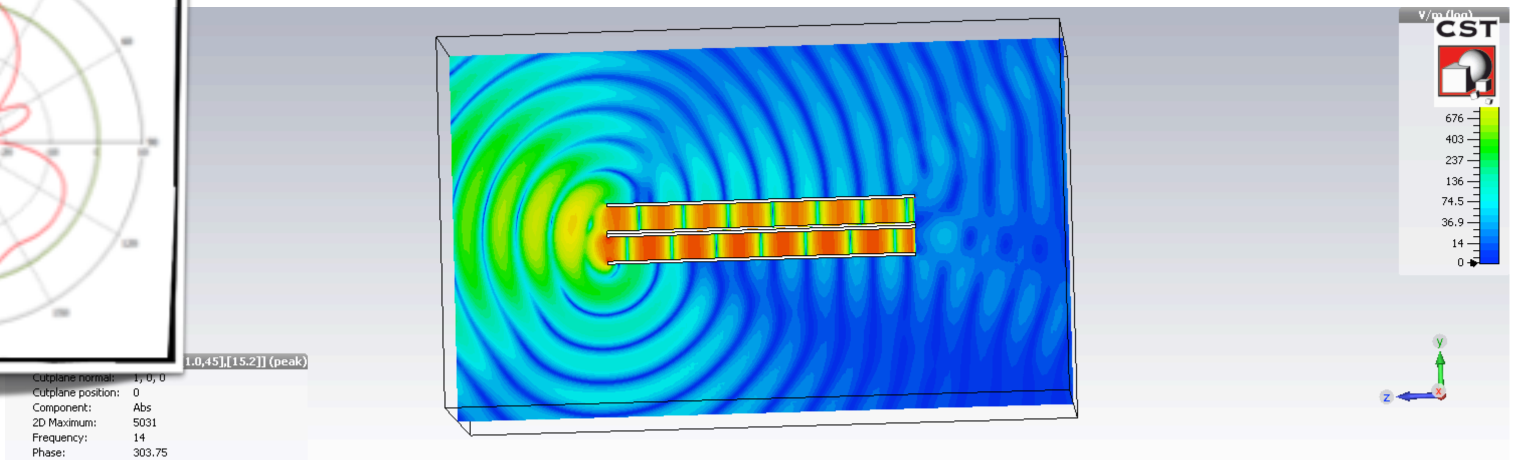
Optimization of EBW generation is possible via suitable microwave launching schemes

Launcher by "two-waveguides-array": lobe tilt by phase shift for otimizing oblique coupling of O-modes --> modal conversion

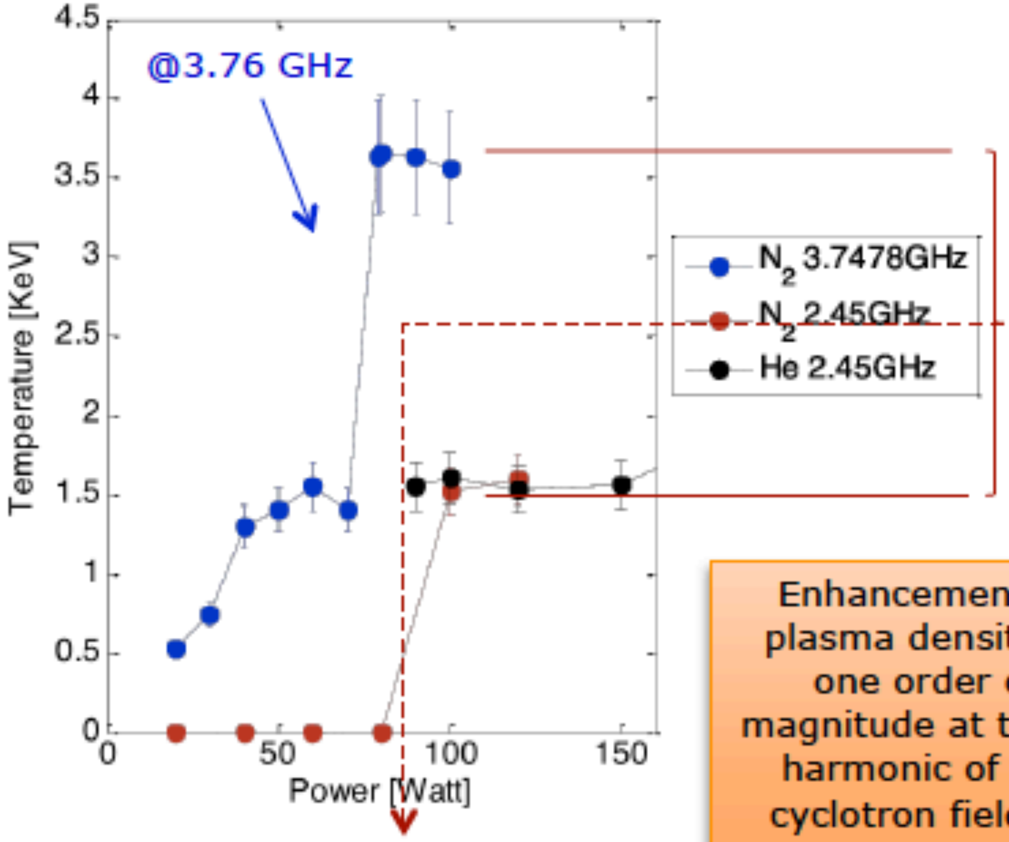




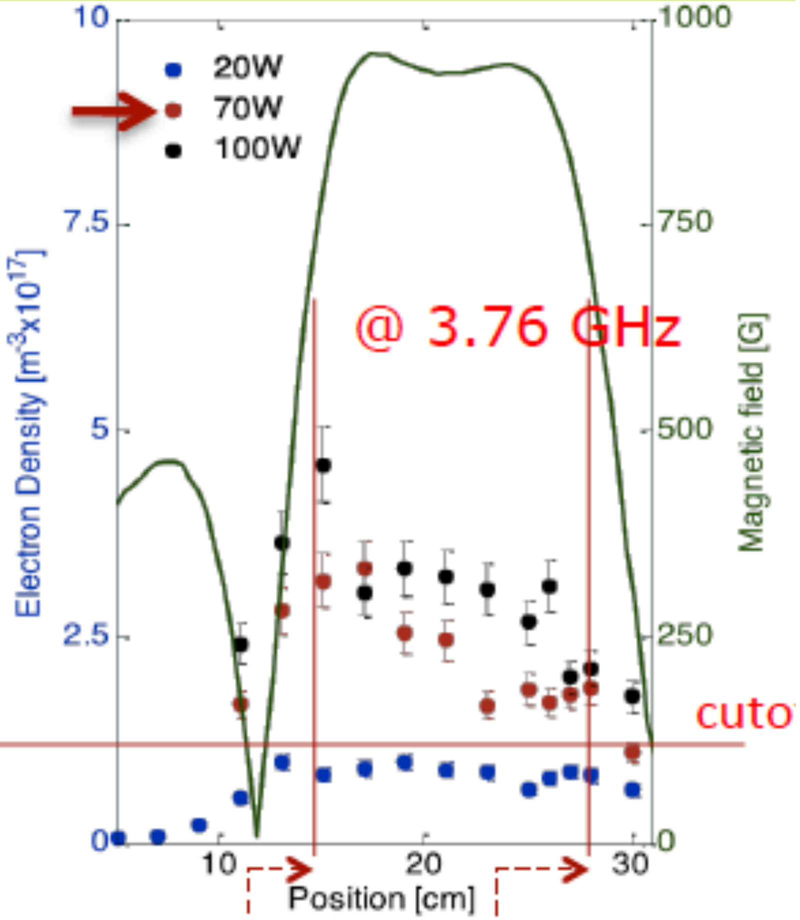




The non linear transition of electron temperature and the cutoff density overcoming confirm that plasma modes were formed



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.

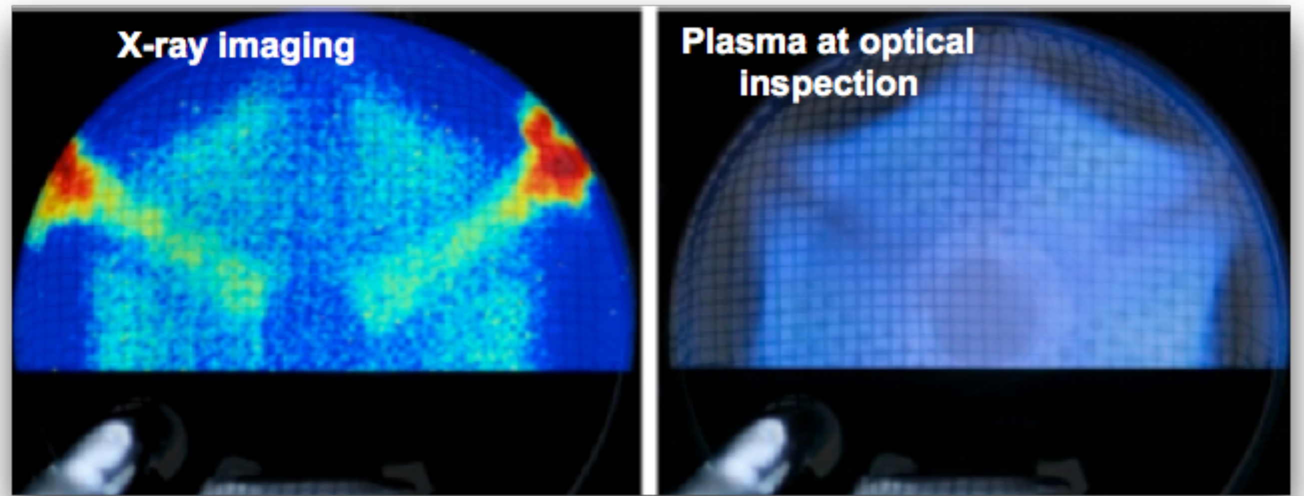
Non-intrusive plasma diagnostics methods

RF	IR	Visible & UV	EUV	Soft-Xray	Hard-Xray
(3 kHz-300 GHz)	(300 GHz-430 THz)	(1,6-12 eV)	(10-120 eV)	(0,12-12 keV)	(10-100 keV)

Optical plasma Observation
Spectroscopy 1D/2D
density-temp. measurement

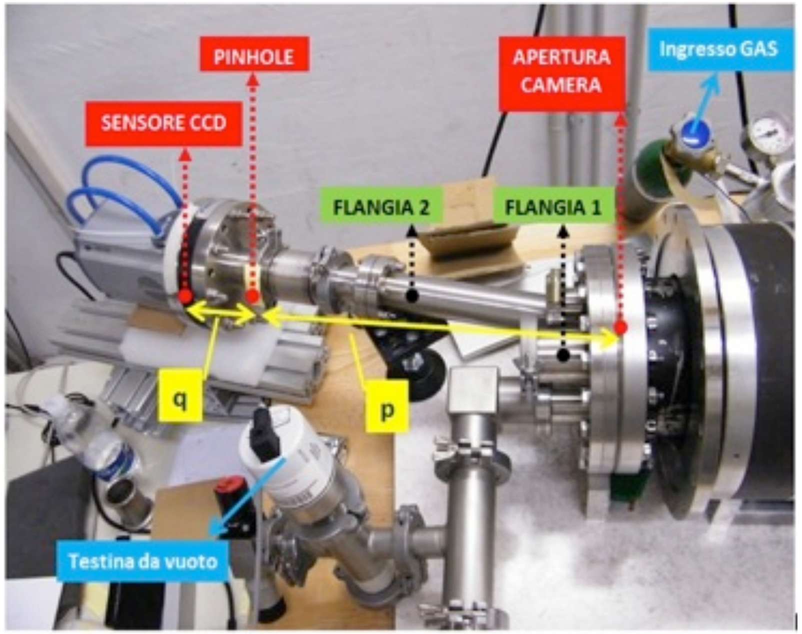
X-ray Pinhole Camera
Imaging & 2D-Spectroscopy
2D energy distribution and (relative) density

SDD - HpGe X-ray detectors
Spectroscopy



The X-ray space-resolved spectroscopy allows to investigate the morphology of the plasma → very important to optimize the energy deposition mechanism.

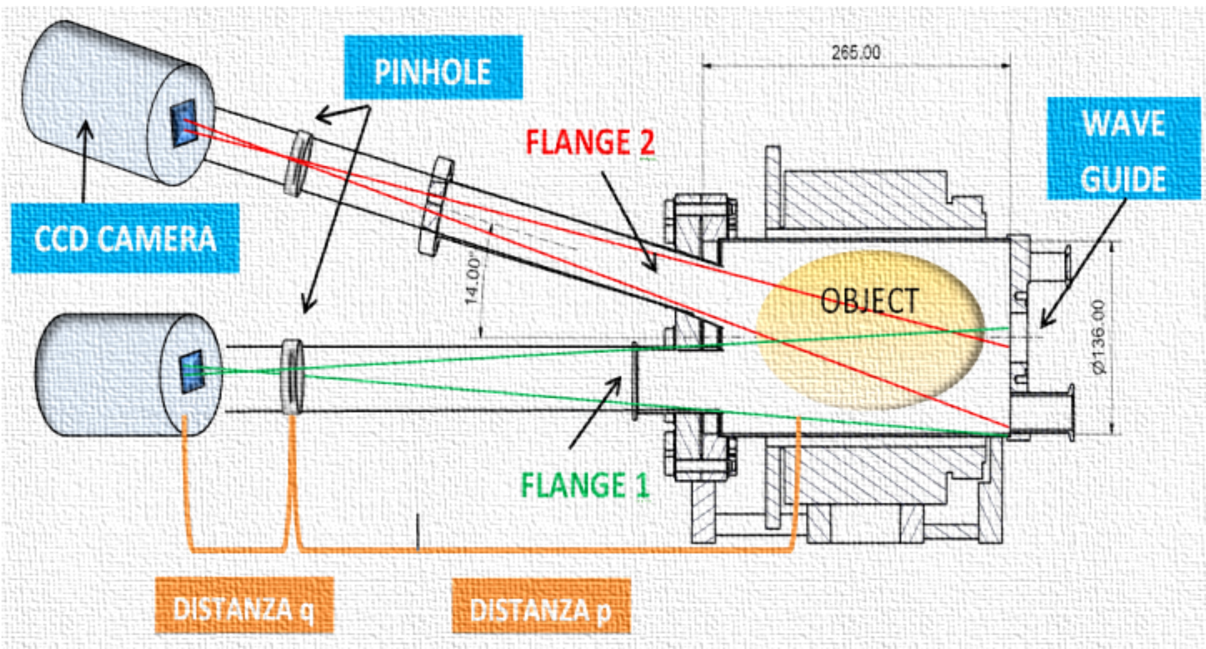
X-ray space resolved spectroscopy:
the X-ray pin-hole camera



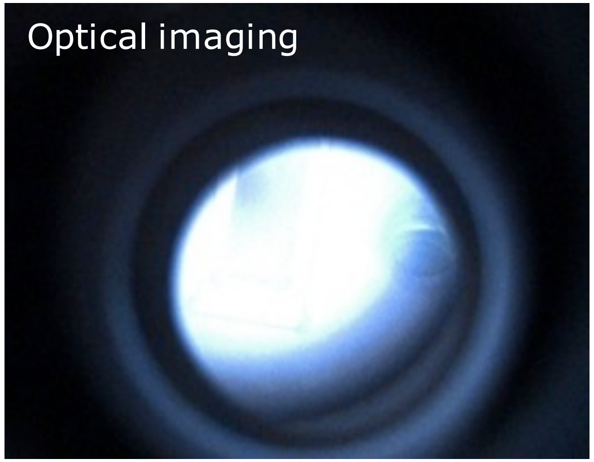
X-ray imaging can be performed with a **pin-hole camera technique**

The pin-hole is mounted between the plasma and a X-ray sensitive **CCD camera having 1024x1024 pixels in the 0.5-30 keV energy domain**

X-ray sensitive CCD - camera



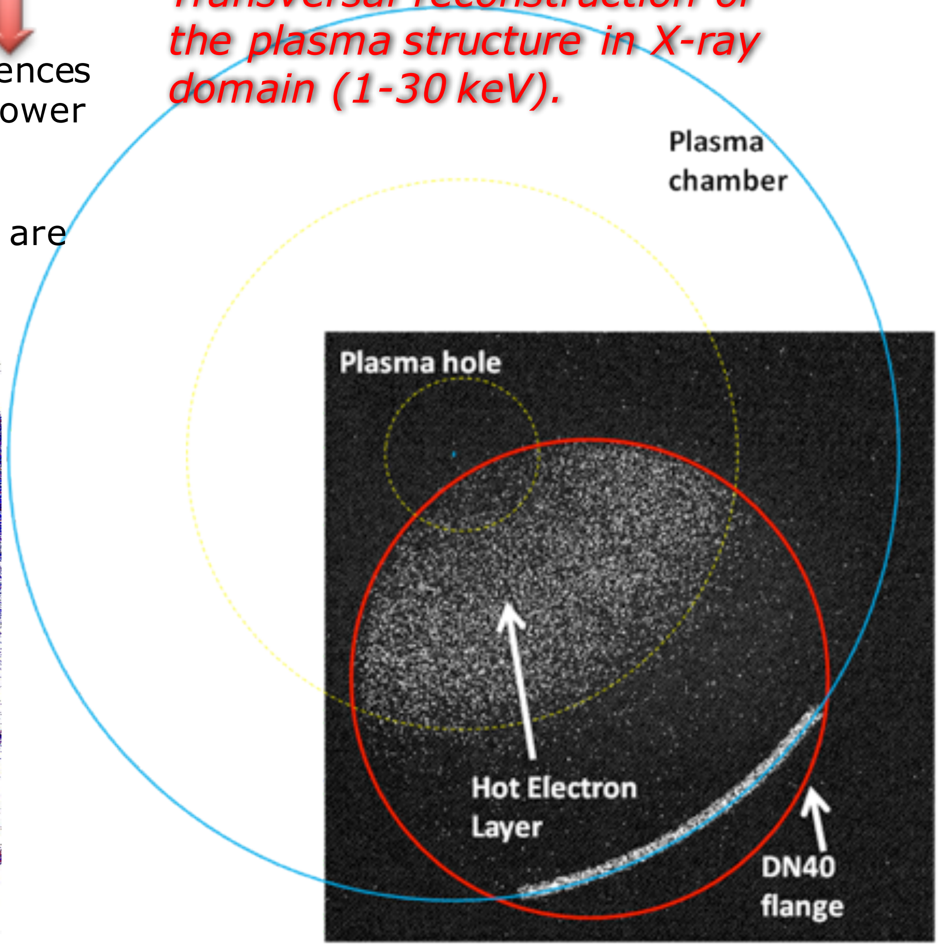
First direct observation of a HOT ELECTRON LAYER in the X-ray energies domain



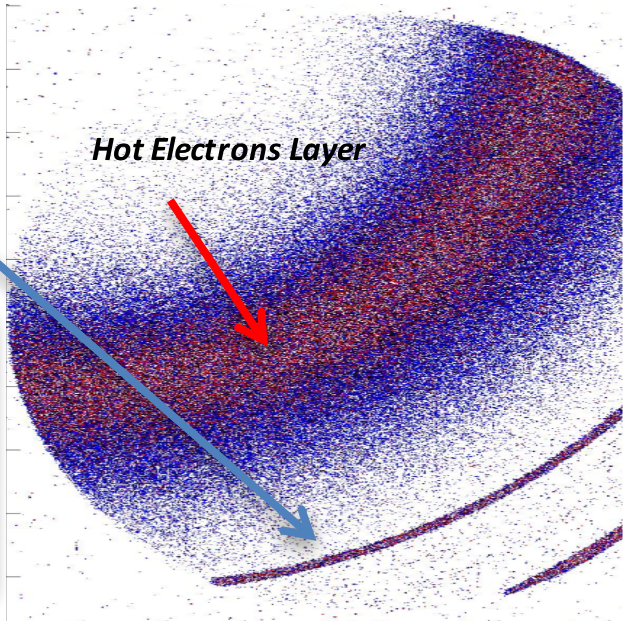
Images in the optical window, taken through an off-axis DN40 flange, evidence the generation of a high-brightness annulus surrounding a dark hole.

X-ray imaging evidences that the pumping power is deposited in the annulus, where the energetic electrons are generated

Transversal reconstruction of the plasma structure in X-ray domain (1-30 keV).



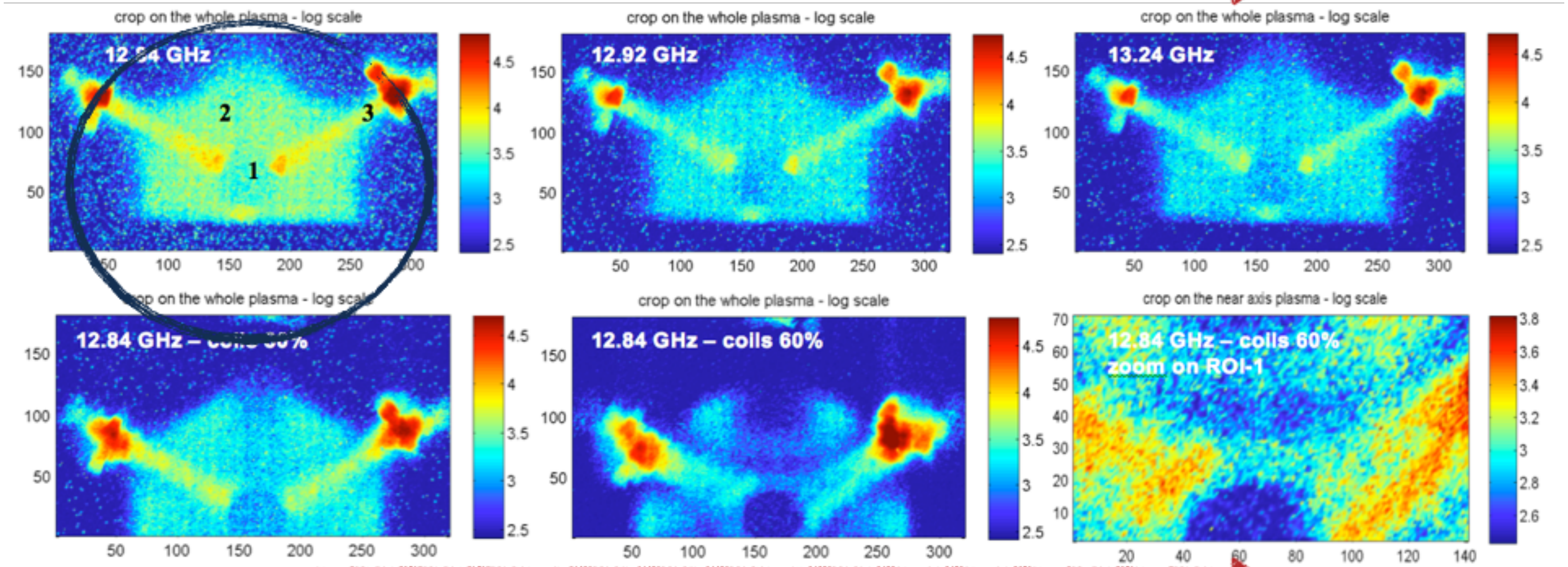
A high brightness strip appears due to electrons impinging on the chamber walls (bremsstrahlung through the stainless steel walls)



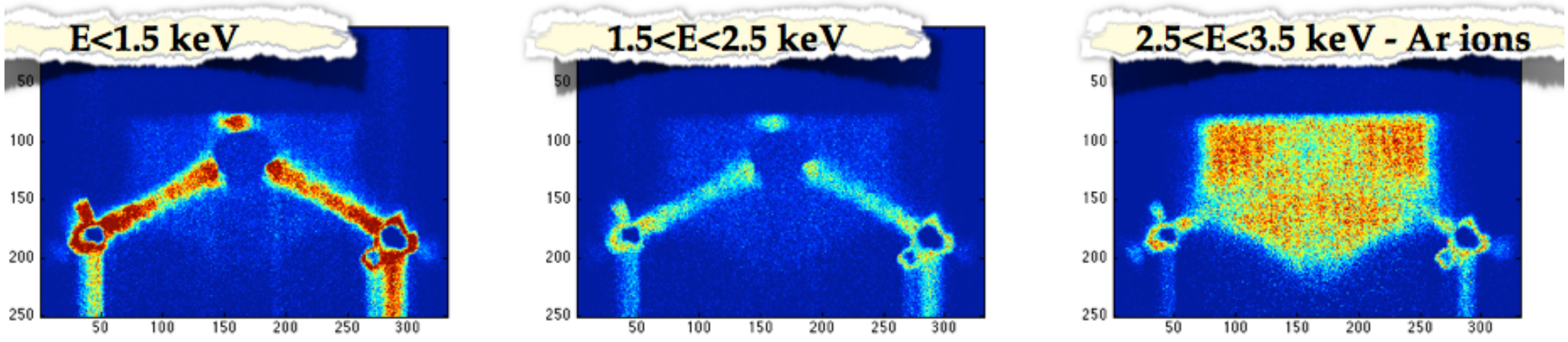
gas: Argon
pressure: 3*10-4 mbar
RF power: 100W
1000 frames - 1sec exposure for each one

Investigation of the plasma structure under different conditions of plasma heating (RF freq. B-field, etc.)

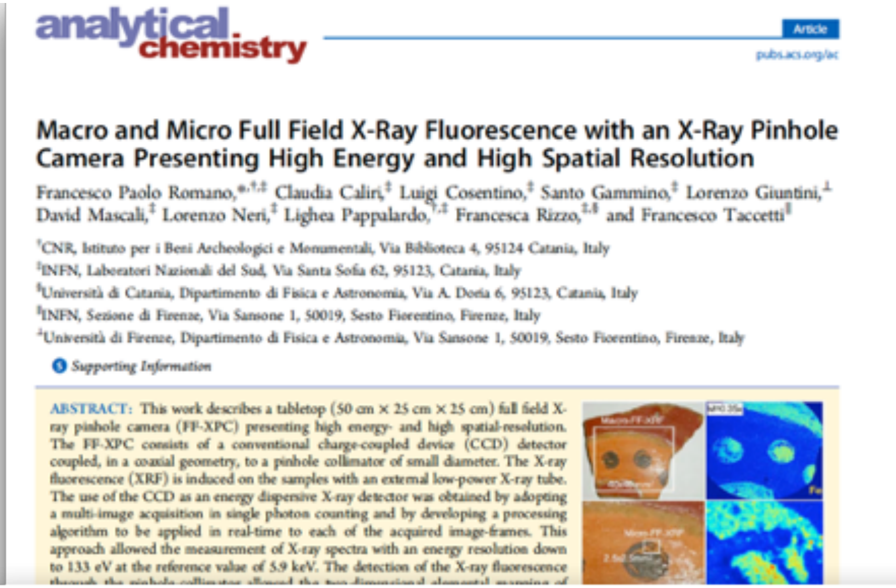
Varying the pumping wave frequency (F.T.E.)



Varying the magnetic field strength



Synergic research with fruitful implications in material analysis and Archaeometry


analytical chemistry

Article

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Macro and Micro Full Field X-Ray Fluorescence with an X-Ray Pinhole Camera Presenting High Energy and High Spatial Resolution

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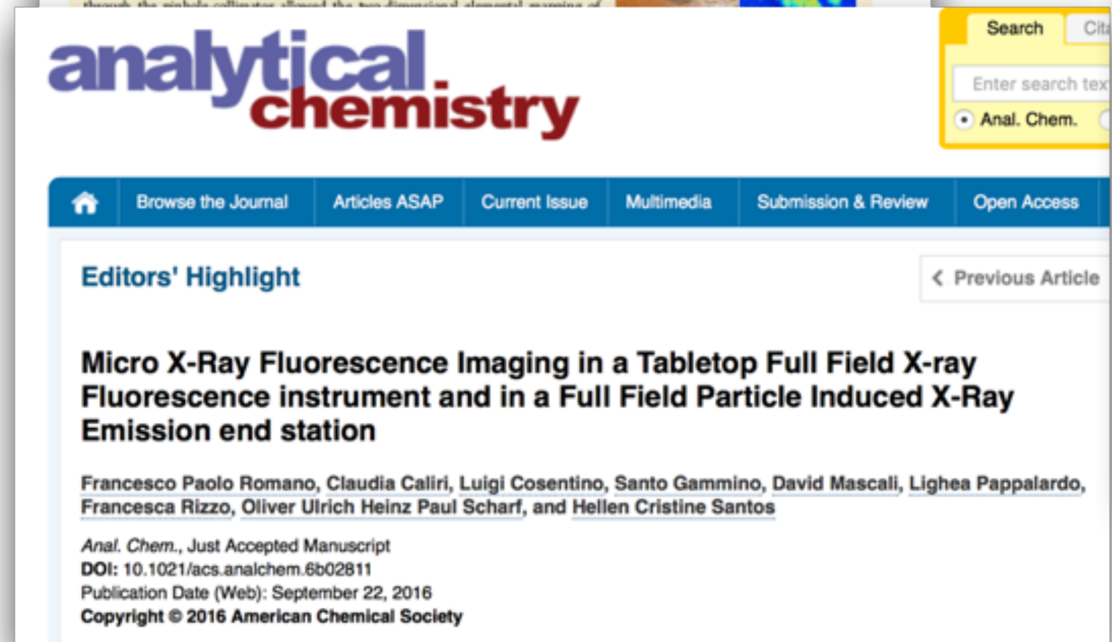
Supporting Information

ABSTRACT: This work describes a tabletop (50 cm × 25 cm × 25 cm) full field X-ray pinhole camera (FF-XPC) presenting high energy- and high spatial-resolution. The FF-XPC consists of a conventional charge-coupled device (CCD) detector coupled, in a coaxial geometry, to a pinhole collimator of small diameter. The X-ray fluorescence (XRF) is induced on the samples with an external low-power X-ray tube. The use of the CCD as an energy dispersive X-ray detector was obtained by adopting a multi-image acquisition in single photon counting and by developing a processing algorithm to be applied in real-time to each of the acquired image-frames. This approach allowed the measurement of X-ray spectra with an energy resolution down to 133 eV at the reference value of 5.9 keV. The detection of the X-ray fluorescence


analytical chemistry

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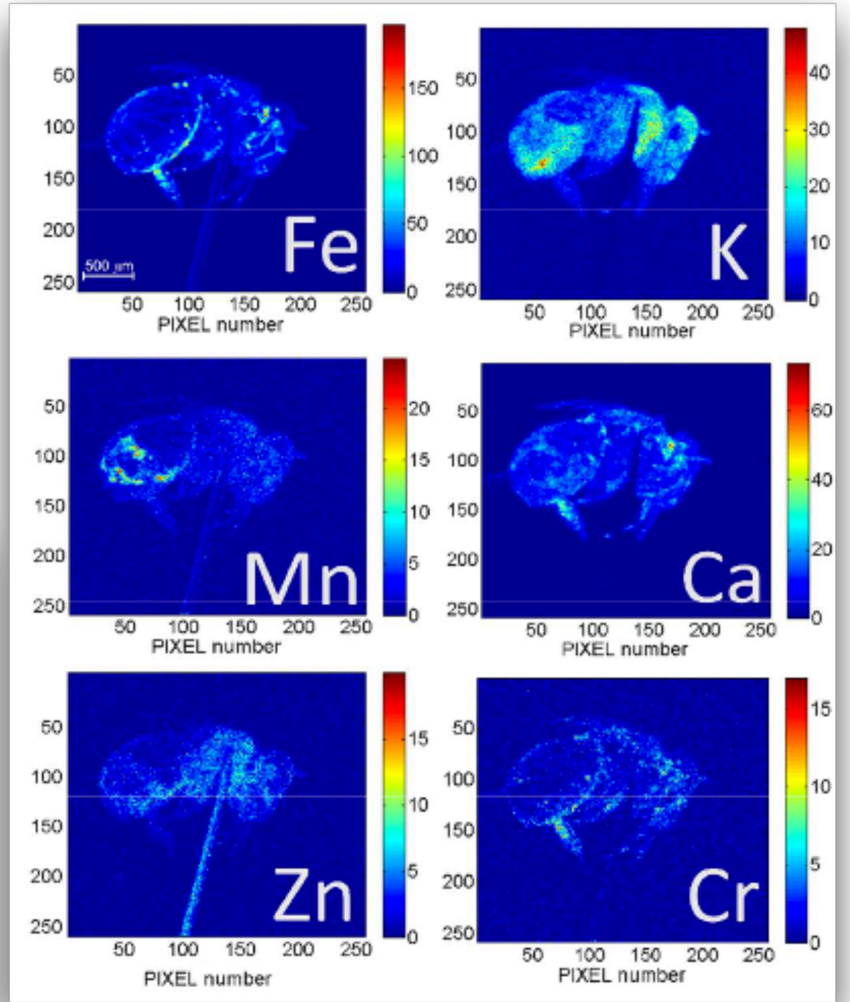
Editors' Highlight

Previous Article

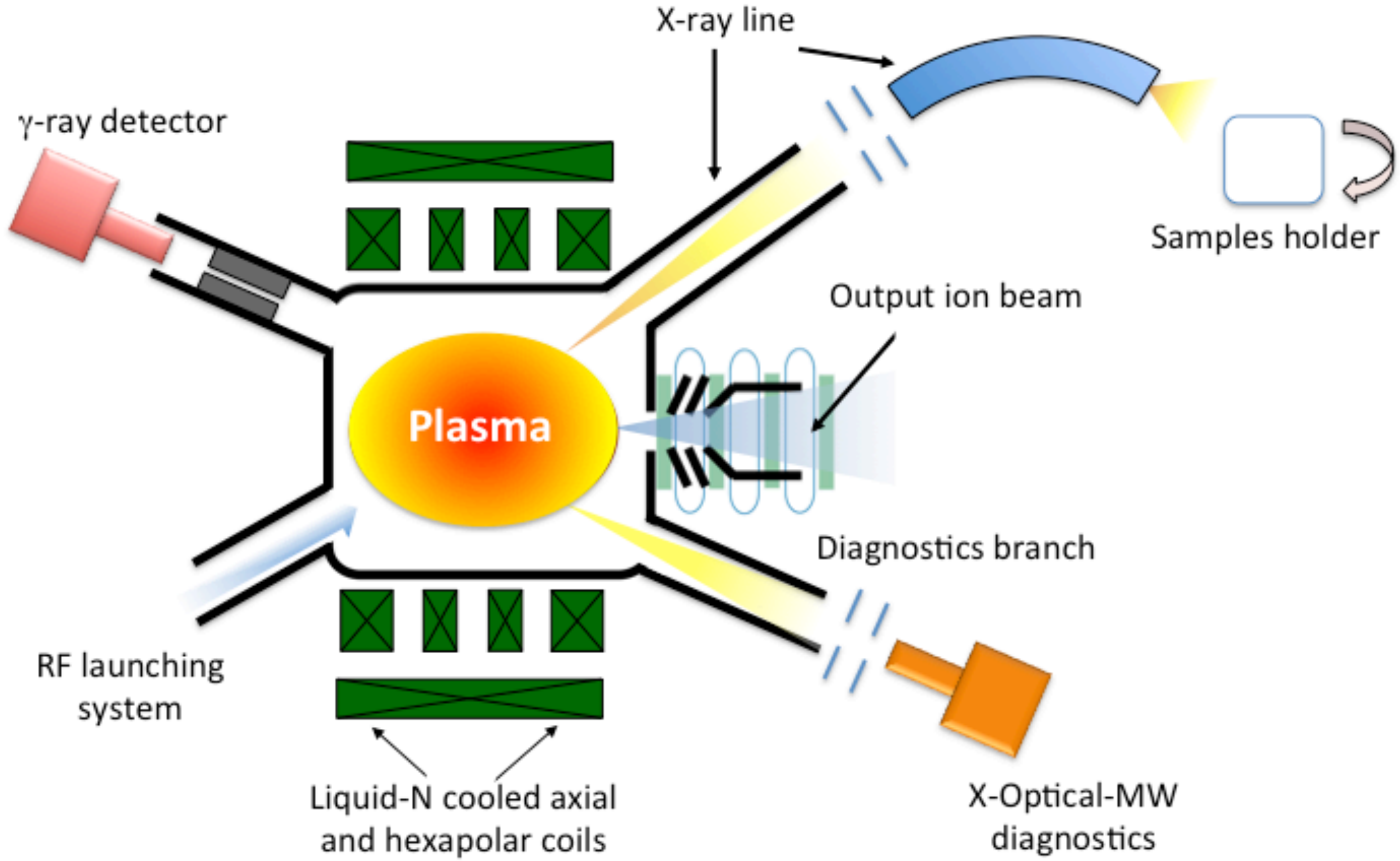
Micro X-Ray Fluorescence Imaging in a Tabletop Full Field X-ray Fluorescence instrument and in a Full Field Particle Induced X-Ray Emission end station

Francesco Paolo Romano, Claudia Caliri, Luigi Cosentino, Santo Gammino, David Mascali, Lighea Pappalardo, Francesca Rizzo, Oliver Ulrich Heinz Paul Scharf, and Hellen Cristine Santos

Anal. Chem., Just Accepted Manuscript
DOI: 10.1021/acs.analchem.6b02811
Publication Date (Web): September 22, 2016



Perspectives: new research field are possible



PANDORA

Plasmas for Astrophysics, Nuclear Decays Observation and Radiation for Archaeometry

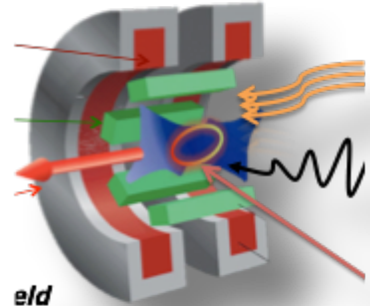
A proposal has been submitted to INFN commissions by D. Mascali & A. Musumarra

A MHD stable,

magnetized plasma,

living several hours or days

with on average constant local density and temperature constant values is an attractive environment for:



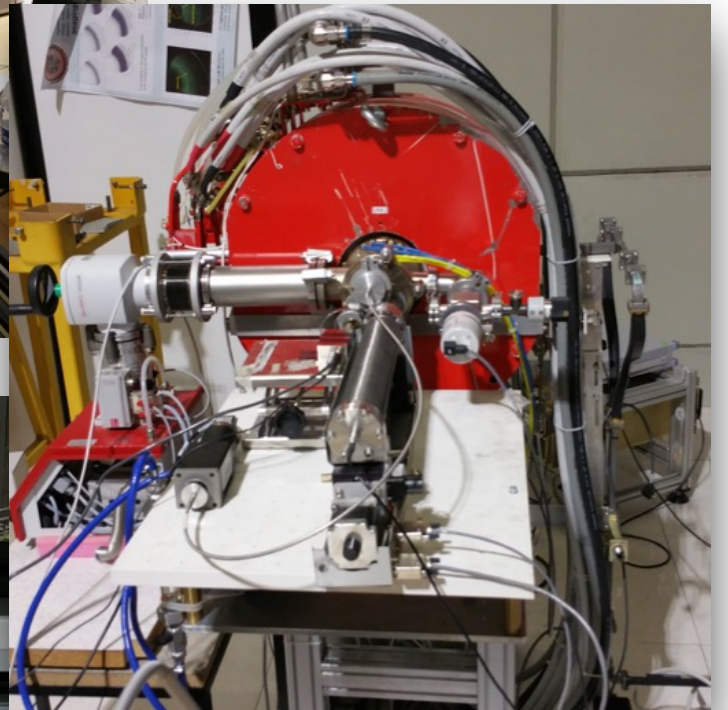
Trapping in a dynamical equilibrium BETA/EC-DECAYING radionuclides, in order to measure their "in-plasma" decay time

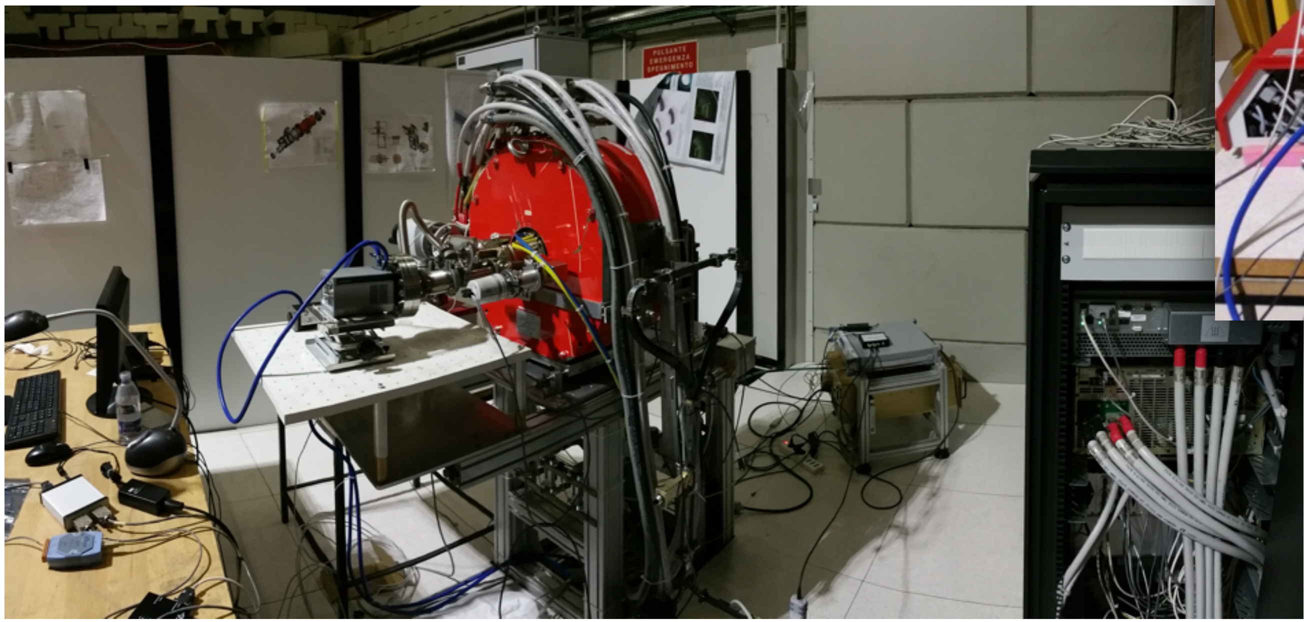
Making "in-laboratory" observations of astrophysical interest, especially in the field of magnetized stars

In case of overdense plasma production via Electron Bernstein Waves, R&D can be done in order to apply the plasma produced UV/X radiation for material analysis

Plasmas for Astrophysics, Nuclear Decays Observation and Radiation for Archaeometry

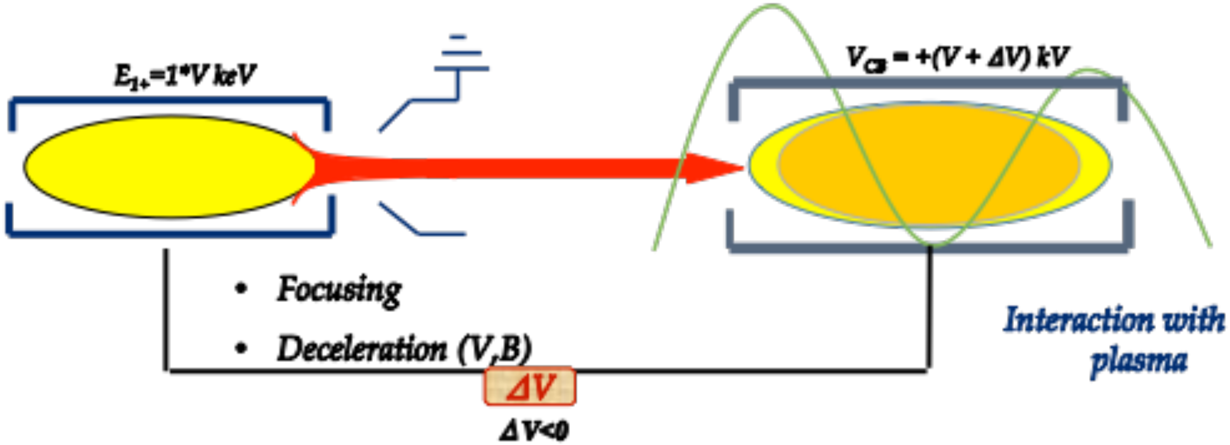
Flexible Plasma Trap





Now operating at LNS

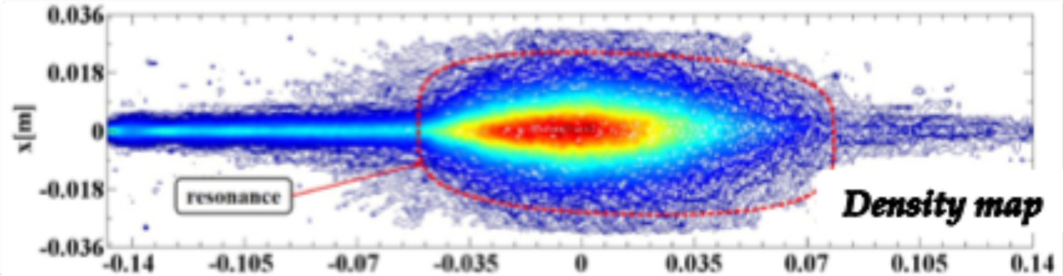
Injection of ^{7}Be in ECR plasma

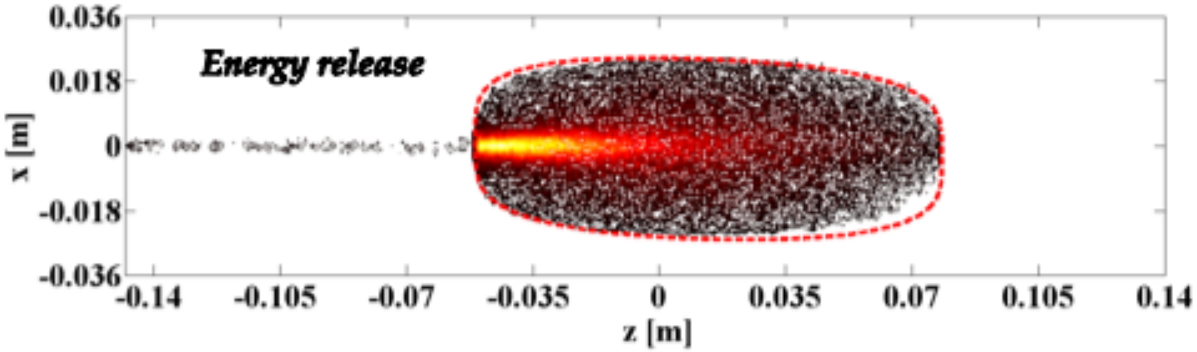


Interaction with the plasma

NUMERICAL SIMULATIONS

Interaction of an ion beam with the ECR plasma (Charge Breeding)





Remarks about past and future

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

Question:

May we maintain this trend for the next decades ?

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).

- ***The increase of magnetic field is close to saturation.***
- ***If you find a wall, you should dig a hole below it!***
- ***The "hole" in our case is an appropriate microwave injector***
- ***Plasma diagnostics and modeling are essential to fulfill the microwave coupling optimization.***
- ***There is room for improvements of the existing sources and large possibilities for the future ECRIS.***

Investment

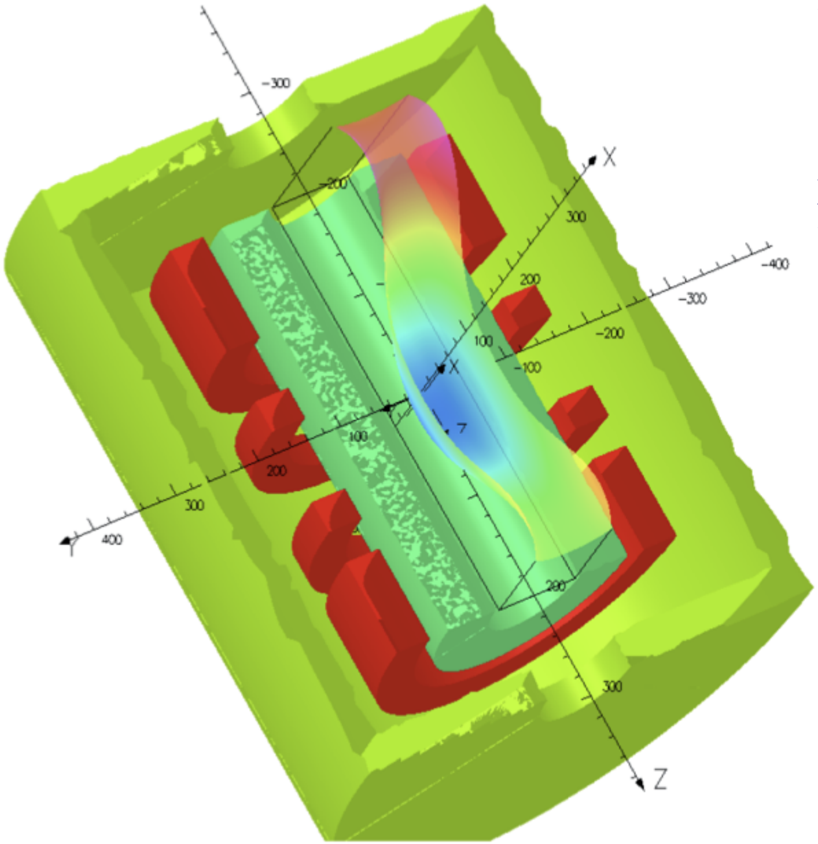
Any equity fund would invest in a tool that increases the asset by a factor 5 or 10 per decade…

The investment in ECRIS has been rewarding in 3 decades 1987-2016.

Why not to continue to invest ?

AISHA

Advanced Ion Source for HAdrontherapy



AISHA is a hybrid ECRIS: the radial confining field is obtained by means of a permanent magnet hexapole, while the axial field is obtained with a **Helium-free superconducting system.**

The **operating frequency of 18 GHz will permit** to maximize the plasma density by employing commercial microwave tubes meeting the **<u>needs of the installation in hospital</u>** environments.

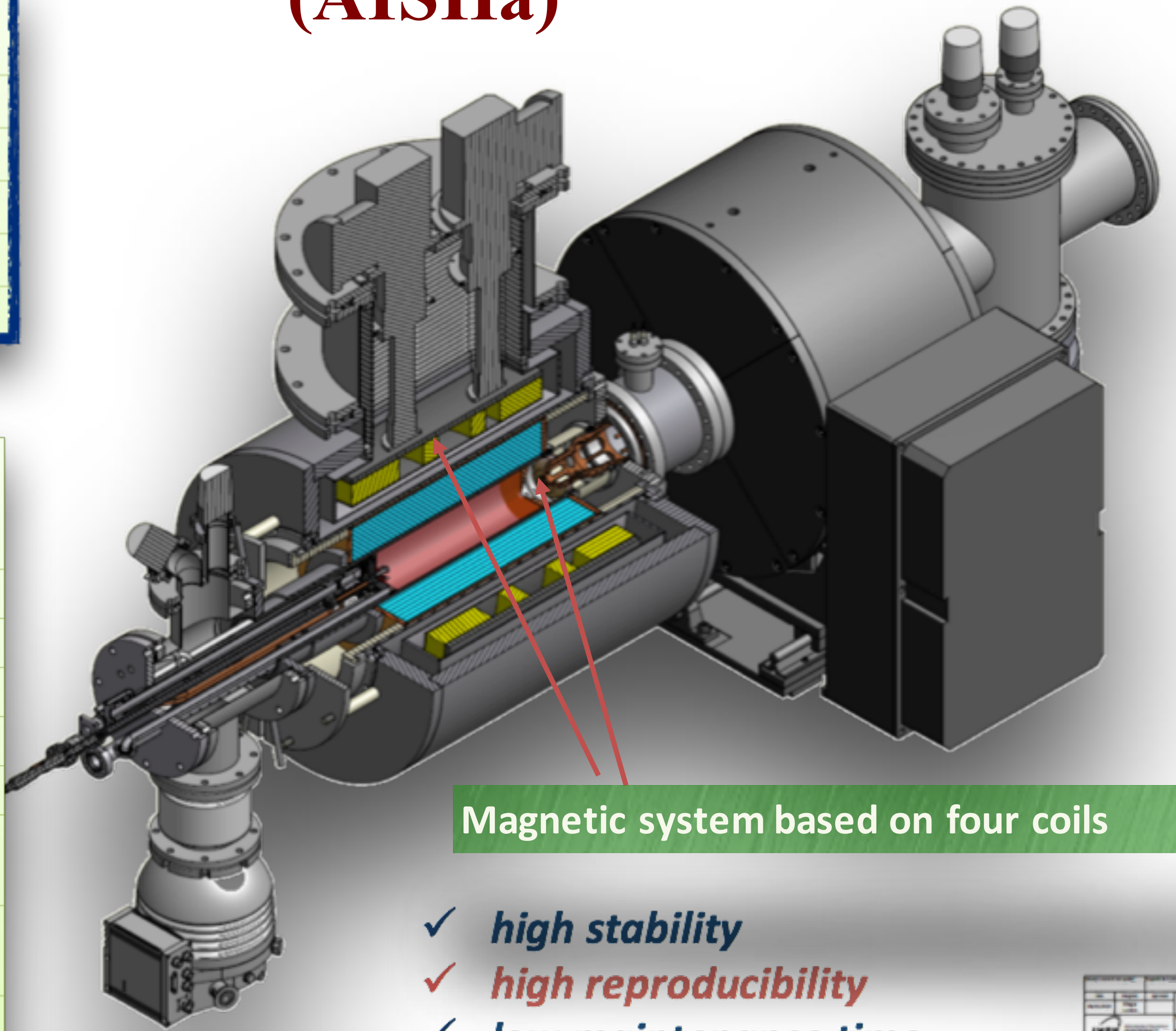
Radial field	1.3 T
Axial field	2.7 T - 0.4 T - 1.6 T
Operating frequencies	18 GHz – 21 GHz
Operating power	1.5 + 1.5 kW (max)
Extraction voltage	40 kV (max)
Chamber diameter / length	Ø 92 mm / 360 mm
LHe	Free
Warm bore diameter	274 mm
Source weight	1400 kg

An example of new source for M.C.I.: the Advanced Ion Source for Hadrontherapy (AISHa)

Parameter	Dimension
ø chamber	92 mm
L chamber	357 mm
Frequency	18 GHz
RF Power (max)	1.5 kW
Extr Voltage (max)	40 kV

Expected Currents

Ion	AISHa (18 GHz + TFH)
H^+	4000
H_2^+	2000
H_3^+	1500
$^3He^+$	2000
$^{12}C^{4+}$	800
$^6Li^{2+}$ - $^7Li^{2+}$	800
$^{10}B^{3+}$ - $^{11}B^{3+}$	600
$^{18}O^{6+}$	1000
$^{21}Ne^{7+}$	500
$^{36}Ar^{12+}$	150



Magnetic system based on four coils

- ✓ *high stability*
- ✓ *high reproducibility*
- ✓ *low maintenance time*
- ✓ *Compact setup*
- ✓ *highly charged ion beams*

AISHA

Advanced Ion Source for HAdrontherapy

- The set of four superconducting coils independently energized realize a ***flexible magnetic trap***, which is fundamental to test alternative heating schemes based on Bernstein waves excitation and heating in sub-harmonics.

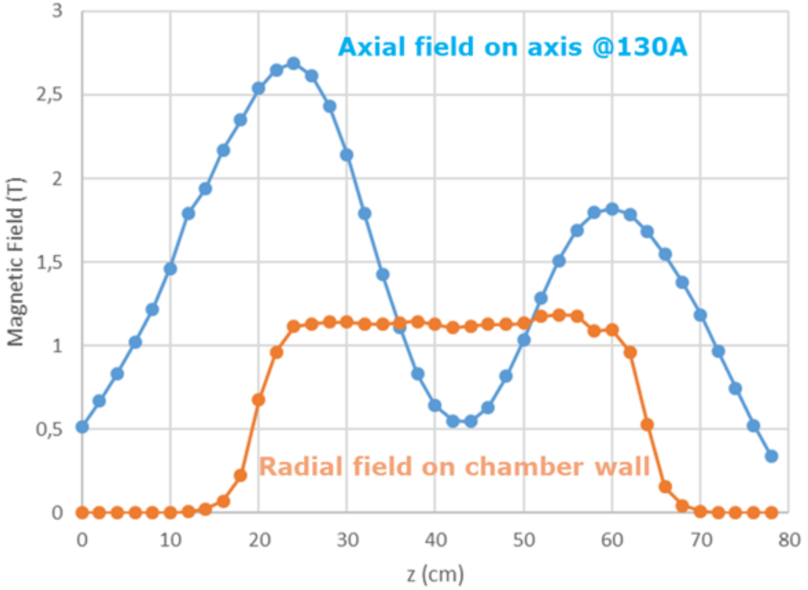
- The use of a ***broadband microwave generator*** able to provide signal with complex spectrum content, will permit to efficiently tune the frequency increasing the electron density and therefore the performance in terms of current and average charge state produced.

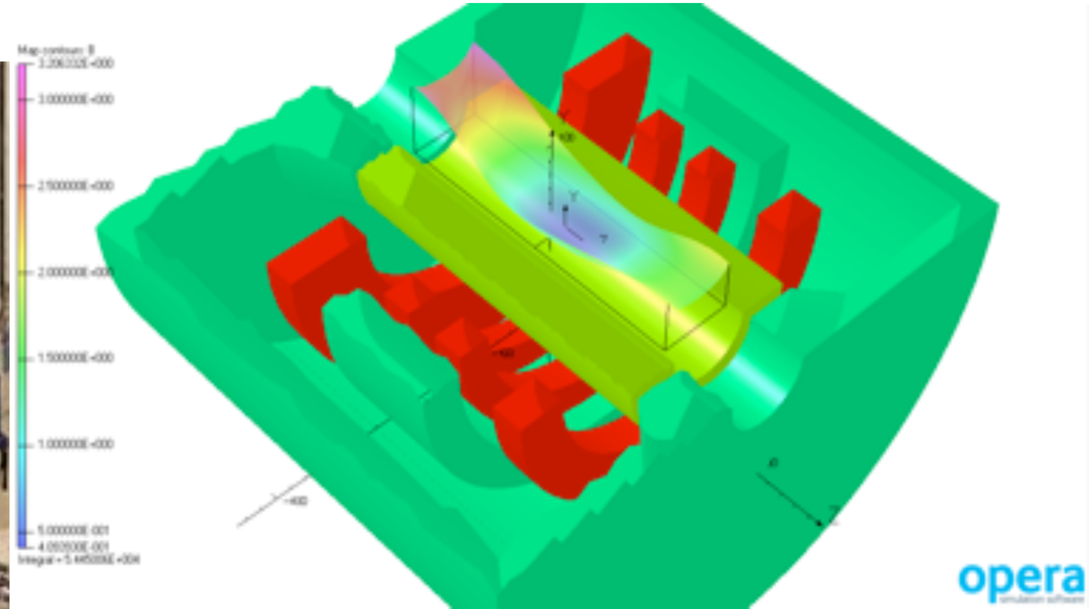
- The chamber dimension and the injection system are designed in order to ***optimize the microwave coupling*** to the plasma chamber taking into account the need of space to house the ***oven for metallic ion*** beam production.

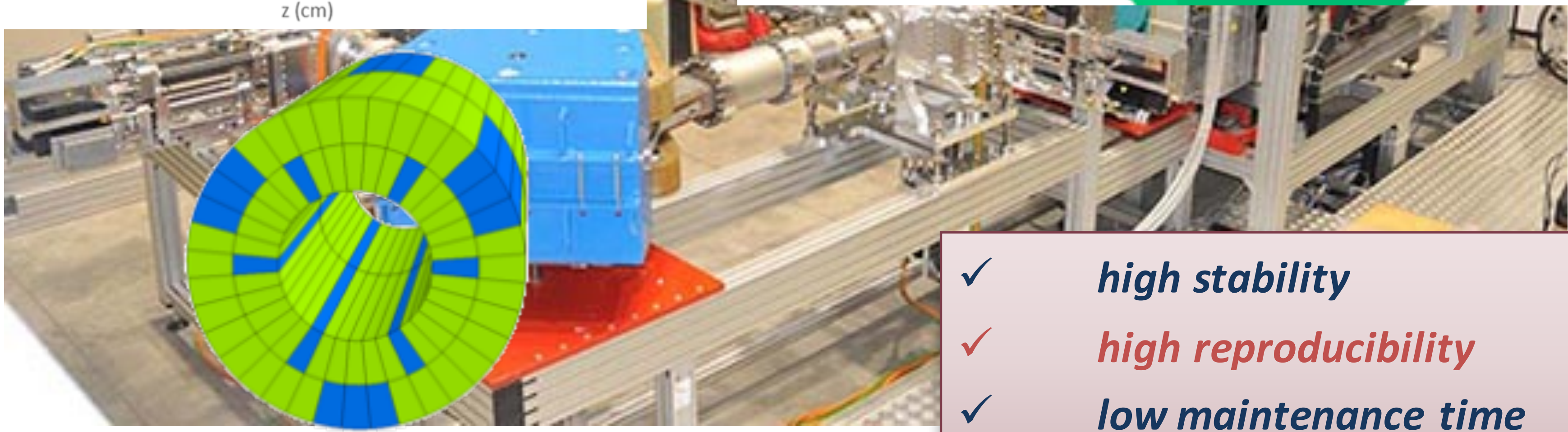
- An adequate study of the ***extraction system*** has been carried out taking into account the production of high current and high charge states.

AISHa

Experimental setup







- ✓ *high stability*
- ✓ *high reproducibility*
- ✓ *low maintenance time*
- ✓ *low space occupation*
- ✓ *highly charged ion beams*

AISHa

Reliable sources for high intensity proton accelerators

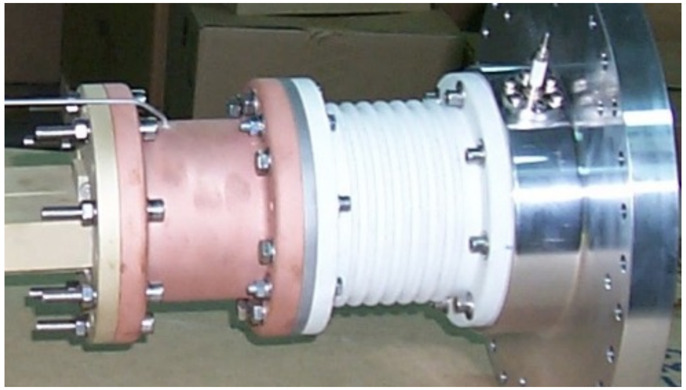
MIDAS, a high efficiency microwave discharge ion source for the EXCYT facility

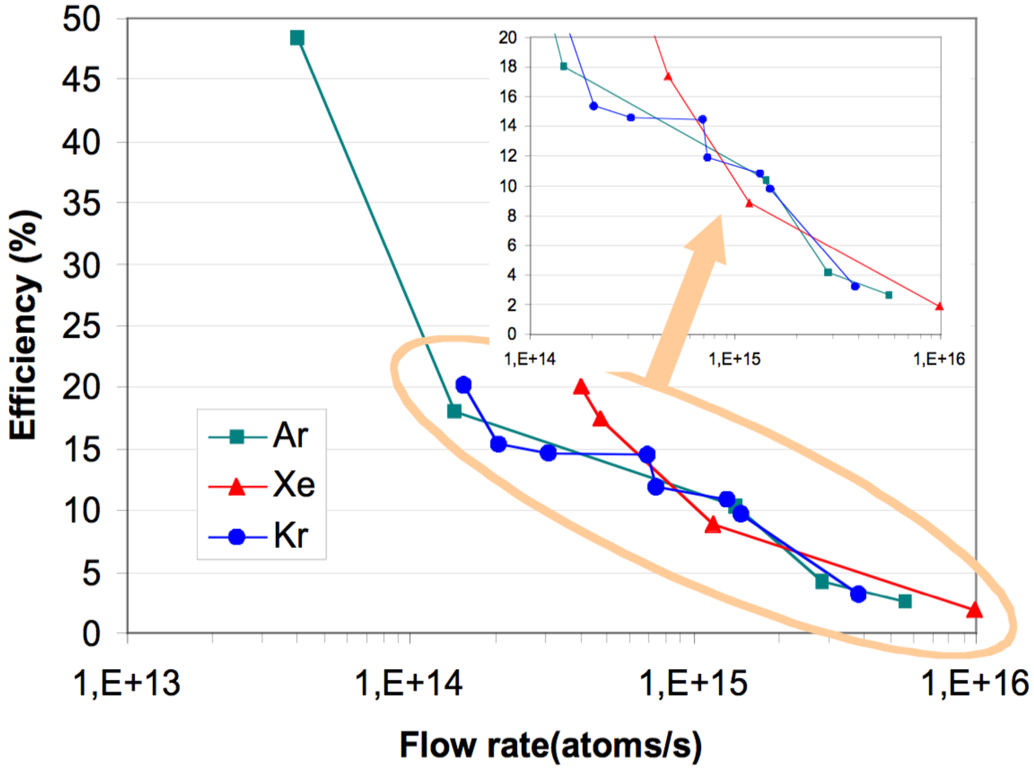
G. Ciavola, S. Gammino, G. Raia, and J. Sura
INFN, Laboratorio Nazionale del Sud, Via S. Sofia 44, 95123 Catania, Italy

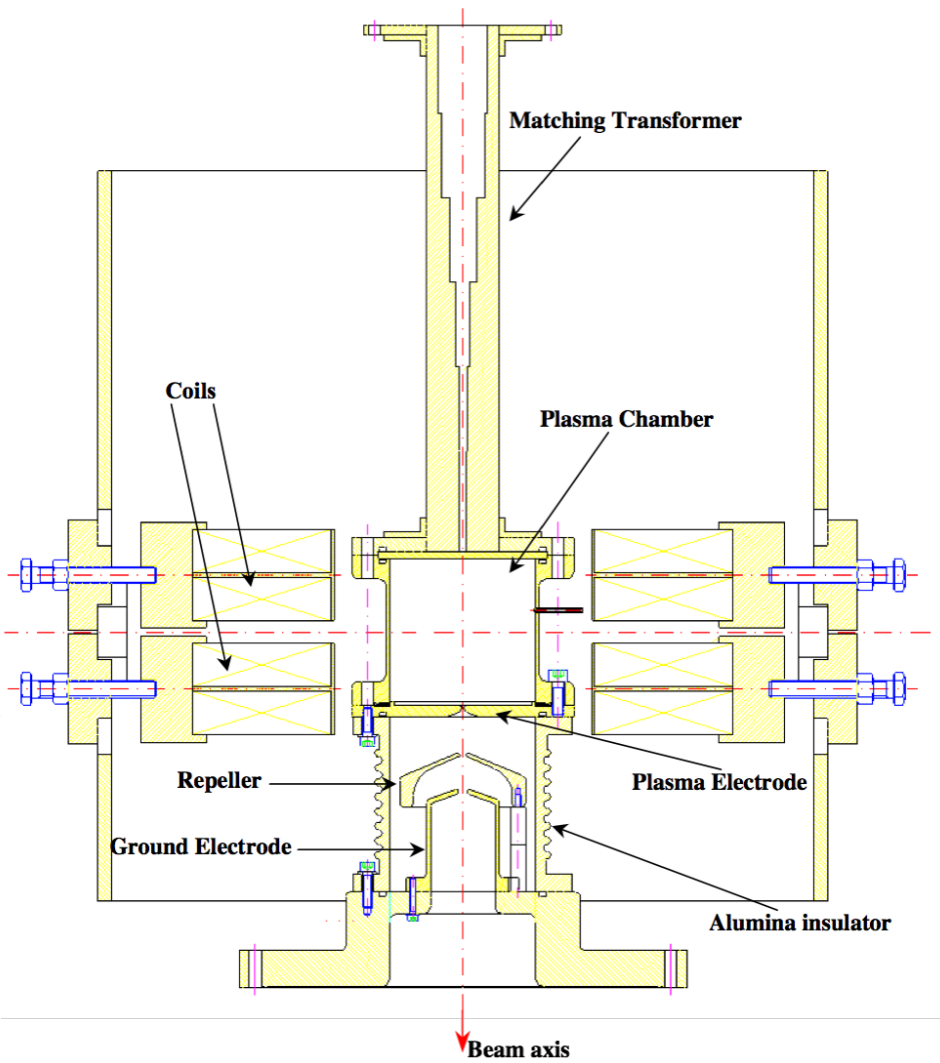
(Presented on 31 August 1993)

A microwave discharge ion source has been designed in order to obtain high efficiencies for positive ionization of the recoils to be produced at the exotics at the cyclotron Tandem facility. After a charge exchange process the negative ions will be injected into the 15-MV Tandem, already working at the Laboratorio Nazionale del Sud. The short ionization time and the fast wall recycling make this source very well suited for the purpose of high efficiency ionization of the recoils. The operational principle and the design are described in the following.

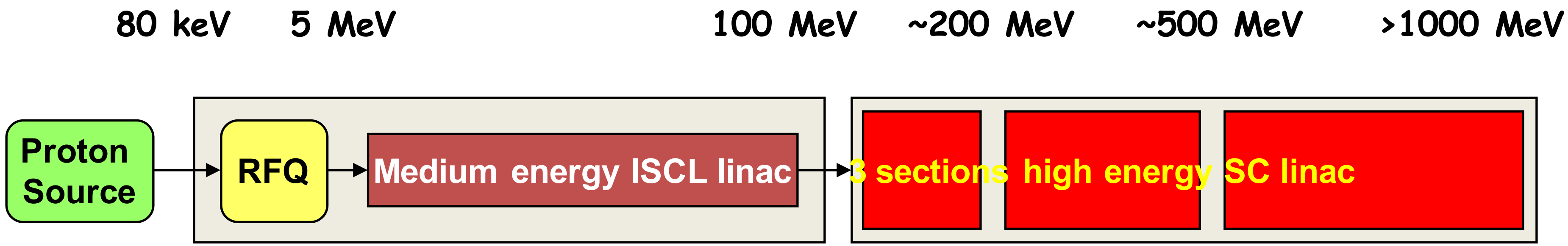
MIDAS




Efficiency (%)
Flow rate(atoms/s)
1,E+13
1,E+14
1,E+15
1,E+16
Ar
Xe
Kr


Matching Transformer
Coils
Plasma Chamber
Repeller
Plasma Electrode
Ground Electrode
Alumina insulator
Beam axis

TRASCO *was devoted to the conceptual study and the prototyping of components for an accelerator driven system for nuclear waste transmutation, and involved research agencies and Italian companies, about 15 years ago. Further programmes from Italian and European agencies supported the evolution of the TRASCO project.*



Source	RFQ	ISCL	High Energy SC Linac
Microwave RF Source High current (3 5 mA) 80 keV	High transmission 95% 30 mA, 5 MeV (352 MHz)	5 - 100 MeV SC linac Baseline design: Reentrant cavities (352 MHz) Alternative design: $\lambda/2$, $\lambda/4$ $8\beta\lambda$ FODO focussing with sc magnets	3 section linac: ➢ 100 - 190 MeV, β=0.47 ➢ 190 - 450 MeV, β=0.65 ➢ 450 – 1000/(1600) MeV, β=0.85 Five(six) cell elliptical cavities Quadrupole doublet focussing: multi-cavity cryostats between doublets ➢ (352.2 MHz CERN/LEP) ➢ 704.4 MHz

The TRASCO–AC Group,
Status of the high current proton accelerator for the TRASCO program. Report No. INFN/TC-00/23

TRIPS (TRasco Intense Proton Source)

Proton beam current:

35 mA dc

Beam Energy:

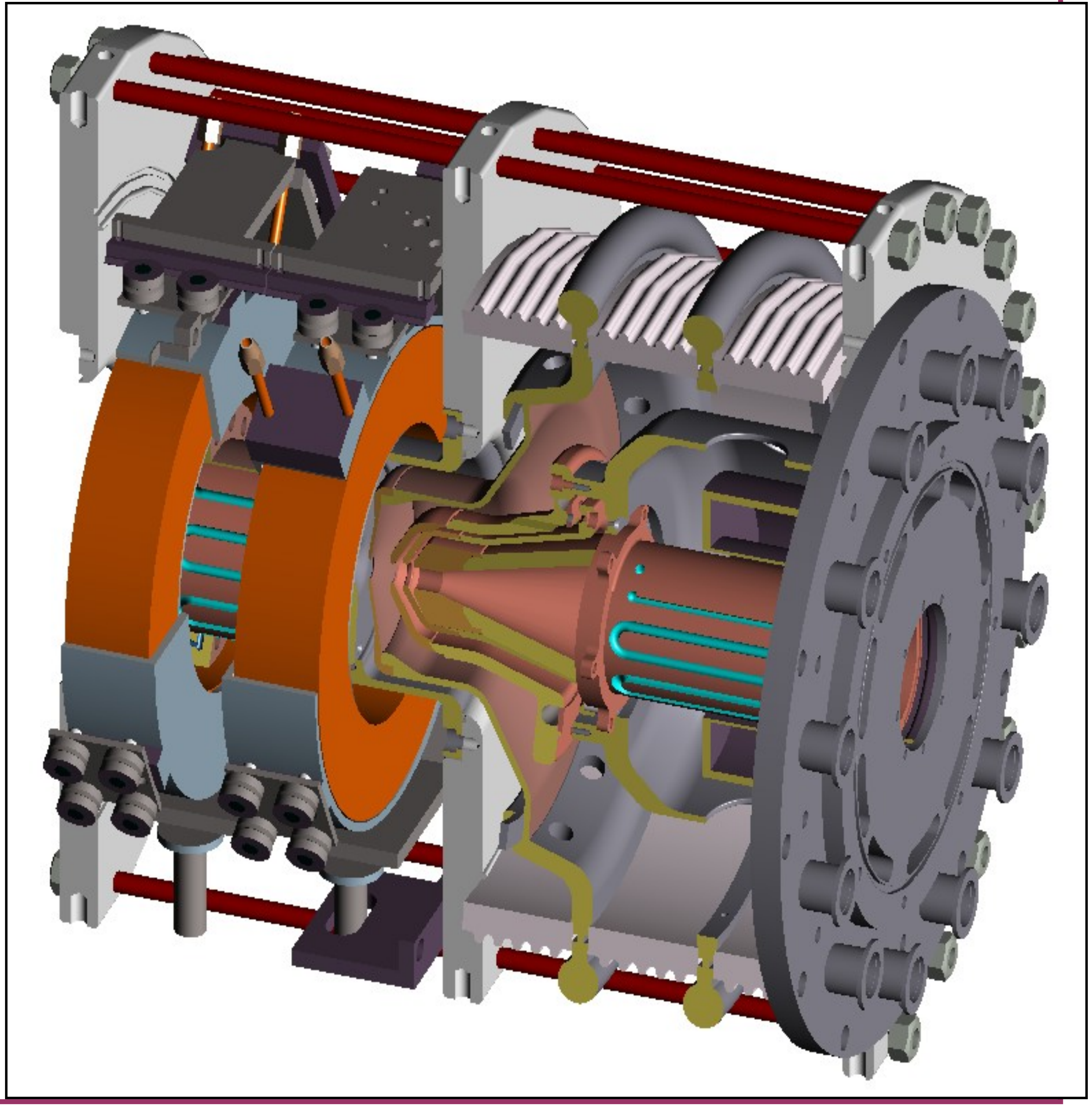
80 keV

Beam emittance:

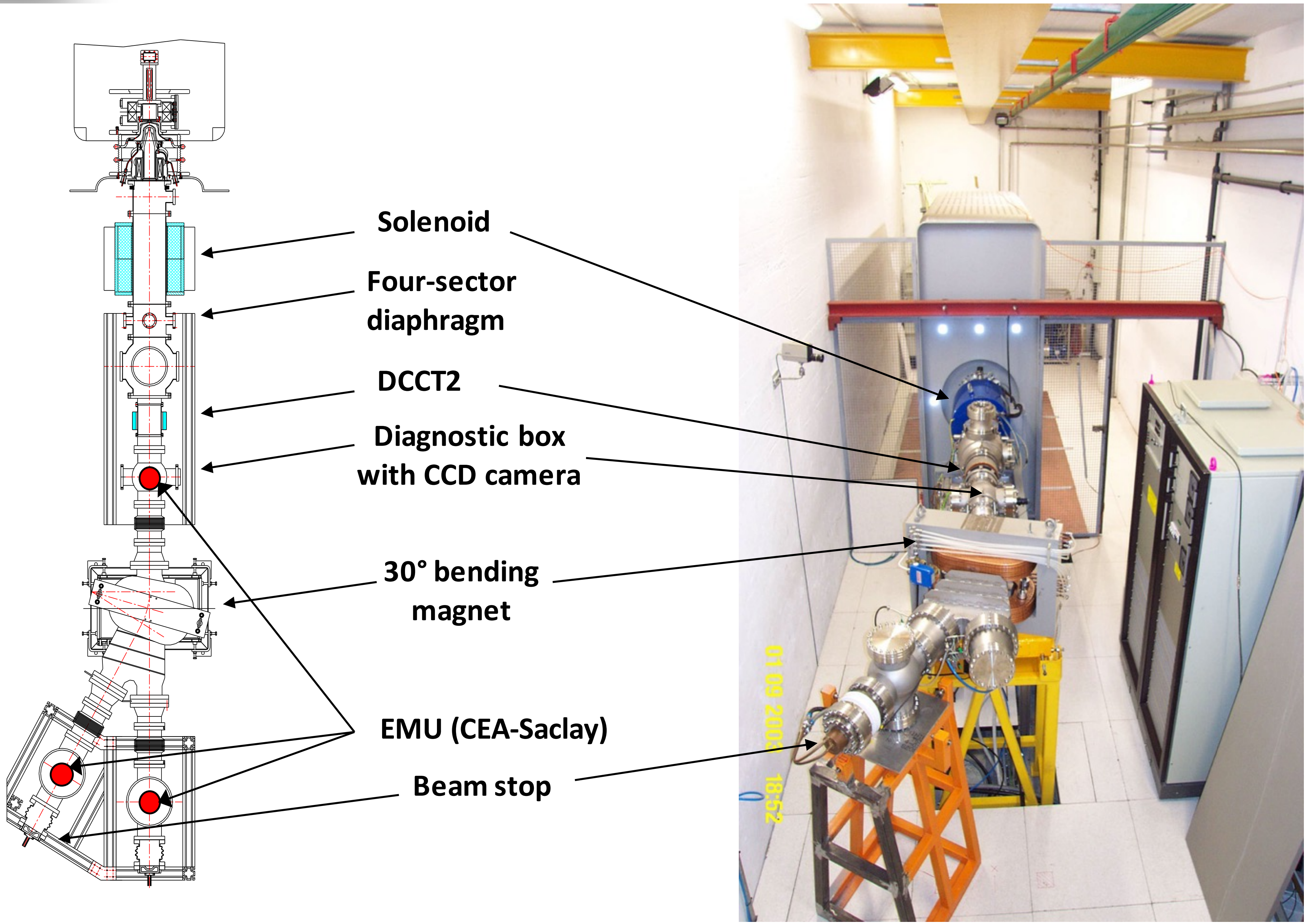
$\varepsilon_{RMS} \leq 0.2\,\pi$ **mm mrad**

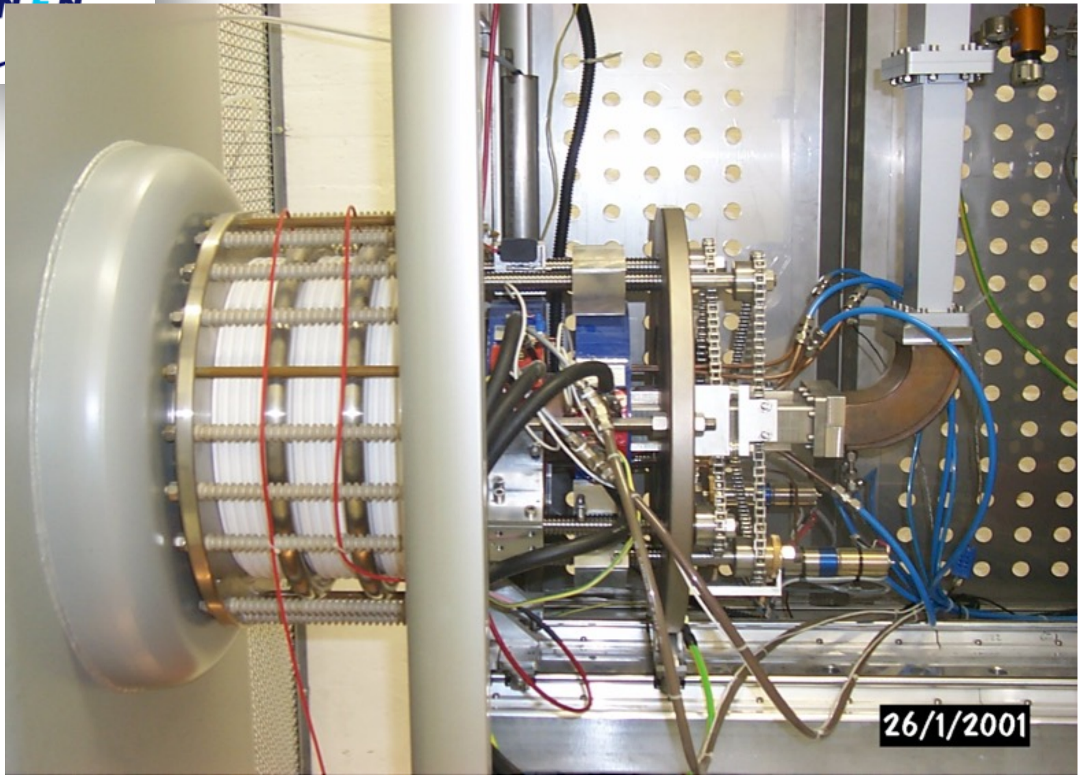
Reliability:

close to 100%



TRIPS (TRasco Intense Proton Source)





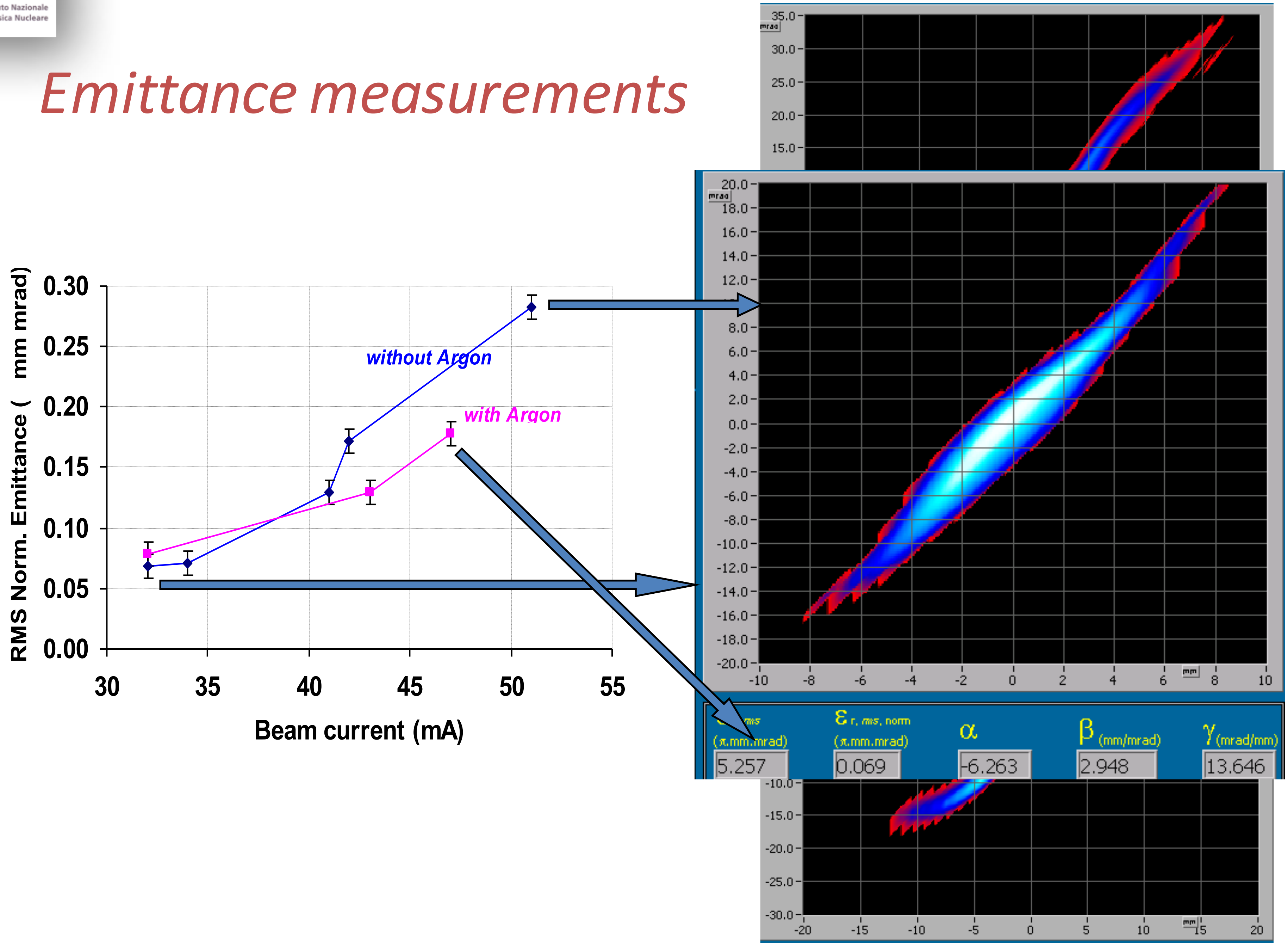
Jan. 2001: completed

11/11/05

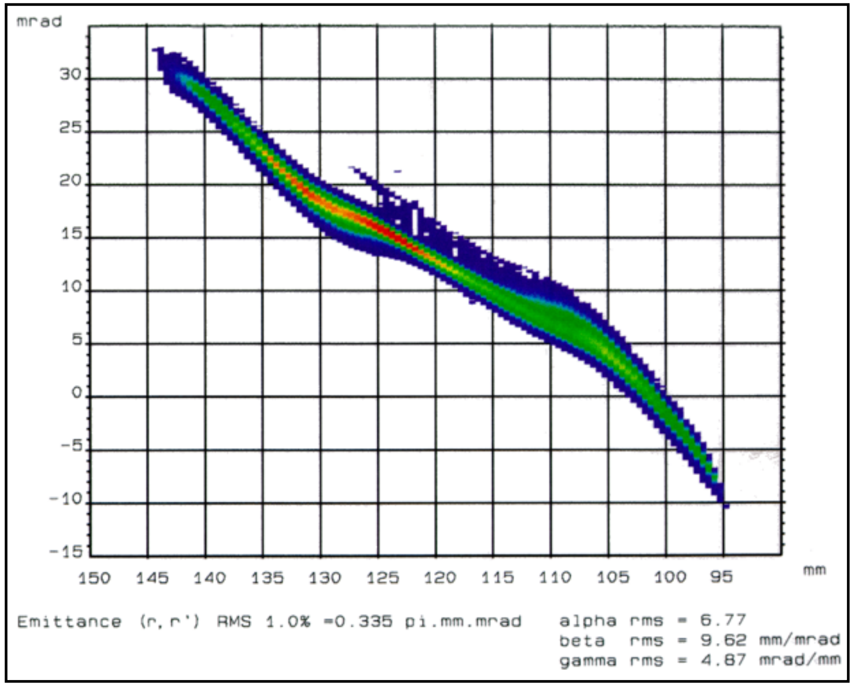
TRIPS moved to LNL

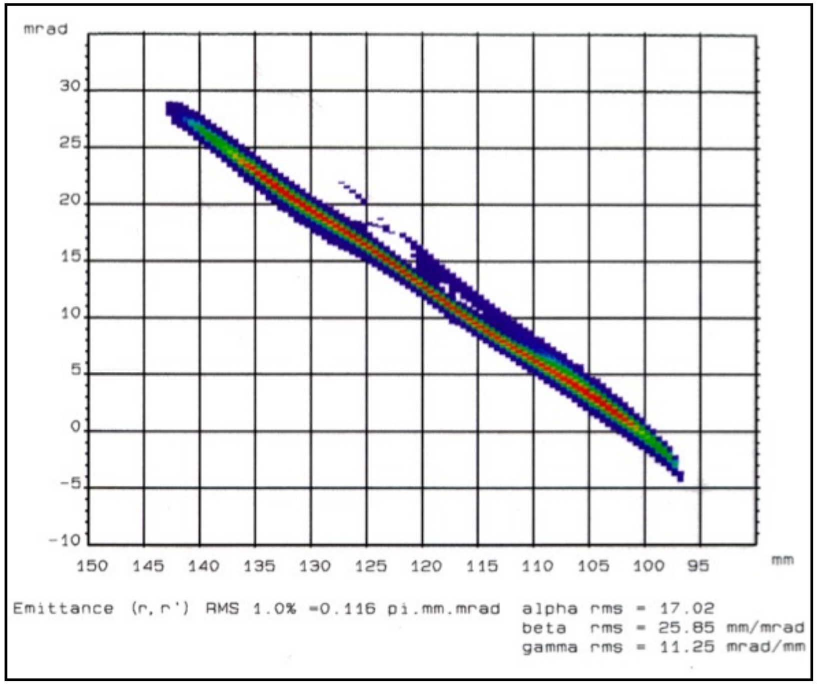
	Requirement	**Status**
Beam energy	80 keV	80 keV
Proton current	35 mA	55 mA
Proton fraction	>70%	80% at 800 W RF power
RF power, Frequency	2 kW (max) @2.45 GHz	Up to 1 kW @ 2.45 GHz
Axial magnetic field	875-1000 G	875-1000 G
Duty factor	100% (dc)	100% (dc)
Extraction aperture	8 mm	6 mm
Reliability	≈100%	99.8% @ 35mA (over 142 h)
Beam emittance at RFQ entrance	≤0.2 πmmmrad	0.07÷0.20 πmmmrad

Emittance measurements



Space charge compensation with ^{84}Kr





Emittance plot (99%) without injecting gas in the beam line:

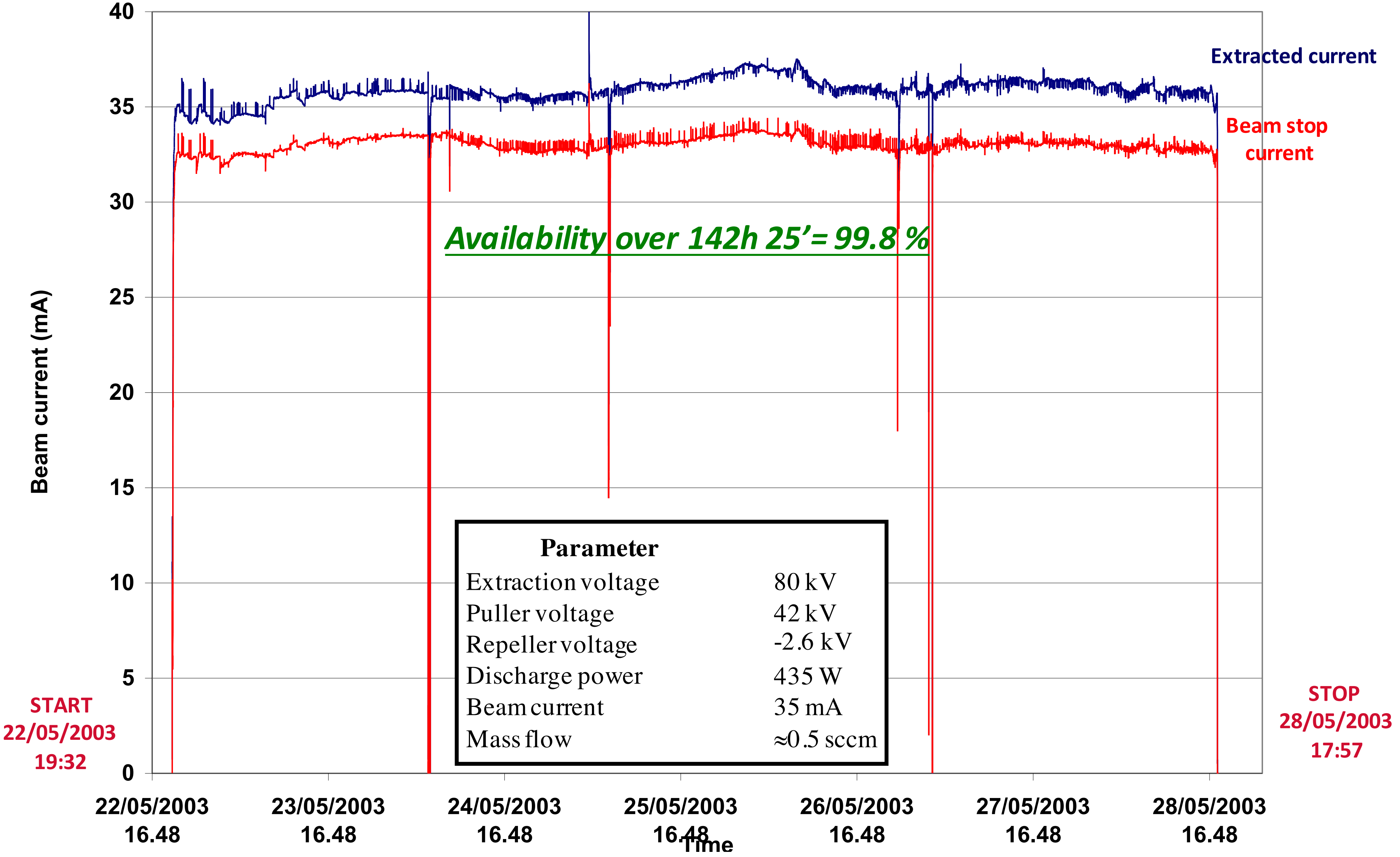
$p=1.8\cdot10^{-5}$ T$\Rightarrow$ **ε_{RMS}=0.335 π mm mrad**

Emittance plot (99%) injecting 84Kr in the beam line:

$p=3.0\cdot10^{-5}$ T$\Rightarrow$ **ε_{RMS}=0.116 π mm mrad**

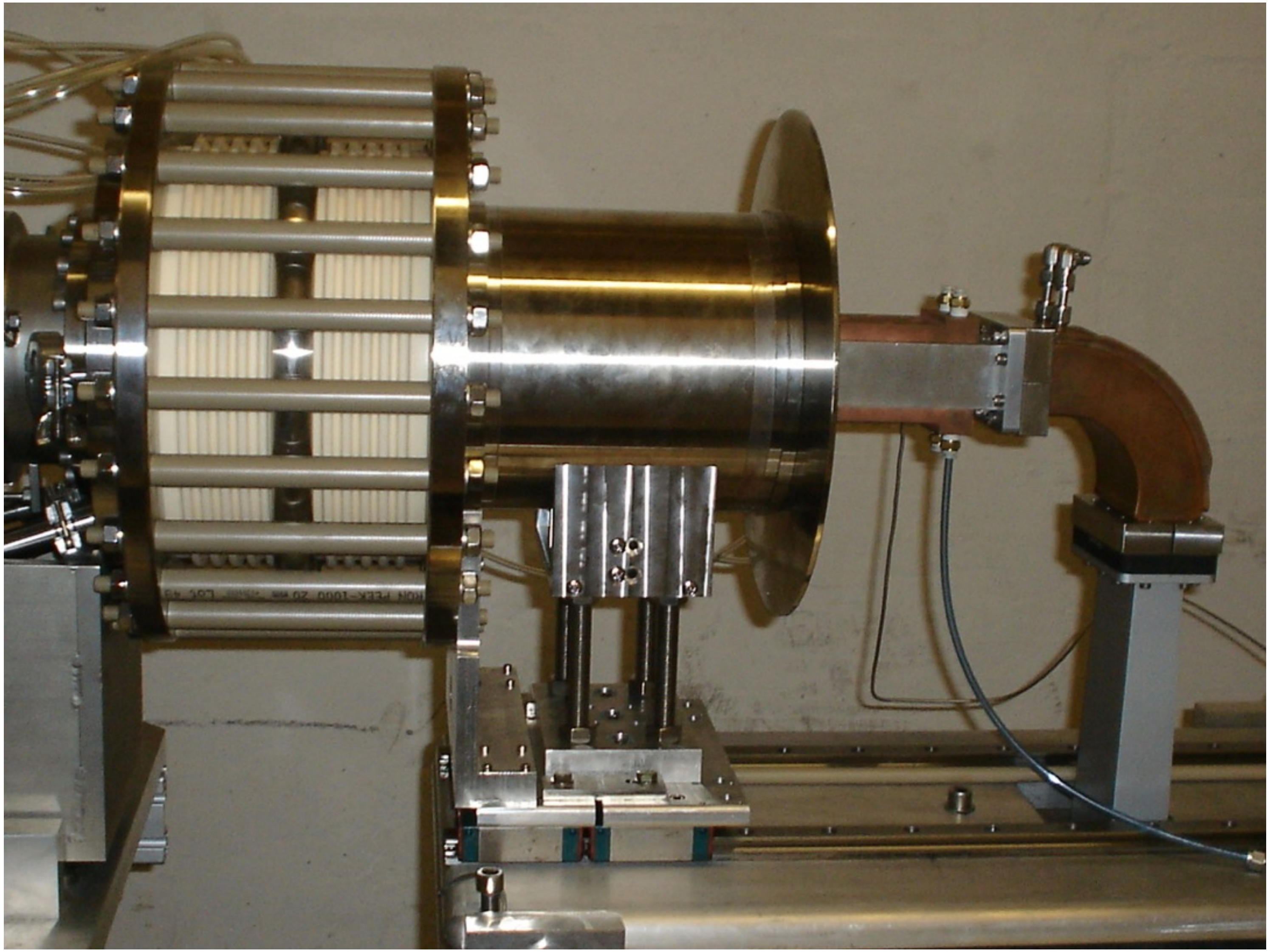
R. Gobin, R. Ferdinand, L.Celona, G. Ciavola, S. Gammino, Rev.Sci.Instr. 70(6),(1999), 2652

TRIPS reliability test: 35mA @ 80kV

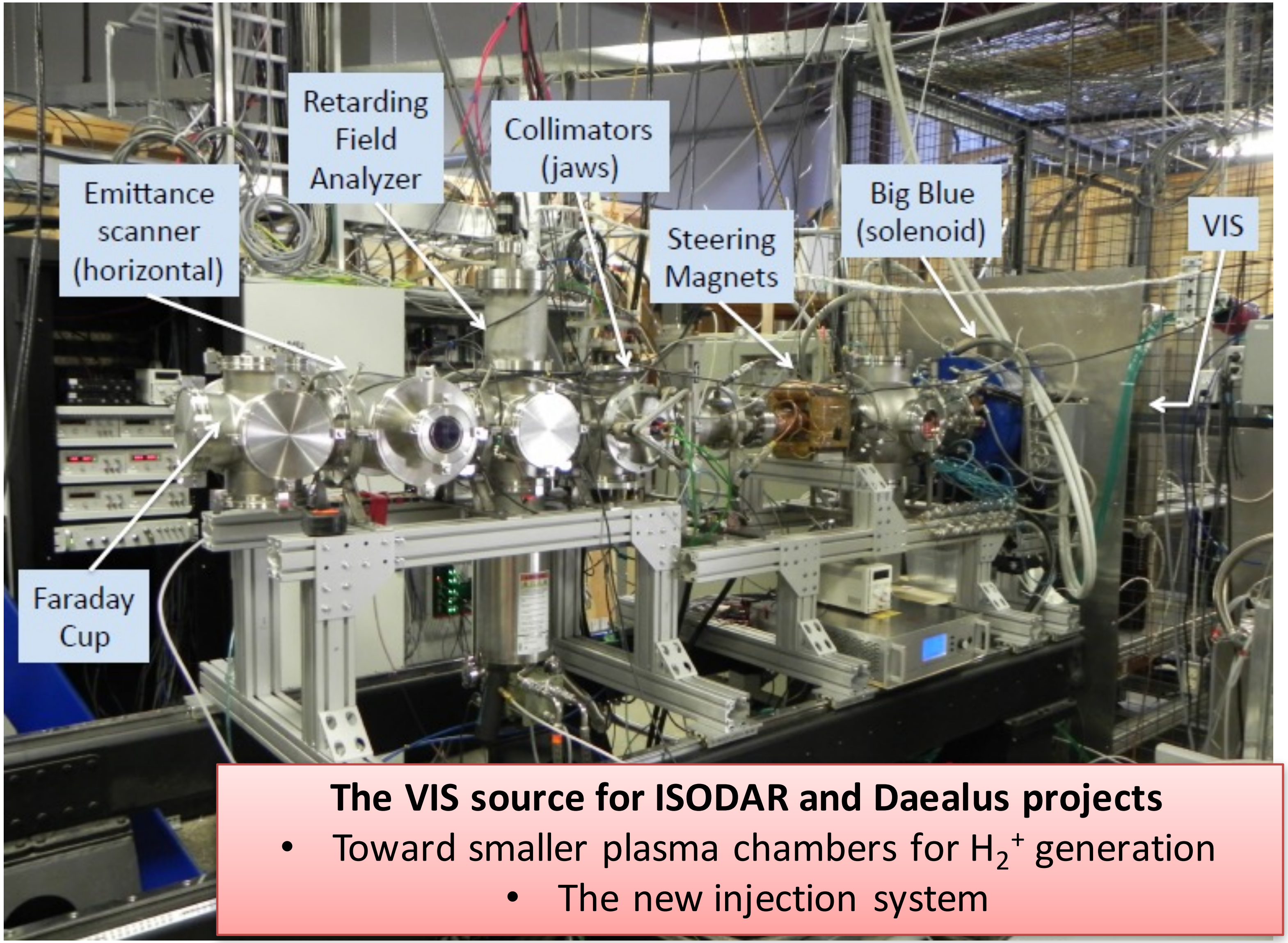


Parameter	
Extraction voltage	80 kV
Puller voltage	42 kV
Repeller voltage	-2.6 kV
Discharge power	435 W
Beam current	35 mA
Mass flow	≈0.5 sccm

Versatile Ion Source (2008)



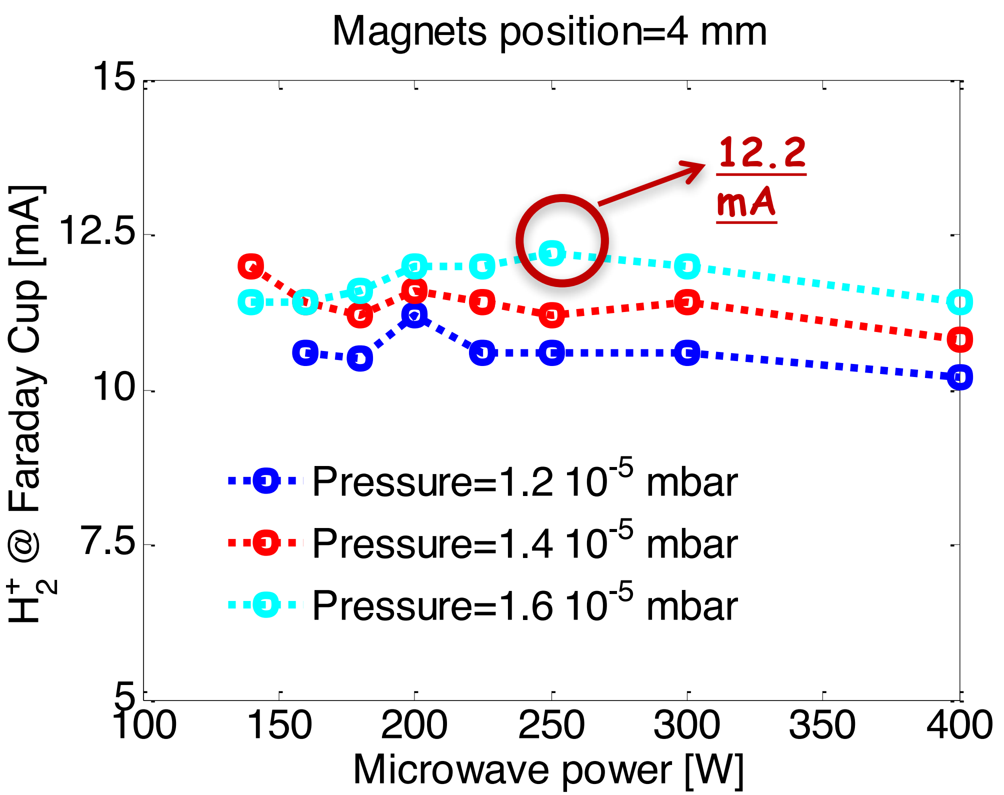
VIS test configuration



The VIS source for ISODAR and Daealus projects

- Toward smaller plasma chambers for H_2^+ generation
- The new injection system

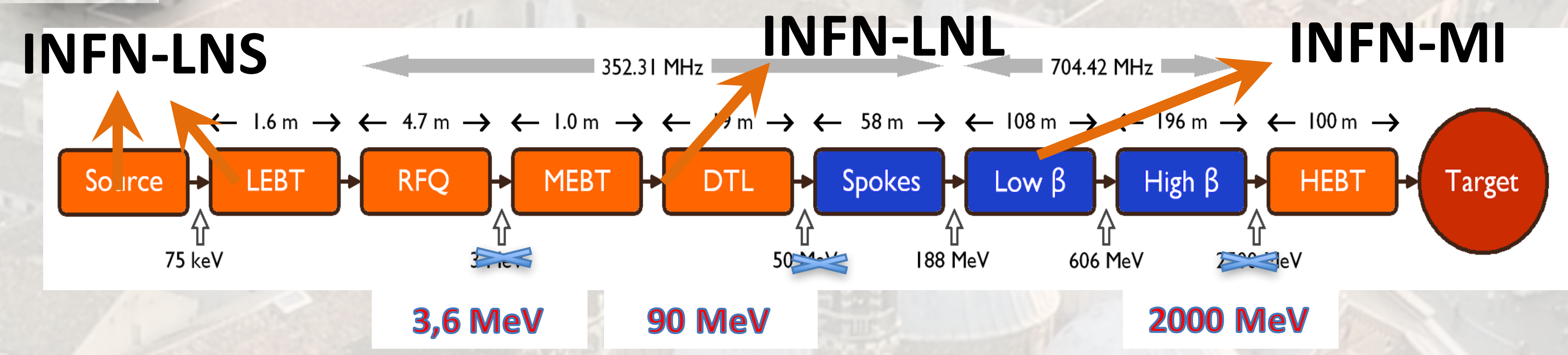
Test Results



12.2 mA H_2^+ absolute maximum obtained during tests

- 9 -------->12.2 mA H_2^+ maximum beam @F.C.
- + 35% total improvement w.r.t. standard VIS chamber
- 75% transmission factor implies source generates >16 mA H_2^+ beam

INFN contribution to the European Spallation Source



INFN is in charge of the management of the WP3-Normal Conducting Linac

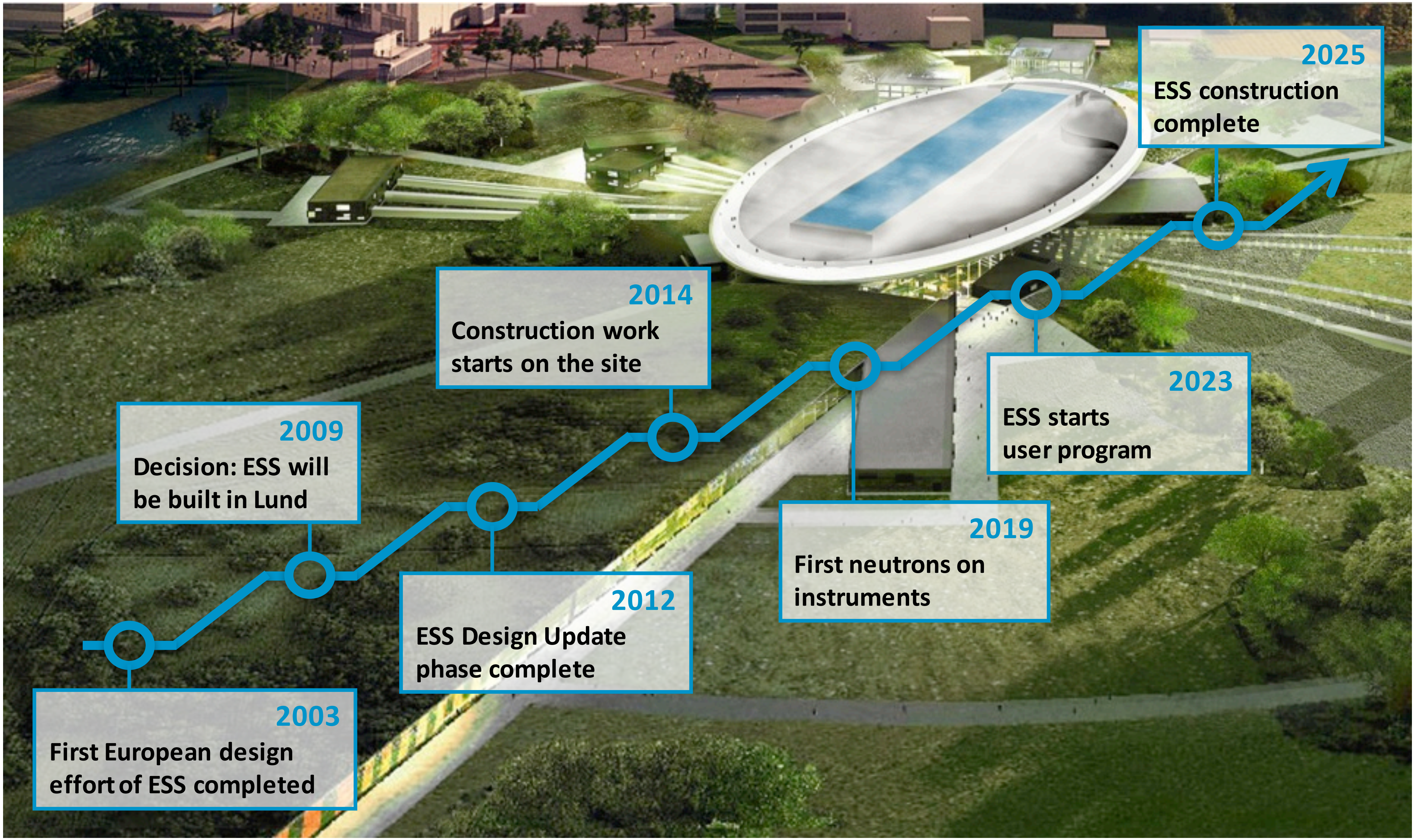
1. **Ion Source & LEBT (INFN-Laboratori Nazionali del Sud, Italy),**
2. **RFQ (CEA-IRFU, France),**
3. **MEBT (ESS Bilbao, Spain)**
4. **Drift Tube Linac with some diagnostics (INFN-Laboratori Nazionali di Legnaro, Italy)**

and of the in-kind contributionof :

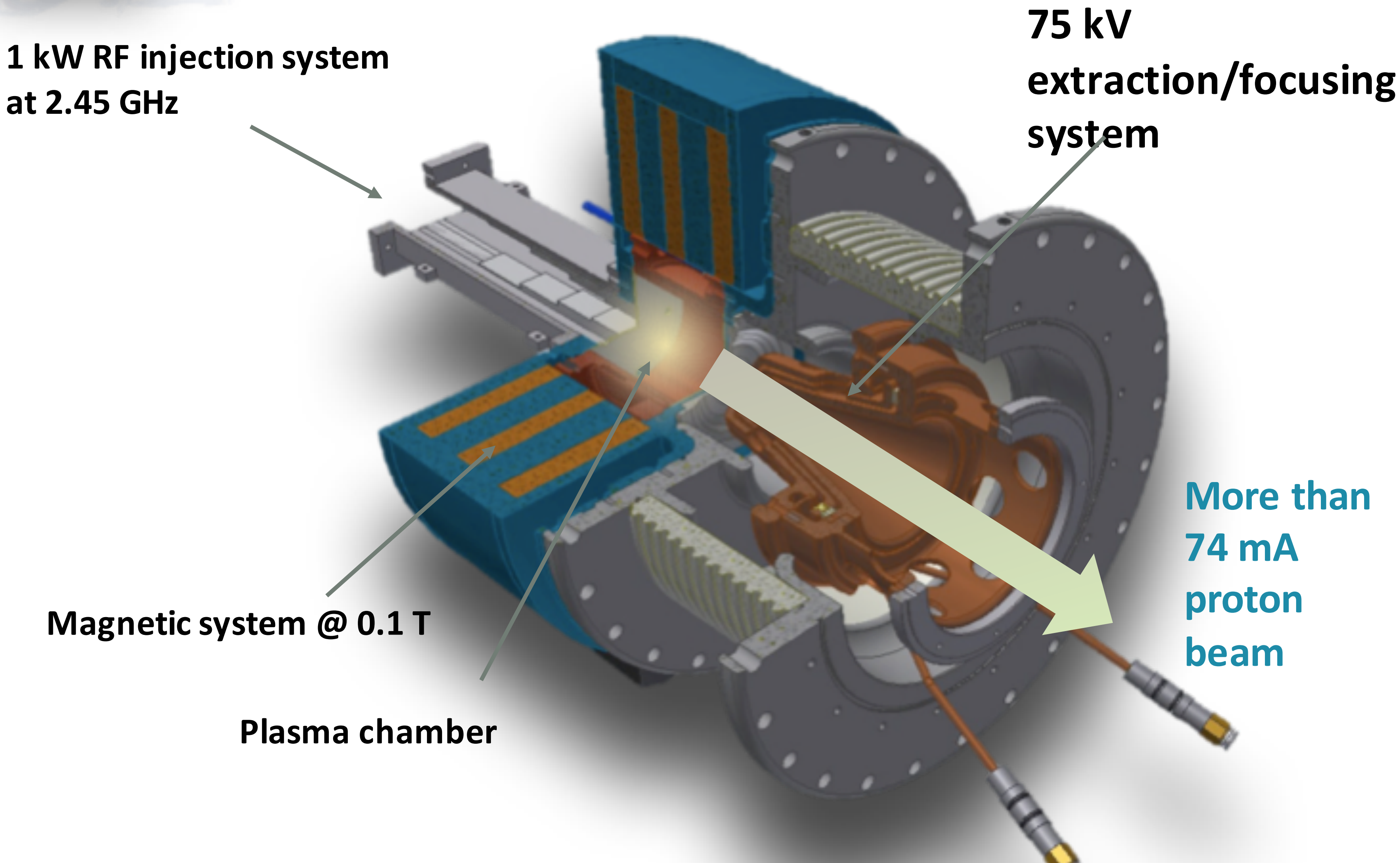
5. **superconducting elliptical cavities for WP5:** INFN is involved in the design and construction of SC elliptical cavities of medium beta section (Milan-Lasa)

→ know-how for ESS construction, industrial background for series construction

Road to realizing the world's leading facility for research using neutrons



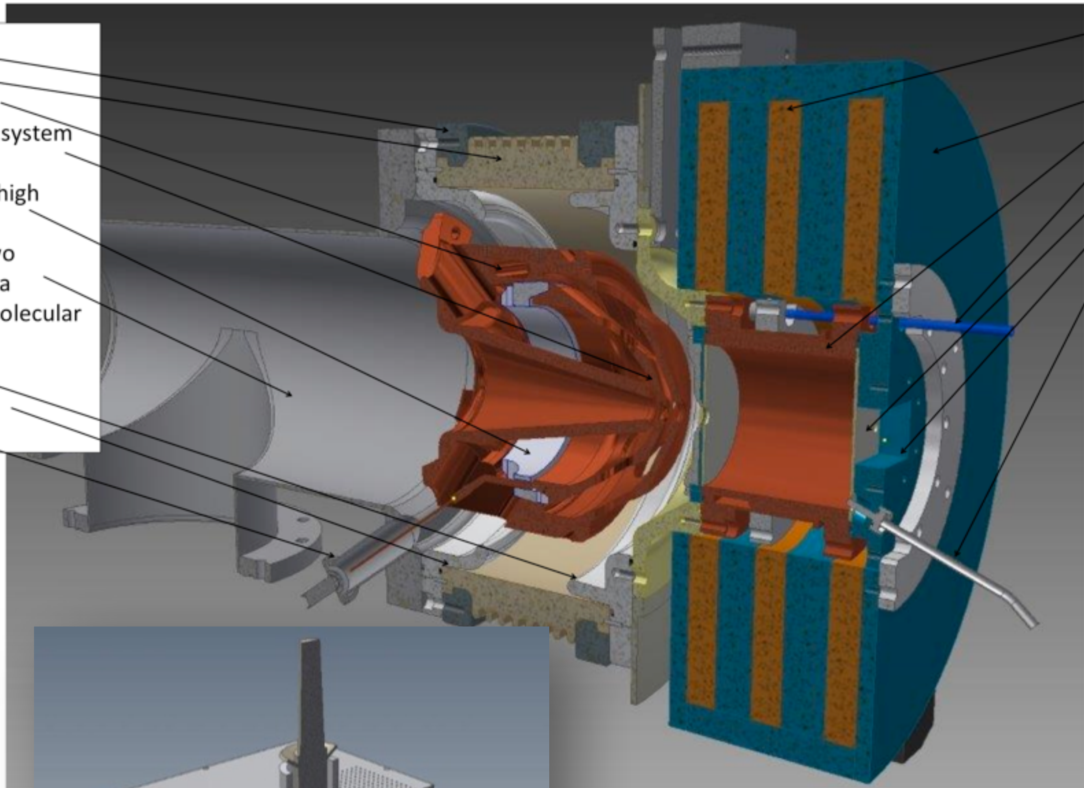
The proton source for ESS accelerator



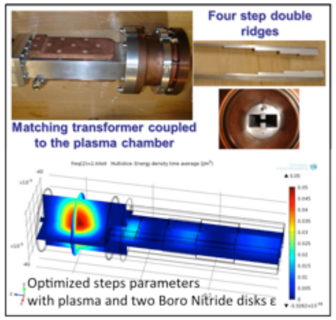
It is possible to envisage the use of such high intensity beams for direct measurements of nuclear astrophysics interest in the < 100 keV range

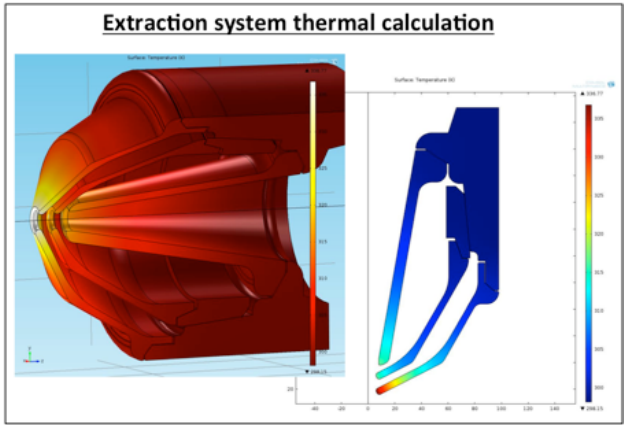
The high intensity proton source for the European Spallation Source

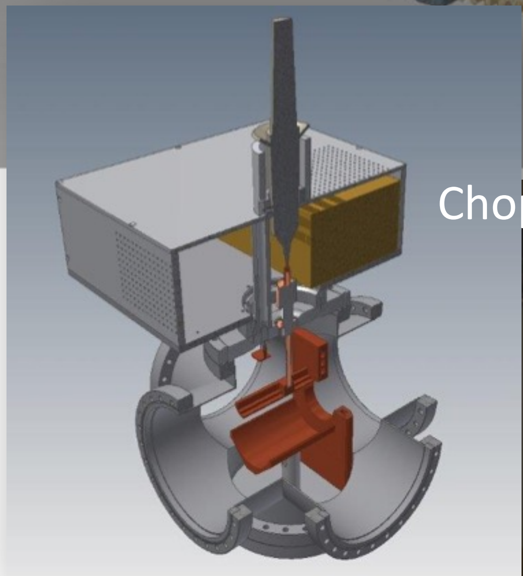
- Peek
- Alumina
- Electrodes water cooling
- Four electrodes extraction system (75 , 0 , -3 , 0 [kV])
- AlN electric insulator with high thermal conductivity
- First LEBT segment with two emittance measurements, a Faraday cup and a turbo molecular pump
- X-ray protection
- Triple point new geometry
- -3kV connection

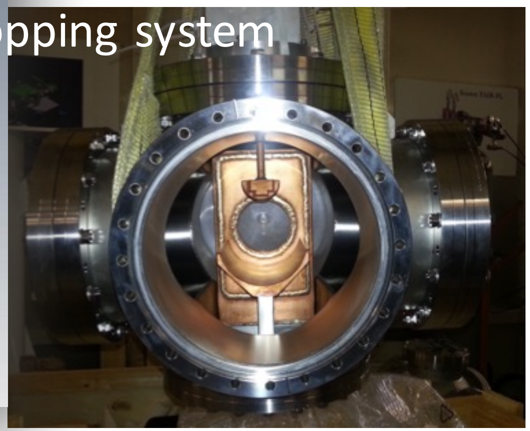


- Three coils magnetic system to test new plasma heating mechanism
- ARMCO magnetic shielding
- Copper plasma chamber
- Water cooling
- Two plasma chamber ends with BN disks
- Microwave injection
- Gas injection



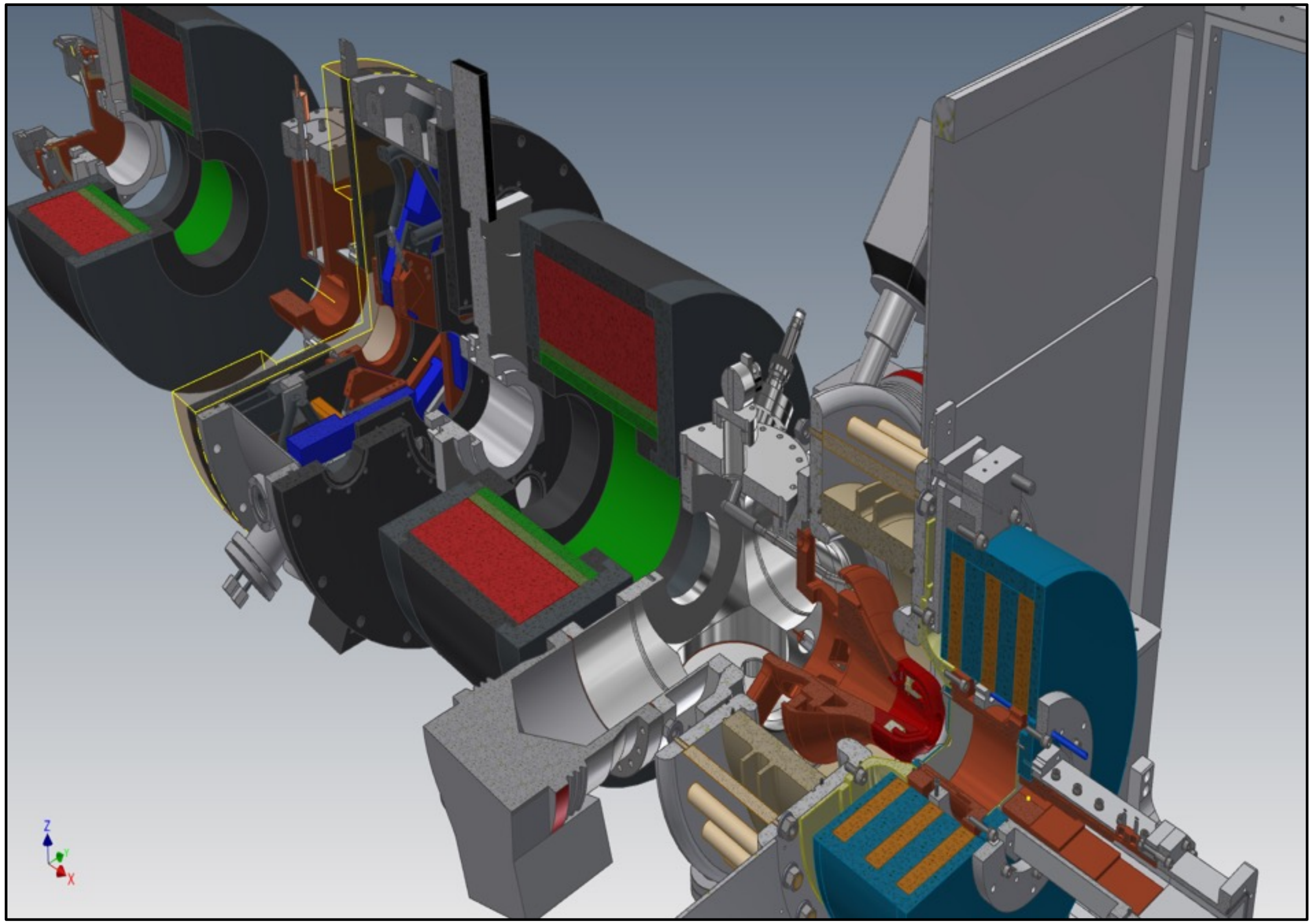






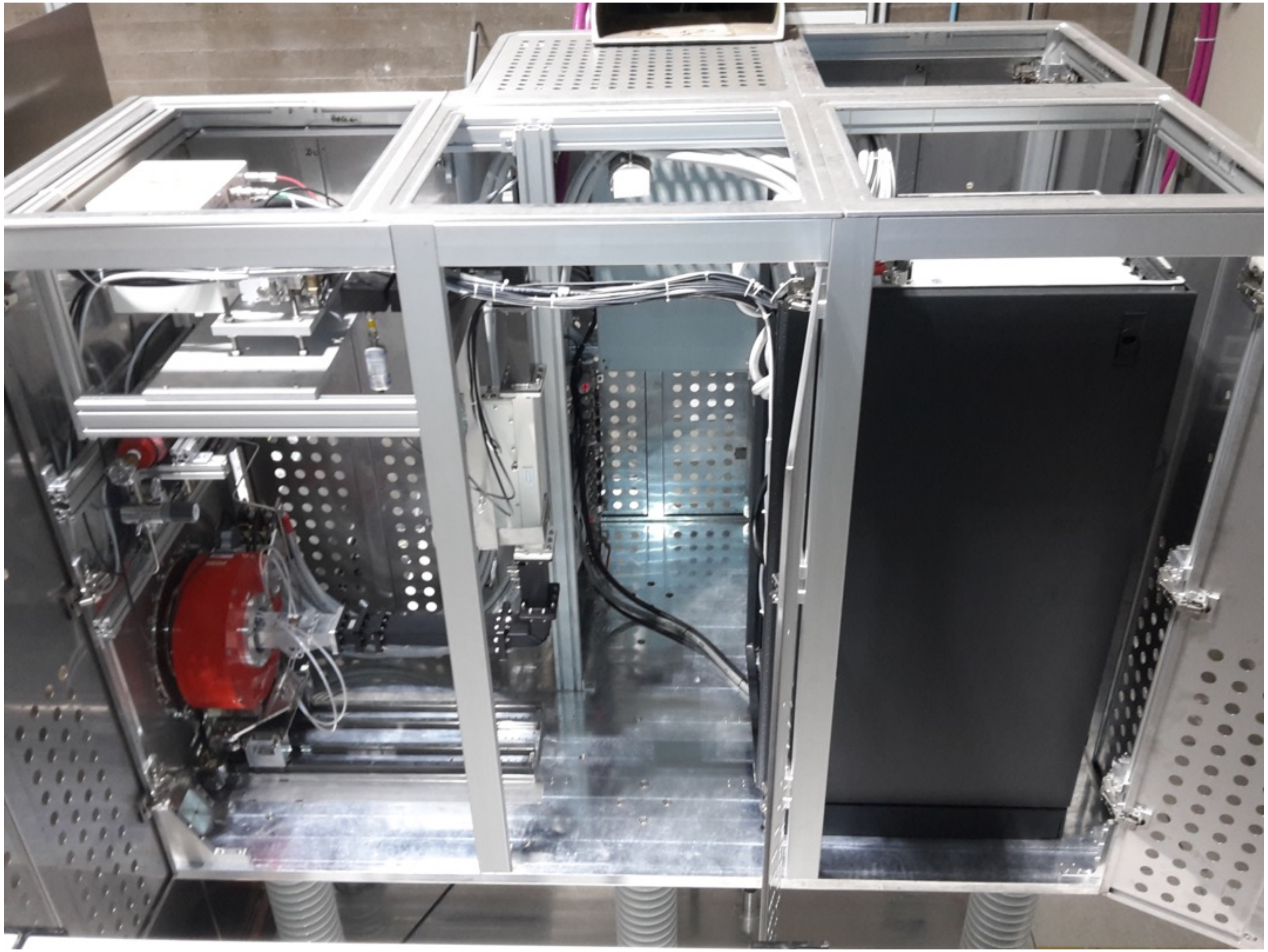
TO BE COMPLETED IN 2016: OK

Ion Source & LEBT



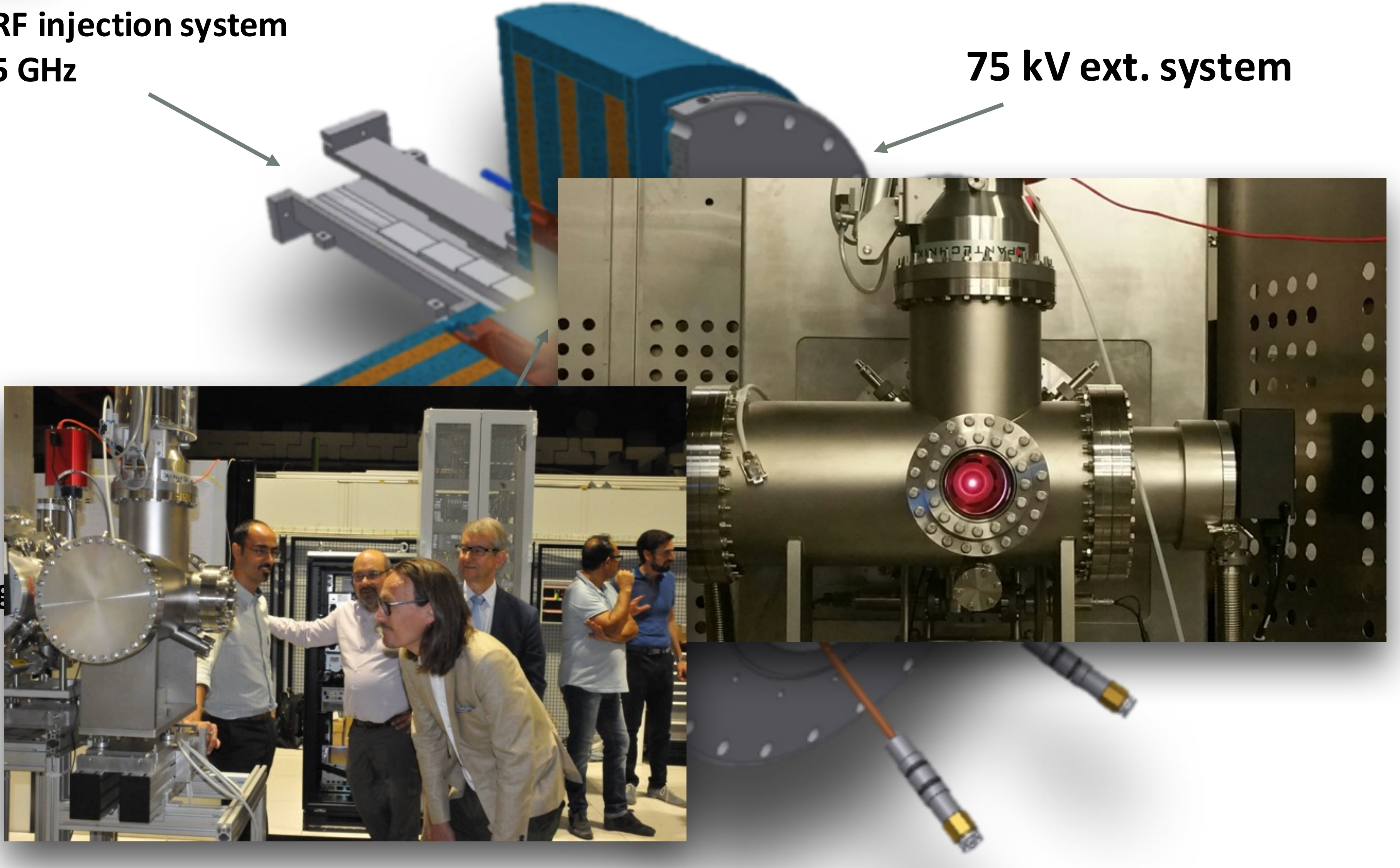
- Maximum proton beam current at the target: 62.5 mA (>90 mA of source's output current)
- Pulse during neutron production: 2.86 ms
- Beam Stability: ±2.5%
- Beam emittance 0.25 π mm mrad
- The peak beam current must be variable from 6.3 mA to 62.5 mA (step size of 6.3 mA, precision of 1.6 mA)

PS-ESS and LEBT
05/08/2016



Source completed
Control system to be completed within end of September

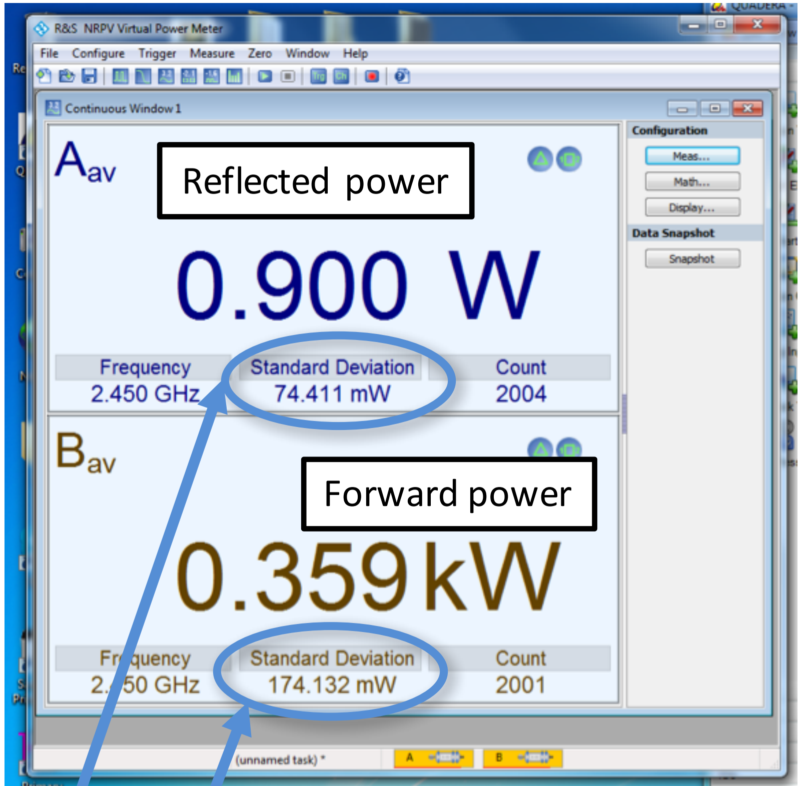
The proton source for ESS accelerator



First Plasma ignited in June'16, first beam one week ago...

Measurement of RF power to plasma matching

Software interface of the two RF probes



Reflected power

Forward power

Standard Deviation

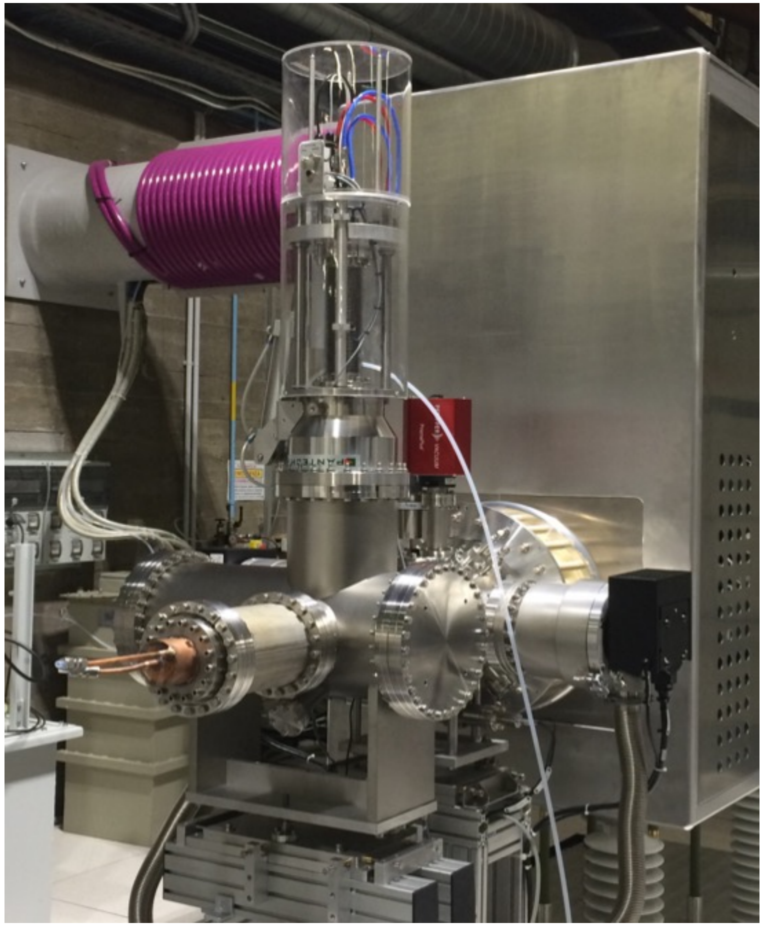
RF probes

Directional couplers

First plasma 15/06/2016

Phase 1: IS with FC and DSM
Phase 2: Phase 1 + EMU

Beam performance	Value	Measurement device
Maximum beam current	> 90 mA	FC
Nominal proton beam current	74 mA	FC
Pulse length	3 ms	
Pulse length maximum	6 ms	
Flat top stability	±2 %	
Pulse to pulse stability	±3.5 %	
Repetition rate	14 Hz	
Repetition rate range	1-14 Hz, 1 Hz step	
Pulse length range	1 ms - 3 ms	
Recovery after 5 s downtime	1 pulse	
Proton fraction	> 75 %	DSM
Beam energy	75 keV	HV power converter
Beam energy fluctuation	± 0.01 keV	
Energy adjustment range	± 5 keV	
Energy adjustment precision	± 100 eV	
Transverse emittance (99 %) at IS-LEBT lattice interface	1.8 µm	EMU
Beam divergence (99 %) at IS-LEBT lattice interface	80 mrad	
Beam alignment at solenoid 1	±0.5 mm	
Beam center offset at IS-LEBT lattice interface	±0.1 mm	
Beam angle offset at IS-LEBT lattice interface	±1 mrad	

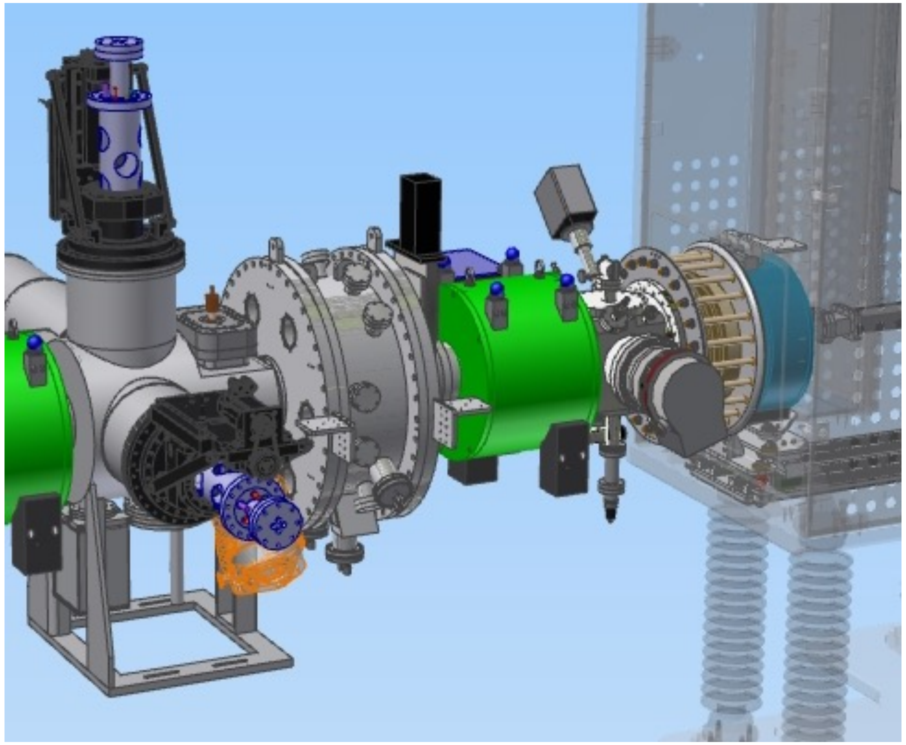


Study of different parameters:

- Insulating/conductive plasma walls
- Magnetic configuration
- Extraction geometry
- Gas injection
- Pressure

Phase 3: beam characterization after the first solenoid

Beam performance	Value	Measurement device
Beam current range	7-74 mA	Faraday cup
Beam current range step size	2 mA	
Beam current precision	±1 mA	
Orbit control with respect to beam axis	±0.5 mm	NPM
Transverse emittance	–	EMU
Beam center offset	–	
Beam angle offset	–	

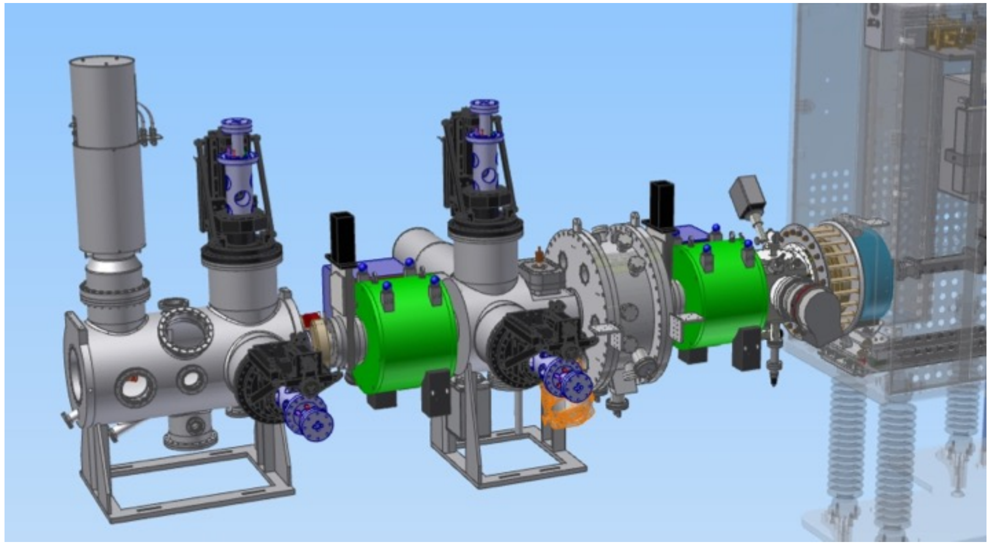


Study of different parameters:

- Addition LEBT gas injection
- LEBT pressure
- Solenoids configuration
- Repelling electrodes voltage

Phase 4: beam characterization at the LEBT-RFQ lattice interface

Beam performance	Value	Measurement device
Nominal beam current	74 mA	ACCT / Faraday cup
Beam current transmission	95 %	
Pulse length	2.86 ms	
Maximum pulse length	2.88 ms	
Pulse length range	0.005-2.88 ms	
Single pulse production	–	
Transmission of transient	>1 %	
Transverse emittance (norm, rms) at LEBT-RFQ lattice interface	0.25 μm	EMU
Transverse emittance (99 %) at LEBT-RFQ lattice interface	2.25 μm	
Beam alignment at LEBT-RFQ lattice interface	±0.1 mm	
Transverse twiss α at LEBT-RFQ lattice interface	1.02 ± 20 %	
Transverse twiss β at LEBT-RFQ lattice interface	0.11 mm ± 10 %	



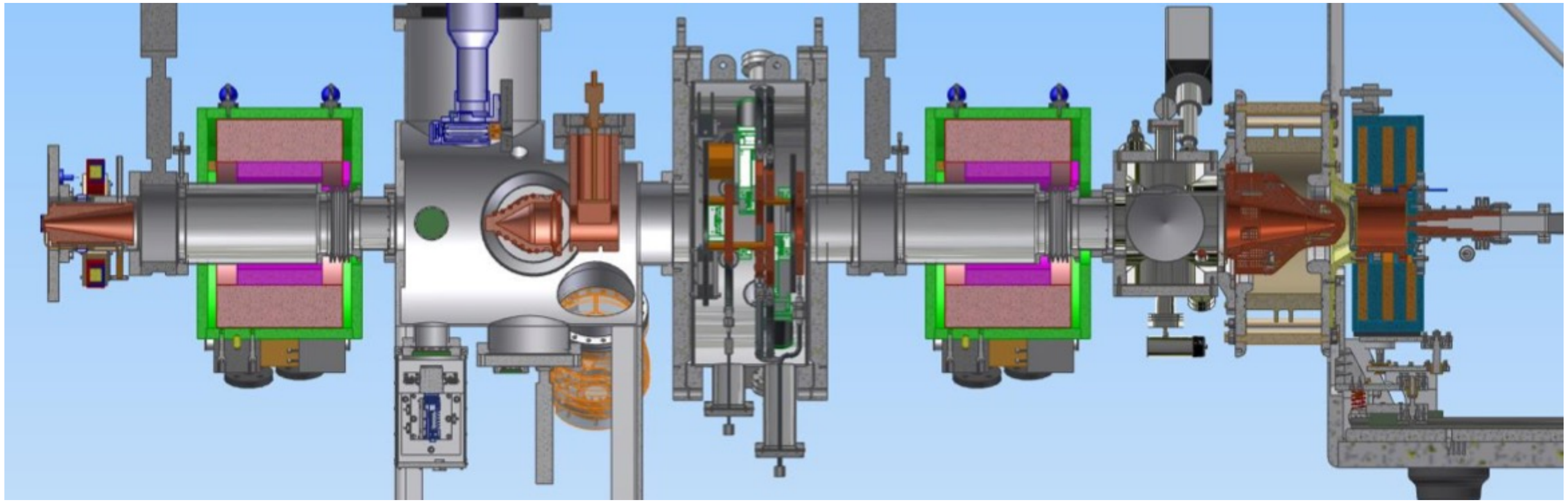
Study of different parameters:

- Addition LEBT gas injection
- LEBT pressure
- Chopper voltage and rise/fall time speed
- Solenoids configuration
- Repelling electrodes voltage

Phase 5: long duration tests (to be completed after RFI)

Consists of several tests:

- study the long-term reliability of the ion source and define which parts get degraded over time,
- study the current range that can be produced by the ion source (6-74 mA, ISrc.SyR-13),
- analyze potential beam trips to evaluate and prevent downtime,
- define a sequence for an automatic start-up of the ion source,
- simulate the time needed to restart the ion source after shut down (16 hours, ISrc.SyR-14),
- simulate the time needed to restart the ion source after maintenance, such as replacing the boron nitride disks (32 hours, ISrc.SyR-15),
- ensure that the different beam requirements can be satisfied at the same time (ISrc.SyR-22, LEBT.SyR-20),
- improve the design (for example of the extraction system) and ion source and LEBT settings to ensure that the requirements settled are satisfied.



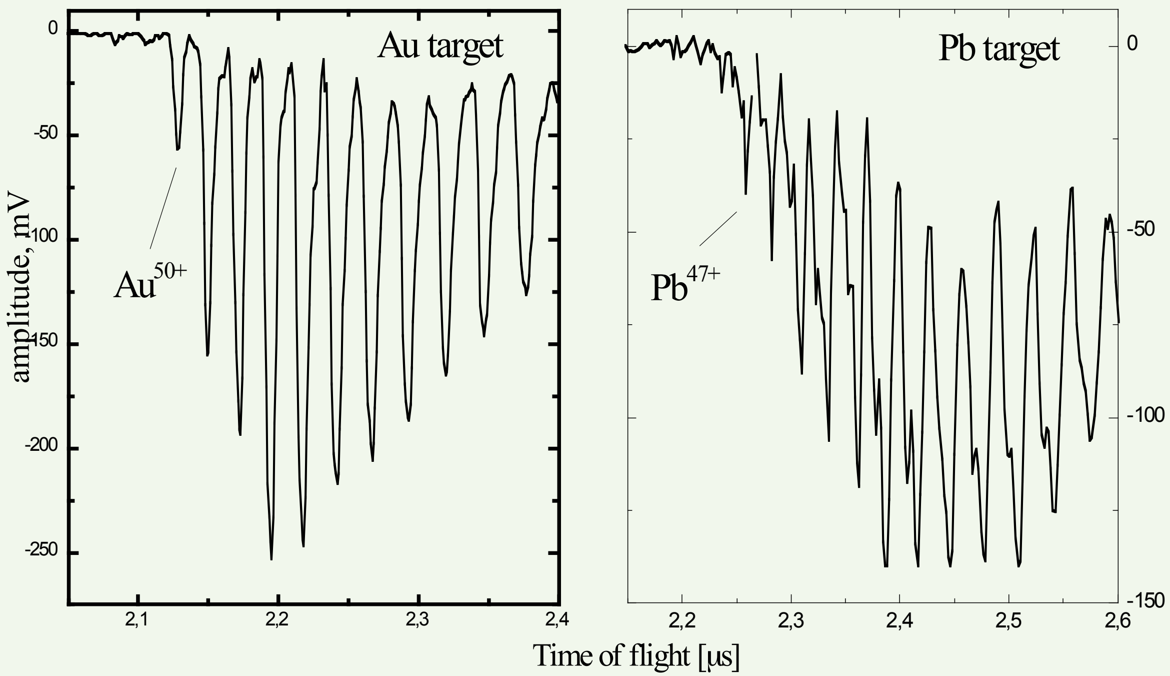
PS-LEBT updated schedule

Feb. 10th, 2015	**Successful CDR**
March to Nov., 2015	**Procurement (second phase)**
Dec. to May 20, 2016	**Tests of source components and ancillaries**
Jun to Nov, 2016	**Full tests of proton source with diagnostics&controls**
May'15 to May 2016	**LEBT Procurement**
Nov. 1st,2016	**Diagnostics available from ESS**
Nov, 2016 to Aug.'17	**Full tests with LEBT**
Nov. 1st, 2017	**First source ready for installation**
July, 16 to Mar,17	**Procurement PS#2**
Sept, 17 to Mar, 18	**Assembly PS#2**
Mar to Sept, 2018	**Tests with diagnostics and controls PS#2**
Nov, 2018	**Delivery PS#2**

To be evaluated: possibility to adapt the PS-ESS design for other needs

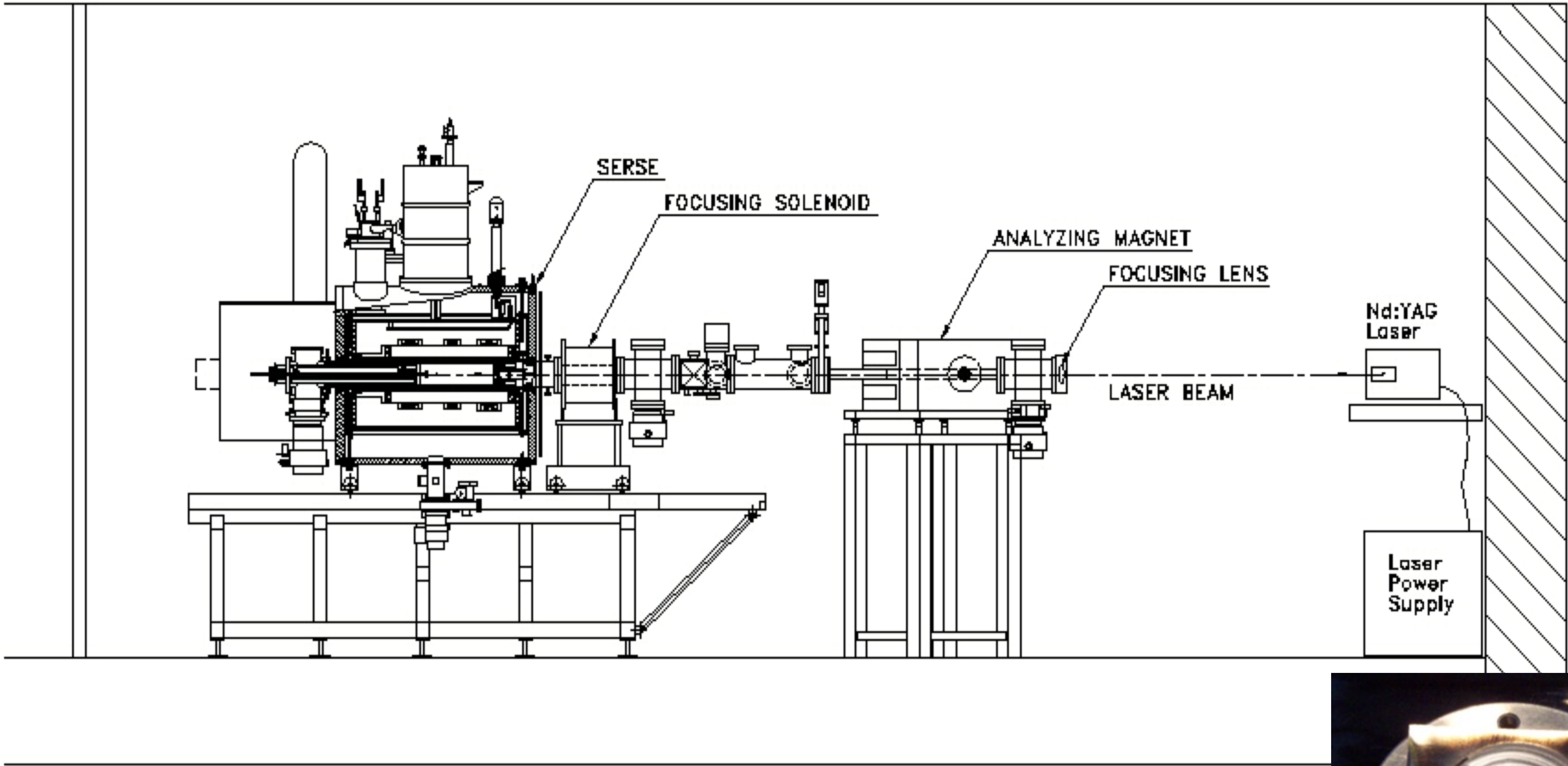
Laser Ion Sources

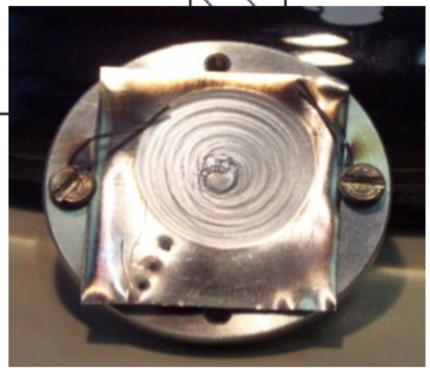
__LASER ION SOURCES__ have been used either to directly produce the highly charged ions and to produce Q<10+ ions that are injected into ECRIS for HCI productions



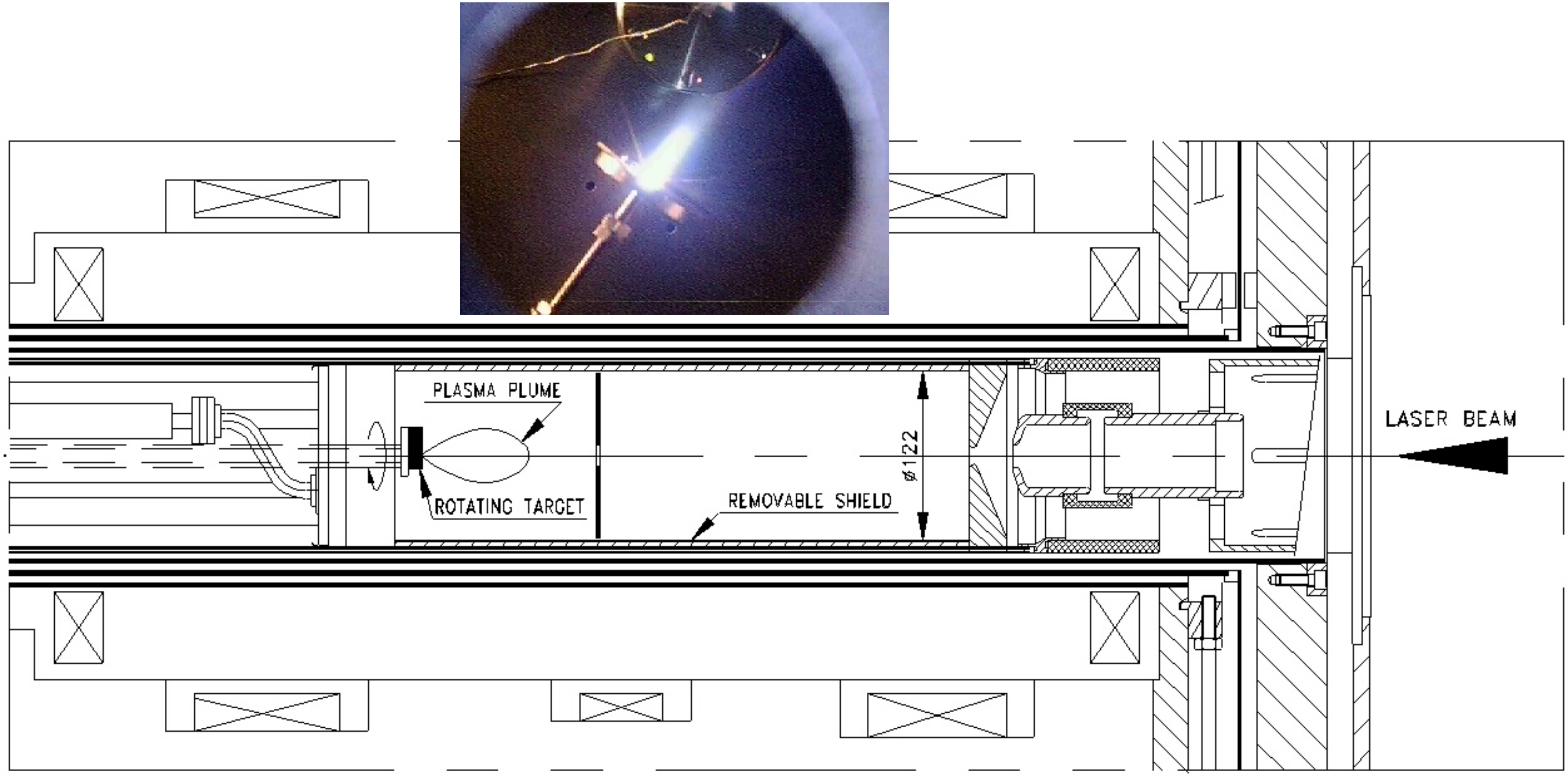
__Limits__ to the adoption of LIS as accelerators' injector:
Emittance, energy spread, reproducibility, stability

ECLISSE project:
The assembly of the hybrid source

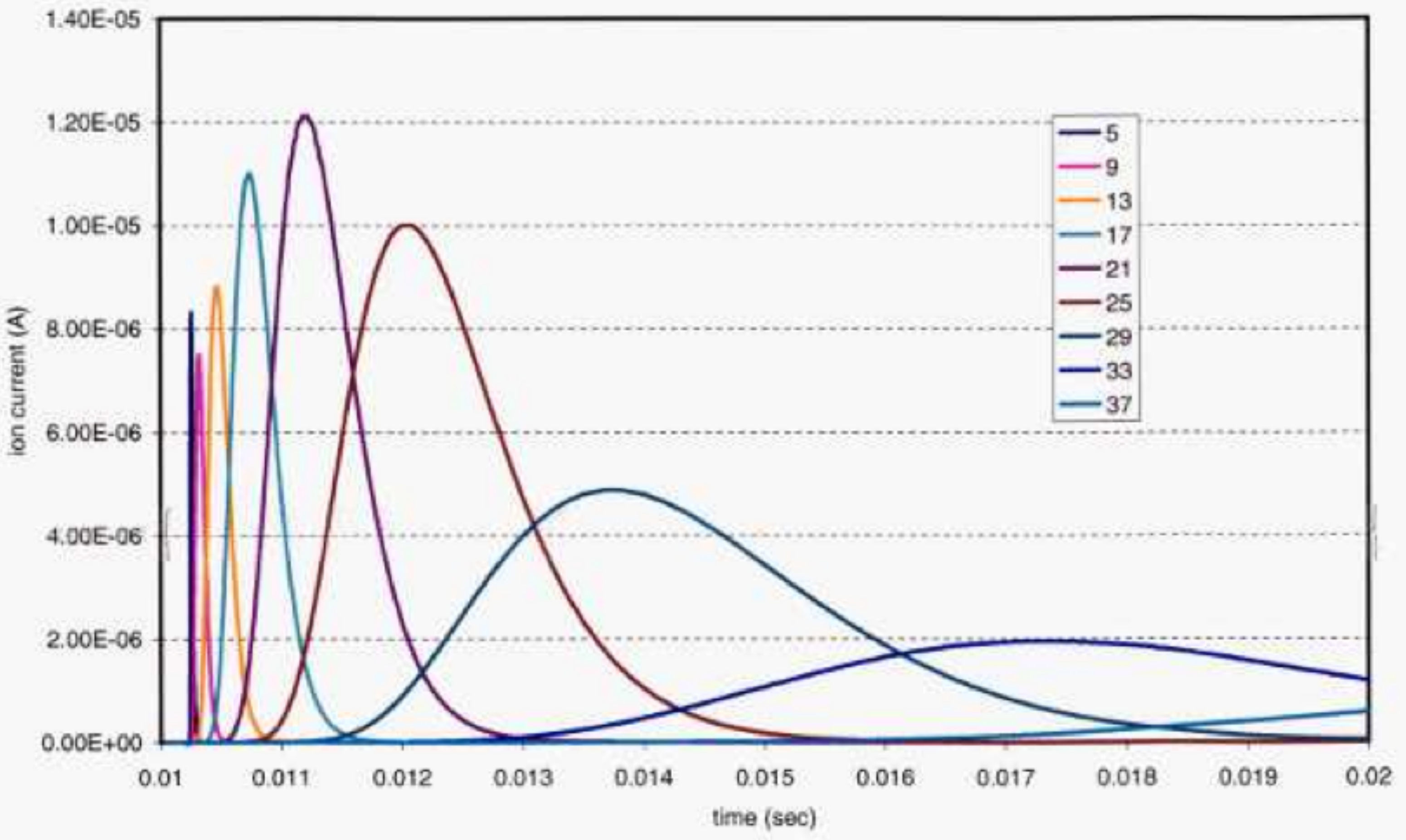




ECLISSE project:
a detail of the plasma chamber

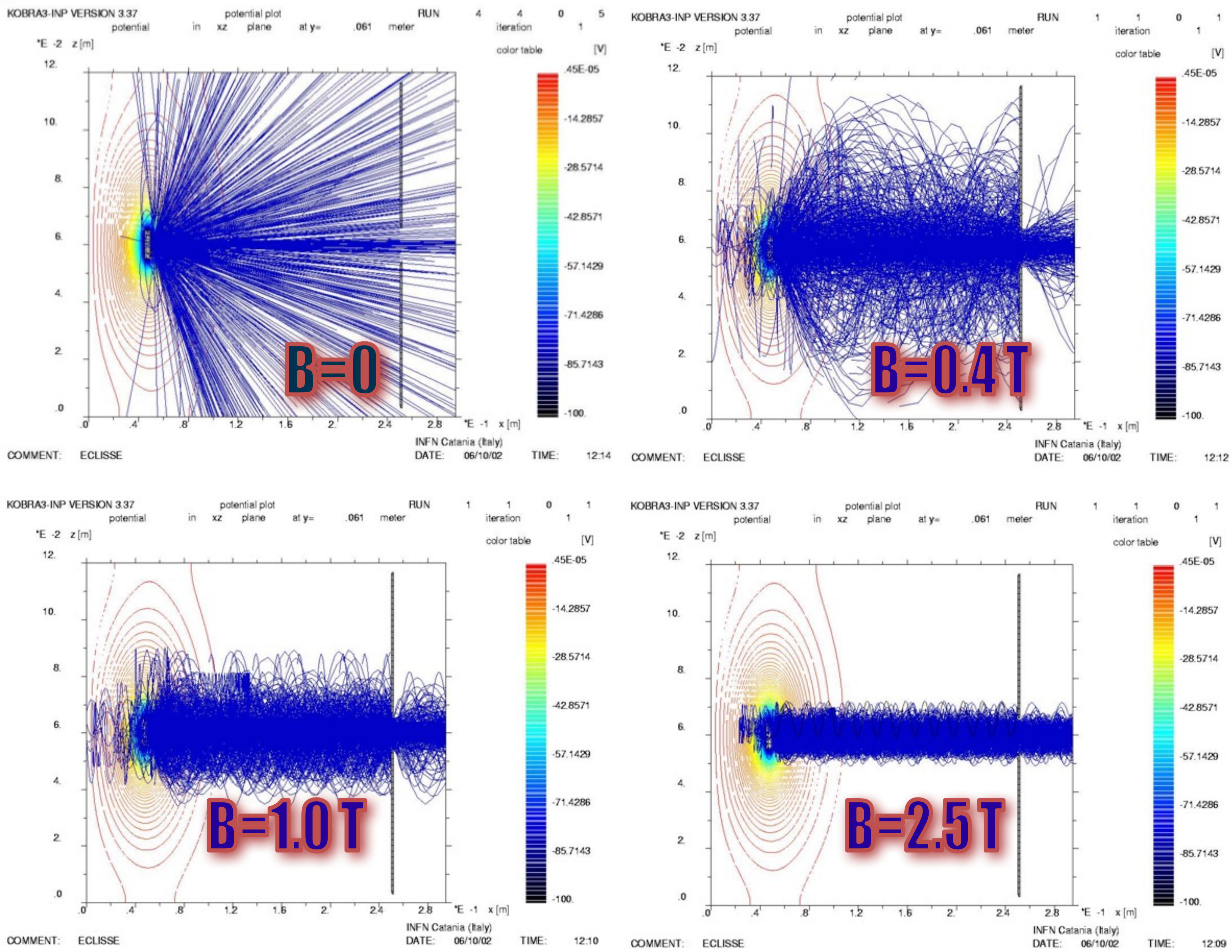


Numerical simulation of ion injection into the ECR source

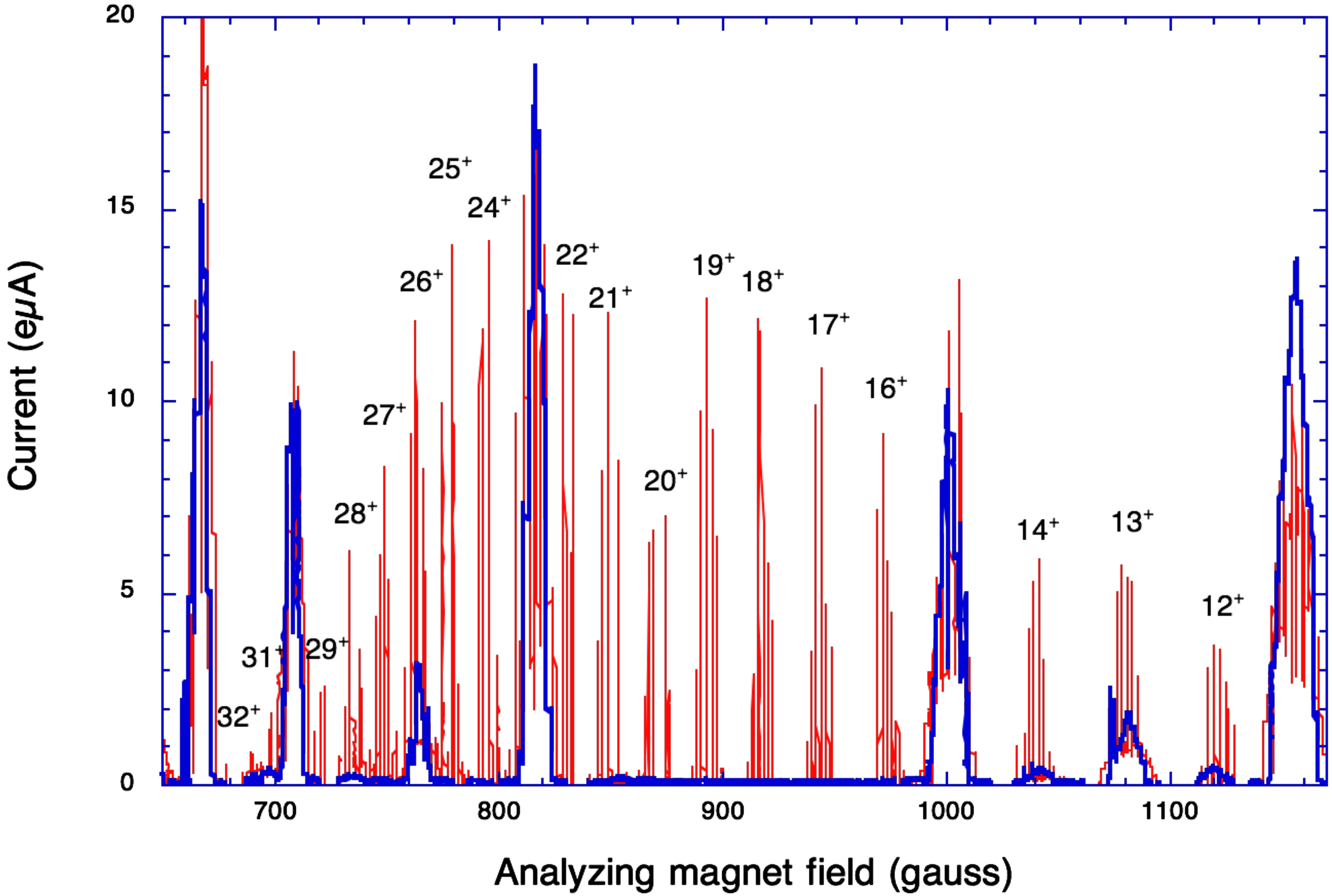


Tantalum ion production vs. time as expected from the ECLISSE experiment.

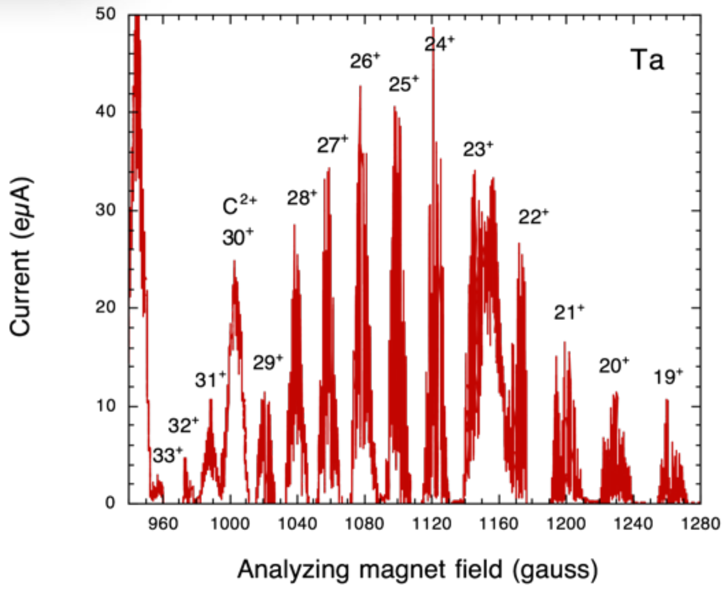
Ion focalization by magnetic field

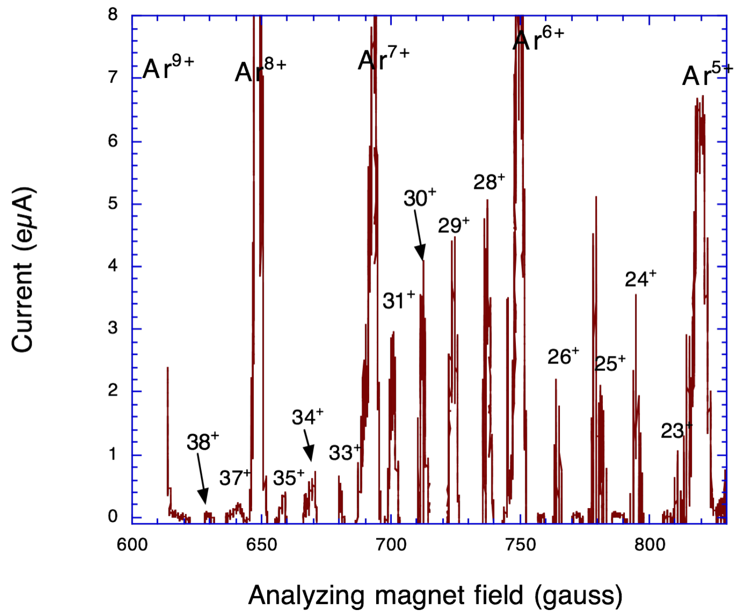


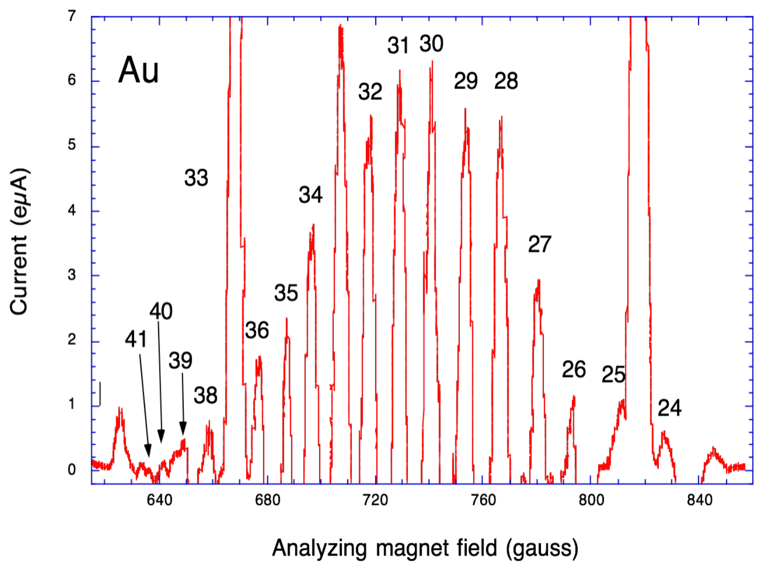
With LIS (red) and without LIS (blue)

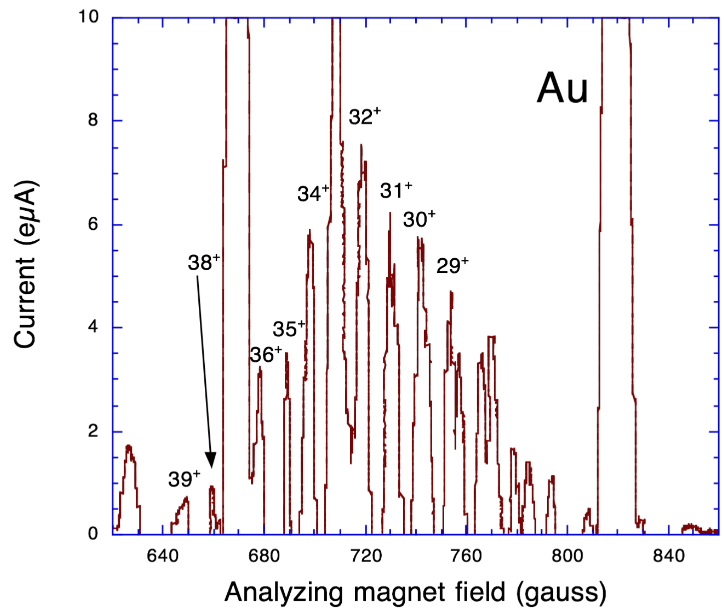


A few charge state distributions



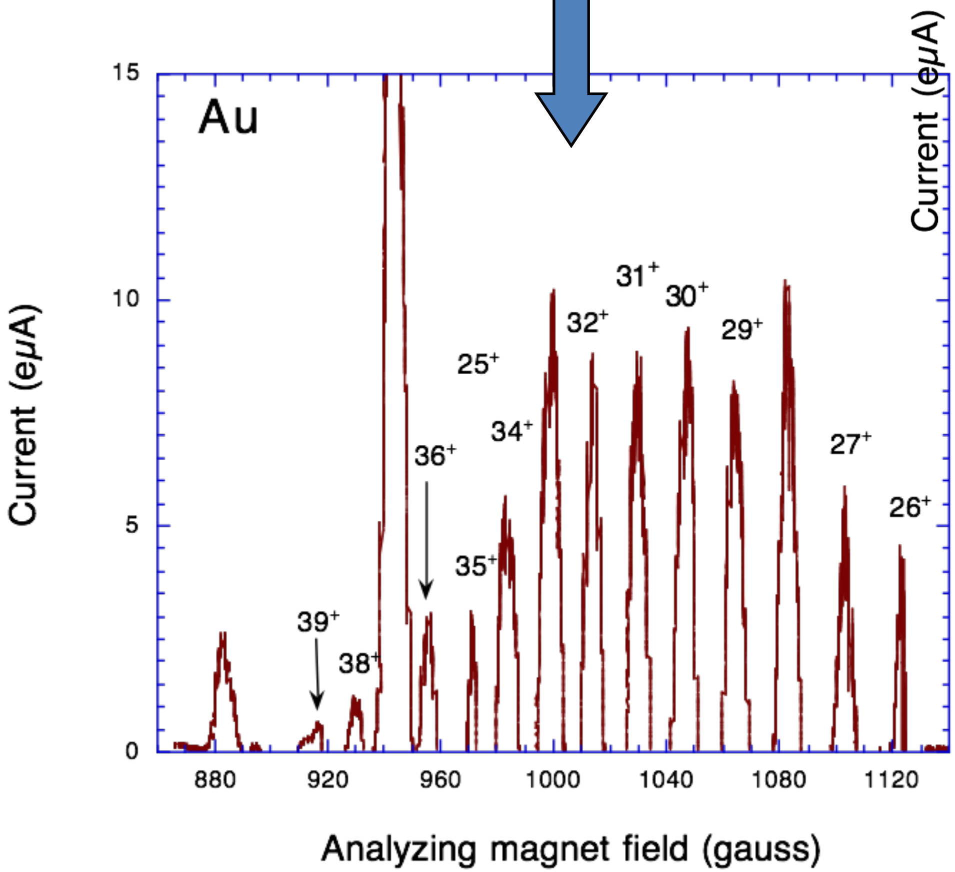


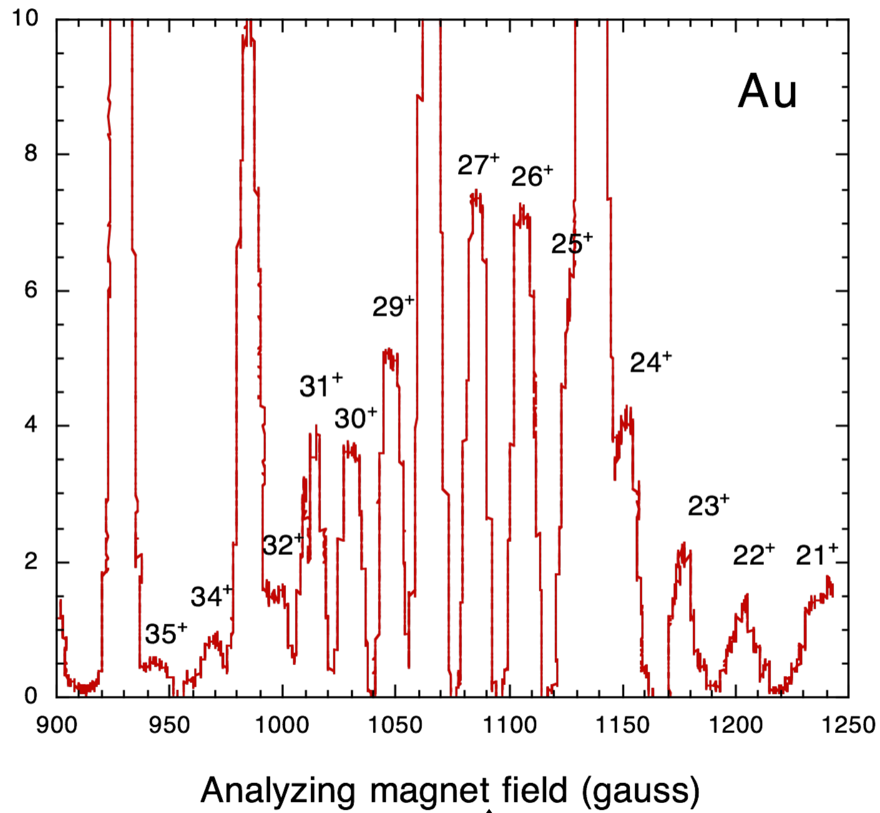




A few charge state distributions

Gold ions produced by LIS





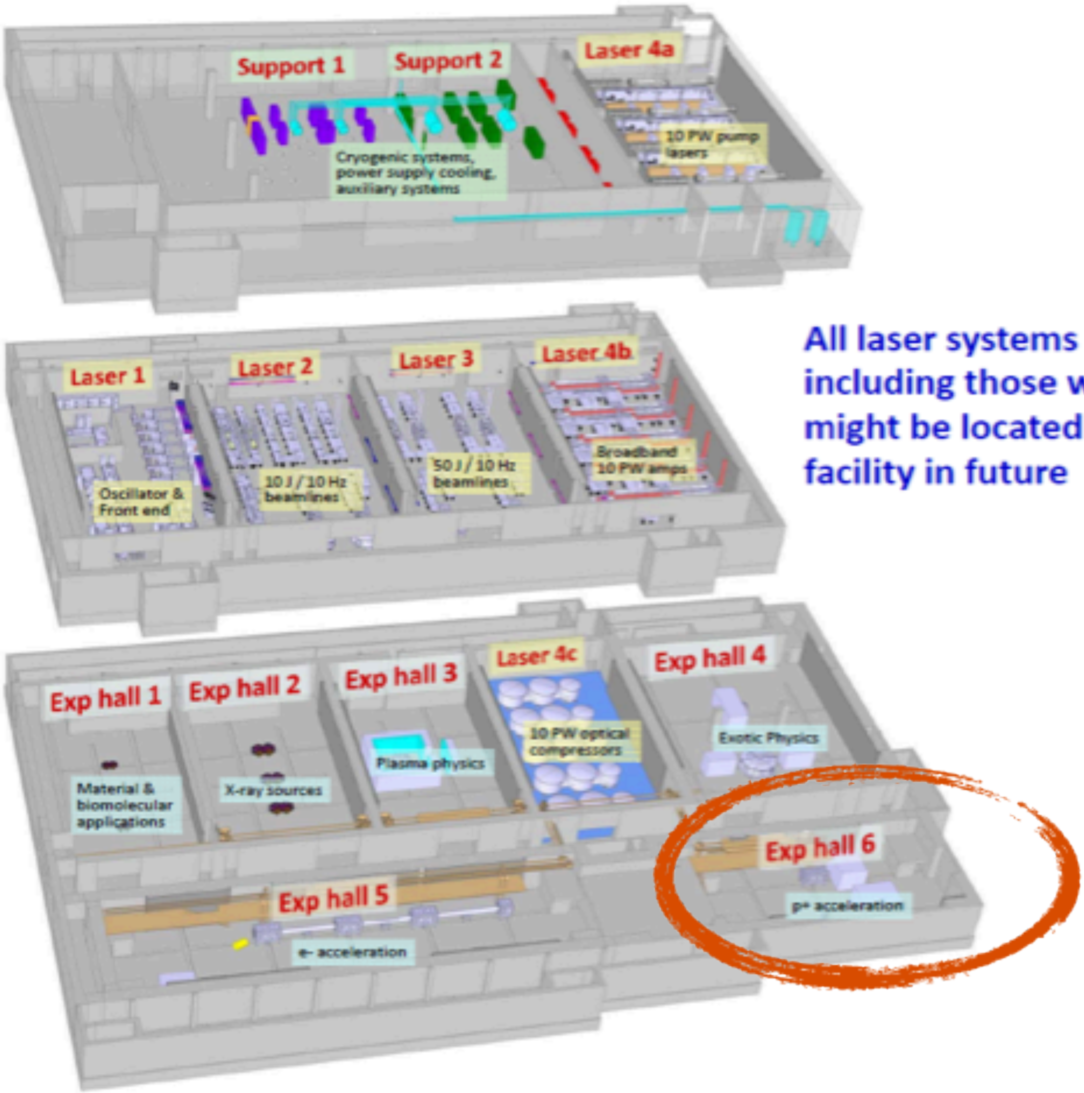
Gold atoms produced by oven

The ECLISSE method is the best one for refractory elements and for some others.

There are some advantages even for elements which can be obtained by conventional methods (oven, sputtering) but the complexity of the setup is too high.

$\Rightarrow$ A large gain can be obtained with 3rd generation ECRIS

Target and ELIMED areas



All laser systems shown, including those which might be located at the facility in future

Radiation therapy room site

Conclusions

A great to the field of positive ion sources have been carried out at INFN during last decades;

The impact of the achievements have been remarkable for many accelerator facilities worldwide and the networking with other R&D teams in other EU laboratories has been precious since '90s.

The amount of challenges in front of us, either for intense beams of highly charged ions and for hundreds of mA of protons and monocharged ions is breathtaking and plenty of ideas for further developments are in the agenda of the INFN researchers for this sake.

The cross-dissemination with other fields of physics and engineering is promising and maybe it will disclose new horizons in other disciplines