Recent development of Ion sources Science & Technology at INFN-LNS, Catania

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Catania - ITALY

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Istituto Nazionale di Fisica Nucleare (INFN)


Ettore Majorana

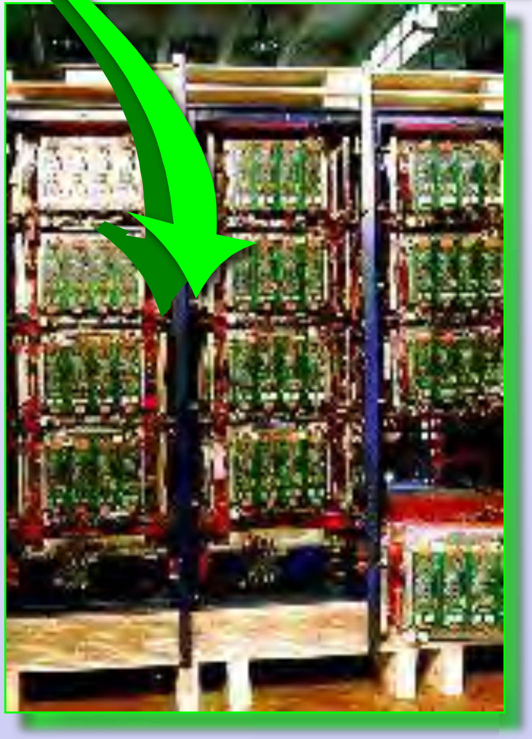
Since the foundation year (1951), it has been devoted to Nuclear and Particle Physics. During last 10 ys, the multidisciplinary applications of NP-PP has become relevant (detectors and accelerators are used in other fields)

ANVUR evaluatation (2004-10) recently placed INFN 1° among Italian research institutions


Enrico Fermi

Research

University



Industry

INFN Laboratories

4 National Laboratories (3 with accelerators), links worldwide

LN Frascati
- Nuclear & Particle Physics
- Nuclear Astrophysics

LN Legnaro
- Nuclear & Particle Physics
- Applications

LN Sud
- Fisica nucleare
- Nuclear Astrophysics
- Applications

LN Gran Sasso
- Cosmic rays
- Nuclear Astrophysics

INFN scientists contributed to the CERN, Geneva, since the early beginning and have had a major role in the major achievements including the Higgs Boson discovery

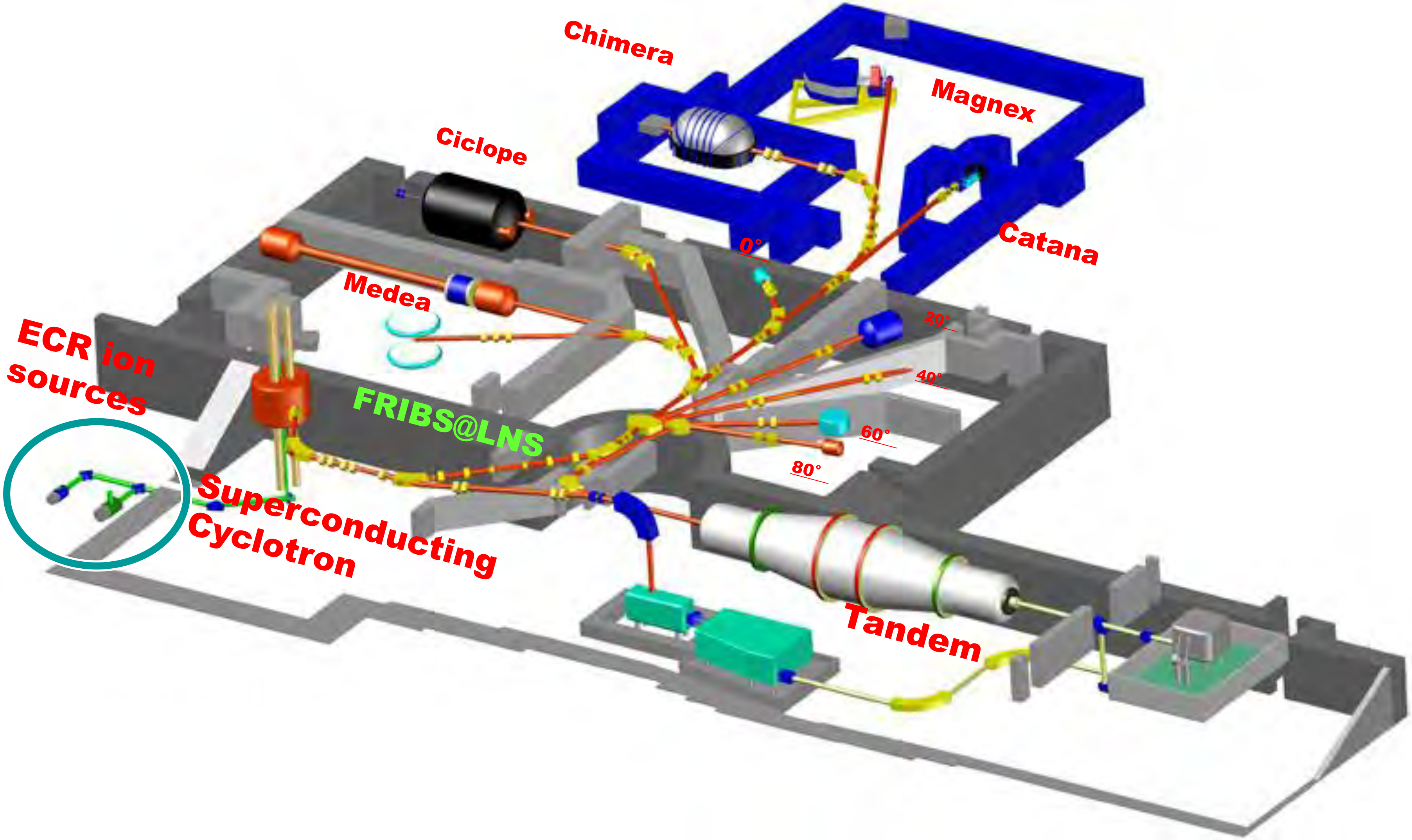
INFN - Laboratori Nazionali del Sud are located in the Catania University campus area

LNS in numbers

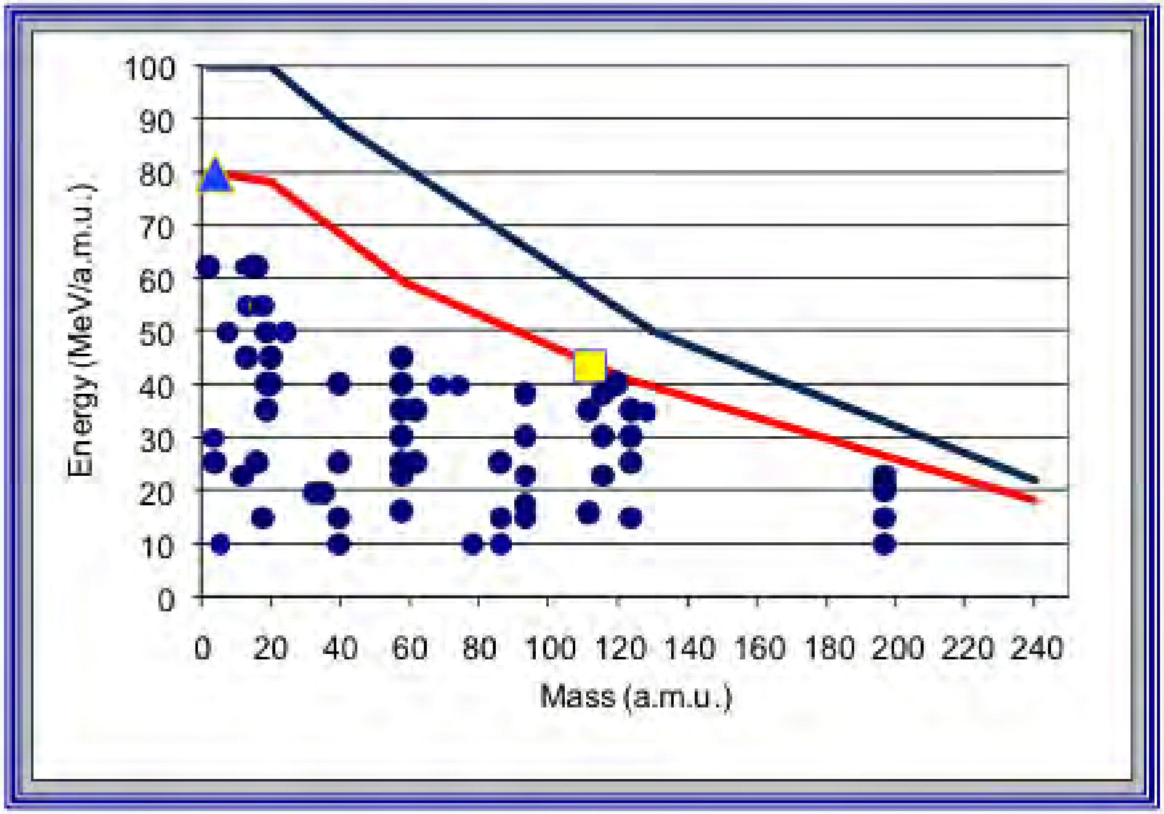
- Staff members: 120 (35 phys. + eng.)
- Associated researchers: 120
- Users (in the last 3 years): 545
- Foreign users: 180
- Annual scientific production: about 150 (papers and proceedings)
- Budget: ~ 11 M€/year (excl. Salaries)

- *Total area: 35000 m^2*
- *Total volume: 97000 m^3*

LNS lay-out: accelerators and experimental halls



Beams developed at the SuperconductingCyclotron

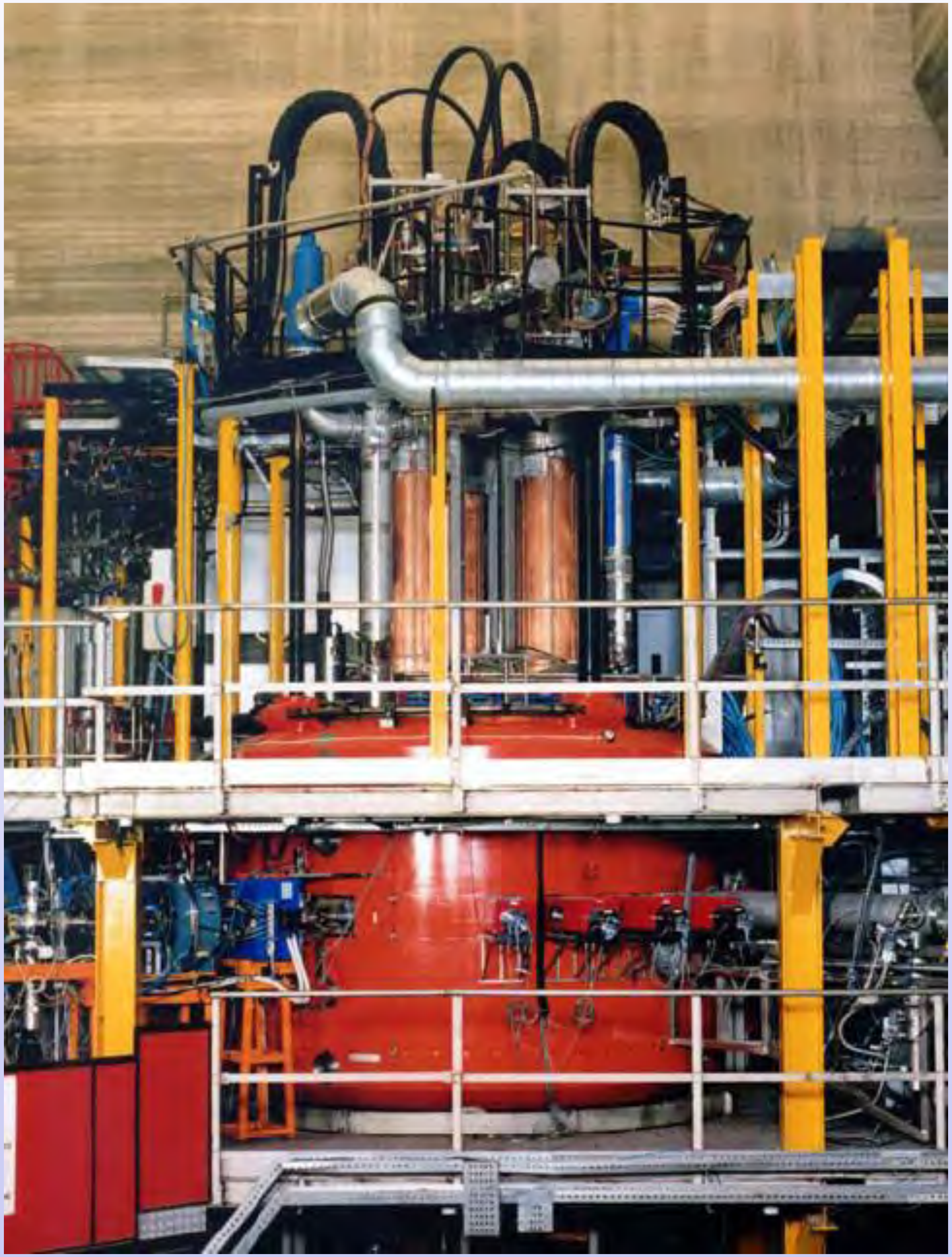


▲ ^{4}He 80 MeV/a.m.u.

■ ^{112}Sn 43.5 MeV/a.m.u.

<u>**Many Beams are unique in Europe**</u>

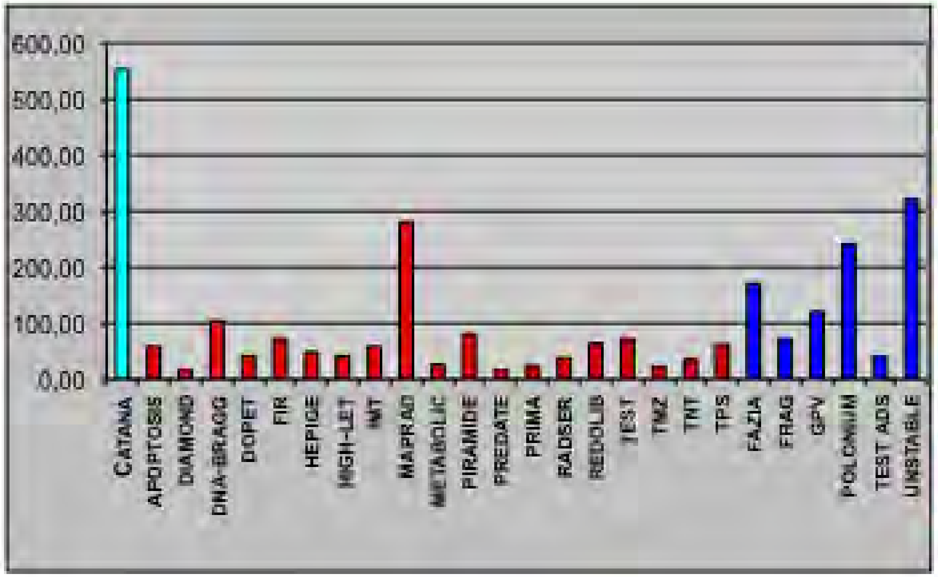
^{A}X	E (MeV/a.m.u.)
H_2^+	62,80
H_3^+	30,35,45
$^{2}D^{+}$	35,62,80
^{4}He	25,80
He-H	10, 21
^{9}Be	45
^{12}C	23,62,80
^{13}C	45,55
^{14}N	62,80
^{16}O	21,25,55,62,80
^{18}O	15,55
^{19}F	35,40,50
^{20}Ne	20,40,45,62
^{24}Mg	50
^{36}Ar	16,38
^{40}Ar	15,20,40
^{40}Ca	10,25,40,45
^{48}Ca	10,45
^{58}Ni	16,23,25,30,35,40,45
^{64}Ni	25,35
^{68}Zn	40
^{74}Ge	40
^{78}Kr	10
^{86}Kr	10,15,20,25
^{93}Nb	15,17,23,30,38
^{112}Sn	15.5,35,43.5
^{116}Sn	23,30,38
^{124}Sn	15,25,30,35
^{129}Xe	20,21,23,35
^{197}Au	10,15,20,21,23
^{208}Pb	10



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

Use of the Superconducting Cyclotron and Tandem beams in 2011

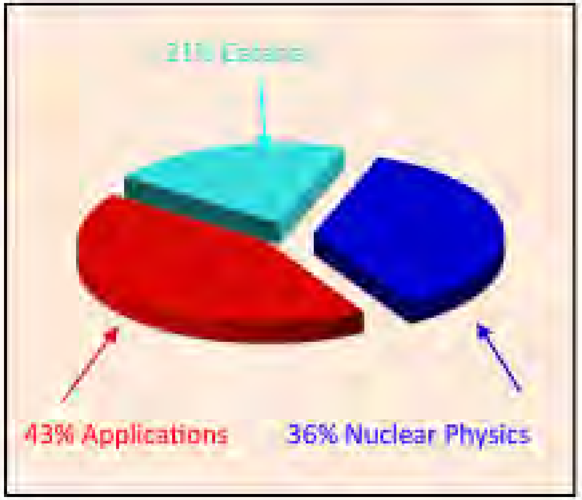


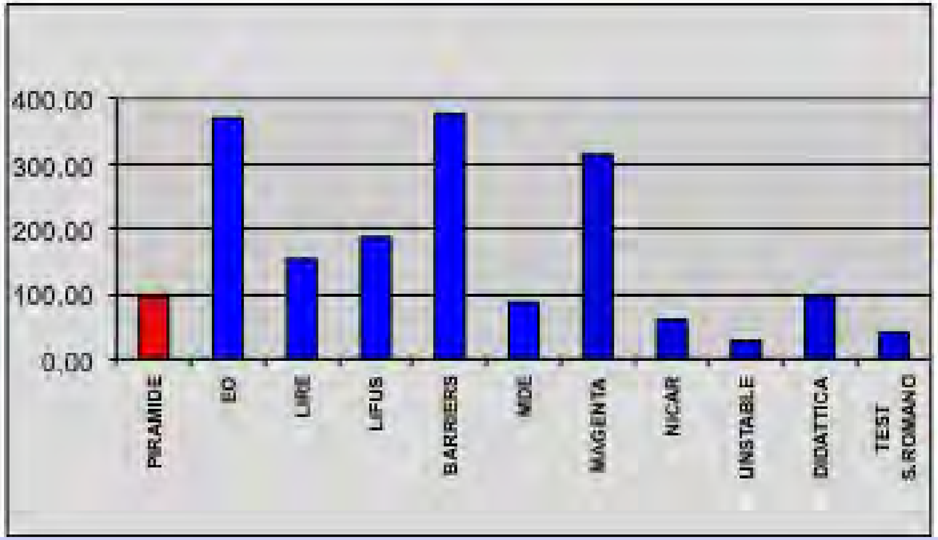
Cyclotron
2672 hours

36%
Nuclear Physics

21%
Catana

43%
Applications

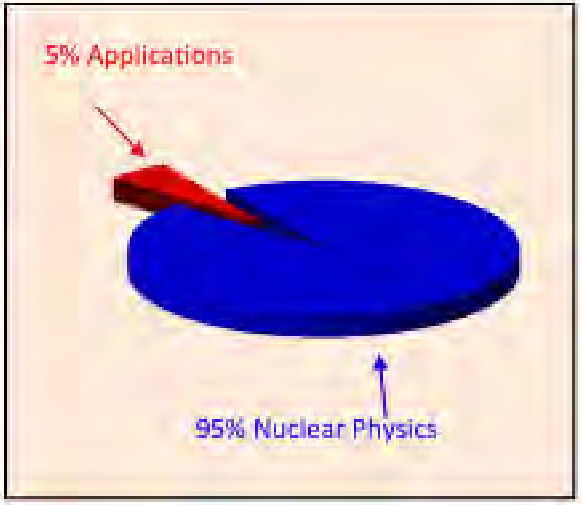




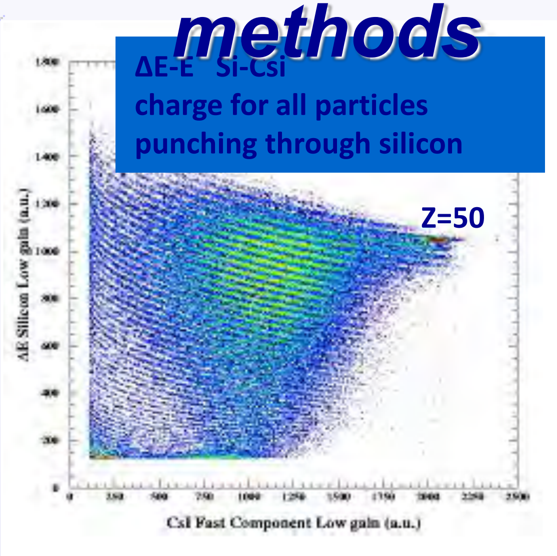
Tandem
1810 hours

95%
Nuclear Physics

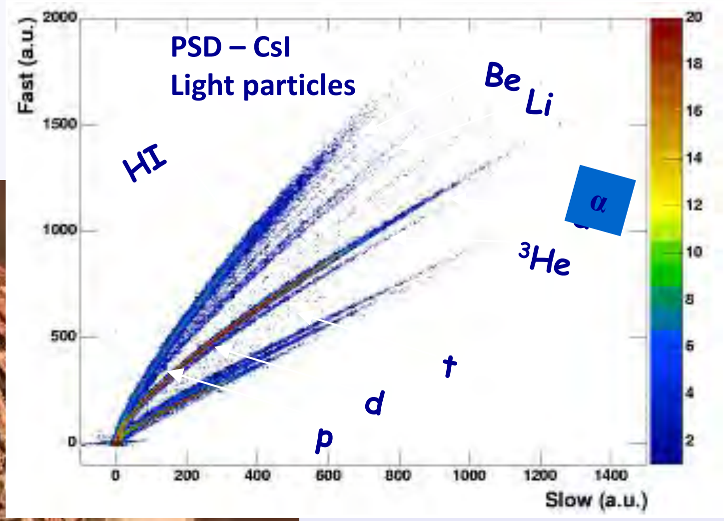
5%
Applications



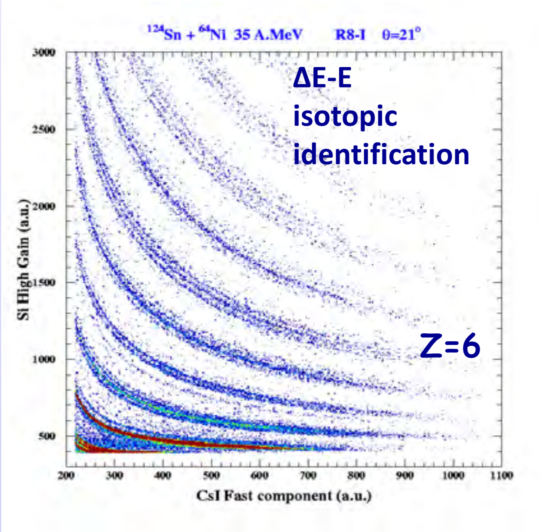
CHIMERA Detector: Identification methods



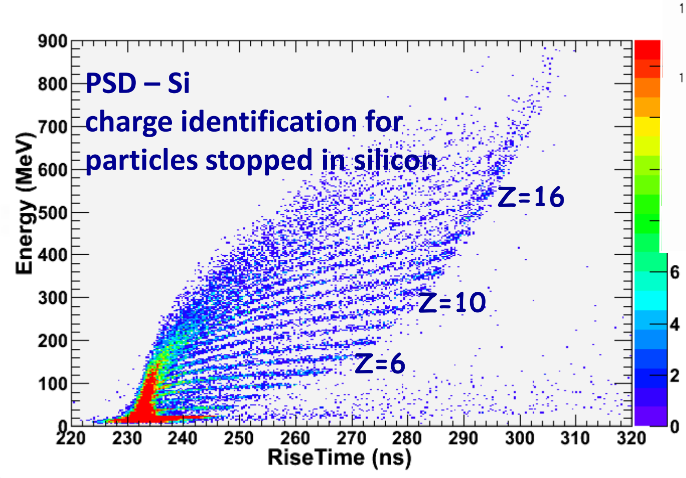
ΔE-E Si-CsI
charge for all particles punching through silicon



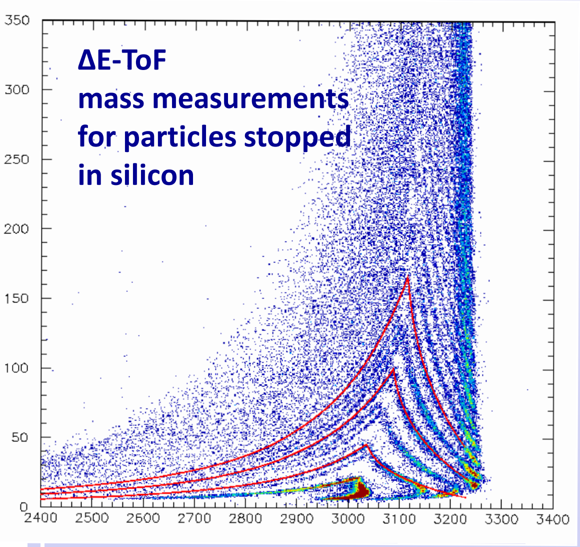
PSD – CsI
Light particles



ΔE-E
isotopic identification

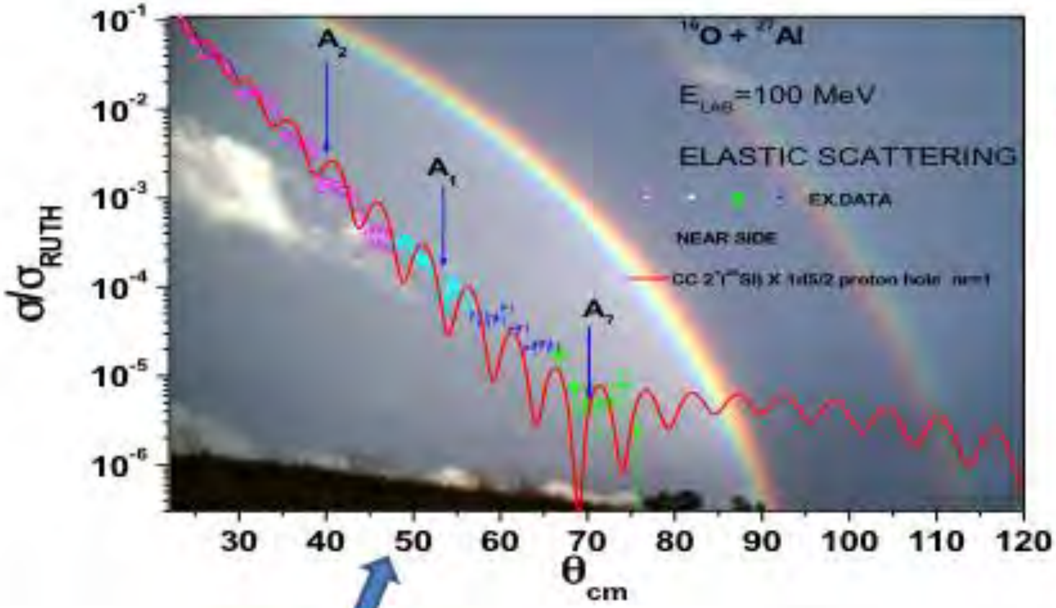


PSD – Si
charge identification for particles stopped in silicon



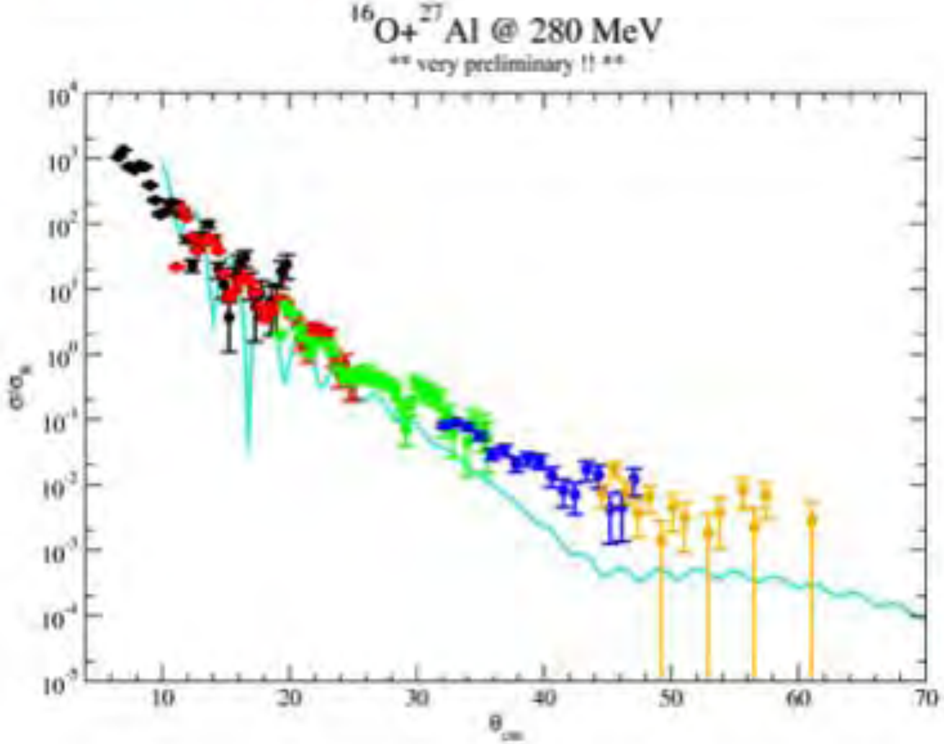
ΔE-ToF
mass measurements for particles stopped in silicon

Nuclear Rainbow in $^{16}O + ^{27}Al$ elastic scattering



Tandem beam

Cyclotron beam



MAGNEX

Nuclear astrophysics: LNS excellence

A great interest in the scientific community moves to the study of nuclear reactions of astrophysical interest. The main goal of nuclear astrophysics is the measurement of cross sections for nuclear reactions that are crucial for the understanding the evolution of the Universe. These reactions are involved in different stellar scenarios, from the first few seconds of the Big Bang which created the seed material for our universe, through to the present energy generation in our Sun which keeps us alive.

The LNS experimental activity in nuclear astrophysics is mainly based on the **Trojan Horse Method (THM)**, which has been developed at LNS and successfully applied in several reactions. Today the THM is considered as the unique indirect technique which allows to overcome the coulomb field effects - coulomb barrier and electron screening - in the **measurements of nuclear reaction cross sections at the astrophysical energies (< 100 keV).**

Catana: eye tumours protontherapy facility (10 yrs after)

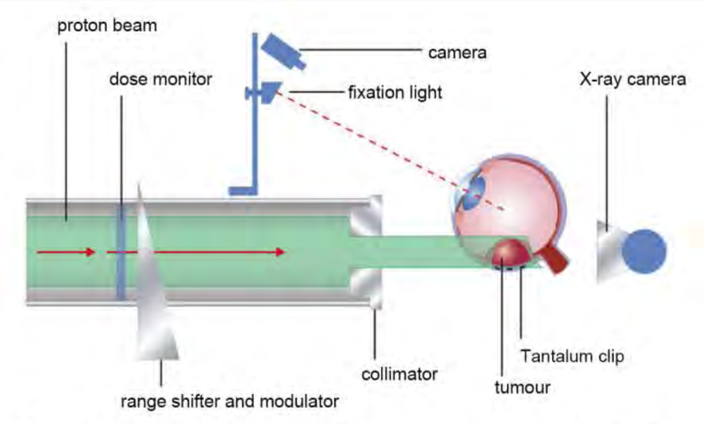
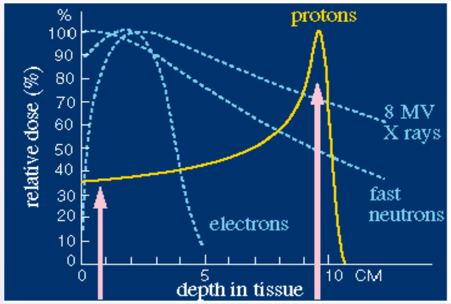


Figure 6: Principle of the irradiation The range shifter and the modulator wheel are represented by the range modulator.

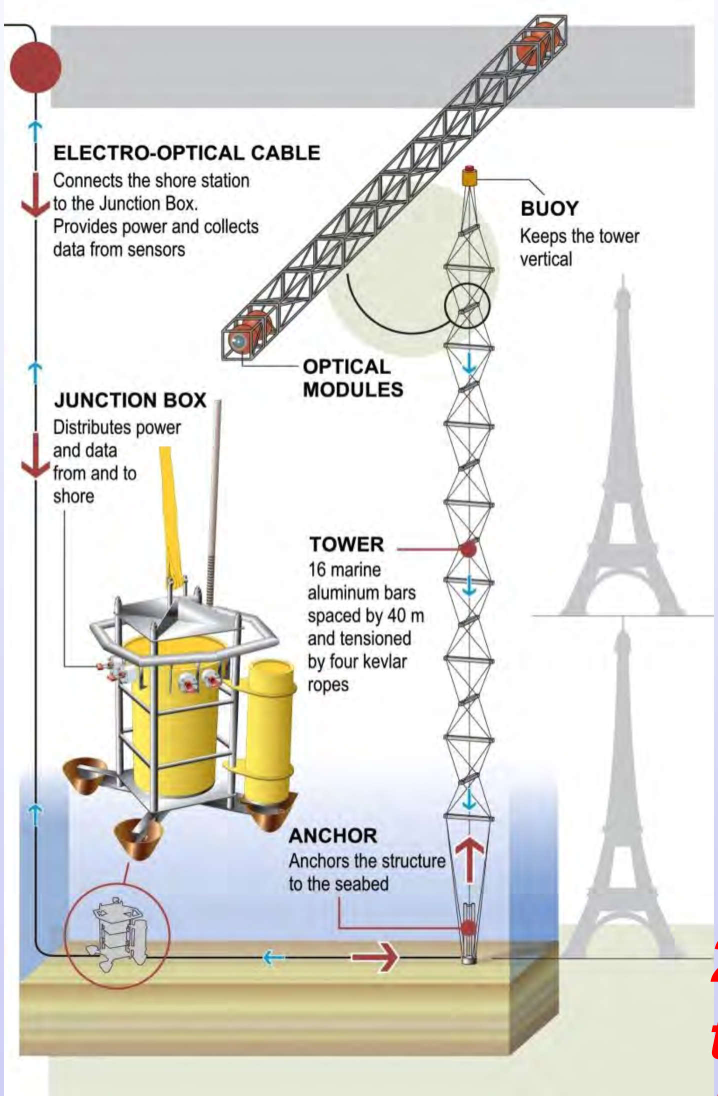


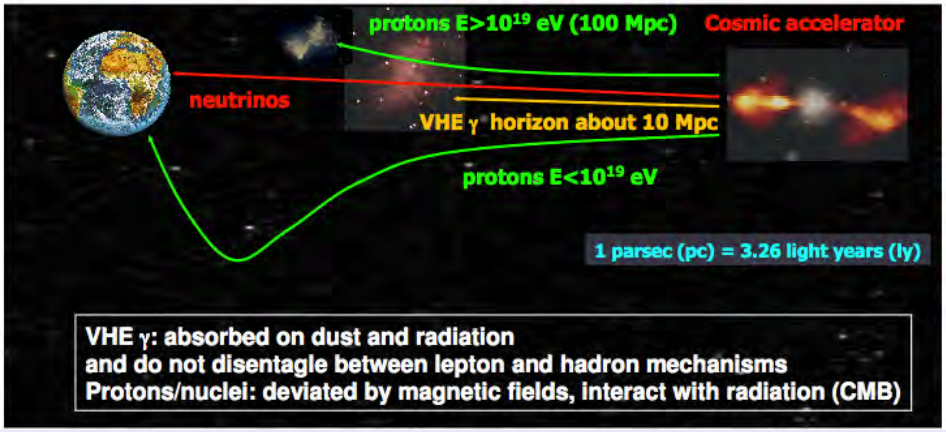
- **350 patients treated (Feb. 2002-Jul 2012)**
- **336 uveal melanomas**
- **8 conjunctival melanoma**
- **6 other malignancies (orbital RMS, non-Hodgkin Lymphoma, various metastases)**
- **Follow-up on 220 patients: 95% of success**

5 sessions on average per year

PT Center at Cannizzaro Hosp. in Catania. Tender in progress (112 M€) with investment from UE. INFN is consultant for the Sicilian Regional Gov. IBA, Varian and BEST are the competitors

NEMO and KM3NeT: High energy neutrino astronomy at LNS





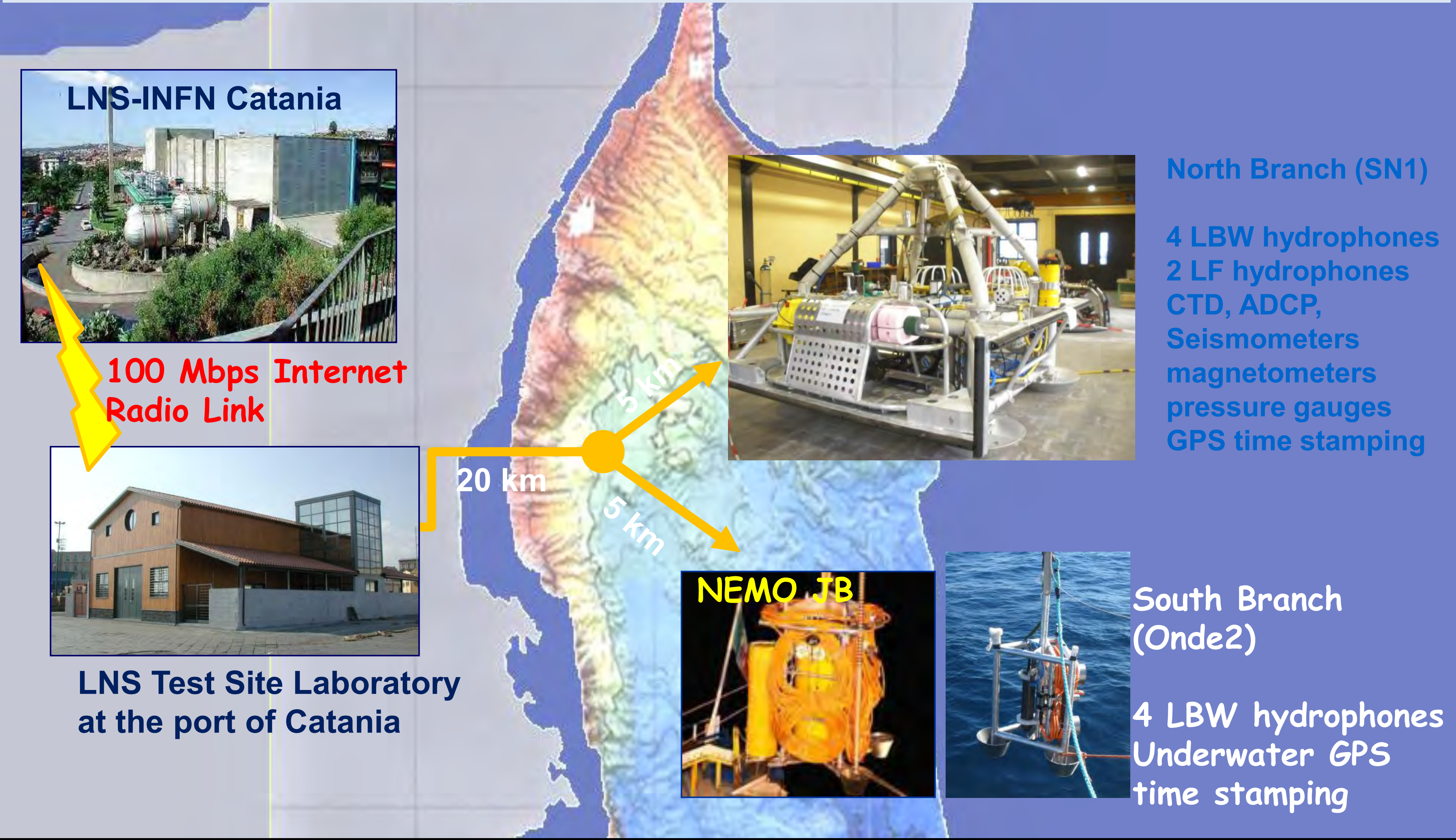
VHE γ: absorbed on dust and radiation
and do not disentagle between lepton and hadron mechanisms
Protons/nuclei: deviated by magnetic fields, interact with radiation (CMB)

Neutrinos will provide unique pieces of information on the High Energy Universe. Detection possible by tracking the secondary muons in a km-cube size array of photosensors in deep sea waters

20.8 M€(PON Funds) are at LNS for the realization of 25 towers at LNS-Porto Palo Lab

The Catania Test Site: a multidisciplinary deep sea-lab

LIDO demo mission of ESONET-EMSO: Refurbishment of SN1 and OnDE observatories
Goals: Bioacoustics, ocean monitoring,Tsunami warning.



LNS-INFN Catania

100 Mbps Internet
Radio Link

LNS Test Site Laboratory
at the port of Catania

North Branch (SN1)

4 LBW hydrophones
2 LF hydrophones
CTD, ADCP,
Seismometers
magnetometers
pressure gauges
GPS time stamping

South Branch
(Onde2)

4 LBW hydrophones
Underwater GPS
time stamping

Infrastructure requested by UCL and CSIC for installation of deep-sea stations in 2013

ELI-Beams and the ELIMED idea

ELI (Extreme Light Infrastructure)

new type of European large scale laser infrastructure specifically designed to produce the highest peak power (10 PW) and focused intensity;

ELI-Beamlines (Czech Rep.)

Hungary

Romania

...

ELIMED

X-ray sources

Exotic physics

...

- Why ELIMED?
  - Realization of a facility at ELI-Beamlines, to *demonstrate the clinical applicability of the laser-driven protons*
  - **Compactness, cost-reduction**, new pioneering treatment modalities

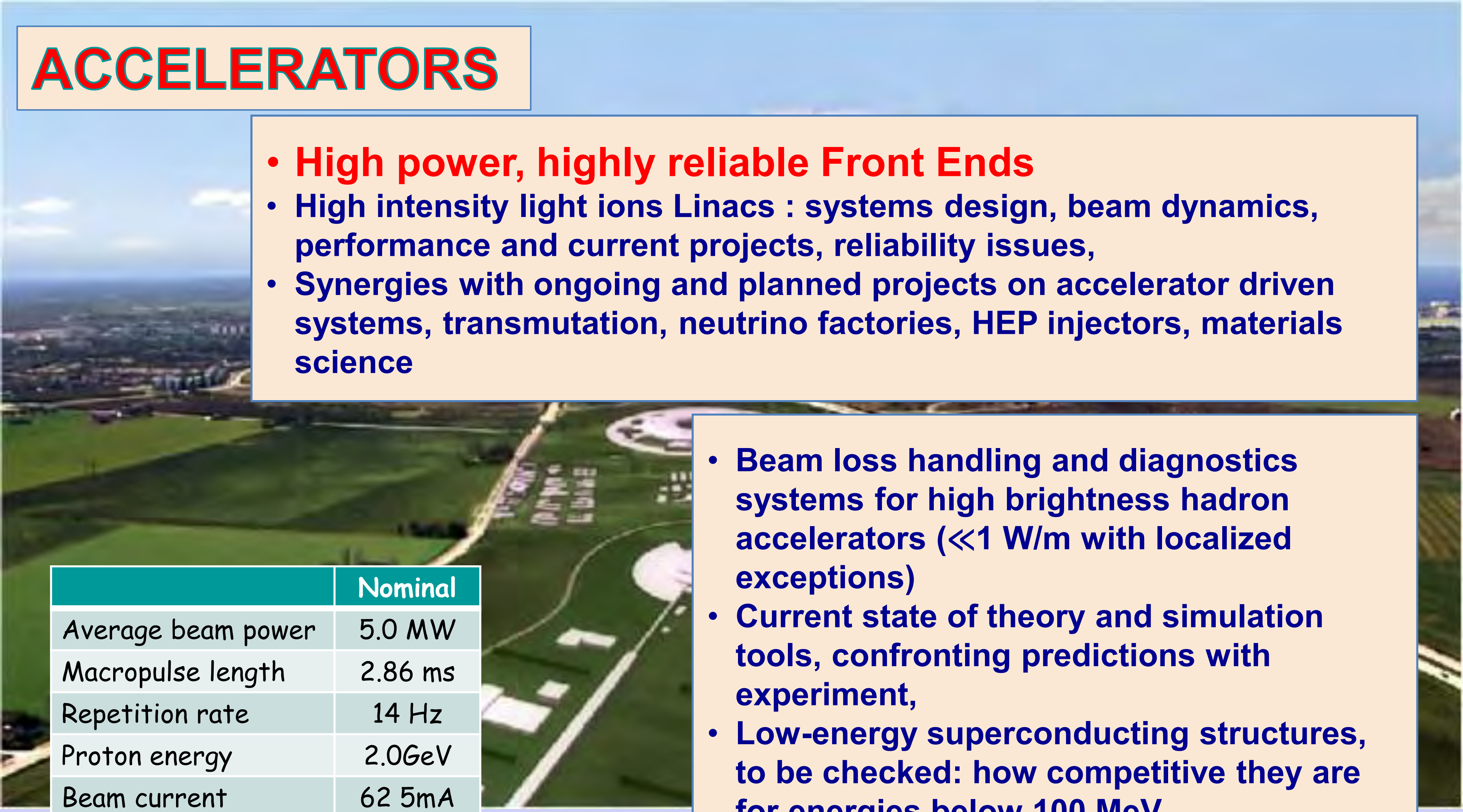

today


tomorrow?

- **Why ELIMED at INFN?**

-The project we are proposing is related to the preparatory phase of ELIMED (2013-2015): optimisation of the proton beams, transport, diagnostic dosimetric

European Spallation Source – Lund (Sweden)



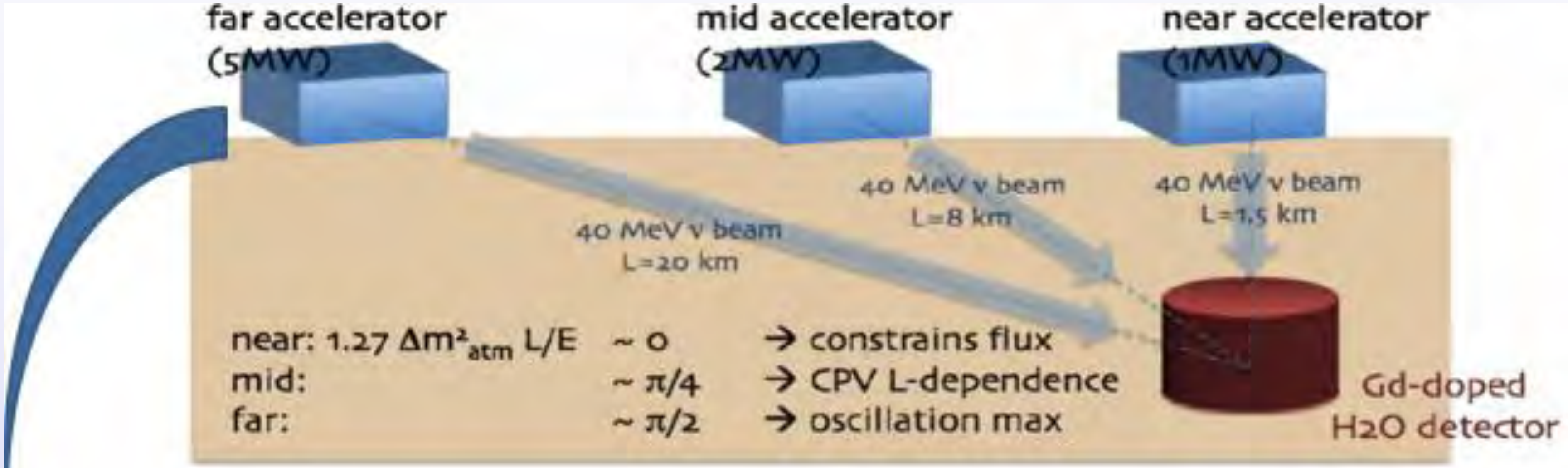
ACCELERATORS

- **High power, highly reliable Front Ends**
- **High intensity light ions Linacs : systems design, beam dynamics, performance and current projects, reliability issues,**
- **Synergies with ongoing and planned projects on accelerator driven systems, transmutation, neutrino factories, HEP injectors, materials science**

	Nominal
Average beam power	5.0 MW
Macropulse length	2.86 ms
Repetition rate	14 Hz
Proton energy	2.0GeV
Beam current	62 5mA
Duty factor	4%
Beam loss rate	< 1 W/m

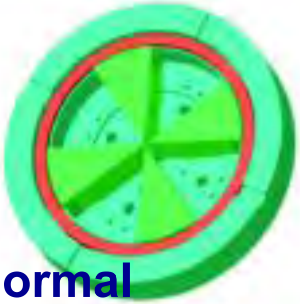
- **Beam loss handling and diagnostics systems for high brightness hadron accelerators (≪1 W/m with localized exceptions)**
- **Current state of theory and simulation tools, confronting predictions with experiment,**
- **Low-energy superconducting structures, to be checked: how competitive they are for energies below 100 MeV…**

DAEδALUS: experiment overview



Accelerator Complex designed by LNS

VIS source for H_2^+ ions



Normal conducting Cyclotron

Superconducting Ring Cyclotron

LNS have a key role in the european framework:

- for stable beams and RIBs at intermediate energy
- Leading role for Nuclear astrophysics (with FRIBs & Excyt beams and Troian Horse Methods)
- Strong contribution at the development of the European/Int. projects: ESS, ELI, Eurisol, DAEδALUS
- Applications of Nuclear Physics: Hadronteherapy, Imaging, Cultural Heritage, Radiobiology.
- international Research Infrastructure for neutrino astrophysis and deep see applications (KM3Net).

Almost any of this activity needs to produce specific ion beams (high current, highly charged, heavy ions, metallic species) and this is the reason for the consideration given to the Ion Sources R&D since second half of ‘80s

Aims and Team members

The R&D Team of INFN-Laboratori Nazionali del Sud have designed different ion sources,

- ***ranging from hydrogen production to heavy elements,***
- ***either for cw and pulsed operations,***
- ***including highly charged beam production for nuclear physics,***
- ***for material studies,***
- ***for hadron therapy***
- ***for industrial applications.***

Scientific output since 2000: 15-20 peer-reviewed publications/year

Ion sources R&D at the Laboratori Nazionali del Sud 1989-today

- ✓ECR theoretical studies, microwave to plasma coupling, diagnostics
- ✓High charge state ECR sources for the Superconducting Cyclotron
  - ➢SERSE
  - ➢CAESAR
- ✓Third generation ECRIS design (GyroSERSE and daughters)
- ✓ECRIS for hadron therapy (Supernanogan, AISHA, CAESAR2)
- ✓Extraction and transport of intense beams
- ✓Intense proton source (TRIPS, VIS, PSESS)
- ✓Hybrid ion source (ECLISSE, ELIMED)
- ✓Laser Ion Source for implanters
- ✓High efficiency source for RIB facility EXCYT
  - ➢MIDAS & MIDAS2
  - ➢ISOLDE-type

Customer:

LNS scientific activities

Other Italian laboratories

International cooperative groups

SME development activities

e.g. TRIPS at LNL in 2006

ECR Sources for CNAO (Nat. Center of Hadron Therapy)


30.03.2007

Two Supernanogan-type sources have been built in 2006 and installed in Pavia in 2007.

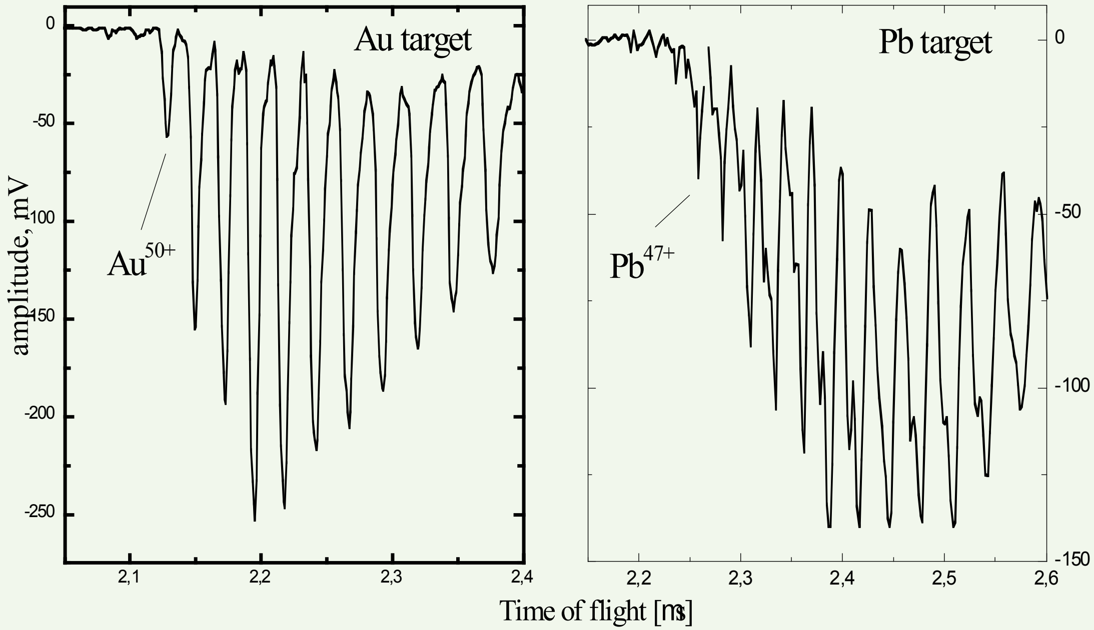
Improvements:

- Frequency tuning:
  larger beam brightness
- New extraction system:
  Better emittance, improved stability
- New gas input system:
  improved stability

The activities nowadays are focused on ECRIS and MDIS and for sake of brevity I will limit the scope of this presentation to these fields, skipping the achievements in Laser Ion Sources comprehension

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

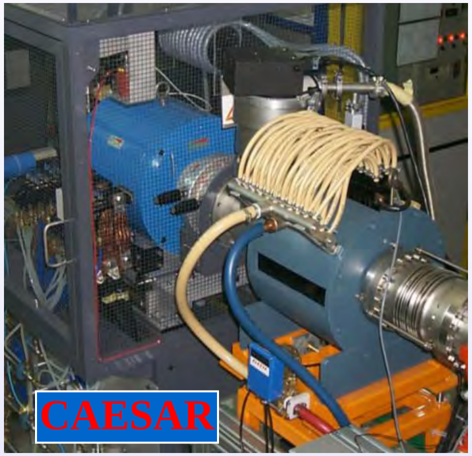


Limits to the adoption of LIS as accelerators' injector:
Emittance, energy spread, reproducibility, stability

Some ECR ion sources and MDIS at INFN-LNS

ECR ion sources for the superconducting cyclotron

SERSE	18 GHz
CAESAR	14 GHz

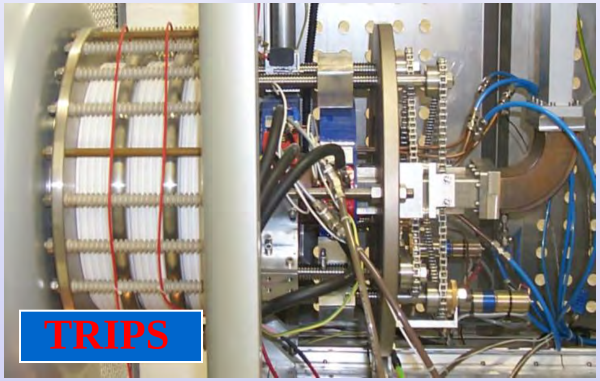


ECR ion sources for next generation facilities

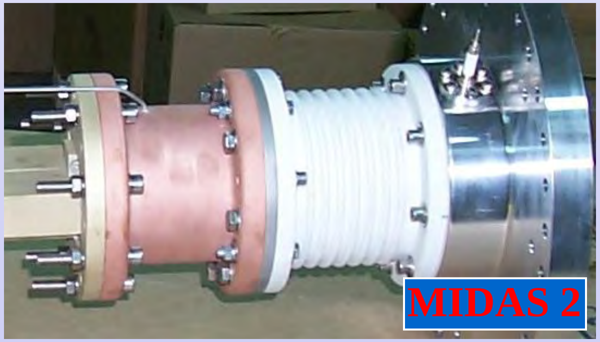
GyroSERSE (28-37 GHz)
ECLISSE

Intense proton beams for ADS&RIBs drivers

TRIPS	2.45 GHz
VIS	2.45 GHz



High efficiency microwave discharge ion sources for RIB ionization



MIDAS	2.45 GHz
MIDAS2	2.45 GHz

INFN-LNS is a reference centre either for the design of high intensity proton sources and of highly charged ion sources

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

The necessity to increase the ECRIS performances

Increase of Ion Charge States

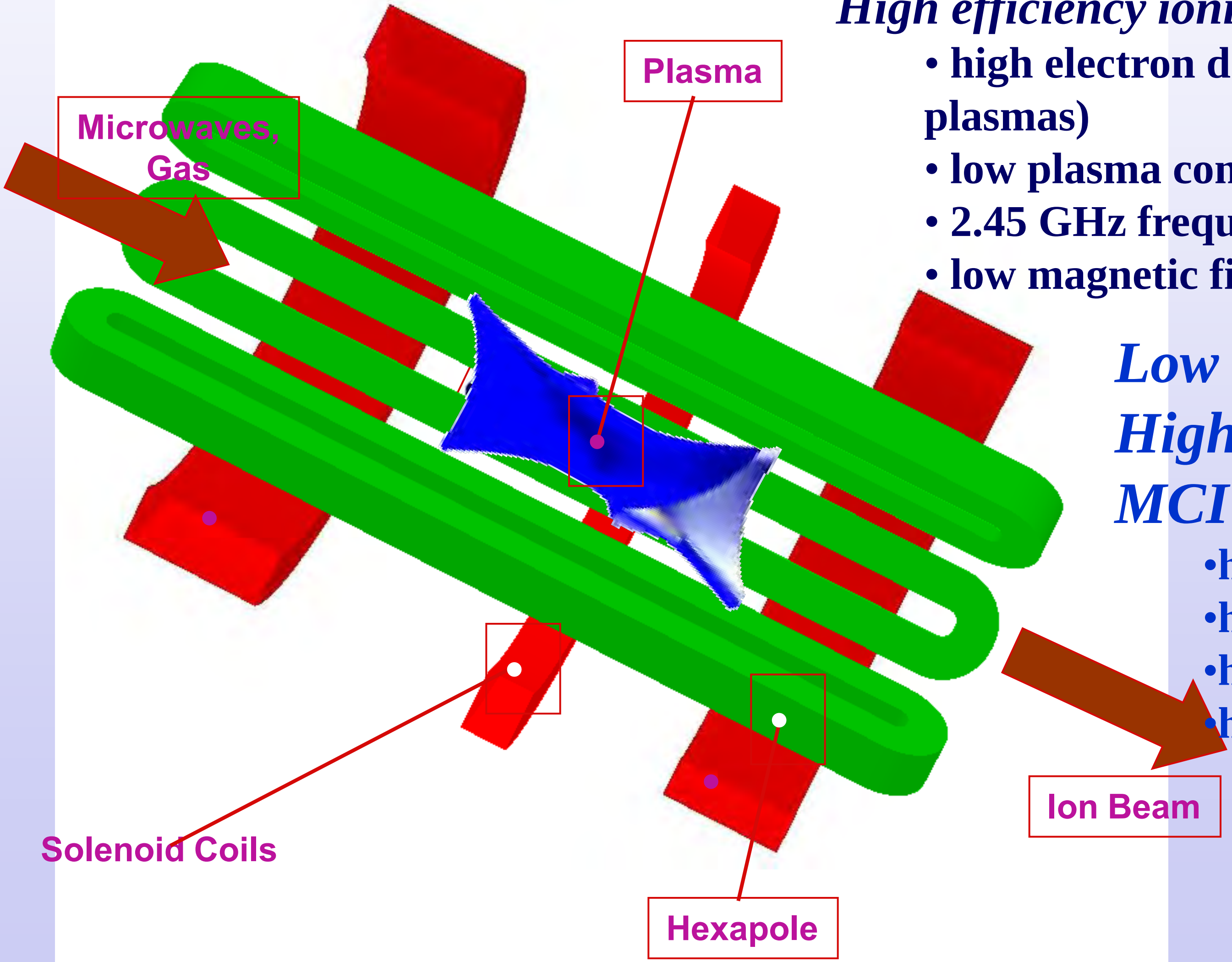
Higher energies attainable by Accelerators

Increase of Ion Current

Decrease of acquisition times for rare events (RIB,SHE)

Increase in ECRIS performances allow us to enhance the Accelerators ones without hardware modifications

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

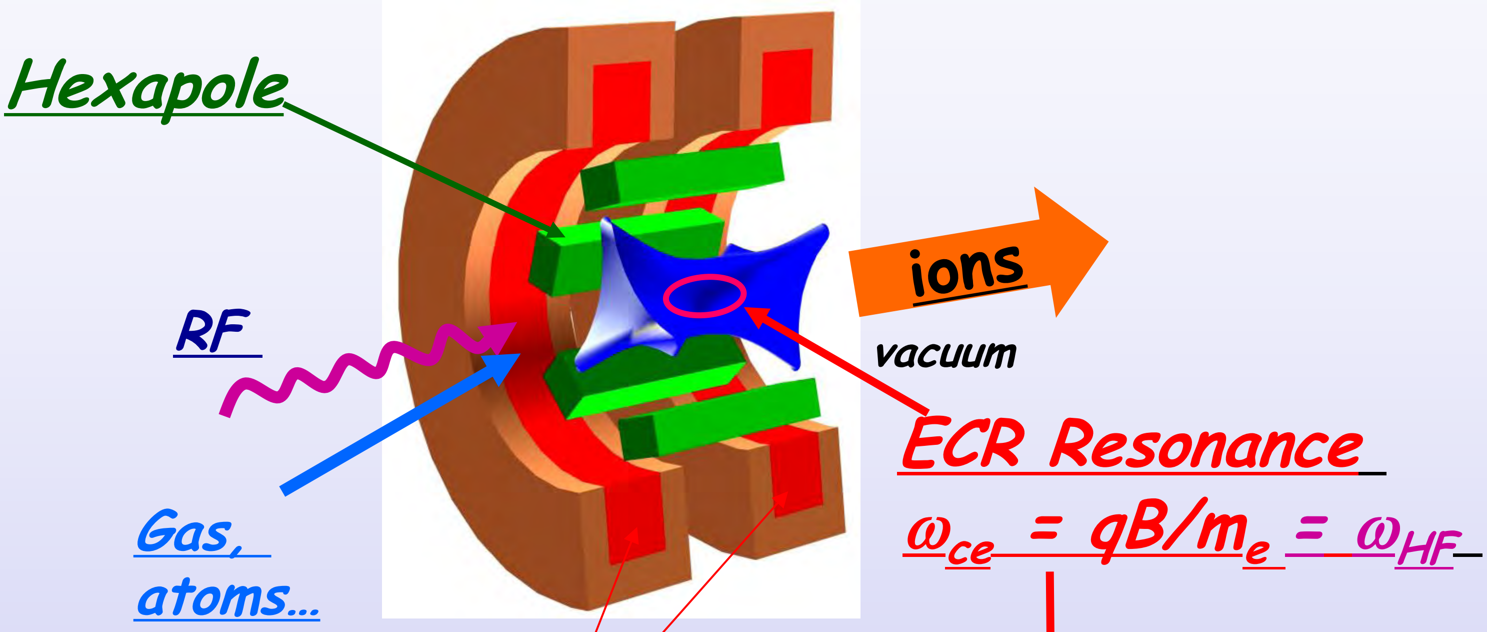
Low current of HCI

High current of LCI and MCI

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

ECR

Multicharged Ion production in a minimum-|B|



Hexapole

RF

Gas, atoms...

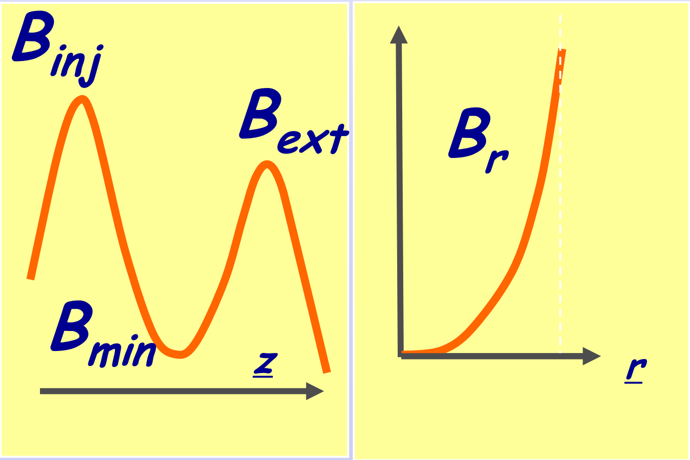
ions

vacuum

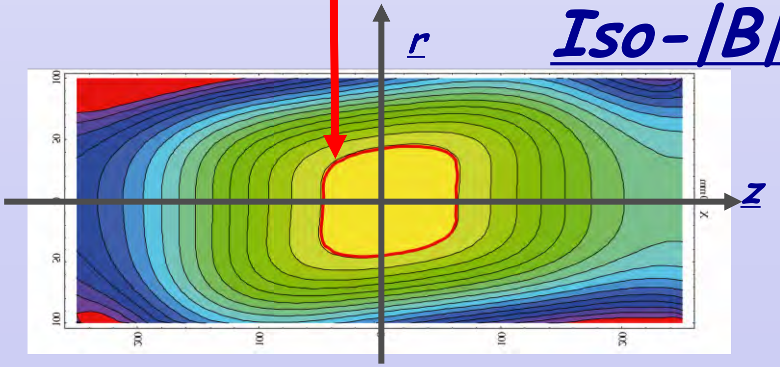
ECR Resonance

$\omega_{ce} = qB/m_e = \omega_{HF}$

Solenoids

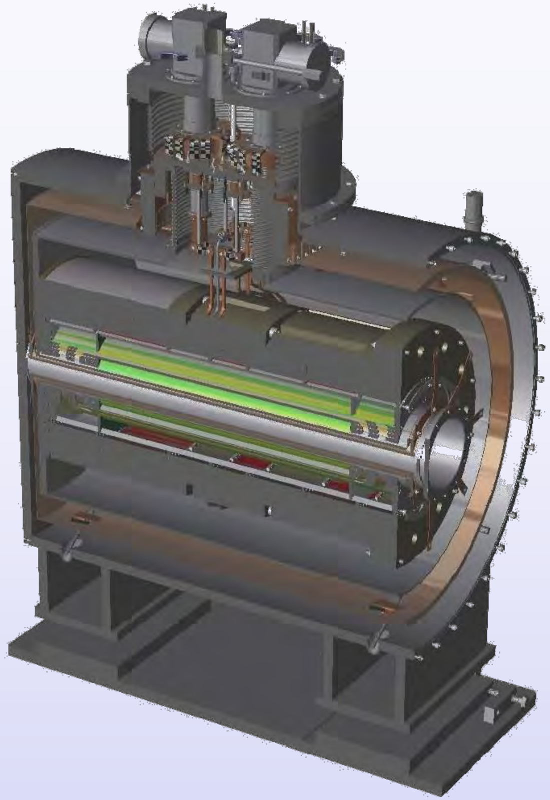


Confinement Axial Confinement Radial

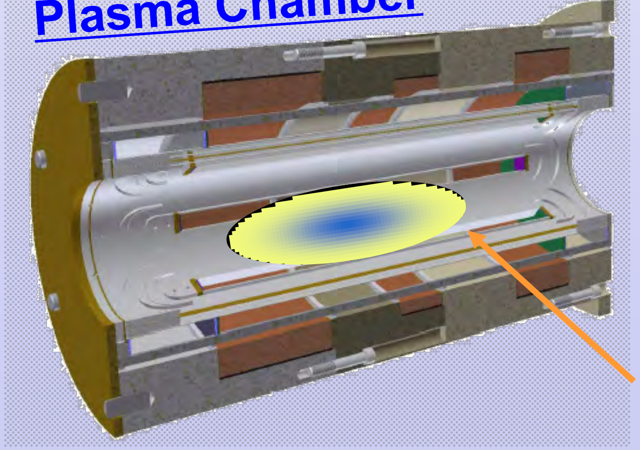


Electron Cyclotron Resonance Ion Sources generate plasmas from gas or vapors and extract the ion content

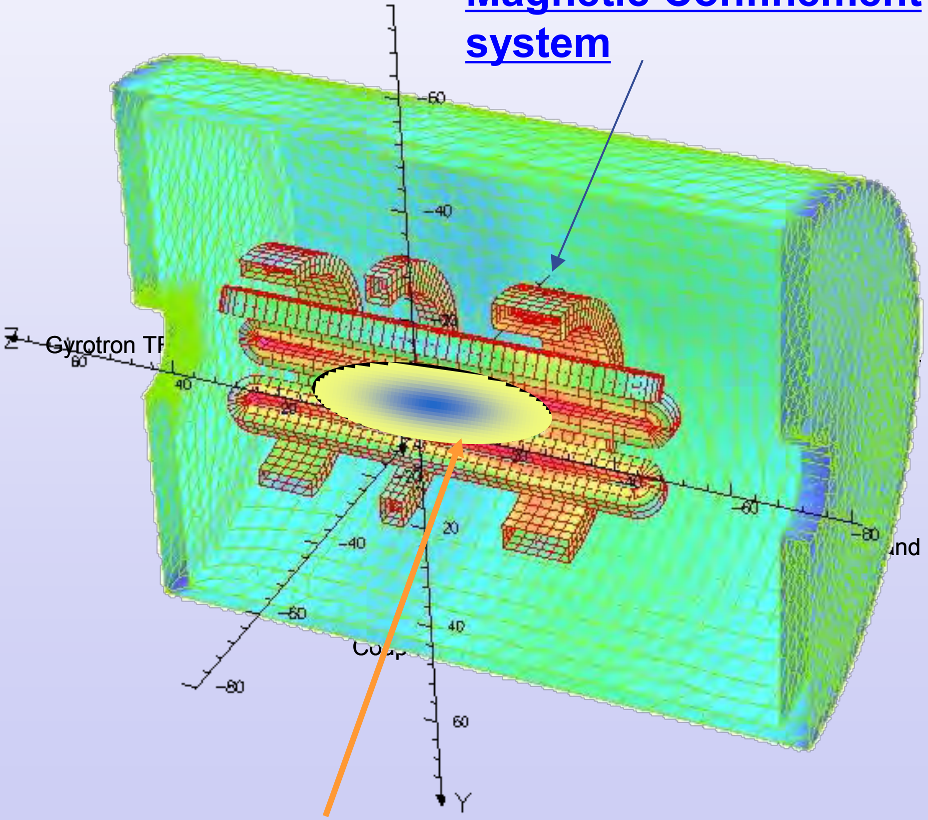
Source Magnets cryostat



Plasma Chamber



Magnetic Confinement system



High Temperature and density plasma

Atomic/Plasma physics background in ECRIS.

The ionization up to high charge state is a step by step process:

1. τ_i is the ion confinement time, that must be long enough to ensure a multiple ionization.
2. the electron temperature must be high enough to ensure ionization down to inner shells of atoms.
3. The electron density must be large enough to ensure that a great number of ions are created per time unit

For fully stripped light ions

$$\boxed{n_e \tau_i \cong 10^{10}\, cm^{-3} \sec \qquad T_e^{opt} = 5\, keV}$$

ECRIS scaling laws

- **1987 From the MINIMAFIOS results R. Geller inferred the scaling laws, which were for a few years the guiding line for ECRIS designers and users:**

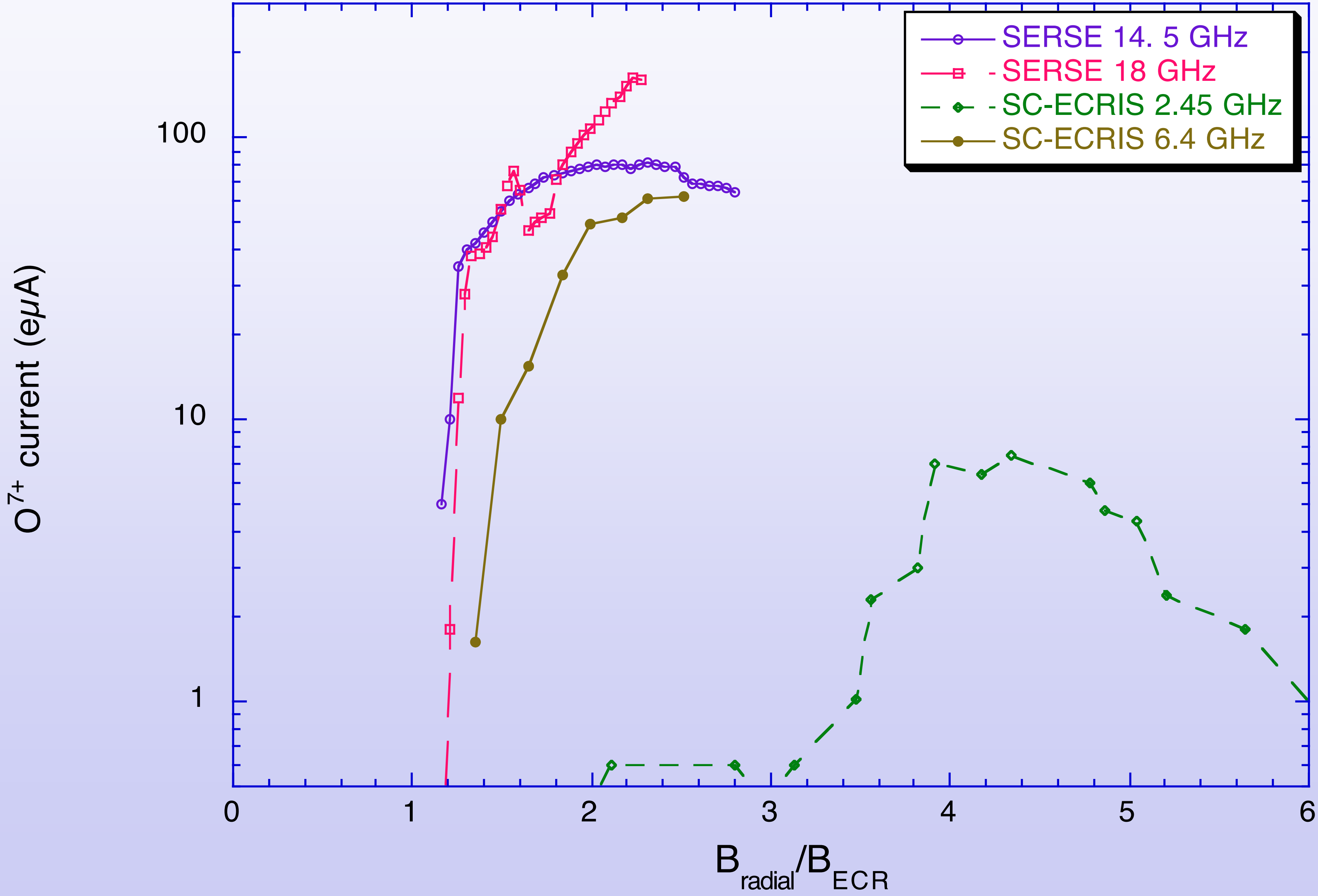
$$I \propto \omega^2 M^{-1} \qquad q_{opt} \propto \log(B^{1.5})$$

- **1990 High B-mode concept . This does not conflict with frequency scaling, but it limits the effectiveness of frequency scaling to the sources with high confinement, i.e.:**

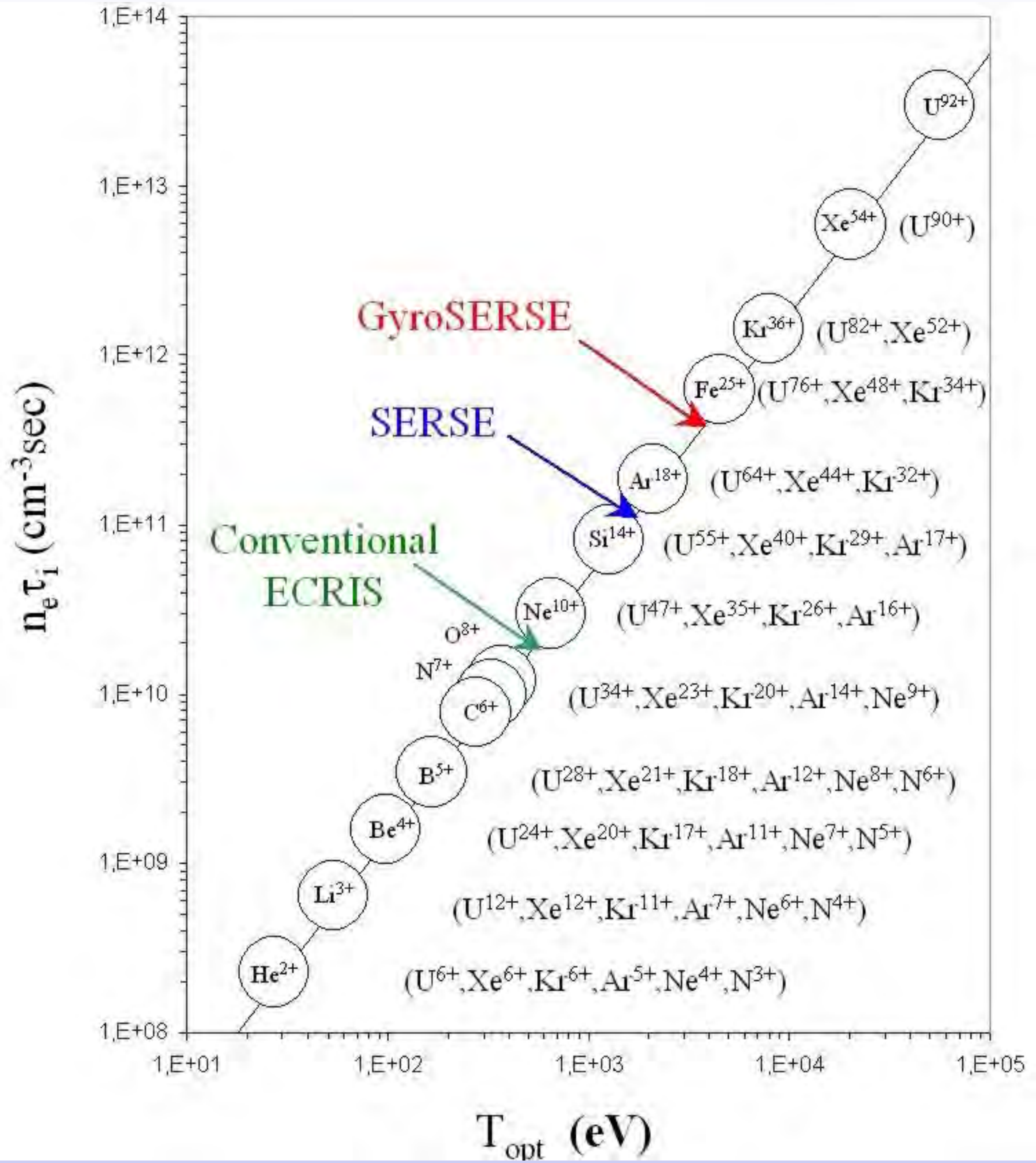
$$n_e K T_e << B^2_{\max} / 2\mu_0 \longrightarrow \frac{B_{\max}}{B_{ECR}} > 2$$

- **1993-1995 Confirmation of HBM with the SC-ECRIS results at 6.4 GHz (LNS-NSCL collaboration).**

ECRIS scaling laws



GOLOVANIVSKI PLOT



Roadmap indicated by the ECR Standard Model

- **Scaling laws, R. Geller, 1987** $I \propto \frac{\omega_{RF}^2}{M}$; $\langle q \rangle \propto \log \omega^{3.5}$
- **High-B Mode concept, Ciavola & Gammino, 1990**

$$\begin{cases} B_{inj} \approx 3B_{ECR} \text{ or more if possible} \\ B_{rad} \geq 2B_{ECR} \\ B_{ext} \leq B_{rad} \end{cases}$$

High Magnetic Fields --- **High Frequency Generators**

↓

SERSE@INFN-LNS,
top level for HCI production (1997-2004)
GyroSERSE Project, developed in the frame of FP5
MS-ECRIS, developed in the frame of FP6

The SERSE ion source at final location in LNS

29/9/1998 11:5

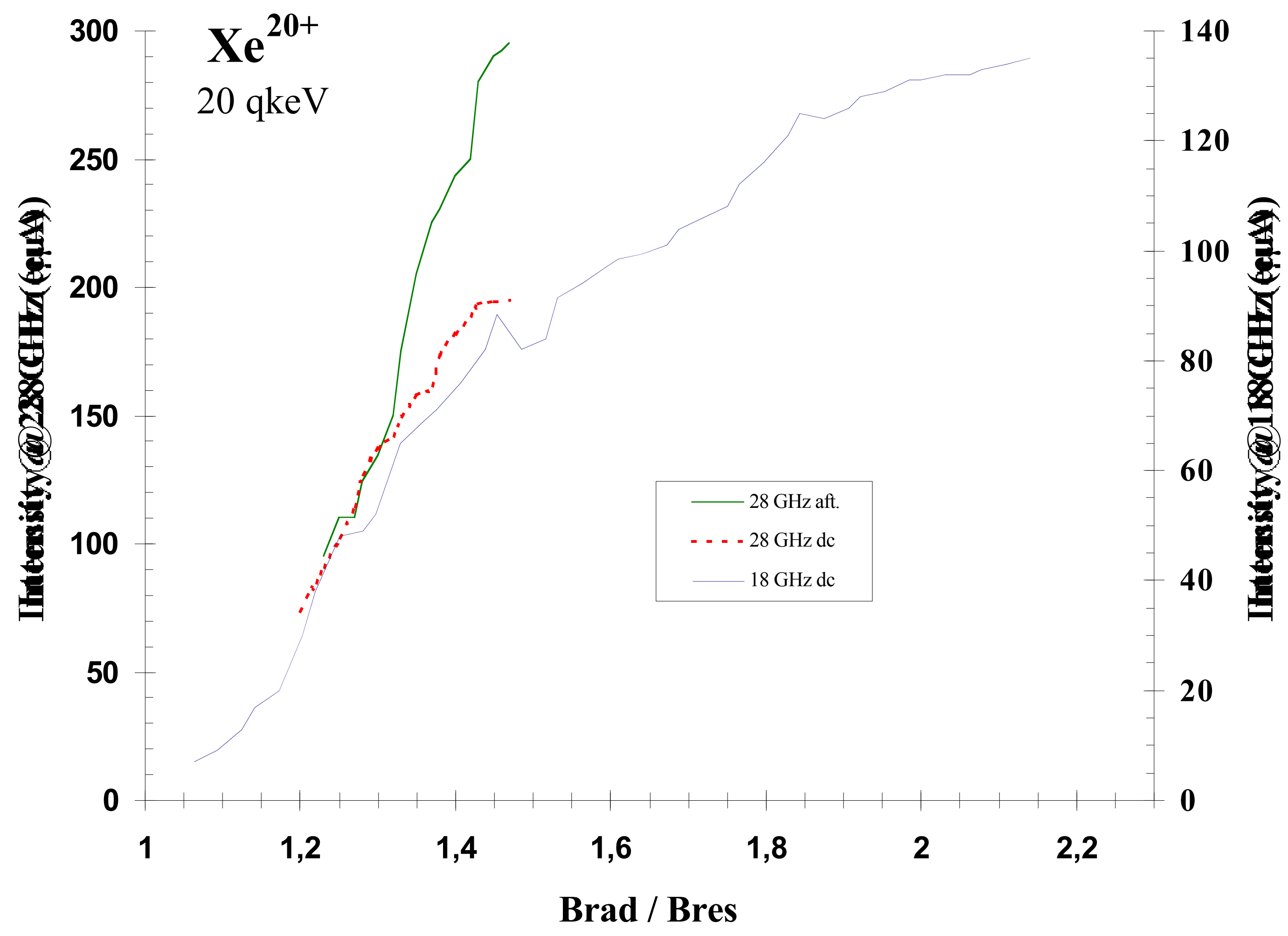
The scaling laws for ECR ion sources and the 'High B mode' concept have been confirmed by the experiments carried out by our team with SC-ECR at Michigan State University (1993-96) and with SERSE at LNS (1998-2000) at variable frequency from 2.45 to 28 GHz. These guidelines have been commonly accepted and for many years the use of larger microwave frequency and the use of "brute force", by increasing the power above 1 kW/liter has been sufficient.

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 1μA Xe42+, 8 μA Xe38+, 100 μA Xe30+

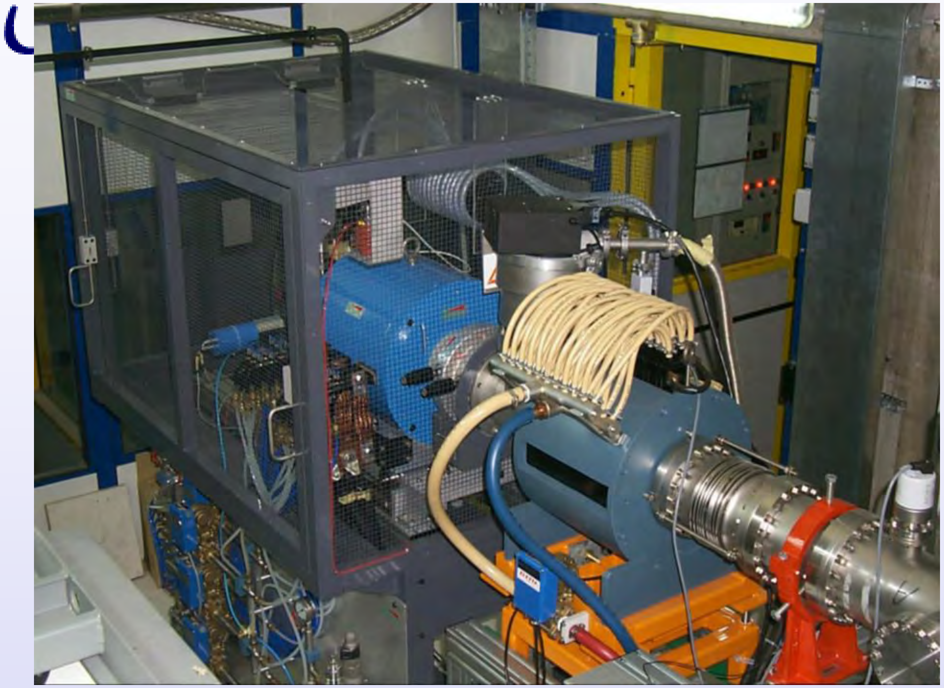
28 GHz tests with SERSE



Evolution of Xe20+ with the radial magnetic field

S. Gammino, G. Ciavola, L. Celona, D. Hitz, A. Girard, G. Melin, Operation of the SERSE superconducting electron cyclotron resonance ion source at 28 GHz, Rev. Sci. Instr., 72 (11) 4090

CAESAR (HBM@14 GHz)



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

Operating frequency	14 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

State of the art of
3rd generation ECRIS

	VENUS	SECRAL	A-PHOENIX	SuSI	RIKEN	MS-ECRIS
B_{radial}	2.1 T	2.0 T	1.6 – 2.2 T	2.0 T	2.0 T	2.7 T
B_{axial}	4.0 T	3.6 T	3.0 T	3.6 T	4.0 T	4.5 T
RF	28 GHz	18-28 GHz	18-28 GHz	24 GHz	28 GHz	28-37 GHz
V_{ext}	20 kV	20-30 kV	60 kV	60 kV	30 kV	40-60 kV
$\phi_{chamber}$	150 mm	126 mm	70 mm	100 mm	150 mm	180 mm

Different 3rd generation ECRIS have been built and excellent results have been obtained, according to the standard model for ECR ion sources but it is clear that to produce still higher intensity beams of highly charged ions, we need to find something else: RF equipment are too expensive and magnets technology is at its maximum.

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).

CONCLUSIONS

- 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 (we will see in the next slides) is an appropriate microwave generator and 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.

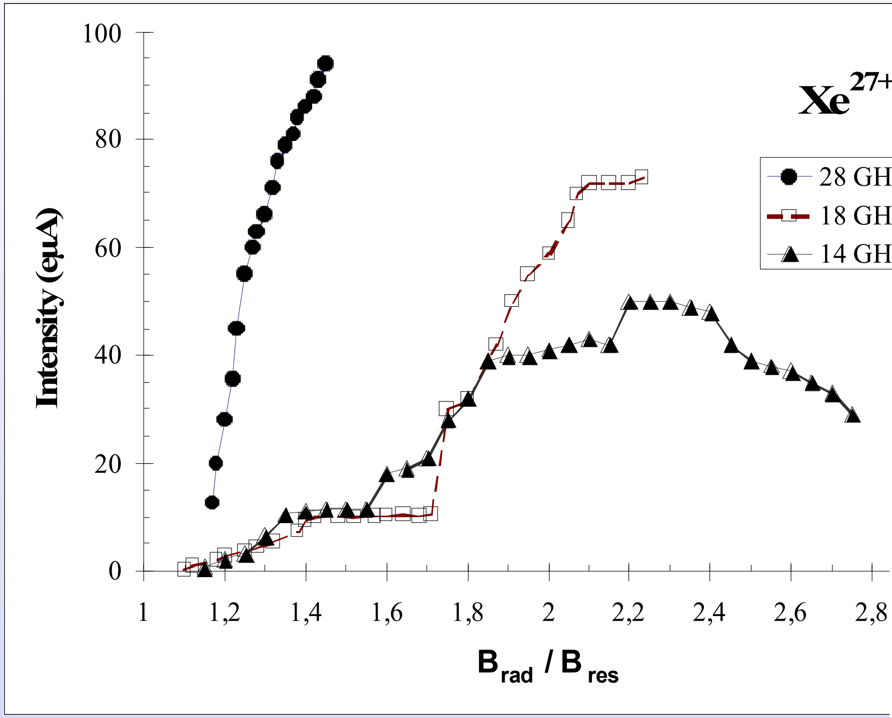
Investment

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 1983-2013.

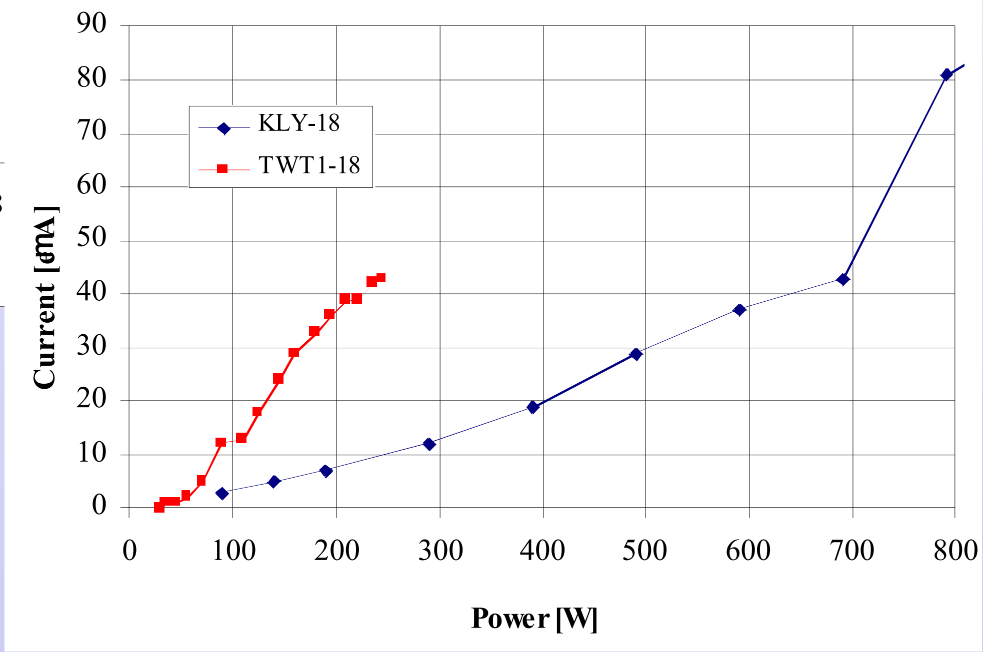
Why not to continue to invest ?

Some experimental 'strange' data

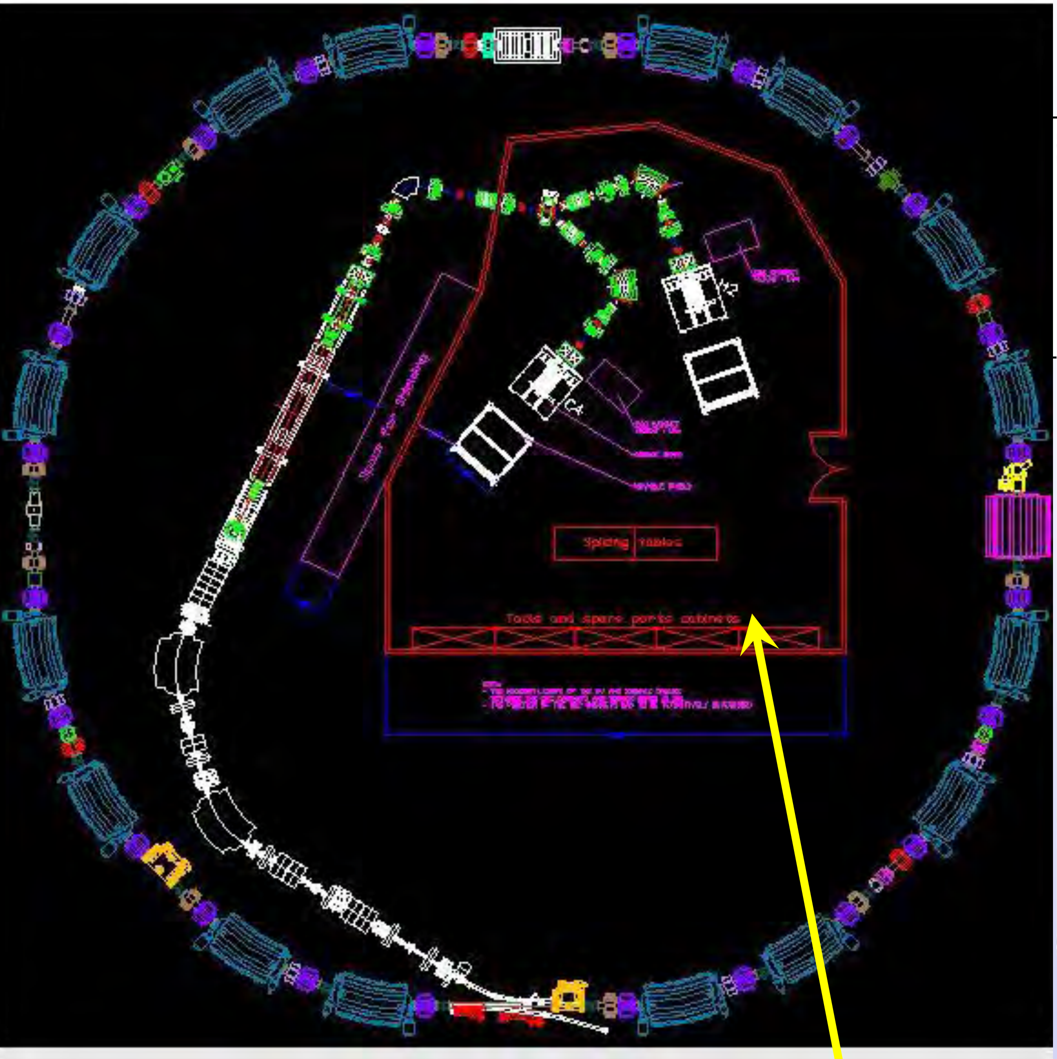


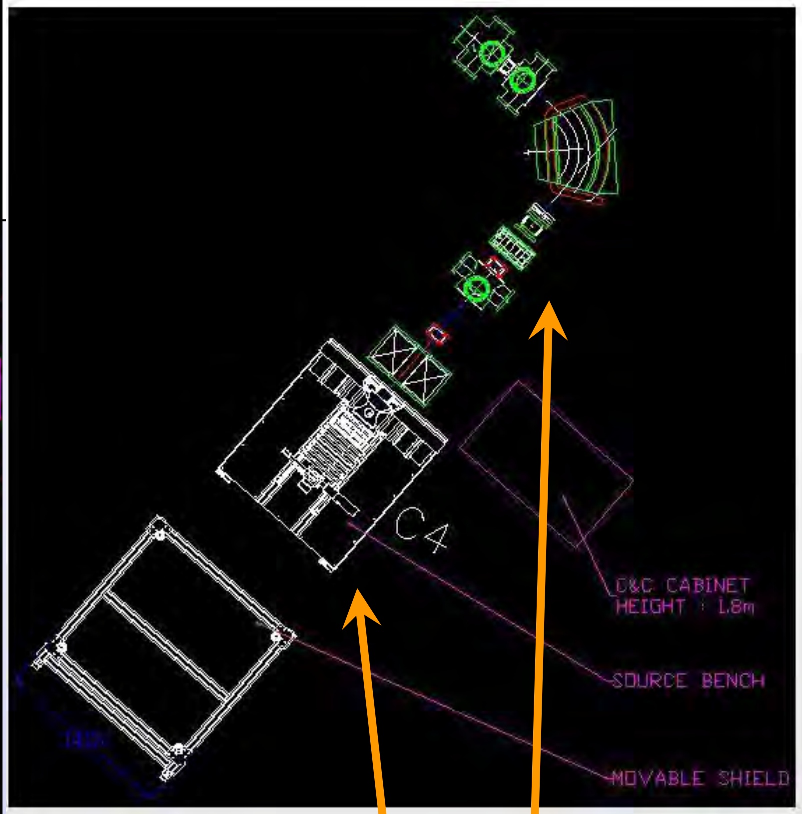
SERSE
Aug-Sept. 2000

SERSE
2001 & 2003



A. Galatà, MSc. Thesis (Oct. 2003)





CNAO layout

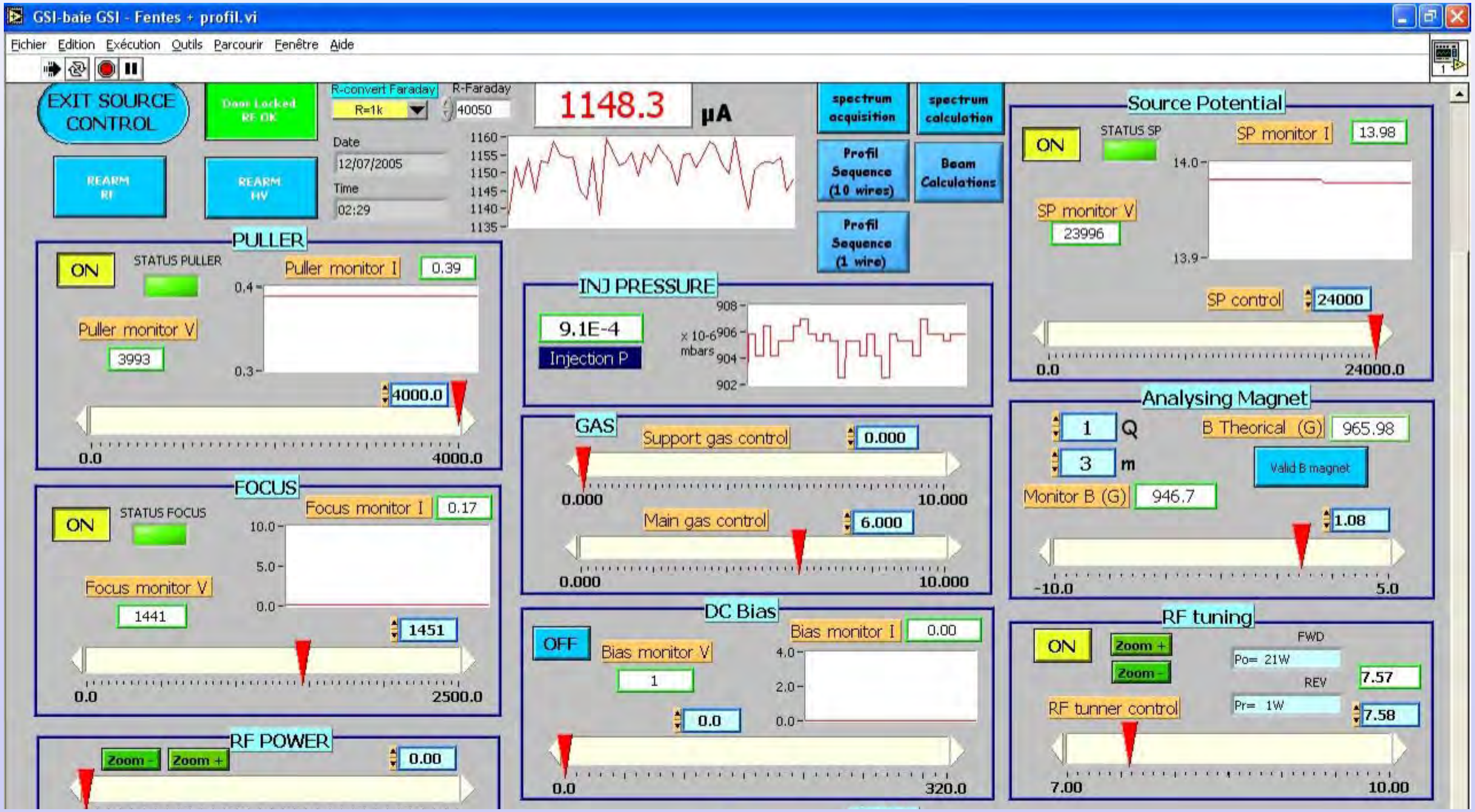
Shielding fence

Supernanogan

LEBT

Sources for the CNAO hadrotherapy centre

H_3+ : the current that could be guaranteed by the company was lower than requested (600 vs 700 µA), but thanks to our suggestions (in particular the frequency tuning), the current of 700 µA can be guaranteed and 900 µA - 1100 µA can be obtained.



GSI-baie GSI - Fentes + profil.vi

R-convert Faraday: R=1k
R-Faraday: 40050
Date: 12/07/2005
Time: 02:29
1148.3 µA

PULLER
Puller monitor I: 0.39
Puller monitor V: 3993
4000.0

FOCUS
Focus monitor I: 0.17
Focus monitor V: 1441
1451

RF POWER
0.00

INJ PRESSURE
9.1E-4 Injection P

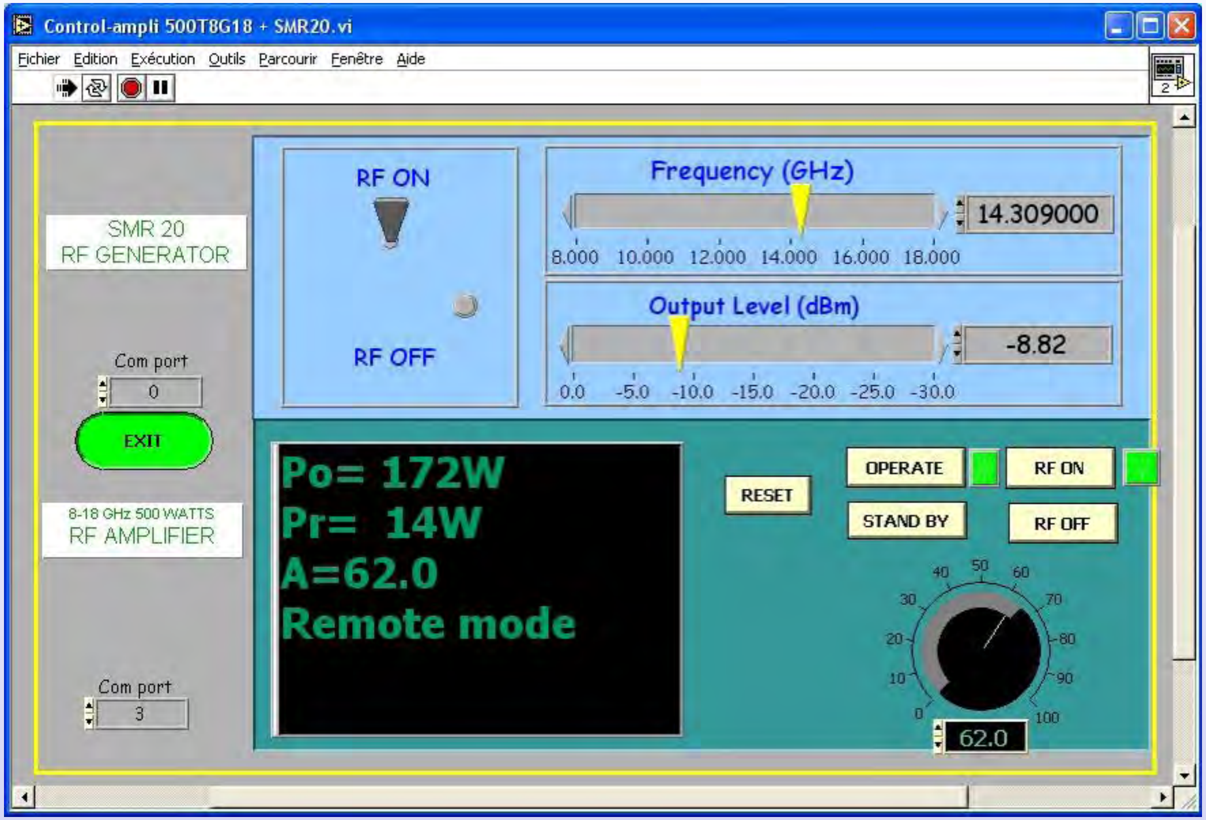
GAS
Support gas control: 0.000
Main gas control: 6.000

DC Bias
Bias monitor I: 0.00
Bias monitor V: 1
0.0

Source Potential
SP monitor I: 13.98
SP monitor V: 23996
SP control: 24000

Analysing Magnet
Q: 1
m: 3
B Theorical (G): 965.98
Monitor B (G): 946.7
1.08

RF tuning
FWD Po= 21W
REV Pr= 1W
7.57
RF tunner control: 7.58



Frequency (GHz) 14.309000

Output Level (dBm) -8.82

Com port 0

Com port 3

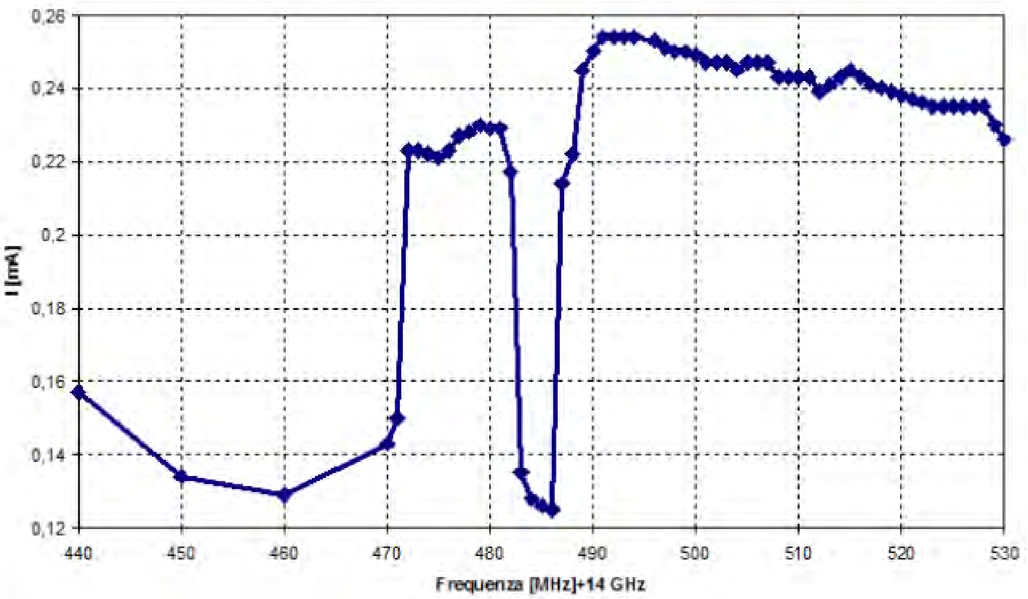
Po= 172W
Pr= 14W
A=62.0
Remote mode

62.0

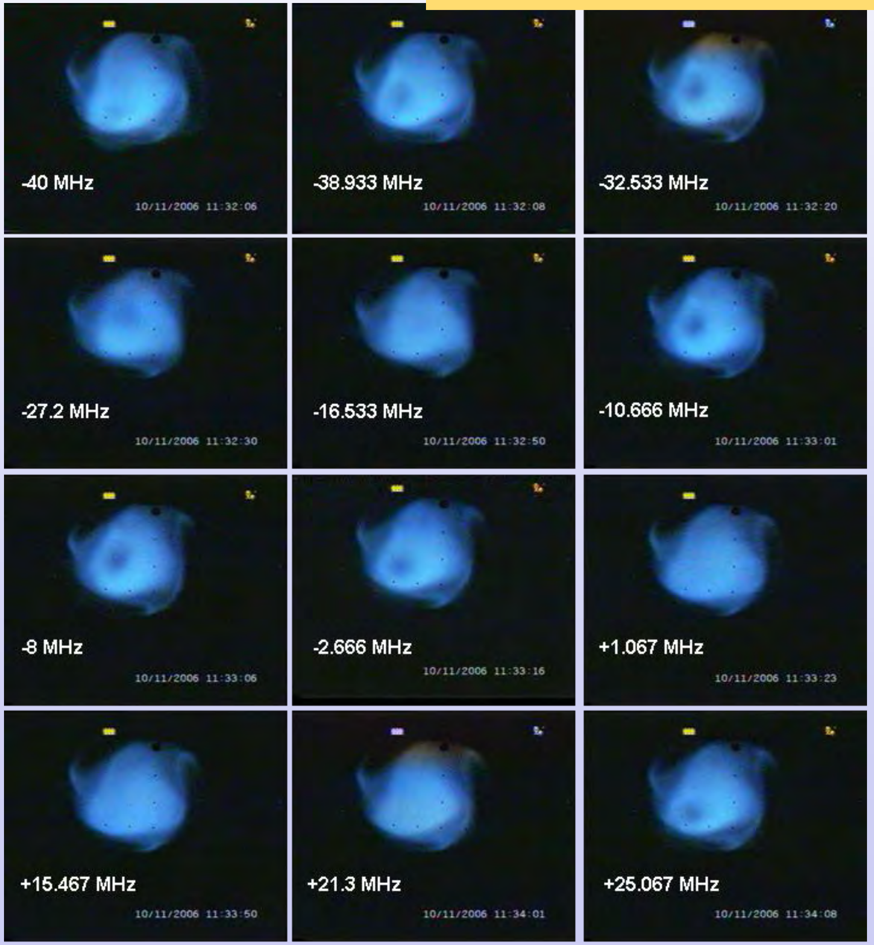
Frequency tuning: easy to be implemented

Similar gain was obtained for C4+, from 200 µA to 255 µA

SUPERNANOGAN - CNAO
S. Gammino - July 2005

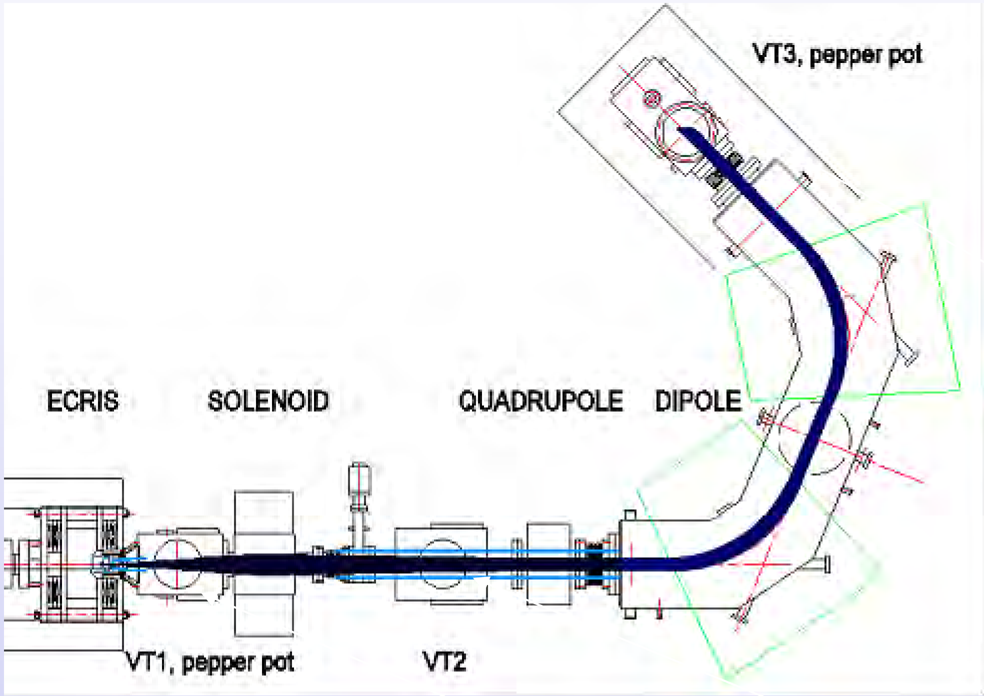


L. Celona et al.



CAPRICE -GSI
fall 2006

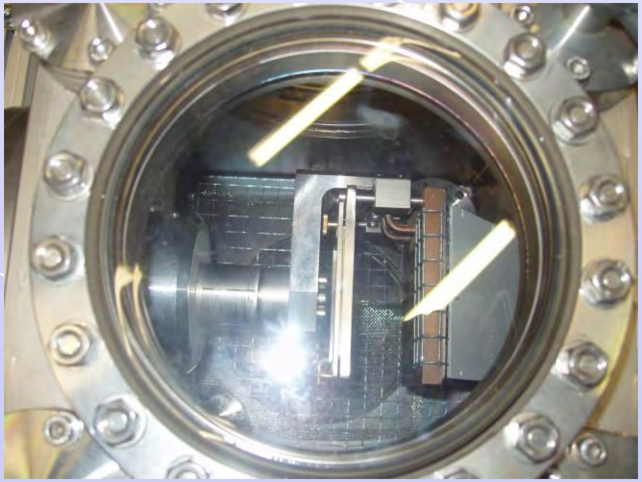
Frequency tuning @ GSI



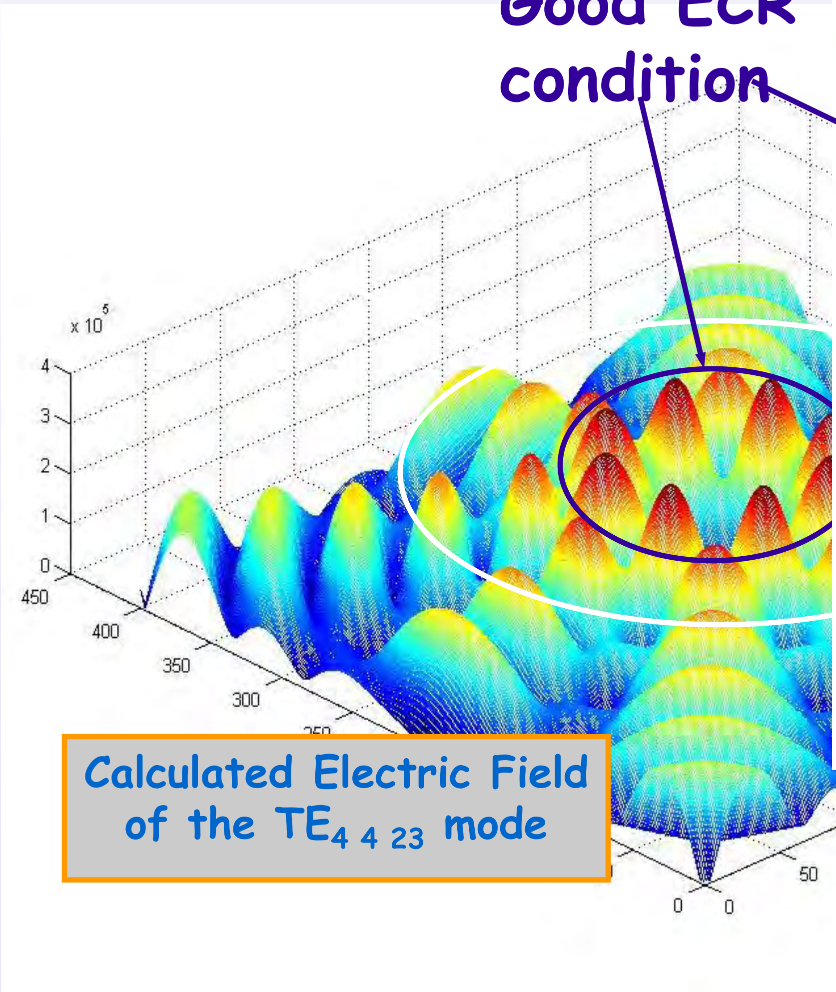
Central operating frequency: 14.5 GHz

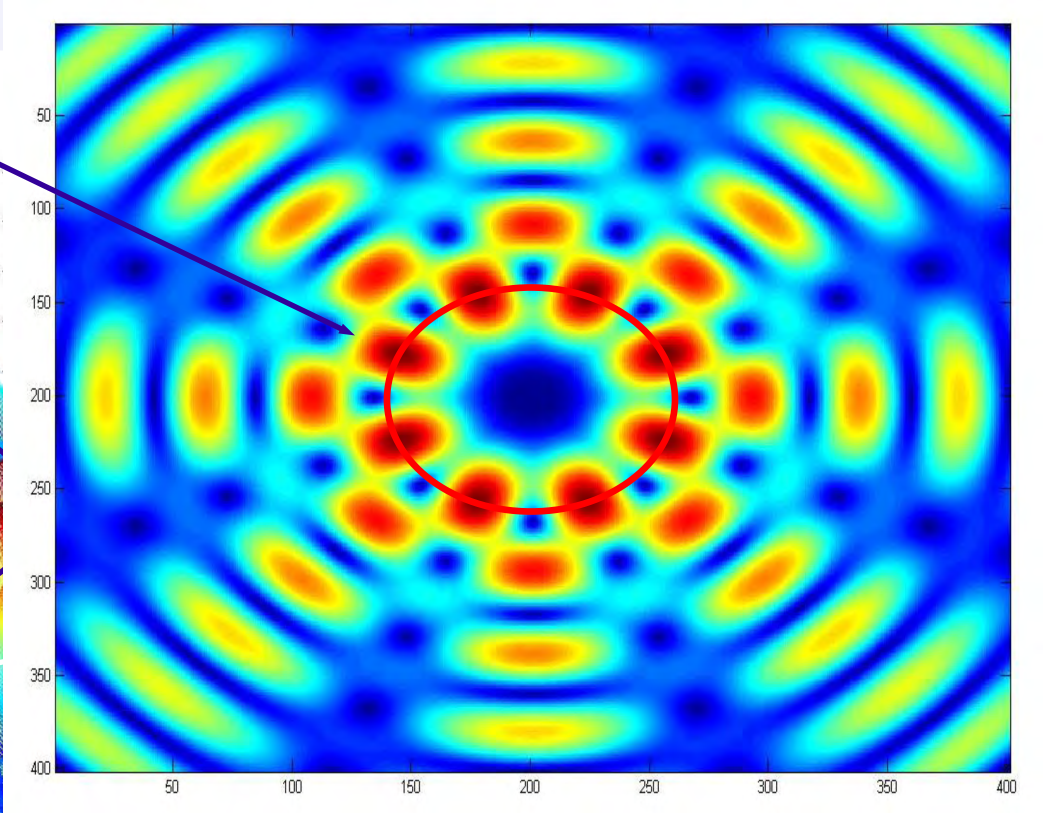
Frequency sweep: ±40 MHz (klystron frequency range)

Sweeping time: 150 sec



Optimization of the RF energy transfer



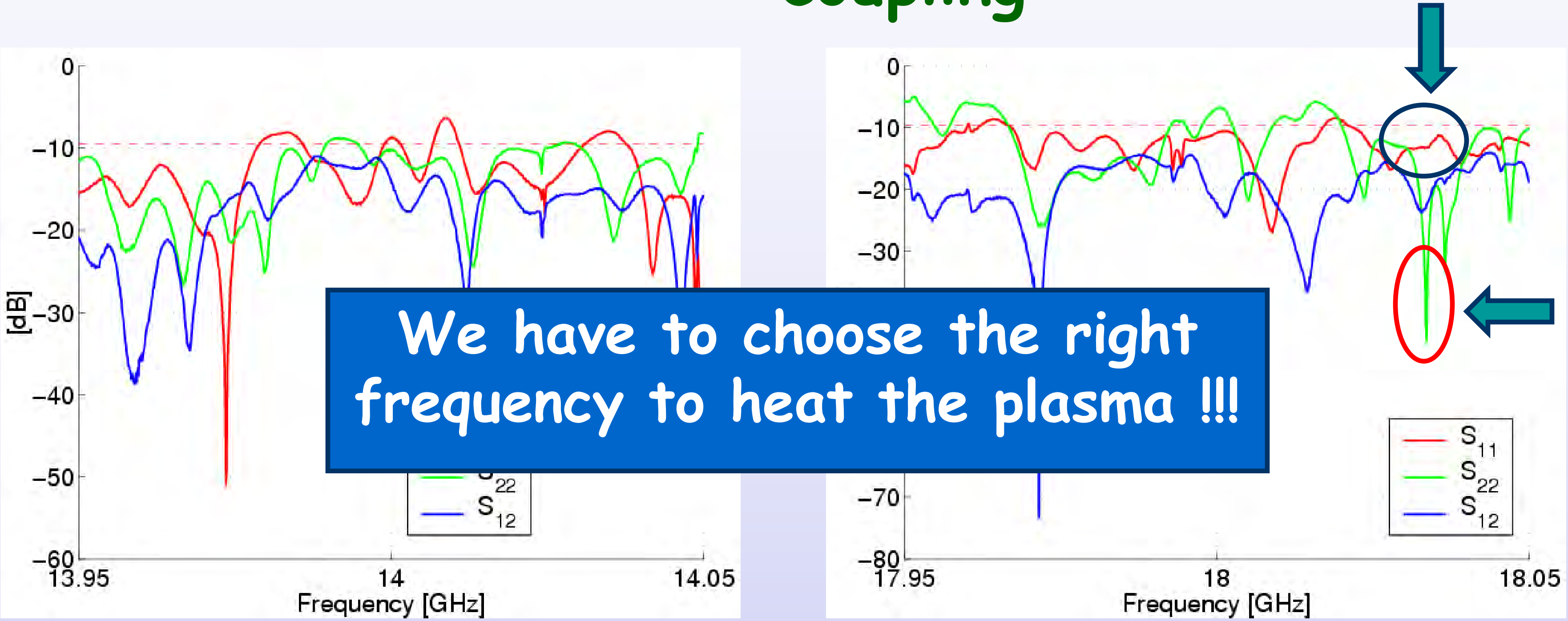


Good ECR condition

Calculated Electric Field of the TE$_{4\ 4\ 23}$ mode

Optimization attainable by adjusting the magnetic field profile.

Plasma chamber-MW generators coupling

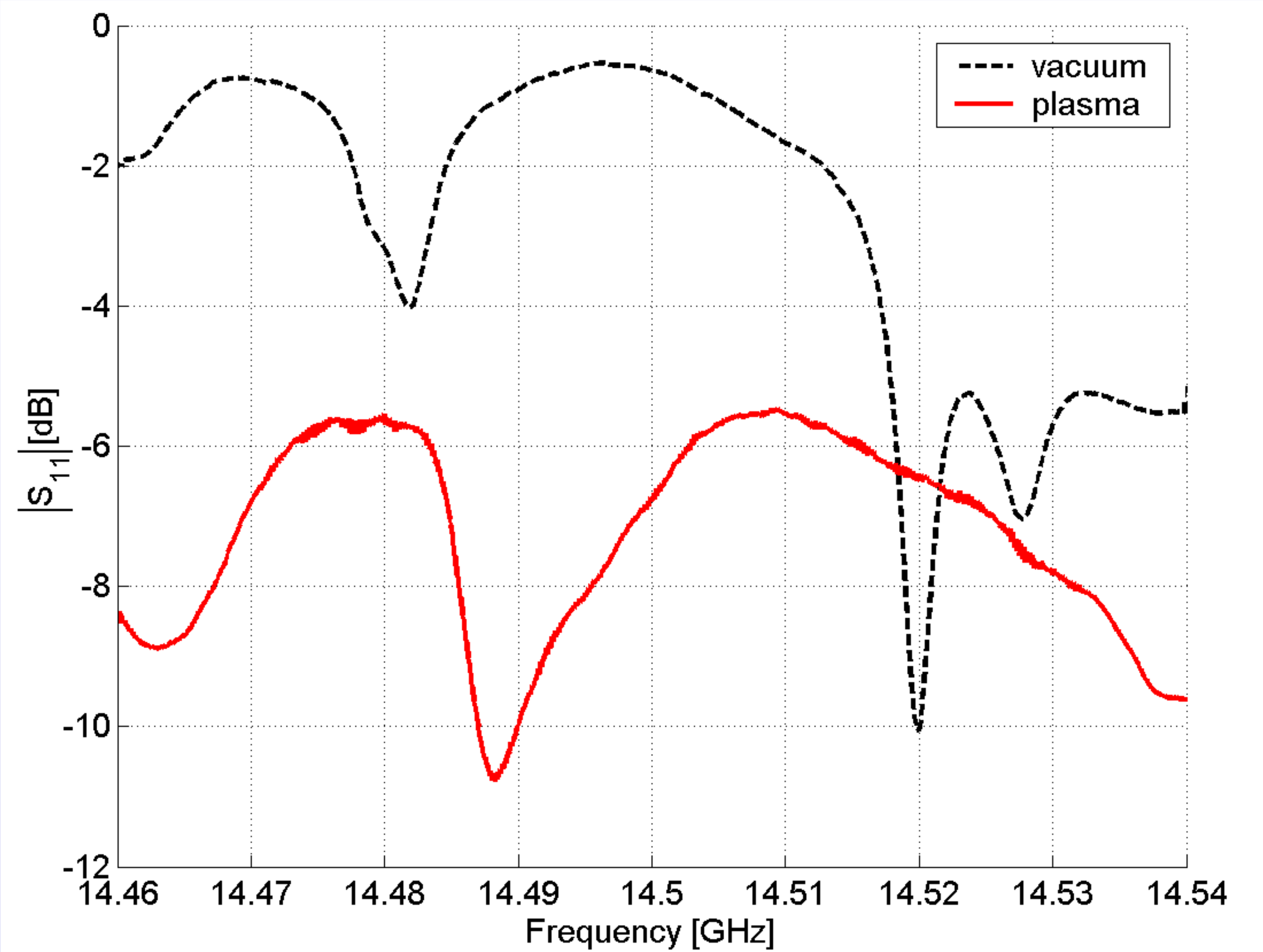


We have to choose the right frequency to heat the plasma !!!

1. Defined modes exist in the plasma chamber;

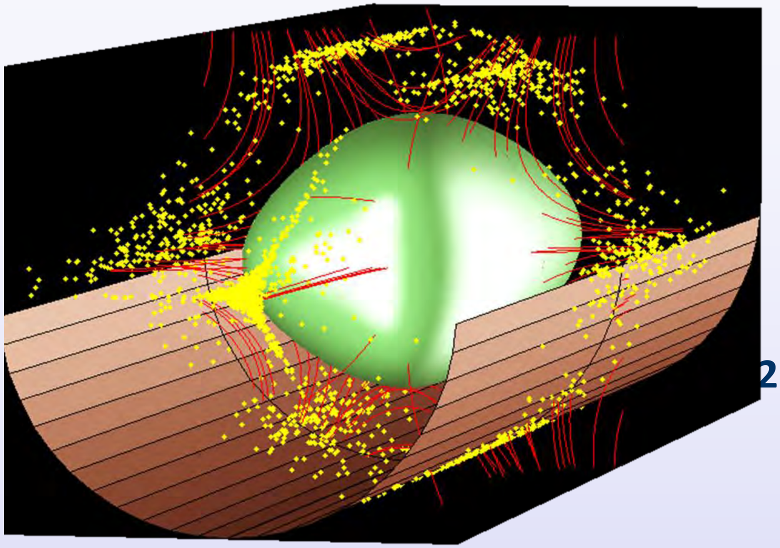
2. Differences about the microwave coupling are evident for the two MW ports.

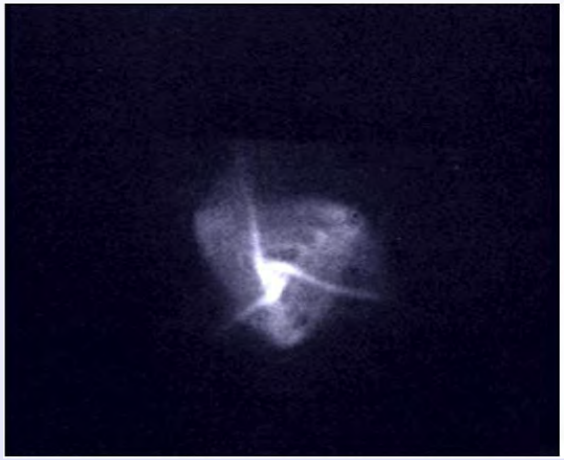
Frequency tuning: some experimental observations



Ion Dynamics and Beam Formation

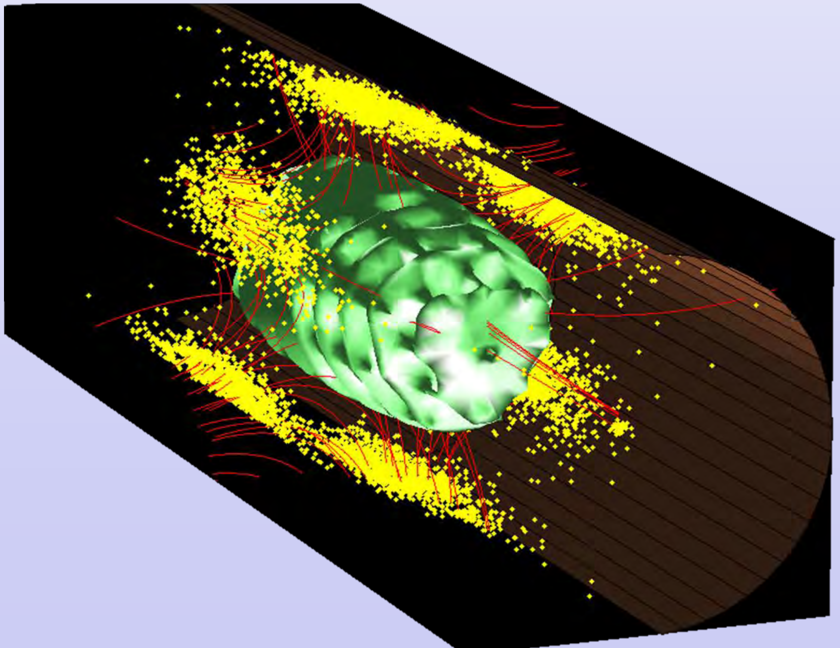
The plasma dynamics affects heavily the beam emittance

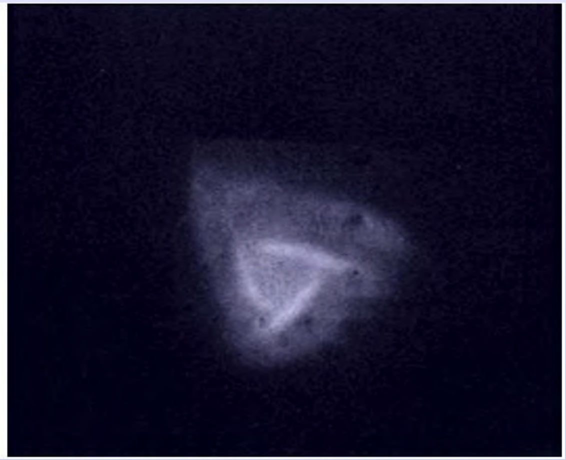




1) **Optimal Source performances:** Higly Charged ions concentrated in the center of the extracted beam

2) **Bad Source performances:** ion scattering injects lowly charged ions in the loss cone. The beam periphery is populated by LCI





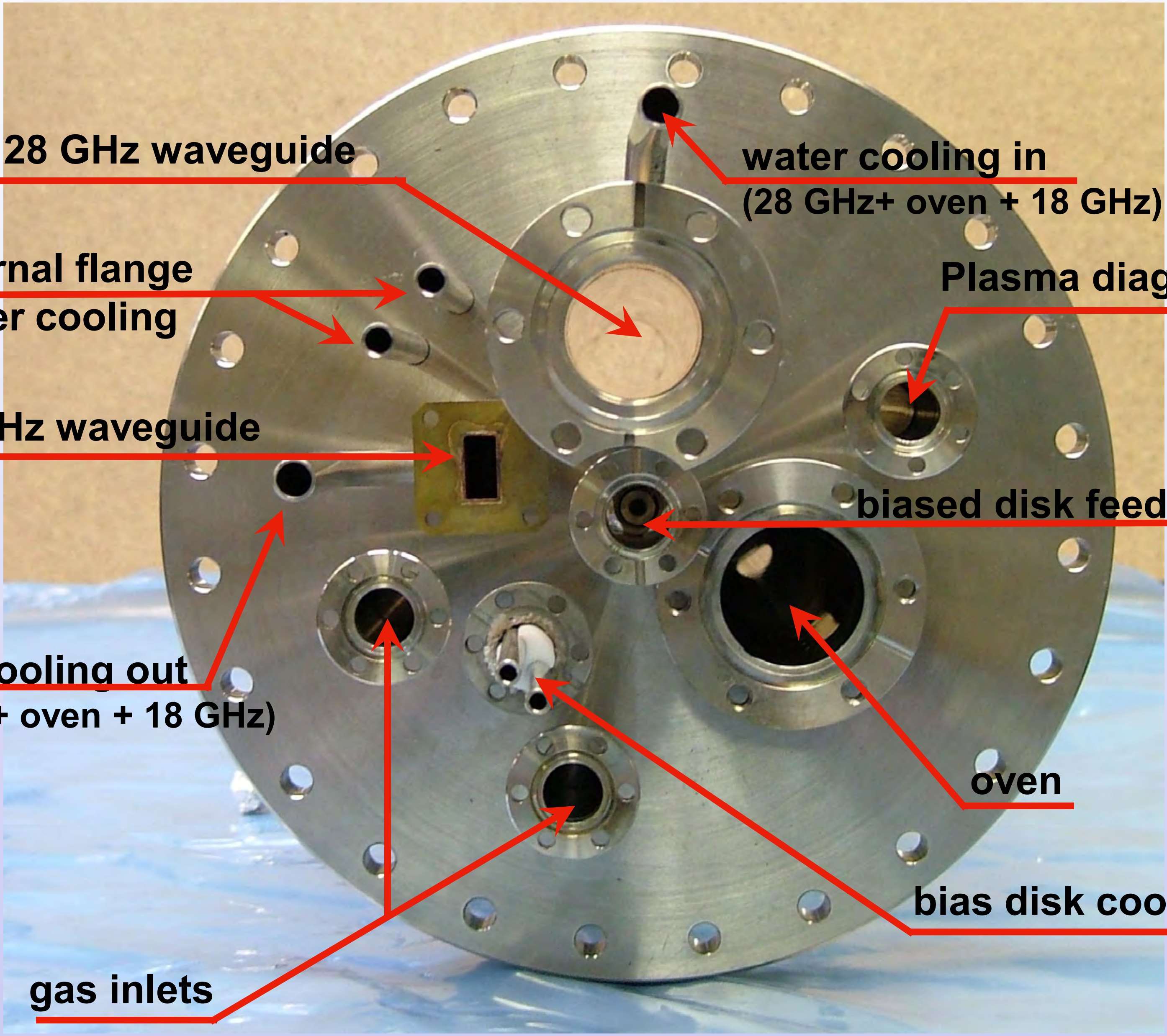
Also the beam formation and handling may take advantage from Frequency Tuning

[D. Mascali et al. *Plasma ion dynamics and beam formation in Electron Cyclotron Resonance Ion Sources*, submitted to Rev. Sci. Instrum.]

Evidences

- 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.

Injection flange of MS-ECRIS



28 GHz waveguide

water cooling in
(28 GHz+ oven + 18 GHz)

Internal flange
water cooling

Plasma diagnostics

14/18 GHz waveguide

biased disk feedthrough

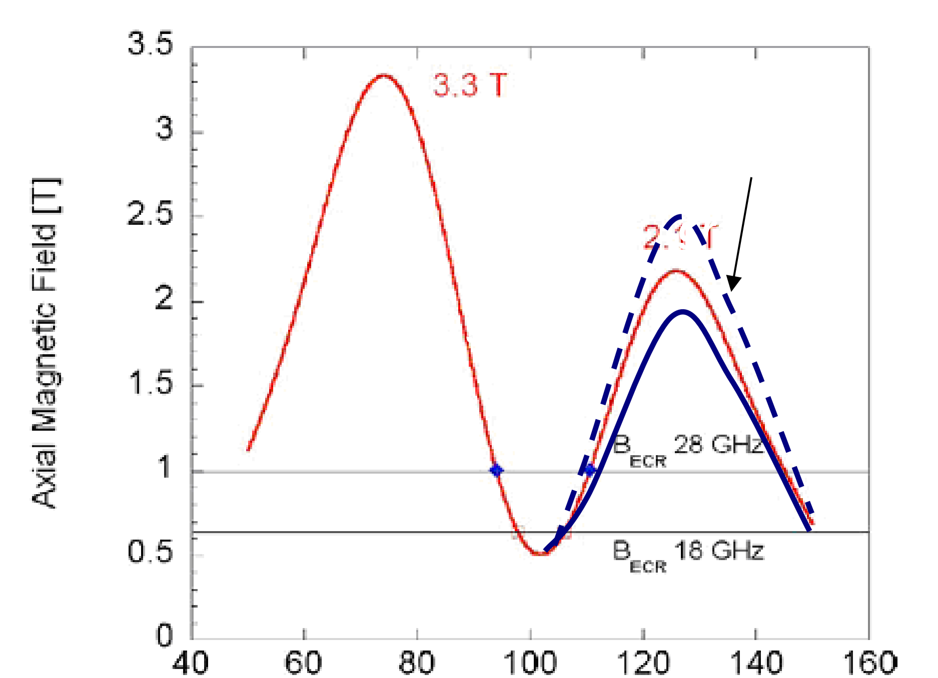
water cooling out
(28 GHz+ oven + 18 GHz)

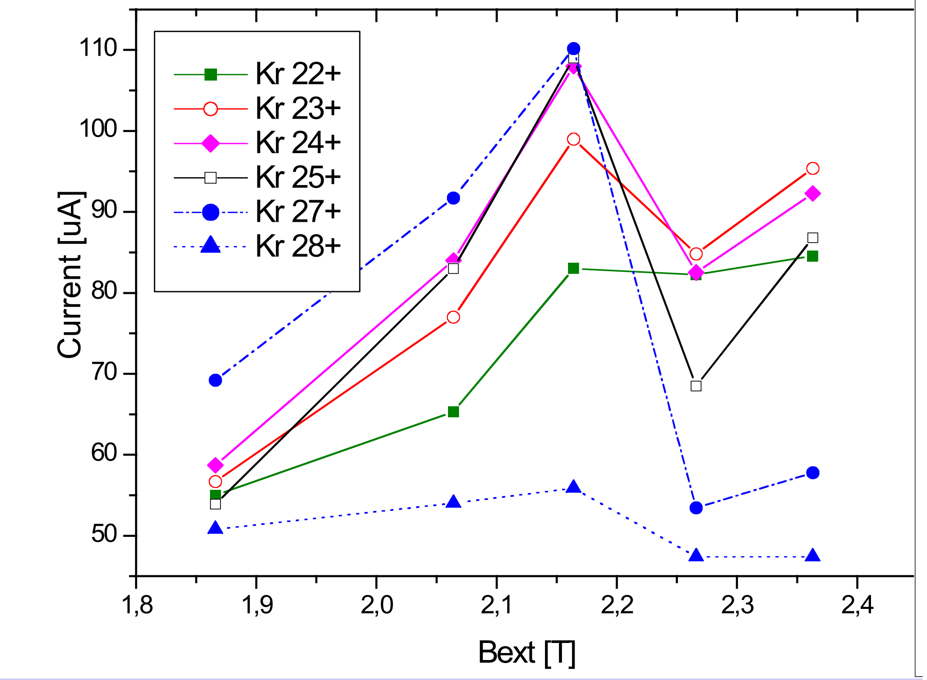
oven

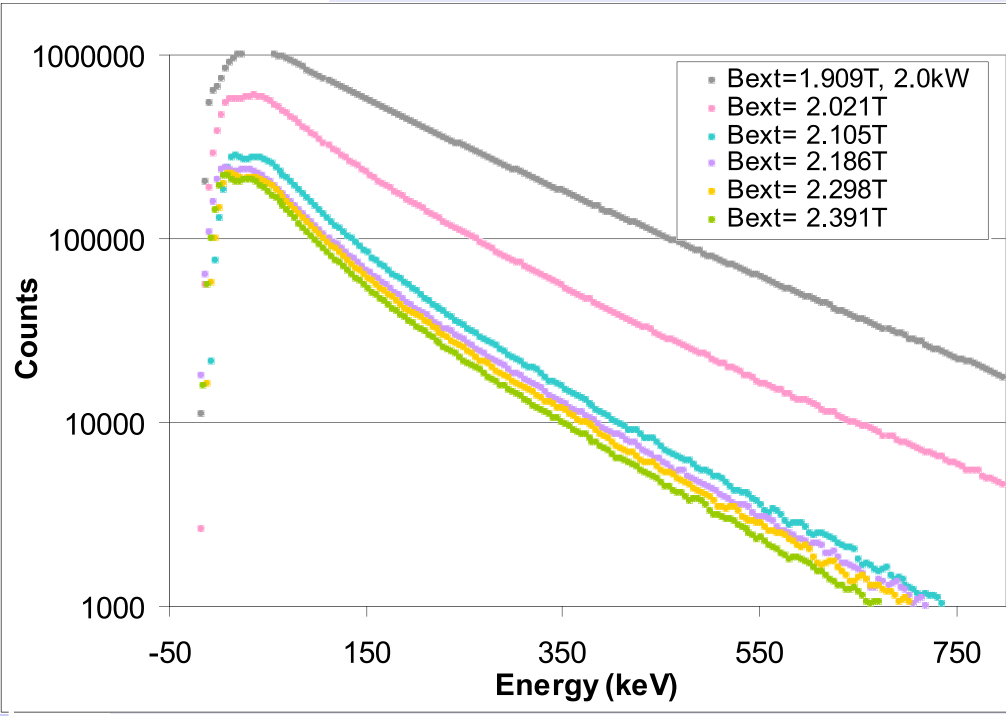
bias disk cooling

gas inlets

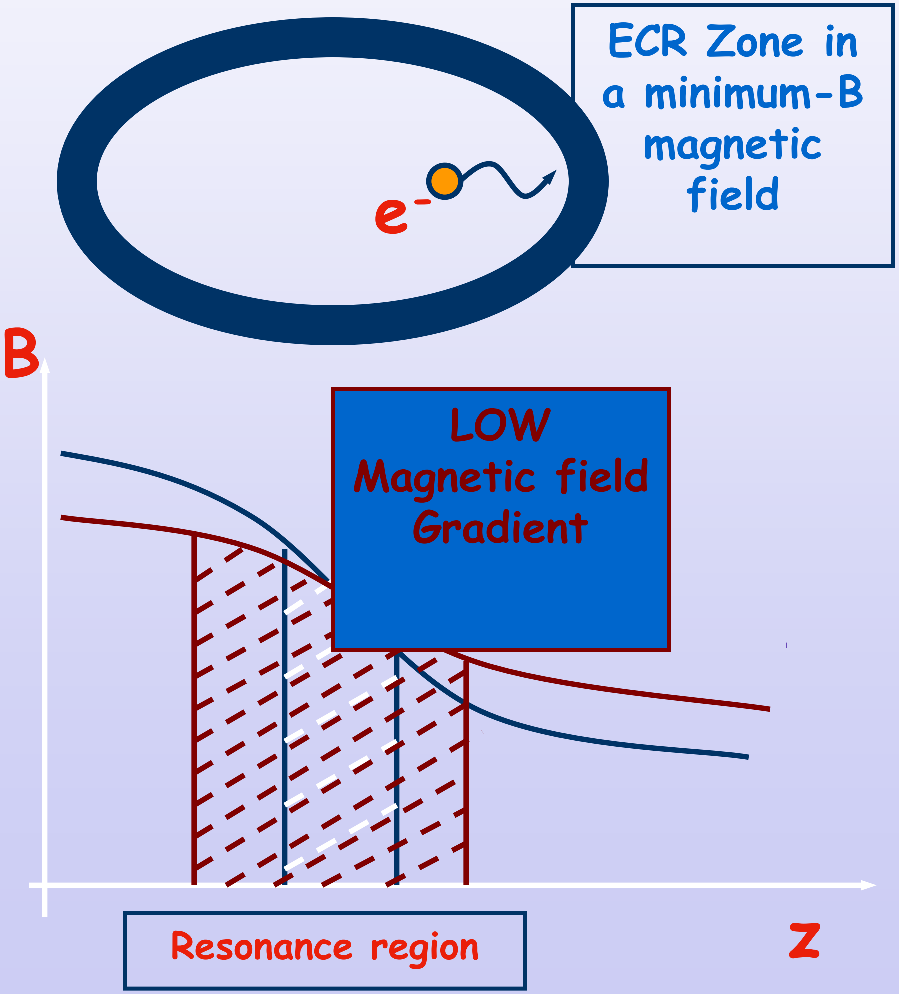
Magnetic field anomalies







Relationship between the electron energy and the magnetic field gradient



The electron energy is inversely proportional to the magnetic gradient intensity

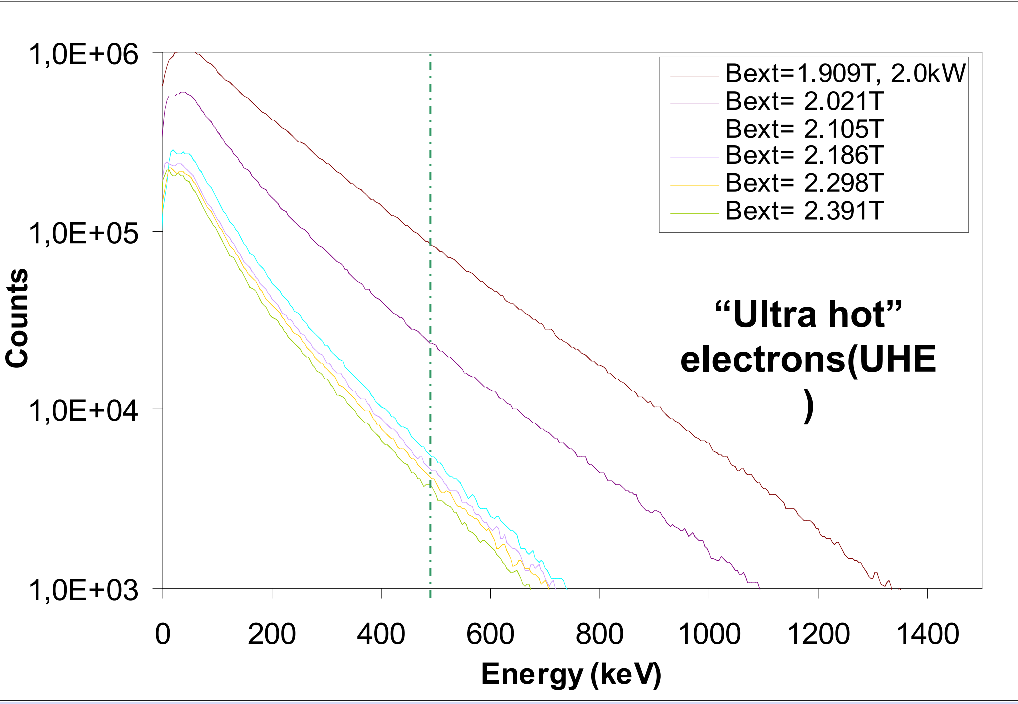
BUT

High Gradients mean better confinement

Hence a compromise has to be reached exploiting the RF energy transfer to the electrons.

Open Questions

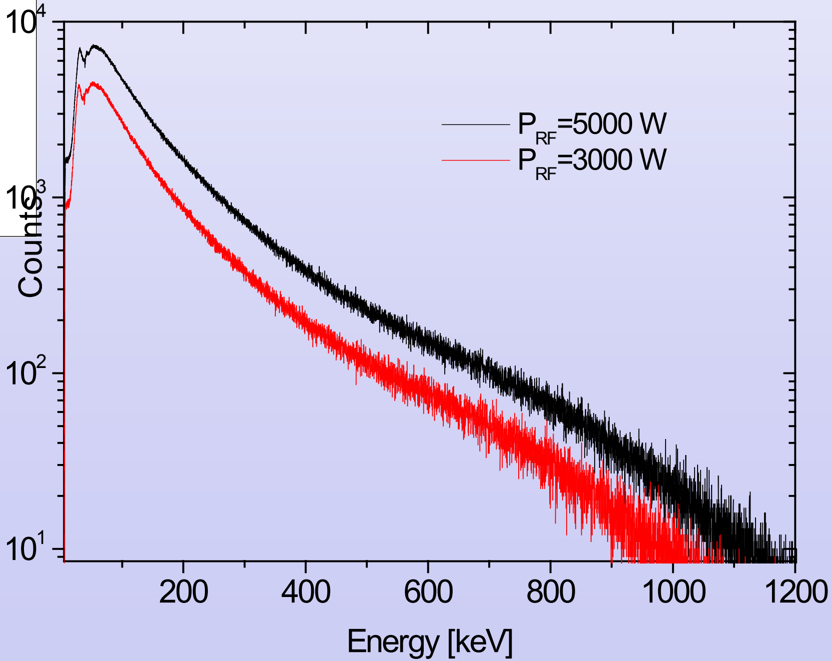
High Energy Electrons (up to 2 MeV)



Energy Barrier according to Liebermann and Lichtenberg model:

Wb=500 keV

The production of the UHE strongly depends on the magnetic field gradient.



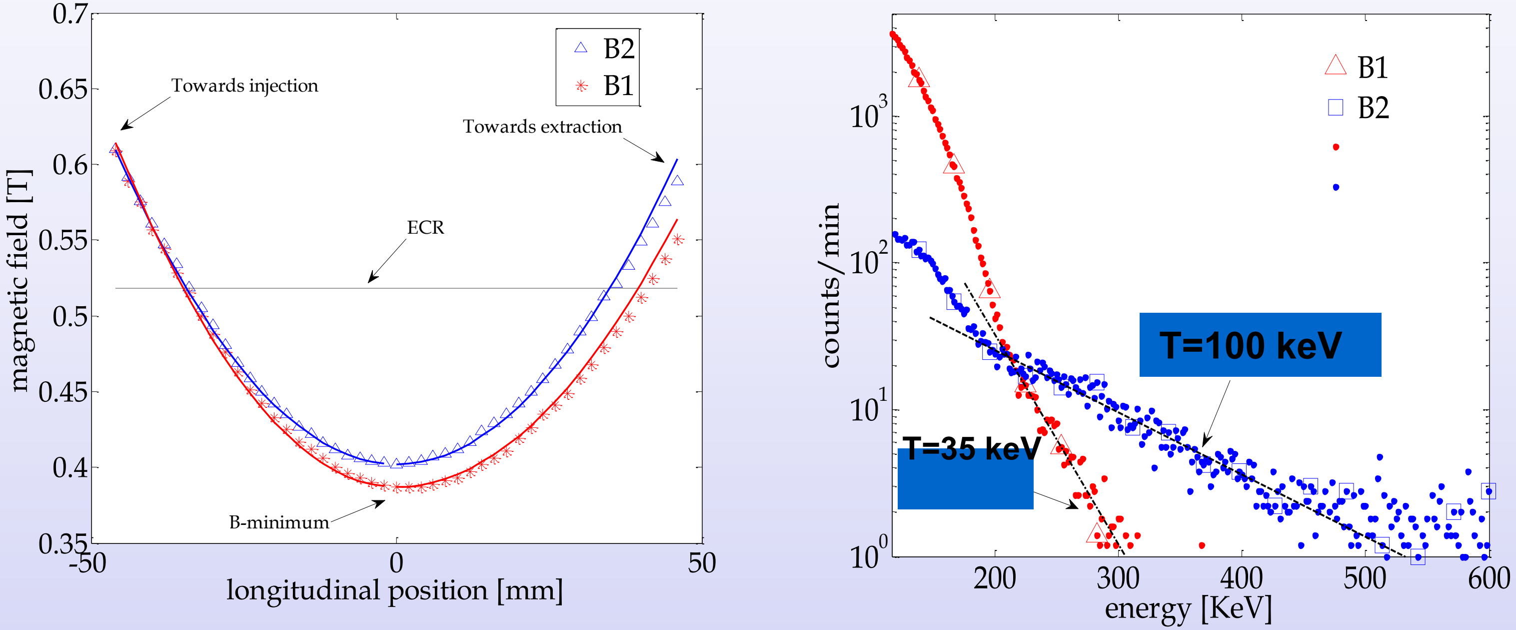
Ref. S. Gammino, G.Ciavola et al, 2008

Evidences

- Sometimes the small changes of magnetic field have remarkable effects on charge state distribution.
- Sometimes the small changes of magnetic field have remarkable effects on X-ray production.
- There is a threshold for the non-linear effects? Other heating scheme are triggered?

In some conditions slight variations of L are critical for hard-X rays generation (exp. with CAESAR)

Comparison of the X-ray spectra obtained with slightly different B profiles



By changing the characteristic length of the mirror trap, L, of just 4mm, we obtained a completely different X-ray spectrum.

	L [mm]	l [mm]	W_b [keV]	$D_{\nu\nu}$ [a.u.]	T^{spec}[keV]	Ef [keV]
B1	60	30	300	100	35	300
B2	64	34	350	105	100	530

In case of turbulent heating induced by mode conversion

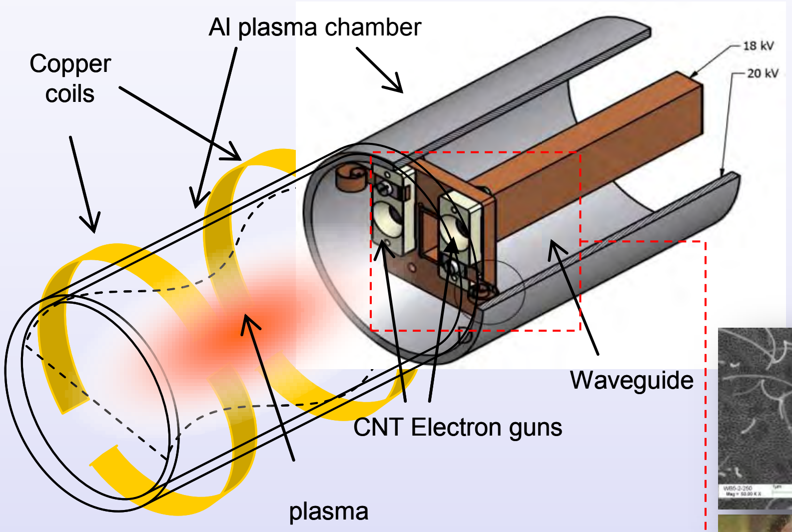
The electrostatic modes, generated at the ECR or/and at the UHR, give small kicks to the bouncing electrons, thus providing an additional randomization of the wave-particle phase!!!

⬇

OVERHEATING AND GENERATION OF SUPRATHERMAL ELECTRONS

Hard X-rays appearently depend on B field detuning

We succeeded in damping hot electrons by launching auxiliary electrons inside the plasma



Al plasma chamber

Copper coils

18 kV

20 kV

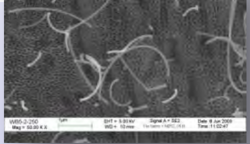
Waveguide

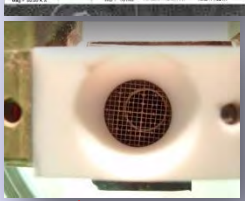
CNT Electron guns

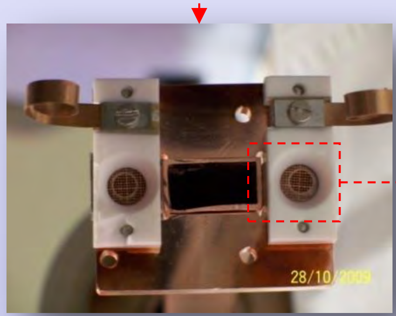
plasma

Electron gun made of a CNTs cathode obtained over a 300 μm thick silicon substrate, a 150 μm thick mica spacer and an anodic copper grid with quad cells of 350 μm side

Measurements of plasma axially emitted X-rays were carried out by using a high purity Ge detector, collimated through lead blocks with a hole of 1 mm²



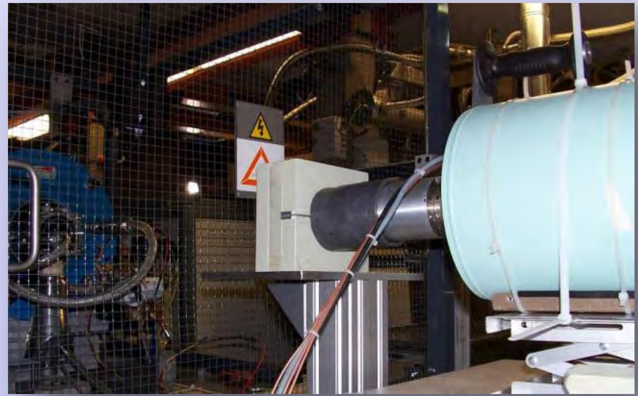




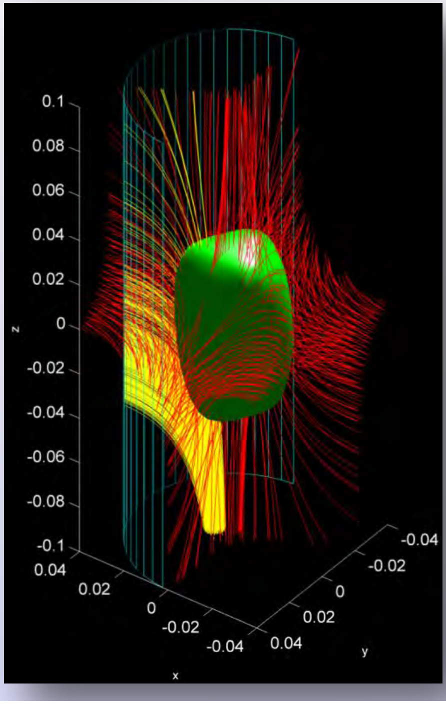
Twin guns placed on the injection waveguide: field emission effect at electric field *E*>2-3 V/μm

$$j^{e}_{CNT} \sim 1 \div 10\ mA/cm^{2}$$

For an emission surface of 0.12 cm². *j* drastically grows with V_{bias}.

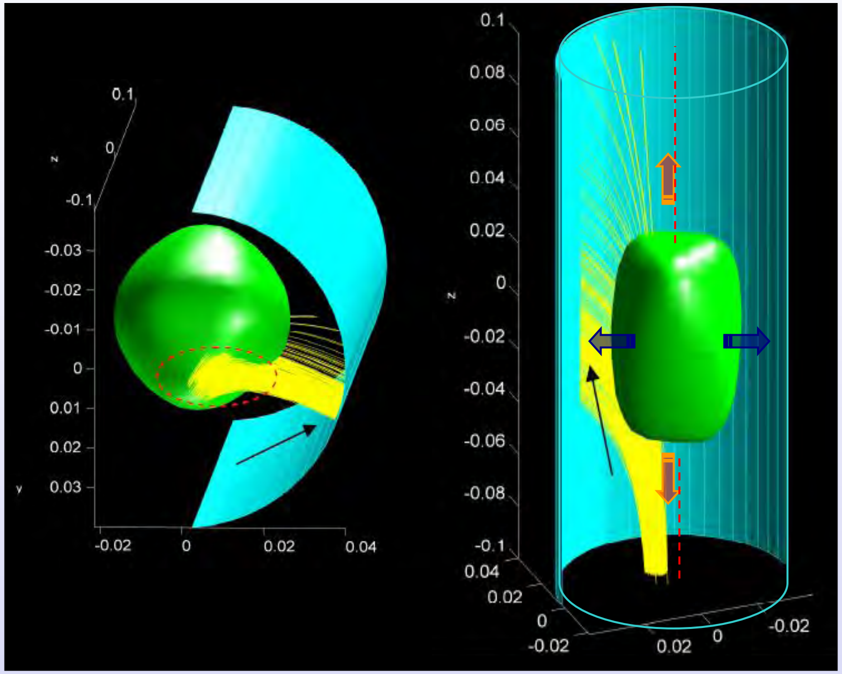


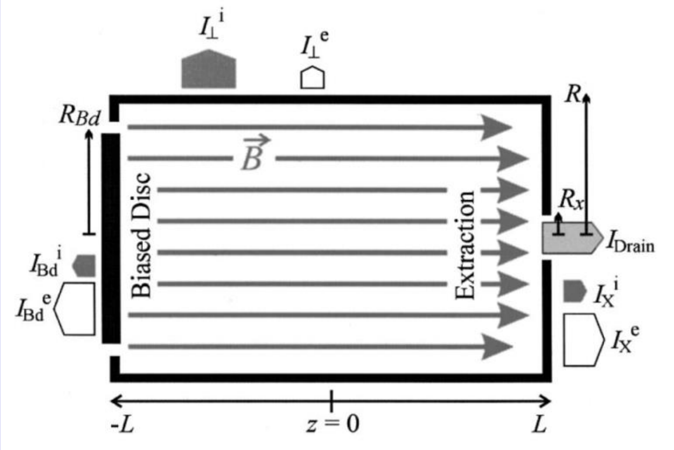
An experiment for damping of hot electrons:
Simulation of electrons injection into the plasma chamber



The CNT guns where placed outside the three-cusps star intercepted by the field lines over the injection endplate

Electrons are guided by the B field over the lateral chamber walls

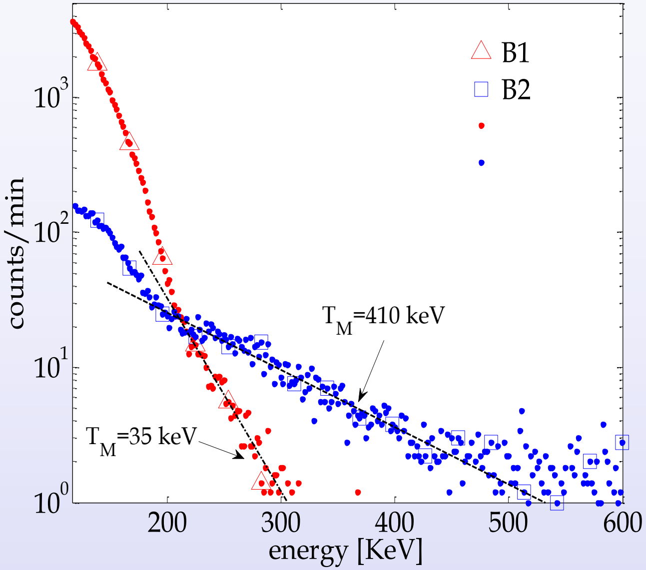




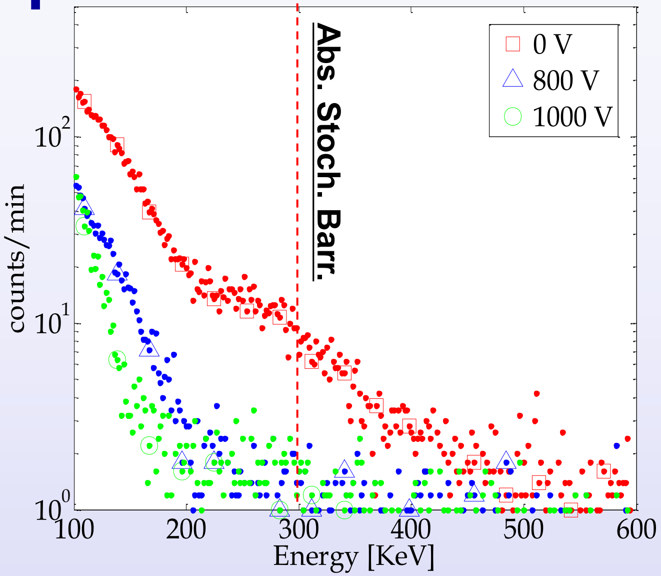
In a magnetized plasma the diffusion is anisotropic and proceeds according to the Simon mechanism: the charge compensation for quasi-neutrality takes place globally and not locally.

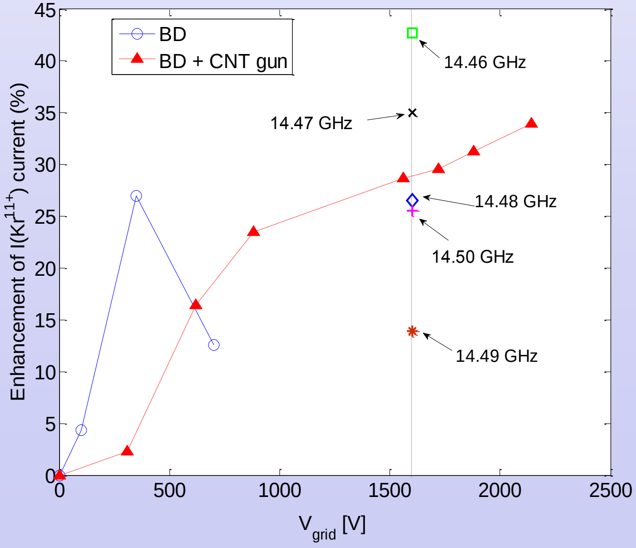
$$I_\perp^i + I_{\mathrm{bd}}^i + I_X^i + I_{\mathrm{bdR}}^i + I_{\mathrm{bd}}^e + I_X^e + I_{\mathrm{bdR}}^e + I_{\mathrm{drain}} = 0$$

An experiment for damping of hot electrons: Results and interpretation



Injecting auxiliary electrons





The experiment demonstrate that the influence of B field is only indirect: the density was changed by CNT electrons and this affected the hot electron production.

The source performances also increased considerably!!

[D. Mascali et al., *in preparation for Physical Review Letters*]

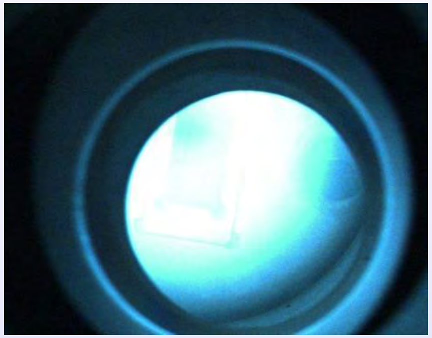
HYPOTHESIS: mode conversion at UHR

A new heating mechanism based on EBW and role of turbulences in determining beam quality

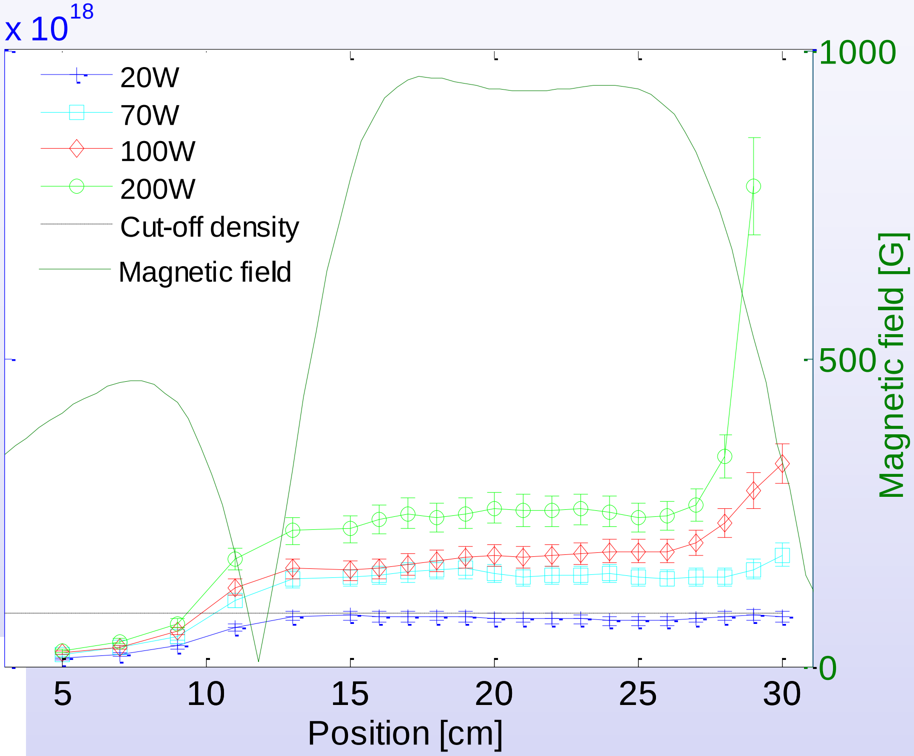
QUESTION: may we transform a problem in resource?

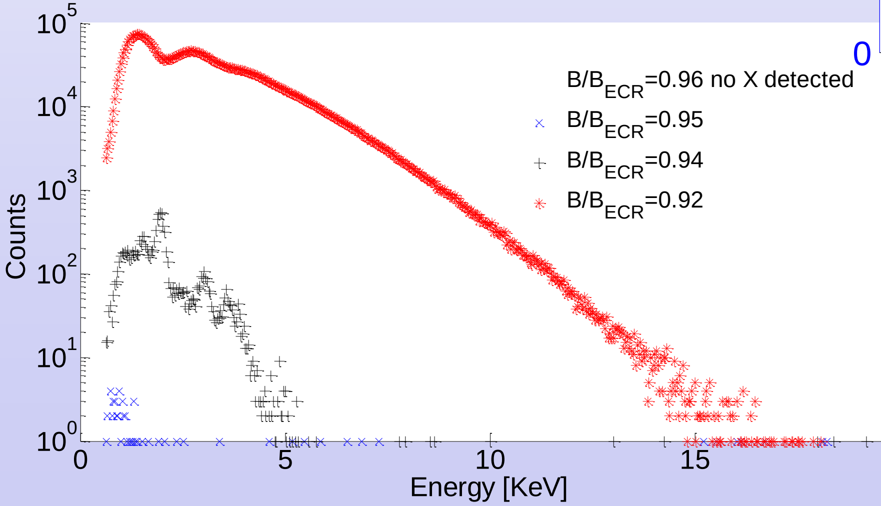
16.03.2011 17:13

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



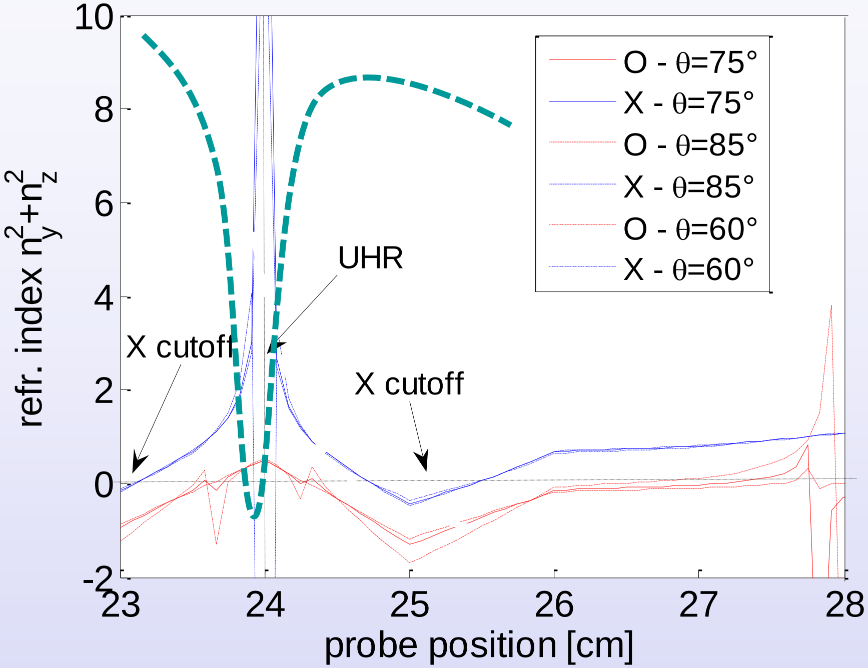
Plasma hole @ 90 W





BW absorption leads to generation of high energy electrons without multi-crossing of the resonance in multi-mirror fields

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



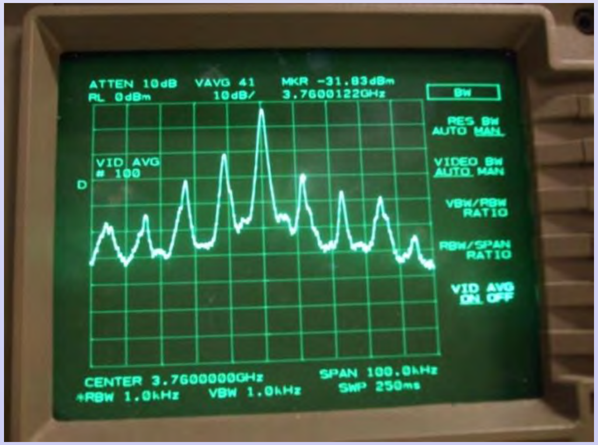
- - - - Plasma density

- - - - Magnetic field

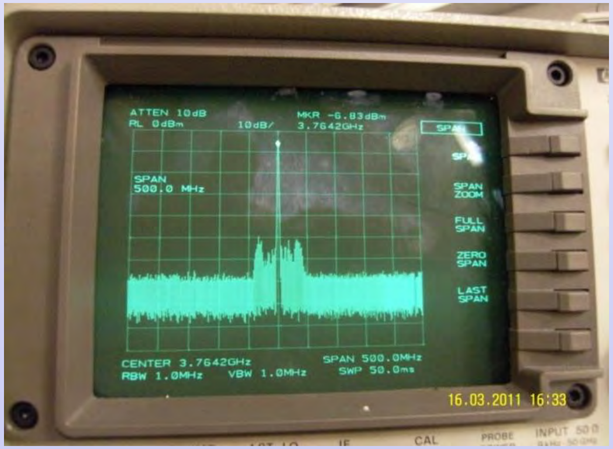
In the 3.76 ± 0.1 GHz, 7 resonant modes exist having *r*=5, 0< *n,ν*<2 (60° < θ < 80°).

Displacement of cutoffs and resonances for these modes is compatible with Budden-type mode conversion scenario

Sidebands are the fingerprint of EBW-generation!!



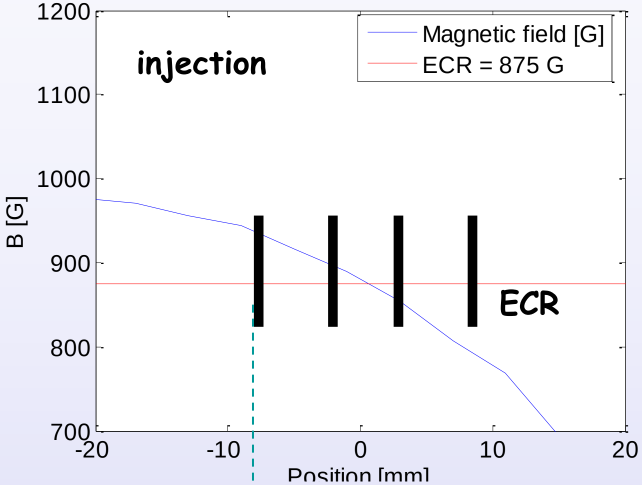
KHz sidebands



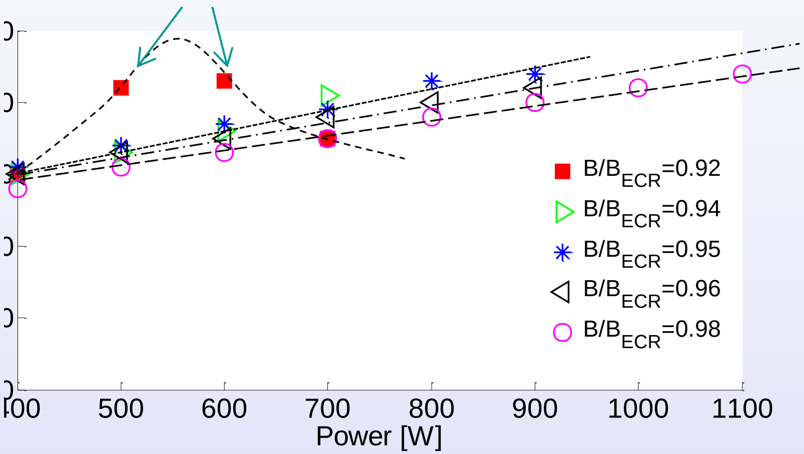
MHz sidebands

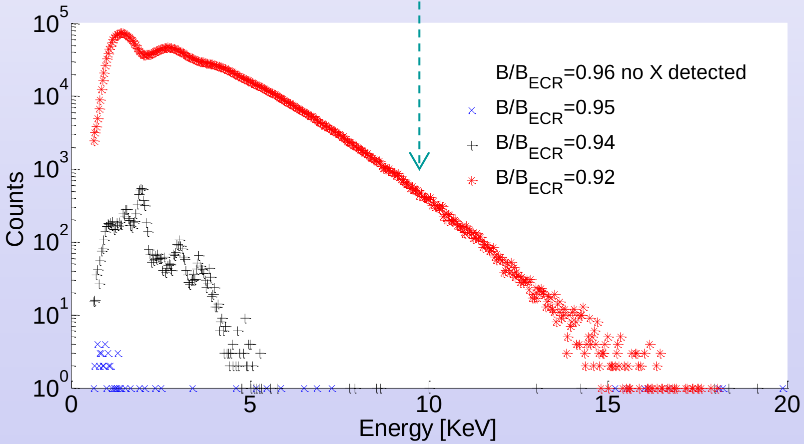
[D. Mascali et al. *Nuclear Instruments and Methods A*

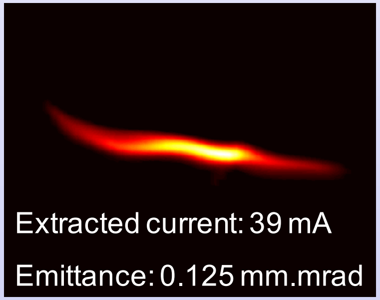
Under-resonance discharge on VIS proton source



Boost of output current at low RF power

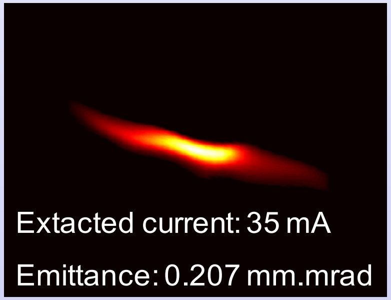





Extracted current: 39 mA

Emittance: 0.125 mm.mrad

No X-rays

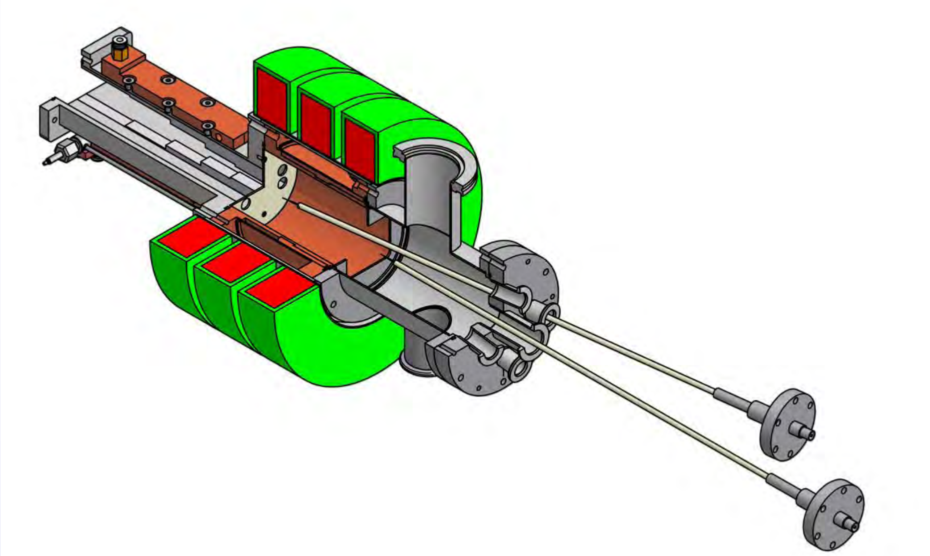

Extacted current: 35 mA

Emittance: 0.207 mm.mrad

X-rays

EBW heating produces high energy electrons even at low RF power. But EBW also cause IAW generation and following ion heating: the emittance grows when turbulences are activated.

NEXT: Understanding by means of two sources



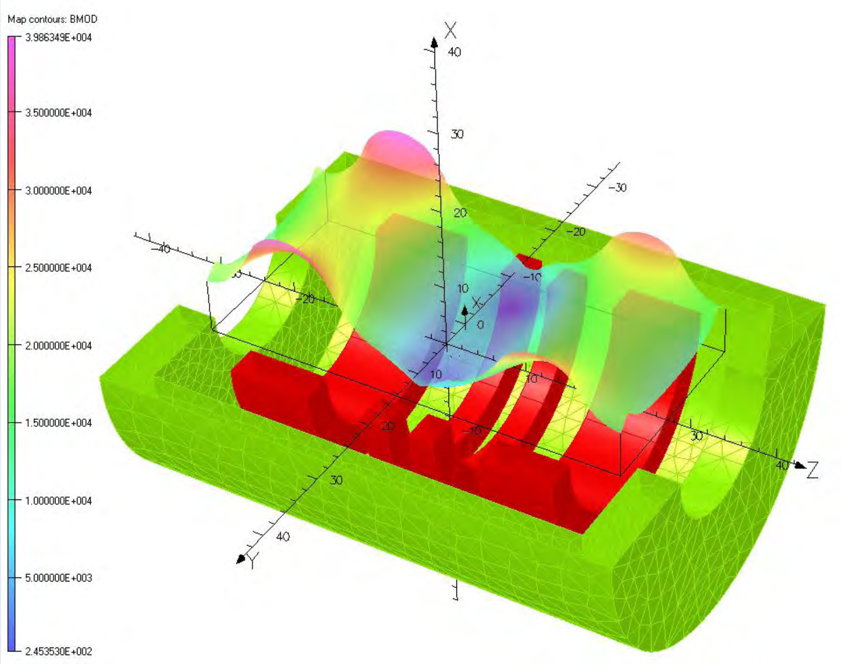
The first one with Simple Mirror magnetic configuration exploiting OXB ignition mechanism

f <10 GHz, P=0.5-5 kW

n=10^{13} cm^{-3}

T=0.5-20 keV

<q>=1-3



The second one based on ECR-heating and B-min structure for producing stabilized plasma (MHD stability ensured) of multi-charged ions

f=18- 24 GHz, P=2.5 kW

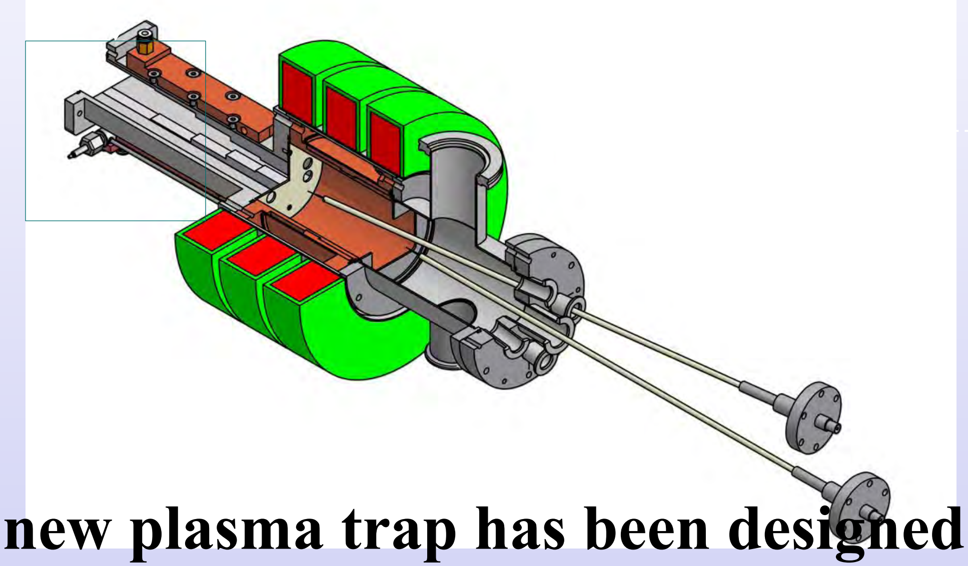
n=10^{13} cm^{-3}

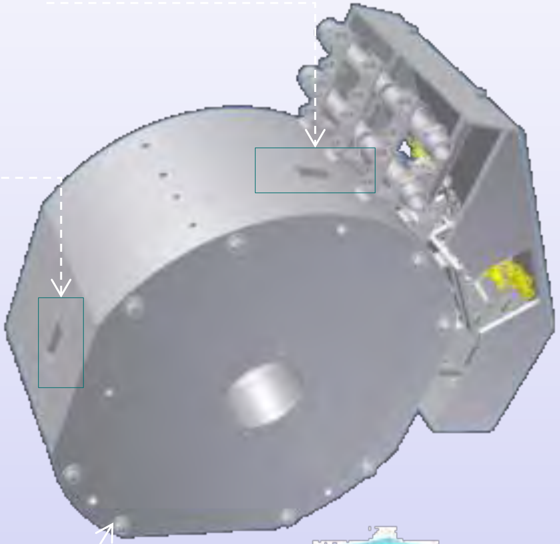
T=10-200 keV

<q> above 20

PLASMA TRAP with versatile B-field

Investigation of EBW-heating under different magnetic field configurations





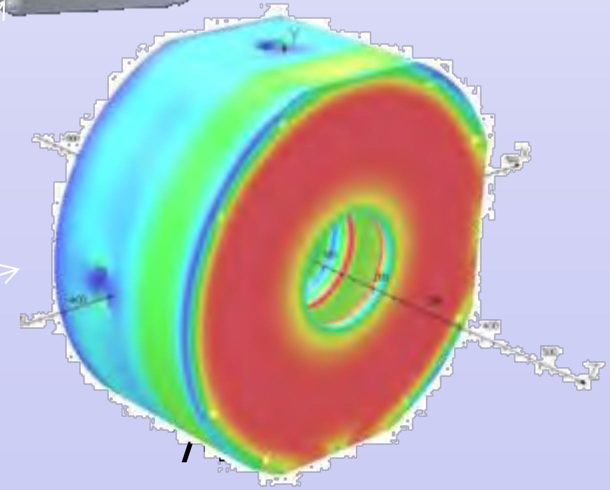
Parallel and perpendicular launching of EM waves

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

X-ray imaging

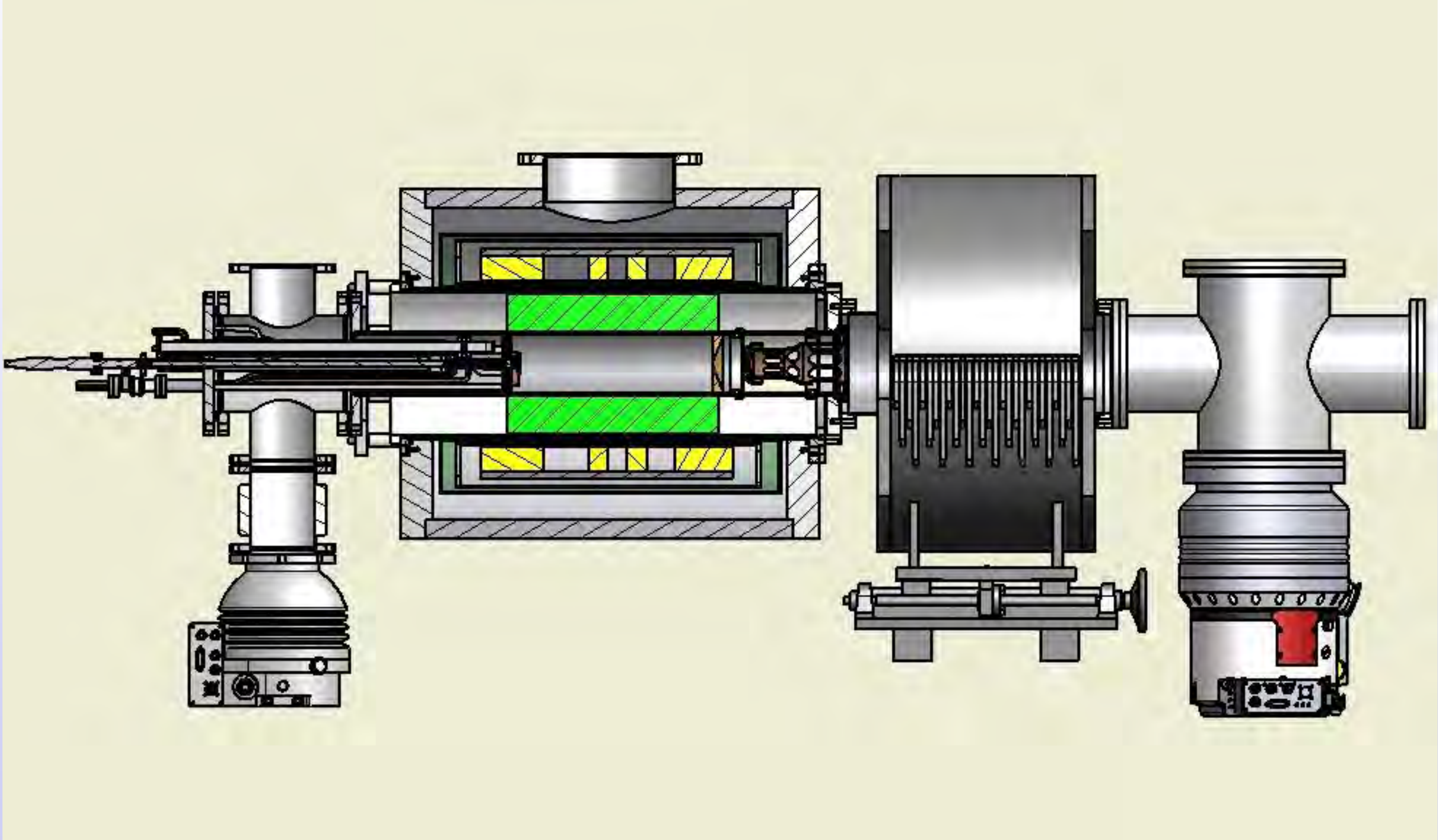
LP measurements

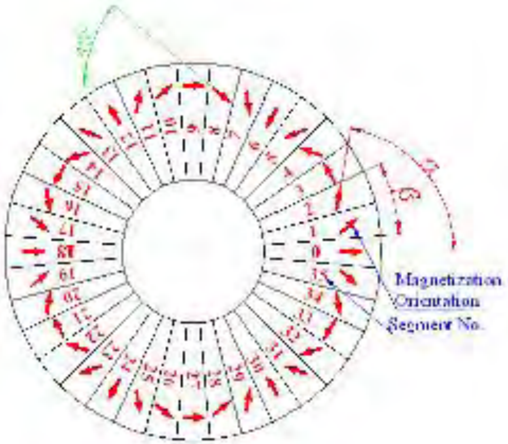
RF diagnostics (spectral analysis)



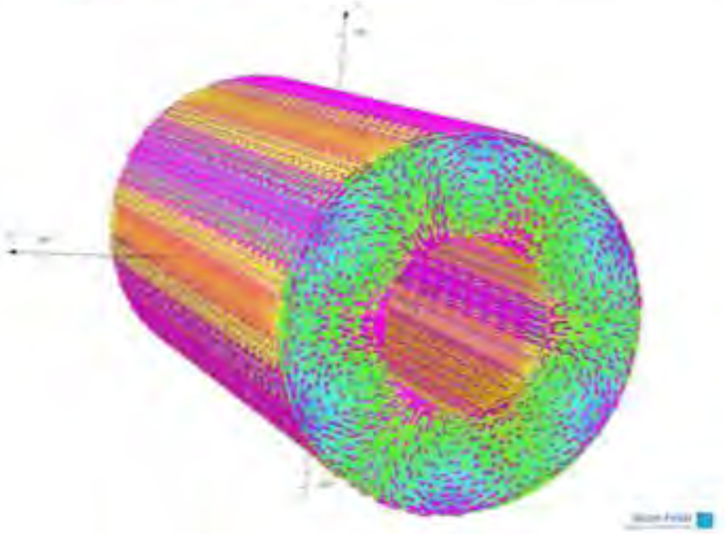
B-field magnets and structure

AISHA assembly



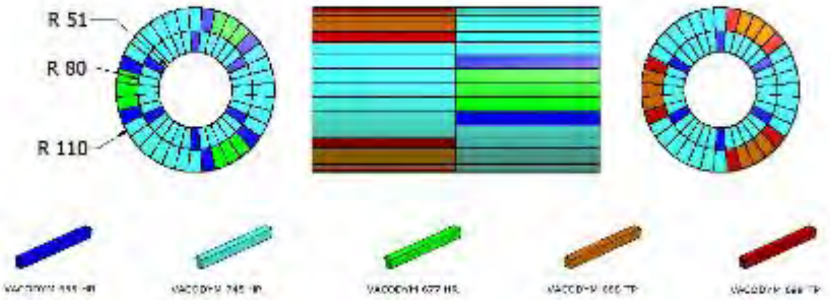


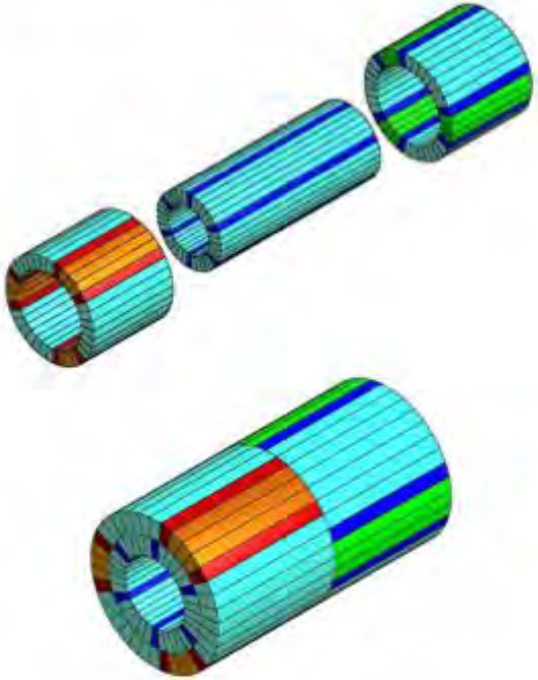
Settori				Direzione di magnetizzazione
0	9	18	27	0
1	10	19	28	40
2	11	20	29	80
3	12	21	30	120
4	13	22	31	160
5	14	23	32	200
6	15	24	33	240
7	16	25	34	280
8	17	26	35	320



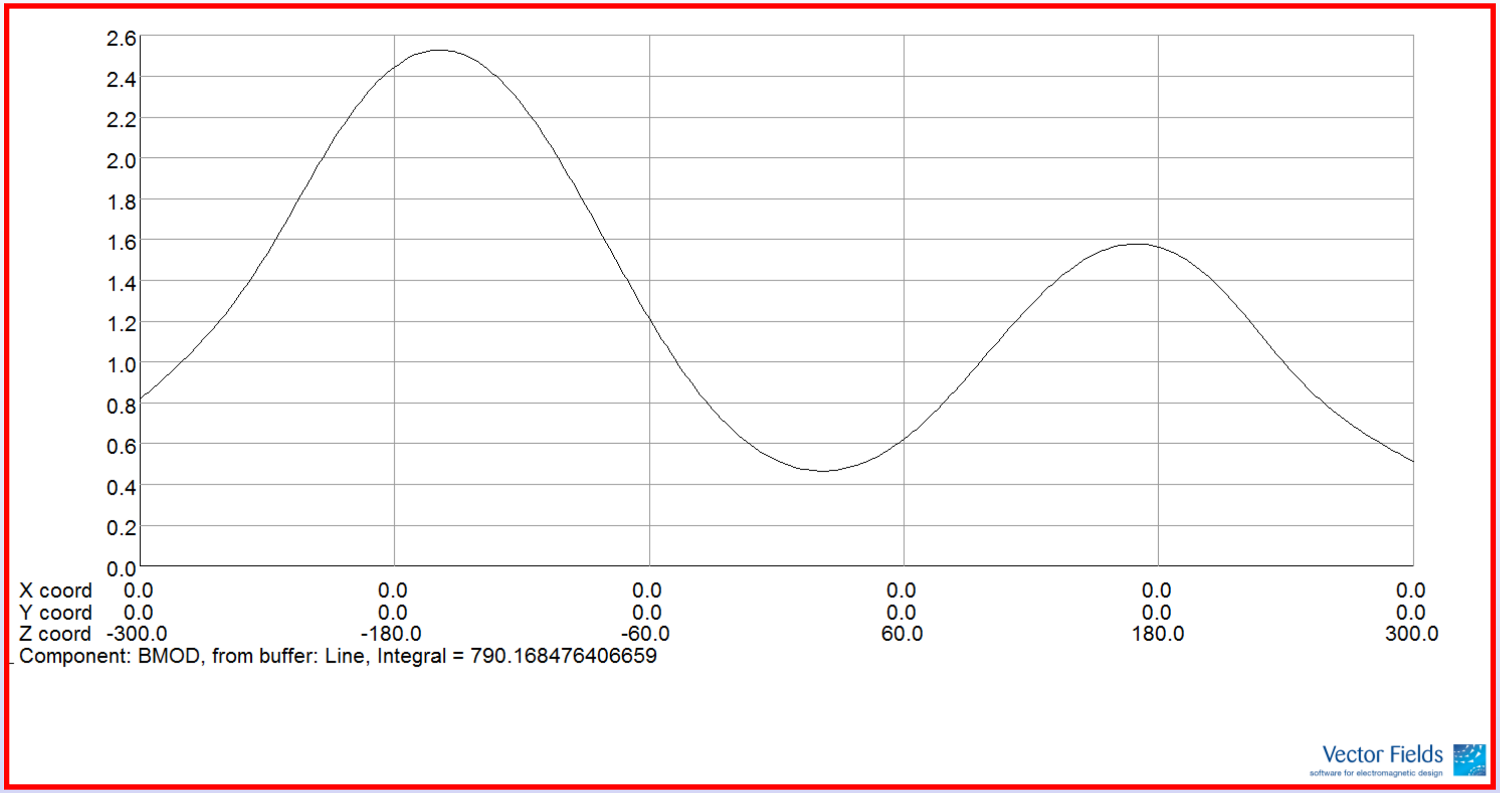
Materiali	Composizione della I parte della shell esterna dell'esapolo												
Vacodym 688 TP			5-7				17-19				29-31		
Vacodym 669 TP		4		8		16		20		28		32	
Vacodym 745 HR	0-3				9-15				21-27				33-35
	Composizione della II parte della shell esterna dell'esapolo												
Vacodym 677 HR	0-1				11-13				23-25				35
Vacodym 655 HR		2		10		14		22		26		34	
Vacodym 745 HR			3-9				15-21				27-33		

Tabella 6 – Composizione della shell esterna dell'esapolo





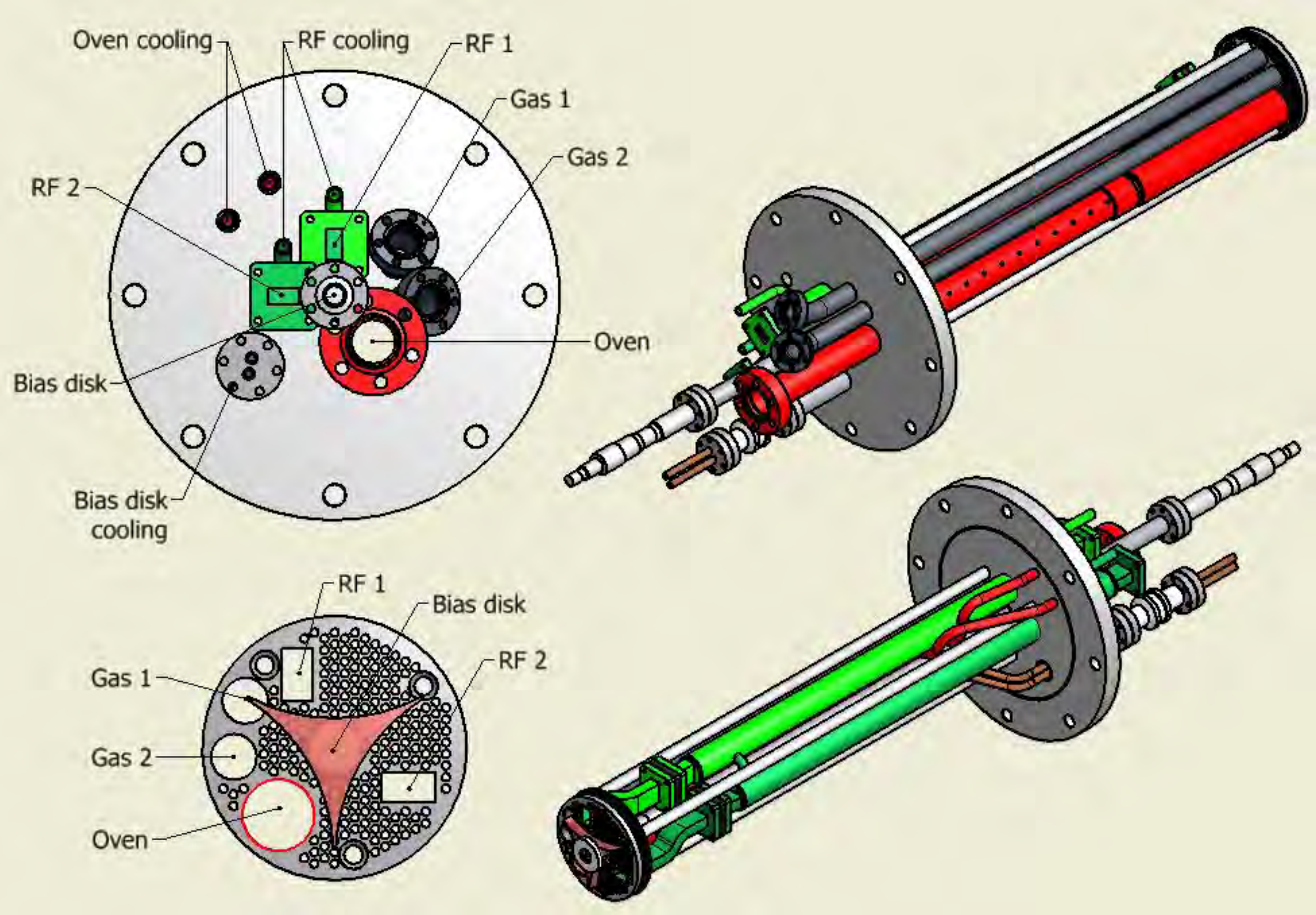
Axial magnetic confinement



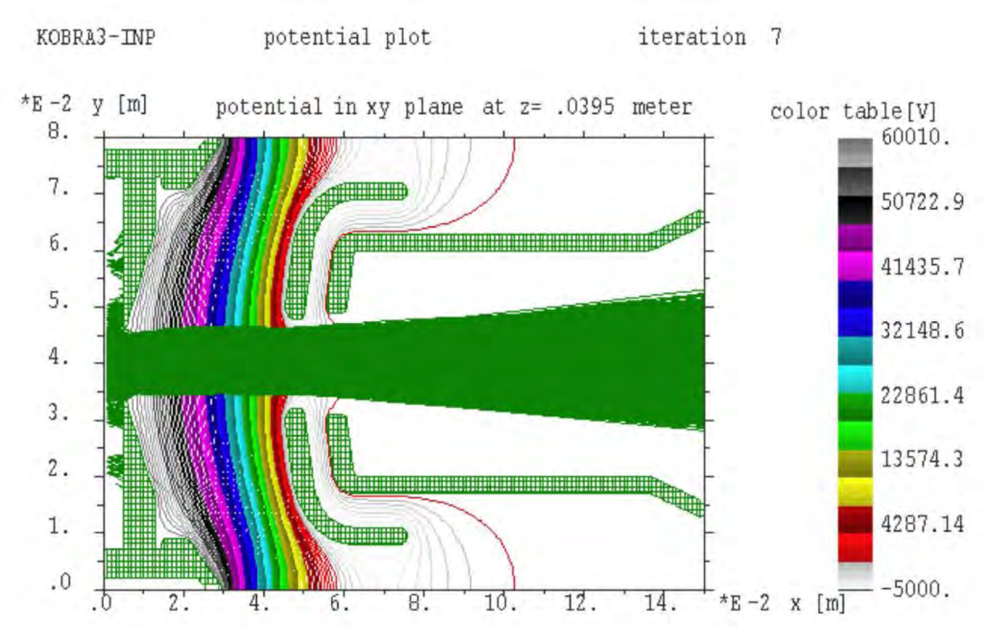
Component: BMOD, from buffer: Line, Integral = 790.168476406659

	INJECTION	MEDIUM 1	MEDIUM 2	EXTRACTION
Inner diameter	120 mm	120 mm	120 mm	120 mm
Outer diameter	160 mm	160 mm	160 mm	160 mm
Length	100 mm	30 mm	30 mm	90 mm
Current density	155 A/mm^2	-110 A/mm^2	-110 A/mm^2	-110 A/mm^2

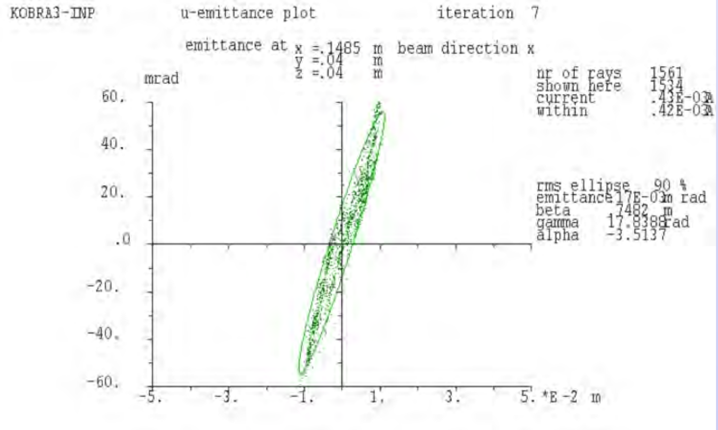
Injection system



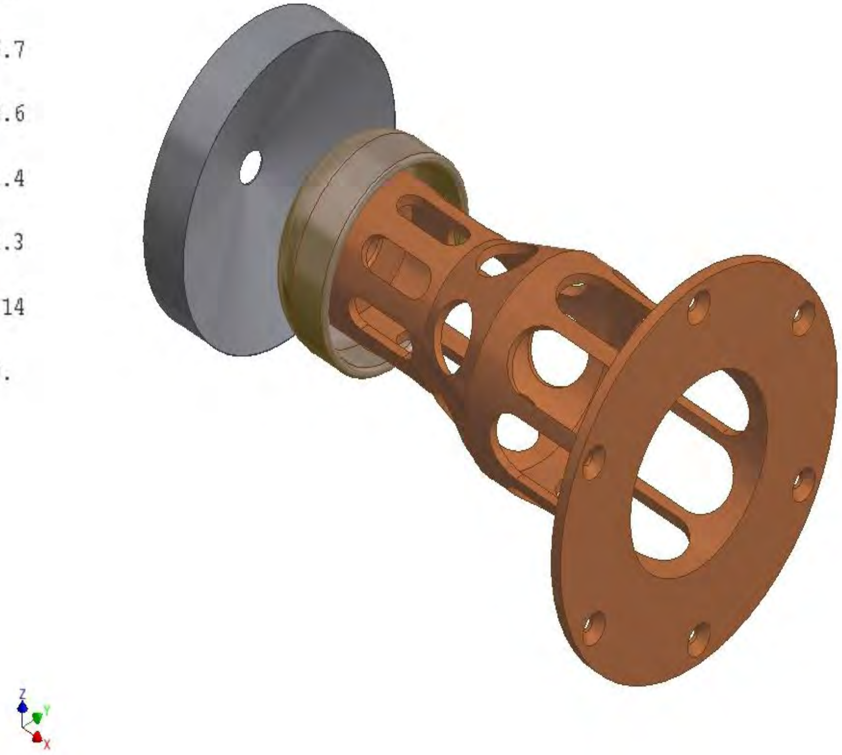
Three electrodes extraction system



```
KOBRA3-INP          potential plot                iteration  7

*E -2  y [m]     potential in xy plane  at z= .0395  meter       color table[V]
```



```
KOBRA3-INP          u-emittance plot              iteration  7

        emittance at  x =.1485  m   beam direction x
                      y =.04    m
                      z =.04    m
                                                  nr of rays    1561
                                                  shown here    1534
                                                  current       .43E-03A
                                                  within        .42E-03A

                                                  rms ellipse    90 %
                                                  emittance.17E-03m rad
                                                  beta        .7482  m
                                                  gamma      17.8388rad
                                                  alpha      -3.5137
```

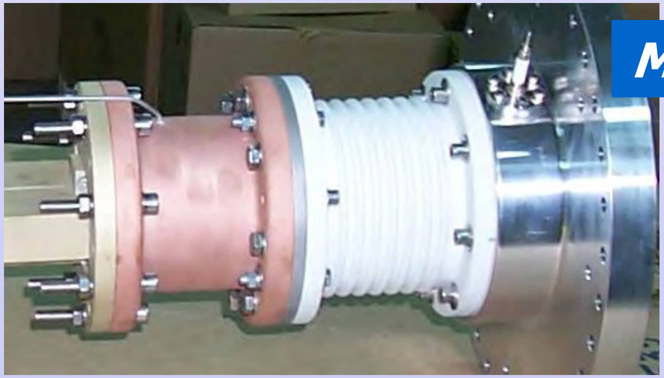


<u>*C4+ (600μA) geometrical emittance: 170 π mm mrad*</u>

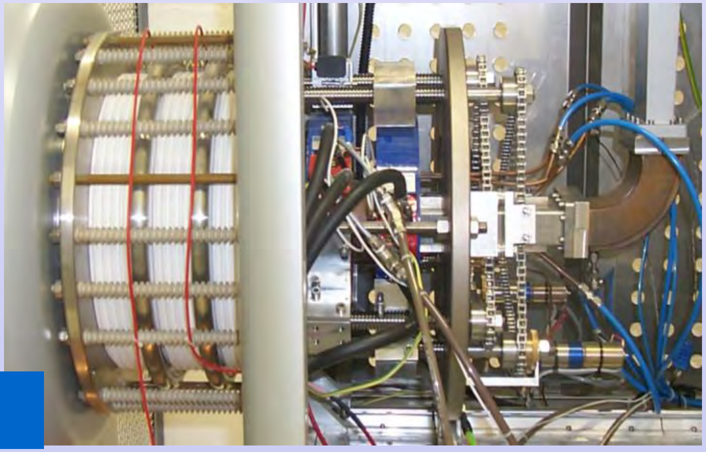
Improvements for monocharged ion sources ?

Microwave discharge ion sources

- ***Intense proton beams generation for next generation RIB facilities, ADS plants and other HPPA (e.g. >30 mA proton with reliability close to 100%)***
- ***Intense deuteron beams production for IFMIF (e.g. 125mA of D^+)***
- ***High efficiency 1+ ionization of recoils produced in TIS complex of radioactive facilities***

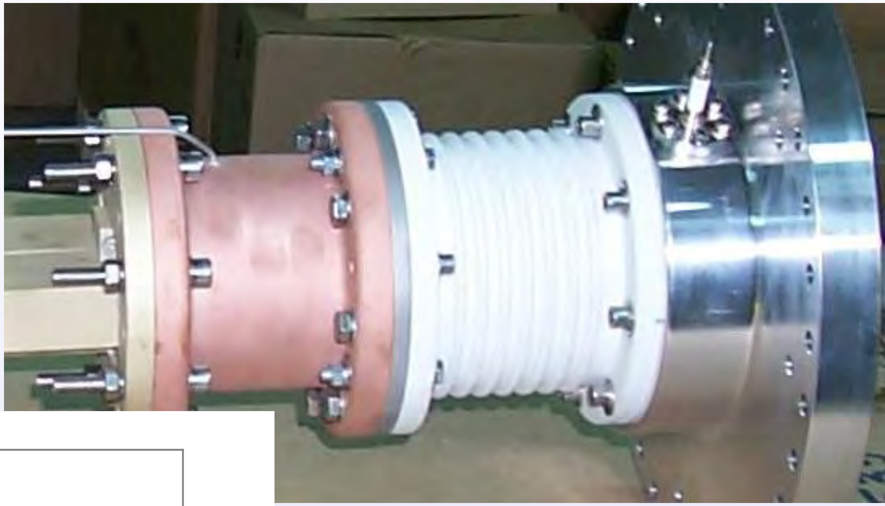


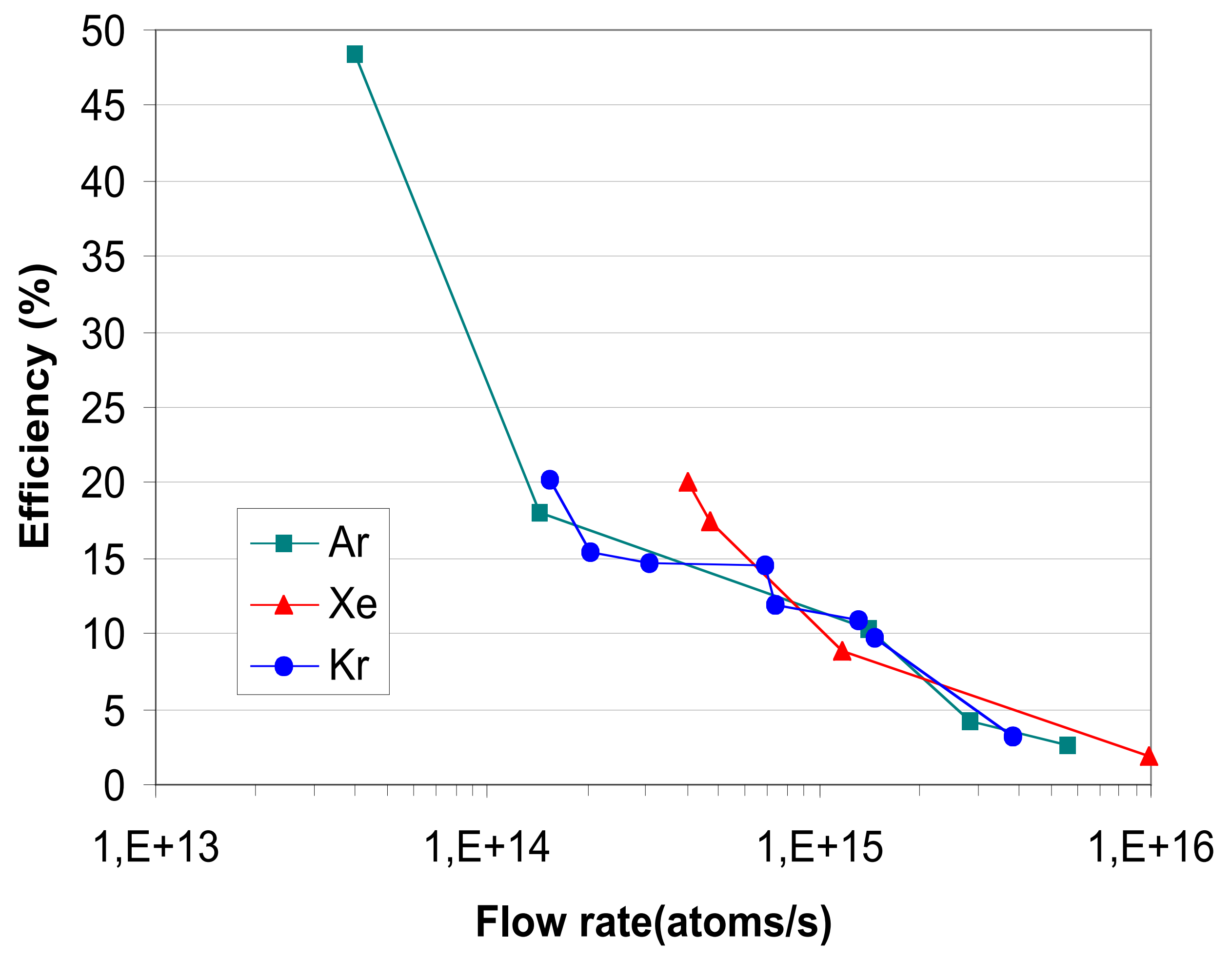
MIDAS2



TRIPS

MIDAS 2

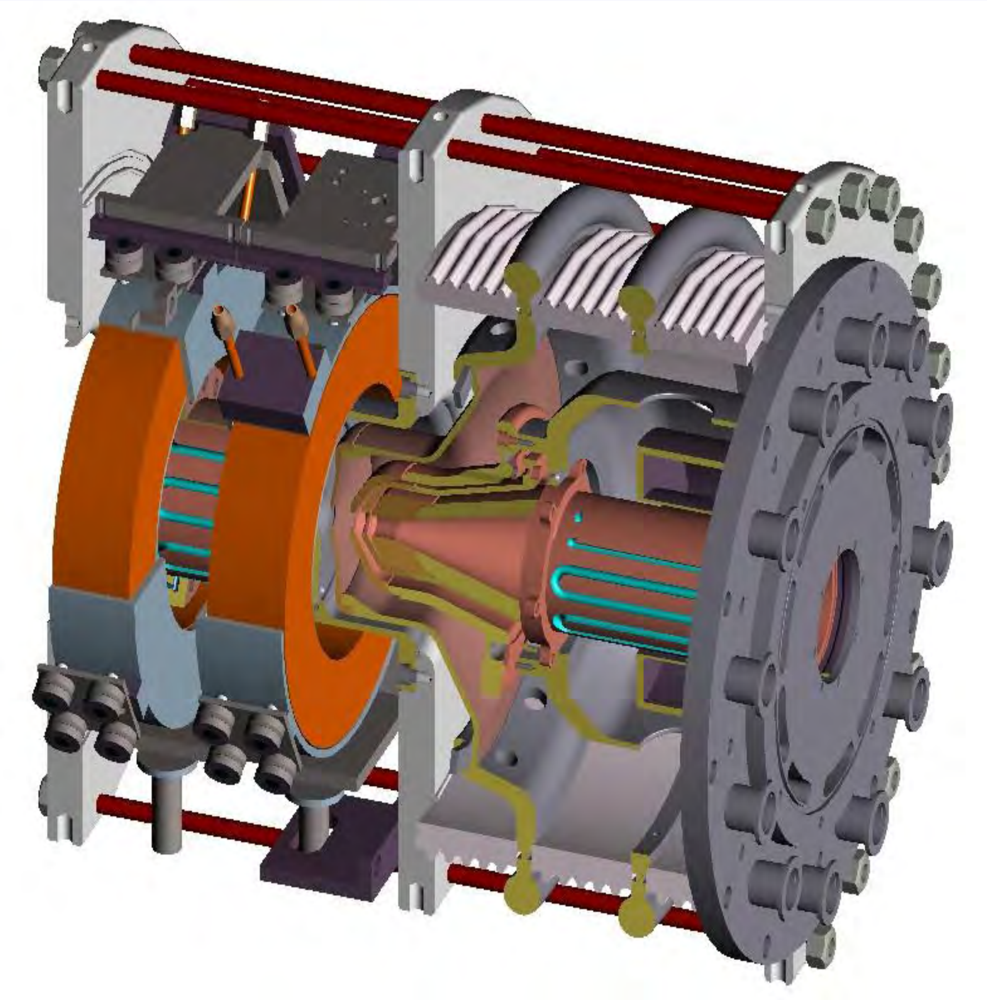


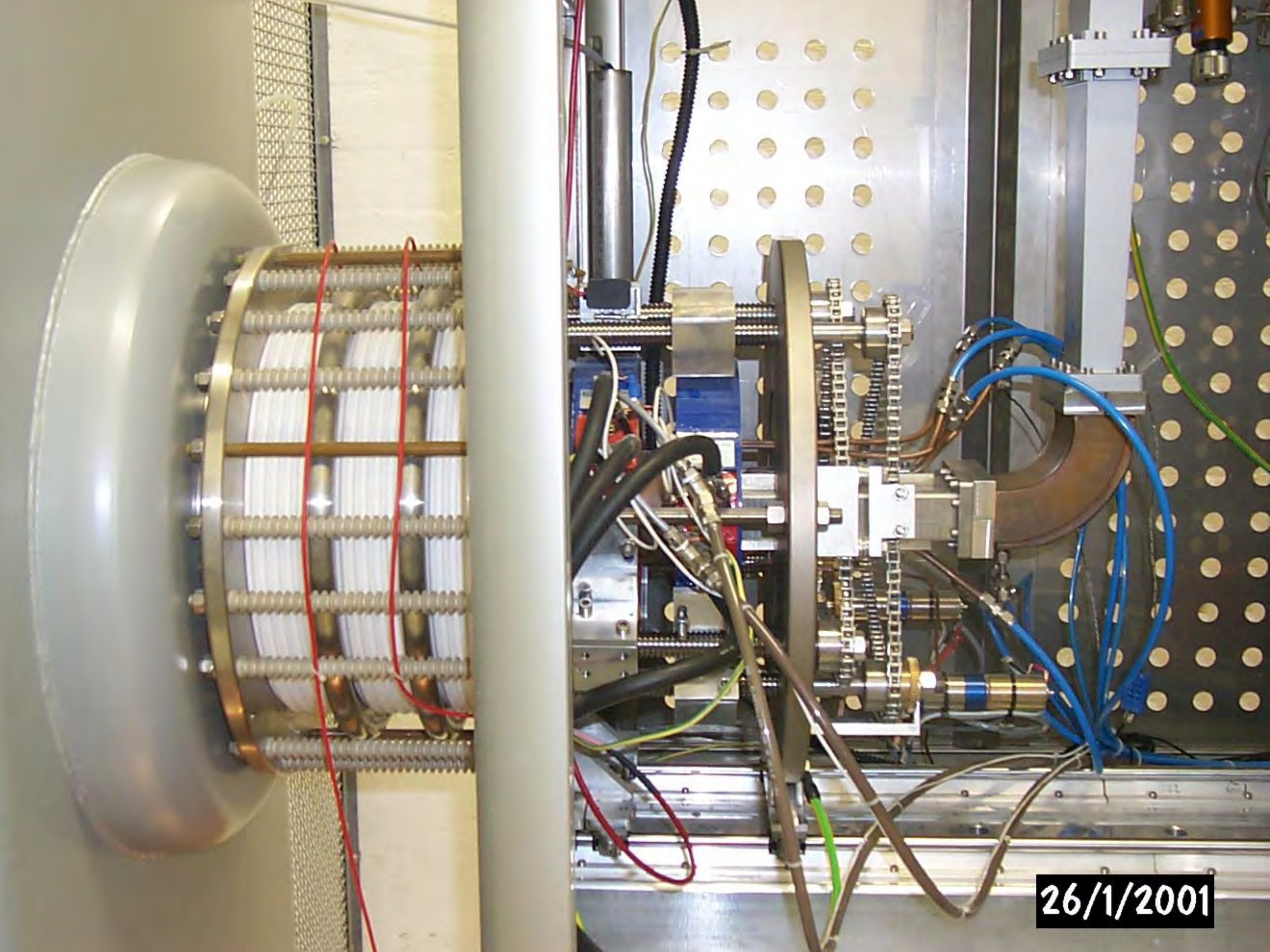


Efficiency (%)
50
45
40
35
30
25
20
15
10
5
0
1,E+13
1,E+14
1,E+15
1,E+16
Flow rate(atoms/s)
Ar
Xe
Kr

TRIPS *(**TRasco** Intense Proton Source)*

Proton beam current:
60 mA dc
Beam Energy:
80 keV
Beam emittance:
$\varepsilon_{RMS} \leq 0.12\ \pi$ ***mm mrad***
Reliability:
close to 100%

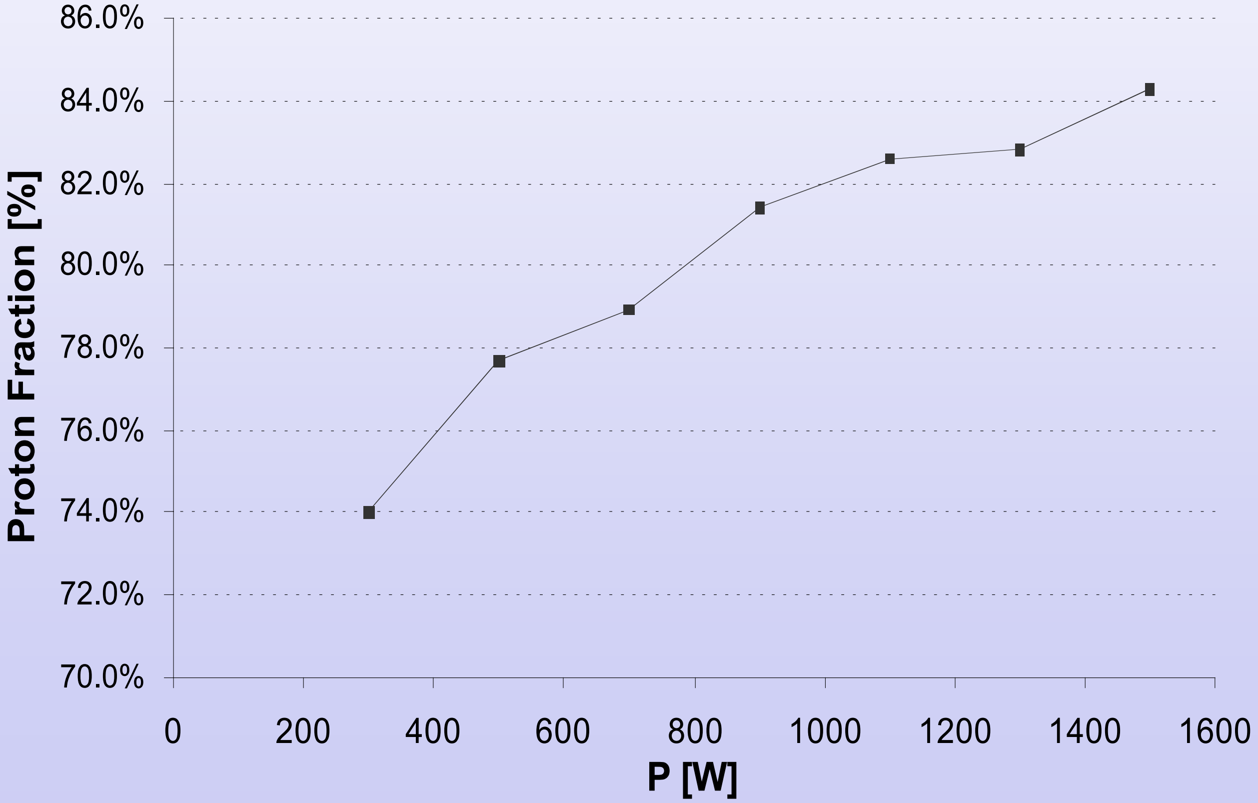




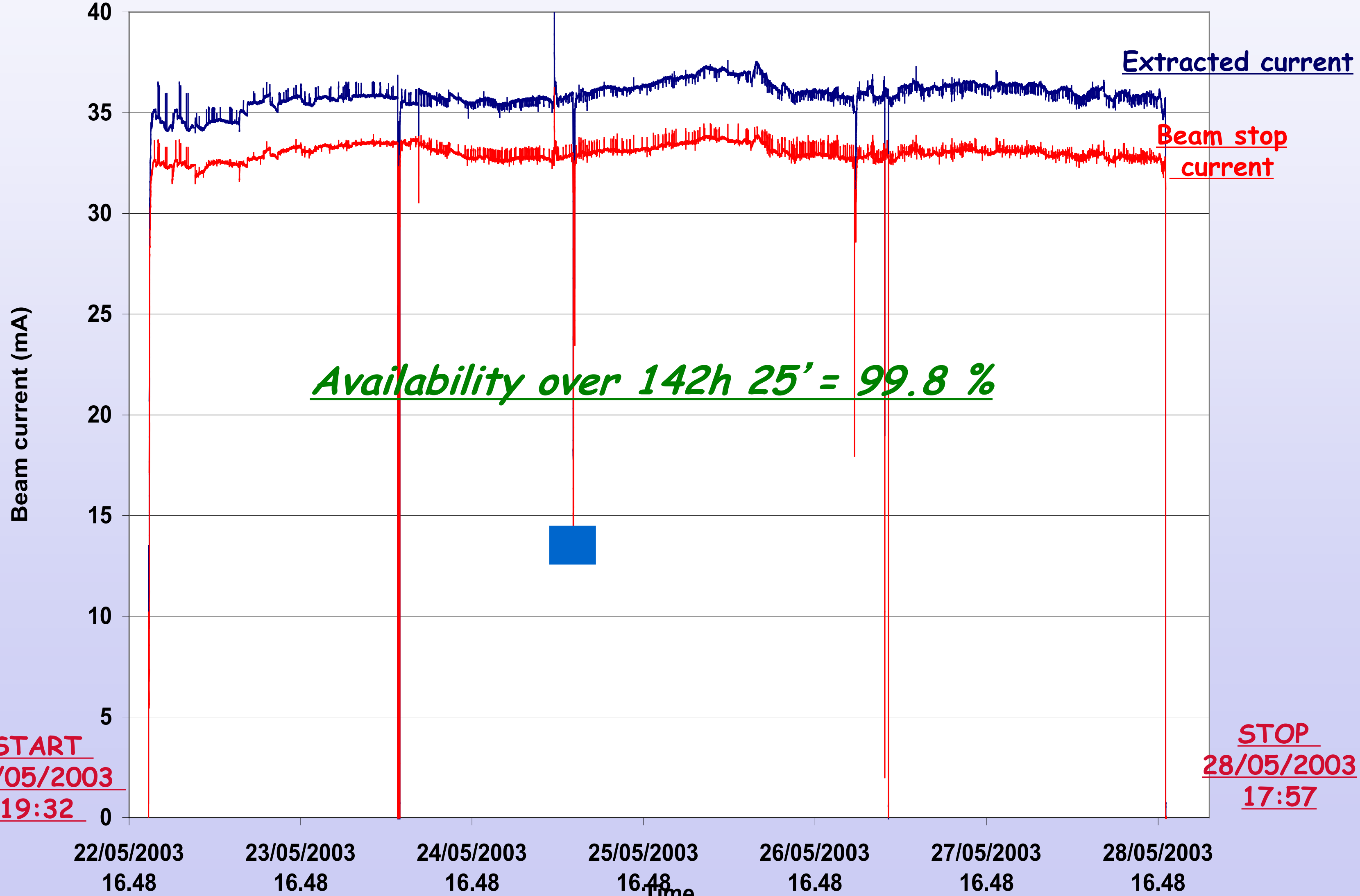
26/1/2001

Proton fraction

✦ 90% was obtained in 2005 at 1 kW with Al_2O_3 tube



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



Availability over 142h 25’ = 99.8 %

START
22/05/2003
19:32

STOP
28/05/2003
17:57

TRIPS operating parameters

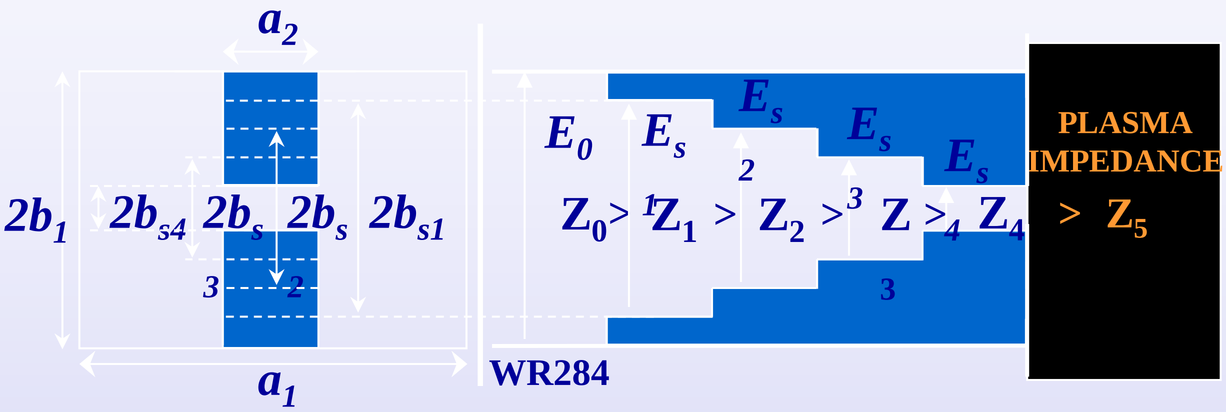
	Requirement	**Status**
Beam energy	80 keV	80 keV
Proton current	35 mA	55 mA
Proton fraction	>70%	80% at 800 W RF power
RF power, Frequency	2 kW (max) @2.45 GHz	Up to 1 kW @ 2.45 GHz
Axial magnetic field	875-1000 G	875-1000 G
Duty factor	100% (dc)	100% (dc)
Extraction aperture	8 mm	6 mm
Reliability	»100%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

11/11/05 TRIPS moved to LNL

Microwave injection and beam extraction optimisation

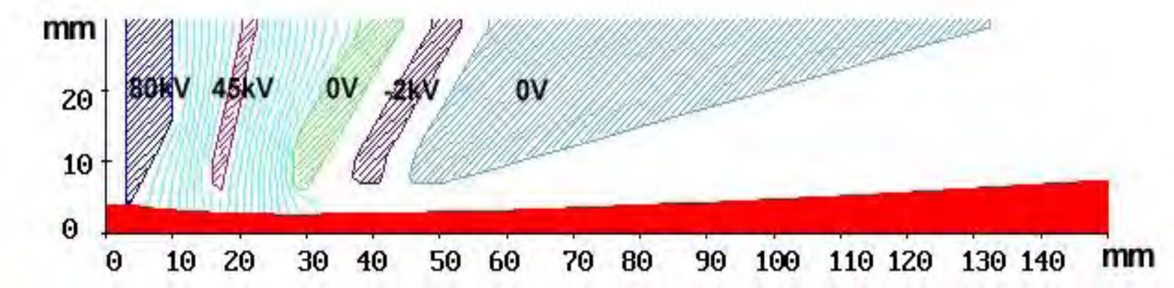
Microwave Injection

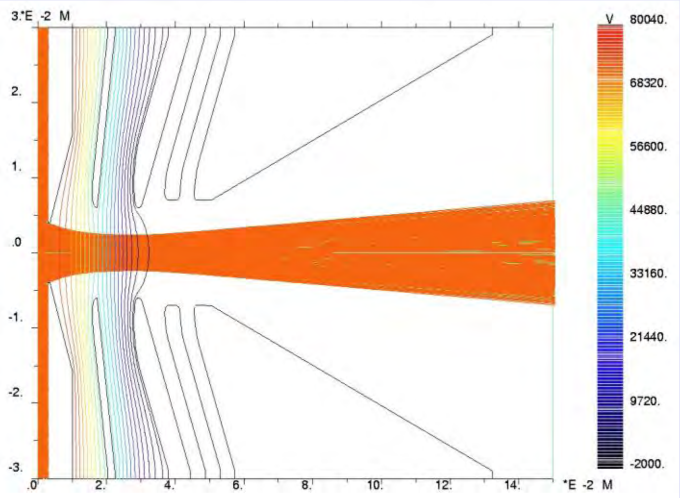
Use of a step binomial matching transformer with a field enhancement factor $(E_{s4}/E_0) \approx 1.95$ (a_2=0.0126 m)



Beam extraction

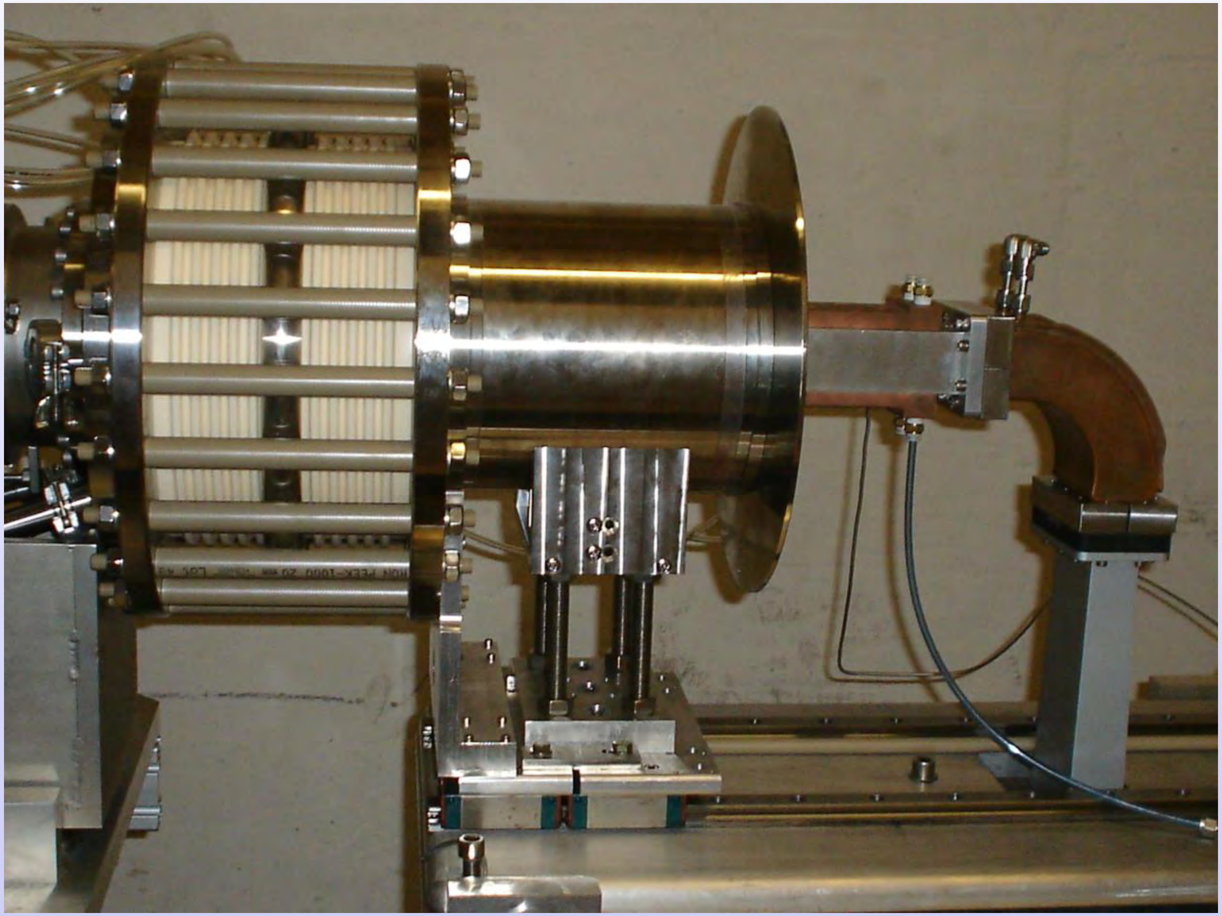
The extraction process has been deeply studied with the aim to increase the source reliability and to keep emittance low.
The used codes were AXCEL-INP and IGUN.





L.Celona, G. Ciavola, S. Gammino, R. Gobin, R. Ferdinand, Rev.Sci.Instr. 71(2),(2000), 771

VIS-Versatile Ion Source (2008)



MDIS

- TRIPS & VIS sources, along with SILHI, the IFMIF source and the MDIS of Beijing built by S. Peng following the suggestion of CEA and INFN people, represent the state of the art. Anyway significant step forwards may be expected by including the know-how above described also in MDIS design

Geometry and "Top-Level" parameters

Accelerator baseline used in this cost estimate. The Accelerator includes a normal conducting front end, a superconducting part, and a high end beam transfer.

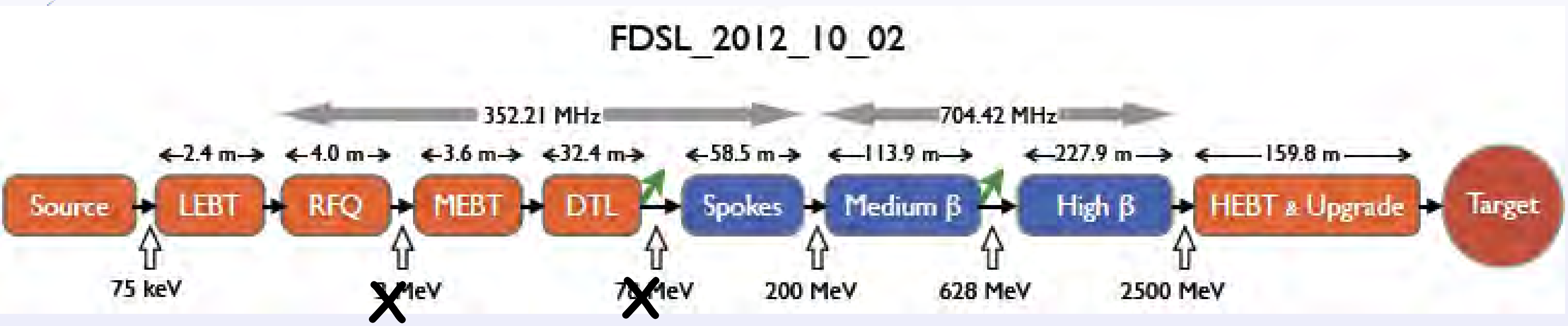


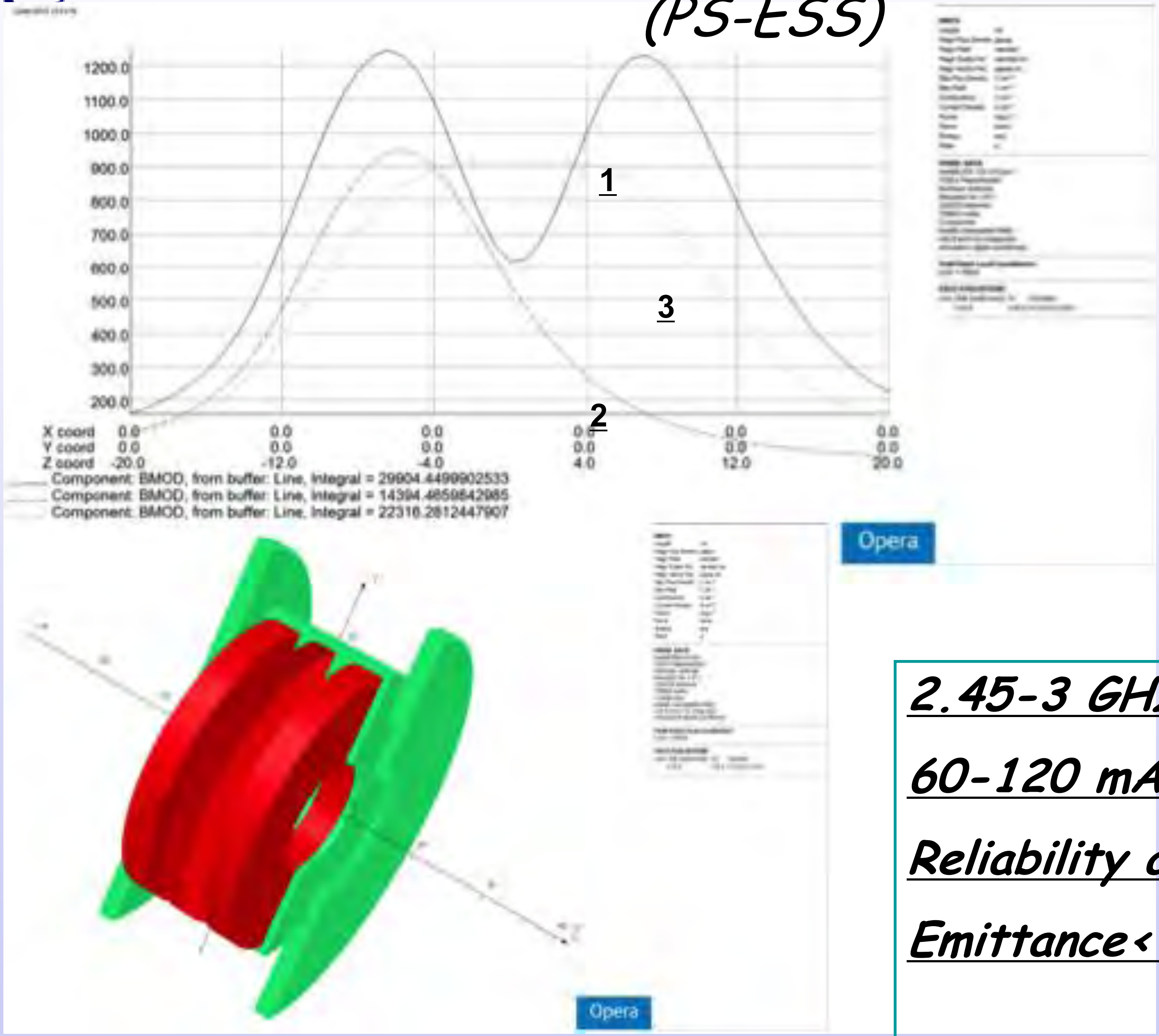
Figure 23 Accelerator sections

Energy	**2.0 GeV**
Beam current	**62.5 mA**
Average beam power	**5 MW**
Accelerator length	**about 600 m**
Pulse length	**2.86 ms**
Repetition rate	**14 Hz**
Max cavity field	**40 MV/m**
Reliability	**> 95%**

On a high level, the deliverables are the accelerating systems that make up the entire accelerator. These are:

- Ion Source (2)
- LEBT (1)
- RFQ (1)
- MEBT (1)
- DTL (4 tanks)
- Spoke SCRF (14)
- Medium Beta SCRF (15)
- High Beta SCRF (30)
- HEBT
- RF power (185 Klystrons, 225 Modulators, 28 HV DC supply, 2 solid state amplifiers, 28

Proton Source for European Spallation Source (PS-ESS)



1. "Simple mirror";
2. "Magnetic Beach"
3. "Off-Resonance configuration"

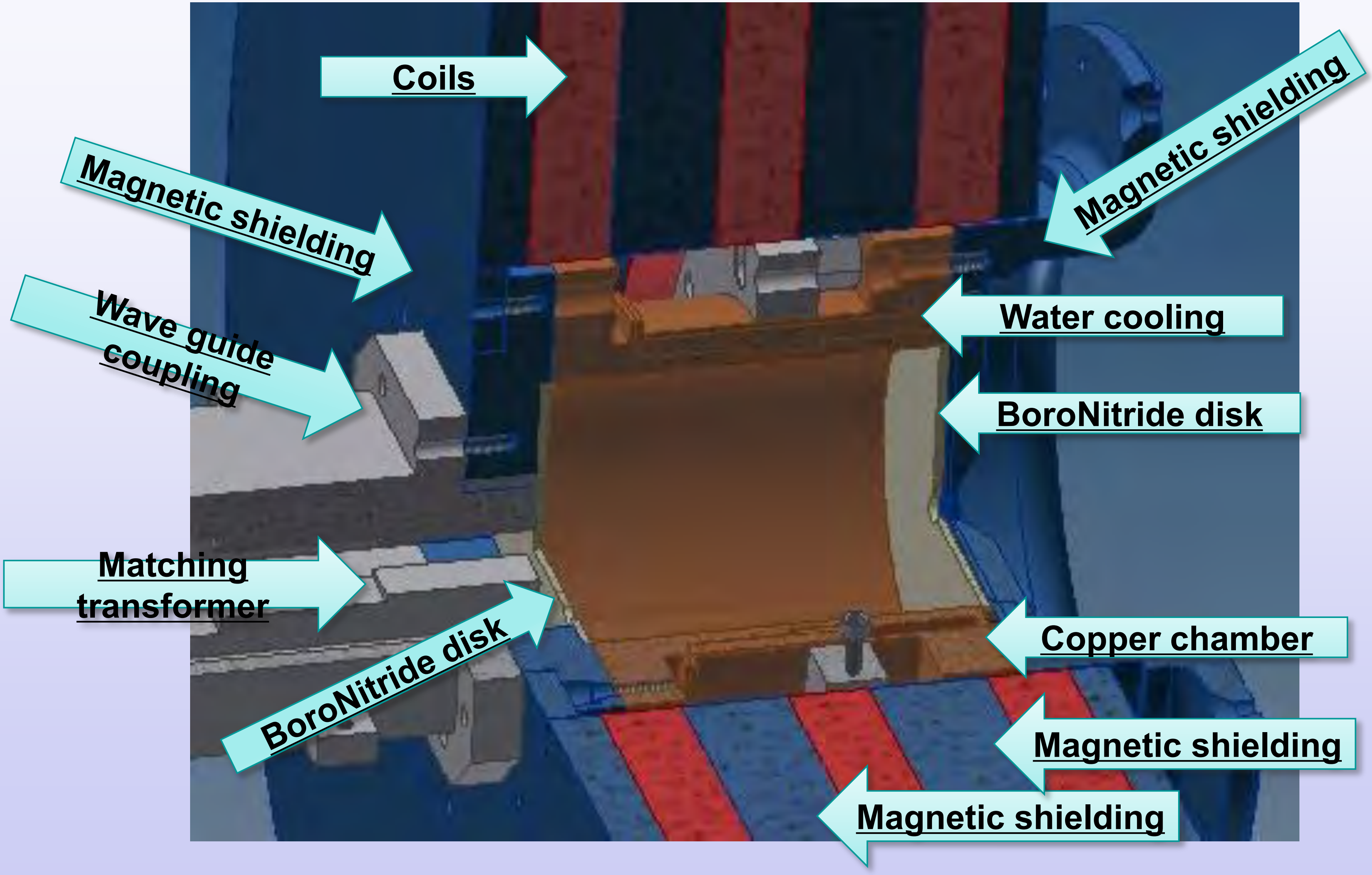
2.45-3 GHz operations

60-120 mA of protons

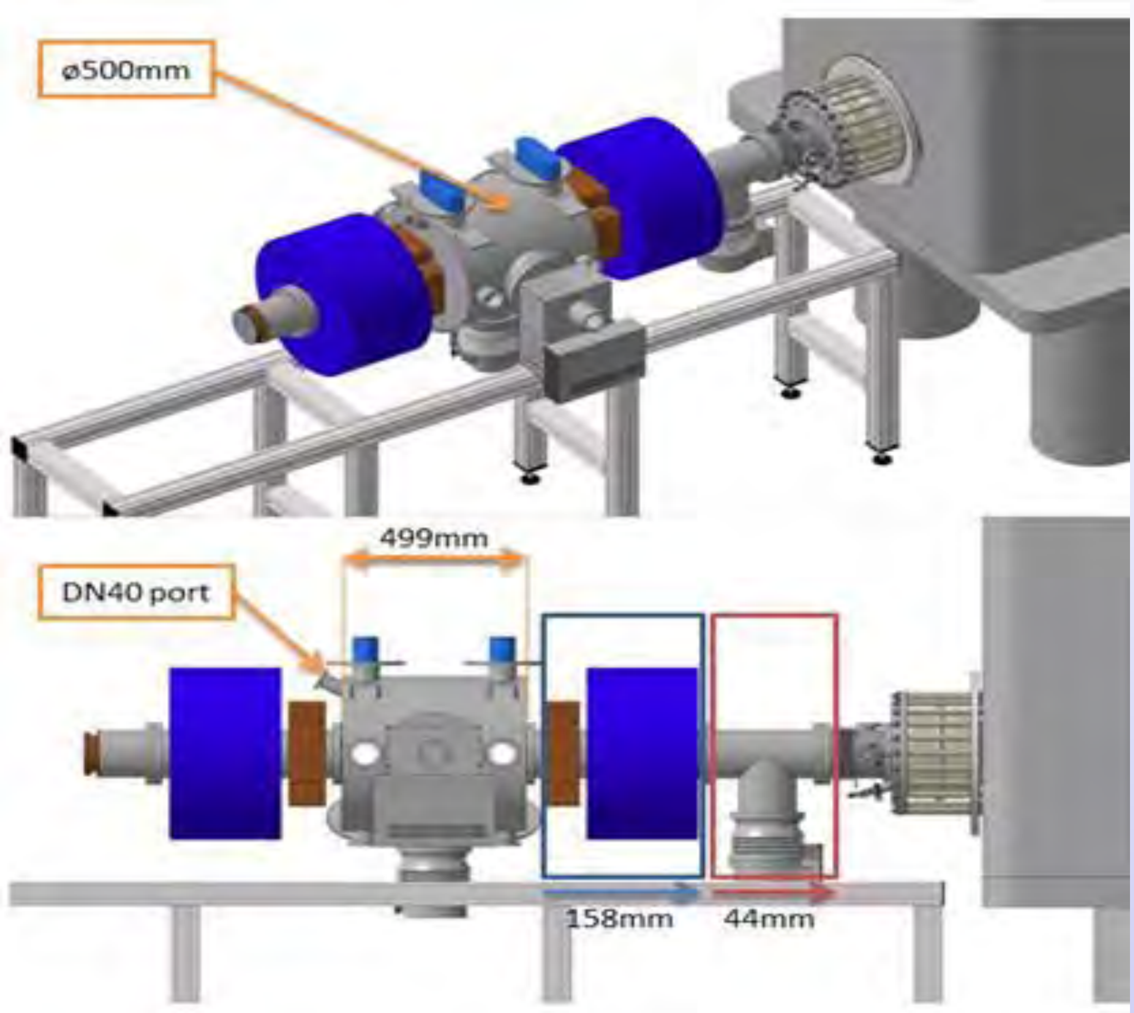
Reliability above 99.9%

Emittance< 0.2π mm mrad

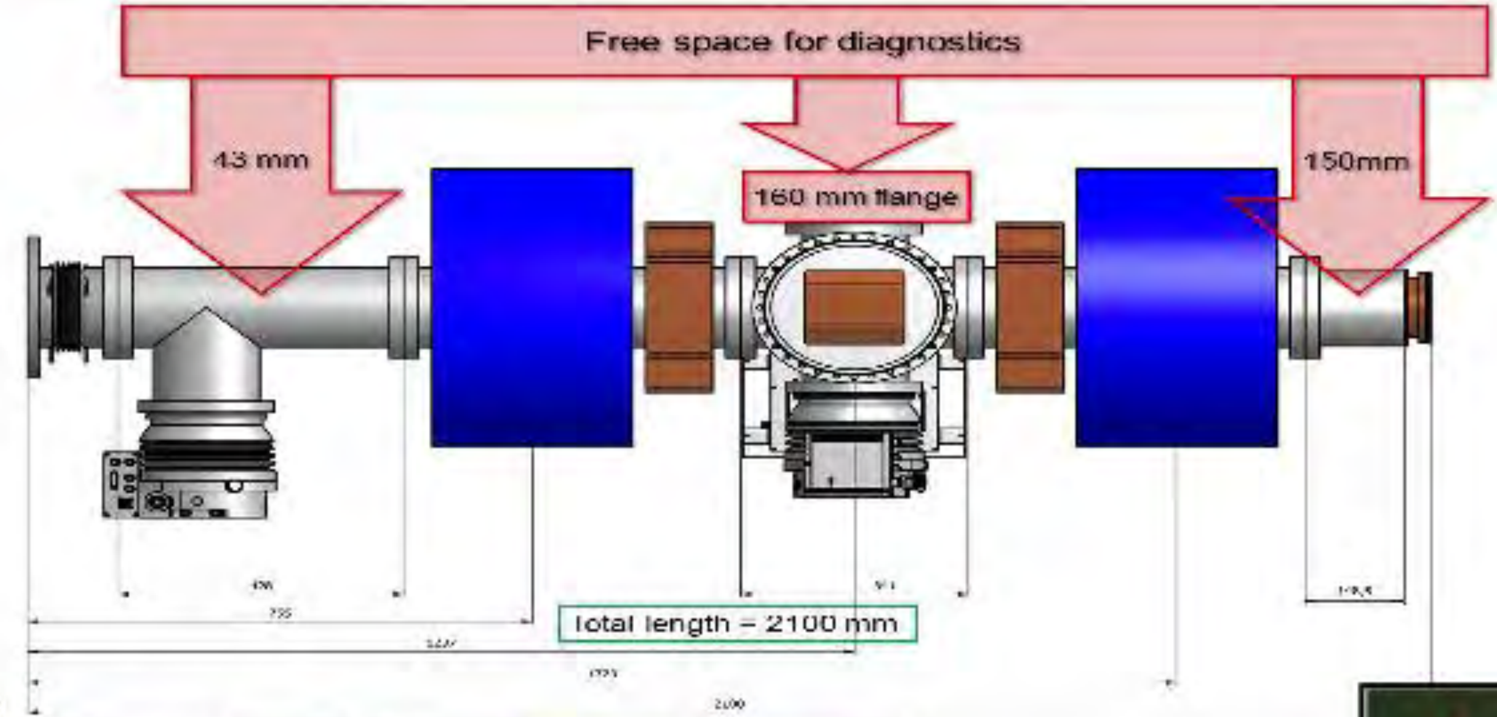
PS-ESS


Coils
Magnetic shielding
Magnetic shielding
Wave guide coupling
Water cooling
BoroNitride disk
Matching transformer
BoroNitride disk
Copper chamber
Magnetic shielding
Magnetic shielding

Low energy beam transfer line (LEBT)



LEBT



- Chopper built at INFN-LNS and already delivered to GANIL for SPIRAL 2

ISODAR

- For the ISODAR design a H_2^+ source is needed, which may be similar to VIS one, but it may be defined after the PS-ESS design will be optimized. The ideal field for H_2^+ optimization will be used to drive the design of a permanent magnet source similar to VIS.

Ion sources R&D Team

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A. Gozzo
L. Lega
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D. Mascali
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