Progresses of Microwave Discharge Ion Sources for the production of high intensity protons and light ions beams at INFN-LNS

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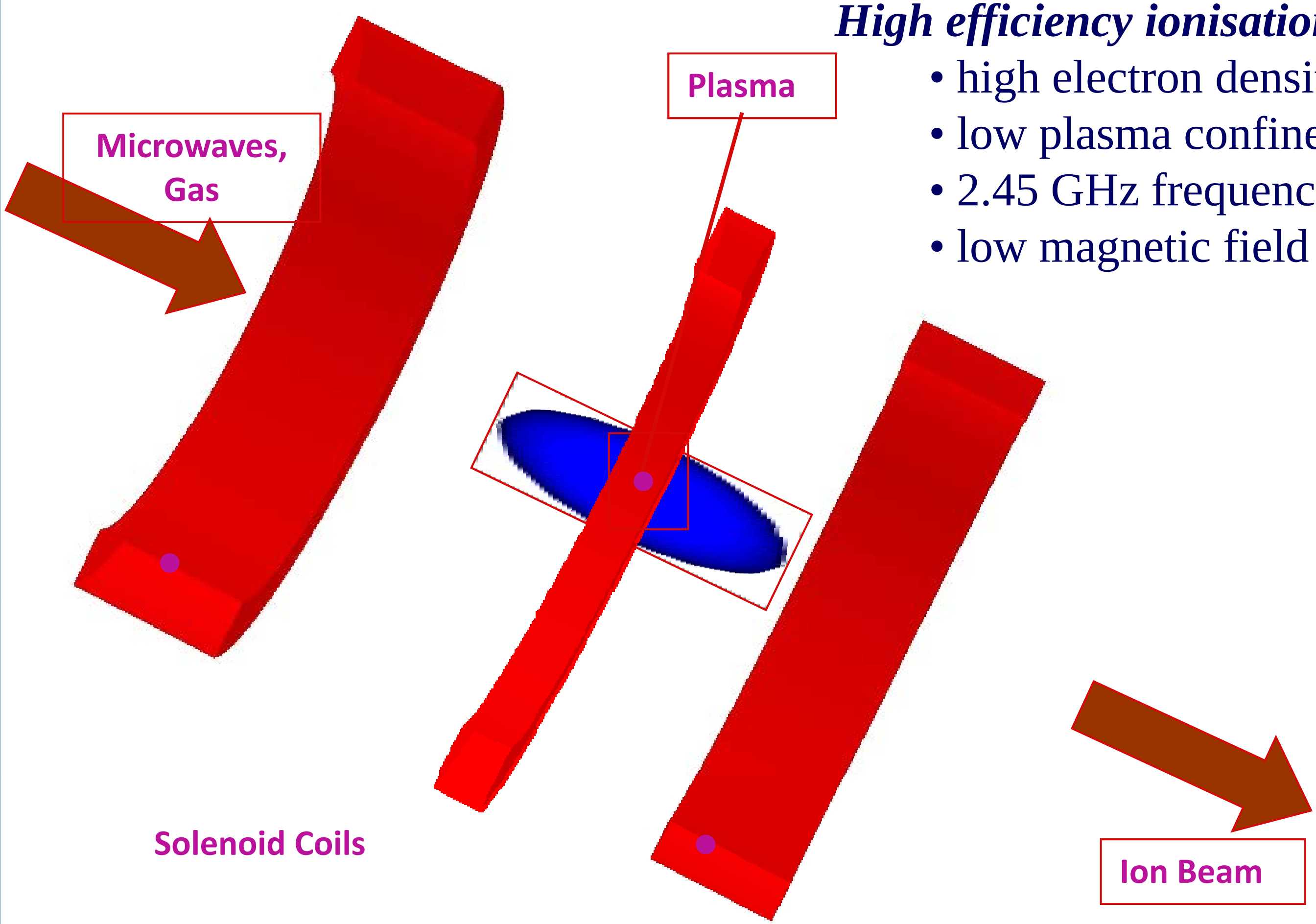
I

Microwave discharge 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

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Overcoming the current limits

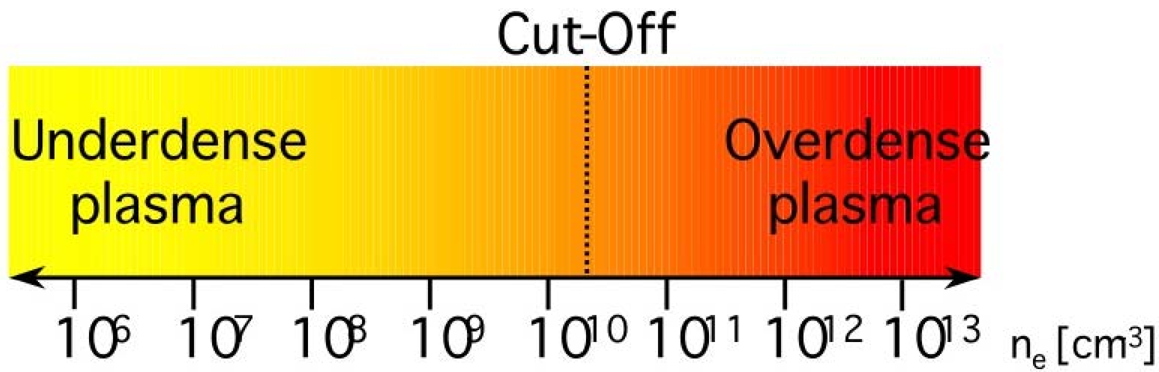
Current ~ 100 **mA** (or larger) for protons and other monocharged species are required for the next years.

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

$$I \sim n_e / \tau_i$$

$$\Downarrow$$

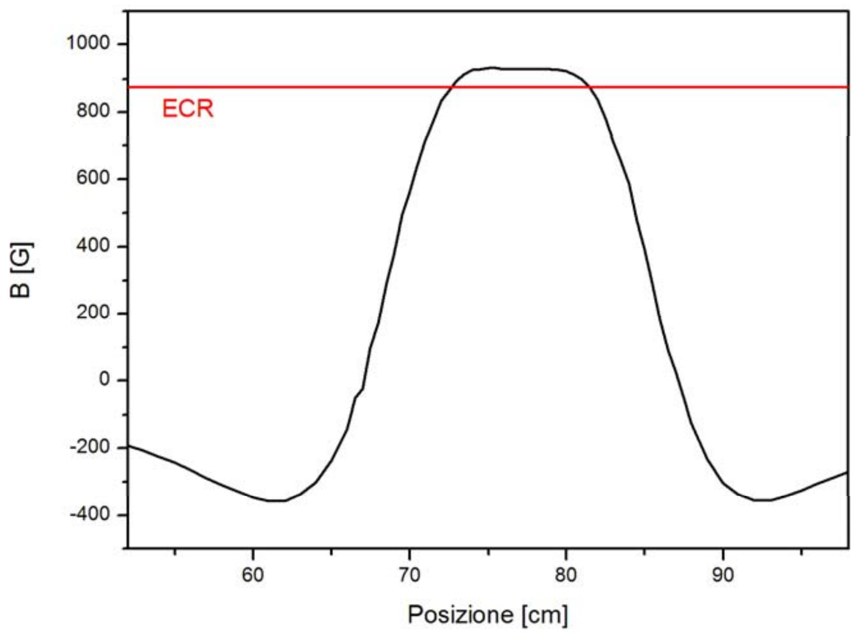
Larger density is required

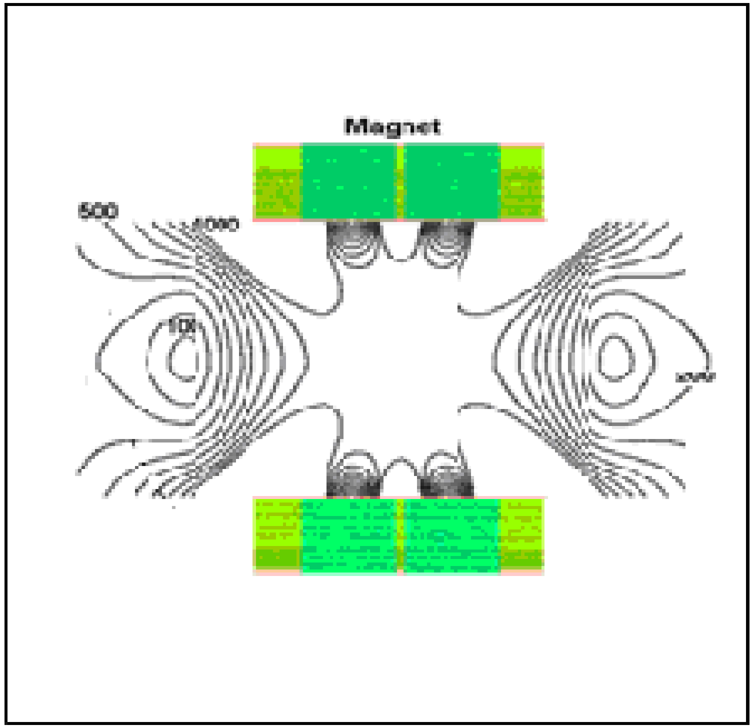


	p/H$^-$	mA	ms	Hz	Duty Factor	π mm. mad
LEDA	p	100	CW	CW	100%	0.25
IPHI	p	100	CW	CW	100%	0.25
TRASCO	p	30	CW	CW	100%	0.2
FAIR	p	100	1	4	0.4%	0.28
PS-ESS	p	74	6	14	8%	0.2
IFMIF	D	125	CW	CW	100	0.2

High reliability and high parameters' reproducibility is requested (i.e. operator-indipendent)

PLASMAS in quasi-constant field traps: MDIS



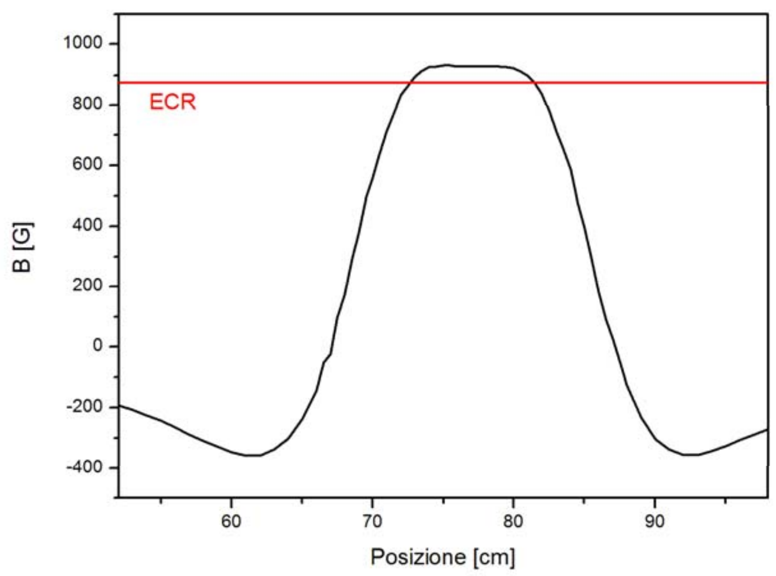


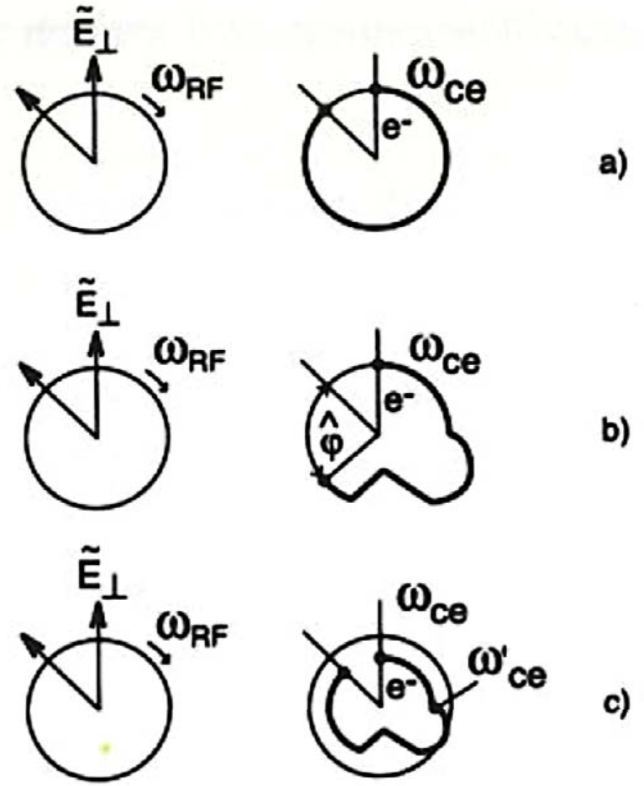
1. Quasi straight magnetic field lines are obtained by means of two solenoids or a permanent magnet.
2. No magnetic confinement (the magnetic field helps the ionization by increasing the electron path inside the chamber)
3. Spontaneous turbulences are possible especially in case of overdense plasmas

Plasma production at $B > B_{ECR}$

The theory of plasma heating in off resonance discharges takes into account the so called **“plasma effervescence”**.

In the case of dense and turbulent plasmas the strong effervescence leads to a collective scattering





In order to recover the synchronization with the rotating wave electric field, a magnetic field higher than B_{ECR} is needed and the acceleration restart (ECR theory extension to the collisional case).

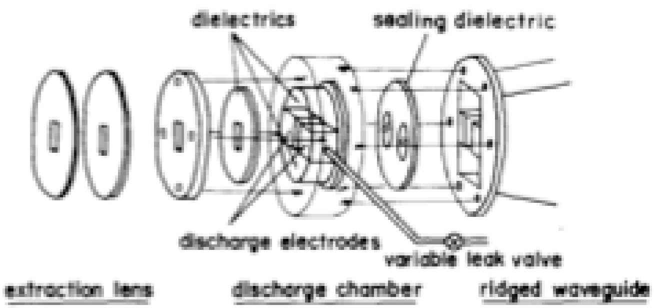
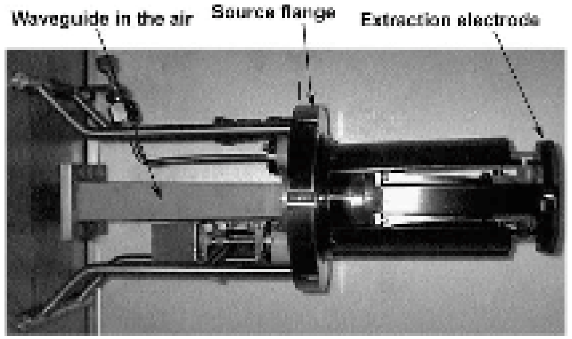


FIG. 1. Components of the microwave ion source.



Microwave ion source for high-current implanter

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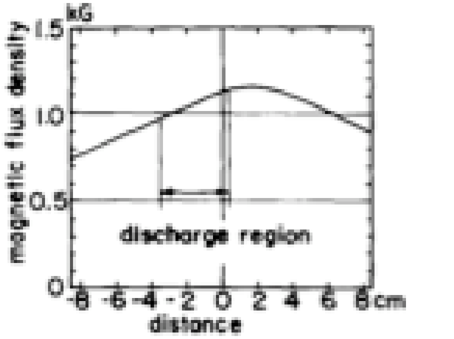
Central Research Laboratory, Hitachi Limited, Kokubunji, Tokyo 185, Japan

(Received 28 November 1977; in final form, 6 March 1978)

As^+ and B^+ ions of 25 mA and 15 mA



(b) Magnetic intensity distribution

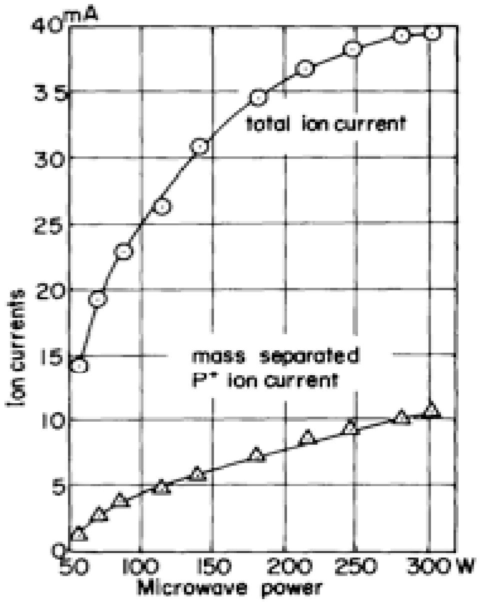


FIG. 8. Dependence of ion currents on incident microwave power.

IV. DISCUSSION

It has been shown that microwave ion sources are highly suitable for high current ion implanter applications. Although separator transmission is not totally satisfactory, a high P^+ ion implantation current is obtained. Increase of separator transmission by improvement of the extraction lens[2] will facilitate the realization of higher speed implanters for bipolar transistor fabrication.

[1] J. H. Freeman, Nucl. Instrum. Methods **22**, 306 (1963).
[2] N. Williams, "A High Current Ion Source for Use on the PR-30 Implanter," 14th Symposium on Electron, Ion and Photon Beam Technology (1977) (unpublished).
[3] G. Lempert and I. Chavet, Nucl. Instrum. Methods **139**, 7 (1976).
[4] N. Sakudo, K. Tokiguchi, H. Koike and I. Kanomata, Rev. Sci. Instrum. **48**, 762 (1977).

Chalk River

Taylor &Wills

Beginning of '90s

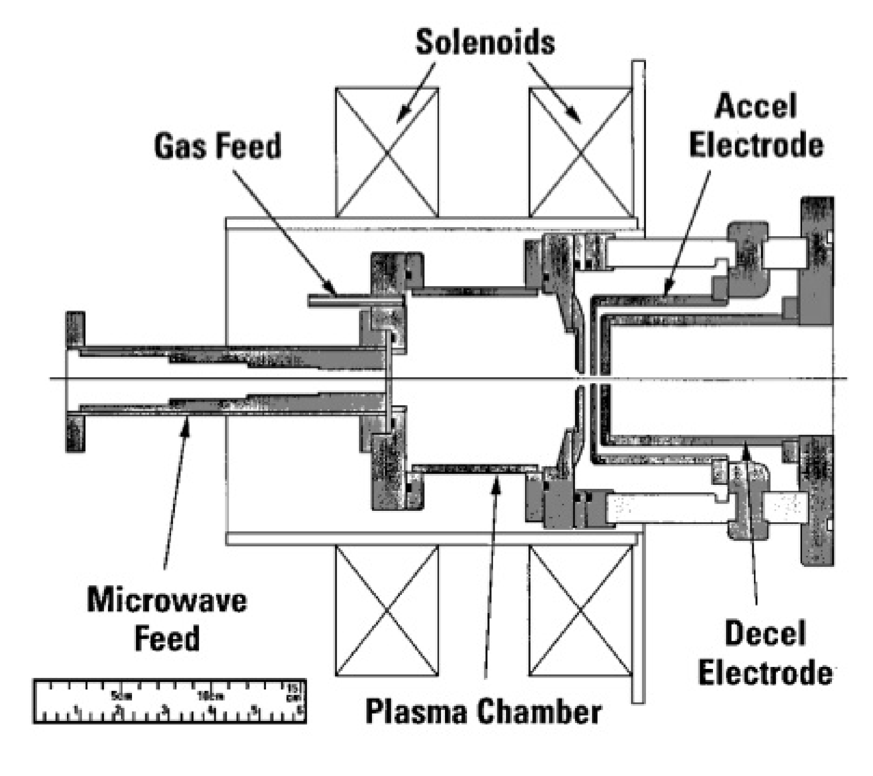
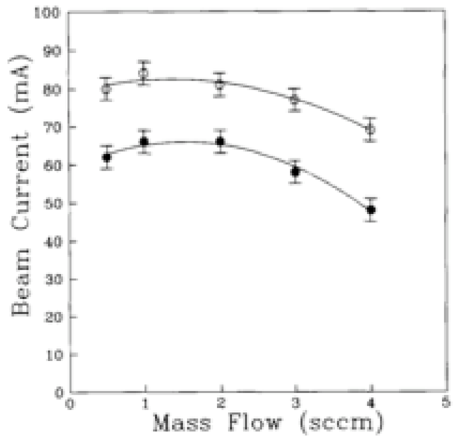
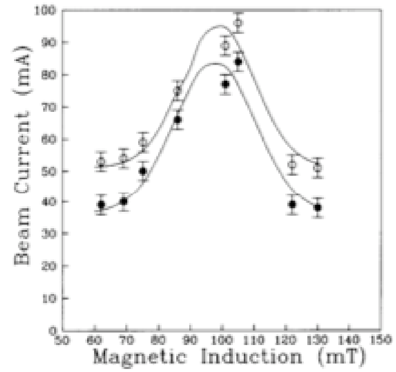
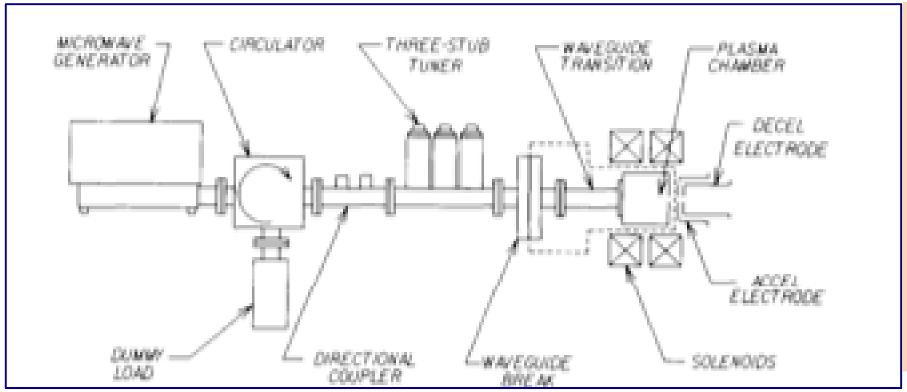


FIG. 1. Microwave-driven Chalk River proton source.

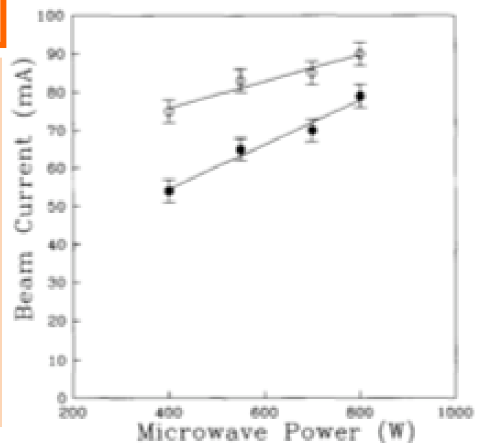






Breakthrough simple design

All successful sources are based on it



Los Alamos source for LEDA

Great result! 75 mA out of the RFQ

low-energy demonstrator accelerator (LEDA)

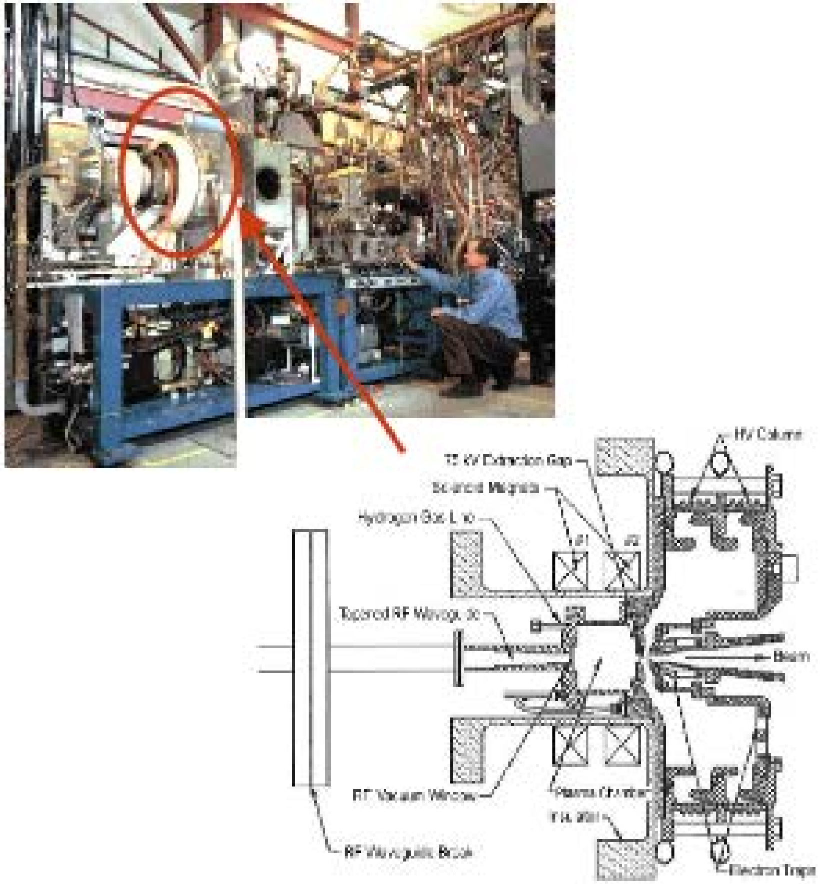


Figure 1. LEDA microwave proton source.

TABLE I. 75 keV injector specifications and status.

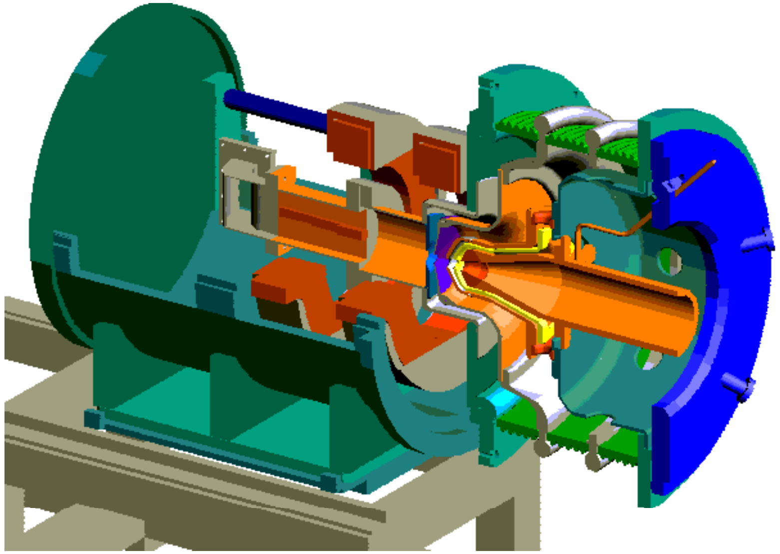
Parameter	1995 Specification	1997 Status
Proton beam current (mA)	110	117
Proton fraction (%)	85	90
Beam energy (keV)	75	75
Discharge power (W), frequency (GHz)	300–450, 2.45	600–800, 2.45
Axial magnetic field (G)	920	875–960
Duty factor (%)	100 (dc)	100 (dc)
Gas flow (sccm)	2.8–8.5	2–5
Emission aperture radius (mm)	4.2	4.3
Extraction gap (mm)	14.5	13.2
Beam noise (%)	±1	±1
Ion source emittance (πmm mrad)	0.13 (rms, normalized)	Not measured
RFQ match point emittance (πmm mrad)	0.20 (rms, normalized)	0.20 (rms, normalized)
αRFQ	1.944	1.944
β_{RFQ} (mm/mrad)	0.1193	0.1193

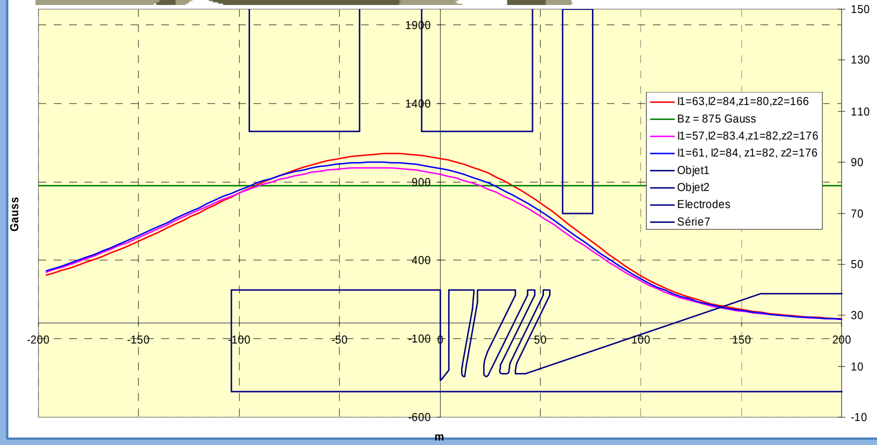
*J. Sherman, et. al. *RSI*, vol. 69, pp. 1003, 1998

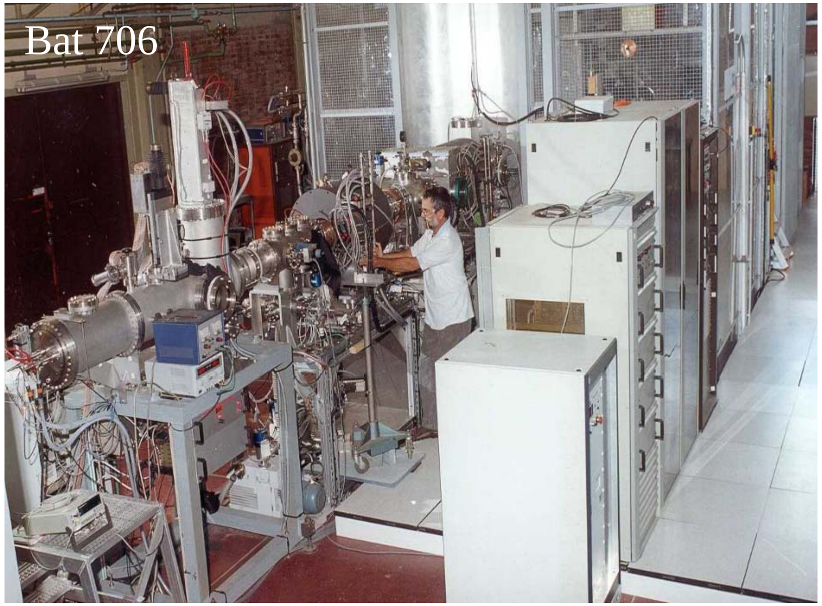
SILHI source and LEBT

SILHI operates at 2.45 or 3 GHz

1 ECR zone at RF entrance







Since 1996, SILHI produces H+ beams with good characteristics:

H+ Intensity > 100 mA at 95 keV

H+ fraction > 80 %

Beam noise < 2%

95 % < Reliability < 99.9 %

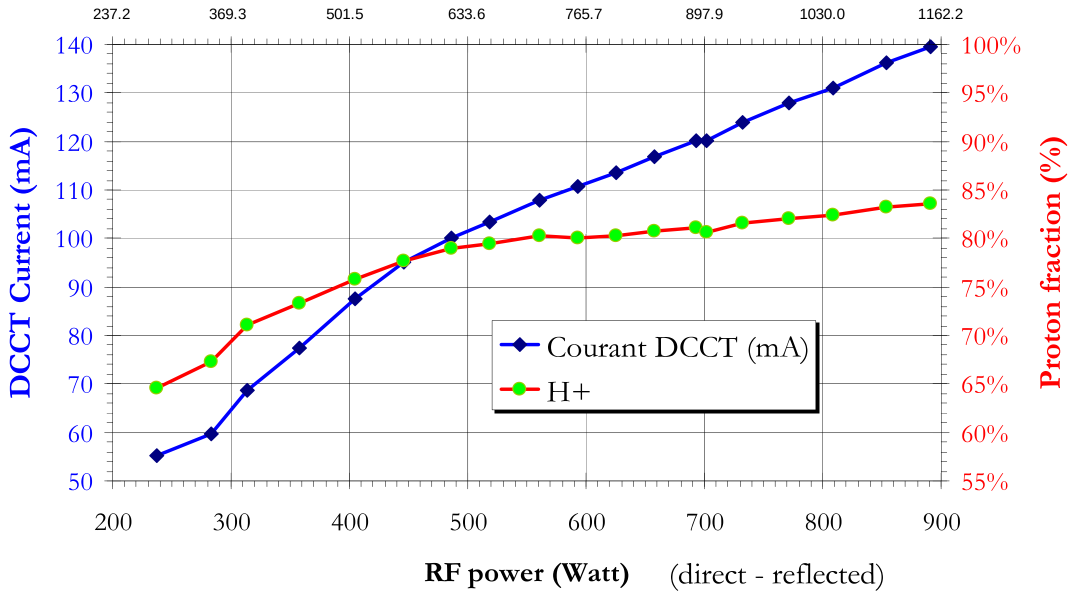
Emittance < 0.2 π mm.mrad

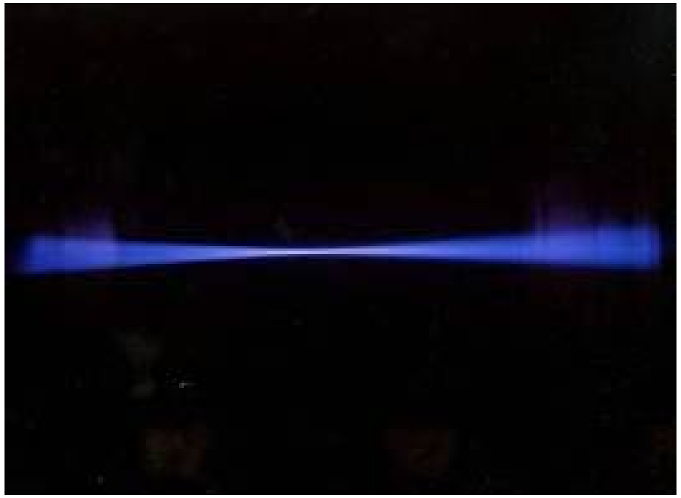
CW or pulsed mode

In CW mode, the source routinely produces

130 mA total (> 80% H^+)

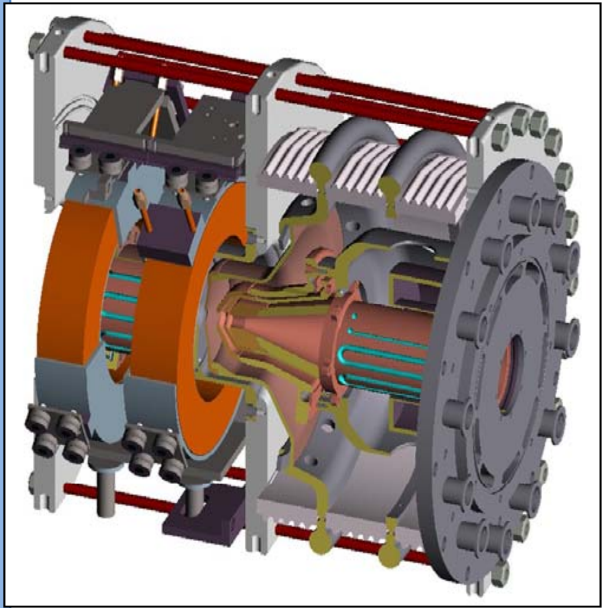
at 95keV

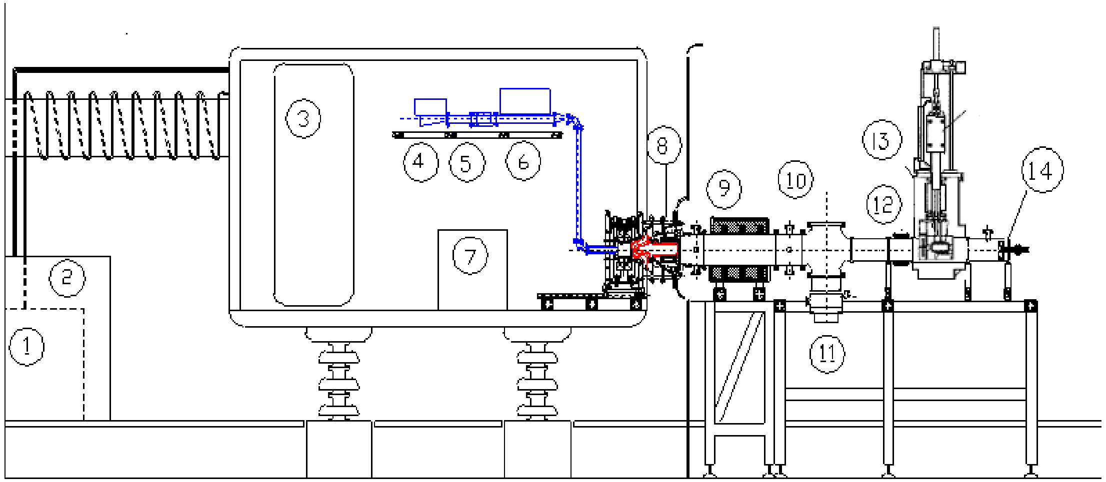




Particles	PROTON		DEUTERON	
Parameters	Requests	Status	Request	Status
Energy [keV]	95	95	95	100
Intermediate Electrode [kV]	55	56	?	50
Proton , Deuteron Current [mA]	100	108	140	129
Total Current [mA] **(I max)**	110	130 **(157)**	155	135 **(166)**
Proton, Deuteron Fraction [%]	> 90	83	> 90	96
Plasma electrode diameter [mm]	-	9	-	9
Current Density [mA/cm²]	140	204	243	212
Availability [%]	AHAP	> 99	AHAP	-
RF Forward Power [W]	< 1200	850	< 1200	900
Duty Factor [%]	100	100	100	0.2 *
H_2 , D_2 Gas Flow [sccm]	< 10	5	< 10	1
Beam Noise rms. [%]	2	1.2	2	1.2
rms normalized emittance [π.mm.mrad]	0.2	0.11 @75 mA	0.2	-

TRIPS (TRasco Intense Proton Source)



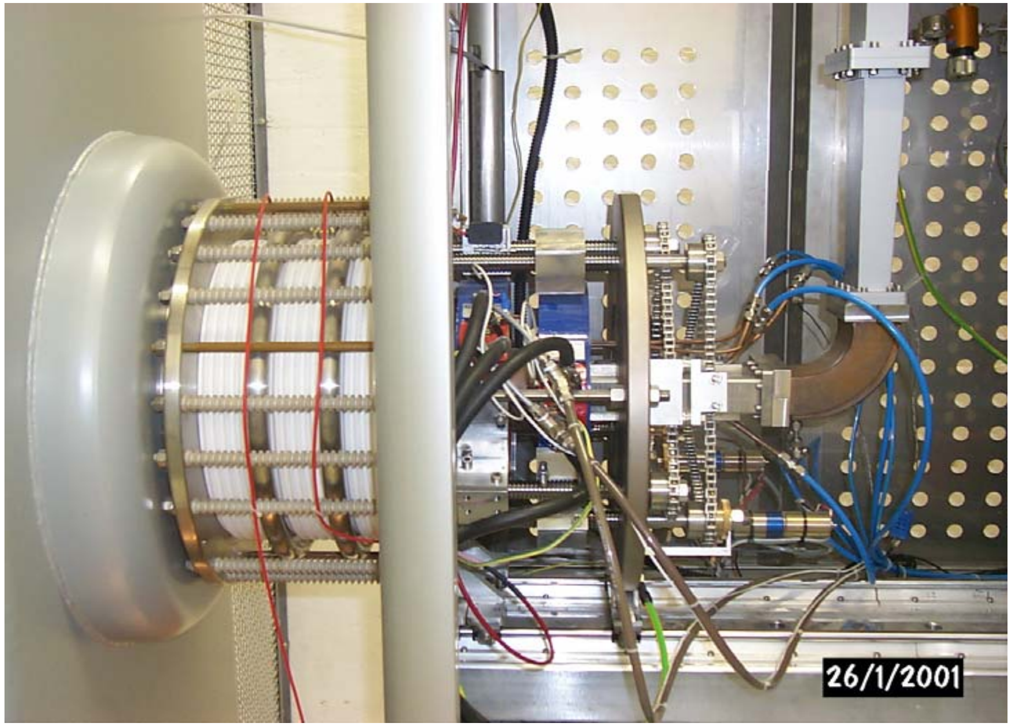


A layout of the whole set-up at INFN-LNS:
1- Demineralizer; 2- 120 kV insulating transformer; 3- 19" Rack for the power supplies and for the remote control system; 4- Magnetron and circulator; 5- Directional coupler; 6 – Automatic Tuning Unit; 7- Gas Box; 8- DCCT 1; 9- Solenoid; 10 – Four sector ring; 11- Turbomolecular pump; 12- DCCT 2; 13- EMU ; 14- Beam stop.

Proton beam current:
35 mA dc
Beam Energy:
80 keV
Beam emittance:
$\varepsilon_{RMS} \leq 0.2\ \pi$ ***mm mrad***
Reliability:
close to 100%

Based on CRNL-LANL-CEA design
MANY INNOVATIONS

TRASCO INTENSE PROTON SOURCE (TRIPS)



Beam energy 80 keV

Current up to 60 mA

Proton fraction > 80%

RF power < 1 kW @ 2.45 GHz

CW mode

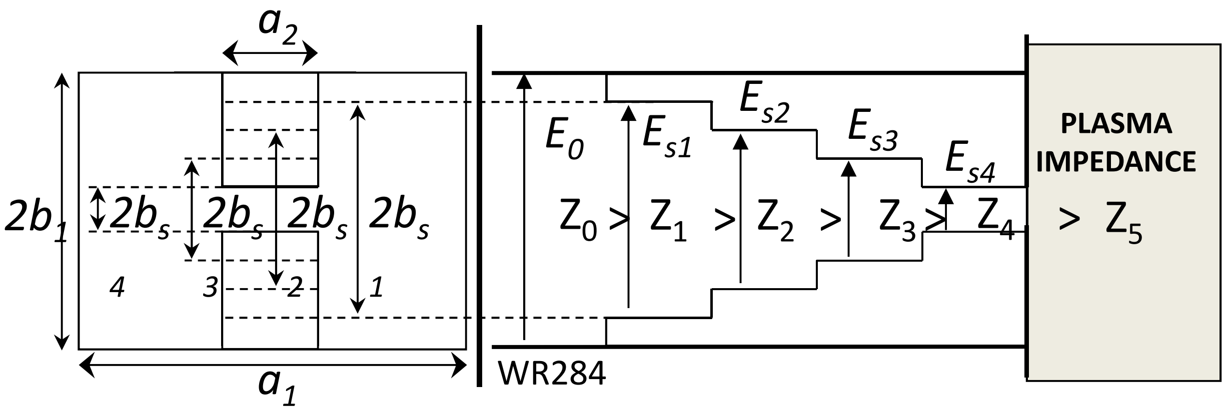
Reliability 99.8% over 142 h (35 mA)

Emittance 0.07 π mm mrad (32 mA)

Microwave injection and beam extraction optimisation

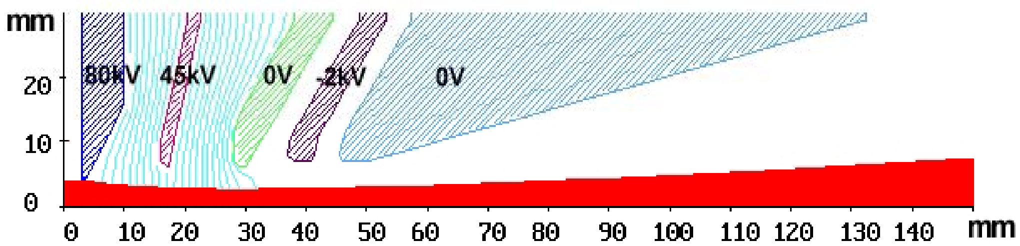
Microwave Injection

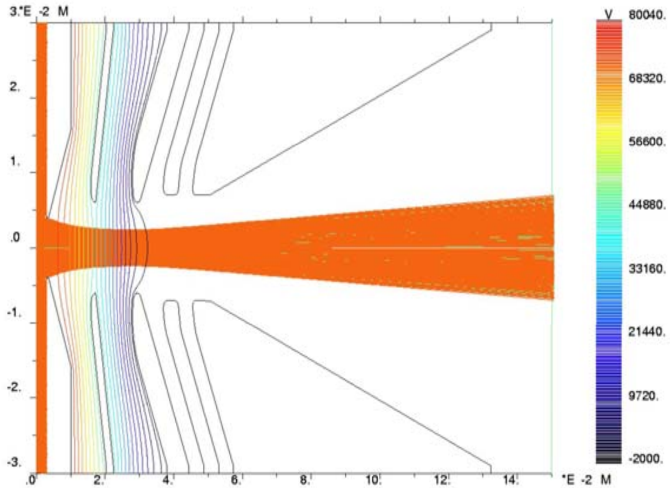
Use of a step binomial matching transformer with a field enhancement factor (E_{s4}/E_0)≈ 1.95 (a_2=0.0126 m)



Beam extraction

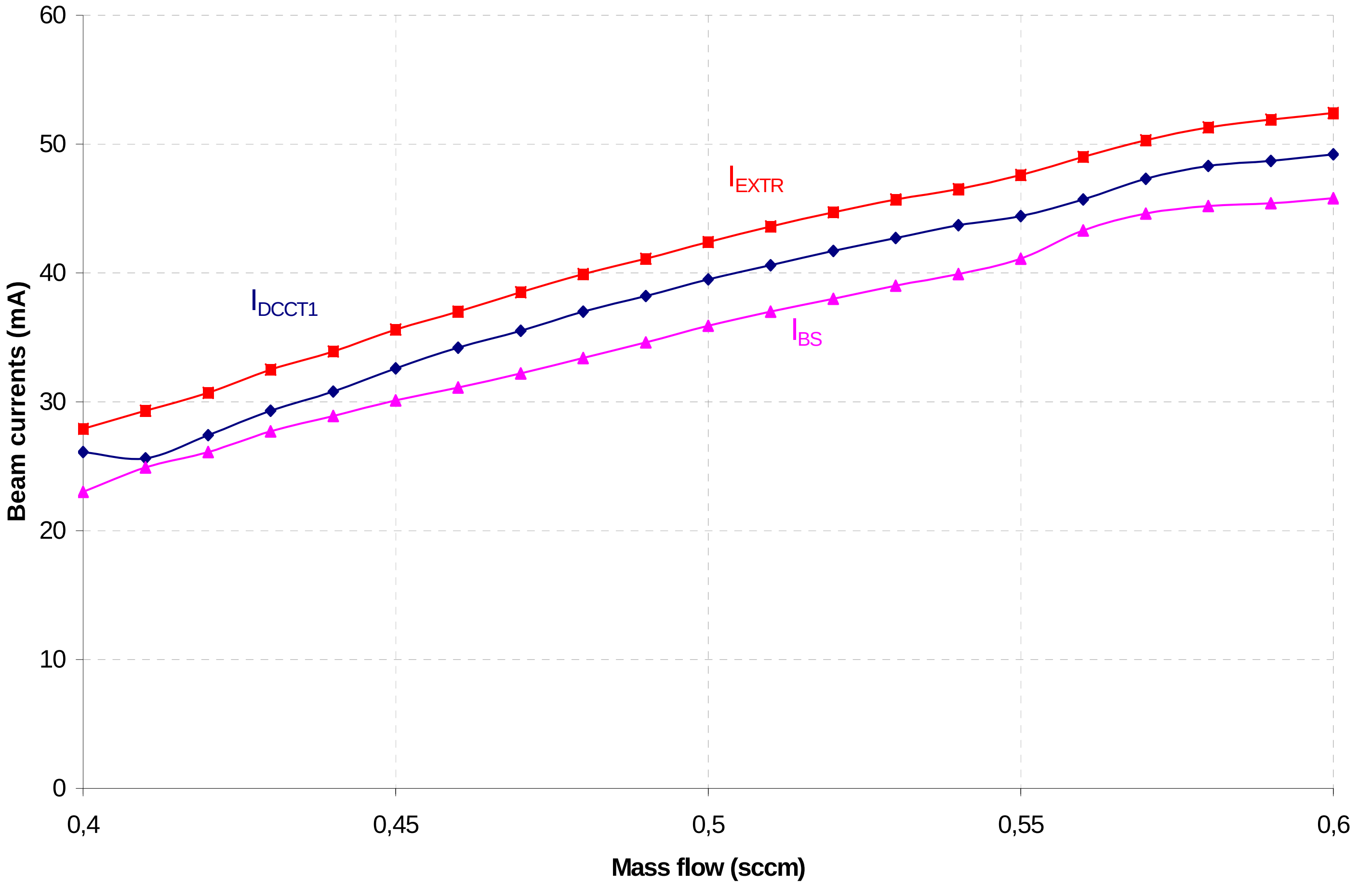
The extraction process has been deeply studied with the aim to increase the source reliability and to keep emittance low.
The used codes were AXCEL-INP and IGUN.



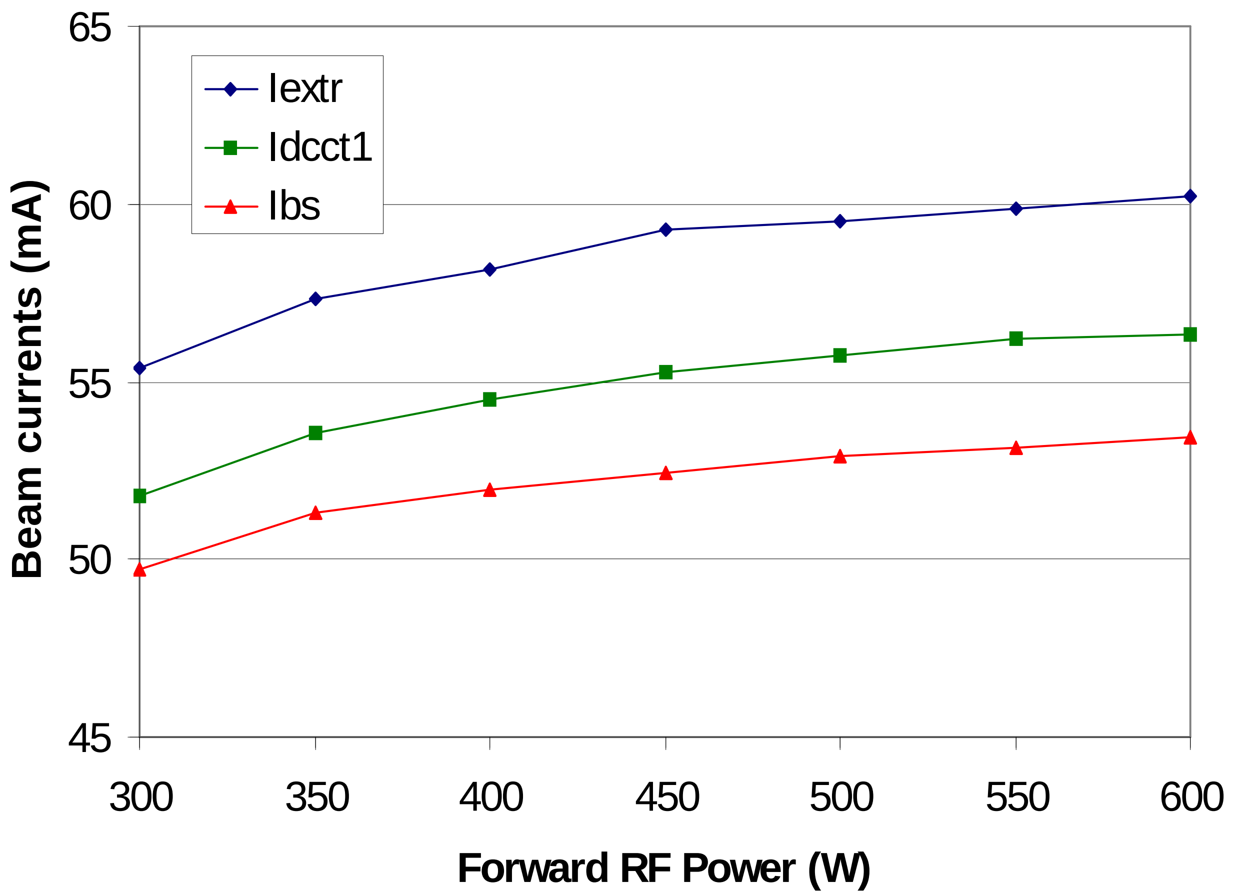


L.Celona, G. Ciavola, S. Gammino, R. Gobin, R. Ferdinand, Rev.Sci.Instr. 71(2),(2000), 771

TRIPS performance vs. mass flow@450W



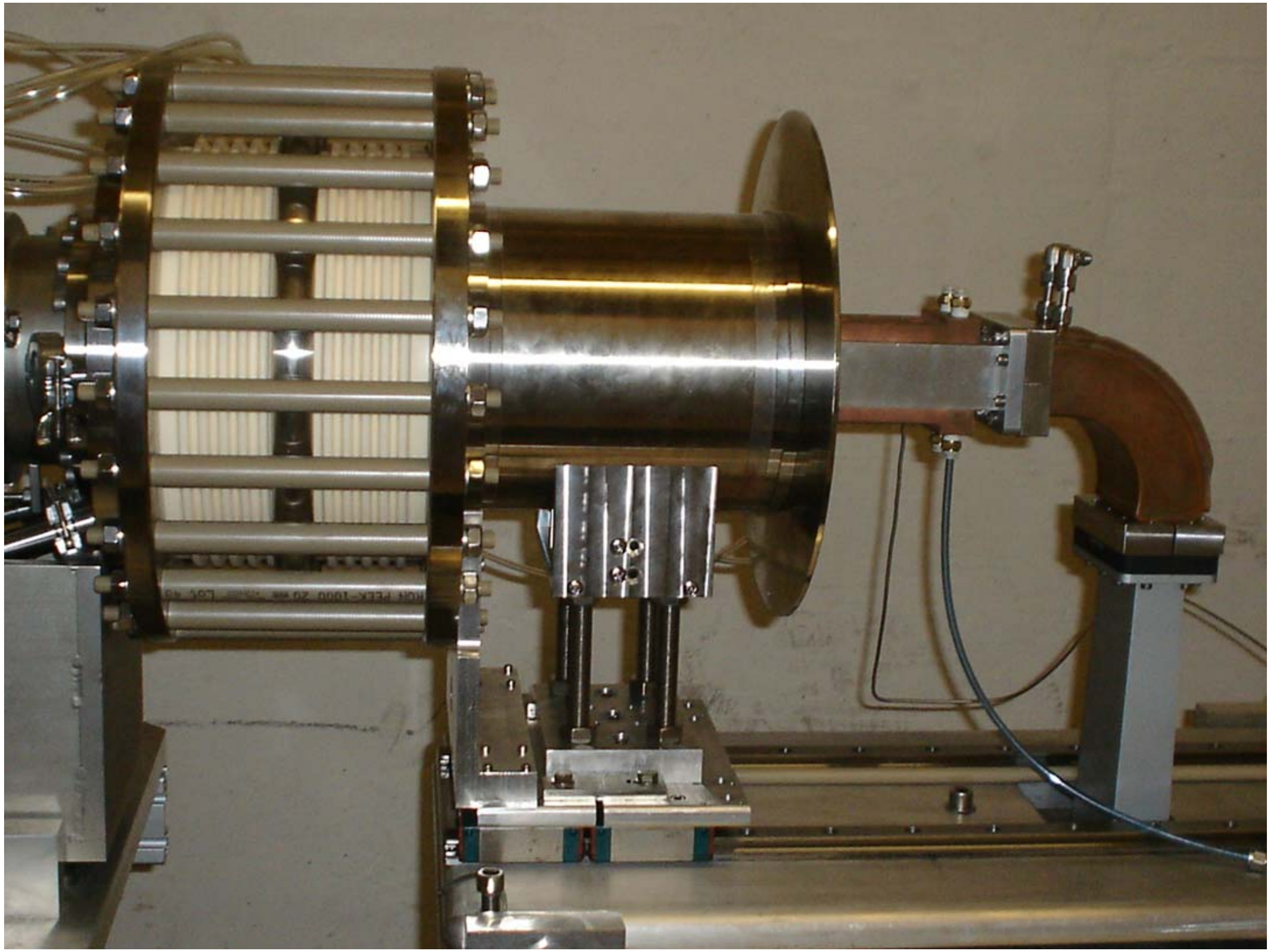
TRIPS performance vs. forward power



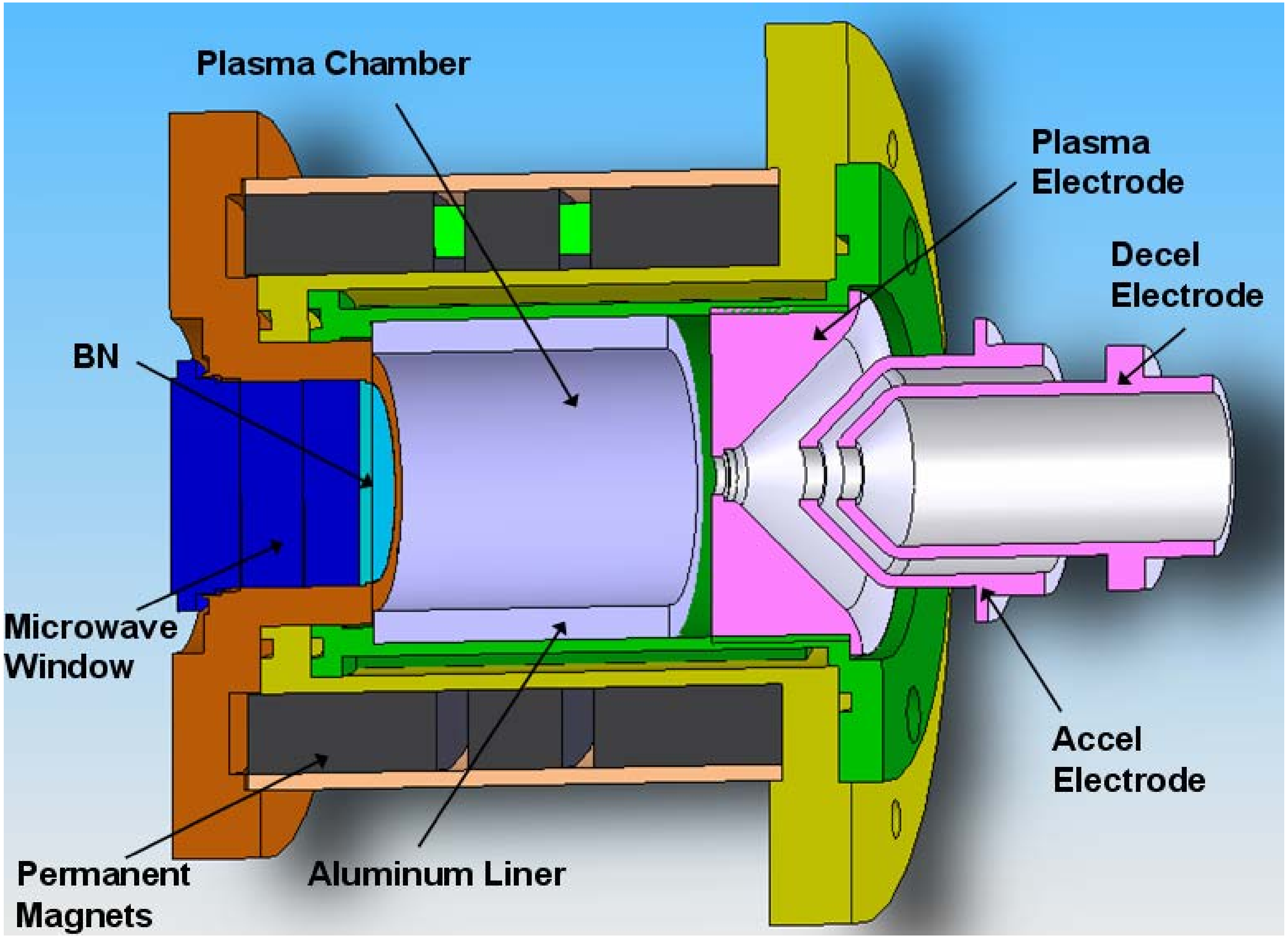
Operating voltage = 80 kV
Optimized magnetic field profile
Electron donor= BN disks

Mass flow= 0.6 sccm
Extraction aperture = 6 mm
Current density up to 210 mA/cm² (near J_{child})

Versatile Ion Source (2008)



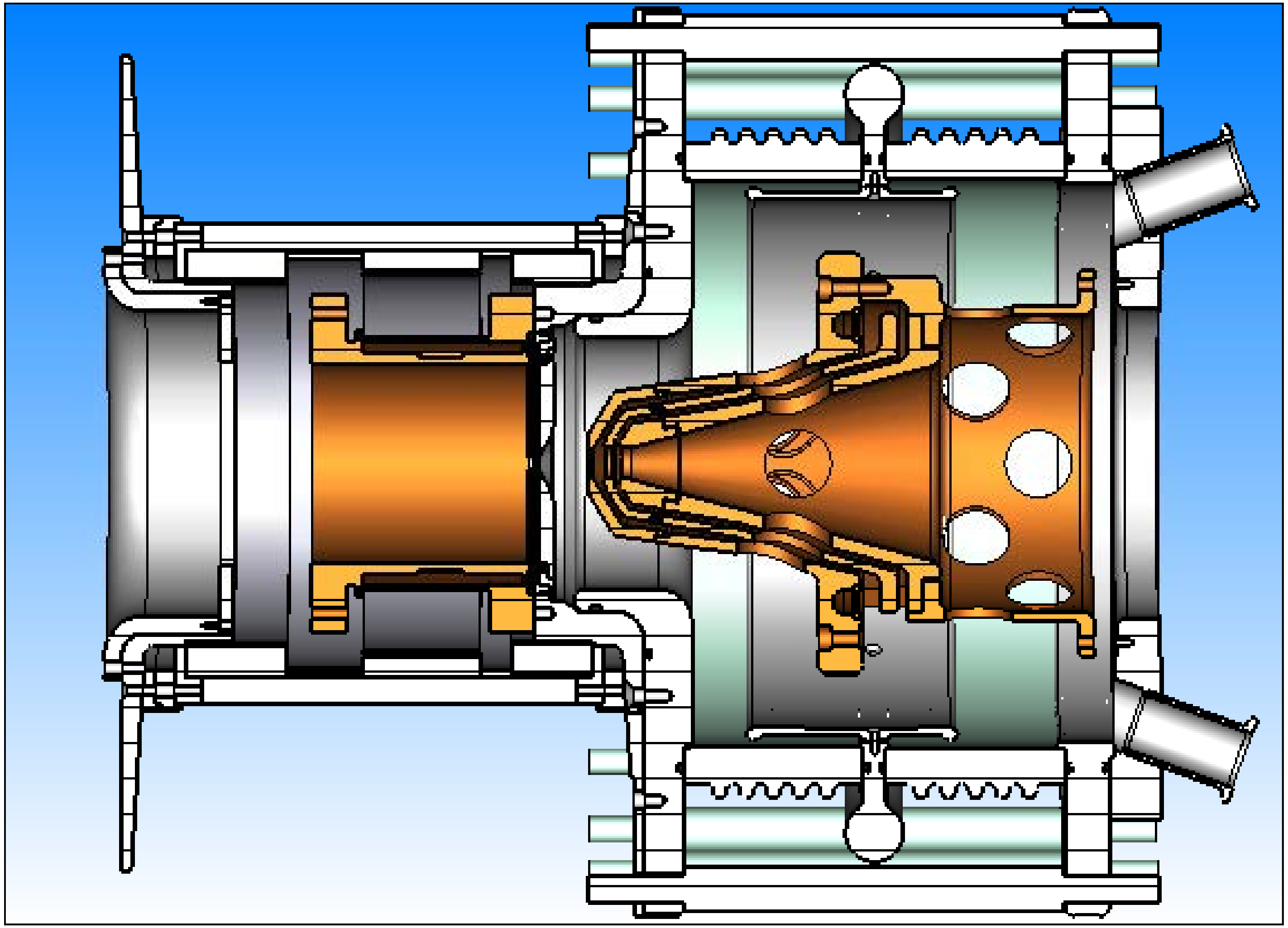
Peking PM source – 100 mA



*Essential items for the **future** developments:*

- *Beam handling*
- *Beam ripple*
- *Ability to operate in pulsed mode*
- *Reliability*
- *Possible improvement to beam brightness*
- *Space charge compensation*

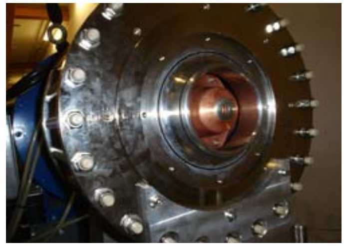
ION EXTRACTION SYSTEM



YOU ARE NOT OBLIGED TO DESIGN COMPLEX SYSTEM

ION EXTRACTION SYSTEM



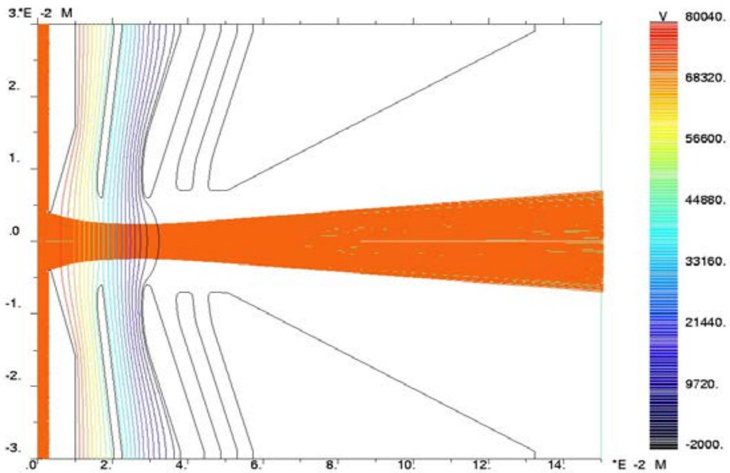
TRIPS Five-electrodes topology

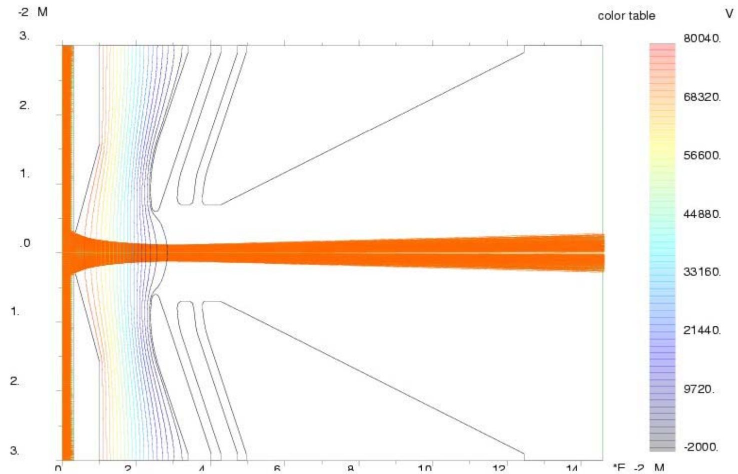
• on-line optimisation of the extracted beam

• wide range of operations (10-60 mA)

VIS Four-electrodes topology

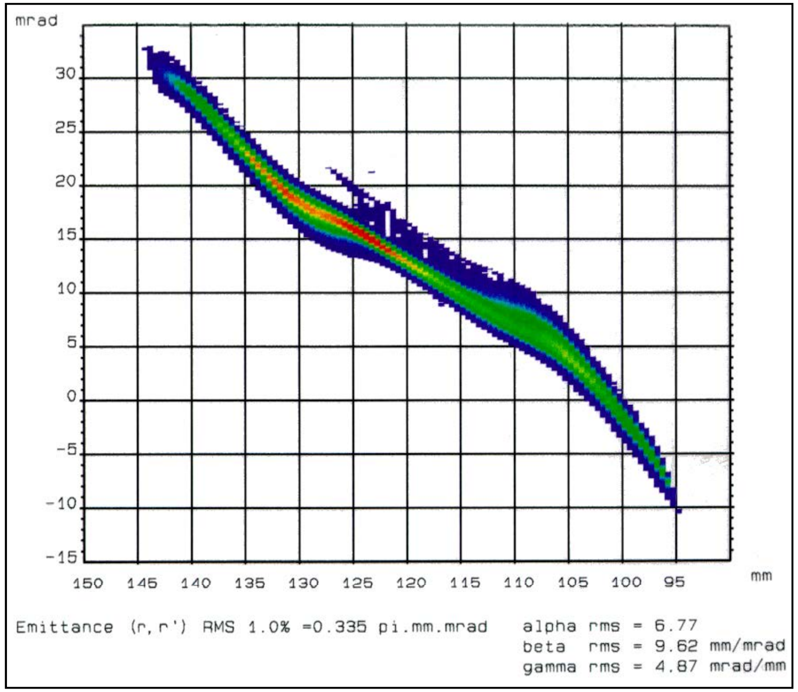
optimized for a 40 mA beam (90% proton, 10% H_2^+)

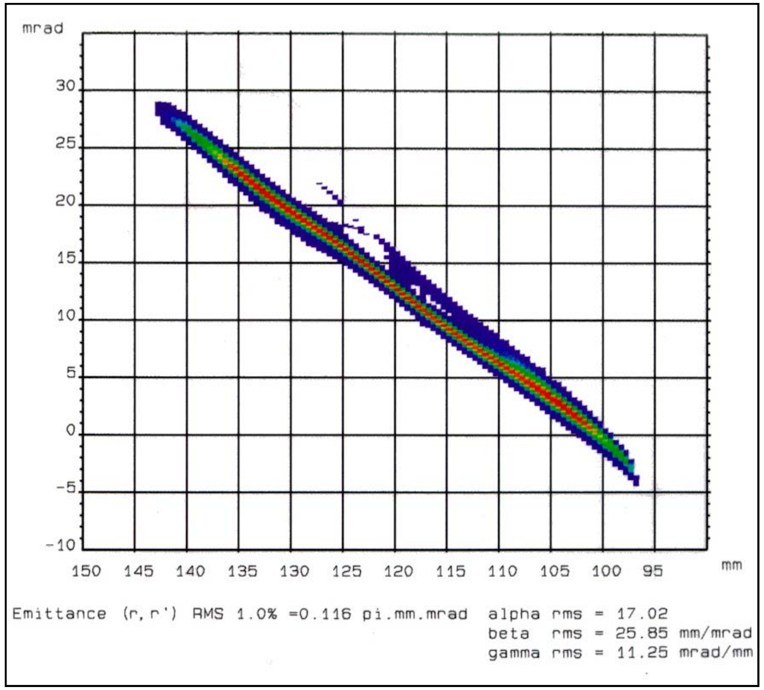




Rms normalized emittance calculated with Axcel code is 0.04 π mm mrad.

Space charge compensation with ^{84}Kr





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

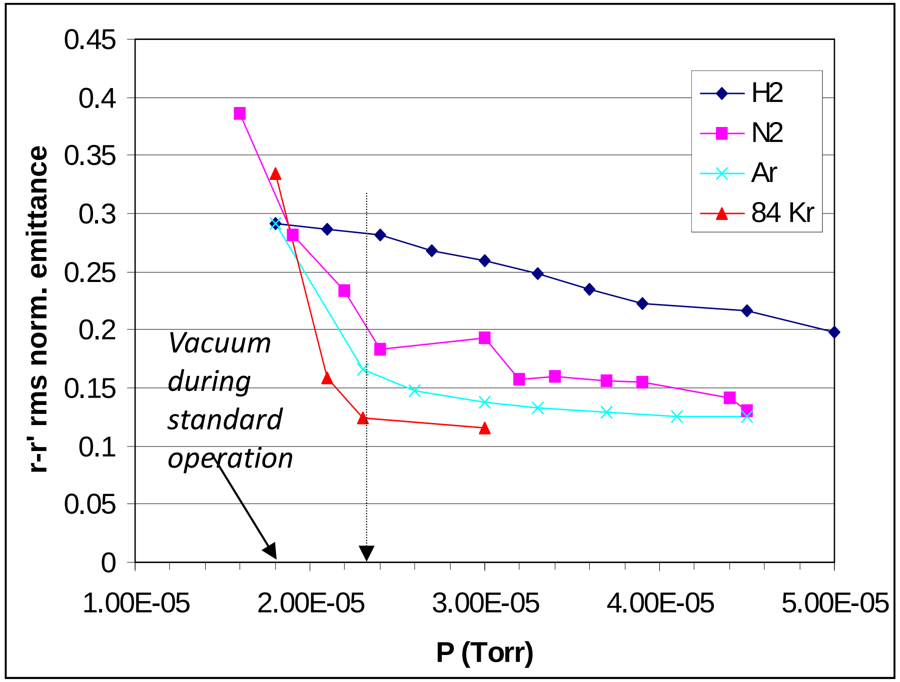
p=1.8·10^{-5} T⇒ **ε_{RMS}=0.335 π mm mrad**

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

p=3.0·10^{-5} T⇒ **ε_{RMS}=0.116 π mm mrad**

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

Space charge compensation with H_2, N_2, Ar, Kr



- *In all the cases considered, a decrease of beam emittance has been observed with the increase of beam line pressure.*
- *Using ^{84}Kr gas addition a decrease of a factor three in beam emittance has been achieved losing less than 5% of the beam current with a small increase of pressure (from 1.8E-5 Torr to 2.4E-5 Torr).*

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

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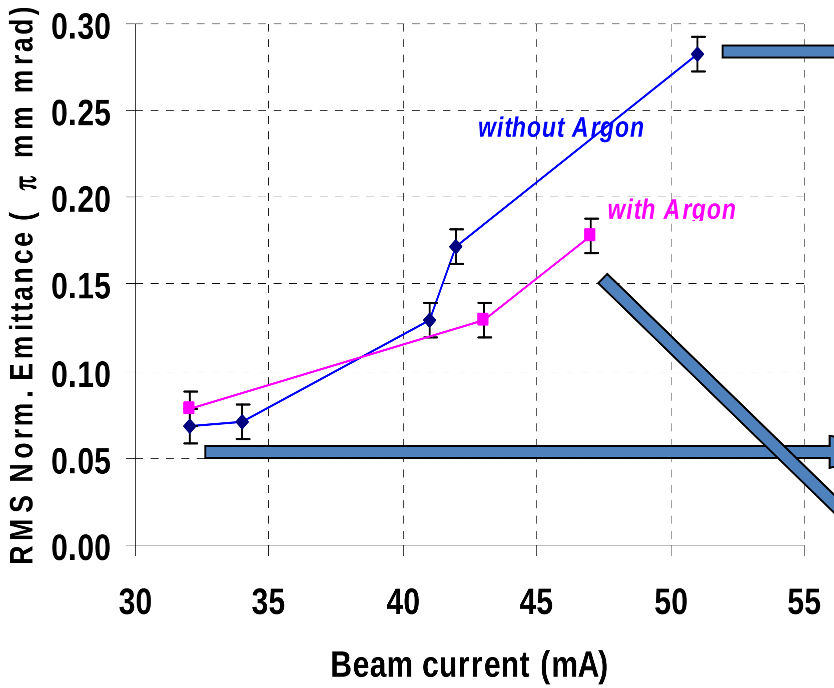
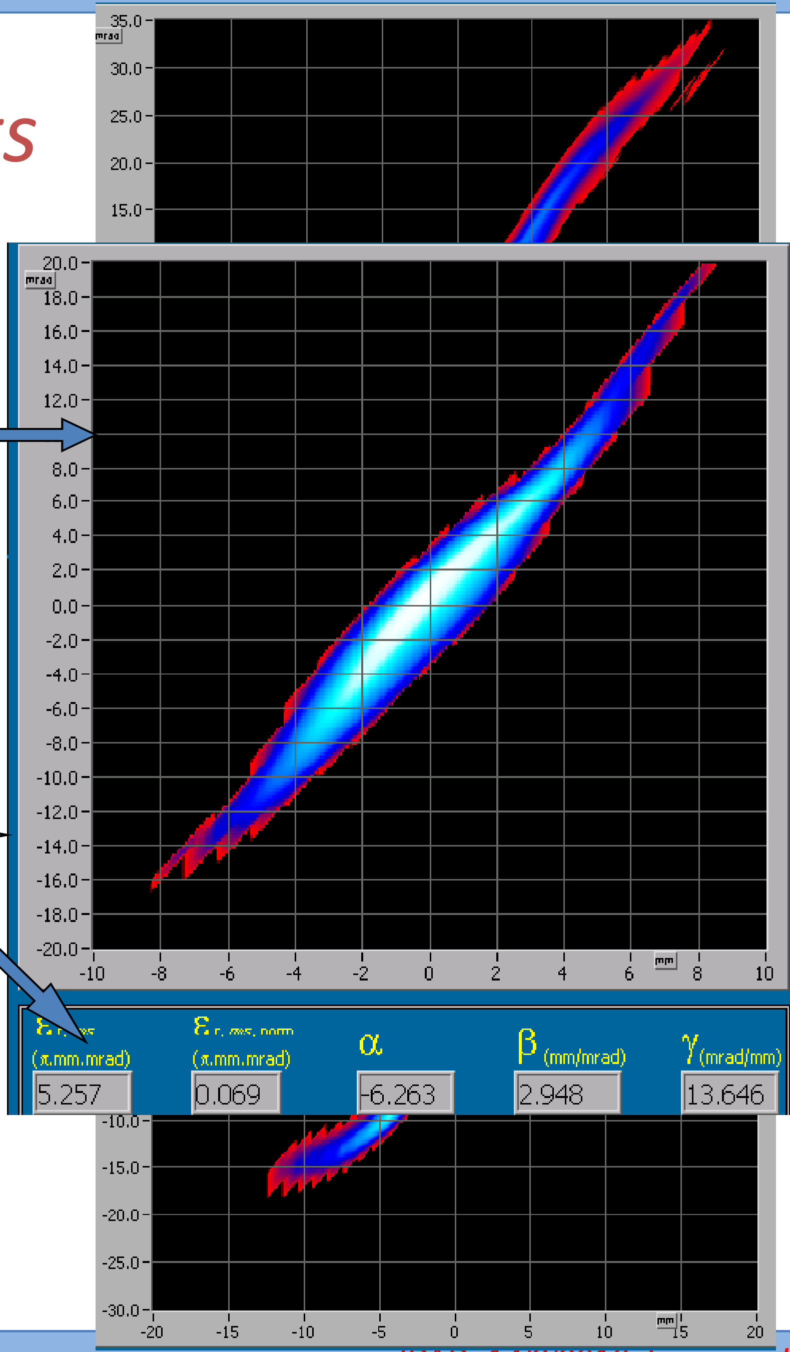
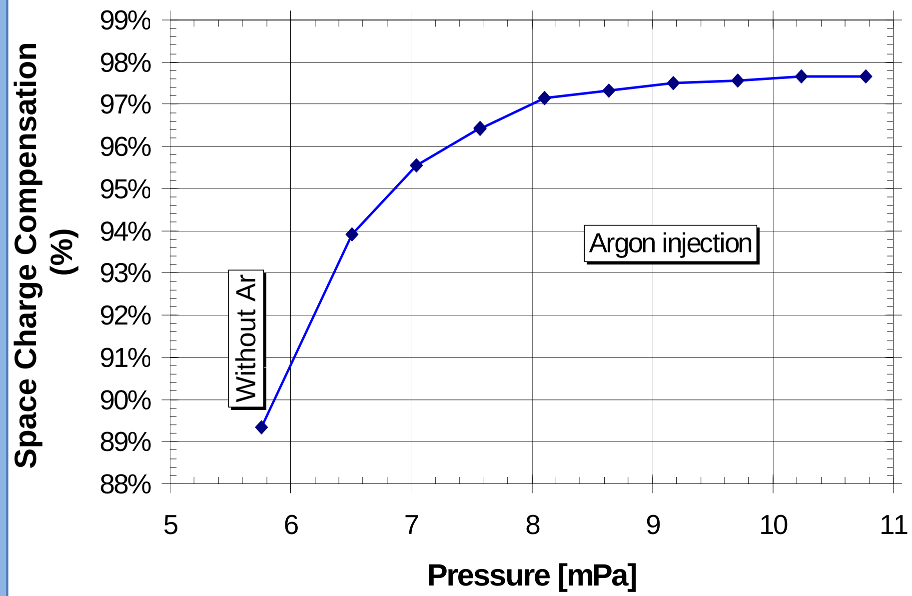
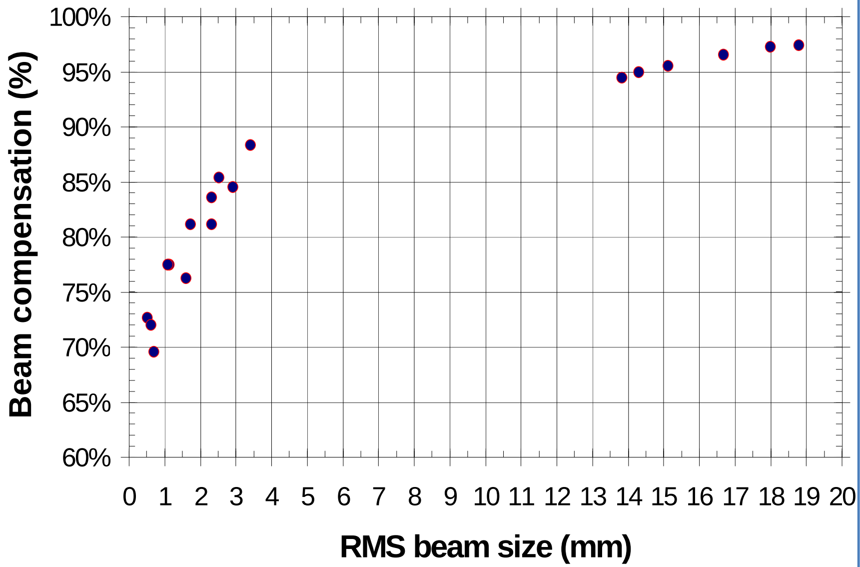
Emittance measurements





FGA measurements

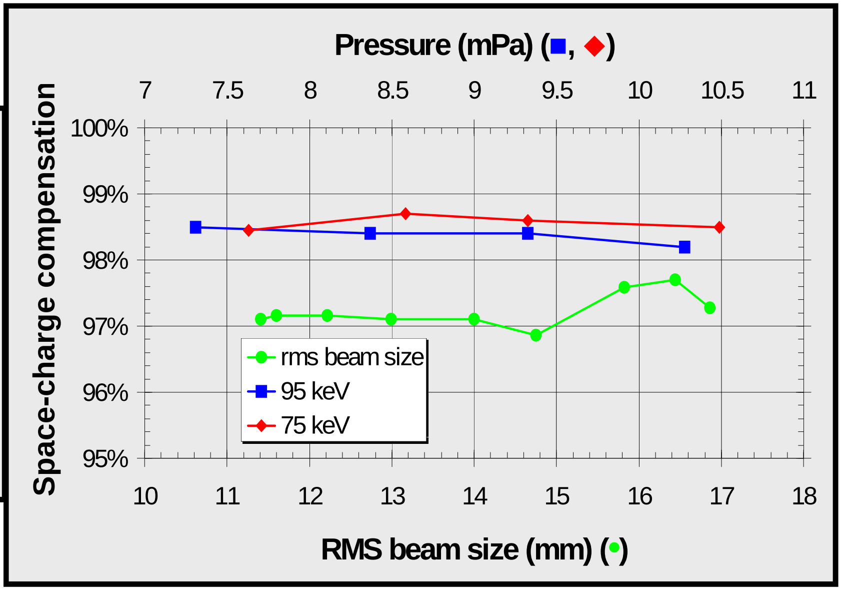




P. Y. Beauvais, R. Gobin, R. Ferdinand, L.Celona, G. Ciavola, S. Gammino,J. Sherman, Rev.Sci.Instr. 71(3),(2000), 1413

Space charge compensation analysis (SILHI)

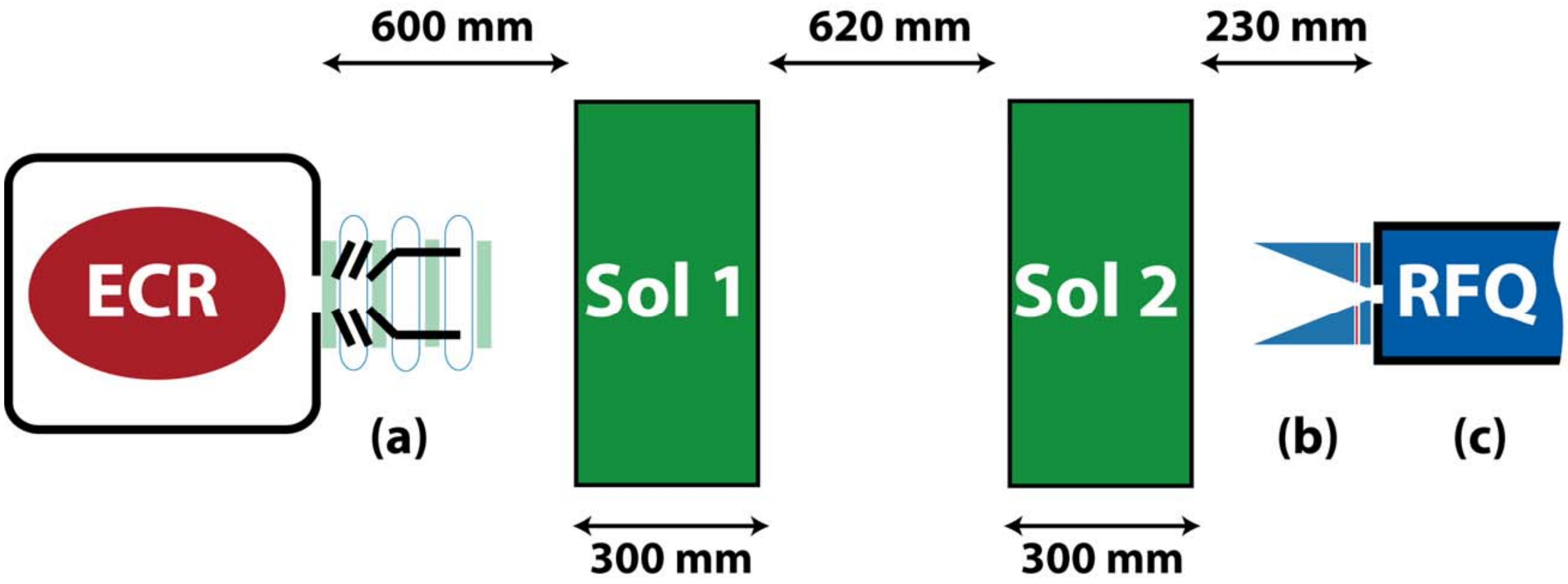
Upstream *the 1st solenoid (source exit)*
Low variation whatever :
- beam size,
- added gas,
- energy settings



Downstream the 1st solenoid,
Large variation vs electron flux (gas injection, beam stop, beam losses) and beam size

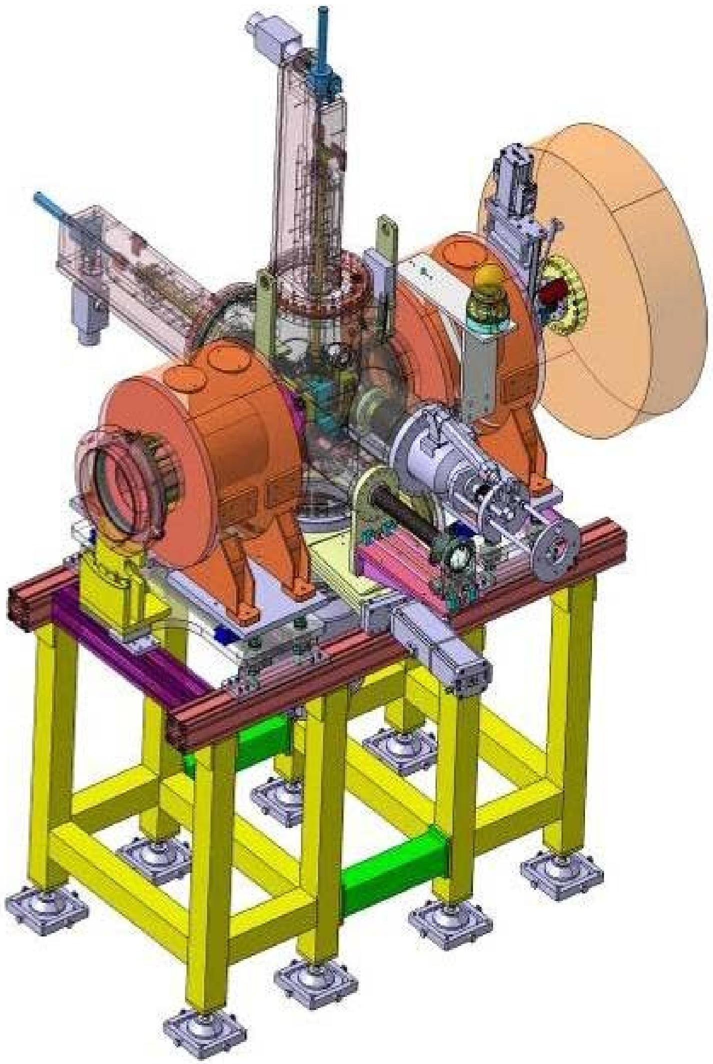
Between 70 and 98%

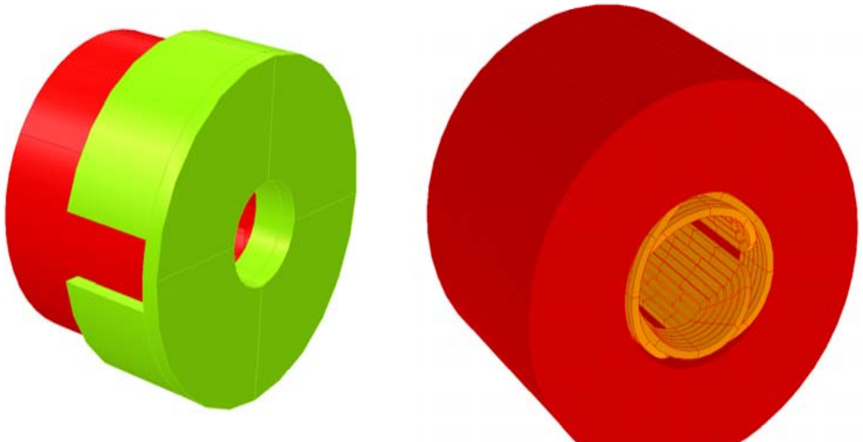
IFMIF Beam Line Layout



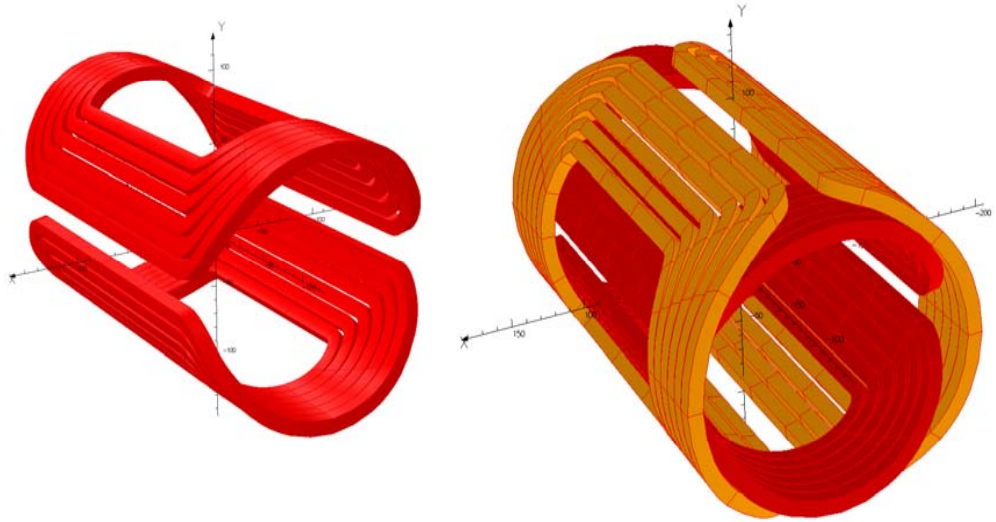
Total Beam Line Length : 2.050 m

Shorter LEBT: solenoids with H+V steerers inside





A 3D simulation has been studied to verify the possible field integral achievable and the compatibility with the beam dynamics requirements.



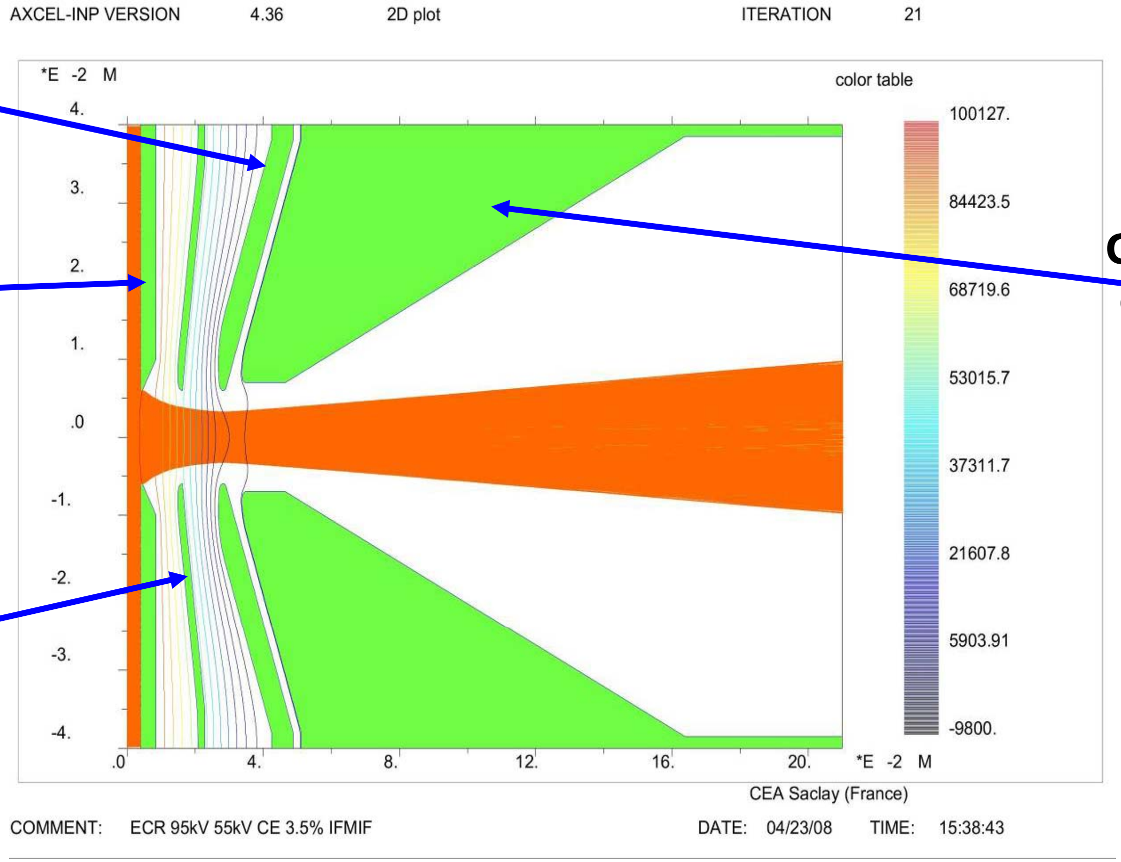
IFMIF extraction system

100 KeV, 175 mA total beam current, 1560 A/m² (Φ 12mm)

e- screening electrode
Φ12mm
-9.8 kV

Plasma electrode
Φ12mm
45° angle
100 kV

Intermediate electrode
Φ12mm
Adjustable
57 kV



Grounded electrode
Φ14mm
0 kV

Child-Langmuir law ⇨ *space charge limited beam current* :

$$I = \frac{4\pi}{9}\epsilon_0 \left(\frac{2q}{m}\right)^{1/2} \frac{V_0^{3/2} r_s^2}{d^2} \quad [A]$$

IFMIF: rs=6 10-3m, d=25mm, V0=100000 V, q/m(D+)=4.79 107, 4pe0/9=1/81*10-9

I=3.8212*(rs/d)²=0.220 A

Reliability

Reliability is affected by

-**Sparks in the extraction system**

-**External sparks**

-**Mechanical components aging**

-**Electronics faults in the control units**

-**Power supplies failure**

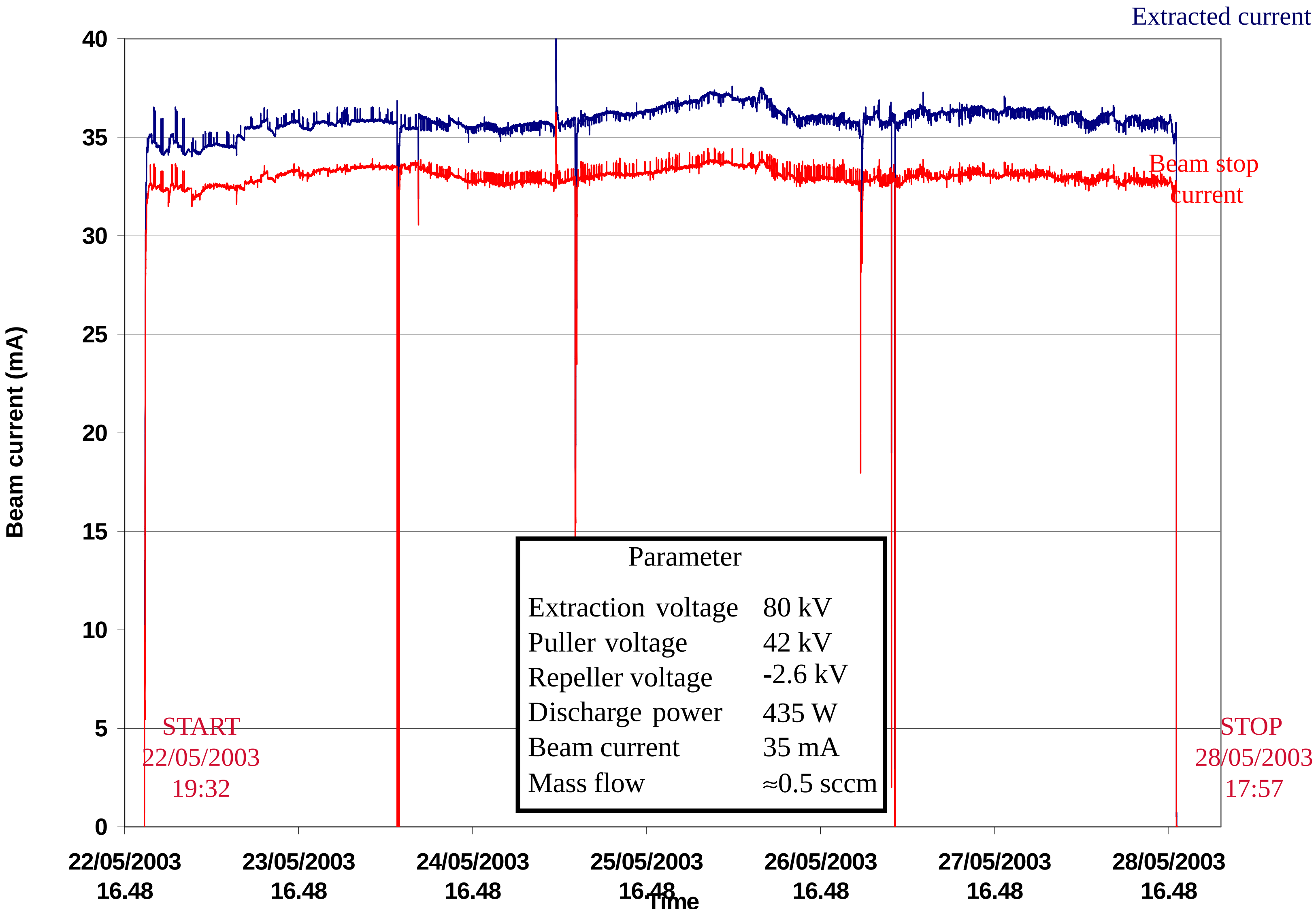
-The use of EMI resistant electronics and the implementation of auto-reset procedures has permitted a remarkable increase of reliability.

-Different campaigns have been made at LANL, CEA, INFN-LNS, sometimes exceeding 99.8 % availability

-The use of **sources with permanent magnets** is a convenient step forward, as it permits to avoid solenoids/power supply faults and to limit the plasma parameters drifts.

TRIPS RELIABILITY TEST

TRIPS Extracted Current: Availability over 142 h 25 min = 99.8 %



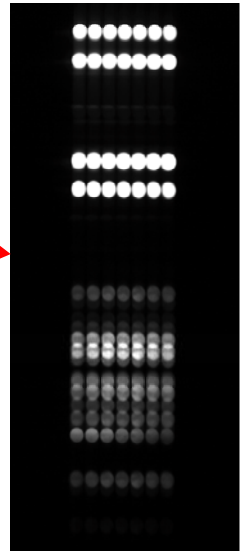
Parameter	
Extraction voltage	80 kV
Puller voltage	42 kV
Repeller voltage	-2.6 kV
Discharge power	435 W
Beam current	35 mA
Mass flow	≈0.5 sccm

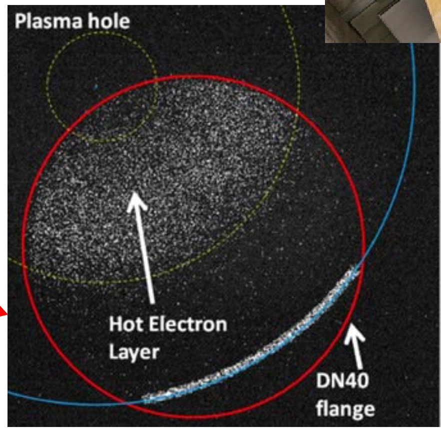
Possible improvements

- Current (electron donors, Al_2O_3 inside the chamber, e-gun)
- Larger dimension to improve the plasma uniformity close to the extraction
- Larger frequency ? Emittance? Energy spread?
- 2.45 GHz + second frequency? To be tested, but
- Brightness improvement (extraction studies, compact LEBT, space charge compensation to be optimized (atomic physics may help?), plasma formation process
- Reliability (Permanent magnets, Controls)

But additional improvements will originate by plasma studies with improved diagnostics

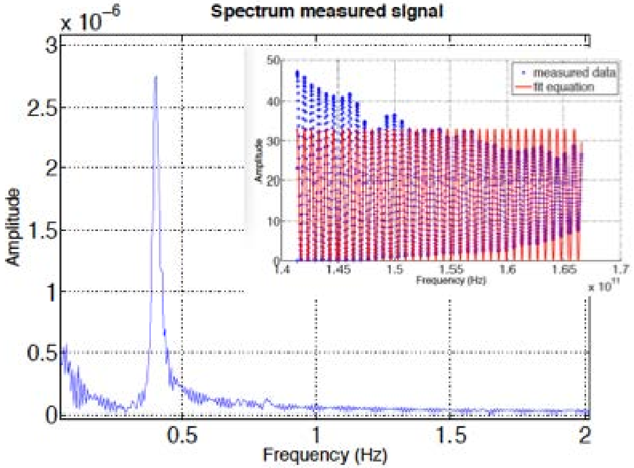
- Microwave interferometry
- Optical metods
- X-ray detection

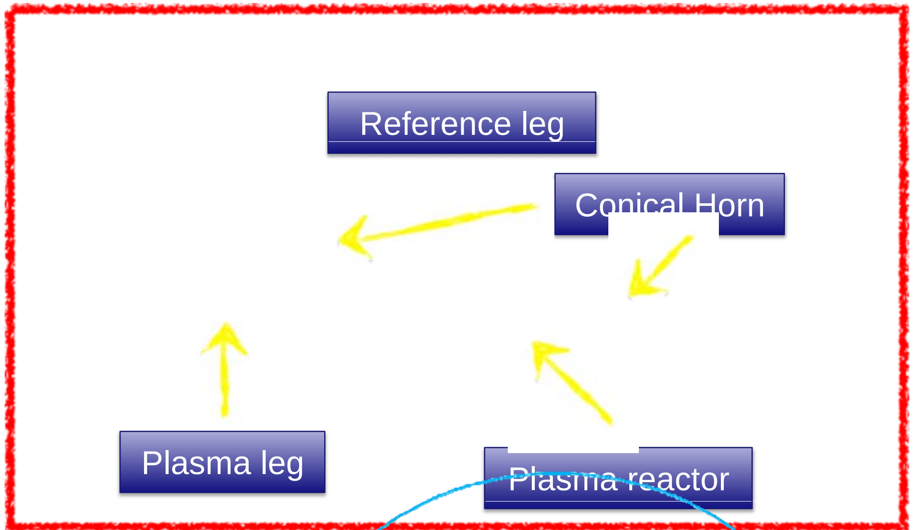




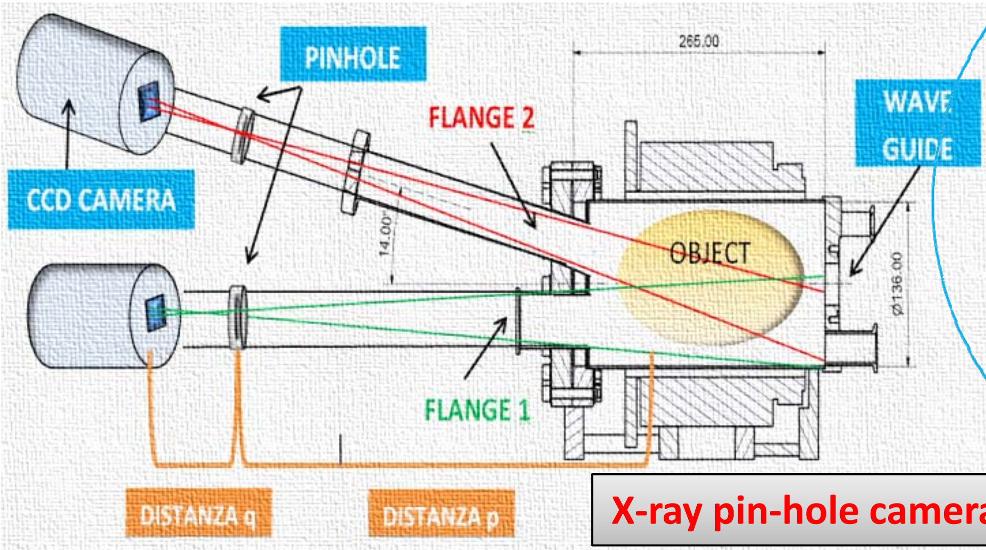
PS-ESS will be commissioned during 2016 and it will permit to study all issues above, along with the "sister" testbench FPT that for some cases will be the ideal setup.

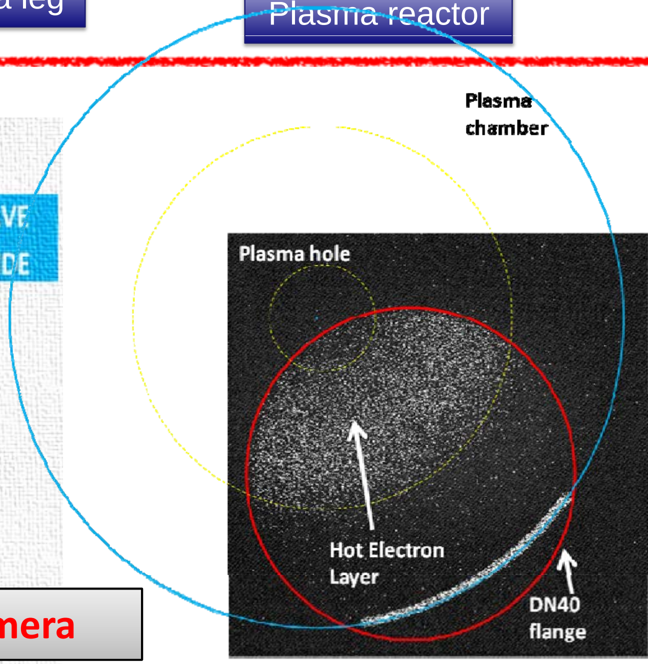
Main plasma diagnostics @LNS





Frequency sweep microwave interferometer





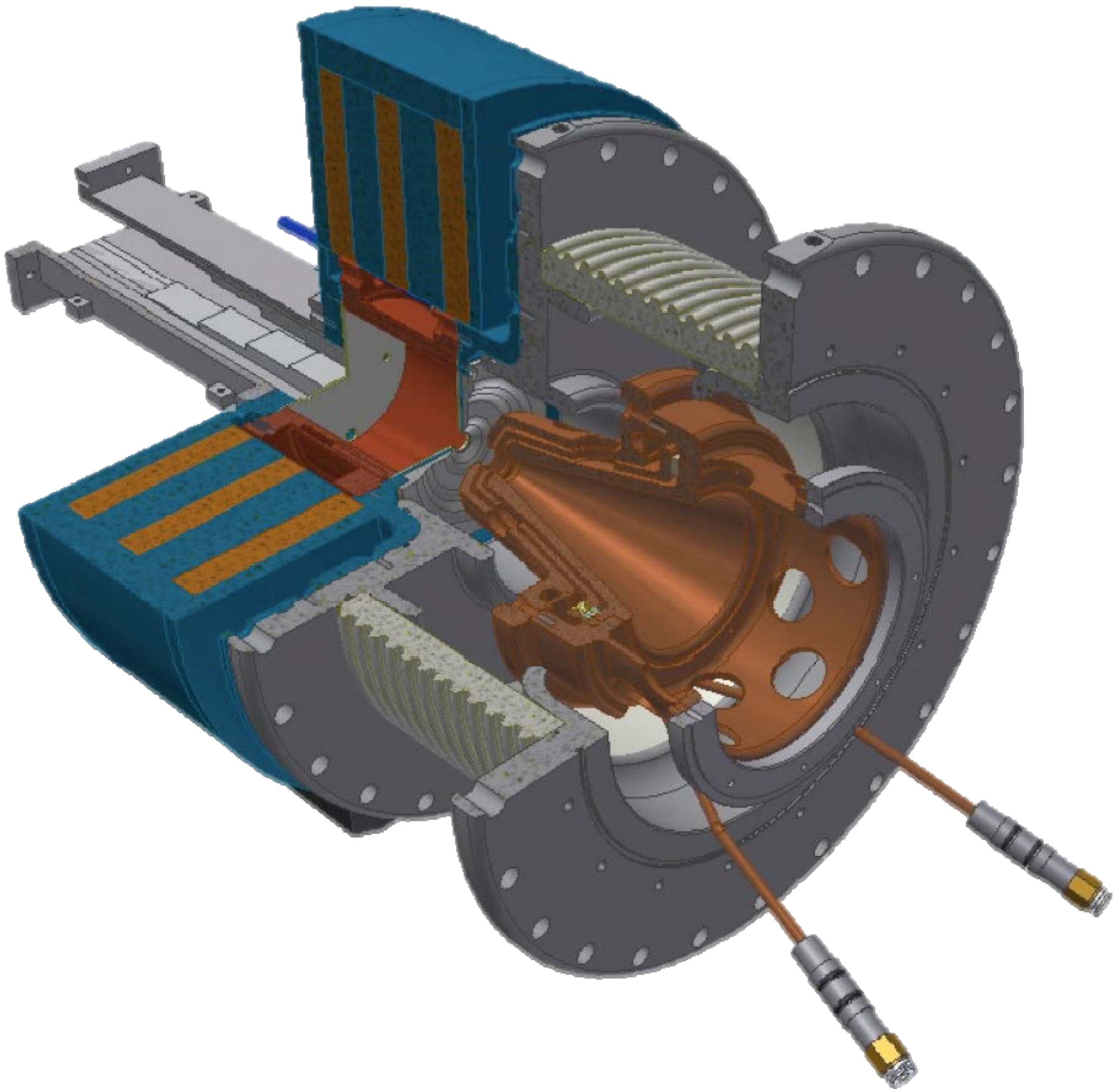
X-ray pin-hole camera

INFN contribution to the accelerator design

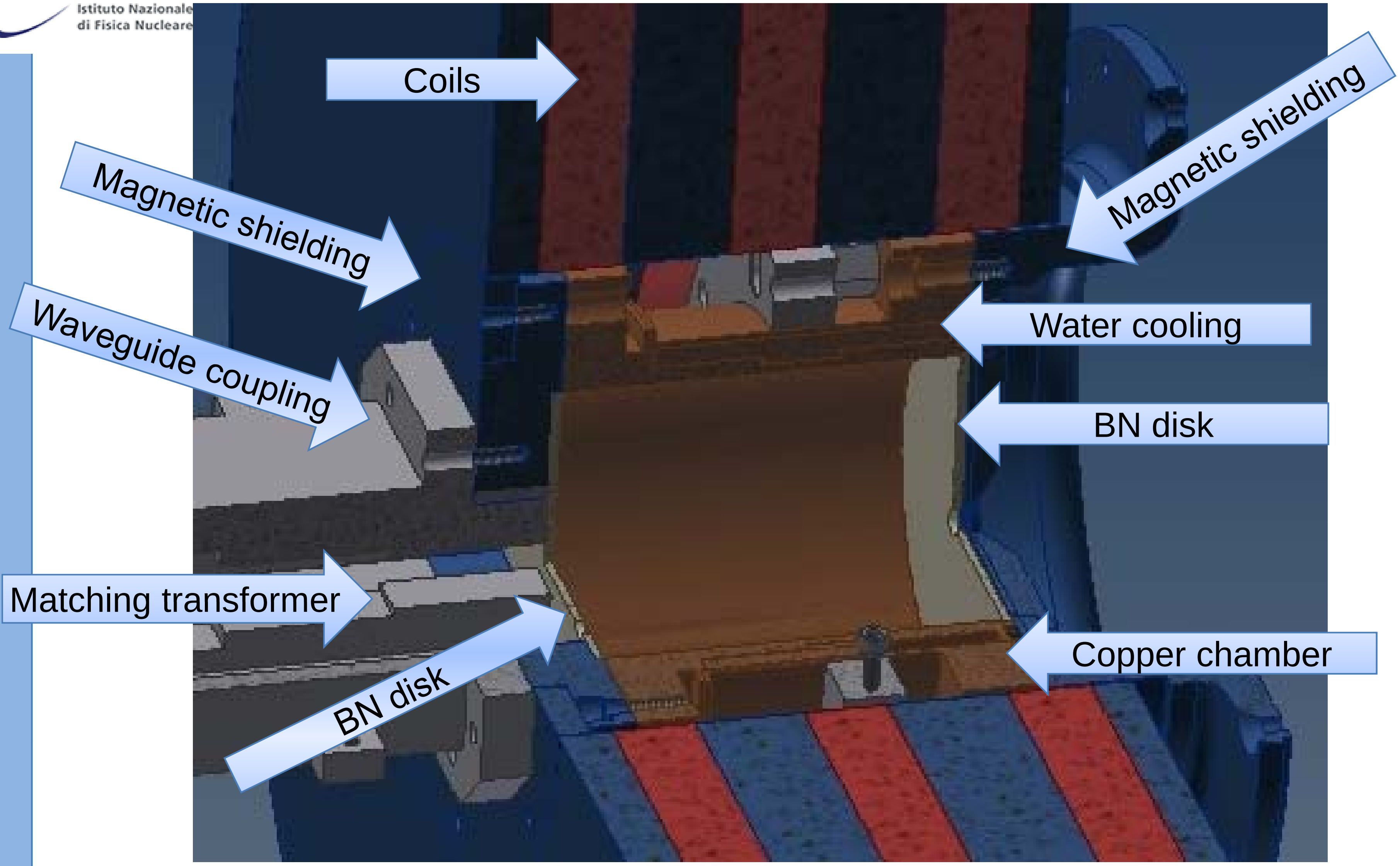
The ESS Proton Source prototype

- From R&D activities on plasma based compact sources to the PS-ESS design;
- Searching a balance between innovative solutions and robust design;
- Flexibility required for the magnetic field and RF system;

The Proton Source for ESS

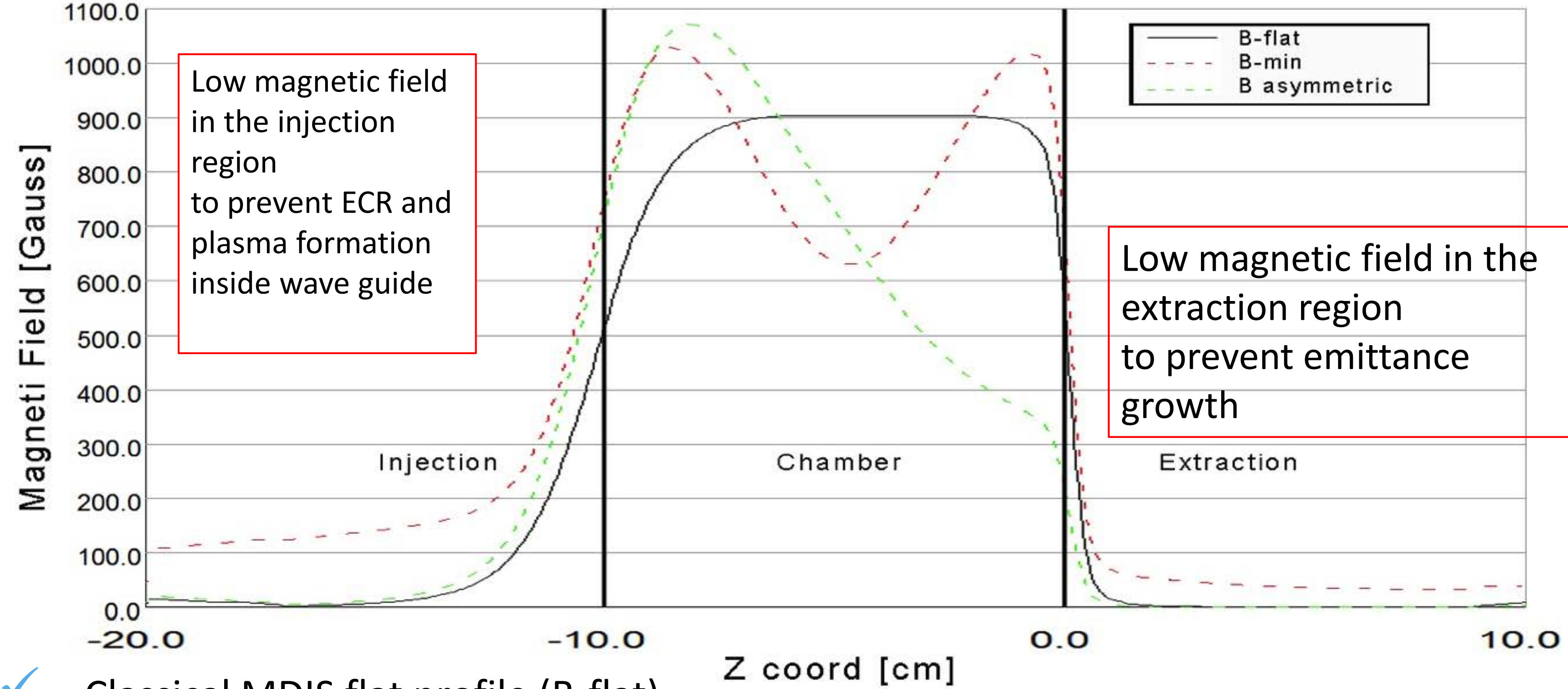


Body Source



Coils
Magnetic shielding
Magnetic shielding
Waveguide coupling
Water cooling
BN disk
Matching transformer
BN disk
Copper chamber

Flexible magnetic system

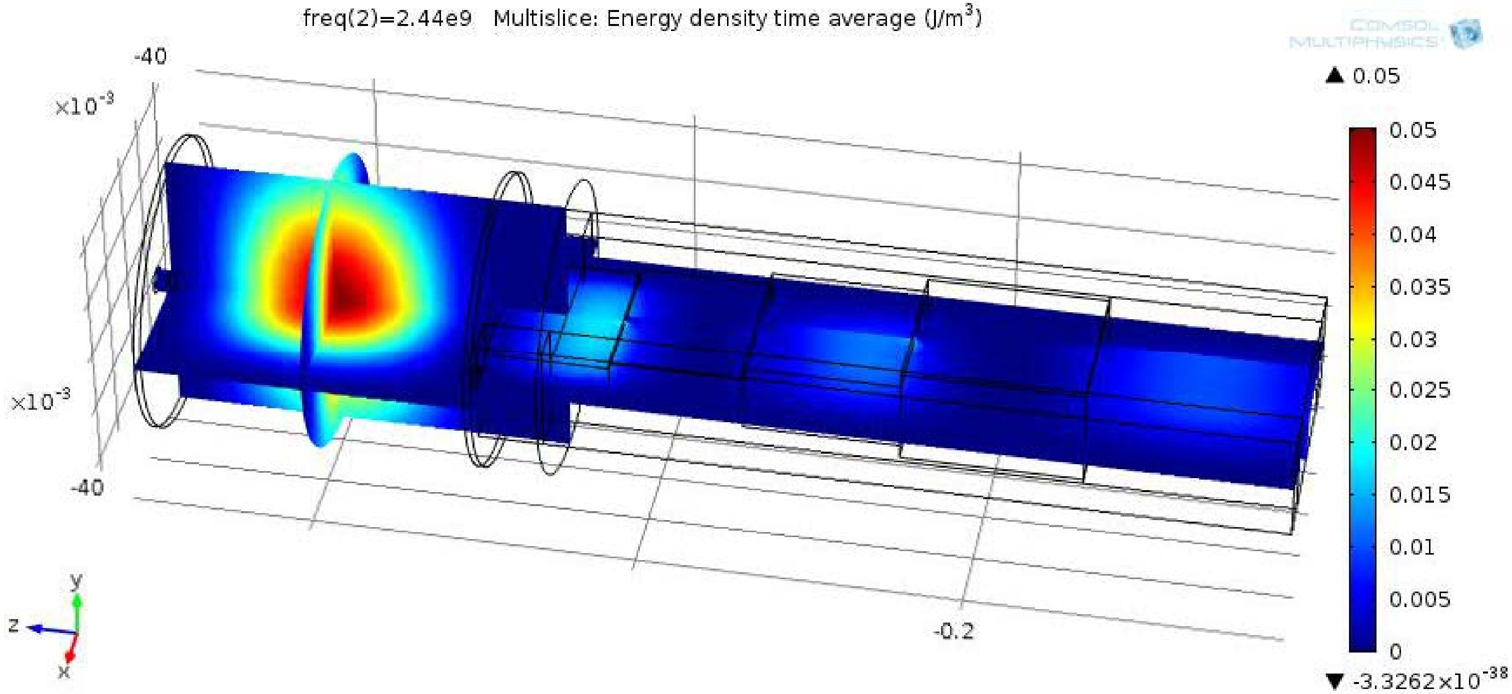


- ✓ Classical MDIS flat profile (B-flat)

- ✓ Simple-mirror (B-min) for the prolongation of H_2^+ molecule lifetime, thus increasing ionization efficiency and proton fraction

- ✓ Magnetic beach (B-asymmetric) making possible Bernstein Waves (BWs) formation through inner-plasma conversion of the input electromagnetic waves.

PS-ESS refinement



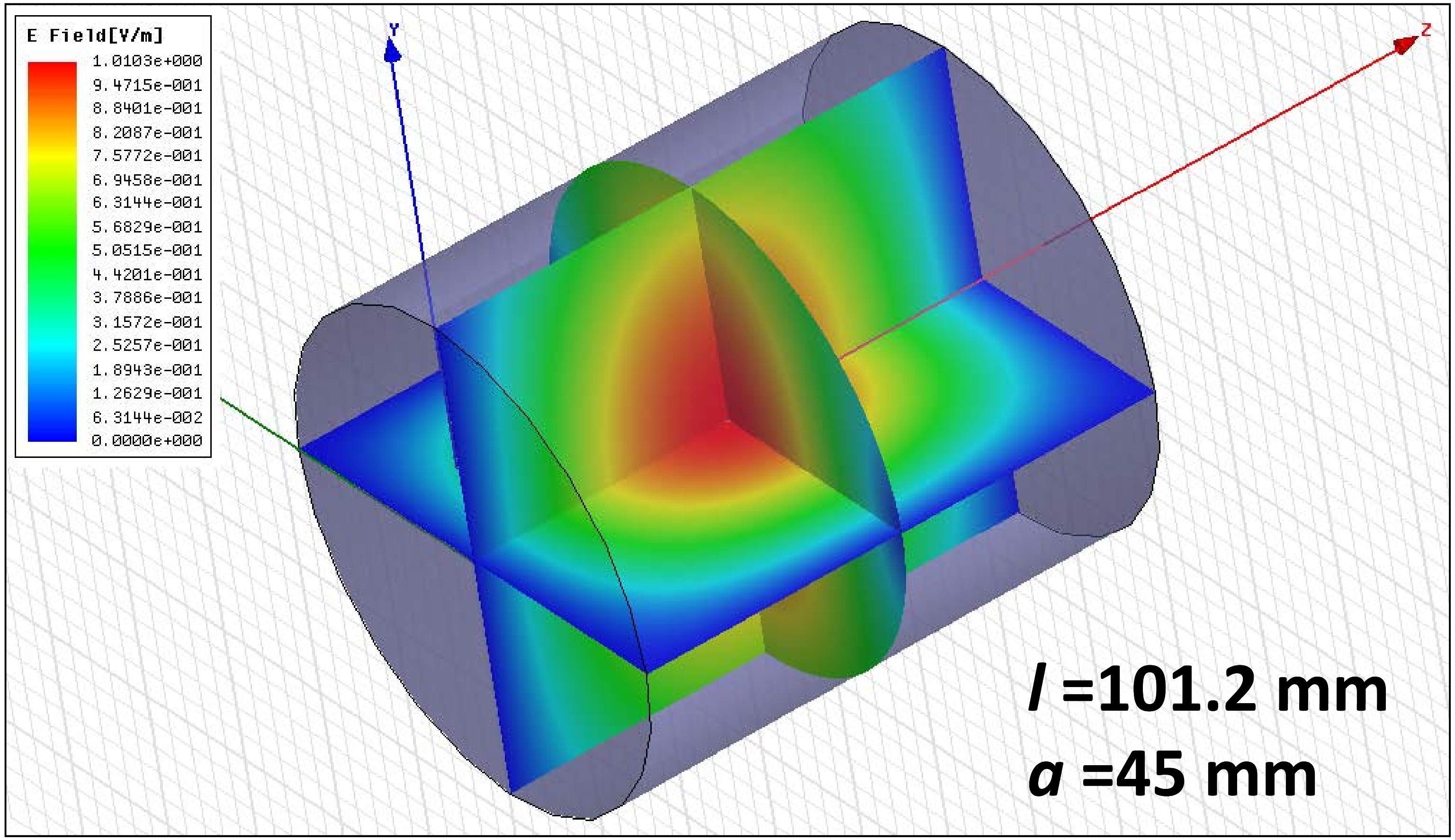
Optimization of all geometrical parameters of the matching transformer:
Step width, height, length, number

Cavity frequency domain study with real dimensions an real materials:

Copper chamber cylinder
Two Boron Nitride insulators disks
Aluminum waveguide
Extraction hole

PLASMA CHAMBER OPTIMIZATION

PARAMETRICAL ANALYSIS RESULTS-TE_{111} MODE

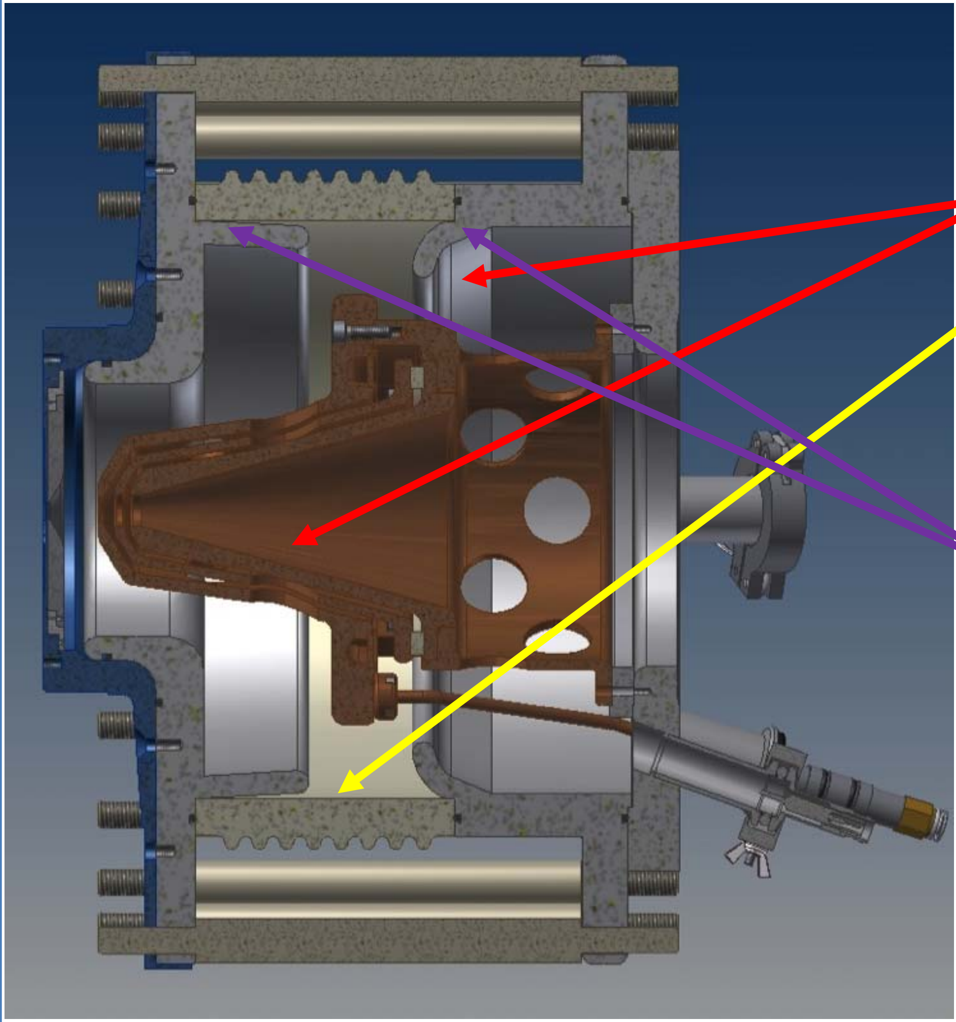


TE_{111} ELECTRIC FIELD DISTIBUTION INSIDE THE CYLINDRICAL RESONANCE CAVITY

REQUIREMENTS FOR ESS

• Large current	(74 mA proton, about 90 mA total)
• Low emittances	(0.25π mm mrad)
• Long lifetime	
• High reliability	(>99%)
• Pulsed operation	(2.86 ms-14 Hz)
• Short pulse rise time	(100 ns)

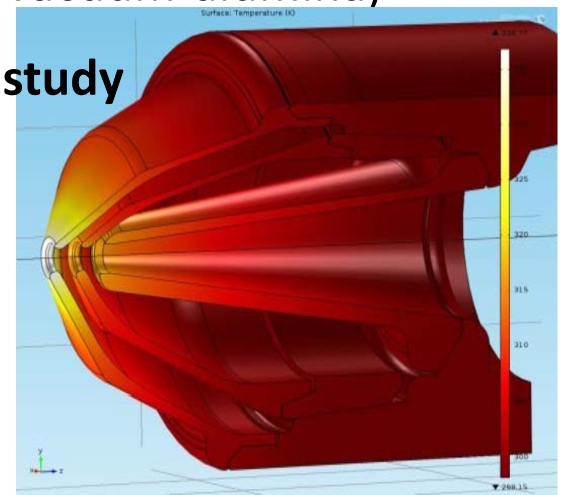
Upgrade of VIS extraction system



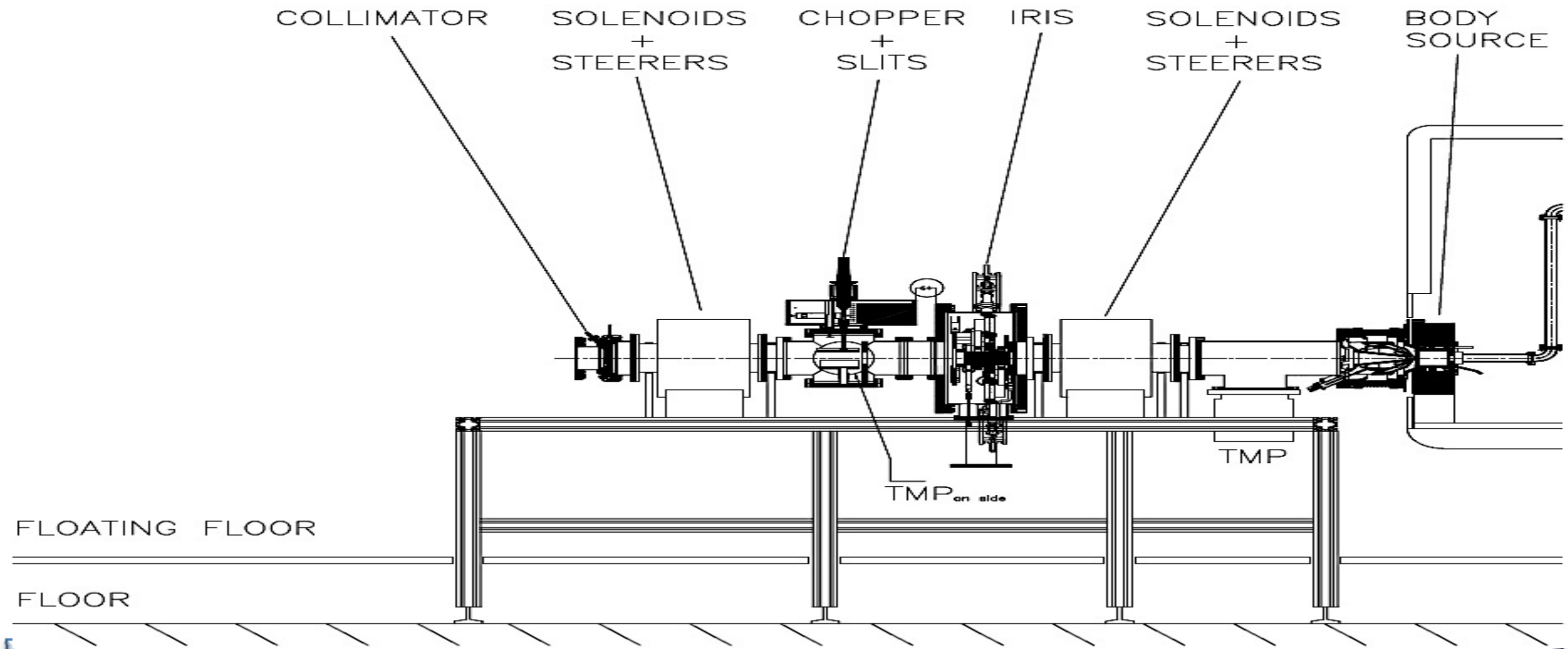
Improvements introduced:

- Improved ground shielding
- Single alumina
- All electrodes are cooled, also repeller by using AlN insulator
- New triple point design (metal-vacuum-alumina)

Thermal study



PS-ESS#1 + LEBT

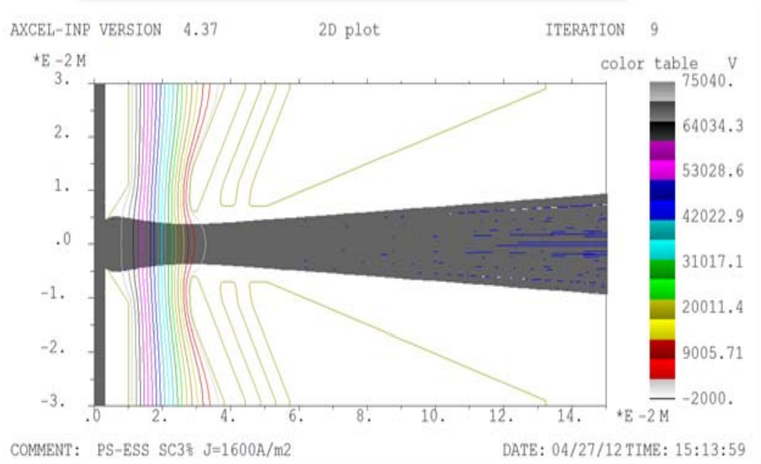


Picture to update with the new length:

- *270 mm : extraction system (starting from the plasma electrode)*
- *100 mm : cable from extraction system ; beam-current-transformer*
- *400 mm : first solenoid ; bellow*
- *60 mm : gate-valve*
- *300 mm : iris*
- *350 mm : chopper*
- *400 mm : diagnostic box*
- *400 mm : second solenoid ; bellow*
- *320 mm : gate-valve ; beam-current-transformer ; collimator ; repeller electrode with cable ;*

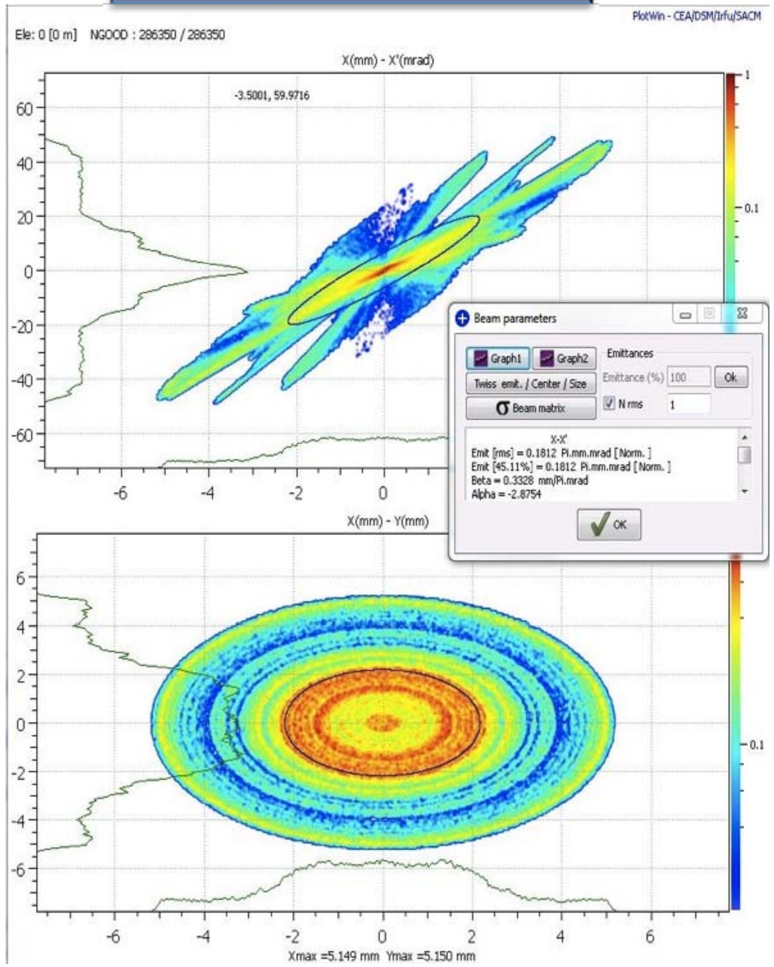
Simulation of extraction

A multi-parametric optimization of the geometry was done using AXCEL 2D axial symmetric simulation



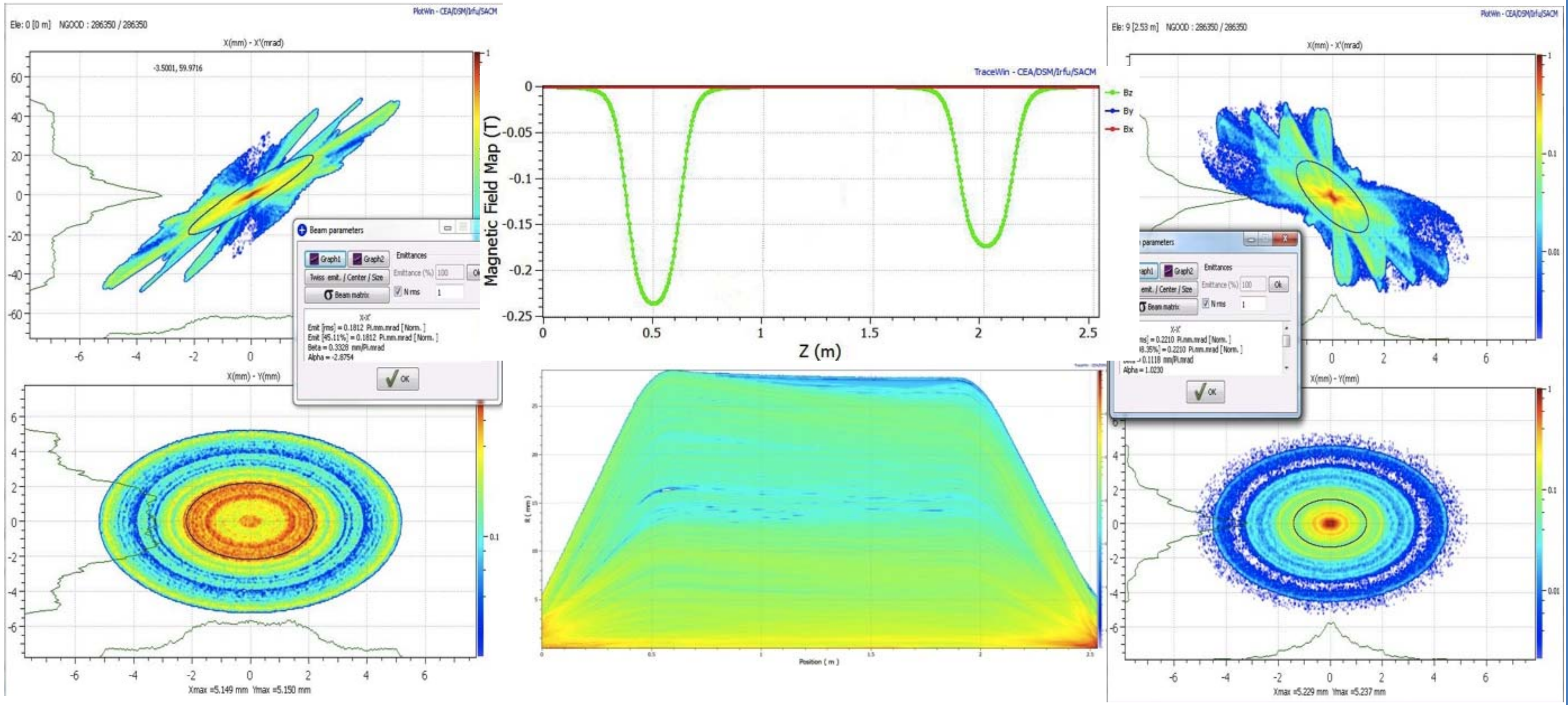
Own code for the conversion to a 3D beam distribution that take care about the representativeness and the axial symmetry

3D beam distribution for TraceWin calculation



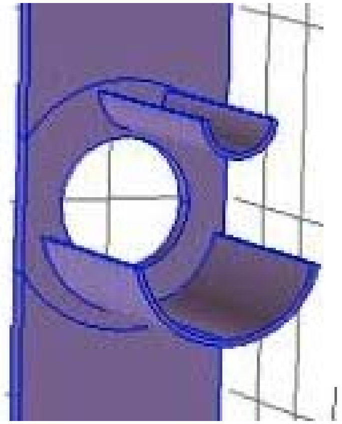
Beam transport optimization

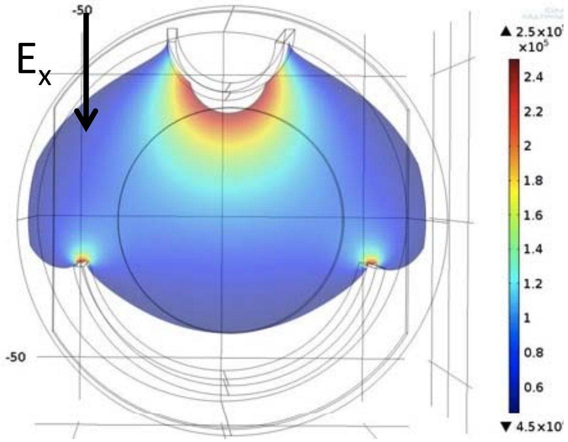
The total beam current used in the simulation was 92.5 mA: the proton fraction considered was 80%, 20% was H_2^+. Optimization of solenoids field lead to 0.22 π *mm mrad* of beam emittance (required<0.25) close to RFQ.

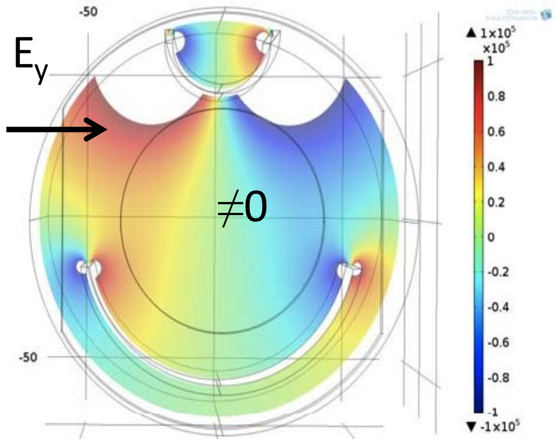


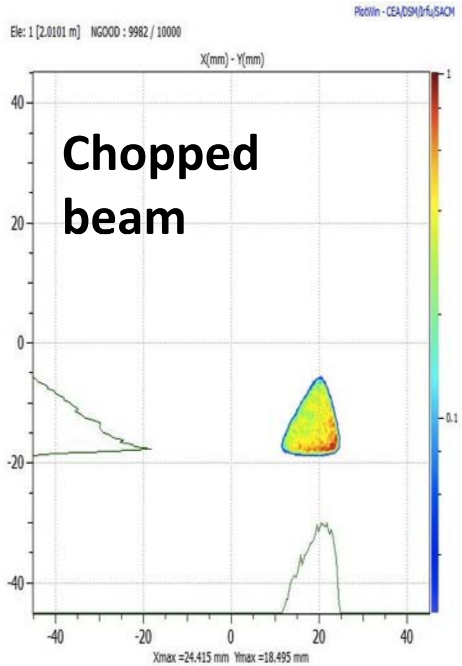
… not only for the full beam, but also when the iris is used:
same twiss parameters can be obtained from 100 % to 10 % of selected beam.
It is obvious that the emittance decrease a lot proportionally to the cut.
Experimental check is needed to measure the effect of a not ideal iris geometry.

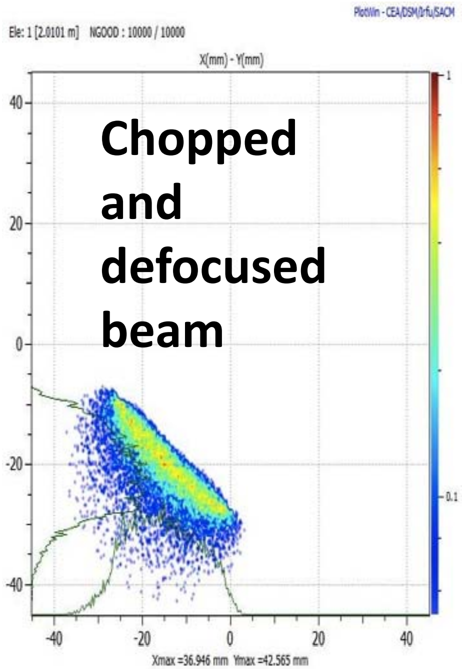
Defocusing chopper



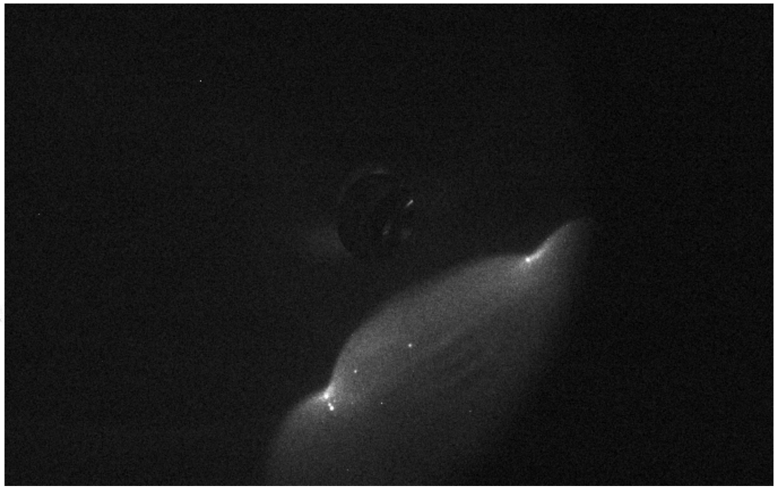




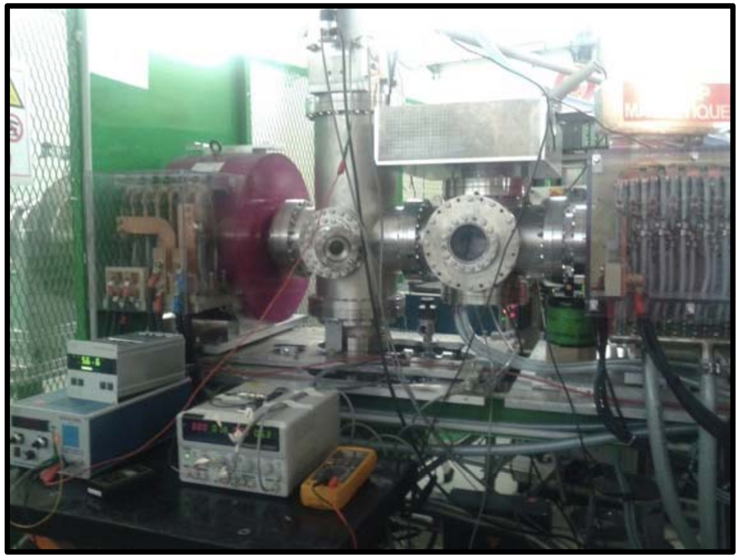




Experimental test done at CEA with our prototype



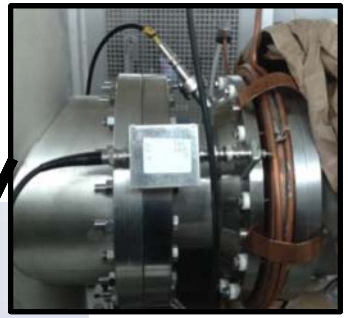
Chopper and collimator test at CEA-Saclay

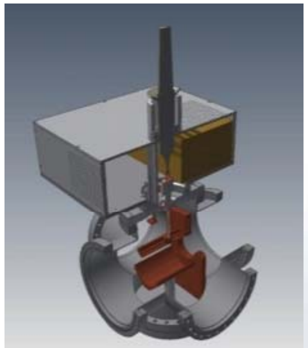


HV chopper electronics

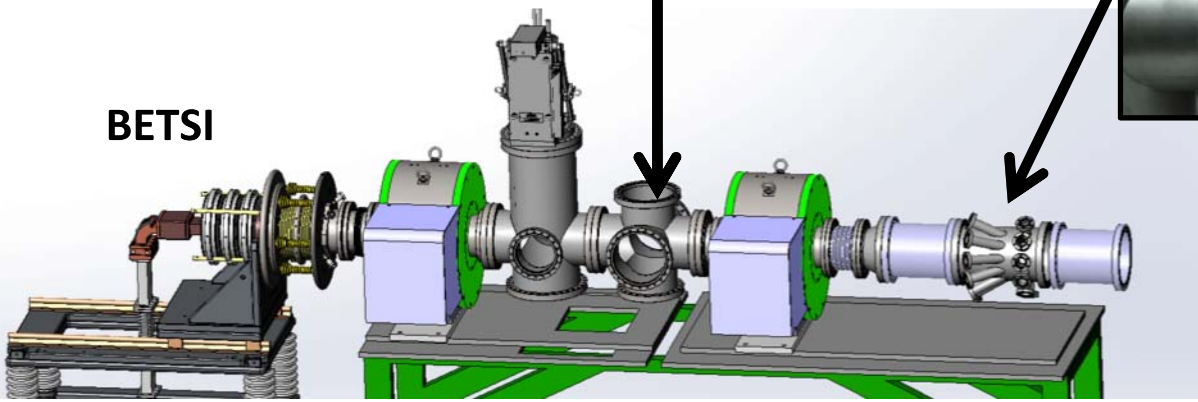
Chopper

Collimator

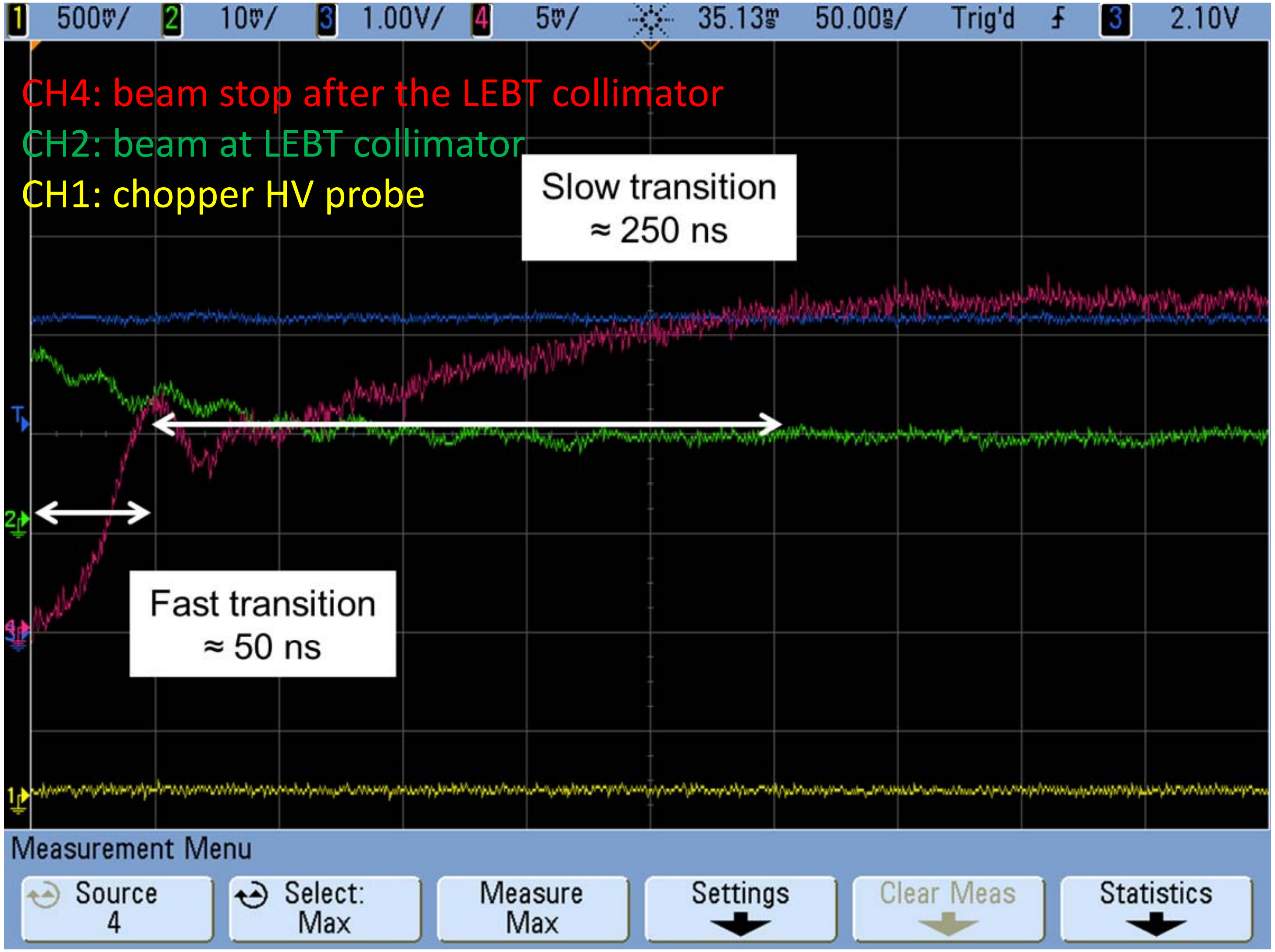




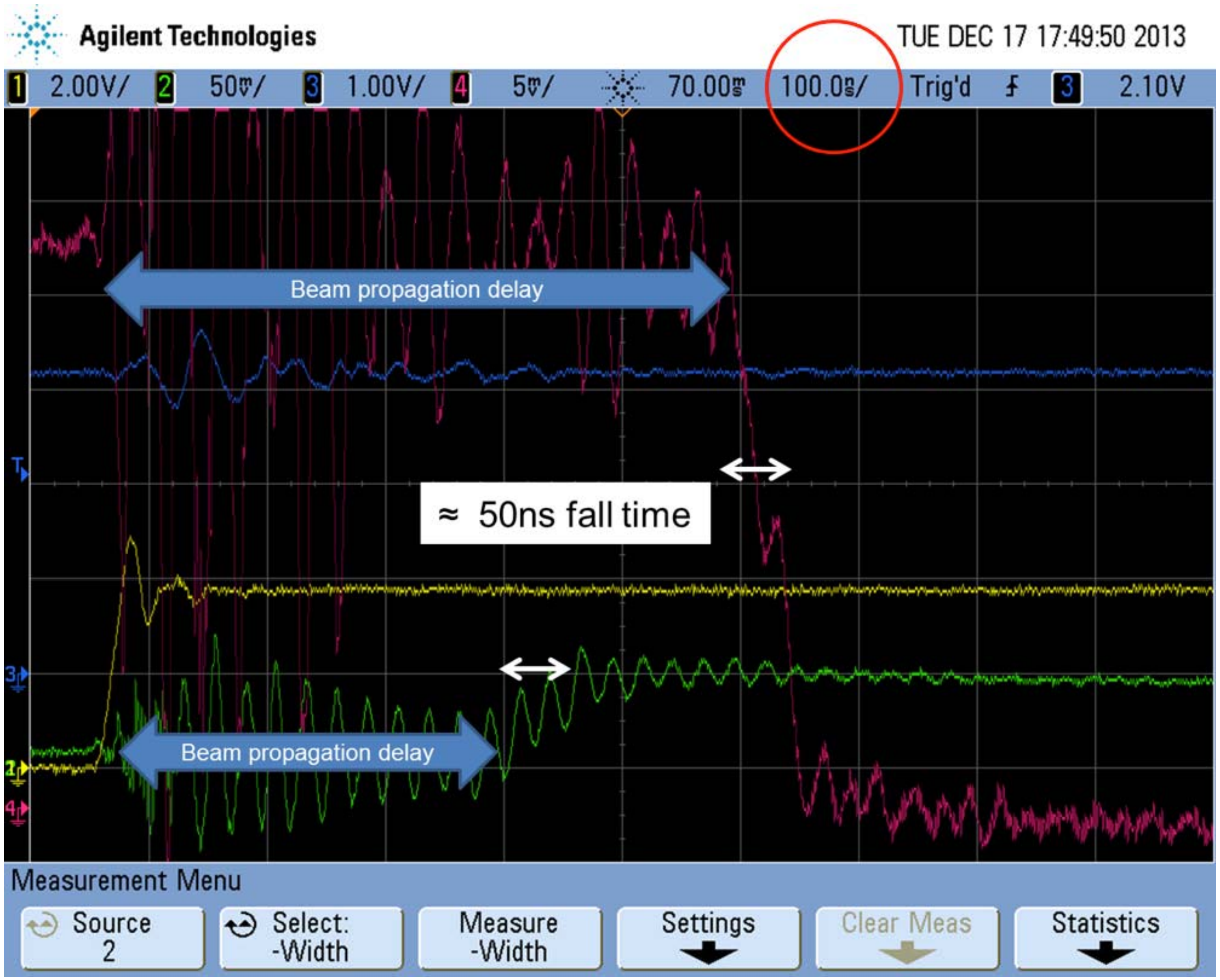
BETSI



Beam pulse rise time



Beam pulse fall time

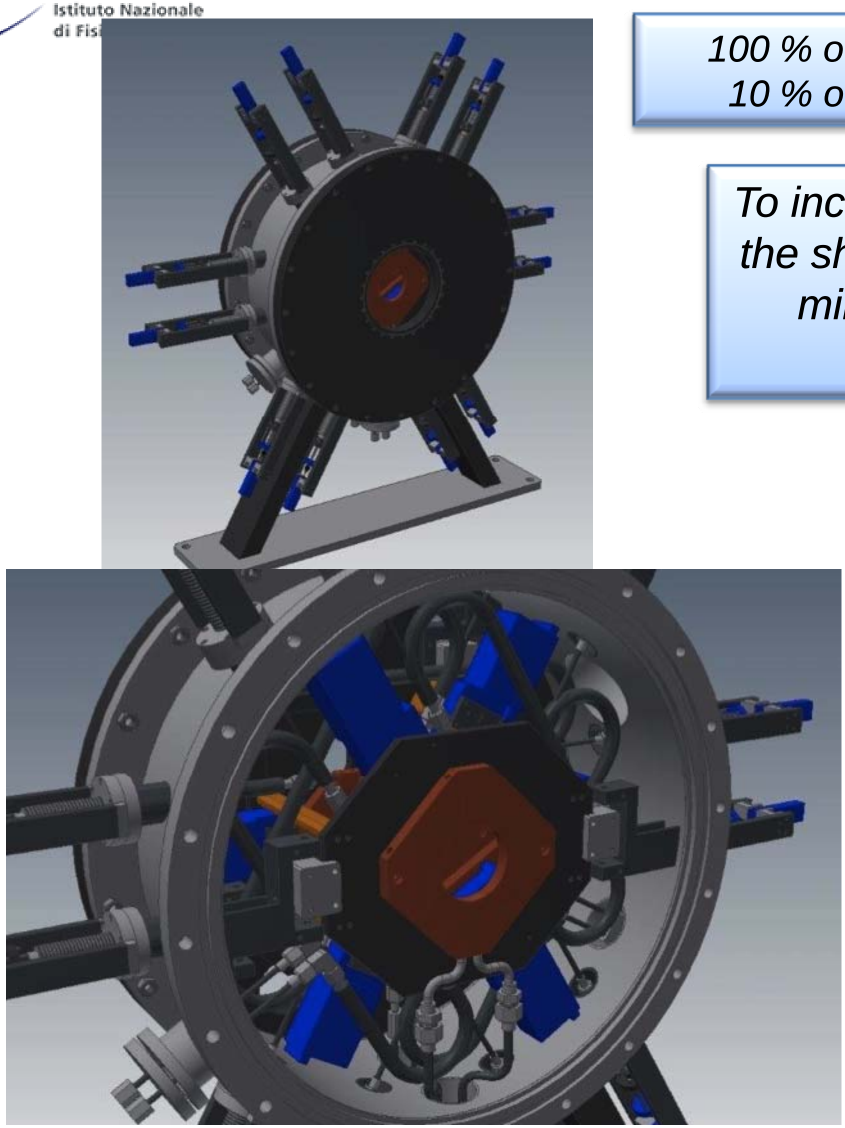


Ch4: Beam Stop (Rτ = 5,5 ohm; C = 183 pf ; Rτ * C = 1 ns)

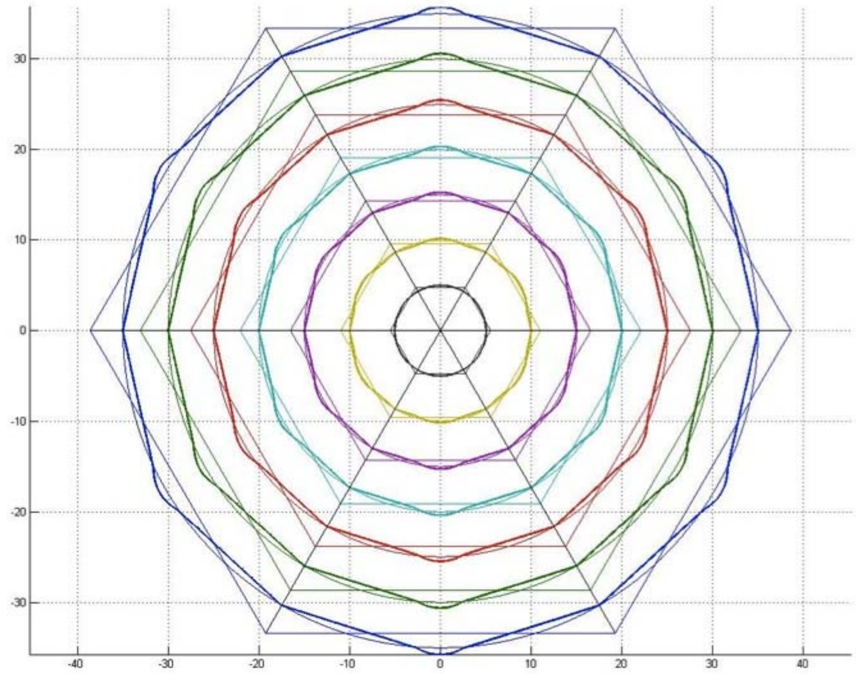
Ch2: Collimatore (Rτ = 5,5 ohm; C = 534 pf ; Rτ * C = 2,9 ns)

Movable iris: 0 to 40 mm radius, 600 W, 300 mm length

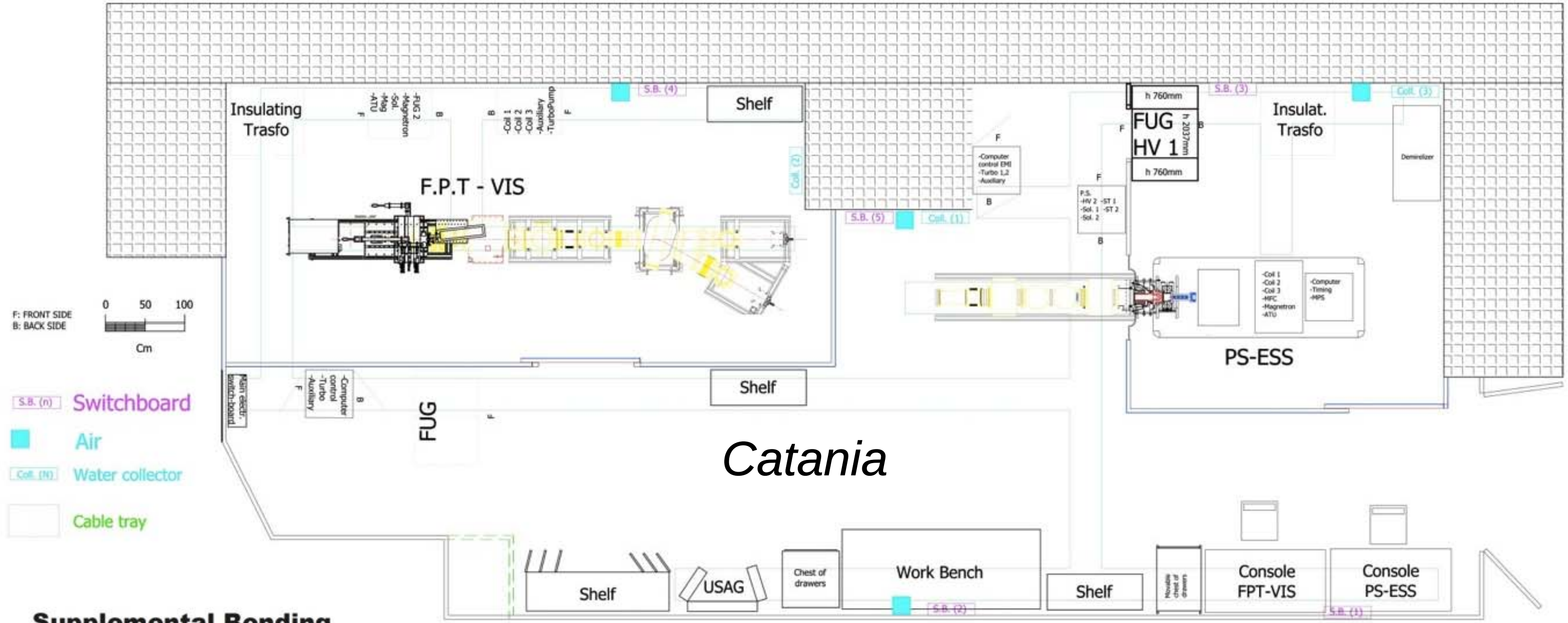
100 % of beam => 30 mm radius
10 % of beam => 5 mm radius



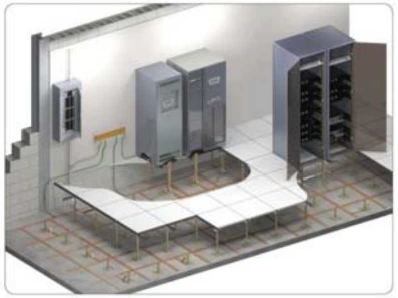
To increase the axial symmetry of the selected beam the shape of the six blades was chosen merging the minimum circumference of 5 mm radius and a dodecagonal shape



ESS site preparation at INFN-LNS

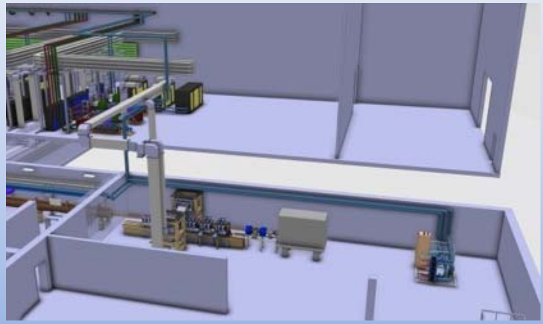


Supplemental Bonding

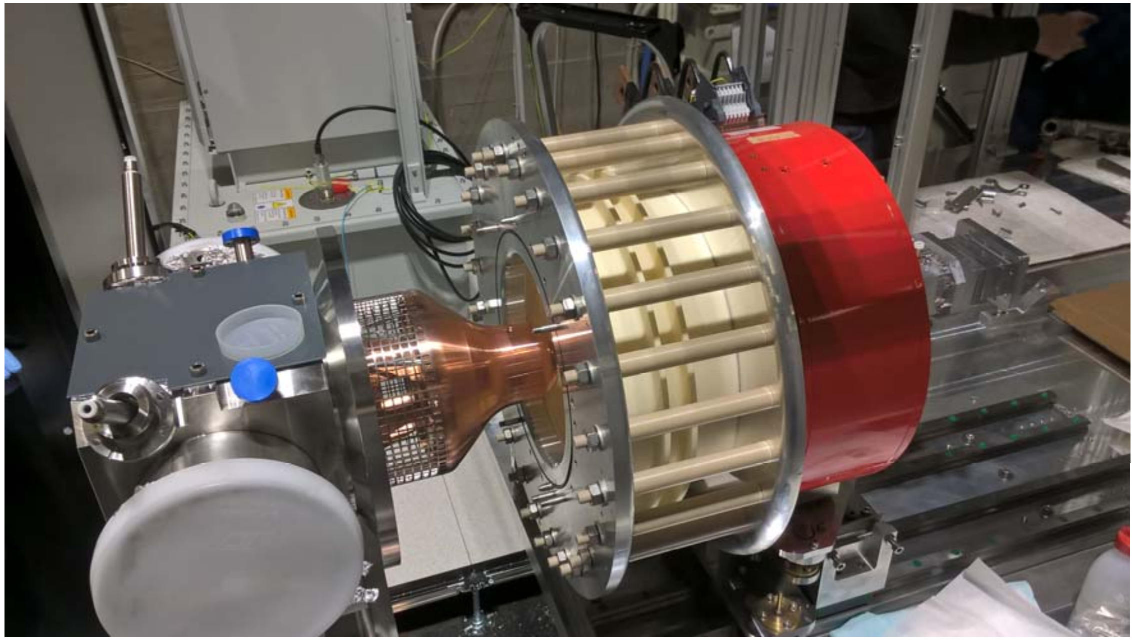


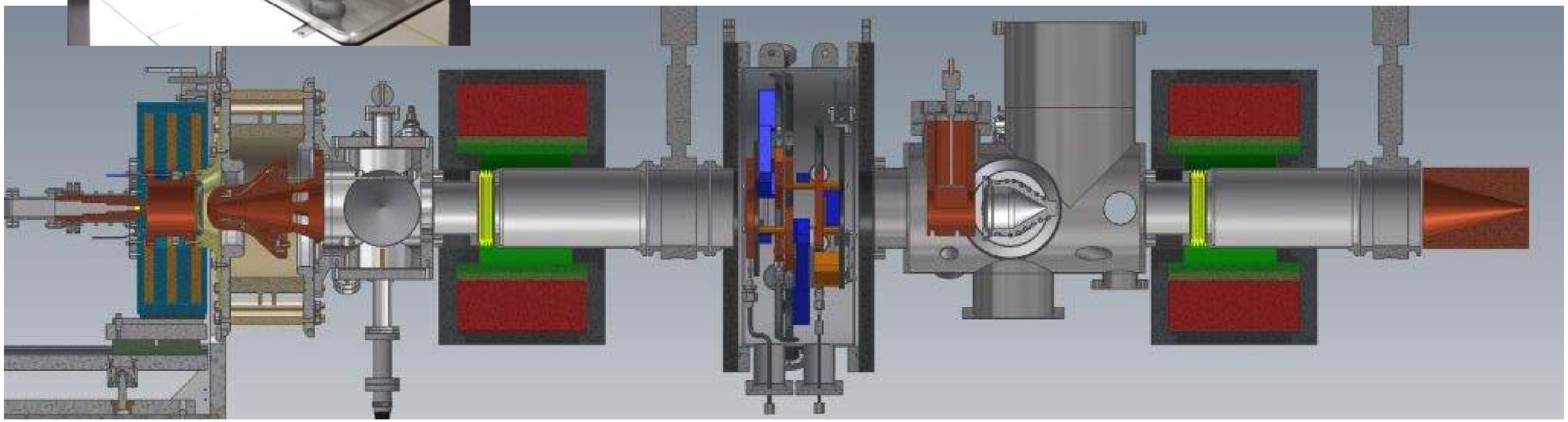
High Frequency Bonding for H.V. sparks

ESS-AB Lund (Sweden)

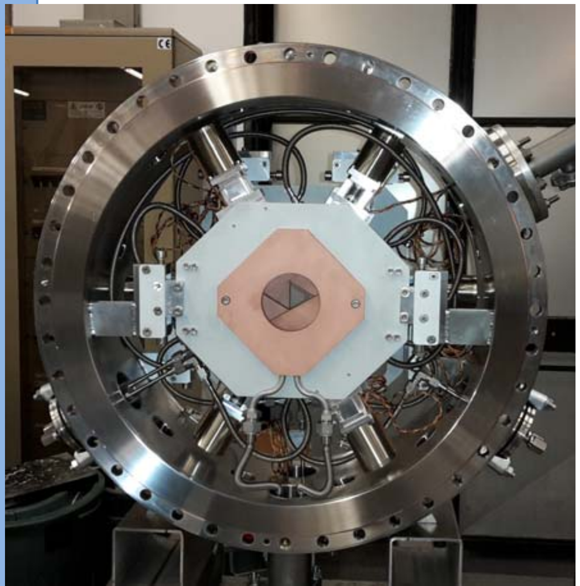


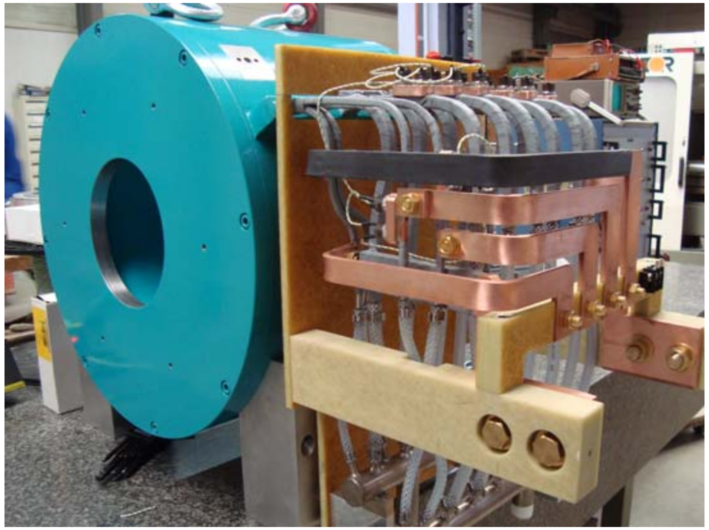
Platform, Source, Extraction and First LEBT element

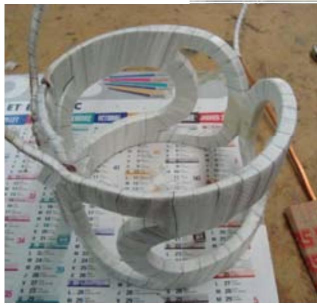


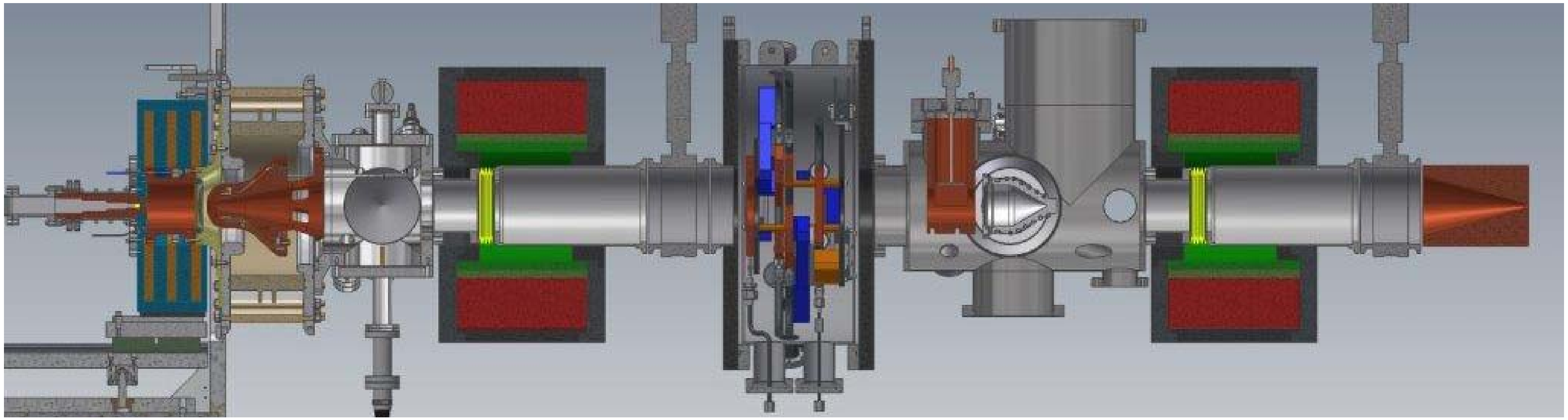


Iris, Solenoid, Steerer and pipe with gas injection and bellow

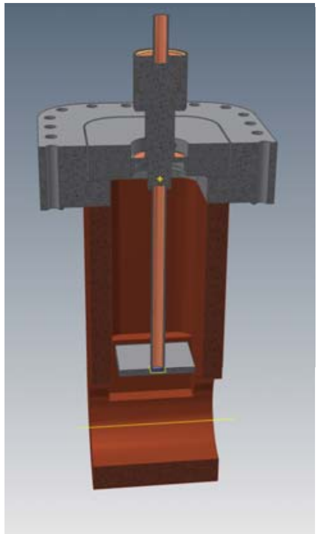


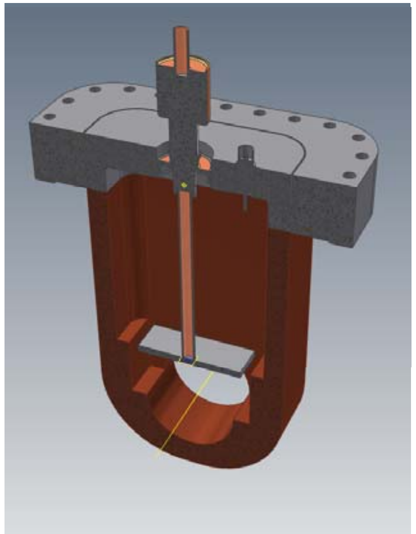


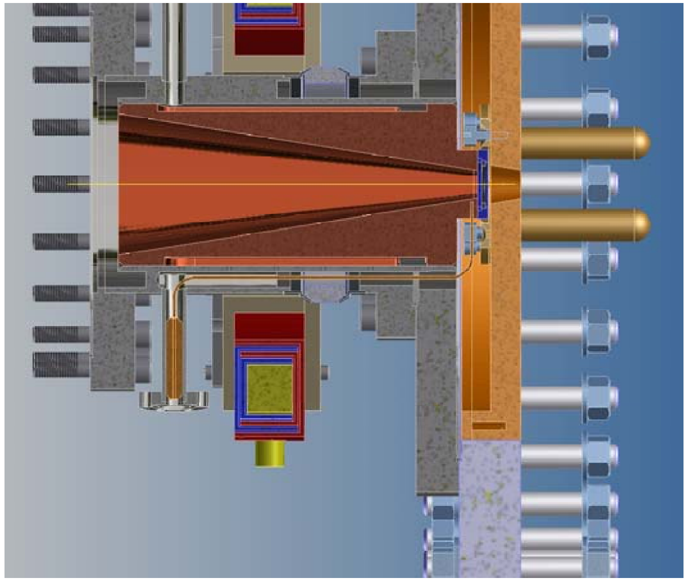


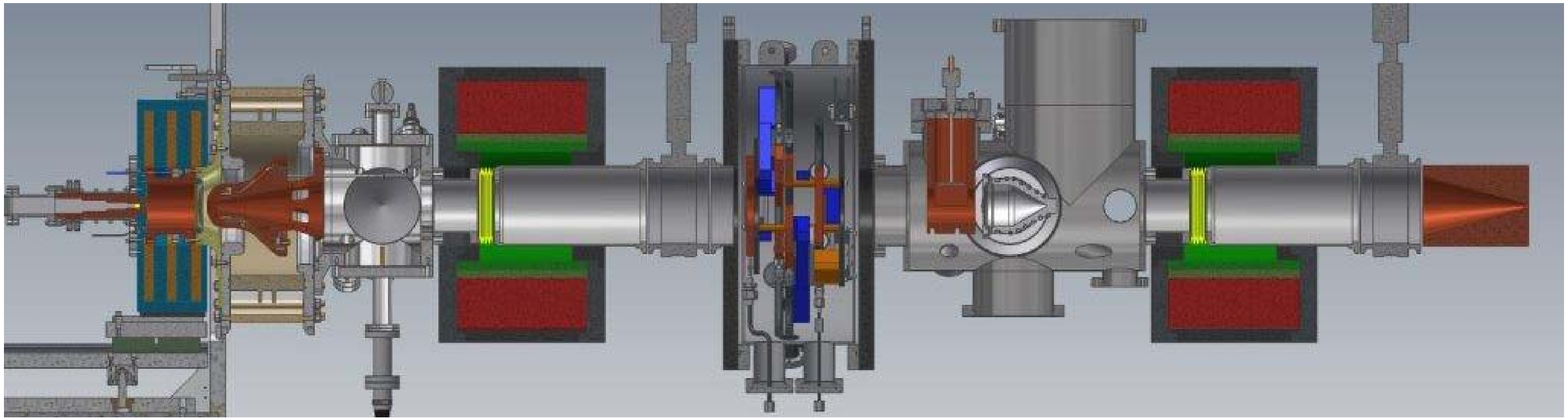


New chopper and LEBT collimator with integrated ACCT and repeller electrode









How to increase the electron density ?

I. “Passive" methods, like the use of electron donors.

At INFN-LNS the insertion of a thick Al_2O_3 tube inside the TRIPS plasma chamber increased current and stability.

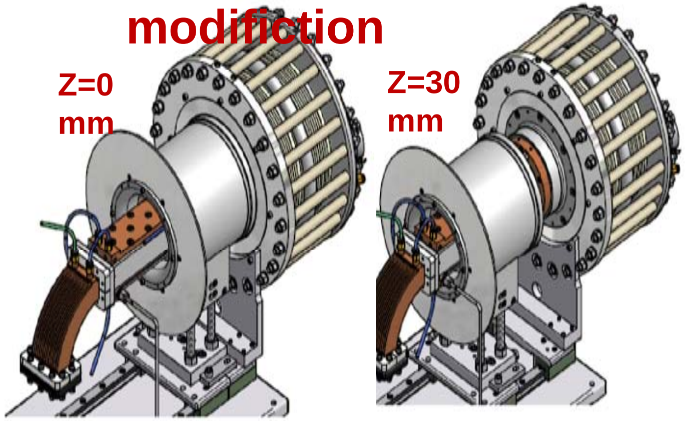
II. “Active" solutions include alternative plasma heating mechanisms, with particular attention to Bernstein Waves generation.

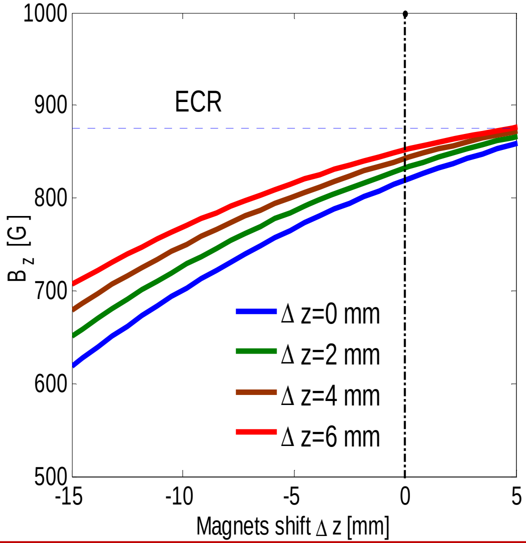
1. The case of a high frequency microwave discharge source has been considered, at 5 GHz instead of the usual 2.45 GHz.

1. Electrostatic heating at 2.45 GHz may be done by increasing the BW creation efficiency with a proper microwave injection angle → single cut antennas (waveguides) launching O waves in a proper direction with respect to the magnetic field lines.

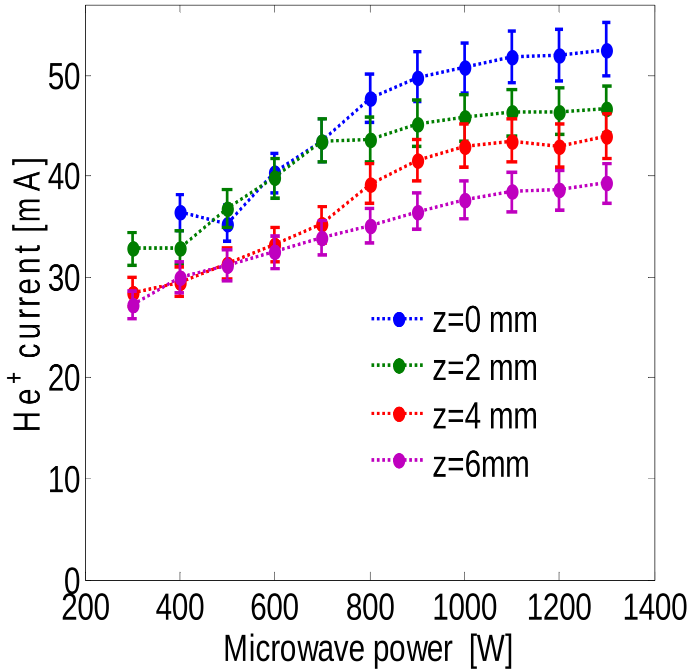
Generation of High intensity He$^+$ beam

Magnetic field slight modifiction





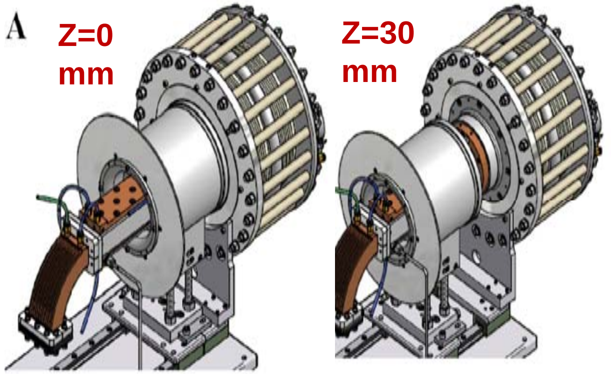
Pressure: $6 \cdot 10^{-5}$ mbar
Extraction hole: 10 mm
Alumina and BN nested in plasma chamber

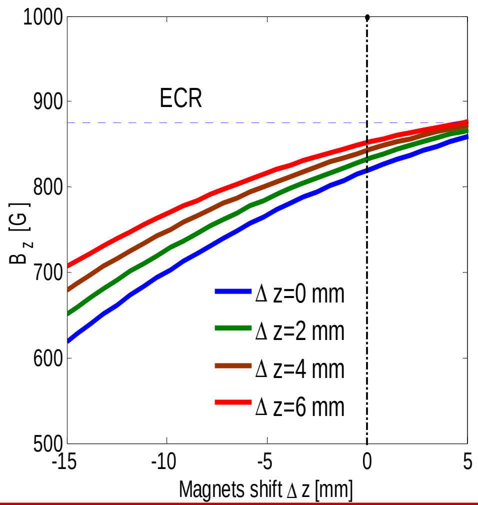


More than 50 mA He$^+$ have been obtained at z=0 position

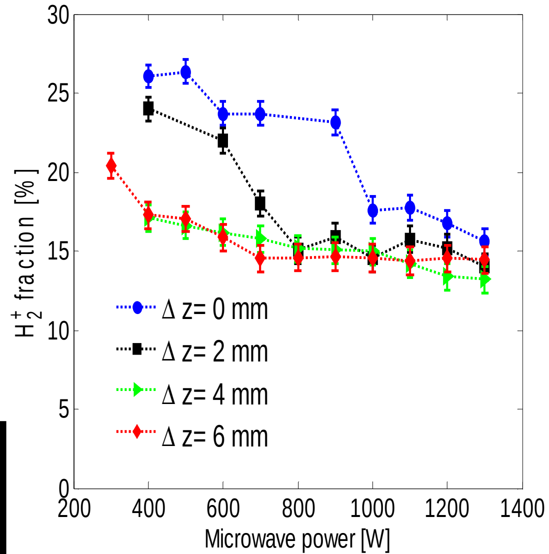
The influence of the magnetic field on the proton fraction

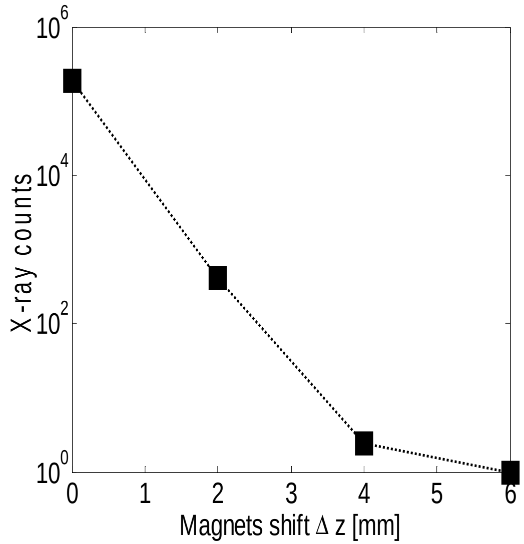
Magnetic field slight modifiction



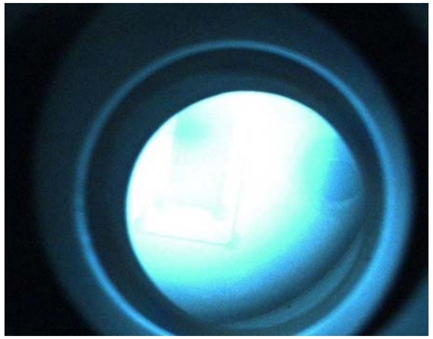


Several keV x-rays are generated at Z=0,2 magnets position: Connection between magnetic field and EEDF!

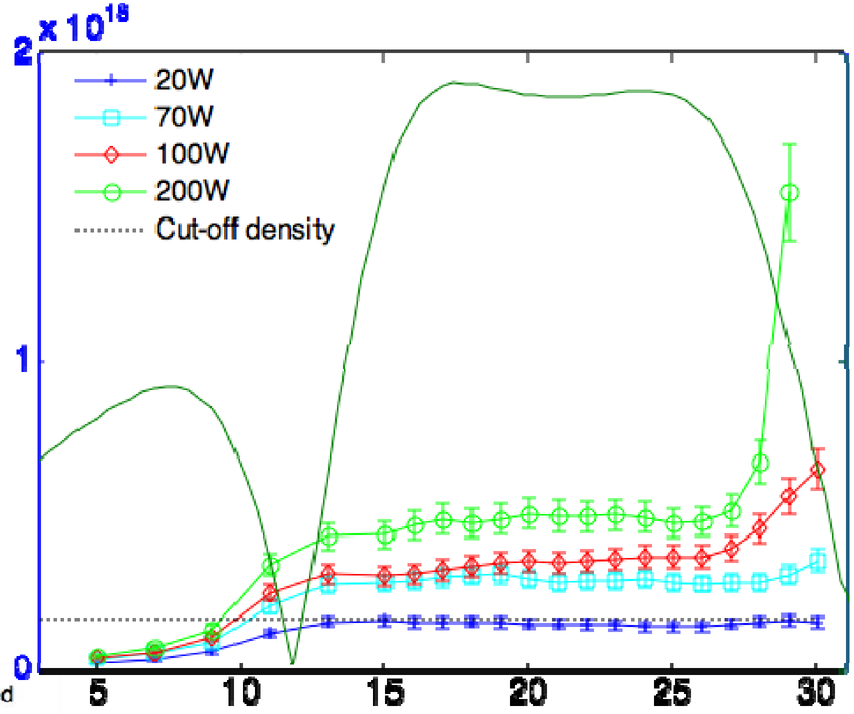


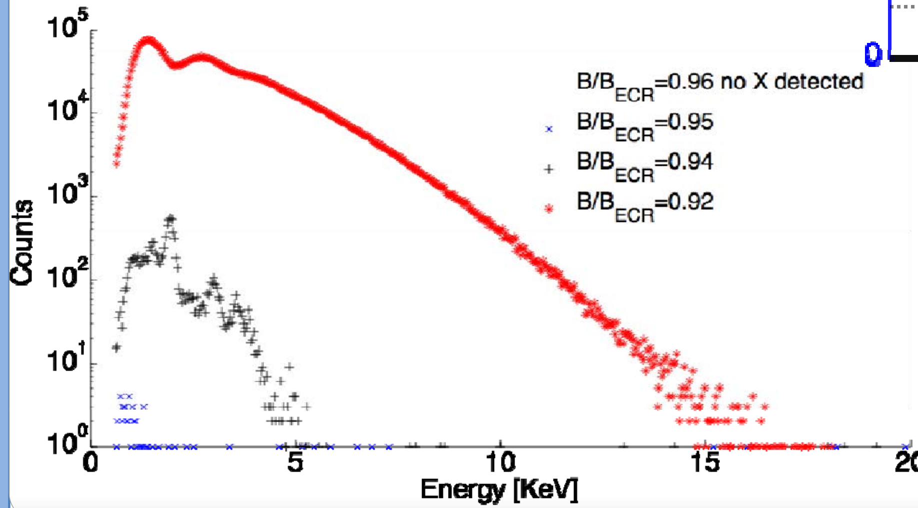


Generation of extremely overdense @3.76 GHz plasmas through EBW-heating in flat-B-field devices



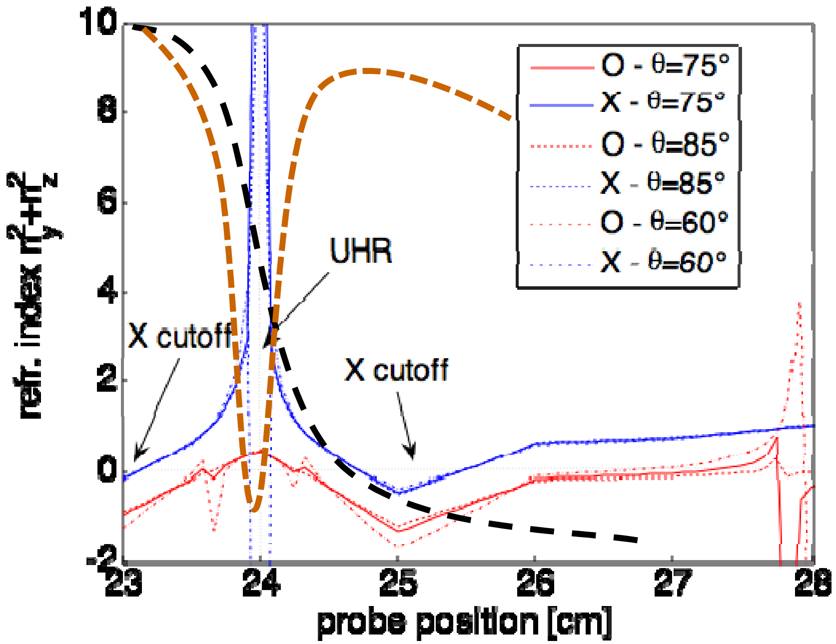
Plasma hole @ 90 W





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



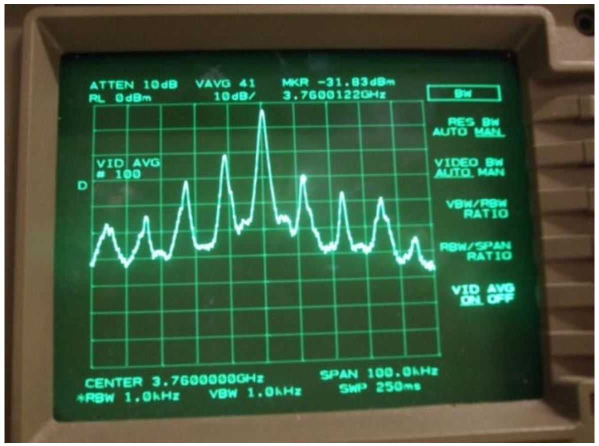
Plasma density

Magnetic field

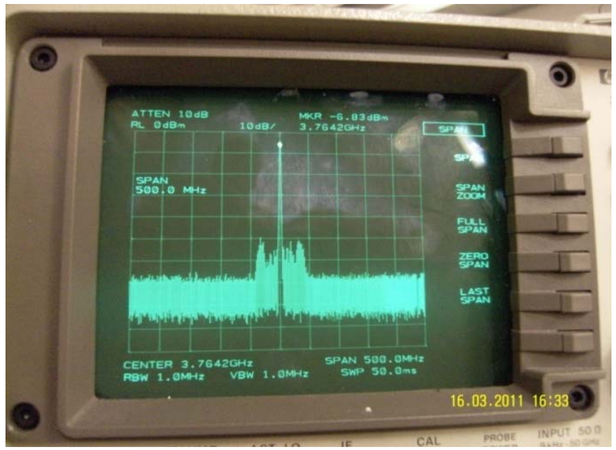
In the 3.76 ± 0.1 GHz, 7 resonant modes exist having *r*=5, 0< *n*,{ <2 (60° < (< 80°).

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

Sidebands are the fingerprint of EBW-generation!!

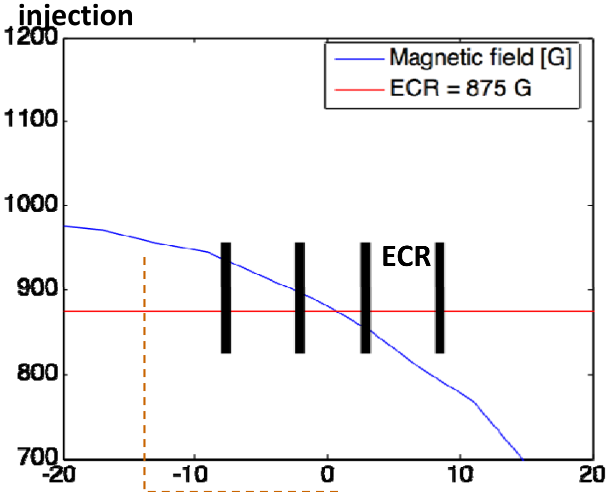


KHz sidebands

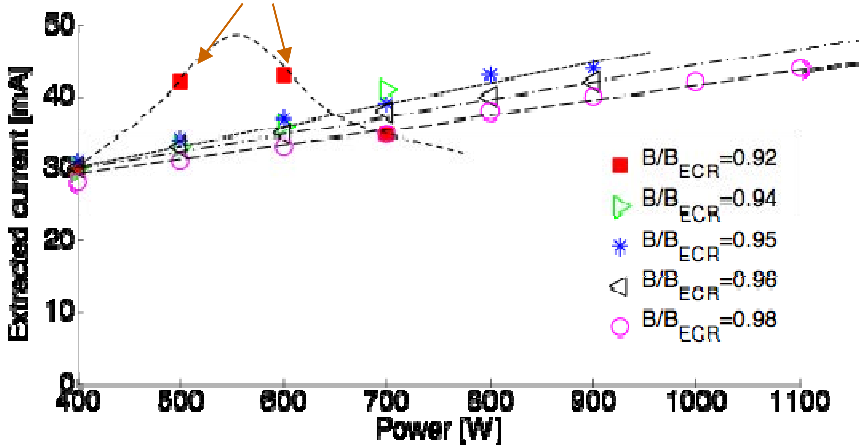


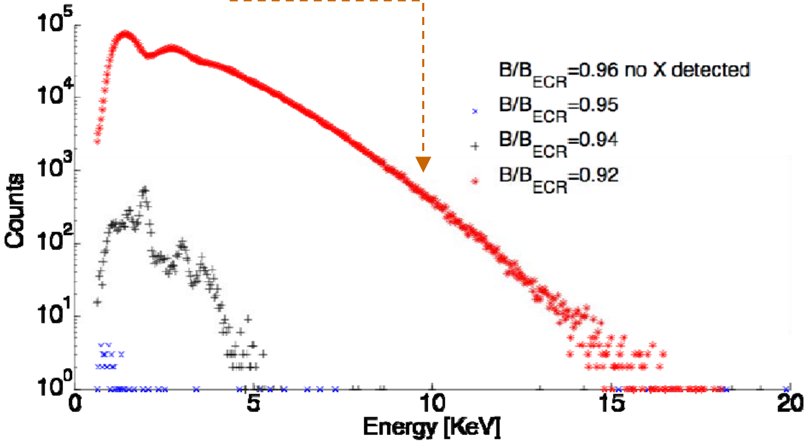
MHz sidebands

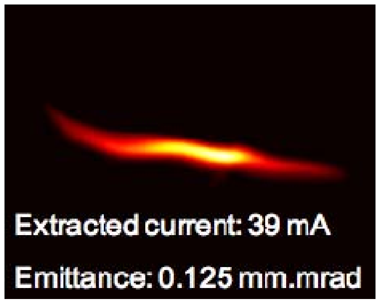
Under-resonance discharge on VIS proton source



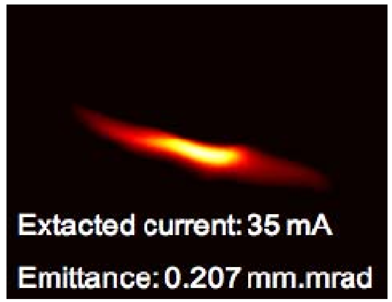
Boost of output current at low RF power







No X-rays



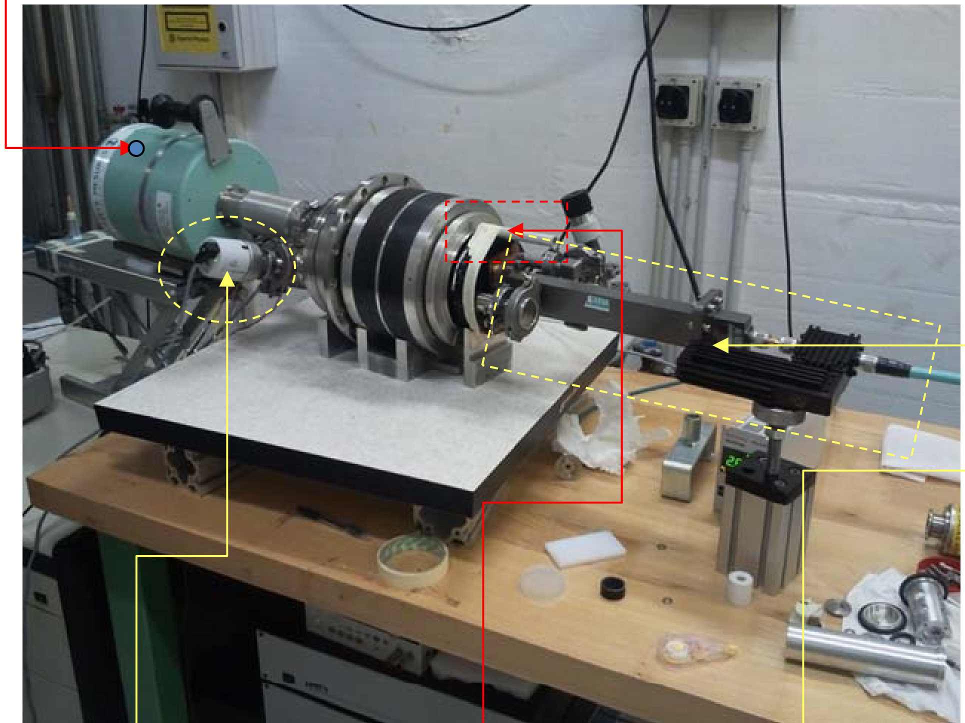
X-rays

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.

Experimental apparatus for mode conversion detection

Set-up for X-ray spectroscopy and CCD imaging

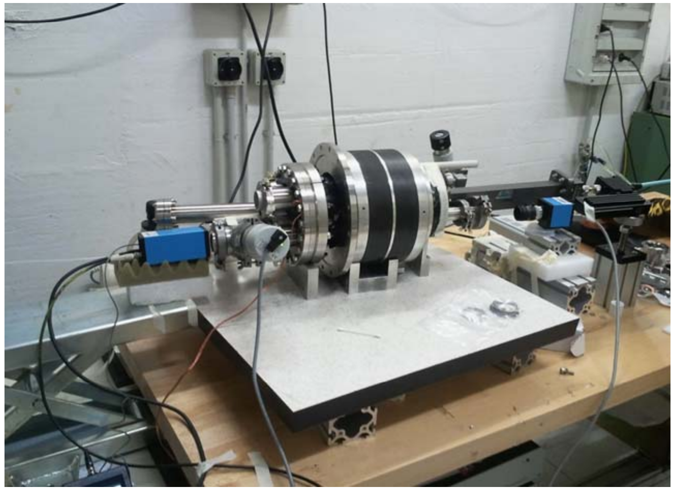
H-Ge X-ray detector



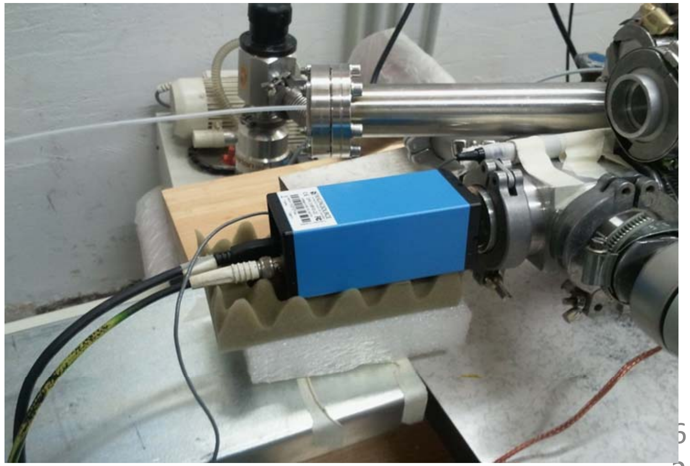
Pressure gauge

Hall probe for measurement of the magnetic field

Microwave line with insulator



Positioning of the CCD for the pass-band filters measurements (plasma imaging).



CCD imaging during plasma startup at different P_{RF}

200 μs 400 μs 600 μs

PLASMA HOLE FORMATION

20 W Increasing power 90 W

Well established items

- Larger current, larger brightness, better reliability seem to be realistically achievable in few years' term
- There are 'billion $' projects leading the run (ESS and IFMIF for p,d)
- Study of pulsed operation (2 ms-20 Hz) needs more insights
- Looking for short pulse rise time (100 ns)
- Beam dynamics vs. plasma simulations
- LEBT optimization
- Plasma chamber dimensions are not free parameters
- Electron donors may help
- Microwave coupling is a useful "knob"
- Magnetic field probably less…
- **Space charge will be always a nightmare!**

A special remark

- **The time that ion sources people did their job and LEBT/diagnostics people were on their own IS OVER.**

- **No developments will be possible without a close cooperation between these different tasks.**

- **In future, at least for intense current sources, one should discuss not of**

ION SOURCES + a LEBT

ION SOURCES & their LEBT