Microwave Discharge Ion Sources

Luigi Celona

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud
Via S. Sofia 64 – 95123 Catania
Italy

Applications based on intense proton beams

- *ADS for nuclear waste transmutation (and Energy production)*
- *Radioactive ion beams*
- *Intense neutron spallation sources*
- *Radiation processing*
- *Neutrino factory*

- *Power range: 100 KW÷10 MW*
- *Energy range: 100 MeV ÷2 GeV*
- *Average current: 100 μA ÷30 mA*
- *Pulsed or CW*

Proton driver	Energy (GeV)	Beam power (MW)
ADS: XADS Ind. burner	~ 0.6 ~ 1	~ 5 ~ 50
Spall. neutron source (ESS)	1.33	5
Irradiation facility	~ 1	>10
Neutrino factory (CERN)	2.2	4
RIB: "one stage" "two stages"	~ 0.2 ~ 1	~ 0.1 ~ 5-10

		keV	mA	ms	Hz	π mm. mad
LEDA	p	75	100	CW	CW	0.25
IPHI	p	95	100	CW	CW	0.2
TRASCO	p	80	35	CW	CW	0.2
FAIR	p	95	100	1	4	0.3
ESS	p	75	60/90	2.84	14	0.25
IFMIF	D^+	100	2×125	CW/1	1-20	0.2
MYRRHA	p	100	4	CW	CW	
DAEδALUS	H_2^+		40			0.3
SPL	H^-		80	2.8	50	0.2
SNS	H^-	65	50	1	60	0.2
JKJ	H^-		30	0.5	50	0.25
ADSS	H^-		25	0.5	25	

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

Basic principles

HYPOTHESIS: ABSENCE OF MAGENTIC FIELD, PLANE AND MONOCROMATIC WAVE

$$E = E_0 e^{i(kz-\omega t)}$$

For propagation into the plasma must be: k>0

$$k^2 \approx \frac{\omega^2}{c_0^2}\left(1-\frac{\omega_{pe}^2}{\omega^2}\right) = \frac{\omega^2-\omega_{pe}^2}{c_0^2}$$

It means: $\omega > \omega_{pe} \longrightarrow$

$$\begin{cases} \omega_{pe}^2 = \dfrac{n_c e^2}{\varepsilon_0 m_e} \\ n_c = \dfrac{\varepsilon_0 m_e \omega_{pe}^2}{e^2} = 1.2283 \cdot 10^{-2} \cdot f^2 \left[m^{-3}\right] \end{cases}$$

$\Downarrow$

Upper limit to density: $n<n_c$

The introduction of a magnetic field opens different coupling mechanism:

- ***ELECTRON CYCLOTRON RESONANCE (ECR)*** ***(see T. Thuiller lectures)***

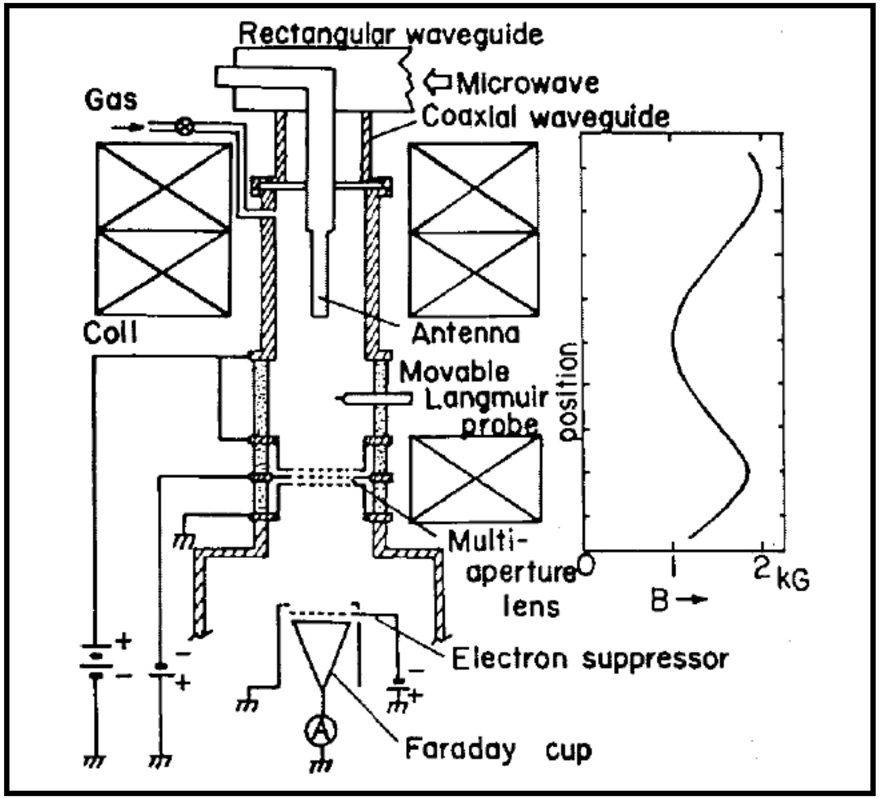
B-min magnetic configuration – ECR heating occurs at $B_{ECR} = \dfrac{m_e \omega}{e}$ RHCP wave strongly coupled

- ***OFF RESONANCE HEATING***

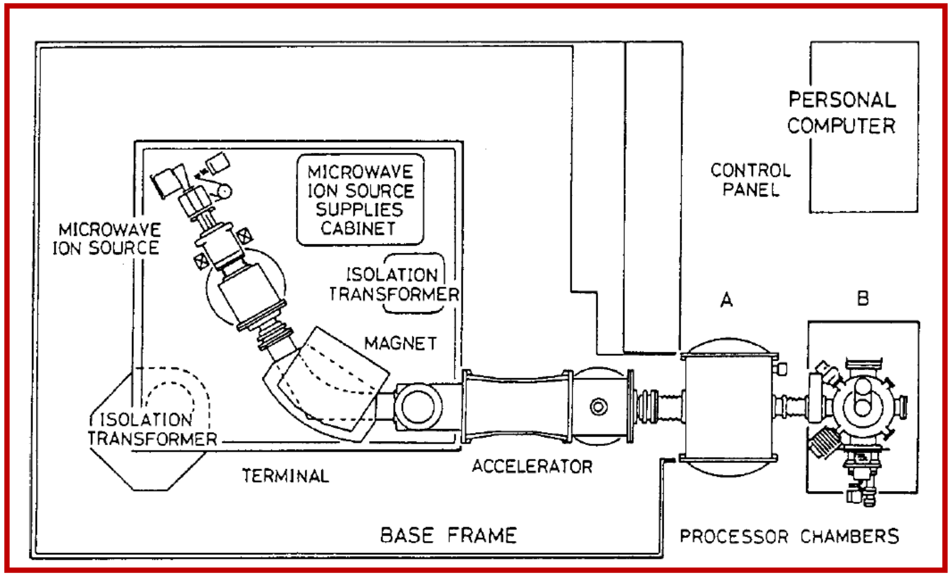
Energy absorbed by off resonance heating process

K. Golovanivsky
ECRIS plasmas: stochastic heating or Langmuir caviton collapses"
Proc. 11th ECRIS Workshop (1993), KVI , 996

Pioneeristic work

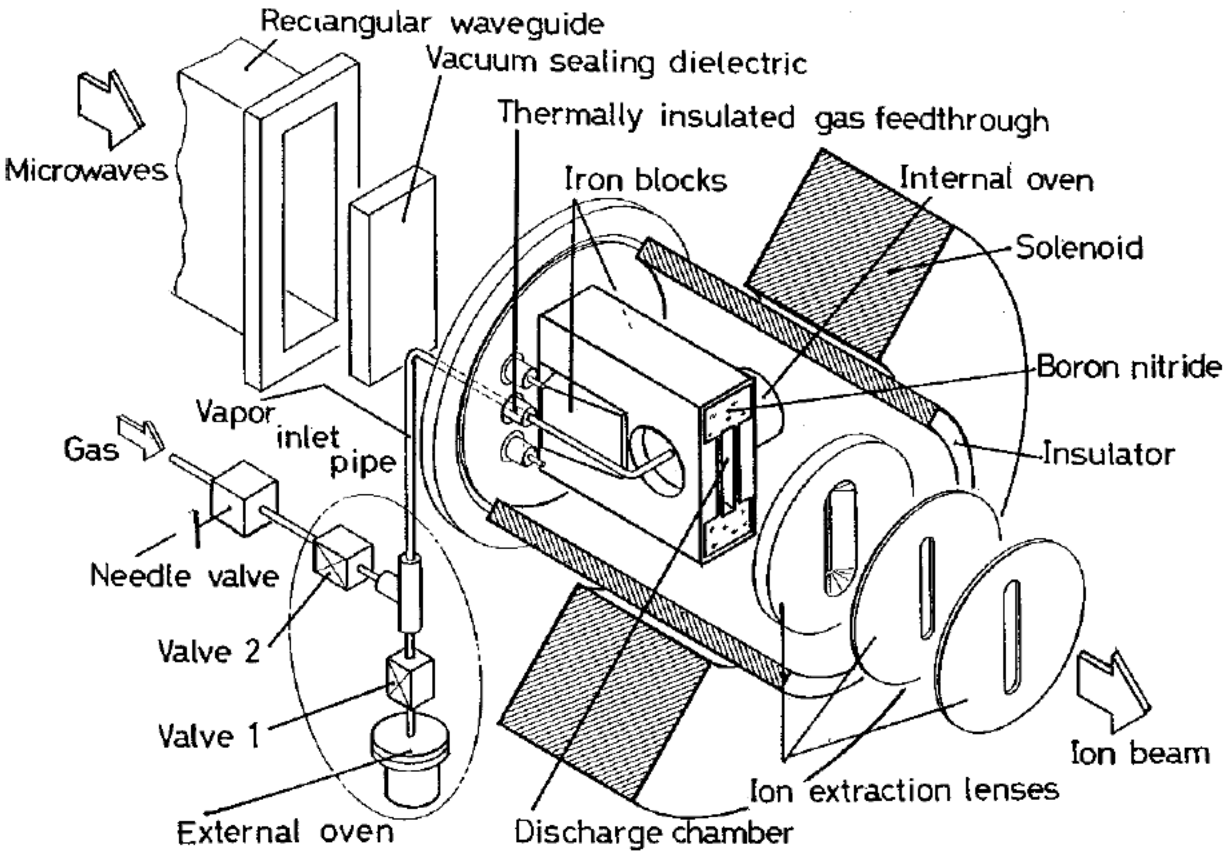


Sakudo 35 ys ago



Later on, Okada and others in Japan and elsewhere produced tens of mA of B^+, As^+, P^+ and other monocharged ions, but Sakudo is recognized to be the pioneer.

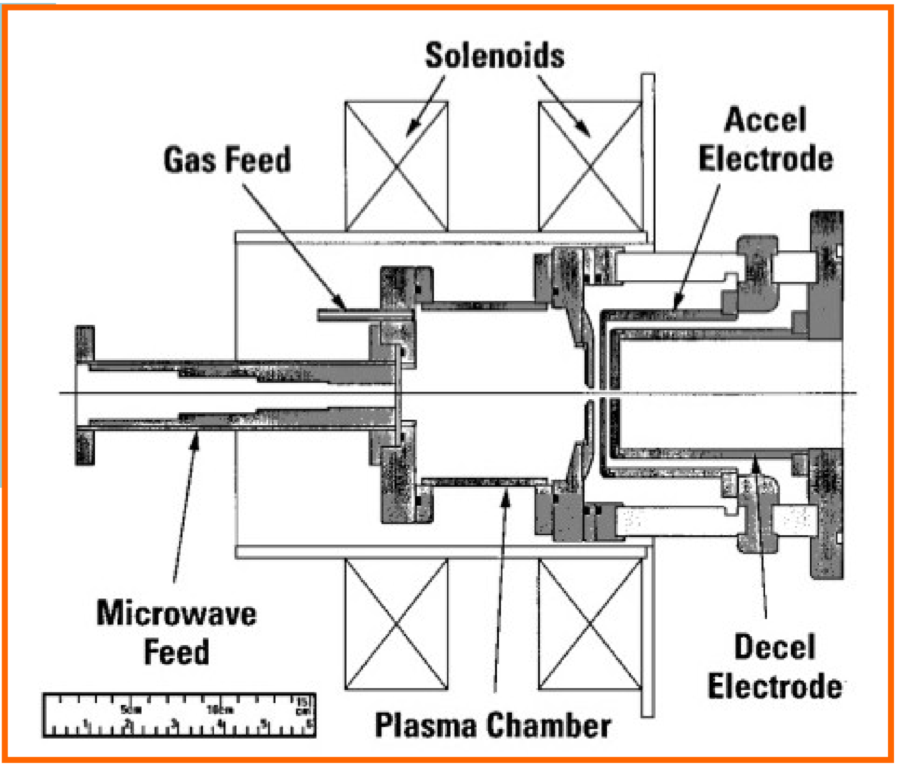
First Ion Implanter



Chalk River

Taylor &Wills

Beginning of ’90s



Breakthrough simple design

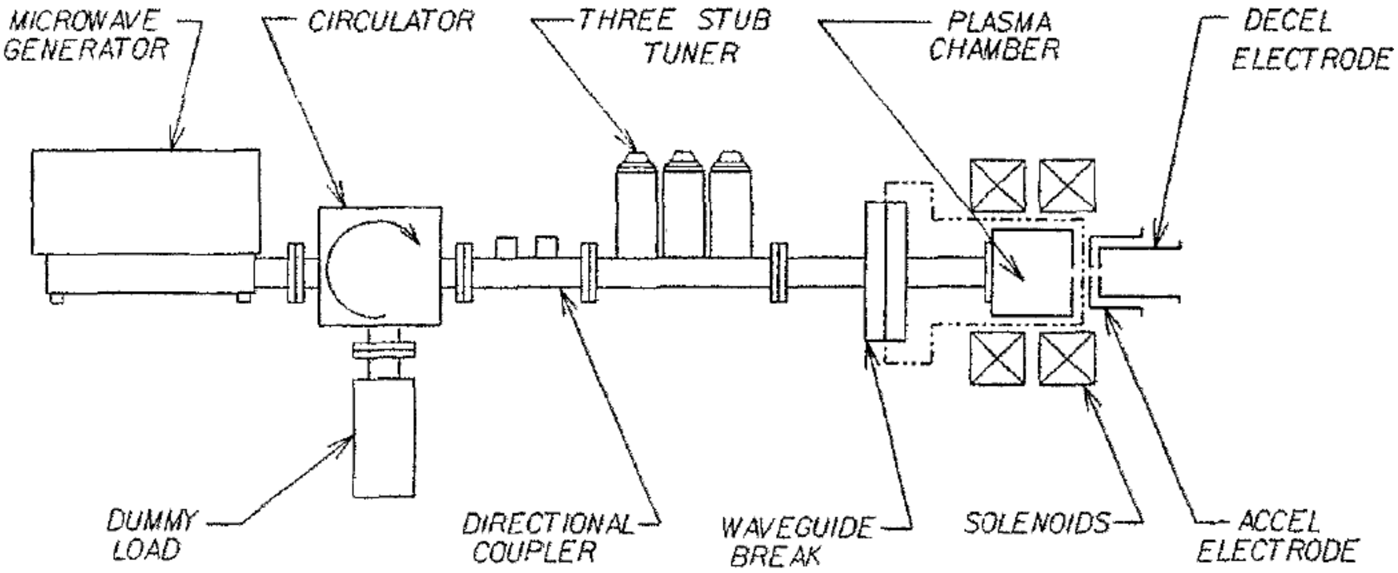
All successful sources are based on it

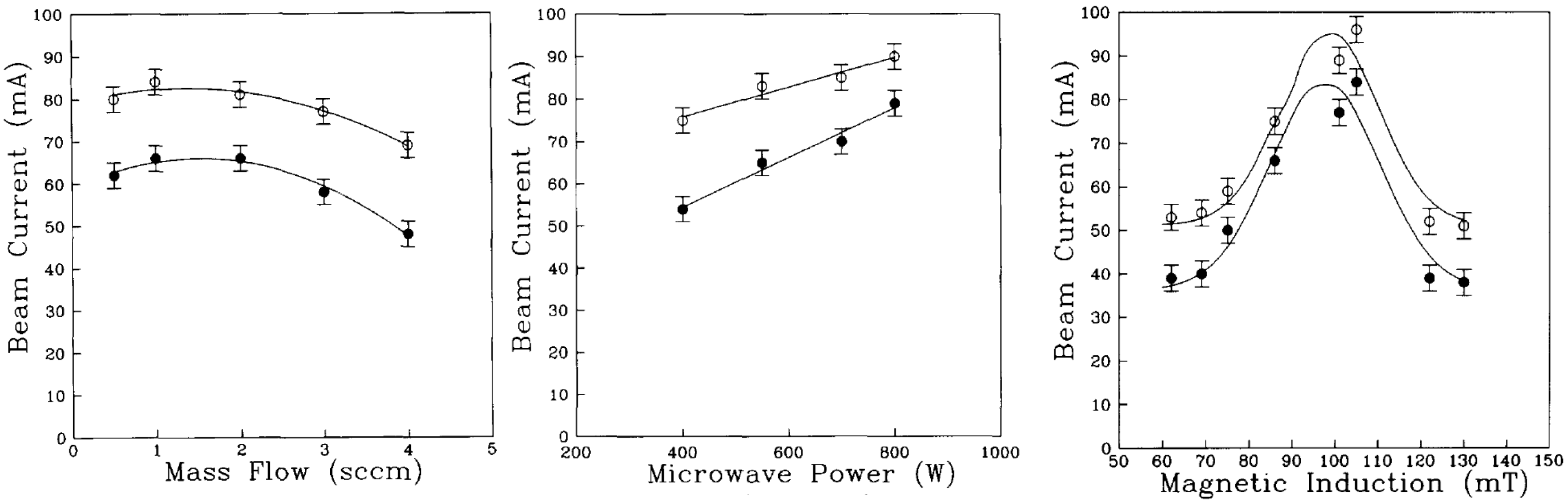
Discharge RF Power	**800W @ 2.45 GHz**
Total beam current	**96 mA**
Proton fraction	**86 %**
Proton beam	**82.5 mA**
Beam energy	**50 keV**
Beam emittance (rms norm.)	**0.13 π mm mrad**
Hydrogen mass flow	**≈2 sccm**

Chalk River

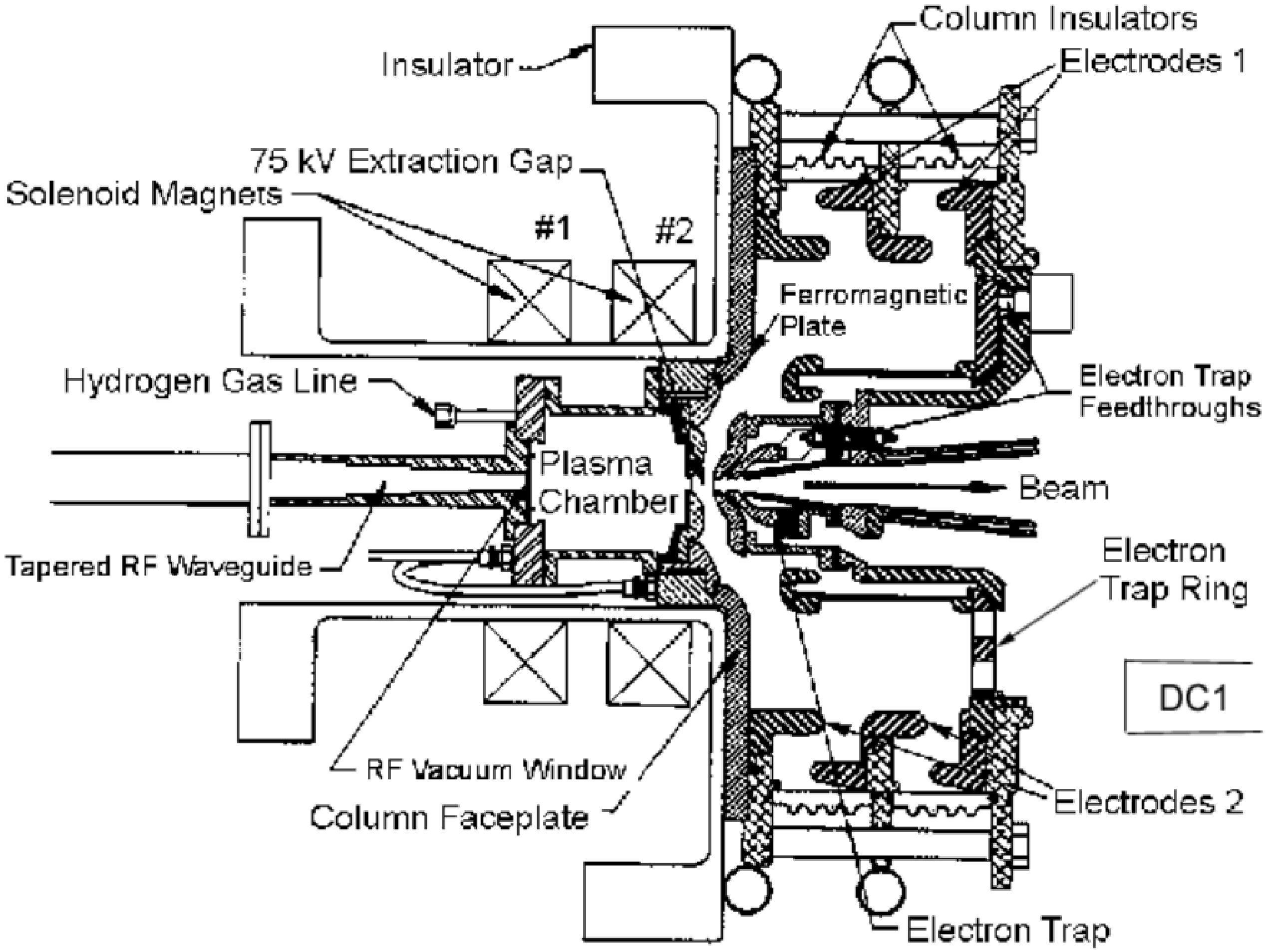
Taylor &Wills

Beginning of '90s

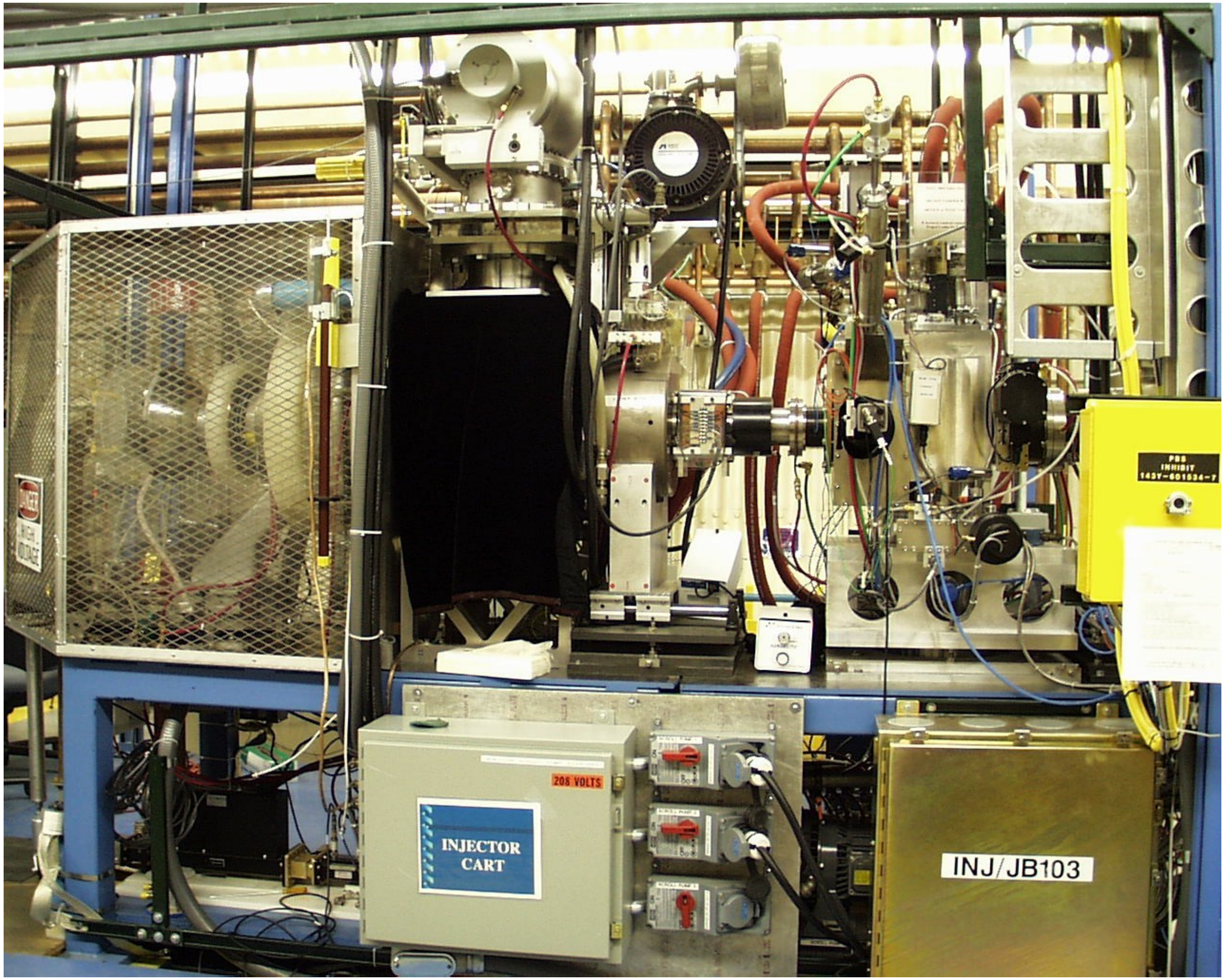




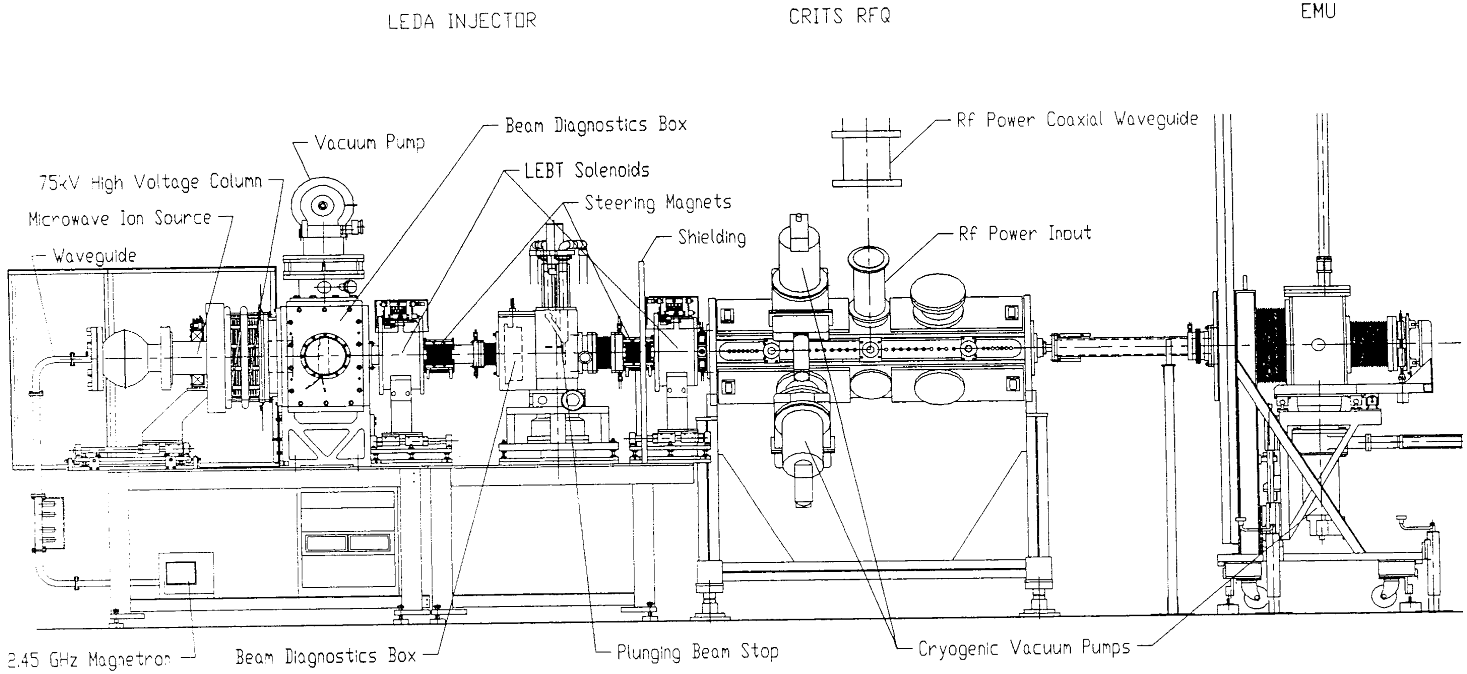
Los Alamos source for LEDA

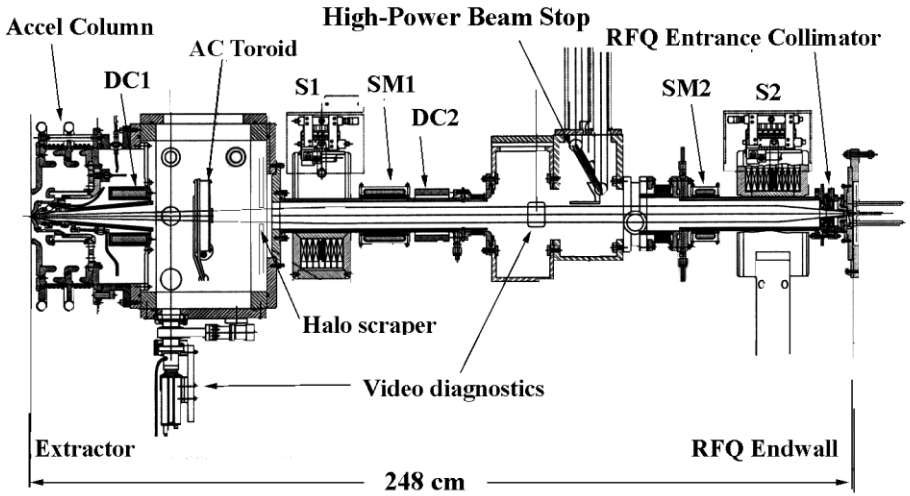


Injector Parameter	**Value**
H_2 gas flow (sccm)	4.1
Ion source pressure (mTorr)	2
Ion source gas efficiency (%)	24
Discharge power, 2.45 GHz (kW)	1.2
Beam energy (keV)	75
High voltage power supply current (mA)	165
DC1 current (mA)	154
DC2 current (mA)	120
Proton fraction (%)	90
Injector emittance (πmm-mrad) (1rms norm)	0.18


DANGER
HIGH VOLTAGE
PBS
INHIBIT
143Y-601534-7
208 VOLTS
INJECTOR
CART
INJ/JB103

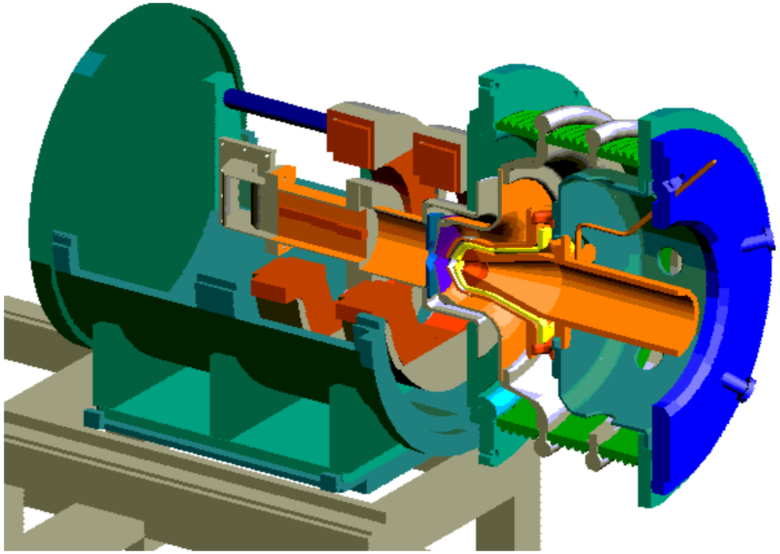
Los Alamos source for LEDA

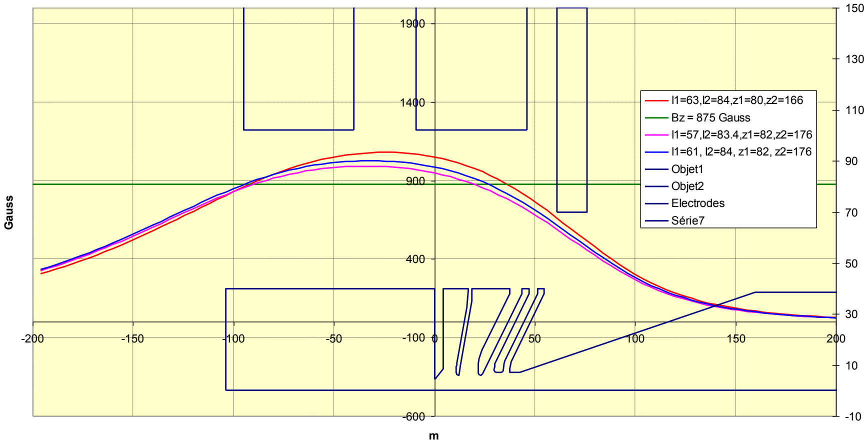




- Beam currents measured at DC1, DC2, and in the RFQ entrance collimator for 6.7 MeV RFQ.
- Beam focusing accomplished with LEBT solenoid magnets S1 and S2.
- Beam centroid controlled with steering magnets SM1 and SM2.

SILHI source and LEBT





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 %

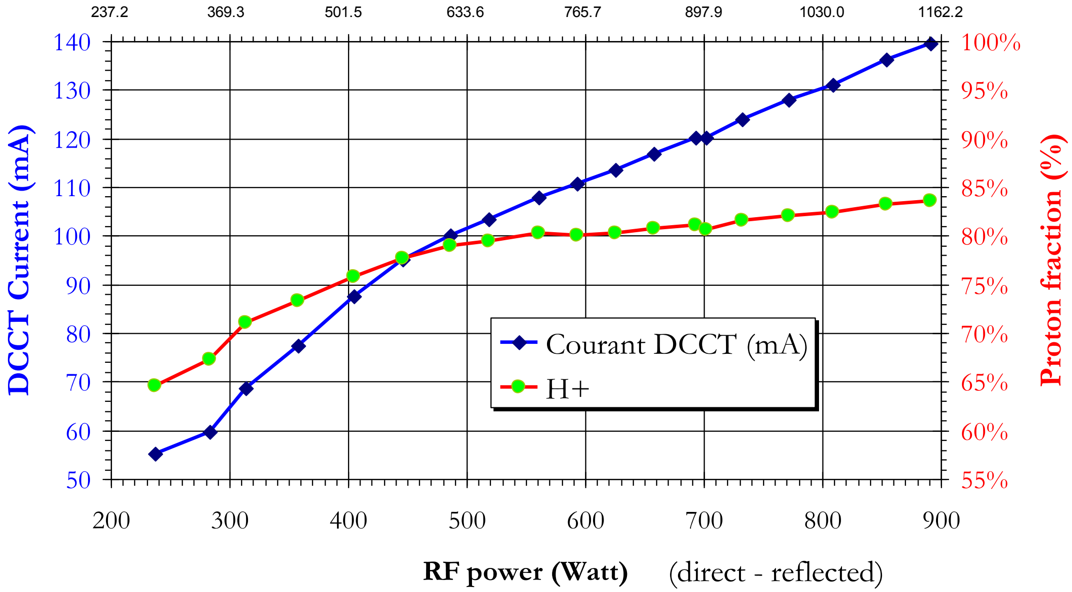
Emittance < 0.2 π mm.mrad

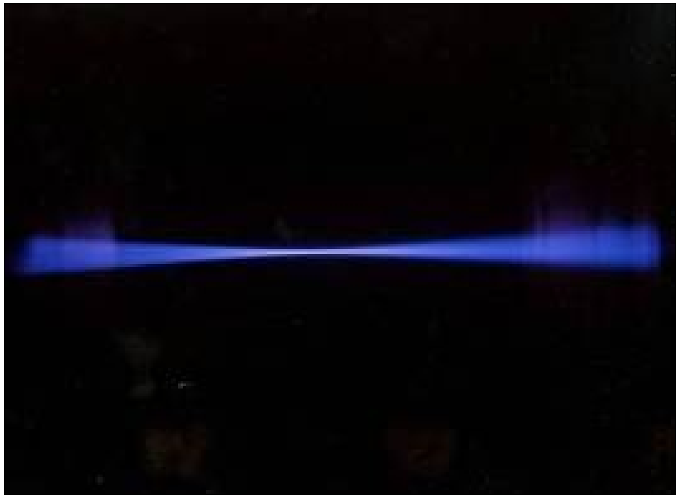
CW or pulsed mode

In CW mode, the source routinely produces

130 mA total (> 80% H^+)

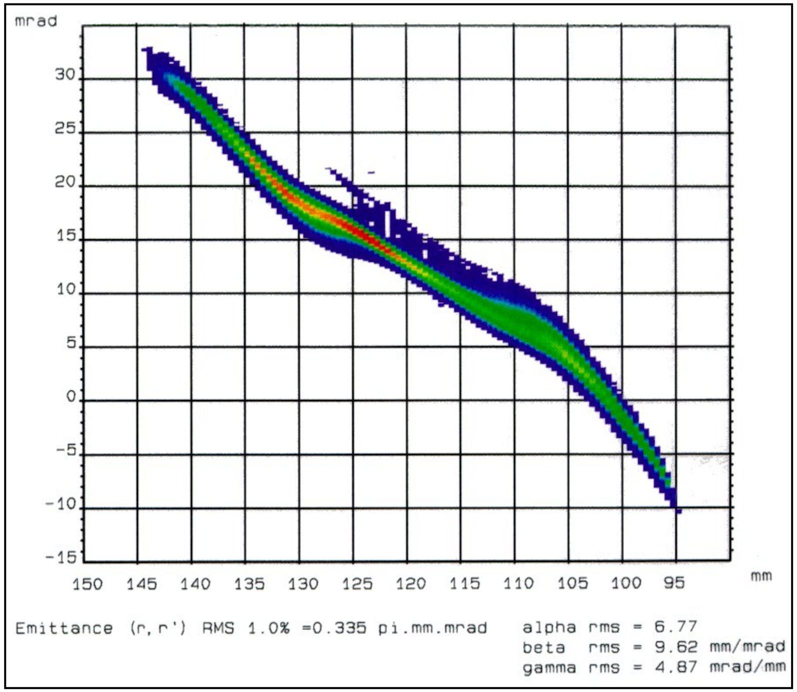
at 95keV





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/cm^2]	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. [%] rms normalized emittance [π.mm.mrad]	2 0.2	1.2 0.11 @75 mA	2 0.2	1.2 -

Space charge compensation with ^{84}Kr

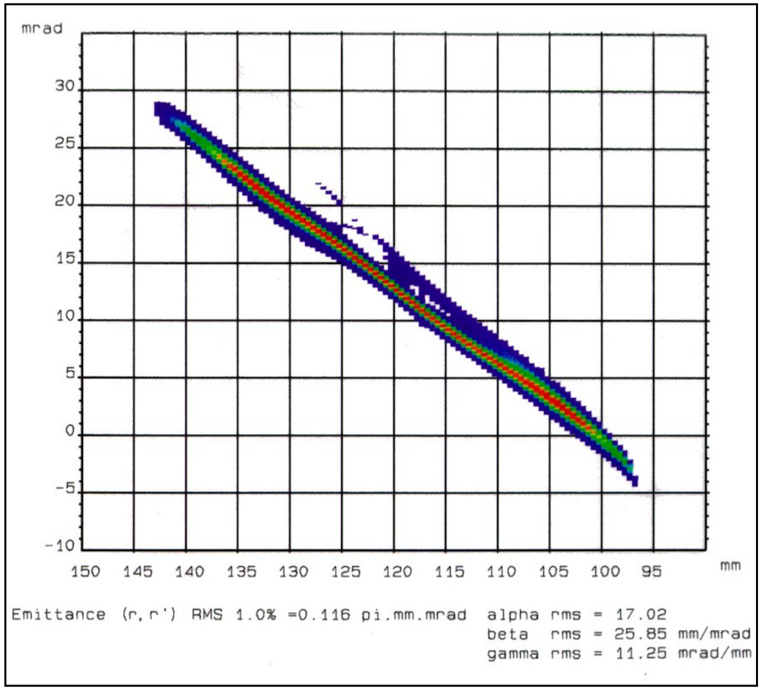


Emittance (r,r') RMS 1.0% =0.335 pi.mm.mrad

alpha rms = 6.77

beta rms = 9.62 mm/mrad

gamma rms = 4.87 mrad/mm



Emittance (r,r') RMS 1.0% =0.116 pi.mm.mrad

alpha rms = 17.02

beta rms = 25.85 mm/mrad

gamma rms = 11.25 mrad/mm

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

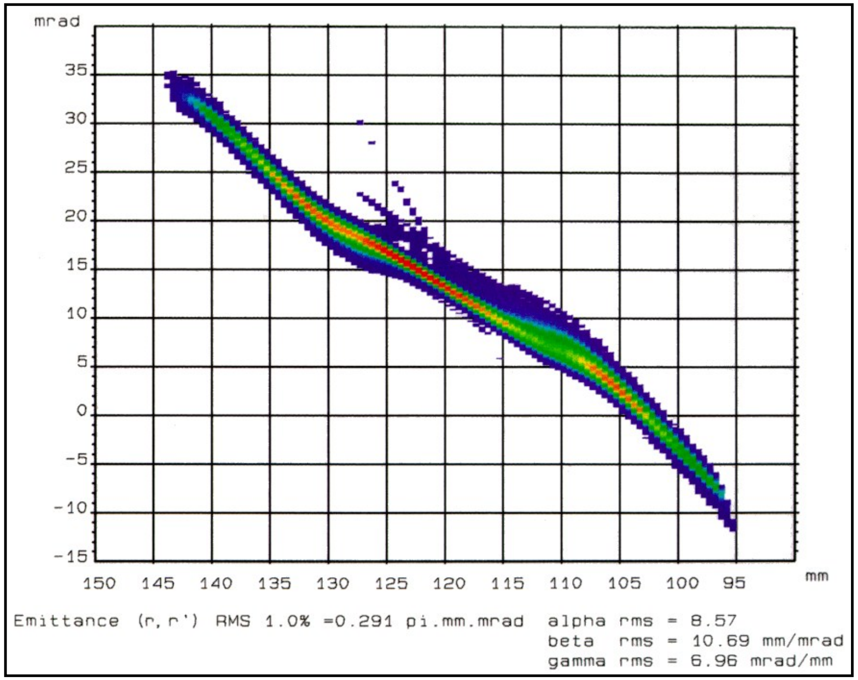
p=1.8·10^{-5} T⇒ **ε_{RMS}=0.335 π mm mrad**

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

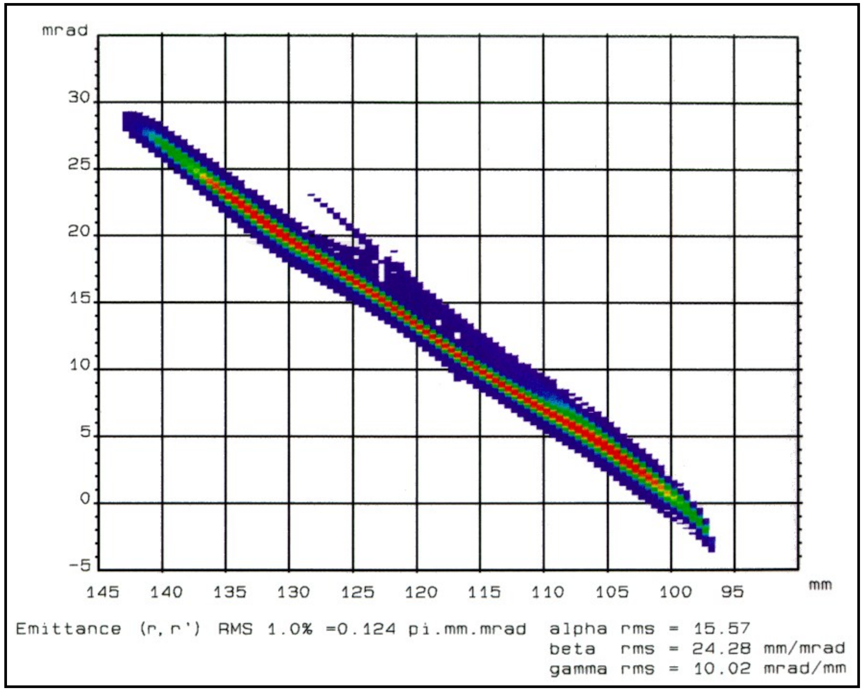
p=3.0·10^{-5} T⇒ **ε_{RMS}=0.116 π mm mrad**

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

Space charge compensation with Ar



Emittance (r,r') RMS 1.0% =0.291 pi.mm.mrad
alpha rms = 8.57
beta rms = 10.69 mm/mrad
gamma rms = 6.96 mrad/mm



Emittance (r,r') RMS 1.0% =0.124 pi.mm.mrad
alpha rms = 15.57
beta rms = 24.28 mm/mrad
gamma rms = 10.02 mrad/mm

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

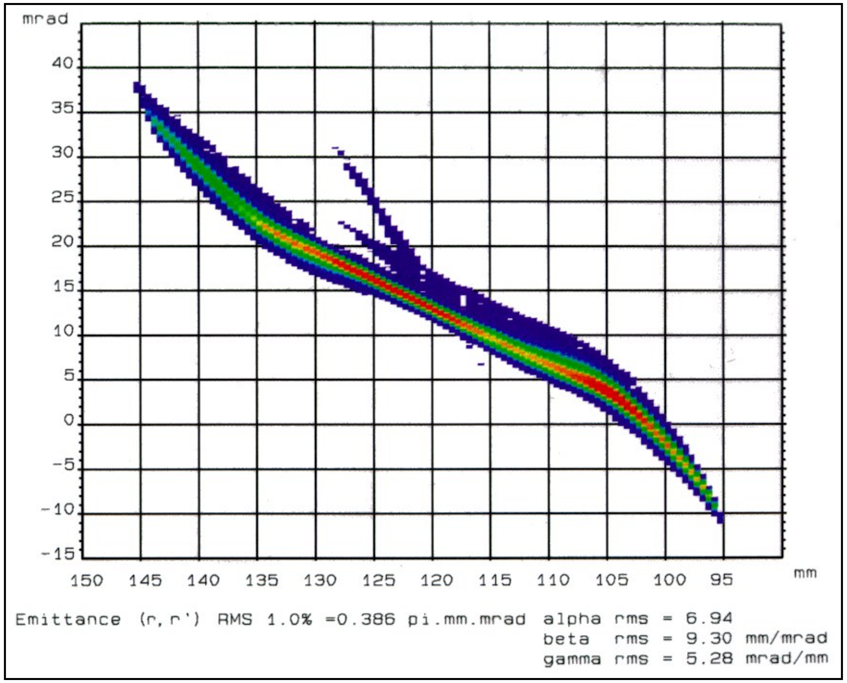
p_1=1.8·10^{-5} T, p_2= 1.2·10^{-5} T ⇒ **ε_{RMS}=0.291 π mm mrad**

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

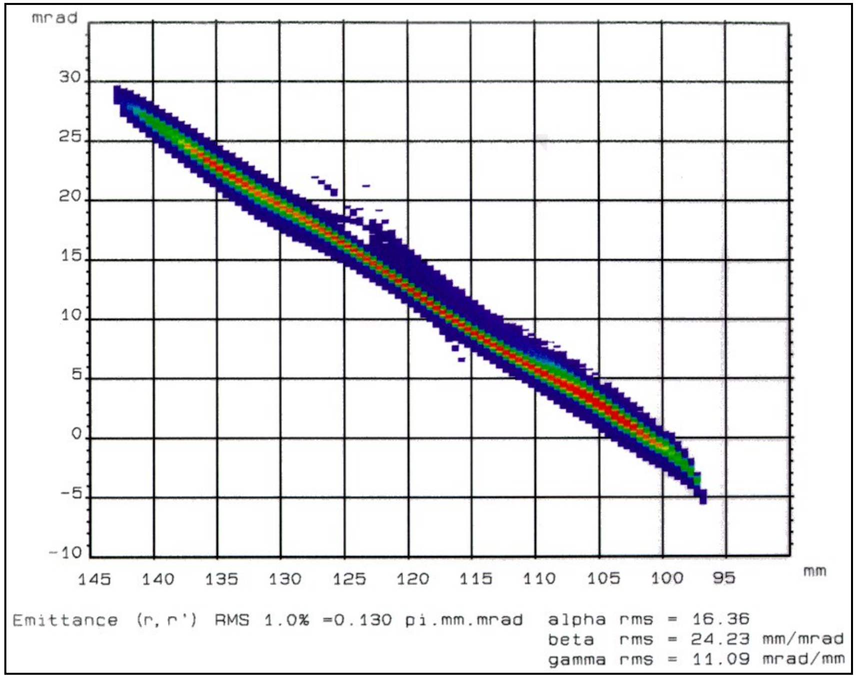
p_1=4.5·10^{-5} T, p_2= 4.4·10^{-5} T ⇒ **ε_{RMS}=0.124 π mm mrad**

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

Space charge compensation with N2



```
Emittance (r,r') RMS 1.0% =0.386 pi.mm.mrad alpha rms = 6.94
                                            beta  rms = 9.30 mm/mrad
                                            gamma rms = 5.28 mrad/mm
```



```
Emittance (r,r') RMS 1.0% =0.130 pi.mm.mrad alpha rms = 16.36
                                            beta  rms = 24.23 mm/mrad
                                            gamma rms = 11.09 mrad/mm
```

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

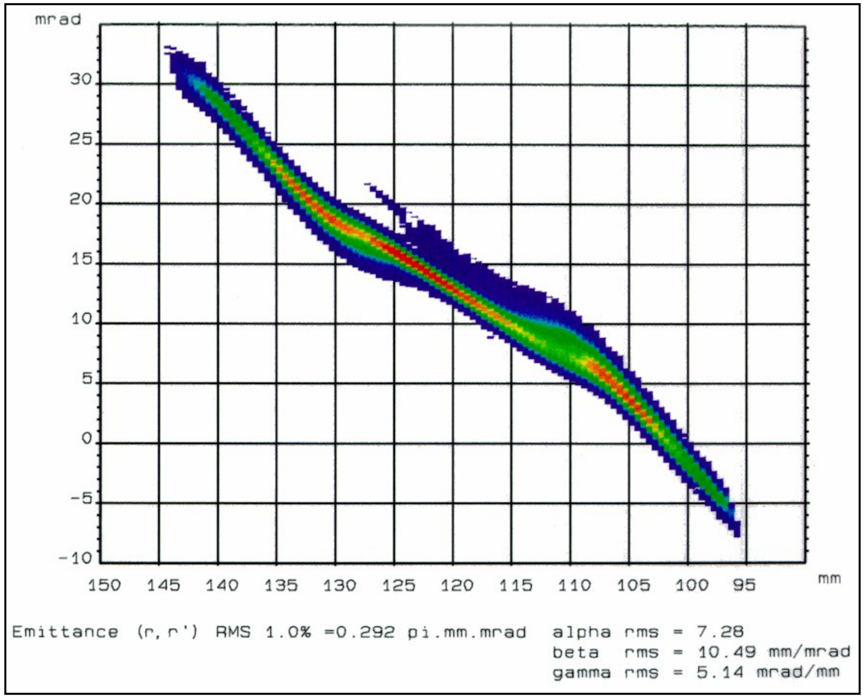
p_1=1.6·10^{-5} T, p_2= 1.2·10^{-5} T ⇒ **ε_{RMS}=0.386 π mm mrad**

Emittance plot injecting N2 in the beam line:

p_1=4.5·10^{-5} T, p_2= 4.5·10^{-5} T ⇒ **ε_{RMS}=0.13 π mm mrad**

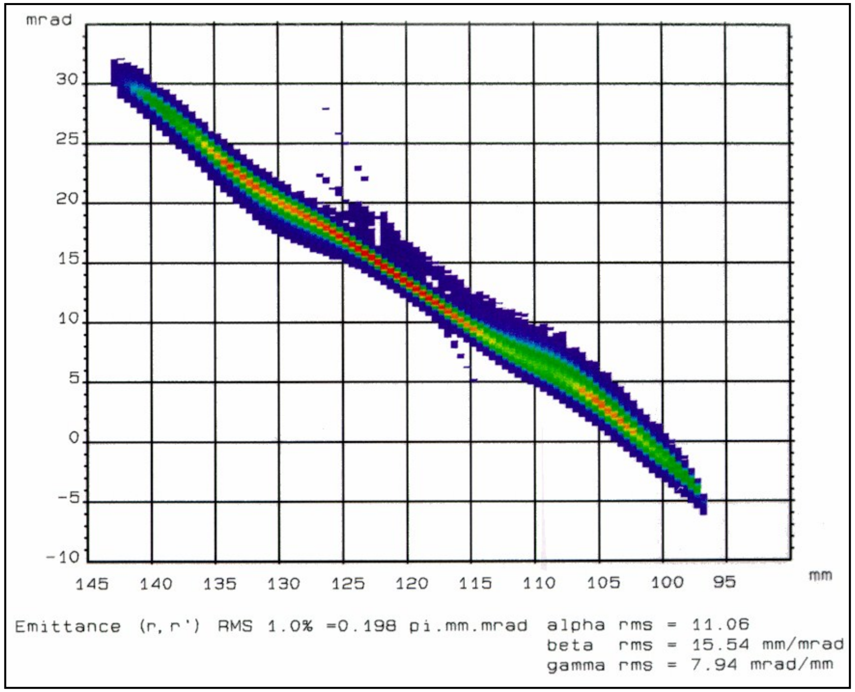
R. Gobin, R. Ferdinand, L.Celona, G. Ciavola, S. Gammino, Rev.Sci.Instr. 70(6),(1999), 2652

Space charge compensation with H2



Emittance (r,r') RMS 1.0% =0.292 pi.mm.mrad

alpha rms = 7.28
beta rms = 10.49 mm/mrad
gamma rms = 5.14 mrad/mm



Emittance (r,r') RMS 1.0% =0.198 pi.mm.mrad

alpha rms = 11.06
beta rms = 15.54 mm/mrad
gamma rms = 7.94 mrad/mm

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

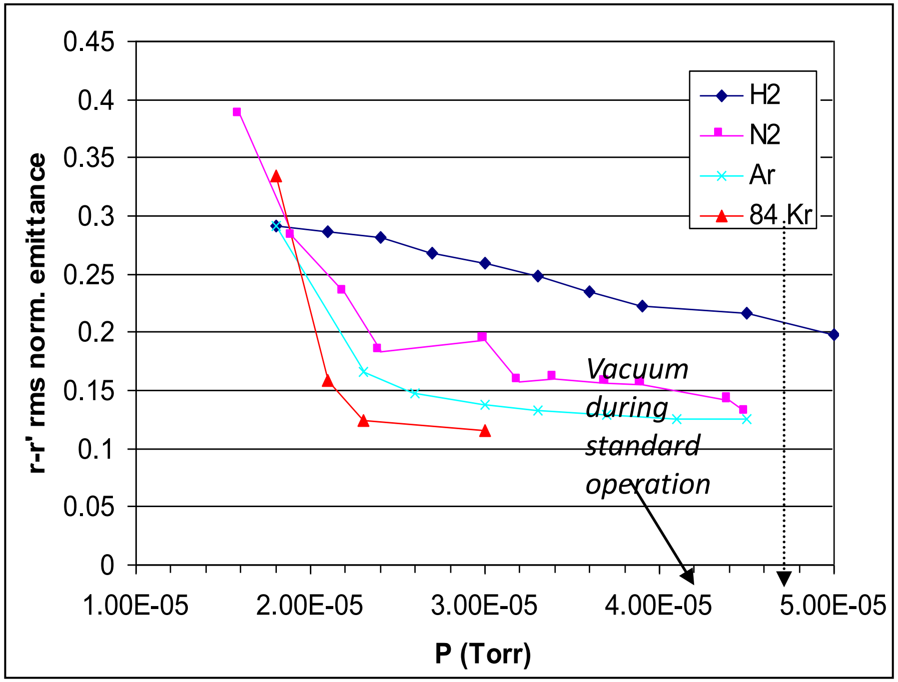
$p_1=1.6\cdot10^{-5}$ T, $p_2= 1.2\cdot10^{-5}$ T $\Rightarrow$ **ε_{RMS}=0.292 π mm mrad**

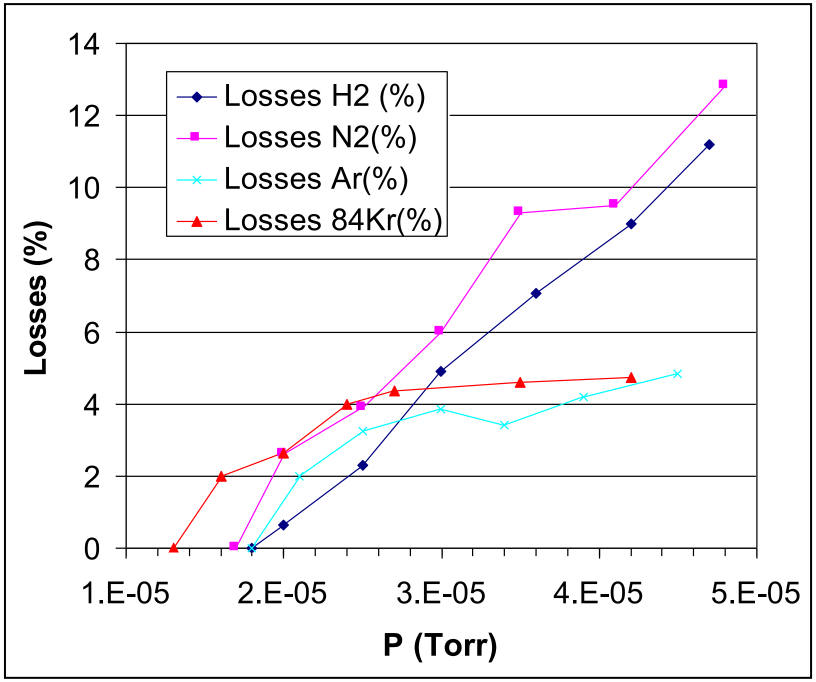
Emittance plot (99%) injecting H2 in the beam line:

$p_1=5\cdot10^{-5}$ T, $p_2= 4.9\cdot10^{-5}$ T $\Rightarrow$ **ε_{RMS}=0.198 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

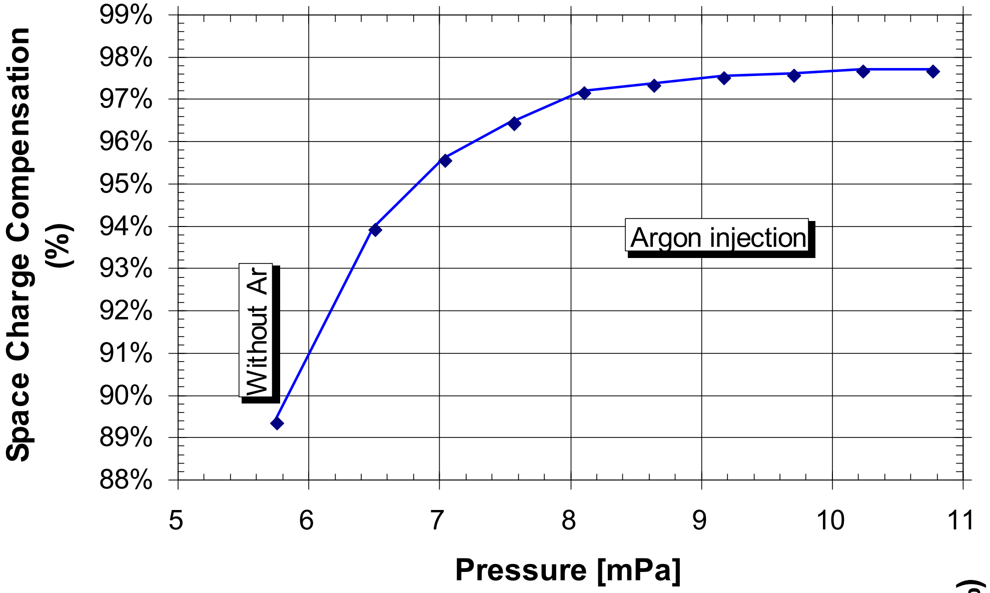


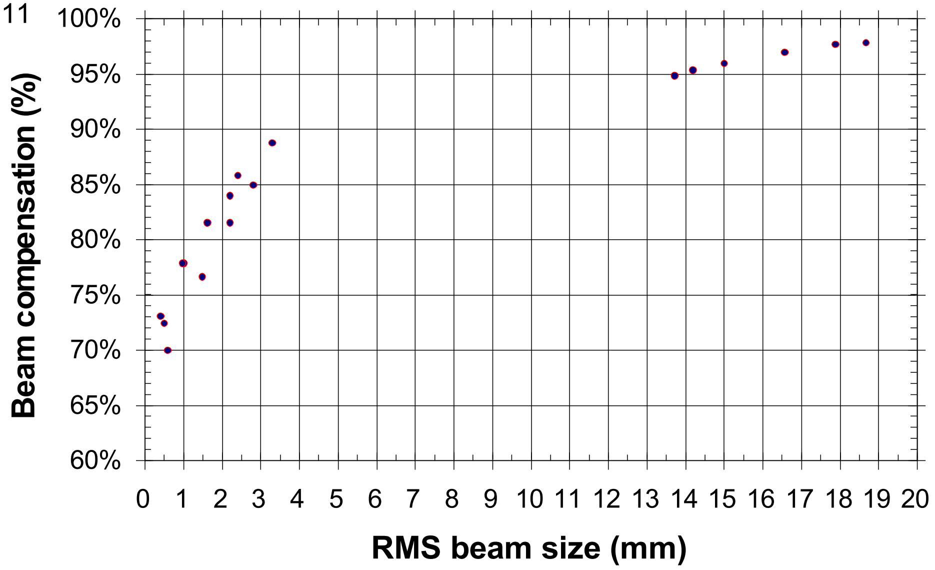


- *In all the cases considered, a decrease of beam emittance has been observed with the increase of beam line pressure.*
- *Using ^{84}Kr gas addition a decrease of a factor three in beam emittance has been achieved losing less than 5% of the beam current with a small increase of pressure (from 1.8E-5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

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

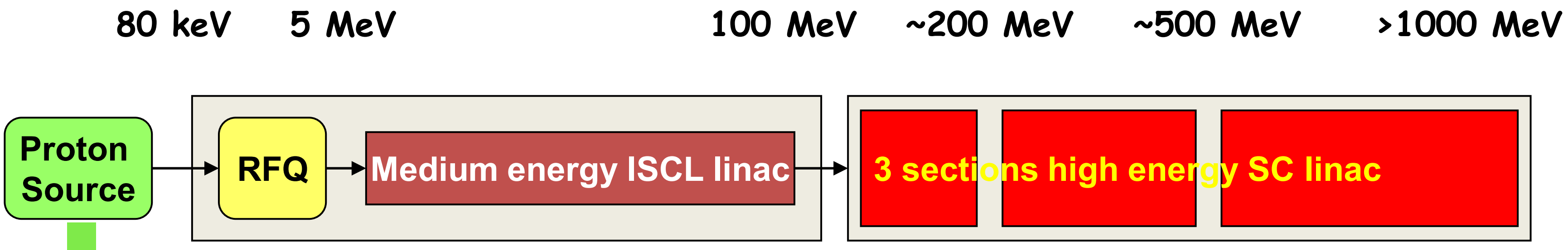
TRIPS performance vs. forward power





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

The TRASCO linac (1 GeV, 30 mA)



Proton beam current: *35 mA dc*

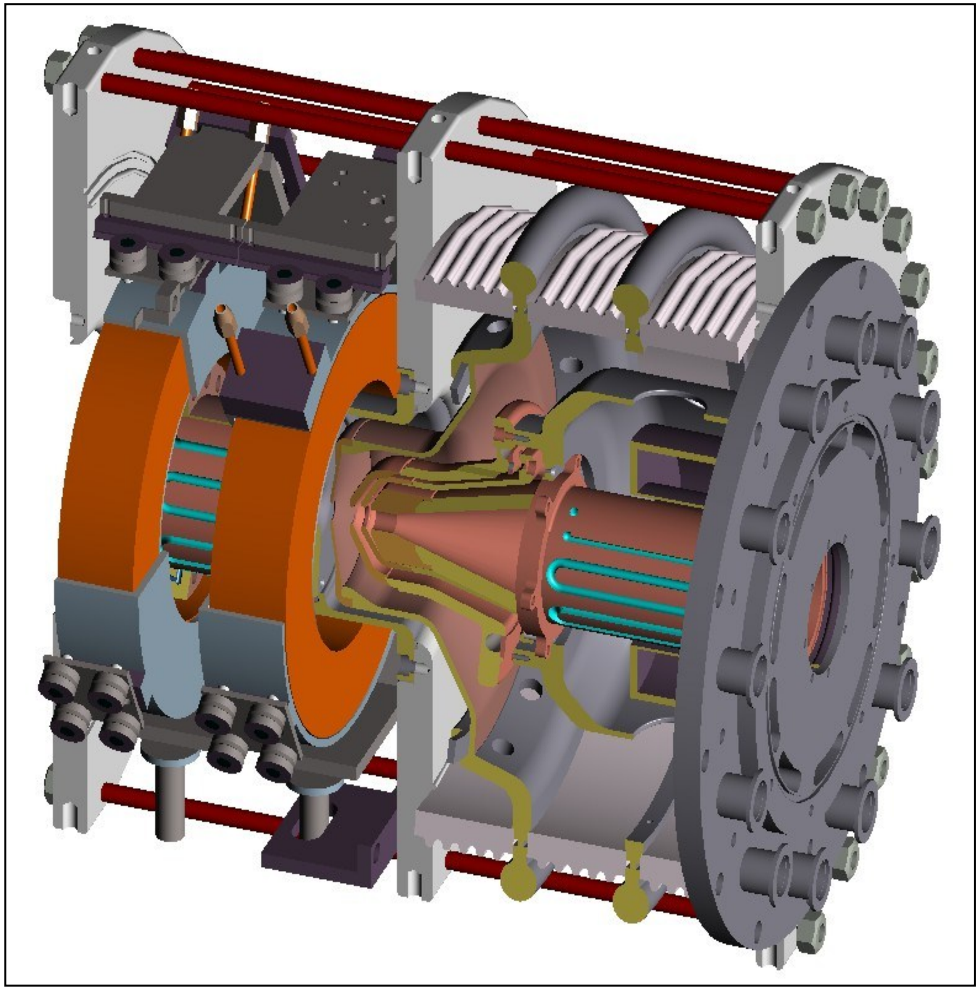
Beam Energy: *80 keV*

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

Reliability: *close to 100%*

TRIPS (TRasco Intense Proton Sources) requirements

TRIPS (TRasco Intense Proton Source)



Proton beam current:

35 mA dc

Beam Energy:

80 keV

Beam emittance:

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

Reliability:

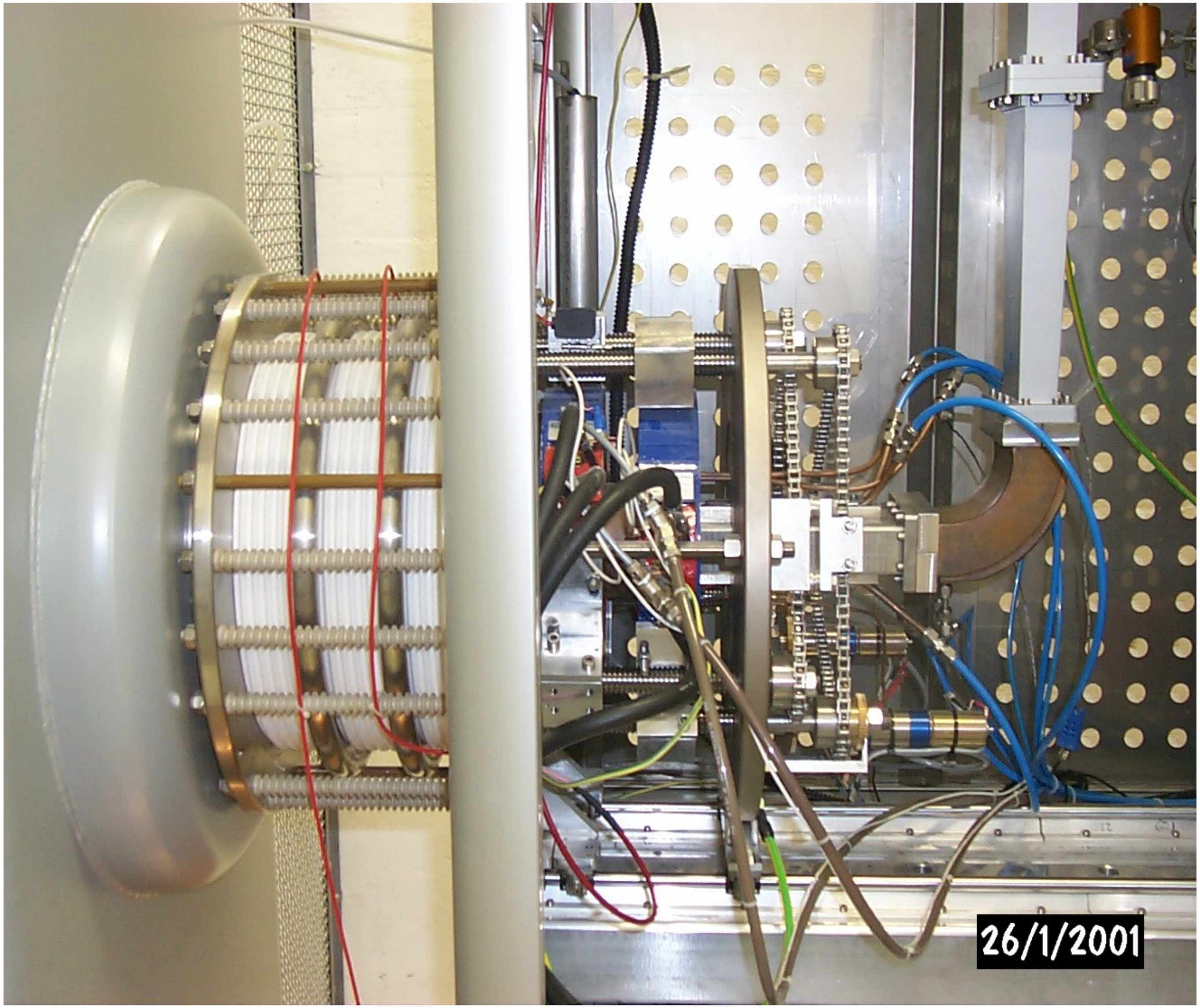
close to 100%

Based on CRNL-LANL-CEA design
MANY INNOVATIONS

TRIPS operating parameters

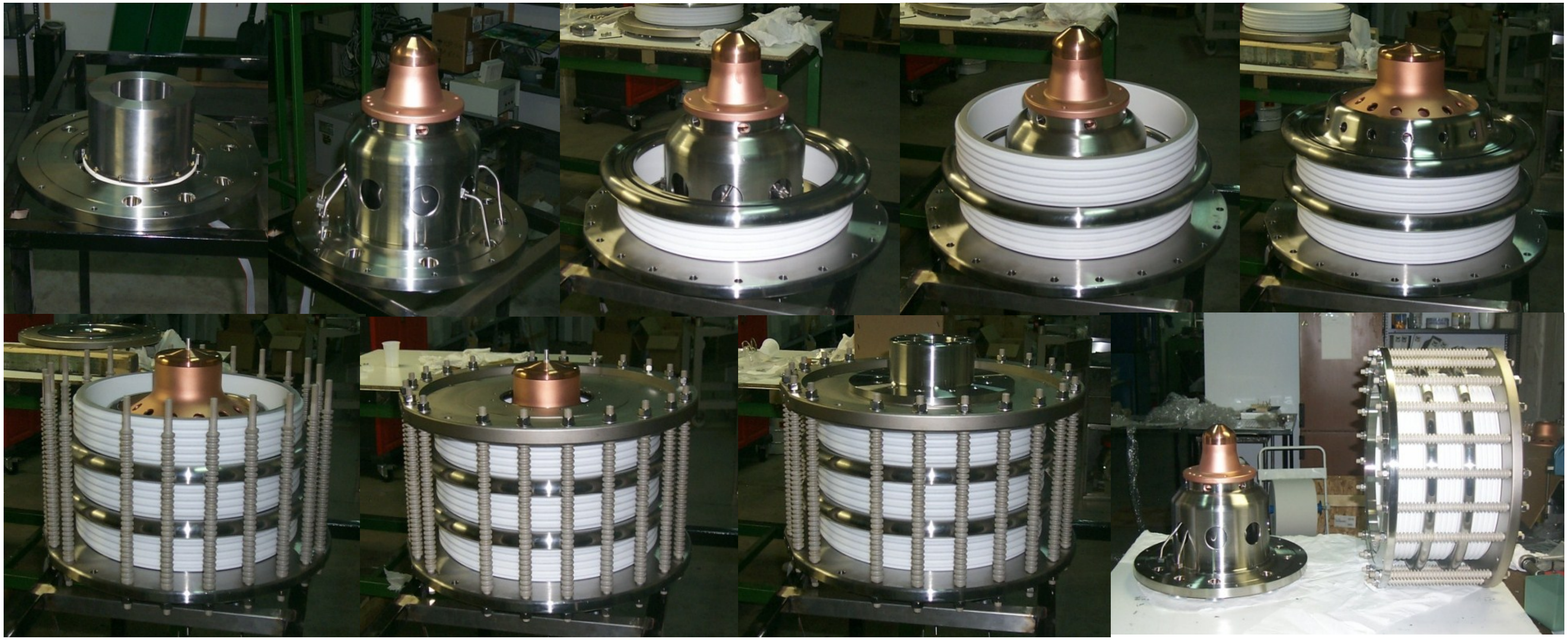
	Requirement	**Status**
Beam energy	80 keV	80 keV
Proton current	35 mA	55 mA
Proton fraction	>70%	≈90% (estimated)
RF power, Frequency	2 kW (max) @2.45 GHz	Up to 1 kW @ 2.45 GHz
Axial magnetic field	875-1000 G	875-1000 G
Duty factor	100% (dc)	100% (dc)
Extraction aperture	8 mm	6 mm
Reliability	≈100%	99.8% @ 35mA (over 142 h)
Beam emittance at RFQ entrance	≤0.2 πmmmrad	0.07πmmmrad @ 32 mA

TRIPS (TRasco Intense Proton Source)

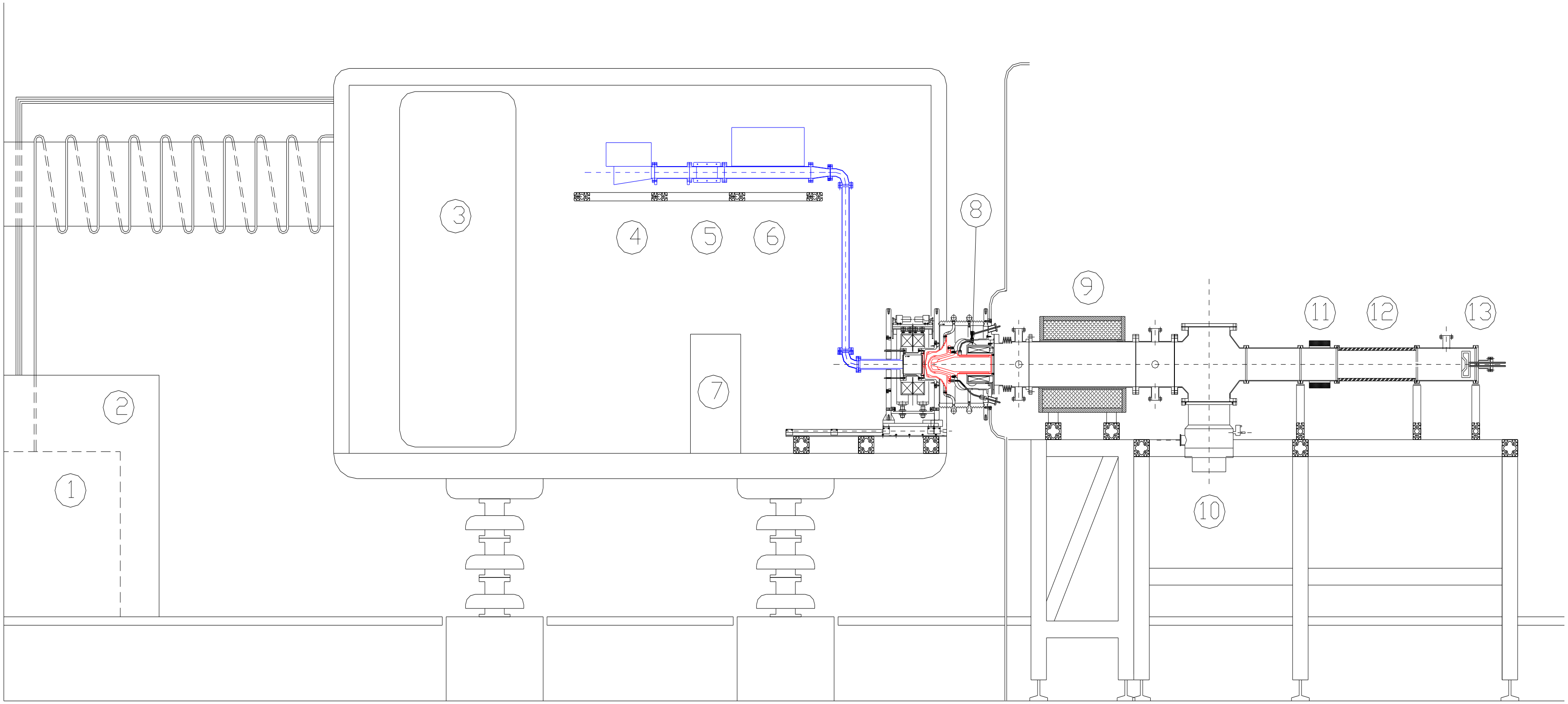

26/1/2001

Extraction electrodes

TRIPS mounting procedure: from the grounded flange to the 100 kV flange.



TRIPS experimental layout

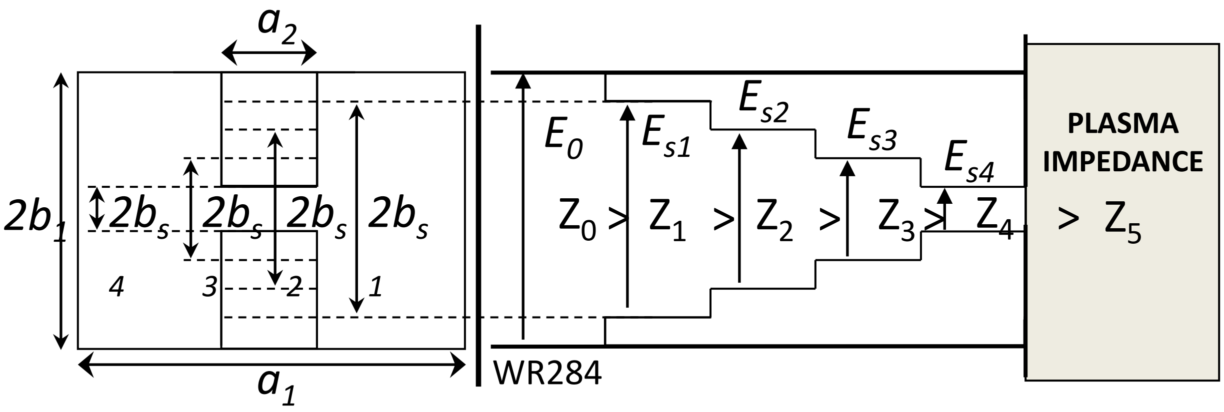


A layout of the whole set-up at INFN-LNS:
1- Demineralizer; 2- 120 kV insulating transformer; 3- 19” Rack for the power supplies and for the remote control system; 4- Magnetron and circulator; 5- Directional coupler; 6 – Automatic Tuning Unit; 7- Gas Box; 8- DCCT 1;
9- Solenoid; 10- Turbomolecular pump;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

Microwave injection and beam extraction optimisation

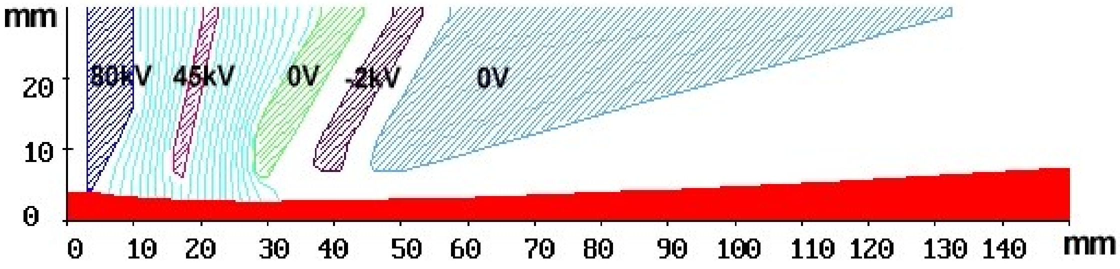
Microwave Injection

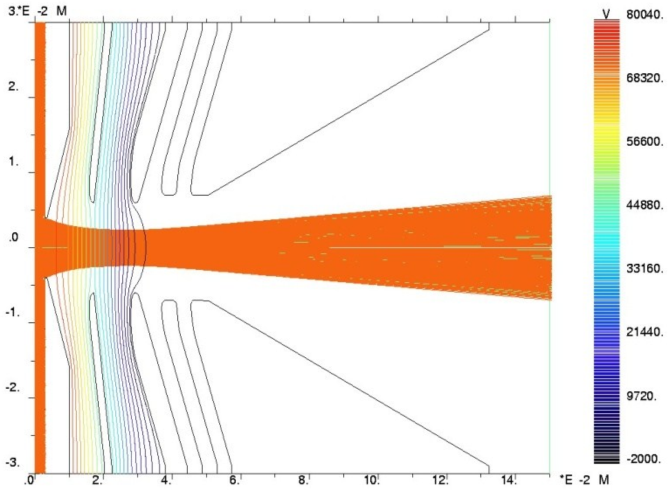
Use of a step binomial matching transformer with a field enhancement factor $(E_{s4}/E_0) \approx 1.95$ $(a_2 = 0.0126\ \mathrm{m})$



Beam extraction

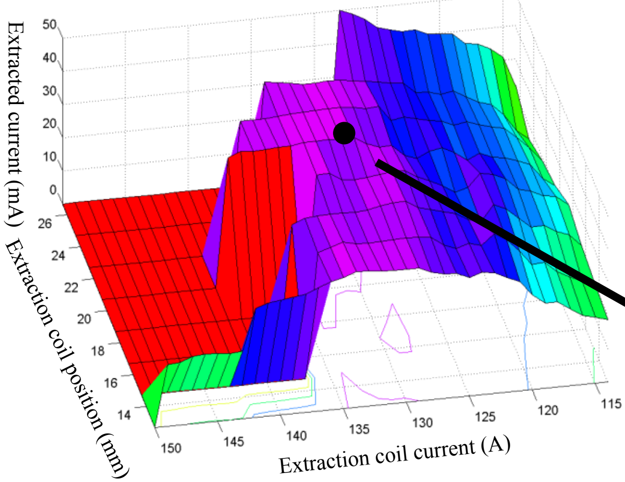
The extraction process has been deeply studied with the aim to increase the source reliability and to keep emittance low.
The used codes were AXCEL-INP and IGUN.

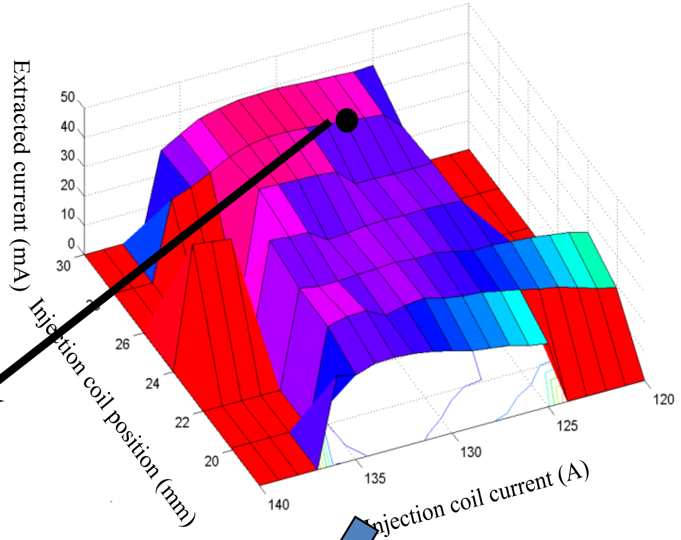




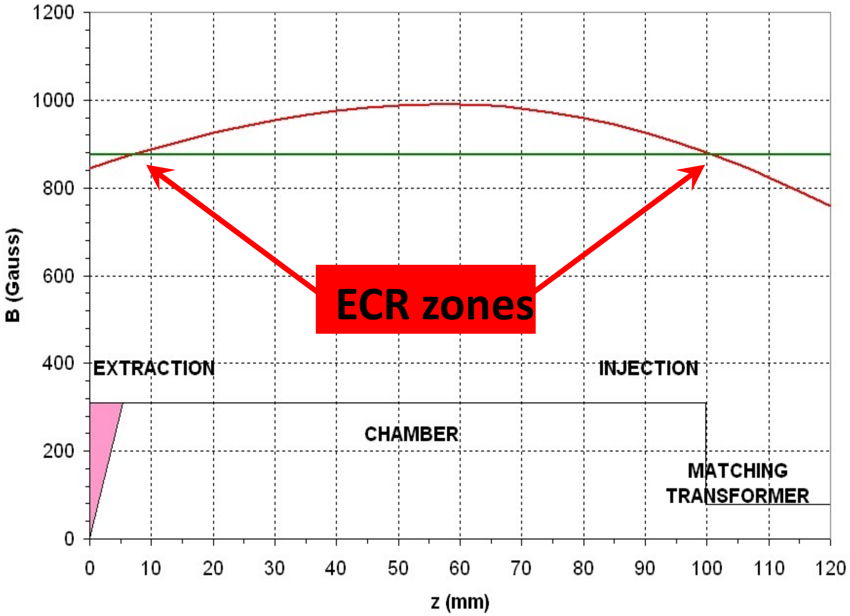
L.Celona, G. Ciavola, S. Gammino, R. Gobin, R. Ferdinand, Rev.Sci.Instr. 71(2),(2000), 771

Optimum magnetic field profile

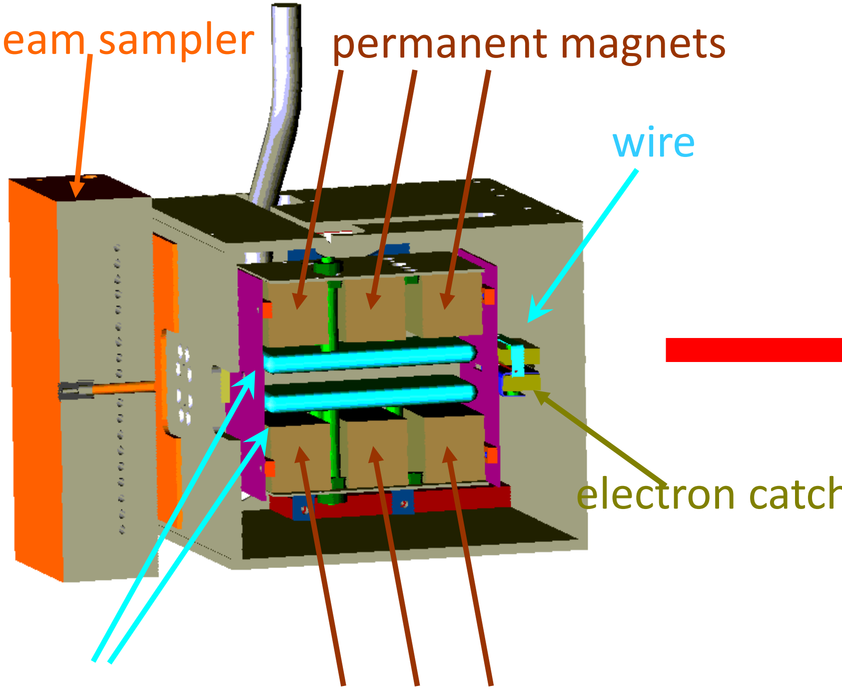




Best operational point:
Extraction coil: pos= 22 mm
curr=128 A



LEBT with Saclay EMU



beam sampler

permanent magnets

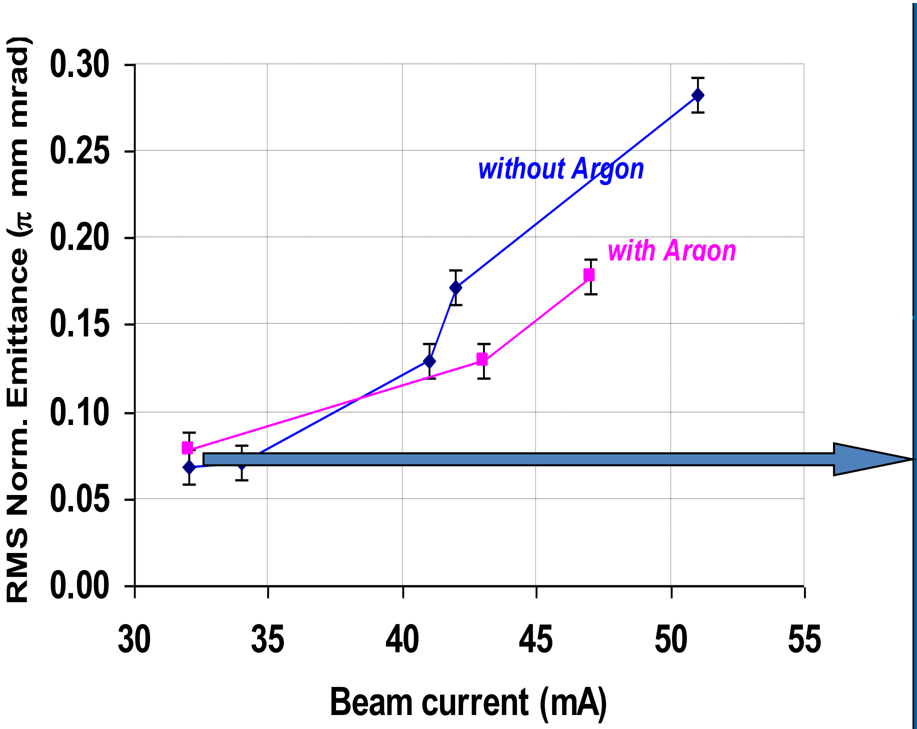
wire

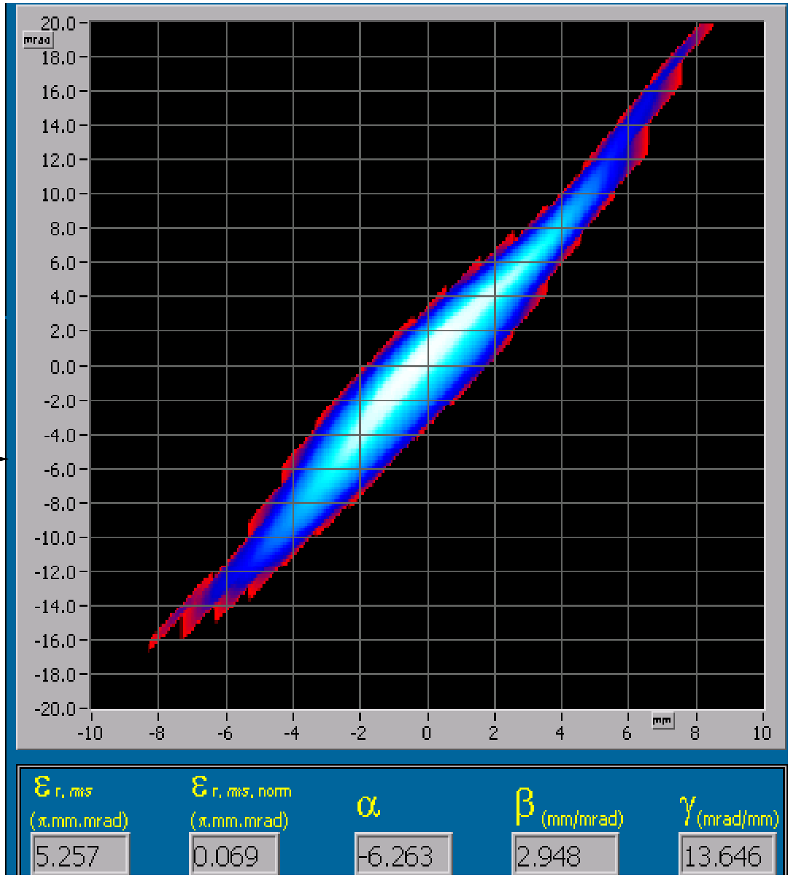
electron catcher

HV electrodes

permanent magnets

Emittance measurements at nominal current

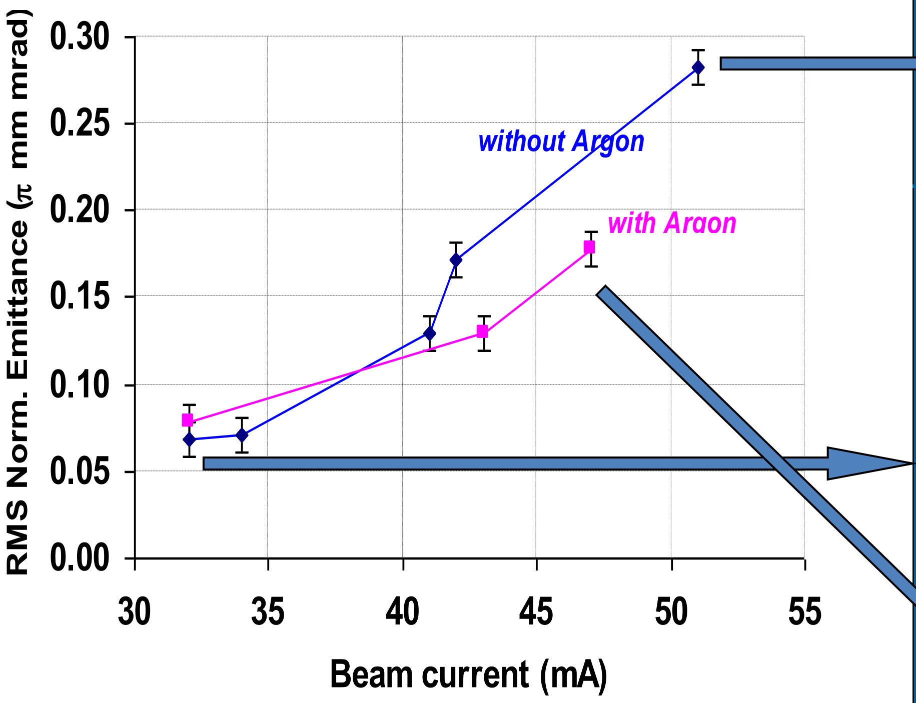


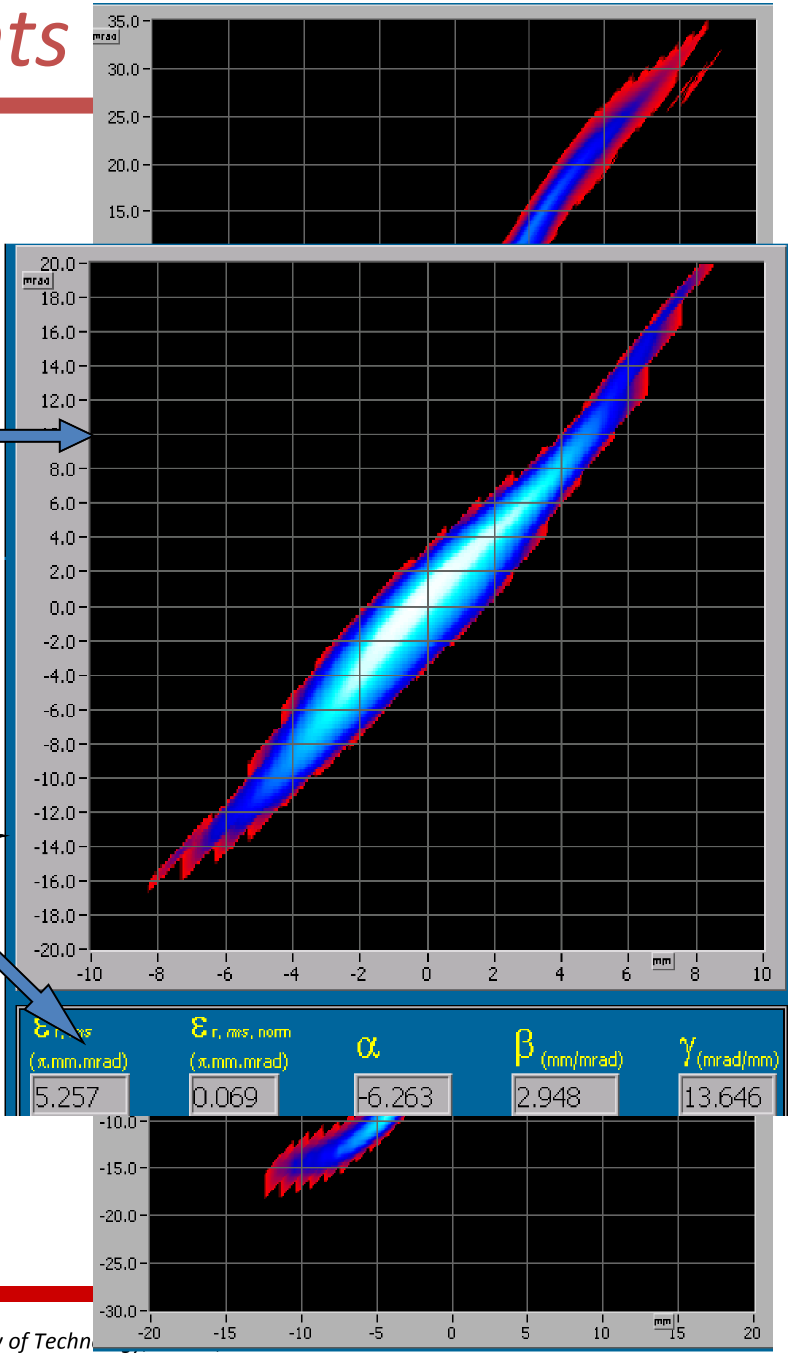


$\varepsilon_{r,rms}$ (π.mm.mrad)	$\varepsilon_{r,rms,norm}$ (π.mm.mrad)	α	β (mm/mrad)	γ (mrad/mm)
5.257	0.069	-6.263	2.948	13.646

The measured value is slightly above the theoretical value and in good agreement with the AXCEL calculation.

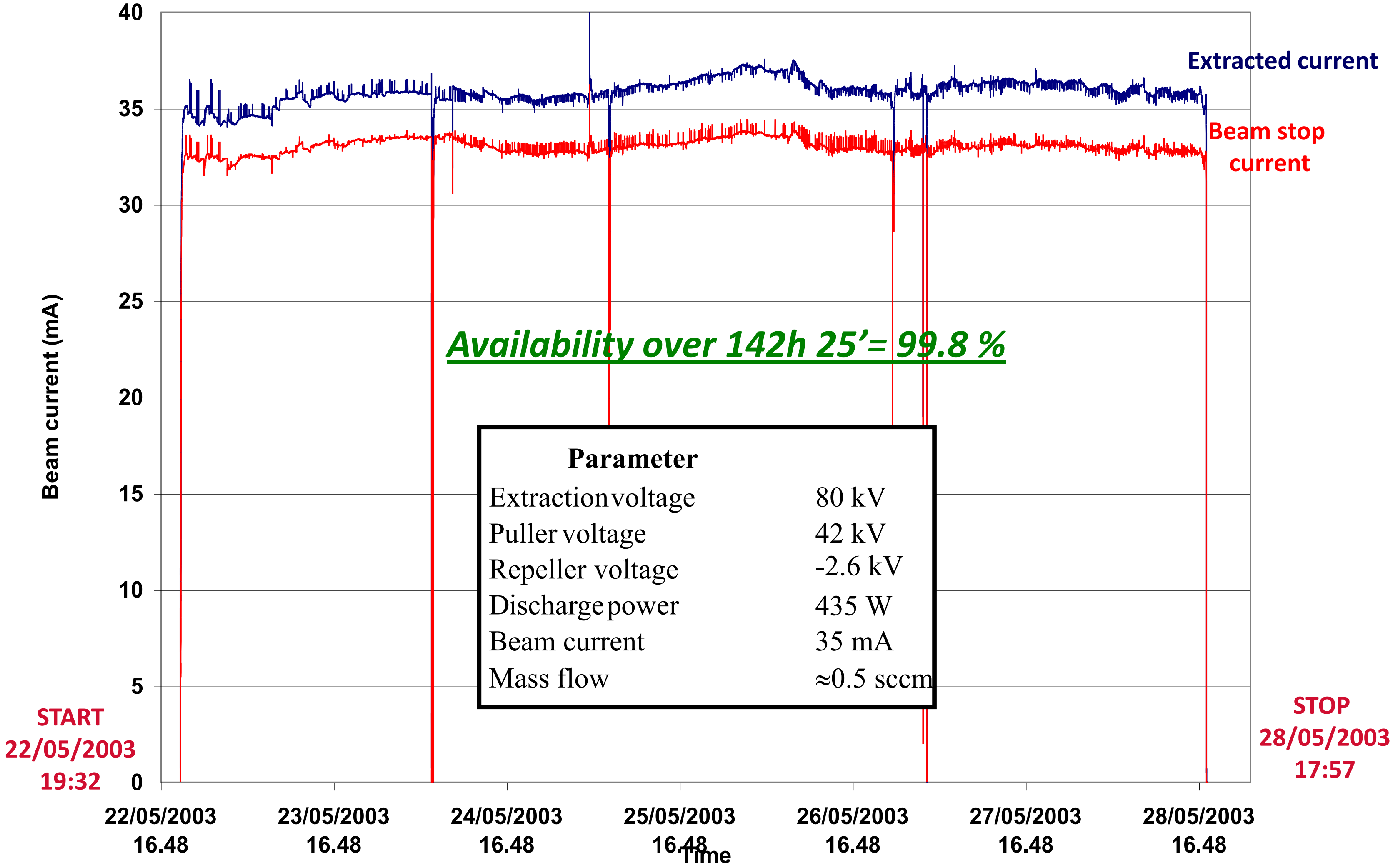
Emittance measurements





$\varepsilon_{r,\,rms}$ (π.mm.mrad)	$\varepsilon_{r,\,rms,\,norm}$ (π.mm.mrad)	α	β (mm/mrad)	γ (mrad/mm)
5.257	0.069	-6.263	2.948	13.646

TRIPS reliability test: 35 mA @ 80 kV



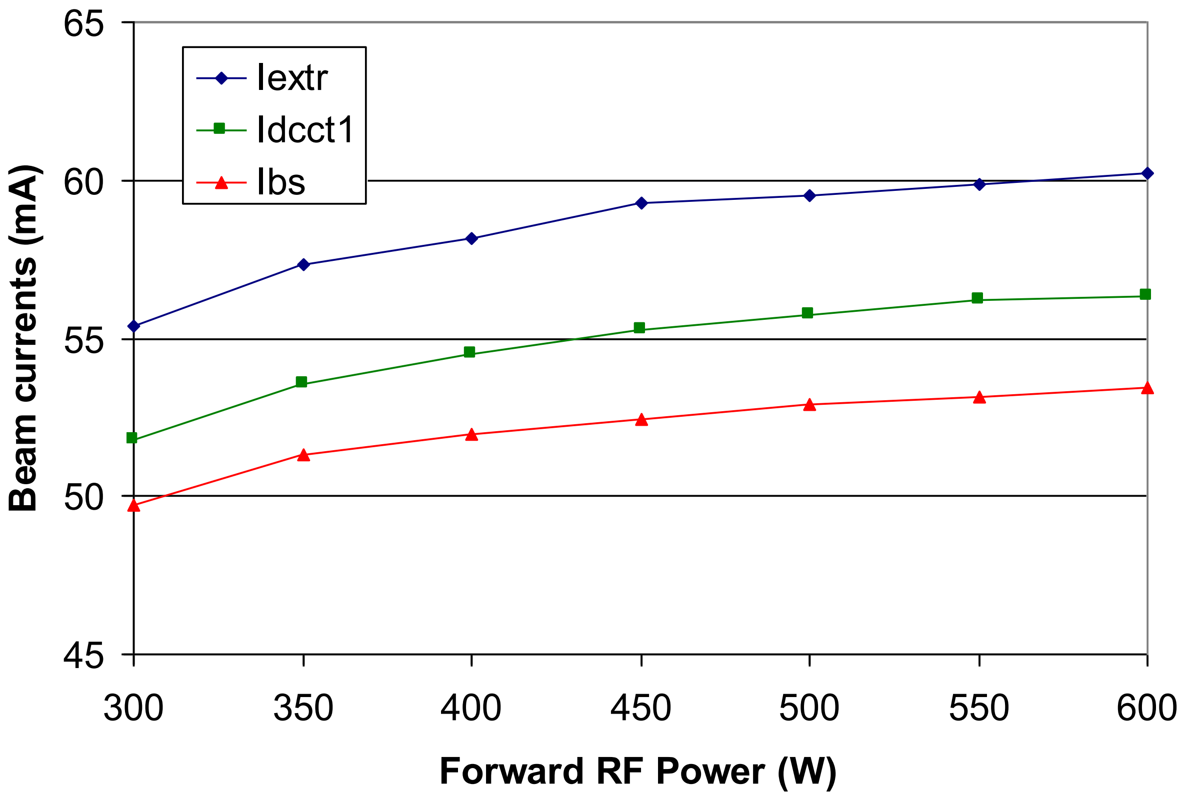
START
22/05/2003
19:32

STOP
28/05/2003
17:57

Availability over 142h 25'= 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

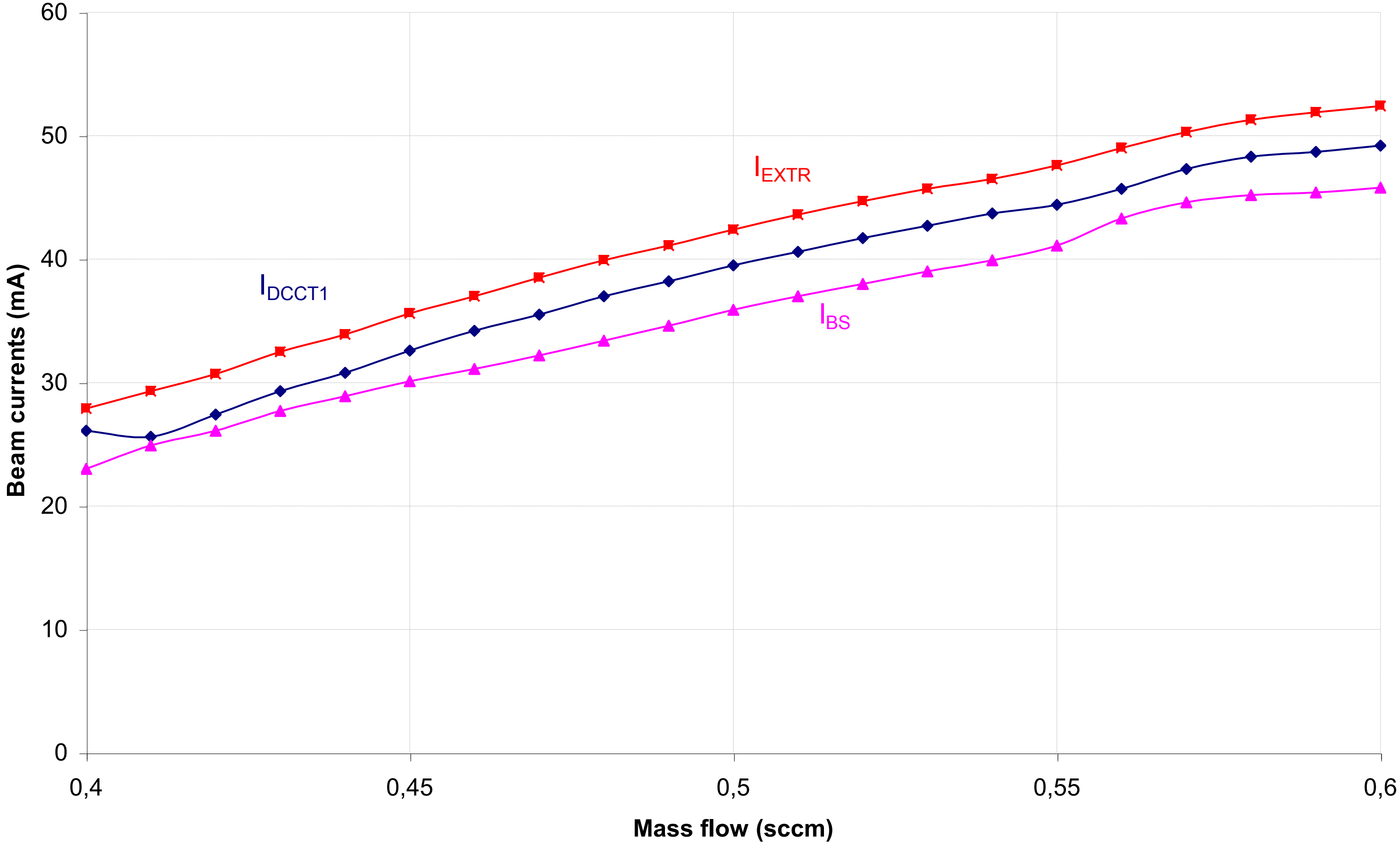
TRIPS performance vs. forward power



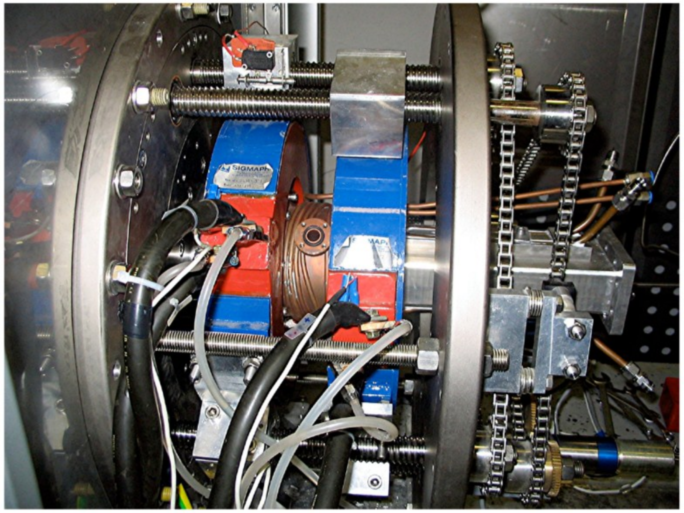
Operating voltage = 80 kV
Optimized magnetic field profile
Electron donor= BN disks

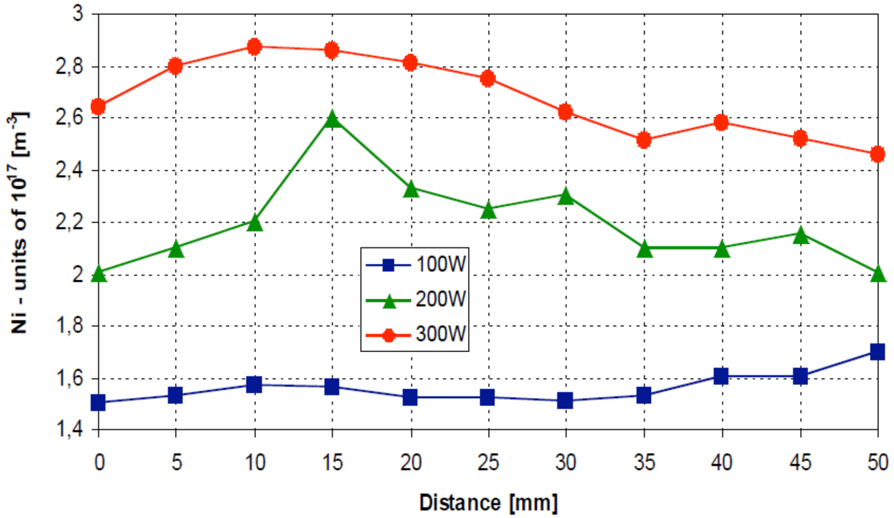
Mass flow= 0.6 sccm
Extraction aperture = 6 mm
Current density up to 210 mA/cm²
(close to J_{child})

TRIPS performance vs. mass flow @ 450 W



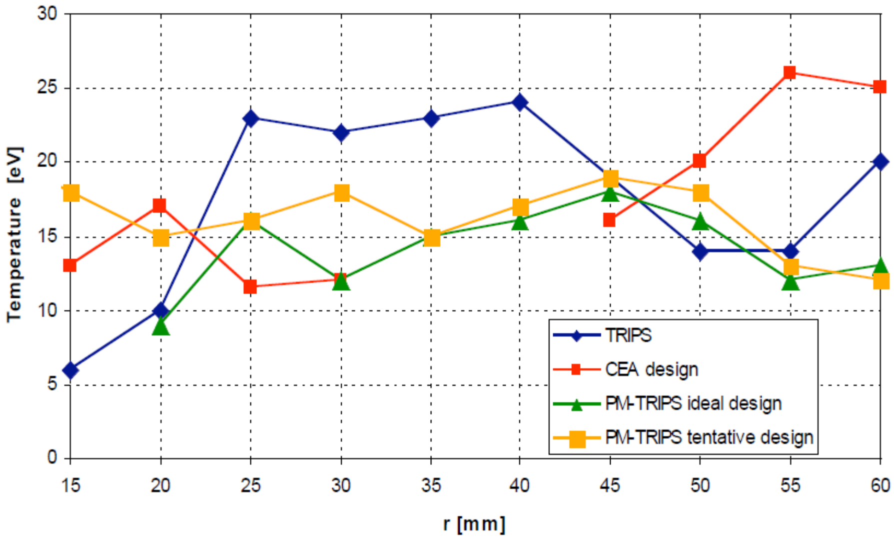
Typical densities and temperatures of MDIS plasmas





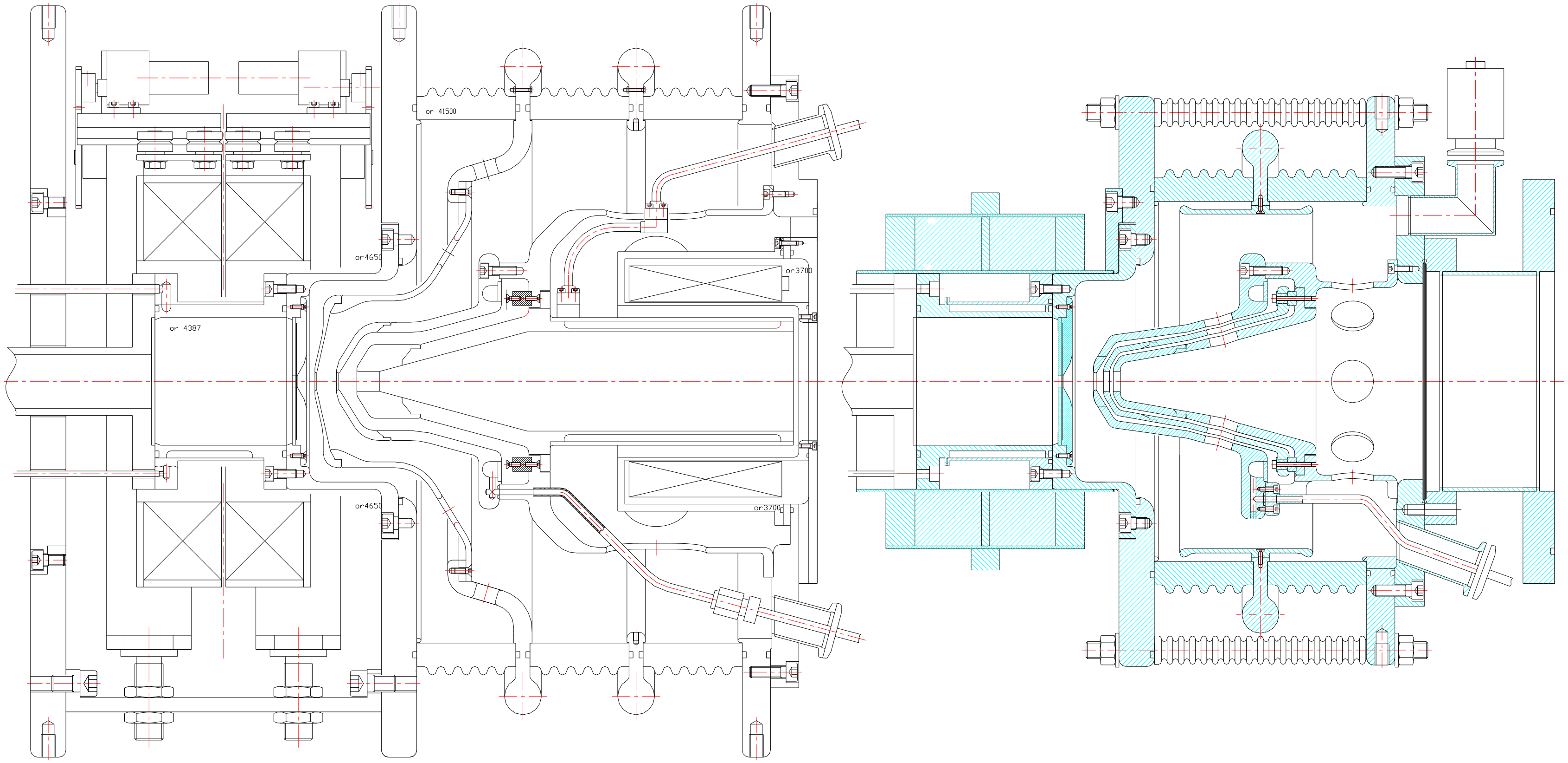
Density of ions along the chamber axis

Langmuir Probe measurements



Electron temperature of the bulk plasma

TRIPS vs. VIS

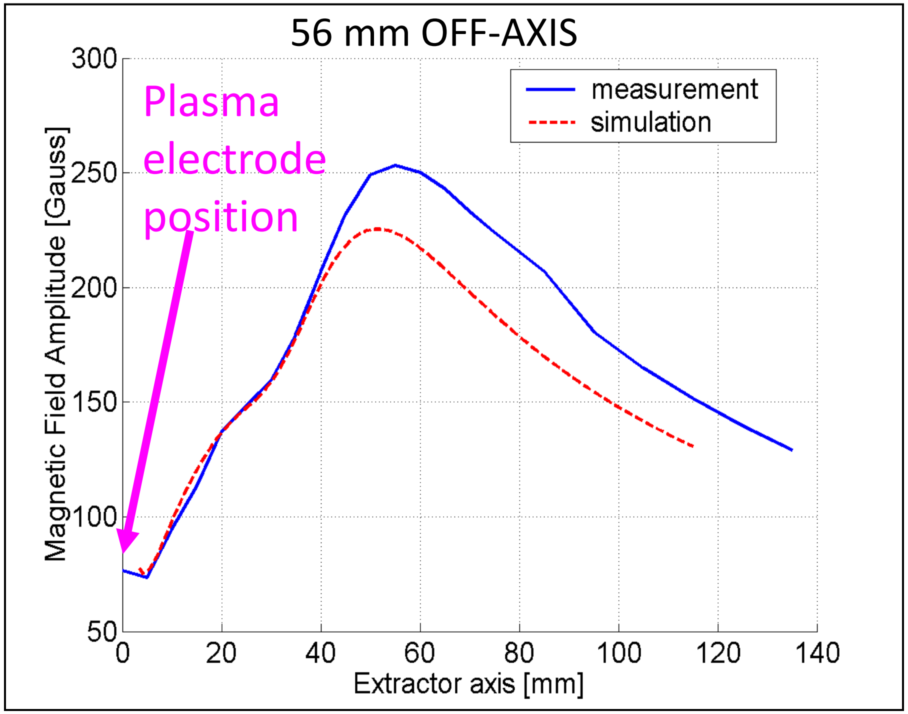


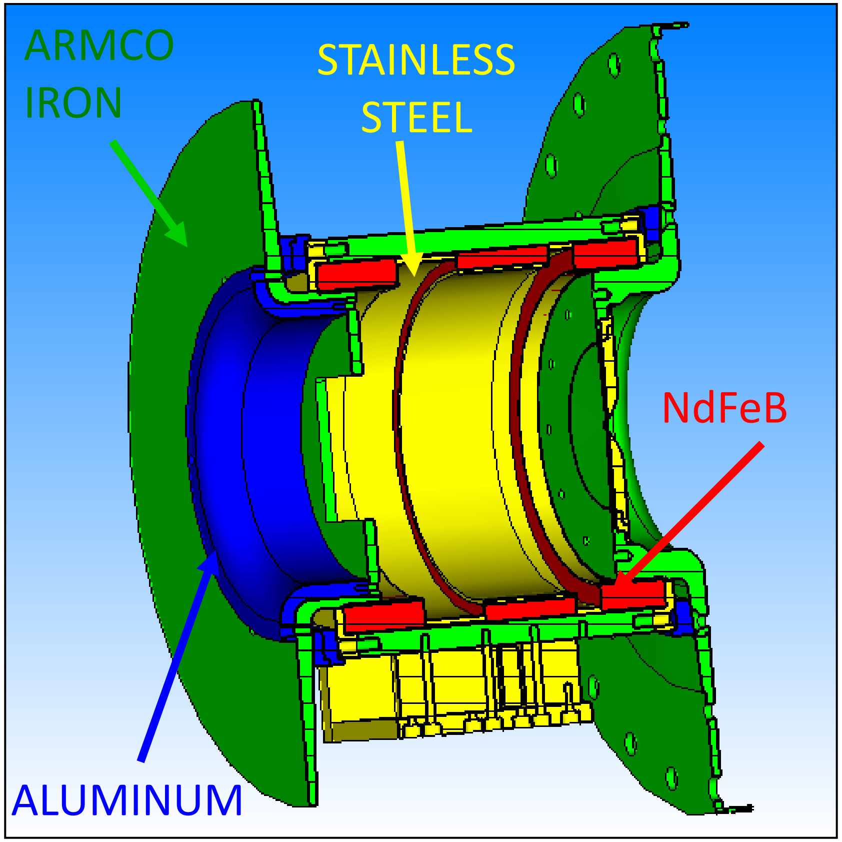
- New extraction system and accelerator column simplified to reduce the dimensions.
- New ionisation chamber.

- Insulation of coils, microwave and gas system to eliminate the HV-platform (implies a further simplification of the electronics involved in the control of the source because all the instrumentation will be placed at ground potential).

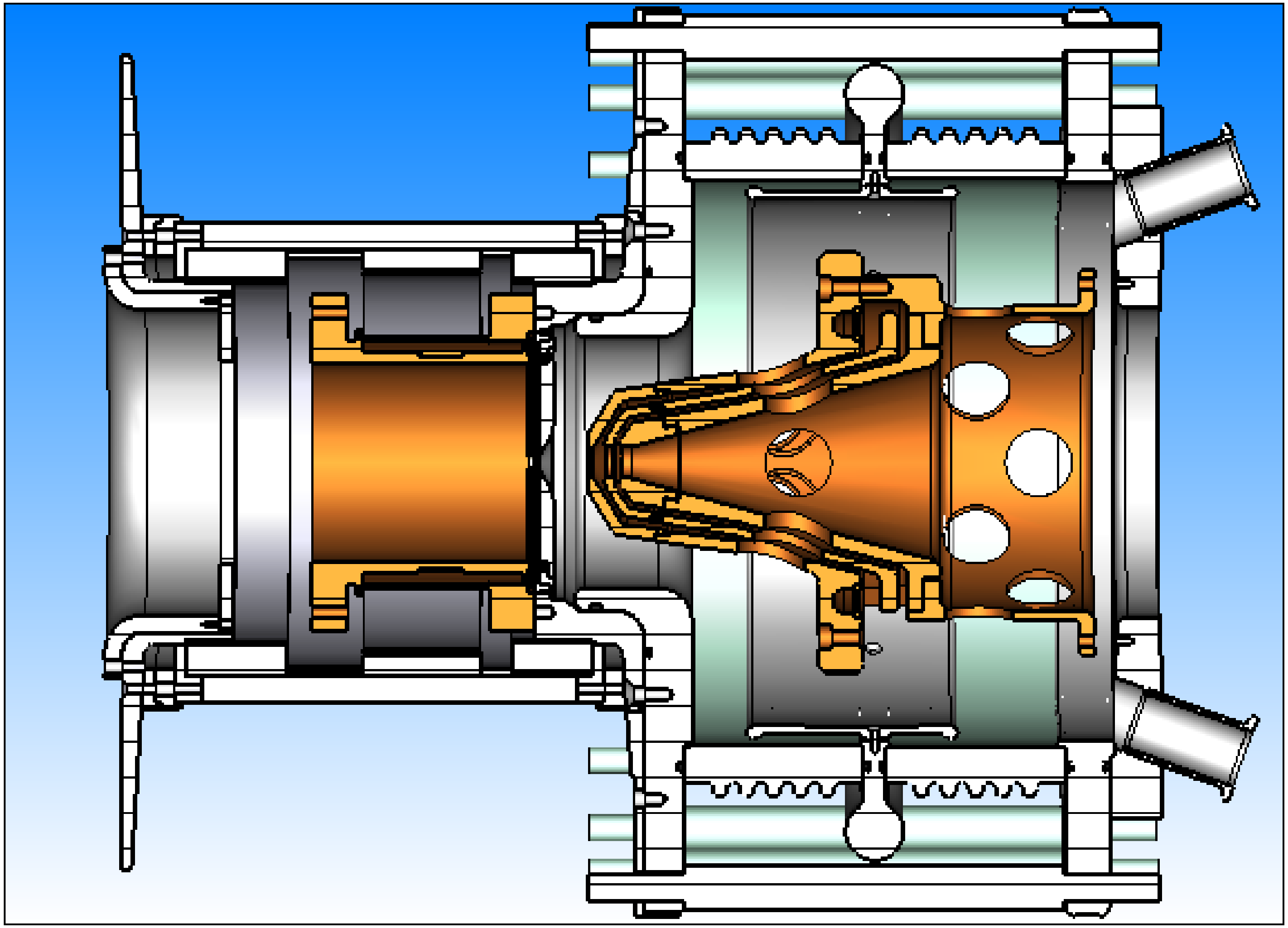
NEW MAGNETIC SYSTEM

- Based on three rings of NdFeB permanent magnets
- The ARMCO iron components lower the off axis magnetic stray field values, detrimentals for the reliability, by keeping high the field inside the plasma chamber
- Very good matching between the measurements and the numerical simulation carried out with the OPERA code



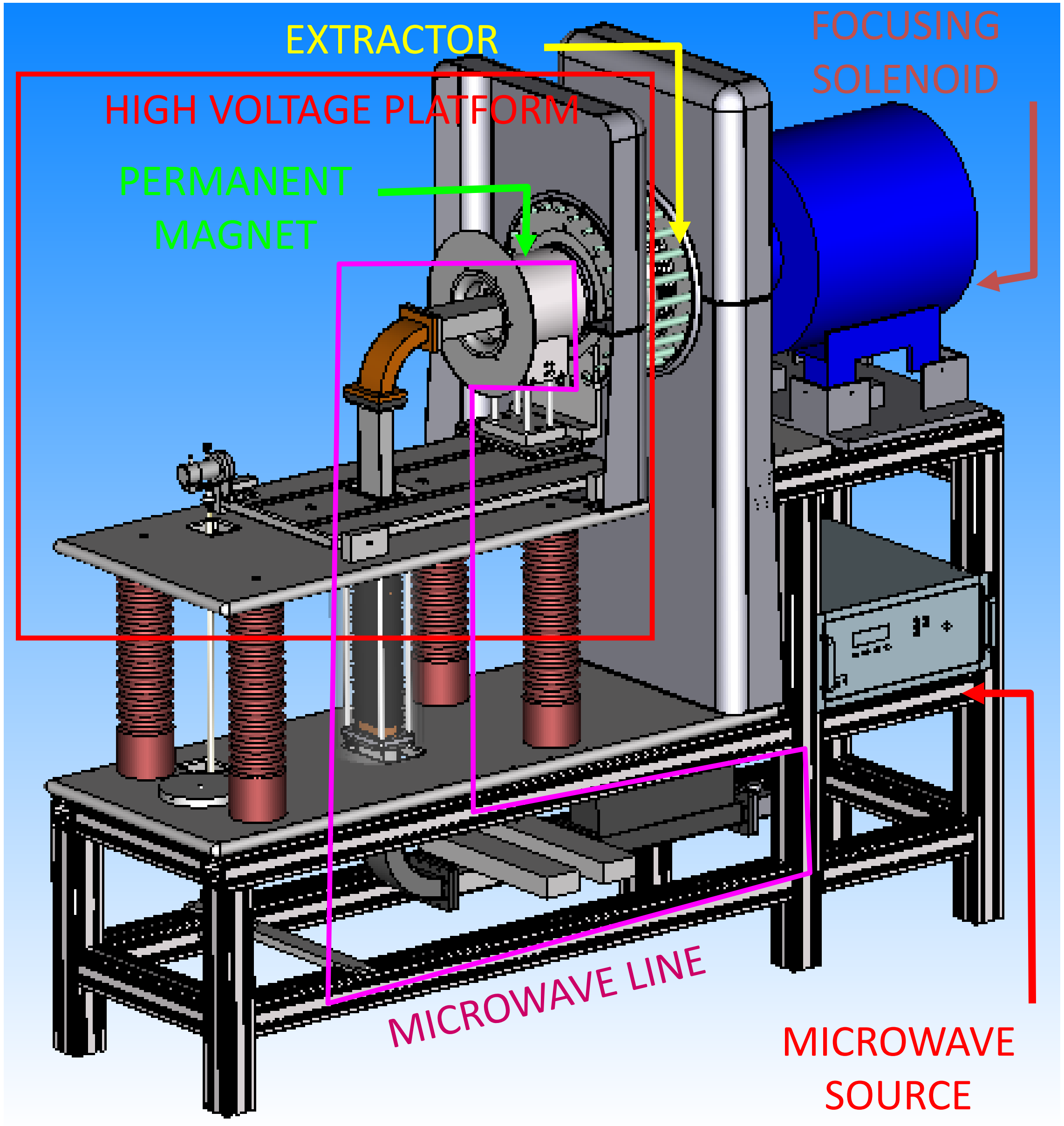


ION EXTRACTION SYSTEM

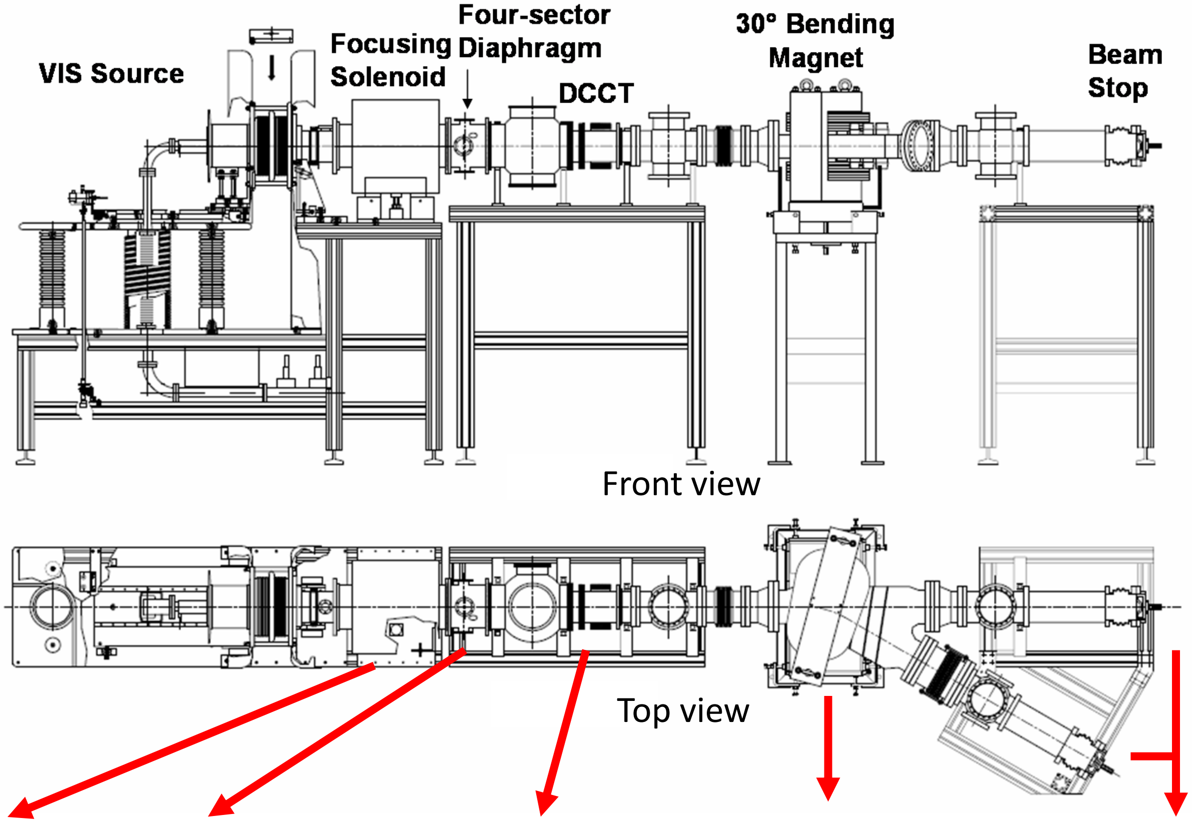


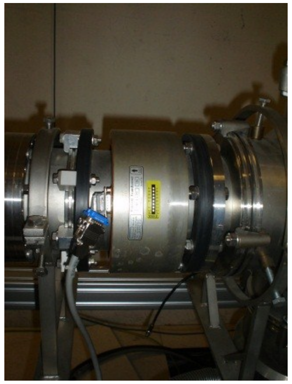
YOU ARE NOT OBLIGED TO DESIGN COMPLEX SYSTEM

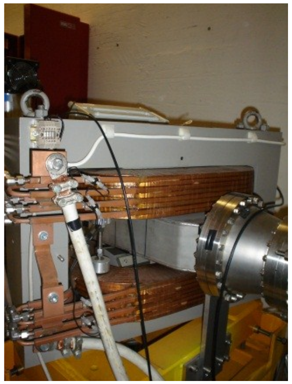
VIS DESCRIPTION



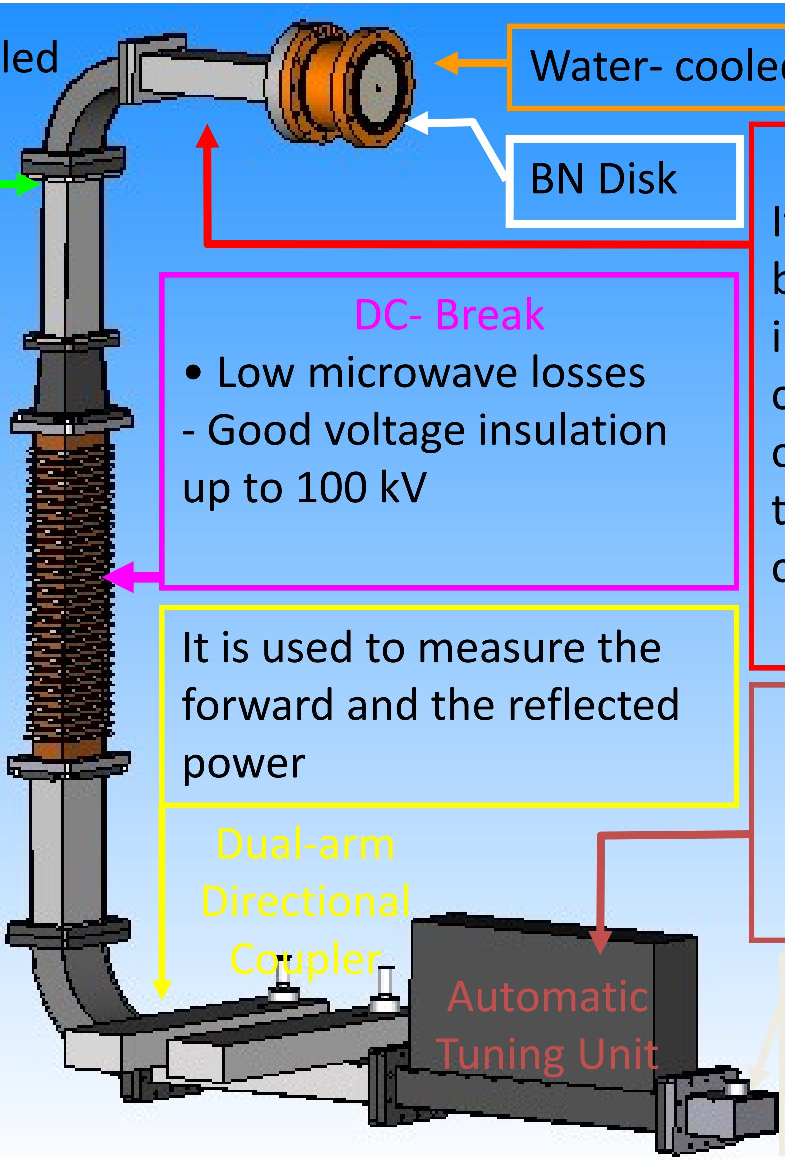
VIS BEAM LINE DESCRIPTION







MICROWAVE LINE 1/3



Water-cooled
Bend

Water- cooled copper plasma chamber

BN Disk

Matching Transformer

It realizes a progressive match between the waveguide impedance and the plasma chamber impedance, thus concentrating the electric field at the center of the plasma chamber

Microwave pressure window

Placed behind the bend in order to avoid any damage due to the back-streaming electrons

DC- Break

- Low microwave losses

- Good voltage insulation up to 100 kV

It is used to measure the forward and the reflected power

Dual-arm Directional Coupler

Adjusts the modulus/phase of the incoming wave to match the plasma impedance

Automatic Tuning Unit

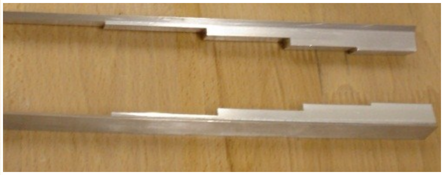
Waveguide /Coax Adapter

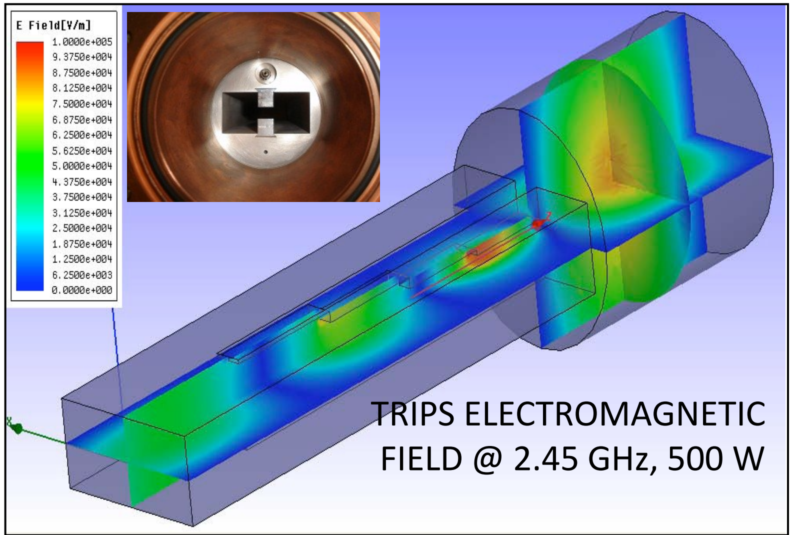
Excytes the TE_{10} dominant mode in WR340 waveguide

MW LINE 2/3: MATCHING TRANSFORMER

Matching transformer coupled to the plasma chamber

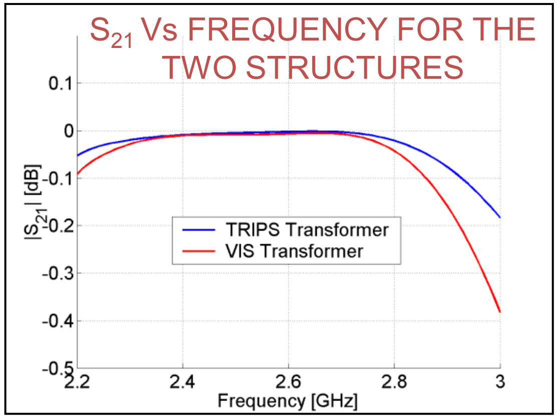
Four step double ridges





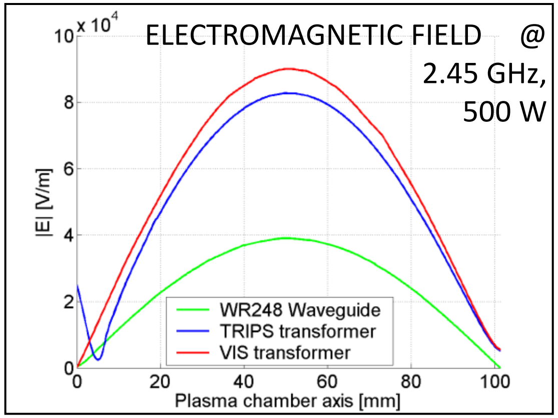
TRIPS ELECTROMAGNETIC FIELD @ 2.45 GHz, 500 W

S_{21} Vs FREQUENCY FOR THE TWO STRUCTURES

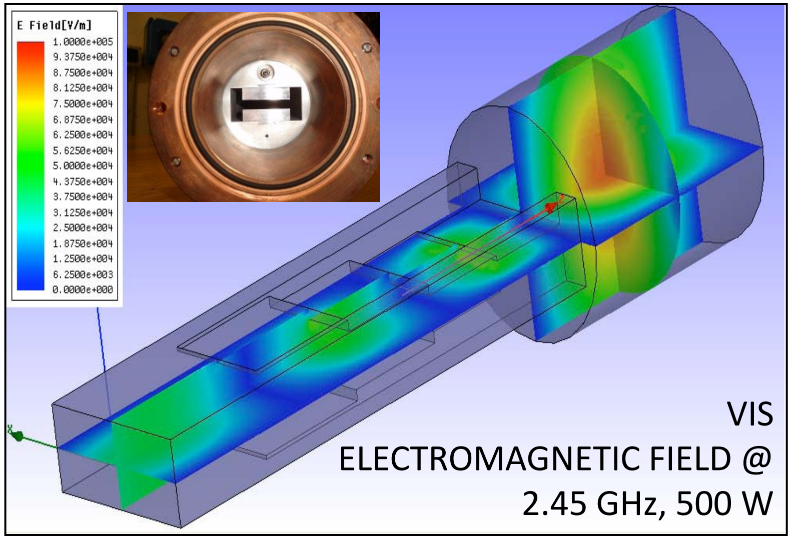


VIS TRANSFORMER INSERTION LOSS 0.0085 dB @ 2.45 GHz

ELECTROMAGNETIC FIELD @ 2.45 GHz, 500 W



10 % ENHANCEMENT WITH VIS TRANSFORMER

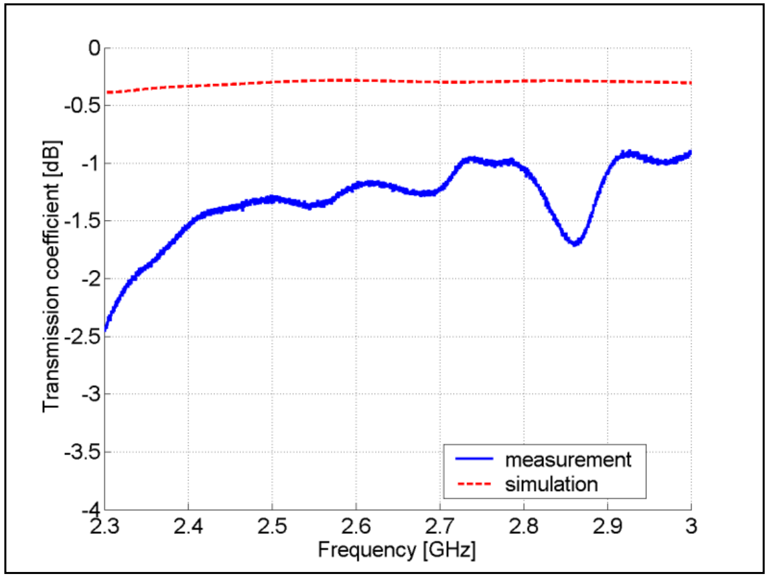


VIS ELECTROMAGNETIC FIELD @ 2.45 GHz, 500 W

MW LINE 3/3 WAVEGUIDE DC-BREAK

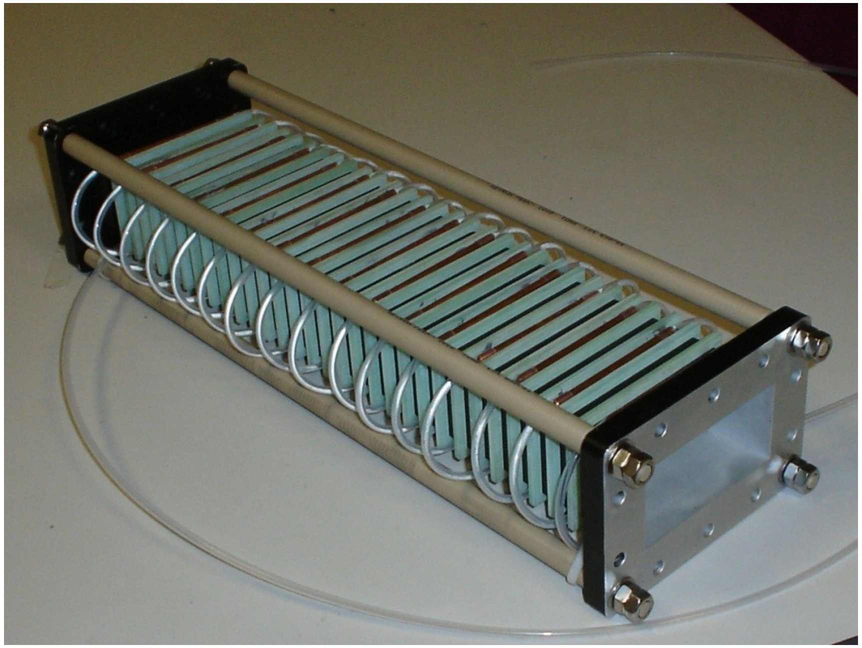
DESCRIPTION

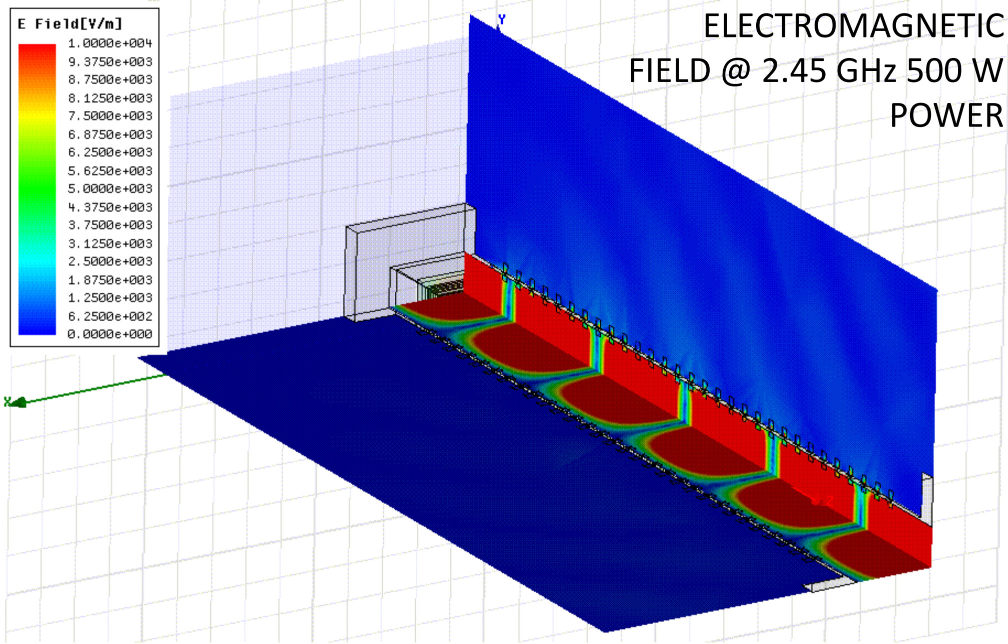
It consists of 31 aluminum sections of a WR340 waveguide insulated one each other by means of 30 fiberglass disks 0.5 mm thick in the metal separation gap



PERFORMANCES

- Electrical Insulation up to 100 kV
- Transmission coefficient -1.4 dB @ 2.45 GHz
- Low radiated electromagnetic field

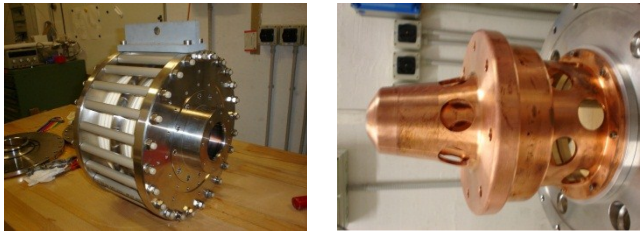




ELECTROMAGNETIC FIELD @ 2.45 GHz 500 W POWER

ION EXTRACTION SYSTEM

The extraction geometry will employ only four electrodes. A plasma electrode at 80 kV voltage, two water-cooled grounded electrodes screening electrode and a 3.5 kV negatively biased electrode inserted between the two grounded electrodes in order to avoid secondary electrons due to residual gas ionisation going up to the extraction area.

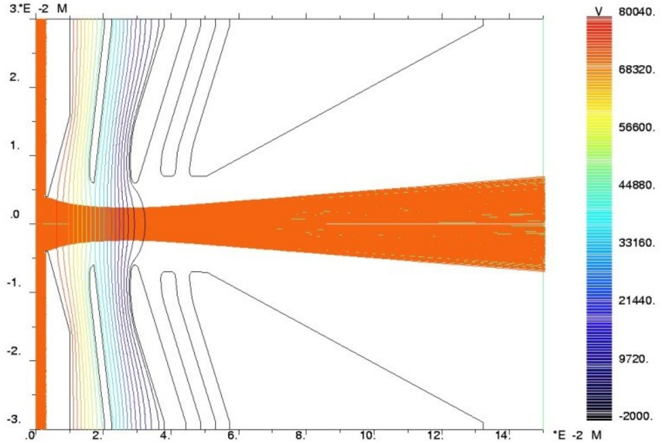


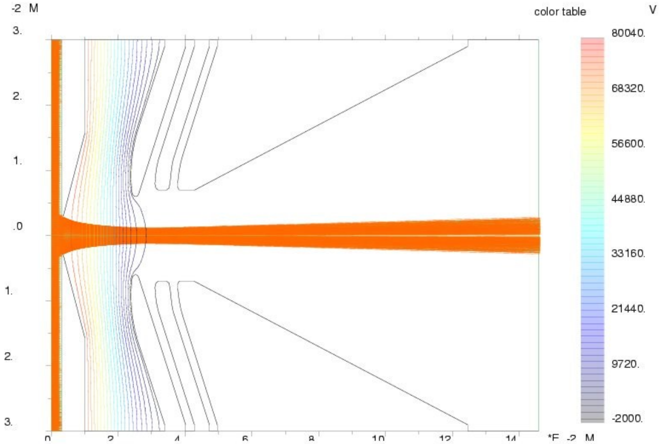
TRIPS Five-electrodes topology

- on-line optimisation of the extracted beam
- wide range of operations (10-60 mA)

VIS Four-electrodes topology

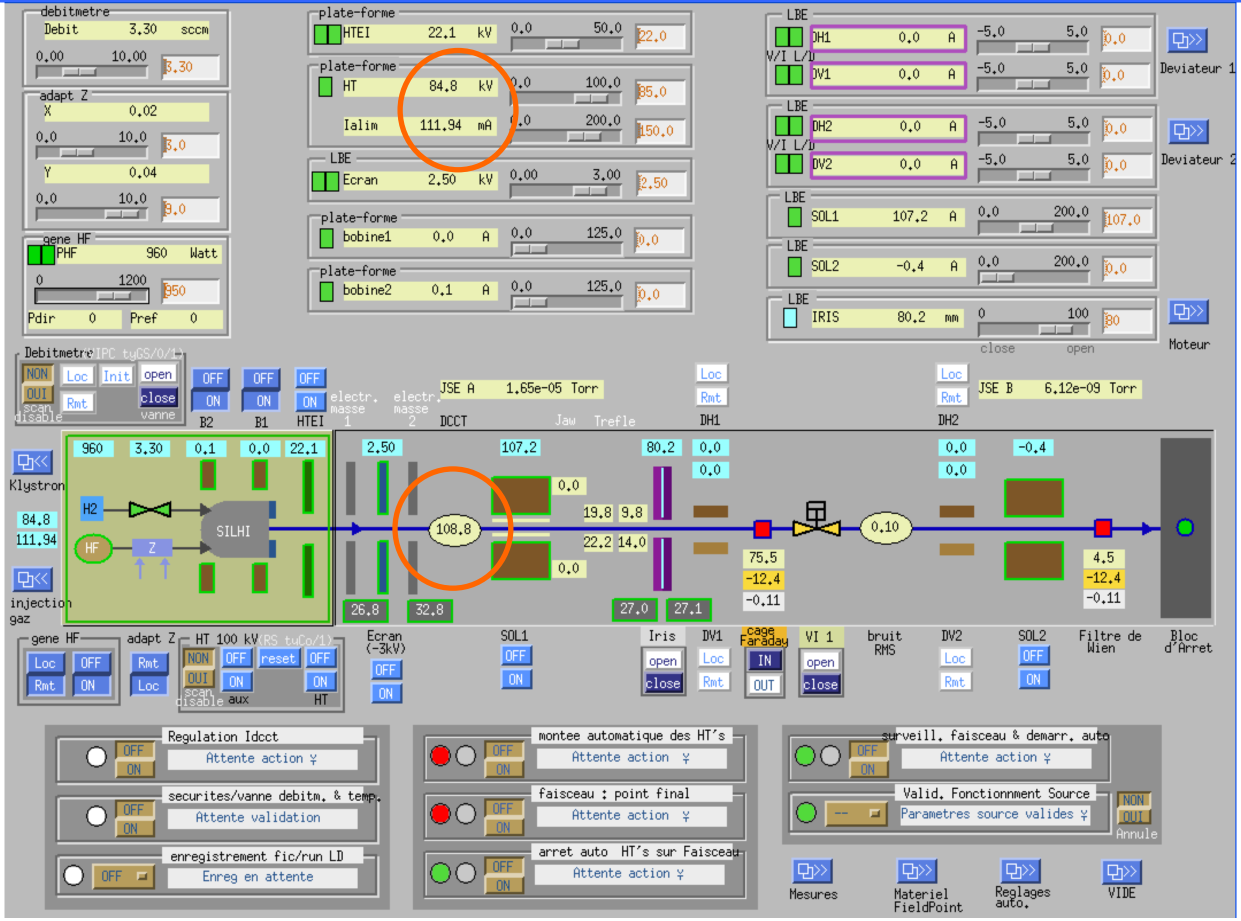
optimized for a 40 mA beam (90% proton, 10% H_2^+)





The rms normalized emittance calculated with Axcel code, 11 cm far from the extraction electrode is 0.04 π mm mrad.

High Intensity PM source (CEA, Saclay)



debitmetre
Debit 3,30 sccm
0,00 10,00 3,30

adapt Z
X 0,02
0,0 10,0 3,0
Y 0,04
0,0 10,0 9,0

gene HF
PHF 960 Watt
0 1200 950
Pdir 0 Pref 0

plate-forme
HTEI 22,1 kV 0,0 50,0 22,0

plate-forme
HT 84,8 kV 0,0 100,0 85,0
Ialim 111,94 mA 0,0 200,0 150,0

LBE
Ecran 2,50 kV 0,00 3,00 2,50

plate-forme
bobine1 0,0 A 0,0 125,0 0,0

plate-forme
bobine2 0,1 A 0,0 125,0 0,0

LBE V/I L/D
DH1 0,0 A -5,0 5,0 0,0
DV1 0,0 A -5,0 5,0 0,0

LBE V/I L/D
DH2 0,0 A -5,0 5,0 0,0
DV2 0,0 A -5,0 5,0 0,0

LBE
SOL1 107,2 A 0,0 200,0 107,0

LBE
SOL2 -0,4 A 0,0 200,0 0,0

LBE
IRIS 80,2 mm 0 100 80

JSE A 1,65e-05 Torr
JSE B 6,12e-09 Torr

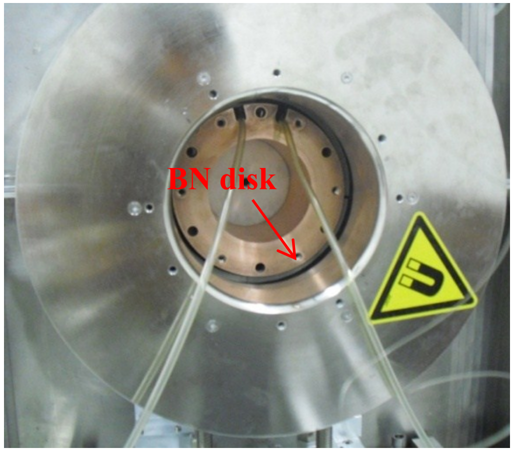
Regulation Idcct: Attente action
securites/vanne debitm. & temp.: Attente validation
enregistrement fic/run LD: Enreg en attente
montee automatique des HT's: Attente action
faisceau : point final: Attente action
arret auto HT's sur Faisceau: Attente action
surveill. faisceau & demarr. auto: Attente action
Valid. Fonctionnment Source: Parametres source valides

109 mA à 85 kV (75% H^+) with extraction hole 9 mm

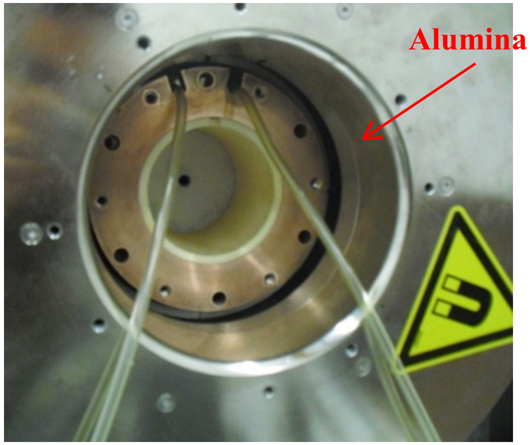
The PM source of Saclay produced 85 mA total beam at 80 kV, for 4 days with no beam off

Passive method to increase and to improve the intensity of the ion beam

BN disk and wall coating effects



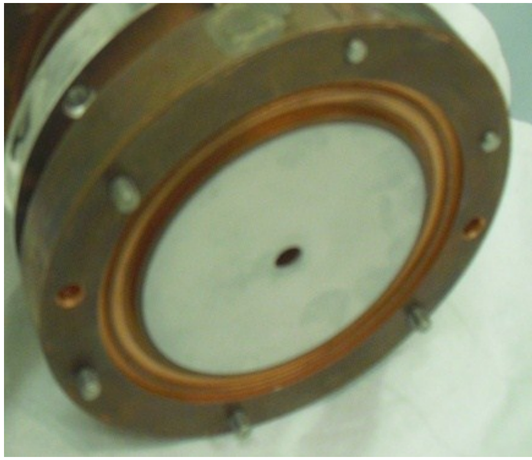
Configuration with BN disk and alumina



Configuration with BN disk and no alumina

AL_2O_3

- Inner diameter: 79 mm.
- Outer diameter: 89.5 mm.
- Length: 95 mm.



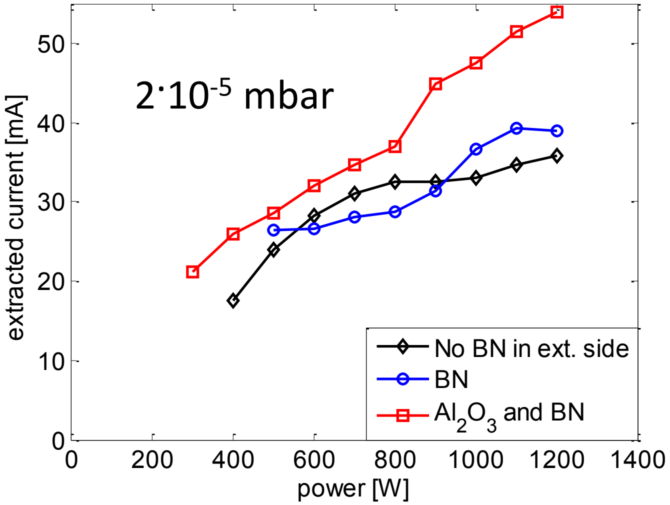
BN

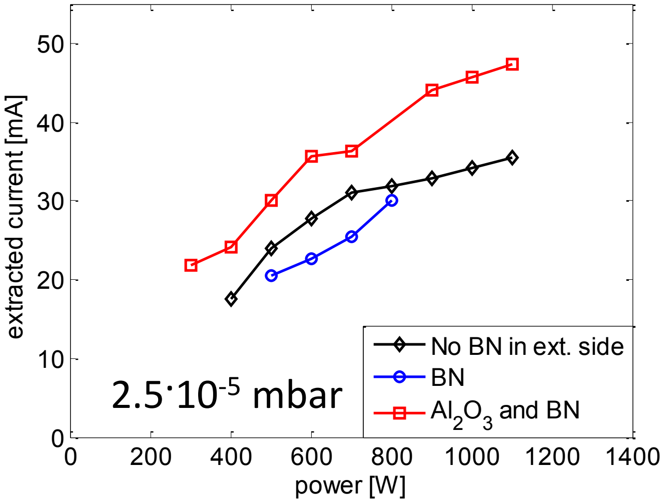
- Inner diameter: 7.8 mm.
- Outer diameter: 89.5 mm.

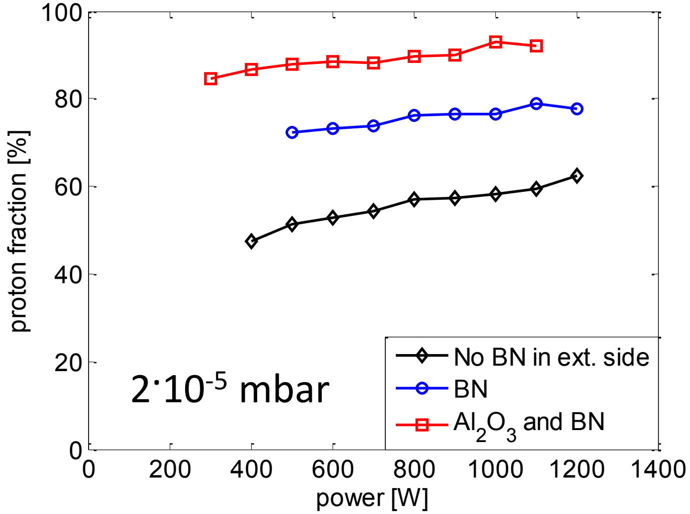
thick BN plates are located at two extremities of the plasma chamber.

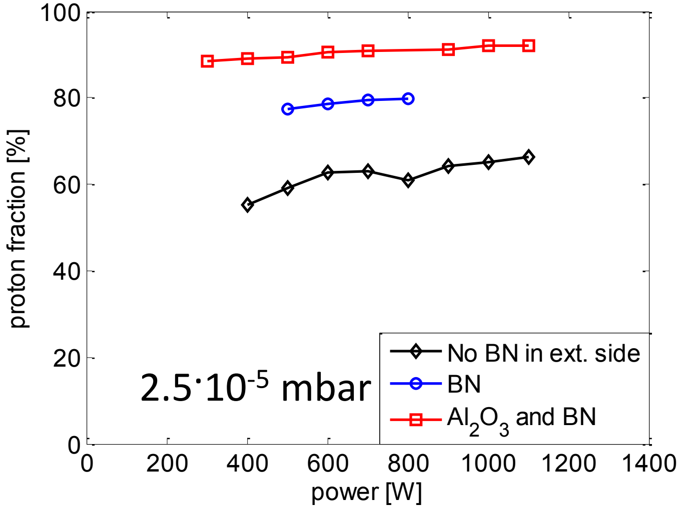
Al_2O_3 tube is nested within the plasma chamber, it covers the entire walls from one side to other

Figures show the trends of the extracted current and the proton fraction as a function of microwave powers at $2 \cdot 10^{-5}$ mbar (on the left) and at $2.5 \cdot 10^{-5}$ mbar (on the right) . The improvement of the performance with the use of the alumina tube and of the disk of BN disk can be explained by means of two different theories. For the first one the BN and the alumina are electron donors that influence the plasma essentially by emitting cold electrons. The second one explains this phenomenon by introducing the Simon currents within the plasma.









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 as it is SNS for H^-)
- 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 a free parameter
- Electron donors may help
- Microwave coupling may give some positive surprise
- Magnetic field probably not…
- Space charge will be always a nightmare!