Evolution of Microwave Discharge Ion Sources

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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^+	65	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: $\omega > \omega_{pe}$ →

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

↓

Upper limit to density: $n<n_c$

The introduction of a magnetic field opens different coupling mechanism:

- ***ELECTRON CYCLOTRON RESONANCE (ECR)***

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

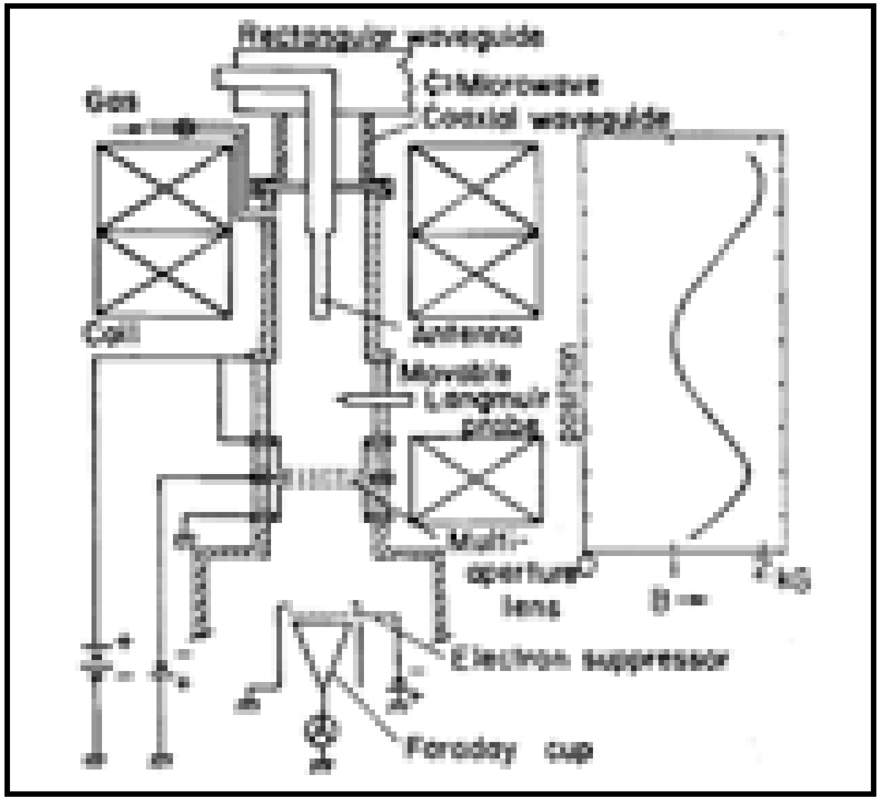
- ***OFF RESONANCE HEATING***

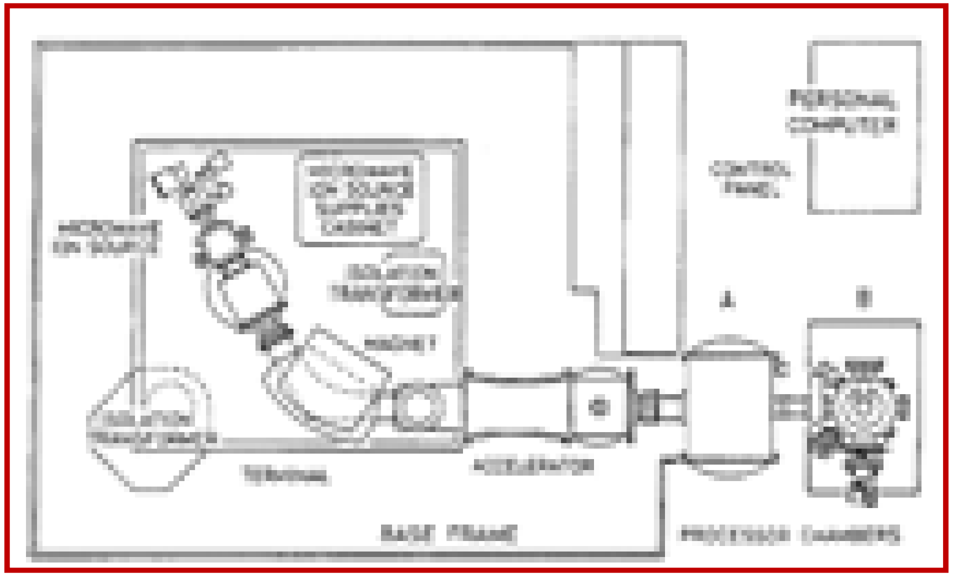
Energy absorbed by off resonance heating process

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

Pioneeristic work

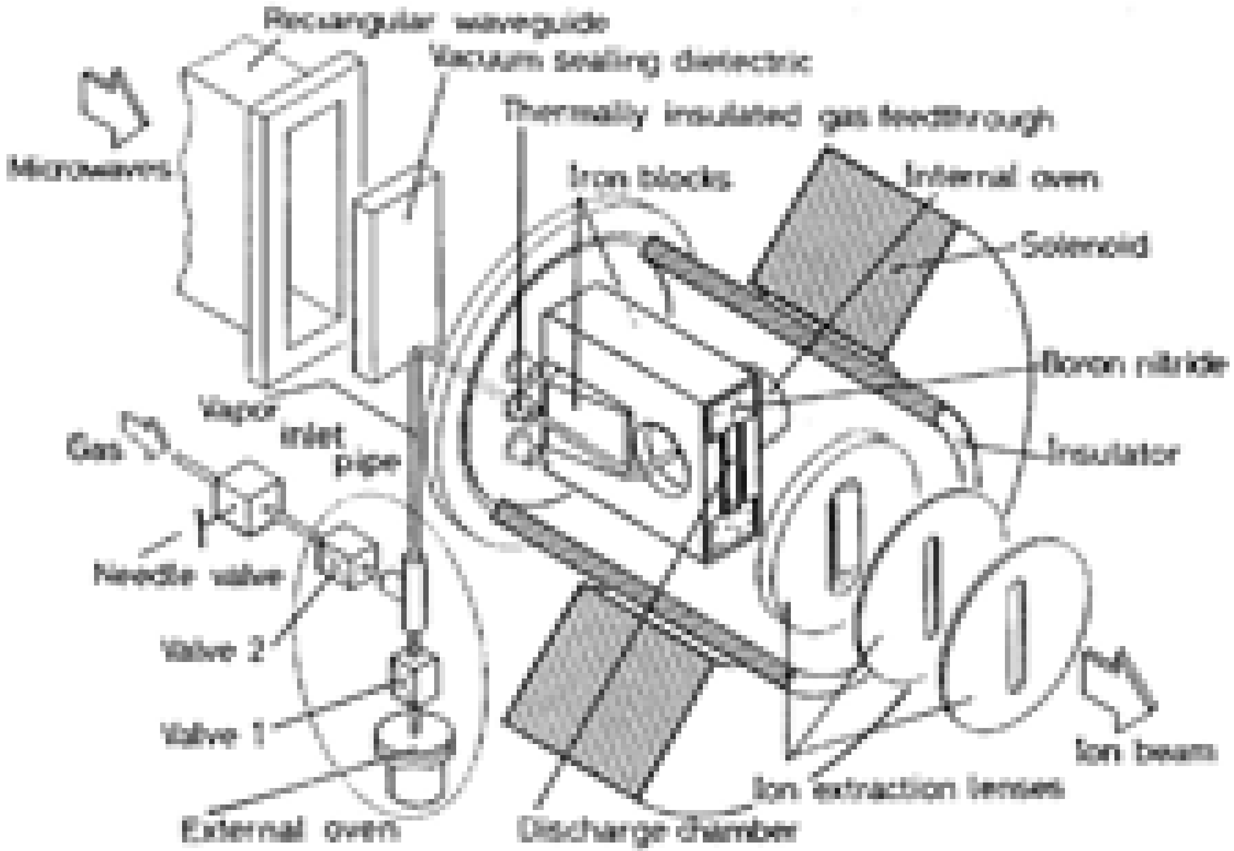
Sakudo
40 ys ago





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.

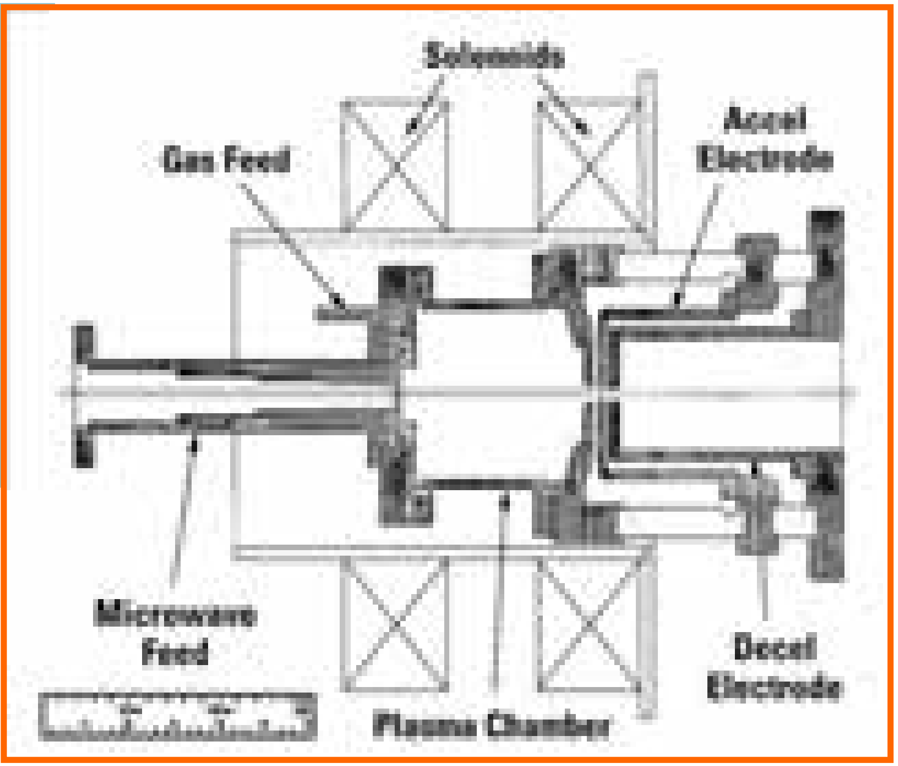
First Ion Implanter



Chalk River

Taylor &Wills

Beginning of '90s



Breakthrough simple design

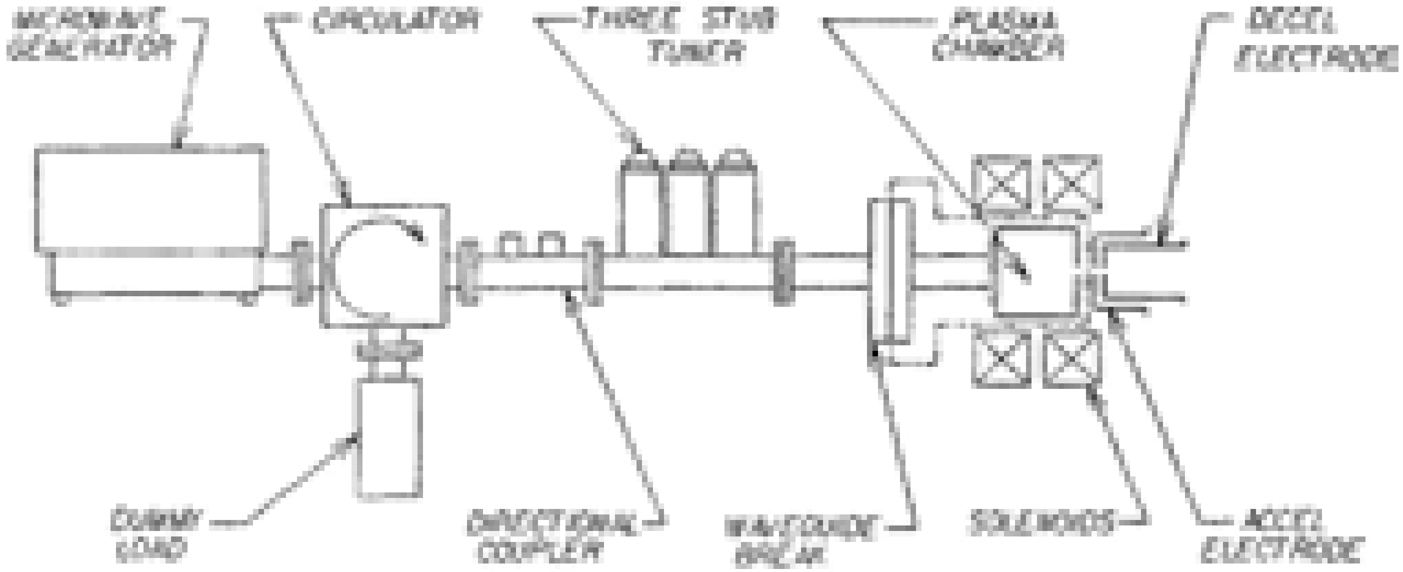
All successful sources are based on it

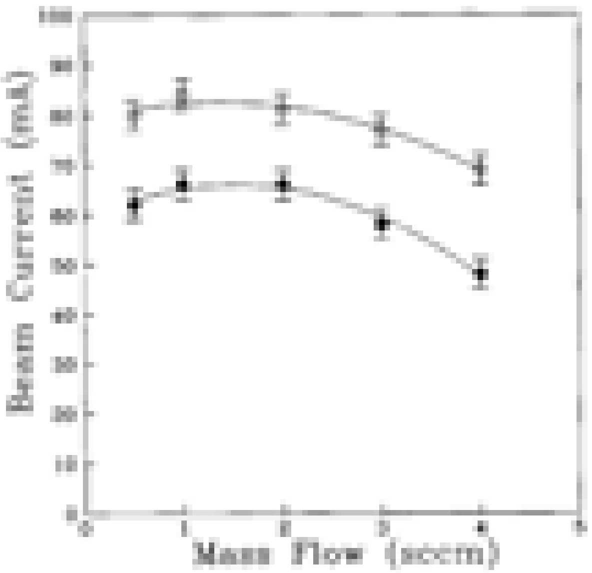
Discharge RF Power	**800W @ 2.45 GHz**
Total beam current	**96 mA**
Proton fraction	**86 %**
Proton beam	**82.5 mA**
Beam energy	**50 keV**
Beam emittance (rms norm.)	**0.23 π mm mrad**
Hydrogen mass flow	**$\approx$2 sccm**

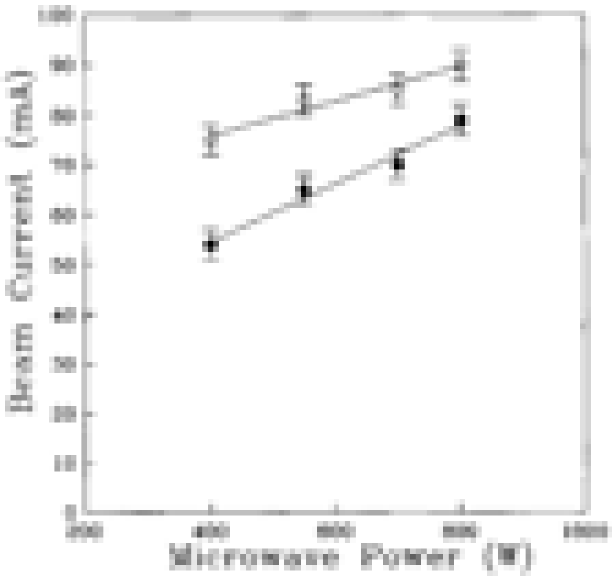
Chalk River

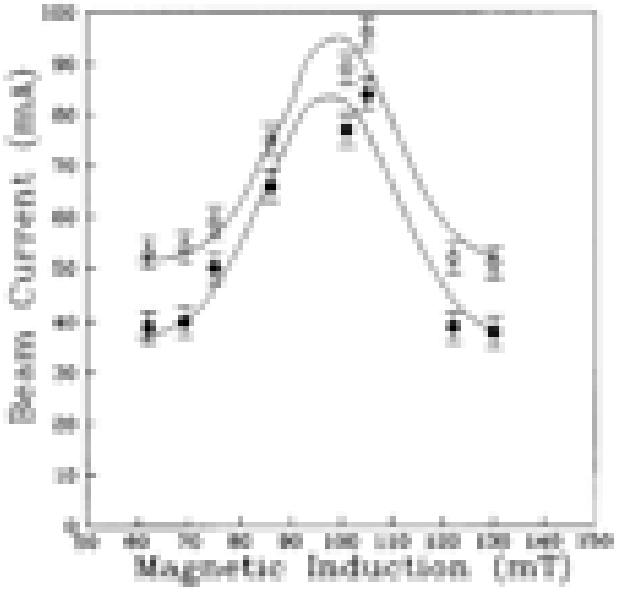
Taylor &Wills

Beginning of '90s





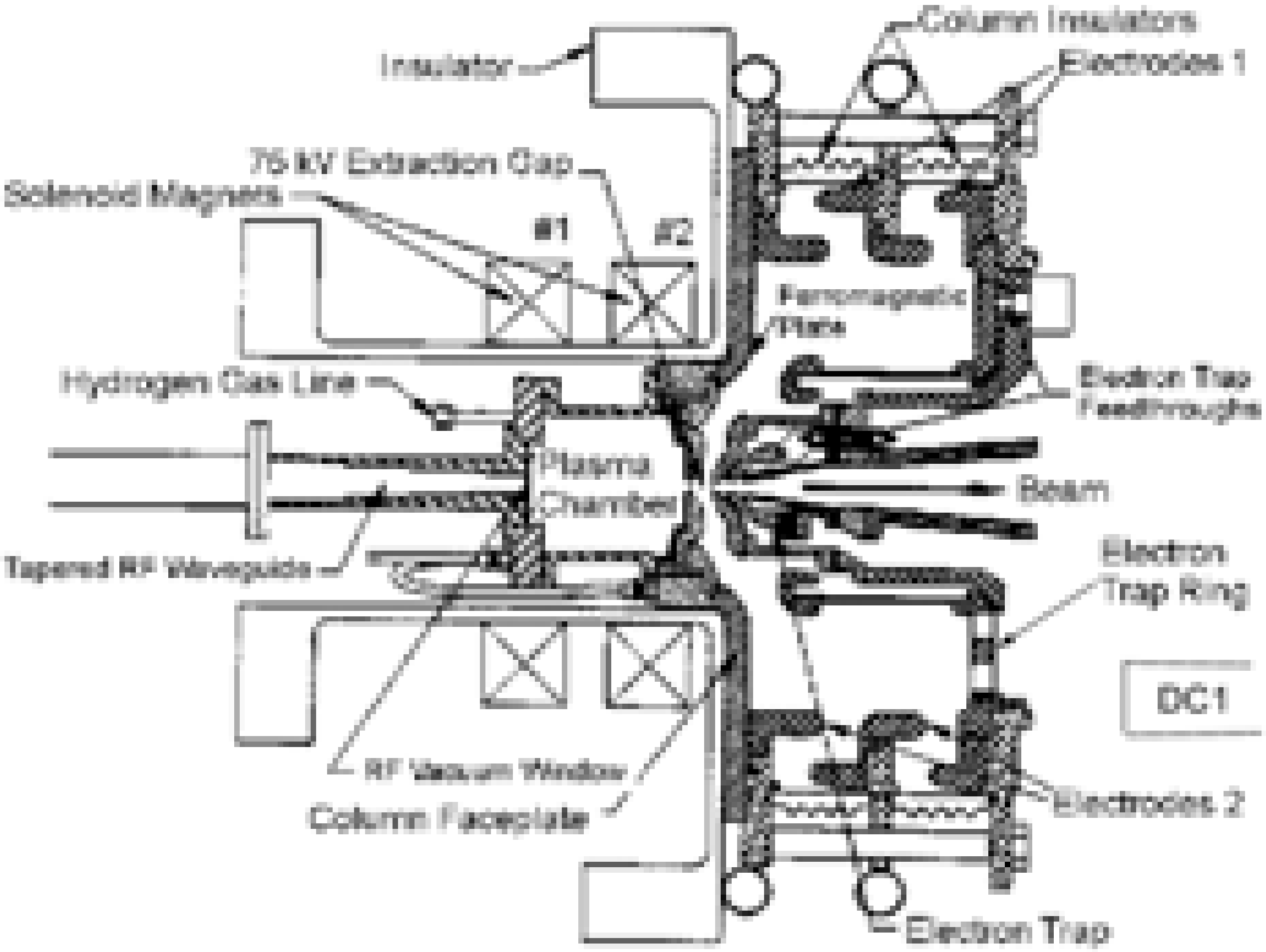


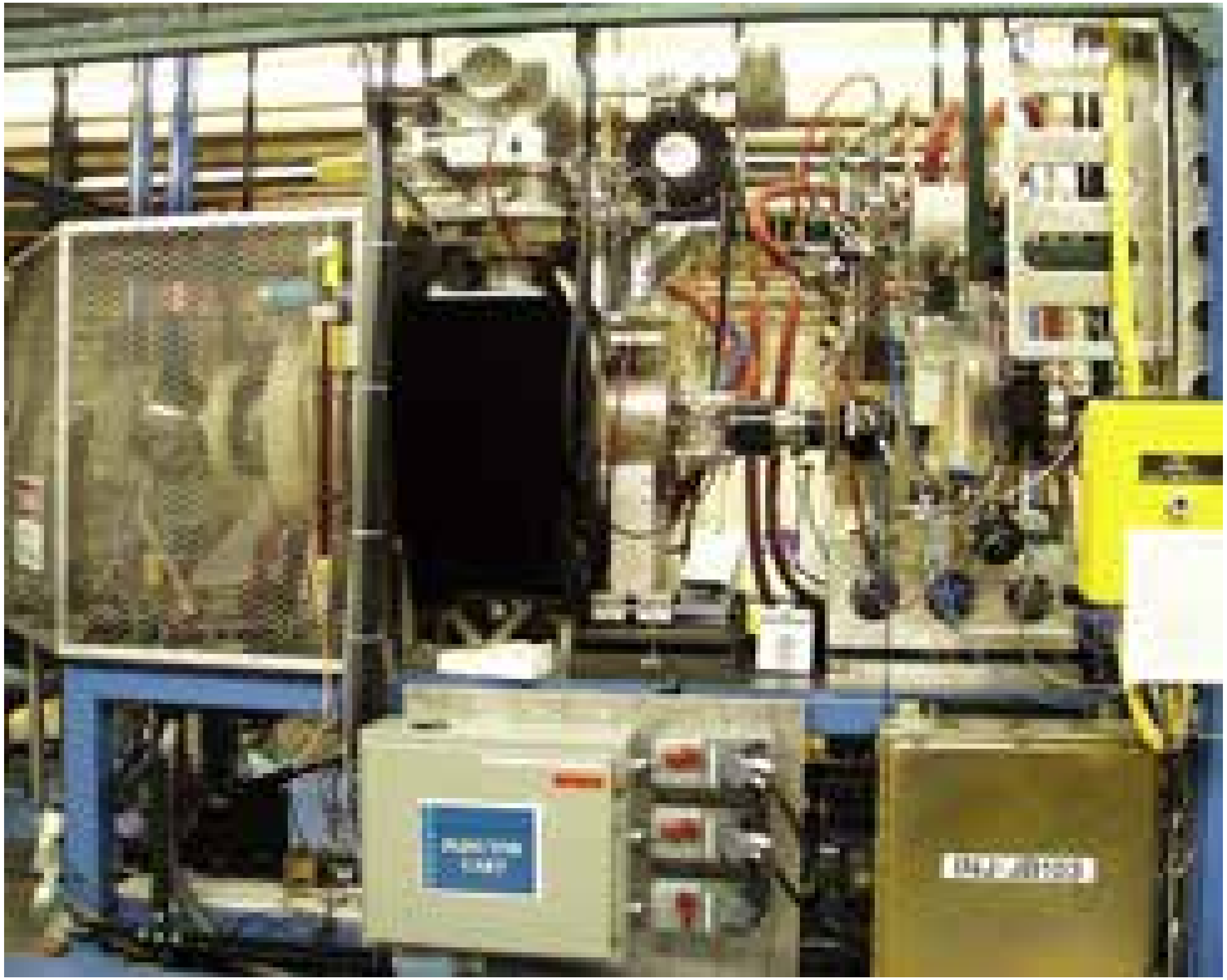


Main troubles:

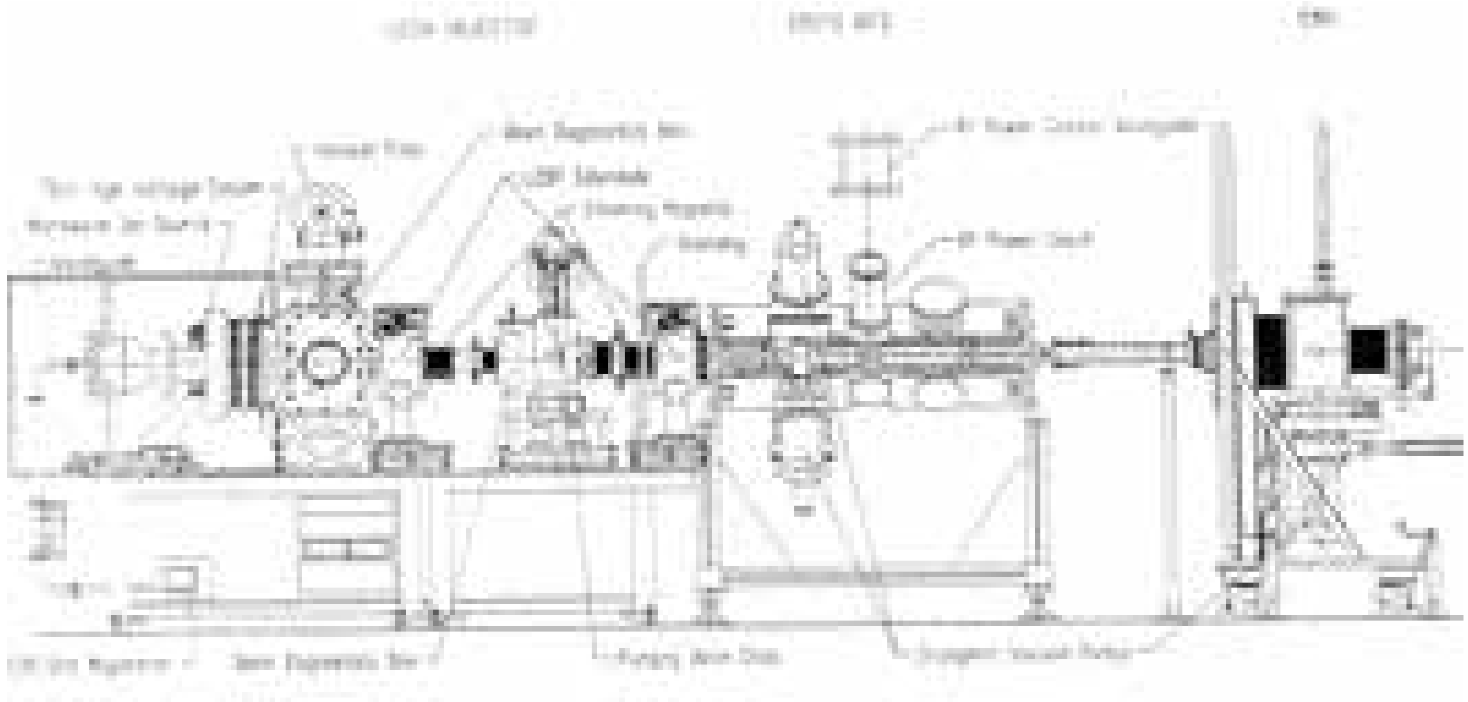
- **Losses in extraction**
- **Source reliability**
- **Emittance too high**
- **Current still not at the values needed**

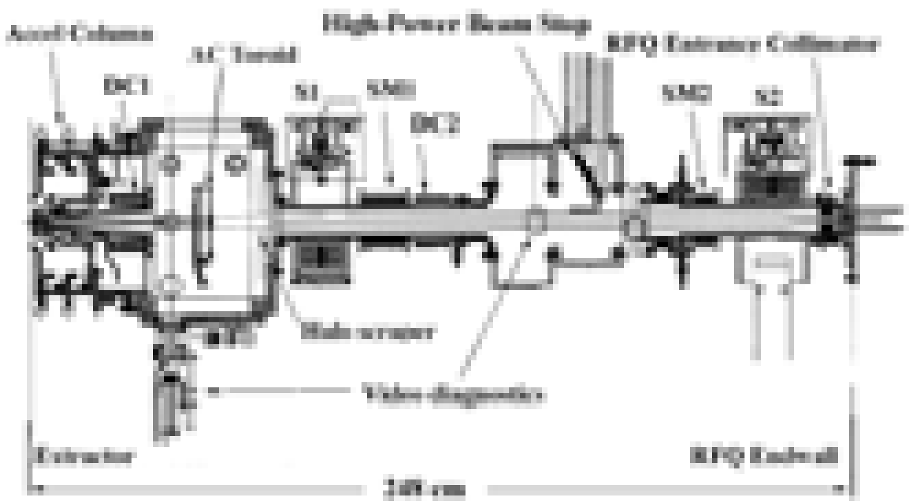
Los Alamos source for LEDA





Los Alamos source for LEDA





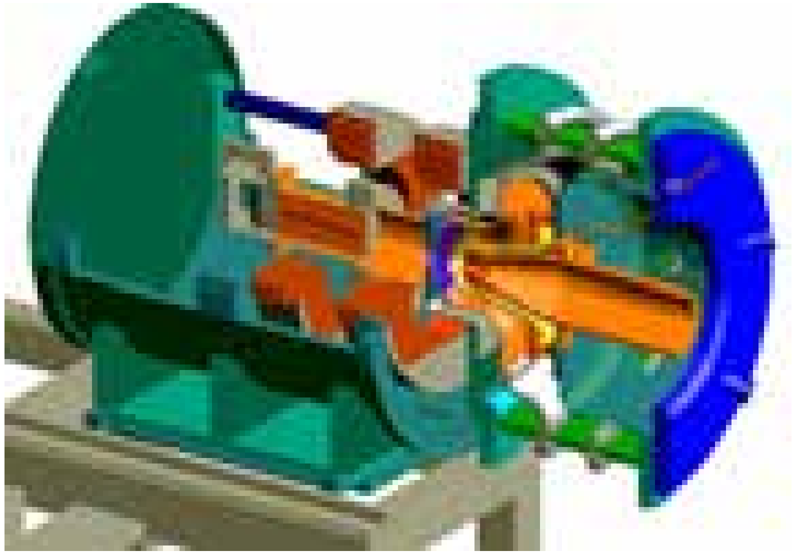
- Beam currents measured at DC1, DC2, and in the RFQ entrance collimator for 6.7 MeV RFQ.
- Beam focusing accomplished with LEBT solenoid magnets S1 and S2.
- Beam centroid controlled with steering magnets SM1 and SM2.

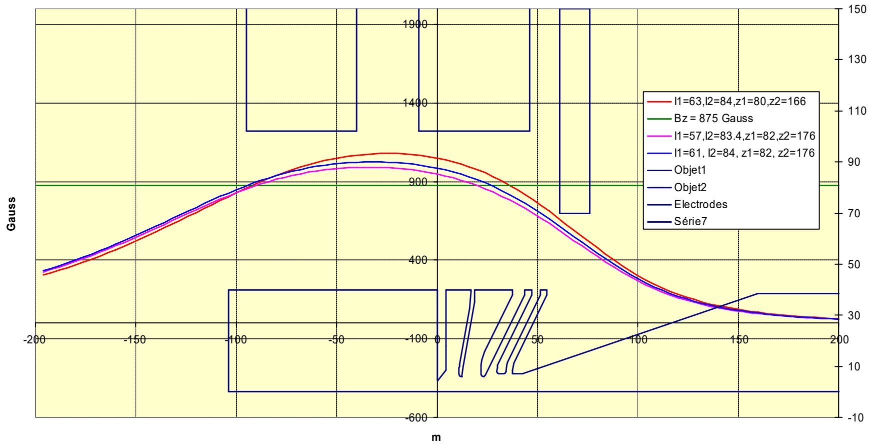
Injector Parameter	Value
H_2 gas flow (sccm)	4.1
Ion source pressure (mTorr)	2
Ion source gas efficiency (%)	24
Discharge power, 2.45 GHz (kW)	1.2
Beam energy (keV)	75
High voltage power supply current (mA)	165
DC1 current (mA)	154
DC2 current (mA)	120
Proton fraction (%)	90
Injector emittance (πmm-mrad)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

Main troubles:

- ~~**Losses in extraction**~~
- **Source reliability**
- **Emittance too high**
- ~~**Current still not at the values needed**~~
- **Remote control «infant mortality…»**

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 %

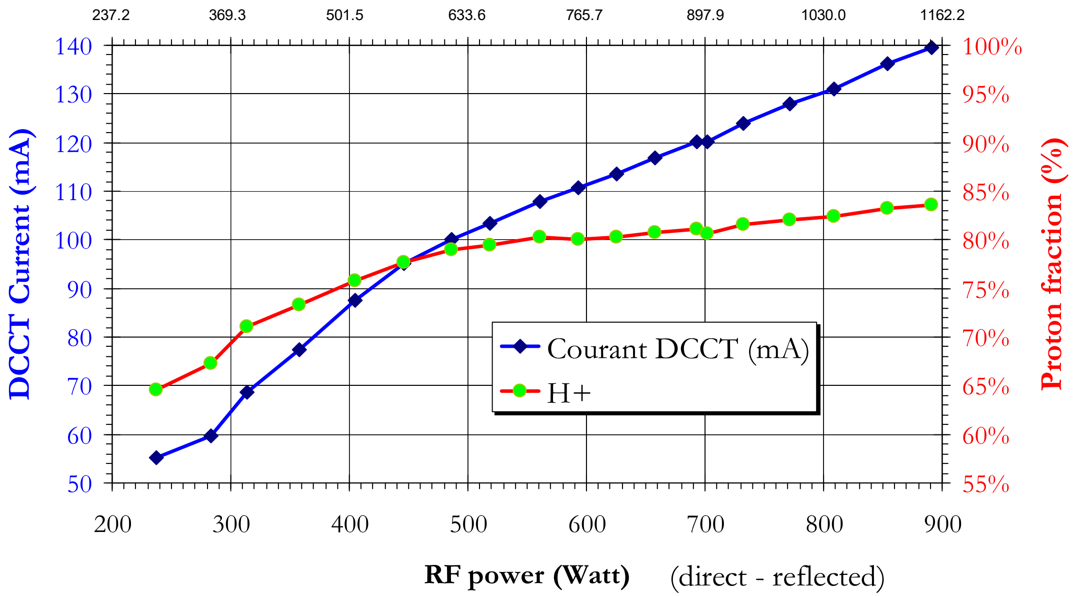
Emittance < 0.2 π mm.mrad

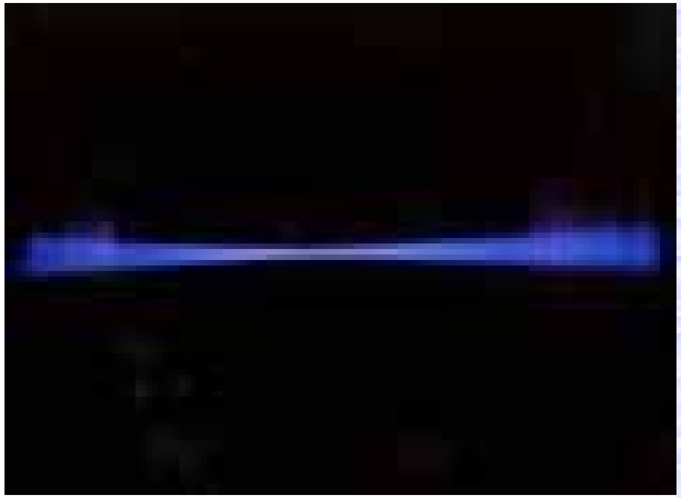
CW or pulsed mode

In CW mode, the source routinely produces

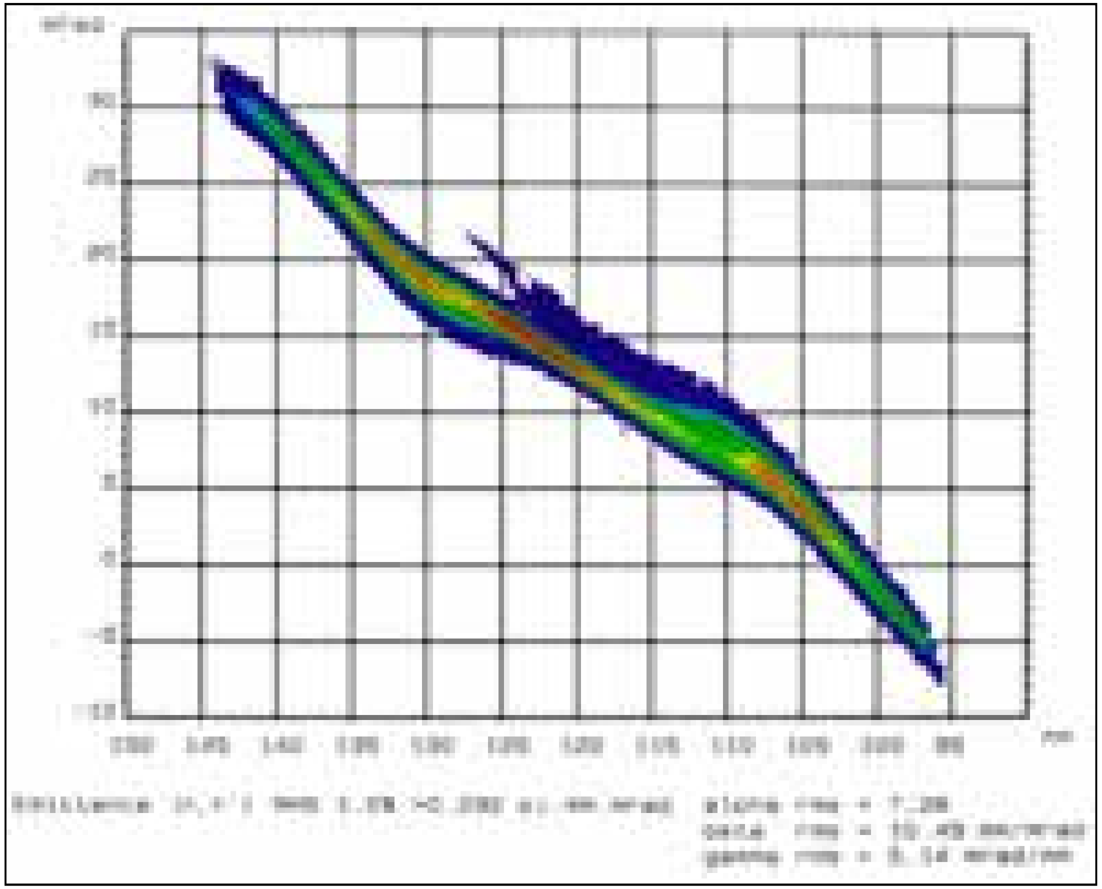
130 mA total (> 80% H^+)

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	155 (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	-

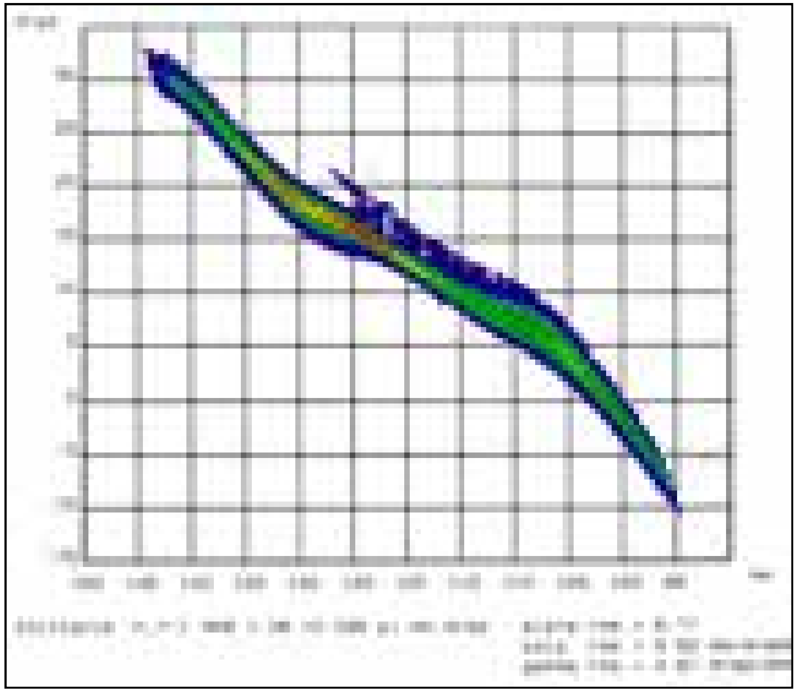


Emittance plot (99%) :

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

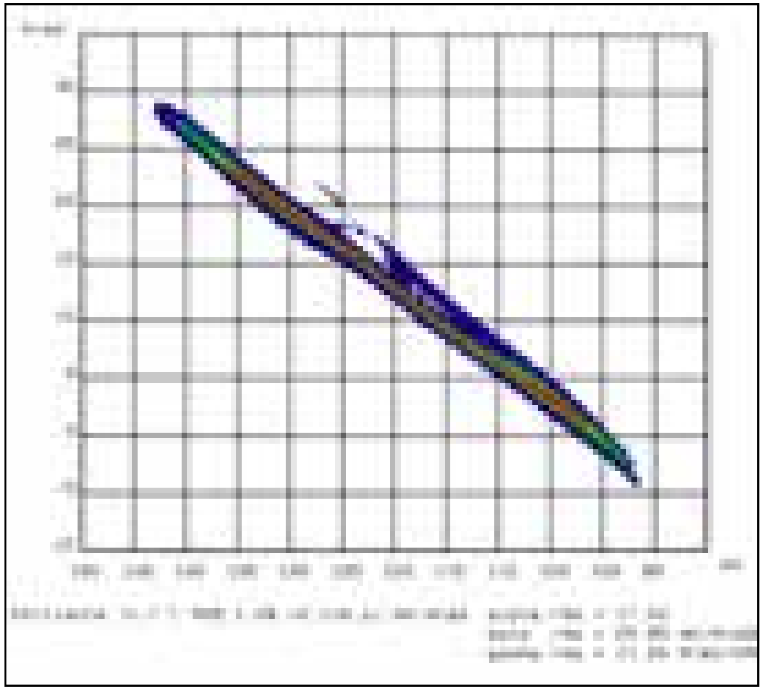
INFN-CEA campaign aimed to minimize emittance

Space charge compensation with ^{84}Kr



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

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

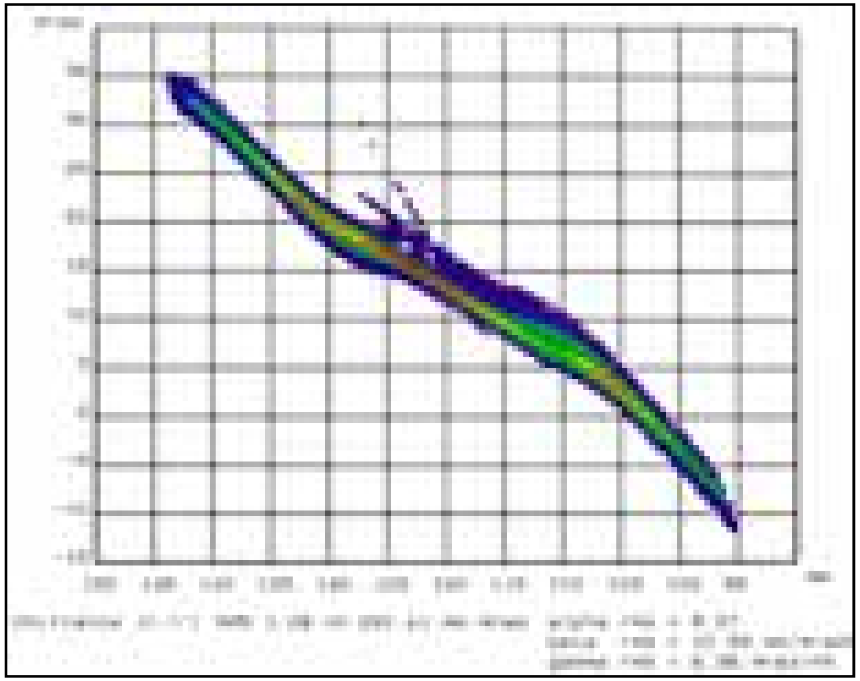


Emittance plot (99%) injecting 84Kr in the beam line:

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

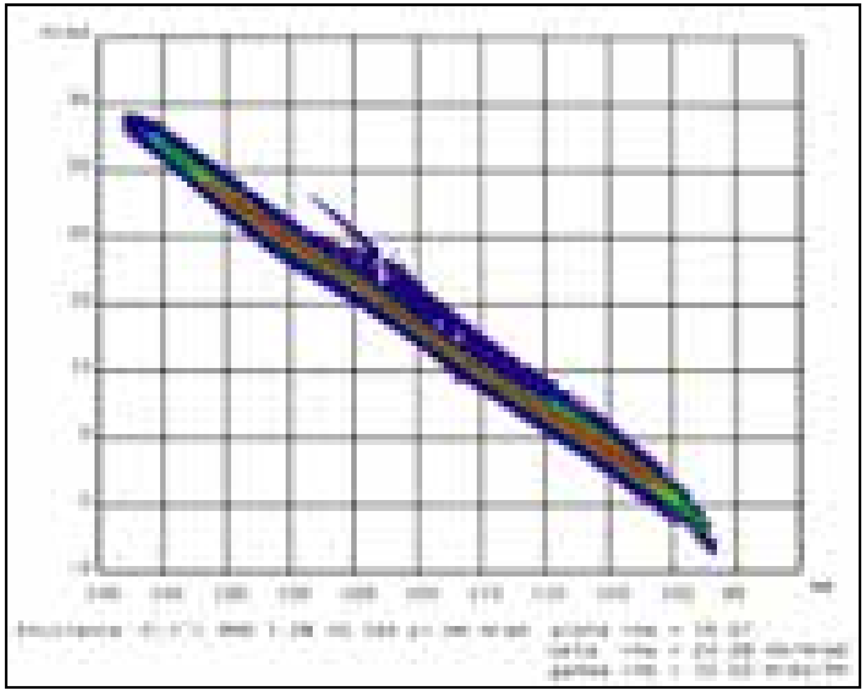
R. Gobin, R. Ferdinand, L.Celona, G. Ciavola, S. Gammino, Rev.Sci.Instr. 70(6),(1999), 2652

Space charge compensation with Ar



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

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

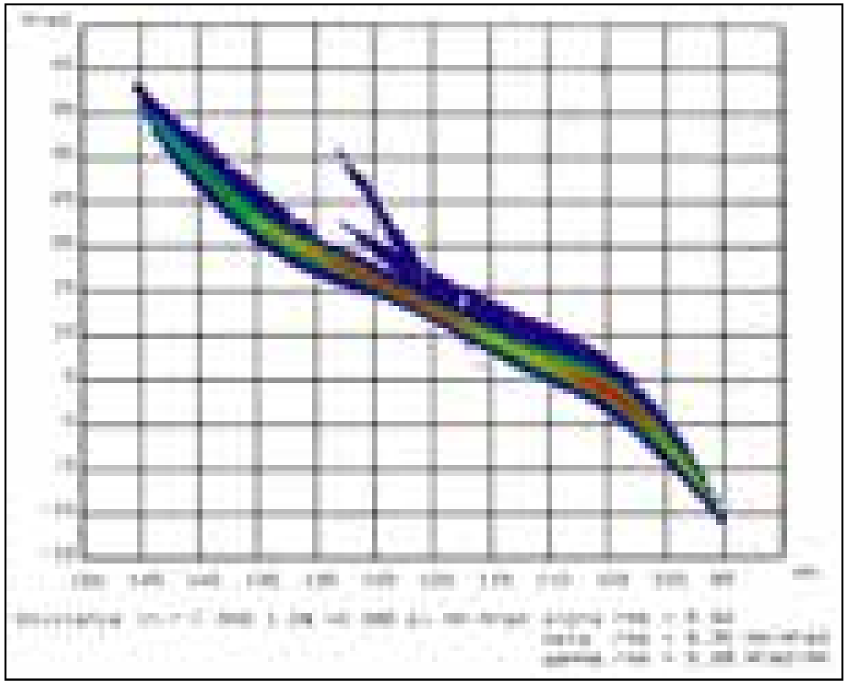


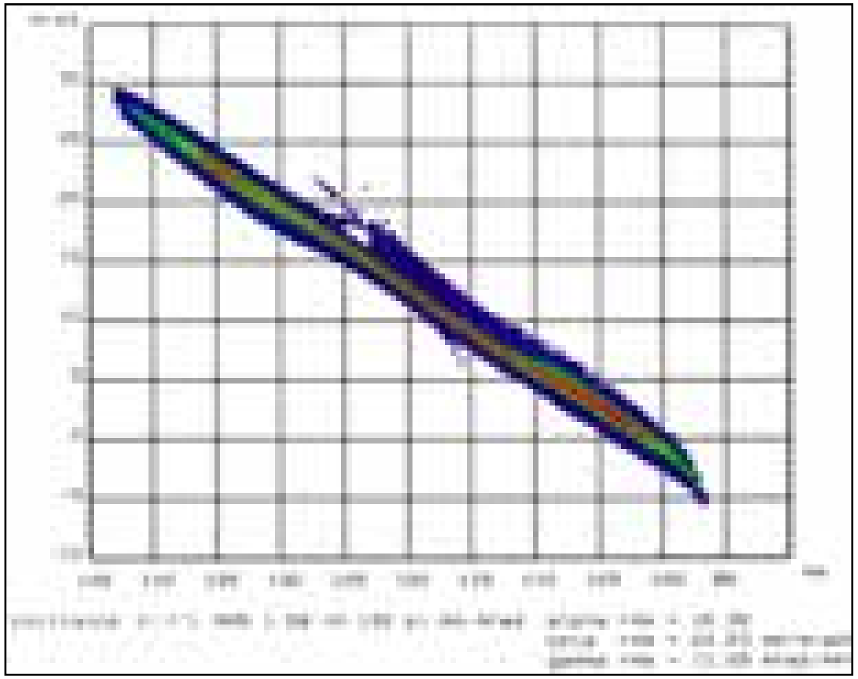
Emittance plot (99%) injecting Ar in the beam line:

p_1=4.5·10^{-5} T, p_2= 4.4·10^{-5} T $\Rightarrow$ **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 plot (99%) without injecting gas in the beam line:

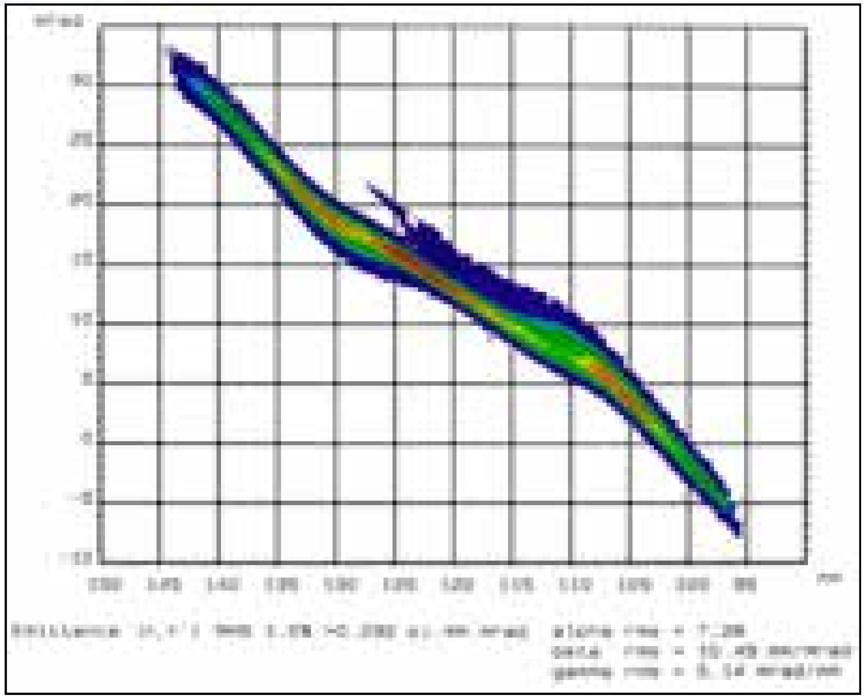
p_1=1.6·10^{-5} T, p_2= 1.2·10^{-5} T ⇒ **ε_{RMS}=0.386 π mm mrad**

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**

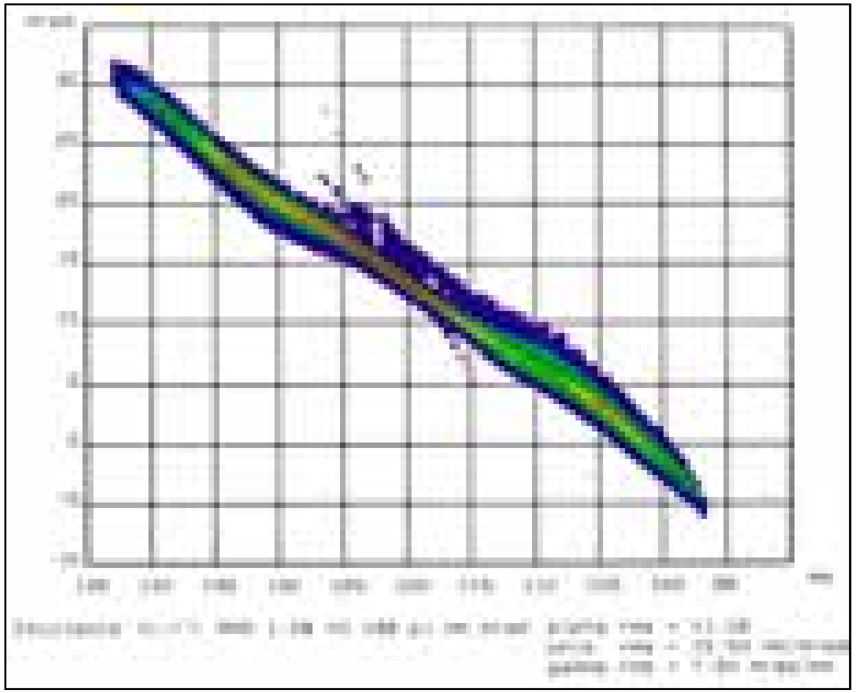
R. Gobin, R. Ferdinand, L.Celona, G. Ciavola, S. Gammino, Rev.Sci.Instr. 70(6),(1999), 2652

Space charge compensation with H2



Emittance 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}=0.292 π mm mrad**

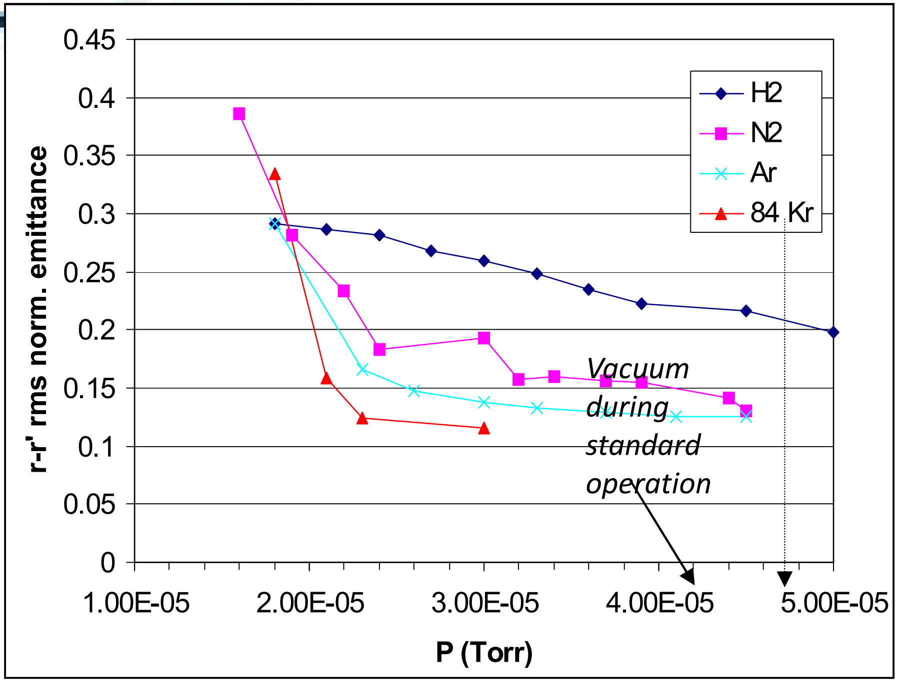


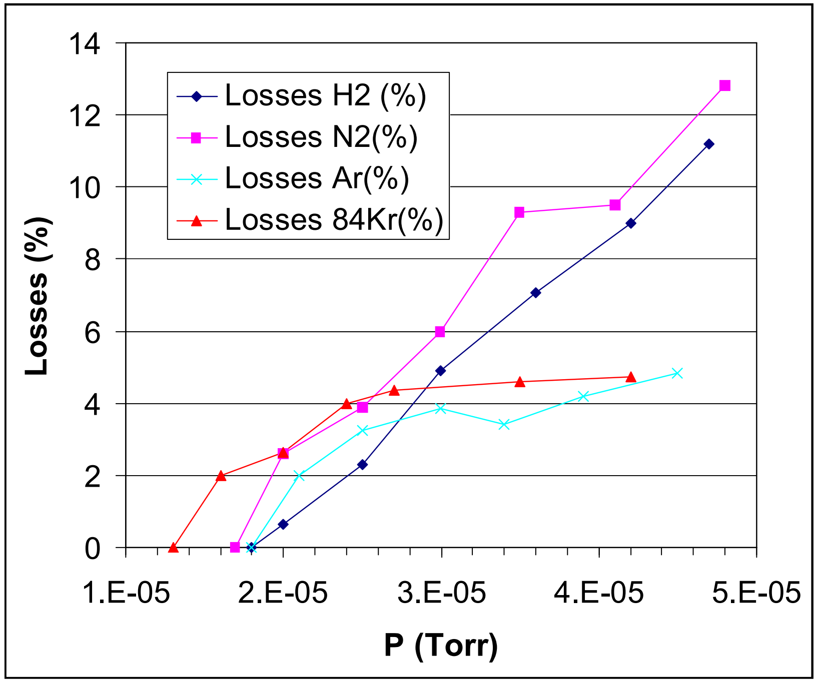
Emittance plot (99%) injecting H2 in the beam line:

p_1=5·10^{-5} T, p_2= 4.9·10^{-5} T ⇒ **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

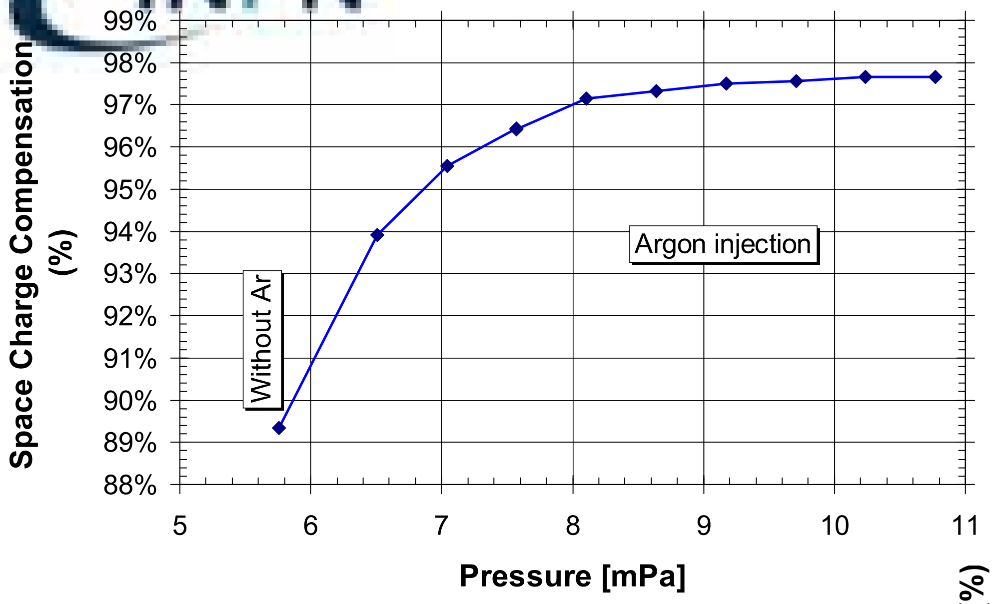


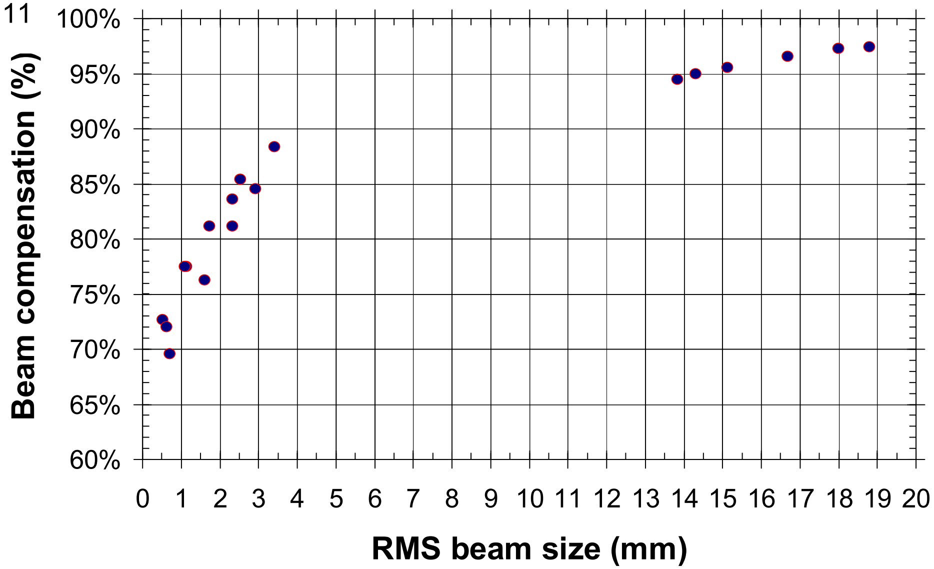


- ***In all the cases considered, a decrease of beam emittance has been observed with the increase of beam line pressure.***
- ***Using ^{84}Kr gas addition a decrease of a factor three in beam emittance has been achieved losing less than 5% of the beam current with a small increase of pressure (from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





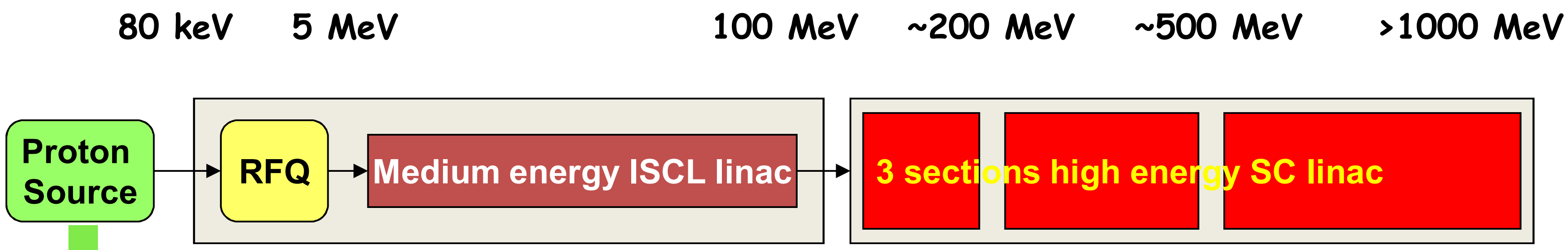
P—Y. Beaubais, R. Gobin, R. Ferdinand, L.Celona, G. Ciavola, S. Gammino,J. Sherman, Rev.Sci.Instr. 71(3),(2000), 1413

Investigation gave some ideas how to solve these issues

Main troubles:

- ~~**Losses in extraction**~~
- **Source reliability**
- **Emittance too high**
- ~~**Current still not at the values needed**~~
- **Remote control «infant mortality…»**

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:

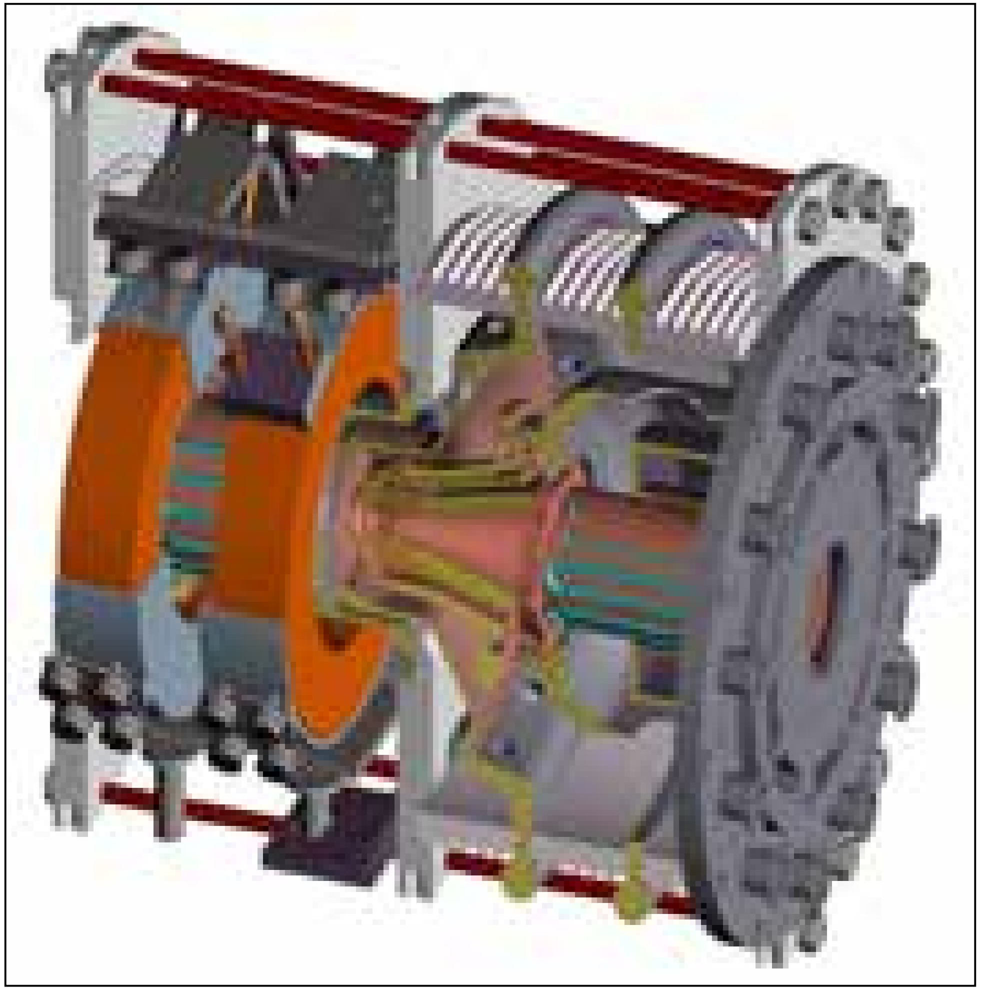
80 keV

Beam emittance:

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

Reliability:

close to 100%

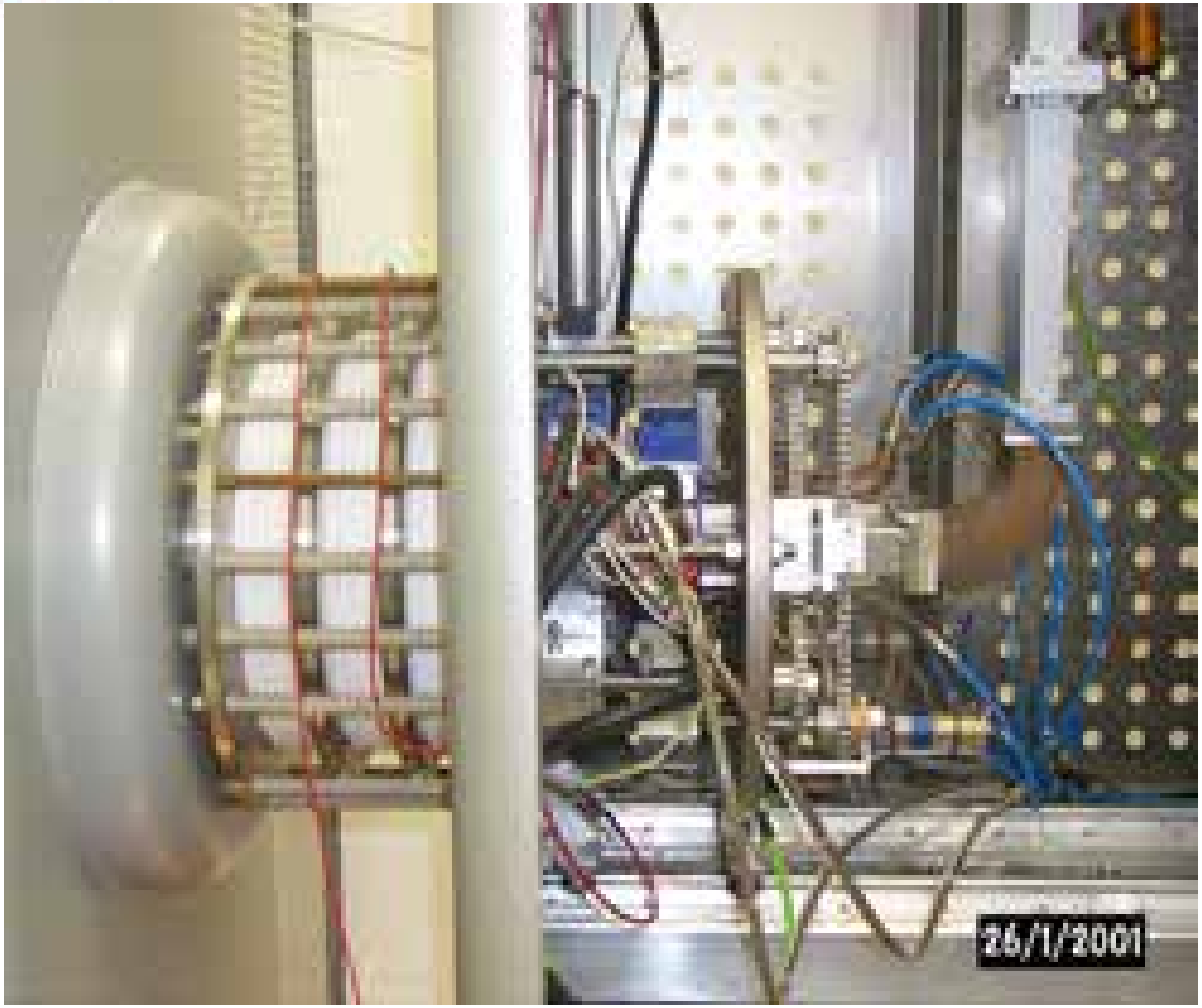


Based on CRNL-LANL-CEA design
MANY INNOVATIONS

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

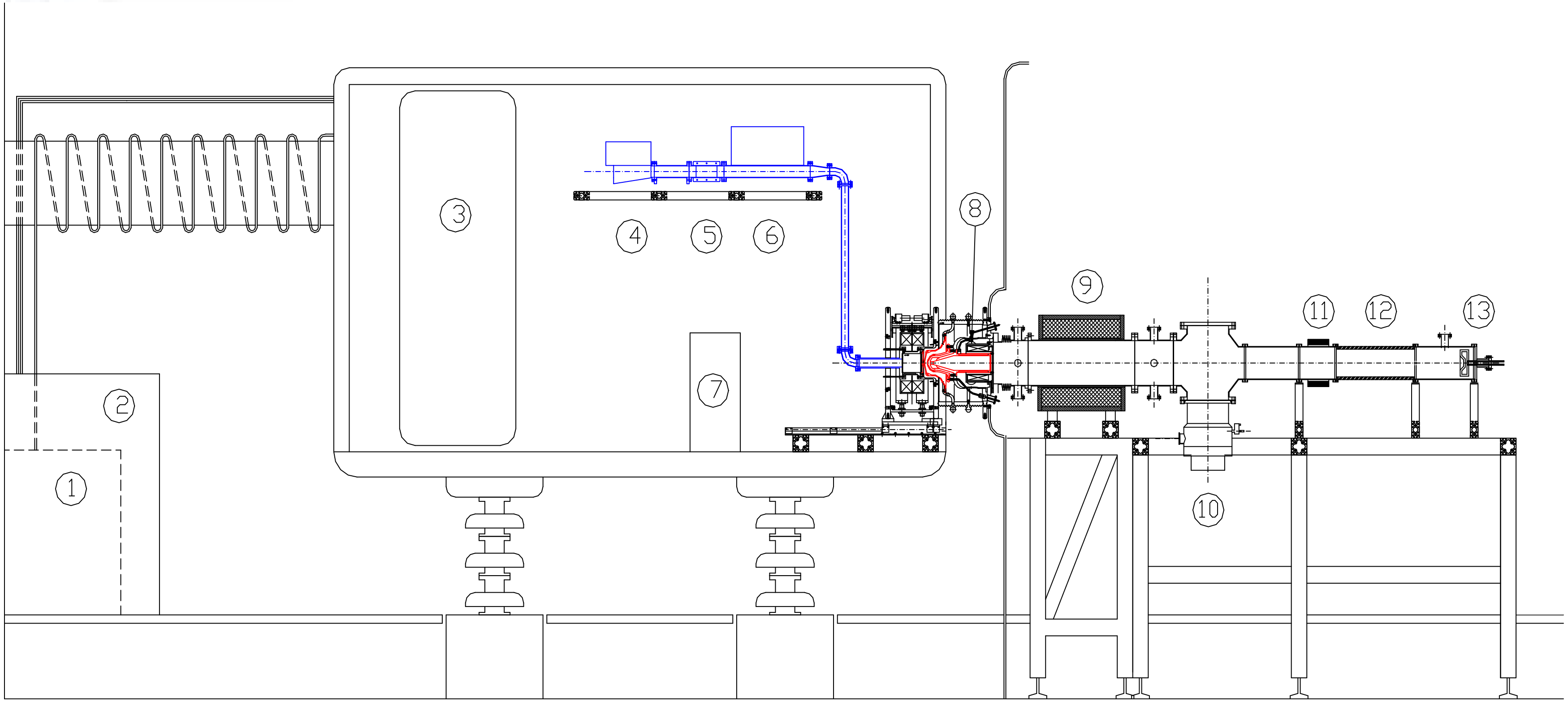
TRIPS (TRasco Intense Proton Source)



Extraction electrodes

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

TRIPS experimental layout

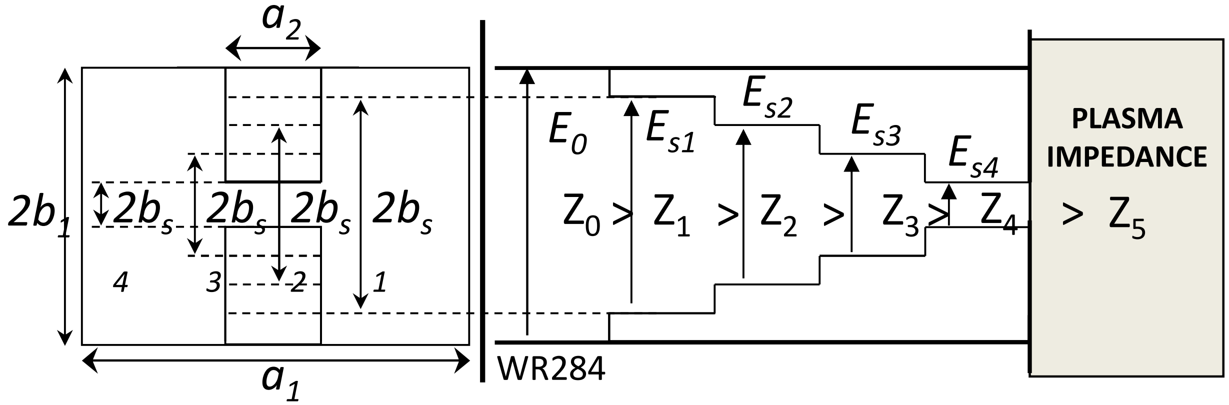


A layout of the whole set-up at INFN-LNS:
1- Demineralizer; 2- 120 kV insulating transformer; 3- 19” Rack for the power supplies and for the remote control system; 4- Magnetron and circulator; 5- Directional coupler; 6 – Automatic Tuning Unit; 7- Gas Box; 8- DCCT 1;
9- Solenoid; 10- Turbomolecular pump;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

Microwave injection and beam extraction optimisation

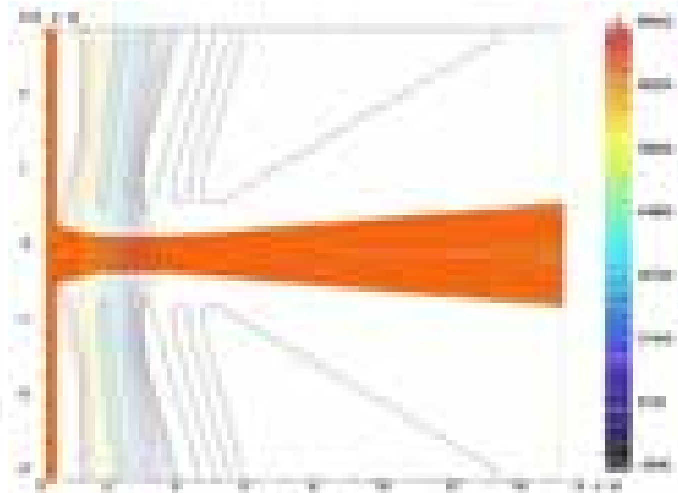
Microwave Injection

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



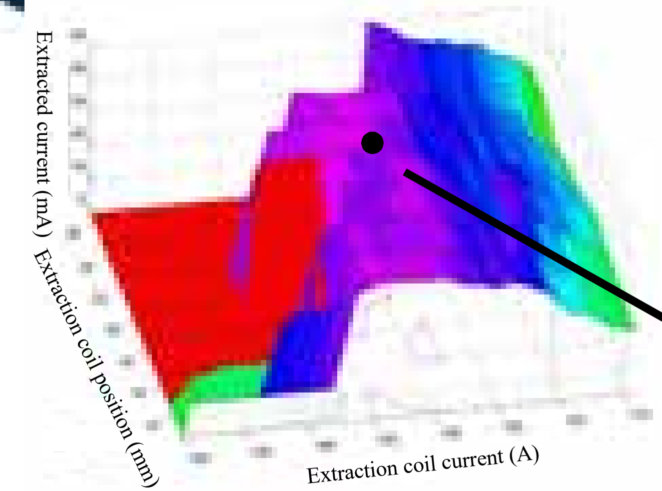
Beam extraction

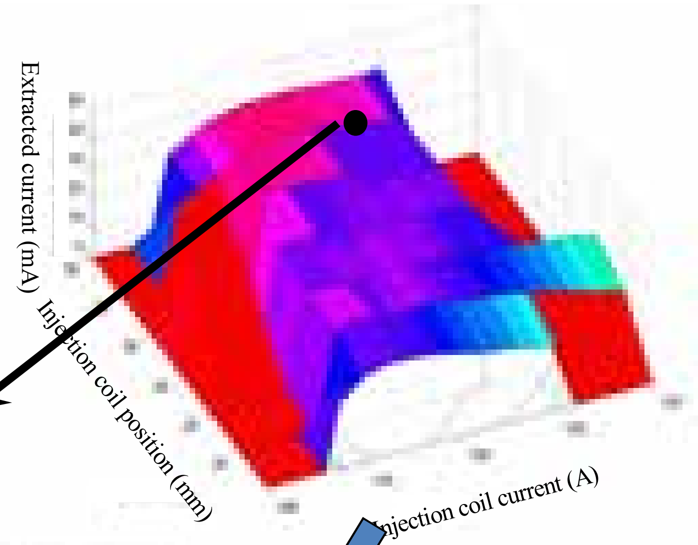
The extraction process has been deeply studied with the aim to increase the source reliability and to keep emittance low.
The used codes were AXCEL-INP and IGUN.



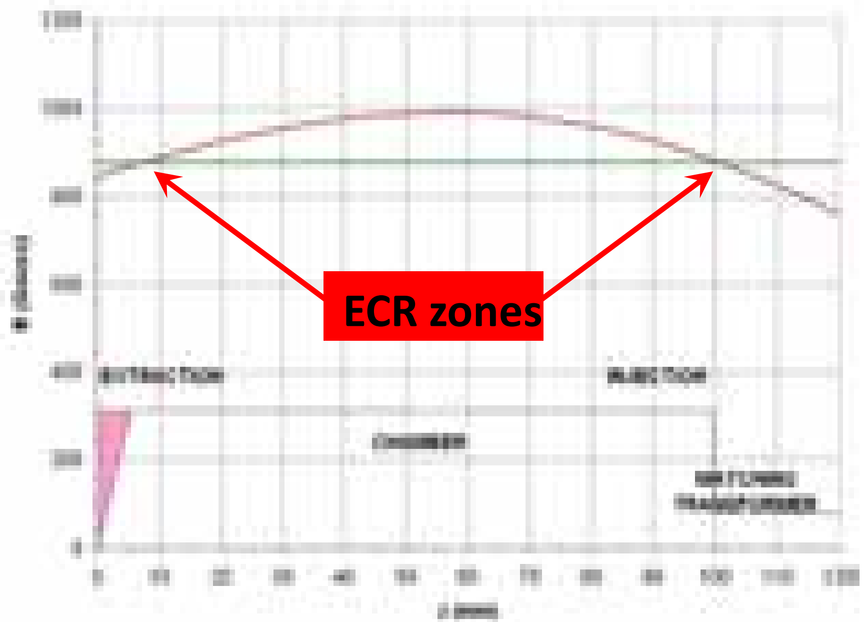
L.Celona, G. Ciavola, S. Gammino, R. Gobin, R. Ferdinand, Rev.Sci.Instr. 71(2),(2000), 771

Optimum magnetic field profile

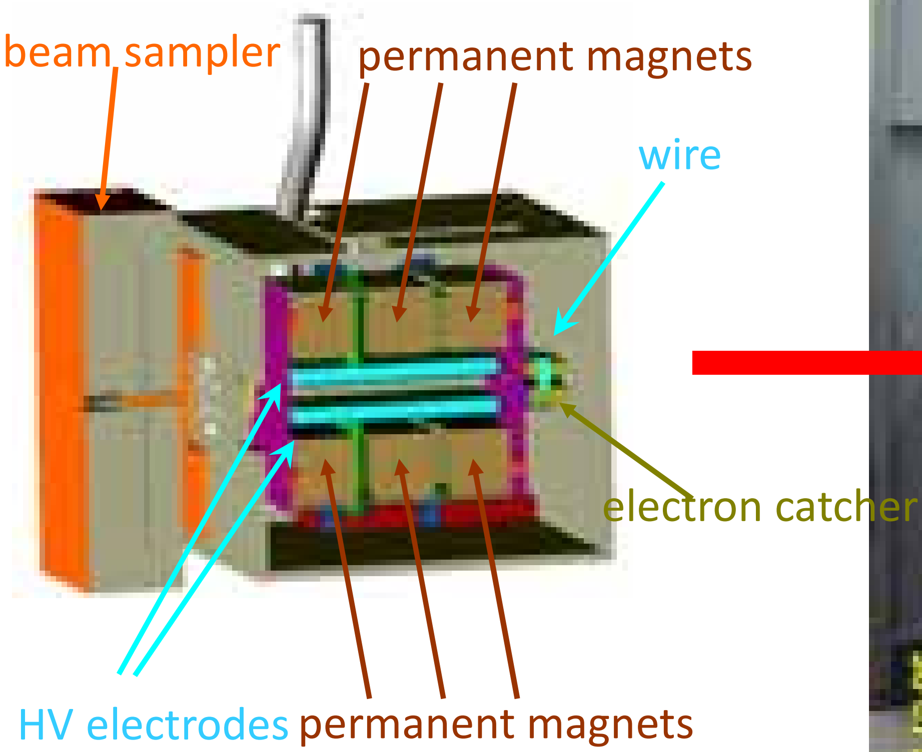




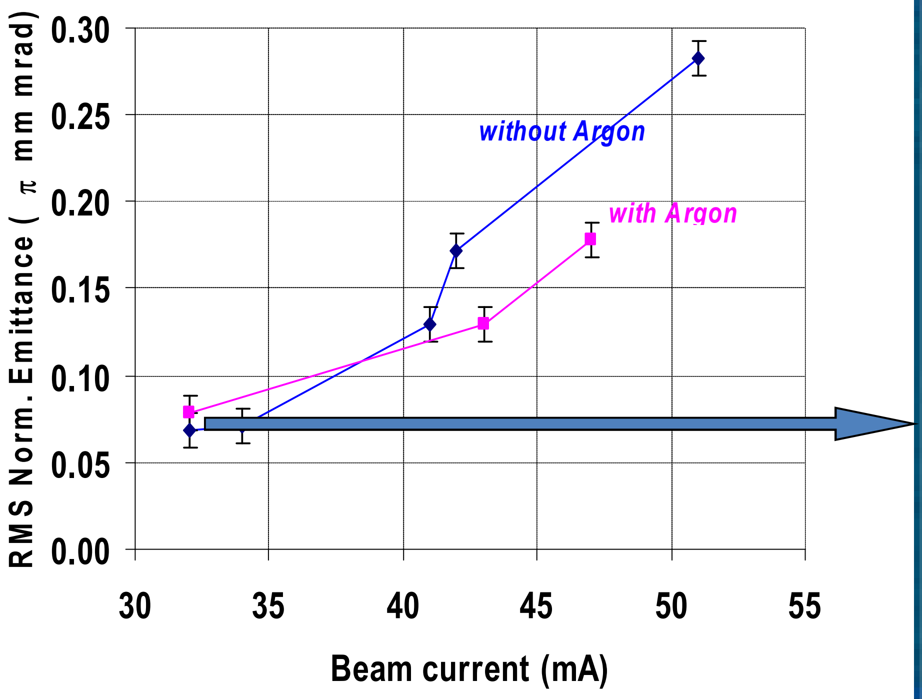
Best operational point:
Extraction coil: pos= 22 mm
curr=128 A

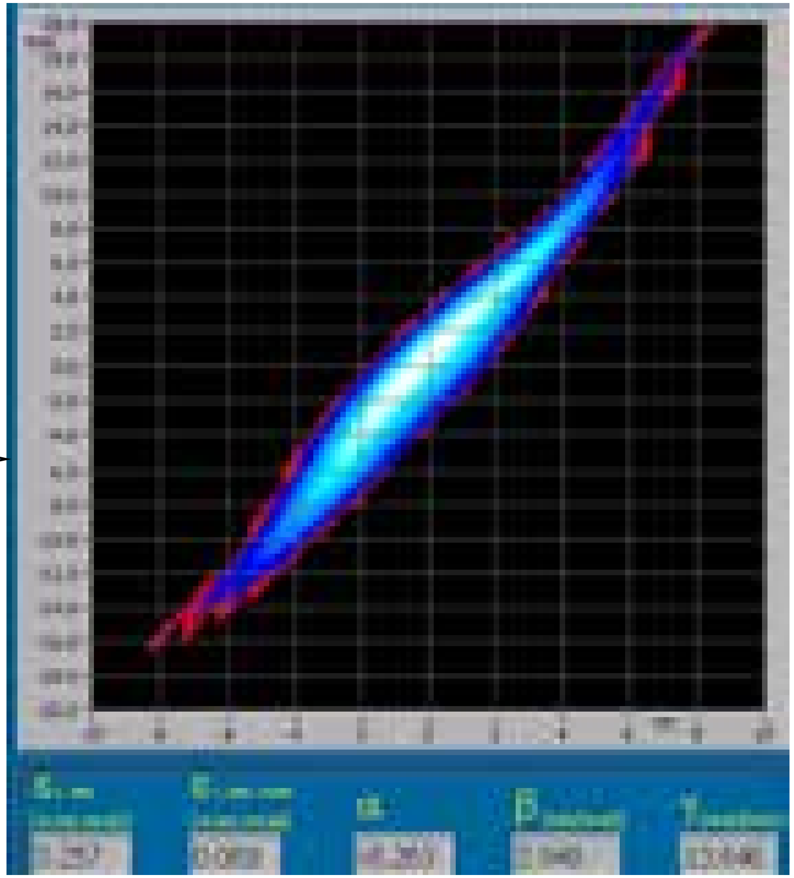


LEBT with Saclay EMU



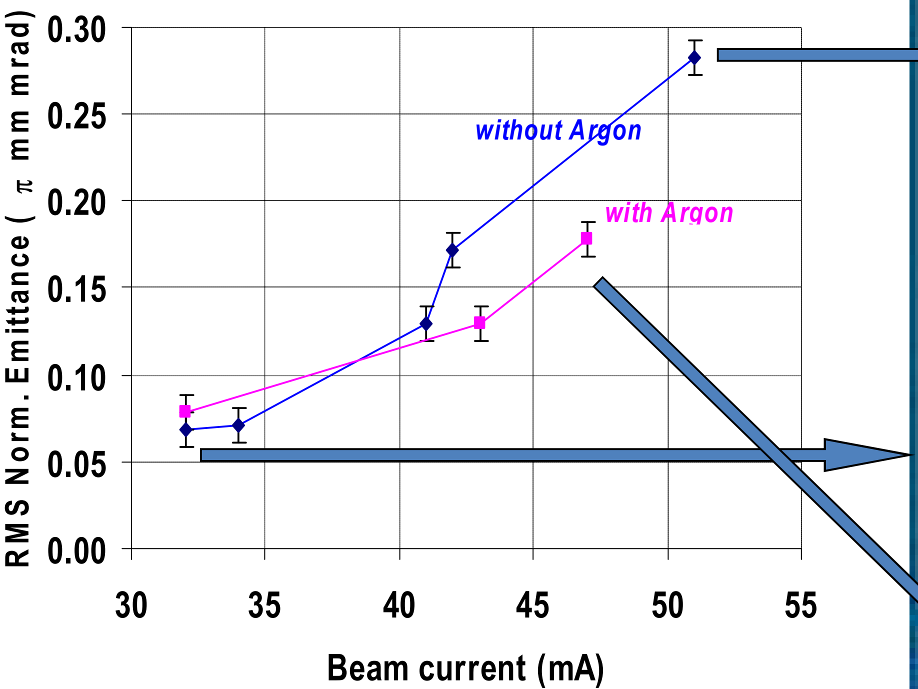
Emittance measurements at nominal current

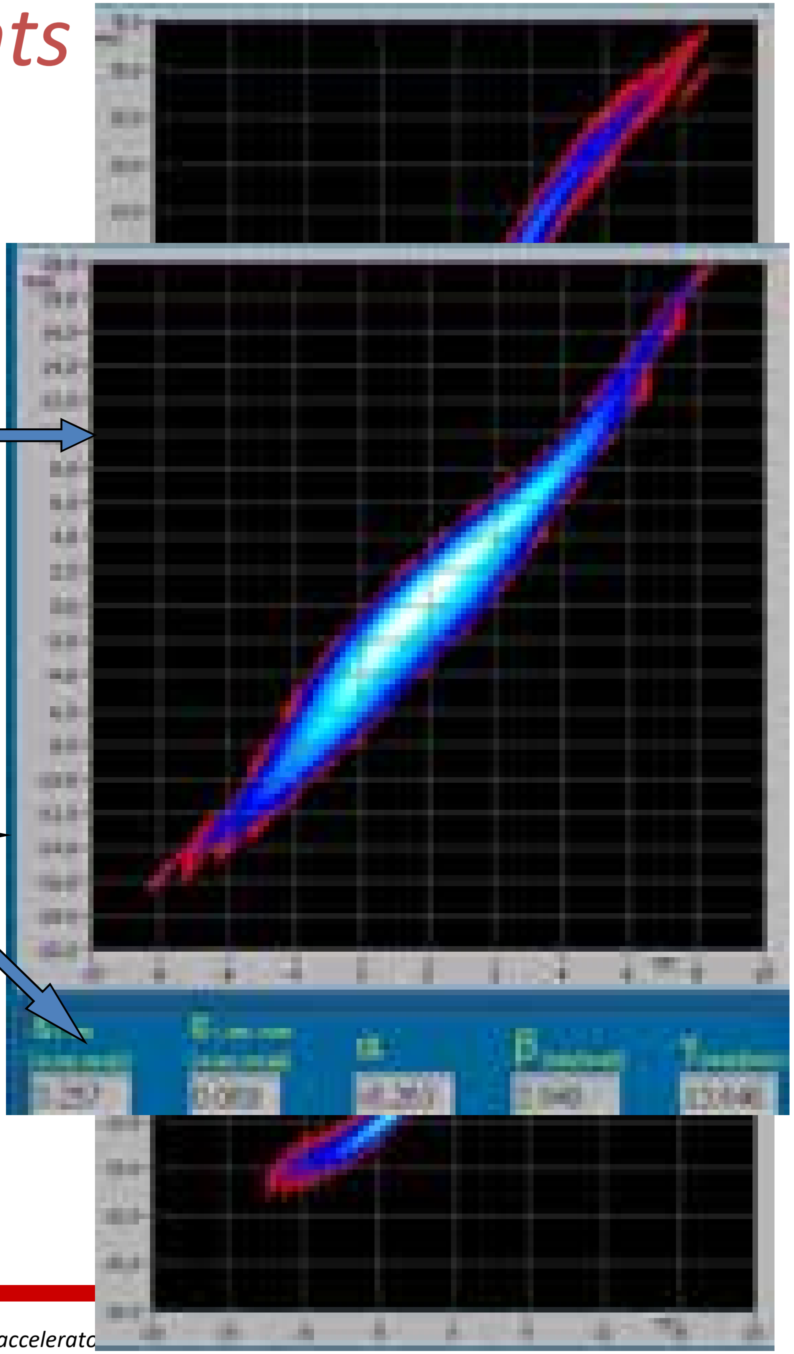




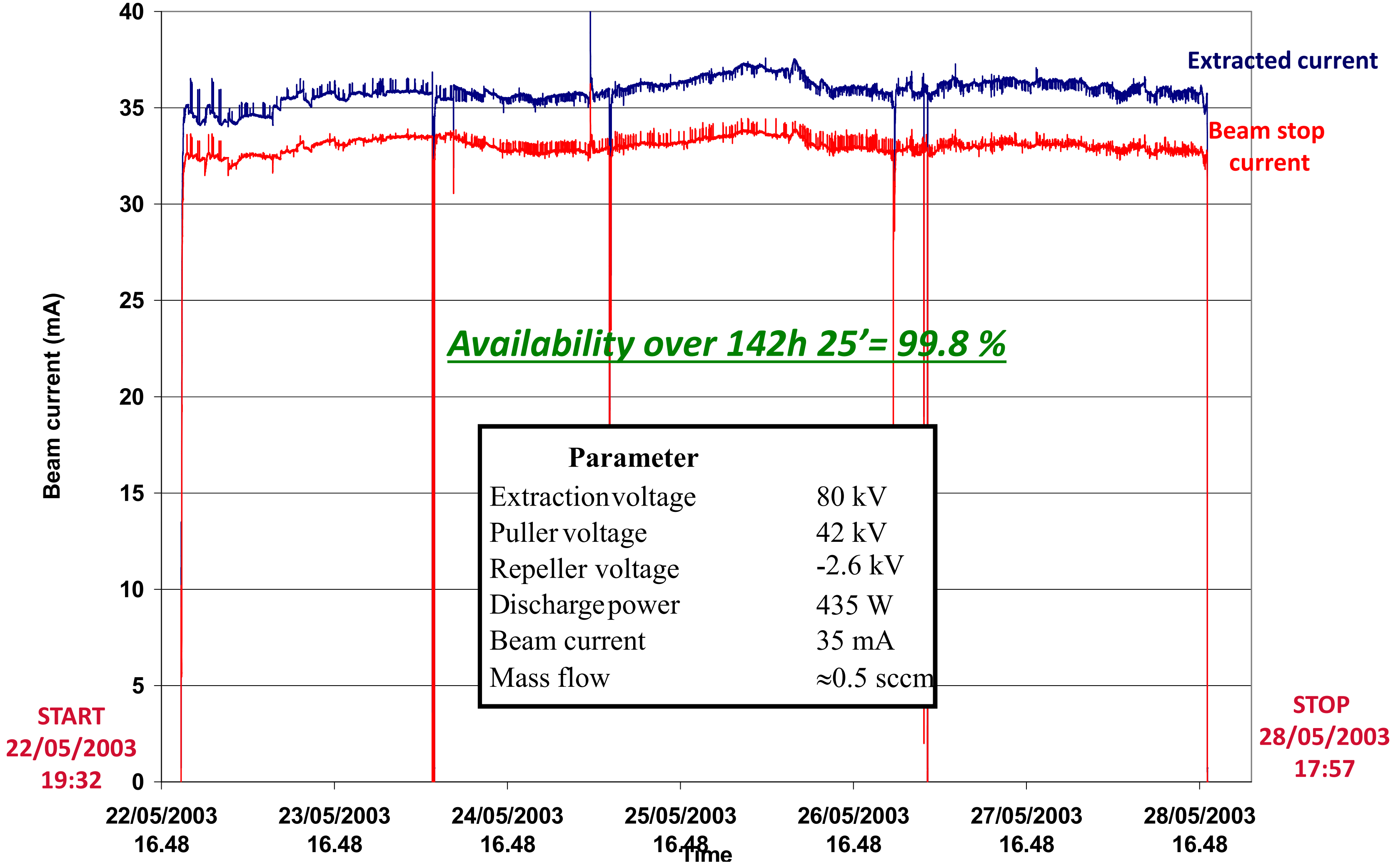
The measured value is slightly above the theoretical value and in good agreement with the AXCEL calculation.

Emittance measurements



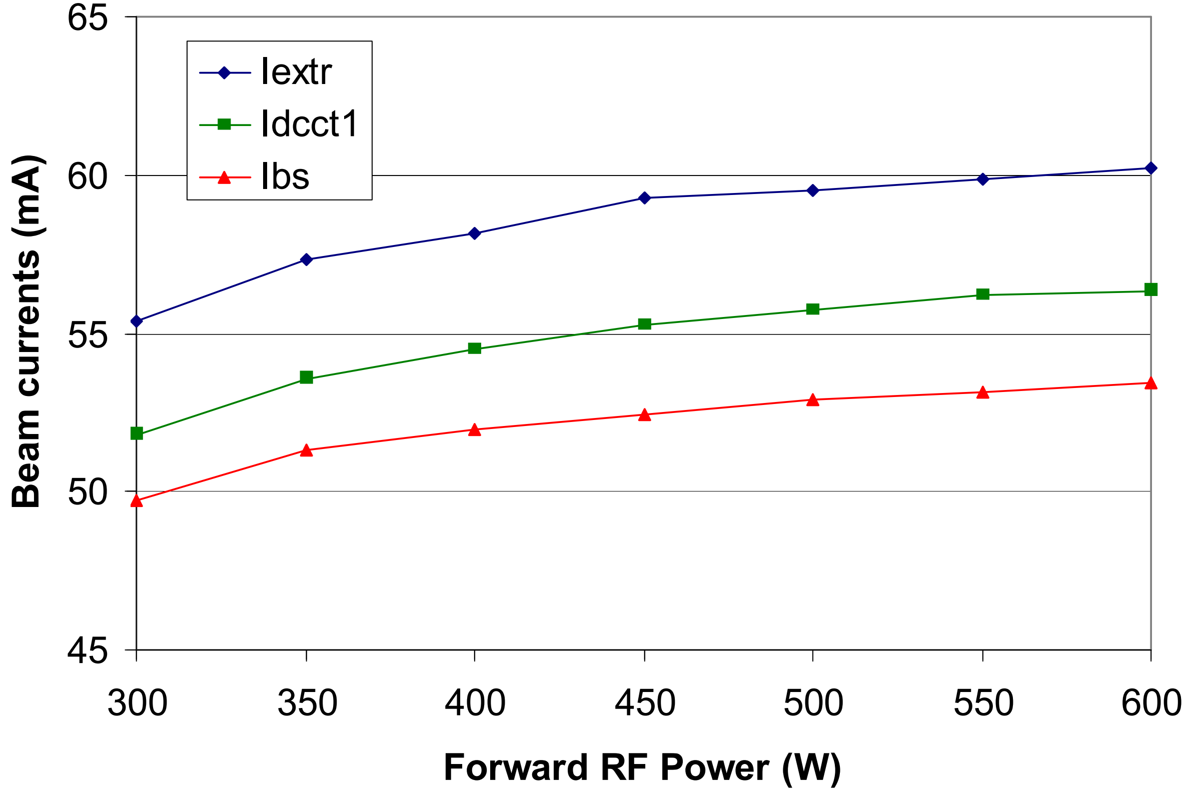


TRIPS reliability test: 35 mA @ 80 kV



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

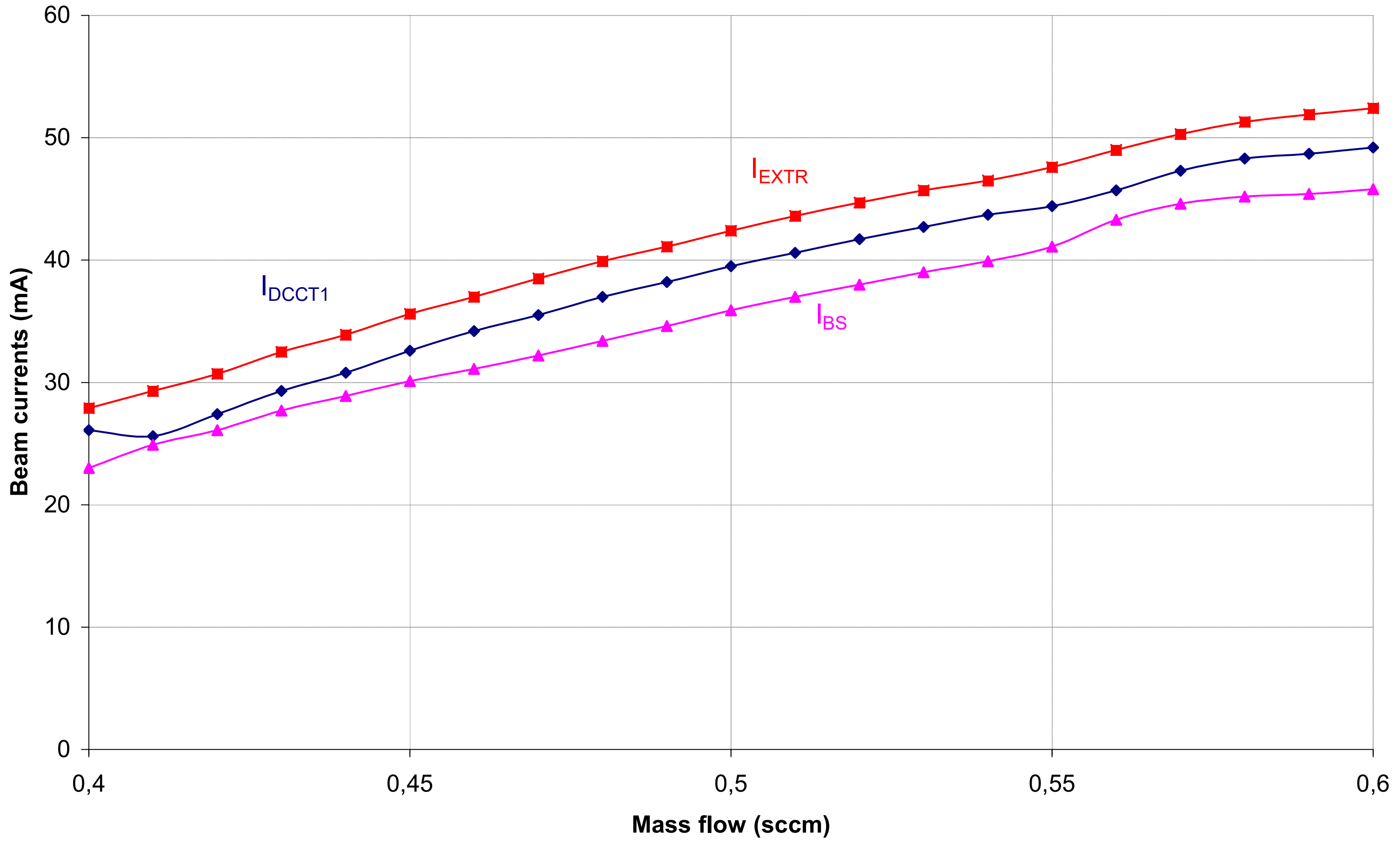
TRIPS performance vs. forward power



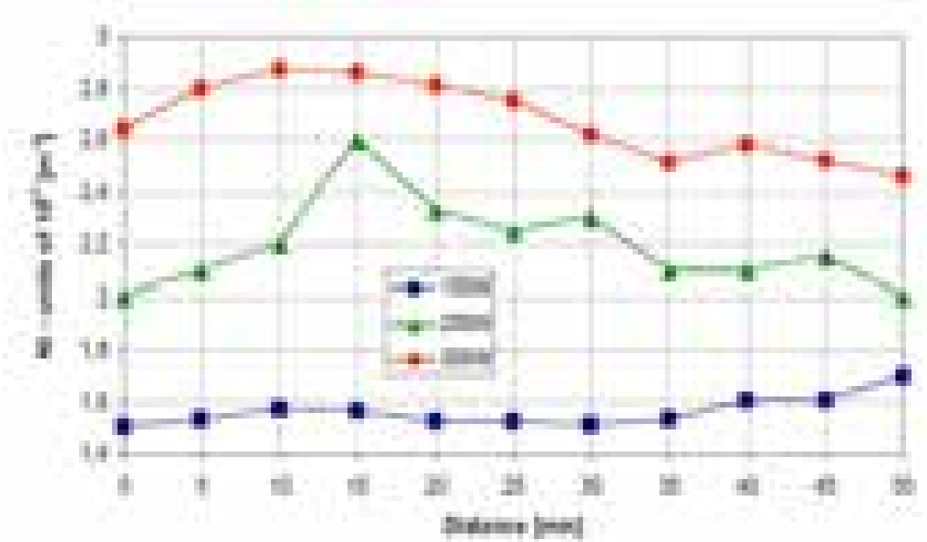
Operating voltage = 80 kV
Optimized magnetic field profile
Electron donor= BN disks

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

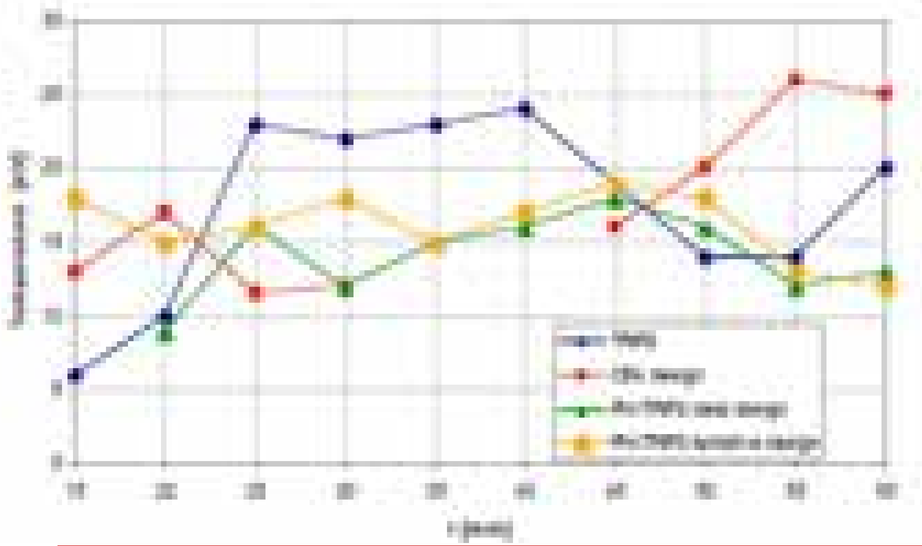
TRIPS performance vs. mass flow @ 450 W



Typical densities and temperatures of MDIS plasmas



Density of ions along the chamber axis



Langmuir Probe measurements

Electron temperature of the bulk plasma

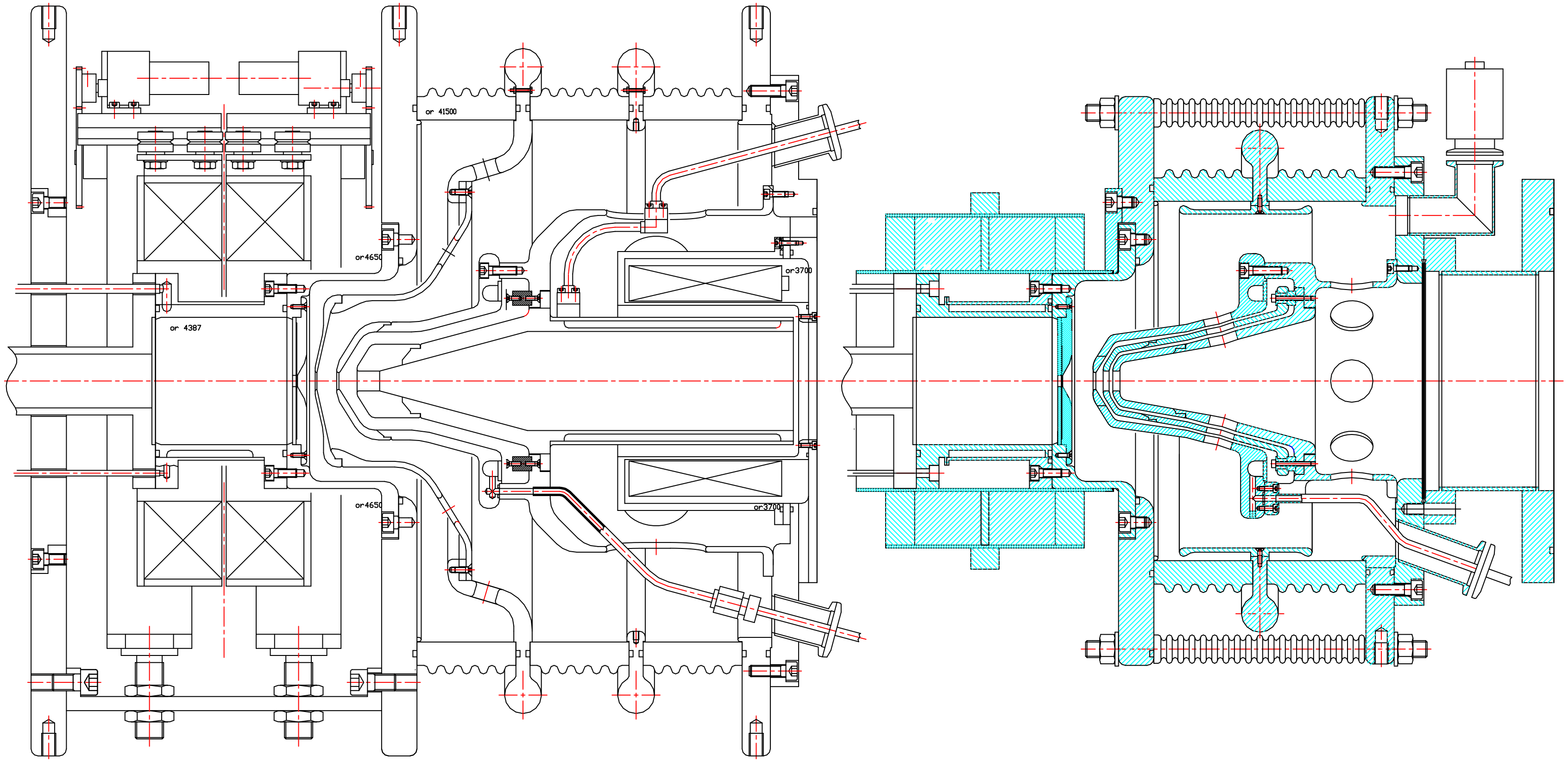
Investigation gave some ideas how to solve these issues

Main troubles:

- ~~Losses in extraction~~
- Source reliability — Injection, Magnetic field, Extraction
- ~~Emittance too high~~ — Extraction, Beam optics
- ~~Current still not at the values needed~~
- Remote control «infant mortality…»

Better comprehension of phenomena, solutions found

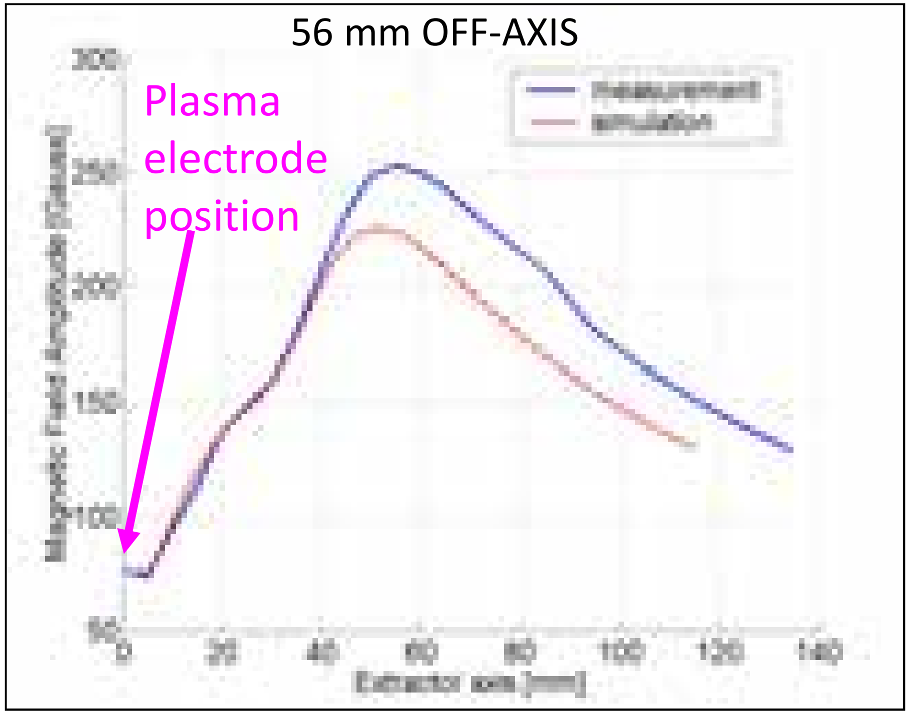
TRIPS vs. VIS

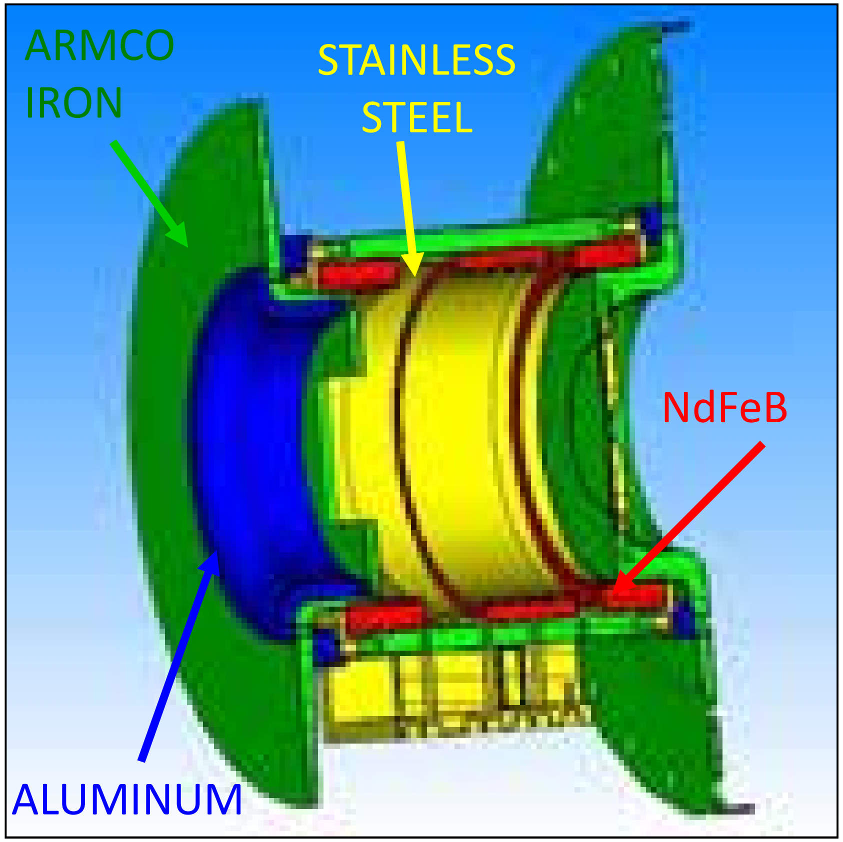


- New extraction system and accelerator column simplified to reduce the dimensions.
- New ionisation chamber.
- Insulation of coils, microwave and gas system to eliminate the HV-platform (implies a further simplification of the electronics involved in the control of the source because all the instrumentation will be placed at ground potential).

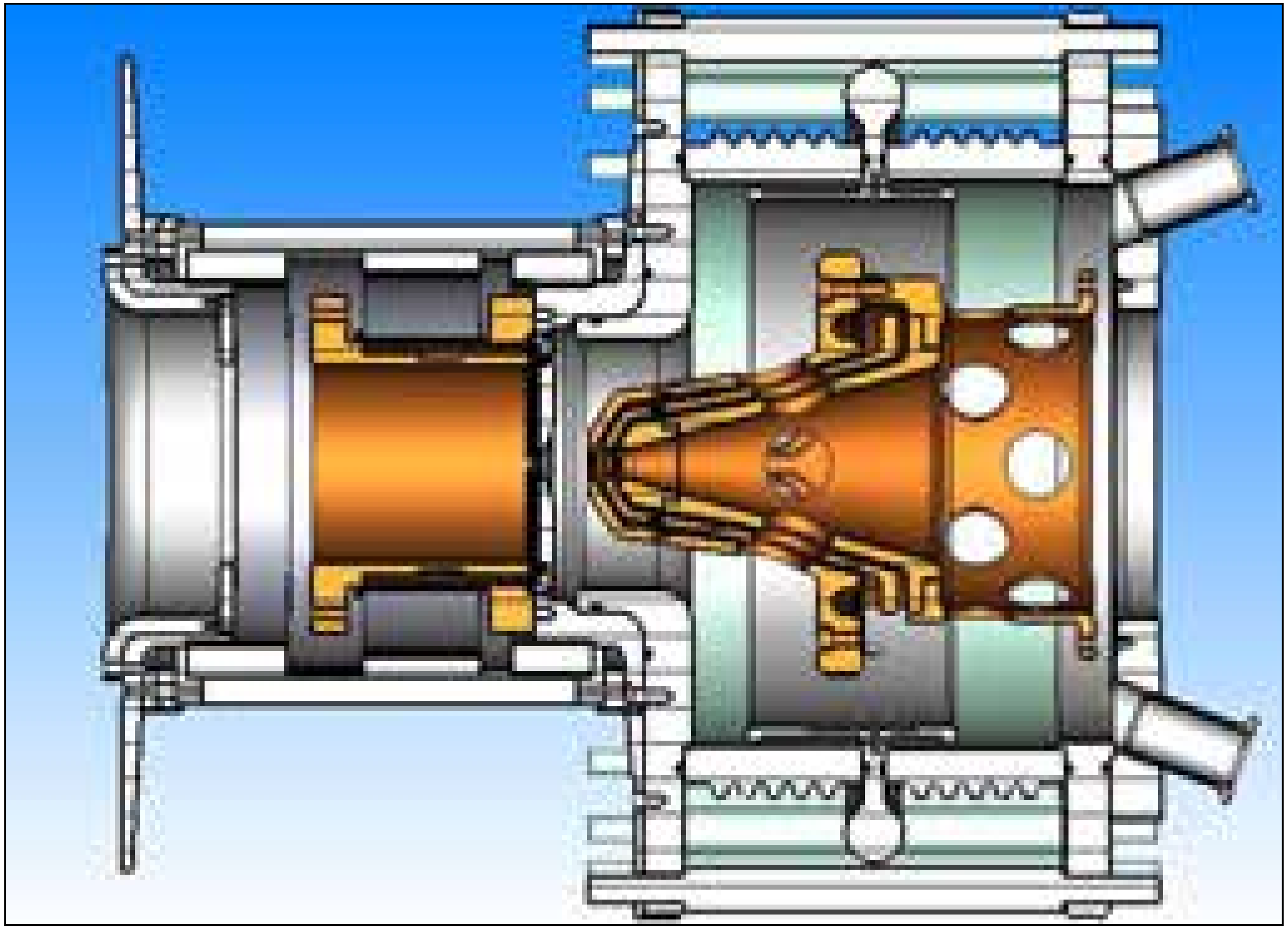
NEW MAGNETIC SYSTEM

- 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



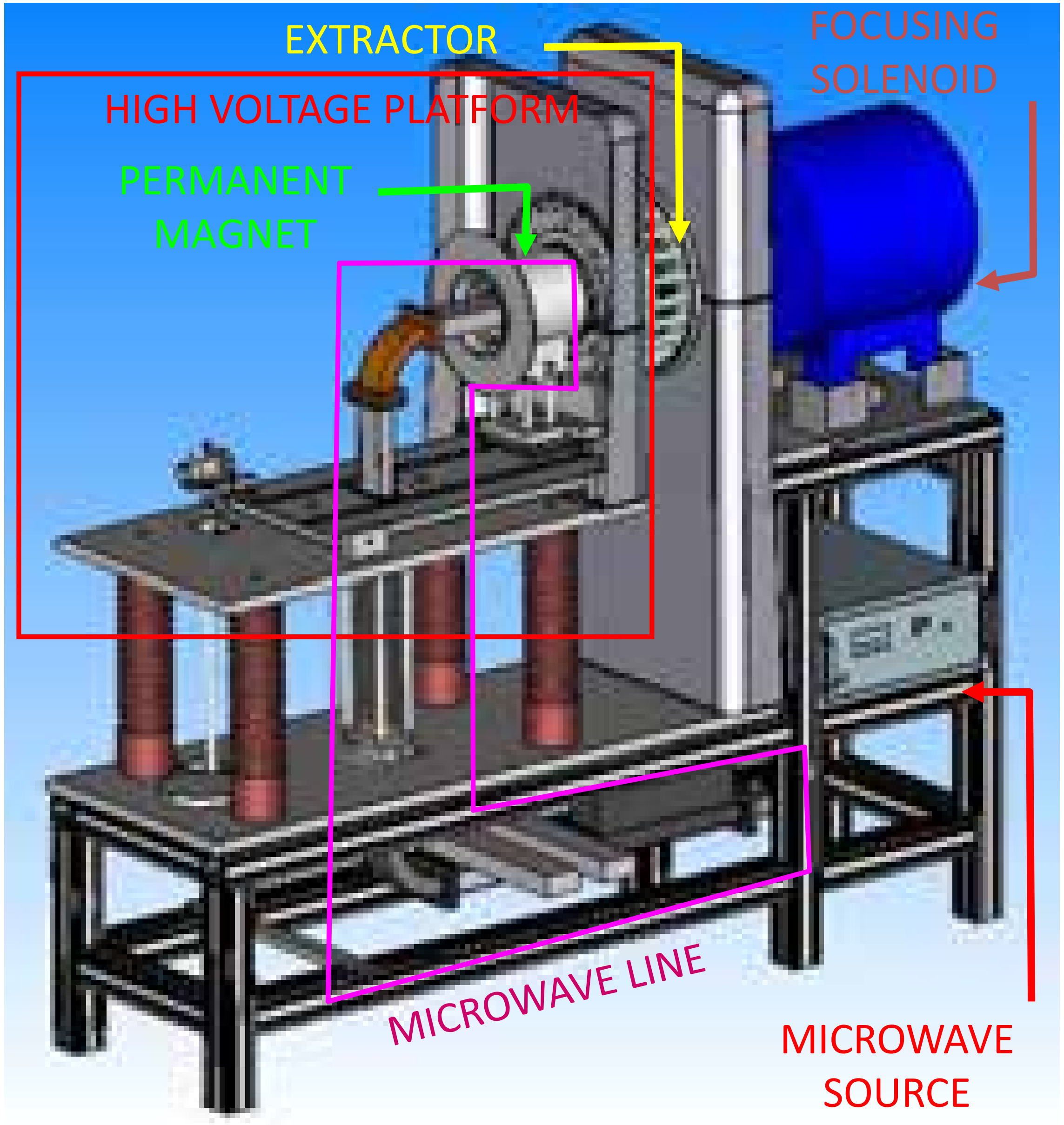


ION EXTRACTION SYSTEM

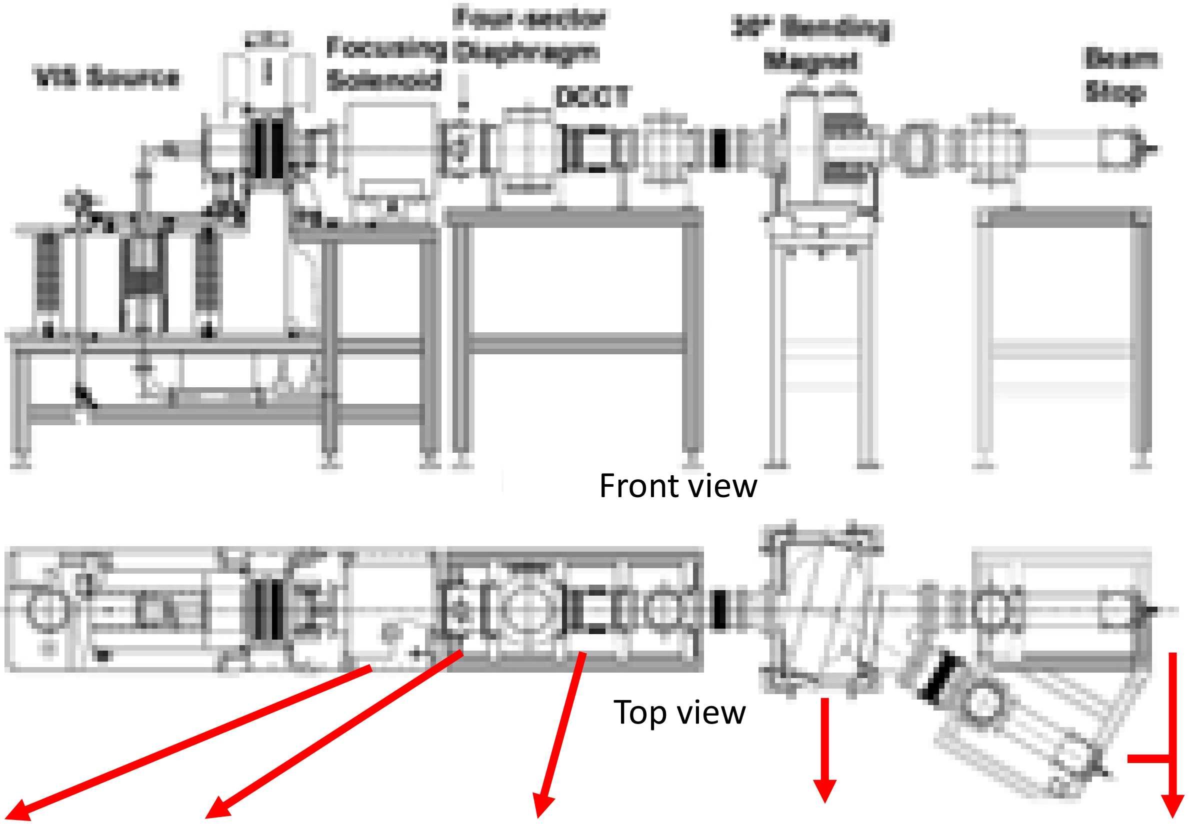


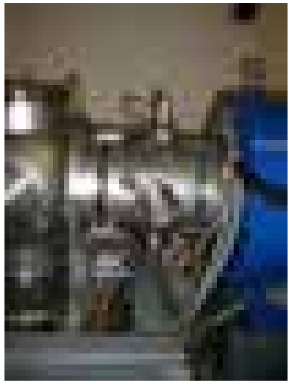
YOU ARE NOT OBLIGED TO DESIGN COMPLEX SYSTEM

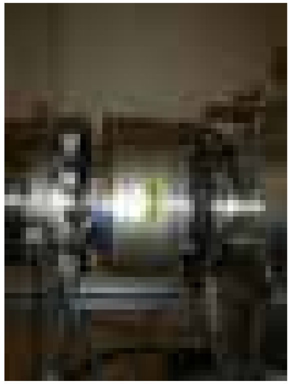
VIS DESCRIPTION

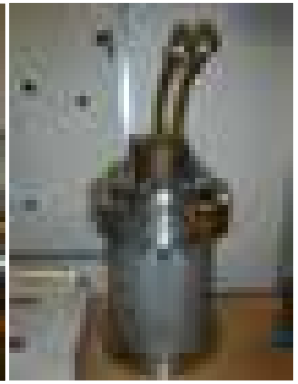


VIS BEAM LINE DESCRIPTION

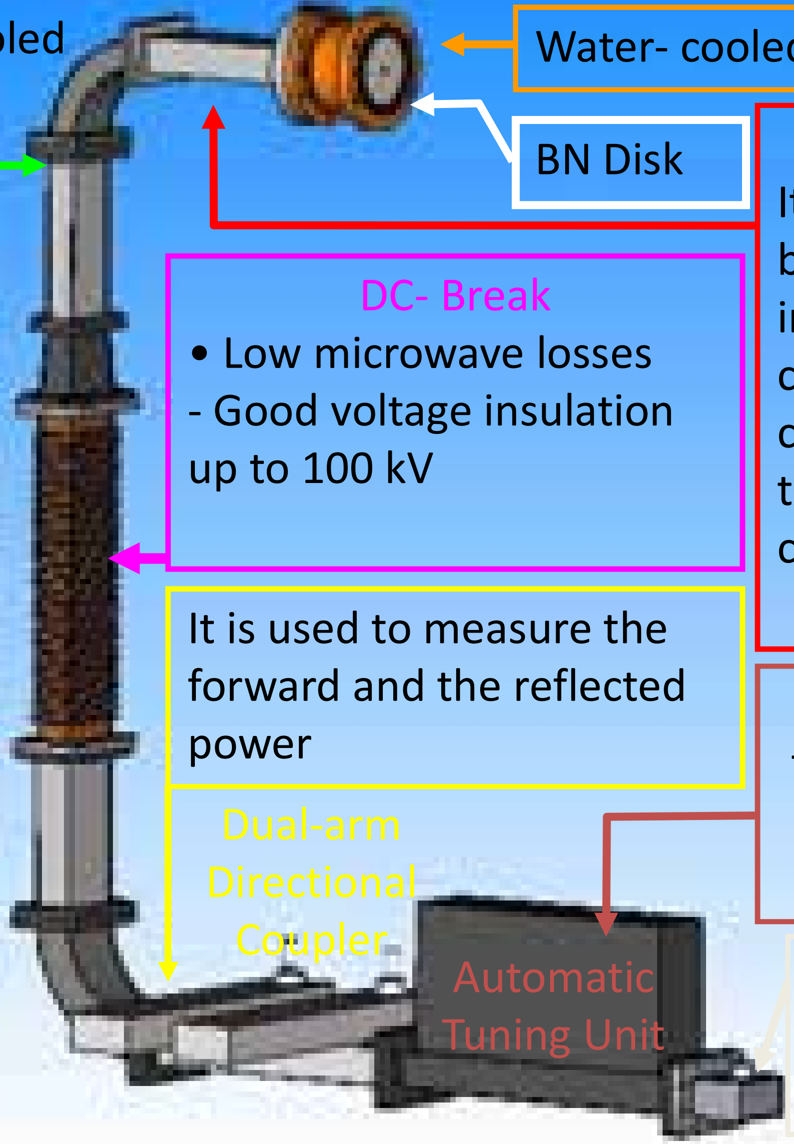






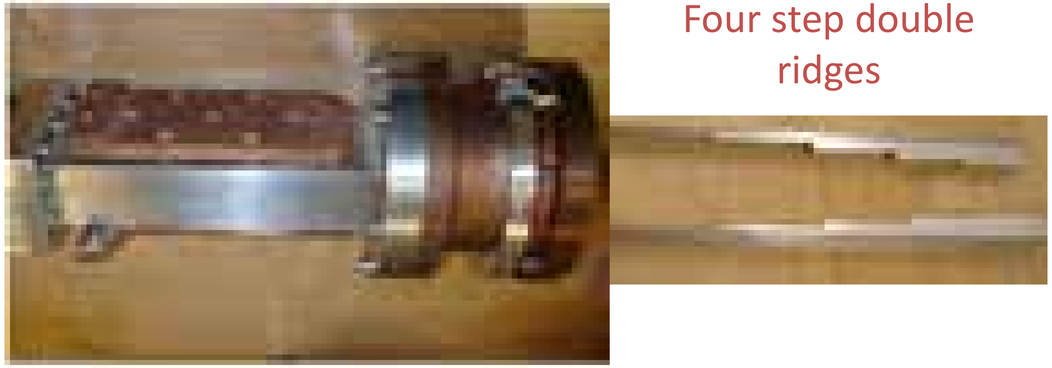


MICROWAVE LINE 1/3

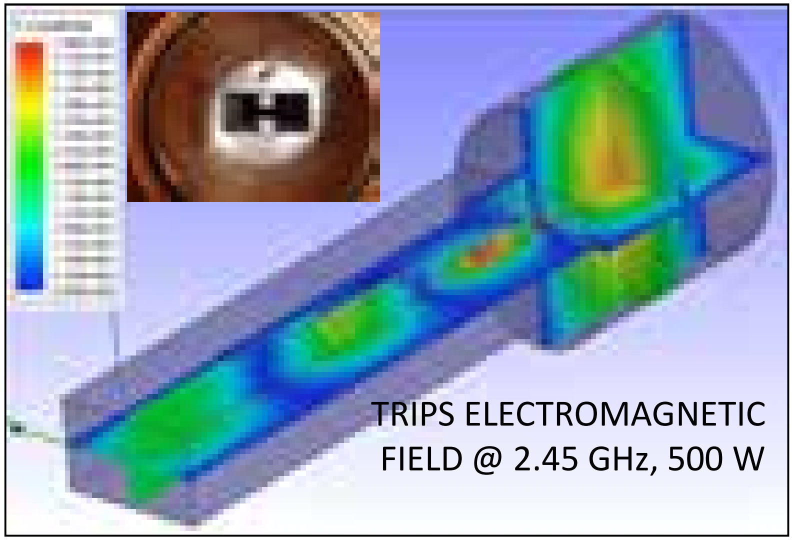


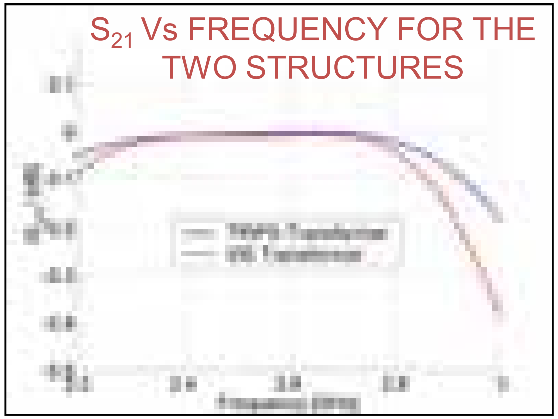
MW LINE 2/3: MATCHING TRANSFORMER

Four step double ridges

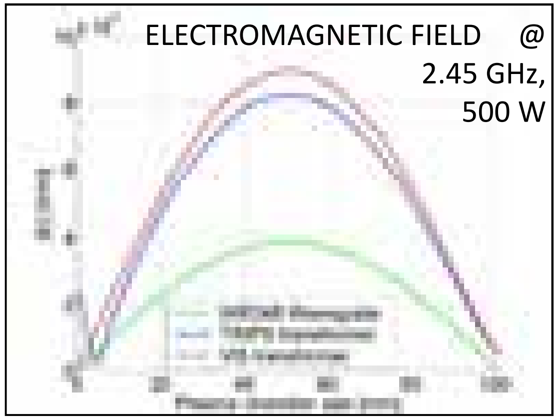


Matching transformer coupled to the plasma chamber

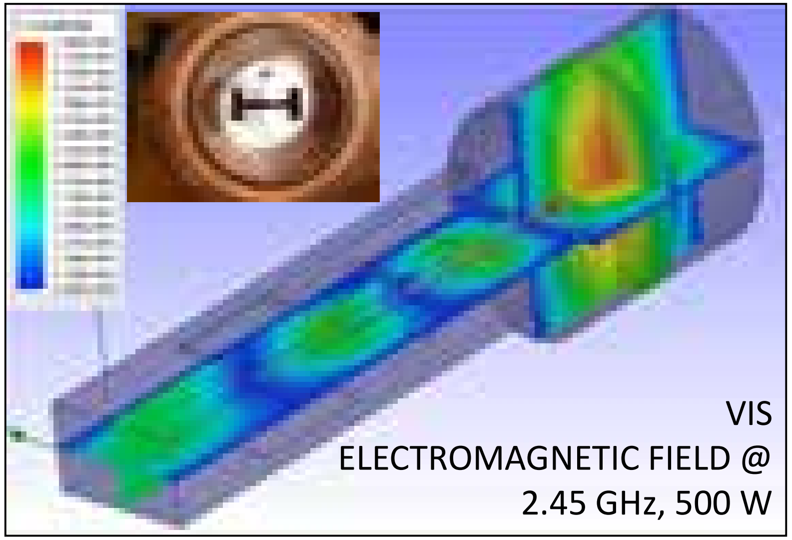




VIS TRANSFORMER INSERTION
LOSS 0.0085 dB @ 2.45 GHz



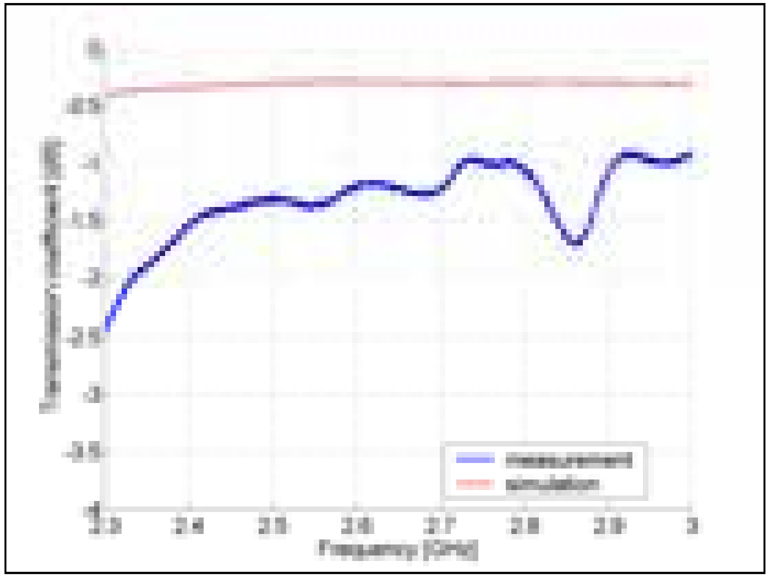
10 % ENHANCEMENT WITH VIS TRANSFORMER



MW LINE 3/3 WAVEGUIDE DC-BREAK

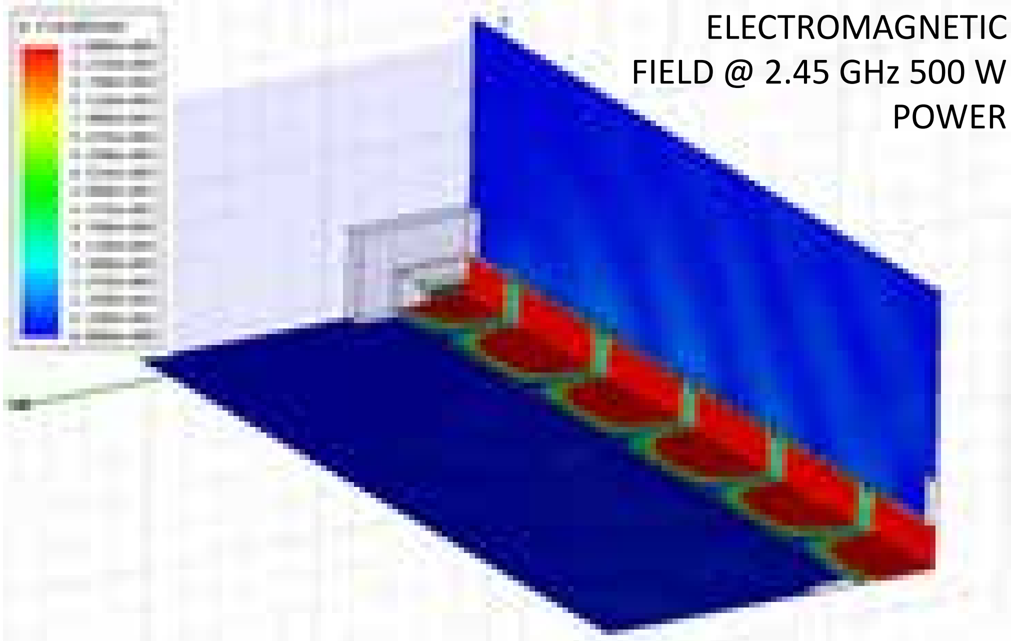
DESCRIPTION

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

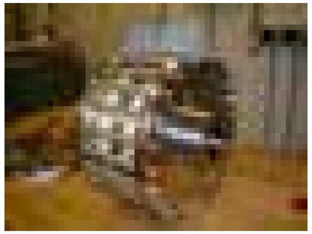
- Electrical Insulation up to 100 kV
- Transmission coefficient -1.4 dB @ 2.45 GHz
- Low radiated electromagnetic field

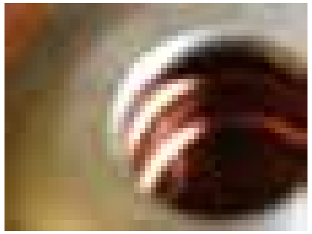


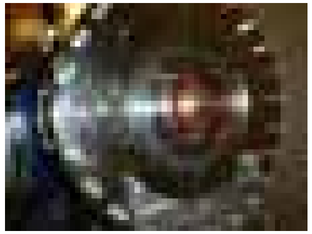
ELECTROMAGNETIC FIELD @ 2.45 GHz 500 W POWER

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.





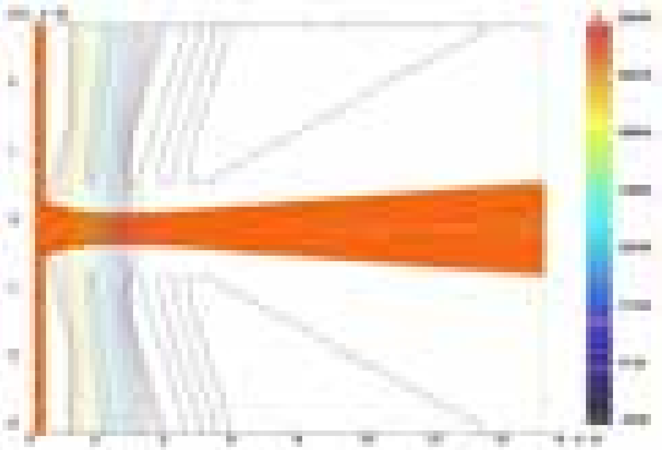


TRIPS Five-electrodes topology

- 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.

Investigation gave some ideas how to solve these issues

Main troubles:

- ~~Losses in extraction~~
- ~~Source reliability~~
- ~~Emittance too high~~
- ~~Current still not at the values needed~~
- ~~Remote control «infant mortality…»~~

Injection, Magnetic field, Extraction

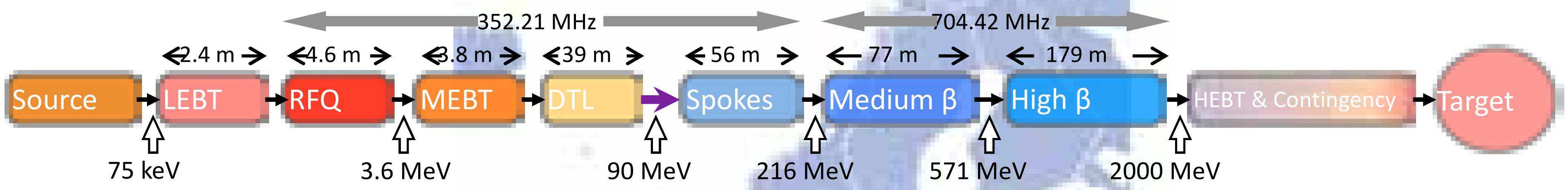
Extraction, Beam optics

Better comprehension of phenomena, solutions found


Journey to deliver the world's leading facility for research using neutrons
Proton source and LEBT: Ready For Installation 03/11/2017
2003 First European design effort of ESS completed
2009 Decision: ESS will be built in Lund
2012 ESS Design Update phase complete
2014 Construction work starts on the site
2019 First beam on Target
2023 ESS starts user program
2025 ESS construction complete

Italian In-Kind Contribution:

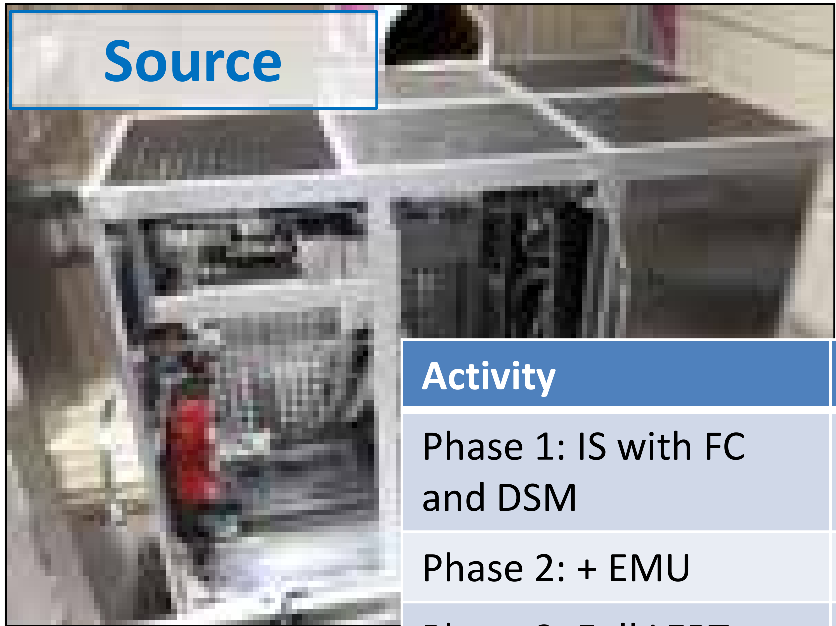
Proton Source, LEBT	INFN-LNS
DTL	INFN-LNL
T-REX, VESPA	CNR
RF systems, Magnets&PS, diagnostics	Elettra

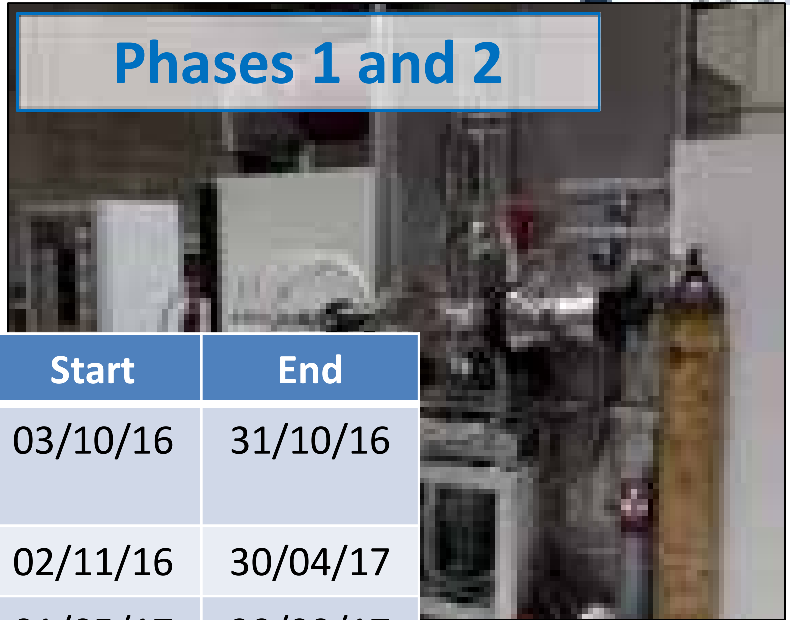


Partners for proton source and LEBT:

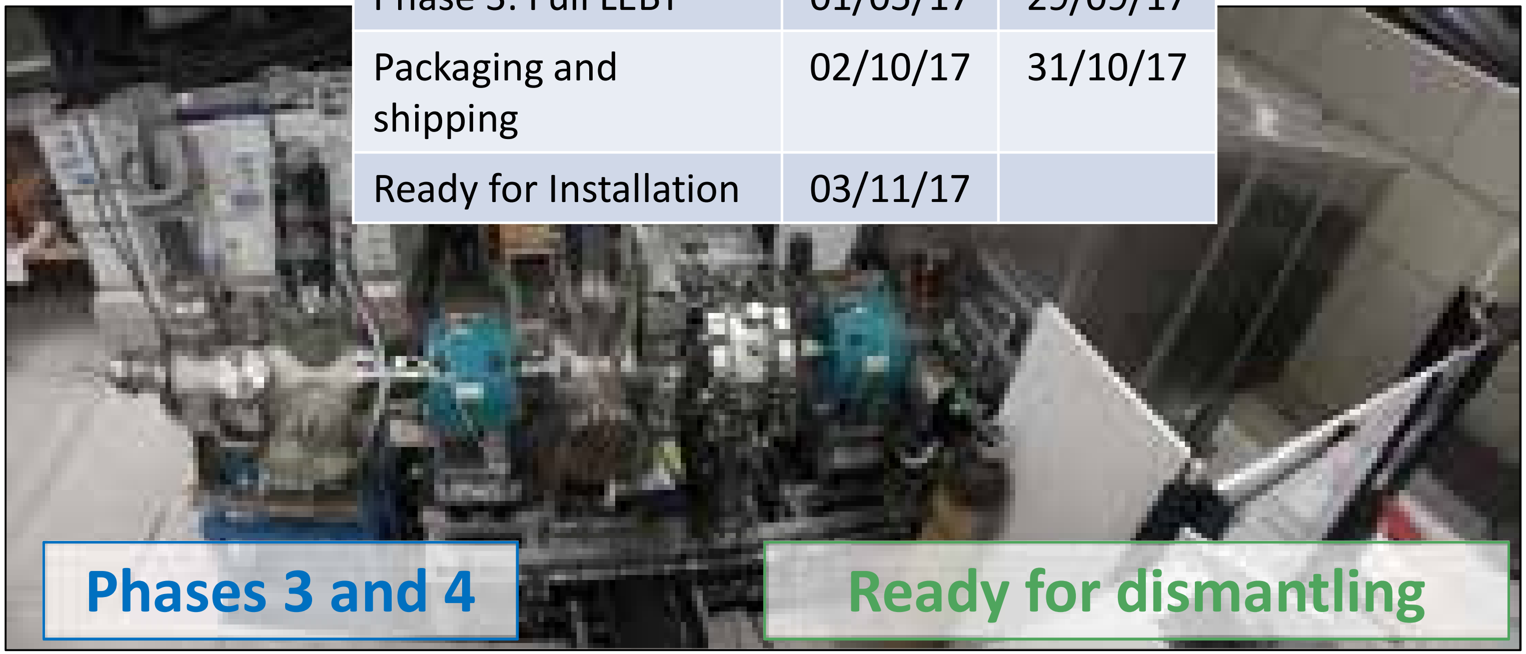
INFN-LNS	WP leader, Overall design, Construction, Commissioning, Installation
ESS	Vacuum, Controls, Beam diagnostics
CEA	Controls, Beam diagnostics

Ion Source and LEBT



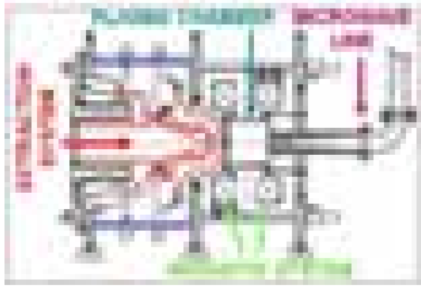


Activity	Start	End
Phase 1: IS with FC and DSM	03/10/16	31/10/16
Phase 2: + EMU	02/11/16	30/04/17
Phase 3: Full LEBT	01/05/17	29/09/17
Packaging and shipping	02/10/17	31/10/17
Ready for Installation	03/11/17	

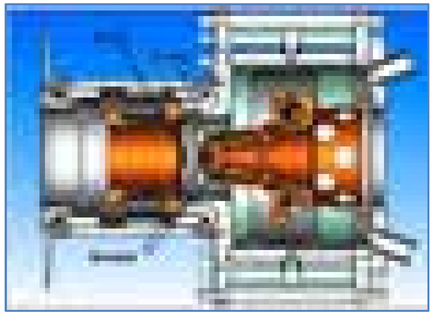


INFN-LNS background

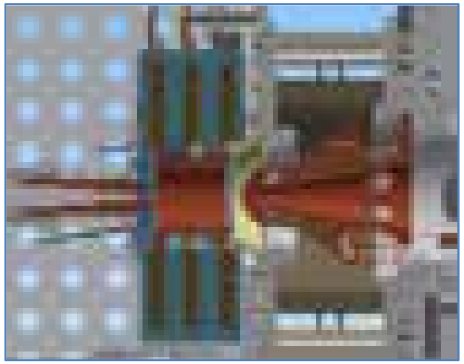
TRIPS (2001)



VIS (2008)



PS-ESS (2016)



Performance	Value
Beam energy	80 Kev
Proton beam current	55 mA
Proton fraction	≈80%
RF frequency	2.45 GHz
RF power	Up to 1 kW
Axial magnetic field	875-1000 G
Duty factor	100 % (DC)
Extraction aperture	6 mm
Reliability	99.8% @ 35 mA
Transverse emittance (σ)	0.07 pi.mm.mrad @ 35 mA
Start-up after maintenance	32 hours

+ 25%

from dc to pulsed

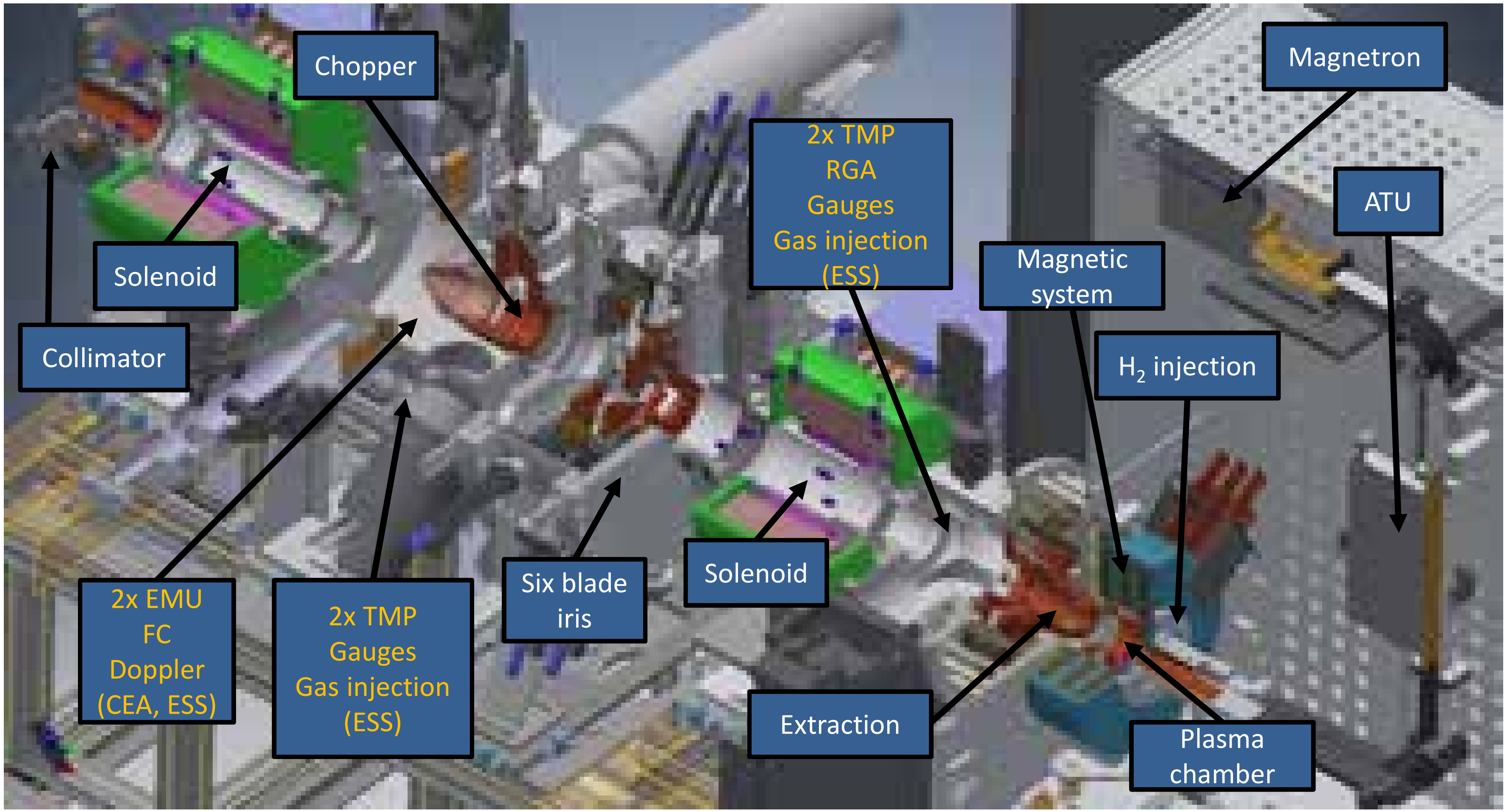
High stability

Low emittance

Easy maintenance

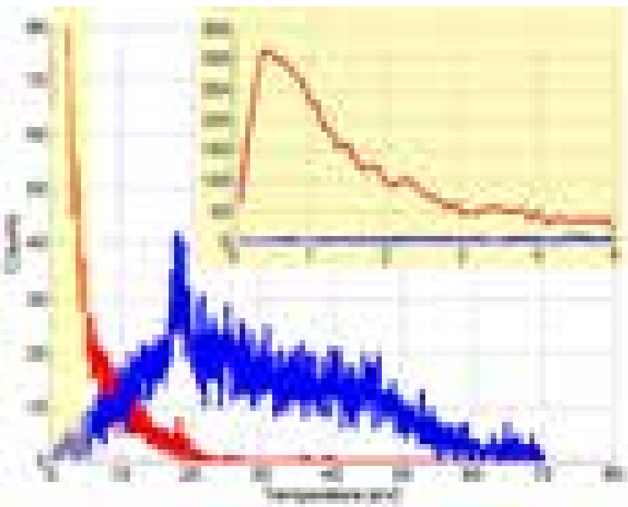
Requirement	Value
Beam energy	75 ± 5 keV
Energy adjustment	± 0.01 keV
Total beam current	> 90 mA
Proton beam current	74 mA
Proton beam current range	6.7 - 74 mA
Resolution	1.6 mA
Proton fraction	> 75%
Pulse length	6 ms
Pulse flat top	3 ms
Repetition rate	14 Hz
Pulse to pulse stability	± 3.5 %
Flat top stability	± 2 %
Transverse emittance (99%)	1.8 pi.mm.mrad
Beam divergence (99%)	< 80 mrad
Start-up after maintenance	< 32 hours

Proton Source and LEBT at INFN-LNS

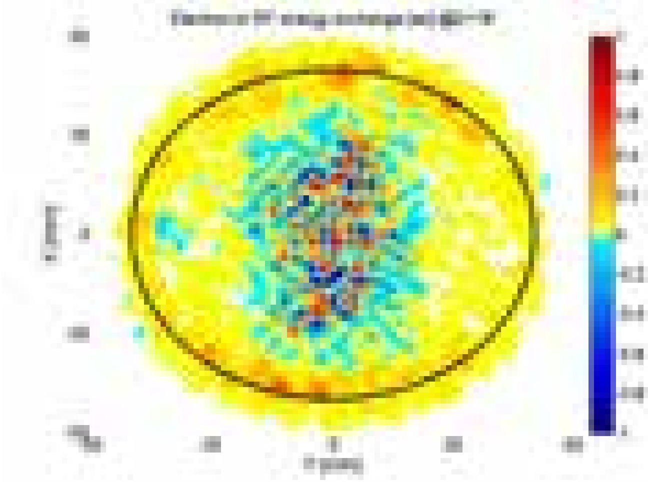


Plasma modeling

Electron Energy Distribution Function

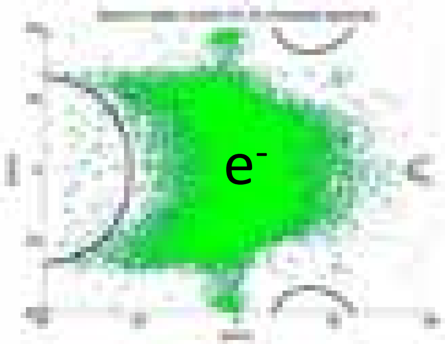


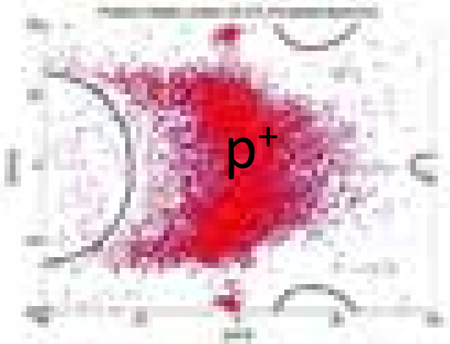
RF energy adsorption



Ion formation

Generation maps



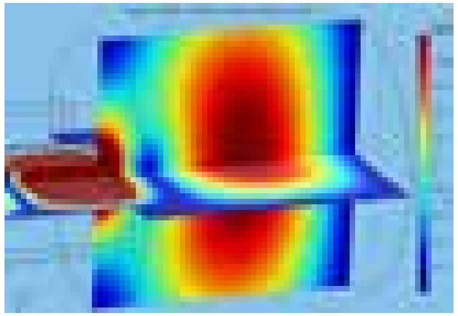


L. Neri et al. "Recent progress in plasma modelling at INFN-LNS", Rev. Sci. Instrum. 2016 Feb, 87(2):02(A)505

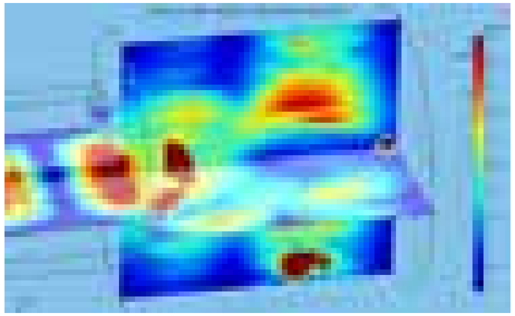
Microwave to plasma coupling

3D full wave e-m simulation in presence of the electron plasma density and strong magnetic field has driven the design of **the matching transformer**

Empty cavity

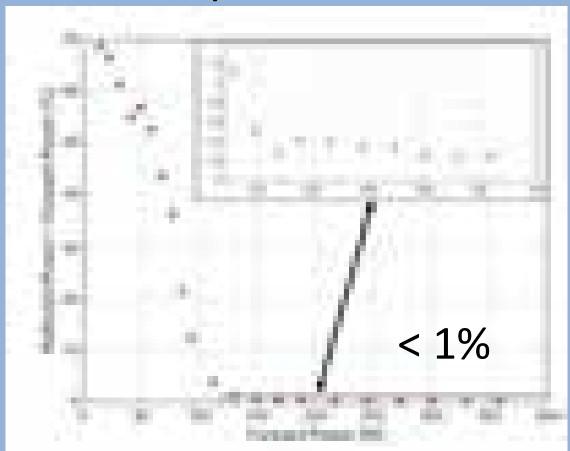


Cold tensor plasma approximation



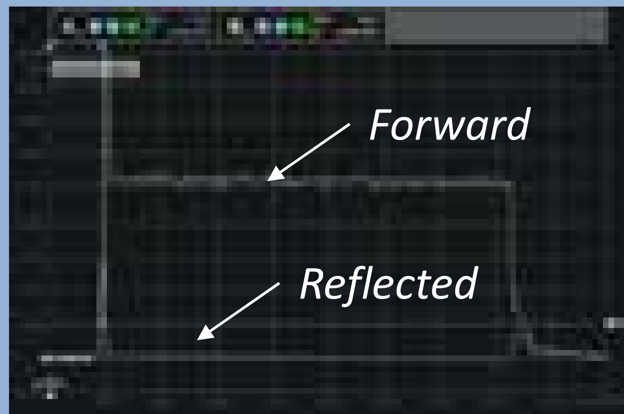
G. Torrisi et al. "Full-wave FEM simulations of electromagnetic waves in strongly magnetized non-homogeneous plasma", JEWA 2014 vol. 20, no. 9, 1085-1099

Low measured reflected power



High measured stability of forward and reflected power

Measured forward and reflected pulsed power



G. Torrisi et al. "Microwave injection and coupling optimization in ECR and MDIS ion sources", Proc.of IPAC'17

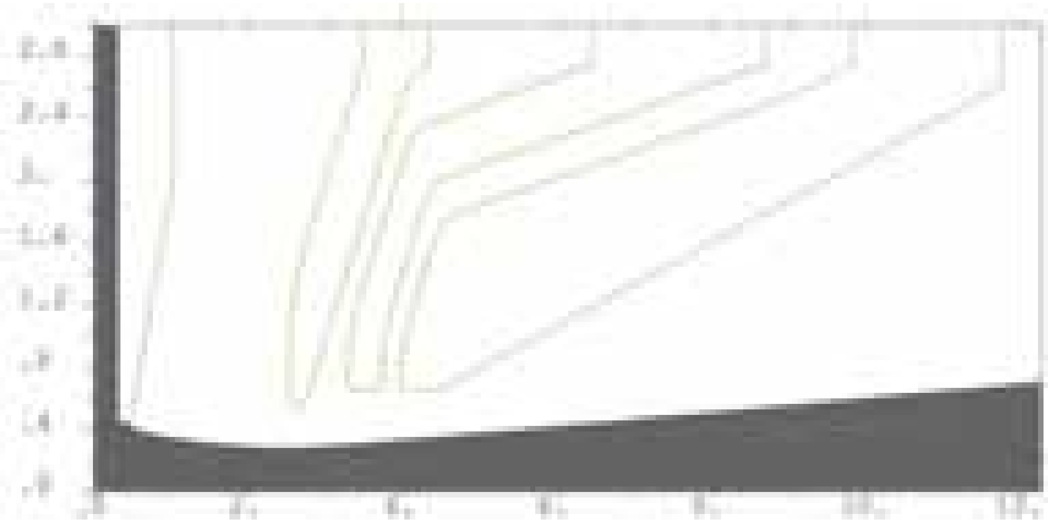
Beam extraction system

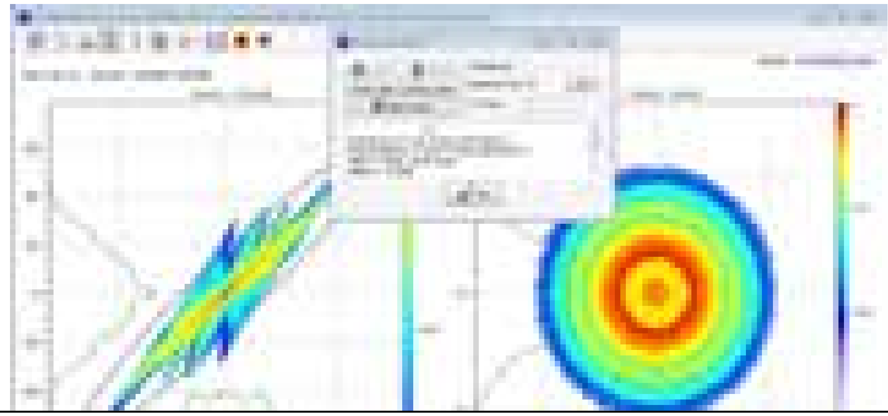
Axcel 2D beam input parameters:

Some simulation parameters:
Mesh = 1096 x 1424
Ip = 10
N°particles = 21920
kTe = 15 eV
kTi = 0.25 eV
pot. Plasma = 20 V
I tot = 0.0925 A
I protoni = 0.074 A
I H2 = 0.0185 A

To increase flexibility an interchangeable geometry was designed and different type of electrodes were manufactured

Simulations to optimized for larger current and minimize beam emittance



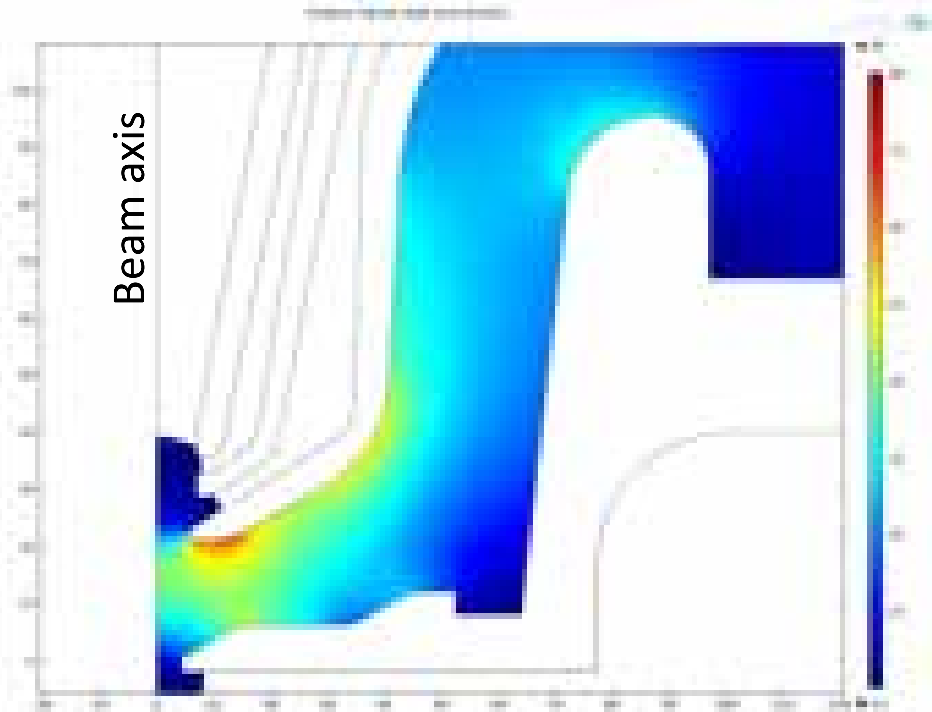


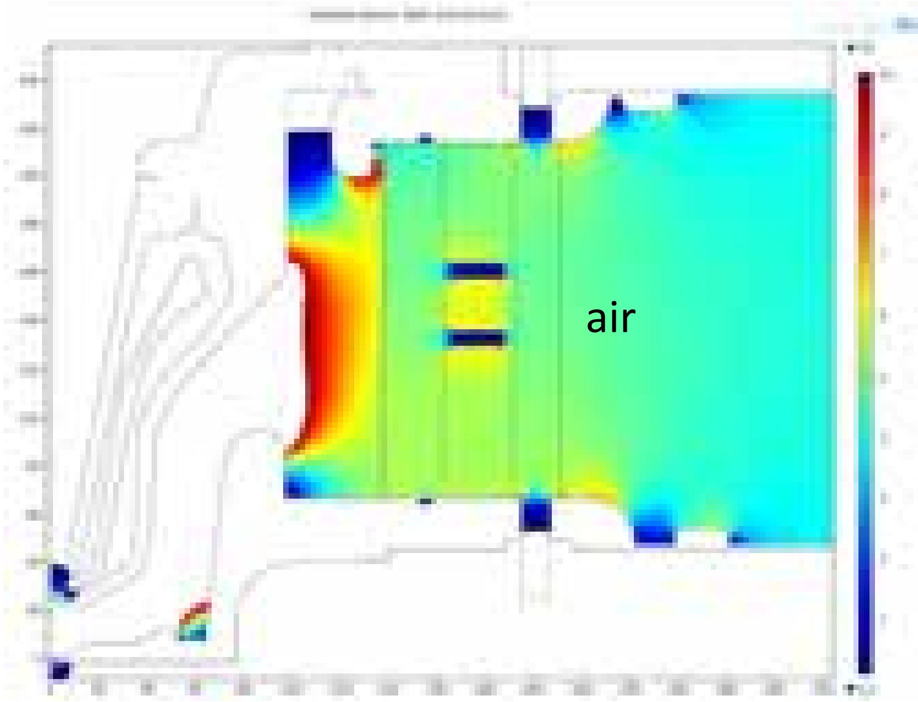
Emit [99%]=1.492 **(< 1.8)** Pi.mm.mrad [Norm]
Max Divergence= 55 **(< 80)** mrad

Extraction column design

- **Minimization off-axis electric field**
- **Electric field mimimazion at triple point** (< 6.4 kV/cm)

- **X Ray protection**
- **Single alumina** to minimize the electric field on the external surface (< 6.6 kV/cm)

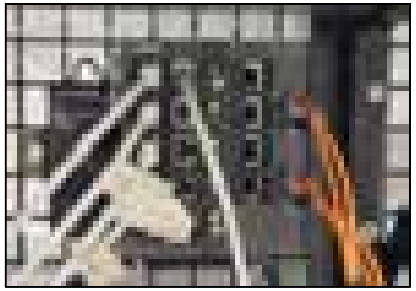




State-of-art sparks immunity during beam operation at 75 kV.
Extraction column tested up to 90 kV.

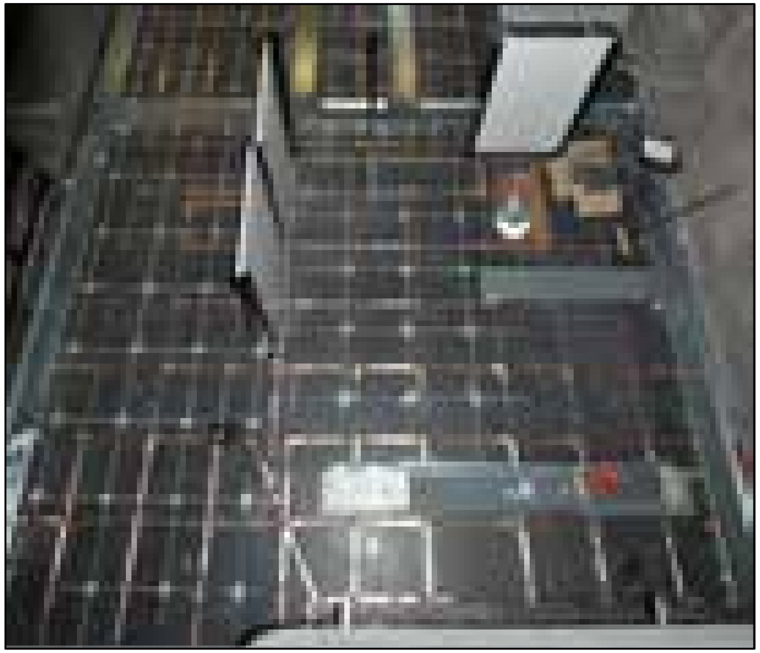
Increase electronics strength against discharge

Wide use of optical fibers

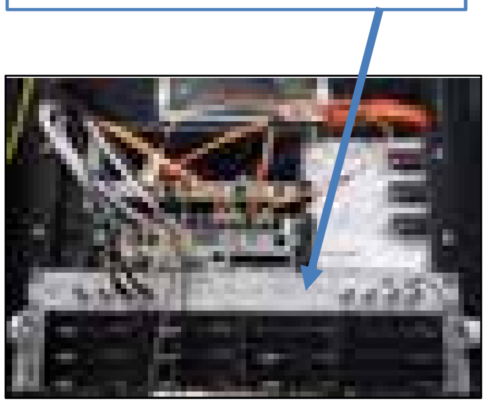


Shielded sub-rack on the HV platform

Grounding grid



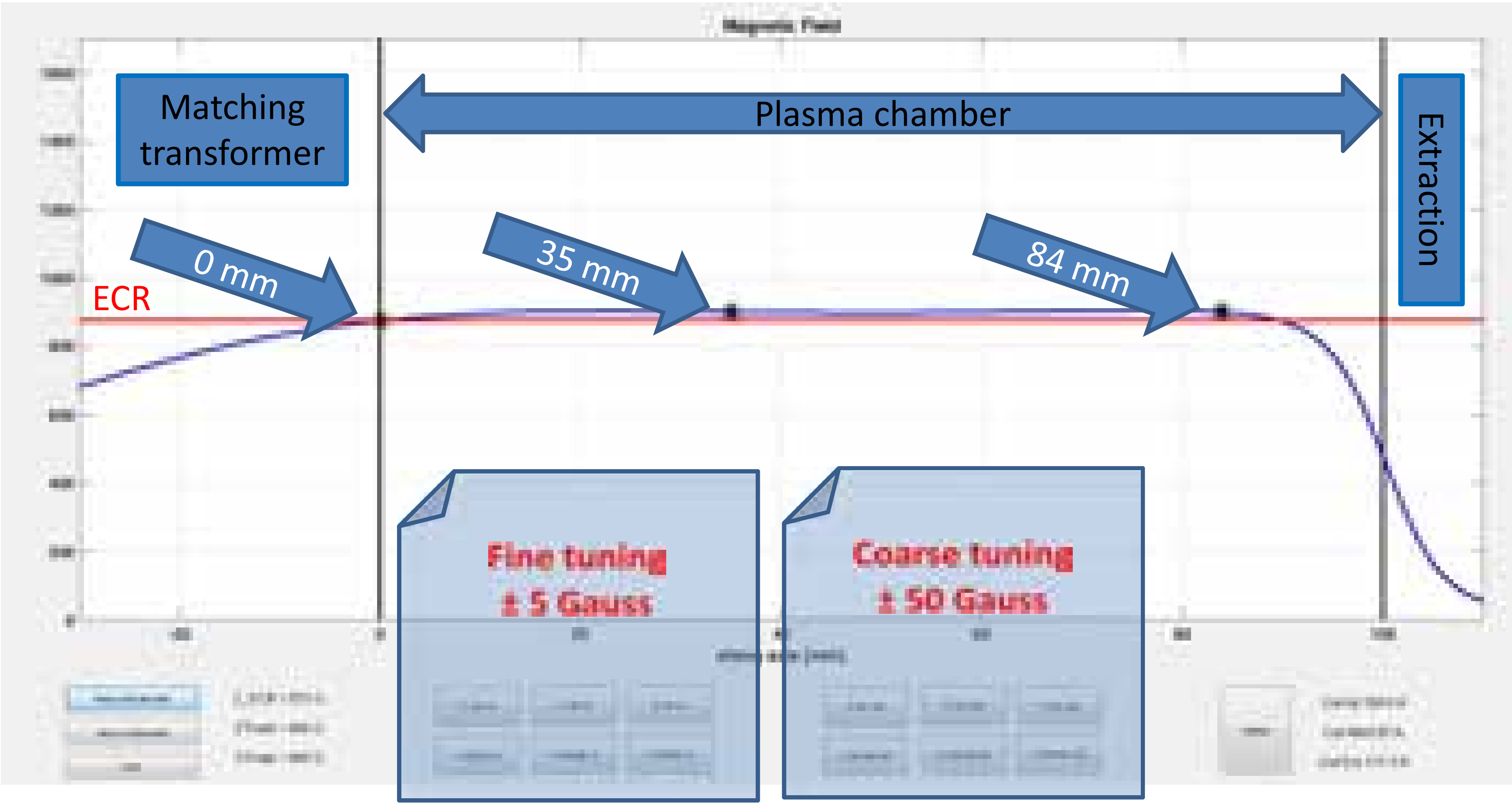
FC voltage protection



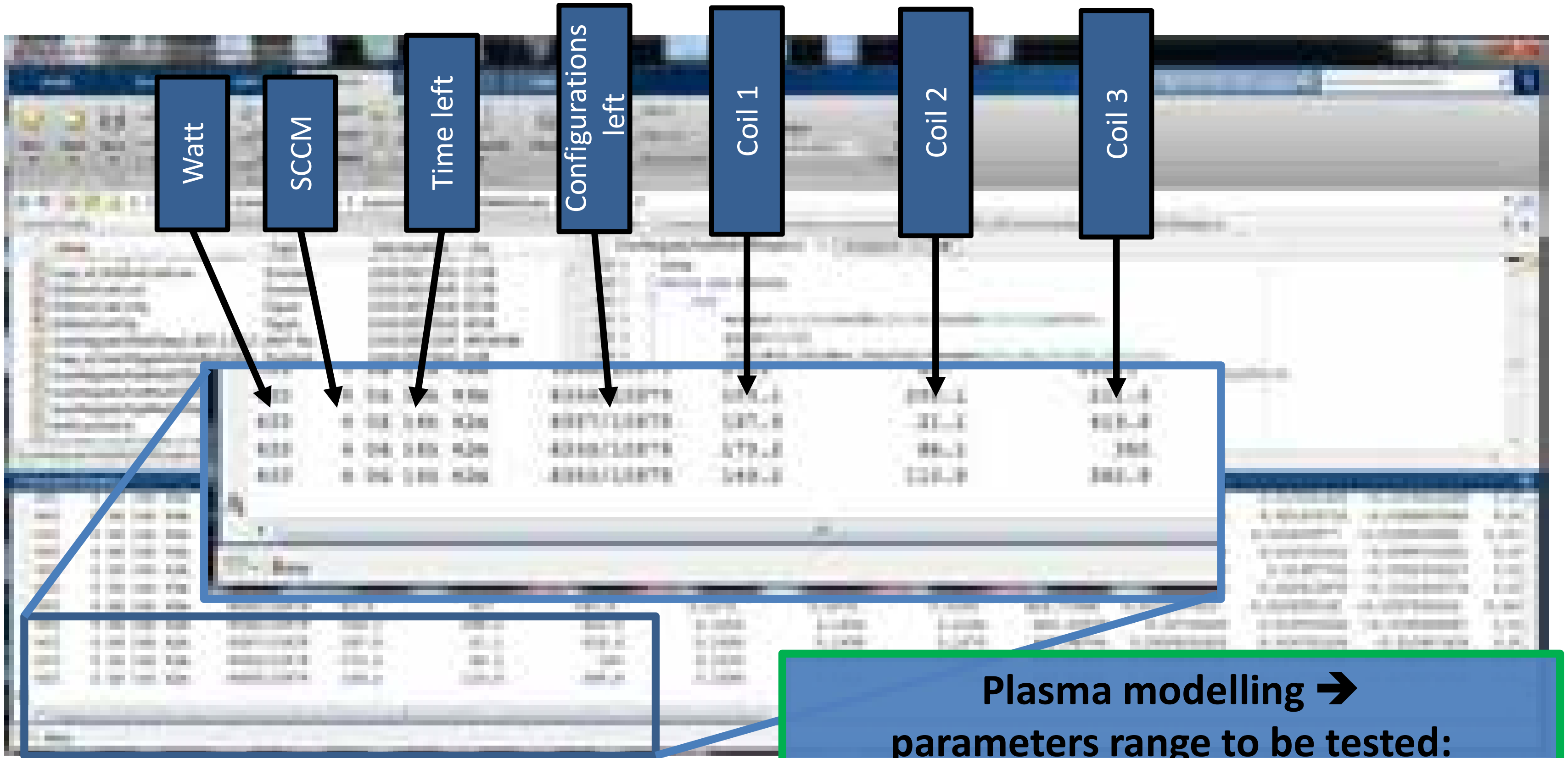
Shielded sub-rack at ground

Magnetic system control interface

Very high magnetic flexibility required a dedicated interface developed at INFN that enable direct control and high reproducibility



Semi-automatic characterization too



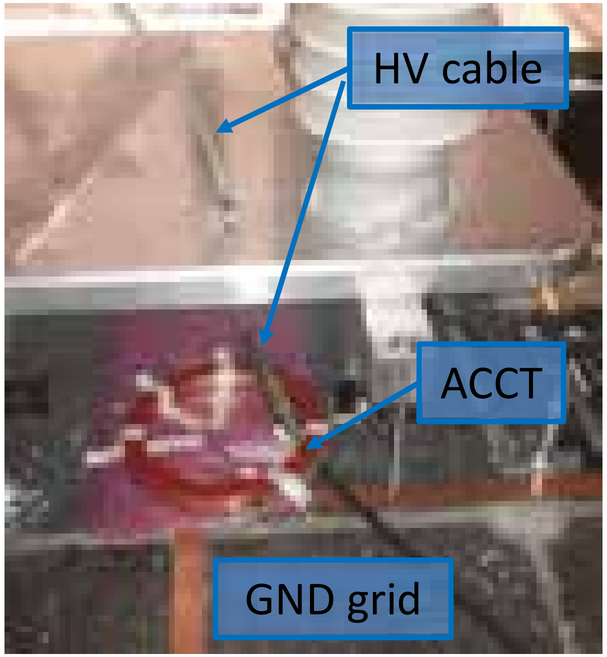
From the 23/01/2017 the source is extracting beam seamless, more than 300˙000 tested configurations, no stops due to sparks.

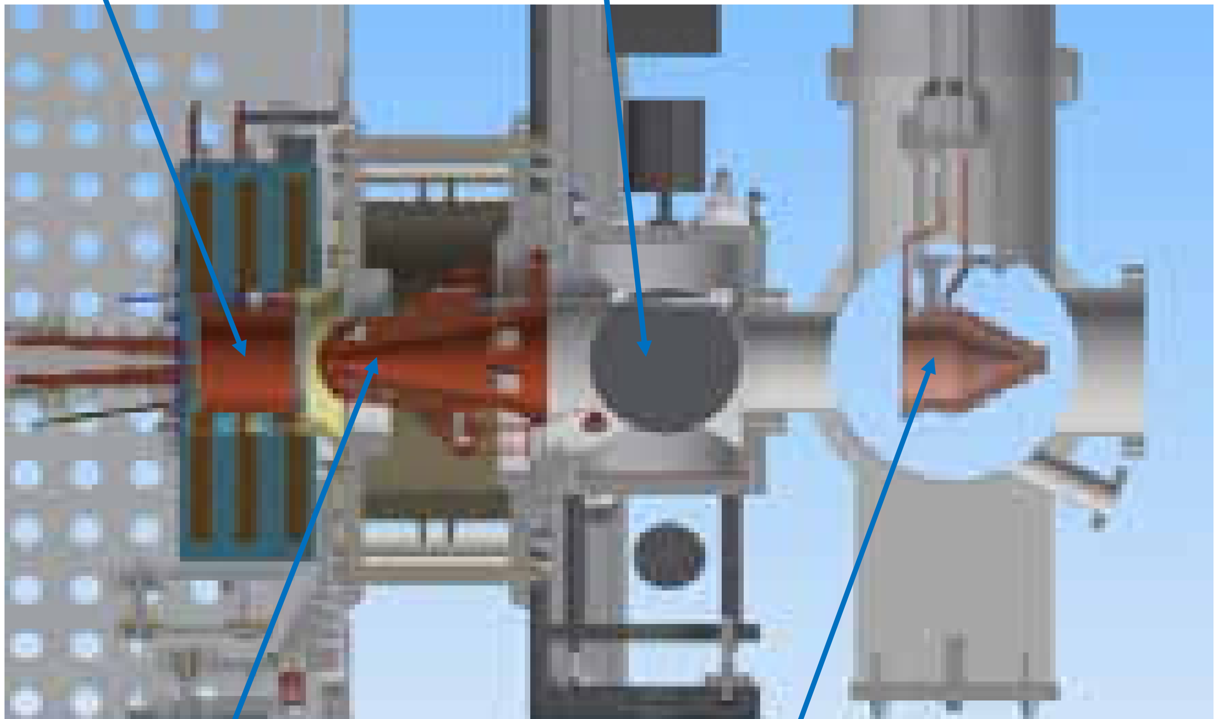
Plasma modelling ➔
parameters range to be tested:

Field @ 0 mm ==> 835:20:975 Gauss
Field @ 35 mm ==> 795:40:1395 Gauss
Field @ 84 mm ==> 675:40:1995 Gauss
H2 flow ==> 2:1:5 SCCM
RF power ==> 600:200:1200 Watt

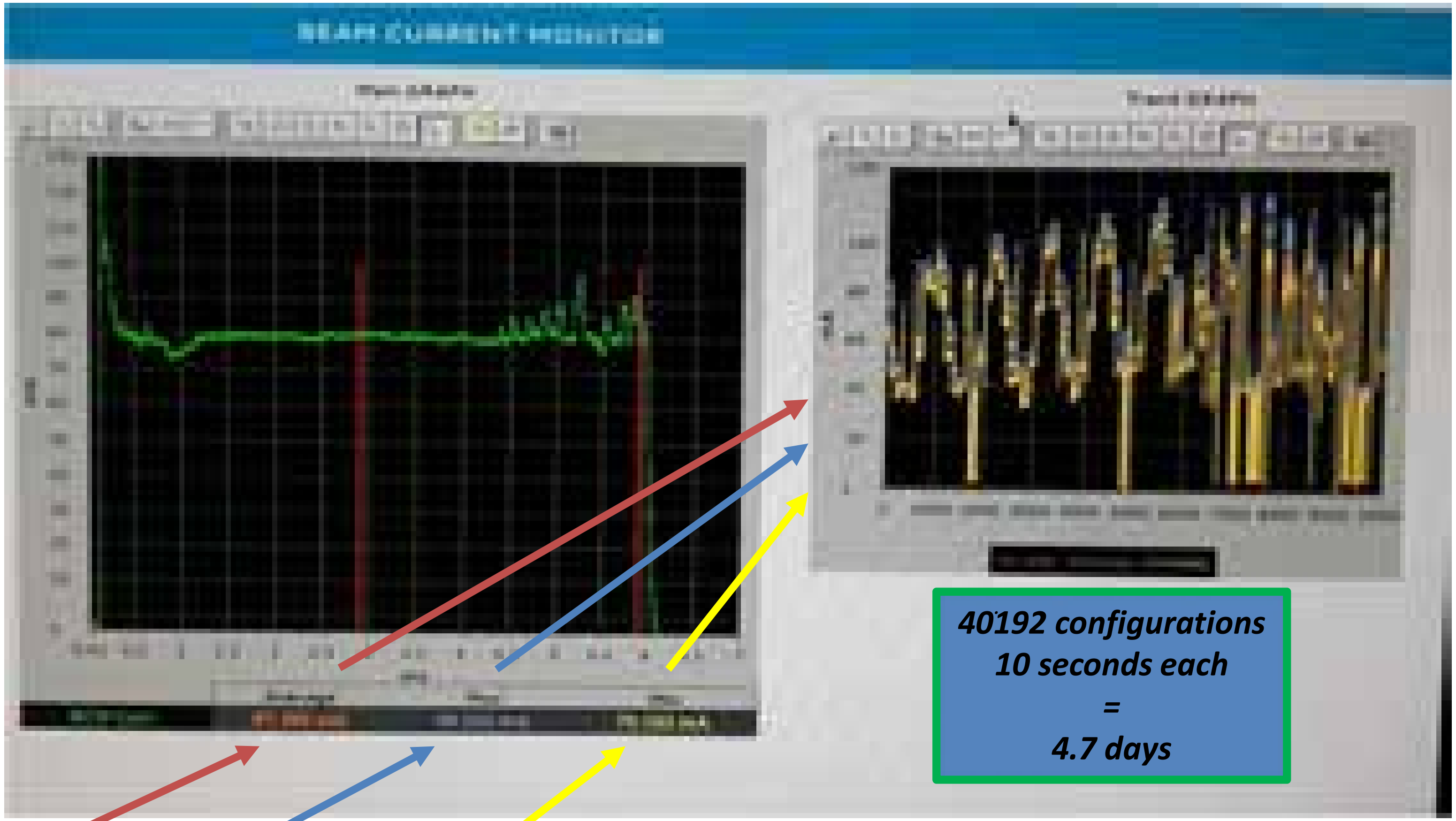
40192 configurations

Commissioning setup phases 1 and 2





Semi-automatic characterization

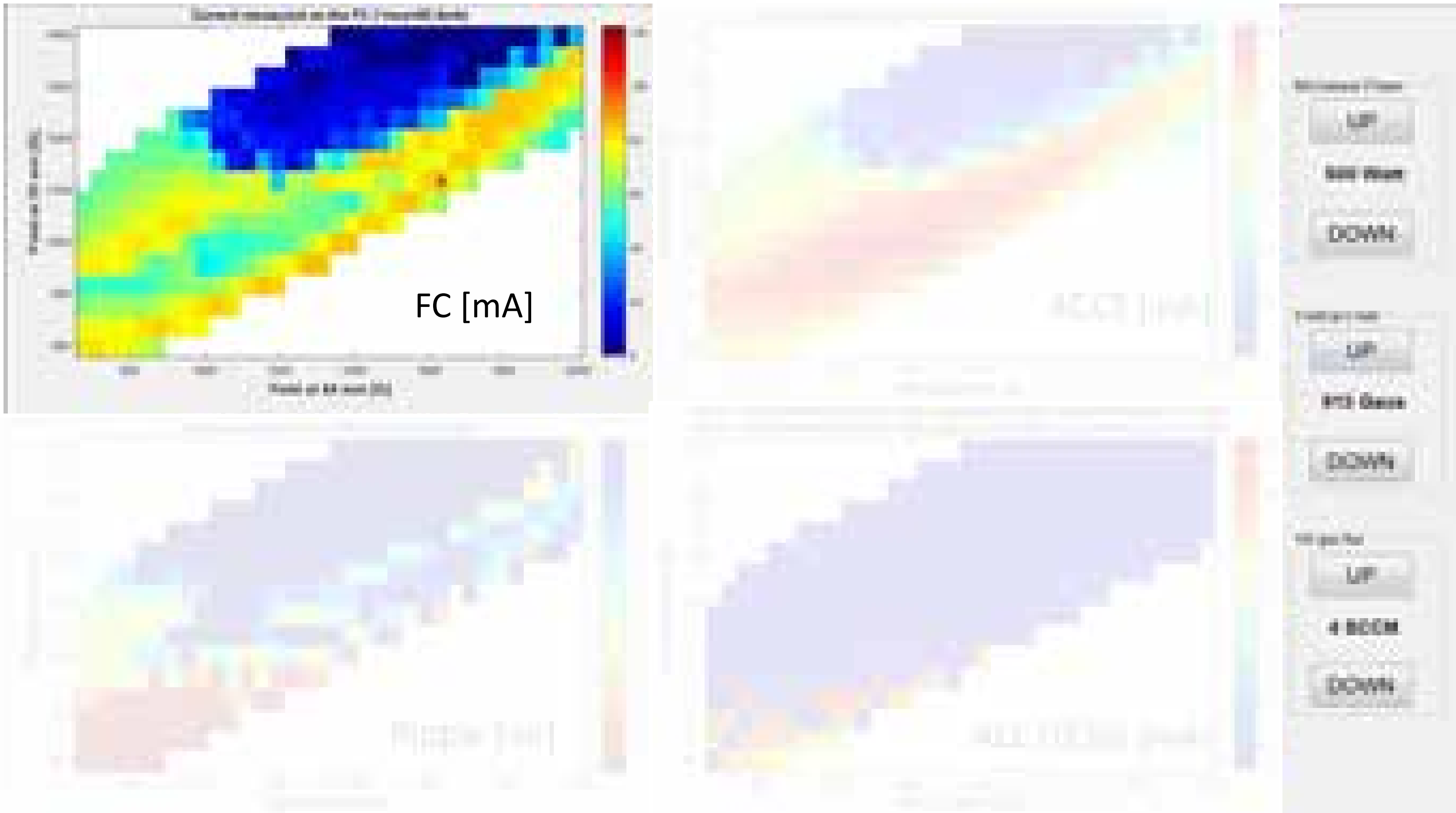


40192 configurations
10 seconds each
=
4.7 days

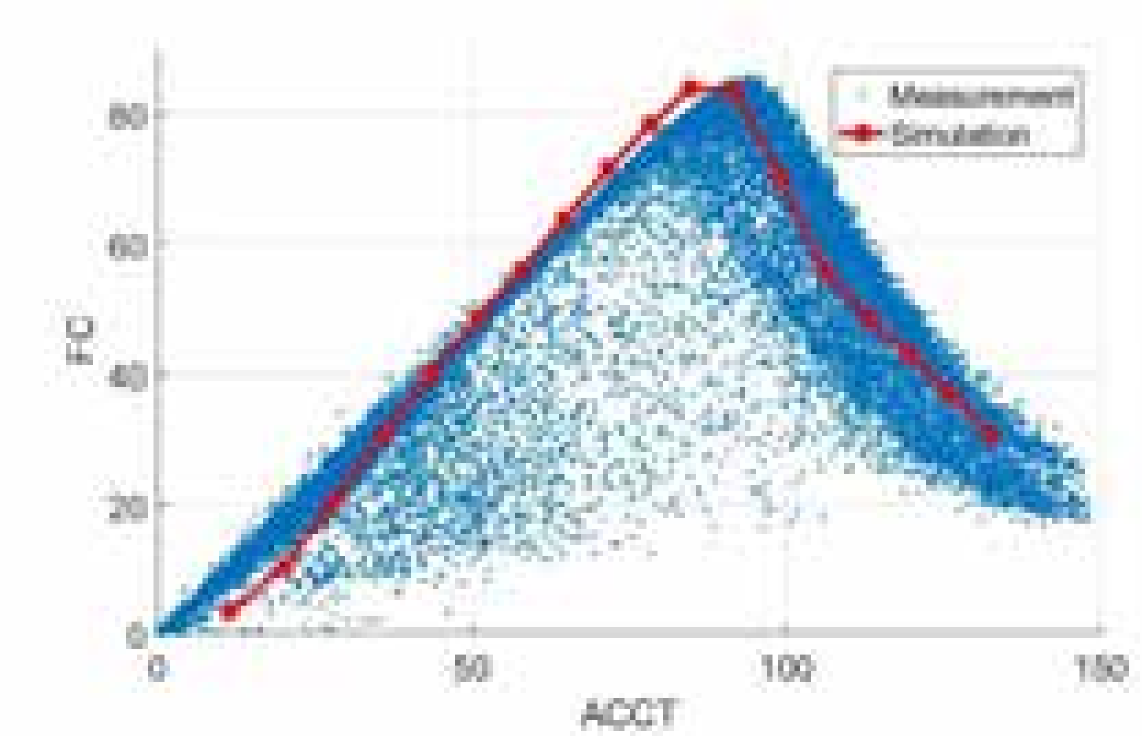
In the graphical interface: average, maximum and minimum are evaluated and the trend showed for the beam pulse between 2.9 ms and 5.9 ms .

In the semi-automatic characterization code 26 parameters and two wave forms (@1Ms/s) are saved for each pulse produced at nominal repletion rate of 14Hz.

Data analysis of thousands of different configurations



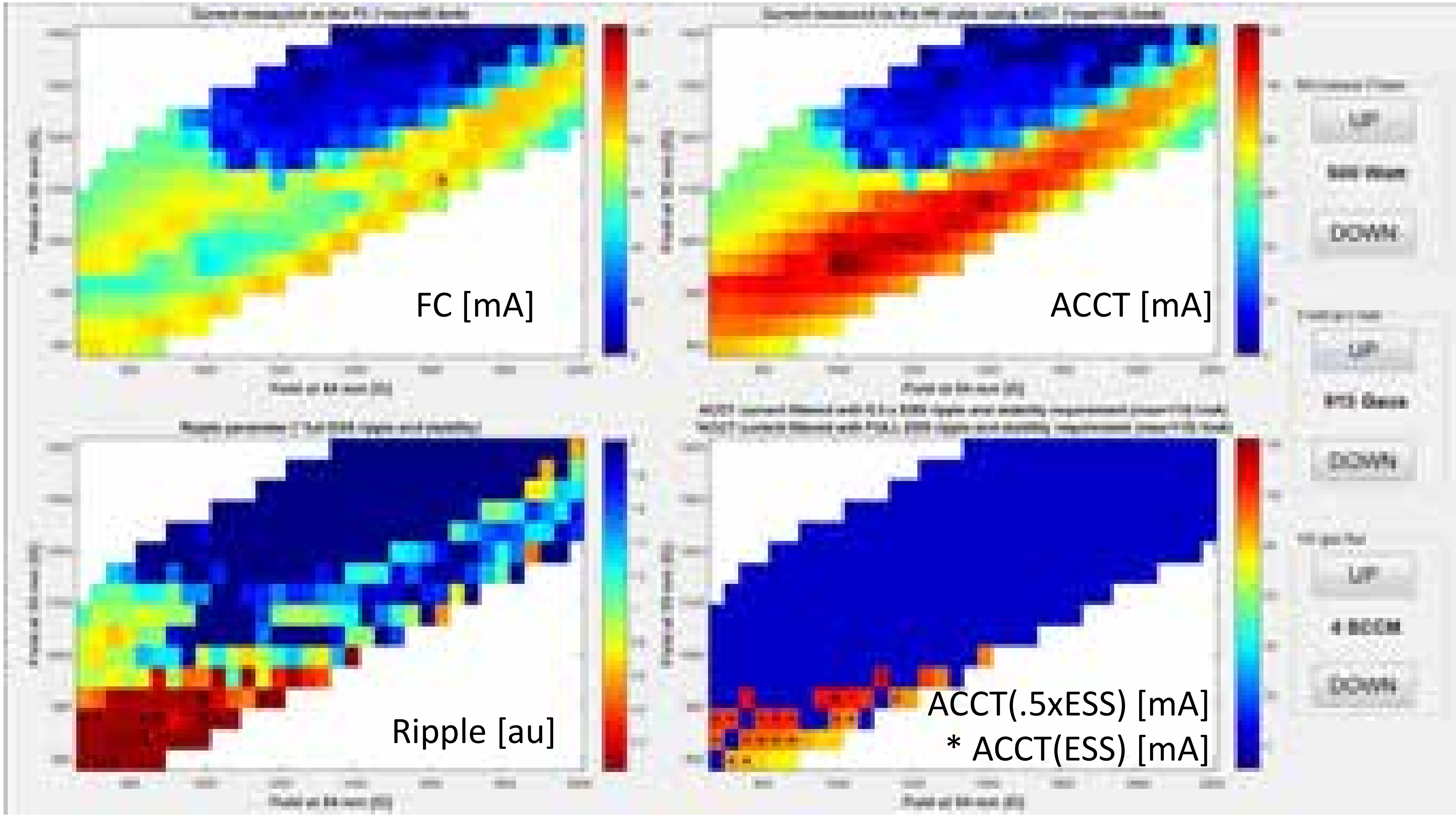
Fraction of beam current collected the Faraday Cup



Courtesy of O. Midttun (*University of Bergen*)

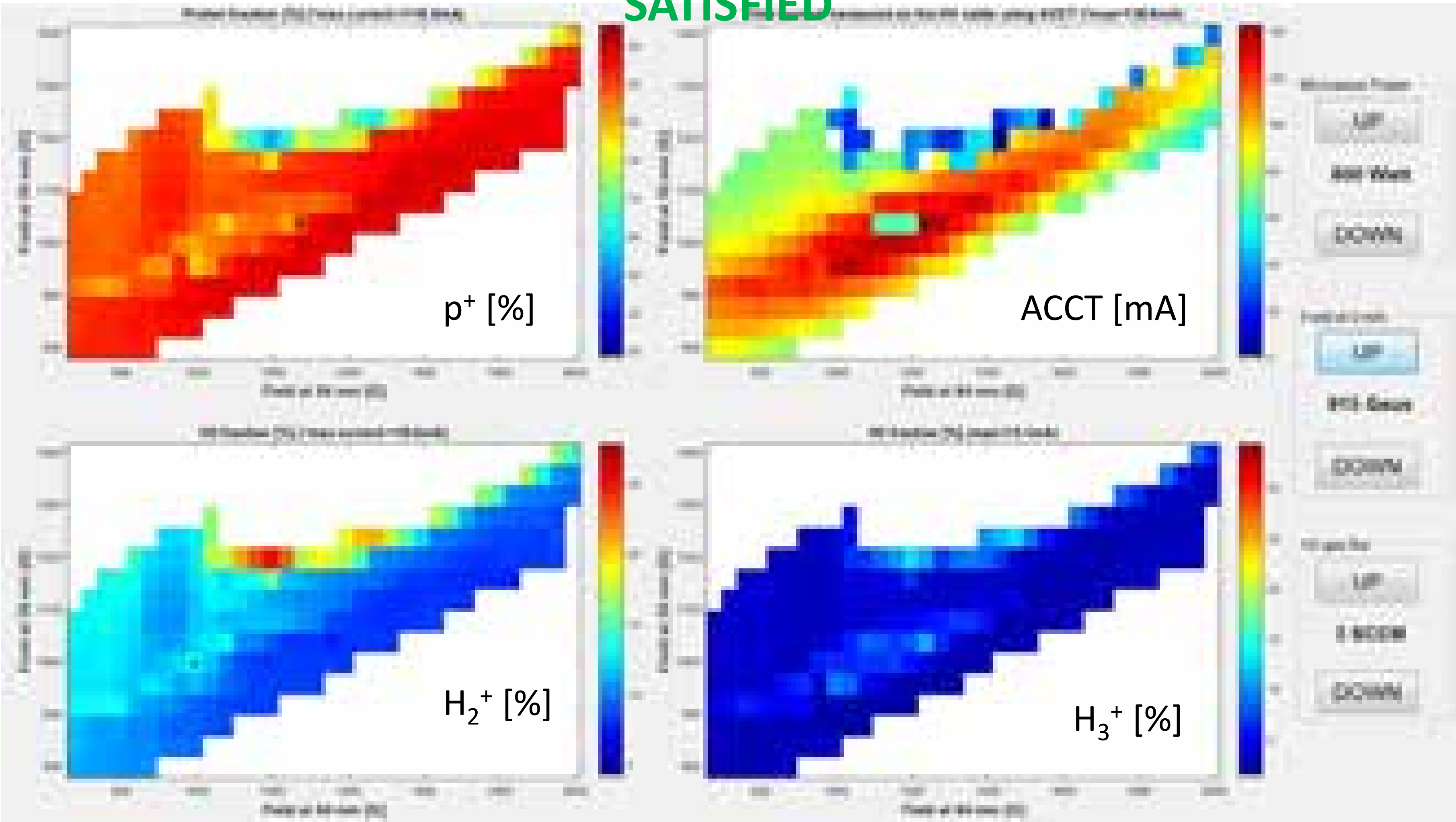
Increasing the plasma density increase the meniscus concavity and the divergence of the extracted beam.
Simulation done with IBSimu shows good agreement with experimental data.

Data analysis of thousands of different configurations



Doppler shift measurement beam characterization

Proton fraction > 75%
SATISFIED



ESS stable configurations versus injected H_2 gas flux and microwave power

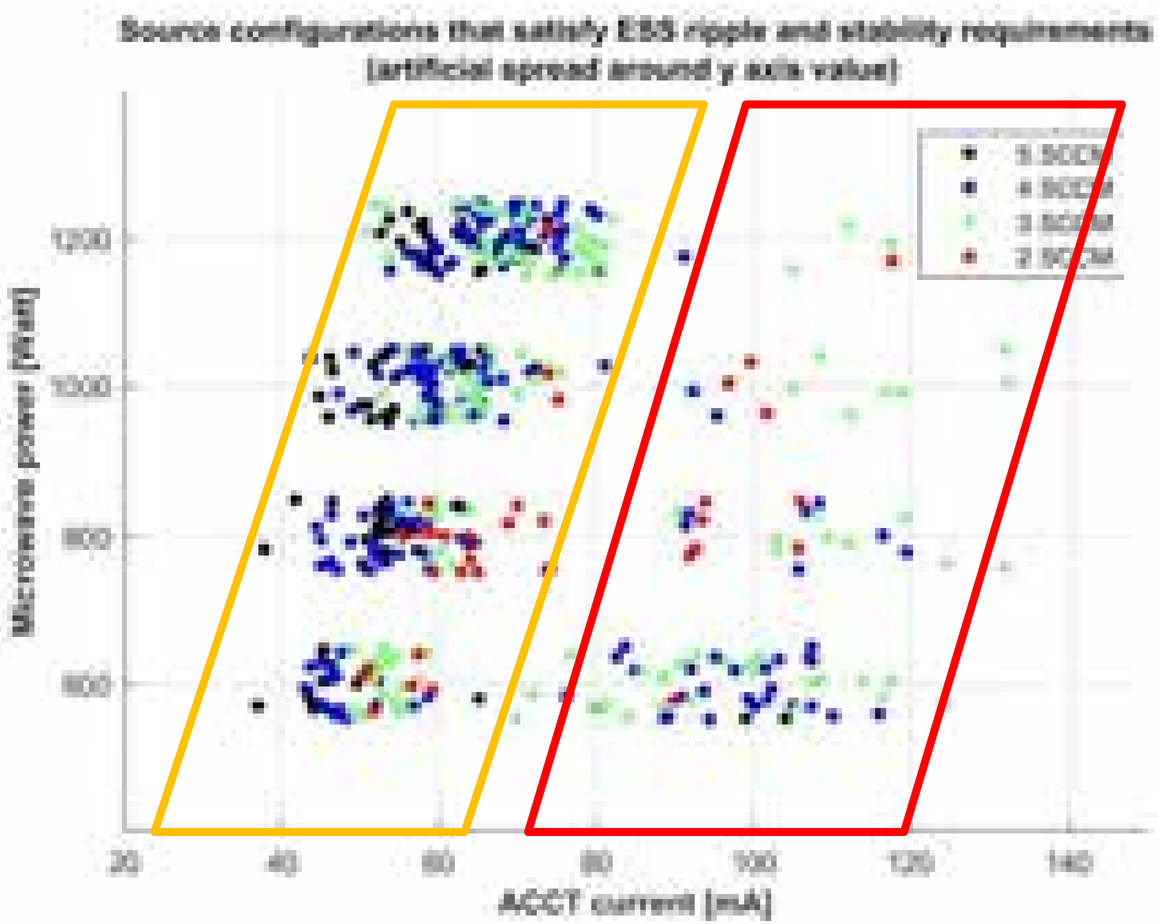
Total current = 100 mA **SATISFIED**

Increasing the injected microwave power increase the energy transfer and consequently the plasma density

Each point is a large operative range (20 Gauss x 40 Gauss x 40 Gauss x 1 SCCM x 200 Watt)

Lower current (2-5 sccm)

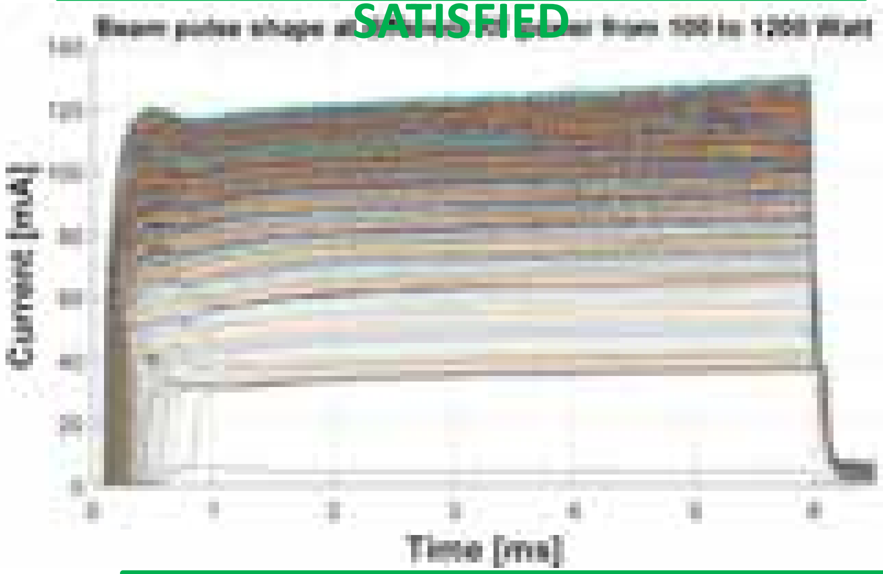
High current (2-4 sccm)



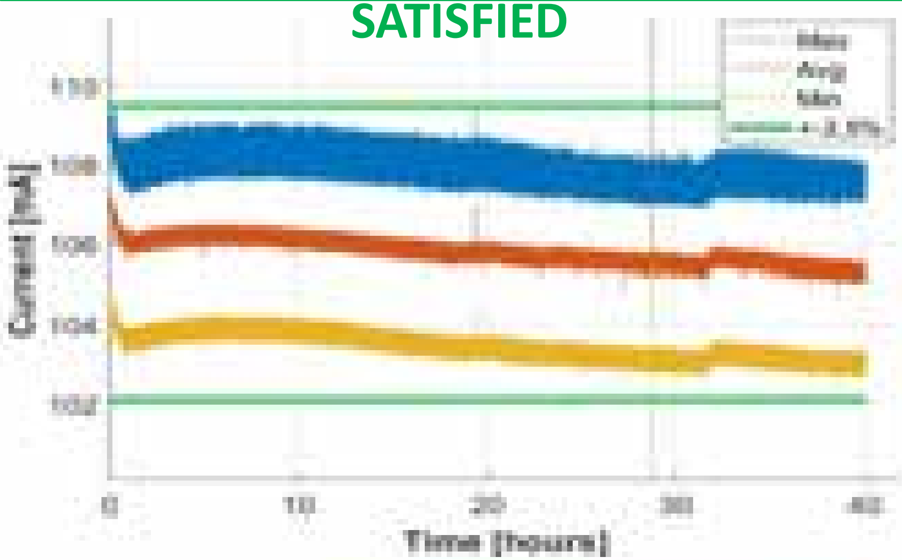
ESS nominal configuration

109 A coil1; 67 A coil2; 228 A coil3; 3 SCCM H_2

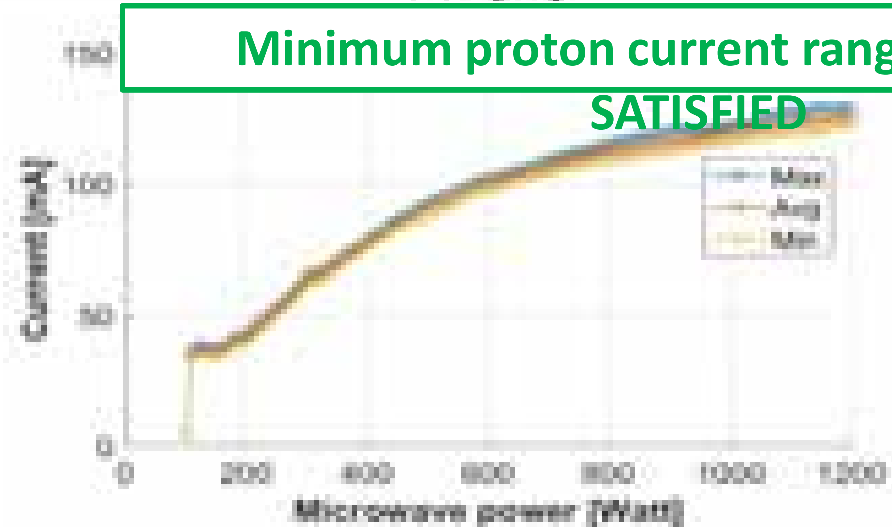
Intra-pulse stability < ±2% SATISFIED

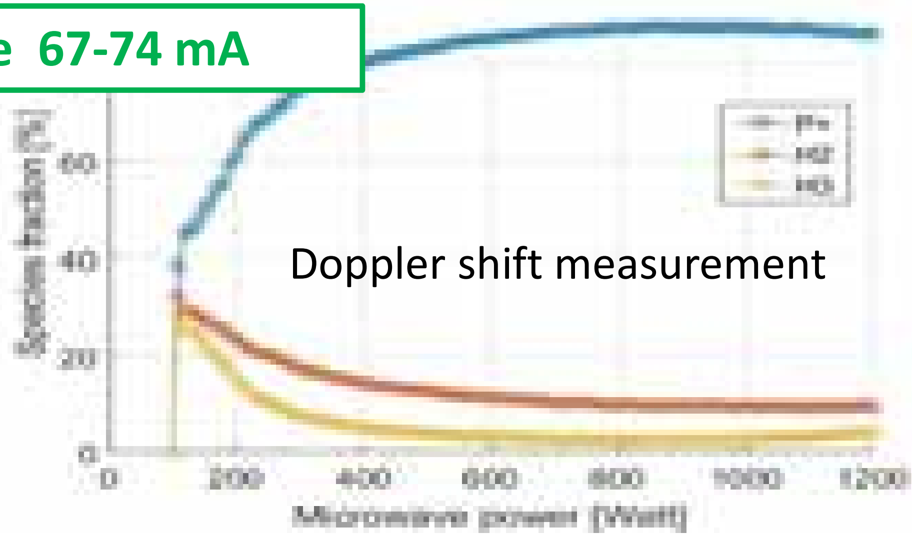


Pulse to pulse stability < ± 3.5% SATISFIED



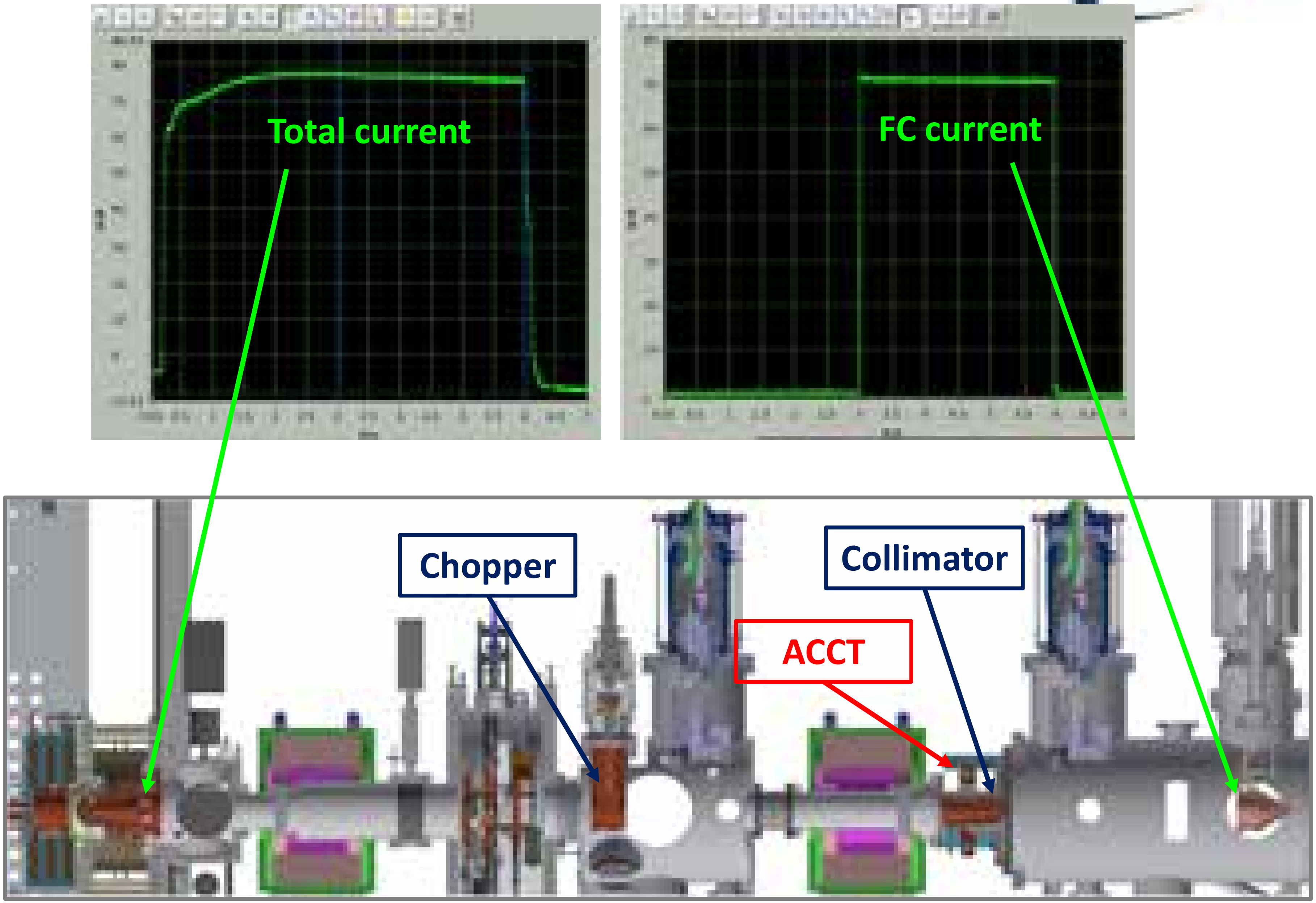
Minimum proton current range 67-74 mA SATISFIED





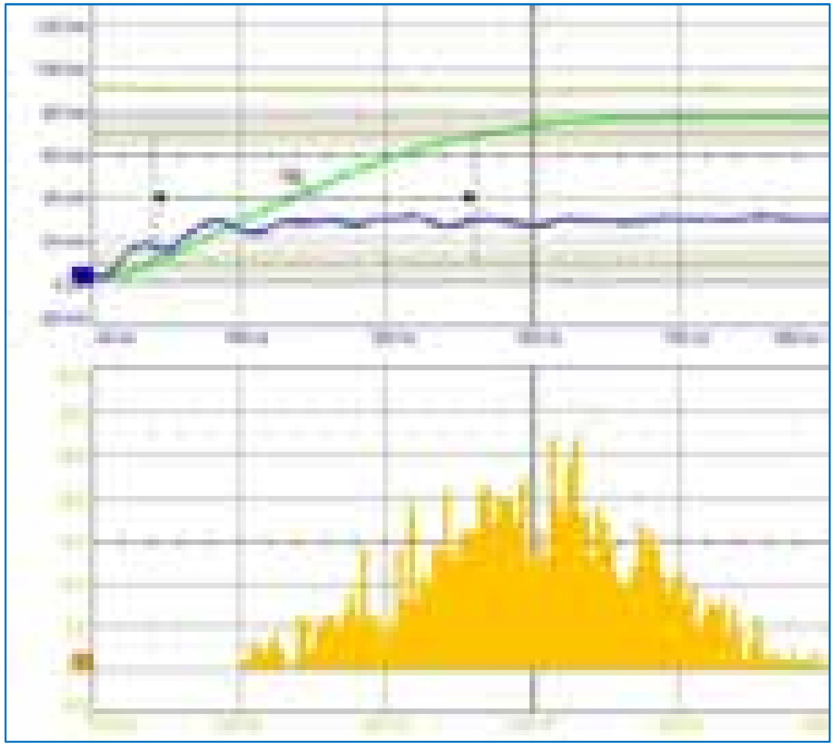
Doppler shift measurement

Chopping performaces

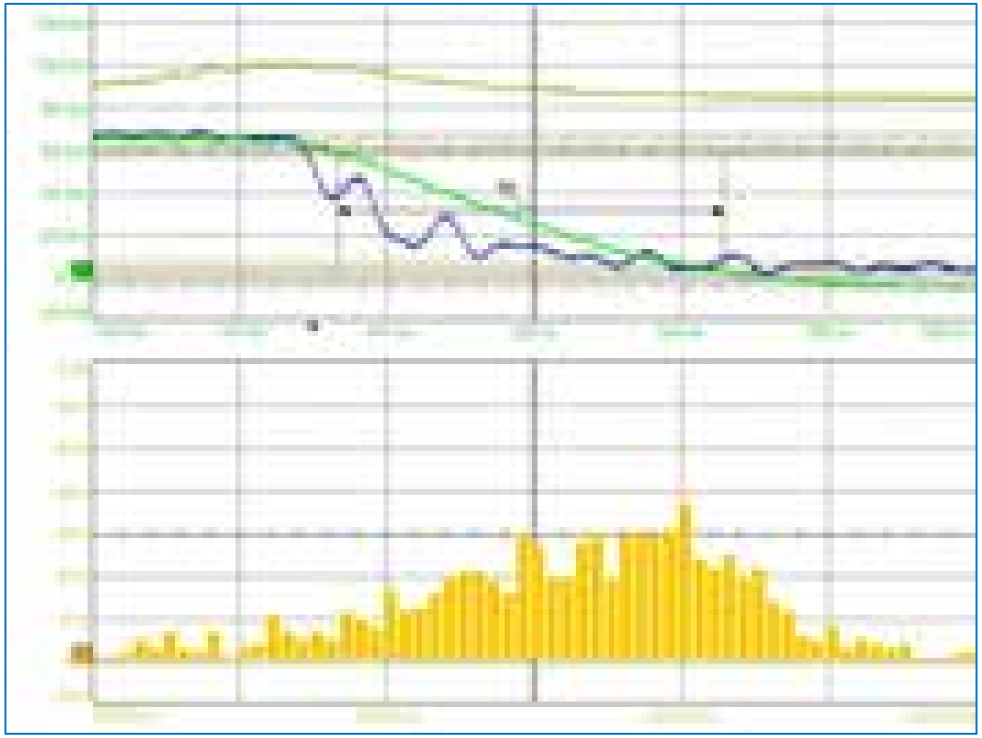


Chopping performaces

Rise time: 430ns



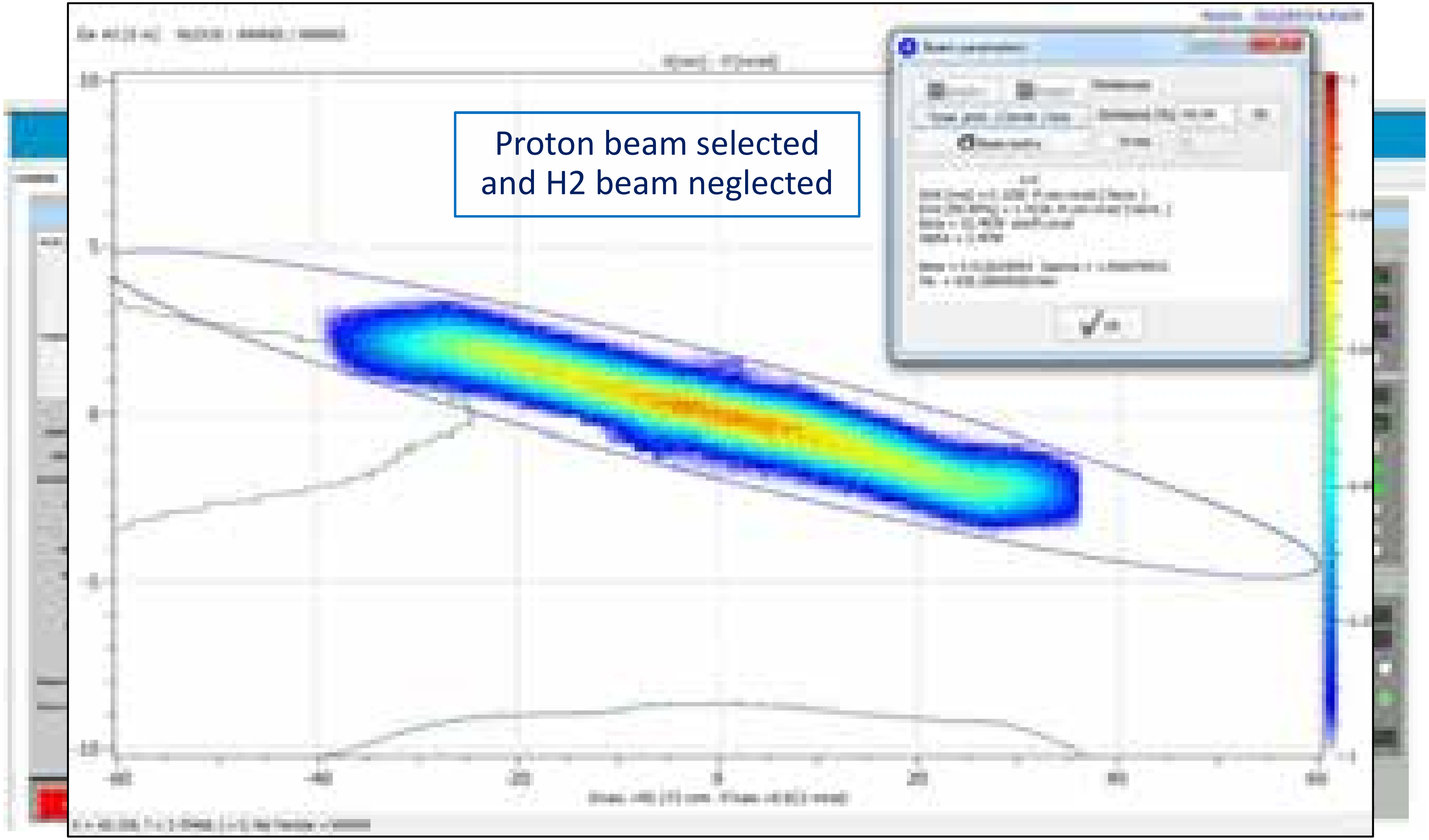
Fall time: 519 ns



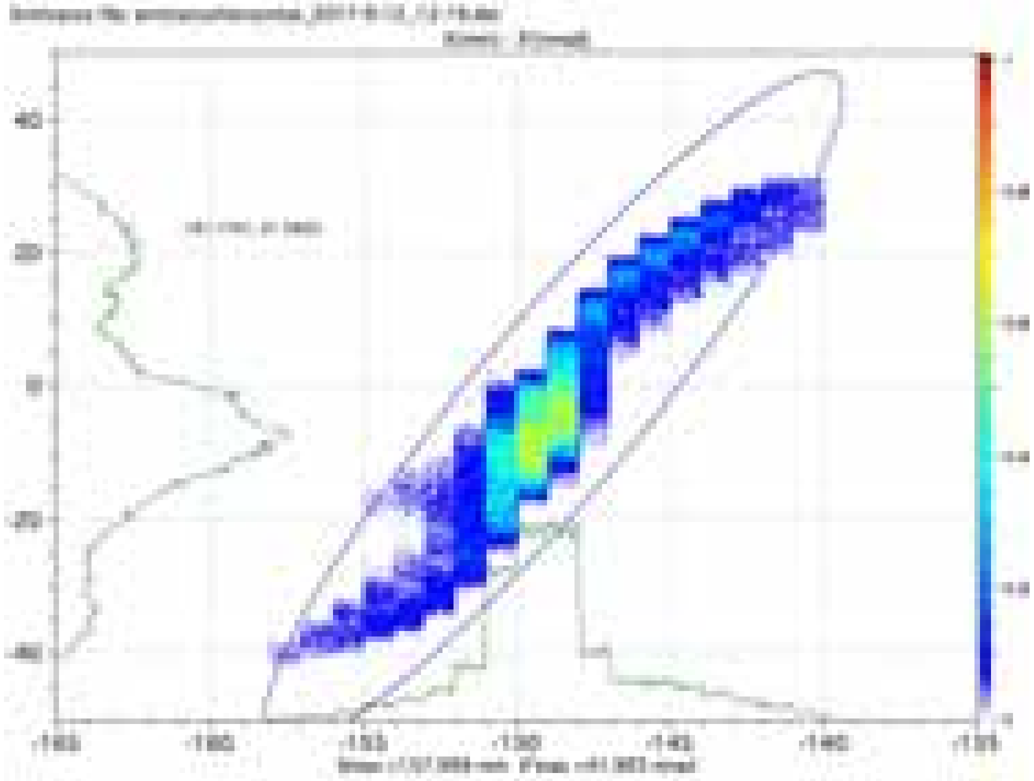
Beam pulse shape measured with the ACCT located at the end of the LEBT

Beam emittance at the center of the LEBT

A parallel beam is obtained between the two solenoids
Emittance (99%): 1.43 π.mm.mrad

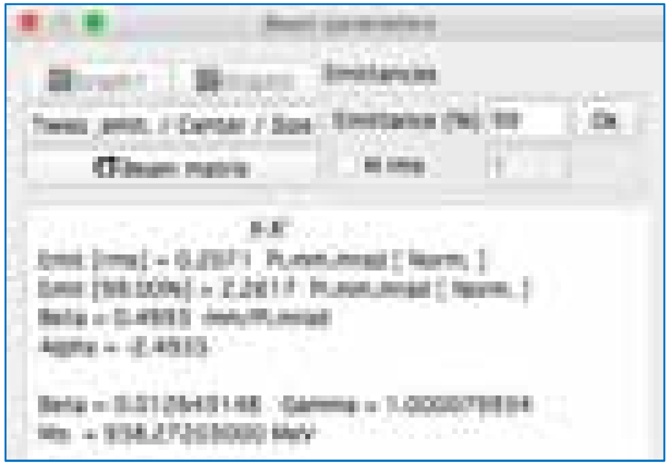


Beam emittance at RFQ location



Emittance measured after 100 mm of the RFQ beam lattice interface.

Back tracing simulation under going to evaluate twiss parameters at LEBT-RFQ beam lattice interface



Transverse emittance SATISFIED
Emit [rms] < 0.25 Pi.mm.mrad
Emit [99%] < 2.25 Pi.mm.mrad

Site Acceptance Review

	Name
Authors	Øystein Midttun Lorenzo Neri Cyrille Thomas

- ☑ Requirement achieved
- ☒ Requirement not achieved
- ■ Requirement not possible to verify because of reduced commissioning time or missing beam instrumentation

ION SOURCE PERFORMANCE AT THE END OF COMMISSIONING PHASE 2

Requirement	Value	Status
Nominal beam current	74 mA	☑
Maximum beam current	> 90 mA	☑
Proton beam current range	67 – 74 mA	☑
Proton fraction	> 75 %	☑
Pulse length	6 ms	☑
Flat top stability	± 2 %	☑
Pulse to pulse stability	± 3.5 %	☑
Beam energy	75 keV	☑
Beam energy fluctuation	± 0.01 keV	☑
Transverse emittance (99%)	1.8 π.mm.mrad	■
Start-up after maintenance	< 32 hours	☑

ION SOURCE AND LEBT PERFORMANCE AT THE END OF COMMISSIONING PHASE 4

Requirement	Value	Status
Nominal beam current	70 mA	☑
Transmission	> 95 %	☑
Beam current range	6 – 70 mA	☑
Beam current precision	1 mA	☑
Vacuum pressure	< 6e-5 mbar	☑
Beam pulse flat-top length	0.05 - 2.86 ms	☑
Beam pulse rise/fall time	< 1 µs	☑
Transverse emittance (99%)	1.25 π.mm.mrad	☑
Twiss parameter α	1.02 ± 20 %	■
Twiss parameter β	1.02 ± 20 %	■

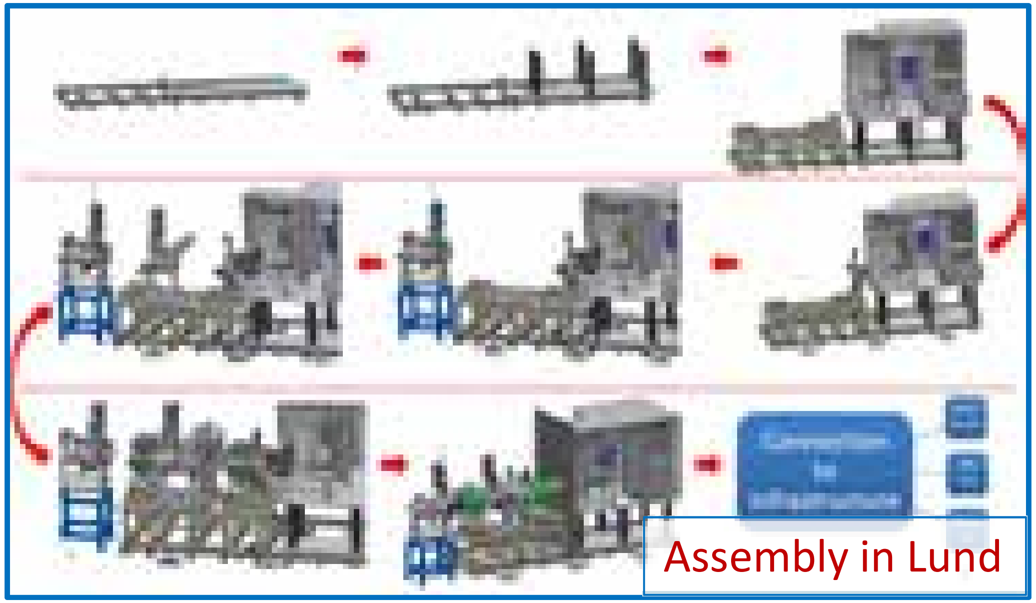
Main troubles

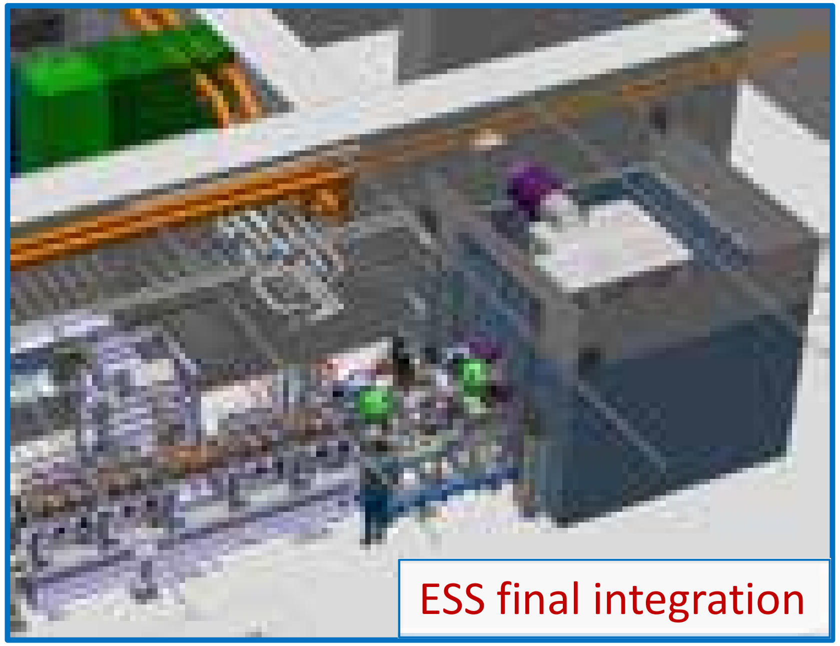
- ~~Losses in extraction~~
- ~~Source reliability~~
- ~~Emittance too high~~
- ~~Current still not at the values needed~~
- ~~Remote control «infant mortality…»~~

ESS final integration

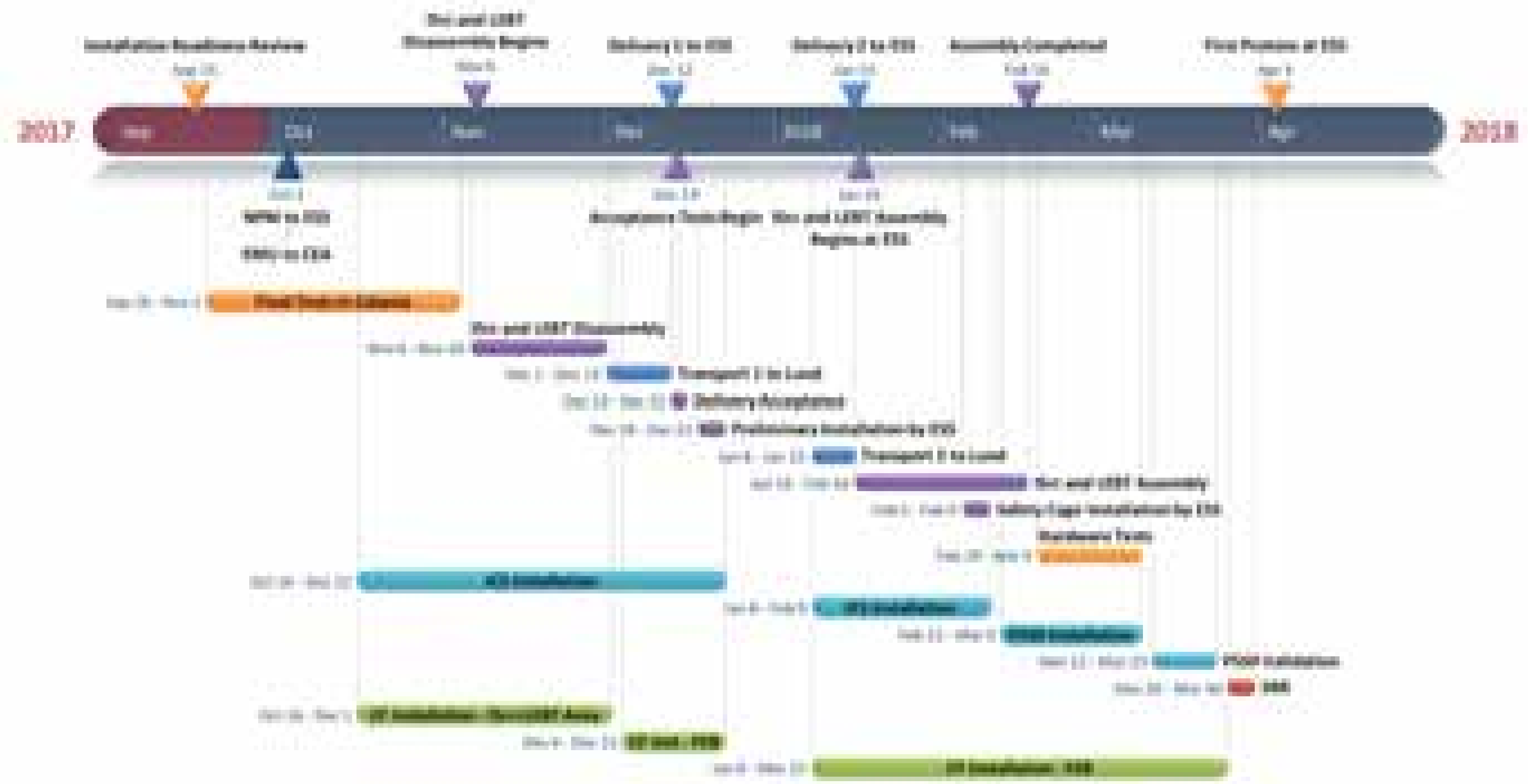

Dismantling


Packaging and transport

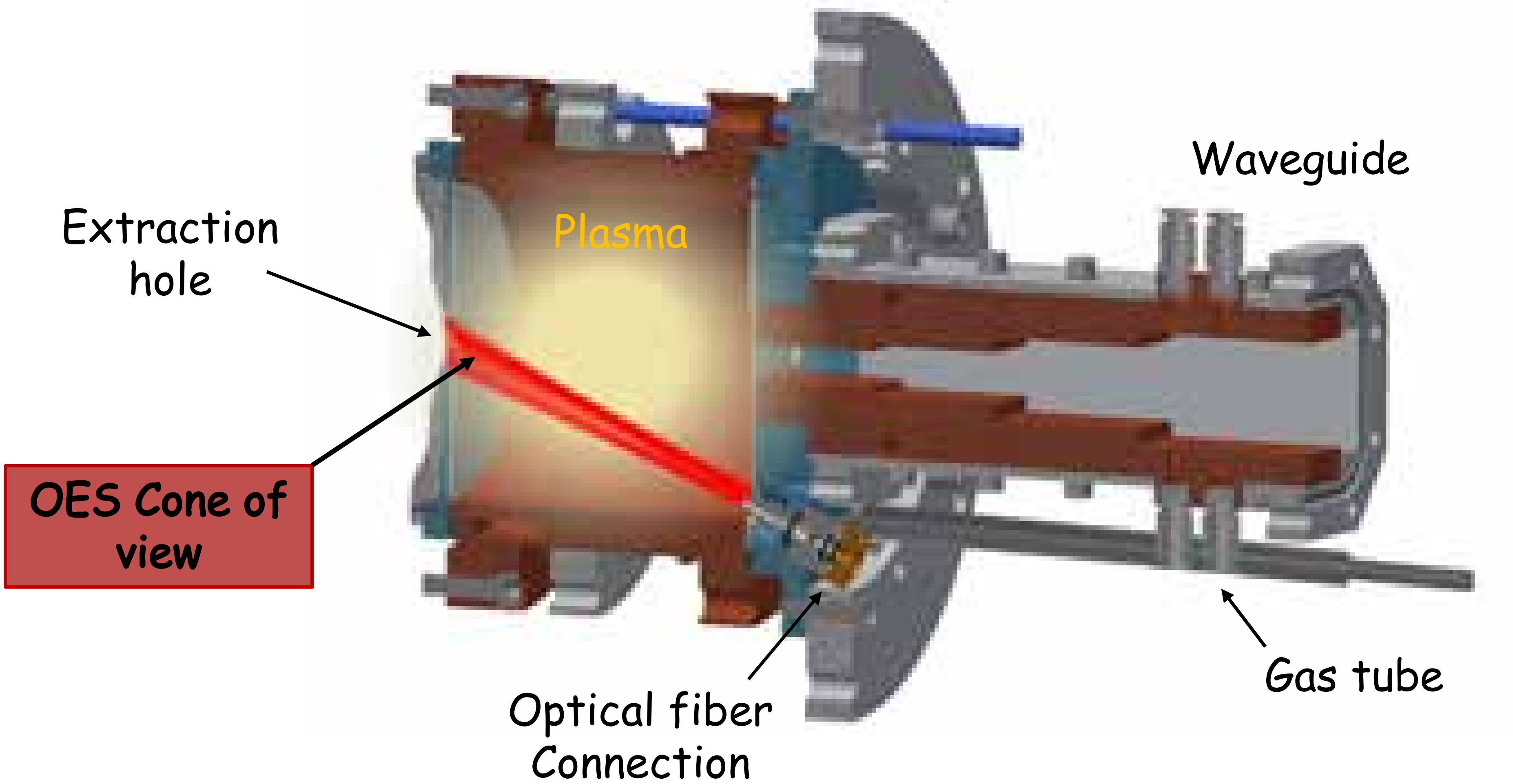

Assembly in Lund


ESS final integration

Time line


2017
2018
Installation Readiness Review
Delivery 1 to ESS
Delivery 2 to ESS
Assembly Completed
First Protons at ESS
Acceptance Tests Begin
Transport 1 to Lund
Delivery Acceptance
Transport 2 to Lund
Hardware Tests

OES measurements

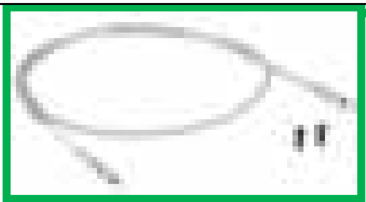


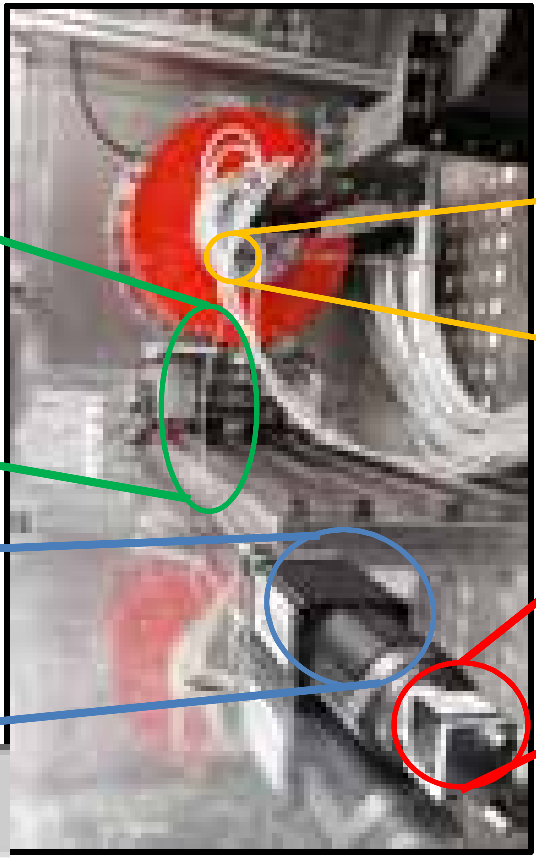
The Optical fiber is connected to the gas tube, via a quartz window and an adapter;

OES cone of view intercepts the plasma extraction region;

The OES experimental set-up

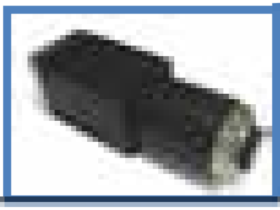
Optical fiber
Core diameter: 1500 ± 30 μm
Wavelength range: 300-1200 nm





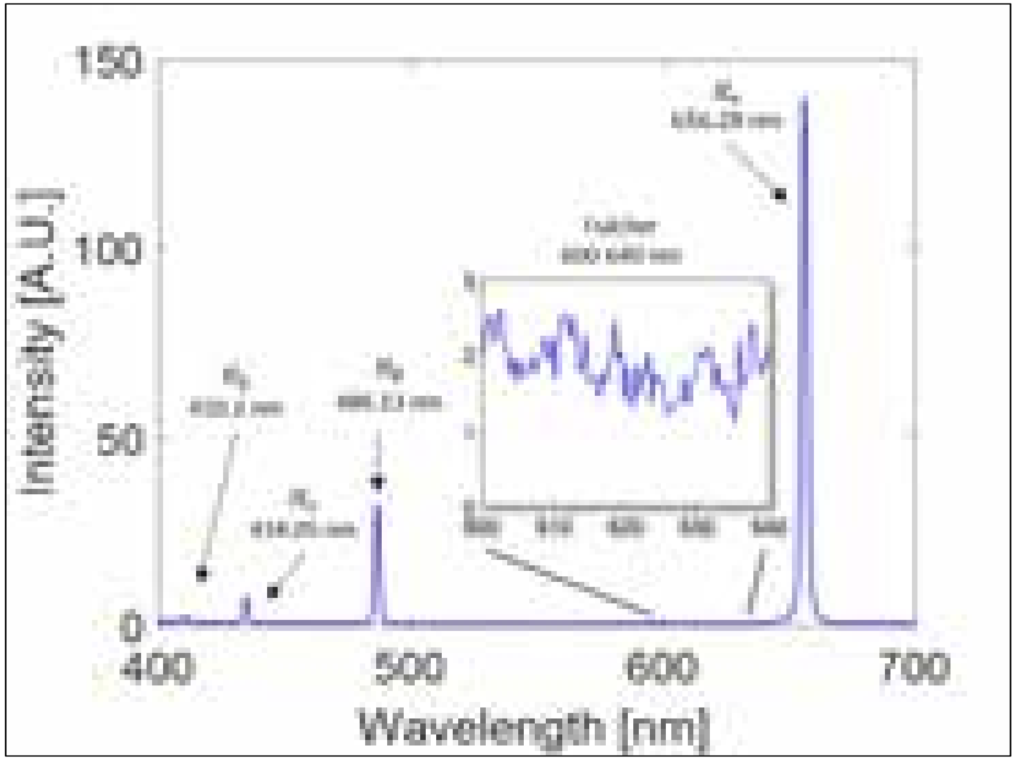
O. Fiber – gas input adapter

CMOS CAMERA (acA2040-90um)
Sensor size: 2048 × 2048 pixel
Optical size: 1’’
Pixel size: 5.5μm × 5.5μm



ImSpector-V8E Spectrometer
Spectral range: 400-1000 nm
Spectral resolution: 2nm

OES Theoretical and experimental approach



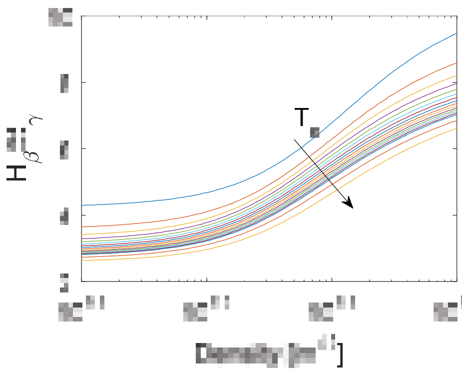
The comparison between theoretical and experimental line ratio permits to evaluate the plasma parameters

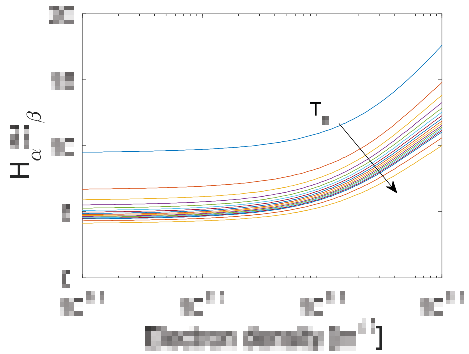
$H_\alpha/H_\beta,\ H_\beta/H_\gamma \longrightarrow T_e,\ n_e$

$H_\gamma/\int F.band \longrightarrow n(H)/n(H_2)$

Collisional Radiative (CR) model
rate equations for each state of the particle together with the coupling to other particles

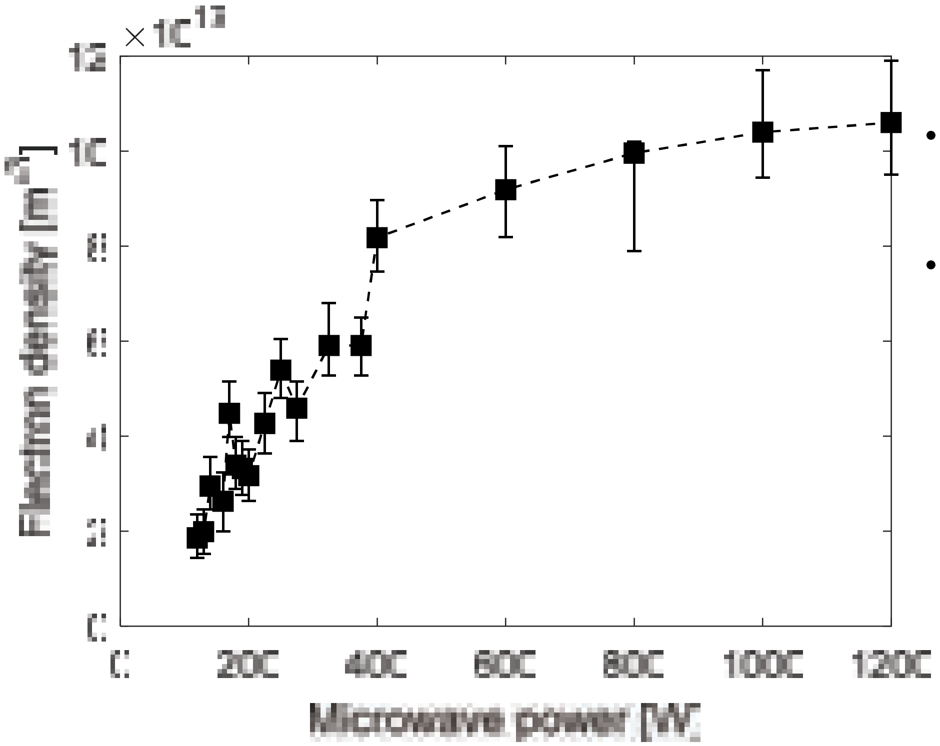
CR models from Yacora developed by Max Plank institute (https://www.yacora.de)





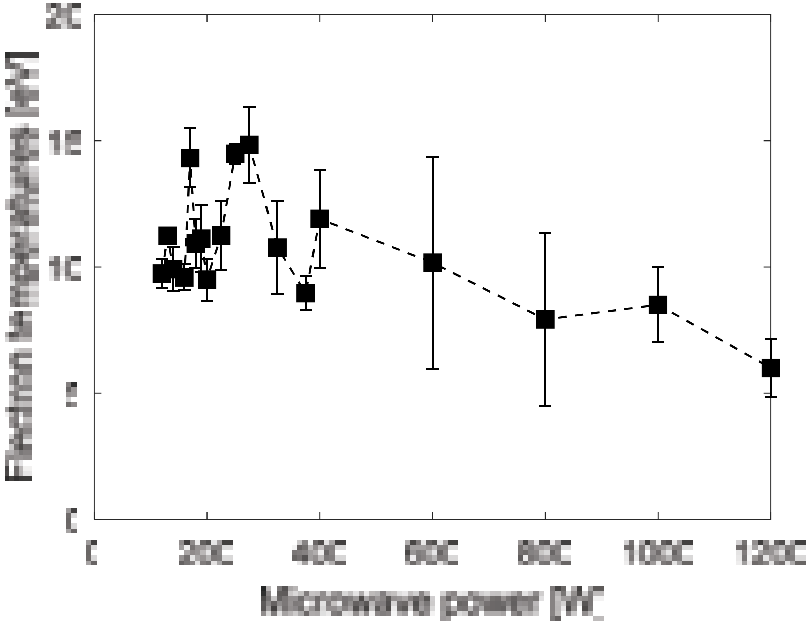
*D. Wünderlich and U. Fantz, Atoms 4, **2016**, 26*

Results: the electron density



- Electron density overcomes density cut-off at 2.45 GHz ($n_{cut\text{-}off}$: $8.75 \cdot 10^{16}$ m^{-3});
- Density saturates above 400 W at $0.9\text{-}1 \cdot 10^{18}$ m^{-3} – **10 times overdense plasma generated**;

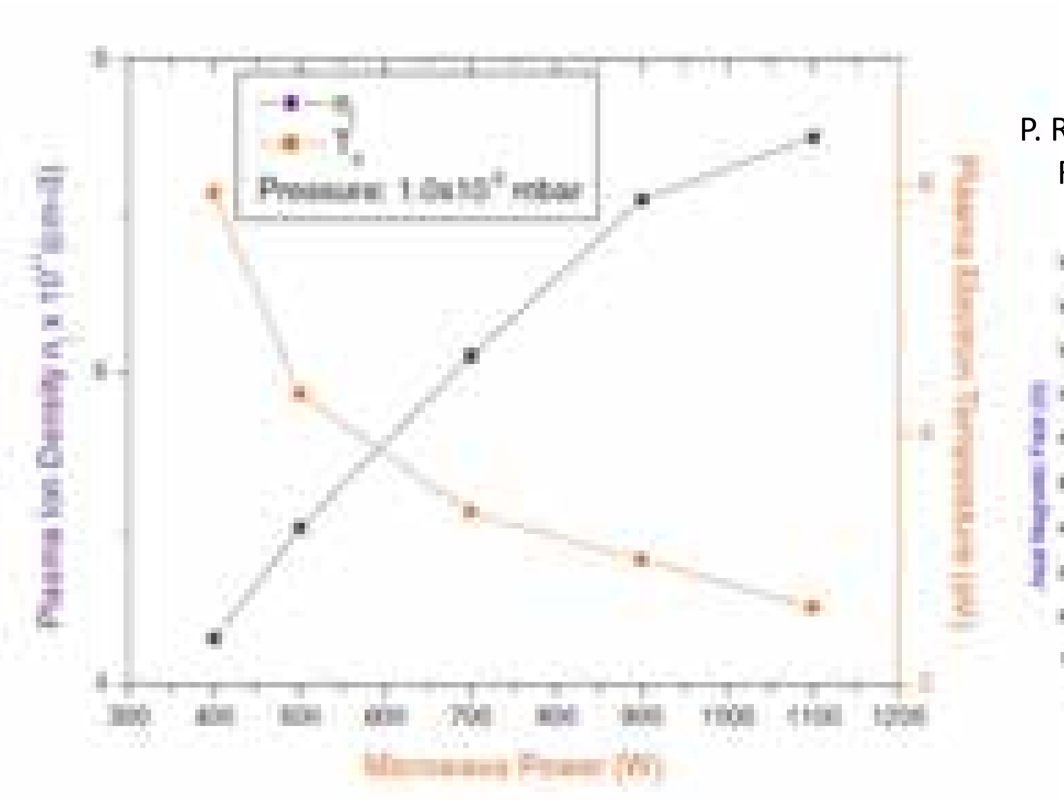
Results: the electron temperature



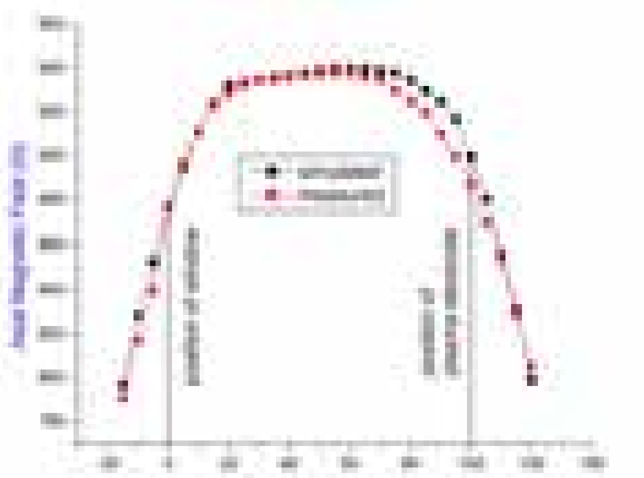
- Electron temperature is in the range **5-15 eV**;
- **Temperature slightly decreases** with power:
  Decrease of electron mean free path?
  Coupling between electron and ion populations at higher density?
- Similar **trend measured by LP by other authors**

(P. Roychowdhury, and D. P. Chakravarthy, Rev. Scie. Instrum. 80, 123305, 2009)

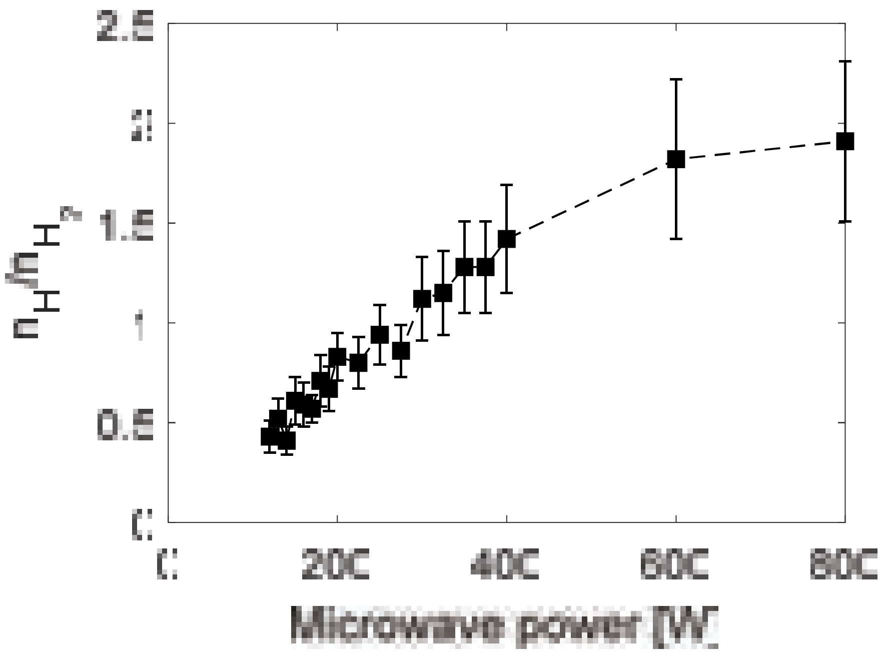
LP measurements in similar conditions



P. Roychowdhury, and D. P. Chakravarthy,
Rev. Scie. Instrum. 80, 123305, 2009



The atomic to molecular neutral relative abundances



- The $n(H)/n(H_2)$ ratio increases from 0.5 to around 2;
- Knowledge of $n(H)/n(H_2)$ enables the n(H) and $n(H_2)$ evaluation:
- **Neutral pressure** is **measured in the LEBT** and then **evaluated in plasma chamber by Comsol** simulation.
- $P_{tot}=\sum_i N_i k T_{neutral}$ $\xrightarrow{T_{neutral} \sim 0.25 \text{ eV}}$ n(H), $n(H_2)$

Is it possible to evaluate proton fraction or H_2^+ fraction from this information?

0-dimensional model

Volume-averaged model looking for averaged value of plasma parameters

1. Elementary **atomic and molecular collision processes**, (excitation/radiation, ionization, dissociation, recombination, etc);
2. **Particle losses** and **recycling** at walls;
3. **Active pumping and gas injection**;
4. **RF heating of electrons**;

Self-consistence balance equations

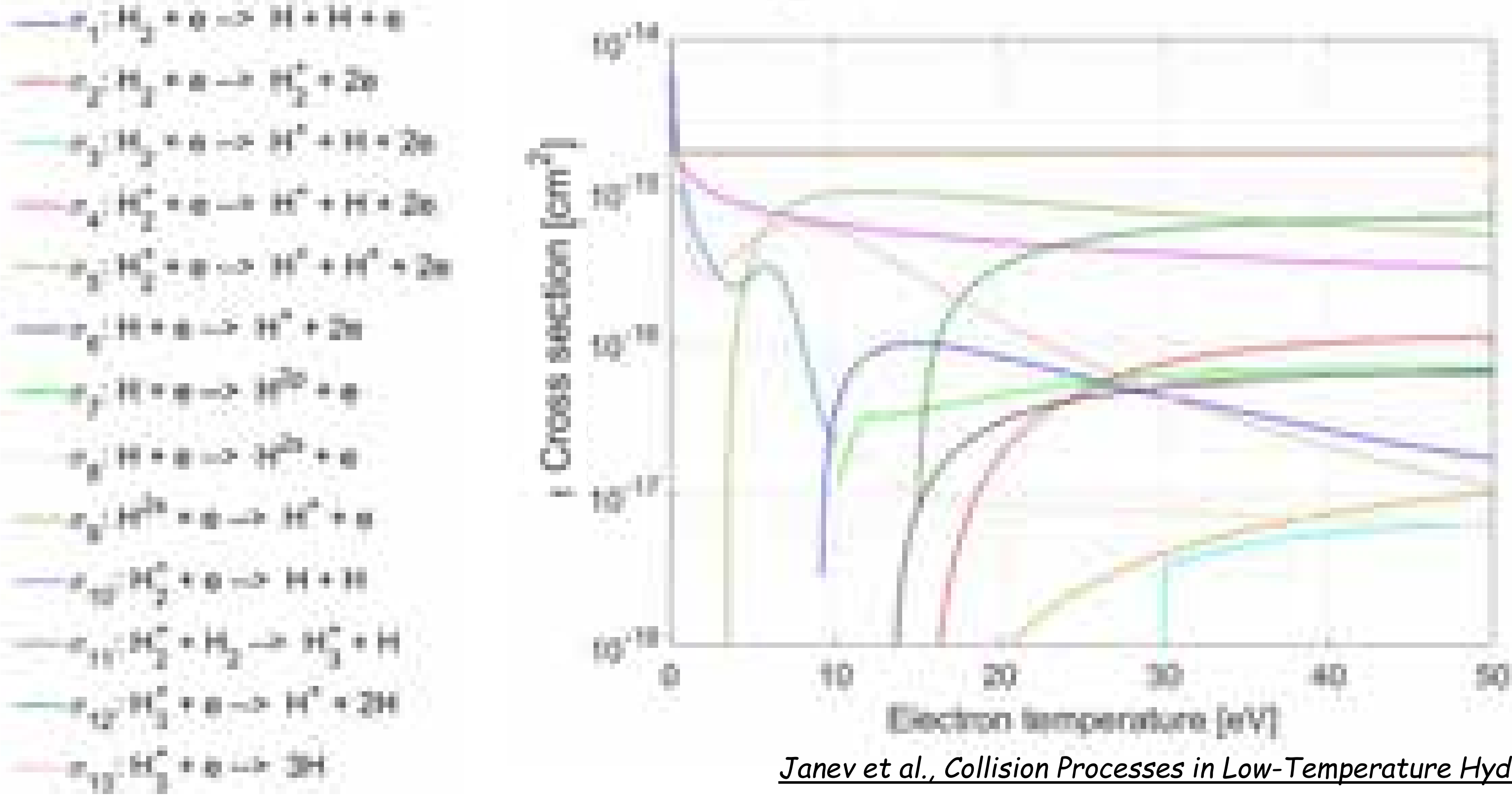
$$\frac{dn_p}{dt} = \sum_{j<k} \sum_i c^i_{jk,p} K^i_{jk} n_j n_k - \frac{n_p}{\tau_p} + Q_{R,p} - Q_{L,p}$$

Particle balance equations

$$\frac{3}{2}\frac{d n_p \overline{T}_p}{dt} = \dot{E}_p = \sum_{j<k} \sum_i c^i_{jk,p} E^i_{jk,p} K^i_{jk} n_j n_k + \sum_j E_{jp} K^{el}_j n_j n_p$$
$$- \frac{3}{2}\frac{n_p \overline{T}_p}{\tau_{E,p}} + Q_{RE,p} - Q_{LE,p} + P_{RF,p}$$

Power balance equations

Main processes and relative cross sections in a hydrogen plasma



Janev et al., Collision Processes in Low-Temperature Hydrogen Plasmas

semiempirical 0-dimensional model

Solution of balance equations

$$\frac{dn(H^+)}{dt} = n(H_2)n_e<\sigma v>_3 + n(H_2)n_e<\sigma v>_4 + 2\mathbf{n(H_2^+)}n_e<\sigma v>_5 + n(H)n_e<\sigma v>_6 + n(H^{2s})n_e<\sigma v>_9 + \mathbf{n(H_3^+)}n_e<\sigma v>_{12} - \mathbf{n(H^+)}/\tau(H^+) = 0$$

$$\frac{dn(H_2^+)}{dt} = n(H_2)n_e<\sigma v>_2 - \mathbf{n(H_2^+)}n_e<\sigma v>_4 - \mathbf{n(H_2^+)}n_e<\sigma v>_5 - \mathbf{n(H_2^+)}n_e<\sigma v>_{10} - \mathbf{n(H_2^+)}N(H_2)<\sigma v>_{11} - \mathbf{n(H_2^+)}/\tau(H_2^+) = 0$$

$$\frac{dn(H_3^+)}{dt} = \mathbf{n(H_2^+)}N(H_2)<\sigma v>_{11} - \mathbf{n(H_3^+)}N(H_2)<\sigma v>_{12} - \mathbf{n(H_3^+)}N(H_2)<\sigma v>_{13} - \mathbf{n(H_3^+)}/\tau(H_3^+) = 0$$

$$\mathbf{n(H^+)} + \mathbf{n(H_2^+)} + \mathbf{n(H_3^+)} = n_e$$

Input parameters

n_e, T_e, $n(H)/n(H_2)$

Unknowns:

$n(H^+)$, $n(H_2^+)$, $n(H_3^+)$, τ

Hypothesis:

Free parameters:

T_i:1 eV $T_{n.}$:0.25 eV

Electron induced reaction:

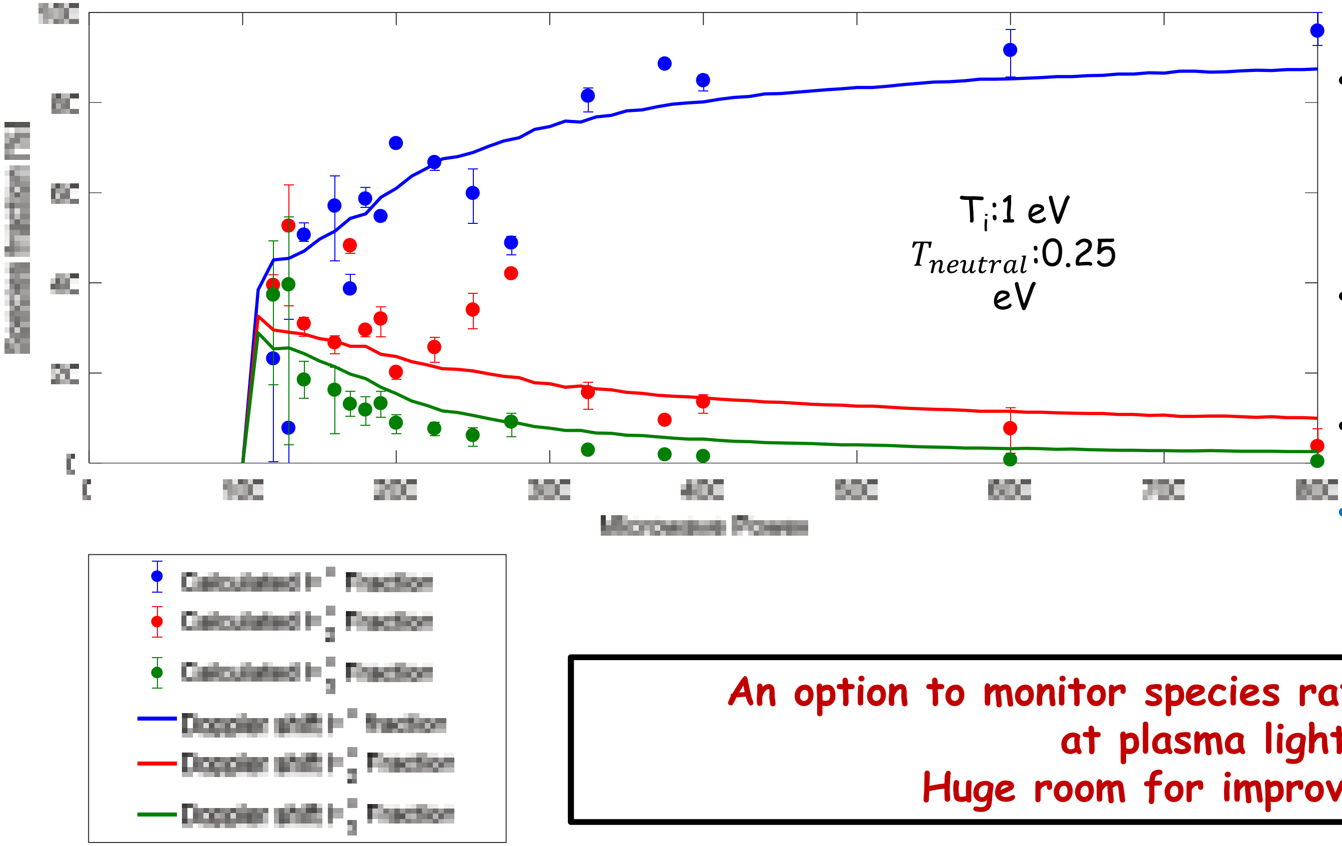
$t_e >> T_i$, T_n

Ion induced reaction:

$T_i >> T_n$

OES Plasma Paramenters: n_e, T_e, $n(H)/n(H_2)$ → Semiempirical 0-dimensional model → **In plasma Ion abundances:** $\mathbf{n}_{pl}(H^+)$, $\mathbf{n}_{pl}(H_2^+)$, $\mathbf{n}_{pl.}(H_3^+)$ → Child-Langmuir hypothesis @extraction Dependence on $1/\sqrt{m}$ → **Beam parameters:** Species fraction, $I_{extr.}$

Evaluation of species fraction: results

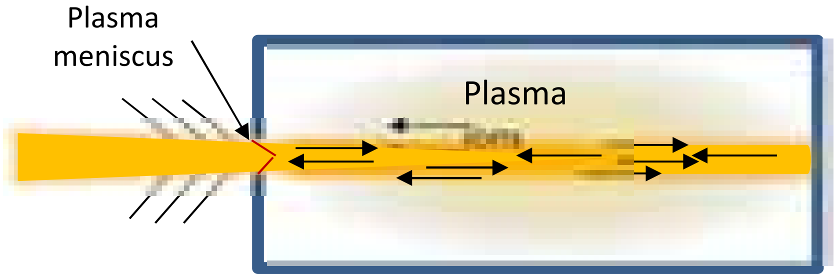


- The model give a **rough prediction of the species fraction**, especially at higher power;
- H^+ fraction is predicted with satisfactory precision
- Constant T_i, T_n assumed.
- **Further measurements needed** to validate the model in continuous wave!

An option to monitor species ratio just by looking at plasma light!
Huge room for improvements;

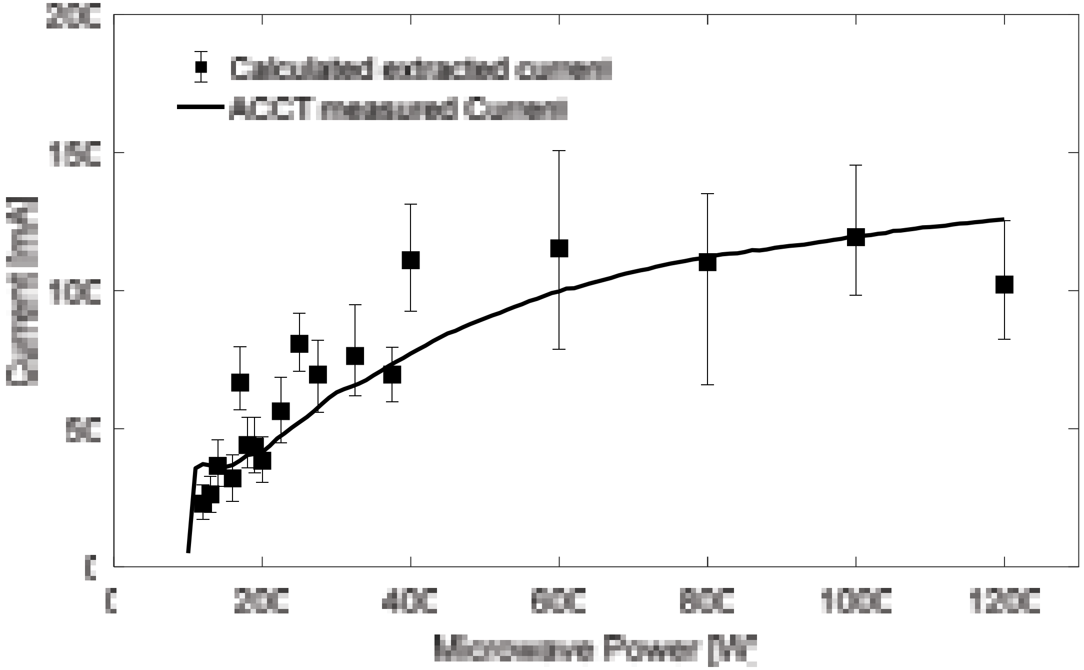
Evaluation of extracted current: hypothesis

1. Ions moves along a flux tube parallel to the magnetic field ($D_{\parallel} >> D_{\perp}$) having radius equal to the extraction hole r;
2. All ions who reach plasma meniscus are extracted;
3. Ions enter the extraction region with Bohm velocity V_B: $\sqrt{\frac{kT_e}{M}}$
4. $\int f(+v_z) = \int f(-v_z)$ just 1/2 of the ions move towards the extracton hole;



$$J_{extr.} \sim \frac{1}{2} q n_e V_B \Longrightarrow I_{extr.} \sim \frac{1}{2} \pi r^2 \sqrt{\frac{kT_e}{M}} n_e$$

Evaluation of extracted current: results



- The semiempirical model is able to give a rough prediction of the extracted current measured by ACCT;

$$I_{extr.} \sim \frac{1}{2}\pi r^2 \sqrt{\frac{kT_e}{M}}\, n_e$$

- Also in this case, **OES could be used as a monitor of proton source performances;**

- Further measurements are needed to validate the model in CW and in HV conditions


Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud 09/11/2017
Sorgente di protoni e linea di trasporto a bassa energia per
l'European Spallation Source (Svezia)
INFN