Beam commissioning of the high intensity proton source developed at INFN-LNS for ESS

L. Celona, L. Neri, S. Gammino, O. Leonardi, A. Miraglia, G. Torrisi, F. Chines, G. Castro, D. Mascali, G. Calabrese, G. Manno, M. Mazzaglia

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

Journey to deliver the world's leading facility for research using neutrons

EUROPEAN SPALLATION SOURCE

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

Proton source and LEBT: Ready For Installation
03/11/2017

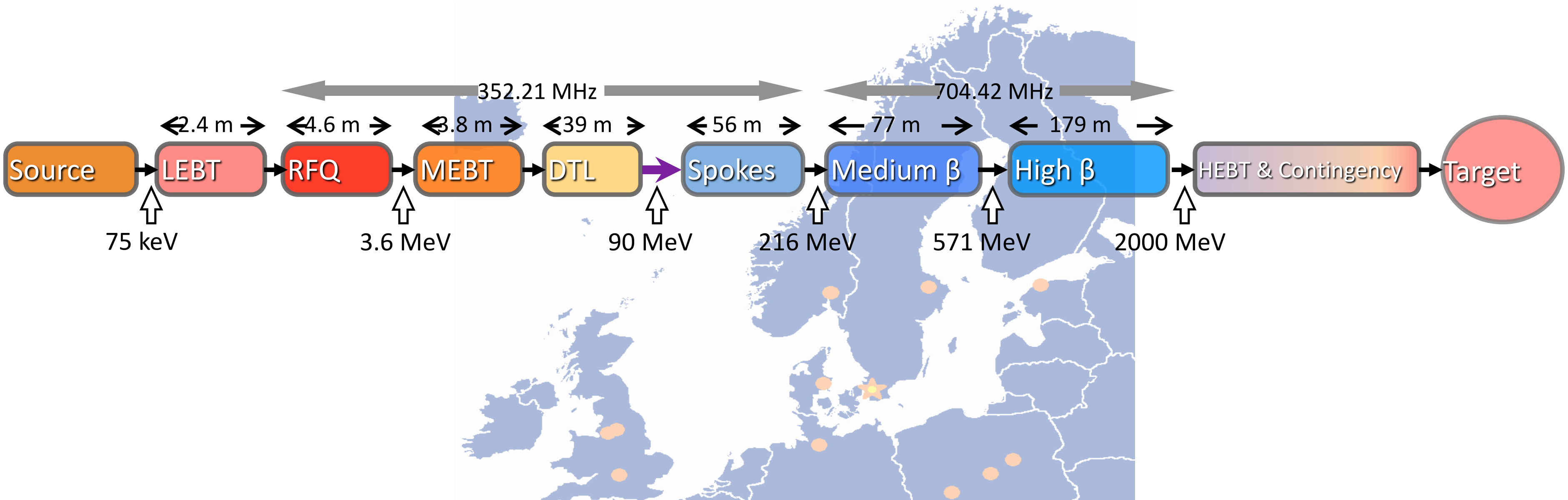
2019
First beam on Target

2023
ESS starts user program

2025
ESS construction complete

Italian In-Kind Contribution:

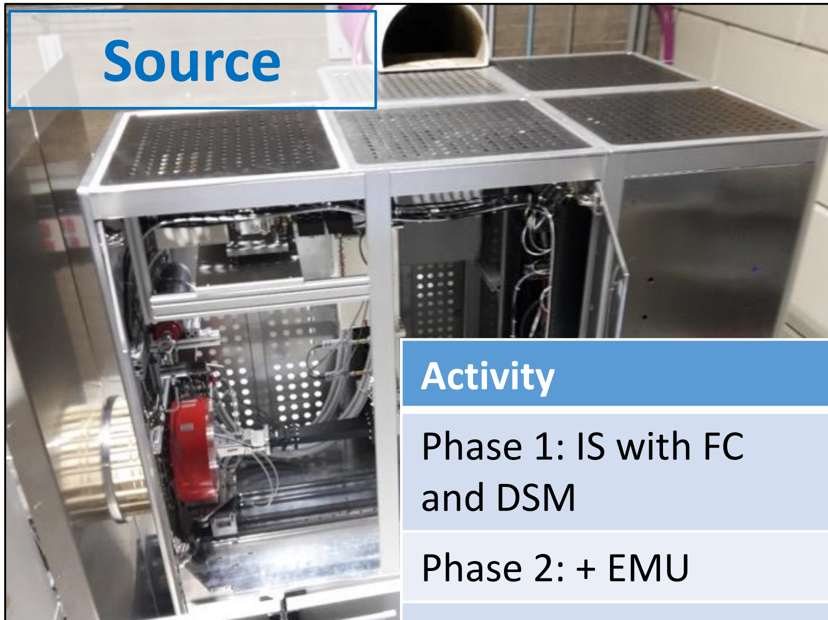
Proton Source, LEBT	INFN-LNS
DTL	INFN-LNL
T-REX, VESPA	CNR
RF systems, Magnets&PS, diagnostics	Elettra

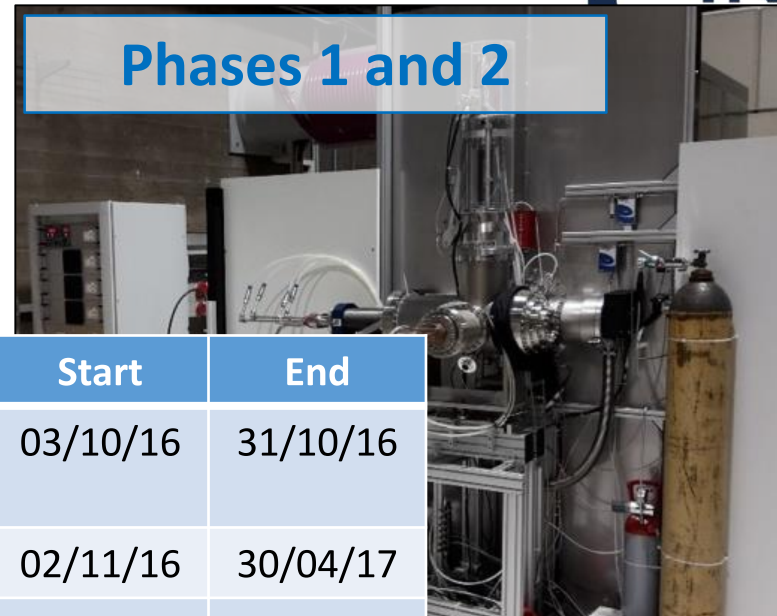


Partners for proton source and LEBT:

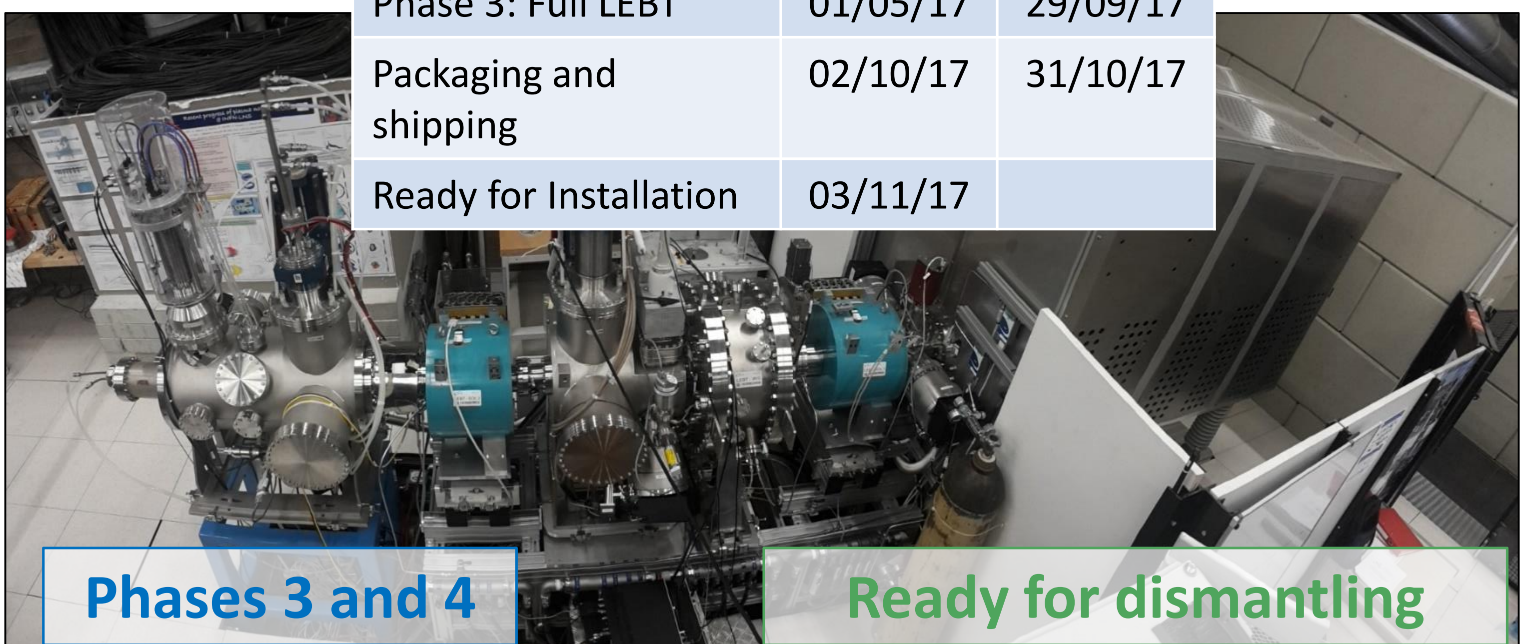
INFN-LNS	WP leader, Overall design, Construction, Commissioning, Installation
ESS	Vacuum, Controls, Beam diagnostics
CEA	Controls, Beam diagnostics

Ion Source and LEBT



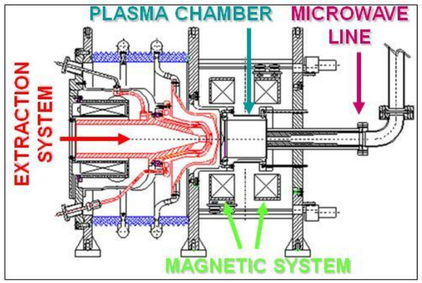


Activity	Start	End
Phase 1: IS with FC and DSM	03/10/16	31/10/16
Phase 2: + EMU	02/11/16	30/04/17
Phase 3: Full LEBT	01/05/17	29/09/17
Packaging and shipping	02/10/17	31/10/17
Ready for Installation	03/11/17	

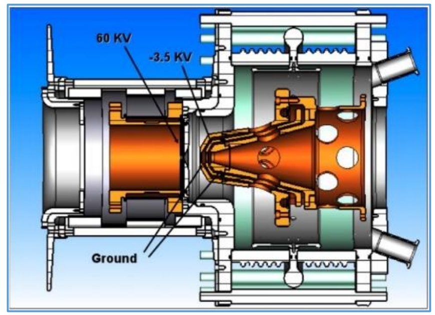


INFN-LNS background

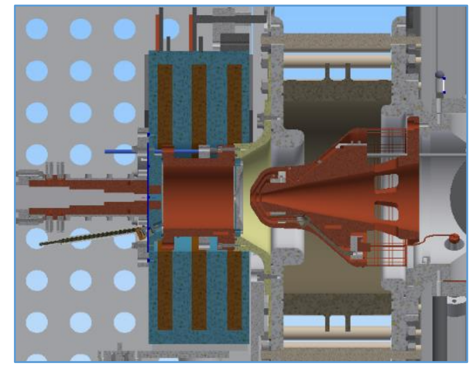
TRIPS (2001)



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

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

+ 25%

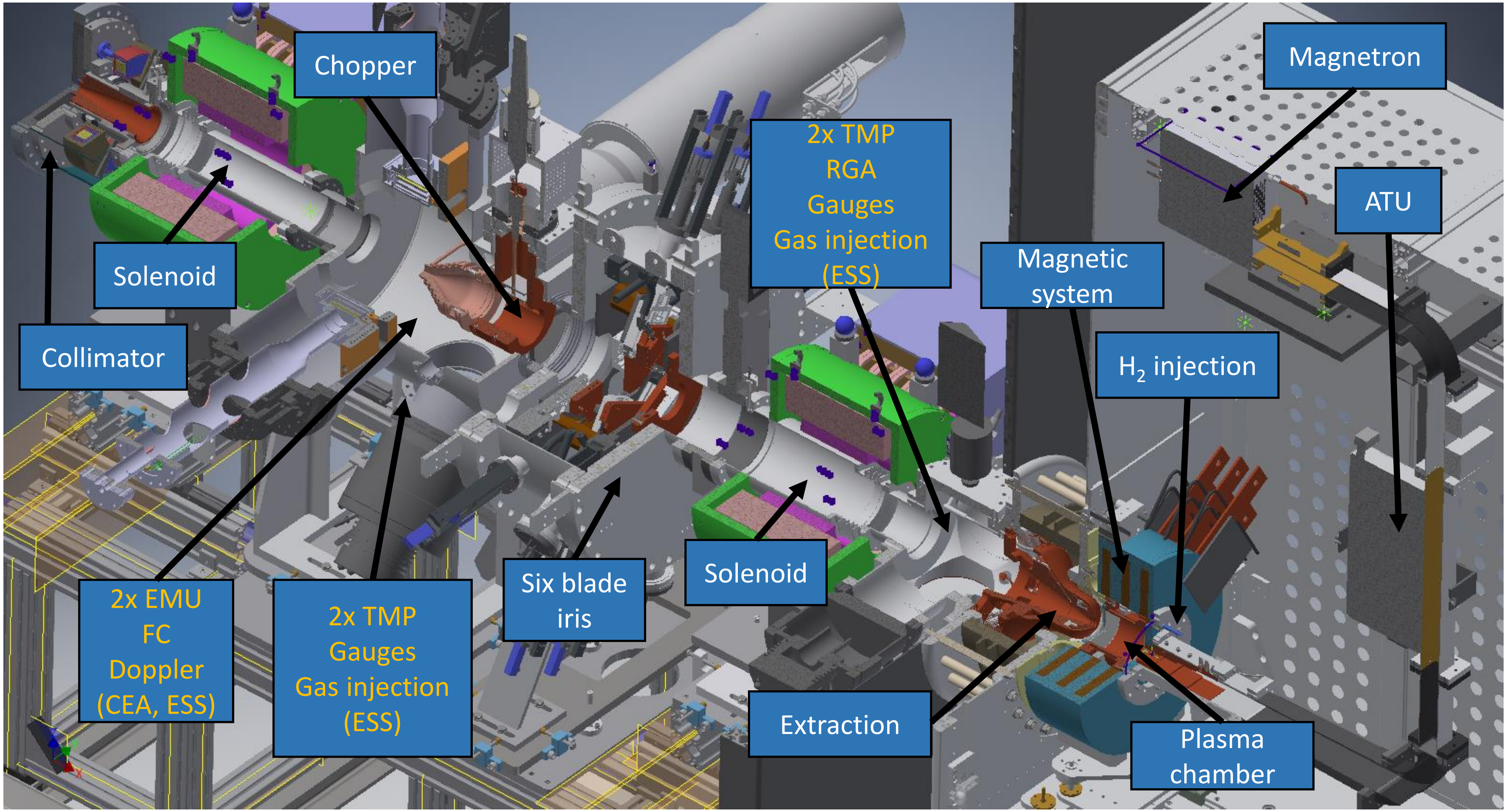
from dc to pulsed

High stability

Low emittance

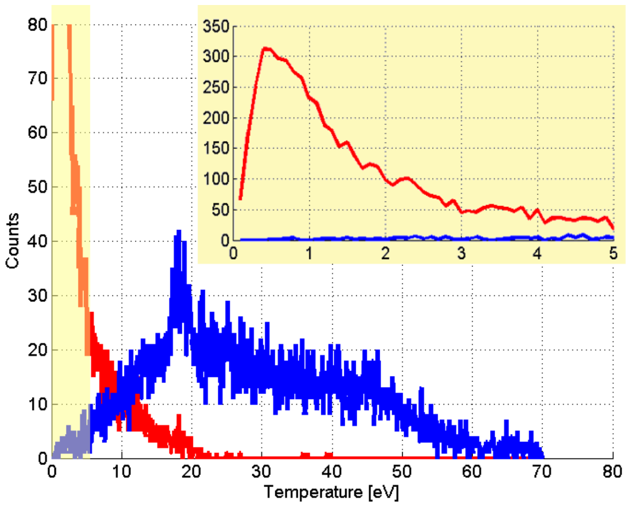
Easy maintenance

Proton Source and LEBT at INFN-LNS

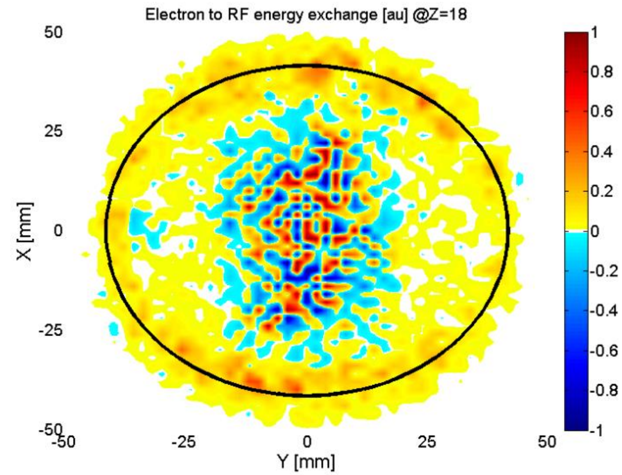


Plasma modeling

Electron Energy Distribution Function



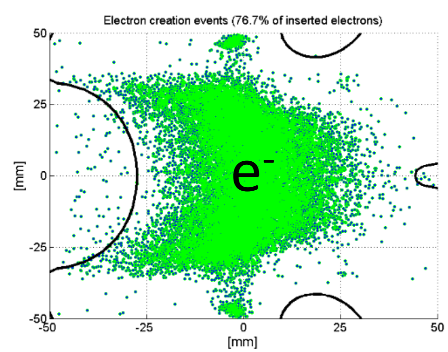
RF energy adsorption

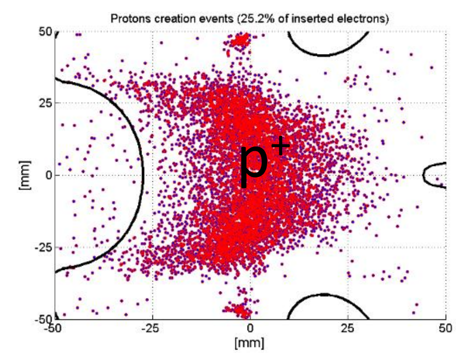


Ion formation

$H_2 + e \rightarrow H + H + e,$	$E_{th} = 9.2$ eV,
$H_2 + e \rightarrow H_2^+ + e + e,$	$E_{th} = 15.42$ eV,
$H_2 + e \rightarrow H^+ + H + e + e,$	$E_{th} = 18.15$ eV,
$H_2^+ + e \rightarrow H^+ + H + e,$	$E_{th} = 12$ eV,
$H_2^+ + e \rightarrow H^+ + H^+ + e,$	$E_{th} = 15.2$ eV,
$H + e \rightarrow H^+ + e + e,$	$E_{th} = 13.6$ eV,
$H + e \rightarrow H^{*2p} + e,$	$E_{th} = 10.2$ eV,
$H + e \rightarrow H^{*2s} + e,$	$E_{th} = 10.2$ eV,
$H^{*2s} + e \rightarrow H^+ + e,$	$E_{th} = 3.4$ eV,
$H_2^+ + e \rightarrow H + H,$	$E_{th} = 0$ eV,

Generation maps



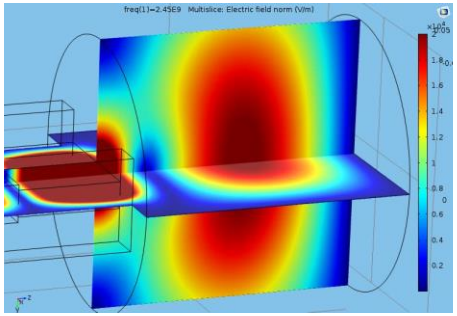


L. Neri et al. "Recent progress in plasma modelling at INFN-LNS", Rev. Sci. Instrum. 2016 Feb, 87(2):02(A)505

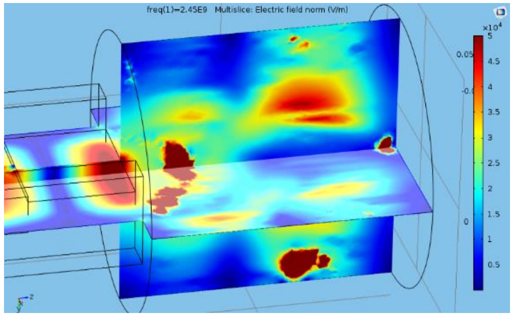
Microwave to plasma coupling

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

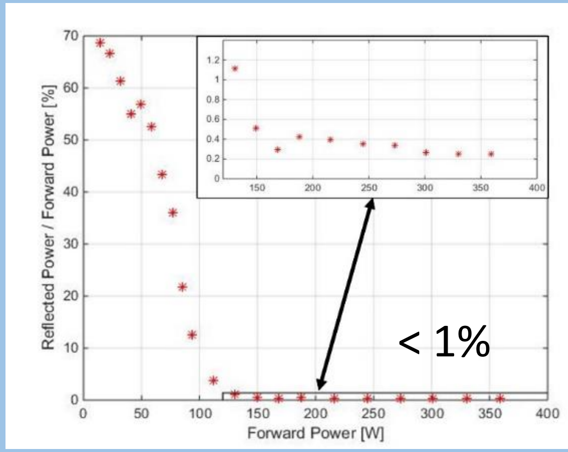


Cold tensor plasma approximation

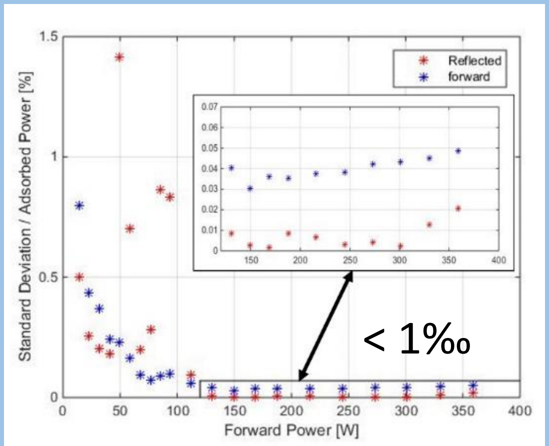


G. Torrisi et al. "Full-wave FEM simulations of electromagnetic waves in strongly magnetized non-homogeneous plasma", JEWA 2014 vol. 20, no. 9, 1085-1099

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

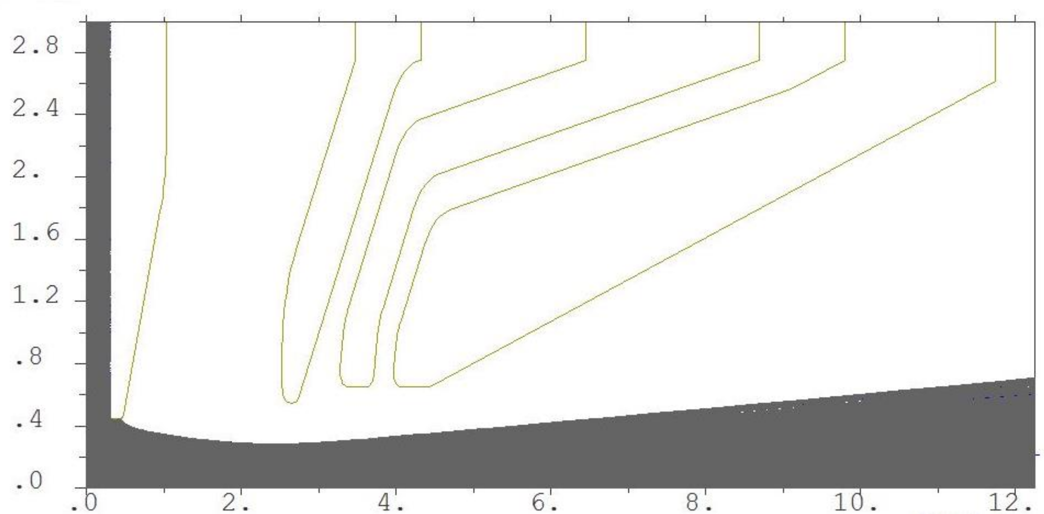
Beam extraction system

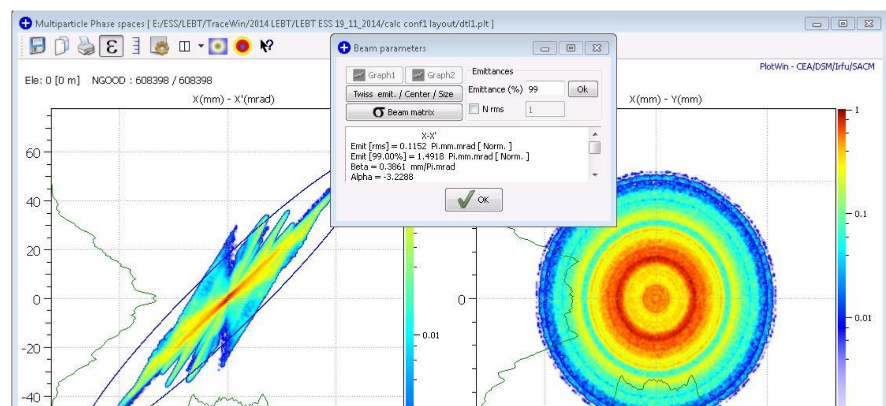
Axcel 2D beam input parameters:

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



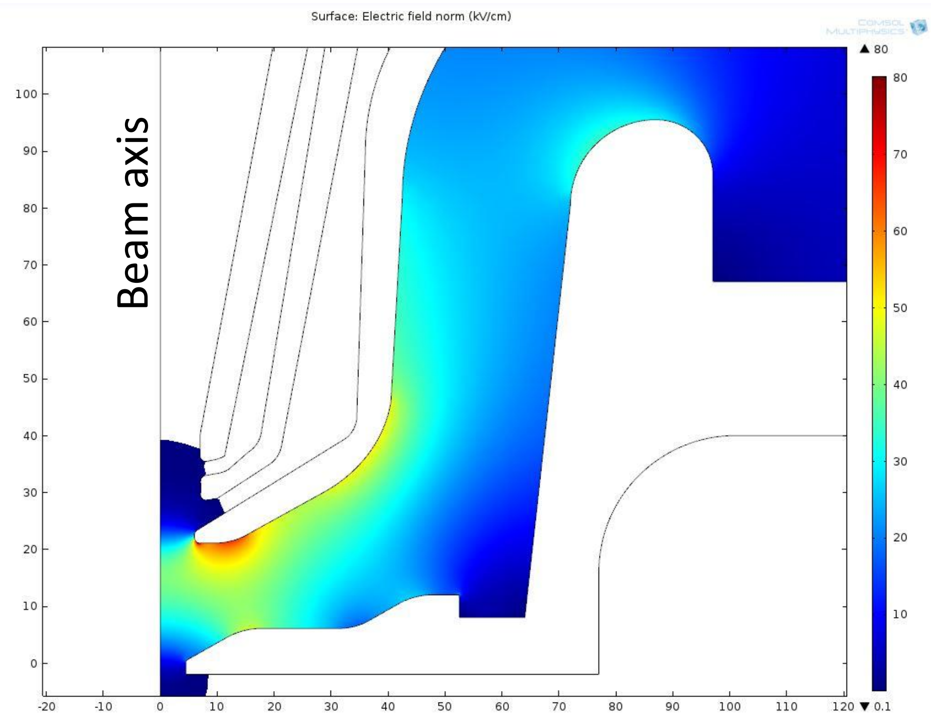


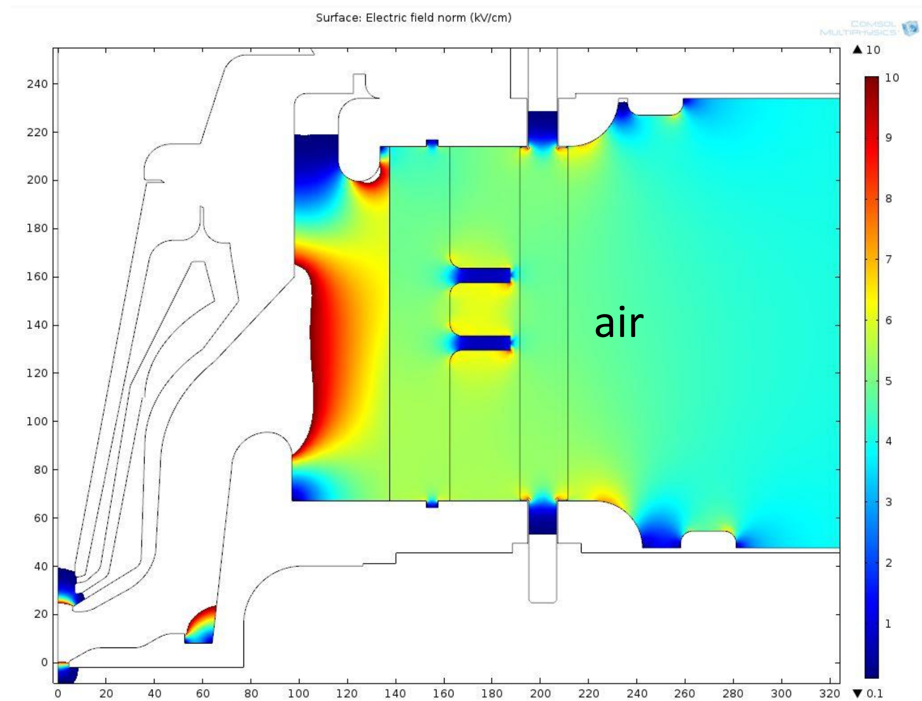
Emit [99%]=1.492 **(< 1.8)** Pi.mm.mrad [Norm]
Max Divergence= 55 **(< 80)** mrad

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)

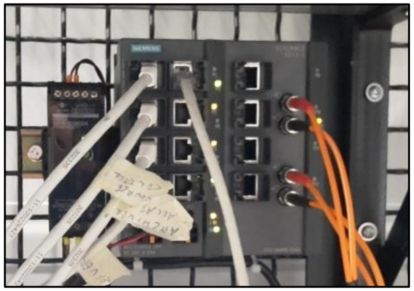




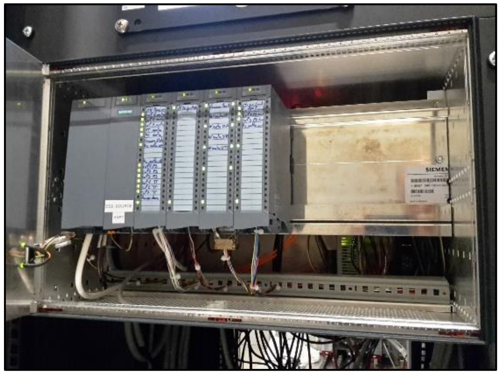
State-of-art sparks immunity during beam operation at 75 kV.
Extraction column tested up to 90 kV.

Increase electronics strength against discharge

Wide use of optical fibers

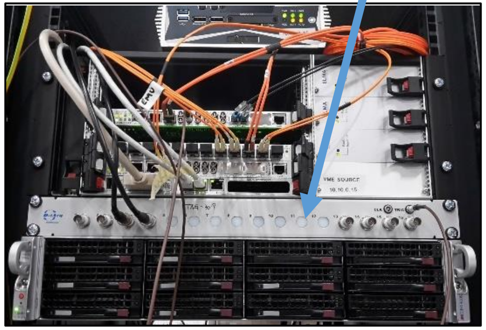


Shielded sub-rack on the HV platform



Grounding grid

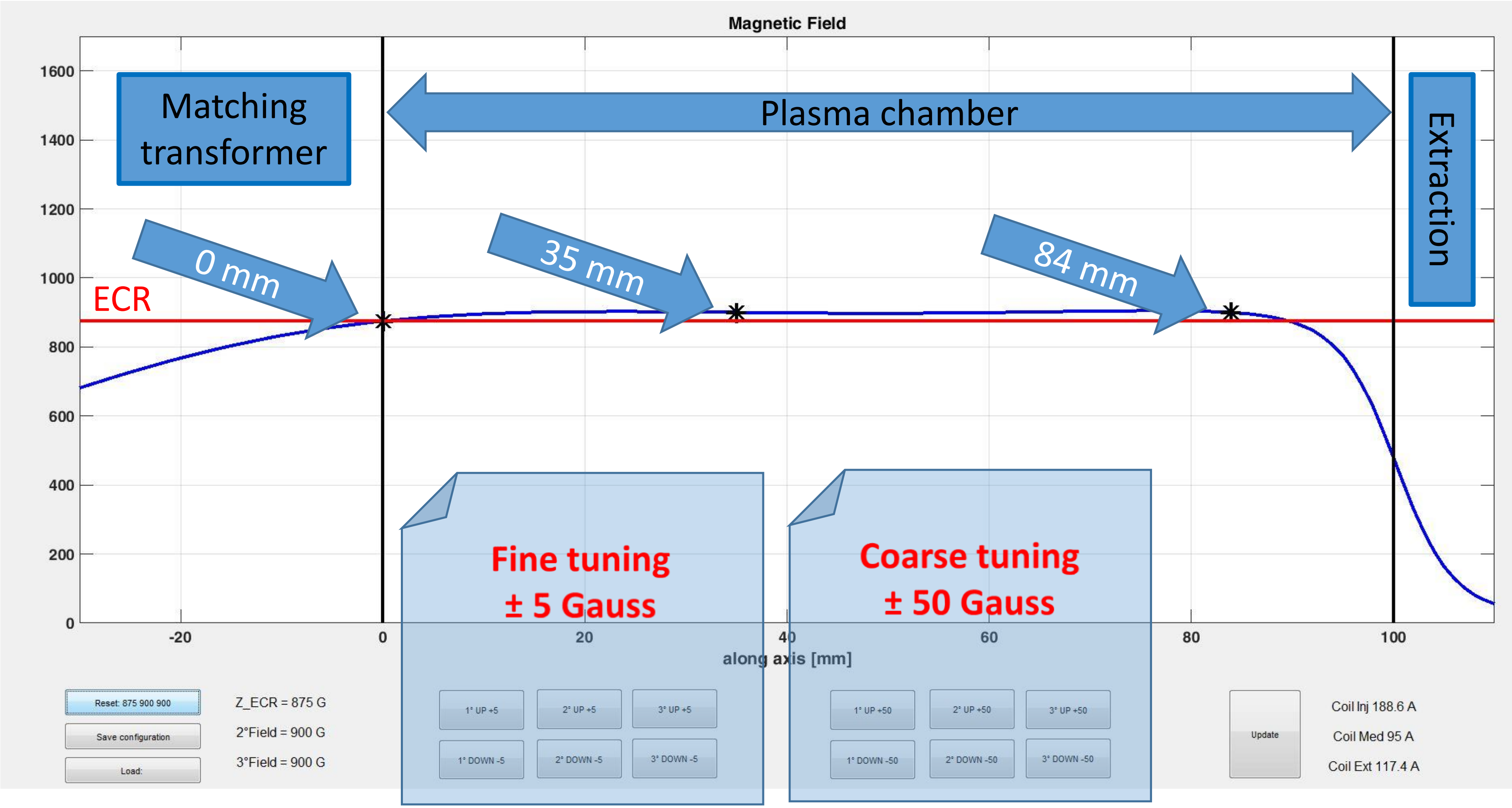
FC voltage protection



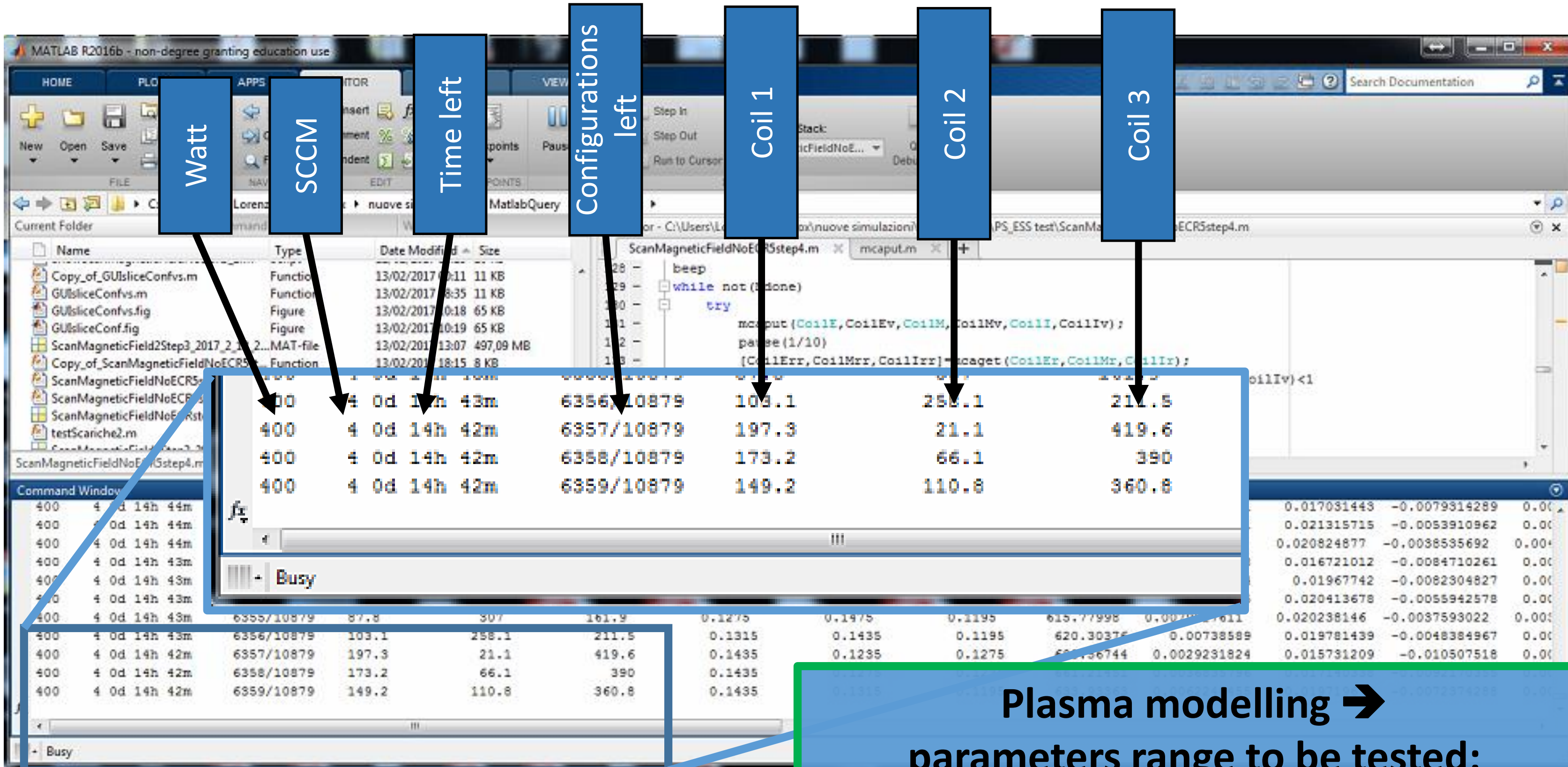
Shielded sub-rack at ground

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 tool



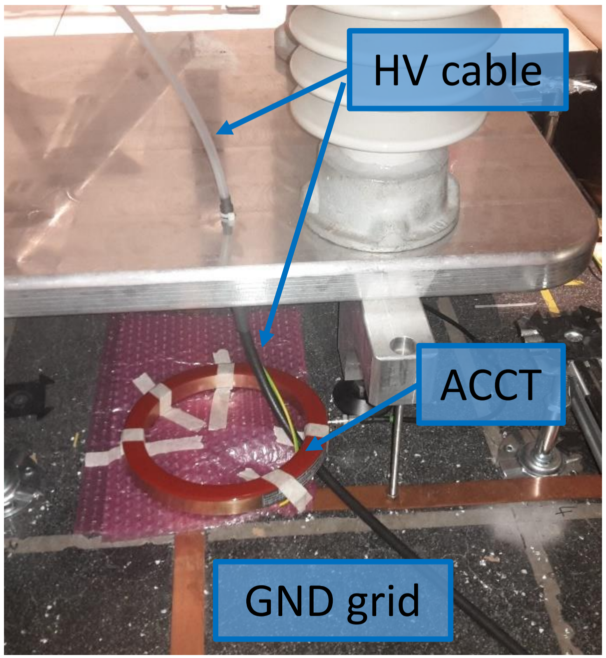
From the 23/01/2017 the source is extracting beam seamless, more than 300˙000 tested configurations, no stops due to sparks.

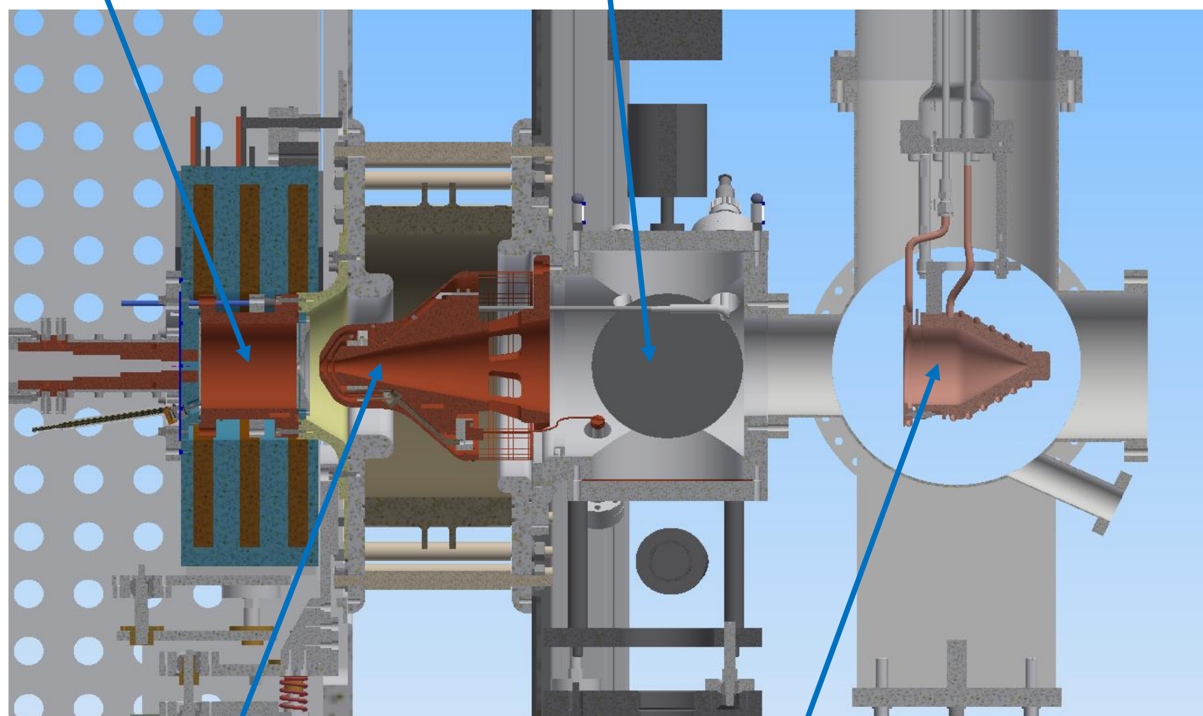
Plasma modelling ➔
parameters range to be tested:

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

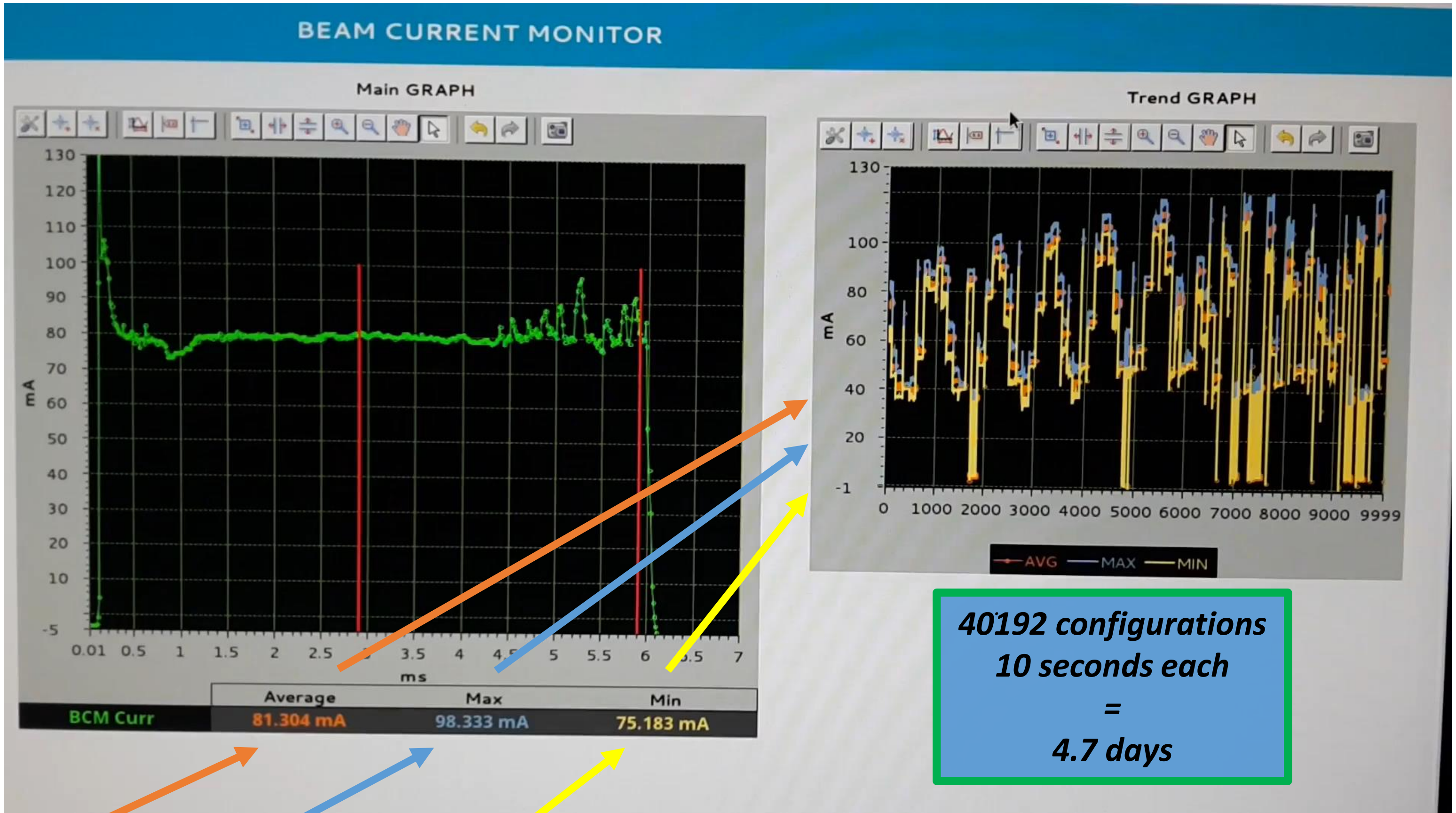
40192 configurations

Commissioning setup phases 1 and 2





Semi-automatic characterization

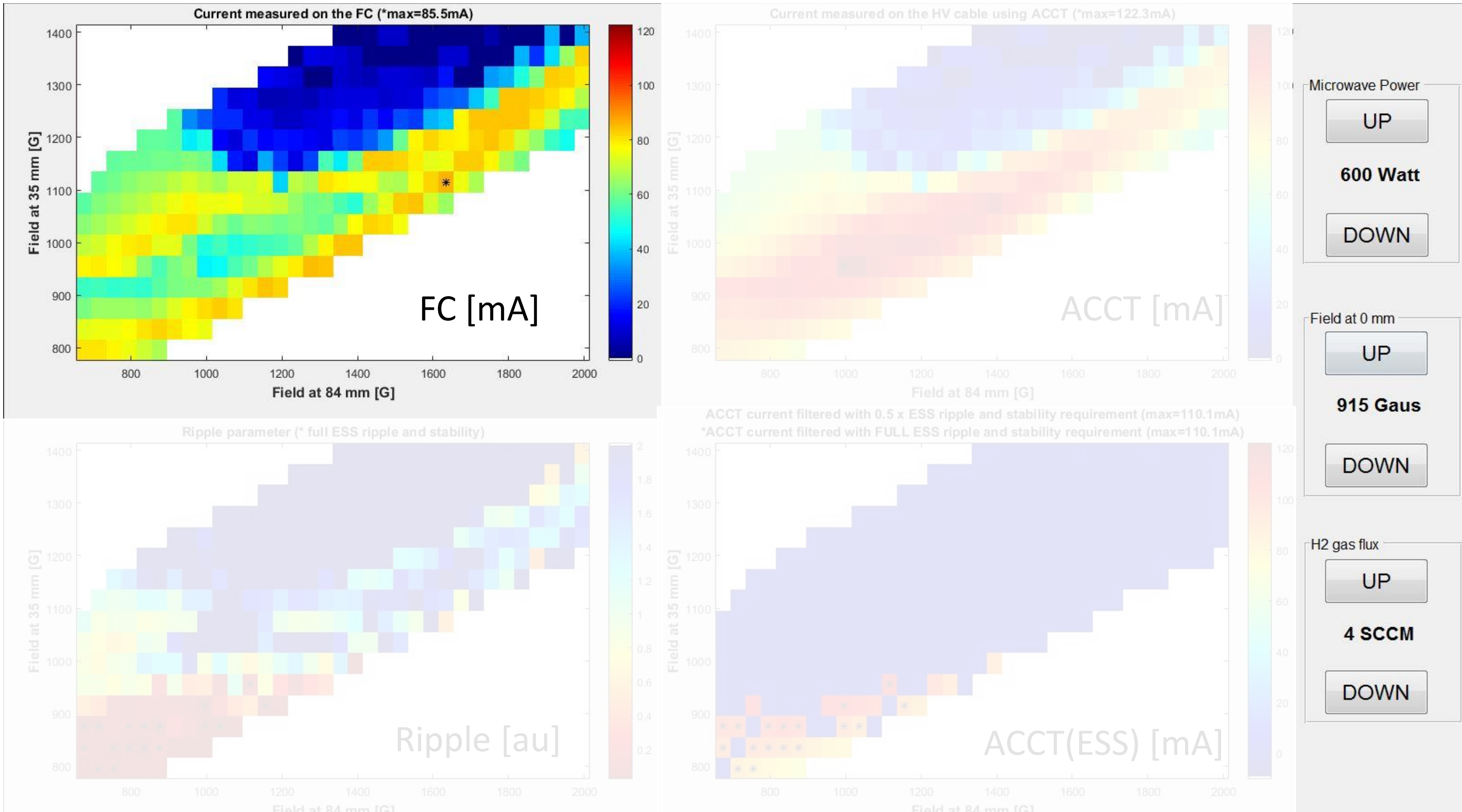


40192 configurations
10 seconds each
=
4.7 days

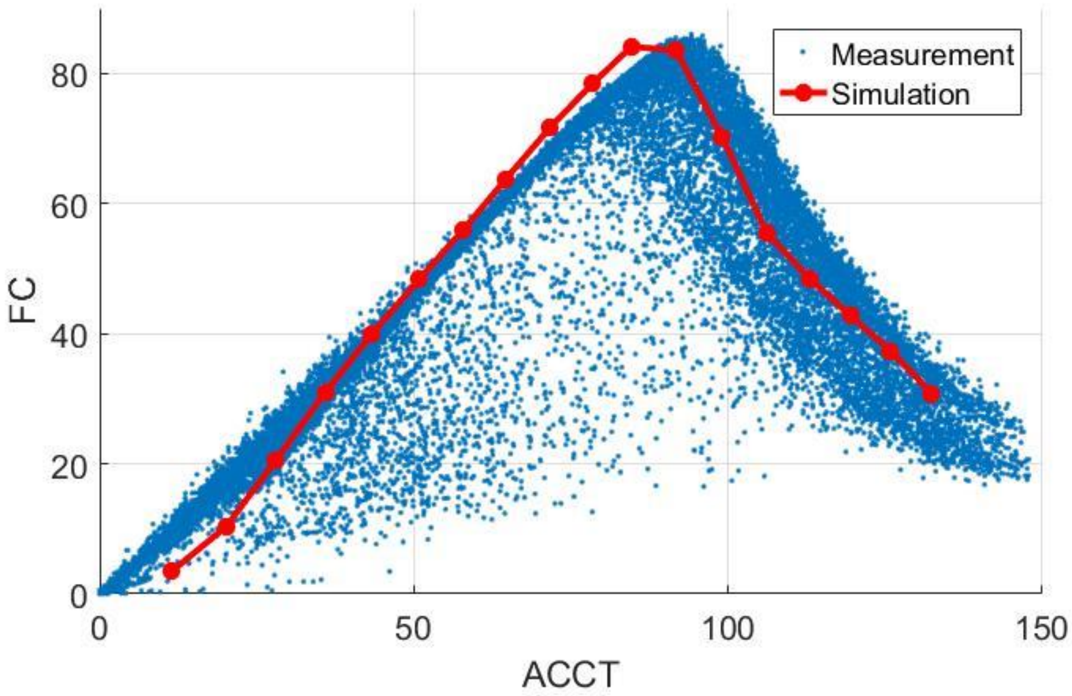
In the graphical interface: average, maximum and minimum are evaluated and the trend showed for the beam pulse between 2.9 ms and 5.9 ms .

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



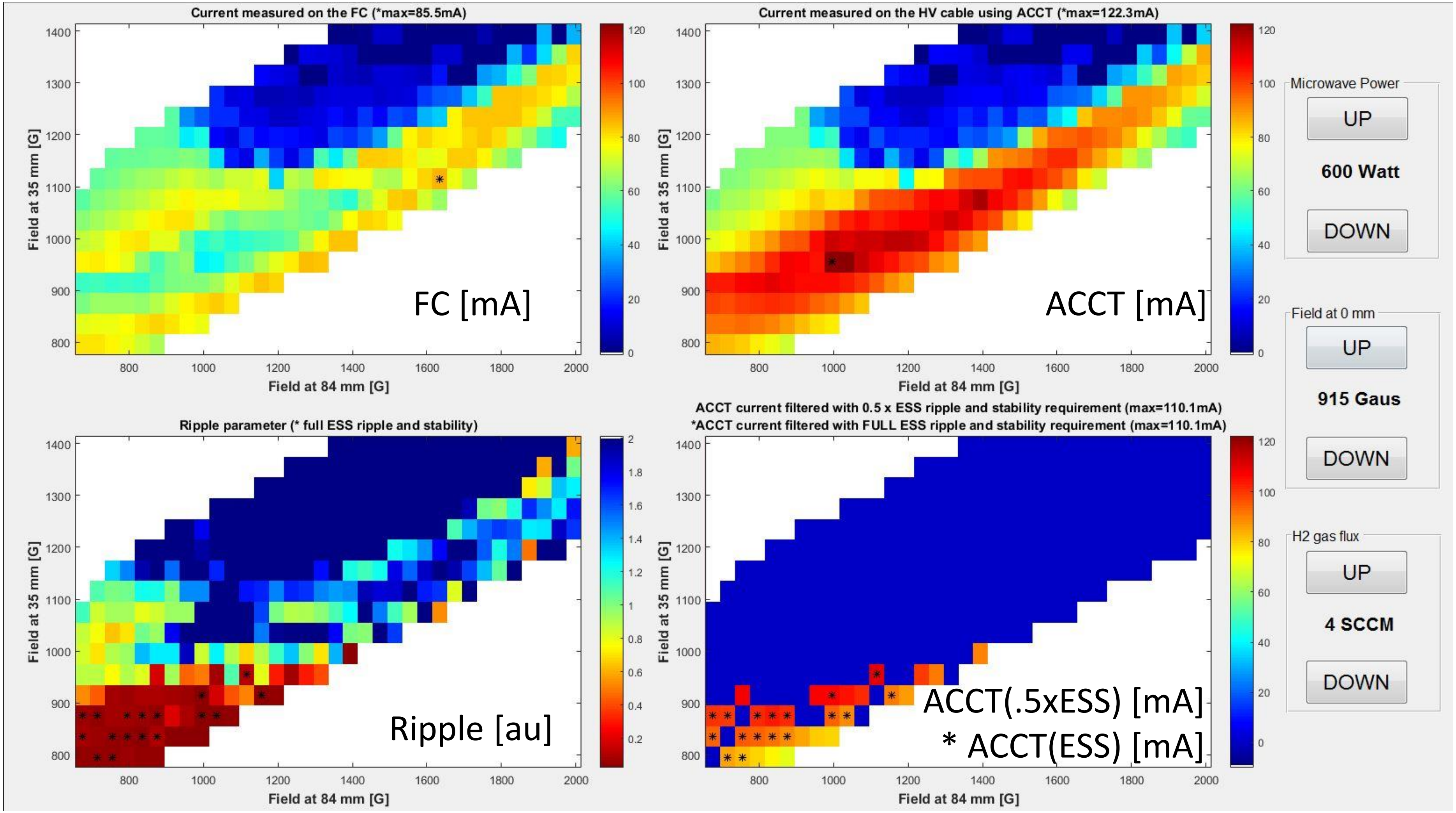
Fraction of beam current collected the Faraday Cup



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

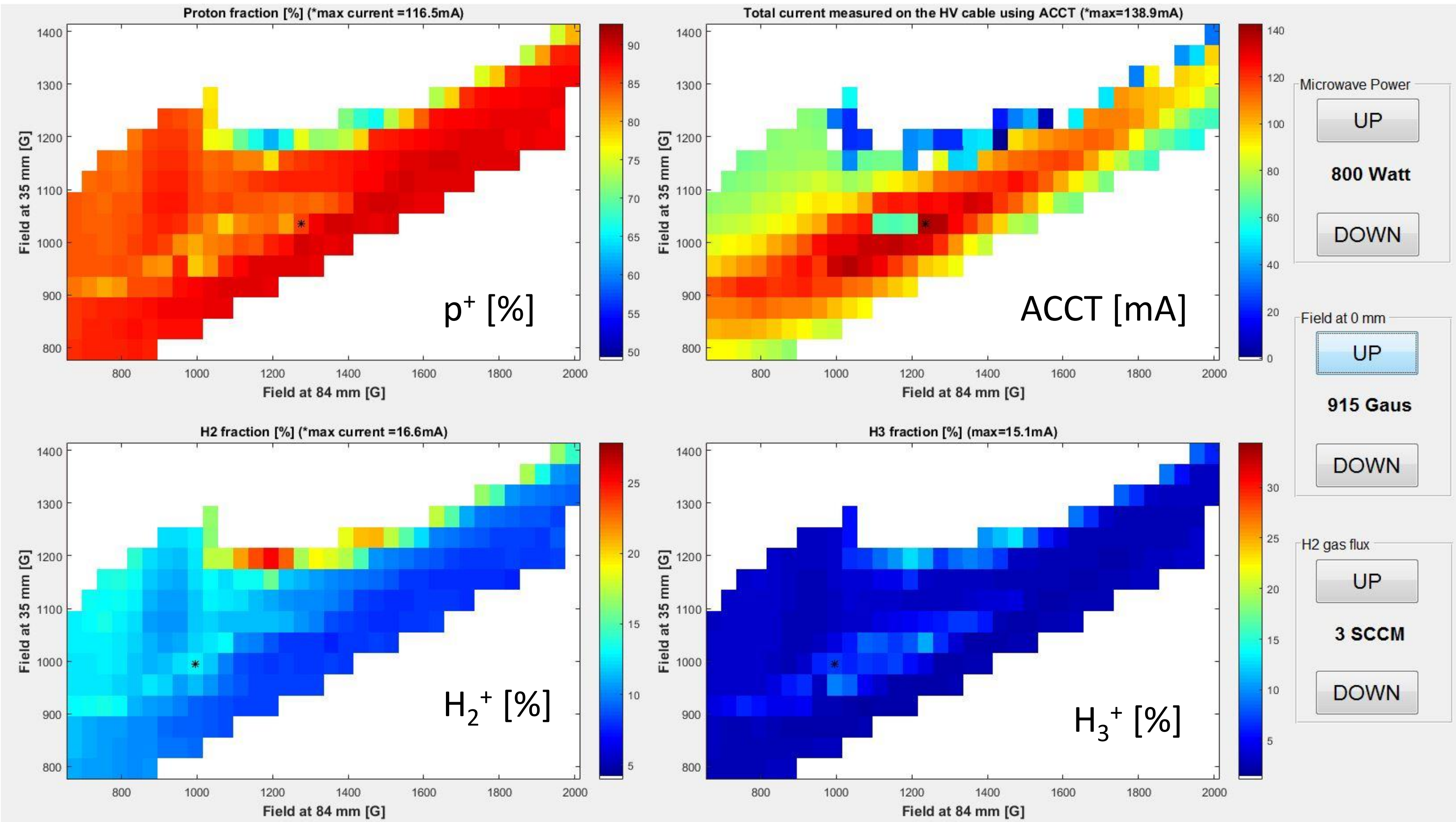
Increasing the plasma density increase the meniscus concavity and the divergence of the extracted beam.
Simulation done with IBSimu shows good agreement with experimental data.

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

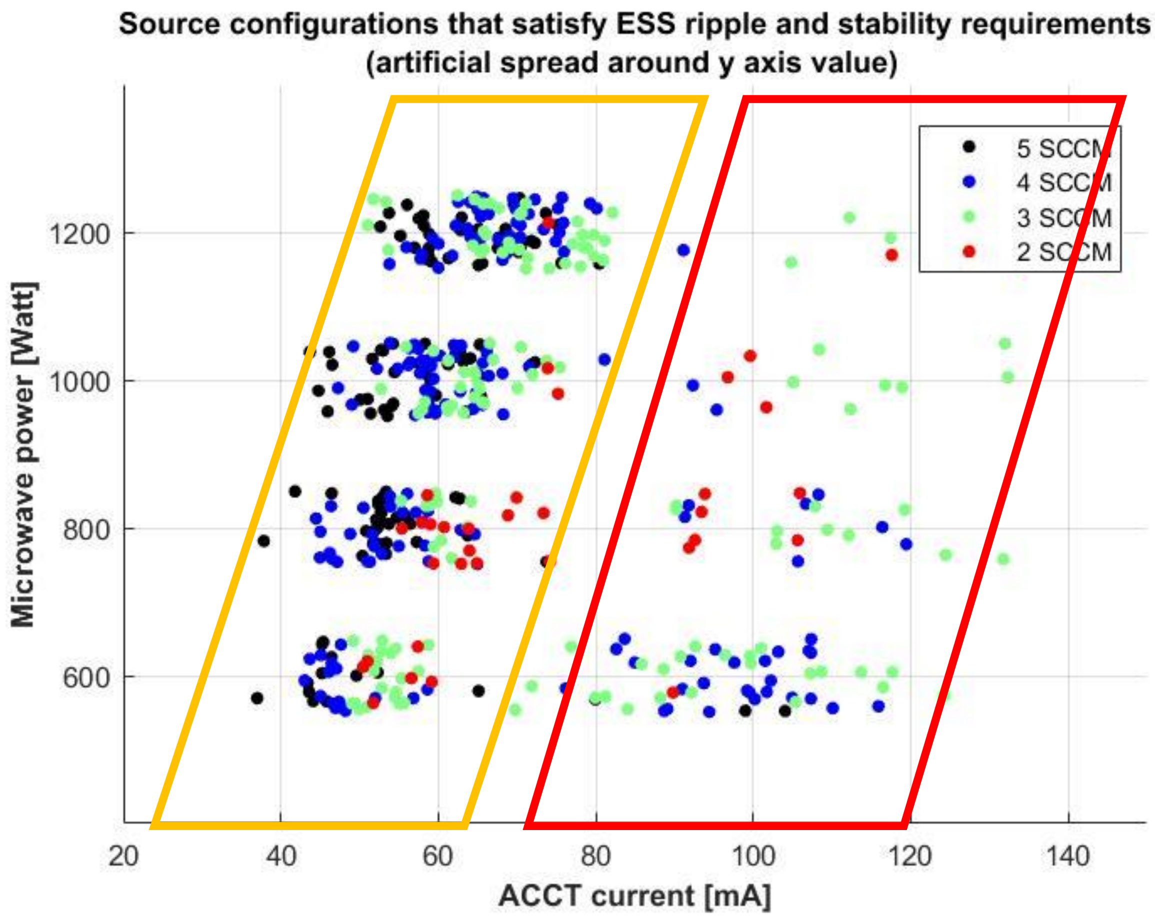
Total current = 100 mA SATISFIED

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)

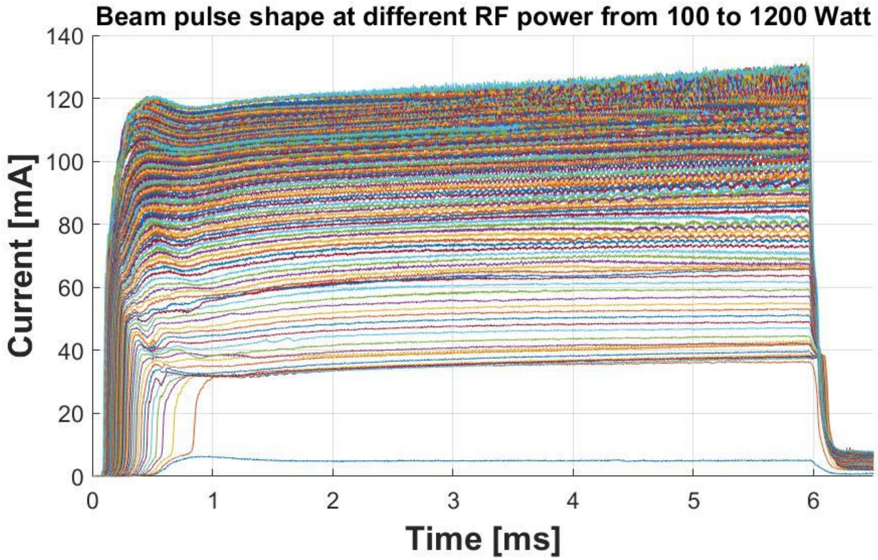
High current (2-4 sccm)



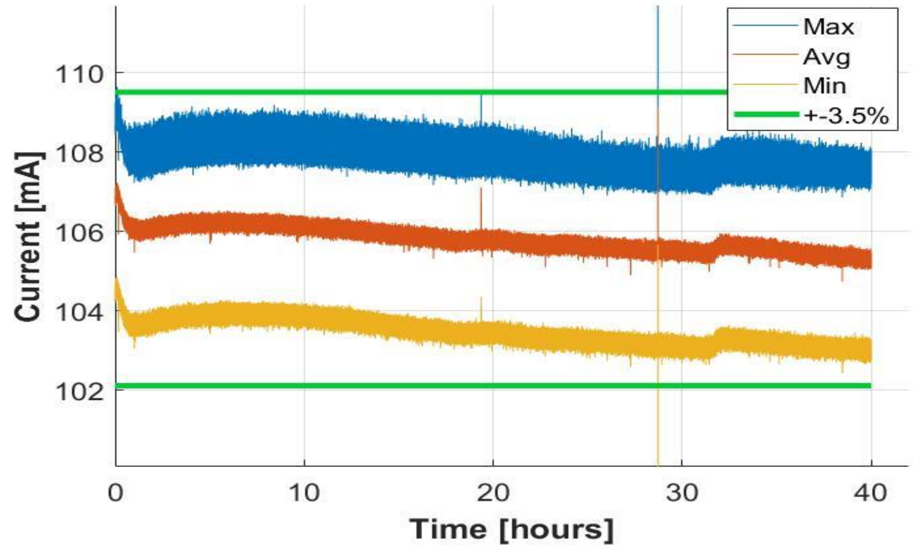
ESS nominal configuration

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

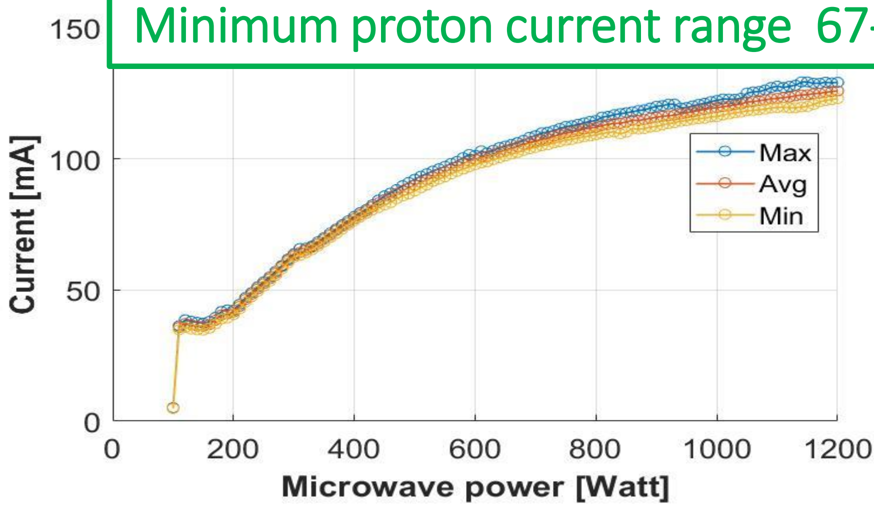
Intra-pulse stability < ±2% SATISFIED

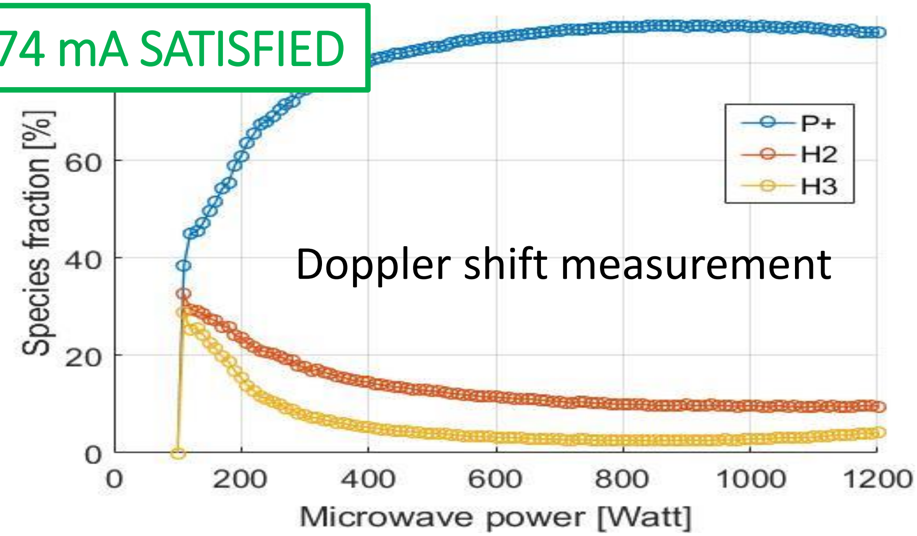


Pulse to pulse stability < ± 3.5% SATISFIED

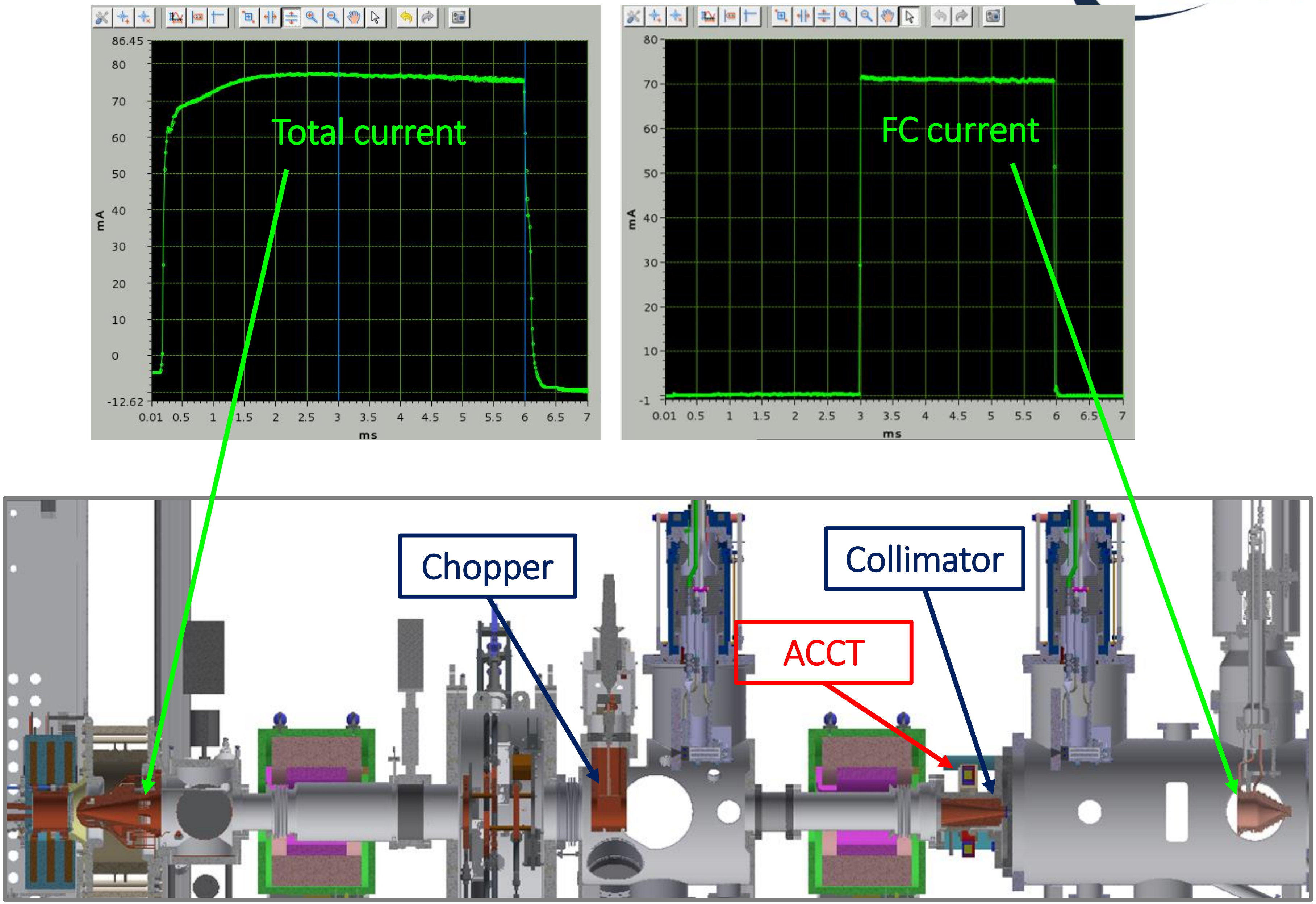


Minimum proton current range 67-74 mA SATISFIED



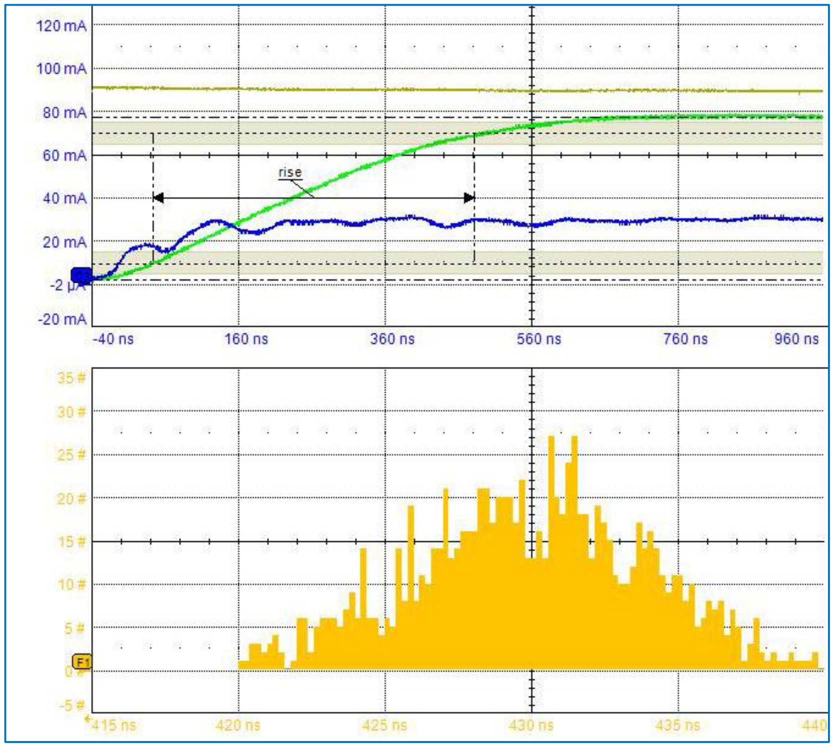


Chopping performaces

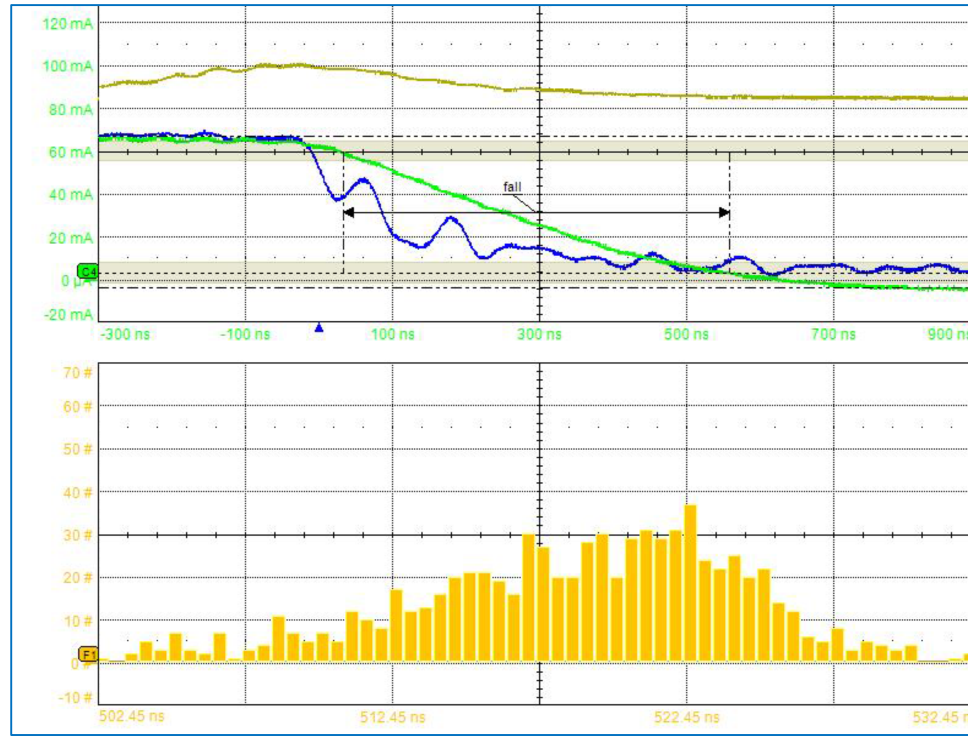


Chopping performaces

Rise time: 430ns



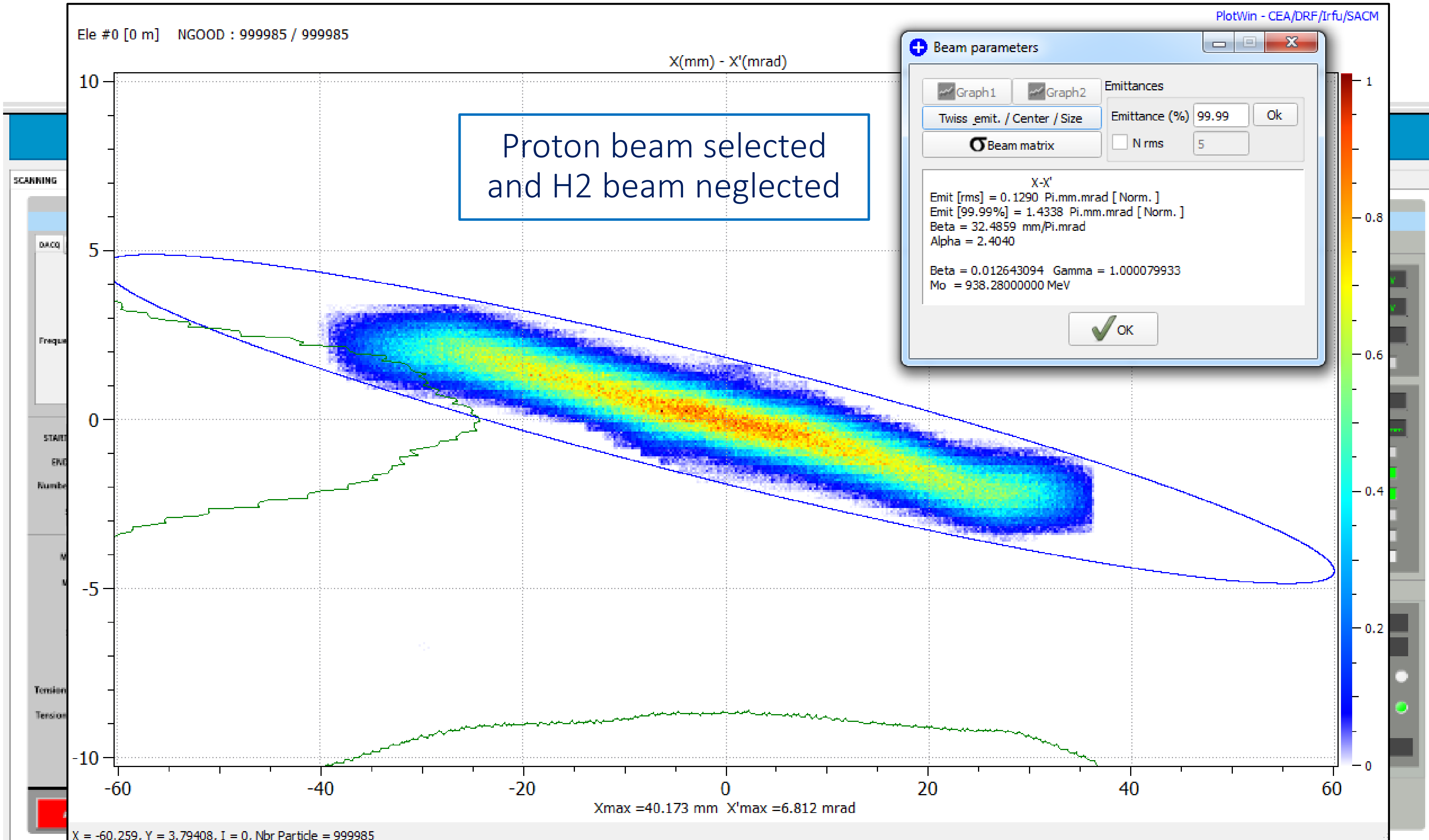
Fall time: 519 ns



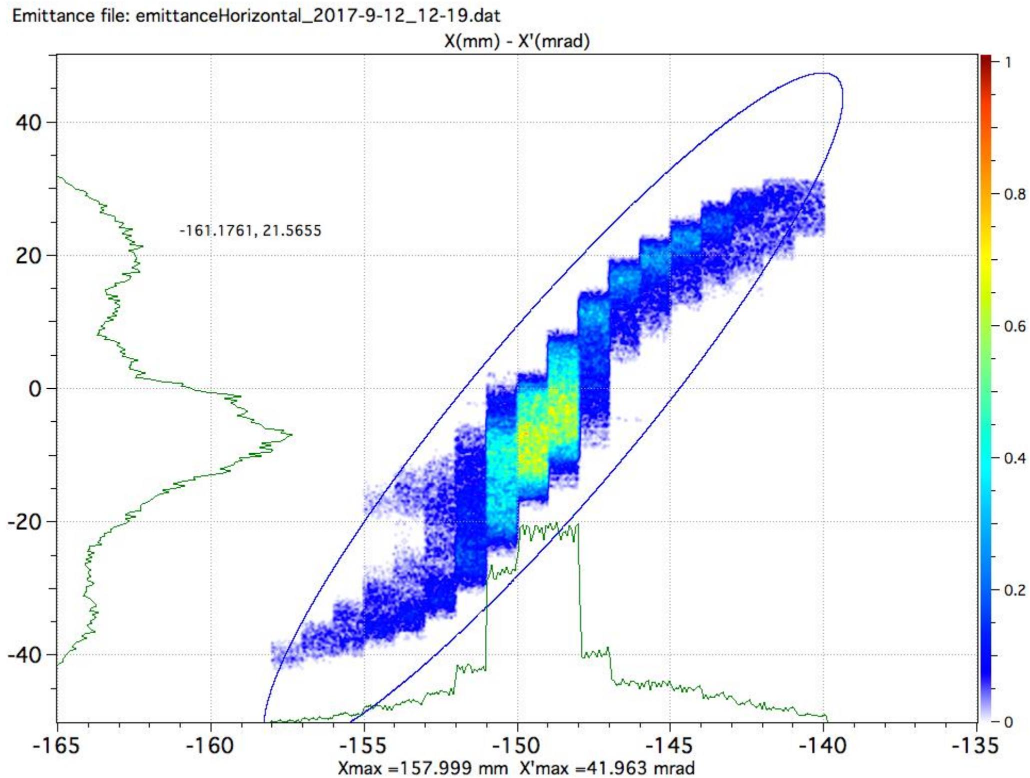
Beam pulse shape measured with the ACCT located at the end of the LEBT

Beam emittance at the center of the LEBT

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

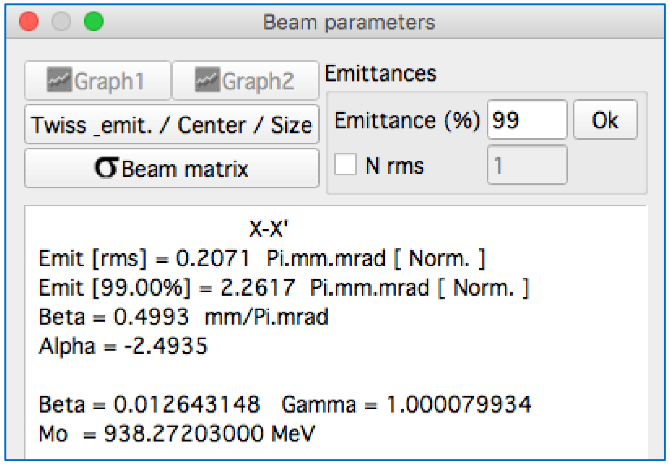


Beam emittance at RFQ location



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

Beam extraction and Transport simulations in O. Midttun et al., T7_We_24

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	☑

Stable EMU was not provided in time

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

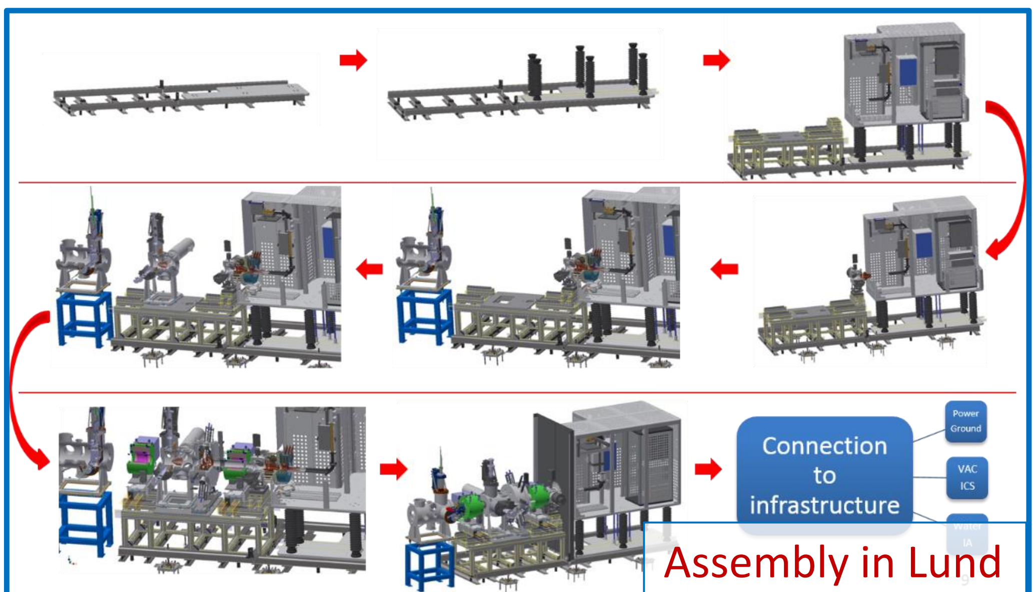
Requirement	Value	Status
Nominal beam current	70 mA	☑
Transmission	> 95 %	☑
Beam current range	6 – 70 mA	☑
Beam current precision	1 mA	☑
Vacuum pressure	< 6e-5 mbar	☑
Beam pulse flat-top length	0.05 - 2.86 ms	☑
Beam pulse rise/fall time	< 1 μs	☑
Transverse emittance (99%)	1.25 π.mm.mrad	☑
Twiss parameter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

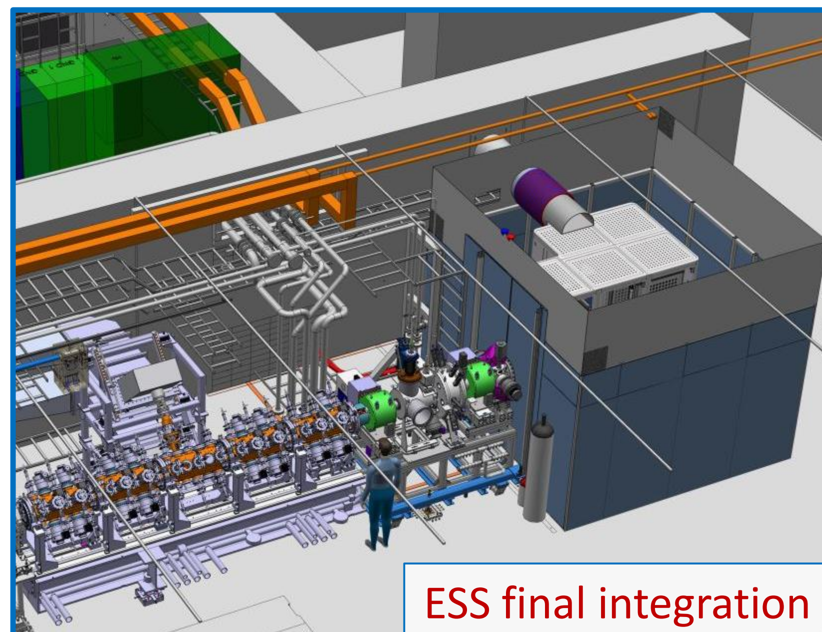
Back tracing simulation under going

Ready for ....

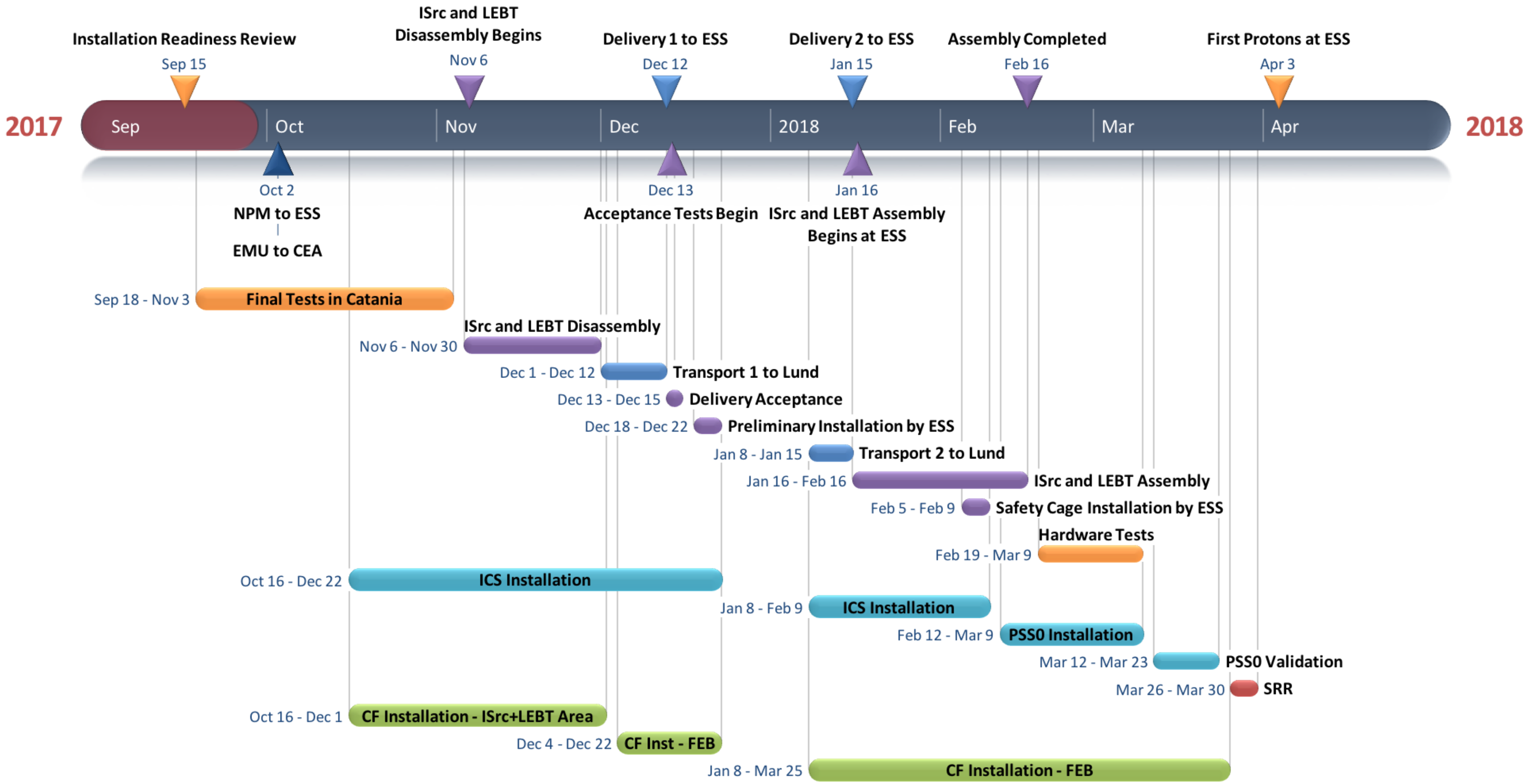

Dismantling


Packaging and transport


Connection to infrastructure
Power Ground
VAC ICS
Assembly in Lund

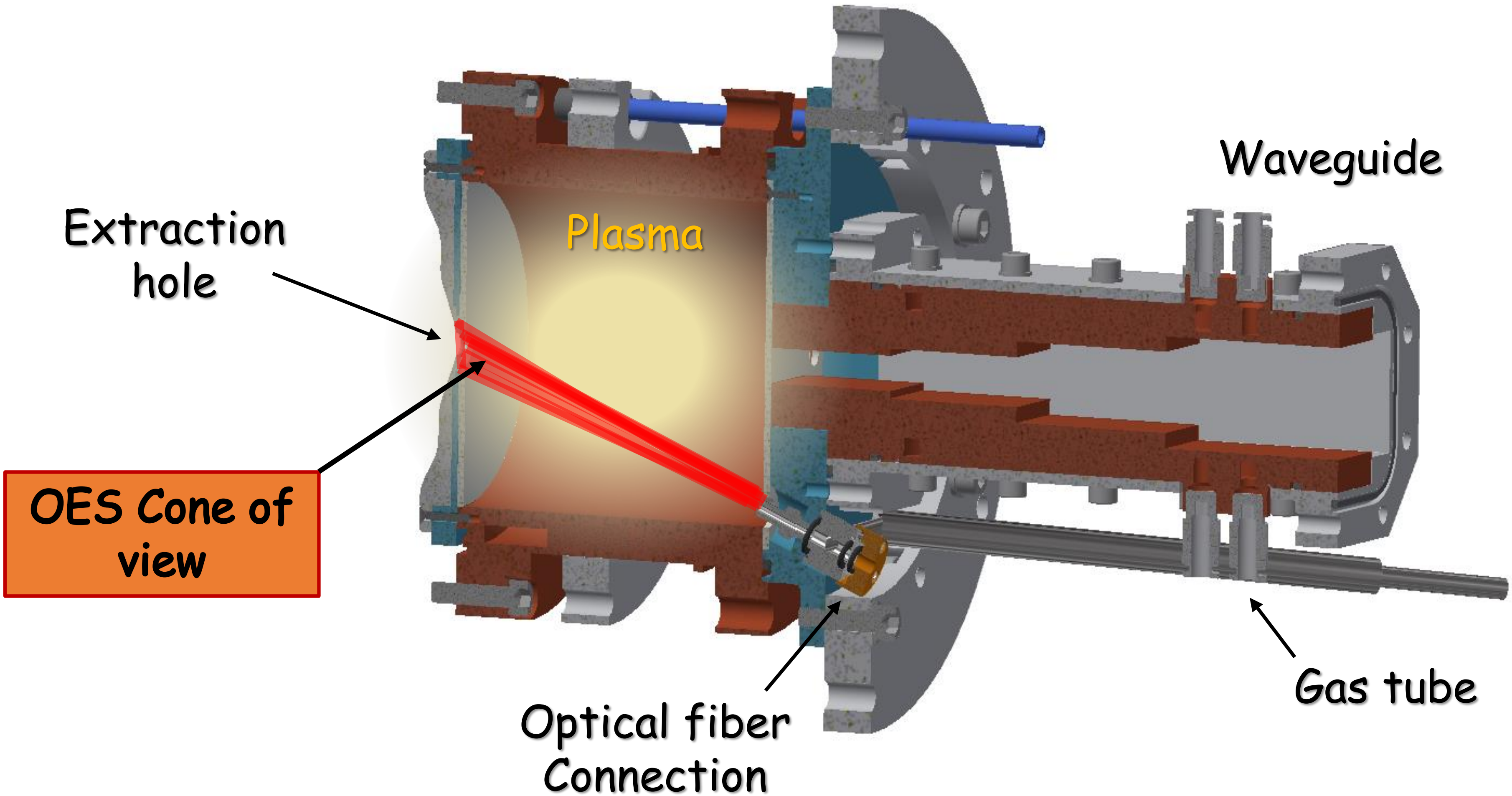

ESS final integration

Time line



2017
2018
Sep
Oct
Nov
Dec
2018
Feb
Mar
Apr
Installation Readiness Review
Sep 15
ISrc and LEBT Disassembly Begins
Nov 6
Delivery 1 to ESS
Dec 12
Delivery 2 to ESS
Jan 15
Assembly Completed
Feb 16
First Protons at ESS
Apr 3
Oct 2
NPM to ESS
EMU to CEA
Dec 13
Acceptance Tests Begin
Jan 16
ISrc and LEBT Assembly Begins at ESS
Sep 18 - Nov 3
Final Tests in Catania
ISrc and LEBT Disassembly
Nov 6 - Nov 30
Dec 1 - Dec 12
Transport 1 to Lund
Dec 13 - Dec 15
Delivery Acceptance
Dec 18 - Dec 22
Preliminary Installation by ESS
Jan 8 - Jan 15
Transport 2 to Lund
Jan 16 - Feb 16
ISrc and LEBT Assembly
Feb 5 - Feb 9
Safety Cage Installation by ESS
Hardware Tests
Feb 19 - Mar 9
Oct 16 - Dec 22
ICS Installation
Jan 8 - Feb 9
ICS Installation
Feb 12 - Mar 9
PSS0 Installation
Mar 12 - Mar 23
PSS0 Validation
Mar 26 - Mar 30
SRR
Oct 16 - Dec 1
CF Installation - ISrc+LEBT Area
Dec 4 - Dec 22
CF Inst - FEB
Jan 8 - Mar 25
CF Installation - FEB

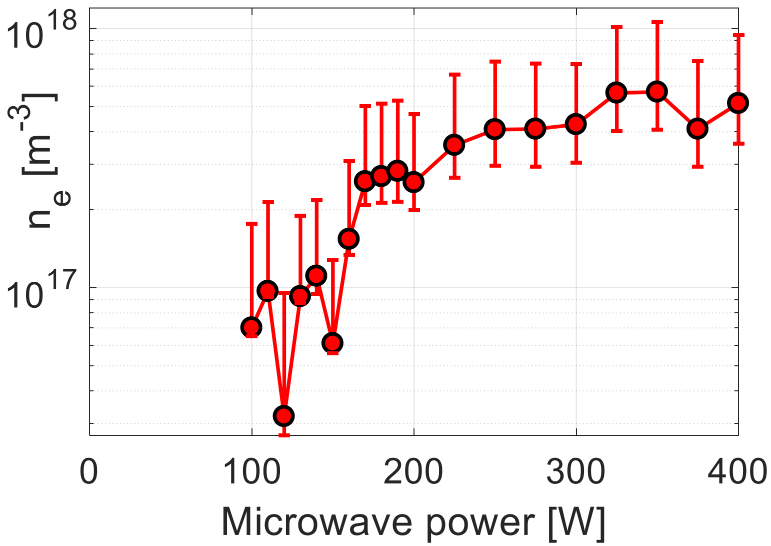
OES measurements



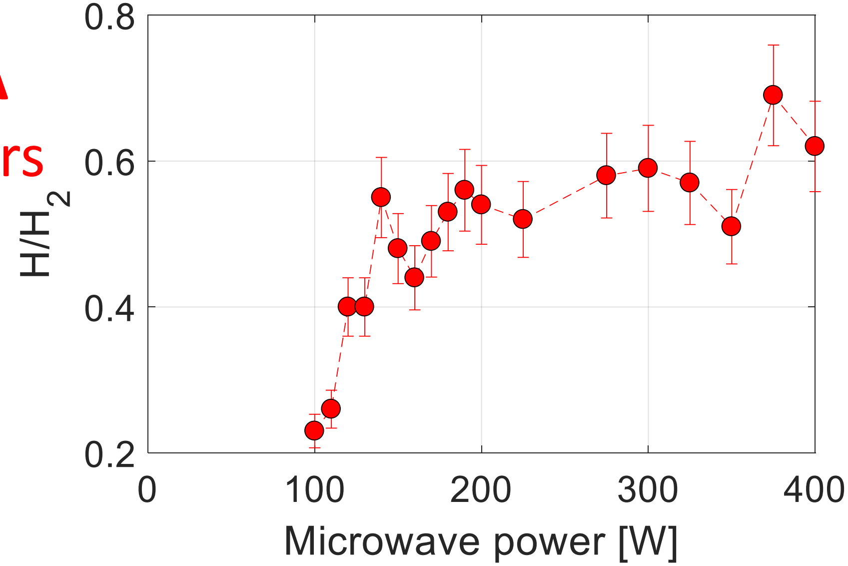
The Optical fiber is connected to the gas tube, via a quartz window and an adapter;

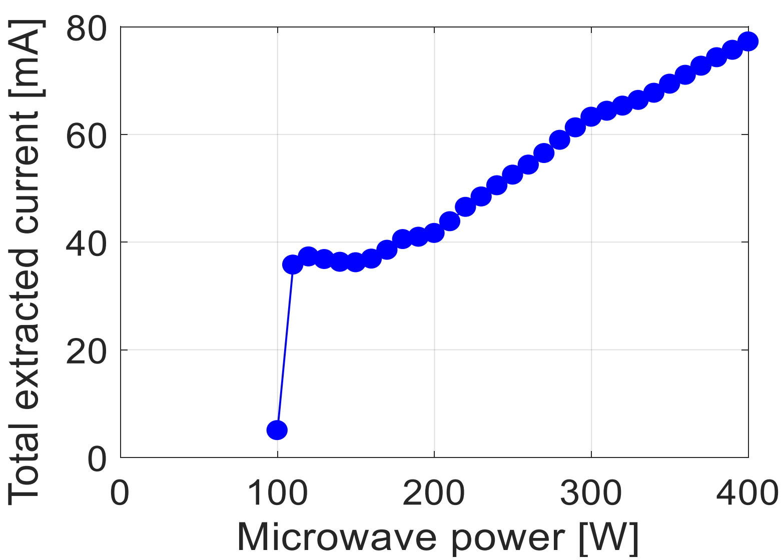
OES cone of view intercepts the plasma extraction region;

From plasma to beam parameters

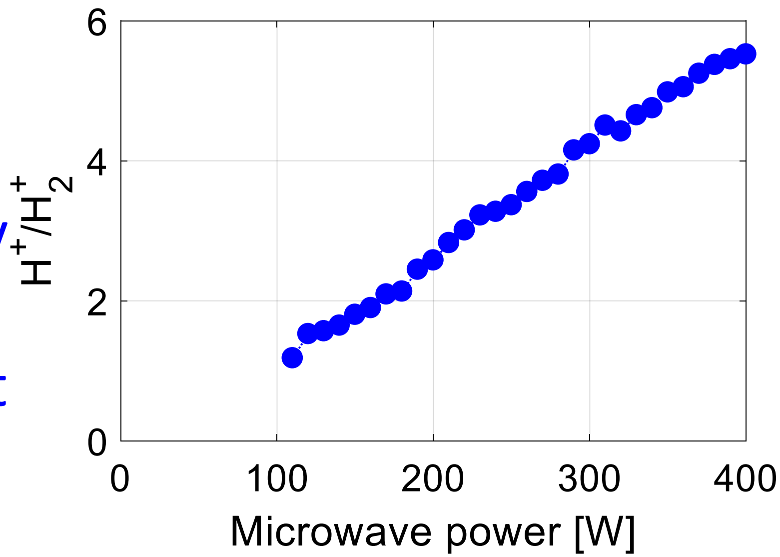


PLASMA
parameters
by OES





BEAM
parameters
Measured by
ACCT and
Doppler shift



Conclusion & Perspectives

- The source works flawless since beginning of the year, some minor troubles typical of the commissioning phase have been met and solved.
- The source performance fully satisfy the ESS requirements
- Fast characterization procedure and data analysis have been the key points to speed up the commissioning phases, exploring source performance in a wide operational range
- First documentation has been provided to ESS (Drawings, Diagrams, FAT, …)
- Second source procurement ongoing

Thanks for your attention

Comments are welcome

Thanks to all INFN-LNS staff to valuable support provided during all the phases of the project.

The collaboration with ESS and CEA was intense, profitable, always solution oriented.

ECRIS 2018
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STAY TUNED!