Intermediate commissioning results of the required 140 mA/100 keV CW D^+ ECR injector of LIPAc, IFMIF's prototype

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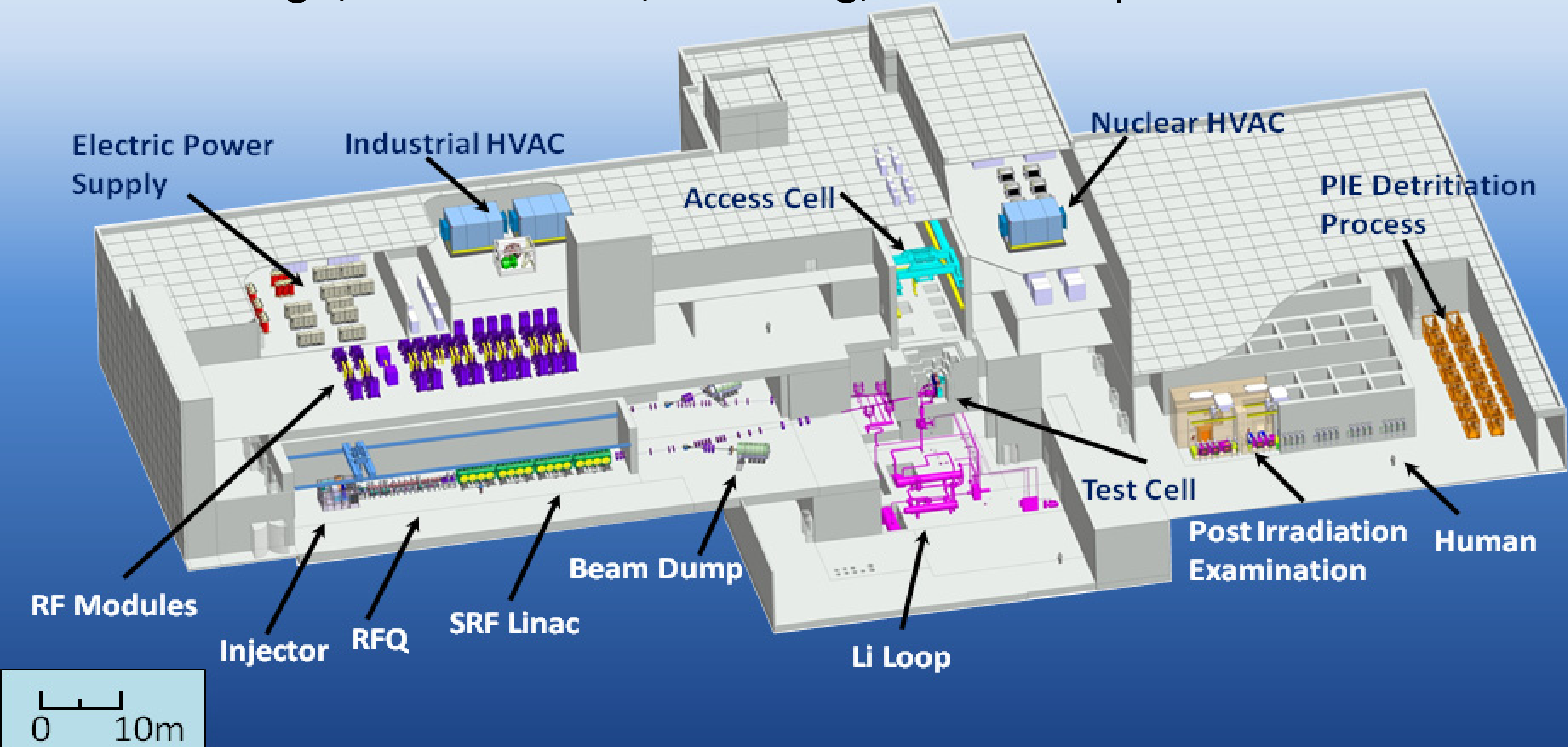
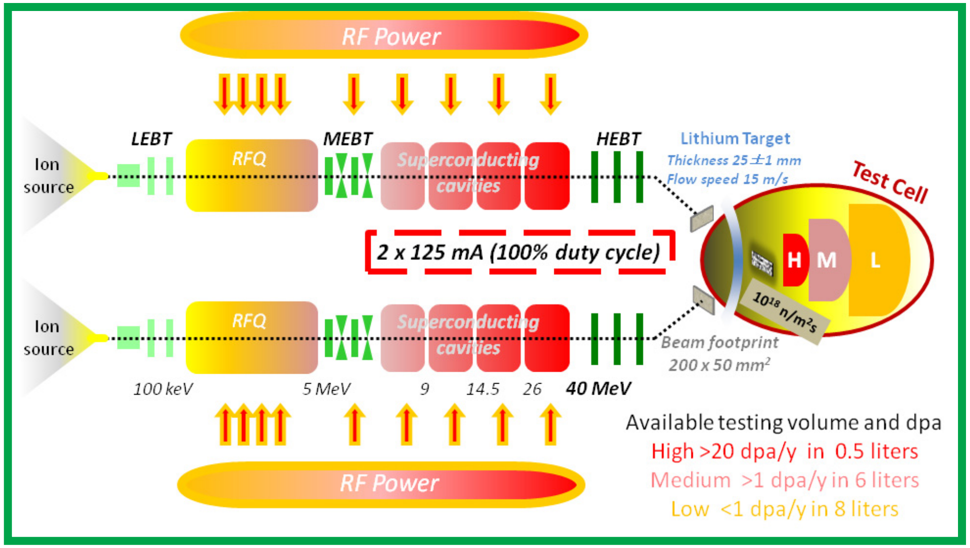
What is IFMIF?

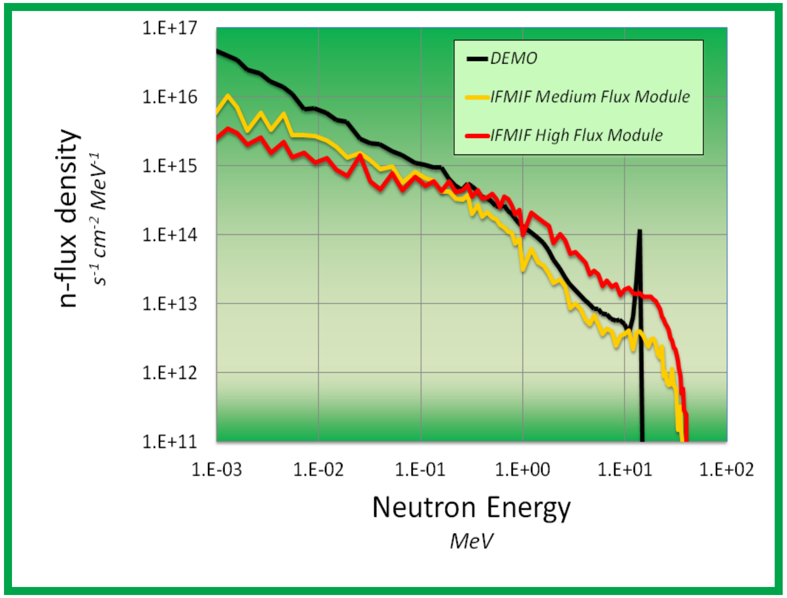
IFMIF (International Fusion Materials Irradiation Facility) is a projected accelerator-driven-type neutron source using Li(d,n) reactions aiming at providing a material irradiation database for the design, construction, licensing, and safe operation of DEMO.



IFMIF Concept



- ✓ **Two concurrent 125 mA CW deuterons beam at 40 MeV impact with a beam footprint of 200 mm x 50 mm on a liquid Li screen flowing at 15 m/s**



- ✓ **A flux of neutrons of ~10^{18} $m^{-2}s^{-1}$ is generated in the forward direction with a broad peak at 14 MeV**

  and irradiate three regions
  >20 dpa/y in 0.5 liters
  >1 dpa/y in 6 liters
  <1 dpa/y in 8 liters

- ✓ **A test cell and a post irradiation examination facility are used to qualify fusion reactor materials**

IFMIF/EVEDA Project under BA Activities

- ✓ Since 2007, IFMIF/EVEDA (Engineering Validation and Engineering Design Activities) under the Broader Approach Agreement between EU and Japan

- ✓ Validation Activities:
  1. Accelerator Facility
  2. Target Facility
  3. Test Facility

…to produce an integrated engineering design of IFMIF and the data necessary for future decisions on the construction, operation, exploitation and decommissioning of IFMIF, and to validate continuous and stable operation of each IFMIF subsystem

7 countries involved
with the respective main research labs in Europe
and main labs and universities in Japan

Linear IFMIF Prototype Accelerator - LIPAc

Features of IFMIF vs LIPAc

D^+ accelerator

125 mA CW for both

40 MeV vs 9 MeV

High current/Low energy for both

➔ High space charge issues for both

So are LIPAc as IFMIF

within present accelerator technology

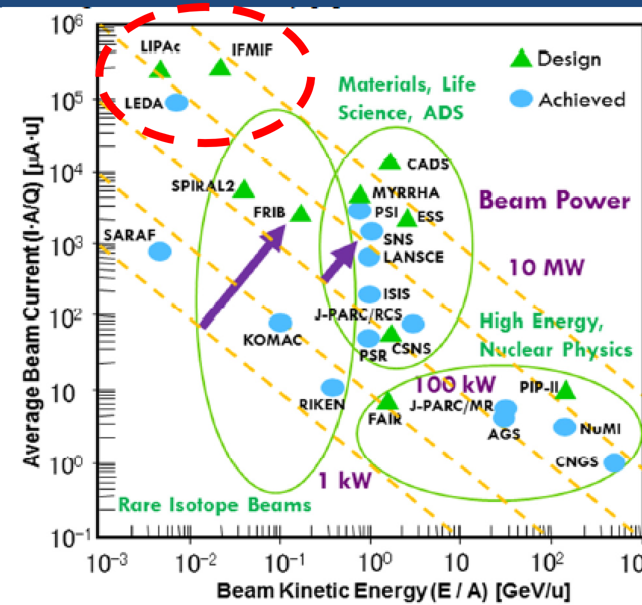
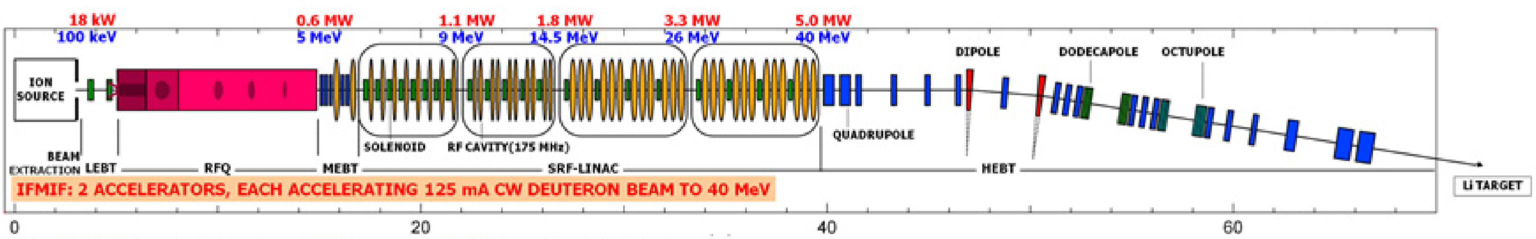
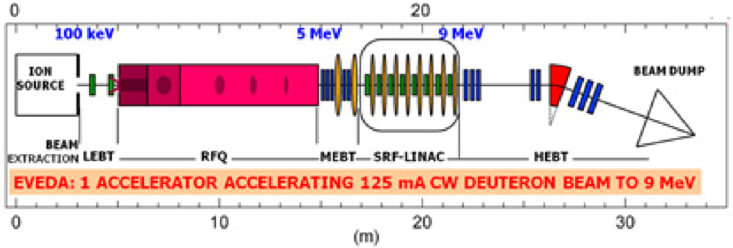


Figure 1: Hadron accelerator power frontier.

WEI, J. et al., *The very high intensity future*, ***IPAC 2014, Dresden***



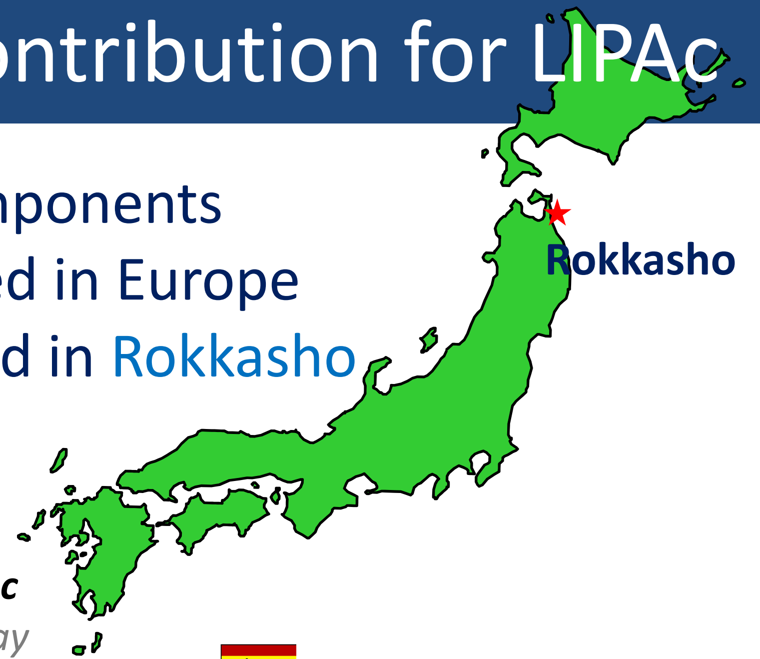
40 MeV
125 mA
5 MW



9 MeV
125 mA
1.125 MW

NGHIEM, P.H.P. et al., *The IFMIF-EVEDA Challenges in Beam Dynamics and their Treatment*, **Nucl. Inst. Meth. 654 (2011) 63–71**

Breakdown of contribution for LIPAc



Most accelerator components
designed and constructed in Europe
Installed and commissioned in Rokkasho

Injector + LEBT
CEA Saclay

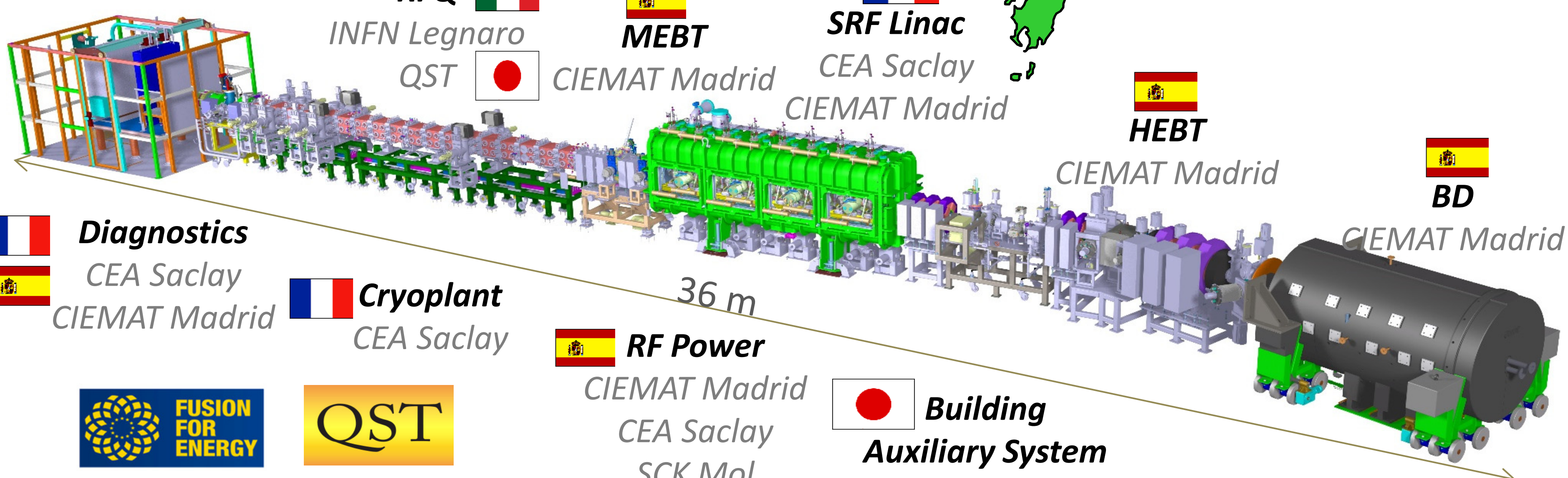
RFQ
INFN Legnaro
QST

MEBT
CIEMAT Madrid

SRF Linac
CEA Saclay
CIEMAT Madrid

HEBT
CIEMAT Madrid

BD
CIEMAT Madrid



Diagnostics
CEA Saclay
CIEMAT Madrid

Cryoplant
CEA Saclay

RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

Building
Auxiliary System
Control system
Installation
QST

Phase A: injector commissioning

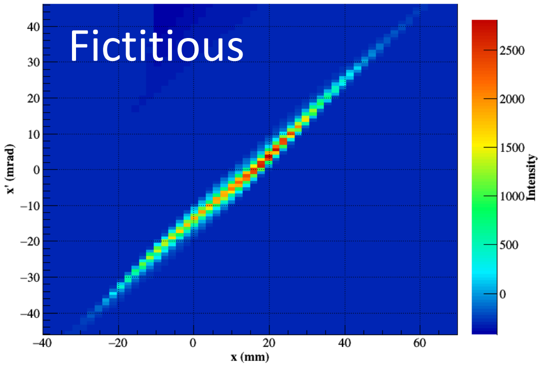
- ✓ **Injector commissioning started at Rokkasho in November 2014 and continues in 2016 interleaved with RFQ installation to optimize schedule**
  - ➢ Injector composed of a 2.45 GHz ECR ion source and of a LEBT line to transport and match the beam into the RFQ thanks to a dual solenoid focusing system
- ✓ **Requirements at the RFQ entrance in order to meet LIPAc objectives:**

Requirements	Target value
Particles	D^+
Output energy	100 keV
Output D^+ current	140 mA
D^+ fraction	99 %
Beam current noise	1 % rms
Normalized rms transverse emittance*	0.25 π.mm.mrad
Duty factor	CW
Beam turn-off time	< 10 μs

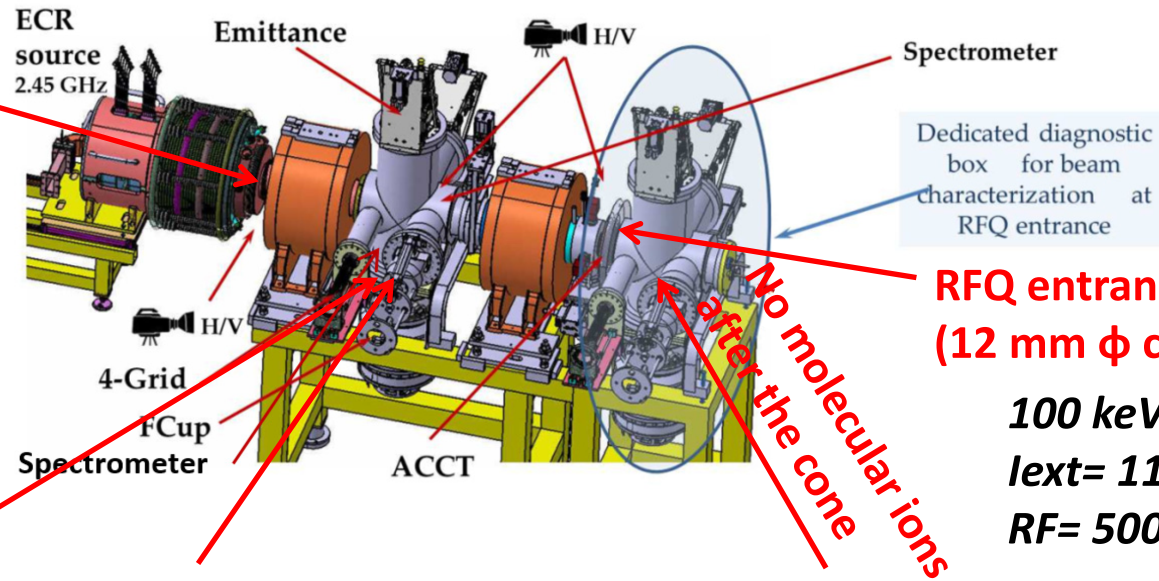
* To minimize losses down to 4% in the RFQ, target emittance is of 0.25 π mm.mrad (acceptable value of 0.30 π mm.mrad for 10% losses) **+ well-matched Twiss parameters**

Injector commissioning approach

Phase A3: in discussion



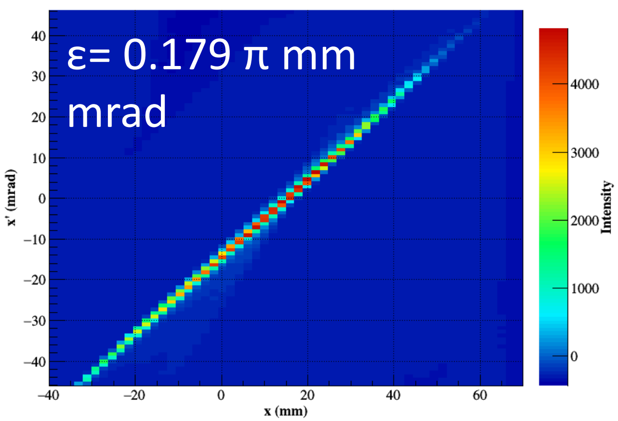
To characterize the source



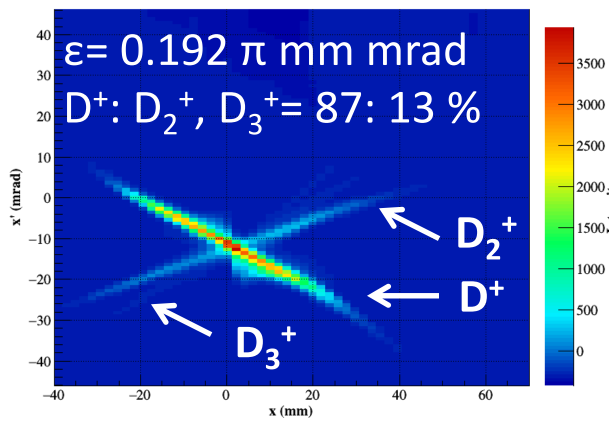
RFQ entrance (12 mm ϕ cone)

100 keV D^+
Iext= 111 mA
RF= 500 W

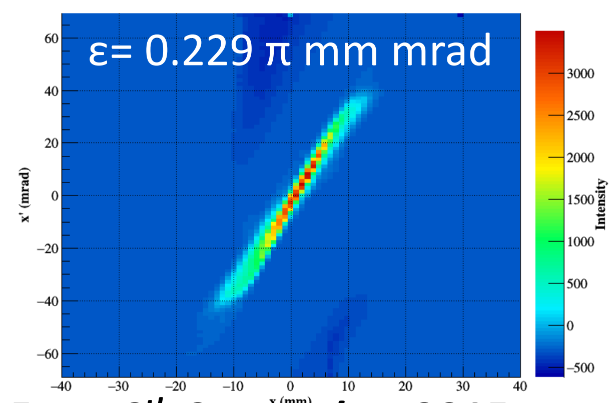
Phase A1: no solenoid currents



Phase A1: between 2 solenoids



Phase A2: after the RFQ cone



From 22nd April to 8th September 2015:
Plasma and 5-electrode beam extraction system optimization

From 9th September 2015 to November 2016: Reach the injector requirements

Injector commissioning approach

✓ The generalised perveance, figure of merit for space charge issues, is world highest in LIPAc due to high current and low energy ➔ Emittance growth

$$K = \frac{eI}{2\pi\varepsilon_0 m_0 v^3 \gamma^3}$$

✓ Deuterons present high inelastic cross sections

- ➢ Commissioning would be difficult if done with D^+ but H^+ at half energy and half intensity behave as D^+ at nominal conditions in terms of perveance

➔ *Commissioning is also done with 70 mA/50 keV H^+ beam to avoid activation and ease maintenance activities (D^+ commissioning objective: 140 mA/100 keV)*
However, injector design optimized to produce high intensity 100 keV D^+ beam

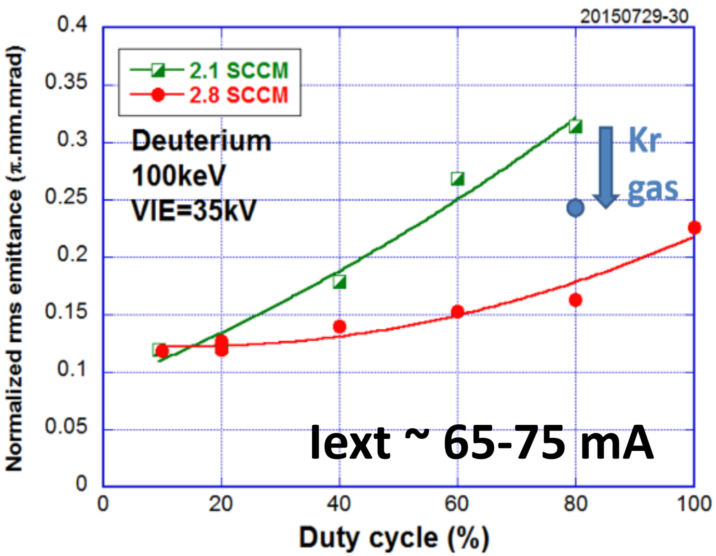
✓ Electrostatic chopper used to provide sharp beam pulses of short length (50-100 µs) for machine protection system in view of the RFQ commissioning

➔ *Commissioning from low DC with short pulses (chopper) up to CW operation*

Phase A1 with 100 keV D^+ beam

Plasma electrode of 10 mm ϕ as a first step of commissioning

- ✓ Beam currents up to 113 mA were extracted at 1000 W of injected RF power
- ✓ The duty cycle was increased up to CW operation to study if the beam characteristics remain the same while keeping the same injector parameters
- ✓ It was observed an increase of emittance with the increase of duty cycle
- ✓ But the emittance growth was smaller when increasing D_2 gas flow rate



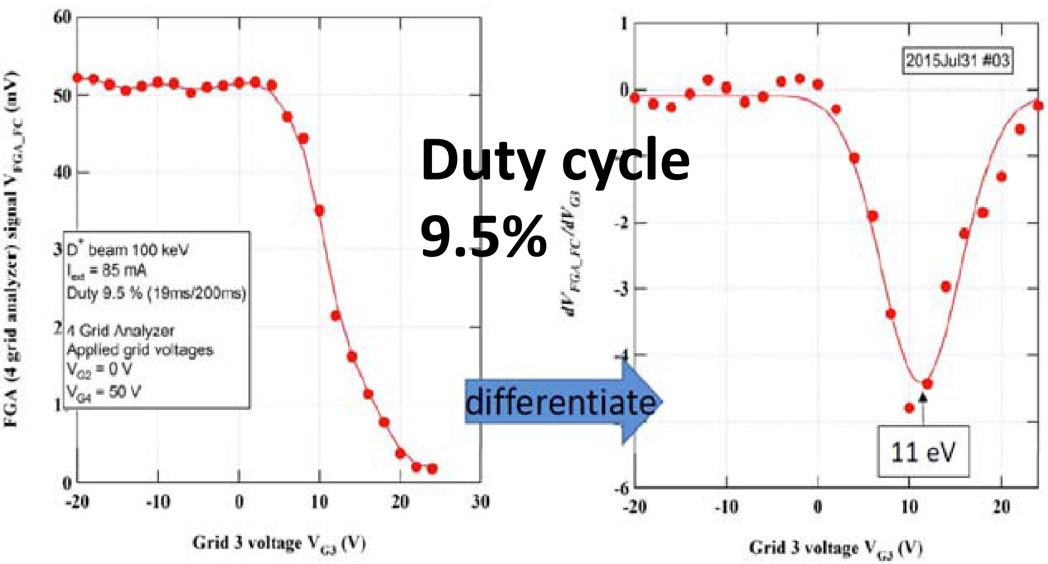
- ➢ This trend of emittance growth with DC may be connected to various experimental conditions (including starting conditions)
- ➢ The emittance could be improved at high duty cycle only by injecting Krypton gas in-between the 2 solenoids of the LEBT

Phase A1 with 100 keV D+ beam

Plasma electrode of 10 mm ϕ as a first step of commissioning

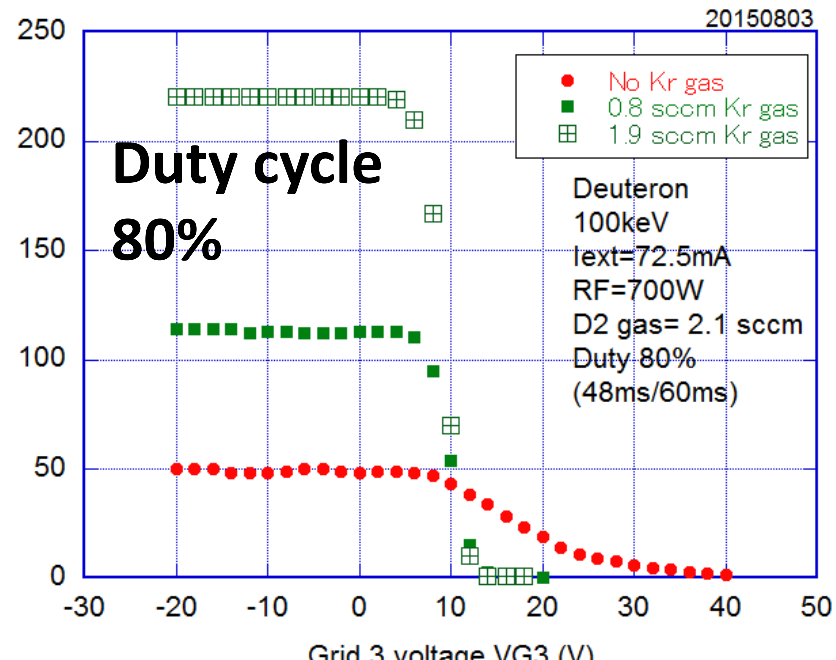
- ✓ Space potential measurements of the beam plasma were done between the two solenoids of the LEBT at 10% and 80% duty cycle using a 4-Grid analyser
- ✓ The space charge potential was centred on 11 eV at 10% DC. It increased to 16 eV at 80% DC but it decreased to less than 10 eV with Kr gas injection

We performed space charge compensation at high duty cycle!!!



Faraday cup signal in the FGA plotted as a function of 3rd grid voltage

Energy distribution of injected ions



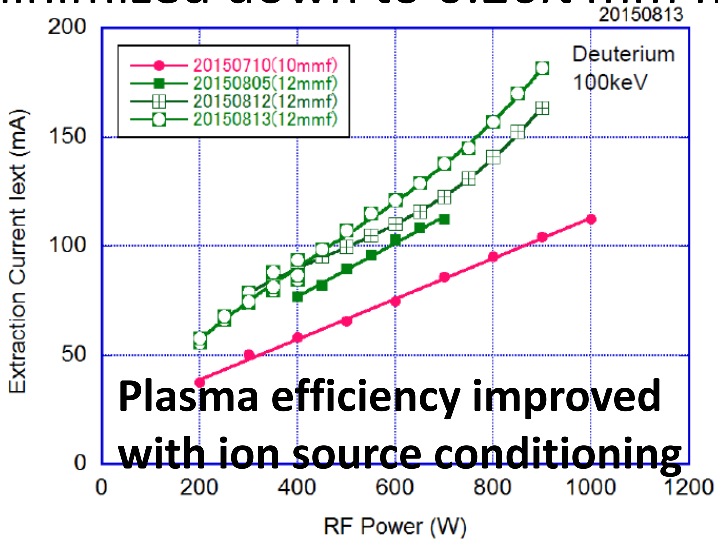
Phase A1 with 100 keV D⁺ beam

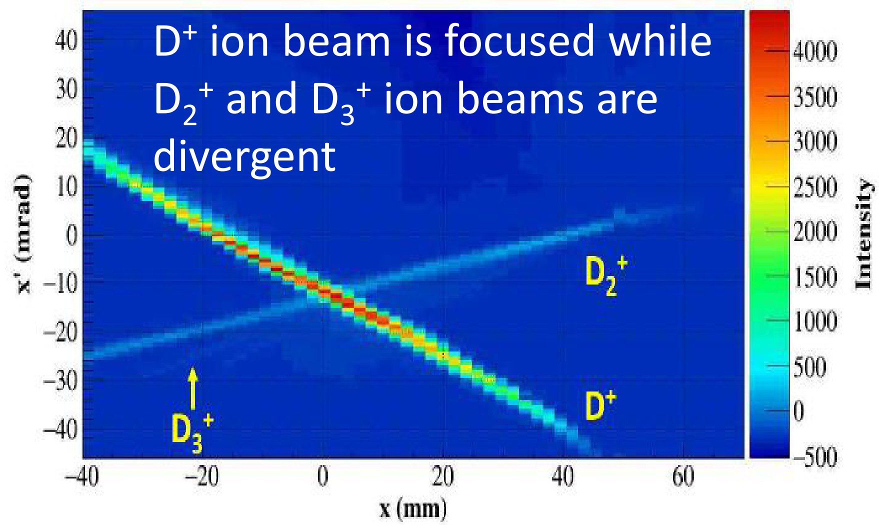
Plasma electrode of 12 mm φ

- ✓ After optimization of plasma source parameters, currents as high as 186 mA could be extracted with an injected RF power of 950 W at 9.8% duty cycle

- ✓ Increase of D^+ fraction ratio with the I_{ext}: already of 90% for I_{ext}~ 100 mA
  ➔ Confirms that the injector design was well optimized for 100 keV D^+ beam

- ✓ For an extracted current of 153 mA at 9.5% duty cycle, the emittance was minimized down to 0.26π mm·mrad (FC between the LEBT solenoids: 134 mA)

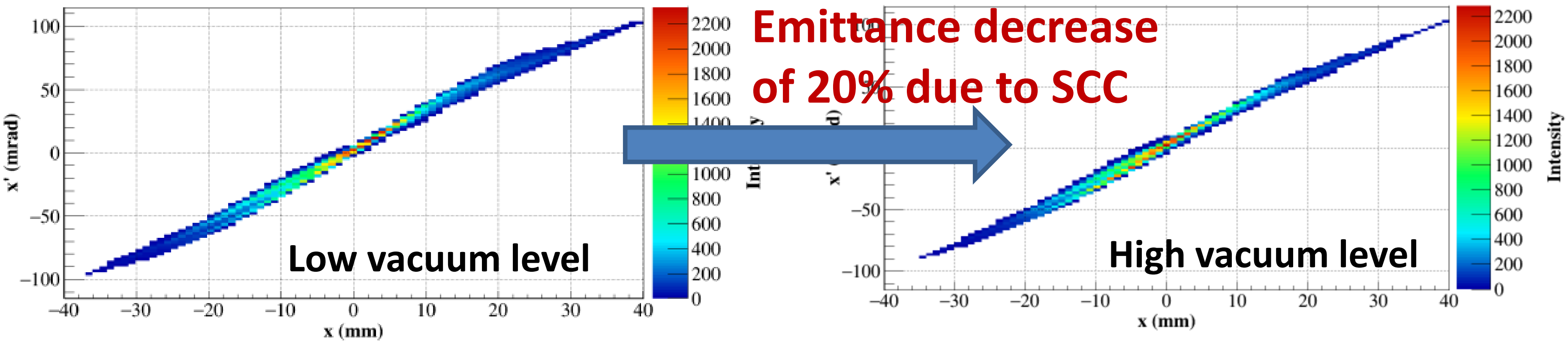




Phase A2: Improvements to bring

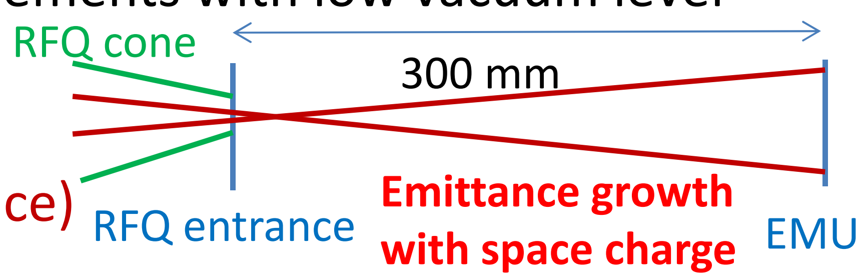
Study of Space Charge Compensation (SCC) in 2nd diagnostic chamber

- ✓ Vacuum level more than 10 times lower than in the 1st diagnostic chamber
- ✓ Emittance measured with low and high vacuum level (shutdown of the pump)



- ✓ Unfortunately, this test was performed very recently and the emittance results presented today are from measurements with low vacuum level

➔ Results can be most probably improved simply by increasing this vacuum level (ε of 0.25 π mm.mrad at the RFQ entrance)

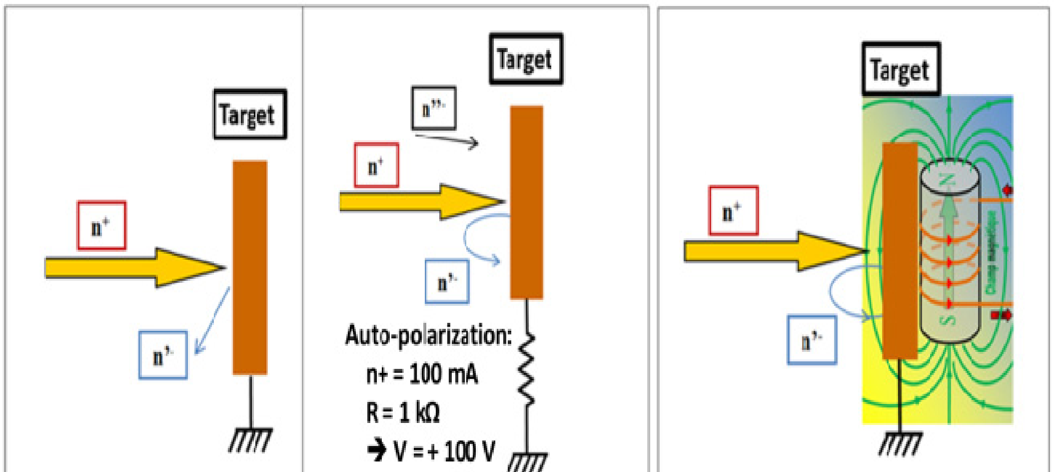


➔ Modifications are on-going in order to inject H_2/D_2/Kr gas in the 2nd chamber

Phase A2: Improvements to bring

Improvement of Beam Stop (BS) current measurement

- ✓ In this presentation, results of currents measured on the self-biased BS are from electrical measurements (same principle as for a Faraday cup)
- ✓ Although an electrode repeller is located just upstream the end of the RFQ cone, currents may be underestimated due to secondary electrons generated by the beam hitting the end of the cone and the 2nd diagnostic chamber

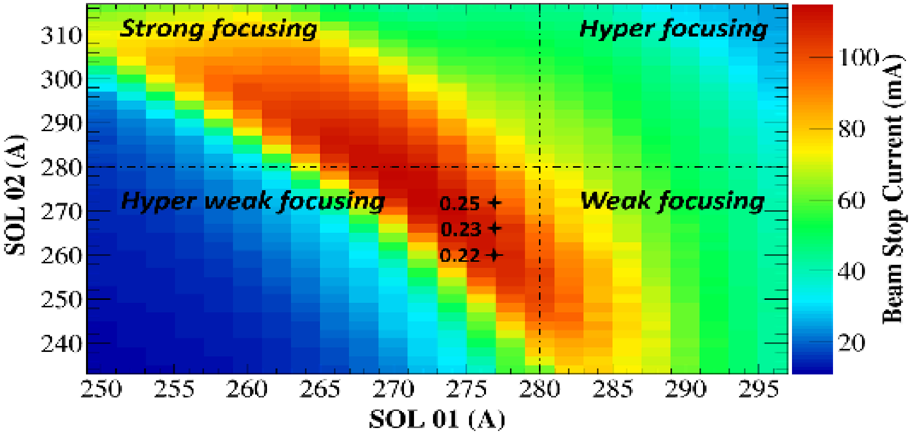


Production of secondary electrons | Auto-polarization to remove the contribution of secondary electrons on the measurements | Dipolar magnetic field to remove the contribution of secondary electrons on the measurements

- ➢ A calorimetric measurement system of high resolution has just been developed
- ➢ Moreover, a permanent magnet will be installed very soon behind the beam stop to push back secondary electrons

Phase A2: 100 keV D^+ beam with ϕ12 mm

✓ For I_{ext}= 150 mA, BS current measured at 10% DC as a function of SOL1 &2



➢ Emittance measured at 3 settings of SOL1&2 (same injector parameters) in the weak focusing area at 10% DC

Emittance under specifications while the BS current was of 104-112 mA

✓ However, the Twiss parameters should be the best matched for the RFQ somewhere in the strong focusing area according to recent simulations

✓ In the next commissioning campaign, the emittance will be measured also in this area with as objective to keep it within specifications.

Duty cycle [%]	20	50
Extracted current [mA]	150	158
BS current [mA]	112	108
Norm. ε [π mm.mrad]	0.23	0.31
D^+ / D_2^+ / D_3^+ ratio [%]	92 / 5 / 3	Not measured

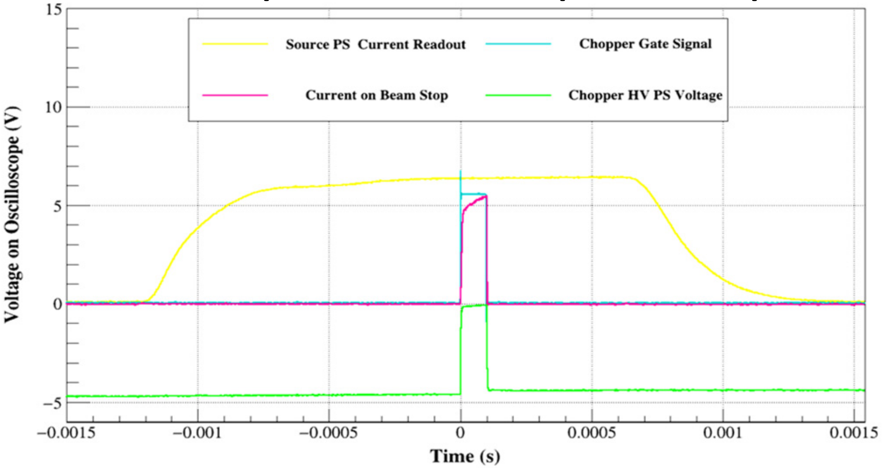
➢ Study at high DC performed for SOL1= 277 A & SOL2= 270 A

Not continued due to technical problems at that time

N.B: Fraction ratios of ion species measured between the two solenoids of the LEBT

Phase A2: 100 keV D^+ beam with ϕ12 mm

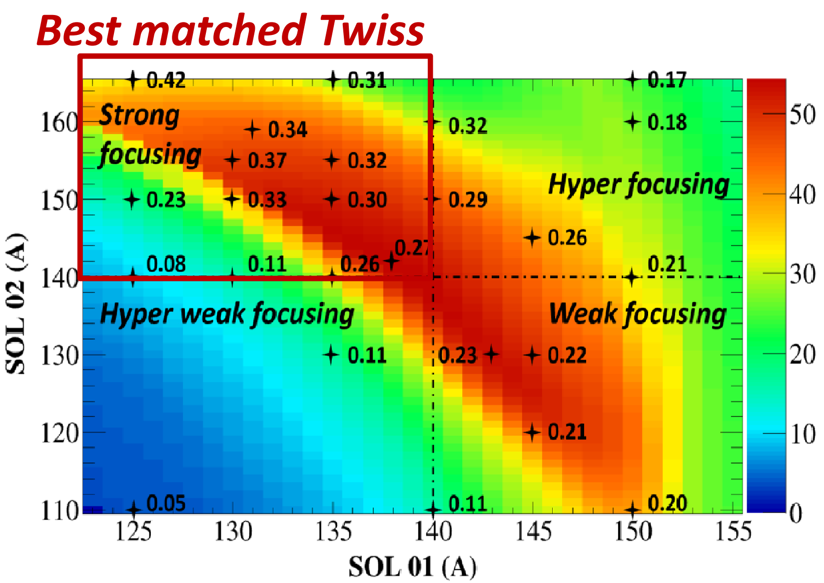
- ✓ Experimental data show that the emittance tends to increase with I_{ext}
- ✓ Higher BS currents were obtained with higher extracted currents but the emittance was over specifications.
- ✓ However, these experiments have to be repeated in the next campaign with calorimetric measurements (and electrical measurements using a magnet) and with injection of D_2 or Krypton gas into the 2nd diagnostic chamber.
- ✓ The electrostatic chopper was tested and could provide sharp beam pulses of 100 µs (source pulses of 2 ms)



- ➢ More beam time will be allocated to fully validate the chopper operation

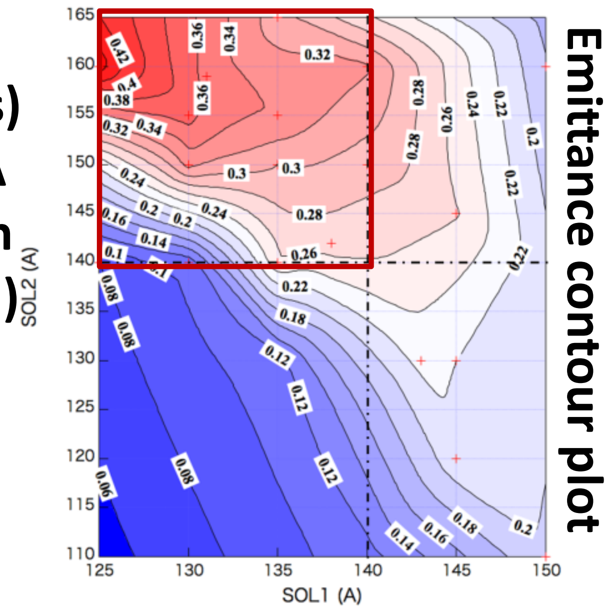
Phase A2: 50 keV H^+ beam with ϕ10 mm

✓ **For I_{ext}= 85 mA:** - BS current measured at 10% DC as a function of SOL1 &2
- Emittance measured at 25 settings of SOL1&2 (10% DC)



H^+ ratio= 73% (between solenoids)
BS current ~ 55 mA (to be checked with calorimetric system)

For Iext> 85 mA: BS current decreases due to large beam divergence (losses)



- ➢ Emittance under specifications in the weak and in the hyper focusing area
- ➢ But increase from the weak to the strong focusing area (as predicted by simulations) and above specifications in half of the strong focusing area
- ➢ By injecting H_2 or Krypton gas in the 2nd diagnostic chamber, emittance can be probably reduced and may be within specifications for any SOL1 & SOL2

Conclusion

- ✓ Commissioning results of 100 keV D^+ and 50 keV H^+ beams reported an emittance within specifications in the weak focusing area for BS currents of 110 mA and 55 mA respectively (electrical measurements) at 10% duty cycle

- ✓ BS currents higher than 110 mA were obtained with D^+ beam by increasing the extracted current but the emittance was then over specifications

- ✓ By injecting Kr gas in 2nd diagnostic chamber, ε may be within specifications in the strong focusing area (best matched Twiss) and for higher BS currents

- ✓ The emittance was degraded with the duty cycle due to a change of plasma conditions probably. However, emittance was improved by injecting Kr gas

- ✓ Injector commissioning continues in October in order to reach requirements
  - Kr gas will be injected in the 2nd diagnostic chamber to learn the real ε
  - Calorimetric measurement will be available as well as a permanent magnet behind the BS to analyze if BS currents were not underestimated

SPARES

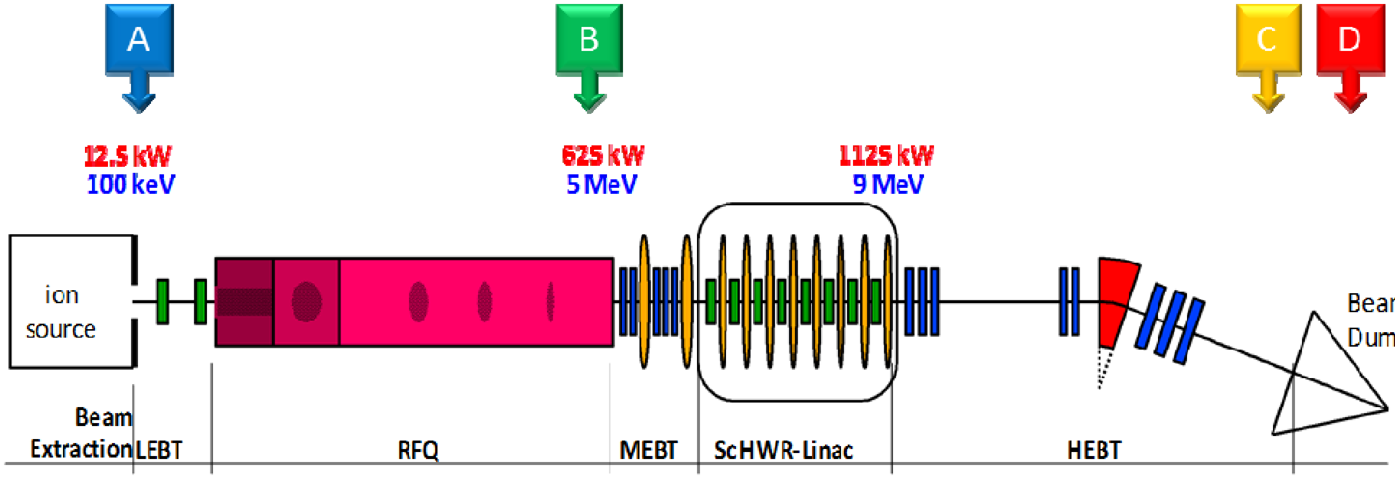
Overall commissioning approach

- ✓ ***Phase A:*** Source + Low Energy Beam Transport Line (LEBT)
  140 mA D^+ current at 100 keV in Continuous Wave (CW)

- ✓ ***Phase B:*** RFQ + Medium Energy Beam Transport + D-Plate + Low Power Beam Dump
  125 mA D^+ current at 5 MeV at 0.1% duty cycle

- ✓ ***Phase C:*** SRF-Linac + High Energy Beam Transport Line + High Power Beam Dump
  125 mA D^+ current at 9 MeV at 0.1% duty cycle

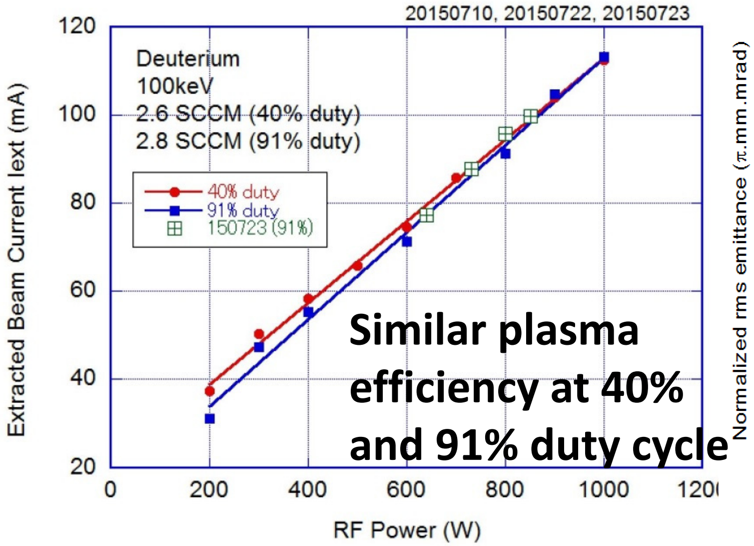
- ✓ ***Phase D:*** Ramp up the duty cycle up to CW

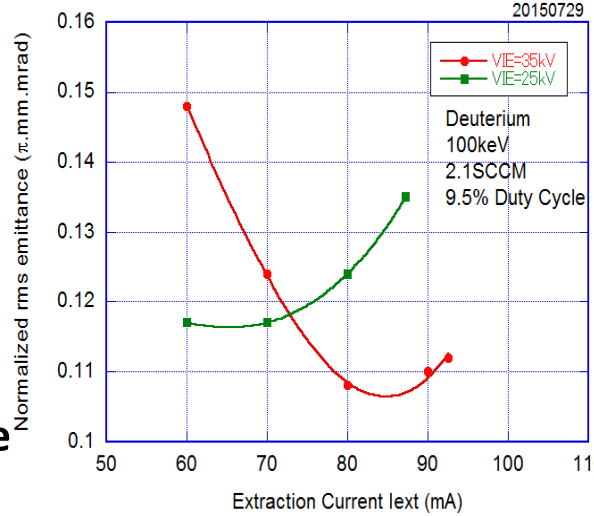


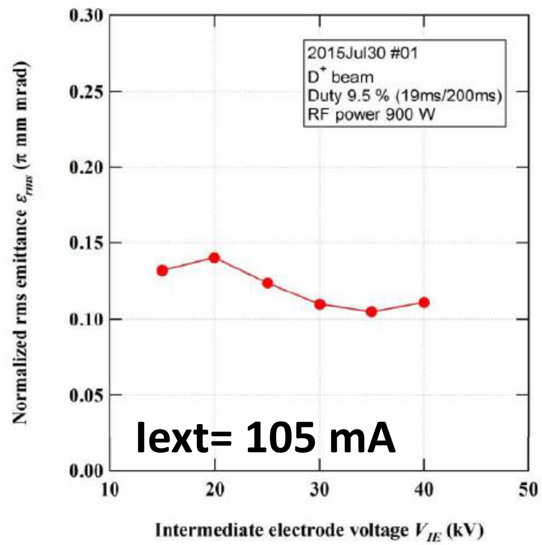
Phase A1 with 100 keV D^+ beam

Plasma electrode of 10 mm ϕ as a first step of commissioning

- ✓ After optimizing the plasma source parameters, the extracted ion current increases almost linearly with the microwave power
- ✓ Beam currents up to 113 mA at 1000 W of input RF power were extracted
- ✓ D^+ fraction ratio was measured to be very high, i.e. 90% for Iext= 105 mA
- ✓ By optimizing the 1st accelerating gap voltage of the extraction system for a given I_{ext}, emittance growth can be minimized (smaller beam divergence)

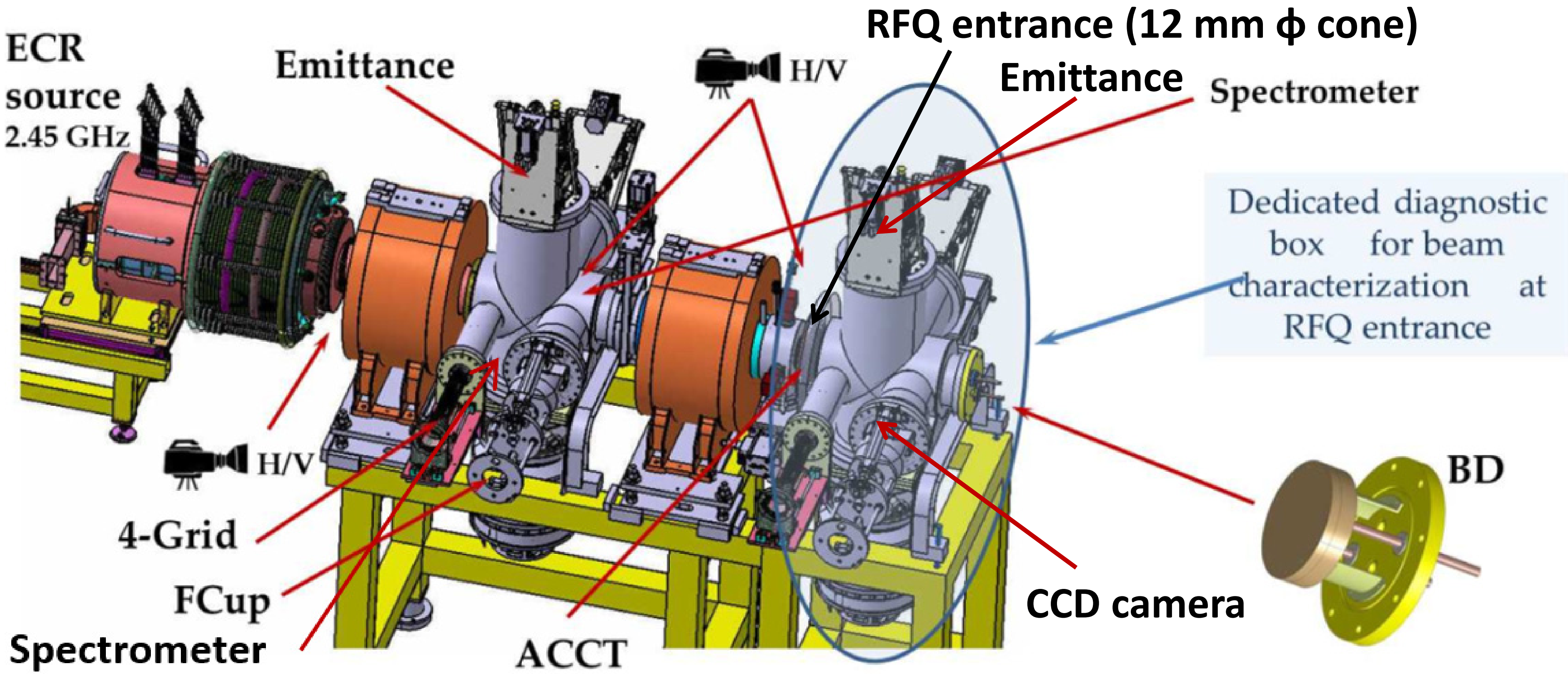


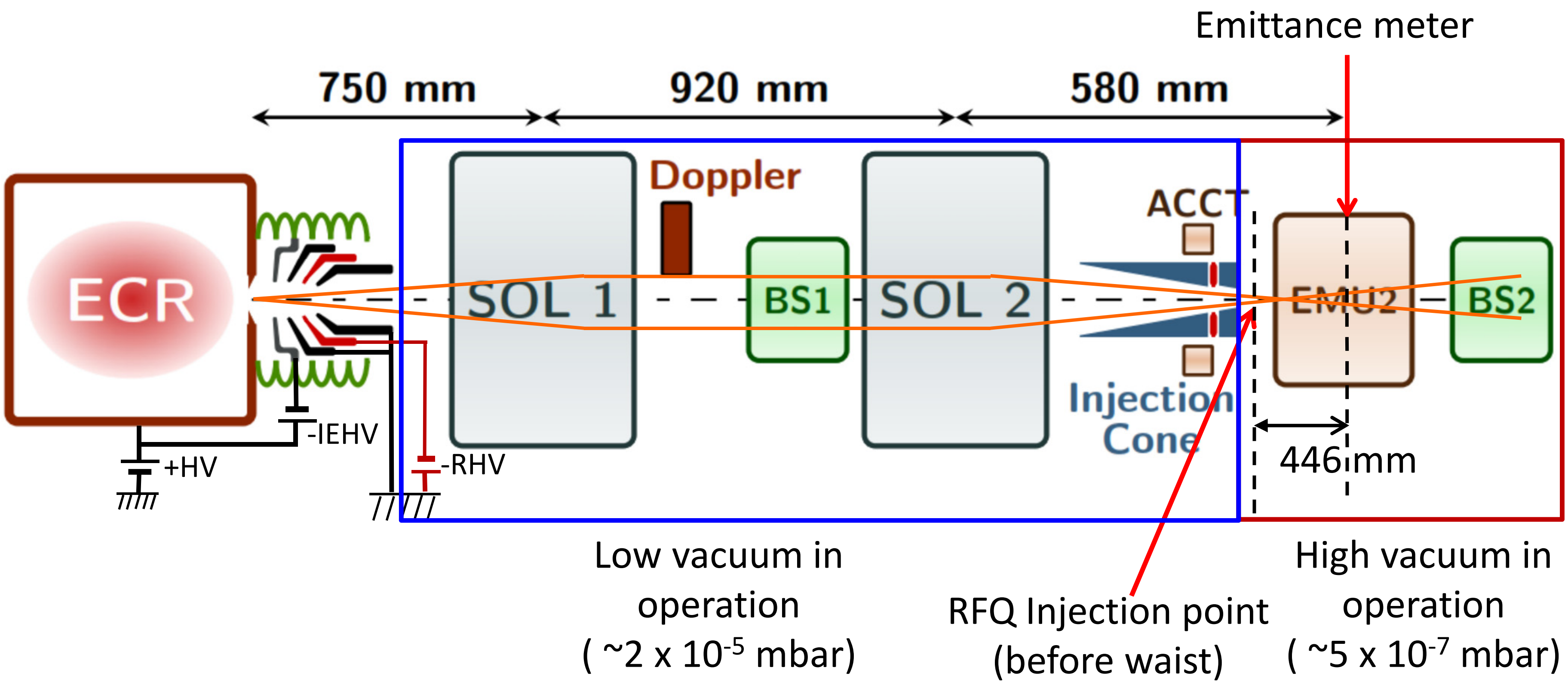




Beam diagnostics of the injector

- ✓ Short LEBT (2.05m) to minimize emittance growth due to space charge
- ✓ Diagnostics despite limited space (limited only to the most essential ones)
- ✓ 2 diagnostic chambers: emittance measured in 1st one (A1) and 2nd one (A2)





Emittance meter
750 mm
920 mm
580 mm
ECR
Doppler
SOL 1
BS1
SOL 2
ACCT
Injection Cone
EMU2
BS2
-IEHV
+HV
-RHV
446 mm
Low vacuum in operation (~2 x 10^{-5} mbar)
RFQ Injection point (before waist)
High vacuum in operation (~5 x 10^{-7} mbar)