DE LA RECHERCHE À L'INDUSTRIE

Conditionnement et caractérisation de l'injecteur IFMIF à Rokkasho au Japon

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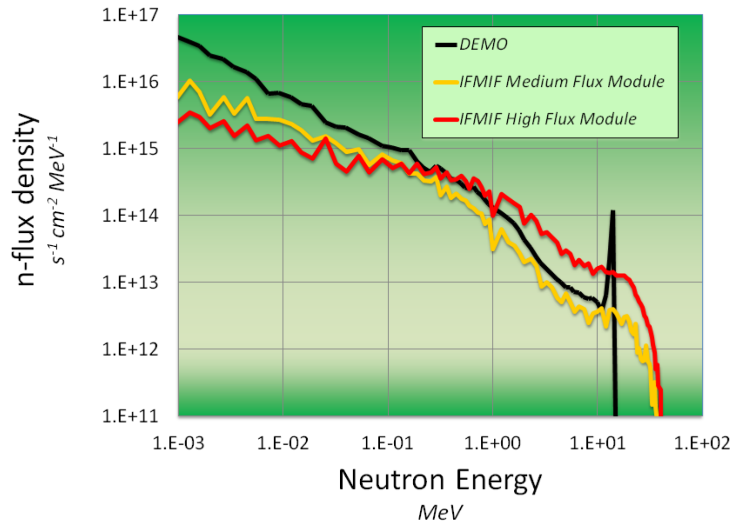
Outline

- **IFMIF project**
- **Injector design (ion source and LEBT)**
- **Transfer to Japan, Installation and Conditioning**
- **D^+ beam characterization**
- **Security and Neutron production**

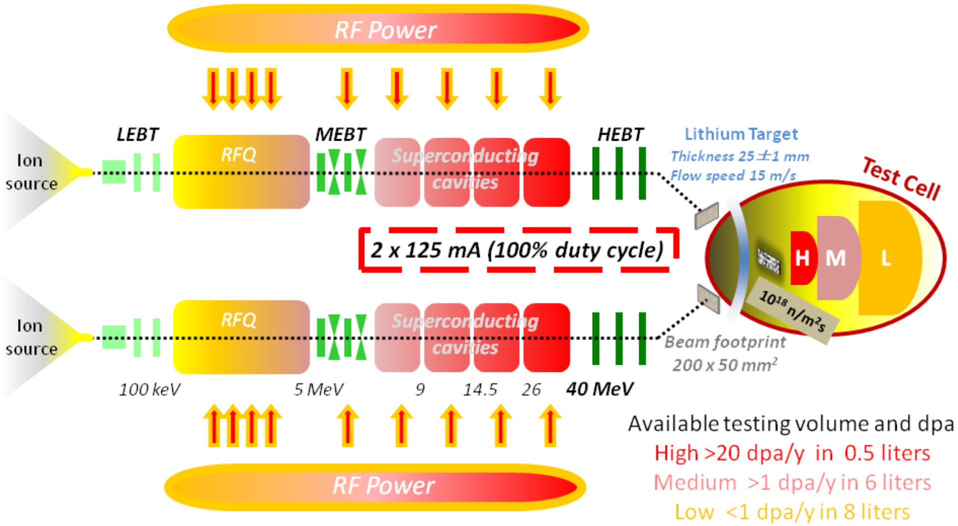
IFMIF PROJECT

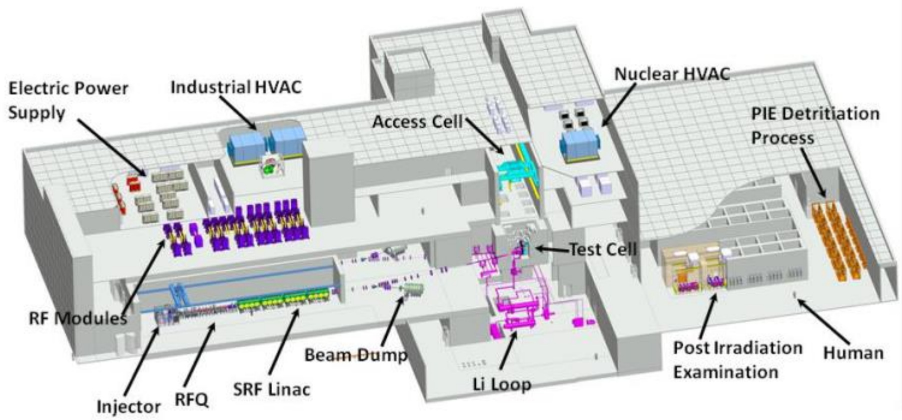
(International Fusion Materials Irradiation Facility)

The aim is the production of a high neutrons flux (10^{18} n m^{-2} s^{-1}) with 14 MeV peak energy



2 D^+ beams (125 mA - 40 MeV) will collide on a liquid Li target





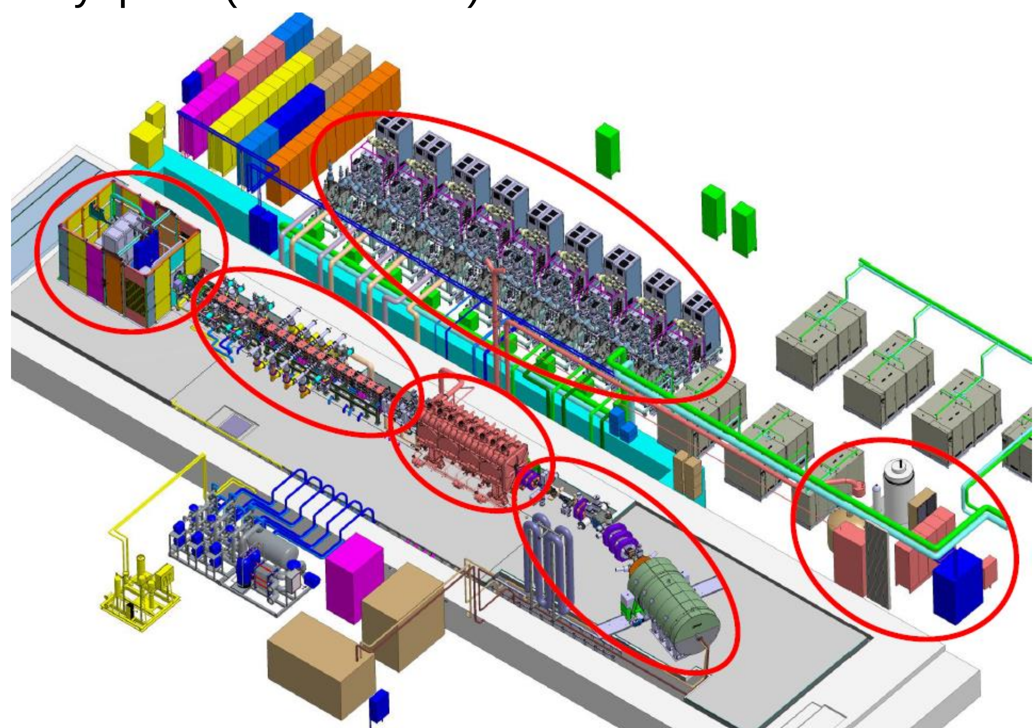
IFMIF PROJECT – VALIDATION PHASE LIPAC
(Linear IFMIF Prototype Accelerator)

LIPAc = prototype for IFMIF which includes all critical accelerator components to be tested at nominal beam current

Installation and test in progress on the Rokkasho site in Japan

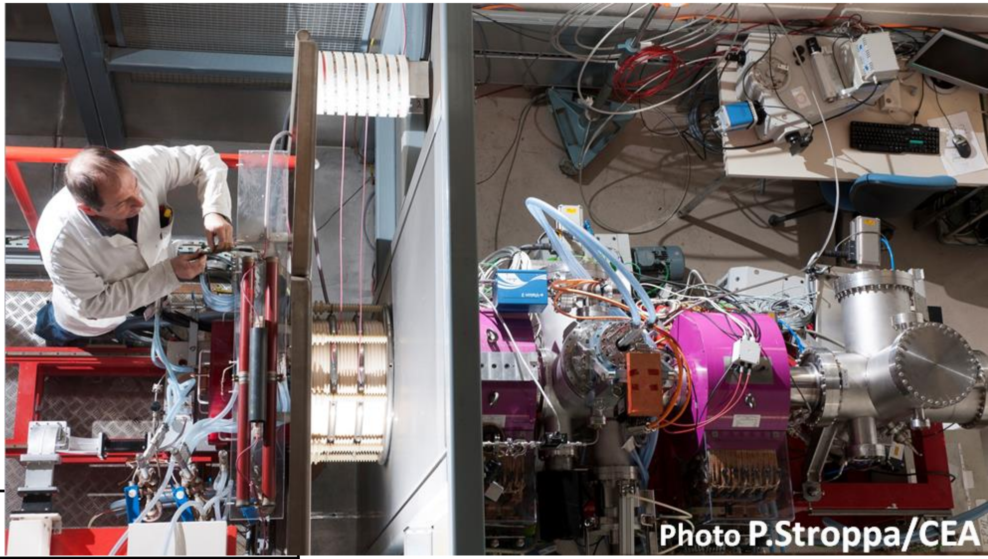
International project

Injector (CEA France)
RFQ (INFN Italy)
Cryomodule (CEA France)
Diagnostics (CEA France, Ciemat Spain)
MEBT + HEBT + Beam dump (Ciemat Spain)
RF power, (Ciemat Spain, CEA France, SCK Belgium)
Cryoplant (CEA France)



Request for IFMIF Injector

IFMIF is the machine
of all the challenges…
and the challenge starts at the Injector level.

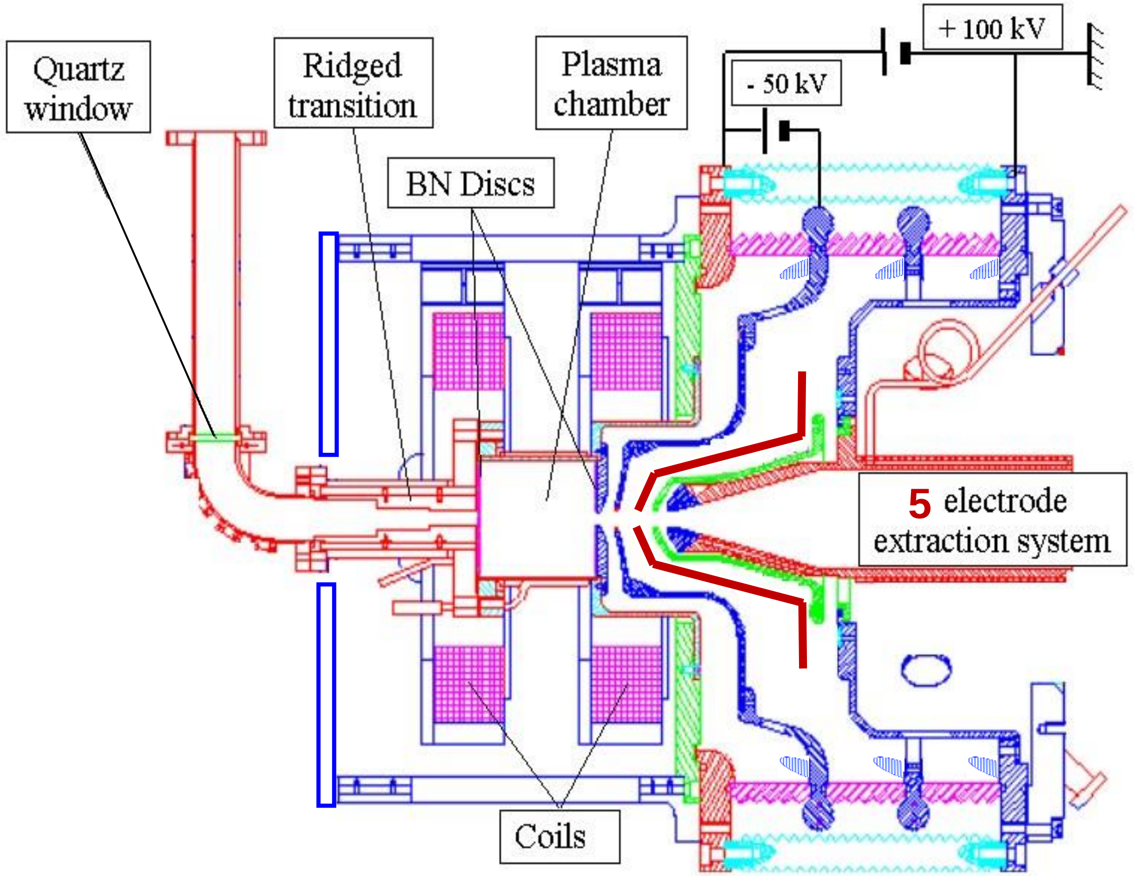


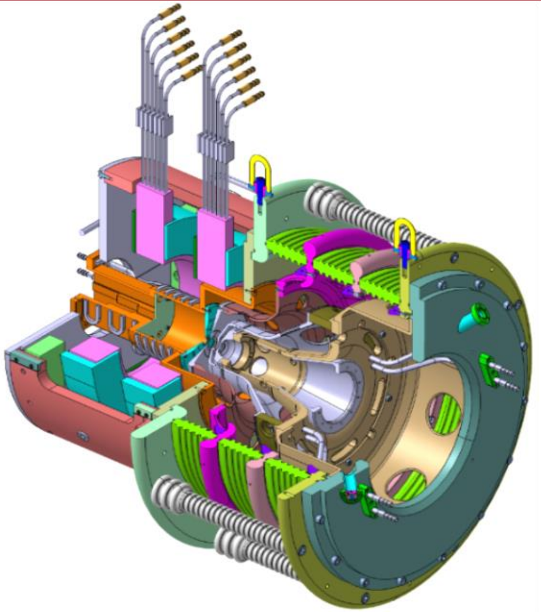
Requirements	Acceptance criteria	Comment
Particle type	**D^+**	H^+ for injector conditioning
Output energy **Energy stability**	**100 keV** **± 100 eV**	Fixed by the RFQ acceptance
Output D^+ current	**140 mA**	RFQ transmission ≥ 90%
Species fraction D^+	**≥ 95 %**	At the output of the LEBT
Beam current noise	**≤ 2 % rms**	At frequencies below ~1 MHz
rms norm. emittance	**≤ 0.30 π mm mrad**	At the output of the LEBT
Duty factor	**CW**	Possibility of pulsed operation.
Modulation capability	**1 ms – CW** **@ 1-20 Hz**	Typically
Beam turn off time	**< 20 µs**	From 100% to 10% beam intensity

IFMIF Injector has been designed, built and tested at CEA/Saclay before shipment to Rokkasho site in Japan

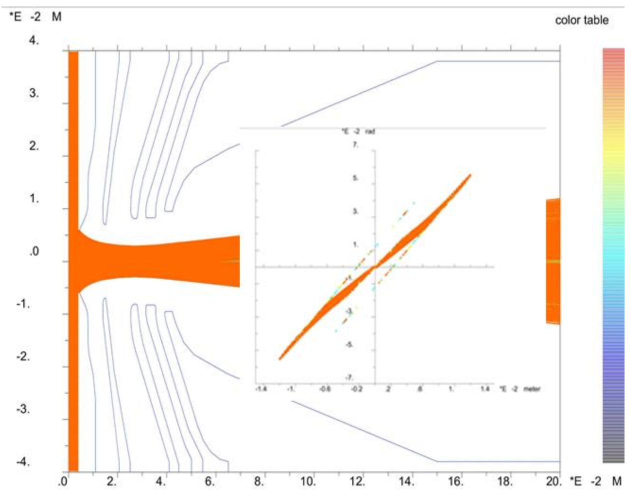
IFMIF Injector Design
Source

The source, operating at 2.45GHz is based on the SILHI concept
(2 coils, ridged waveguide transition, 5 electrode extraction system)



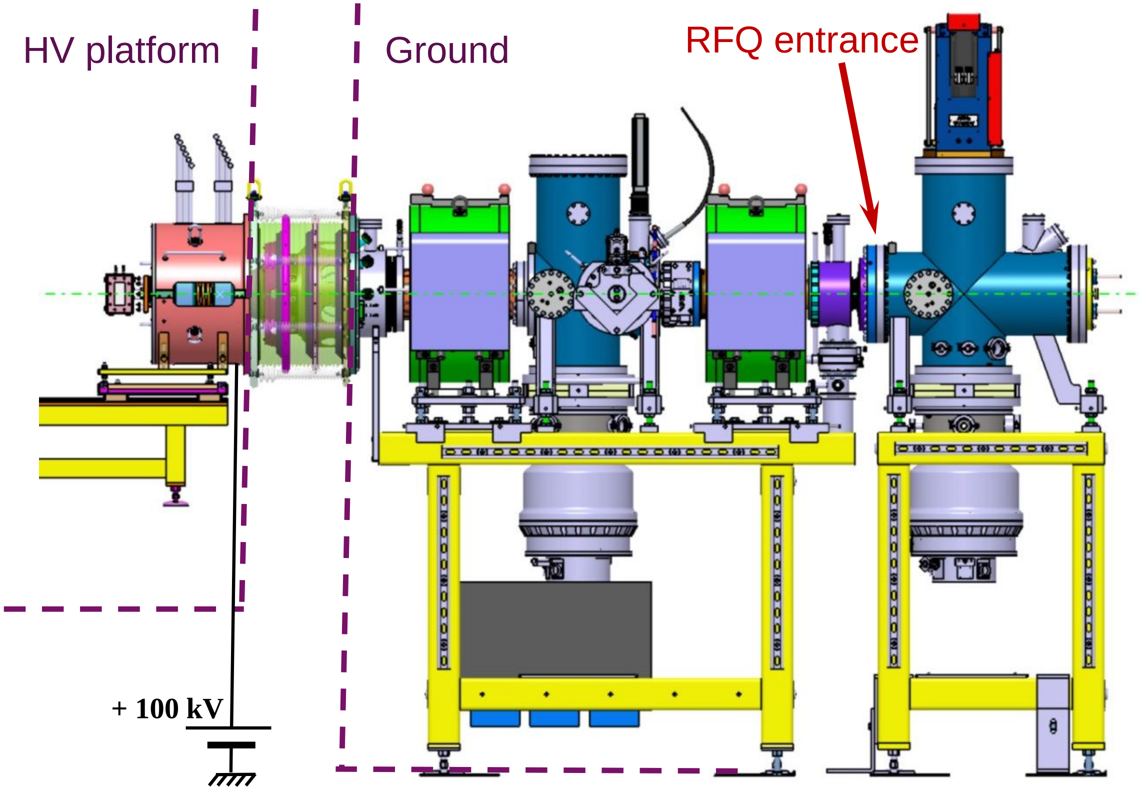


Beam extraction simulations done with Axcel© code

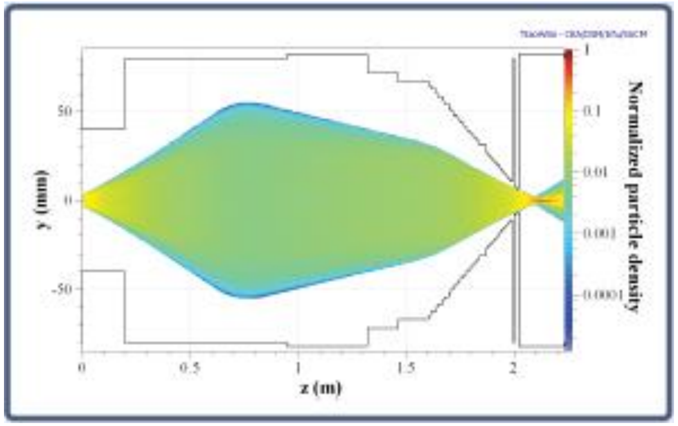


Magnetic and electrostatic simulations done with Opera from Vector Field©

IFMIF Injector Design
LEBT



Beam transport simulations done with SolMaxP and TraceWin codes



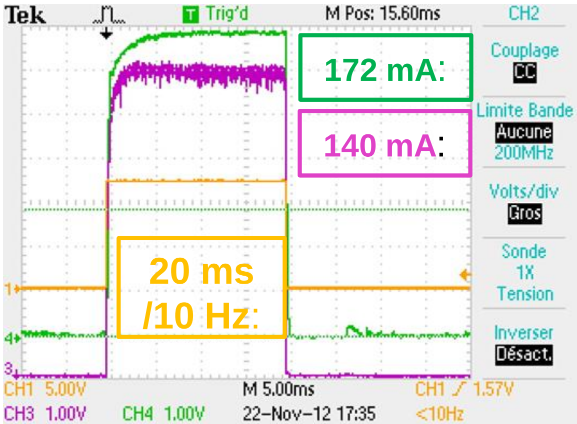
- 2 solenoids LEBT with integrated H/V steerers
- RFQ entrance cone **Φ = 12 mm**
- Short LEBT to minimize emittance growth (2.05 m)
- 2 Turbopumps
- Possible heavy gas injection
- Diagnostics despite limited space

Beam characterization = measurements of:

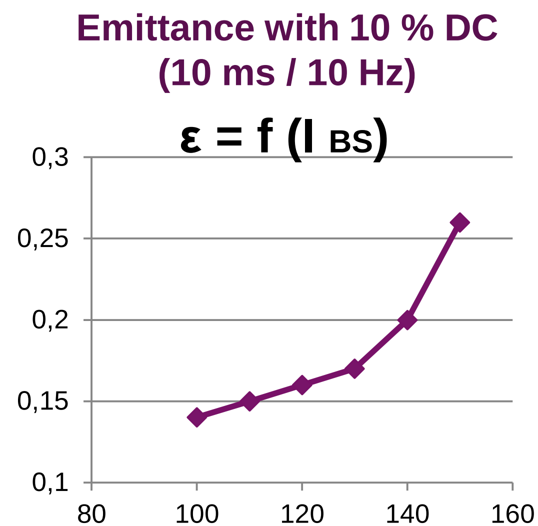
- **Extracted current (PS drain current)**
- **Beam stopper current**
- **ACCT**
- **Profile with CID cameras**
- **Emittance (2 or 3 locations)**
- **Species fractions (Doppler shift and Electric)**
- **Neutron and gamma production**

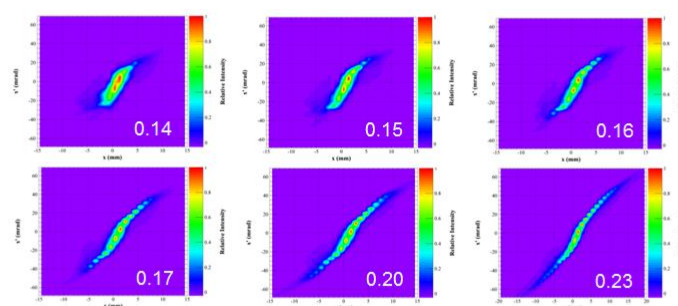
Beam Characterization at Saclay

In November 2012, Beam characterization mostly done in pulsed mode (10 Hz), after the cone, with DC = 10 , 30 and 50% ; then continuous mode



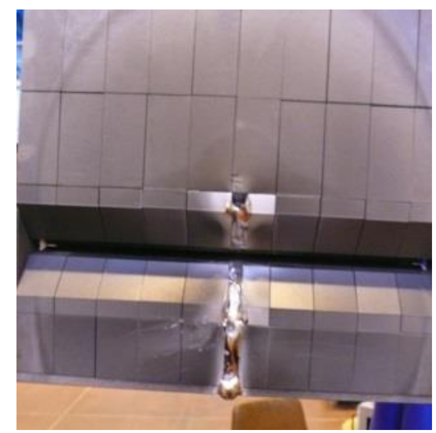
Orange: Source trigger
Green: Source PS delivered current (25 mA/V)
Magenta: Beam Stopper current (20 mA/V)





When increasing DC to 30% and 50%, 140 mA D+ beam emittance increased > 0,3 π mm mrad and spark rate increased

In CW mode, when the beam is focused too much:



An unprecedented D^+ beam of 140 mA at 100 kV has been extracted and transported (with I_{tot} = 175 mA and V_{puller} = - 42 kV)

Transfer to Japan

The IFMIF LIPAc injector has been disassembled and packed at Saclay,

shipped to Hacchinoe port

delivered on the Rokkasho site

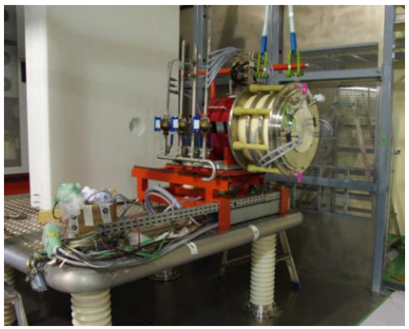
Installation on site:

- Mechanical re-assembly
- Cabling and wiring
- Check-out
- Conditionning (Vacuum, Water cooling, HV)

And start of commissioning





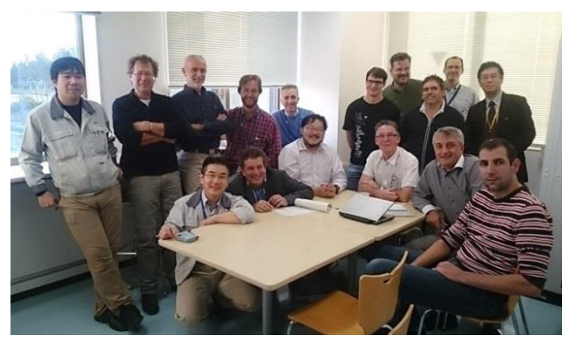
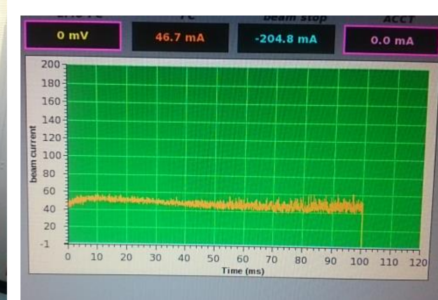





2014/04/01

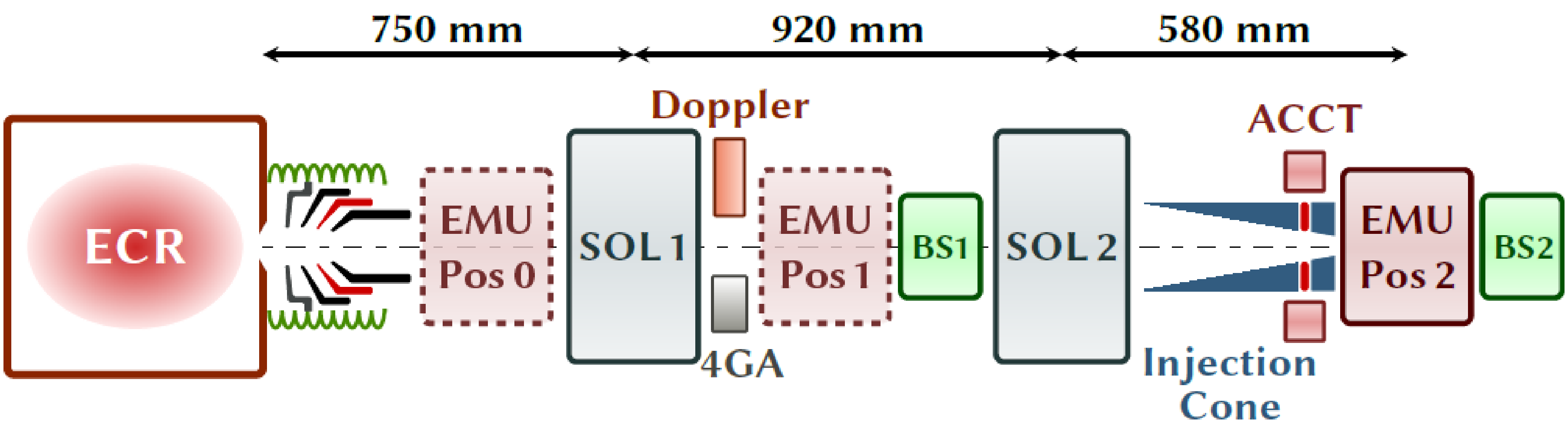




2014/11/17


0 mV
46.7 mA
-204.8 mA
0.0 mA
beam current
Time (ms)
200
180
160
140
120
100
80
60
40
20
-1
0
10
20
30
40
50
60
70
80
90
100
110
120

Conditioning and Commissioning

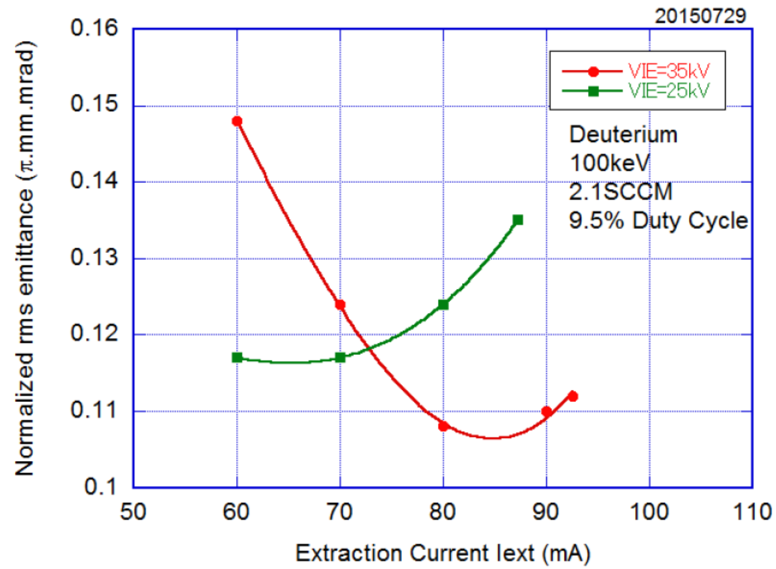
- Mechanical re-installation, cabling, check-out took several months
- Conditioning (pumping, High Voltage, diagnostic tests, 1st plasma and 1st beam) has been performed with hydrogen beams
- Commissioning is done with beam characterization in 2 or 3 phases (1- between both solenoids, 2- after RFQ entrance cone, 3- source exit*) with H+ 50 keV beam and D+ 100 keV beam

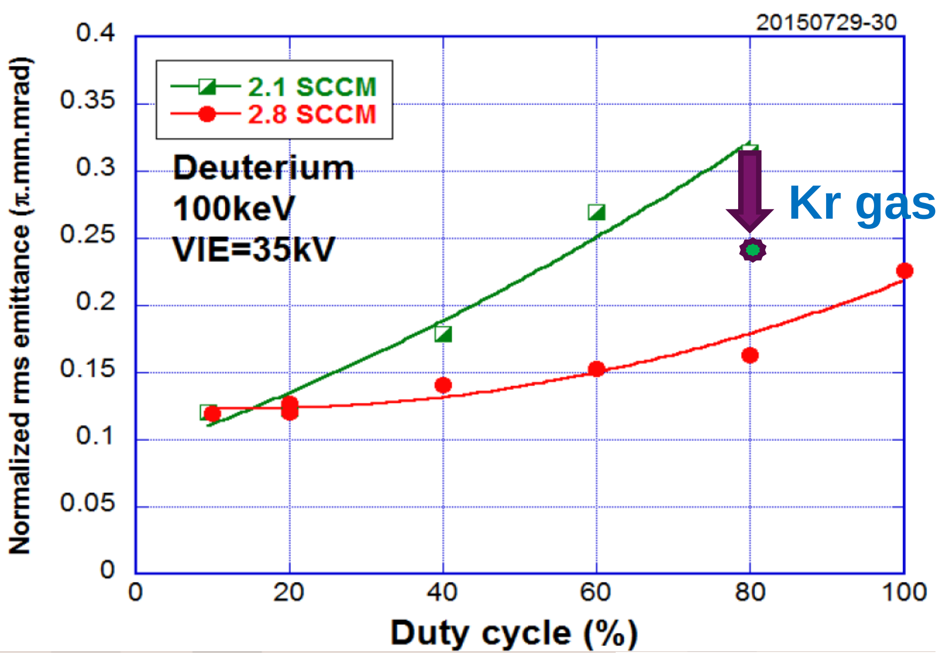


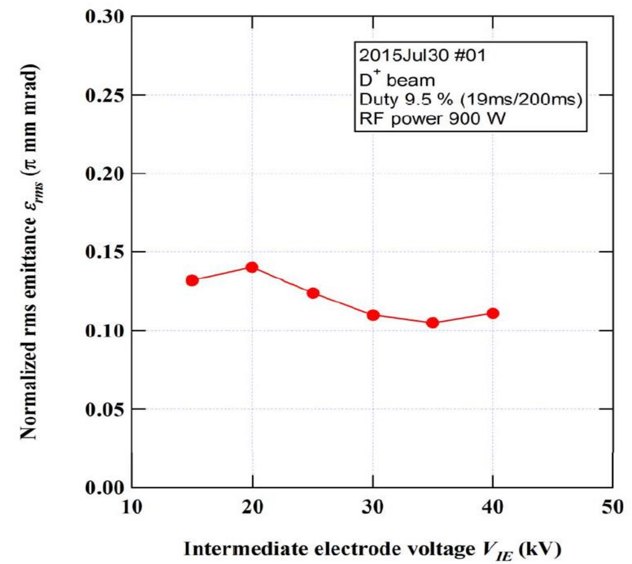
* Decision concerning Phase 3, in the near future

Emittance at 100keV D+ (PE = Φ 10mm)

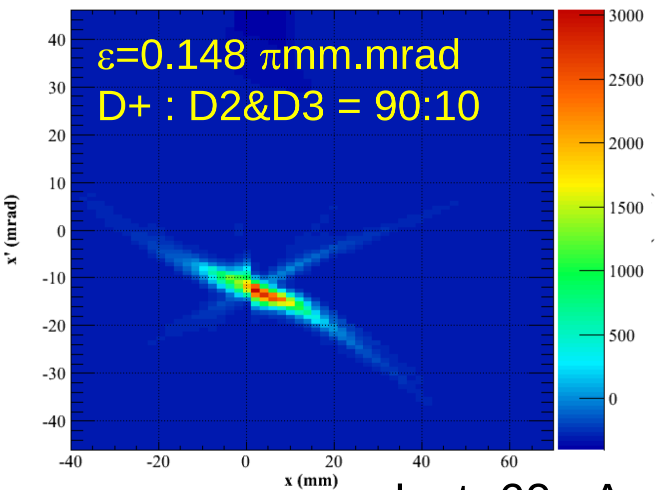
- There is an optimum extraction current and an optimum intermediate electrode voltage to minimize the emittance.
- It was observed that the emittance increases with the duty cycle.
- It was also observed that the emittance growth is improved by increasing the gas flow rate or by injecting Kr gas into LEBT vacuum.



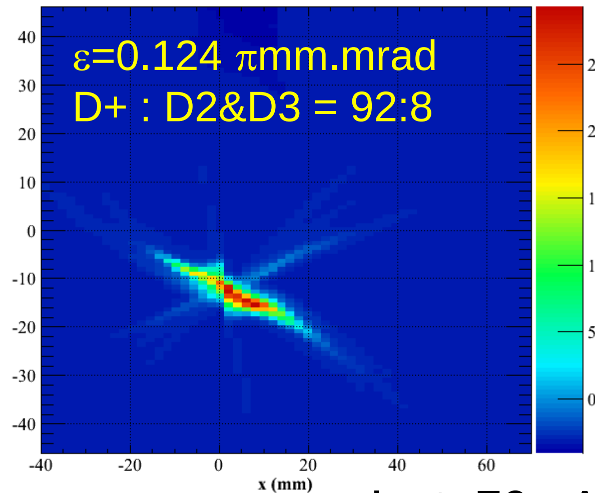




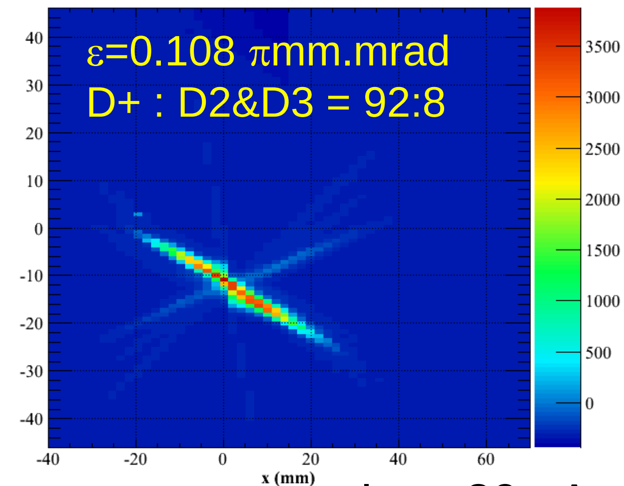
Emittance at 100keV D+ (PE = Φ 10mm)



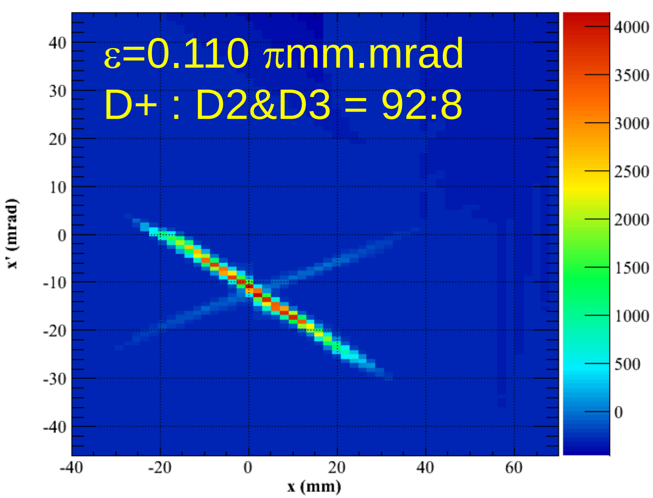
Iext=60mA



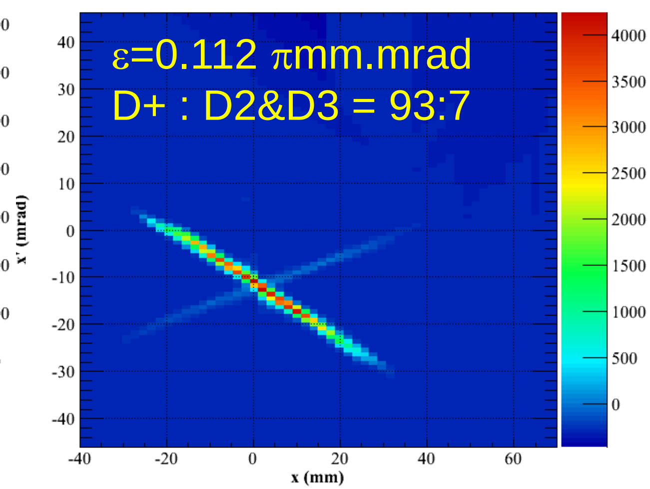
Iext=70mA



Iext=80mA



Iext=90mA



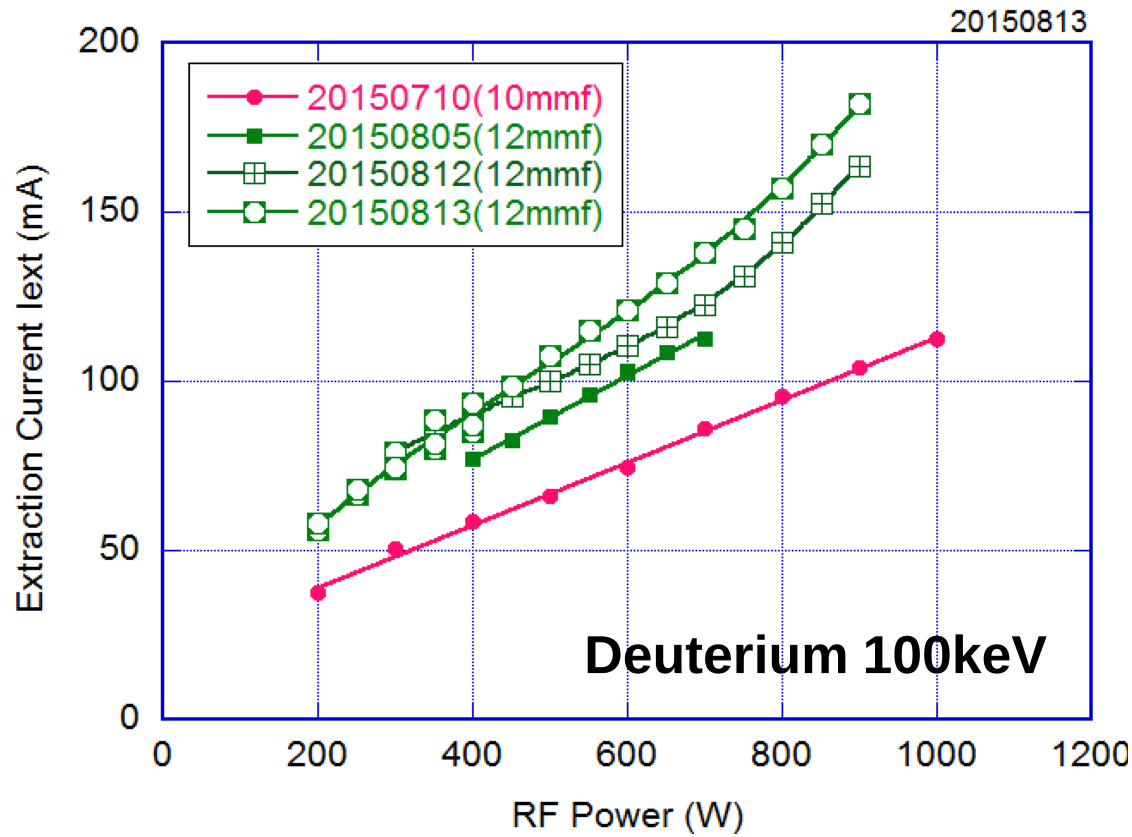
Iext=93mA

Deuterium
100keV
V_{IE}=35kV
2.1 SCCM
10% duty cycle

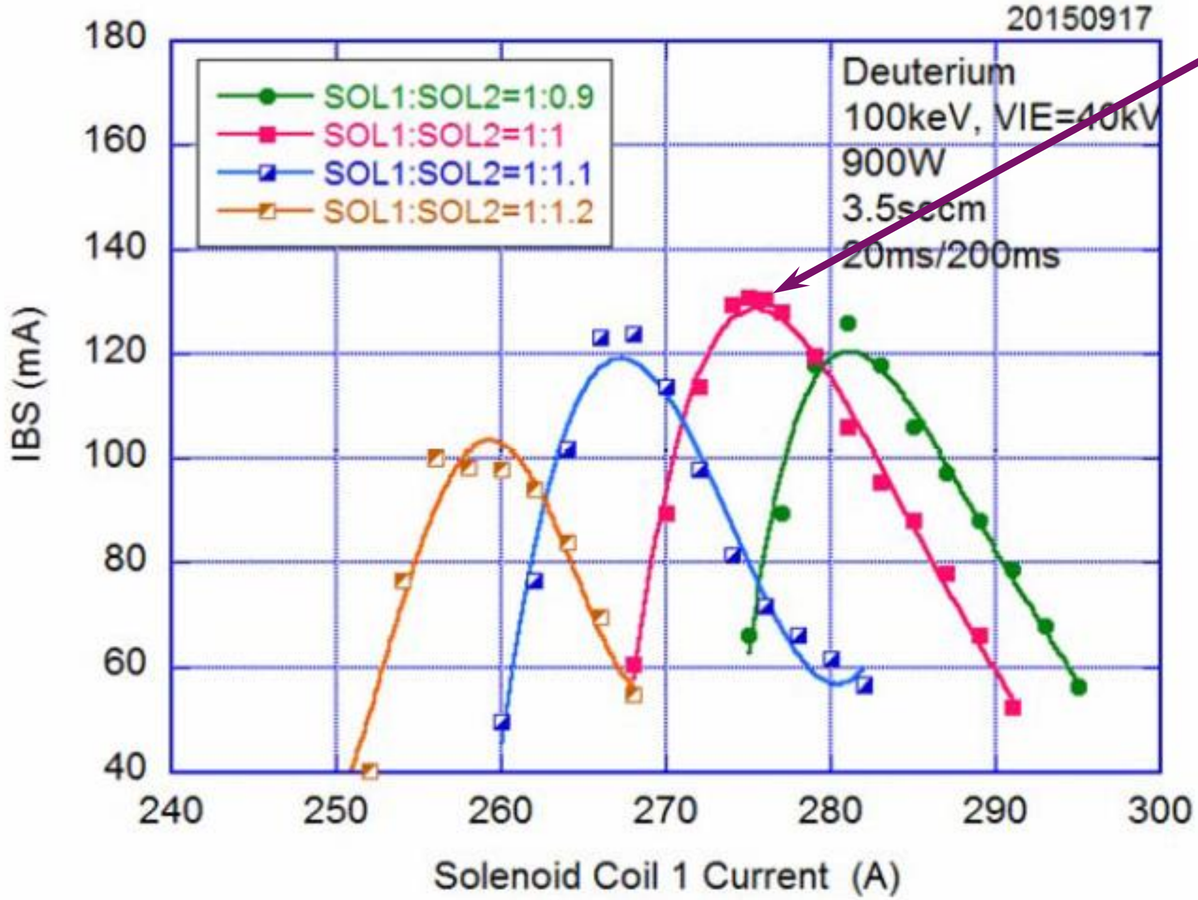
Deuteron Intensity vs RF power

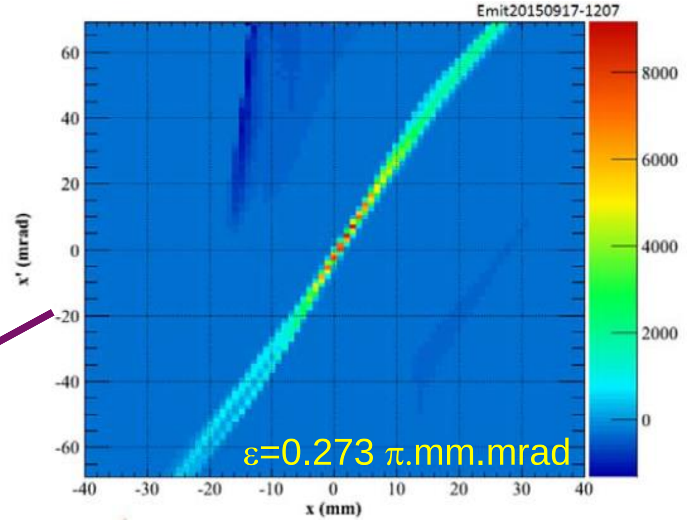
With Φ10 mm plasma electrode and for 2 duty cycles (40 and 91 %)

With Φ10 and 12 mm plasma electrode duty cycle = 9,5 %

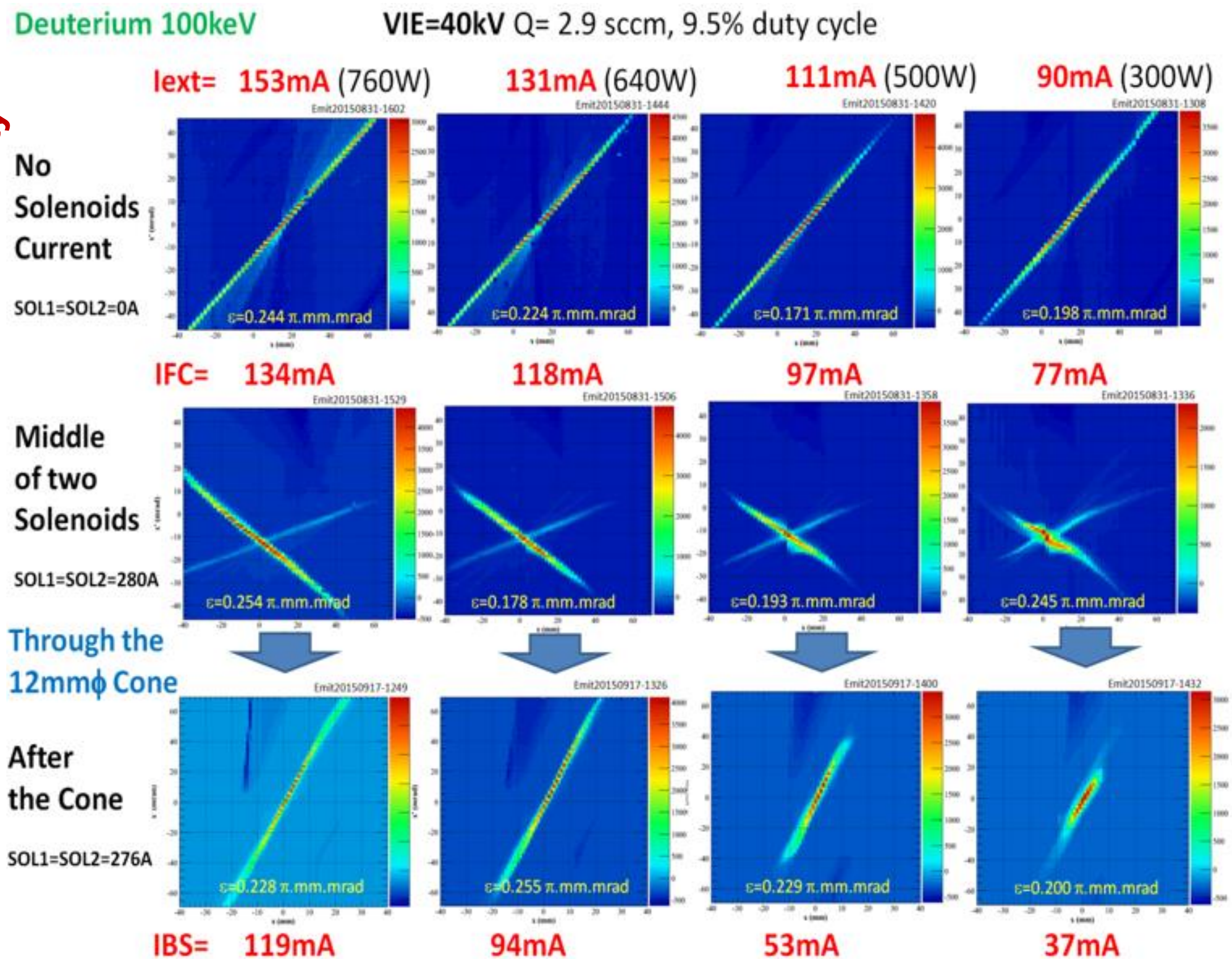


LEBT transmission (PE = Φ 12mm)





Emittance comparison (PE = Φ 12mm)

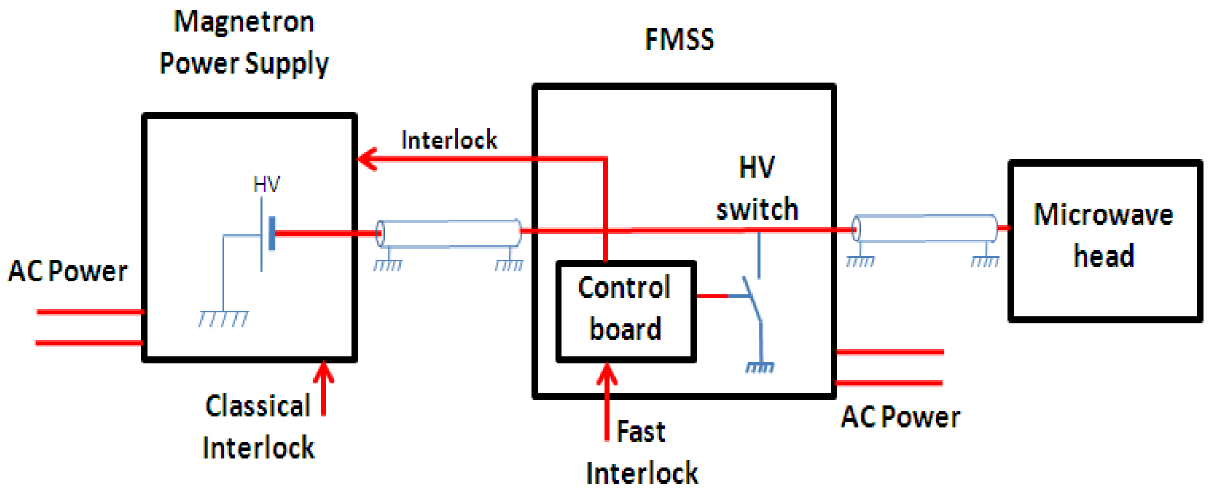


> 85% cone transmission with high intensity

No molecular ions are detected after the cone

Fast Beam Shutdown

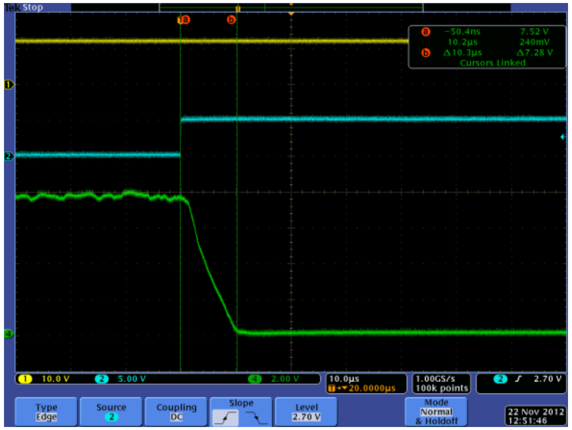
For safety reasons (very high power beam at high energy), the beam has to be switched off within few μs (target < 20 μs)



Sairem© (magnetron provider) developed and provided a fast magnetron shutdown system based on HV switch and control board

All the RF chain is on HV platform

Tests have been done in continuous mode

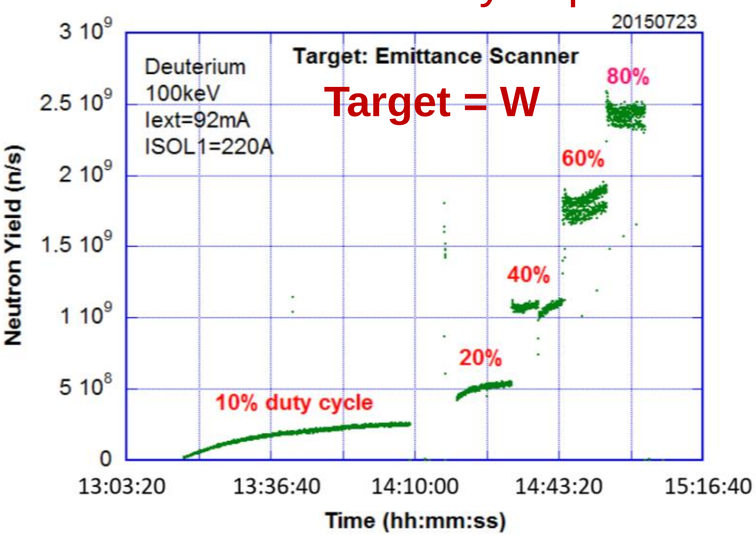


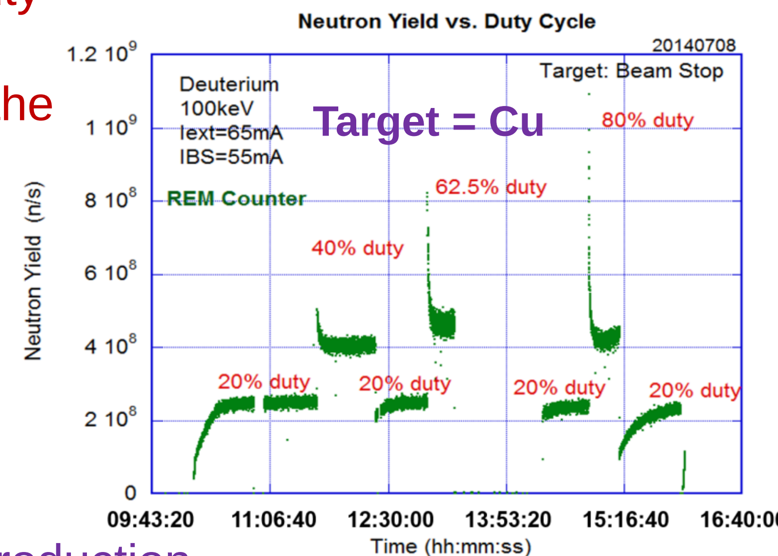
Blue: Fast Interlock at ground level
Green: Beam Stopper current

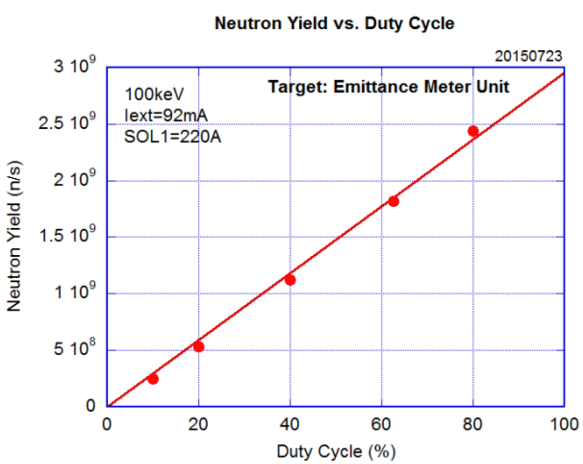
Beam turns off in 10 μs

Neutron Production

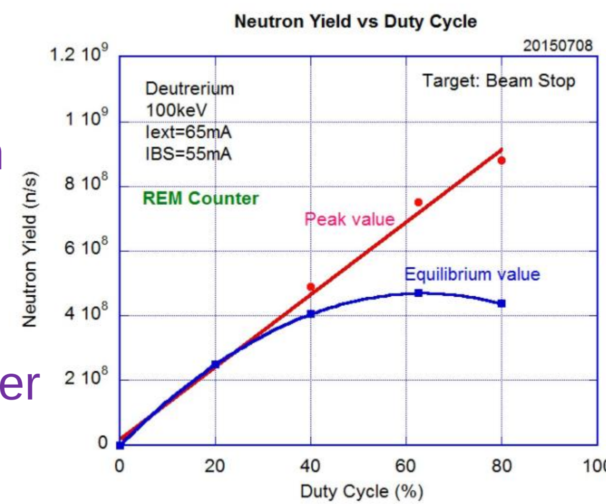
1) Neutron production is a linear function of the duty cycle.
2) Neutron production is also a strong function of the deuterium density implanted near the surface







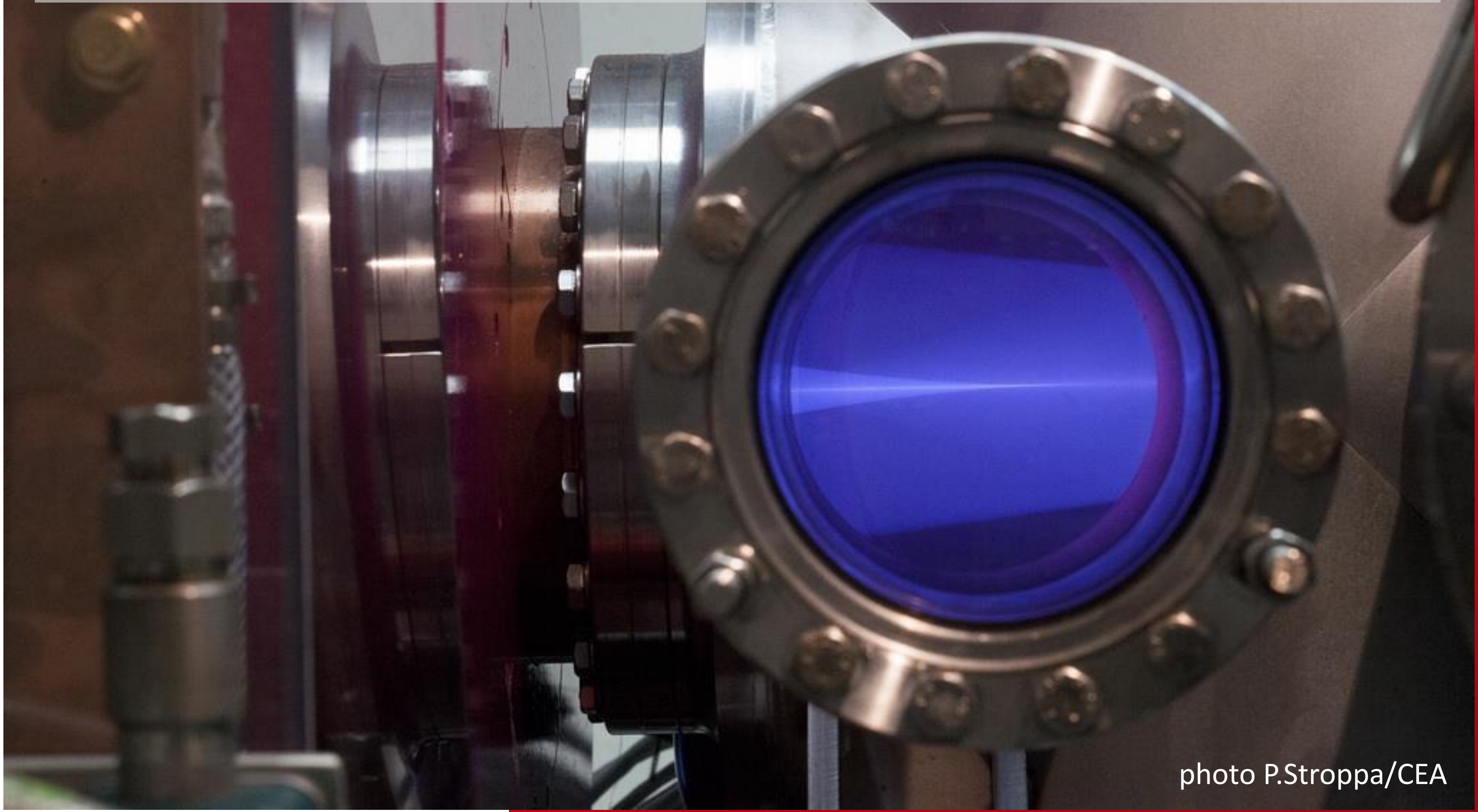
3） Neutron production is saturating at higher duty cycle and higher beam current. This is because the deuteron density is decreasing with increasing the temperature at the surface at higher power density.



Conclusion

- Measurements performed with the IFMIF injector H^+ and D^+ beams proved that the expected challenges start immediately at the source exit and in the low energy beam line.
- Beam power density has to be carefully controlled when using interceptive diagnostics. Non interceptive diagnostics are key elements for such high intensity beams.
- Neutron production depends on the target material and temperature
- Beam characterization (PE = 12 mm) at 10% DC demonstrated the capability to inject 100 keV - 130 mA D+ beam into the RFQ with 0.27 pi.mm.mrad (rms, norm). emittance value.
- 150 mA – 100 keV D+ beam reached beam dump last week
- The goal of the beam commissioning is the characterization of a cw 100 keV - 140 mA D+ beam at the RFQ entrance.

Merci de votre attention



Vue du faisceau à Saclay

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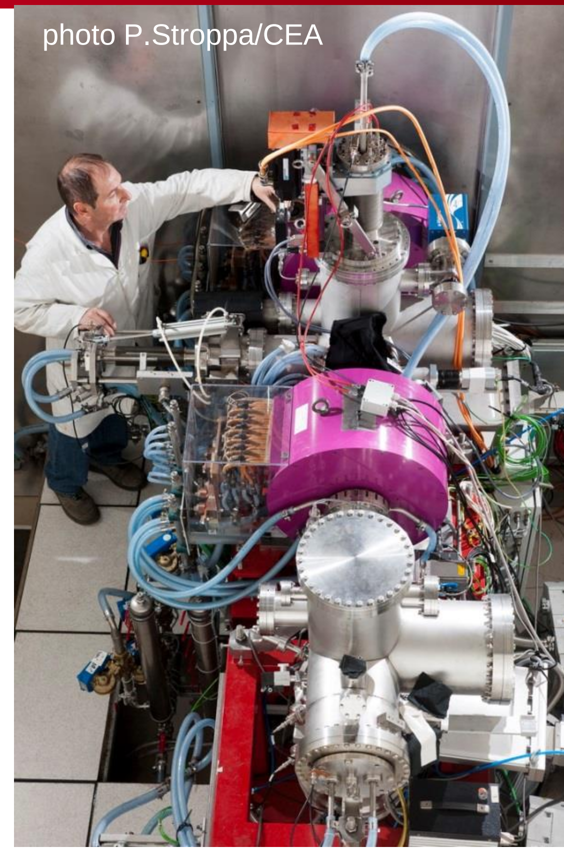
Direction Sciences de la Matière
Institut de Recherche sur les lois Fondamentales de l'Univers
Service Accélérateur, Magnétisme et Cryogénie

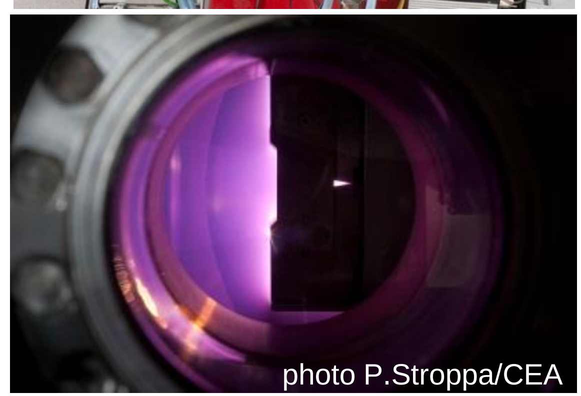
LEBT Diagnostics

- **Thermocouples**
- **EMU – Allison scanner designed for 15 kW continuous beam**
- **Residual Gas Analyzer**
- **4 Grid Analyzer**
- **CID (hardened) cameras**
- **Spectrometer associated with optic fiber for Doppler shift analysis**
- **Faraday cup + Beam Stopper**
- **A large ACCT installed at the RFQ entrance with specific magnetic shielding**

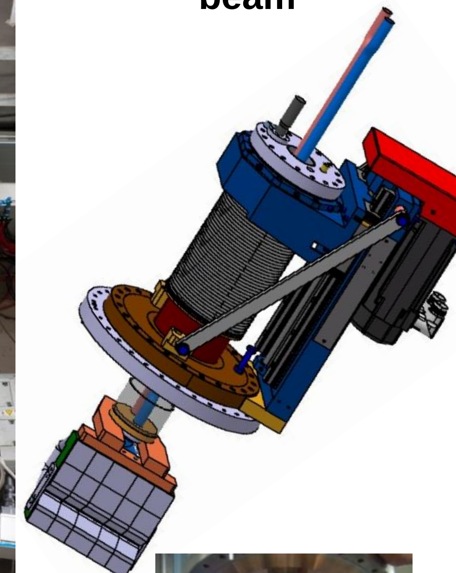
ACCT Bergoz ©

Beam Dump



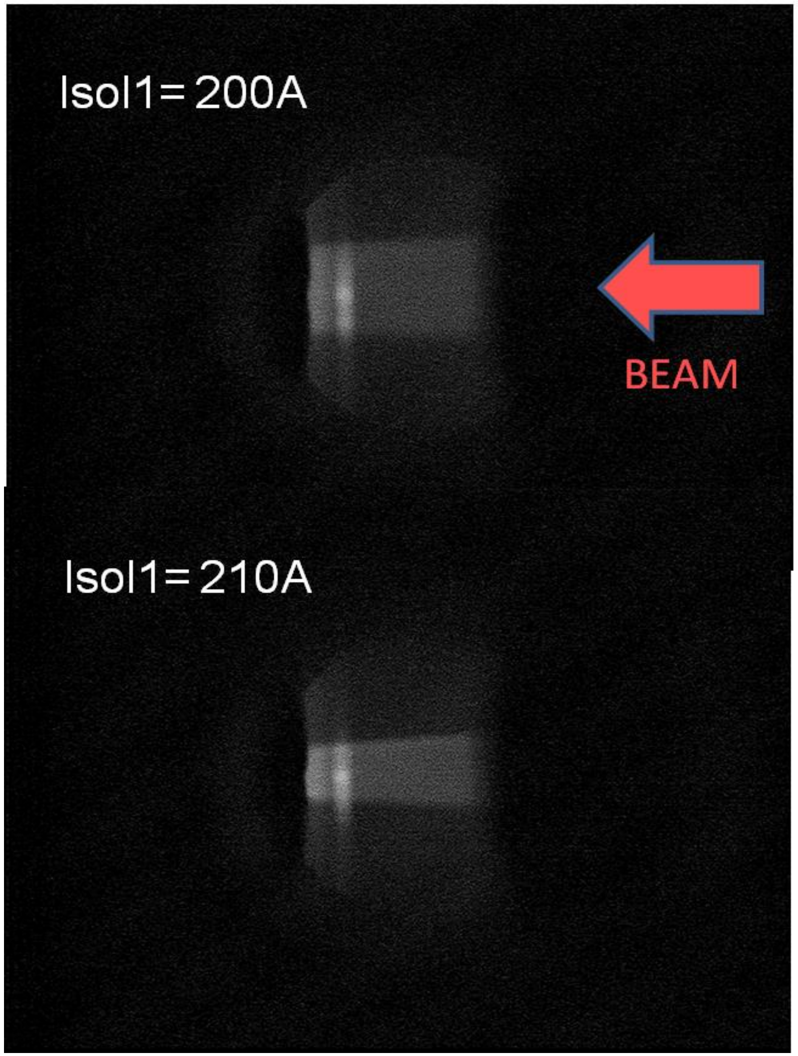


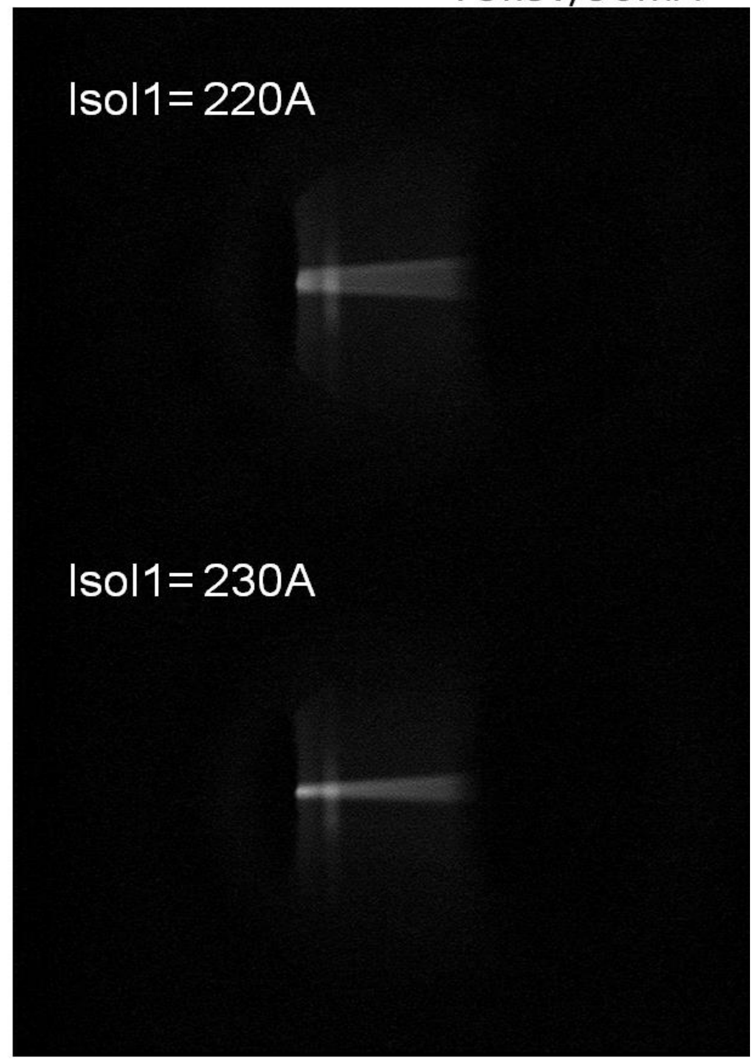
Dedicated EMU designed to bear 15 kW continuous beam



Focusing by Solenoid Coils

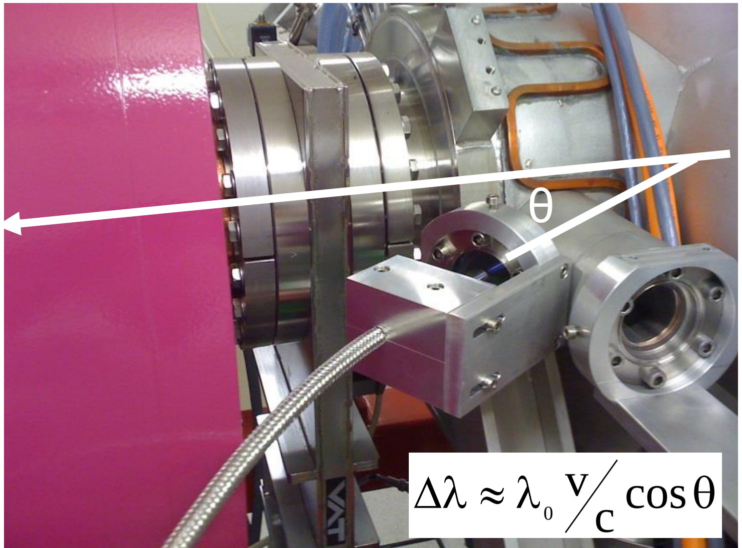
75keV/90mA

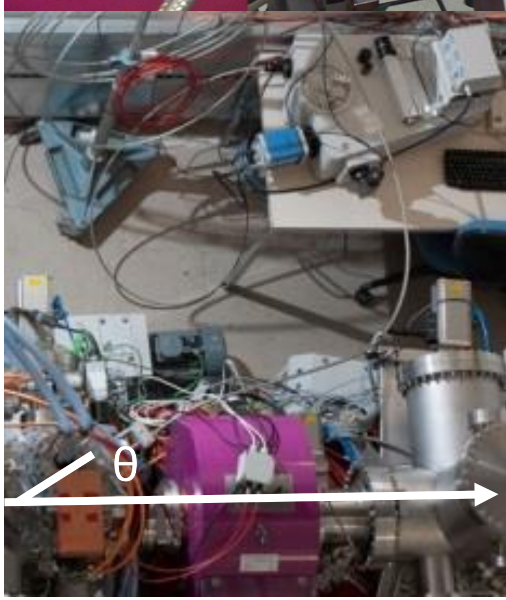




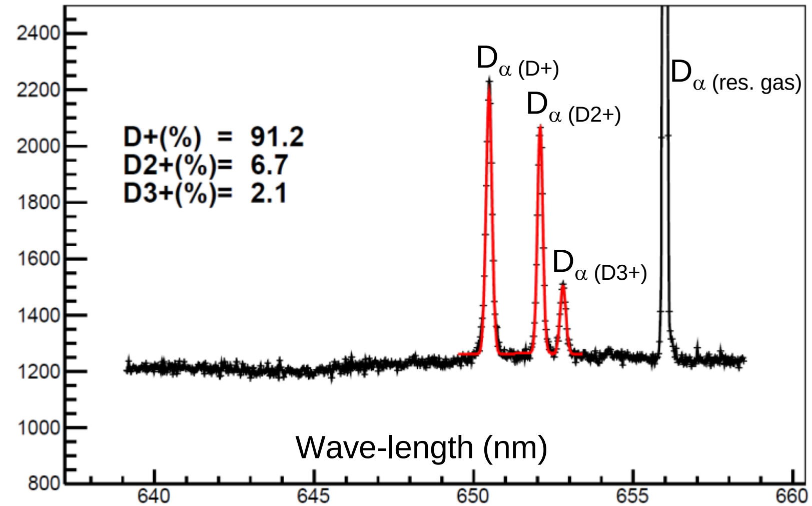
Species fraction measurements Doppler shift analysis

Spectrometer with optical fiber





Species fractions obtained with Doppler shift method for pulsed beam at 50% duty cycle



With primary reactions :
$D^+ + D_2 \rightarrow D^* + D_2^+$
$D_2^+ + D_2 \rightarrow D + D^* + D_2^+$
$D_3^+ + D_2 \rightarrow 2D + D^* + D_2^+$

Taking into account the cross-sections, species fractions are given by:

$$\sigma_{D^+(100keV)} = 1{,}2\times10^{-18}\ cm^2$$
$$\sigma_{D_2^+(100keV)} = 14\times10^{-18}\ cm^2$$
$$\sigma_{D_3^+(100keV)} = 18{,}8\times10^{-18}\ cm^2$$

$$D^+ \, fraction = \frac{n_{D^+}}{n_{D^+} + n_{D_2^+} + n_{D_3^+}}$$

$$n_{D^+} \# \frac{I_{line}(D^+)}{\sigma_{D^+}}$$

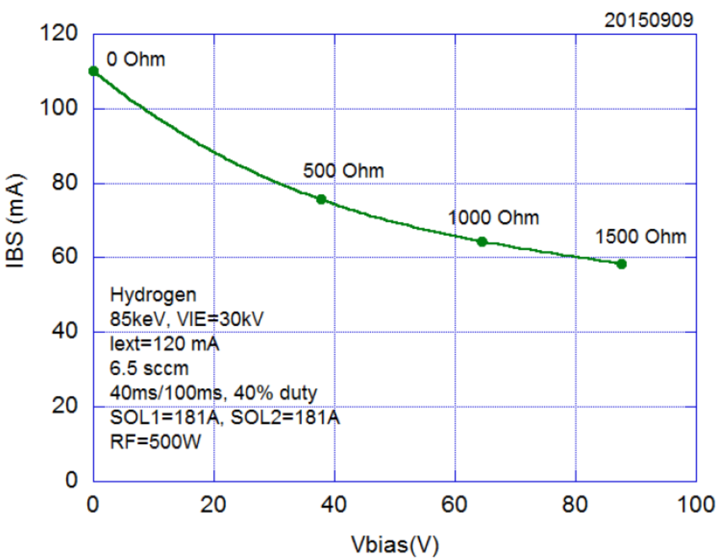
But other primary reactions exist: **$D_n^+ + D_2 \rightarrow D^+ + \ldots$**

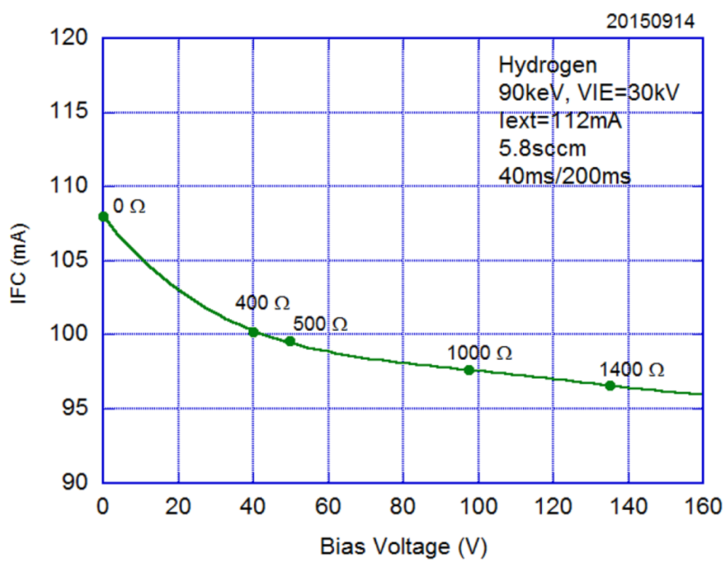
So, 2nd and 3rd shifted peaks are the sum of several reactions

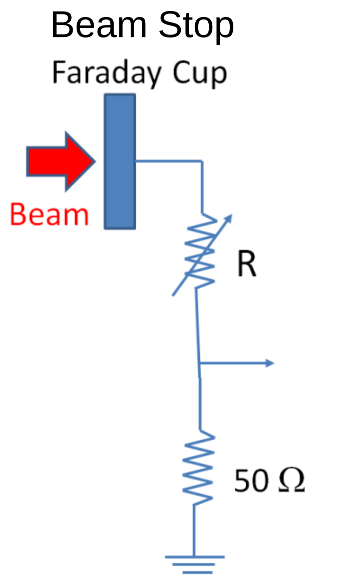
→ Few % errors to be checked in more details

Self biasing of the Faraday Cup and the Beam Stop to suppress the secondary electrons.

- The FC and BS are self-biased by inserting resisters between the beam stop and the earth.
- The Faraday Cup current and the Beam Stop current decreases with the bias voltage. It seems that 100V would be necessary to suppress the secondary electrons.

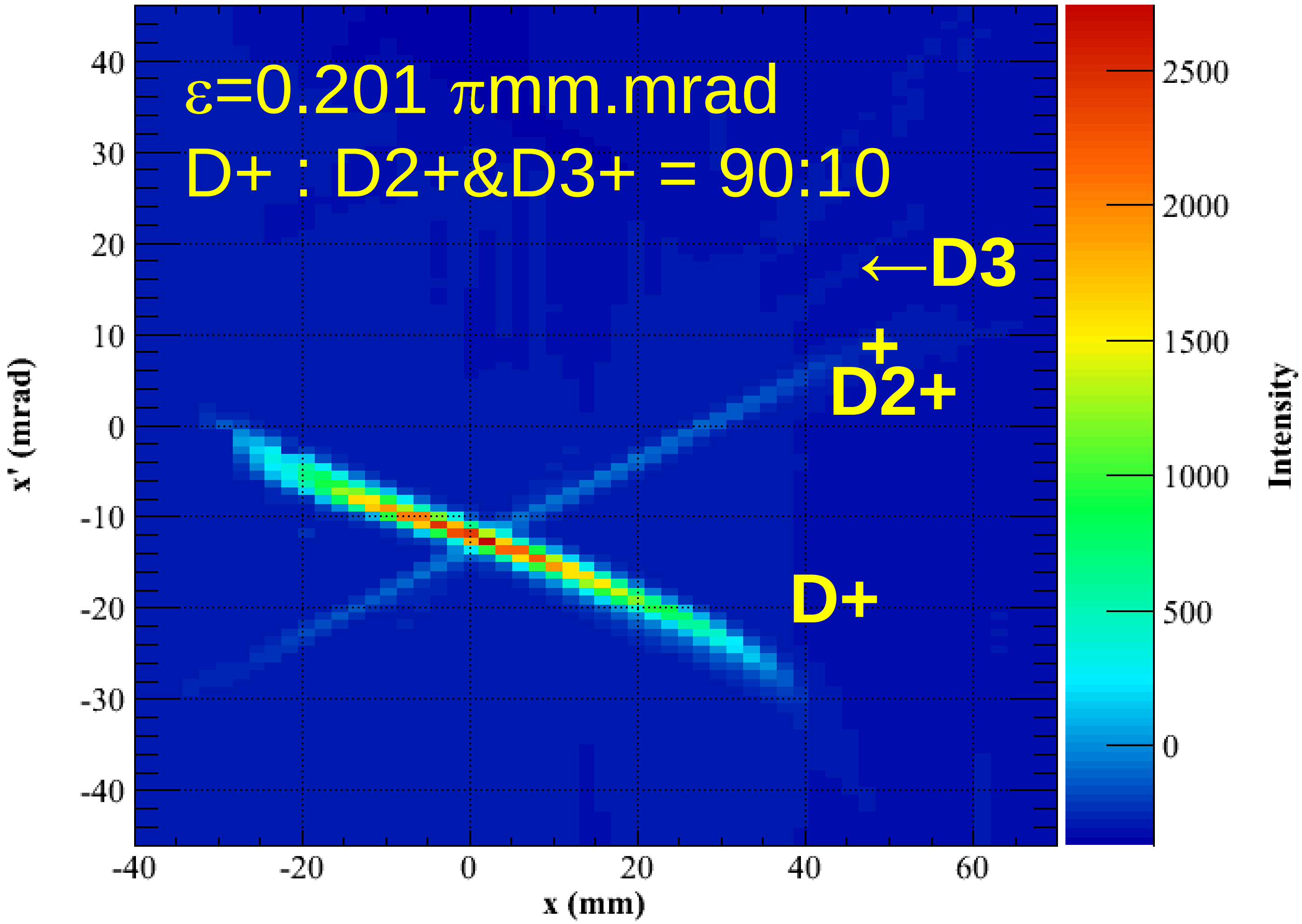






An Emittance Diagram

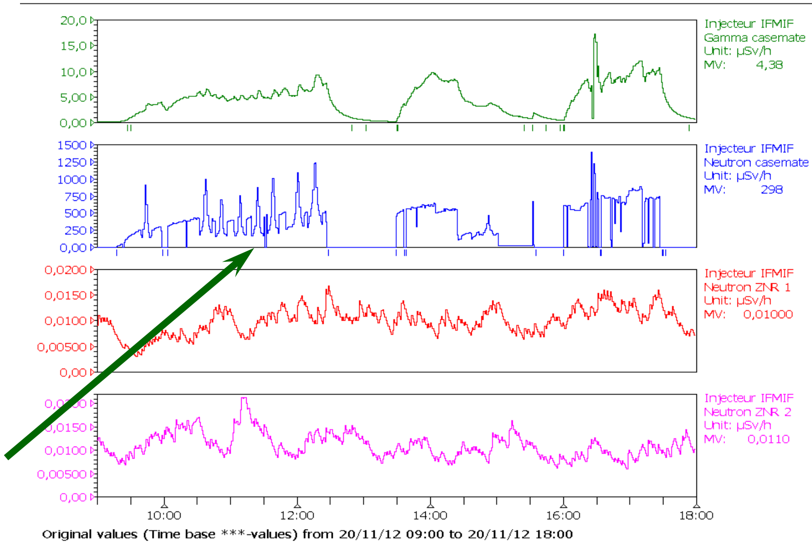
Emit20150803-1153



Deuterium, 100keV, Iext=76mA, 10% duty cycle

Neutron and gamma production

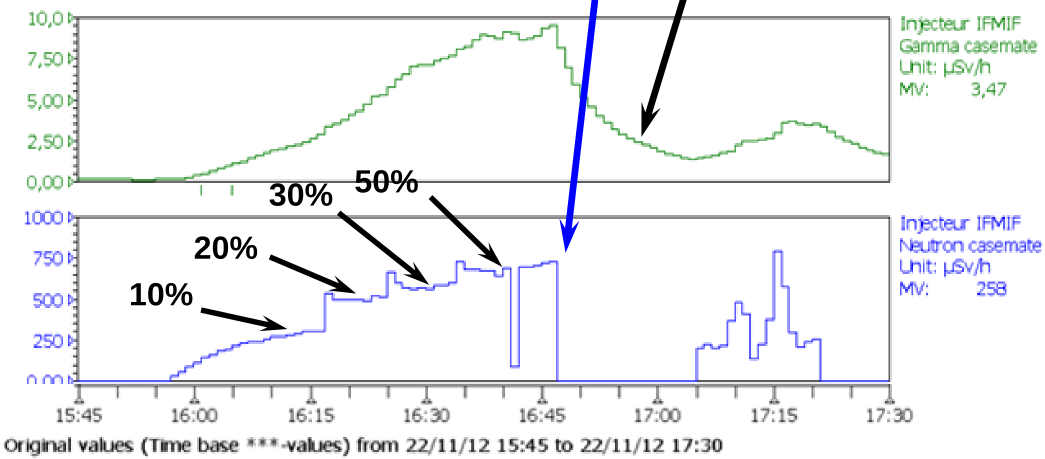
(D,d) reaction lead to neutron production
Saclay site radioprotection system:
1 neutron probe and 1 gamma probe
inside the vault
at respectively (2.2 m and 2.8 m from BS)
and 2 neutron probes outside the vault



Nov. 20th data record, mostly with 10% DC

Several comments:

- **Neutron prod. largely higher than Gamma prod. (x 100)**
- **Picks of Neutron and Gamma when EMU intercepts the beam**
- **Neutron prod. goes fast to zero after beam off**
- **Gamma prod. takes few 10 min to go to zero after beam off**



Data record with Duty Cycle varying from 10 to 50%

Important to note:
Neutron and gamma productions do not proportionally increase with the DC (probably due to outgassing vs target temperature increase)

A neutron probe located at 50 cm from BS indicated neutron prod. value X 20