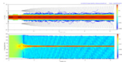
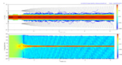
IFMIF-EVEDA RFQ, Measurement of Beam Input Conditions and Preparation to Beam Commissioning

M. Comunian



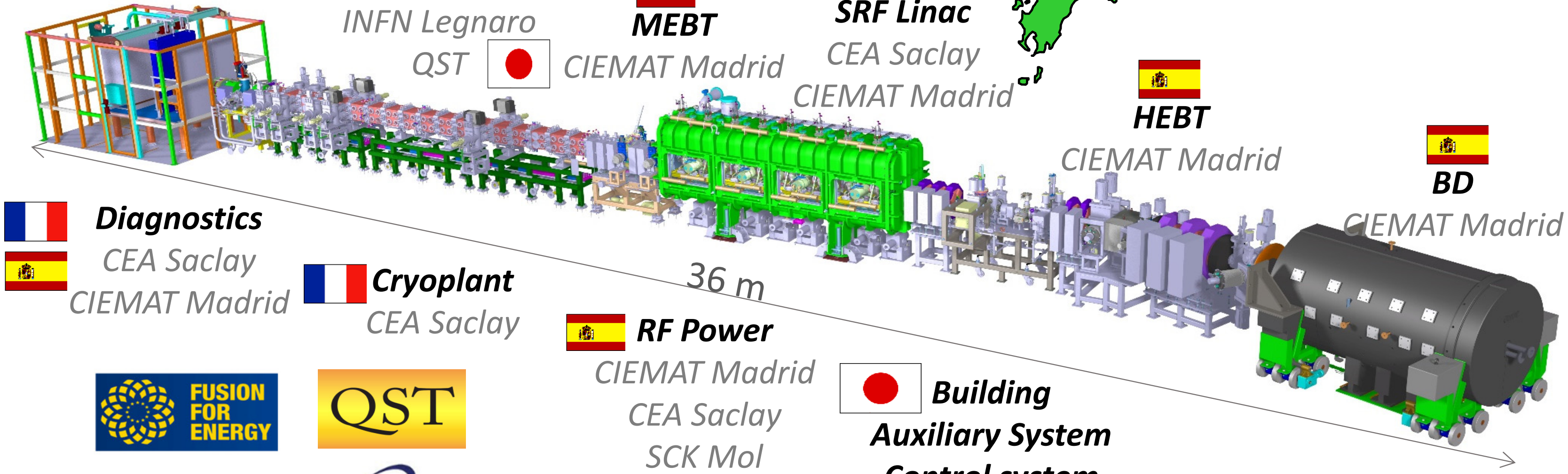
Outline

- IFMIF-EVEDA project
- The RFQ
- The source
- LEBT Layout
- Beam simulation of the Source and LEBT
- Beam measurement on the Source and LEBT
- Beam simulation in the RFQ
- Which lesson have we learned ?
- Conclusion



IFMIF EVEDA PROJECT

Equipment 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

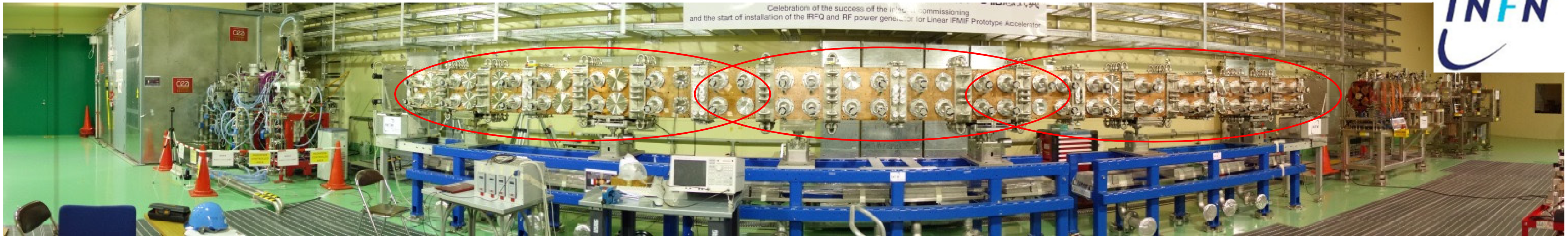
Cryoplant
CEA Saclay

RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

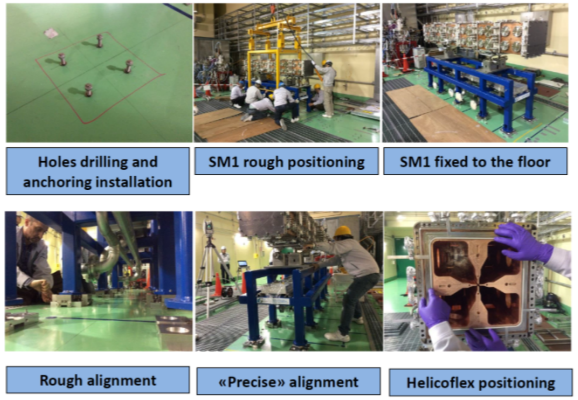
Building
Auxiliary System
Control system
Installation
QST

J. Knaster et al., *CHALLENGES OF LIPAc THE HIGH CURRENT PROTOTYPE ACCELERATOR OF IFMIF/EVEDA*, **IPAC 2016**, **Busan**

RFQ Installation at Rokkasho April 2016



SM1 off-site installation and alignment


Holes drilling and anchoring installation

SM1 rough positioning

SM1 fixed to the floor

Rough alignment

«Precise» alignment

Helicoflex positioning

SM2 installation, alignment and coupling with SM1


SM2 fixed to the floor

Rough alignment

Precise alignment

Spacers installation

SMs connection

SM3 installation, alignment and coupling to SM1+2


Helicoflex positioning

SM3 rough positioning

SM3 rough alignment

Precise alignment

SM3 connection

Curtesy of E. Fagotti, not yet published.

- ECR H^+/D^+ source + LEBT developed by CEA Saclay

D^+ (95% species fraction)

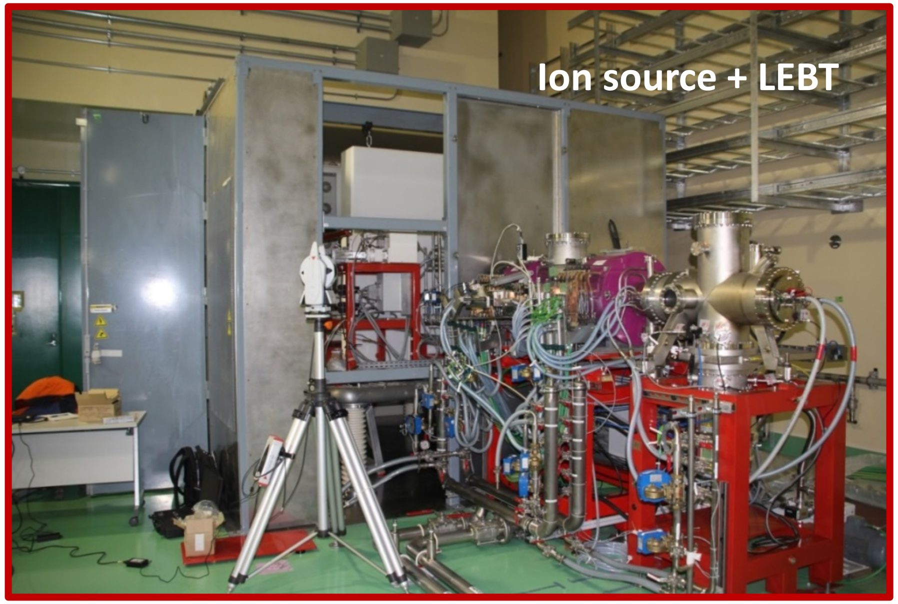
Ion Source ECR (2.45 GHz) - **CW**

E = 100 keV

I = 140 mA

emittance of 0.25 π mm·mrad

Availability > 95%



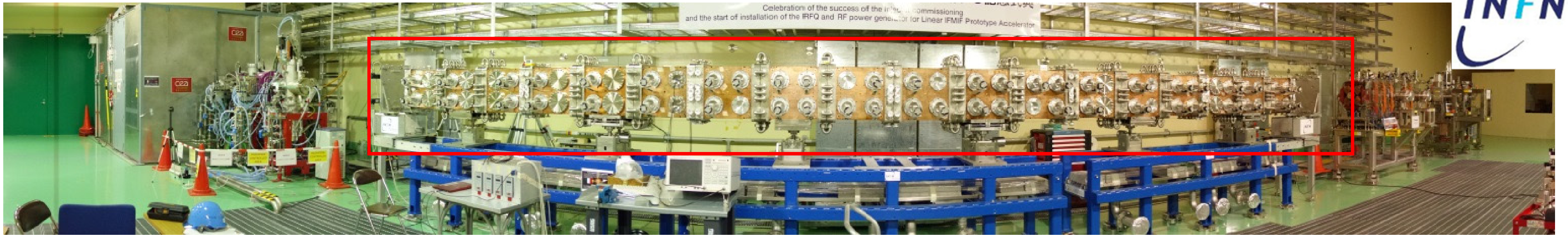
R. Gobin et al., *IFMIF injector acceptance tests at CEA/Saclay: 140 mA/100 keV deuteron beam characterization*, **Rev. Sci. Instr. 85, 02A918 (2014)**

N. Chauvin et al., *Challenges in IFMIF* **HB2016, Malmo**

Design based on SILHI, the High Intensity Light Ion Source of 100 mA 95 keV that is operating in Saclay since 1996

P.Y. Beauvais et al, *First beam of the CEA-Saclay CW high Intensity microwave source*, **PAC 1997, Vancouver**

• RFQ developed by INFN Legnaro



4-vanes RFQ at 175 MHz

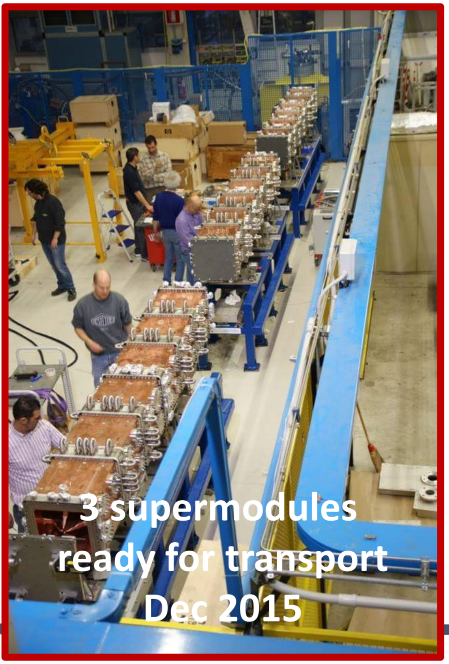
E_{output} = 5 MeV

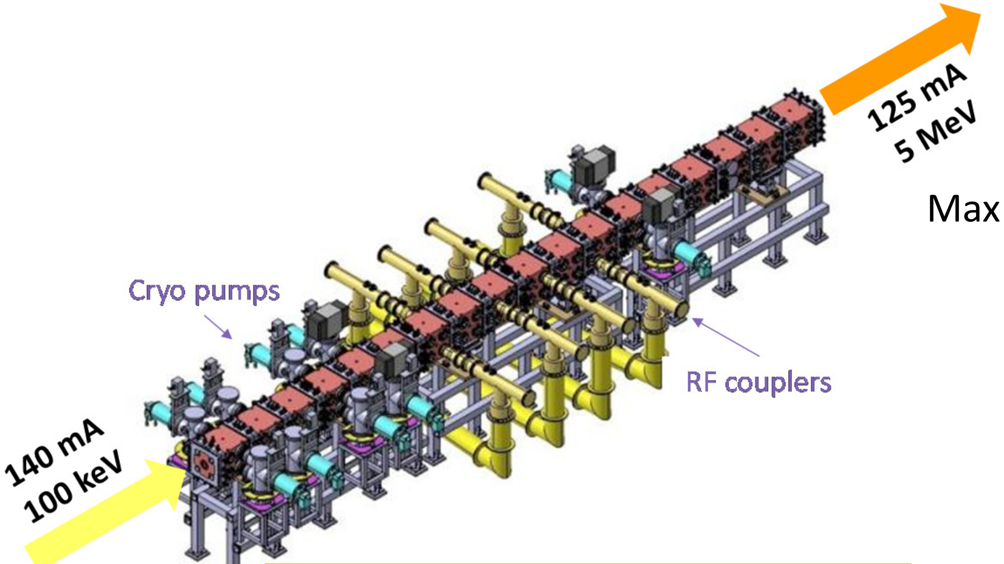
I_{output} = 125 mA in CW

9.7 m long (5.7λ)

Max surface field 25.2 MV/m (1.8 Kp)

A. Pisent et al., *IFMIF/EVEDA RFQ design*, **EPAC 2008**, **Genova**





M. Comunian et al., *Beam dynamics redesign of IFMIF/EVEDA RFQ for a larger input beam acceptance*, **IPAC 2011**, **San Sebastian**

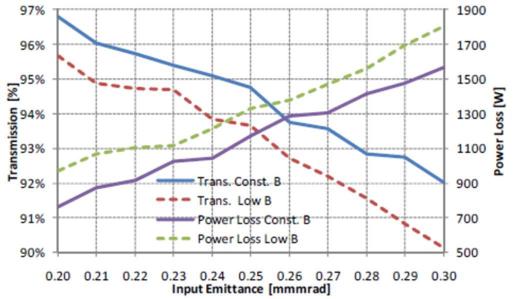


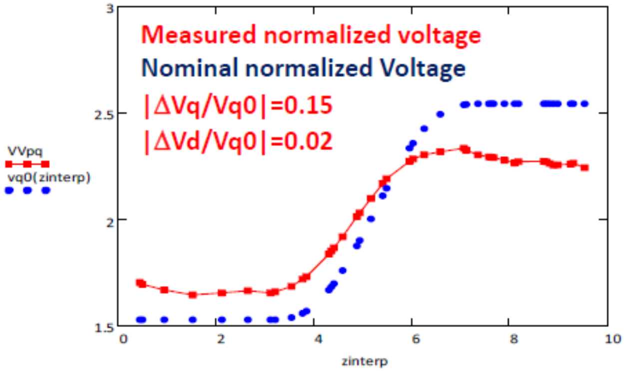
Figure 8: Transmission and power loss as function of the input emittance.

IFMIF RFQ TUNING PROCEDURE

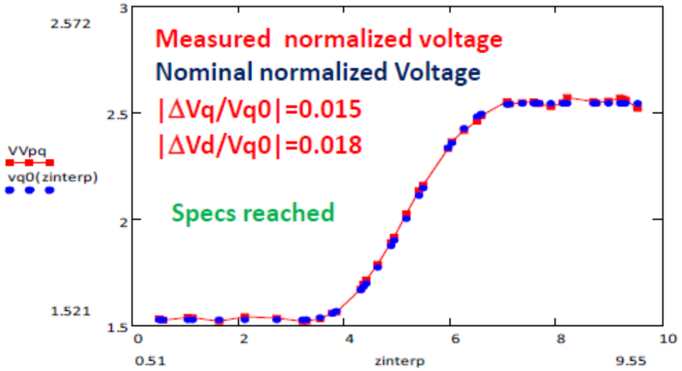
(preliminary)

In the tuning procedure of the IFMIF RFQ, the intra-vane voltage is deducted by magnetic field measurements with metallic bead pulling technique. Initially the measurement is performed with provisional Aluminum tuners and end-cells. In the initial measurement, tuners are at 0 insertion depth, then tuners are adjusted in their insertion depths following the indication of the tuning algorithm, and the end-cell insertion depths are adjusted as well in order to obtain the proper voltage slope at RFQ ends. The mesurements are iteratively repeated up to the attainment of the f0=175 MHz target frequency and of the Vq voltage specification ±2% variation wrt nominal one Vq0 both for Quadrupolar and Dipolar perturbing terms (i.e **|ΔVq/Vq0|< 0.02** and **|ΔVd/Vq0|< 0.02**). The RFQ length is 9.8 m (5.7 λ)

Initial Measurement f0=174.255 MHz



Final Measurement f0=174.994 MHz



Next steps: replacement of the provisional Al End-cells and tuners with definitive Cu ones (in batches) and confirmation measurements

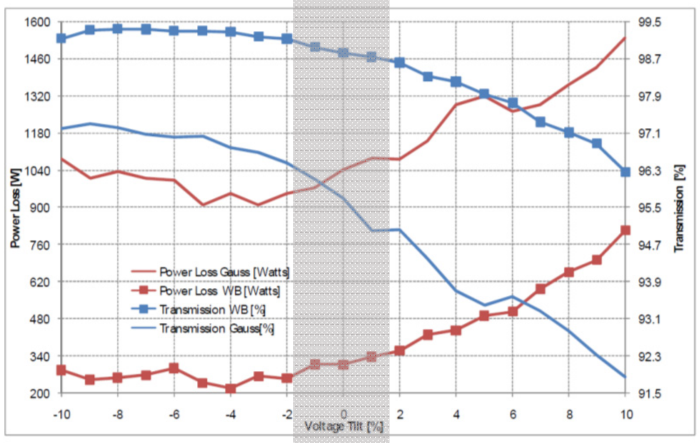
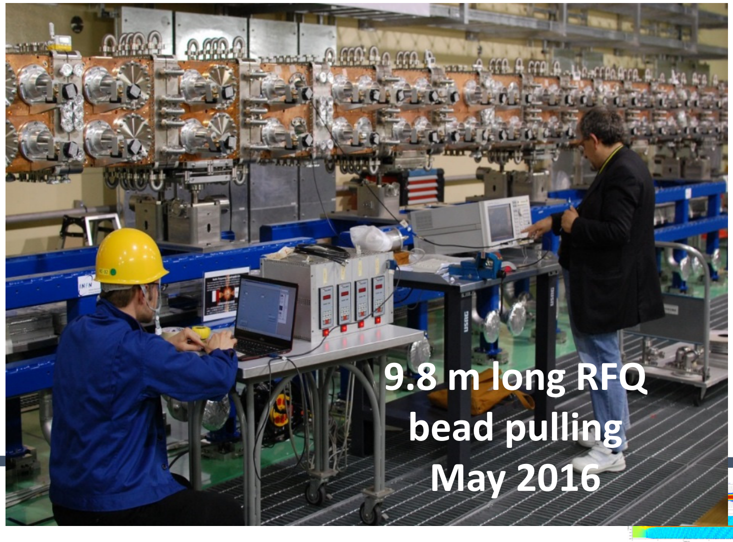


Figure 7: Voltage tilts effects on Transmission and Power loss with gaussian and waterbag input beam distribution.

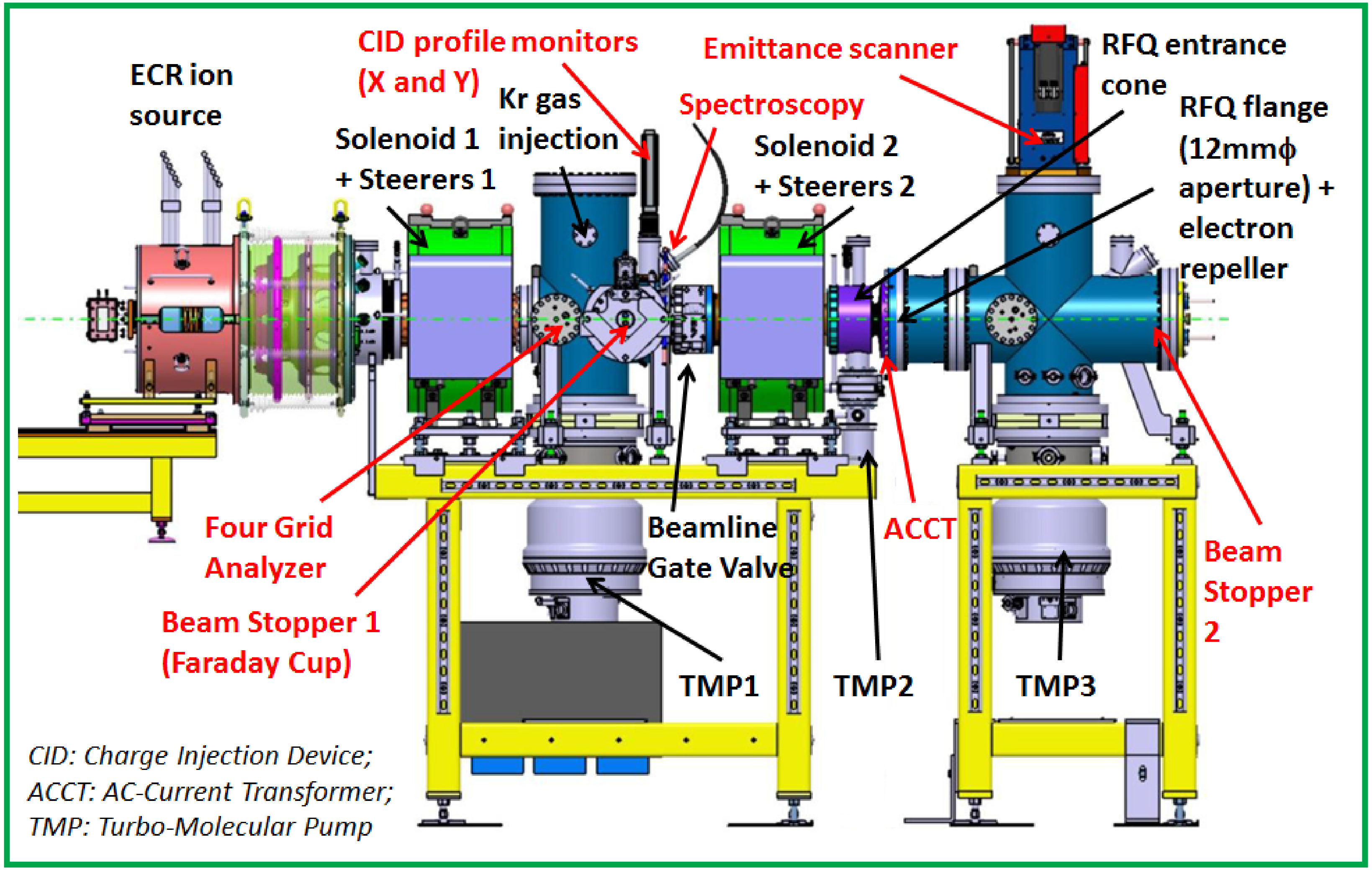
M. Comunian, *THE IFMIF-EVEDA RFQ: BEAM DYNAMICS DESIGN,* ***LINAC2008, Victoria***



9.8 m long RFQ
bead pulling
May 2016

A. Palmieri, *PRESERVING BEAM QUALITY IN LONG RFQS ON THE RF SIDE: VOLTAGE STABILIZATION AND TUNING ,* ***HB2014, East L.***

Present LEBT installation for beam commissioning



CID: Charge Injection Device;
ACCT: AC-Current Transformer;
TMP: Turbo-Molecular Pump

LEBT behaviour:
beam dynamics background

- The neutralisation (99-90%, from *FGA_H_50keV_20160324-1111.dat* and trace-forward) implies after the extraction an emittance dominated beam.

In the LEBT:

$$r_x'' + \cancelto{=0}{\frac{(\gamma_b\beta_b)'}{\gamma_b\beta_b}} r_x' + k_x r_x - \frac{\eta Q}{r_x} - \frac{\varepsilon_x^2}{r_x^3} = 0$$

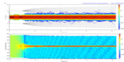
$\varepsilon_x = 4\varepsilon_{x,rms}$ $r_x = r_y$

Q Generalised perveance, η neutralisation factor

$$\frac{SC\ term}{thermal\ term} = \frac{\eta \cdot Q \cdot r^2}{\varepsilon_x^2} = \boxed{3.4\ \ \eta=1} \qquad \boxed{0.034\ \ \ \eta=0.01}$$

even less if emittance growth occurs $\varepsilon_x = \varepsilon_x(s)$

- **The major part of the BD is dominated by the thermal term in the LEBT.**
- **We are sensitive to a couple of percentage difference in the neutralisation, due to the fact that such difference is applied for almost 2 m.**
- From indirect calculation the exit of the extraction source seems to produce a too divergence beam at the first solenoid. Thus, the emittance growth is given mainly by the coupling from the solenoid nonlinearities (mainly) and space-charges. The emittance trend was confirmed experimentally (*beam_report_23032016*) and by simulations (COB20 presentation).
- Therefore, the main objective is to reduce the beam dimensions at the first solenoid.



Simulation Procedure

- Variables to determine: initial input beam parameters
- Neutralisation along the LEBT and after the injection cone

Procedure

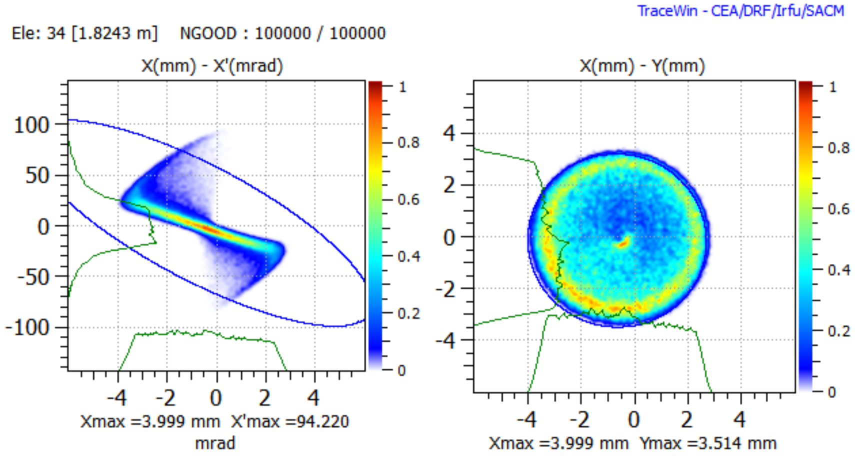
- First simulation of the extraction system.
- Emittance and Twiss parameters trace-forward with a measured neutralisation level before the cone and a guess after. (solenoid 1 and solenoid 2 fixed)
  - Adjustment of the input parameters and emittance.
  - Change of the solenoid values, exploring another point of the scan plot. Are we able to predict the emittance and Twiss?

⇩ Yes ⇩ Explore a far point in term of solenoid plan

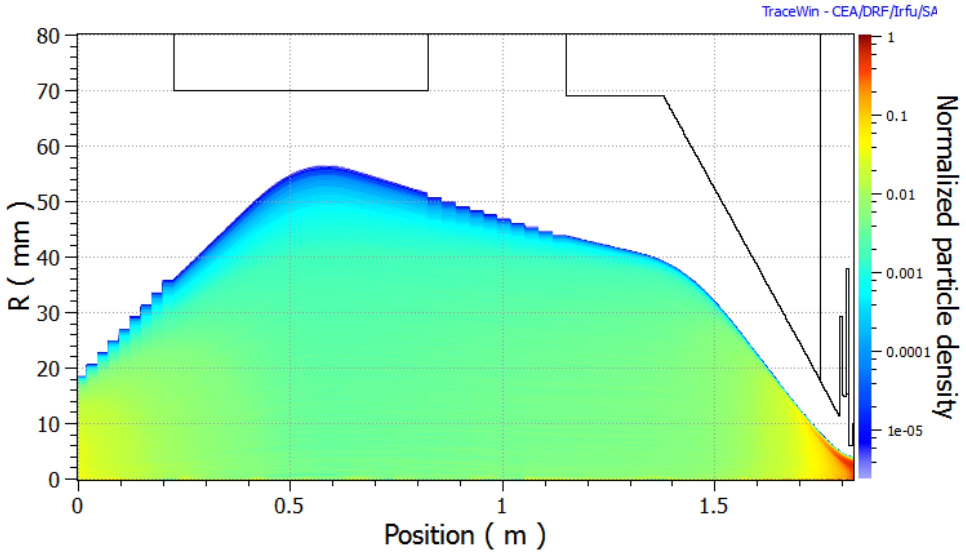
⇩ No ⇩ Change the input beam and/or the neutralisation after the cone.

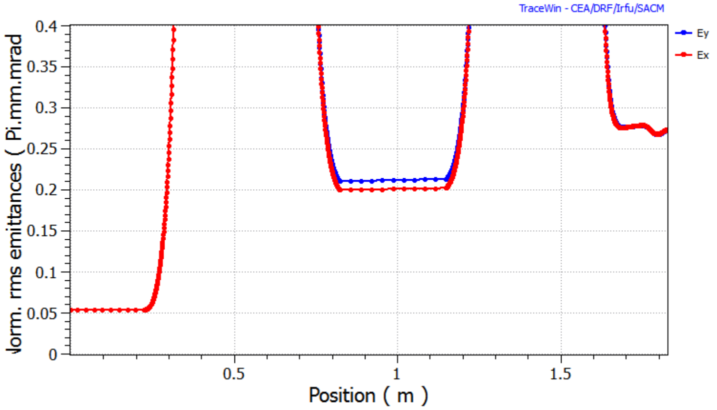
Simulation of LEBT by TraceWin

- Uniform 4D distribution with 5 eV as energy spread used as input beam.
- $\varepsilon_{n,rms} = 0.053677\ \text{mm mrad}, \alpha = -38.5, \beta = 9\ \text{mm/mrad}$
- 55 mA protons (intermediate commissioning)



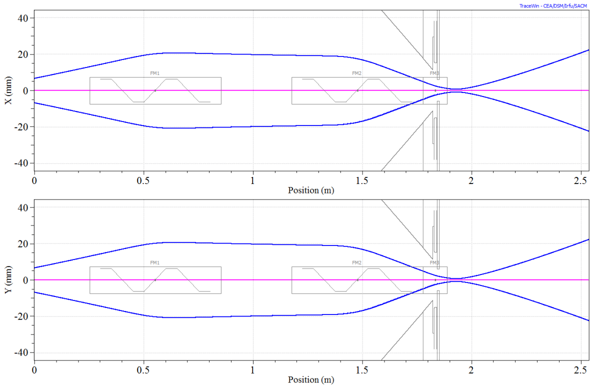
- 0 neutralisation ramp close to the repeller cone
- Solenoid field map and repeller field map



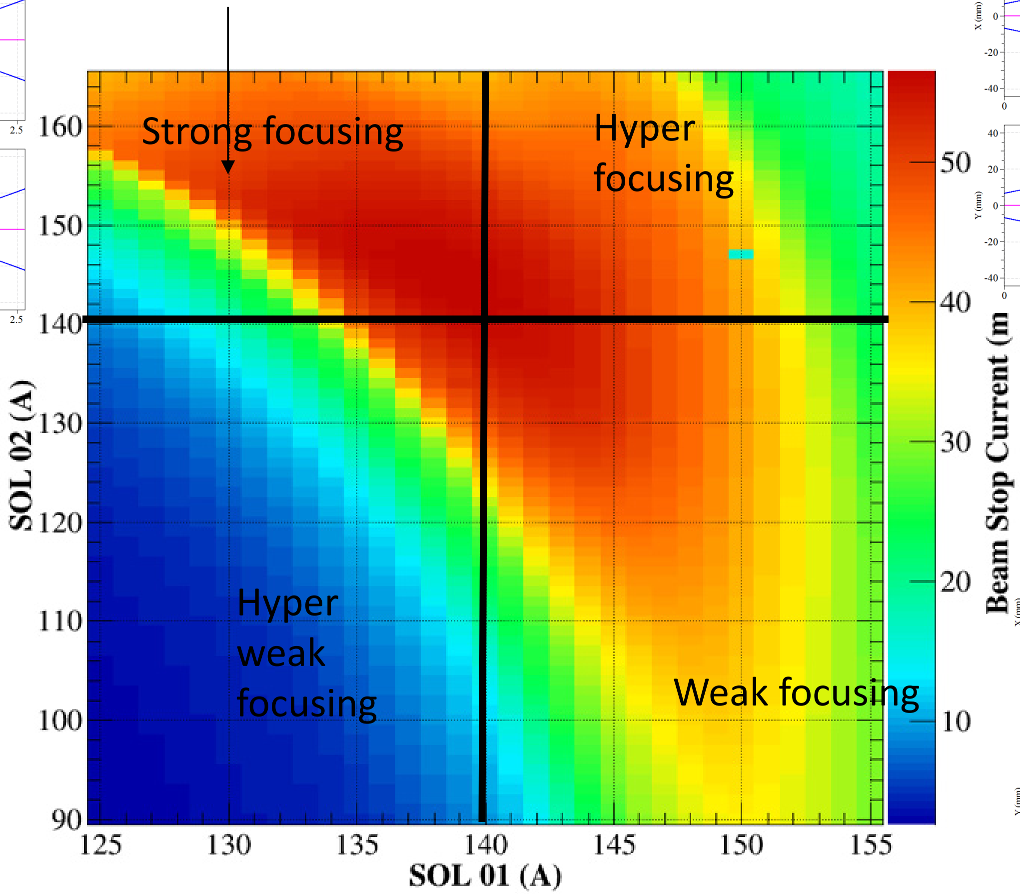


LEBT behaviour

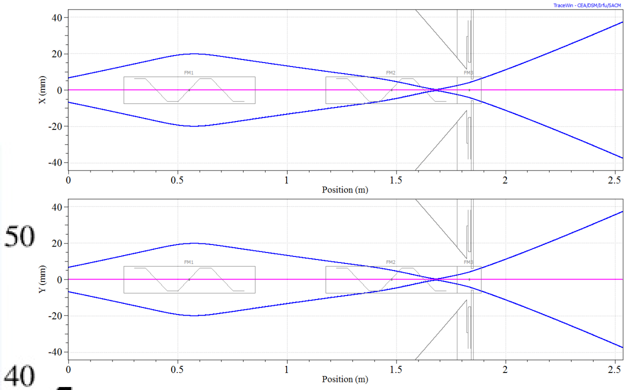
Focus after the cone hole



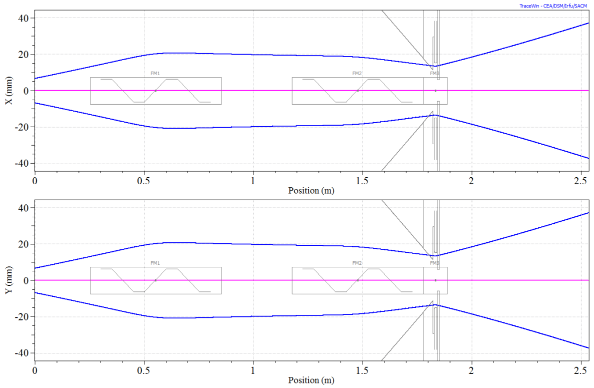
Match zone for the RFQ



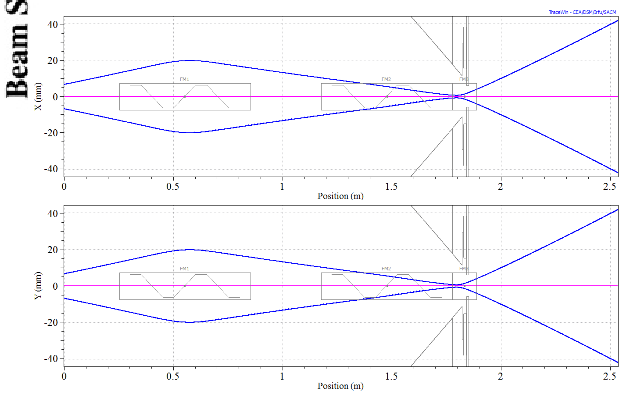
Focus before the cone hole



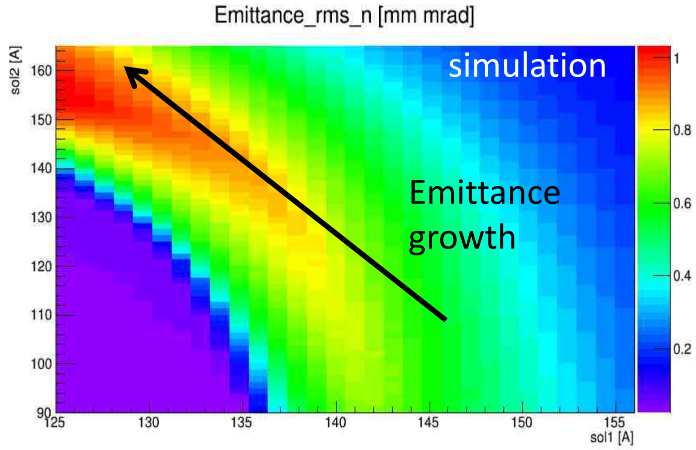
Larger beam size
in the cone hole



Smaller beam size
after the cone hole



Emittance behaviour in the LEBT



The emittance growth is given by two contributes:

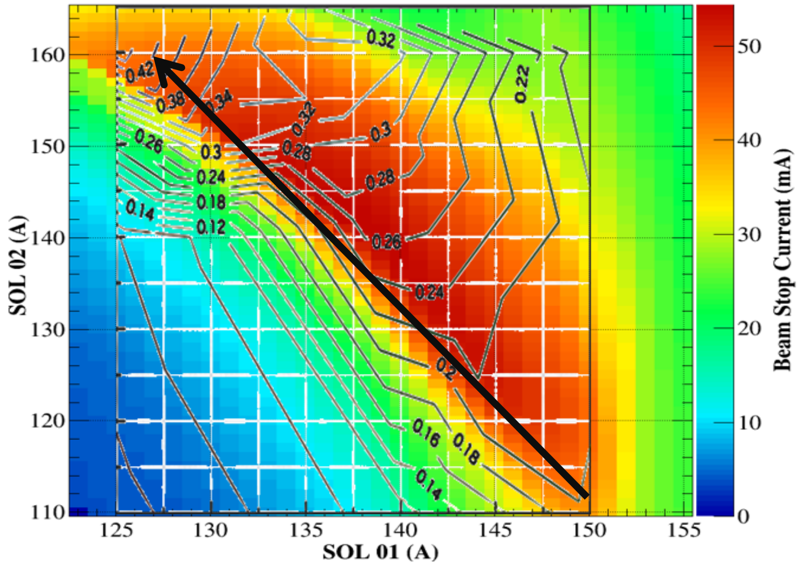
- Unneutralised beam potential
- Non-linearity in the solenoids

$$r_x'' + \frac{\overset{=0}{\cancel{(\gamma_b\beta_b)'}}}{\gamma_b\beta_b} r_x' + k_x r_x - \frac{2Q}{r_x + r_y} - \frac{\varepsilon_x^2}{r_x^3} = 0$$

$$\frac{SC\ term}{thermal\ term} = \frac{\eta \cdot Q \cdot r^2}{\varepsilon_x^2} = 3.4 \quad \eta=1$$

January work point

March measurement



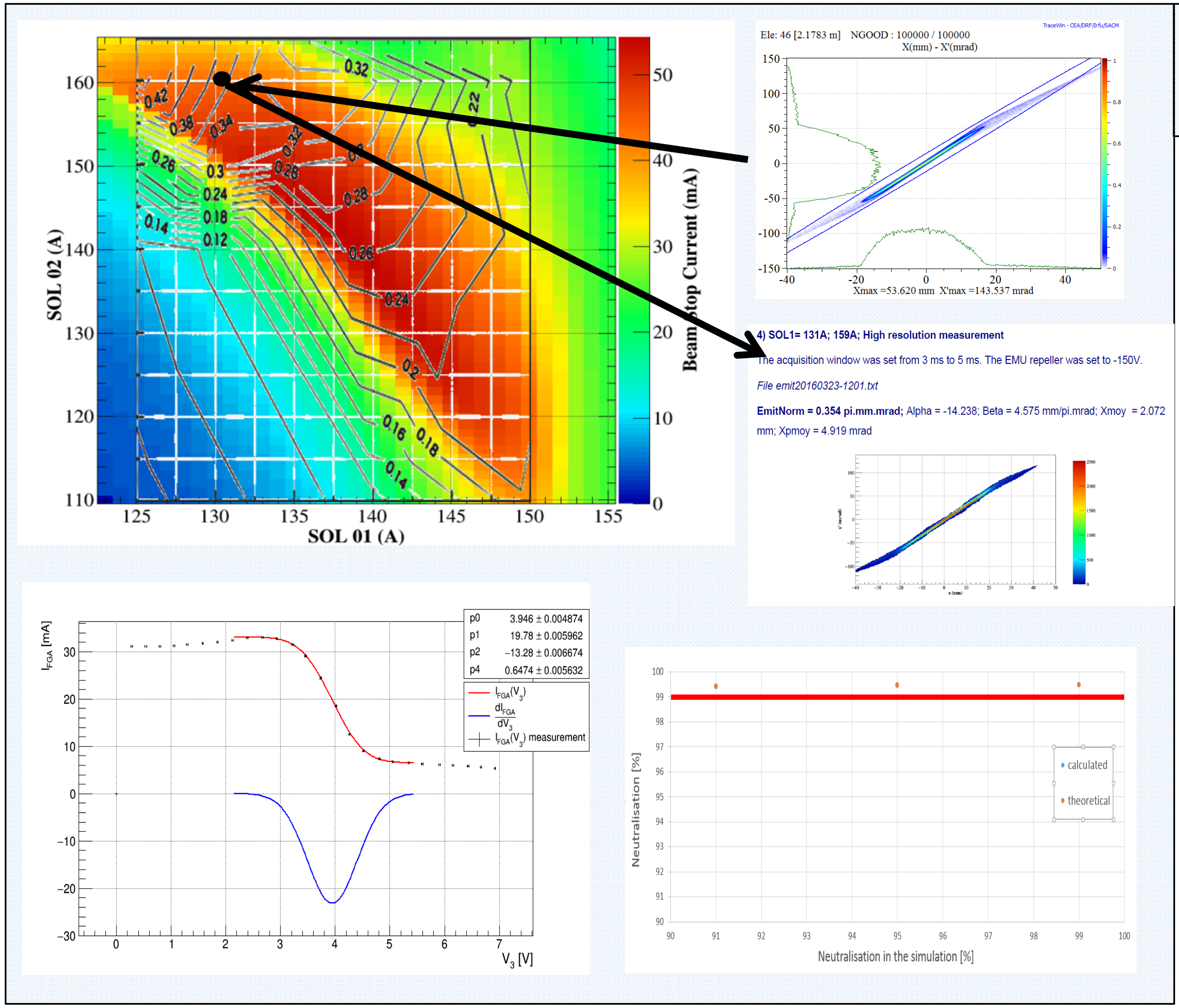
Same trend of simulation confirmed by march 2016 measurements with very different source settings:

- Emittance of the beam @ emittancemeter increases within the same direction (black iso-emittancelines of the plot)

The emittance growth is mainly given by the coupling between the space-charge forces and the first solenoid non-linearity.

March work point

Simulation ↔ measurement



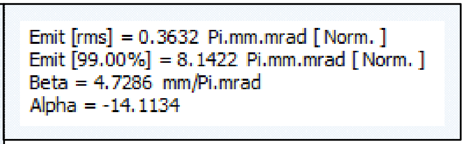
4) SOL1= 131A; 159A; High resolution measurement

The acquisition window was set from 3 ms to 5 ms. The EMU repeller was set to -150V.

File emit20160323-1201.txt

EmitNorm = 0.354 pi.mm.mrad; Alpha = -14.238; Beta = 4.575 mm/pi.mrad; Xmoy = 2.072 mm; Xpmoy = 4.919 mrad

p0	3.946 ± 0.004874
p1	19.78 ± 0.005962
p2	−13.28 ± 0.006674
p4	0.6474 ± 0.005632



Emit [rms] = 0.3632 Pi.mm.mrad [Norm.]
Emit [99.00%] = 8.1422 Pi.mm.mrad [Norm.]
Beta = 4.7286 mm/Pi.mrad
Alpha = -14.1134

Emittance

- Neutralisation after the cone and input beam parameters

Not uncorrelated quantities!

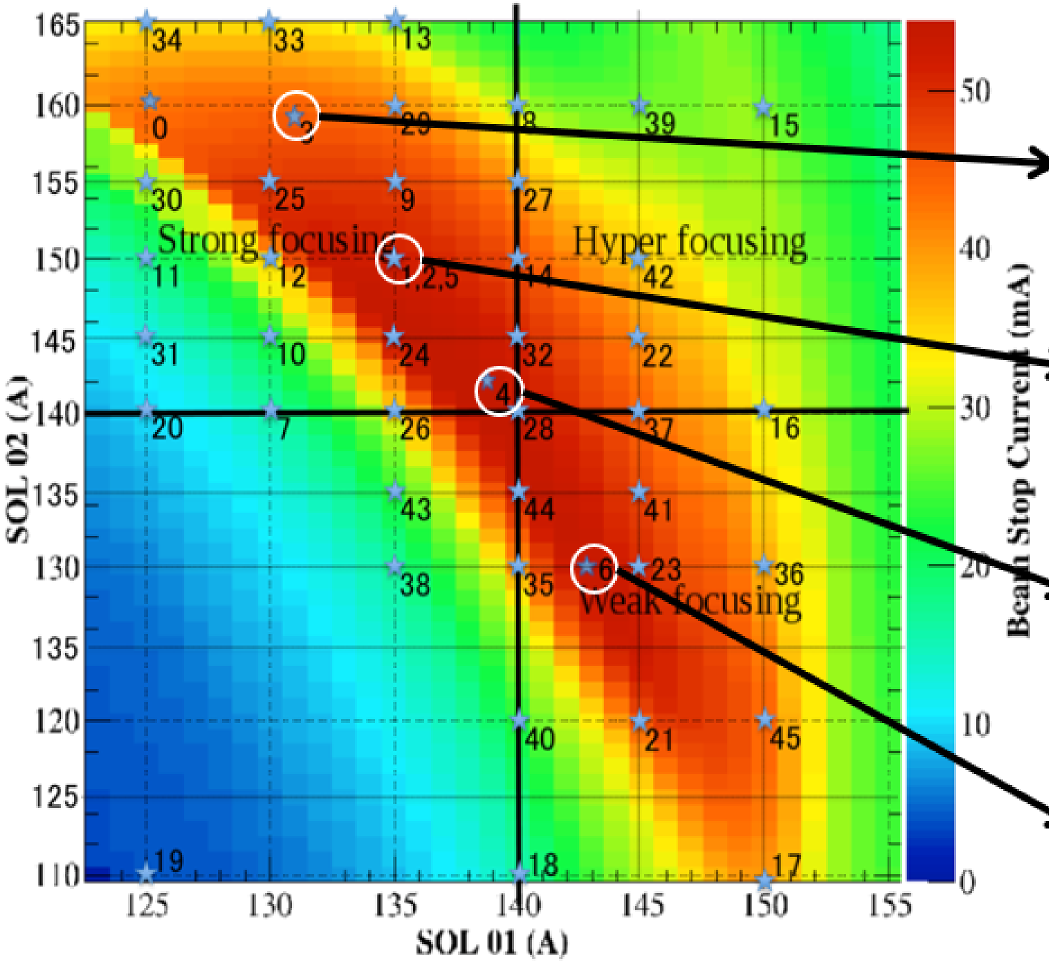
Neutralisation

- 0 neutralisation beam potential estimation

The neutralization level change as function of solenoids values

Other points of comparison measurement <-> simulation

Beam_report_23032016



Meas.

EmitNorm = 0.354 pi.mm.mrad; Alpha = -14.238; Beta = 4.575 mm/pi.mrad;

Sim.

Emit [rms] = 0.3632 Pi.mm.mrad [Norm.]
Emit [99.00%] = 8.1422 Pi.mm.mrad [Norm.]
Beta = 4.7286 mm/Pi.mrad
Alpha = -14.1134

Meas.

EmitNorm = 0.299 pi.mm.mrad; Alpha = -10.648; Beta = 3.295 mm/pi.mrad;

Sim.

Emit [rms] = 0.2958 Pi.mm.mrad [Norm.]
Emit [99.00%] = 5.7302 Pi.mm.mrad [Norm.]
Beta = 2.8204 mm/Pi.mrad
Alpha = -9.0808

Meas.

EmitNorm = 0.271 pi.mm.mrad; (Alpha = -8.230; Beta = 2.533 mm/pi.mrad;

Sim.

Emit [rms] = 0.2858 Pi.mm.mrad [Norm.]
Emit [99.00%] = 5.4330 Pi.mm.mrad [Norm.]
Beta = 2.6291 mm/Pi.mrad
Alpha = -8.6145

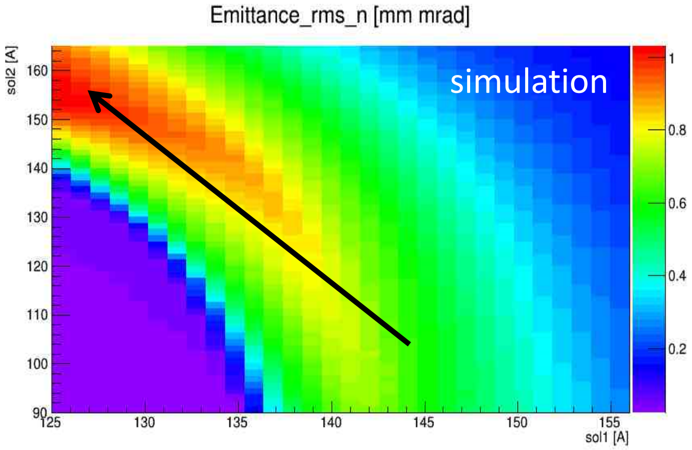
Meas.

EmitNorm = 0.227 pi.mm.mrad; (Alpha = -6.829; Beta = 2.349 mm/pi.mrad;

Sim.

Emit [rms] = 0.2408 Pi.mm.mrad [Norm.]
Emit [99.00%] = 2.8443 Pi.mm.mrad [Norm.]
Beta = 2.5828 mm/Pi.mrad
Alpha = -7.7933

Mismatch at RFQ input

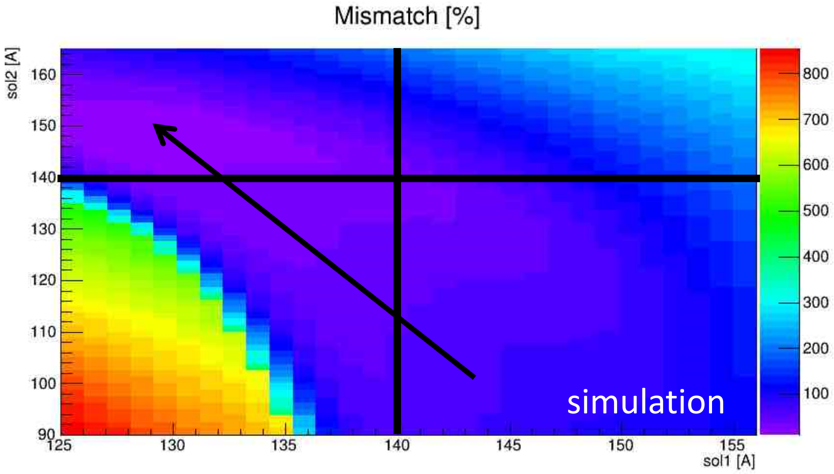


The emittance growth is given by two contributes:

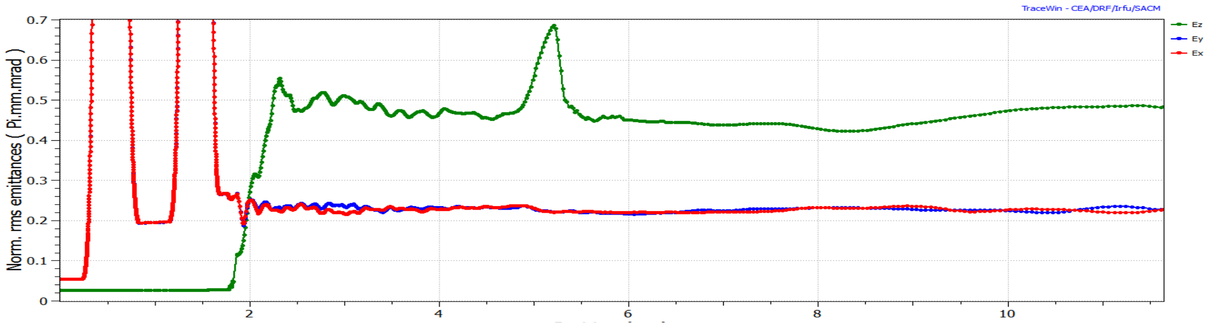
- Unneutralised beam potential
- Non-linearity in the solenoids

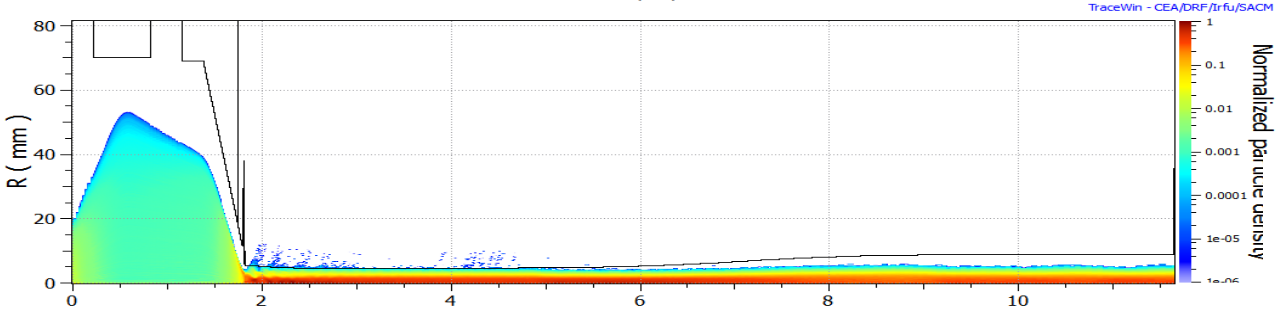
$$\frac{SC\ term}{thermal\ term} = \frac{\eta \cdot Q \cdot r^2}{\varepsilon_x^2} = 3.4 \quad \eta=1$$

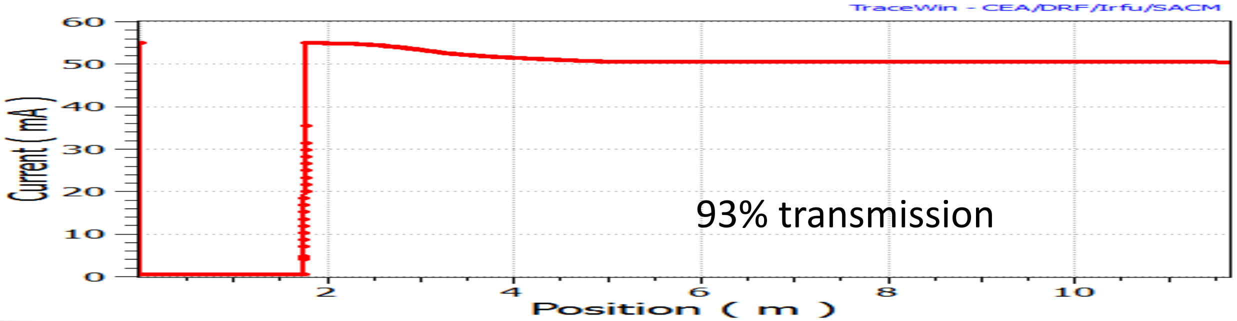
- The mismatch follows manly the opposite trend of the emittance.
- State that the 0 mismatch is not always in the upper left corner, its minimum stays always in the upper left quadrant, in the so called strong focusing zone.
- The 0 mismatch point position depends on the Twiss parameters, neutralization.



Effects on the RFQ transmission

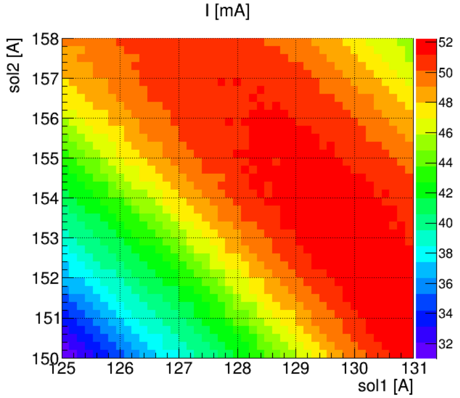


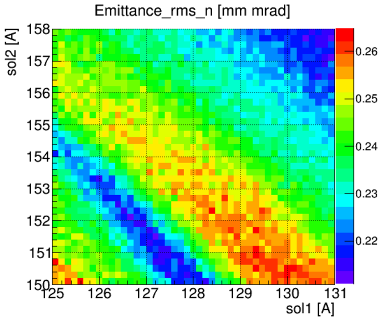


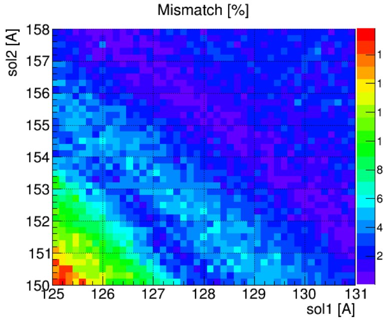


93% transmission

Solenoids scan around the nominal point.







Which lesson do we learn?

- Simulations are mandatory.
- Measurement must be done after the simulations and compare to it.
- Measurements must be fully understood with the simulations especially if there are not in agreement.
- Very difficult to simulate the source beam creation: missing a match between the plasma codes and the PIC codes.
- A part from the extraction column and the RFQ repeller cone the LEBT transport is emittance dominated (proton 50 keV, 50 – 90 mA) due to the neutralization.
- The extraction system dictate the beam behavior in the LEBT.
- Design the next RFQ for larger emittance and lower initial focusing force.

Conclusion

- The commissioning of IFMIF-EVEDA source is on-going.
- The LEBT behavior is well reproduced by the simulation, but some details are still to be investigated.
- The main emittance growth occurs in the LEBT.
- The matching to the RFQ is not “easy”, must be prepared with a good campaign on the LEBT.