Beam dynamics simulation and measurements for the IFMIF/EVEDA project

M. Comunian, L. Bellan, M. Cavenago, E. Fagotti, F. Grespan, A. Pisent,
A. Palmieri, C. Baltador, F. Scantamburlo, L. Antoniazzi, A. Baldo,
D. Bortolato, M. Giacchini, M. montis INFN-LNL, [35020] Legnaro, Italy,
N. Chauvin, CEA, [91190] Gif-sur-Yvette, France
H. Dzitko, F4E, [85748] Garching, Germany

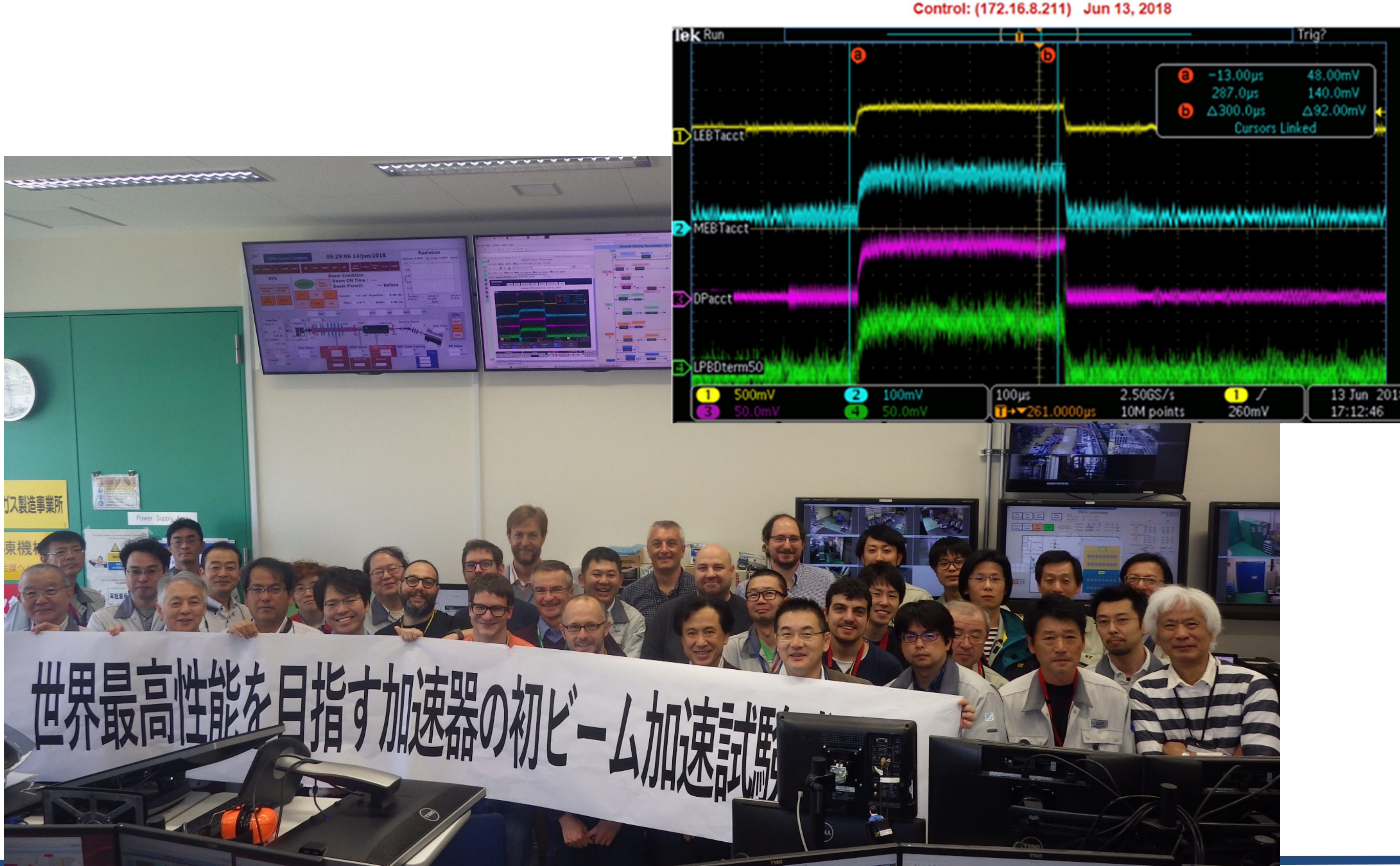
For a general overview see the talk:
Commissioning status of linear IFMIF Prototype Accelerator (LIPAc) A. Kasugai

Outline

- The IFMIF/EVEDA Project
- Beam Dynamics of Source-LEBT-RFQ input:
  - rms Trace-forward method and the problem of the s.c.c.
  - Constant s.c.c. model (TraceWin)
  - Dynamic s.c.c. model (WARP)
- Commissioning plan: first stage proton at low current in pulsed mode.
- First beam results.
- Conclusion and work in progress…

s.c.c=Space Charge Compensation

First H+ 50keV/6mA beam acceleration & transport through RFQ-MEBT-Dplate-LPBD on 13 June



IFMIF EVEDA
Linear IFMIF Prototype Accelerator

Accelerator components from Europe
Beam tests in Japan

100 keV/140 mA D⁺

Injector + LEBT
CEA Saclay

5 MeV/130 mA D⁺

RFQ
INFN
QST
F4E

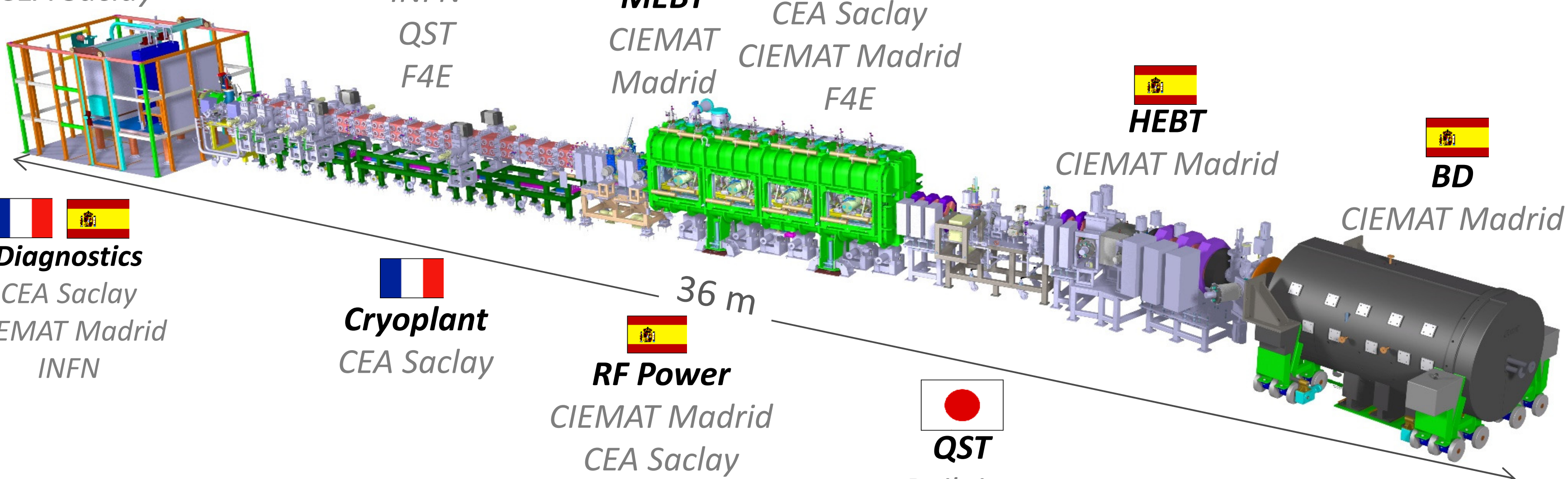
MEBT
CIEMAT Madrid

9 MeV/125 mA D⁺

SRF Linac
CEA Saclay
CIEMAT Madrid
F4E

HEBT
CIEMAT Madrid

BD
CIEMAT Madrid



Diagnostics
CEA Saclay
CIEMAT Madrid
INFN

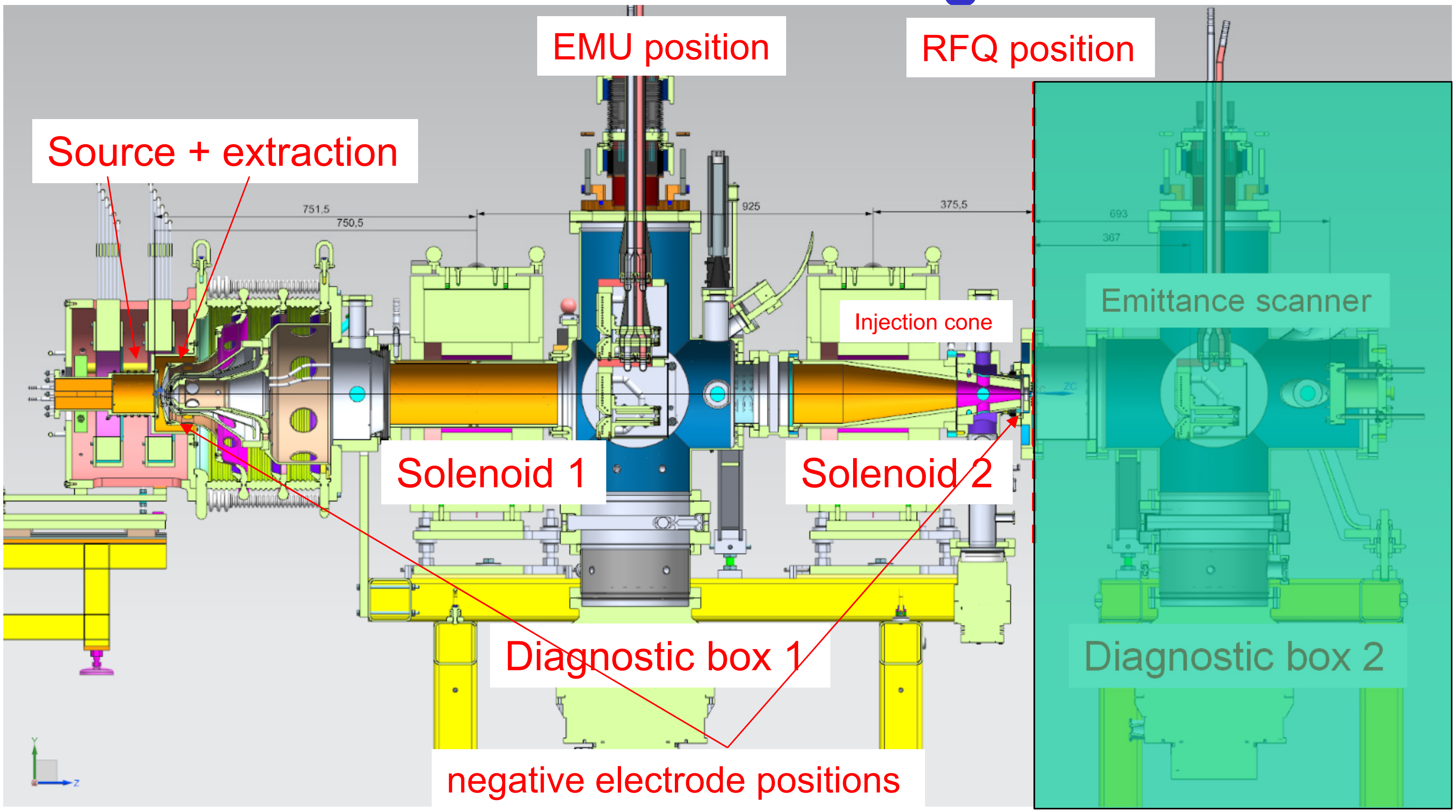
Cryoplant
CEA Saclay

RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

QST
Builging
Auxiliary System
Control System
Installation

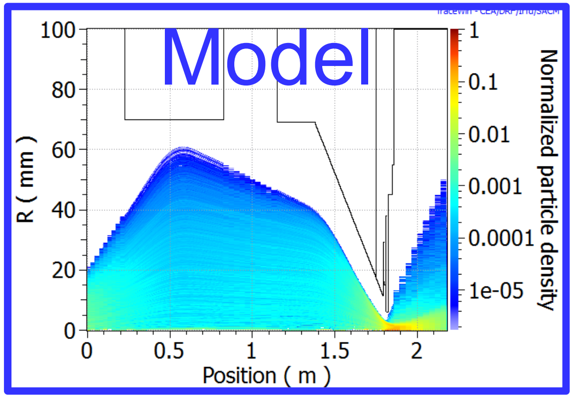
FUSION FOR ENERGY QST

Layout of the source and LEBT during commissioning

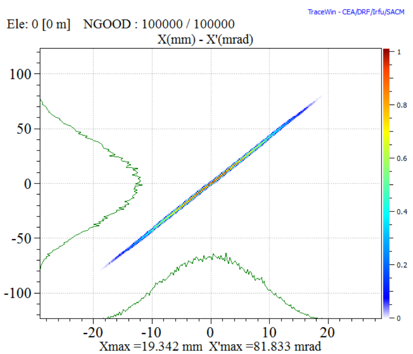


Forward method rms- generalities

Key points:
- It takes the inputs from the measurements, trying to fix as many as possible parameters
- It needs the model from the simulation.
- Estimate the beam input rms emittance and the Courant-Snyder parameters, via an iterative method.

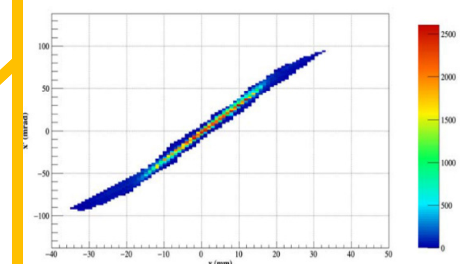


$\varepsilon_{\mathrm{rms}}\ \beta_{rms}\ \alpha_{rms}$

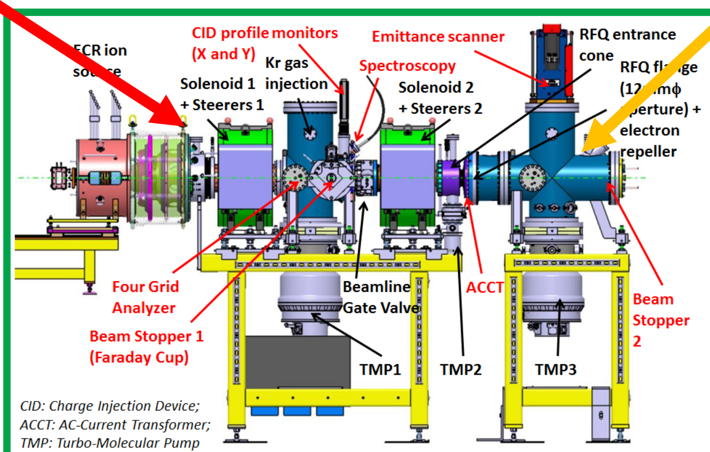


Rms simulated output @ input:

$\varepsilon_{\mathrm{rms}}\ \beta_{rms}\ \alpha_{rms}$



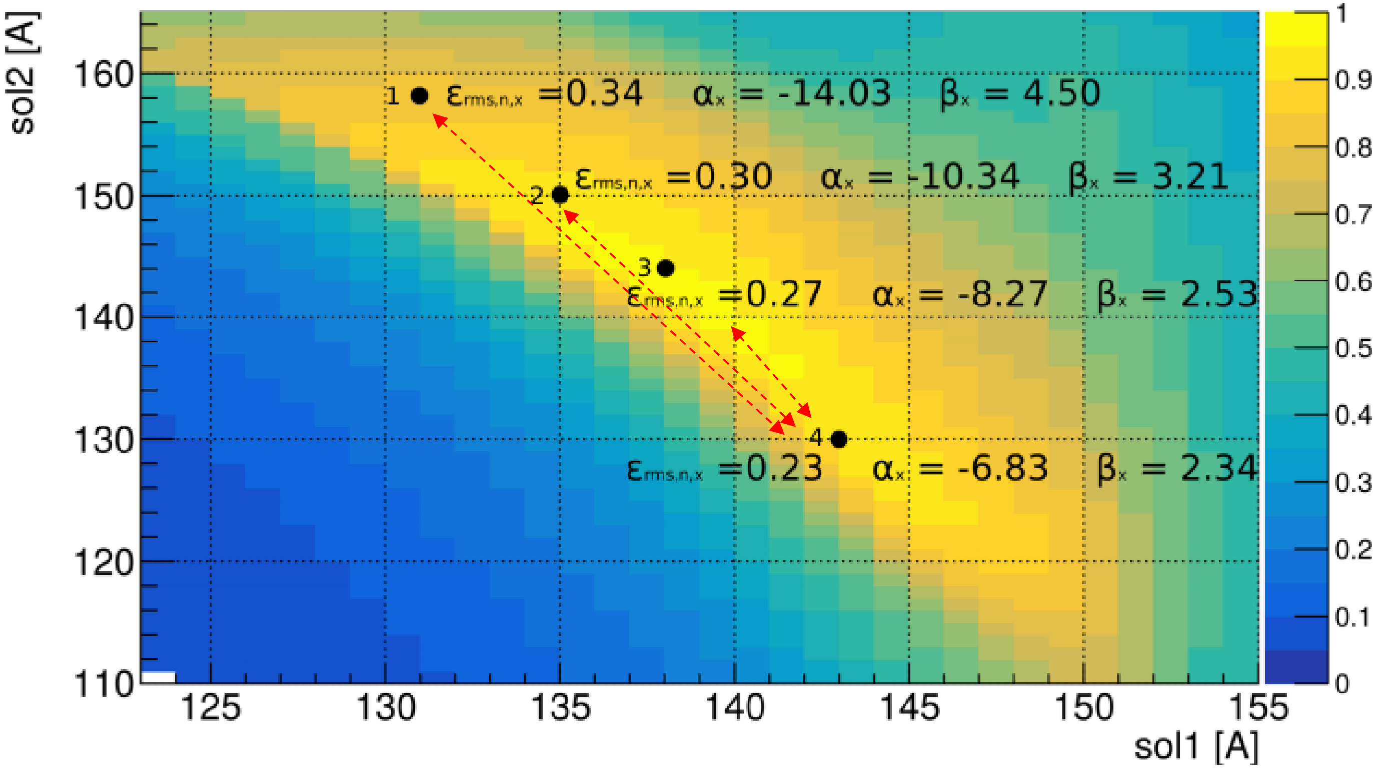
Rms measured input @ output:



Space charge compensation is normally a free parameter

Experimental inputs: proton beam at 50 keV.

exp. BS current (A.U. At 55mA max) and emittance (mmmrad) point



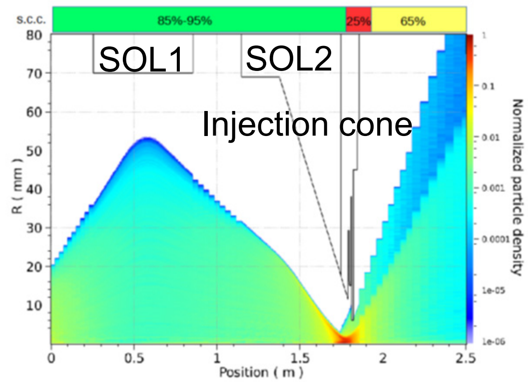
It gives 4 independent equations.

It gives the information on the emittance, transmission and Twiss parameters with respect to the solenoid values.

The agreement between the model can be tested with respect these points.

LEBT space charge compensation, constant and dynamic model

- Two strategies in the frame work of trace forward method were explored in order to take into account of the space-charge compensation in the BD model:
  - The space-charge compensation constant model:

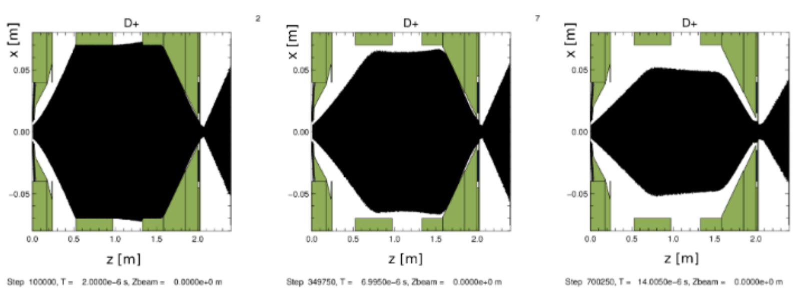


A costant factor is applied to the current of the beam, which depends with respect to the position along the LEBT.

$$s.c.c. = f(z)$$

Software used: TraceWin (s-code)

  - The space-charge compensation dynamic model:



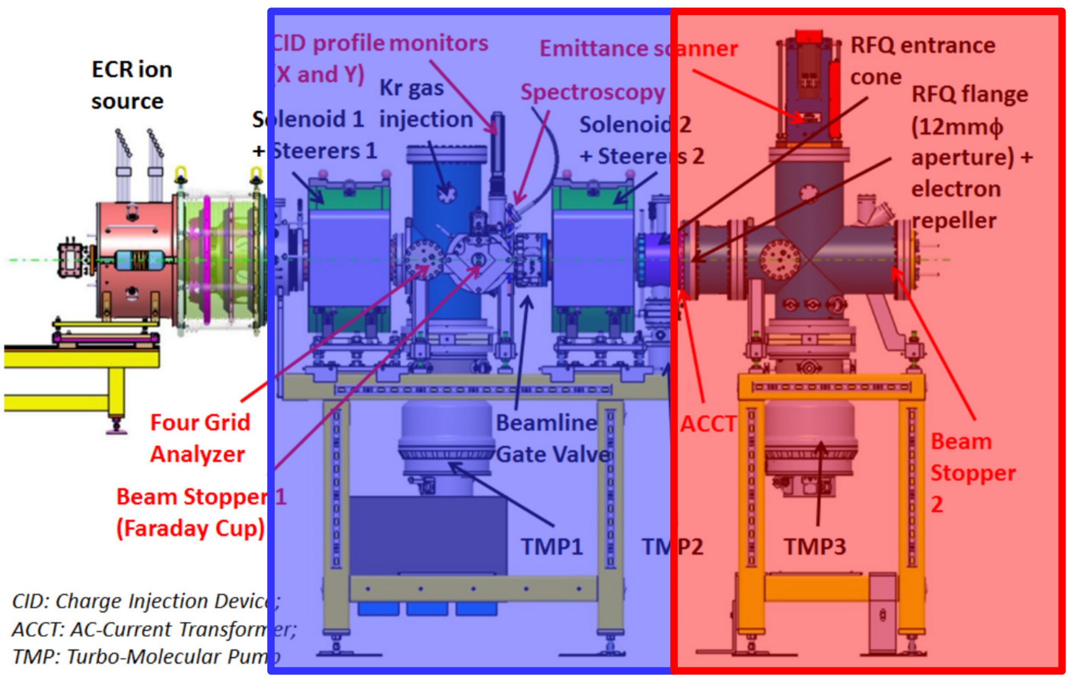
Given the pressure, the cross sections of the various phenomena the software calculates the s.c.c. degree from the self-field compensation, which come from the dynamic equilibrium between the primary plasma (the beam) and the secondary plasma (residual gas ions and electrons). In this case

$$s.c.c. = f(r, z)$$

Software used: WARP (t-code)

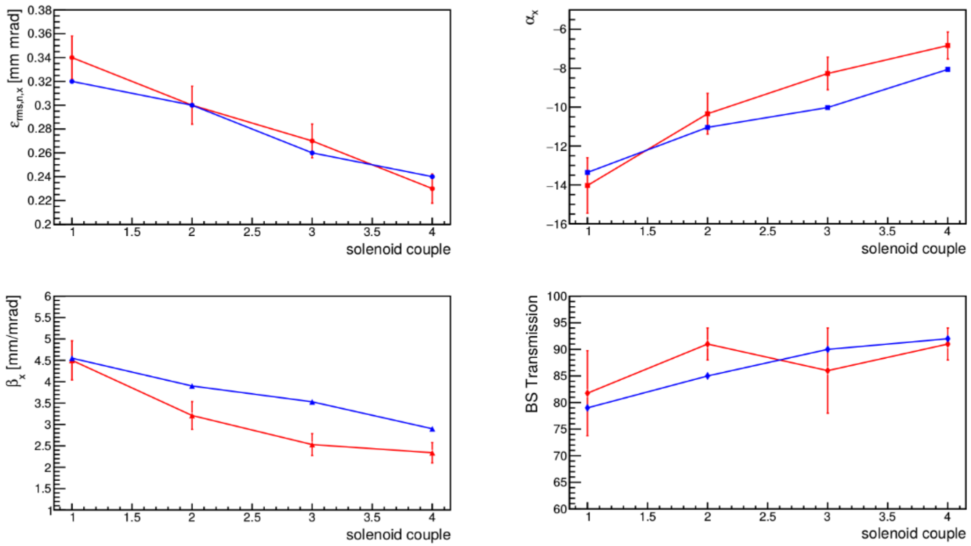
Beam tested with constant model (TraceWin)

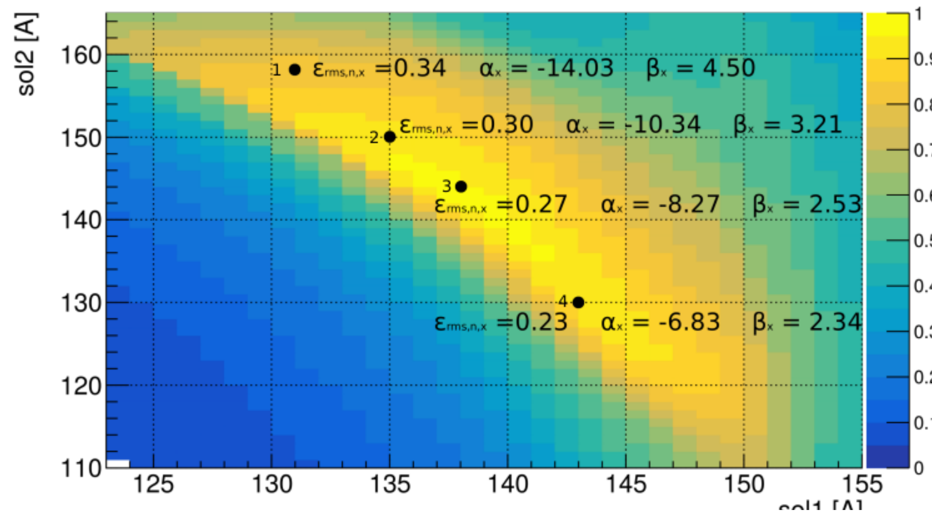
- Proton beam at 55 mA @ 50 keV. Beam transverse initial distribution: 4D waterbag (chosen after testing others), 100000 macroparticles, adaptive mesh of 32 transverse SHEFF cells (over 2.5 sigma) and 16 longitudinal cells. Solenoid field maps and repeller cone field map.
- Gas pressure in the two zones: 10^{-5} mbar and 10^{-7} mbar ⇨ Two values of s.c.c.



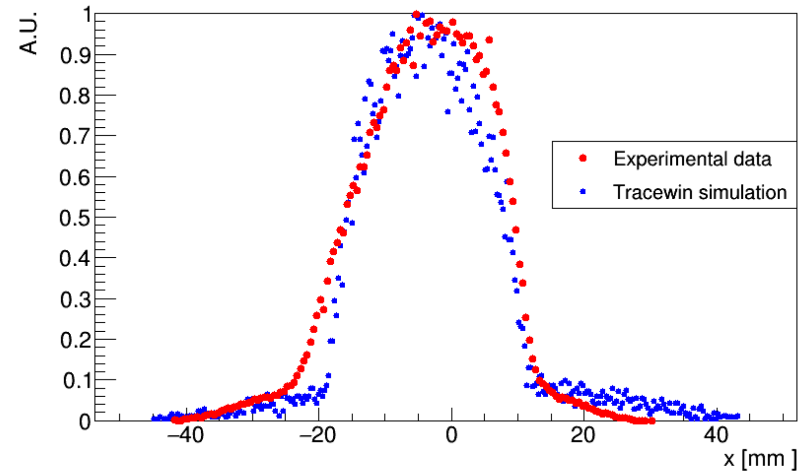
Twiss determination and uncertanties – costant model

Red experimental measurement
Blu simulation

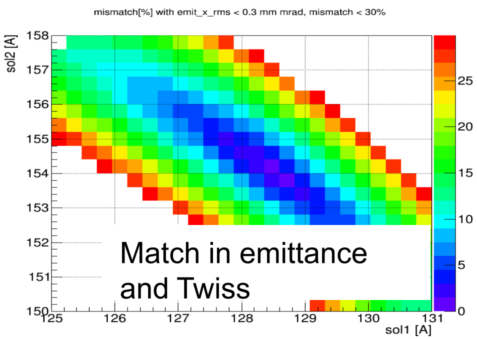




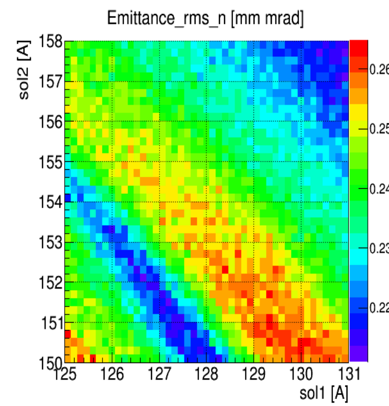
- in order to check the guess on the s.c.c. and on the initial Twiss, several emittance measurements were performed with different solenoid values and used in the trace forward cycle.
- there is an overestimation of the tales, but the beam profile is respected (waterbag core + gaussian)
- the best match parameters are retrieved at the RFQ input point.

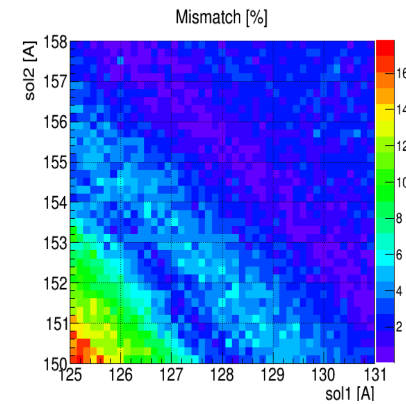


Forward method rms- results

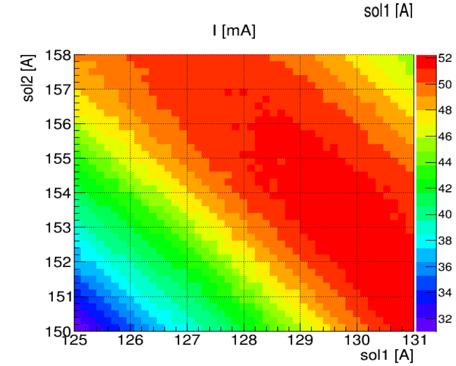


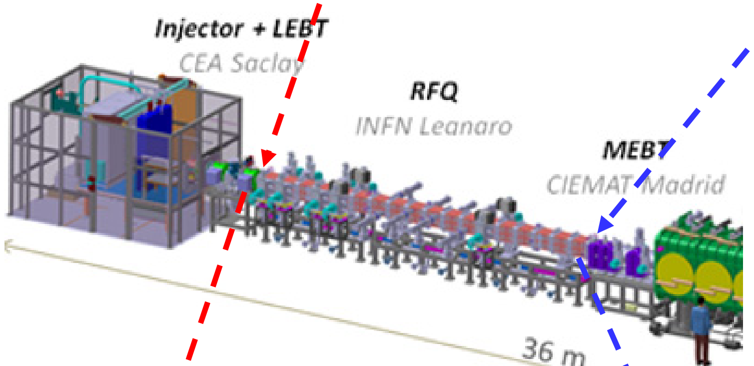
RFQ input

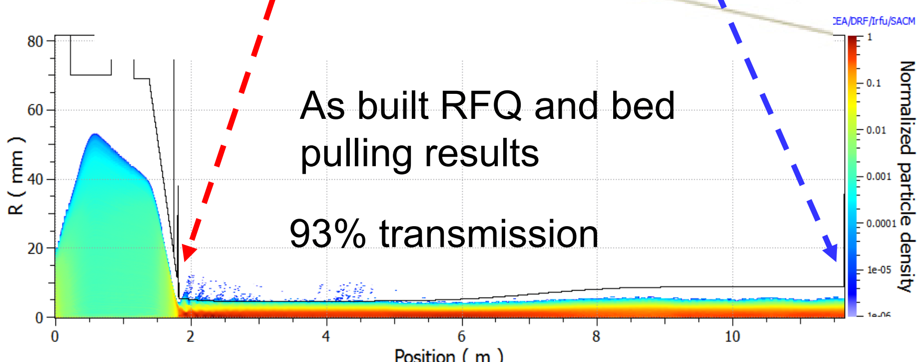




RFQ output

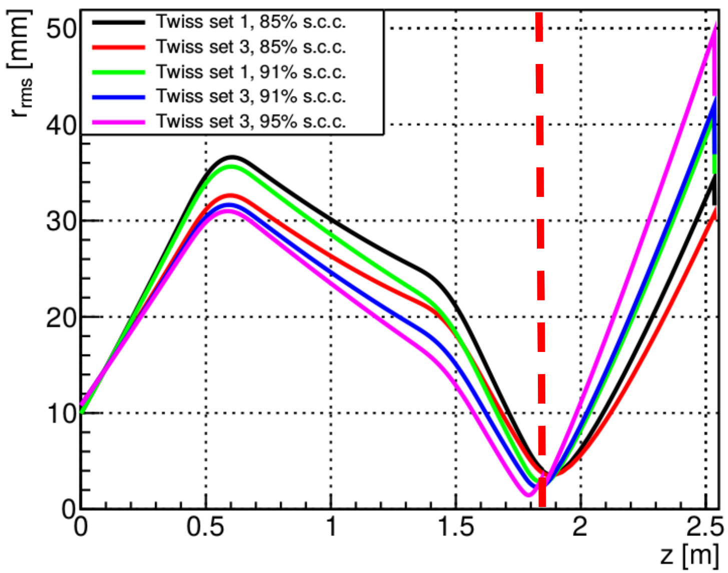


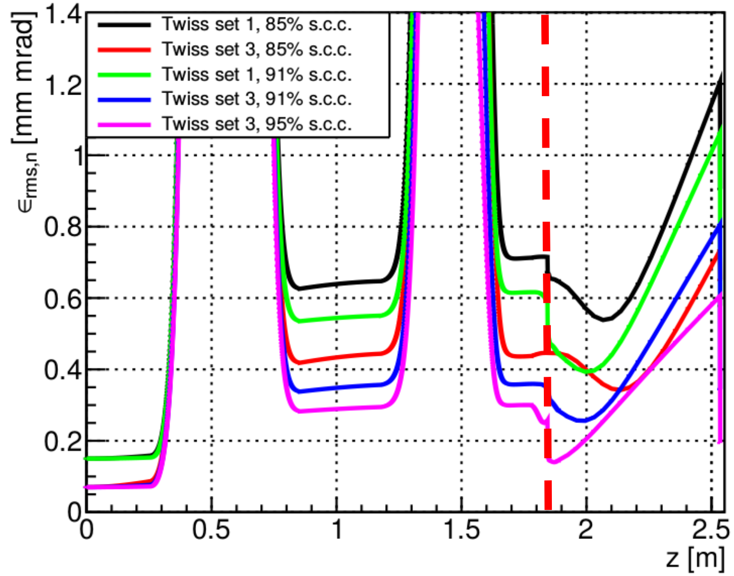




- Transmission and RFQ behavior.
- Method to find the best matching parameters at the RFQ starting from the experimental setup.
- Method to find the best matching parameters at the RFQ starting from the experimental measurement were study and partially tested.

Sensibility to s.c.c. degree - constant model





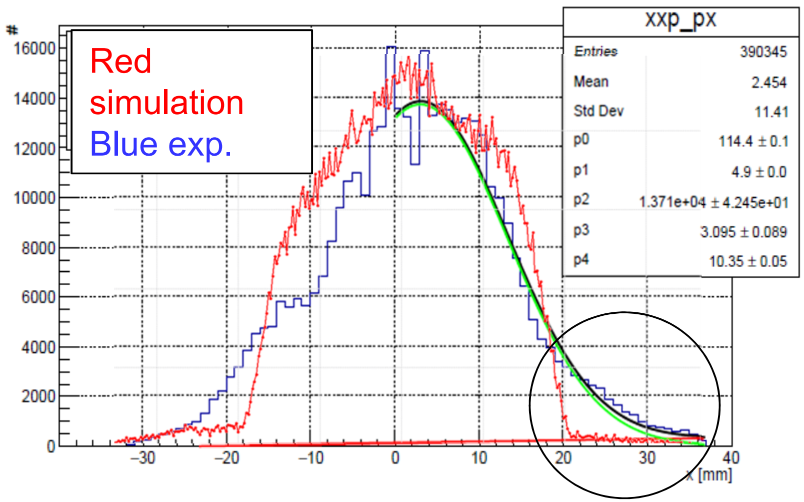
Twiss set	$\varepsilon_{\mathrm{rms,n},x}$	α_x	β_x	a'_{rms}	a_{rms}
1	0.15	-15.9	3.4	46.5	9.9
2	0.1	-15.9	3.4	38.0	8.1
3	0.07	-30.0	8.6	37.7	10.8

- dependence on few degree of s.c.c.
- On the non-linearities of the first solenoid

The beam at the output of the source should minimize the divergence and its dimensions. Indication for extraction designer.

From constant scc to dynamic scc

- The rms type, with constant model, was meant to describe the rms quantities.
- The beam profile benchmark starts to fail for larger perveance beam.
- Another source may be the spatial beam distribution from the source which is not compliant with a 4D Waterbag, Parabolic or Conical.



x-profile of 130 mA D beam at 100 keV

- Not surprising, many effects neglected:
  - Multispecies (H2+, H3+, Residual gas ions, electrons)
  - Neutralization process induced by residual gas ions and beam pipe collision
- RMS cycle was not converging with errors lower than 50% in certain case.

The model needs to be adequate to supply such self consistency.

WARP

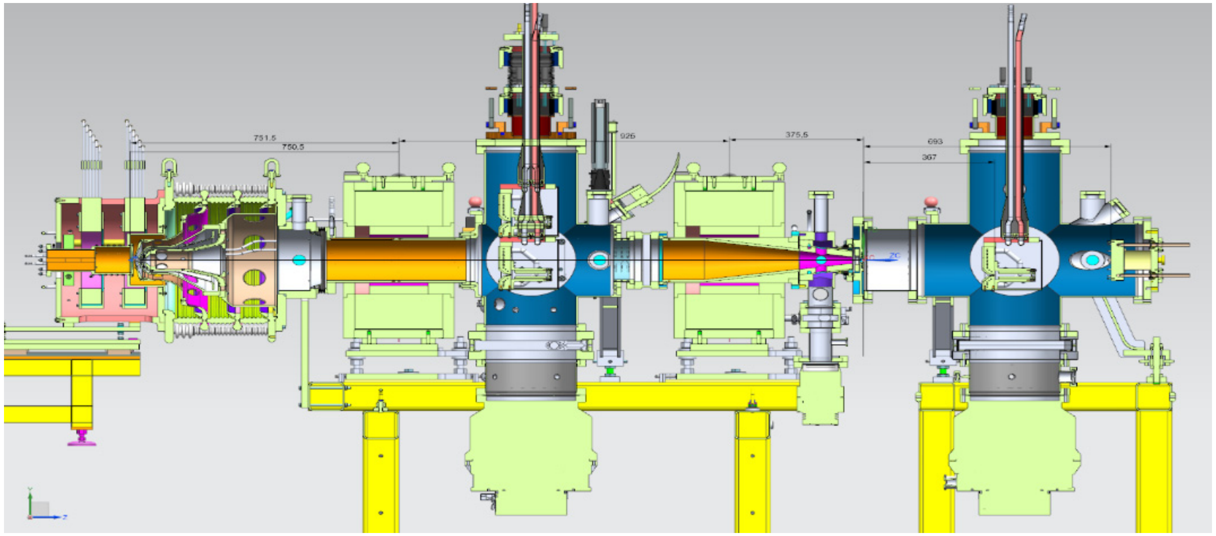
Beam tested with dynamic model (WARP)

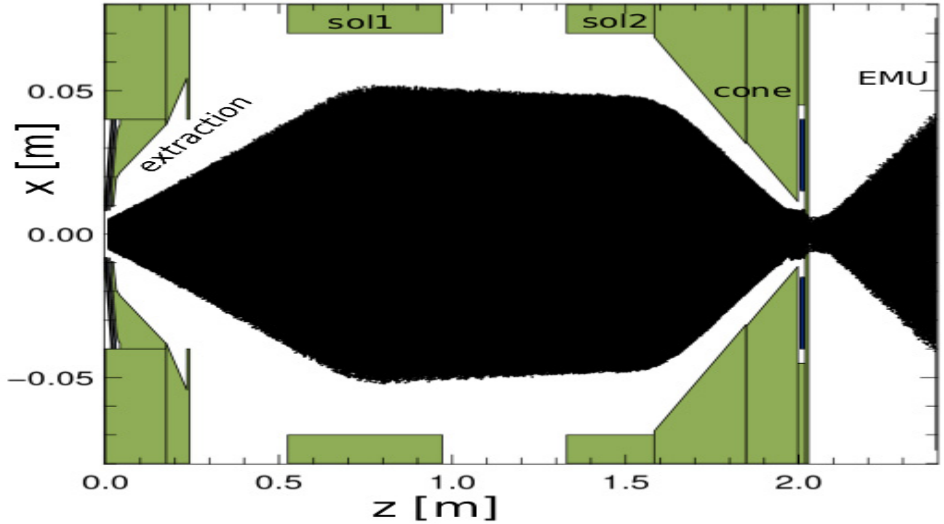
- Deuteron beam 155 mA @ 100 keV (93% D and 7% D_2). Beam transverse initial distribution: 4D parabolic, 30000 macroparticles per bunch, solenoid field maps and repeller cone field map. Beam starts close to the repeller electrode.
- Fixed mesh (with mesh refinement). Smallest mesh cell 0.25 mm:
  - $\Delta x \sim \lambda_D$
  - $n_{mp} \Delta x^3 \sim 100$
  - $\Delta t < (v_e \Delta x)^{-1}$ leapfrog stability
  - Δt enough smaller to resolve space charge waves (ω_p).

$$\lambda_D \Rightarrow \Delta x \Leftrightarrow \Delta t \Leftarrow N_{mp}$$

- Gas pressure in the two zones: 1.3×10^{-6} mbar (half D_2 and half Kr), while 1.3×10^{-5} mbar in the second zone (almost all Kr).
- Boundary conditions are an essential part of the simulation, due to the fact that they will affect the confinement of the electrons.
- Very time consuming simulations: order of weeks.
- Parallelization performed over 20 cores.

Overall view of Warp model

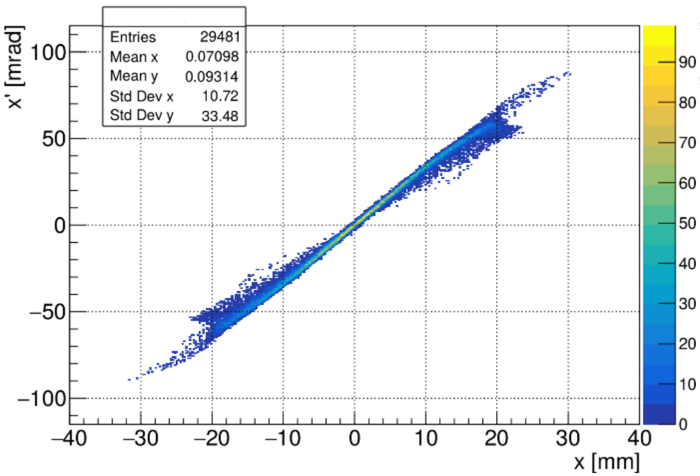




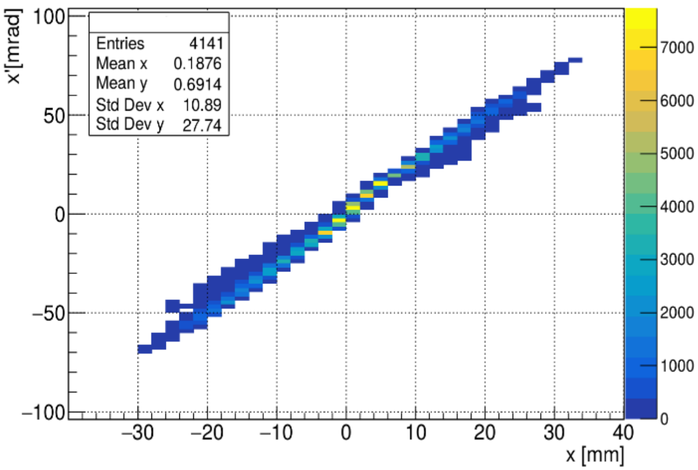
The warp model is with secondary electron from residual gas and Walls (warp+posinst)

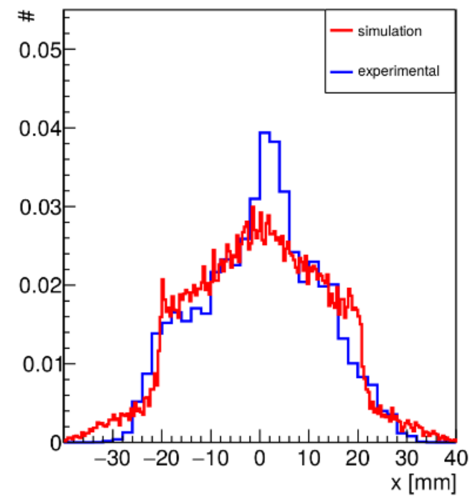
Benchmark with the results with WARP

simulation



measurement



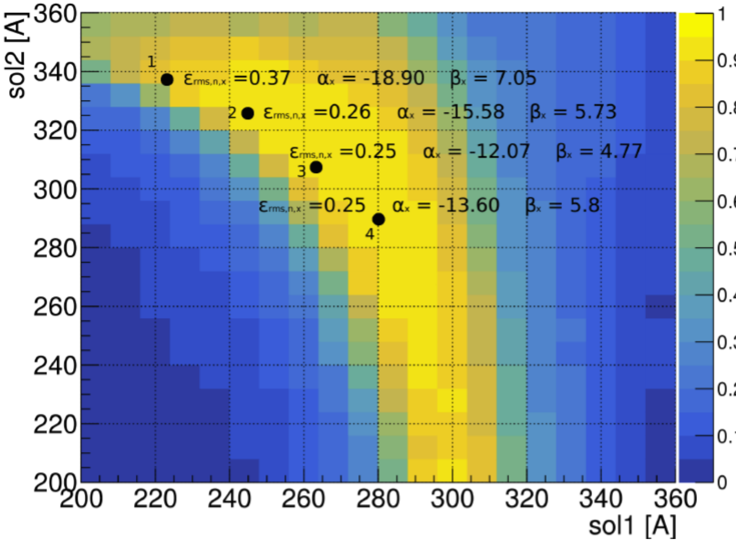


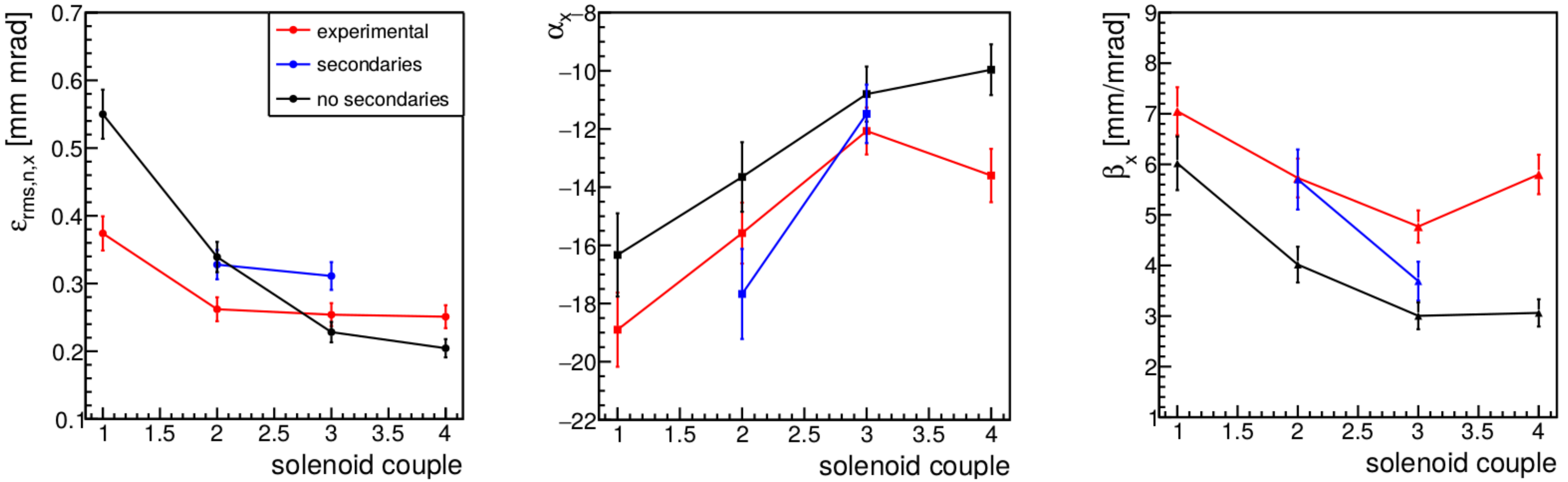
Phase spaces and x projection comparisons.

Benchmark with the results (WARP)

- Trend of the Courant-Snyder parameters with respect to the solenoids values in the LEBT.
- Emittance growing with respect to the solenoid 1 smaller value and solenoid 2 larger value, such as for the proton case. However the emittance growth is smaller.

experimental





Test of the rms distribution: RFQ Output

We tested the «realistic» profile given by the dynamic model with the distribution used in the design stage of the RFQ.

To the q.s. Waterbag and the Gaussian distribution there were given the same Twiss parameters and emittances of the dynamic model output at the RFQ injection. (NOT BEST MATCHED)

This was then tested injecting into the RFQ with TOUTATIS and vanes file with real Voltage shape and R0 with mechanical construction errors.

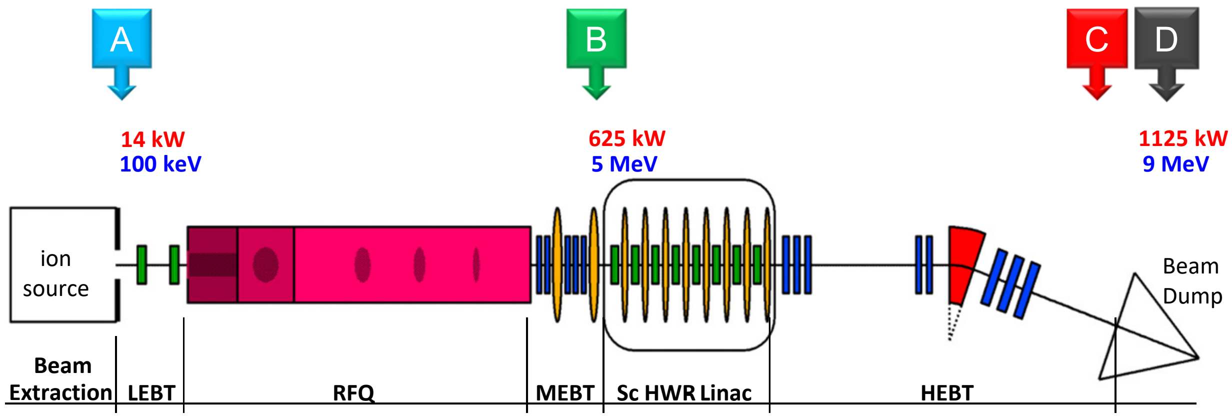
Losses: I_{output} / I_{input}

Dist. Type	Tr. Out Emit.	Long. Emitt.	Halo	Losses	Losses Power
Unit	mmrad	MeVdeg		%	W
Warp	0.20	0.17	3.3	16.0	2.9
Gaussian	0.26	0.20	0.8	16.6	3.0
Waterbag	0.27	0.21	0.4	15.7	2.9

Halo: C. K. Allen and T. P. Wangler, "Beam halo definitions based upon moments of the particle distribution," *Phys. Rev. ST Accel. Beams*, vol. 5, p. 124202, 2002.

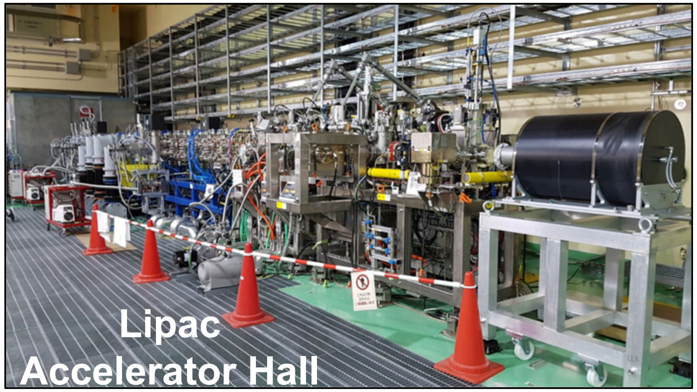
LIPAc Commissioning Plan

- *Phase A:* 140 mA deuteron current at 100 keV in CW **(DC operation postponed after phase B)**
- *Phase B:* 125 mA deuteron current at 5 MeV at 0.1% duty cycle
- *Phase C:* 125 mA deuteron current at 9 MeV at 0.1% duty cycle
- *Phase D:* Ramp up the duty cycle up to CW

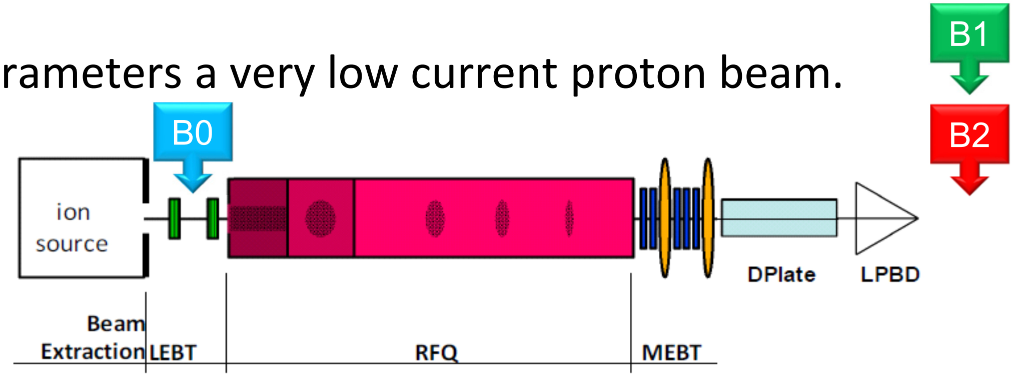


For a general overview see the talk:
Commissioning status of linear IFMIF
Prototype Accelerator (LIPAc) A. Kasugai

Commissioning Phase B details



- *Phase B0:* Characterization of injector parameters between LEBT solenoids. Verification of the possibility to extract and accelerate with the nominal Twiss parameters a very low current proton beam.

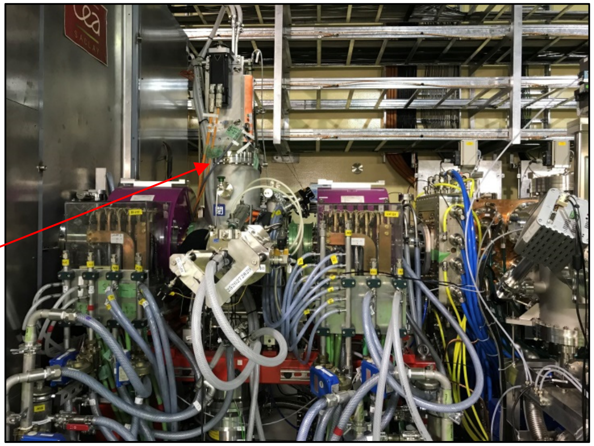


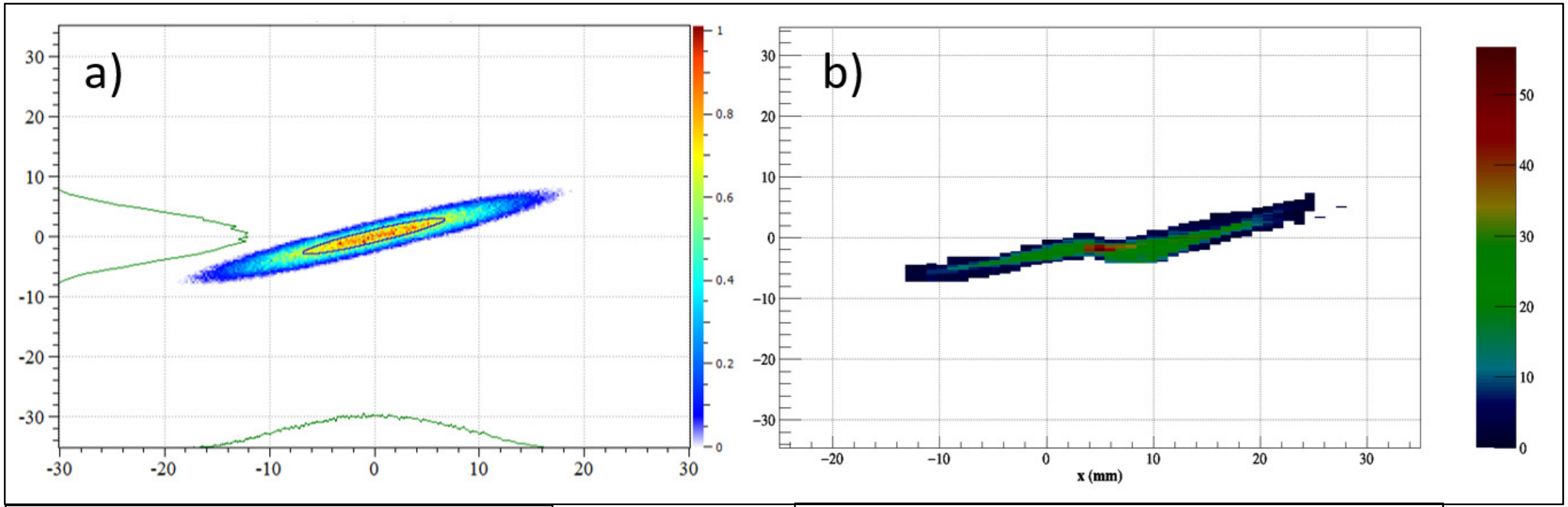
- *Phase B1:* Proton beam at 2.5 MeV with increasing current up to 70 mA with 0.1 % dc. Low current injection will be less sensitive to beam mismatch at RFQ entrance. It will be a test beam for calibration purpose in which all diagnostics, even interceptive ones, could be used.

- *Phase B2:* Deuteron beam at 5 MeV and 125 mA with 0.1 % dc.

Injector - LEBT Commissioning
Characterization at very low current
Phase B0

Comparison simulation/measurement at EMU position for 7 mA proton beam

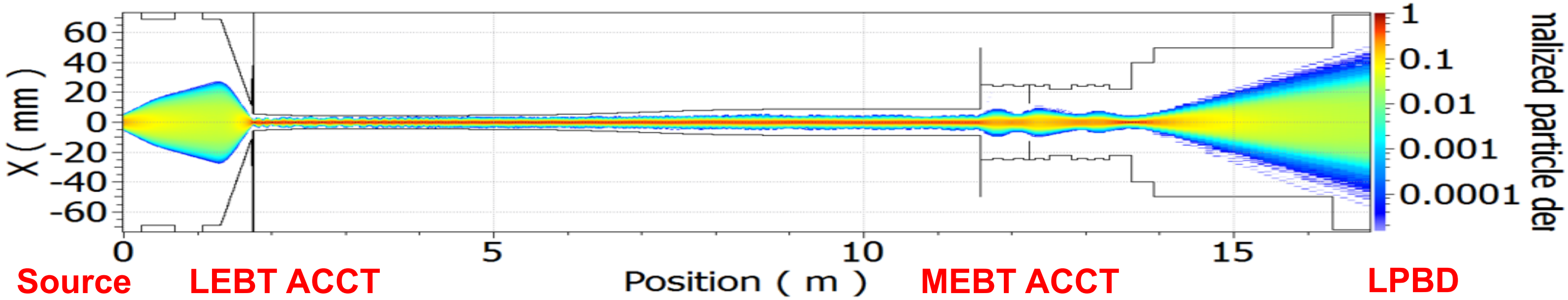


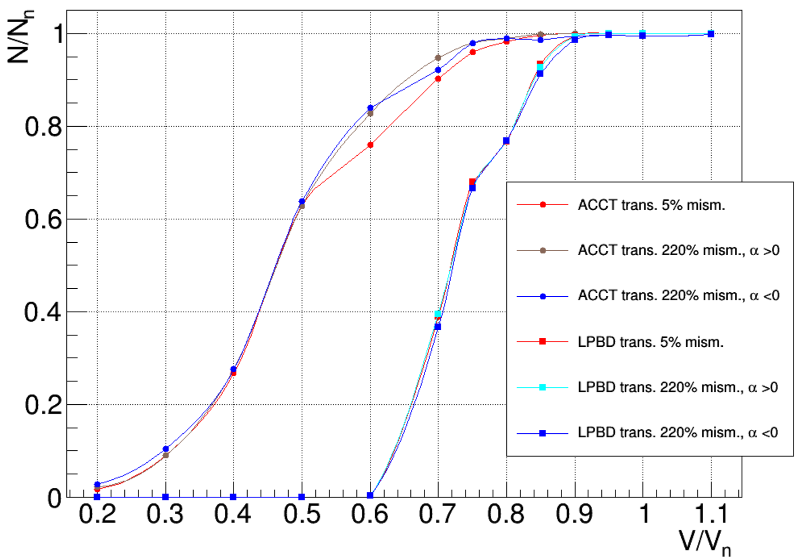


a) Simulated distribution
$\varepsilon_{n,rms}$ = 0.075 mm-mrad

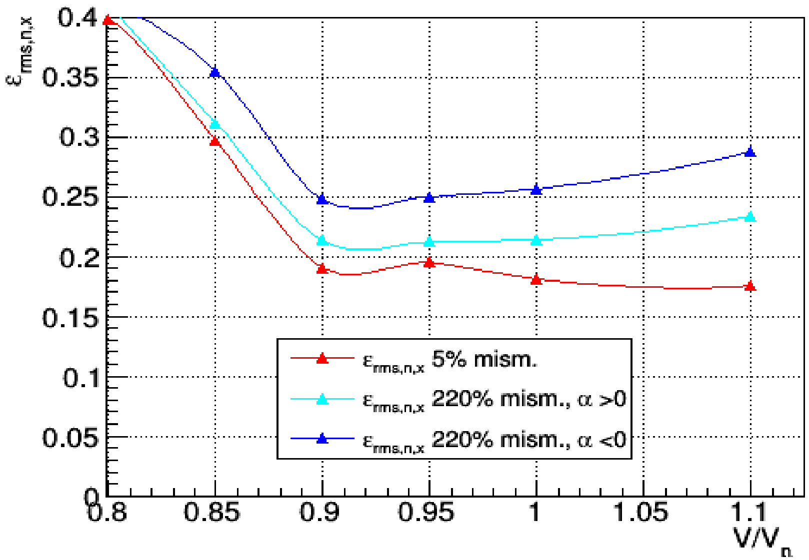
b) Measured distribution
$\varepsilon_{n,rms} = 0.08^{(-0.01+0.004)}$ mm-mrad

Proton Beam at low current (Phase B1)



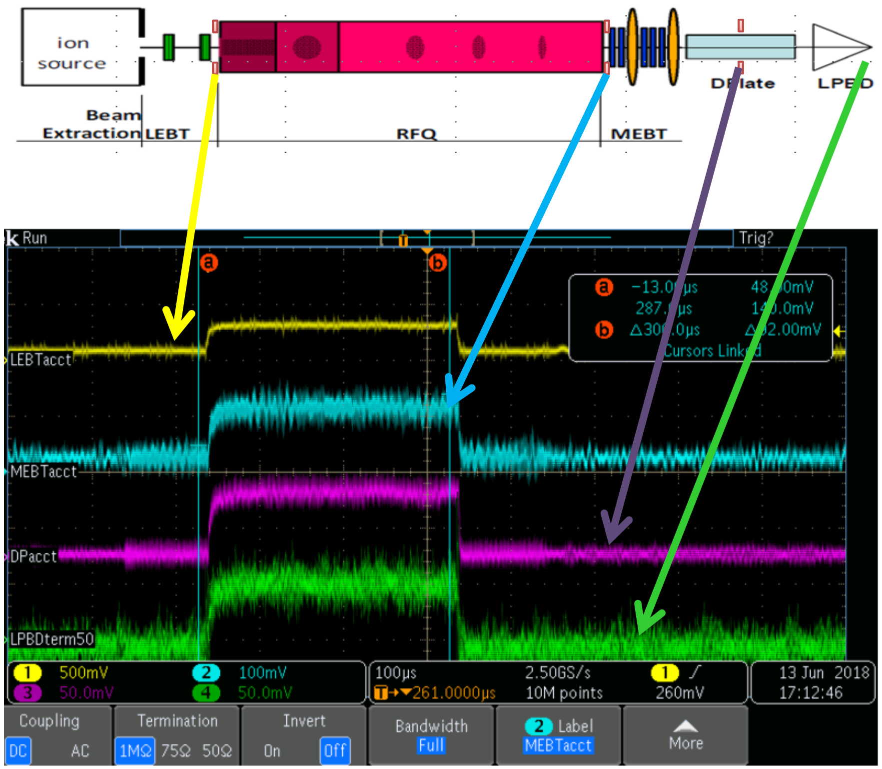


Transmission (N/Nn) from the RFQ input current (LEBT ACCT) to the output of the RFQ (MEBT ACCT) and to the end of the line (LPBD) with respect to different RFQ voltage ratios normalized (V/Vn).



At low current the mismatch is not important

First Beam 13/06/2018



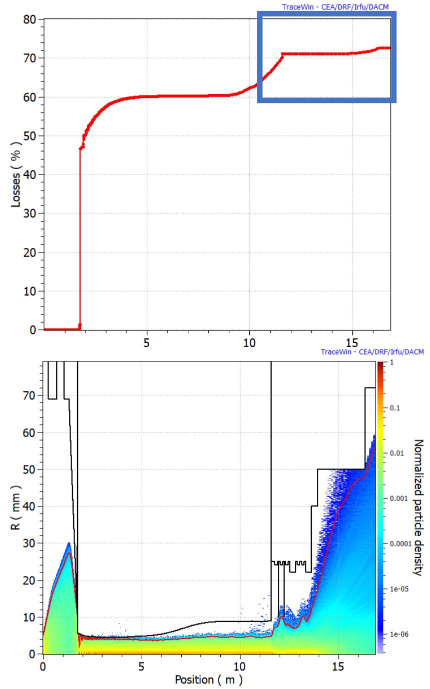
- **RFQ** in amplitude open-loop, **voltage range 70 - 75 kV**;
- **Source** condition:
  - Total extracted current 13 mA
  - pulse 300 micros
  - period 1 second.
- No Doppler shift measurements were possible to determine proton fraction
- At the beginning no beam out the RFQ, only in LEBT ACCT

- After ½ hour of manual LEBT adjustment we arrived at the situation shown in the picture:
  - **LEBT-ACCT 5.3 mA**
  - **MEBT-ACCT 1.7 mA (30%)**
  - **beam dump 1.2 mA (20%)**
- LEBT magnets (see next slide for possible explanation):
  - Sol1=90A
  - Sol2=155A (nom.186A)
  - Steerer1Hor=0, Steerer1Ver=40A
  - Steerer2Hor=0, Steerer2Ver=0.

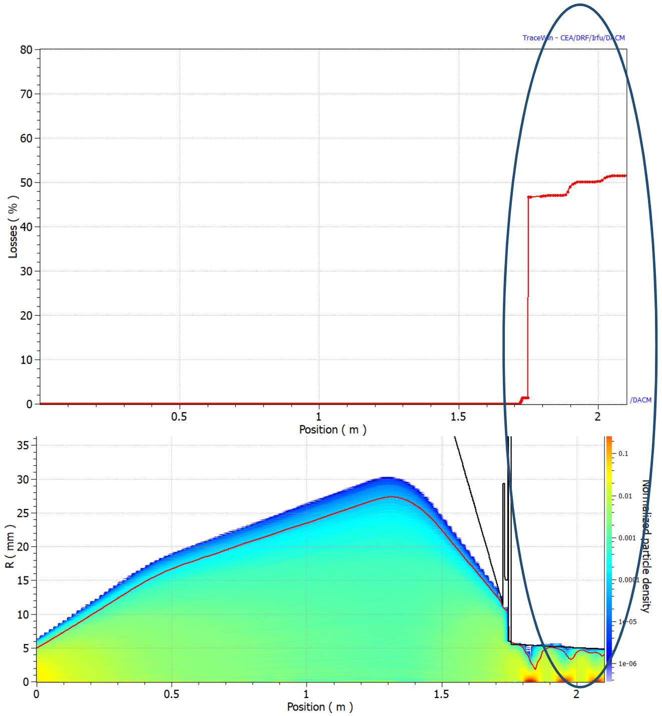
First Beam 13/06/2018
Possible explanation of the actual performances

SOL1= 90 A, SOL2=155 A as in the experiment →weaker Sol2 value allows to fill the RFQ acceptance compensating misalignment effects, but:

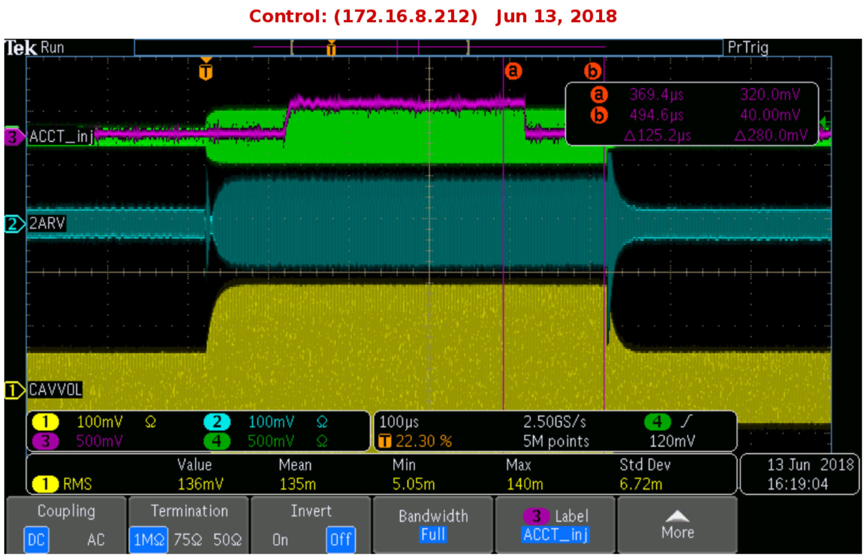
Due to the emittance growth led by RFQ mismatch >>>> 220%. The emittance becomes 5 times the nominal at the MEBT output. Not accelerated particles excluded in Toutatis



We loose half of the beam before the RFQ injection point. This may explain the half current at the ACCT respect to extraction.

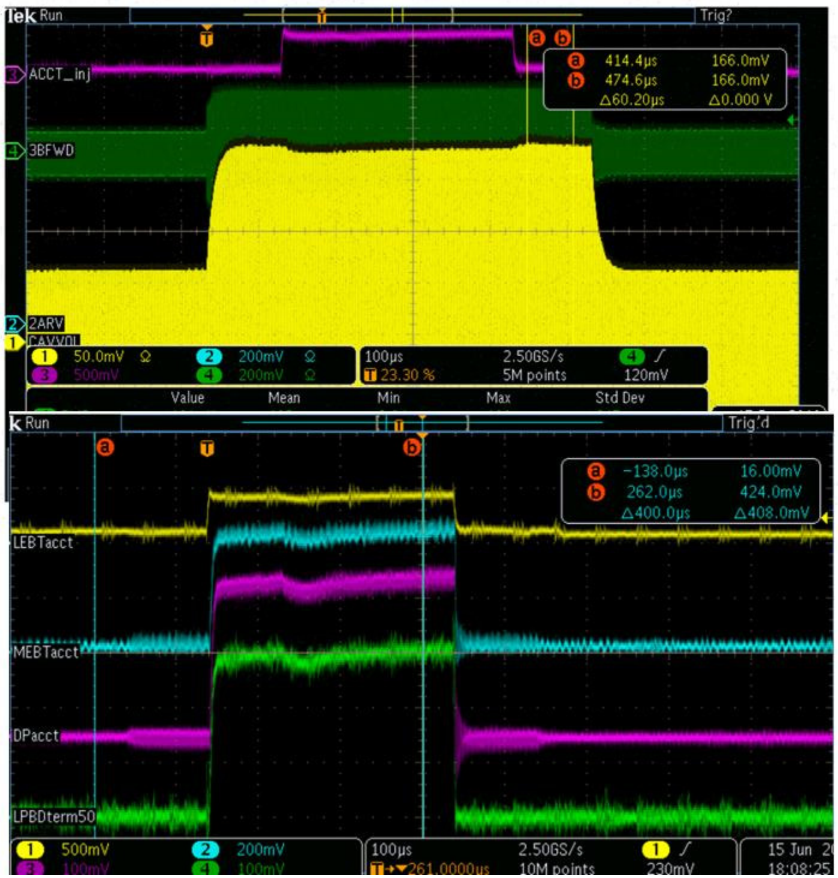


First Beam 13/06/2018



- No voltage drop in the RFQ signal →No beam loading effect;
- No vacuum effects;
- Gamma ray and neutron energy confirmed beam energy higher than 2.2 MeV.
- On 14/06/2018 we reproduced for 1 hour the same situation, RFQ Voltage Locked at 70 kV, and debugged the LEBT scan routine.

Second beam 15/6/2018



- **RFQ** in amplitude close-loop, **voltage 70 kV**
- After running a rountine on LEBT Steerers 1 & 2 we identified a vertical misalignment

- After manually iterateve adjustment of Sol2 and Vert. steerers, we arrived at the situation shown in the picture:
  - **LEBT-ACCT 7.4 mA**
  - **MEBT-ACCT 6.3 mA (85%)**
  - **beam dump 5.4 mA (72%)**
- LEBT magnets:
  - Sol1=90A
  - Sol2=186A (nom.186A!)
  - Steerer1Hor=-20A, Steerer1Ver=80A
  - Steerer2Hor=-20A, Steerer2Ver=20A.

- MEBT **Scrapers** at 10 mm for safety operation
- **Beam loading** observed (not yet measured)

Conclusion

The space charge neutralization is key phenomena that dominates the beam dynamics of the high intensity LEBT. In this talk, a method was applied to achieve an enough robust model to describe the input of the RFQ: the preliminary study shows that despite the very similar power deposition and losses, the second order moments may vary with respect to the standard design distributions, with the same Courant-Snyder parameters in case of mismatched beam. Further studies are foreseen as well as an upgrade of the model with the extraction region included.

The first beam input of IFMIF-EVEDA RFQ has been chosen and deeply studied. Thanks to its robust beam dynamics, it will allow to debug any possible issue of the RFQ in a safety environment. The current of the beam will be then ramp up to 30 mA, to study the effect of the growing space-charge term in the accelerator.

The first days of beam operations have confirmed the results of these simulations, in particular for what the optimum values of the lenses (solenoids) is concerned. An important misalignment between the LEBT and RFQ requires a high value of steerers and requires further tuning work to recuperate the nominal beam transmission (present value is 85%).

Last Slide: Work in progress…

- The BD is able to help a lot during the commissioning, i.e. is mandatory to simulate the accelerator to understand what is going on.

- The first days operation show some results and some problems that needed to be understand, probably due to the alignments from LEBT to RFQ.

- During the commissioning at high current a model of beam distribution, better than Gaussian or Waterbag, is necessary for characterize the losses at high energy.

Many thanks to F4E,QST and all the home institutions for their constant support.
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P. Cara, IFMIF/EVEDA Project Leader

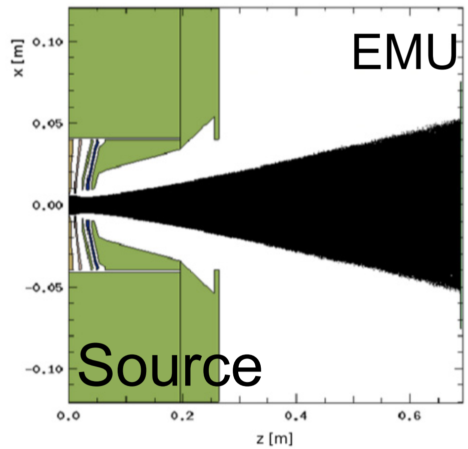
For a general overview see the talk:
Commissioning status of linear IFMIF Prototype Accelerator (LIPAc) A. Kasugai

Backup slides

Perspectives of Dynamic Model (WARP)

- The constant model it is a useful and fast tool to determine the main characteristics of the LEBT. It relies heavily on the experimental results and it is not usable for higher perveances or «hollowed» source beam spatial distribution.
- The dynamics model is «more self-consistent» than the previous and it is applicable to a larger spectra of perveance. However, it is very slow and subject to simulation trend (such as instabilities and trend with the number of particle). Therefore, even in this case, it is essential to use the experimental data to «tune» the model.

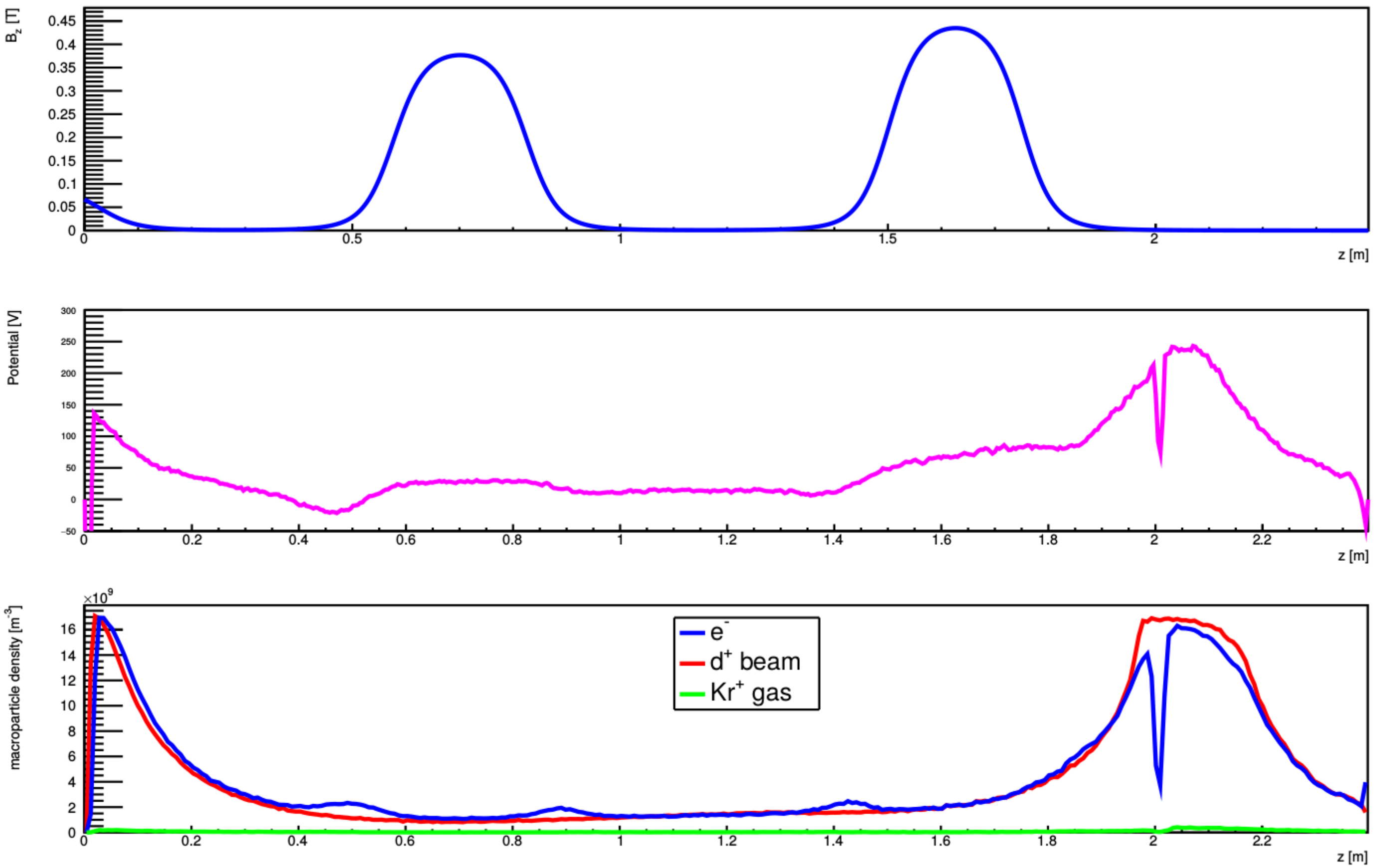
Implementation of the full source extraction is ongoing…



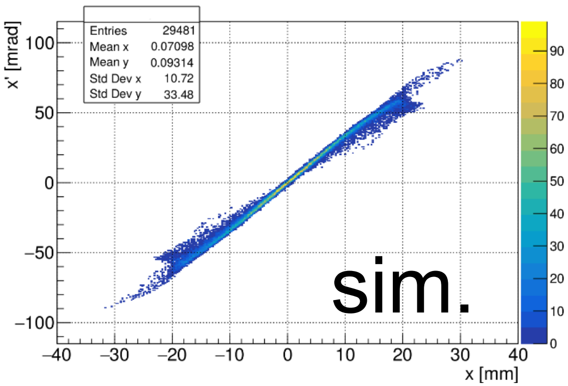
Value	measurement	simulation
σ_{beam}	39.2 $\pm$0.5	22.3 $\pm$4.4
$\varepsilon_{rms,n,x}$	0.44 $\pm$0.03	0.43 $\pm$0.03
α_x	-13.86 $\pm$1.39	-16.31 $\pm$2.00
β_x	14.90 $\pm$1.49	10.93 $\pm$2.61

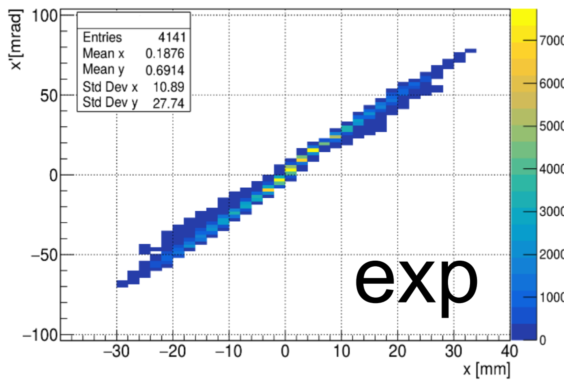
Promising results….

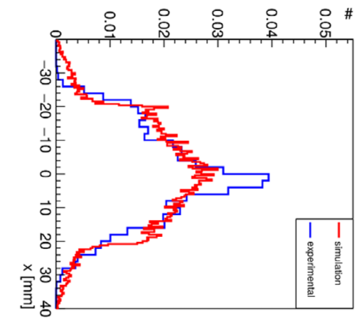
Overall trend of species along axis

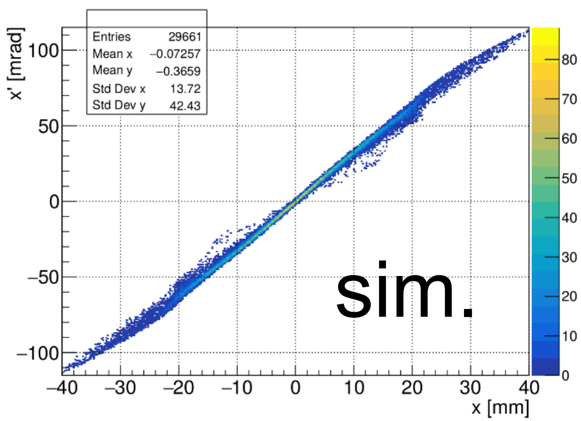


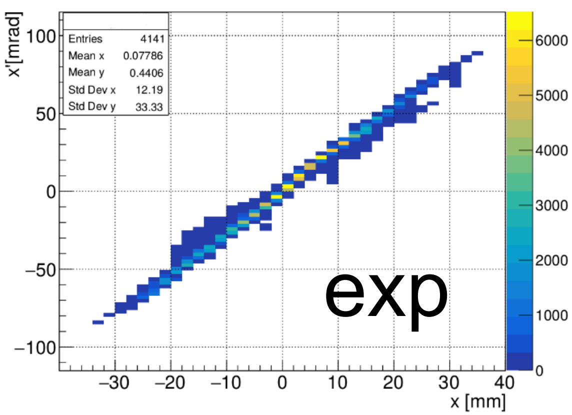
Benchmark with the results

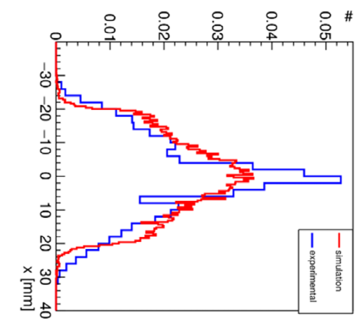




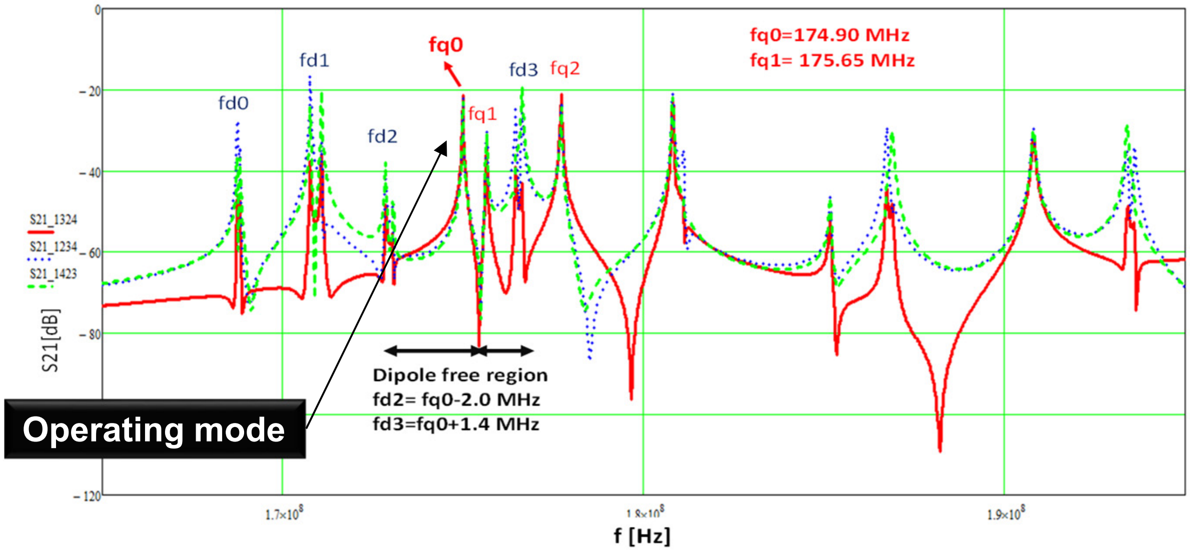


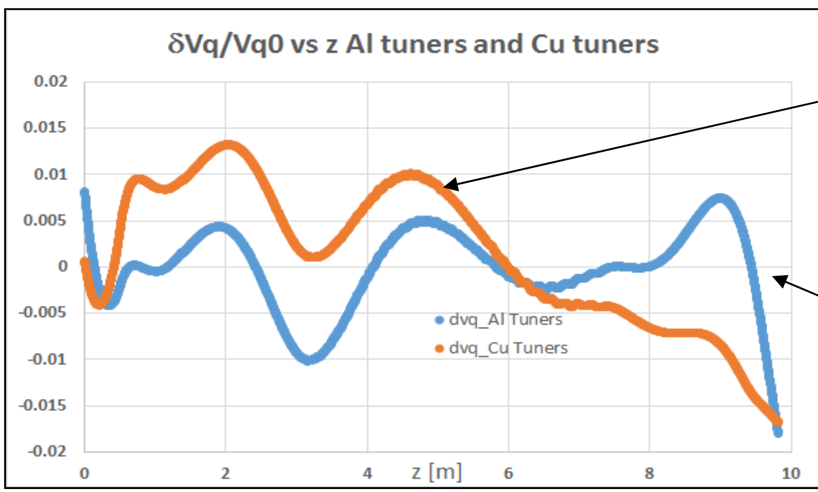


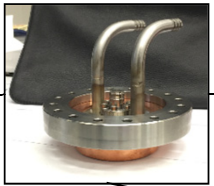


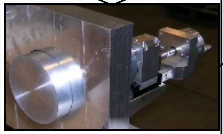


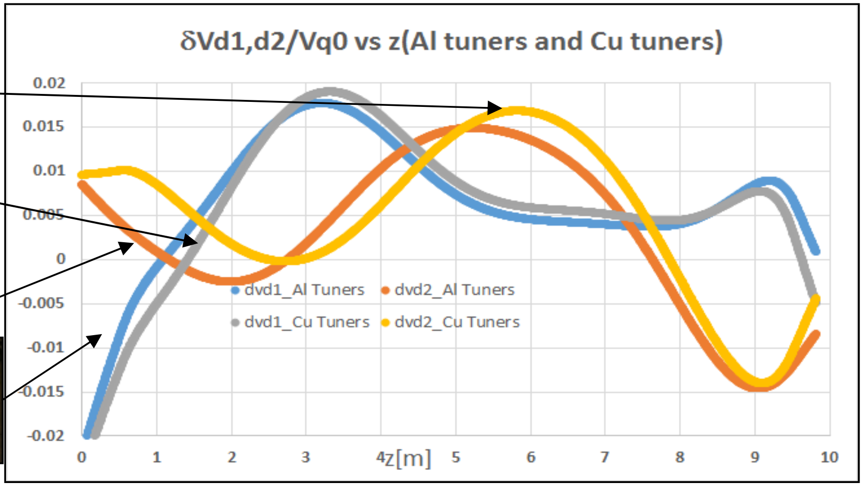
RFQ tuning after final tuners assembly





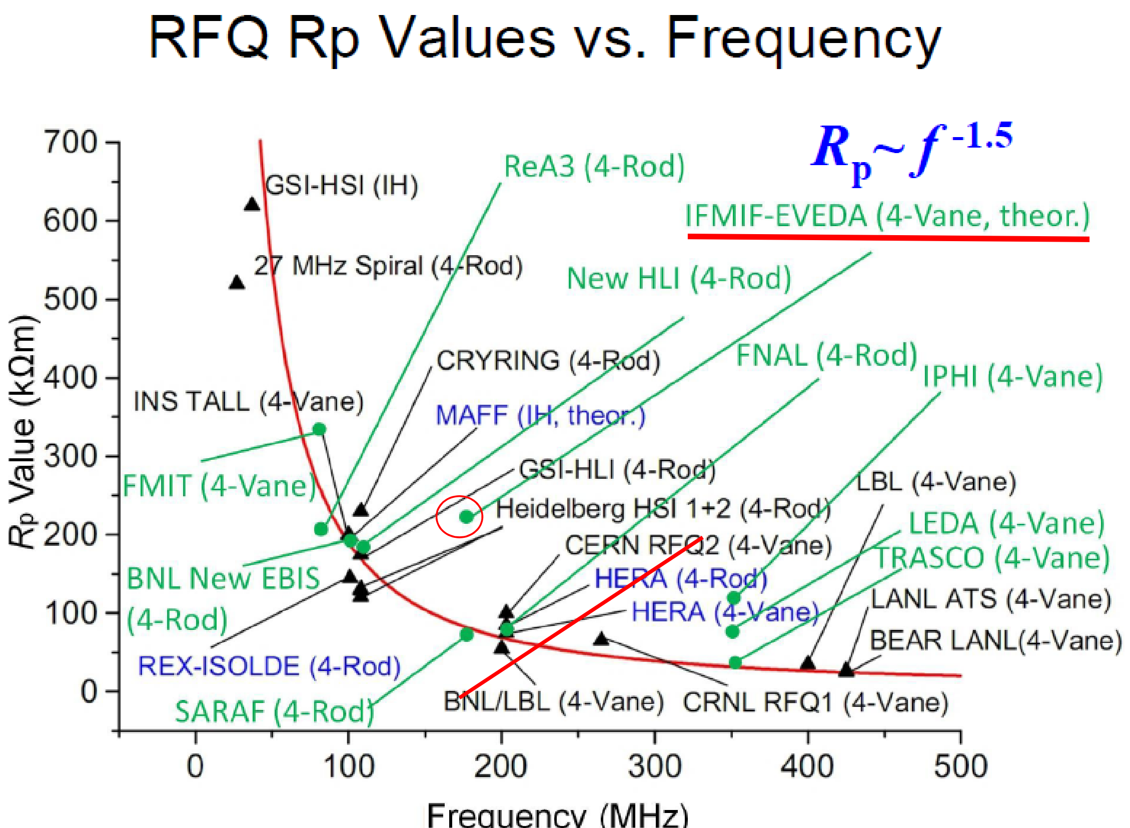






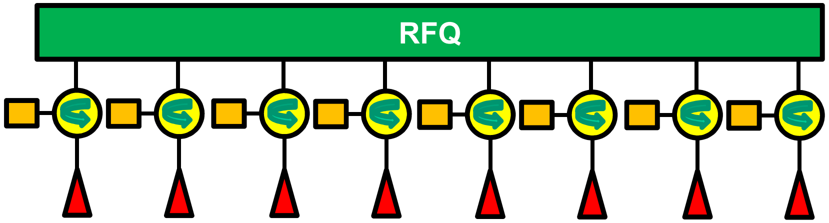
RFQ RF Quality

- The final measured frequency was equal to 174.989 MHz, equivalent to 175.014 MHz, if one takes into account the rescaling to nominal 20 deg temperature and the effects of vacuum and beam loading (-1 deg water temperature correction necessary).
- Quality factor was measured Q_0 **= 13200 ± 200** that is 82% of SUPERFISH value (low tuner losses).
- The excellent shunt impedance of the design was achieved: **R_{sh}=201 kΩ-m**



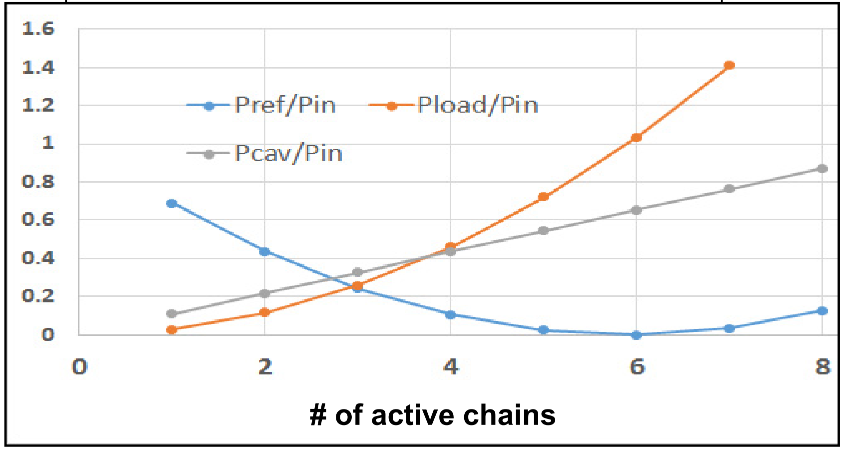
Original transparency by prof. H. Klein

Eight chains coupling challenge



- RF couplers optimized for beam operation
- In conditioning mode without beam, 13% reflected power if foreseen from each chain
- In case of chains amplitude or phase unbalance reflected power amount can increase significantly

Amplitude unbalance (no beam)



- Reflected power decreases with active chains number reaching a minimum with 6 chains.
- Cavity power increases with active chains number
- Reflected power on any inactive chain increases with the number of active chains. It can reach 140% of the single chain input power, with 7 chains active

In case of phase unbalance, calculations show that 400% of nominal power can be reached on unbalanced chain reflected power in case of 180 deg phase error.

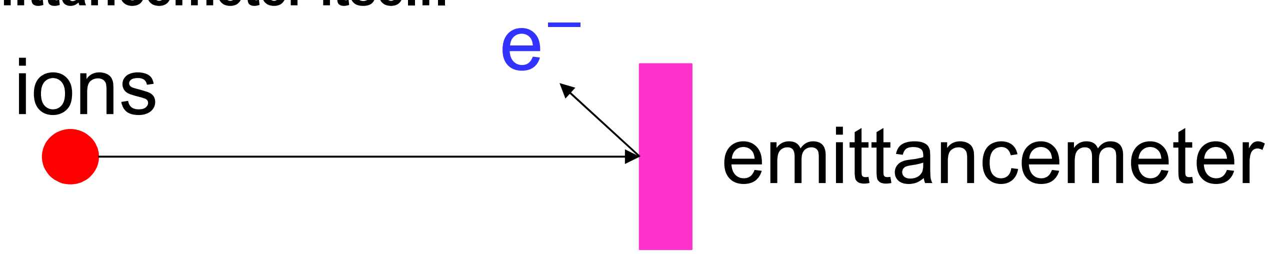
Hint of the effect of the secondary e-

- The vacuum level after the RFQ injection point is of 10^{-7} mbar and therefore low level of neutralization is expected.
- However, from the trace forward process, the level of s.c.c. below 20% do not fit the experimental emittance.

s.c.c.	Meas. $\varepsilon_{\mathrm{rms,n,x}}$	Sim. $\varepsilon_{\mathrm{rms,n,x}}$
87%	0.34 $\pm$0.02	0.32
0%	0.34 $\pm$0.02	0.43

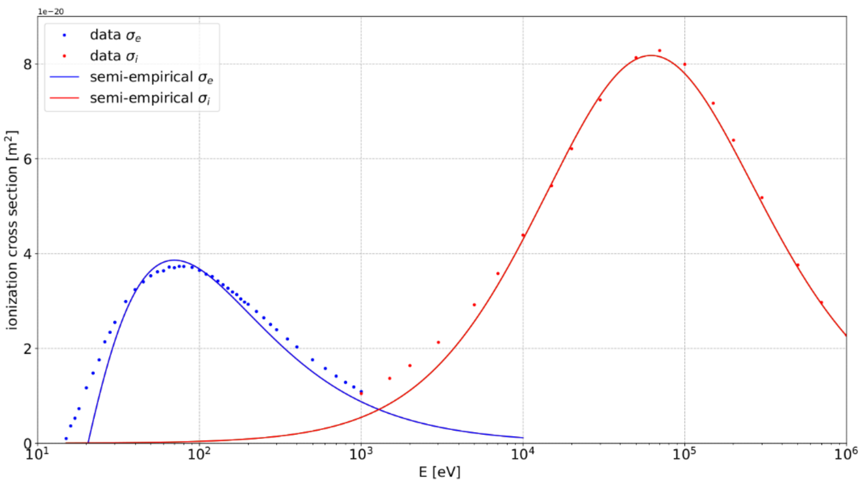
s.c.c.	Meas. I_{BS}	Sim. I_{BS}
87%	50 $\pm$1	46
0%	50 $\pm$1	55

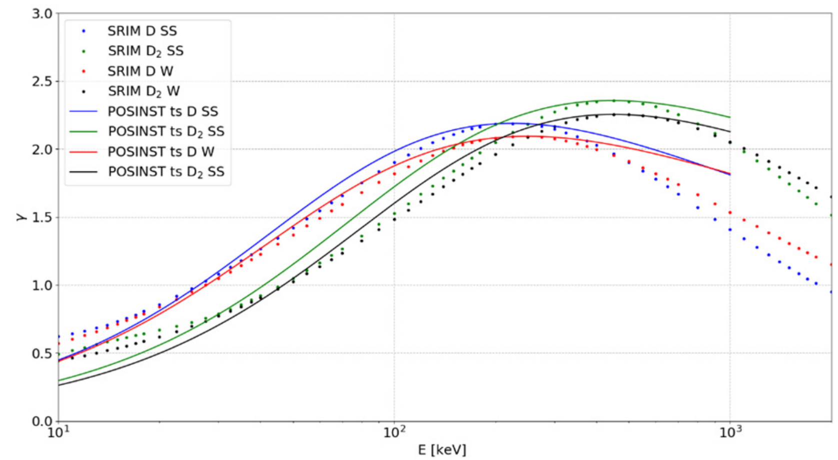
- **This fact suggests some contribution to the s.c.c. by the emittancemeter itself.**



Cross sections from residual gas and walls

Two sources of electrons implemented: from residual gas and collisions with the beam pipe or interceptive diagnostics.





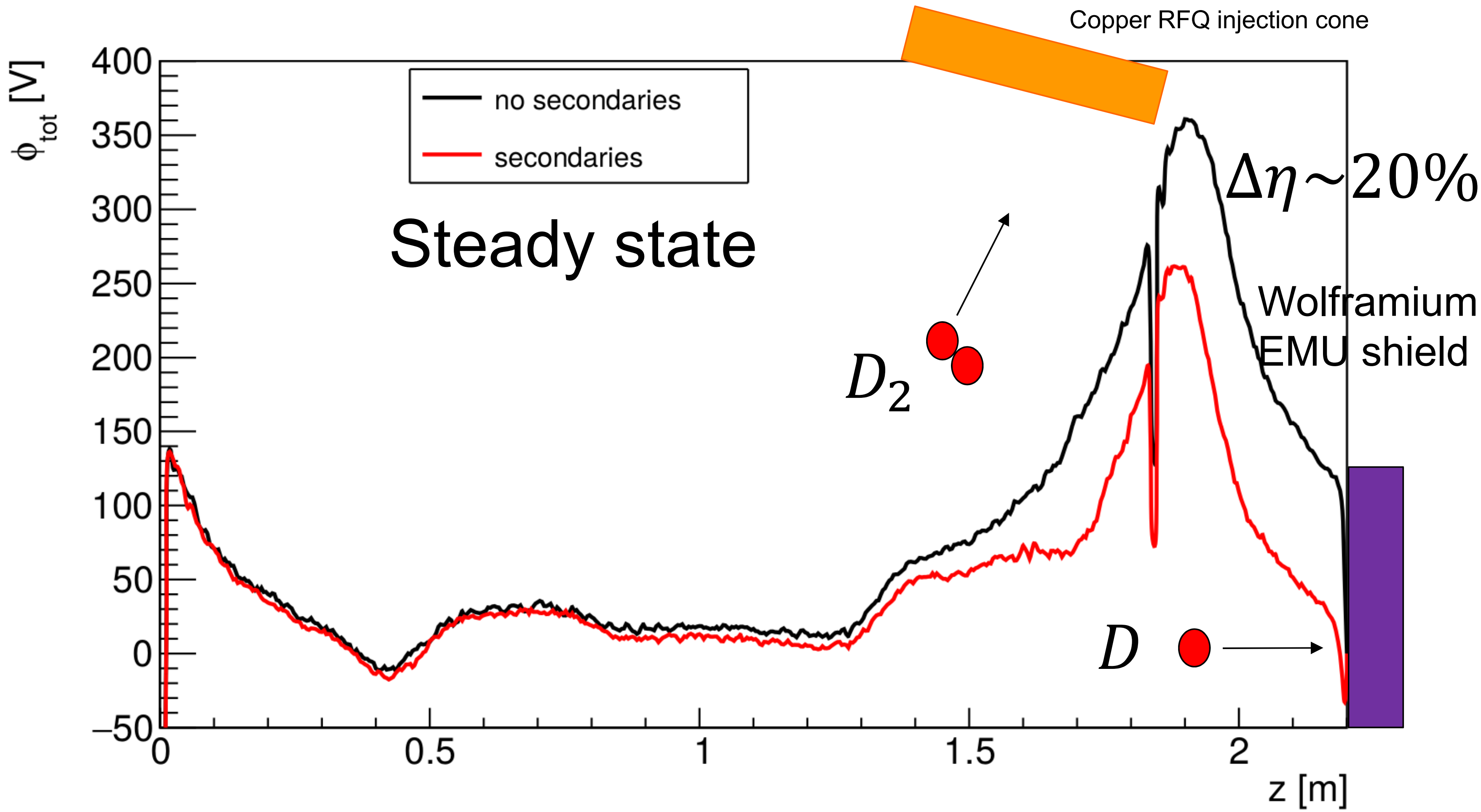
$$\begin{cases} D^+ + Kr \rightarrow Kr^+ + e^- + D^+ \\ D_2^+ + Kr \rightarrow Kr^+ + e^- + D_2^+ \\ D^+ + D_2 \rightarrow D^+ + e^- + D_2^+ \\ D_2^+ + D_2 \rightarrow D_2^+ + e^- + D_2^+ \\ e^- + D_2 \rightarrow D_2^+ + e^- + e^- \\ e^- + Kr \rightarrow e^- + e^- + Kr^+ \end{cases}$$

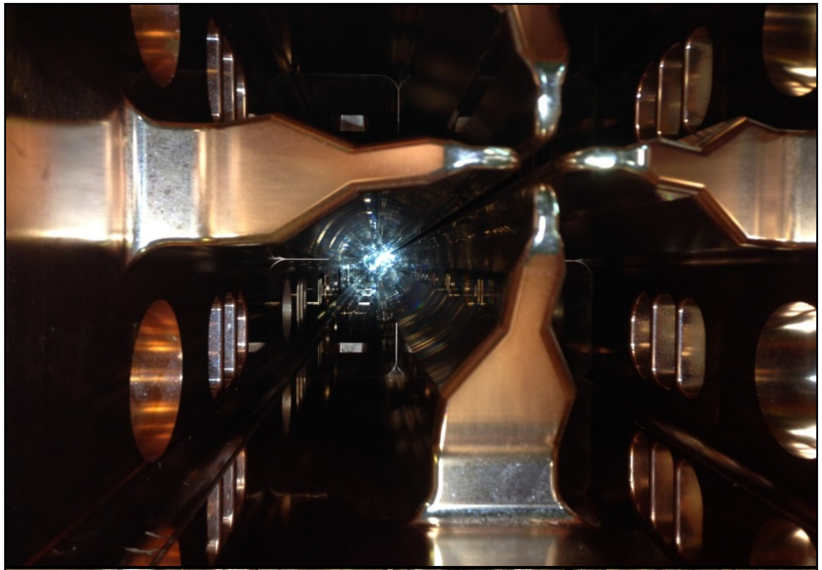
WARP

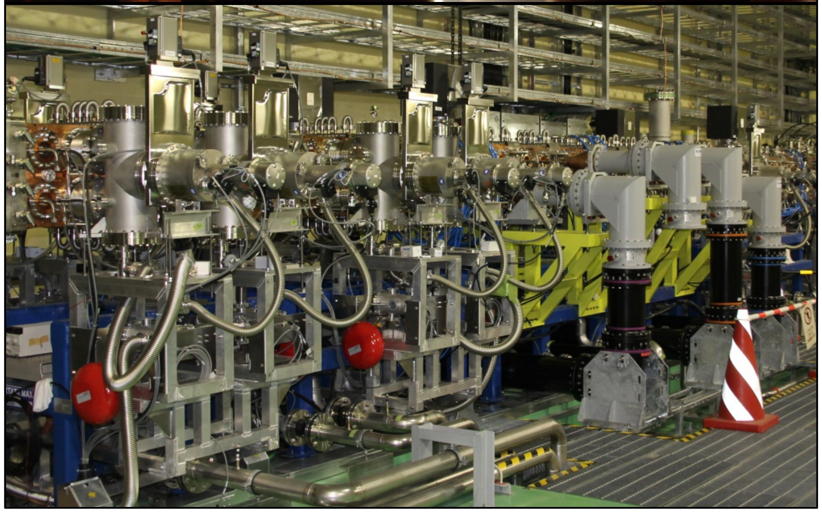
$$\begin{cases} d^+ + SS/Cu \rightarrow e^- \\ d^+ + W \rightarrow e^- \\ d_2^+ + SS/Cu \rightarrow e^- \\ e^- + SS/Cu \rightarrow e^- \end{cases}$$

WARP+POSINST

Secondaries from collisions vs without







IFMIF-EVEDA RFQ

Input/output Energy	0.1-5	MeV
Duty cycle	cw	
Deuteron beam current	125	mA
Operating Frequency	175	MHz
Length (5.7 λ)	9.78	m
Vg (min – max)	79 – 132	kV
R0 (min - max) ρ/R0=.75	0.4135 - 0.7102	cm
Total Stored Energy	6.63	J
Cavity RF power dissipation	550	kW
Maximum dissipated power	86	kW/m
Power density (average-max)	3.5-60	kW/cm^2
Q_0/Q_{sf}=0.82	13200	
Shunt impedance ($<V^2>$)L/P_d	201	kΩ –m
Frequency tuning	Water temp.	