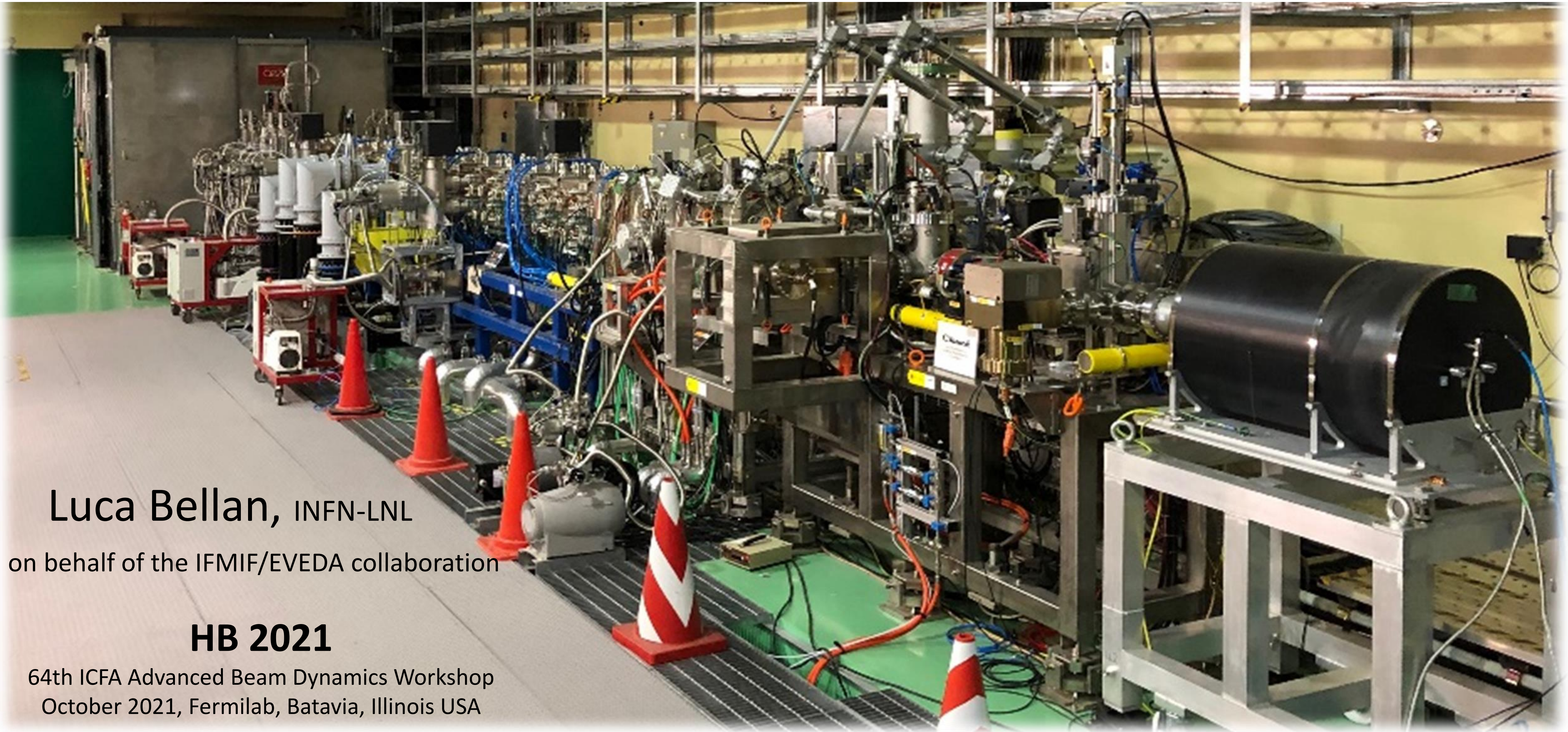
Acceleration of the High Current Deuteron Beam Through the IFMIF-EVEDA RFQ: Confirmation of the Design Beam Dynamics Performances



Luca Bellan, INFN-LNL

on behalf of the IFMIF/EVEDA collaboration

HB 2021

64th ICFA Advanced Beam Dynamics Workshop
October 2021, Fermilab, Batavia, Illinois USA

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- The MEBT (medium energy beam transfer line)
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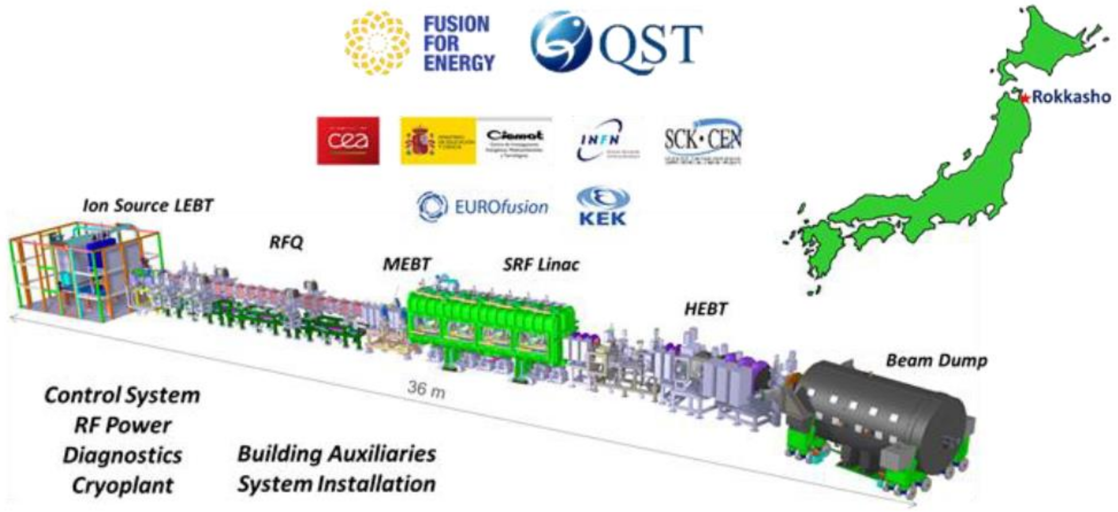
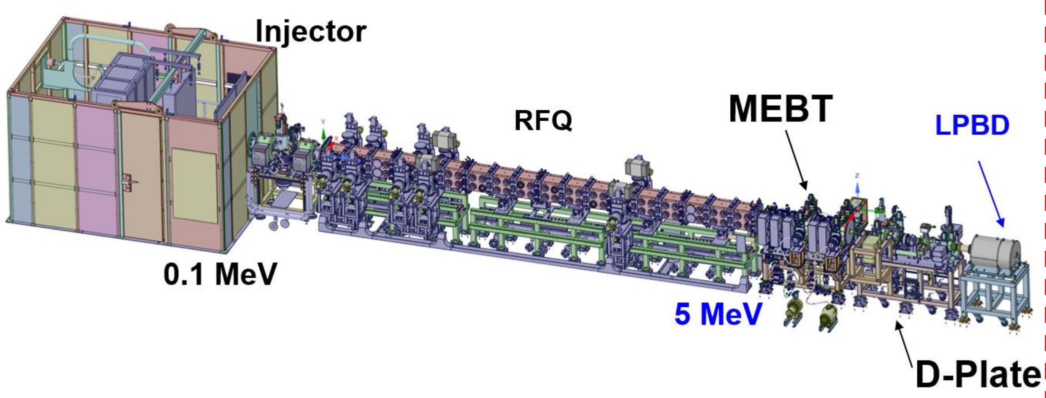
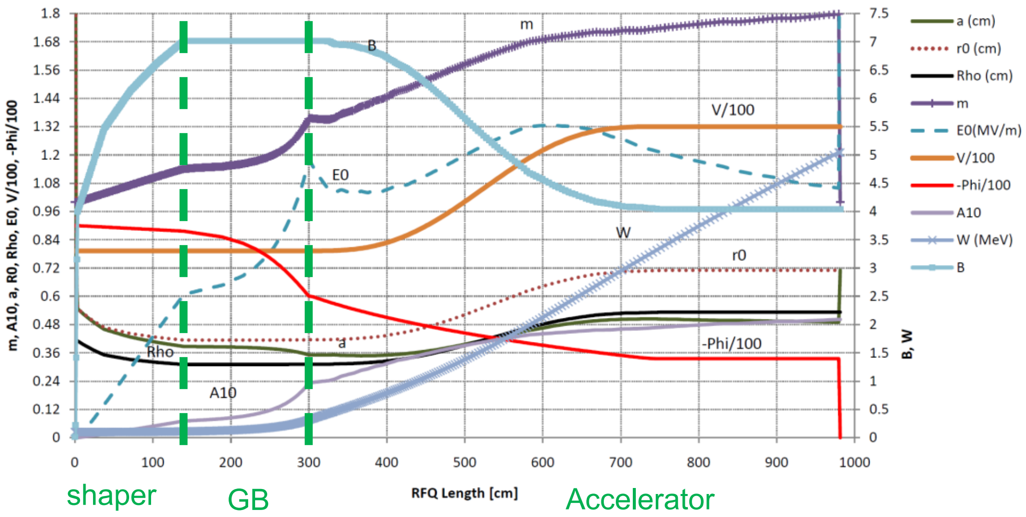
Full IFMIF/EVEDA prototype: 125 mA CW D^+ @ 9 MeV

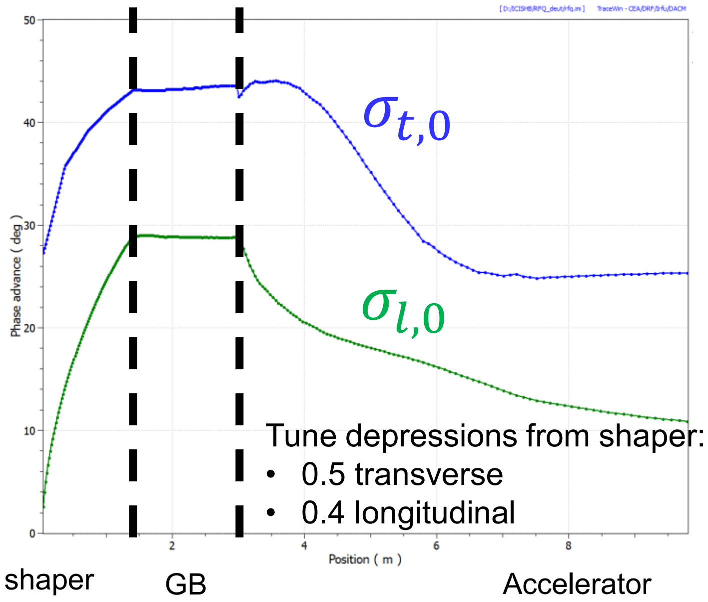


Beam dynamics commissioning phase (0.1% D.C., limited by LPBD)



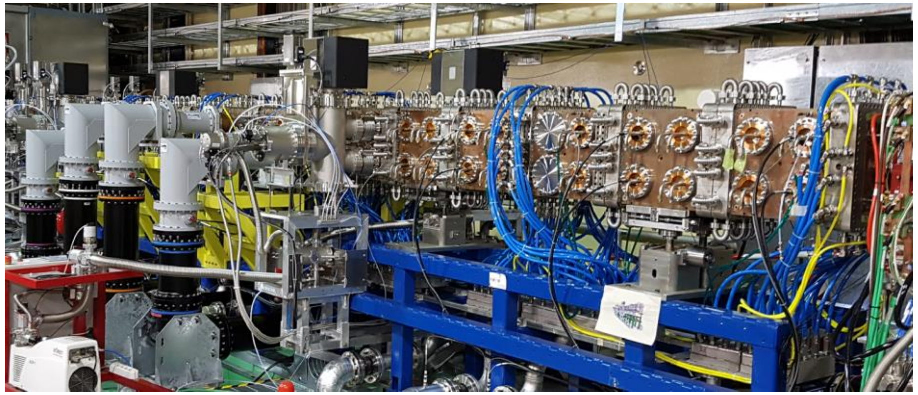
IFMIF Radio Frequency Quadrupole





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/cm²
Q_0/Q_{sf}=0.82	13200	
Shunt impedance (<V²>)L/P_d	201	kΩ–m
Frequency tuning	Water temp.	
N cells (βλ/2)	489	

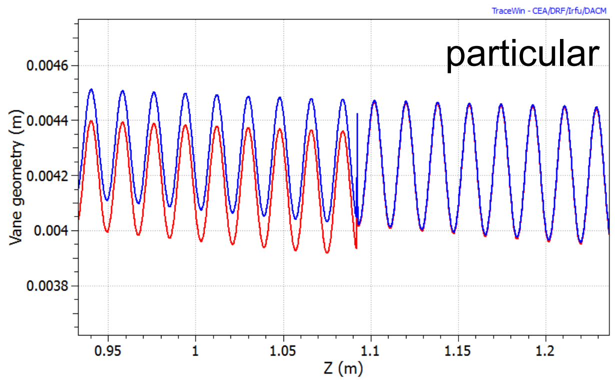
- 4-vane 9.8 m CW RFQ for 125 mA deuteron beam, from 0.1 to 5 MeV, Kilpatrick 1.76
  - **1.85 reached during whole assembly pulsed conditioning.** 6% D.C. at nominal voltage, 20% D.C. at half voltage.
  - **1.94 CW for 5 hours of last supermodule at LNL.**,
- Generalized perveance 10^{-3} to 10^{-5}
- Low B modification, after Critical Design Review, for decreasing input beam requirements from LEBT:
  - rms beam convergence requirement drops from 43 mrad to 24. mrad
  - Transmission for a 4D Gaussian matched (4 sigmas) beam drops from: 95% to **93.7%** (accelerated only considered)
- **Input/output rms normalized transverse emittance: 0.25/0.26 mm mm mrad.**
- Longitudinal rms emittance: 0.2 MeV deg



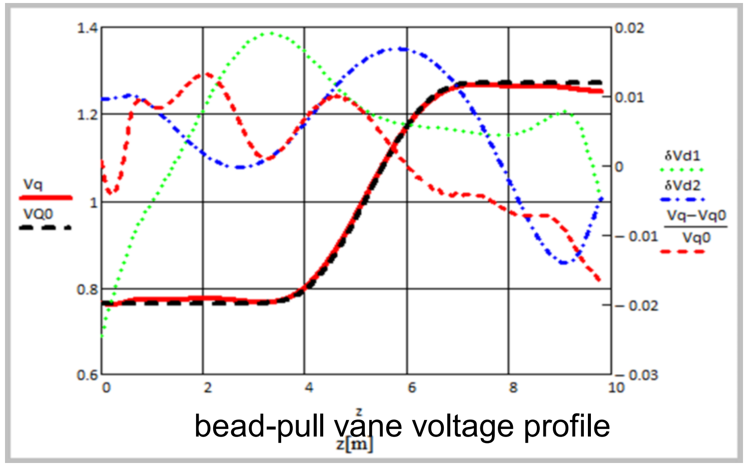
Model background

- The RFQ was integrated in the simulation via the software TOUTATIS
- The model integrated was the “as-built” model.

“As built” model includes:



Mechanical errors



bead-pull vane voltage profile

Parameter	Relative diff. between nominal and as built simulations
$\Delta\varepsilon_{rms,t,n}/\varepsilon_{rms,t,n}$	+3%
$\Delta\varepsilon_{rms,l}/\varepsilon_{rms,l}$	+8%
$\Delta transmission / Nominal\ Transmission$	- 2% (i.e. 91.8%)

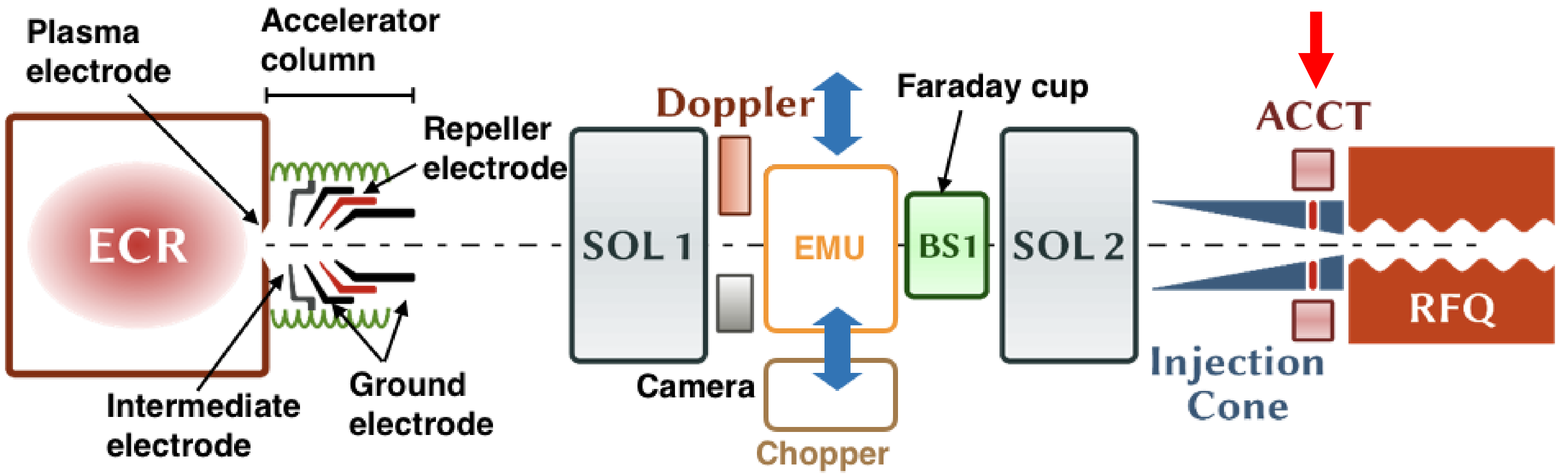
Input matched beam requirements (at RFQ injection point) for 90%> transmission:

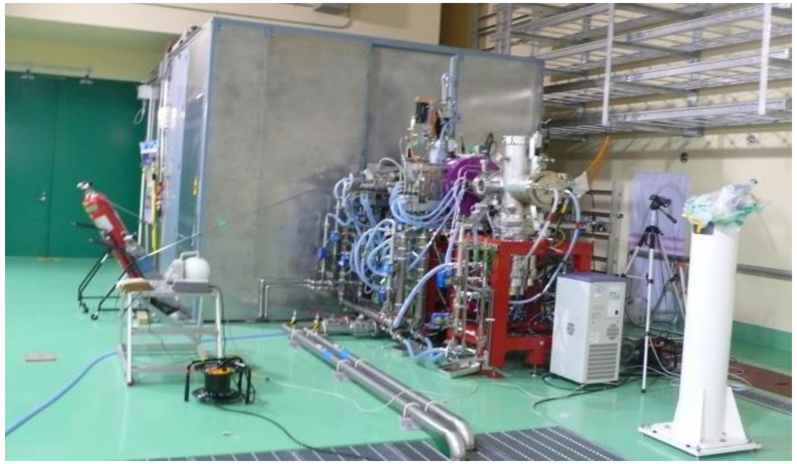
$$I_{beam} \Rightarrow \varepsilon_{Gauss,rms,t,n} \Rightarrow \forall \varepsilon_{rms,t,n} < \varepsilon_{Gauss,rms,t,n}$$

Defined as the maximum rms emittance at I_{beam} that can transmit > 90% of the beam, in case of 4D Gaussian distribution, 4 sigmas cut.

- Not equilibrium distribution from the source (hollow, tales etc..)
    - Design is done following the evolution of the rms quantities evolution (Sacharer equivalent principle) in order to decrease the dependence with respect the input distribution and to built a more general guideline for the input RFQ evaluation

The injector





- ECR ion source type with two coils
- Magnetic LEBT transfer line composed by two solenoids (space charge comp. applies)
- 5 electrode extraction (100 kV- variable – ground – repeller - ground)
- Multispecies beam transport with generalized un-neutralized perveance between 5×10^{-4} to 5×10^{-3}
- **Possibility to extract proton at 50 keV (scaled beam dynamics) to be used as a probe beam and for test at low power**. Chopper implementation for the same reason
- Gas injection (Kr) in the middle of the LEBT for boosting space charge compensation.

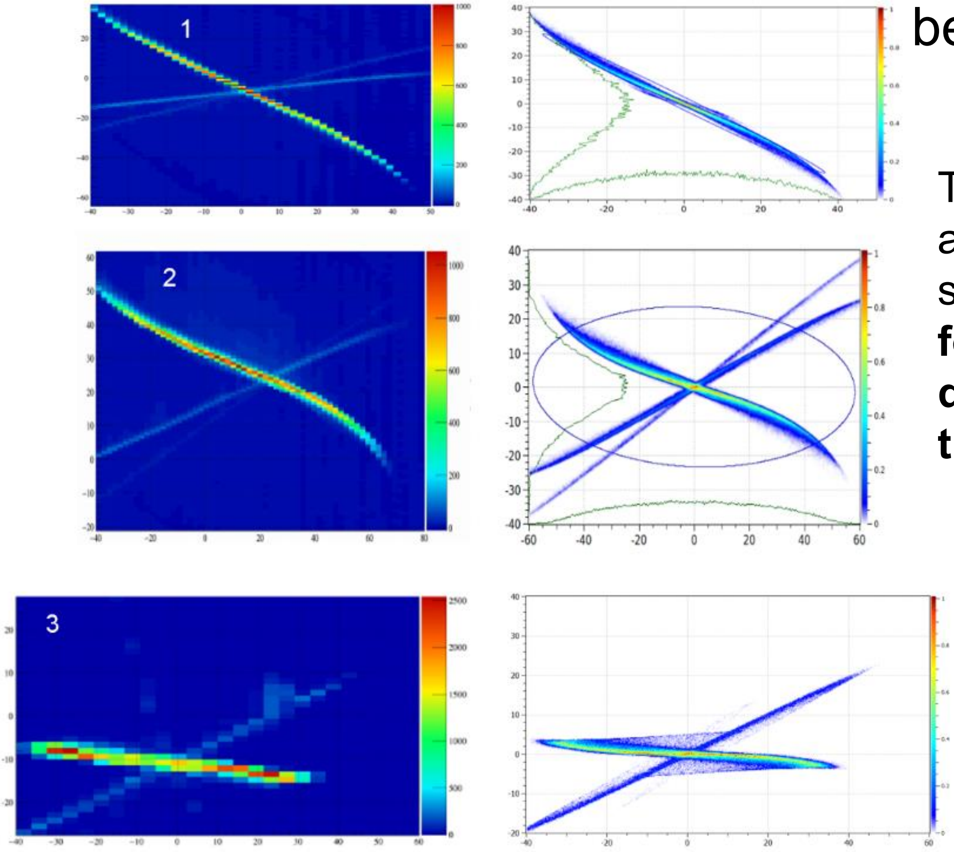
⇨ To supply the required current beam at the RFQ entrance, below $\boldsymbol{\varepsilon_{rms,t,n} < 0.3\ mm\ mrad}$ **(**$\varepsilon_{Gauss,rms,t,n}(125\ \mathrm{mA})$**)**, with ideally 0% mismatch.

⇨ Very difficult to measure the phase spaces at RFQ injection point (power density, technological difficulties).

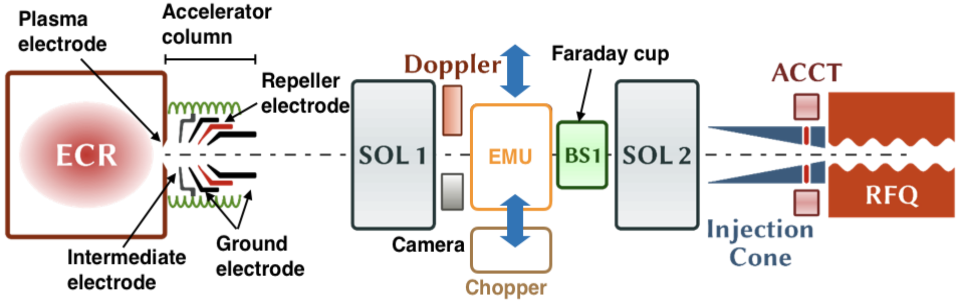
⇨ Measure of the phase spaces in two different points (middle of the solenoids and after RFQ injection cone during injector commissioning). ⇨ Should be interpolated by some support model

Criterion for beam injection into the RFQ

Measured **Simulated**



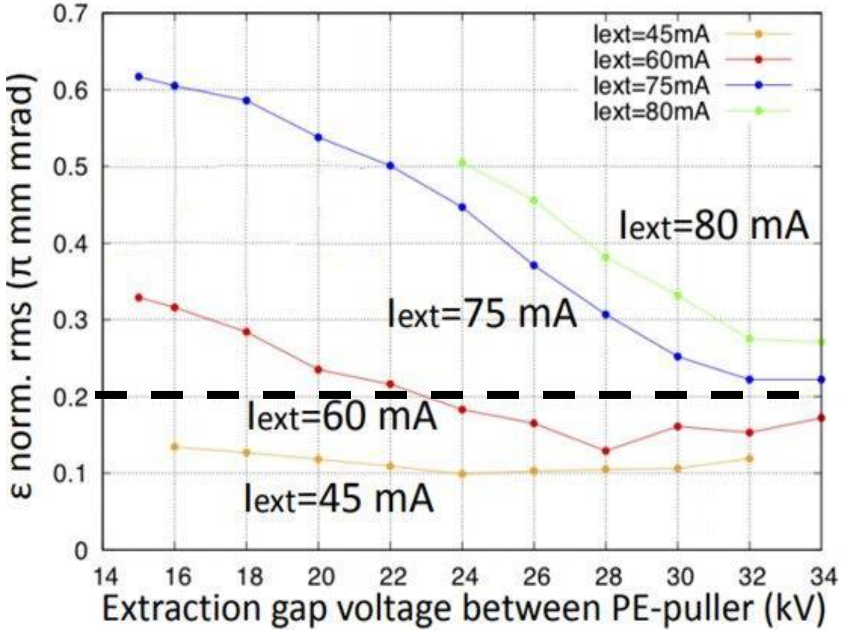
XX' phase spaces between solenoids



The emittance measurements are routinely taken between the solenoids. **Developed a criteria for evaluation of the beam quality before injection into the RFQ**

Cross talk between simulations and measurements

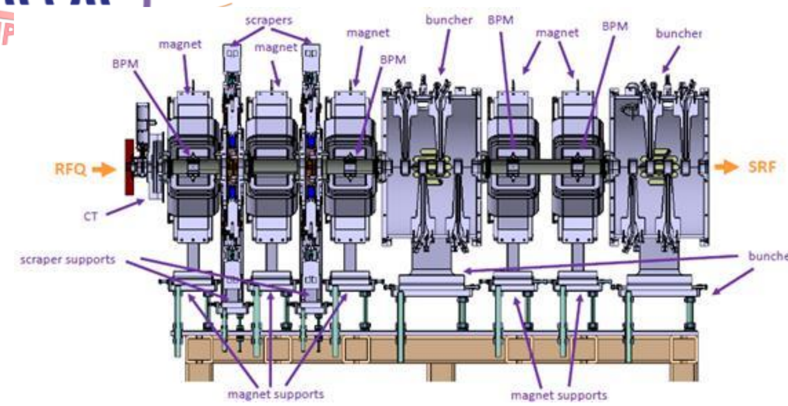
EMU measurements

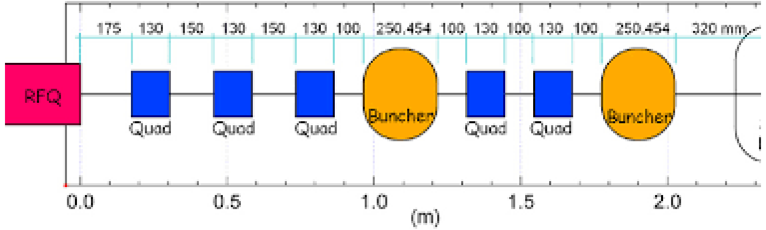


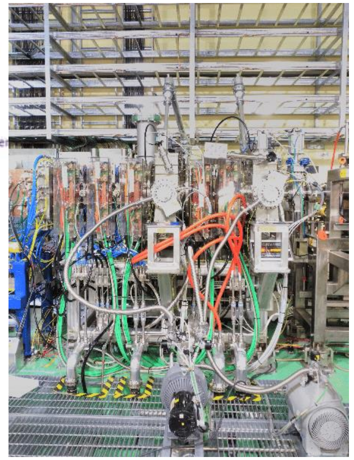
N	Sp.	Energy [keV]	I_{ext} [mA]	$\epsilon_{exp}/\epsilon_{sim}$	$\alpha_{exp}/\alpha_{sim}$	β_{exp}/β_{sim}
1	H^+	50	70	0.25/0.25	14.8/10.7	14.7/13.6
2	H^+	50	87	0.38/0.34	7.3/5.8	18.3/17.4
3	D^+	100	163	0.19/0.19	2.2/1.4	20.7/18.0

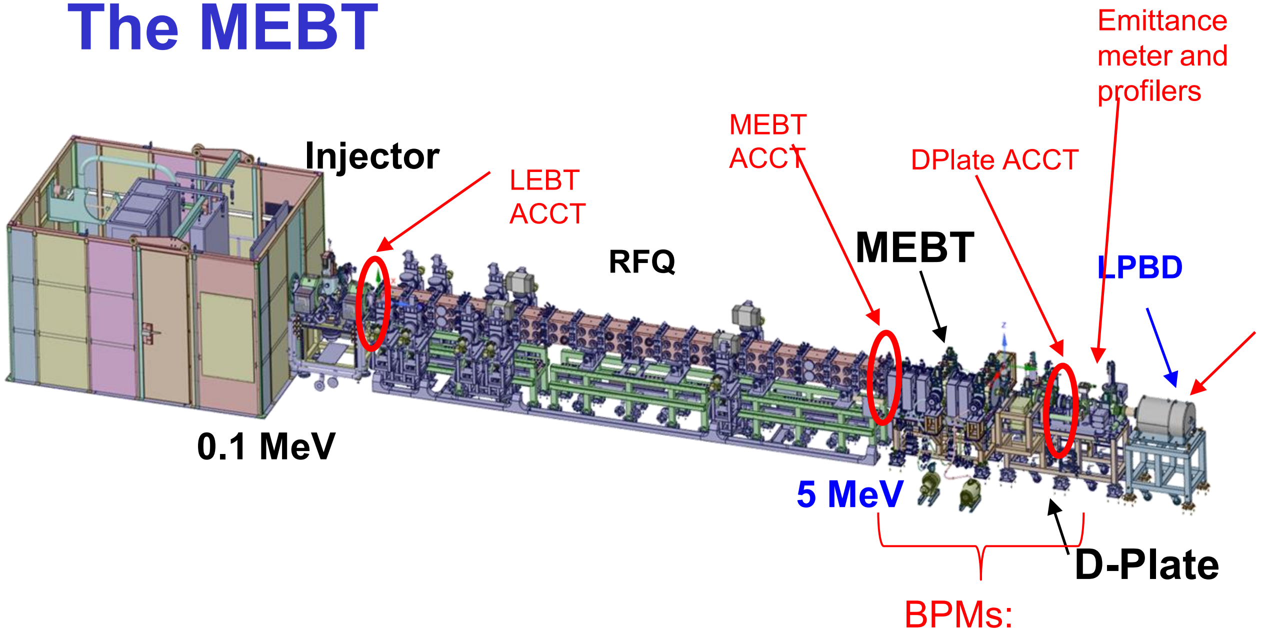
Nominal point selected for injection

The MEBT

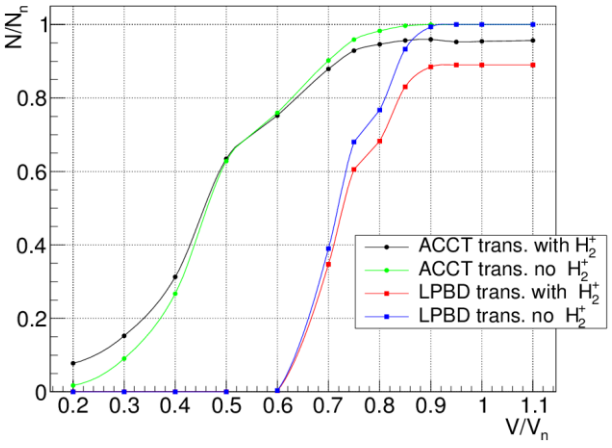


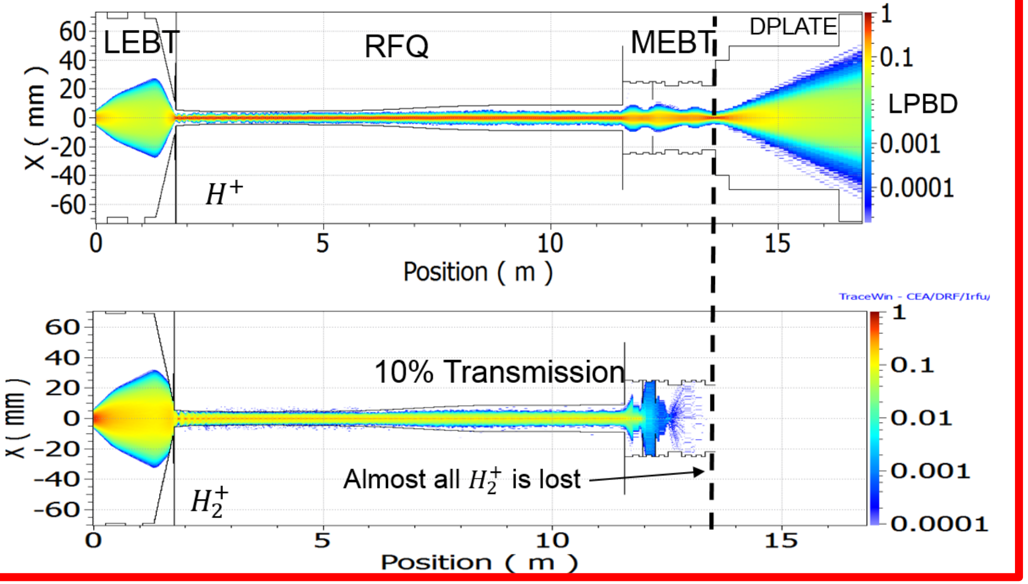






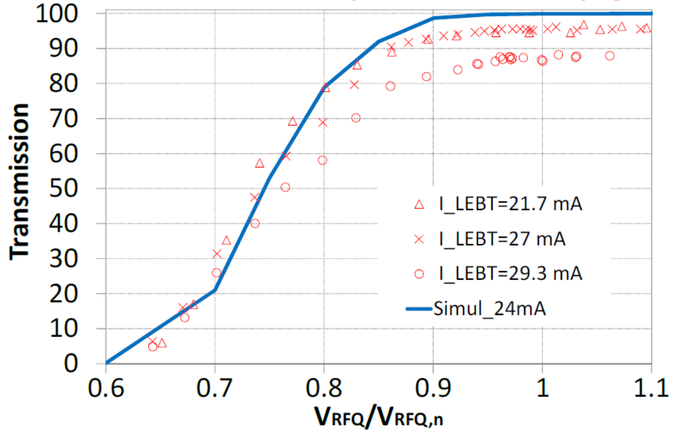
- Compact MEBT line of about 2.346 m
- 5 quadrupoles and 2 bunchers
- Generalized perveance 10^{-5} with nominal beam
- Separates the not accelerated particles, the residual contaminants and, in general, the particles with large $\Delta p/p$ difference. However, since the LEBT ACCT is sensible to contaminants, the overall calibration curve remains affected by them.





Proton beam commissioning results

24-30 mA beam (half perveance) @ 50 keV



Half perveance beam study, outcomes:

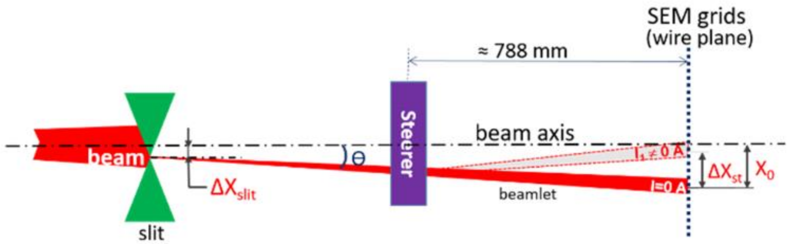
- Emittance after the RFQ check
- Longest pulse accelerated (4.5 ms)
- RFQ can withstand a mismatch of 220%
- Effect of contaminants onto the LEBT ACCT current read-out: down estimation of transmission.

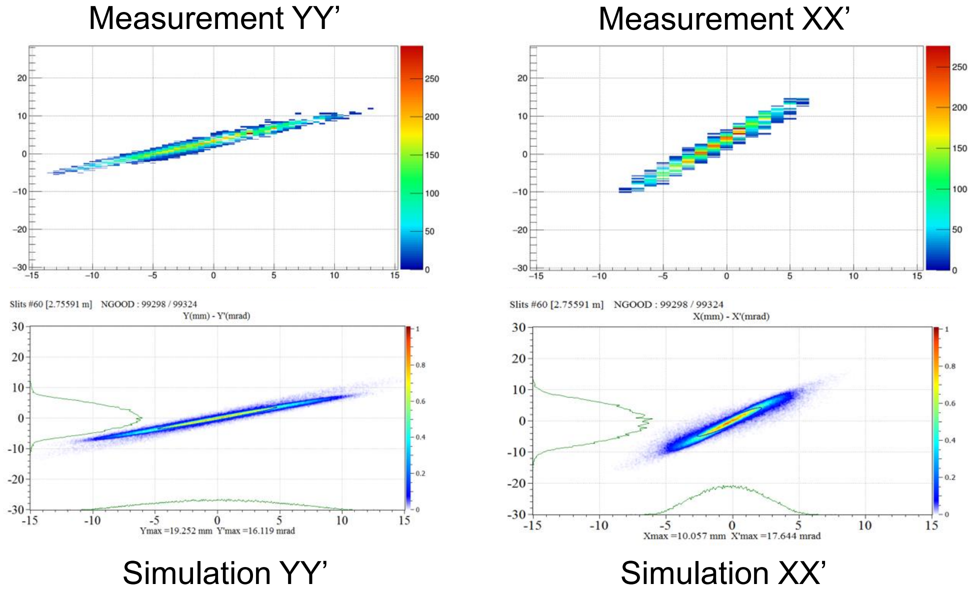
Probe beam (7-10 mA) @ 50 keV

Current value	Steerer setup 1	Steerer setup 2
I_{LPBD}	9.8	9.6
$I_{LEBT,\,ACCT}$	11.9	9.8
T_{exp}	82%	98%

Transverse emittance after the RFQ [1]

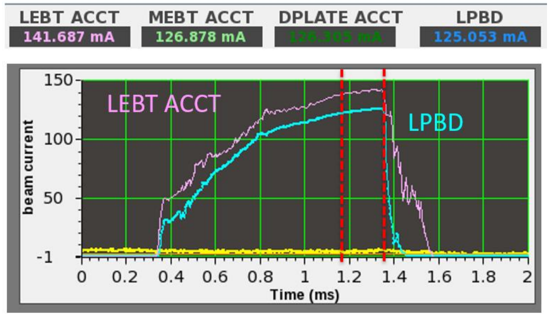
Measurement	Value
V_{rfq} [kV]	70
I_{LPBD}	22.8
$\varepsilon_{exp}/\varepsilon_{sim}$	**0.23/0.23**
β_{exp}/β_{sim}	**6.9/6.1**
α/α_{sim}	**-4.6/4.6**





[1] J. Marroncle et al., "Transverse emittance in 2.5 MeV proton beam on LIPAc, IFMIF's Prototype", in Proc. IBIC'19, Malmö, Sweden, September 2019, pp. 288-293.

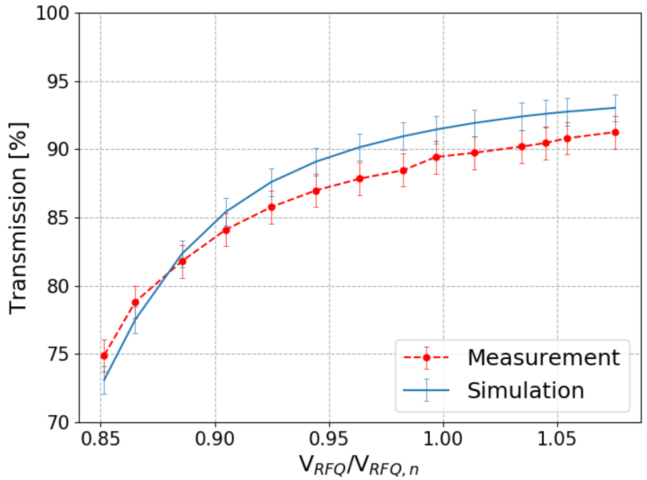
Deuteron beam commissioning results

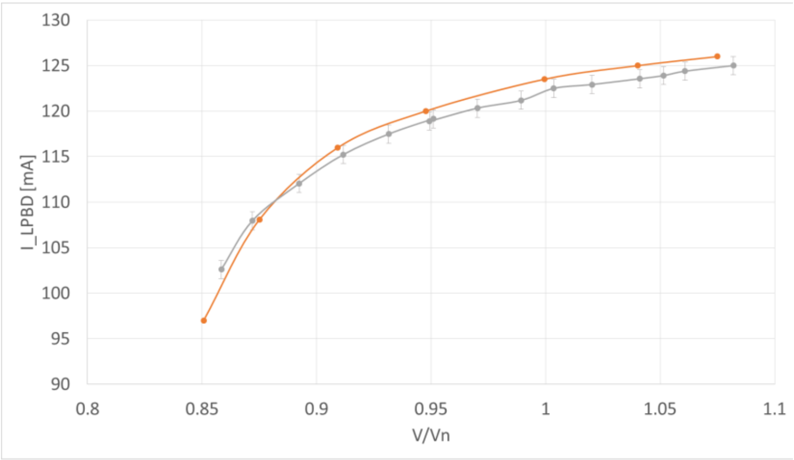


First beam pulse

- 125 mA 1Hz 1 ms beam reached on July 2019.
- Until 9th Aug., stable operation for several hours at 125 mA was succeeded.

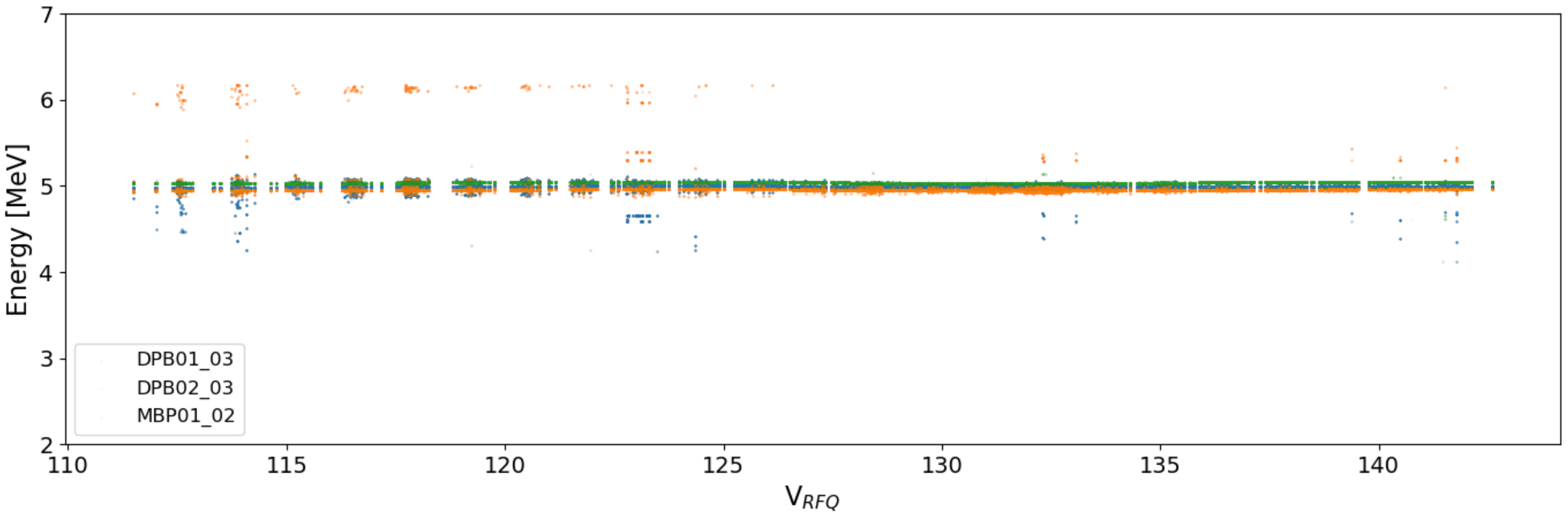
Transmission I_{LPBD}/I_{LEBT} at V/Vn=1	Values and uncertainties [%]
Experimental	89.7 ± 1.2
Sim. D^+ and D_2^+	91.5 ± 1.0
Sim. D^+	92.5 ± 1.0



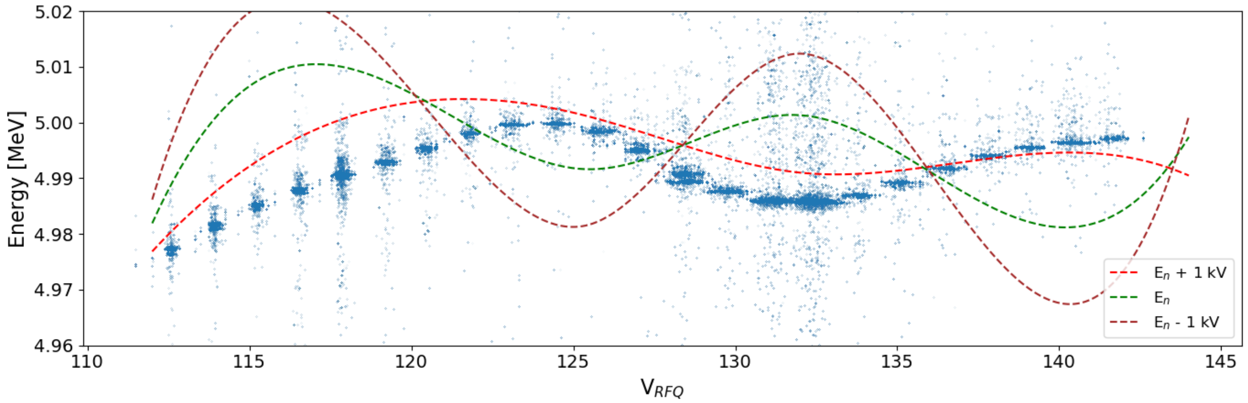


Beam dist.	Year	$\varepsilon_{rms,t,n}$	$\varepsilon_{99\%,t,n}$	Trans.
4D Gaussian (design 4 sigma)	2011	0.25	2.2	91.8 (as-built) 93.7 (design)
Realistic estimated	2019	0.2	3.7208	92.5 ± 1.0 (estimated)

Deuteron beam commissioning: TOF measurments



- The ToF energy from different pair of BPM of the D-Plate and MEBT as function of the RFQ voltage: 5 MeV ± 1% [2]
- Neutron production on LPBD and MEBT scrapers due to $^{27}Al(d,n)$ reaction as expected. [3]



That shape of the ToF-energy curve is linked to the beam energy at the RFQ input. The input beam was around 1 keV higher than nominal input energy (100 keV).

The input energy offset causes synchrotron oscillations of the bunch inside the separatrix and around the nominal energy point.

⇨ Possibility to fine tune the extraction voltage , planned for the next campaign

[2] I. Podadera et al., "Beam commissioning of beam position and phase monitors for LIPAc", in Proc. IBIC'19, Malmö, Sweden, September 2019, pp. 534-538.

[3] K. Kondo et al., "Neutron production measurement in the 125-mA 5-MeV deuteron beam commissioning of Linear IFMIF Prototype Accelerator (LIPAc) RFQ", Nucl. Fusion. September 2021,

Conclusions

- **Test low and half perveance**:
  - Transverse emittances within the expectations as design
  - Low perveance (10 mA) beam transmission close to 100% as expected
- **Test at nominal perveance**:
  - Transmission compatible with what was expected by the design
  - Energy and oscillations within the longitudinal separatrix, compatible with the expectations.

What remains to do, from beam dynamics point of view:

- Measurement of the transverse emittance at nominal perveance
- Estimation of the longitudinal emittance at nominal perveance

What remains to do, from RFQ point of view:

- **CW RF RFQ**
- CW beam, possibly to maintain it for several weeks (under discussion)
- Beam restarted in July 2021, after maintenance shut down, new line for CW test installed specifically and under commissioning