Istituto Nazionale
di Fisica Nucleare
Laboratori Nazionali di Legnaro

Experience from the IFMIF RFQ Commissioning

F. Grespan L. Bellan M. Comunian

Lund, 29-30 Jan 2020

ESS Testing and Commissioning Workshop

Outline

- Assembly a 10 m long RFQ in Rokkasho
- Tuning a 10 m long RFQ in Rokkasho
- RFQ RF Conditioning up to now
- RFQ pulsed beam commissioning
- Matching the Input beam

Accuwheater: “*The snowiest city in the world, with an average of 26 feet — or eight meters — of snowfall every year, is Aomori City in Aomori Prefecture, Japan*.“

«*Rokkasho is not a place, it is an outpost*.» A. Facco

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IFMIF-Lipac RFQ parameters

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 $(\langle V^2 \rangle)L/P_d$	**201**	**kΩ –m**
Frequency tuning	**Water temp.**	
N cells ($\beta\lambda/2$)	**489**	

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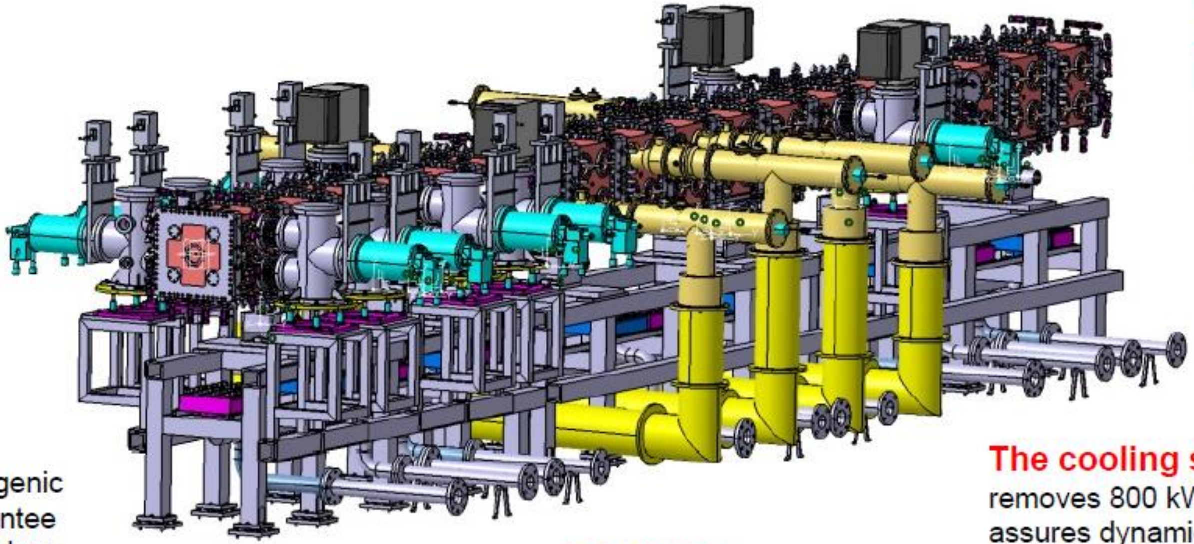
Assembly a 10 m long RFQ



18 modules
each module approx. 550 mm and 600 kg. Modules assembled and aligned in 3 supermodules (separately transported to Japan)

Local Control system
PLC and EPICS, for cooling and vacuum systems, temperature and RF probes.

Vacuum system
10 sets, based on cyogenic pumps (in cyan) guarantee $5*10^{-7}$ mbar with beam loss gas load

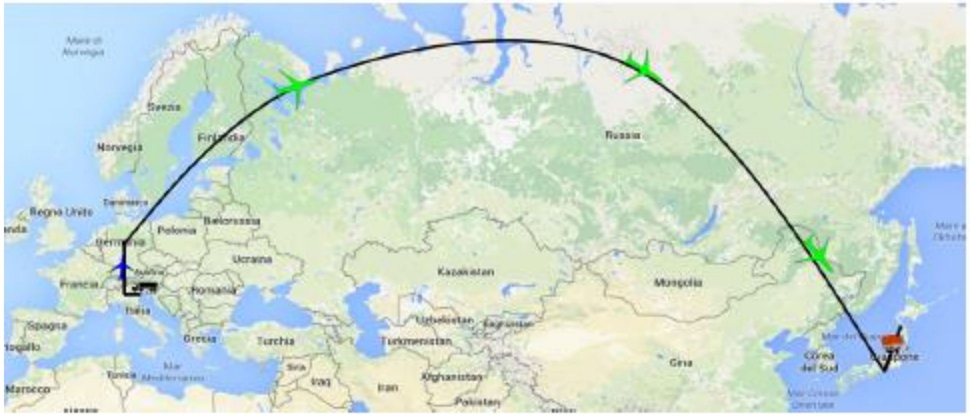
The cooling system
removes 800 kW and assures dynamic RF frequency tuning

RF Power
8 RF systems and power coupler 200 kW each (RF system by CIEMAT)

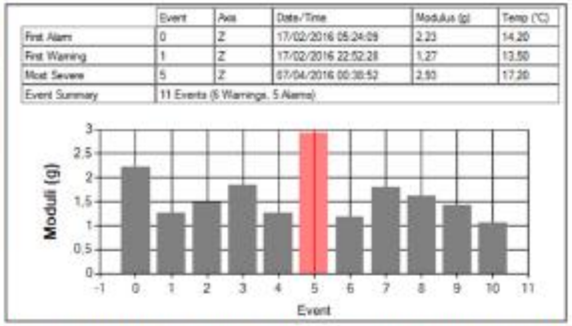
Assembly a 10 m long RFQ

RFQ pre-assembled in 3 super-modules (SMs) in Legnaro, aligned and vacuum tested.
Then shipped to Japan.

Assembly a 10 m long RFQ



SUPERMODULE SHIPMENT

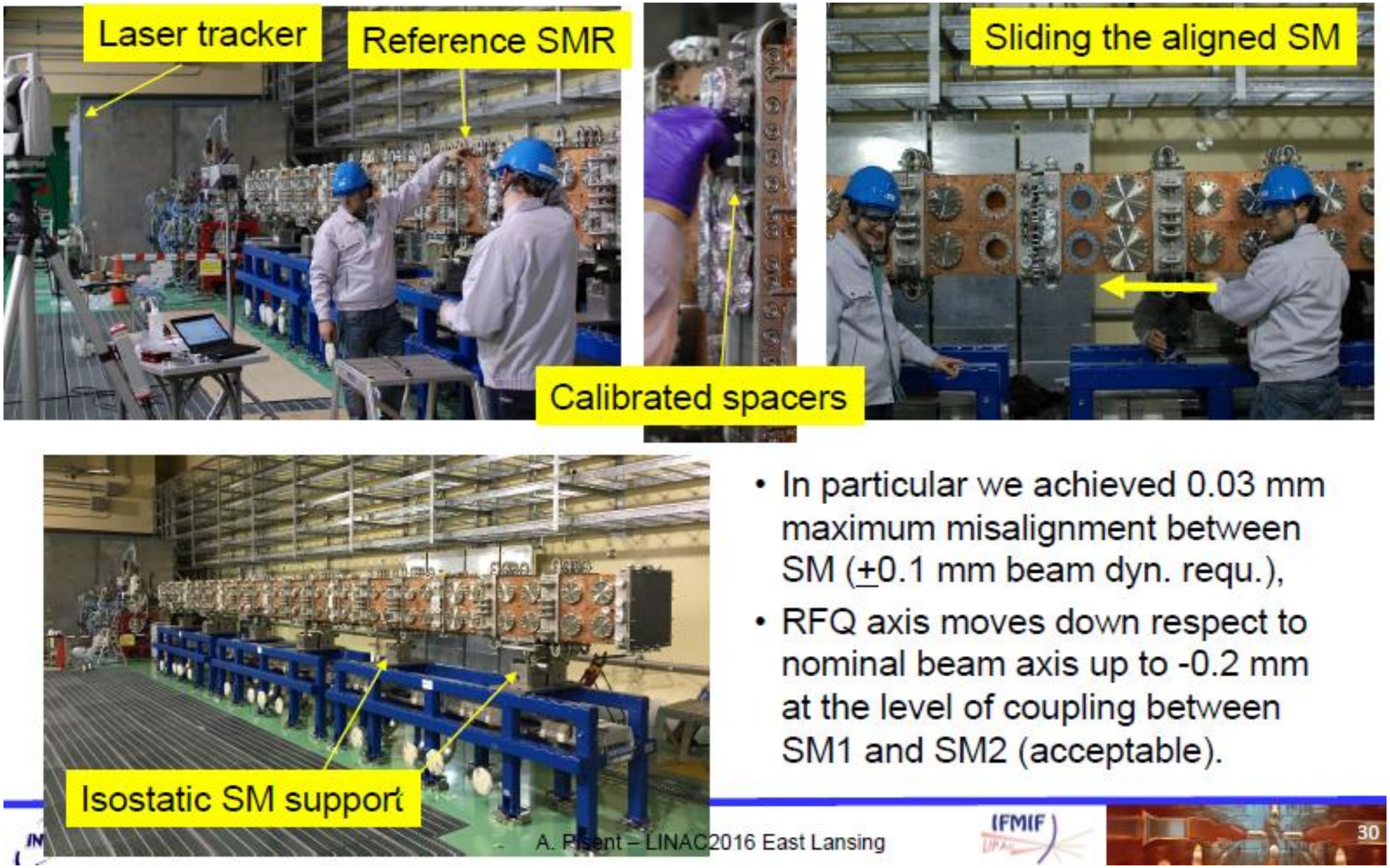


	Event	Axis	Date/Time	Modulus (g)	Temp (°C)
First Alarm	0	Z	17/02/2016 05:24:09	2.23	14.20
First Warning	1	Z	17/02/2016 22:52:28	1.27	13.50
Most Severe	5	Z	07/04/2016 00:38:52	2.93	17.20
Event Summary	11 Events (6 Warnings, 5 Alarms)				

Data extrapolated from the shock recorder mounted on SM2.

- The three SMs were completely assembled at LNL, filled with nitrogen
- Rubber spacers and wood supports were used between to dump vibrations in the box
- Shock recorders, Shocklog 298, were screwed on the top of each SMs.

Assembly a 10 m long RFQ



Laser tracker

Reference SMR

Calibrated spacers

Sliding the aligned SM

Isostatic SM support

- In particular we achieved 0.03 mm maximum misalignment between SM (±0.1 mm beam dyn. requ.),
- RFQ axis moves down respect to nominal beam axis up to -0.2 mm at the level of coupling between SM1 and SM2 (acceptable).

A. Pisent – LINAC2016 East Lansing

Tuning a 10 m long RFQ

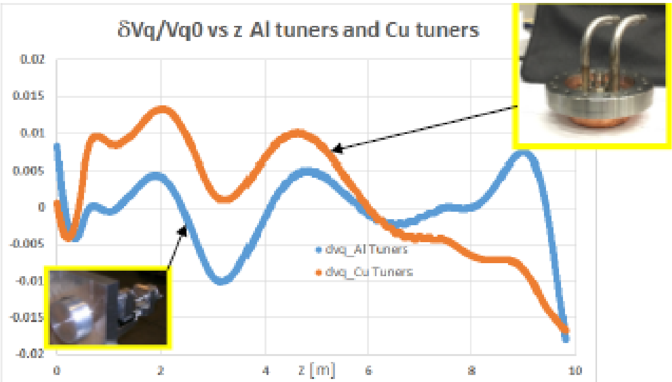
108 tuners to be set

TUNING THE IFMIF 5MEV RFQ ACCELERATOR
A. Palmieri *et al* THPLR049

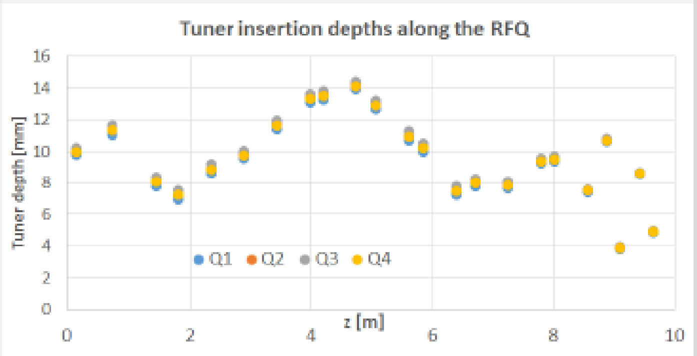
- ±10 μm modulation tolerances
- ±60 μm tolerance R_0 final (incl brazing) equiv to ±1 MHz.
- 108 dummy tuners(±15 mm equiv±1. MHz,) field correction
- Active (water temperature, 10 deg approx ±0.1 MHz,))

Tuning a 10 m long RFQ

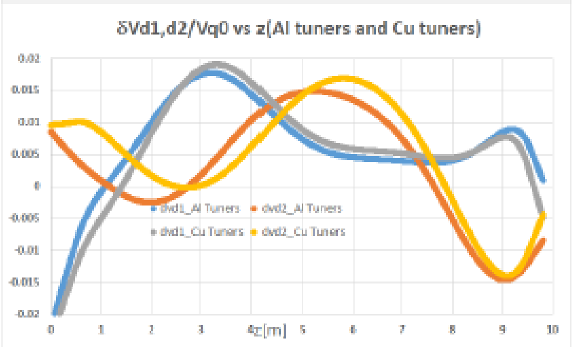
Quadrupole and dipoles with dummy (Al) and final (Cu) tuners



dV_q/V_{q0} vs z for dummy tuners (Al, blue curve) and final tuners (Cu, red curve)



Tuning range -10 +30 mm



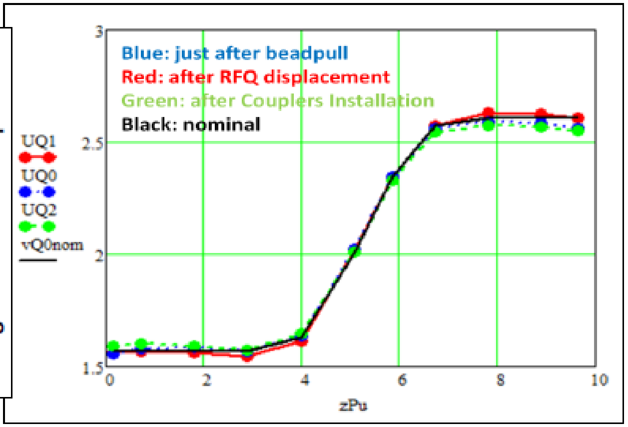
dV_{qd1}/V_{q0} vs z for dummy tuners (Al, blue curve) and final tuners (Cu, red curve)

Tuning performed without couplers and 3 m away from the LEBT in order to allow the conclusion of the LEBT beam characterization.
Coupler perturbation modeled with dedicated tuner penetration calculated with HFSS.

Tuning a 10 m long RFQ

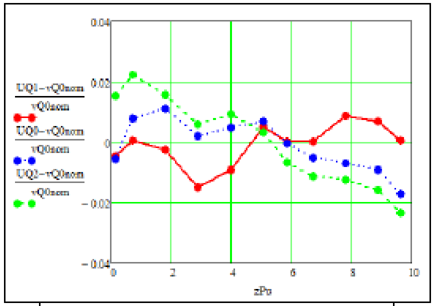
Then moved to final position and checked.
The result voltage is now implemented in the BD simulation as well as the alignment data → **RFQ simulated "as built"**

Final tuning

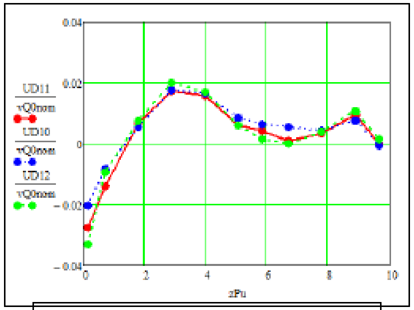


Evolution of the RFQ voltage along the installation phases

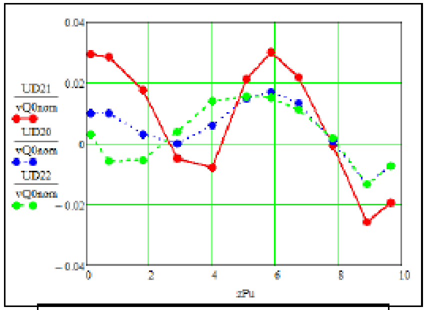
Coup. ID	$\beta(\alpha=0)$	α_{opt} [deg]	β_{meas} after rotation	f[MHz]
07142	0.30	18	0.28	175.018
07144	0.29	16	0.26	175.018
09172	0.36	30	0.26	175.018
09174	0.34	27	0.28	175.018
10201	0.45	39	0.25	175.018
10203	0.43	38	0.29	175.018
12232	0.56	46	0.31	175.018
12234	0.52	44	0.23	175.019



Pert Q voltage component



Pert D1 voltage component

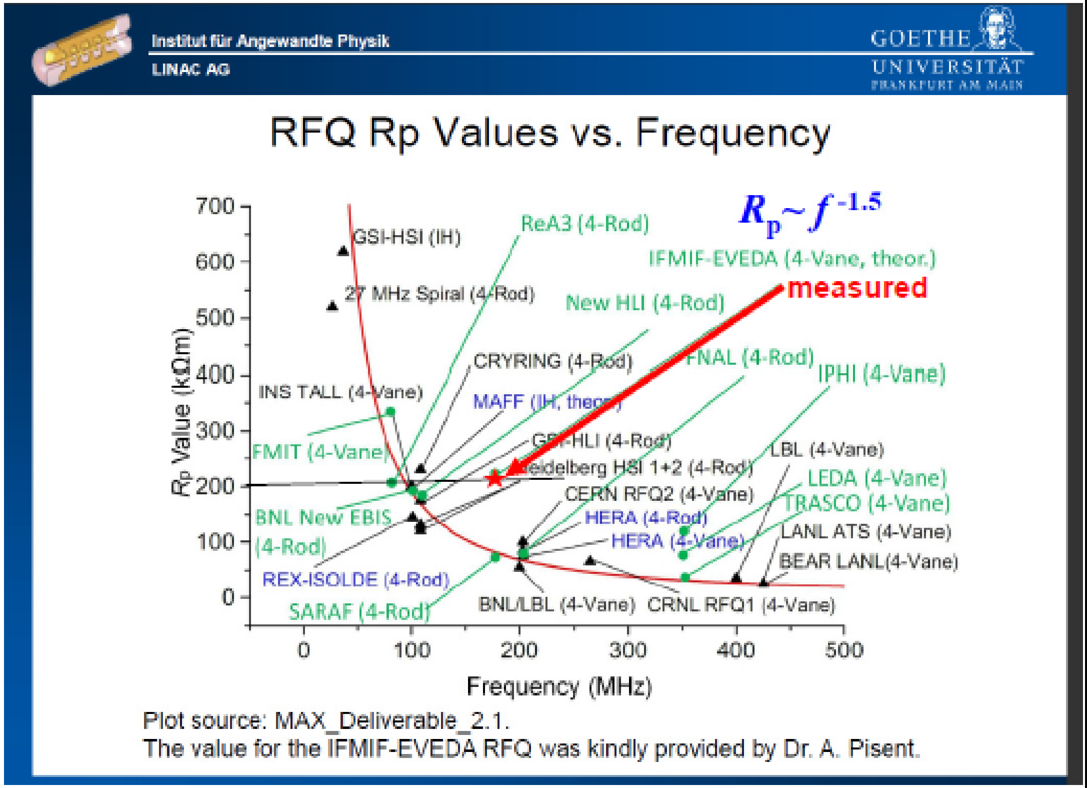


Pert D2 voltage component

RF properties summary

Eigen frequency and shunt impedance achieved

- 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° C temperature and the effects of vacuum and beam loading. Such value corresponds to -1° C water temperature regulation for the vessel.
- **Q_0=13'200±200**
- (82% of SUPERFISH value), low tuner losses
- **Rsh=201 kΩ*m**

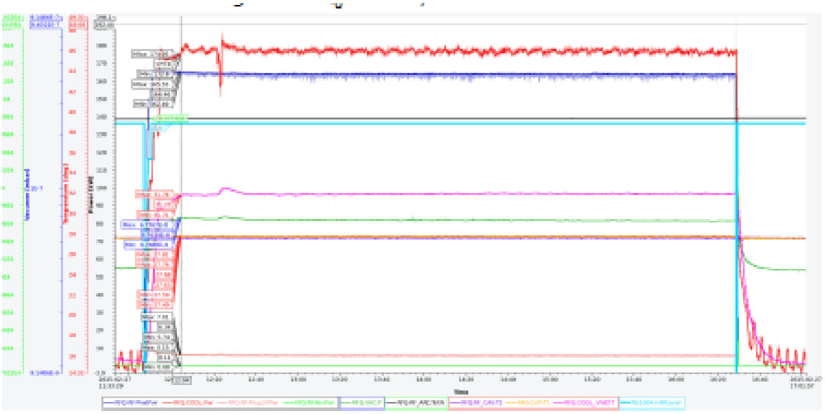


Plot source: MAX_Deliverable_2.1.
The value for the IFMIF-EVEDA RFQ was kindly provided by Dr. A. Pisent.

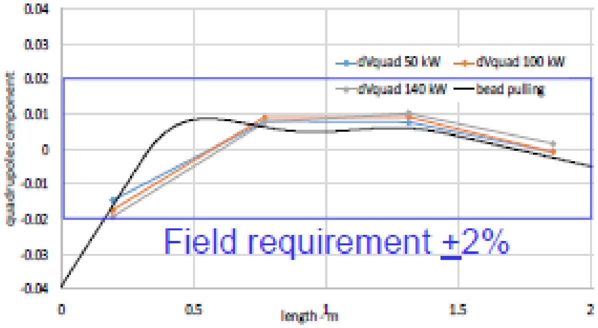
Original transparency by prof. H. Klein

RFQ RF conditioning

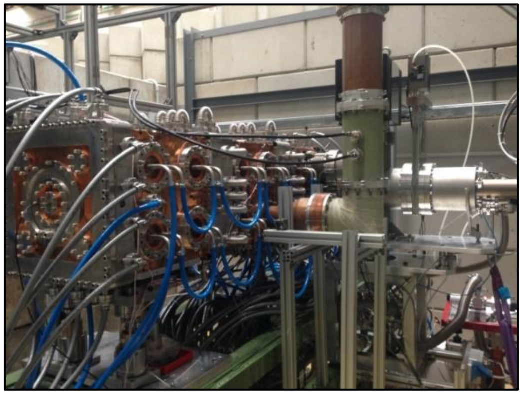
CW operation at nominal voltage demonstrated in Legnaro on a 500 kW test stand to for 3 RFQ modules up to 200 kW maximum RF power. RFQ design validation (Max field limit = 1.8 E_{kp} and max power density = 86 kW/m).



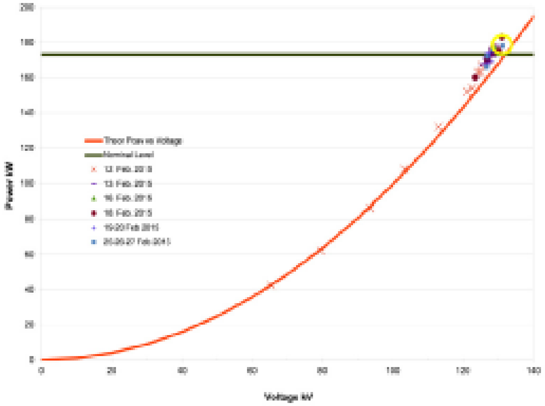
On 27 February '15 the RFQ remained 5 hours at nominal field level. It corresponds to the yellow circle in fig above.



Field configuration (pick up reading) at different RF level



Just one coupler in the LNL test



Cavity power (calorimetric measurements) vs. cavity voltage. The yellow circled dot corresponds to the nominal voltage level.Q_0=12500. i.e. 173 kW vs. 132 kV

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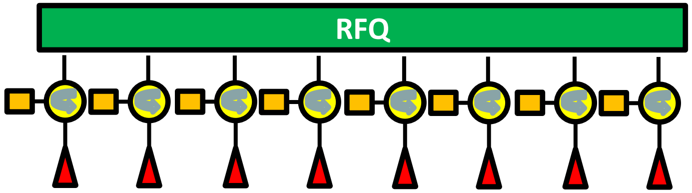
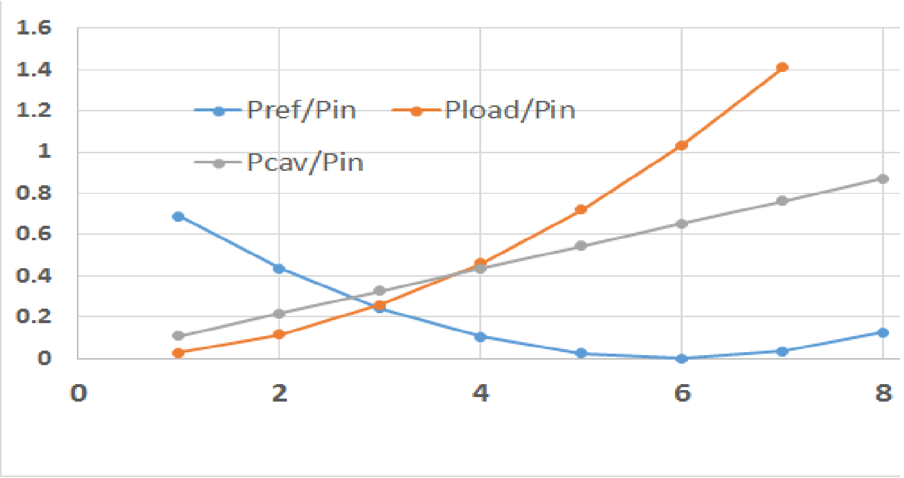
Phasing 8 RF chains

- RF couplers optimized for beam operation
- In conditioning mode without beam, 13% average reflected power from each chain
- In case of chains amplitude or phase unbalance, significant reflected power comes back to circulators



Amplitude unbalance (no beam)

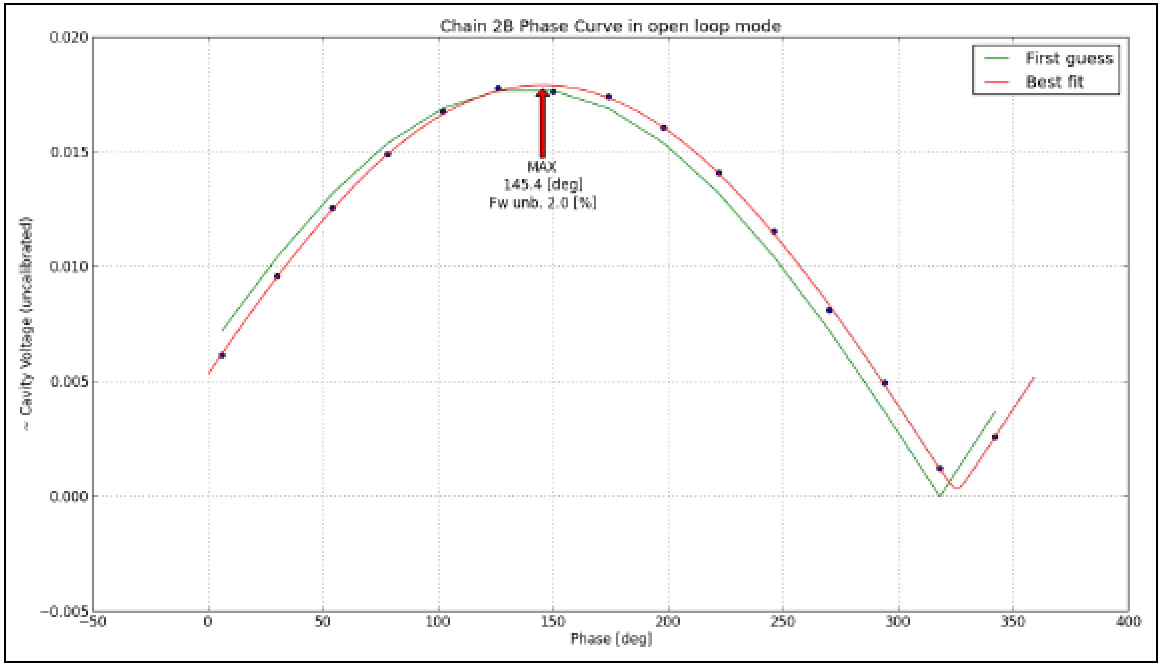


- Reflected power decreases with active chains number reaching a minimum with 6 chains. (Pref/Pin)
- Cavity power increases with active chains number
- Reflected power on any inactive chain increases with the number of active chains. It can reach 140% of the single chain input power, with 7 chains active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

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.

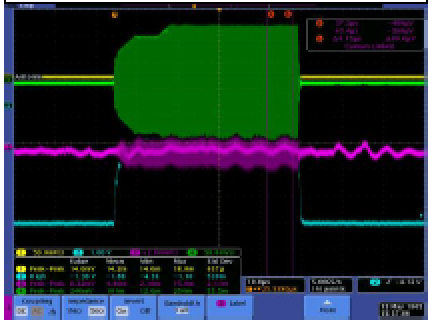
Phasing 8 RF chains

- RFQ power minimization method used to find couplers maximum dephase.
- This method was applied to each of the seven master-slave RF lines couples.
- Final routine took also into account power unbalance.

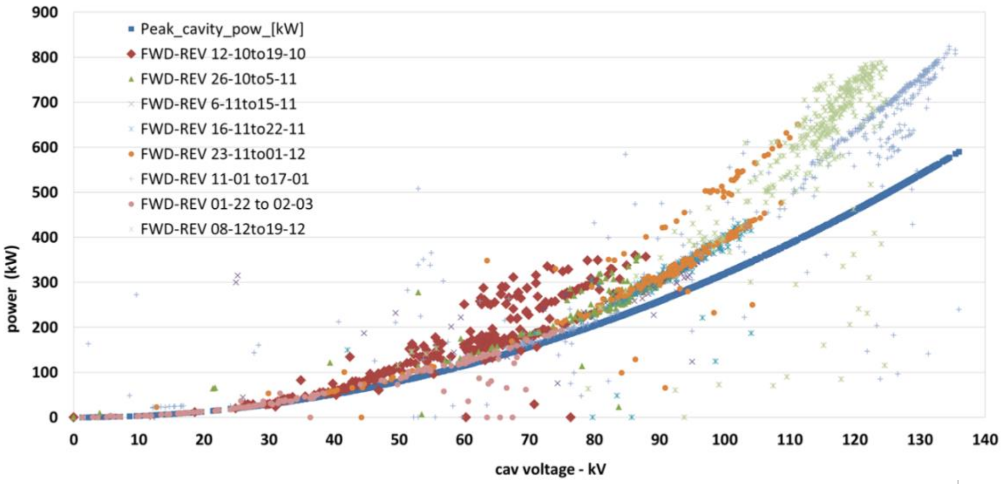


Near right phase

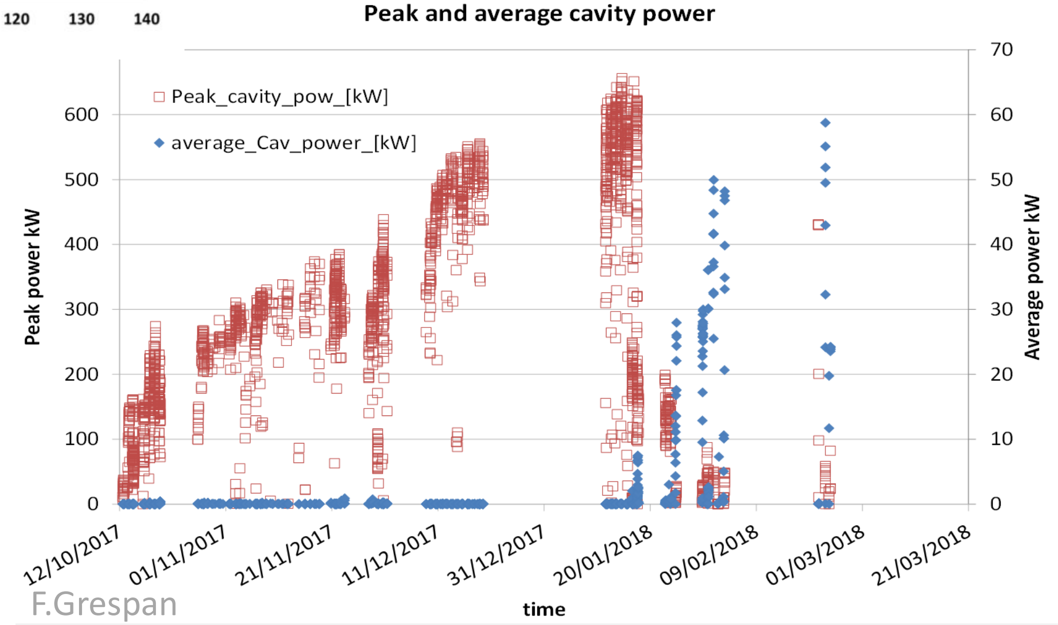
Near maximum dephase



1° part of the conditioning (2017-2018)



Forward power vs cavity voltage during RFQ conditioning.



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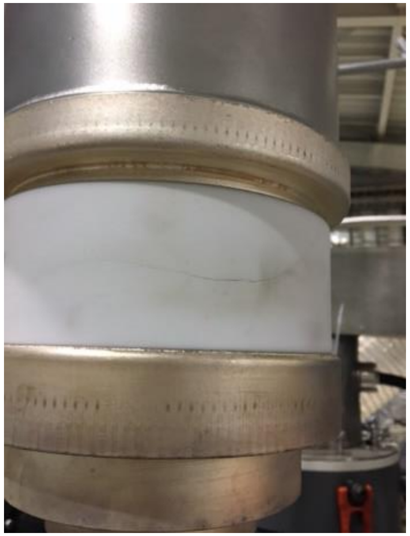
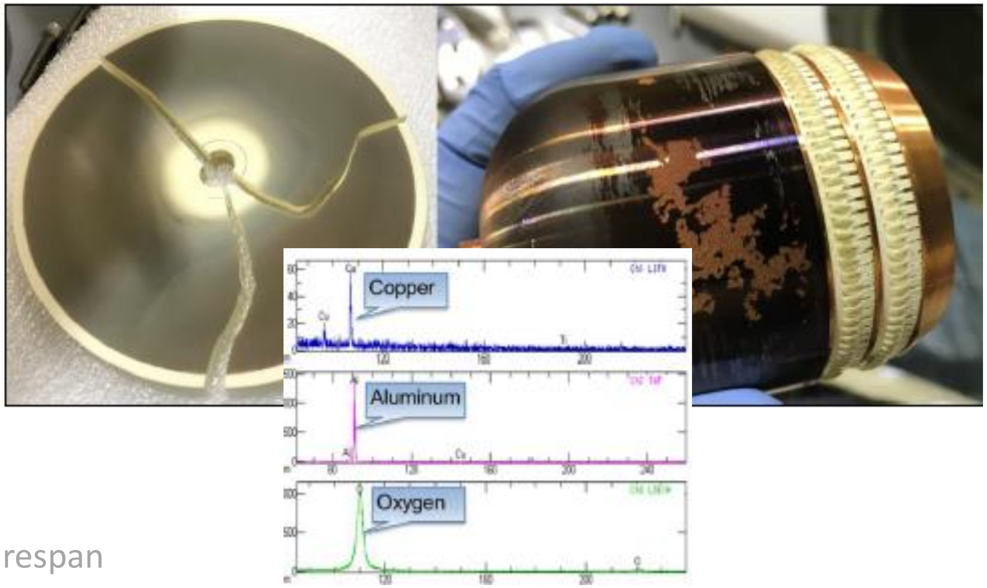
Peak and average cavity power.

Slow down of the conditioning

- **Excessive protections do not allow conditioning process. But lack of protection can destroy components**
- Circulators dummy loads were dimensioned for 50 kW CW nominal power. In pulsed mode they should resist up to 250 kW peak power for less than 100 ms.
- Difficult to keep circulators tuned in low duty cycle operation→reverse power cause HV instability tetrode failure
- RF power injection with cooling system off and cooling interlock disabled: Viton® O’ring melting in one RF window without vacuum break, RF window disassembled and repaired
- During a PPS test, involuntary RF power injection into cavity with interlock system disabled→ Uncontrolled arcing in one RF window caused alumina metallization and subsequent break. Post analysis confirmed copper deposition.





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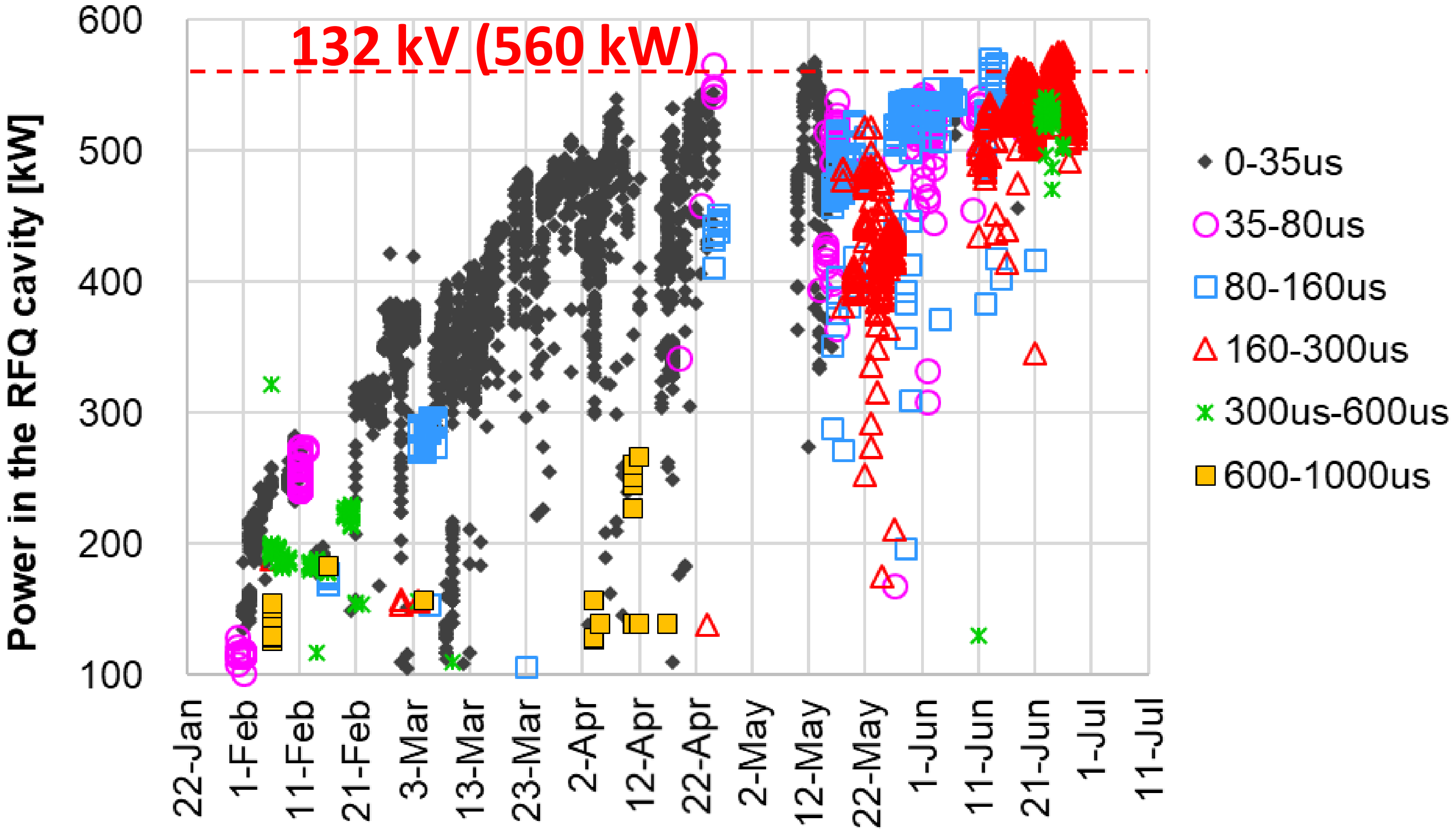
2° part of RF conditioning (2019)



Efficiency of the conditioning was improved after HVPS control adjustment in May.
We reached in July 132 kV / 2.5 ms / 20 Hz (duty 5%).
At proton level, 60 ms / several Hz (duty approx. 20%).

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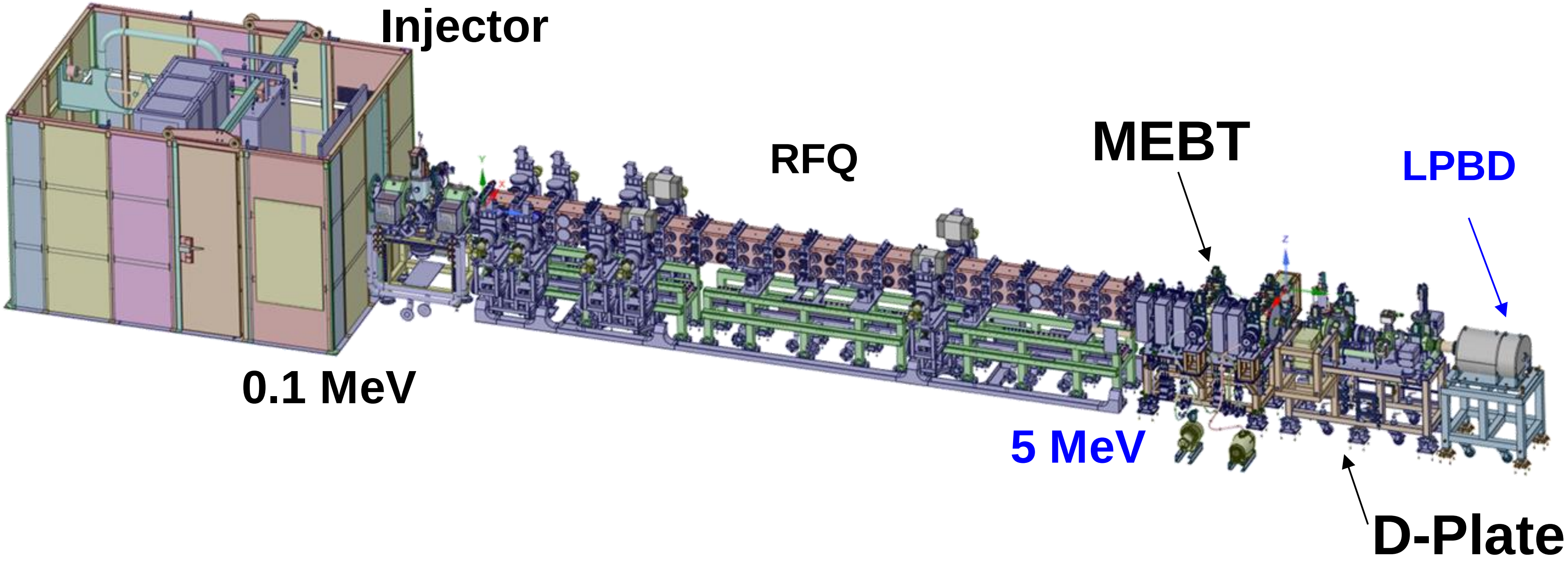
Main feedbacks from conditioning

- Hardware should be dimensioned both for conditioning operation and for normal operation.
- Conditioning can requires RF operation different from beam-case.
- Engineering of accelerator, RF system, vacuum system and beam diagnostics should be robust enough to survive thanks to system protection.
- But it should also be flexible enough to permit operation far from ideal behavior.
- RFQ acts as a perfect eight-ways combiner. During RF-RFQ system engineering, it is of crucial importance the analysis of all possible configurations modes even far from normal operational mode.
- Phase flip or phase change of one over eight chains is one of the most critical configuration. This possibility should be taken into account in multi-amplifier cavity design.
- High power couplers should be precisely phased to avoid high reflected power unbalance. A practical rule should be to limit couplers nominal coupling factor variation into +-4% range.
- RF window cooling system should be directly connected to alumina.

Conditioning status and toward RF CW

- RFQ conditioning at proton level (66 kV) reached 20% maximum duty cycle (20 ms, 10 Hz). Effect on cavity vacuum was negligible
- RFQ conditioning at deuteron level (132 kV) reached 5% maximum duty cycle (5 ms, 10 Hz). Effect on cavity vacuum was negligible.
- Increasing duty cycle, some temperature “hot” spot appeared on three couplers. Thermal camera was used to follow temperature variation during frequency tuning and “hot” spot are verified to be movable with frequency.
- New 200 kW Circulators RF loads replaced the 50 kW old ones (before end of maintenance)
- All circulators well tuned (before end of maintenance).

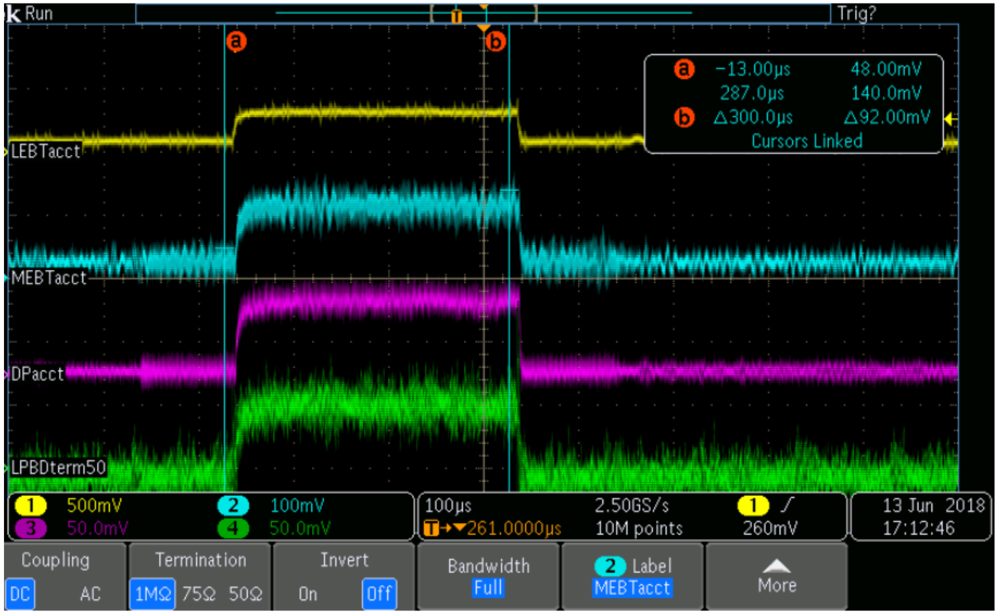
Phase-B beam commissioning of LIPAc



- Demonstrates acceleration of 5.0 MeV deuterons (2.5 MeV protons) by RFQ.
- Target current is 125 mA deuteron in short pulse mode (half for proton).
- The beam is stopped by Low Power Beam Dump (LPBD) with capacity of 1 ms / 1 Hz at 5 MeV, 125 mA (0.625 kW).
- RF power of 560 kW is required as the wall load for deuteron acceleration (Vane voltage of 132 kV) and more than 1.2 MW for the beam operation.
- Perform commissioning of the MEBT buncher as well as all the diagnostics.

2 main milestones (1)

- 1^{st} acceleration of **protons** through RFQ was succeeded on 13 June 2018. The 1^{st} campaign was finished in the beginning of August.
  - We achieved 40 mA at the exit of RFQ (300 us, 1 Hz), however, we required very strong steering at LEBT to obtain the best RFQ transmission.



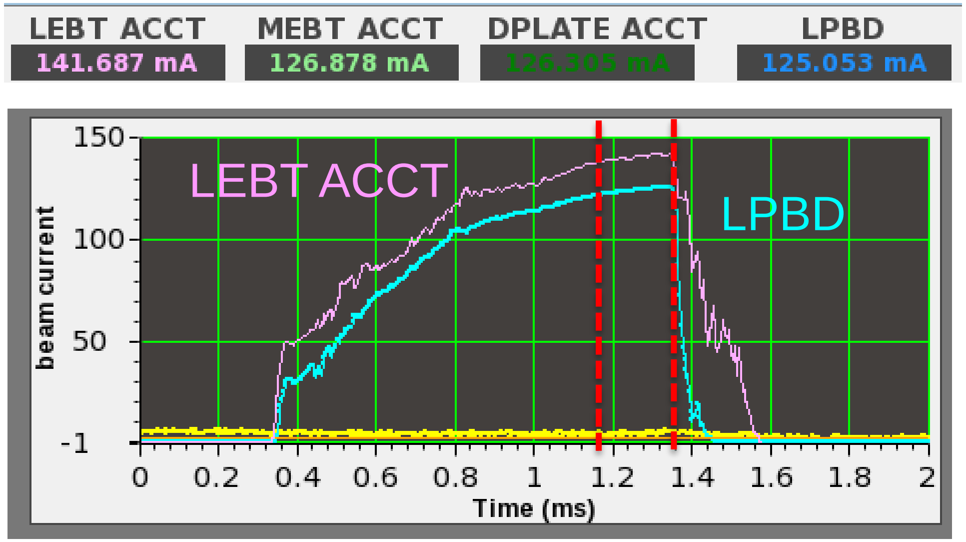
With LEBT magnets at nominal values, no beam was extracted from RFQ. After some manual LEBT adjustment the following results were obtained:

- LEBT-ACCT = 5.3 mA,
- MEBT-ACCT = 1.7 mA (30% transmission),
- LPBD = 1.2 mA (20% transmission).

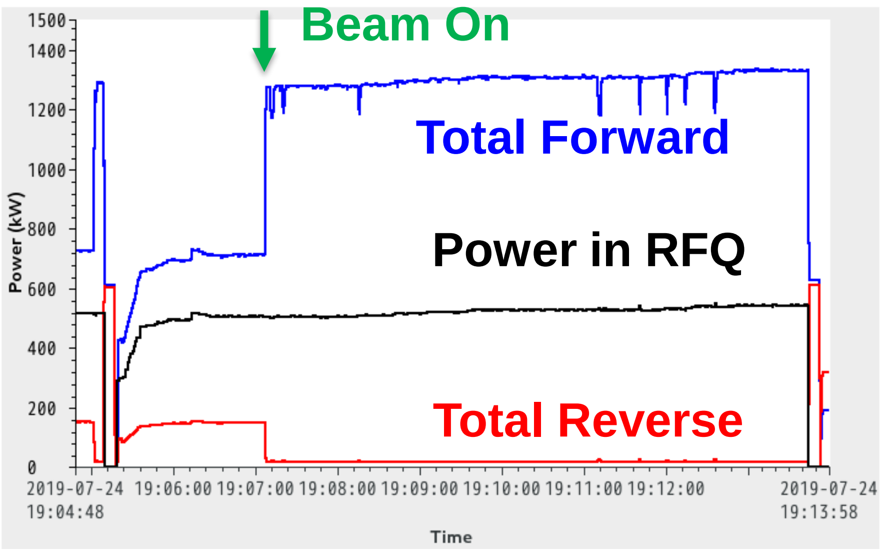
Weaker Sol2 value allows filling the RFQ acceptance compensating misalignment effects, taking advantage of the increased RFQ acceptance for low current beam.

2 main milestones (2)

- 24th July: 1st time to achieve **Deuterons** current of 125 mA-1Hz-1ms at the exit of RFQ with 90% transmission.
  - RF power system works properly to supply the total power more than 1.3 MW.
  - Until 9th Aug, stable operation for several hours at 125 mA was succeeded.



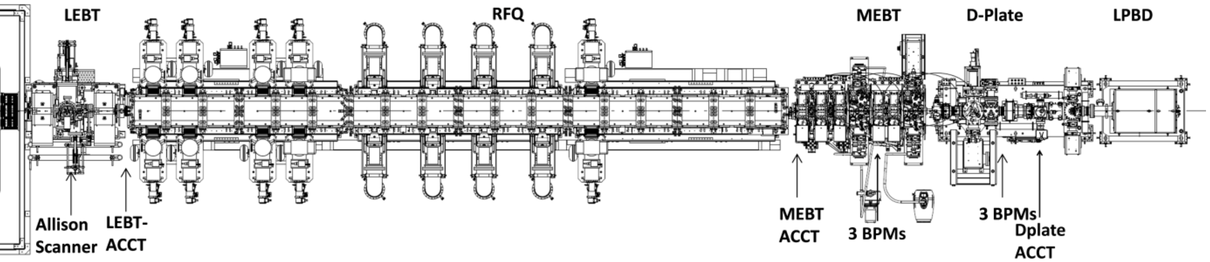
LEBT ACCT	MEBT ACCT	DPLATE ACCT	LPBD
141.687 mA	126.878 mA	126.305 mA	125.053 mA

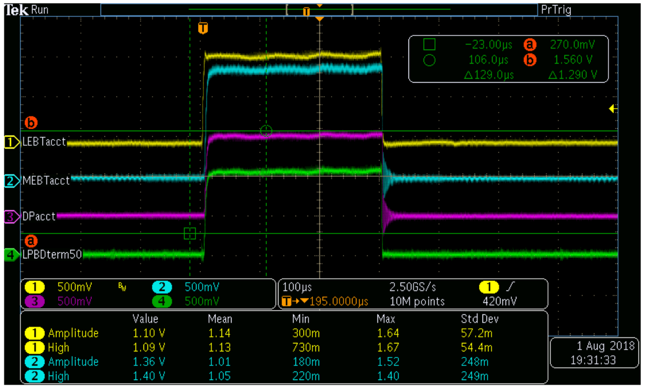


Diagnostic, repeller, chopper

After the first enthusiastic beam commissioning days we found:

- Diagnostics: RGBLM and current monitors V_{scope}~50 Ω·I_{beam} we found for the LPBD 53 Ω, for the MEBT 67 Ω more different but less confusing.





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□  -23.00µs   ⓐ 270.0mV
○  106.0µs    ⓑ 1.560 V
   Δ129.0µs     Δ1.290 V

1  500mV   BW   2  500mV     100µs            2.50GS/s     1  ╱
3  500mV        4  500mV     T→▼195.0000µs    10M points   420mV

              Value    Mean   Min    Max    Std Dev
1 Amplitude   1.10 V   1.14   300m   1.64   57.2m
1 High        1.09 V   1.13   730m   1.67   54.4m
2 Amplitude   1.36 V   1.01   180m   1.52   248m
2 High        1.40 V   1.05   220m   1.40   249m

1 Aug 2018
19:31:33
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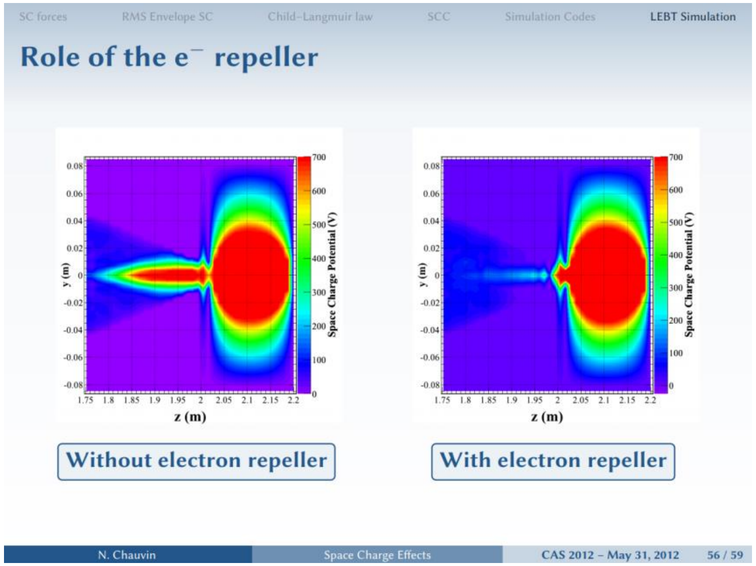


SC forces RMS Envelope SC Child-Langmuir law SCC Simulation Codes **LEBT Simulation**

Role of the e⁻ repeller

Without electron repeller

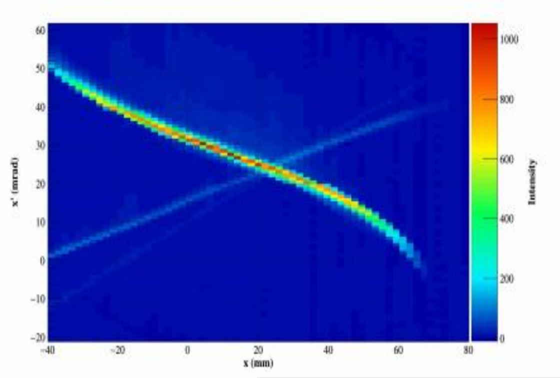
With electron repeller

N. Chauvin | Space Charge Effects | CAS 2012 – May 31, 2012 | 56 / 59

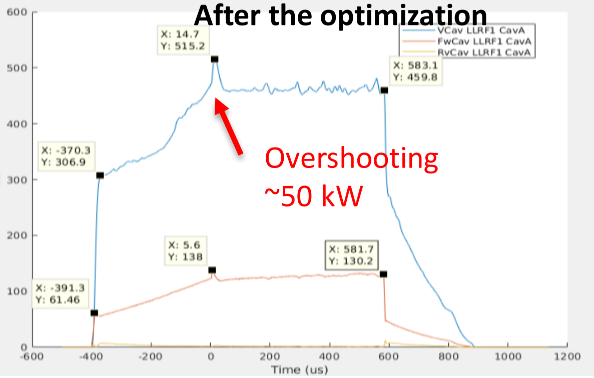
- RFQ repeller (-2.5 kV): we (accidentally) found the repeller electrode at the entrance of RFQ was not properly biased. After the investigation we found a failure of the connector.
- All the high currents RFQ transmissions were affected (optimistically) as well as the neutralization of the LEBT-RFQ matching point

Diagnostic, repeller, chopper

- Doppler shift spectrometer → % of contaminant direct measurement only for higher Duty Cycles. We estimated the contaminant components from the intensity on the emittance measurements



- Chopper. Ok for protons (-4.5 kV). But for deuterons there was always a background current on the LEBT ACCT that required V < -9kV. 26th June a discharge occurred in the LEBT chopper → beam commissioning without chopper by extending RF pulse length. The 1 ms rising time of the source stressed LLRF loops.


After the optimization

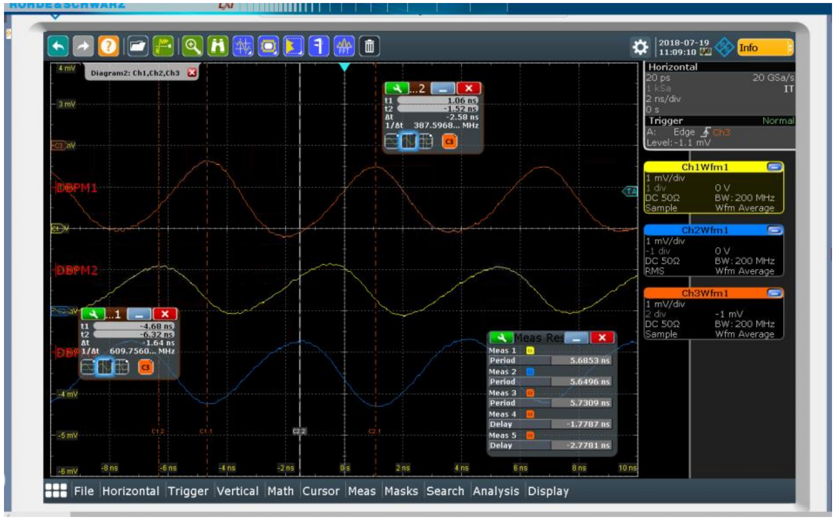
Overshooting ~50 kW

- We found some permanent magnets were installed in LEBT to suppress secondary electrons on FC. After removing that, the maximum RFQ transmission was obtained with zero steering.

Energy out by TOF

- Energy of first protons was measured with bunchers off. The TOF between the three D-Plate BPMs was performed with oscilloscope. The signals are two shifted sine waves at 175 MHz.

	Distance (mm)	δt_{kj} [ns]	δt_{jk} [ns]	Energy [MeV]
BPM1-2	155.8	4.07	4.39	2.52
BPM1-3	1265.3	3.13	4.71	2.48



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Horizontal: 20 ps, 20 GSa/s, 1 kSa, IT, 2 ns/div, 0 s

Trigger: Normal; A: Edge Ch3; Level: -1.1 mV

Ch1Wfm1: 1 mV/div, 1 div, 0 V, DC 50Ω, BW: 200 MHz, Sample, Wfm Average

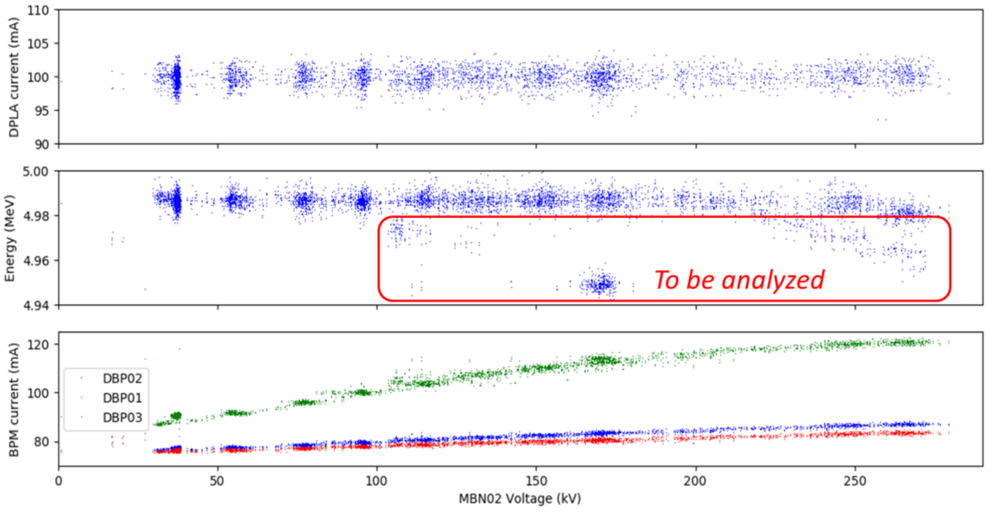
Ch2Wfm1: 1 mV/div, -1 div, 0 V, DC 50Ω, BW: 200 MHz, RMS, Wfm Average

Ch3Wfm1: 1 mV/div, 2 div, -1 mV, DC 50Ω, BW: 200 MHz, Sample, Wfm Average

Cursor 1: t1 -4.68 ns; t2 -6.32 ns; Δt -1.64 ns; 1/Δt 609.7560... MHz

Cursor 2: t1 1.06 ns; t2 -1.52 ns; Δt -2.58 ns; 1/Δt 387.5968... MHz

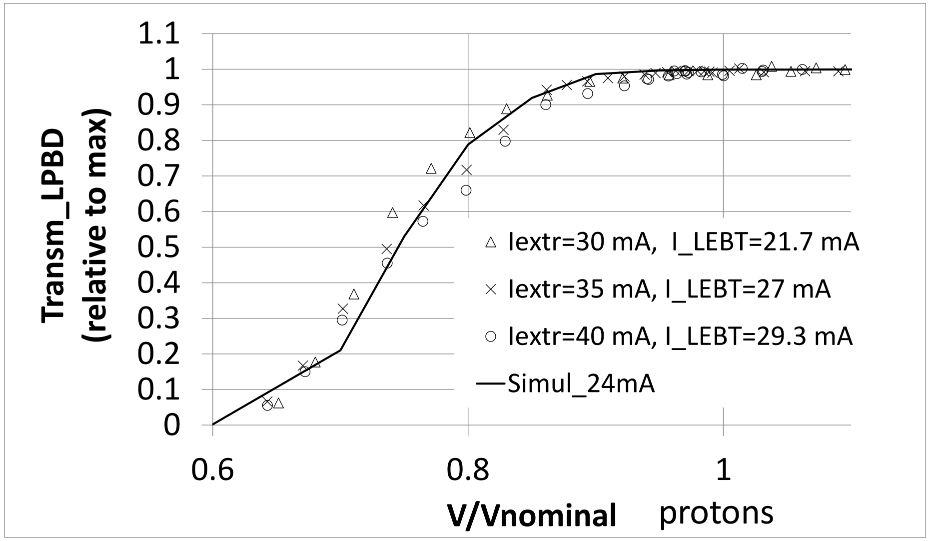
Meas 1 Period 5.6853 ns
Meas 2 Period 5.6496 ns
Meas 3 Period 5.7309 ns
Meas 4 Delay -1.7787 ns
Meas 5 Delay -2.7781 ns

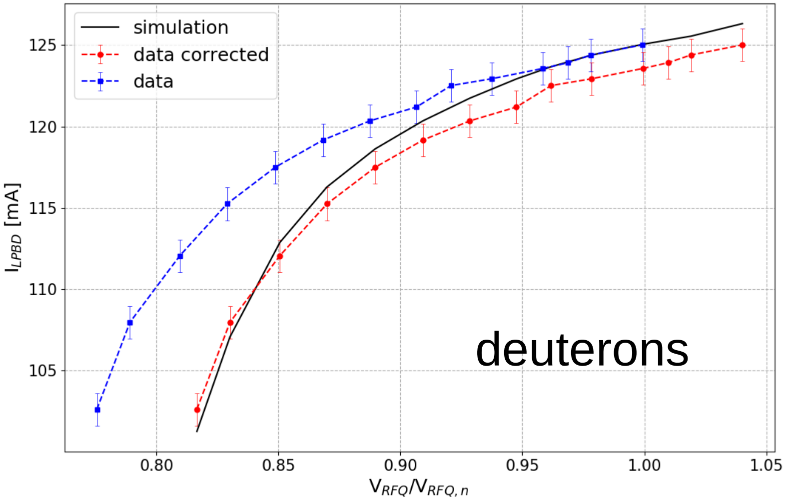


- For Deuterons a routine from CIEMAT colleagues on the D-Plate BPMs was ready and MEBT bunchers were ON.

RFQ Transmission vs.Voltage

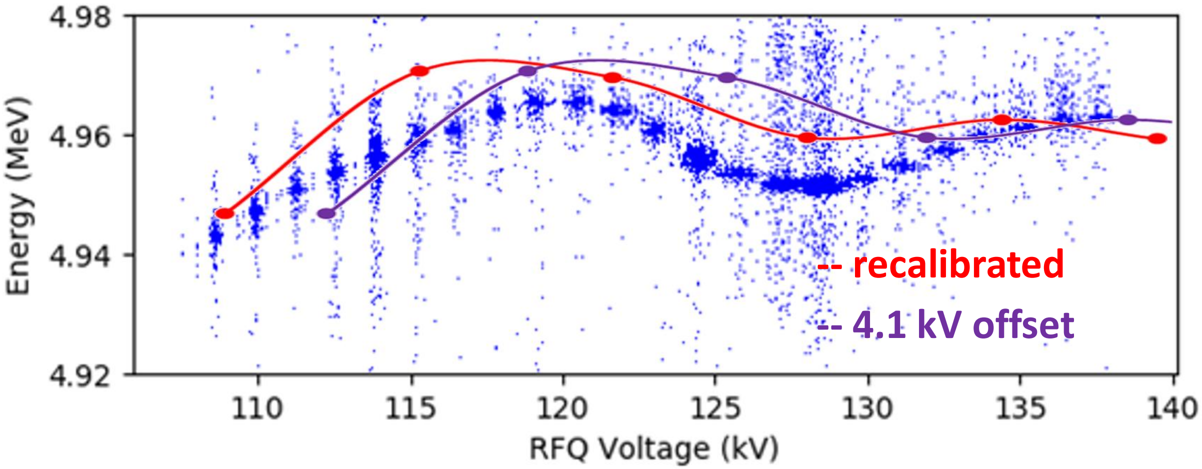
- Transmission vs. Voltage curve is a key characteristic to validate the design of the RFQ
- For protons the agreement was good at different currents
- For deuterons the experimental curve present a different slope: transmission is too high at Vrfq< Vnom.
- After testing different input distribution model, the best explanation is a 3-4kV offset in the voltage measurement, probably due to changed scale of the oscilloscope between proton and deuteros field level





Some other interesting results from TOF

MEBT and Dplate teams measure the TOF via BPM (Thanks to CIEMAT colleagues).



- The BPM measurements also show a calibration of about 4 kV with respect the real cavity voltage (in agreement with the calibration curve.)
- That BPM curve is linked to the energy at the RFQ input. It seems that we are injecting between 1 kV – 0.7 kV higher than nominal input energy (100 kV).

Beam loading

- How the RF generator sees the multi-cell accelerating cavity and beam?
- In particular, which is the effective synchronous phase between Vc and ib?

$$P_b = \frac{1}{2}\left|\widetilde{V_c}\right|\left|\widetilde{i_b}\right| cos\phi = I \sum_i V_i T_i cos\phi_i$$ **beam active power**

$$Q_b = \frac{1}{2}\left|\widetilde{V_c}\right|\left|\widetilde{i_b}\right| sin\phi = I \sum_i V_i T_i sin\phi_i$$ **beam reactive power**

Effective sync.phase

$$\phi = atan\frac{\sum_i V_i T_i sin\phi_i}{\sum_i V_i T_i cos\phi_i}$$

Effective accelerating voltage

$$\left|\widetilde{V_c}\right| = \frac{\sum_i V_i T_i cos\phi_i}{cos\phi}$$

Effective shunt impedance

$$r_s = \frac{\left|\widetilde{V_c}\right|^2}{P_{Cu}}$$

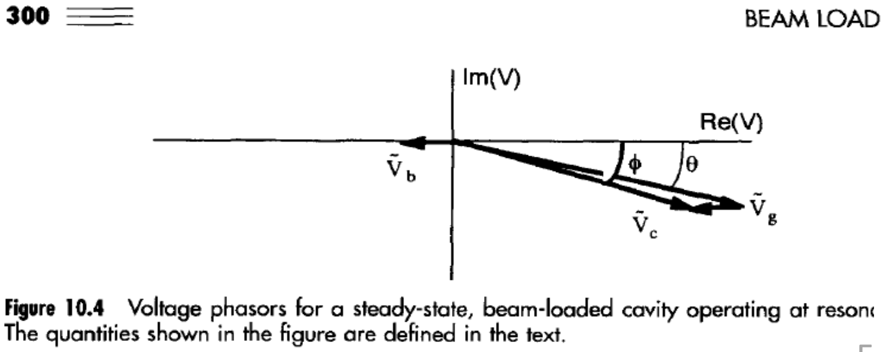
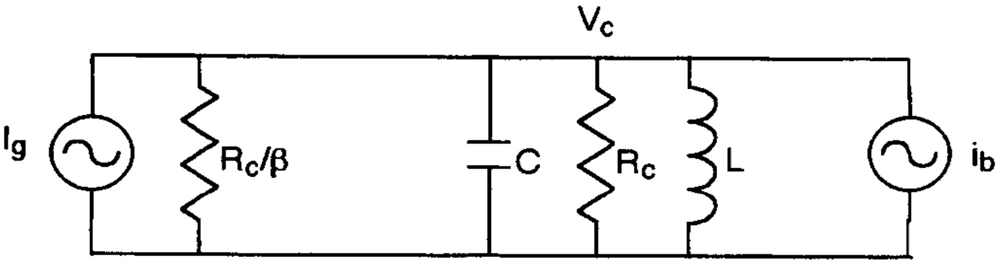
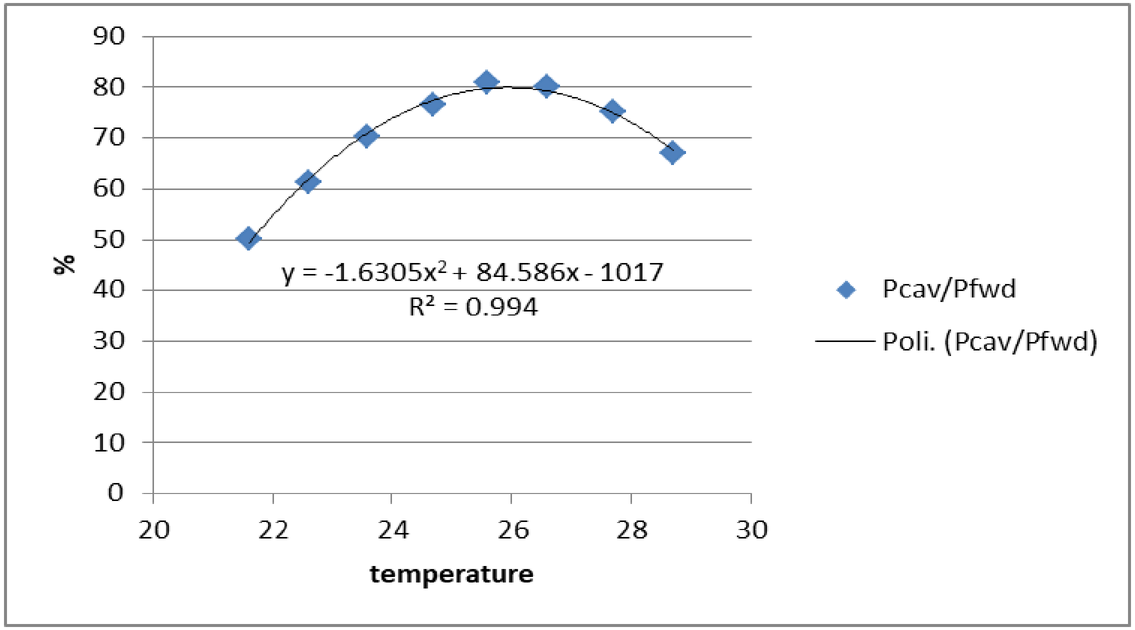

300 BEAM LOADING

Figure 10.4 Voltage phasors for a steady-state, beam-loaded cavity operating at reson
The quantities shown in the figure are defined in the text.



Beam Loading

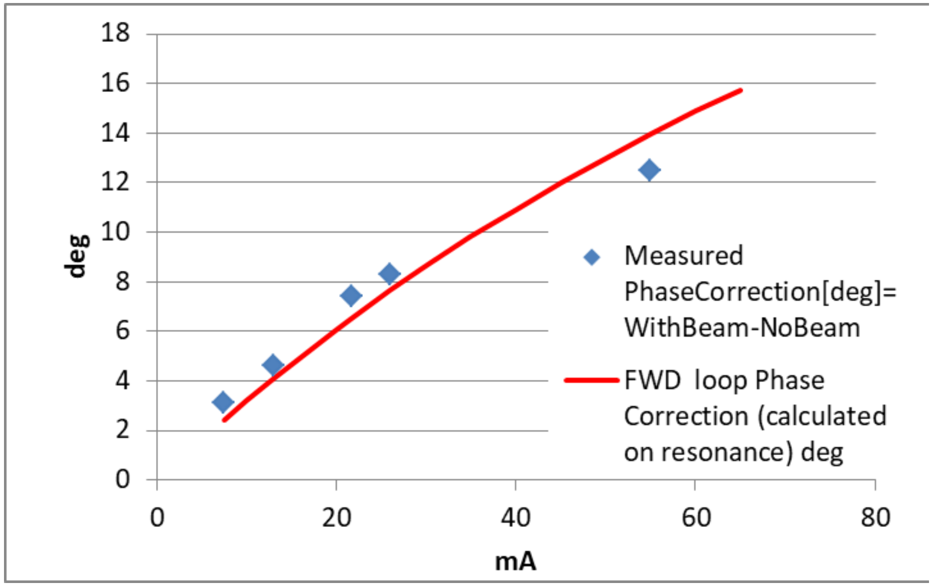
- For 125 mA D+ (or 62.5 mA H+) a +8.1 kHz optimum detuning is required to be at resonance with beam (beam “decreases” the resonant frequency)
- To check it we took 3 different measurements:
  0. But first we checked the cavity resonance as function of temperature → -3kHz/°C

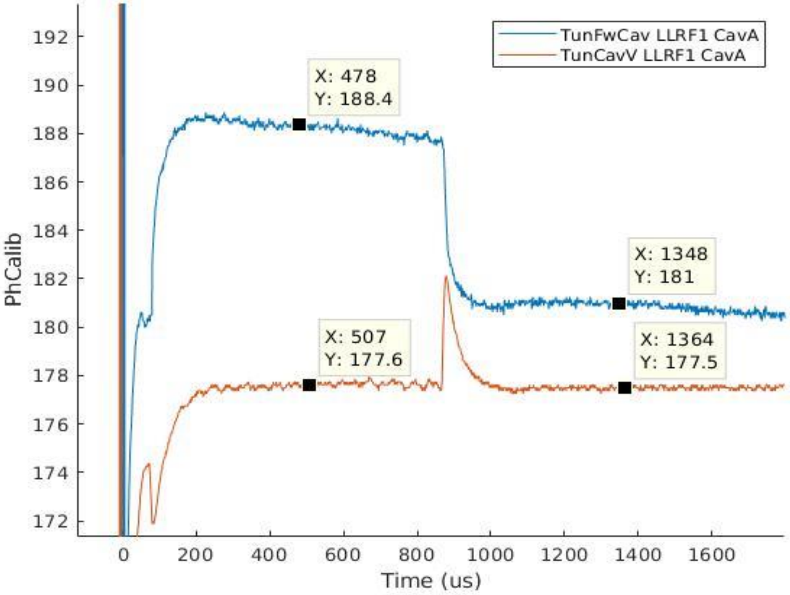


Beam Loading

- For 125 mA D+ (or 62.5 mA H+) a +8.1 kHz optimum detuning is required to be at resonance with beam (beam “decreases” the frequency)
- To check it we took 3 different measurements

1. Measurement of the FWD loop phase correction required by beam entrance at different proton currents (close loop, resonant frequency without beam at 175 MHz)

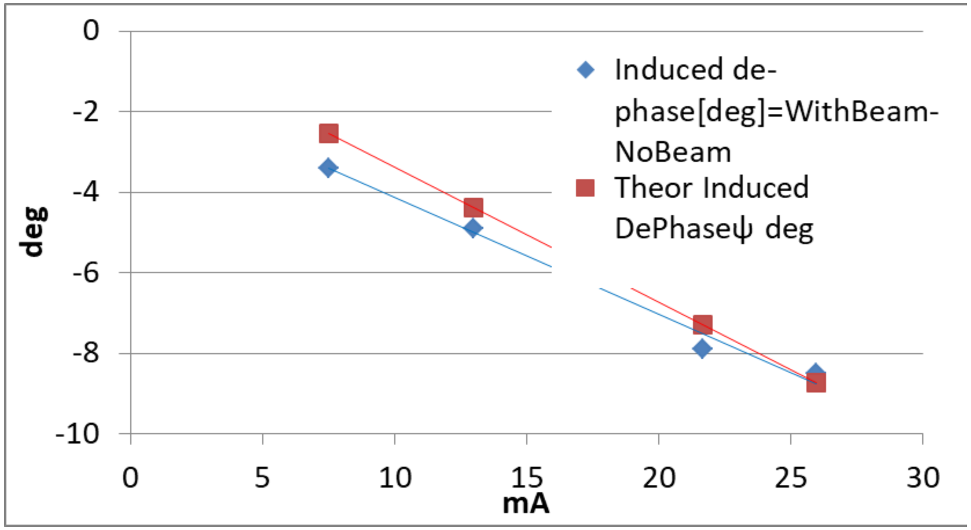


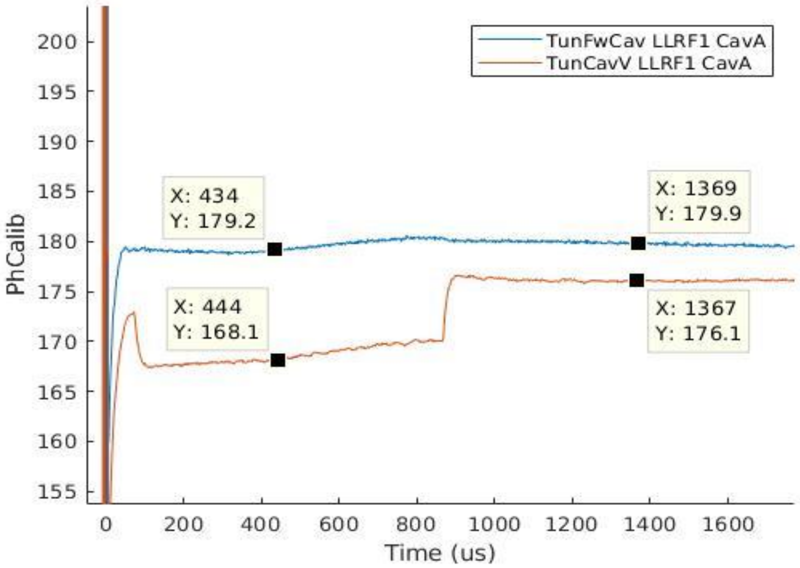


Beam Loading

- For 125 mA D+ (or 62.5 mA H+) a +8.1 kHz optimum detuning is required to be at resonance with beam (beam “decreases” the frequency)
- To check it we took 3 different measurements

2. The beam induced de-phase in the cavity voltage (open loop, resonant frequency with out beam 175 MHz)

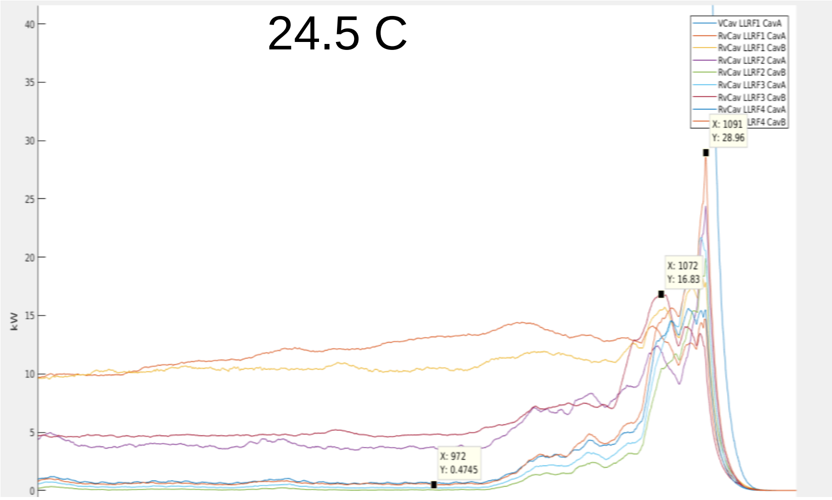


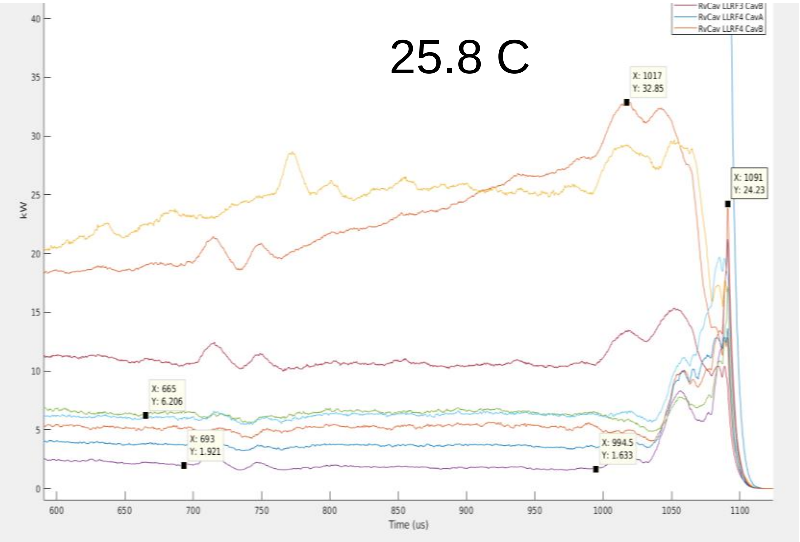


Beam Loading

- For 125 mA D+ (or 62.5 mA H+) a +8.1 kHz optimum detuning is required to be at resonance with beam (beam "decreases" the frequency)
- To check it we took 3 different measurements

3. Minimization of the reverse power with beam, modulating the cavity frequency by temperature (Expected frequency shift with D+ 75 mA is -4.8 kHz that means 1.6 deg C temperature decrease to recover f_{RF}=175 MHz)

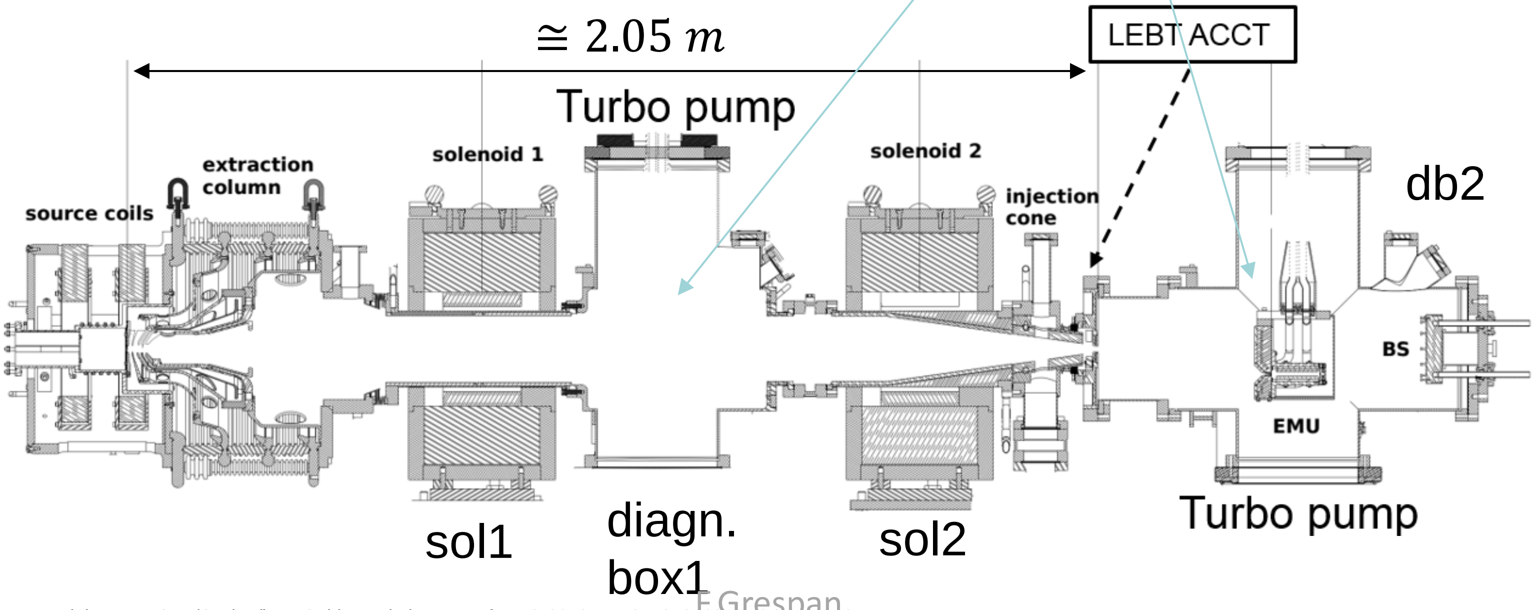




Some focus on Beam input matching

IFMIF-EVEDA Injector commissioning

- ECR ion source type, 1 kW RF power @ 2.45 GHz [0]
- Short LEBT, 2051 mm from PE. Balanced between Ion species separation power and minimization of emittance growth. Typical *generalized perveance*: 4.5×10^{-3} (158 mA given by D (93%) and its molecular ions)
- Few diagnostics: ACCTs, Allison scanner type emittancemeter (EMU, one plane), cct cameras (but only useful at high DC), Doppler shift spectrometer, vacuum gauges and Four Grid Analyser and RGA
- **No IRIS, just RFQ cone as scraper.**



[0] "Final design of the IFMIF injector at CEA/Saclay," R. Gobin et al., in Proc. of IPAC 2013, pp. 3758–3760, JACOW, 2013.

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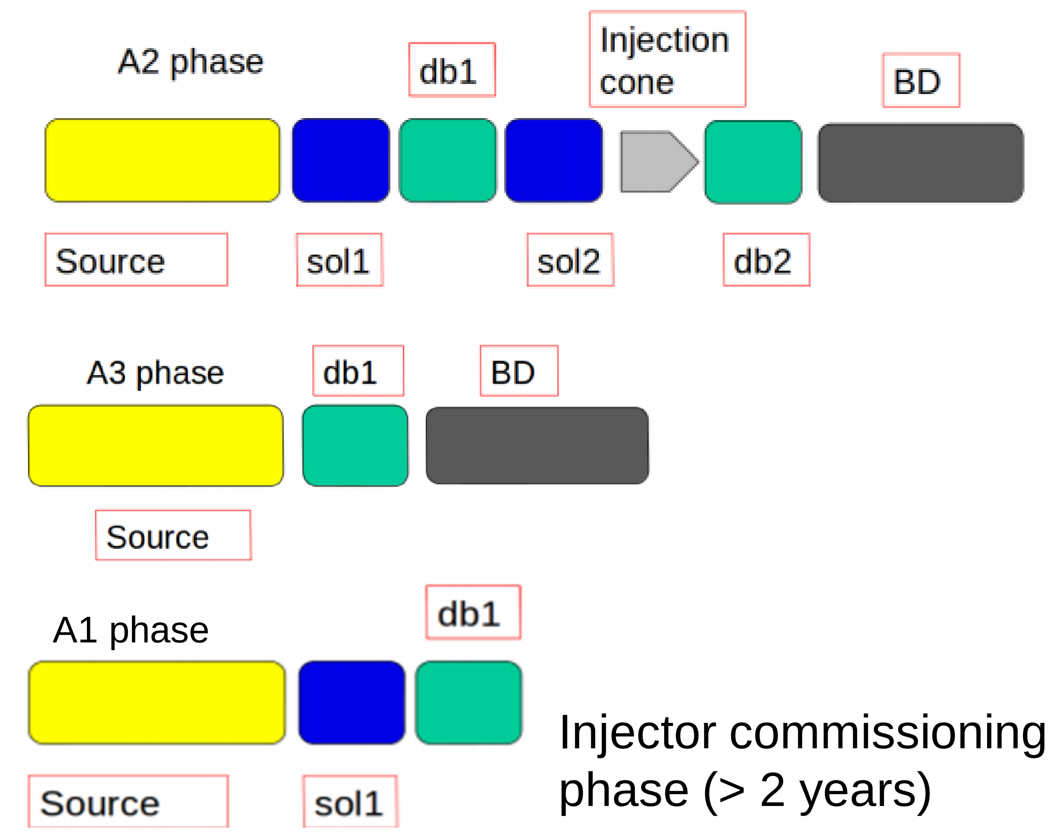
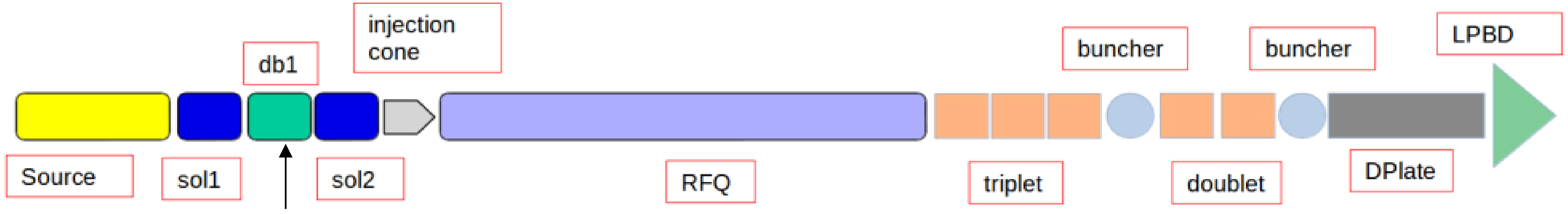
Laboratori Nazionali di Legnaro

Commissioning steps



Injector commissioning phase (> 2 years)

- Check of all the injector components
- Deep study and modellization of the S.C.C (space charge compensation)
- Definition of experimental measurement uncertainties.
- Definition of an experimental criteria to inject into the RFQ
- Definition of simulation model uncertainties
- Definition of injector working point for nominal beam perveance.
- Implementation of a BD model with the study of the injector response with respect to the parameters variation (e.g. solenoids):
  - Estimation of the beam characteristics at the RFQ entrance.



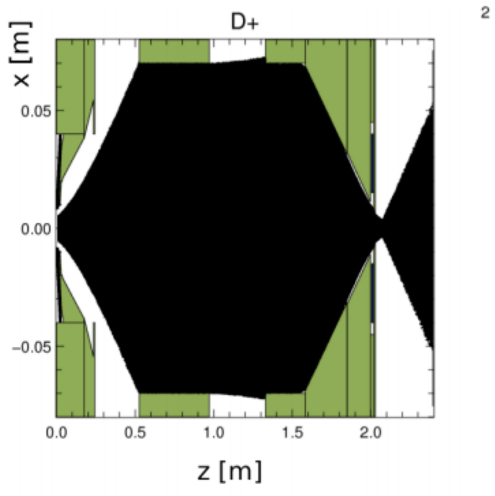
EMU was moved here!

F.Grespan

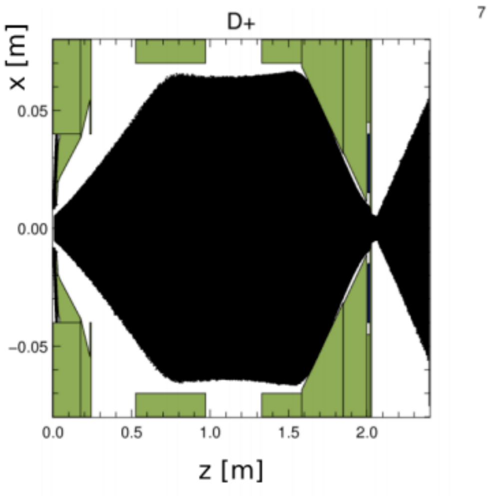
B1 phase

Model and software's

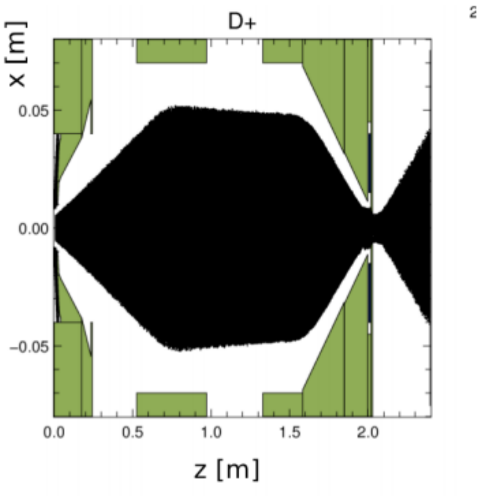
- WARP for space charge compensation patterns and LEBT transport
- IBISIMU extractor
- Tracewin for matching routines and outputs
- Toutatis for RFQ model (as built, RF tuning).



Step 100000, T = 2.0000e−6 s, Zbeam = 0.0000e+0 m

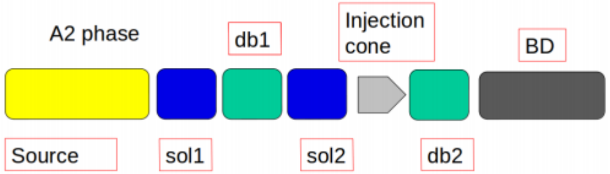


Step 349750, T = 6.9950e−6 s, Zbeam = 0.0000e+0 m

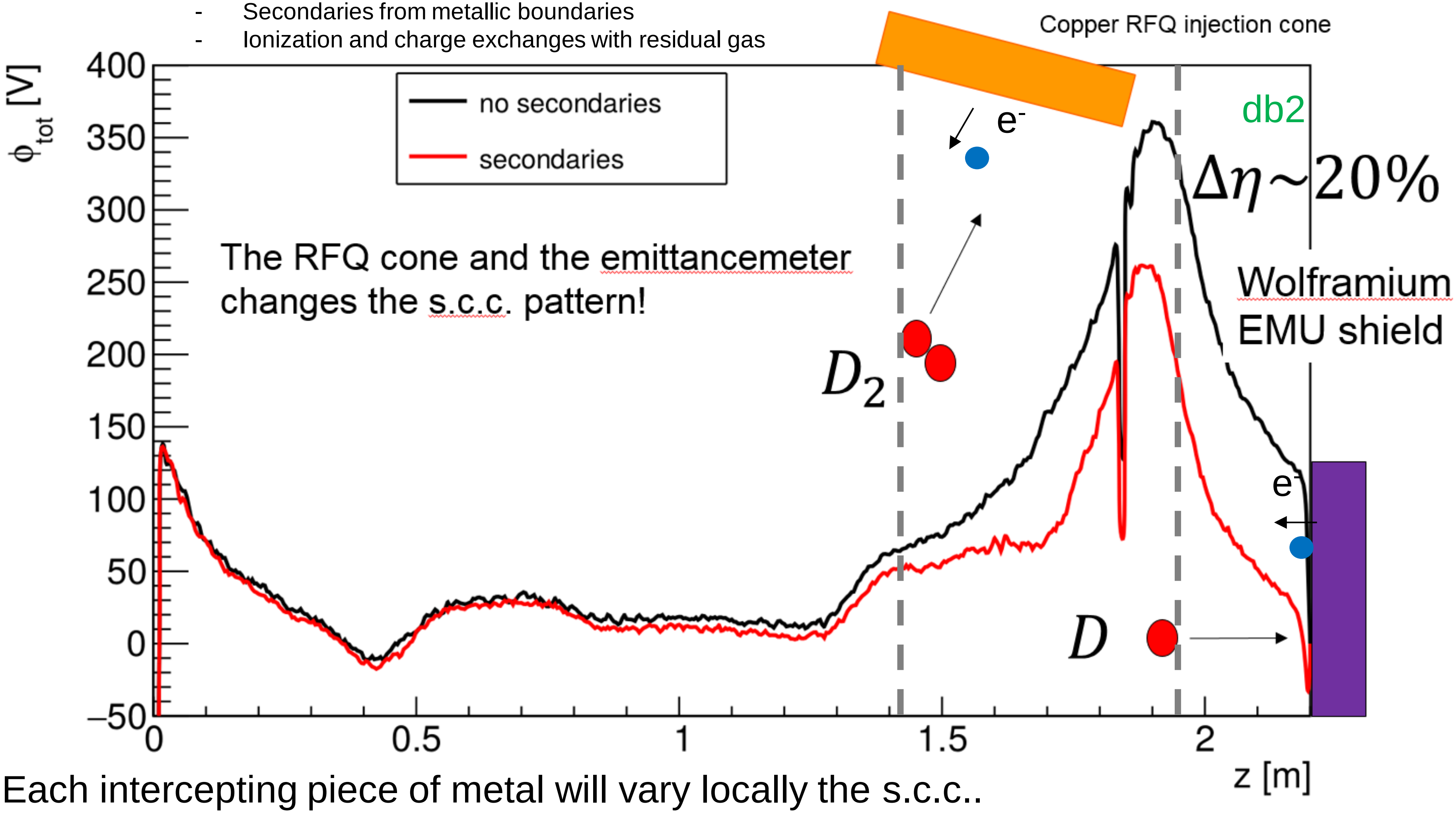


Step 700250, T = 14.0050e−6 s, Zbeam = 0.0000e+0 m

$\phi_{tot}(z)$ along axis



- Secondaries from metallic boundaries
- Ionization and charge exchanges with residual gas



The RFQ cone and the emittancemeter changes the s.c.c. pattern!

Each intercepting piece of metal will vary locally the s.c.c..

[1] "Final Design of the IFMIF-EVEDA Low Energy Beam Transport Line", N. Chauvin, Proceedings of PAC09, 2018
[2] "Beam Dynamics Characterization of the IFMIF/EVEDA RFQ Input Beam", L. Bellan, PhD Thesis, 2018
[3] "Étude de la compensation de la charge d'espace dans les lignes basse énergie des accélérateurs d'ions légers de haute intensité", F. Gérardin, PhD Thesis, 2018

Example of results

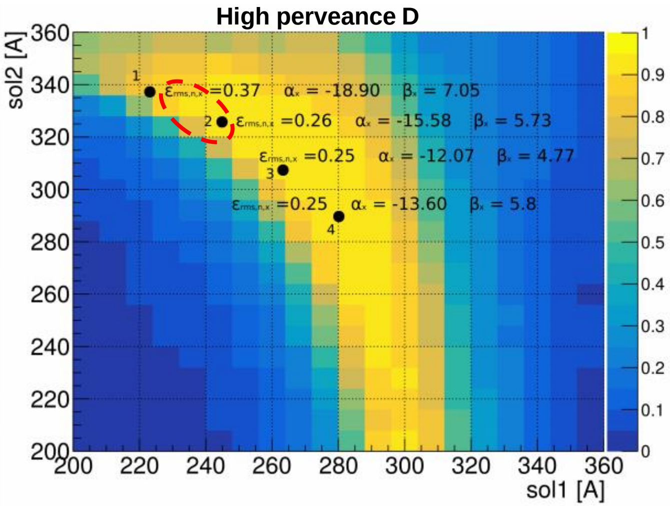


Fig. 6.1 Measured transmission from the extraction to the BS and $\varepsilon_{\mathrm{rms,n},x}$ vs solenoid 1 and solenoid 2 currents for 155 mA 100 keV D beam. The four measurements of the emittance, taken at the emittancemeter position used for the trace-forward are reported.

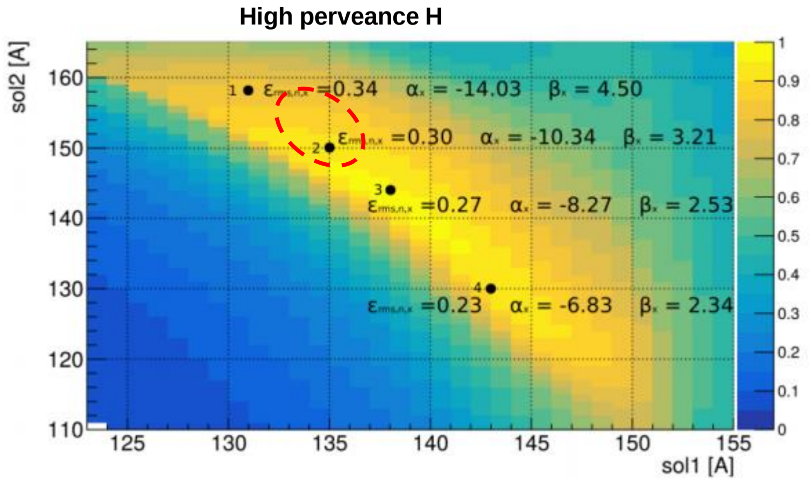
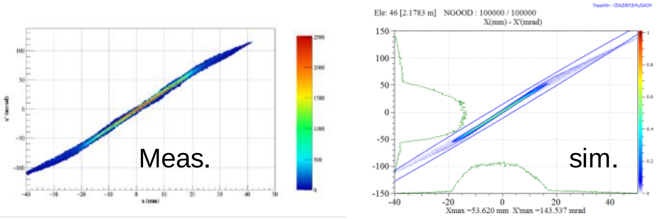
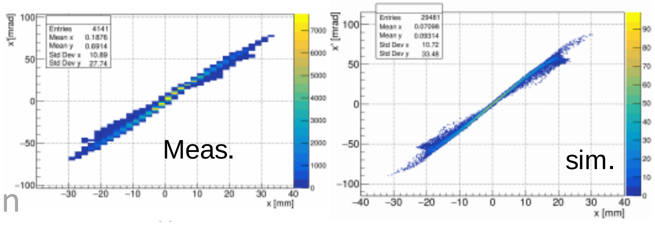


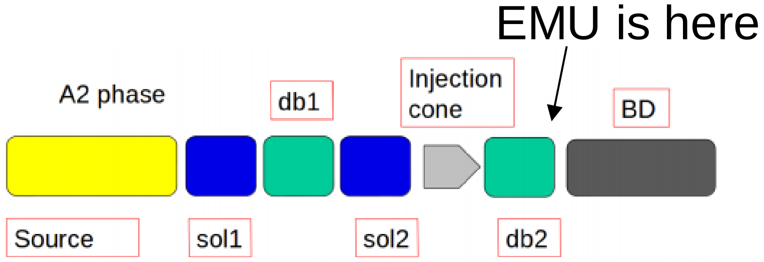
Fig. 5.13 Measured transmission from the extraction up to the BS and $\varepsilon_{\mathrm{rms,n},x}$ (taken at the EMU) vs solenoid 1 or solenoid 2 currents. The four measurements of the emittance used for the trace-forward are reported. 85 mA H beam (nominal + contaminats)

- The emittance depends on the solenoid values.
- More divergent the beam from the source, higher the values of the emittance will be on the upper left side of the solenoid scan plots (where the matching point should be)
- The emittance growth in the source is always lower than the emitttance growth caused by the non-linear part of the solenoids and due to the residual s.c. fields.



RMS quantities difference < 10%

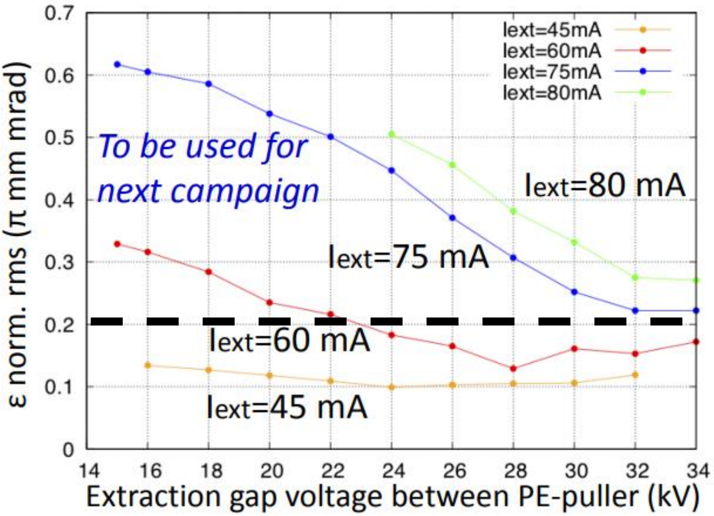


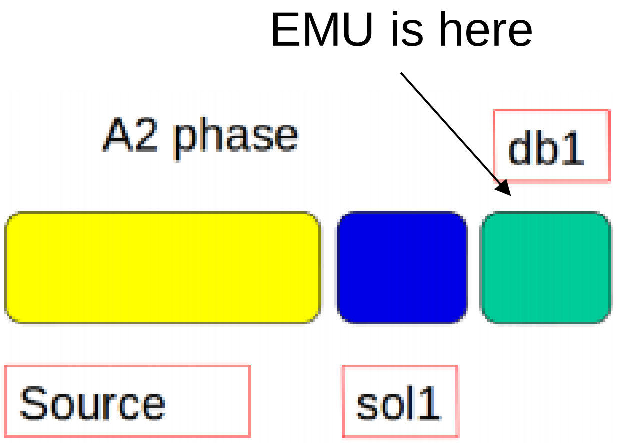


Simulation-experimental criteria for RFQ input beam

Since in RFQ operation the EMU would be located in db1 between LEBT solenoids, we wanted to determine a fast experimental criteria to define if a certain beam from the source is acceptable for the RFQ injection, looking to the emittance measurement after Sol1 (NB: it's a specific of injector and RFQ design)

<u>H+ 50 keV,</u>
<u>PE 9 mm ϕ</u>





1. At fixed solenoid value, several extractor configurations are studied.
2. The emittance between the two solenoid is measured.
3. To limit the emittance growth in the second half of the LEBT <u>for any couple of solenoids</u>, the emittance must be < 0.2 mm mrad normalized rms.
4. This should ensure a transmission of at least 90% of accelerated particles through the RFQ

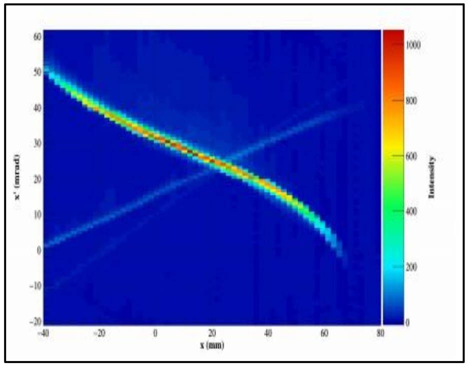
Procedure for first “easy” beam injection

- Low current H beam with 1/6 of nominal perveance (10 mA proton). Thus, beam mismatch accepted from 20% to 200%, boosted by the low current and the low emittance.
- **Probe beam** generation without IRIS: design of a plasma electrode diameter with half aperture respect to the nominal one.
- The MEBT was kept fixed during solenoid scan and steerers optimization.
- **The MEBT acts as an energy separator** (H2+ and H not accelerated are eliminated) with a certain efficiency that needs to be simulated

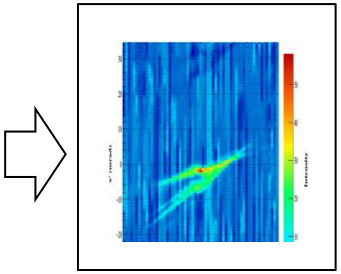
However:

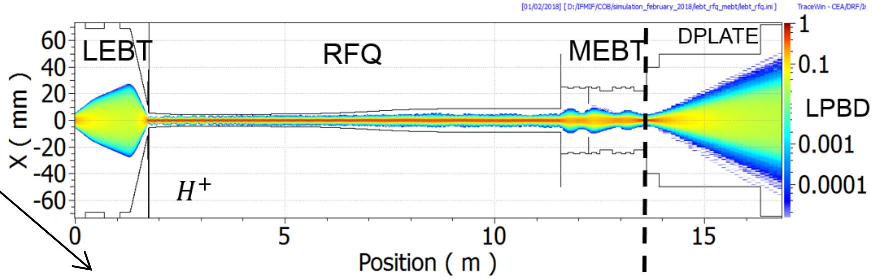
- low current extraction implies low proton fraction.
- Very focused electrostatic optics from the extraction
- Low separation of H^{2+} and H^+ at injection point of RFQ
- **Under estimation of the RFQ transmission**

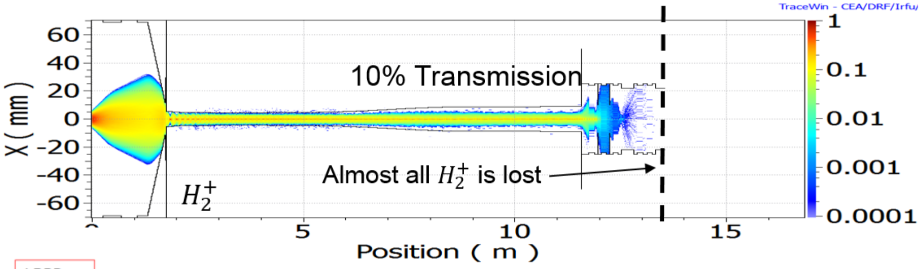
Average maximum proton perveance



Probe beam

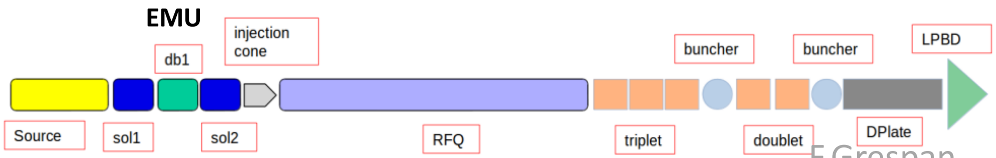






10% Transmission

Almost all H_2^+ is lost



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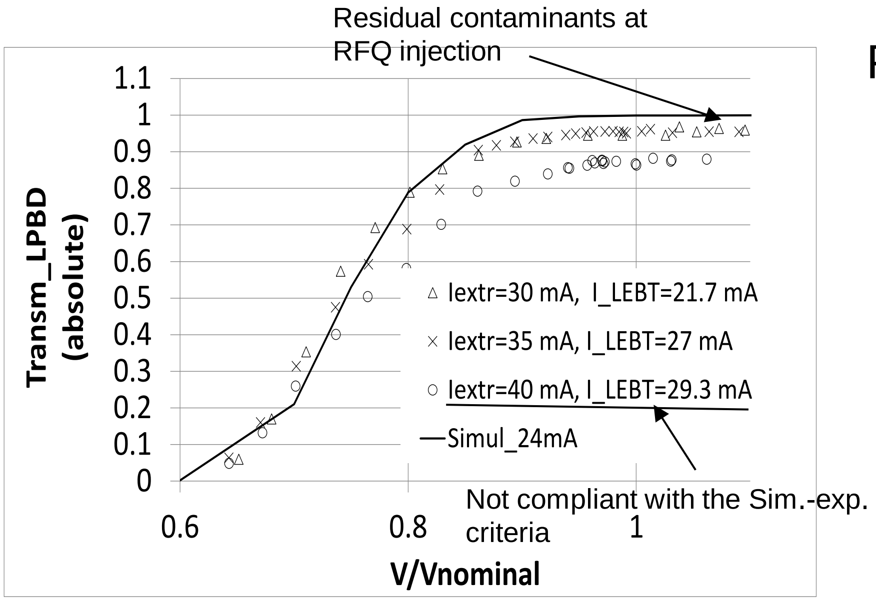
Procedure followed for each RFQ injection point

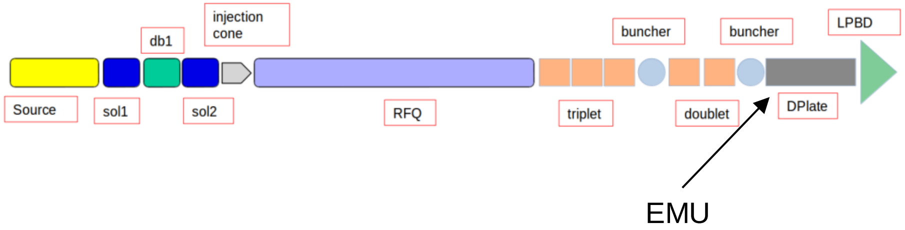
1. Study of the point at the injector level (emittance measurements between the two solenoid). Is it compliant with the criteria?
2. Solenoid set to theoretical value.
3. Steerer optimization looking to the beam dump.
4. Solenoid scan + steerer optimization (routine).
5. Small MEBT tuning.

1/3 perveance proton current

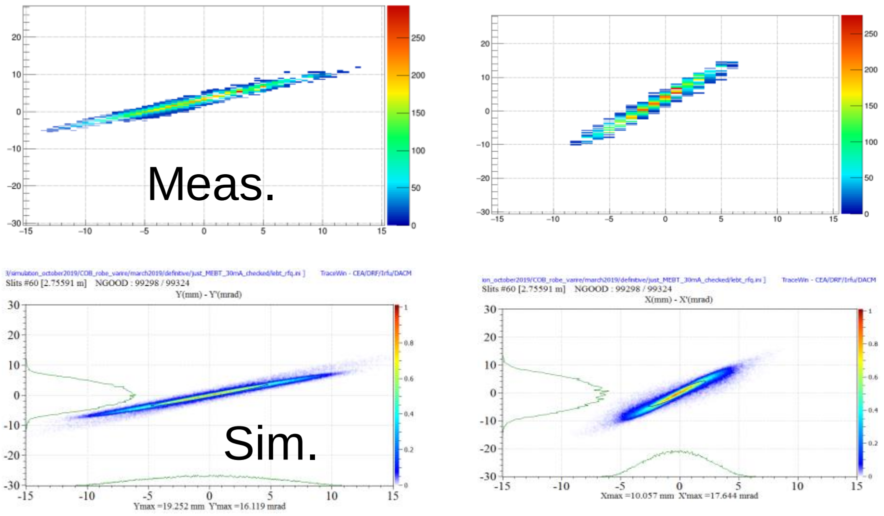


Residual contaminants at RFQ injection

Not compliant with the Sim.-exp. criteria



Post RFQ emittances (21.7 mA proton beam)

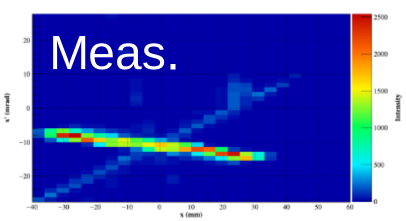


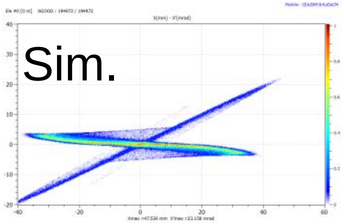
Phase-space plane	yy' [meas/sim]	xx' [meas/sim]
$\varepsilon_{rms,n}$ [mm mrad]	0.237 / 0.24	0.231 / 0.24
β [mm/mrad]	8.03 / 8.1	2.27 / 1.8
α	-5.38/ -6.0	-4.00 / -3.3

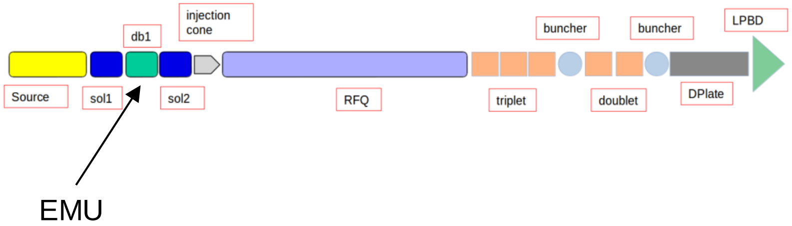
Nominal deuteron current (124 mA)

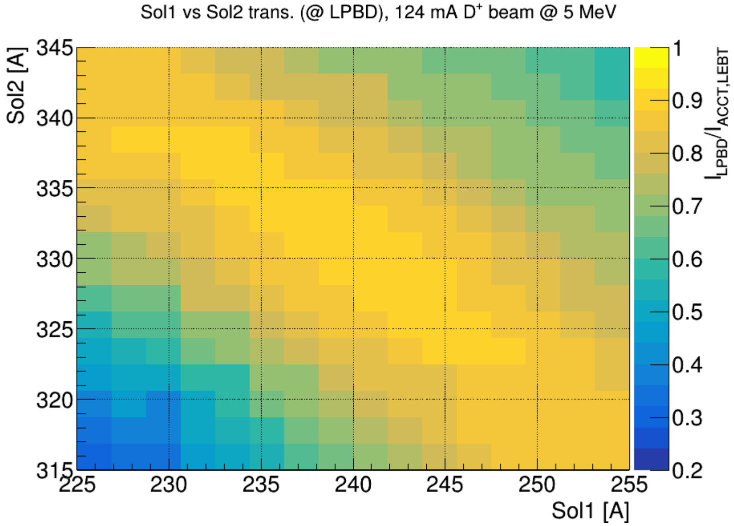
EmitNorm = 0.194 pi.mm.mrad

Alpha = 2.212, Beta = 20.753 mm/pi.mrad,

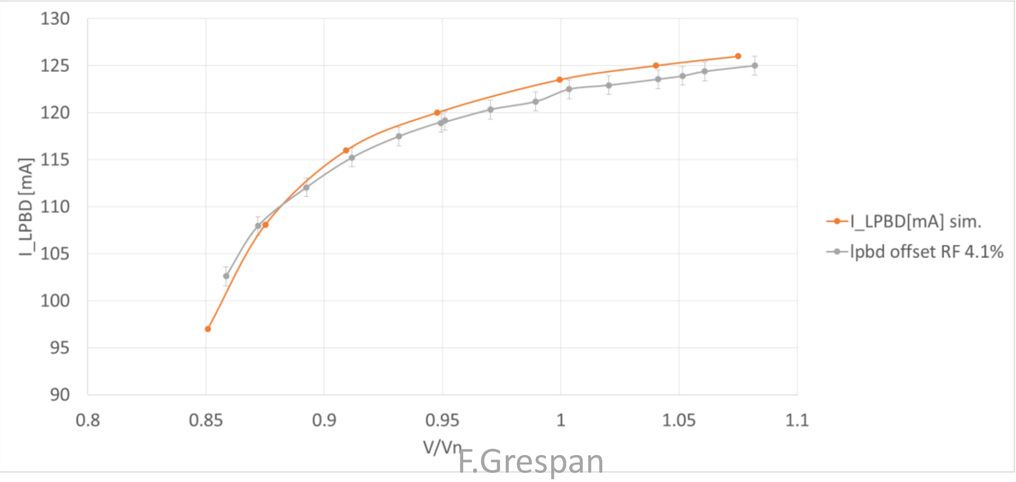







Sol1 vs Sol2 trans. (@ LPBD), 124 mA D^+ beam @ 5 MeV

Transmission map through the RFQ with respect the LEBT solenoids.



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Final considerations on simulations and experiments

- The beam physics in the source and LEBT transport is one of the most challenging in terms of simulations: multi-species ions interacting with residual gas and metallic boundaries, fully immerse an electrostatic and magnetostatic fields. Even with the most powerful simulation tool, a much larger degree of approximation must be included in simulations as errors. It is a full-fledge plasma confinement simulation.
- The situation in terms of precision can be considered even worst if we considered the experimental errors: as an example, in the IFMIF EVEDA injector Allison scanner emittancemeter the estimated error on the emittance value may span the 20% of the value!
- However, despite these complexities, the first order optics (beam envelopes, transmissions, initial settings of the machine) are normally coherent with the easiest simulation models, at least the trends!
- If you start from the extraction with a large divergence beam, you will quickly gain emittance growth due to the nonlinear space charge effects which couples with the solenoids non linarites.
- ***Every time*** **we found a non-consistency of the experimental data with the simulation models, the problem belonged by the experimental setup (measurements and hardware faults)**
- **It is essential to keep in mind the limits of the modelling in such complicate line in order to interpreter correctly the results.**
- **Take all your free time to further experiment on beam commissioning of the front end**
- **Focus on few important measurements! The post analysis will require a large effort.**

Conclusions

We can conclude that the IFMIF EVEDA RFQ is working as expected, both from RF and beam dynamics point of you, passing succesfully many check points.

Thank you.

Back up

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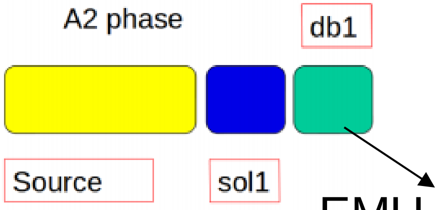
di Fisica Nucleare
Laboratori Nazionali di Legnaro

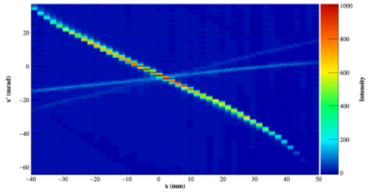
Example of results (2)

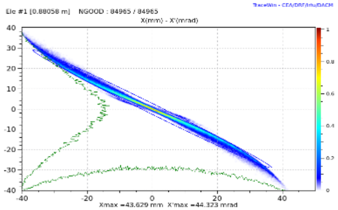


EMU is here

Meas.	Sim.	Meas.	Sim.

Iext = 70 mA H+ 50 keV

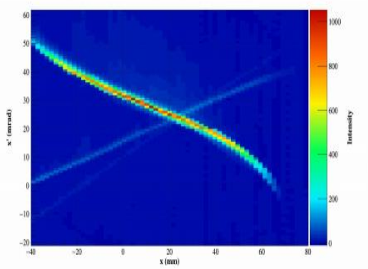


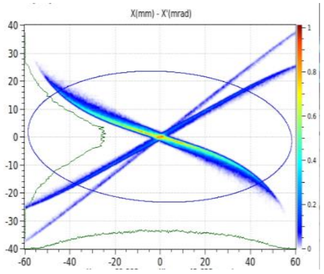


εn=0.250 π mm mrad
α=14.757, β=15.671 mm/π mrad
<x>=0.90 mm, <x'>=-6.28 mrad

X-X'
Emit [rms] = 0.2555 π.mm.mrad [Norm.]
Emit [90.51%] = 1.0219 π.mm.mrad [Norm.]
Beta = 13.5954 mm/π.mrad
Alpha = 10.7054

Iext= 85 mA H+ 50 keV





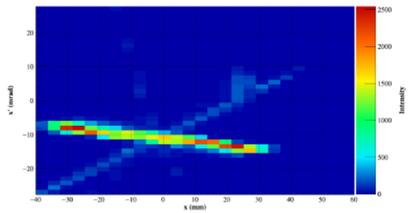
EmitNorm = 0.401 pi.mm.mrad

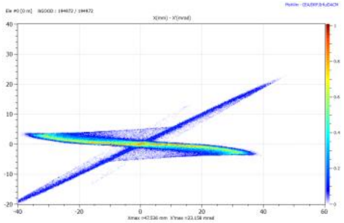
Alpha = 7.260, Beta = 18.281 mm/pi.mrad

<X> = 12.677 mm, <Xp> = 27.321 mrad

X-X'
Emit [rms] = 0.3427 π.mm.mrad [Norm.]
Emit [94.29%] = 1.7136 π.mm.mrad [Norm.]
Beta = 17.4433 mm/π.mrad
Alpha = 5.7850

Iext= 163 mA D+ 100 keV





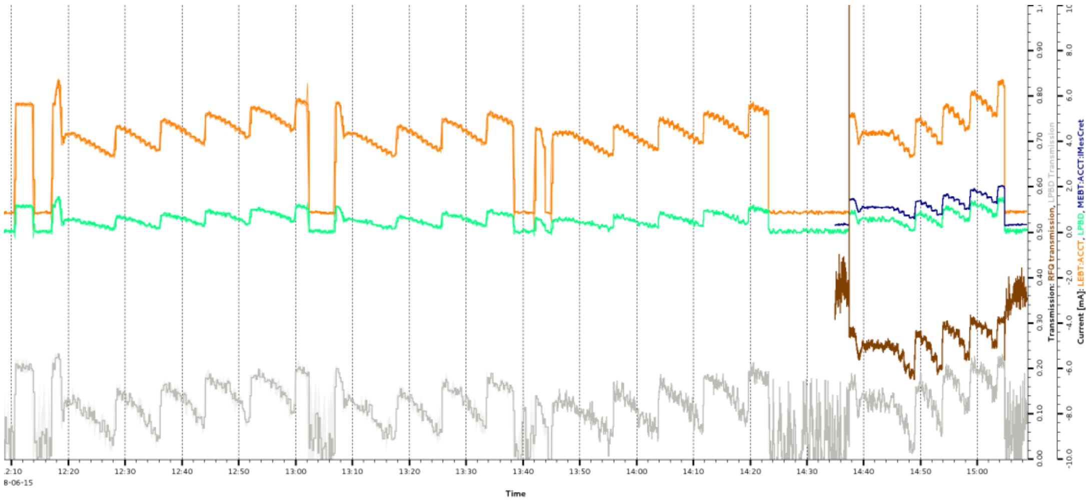
EmitNorm = 0.194 pi.mm.mrad

Alpha = 2.212, Beta = 20.753 mm/pi.mrad

X-X'
Emit [rms] = 0.19 mm mrad
Beta = 18.0 mm/mrad
Alpha = 1.4

Solenoid and steerer scan routine

Problem: large sensibility of the RFQ to misalignment.
No information usable for precise and fast centering.



Implemented solution:

- The RFQ + MEBT is used as a centering diagnostic.
- In order to set the steerers for matching the input at the RFQ, we implement an automatic routine scan.
- The routines changes the steerers (and solenoids) strengths 2 vertical and 2 horizontal looking at specified observable: current at the LPBD, transmission etc.. Time taken for completion, order of several hours!
- Large part of the work involves the implementation of a back up file that can restart the routine from the last interruption (interlocks).

Results: it identify the needs of a large (> 50 A) vertical steerer strength.
Systematic mitigation of the misalignment effect.
Further improvement are foreseen and will be tested in the next campaign.