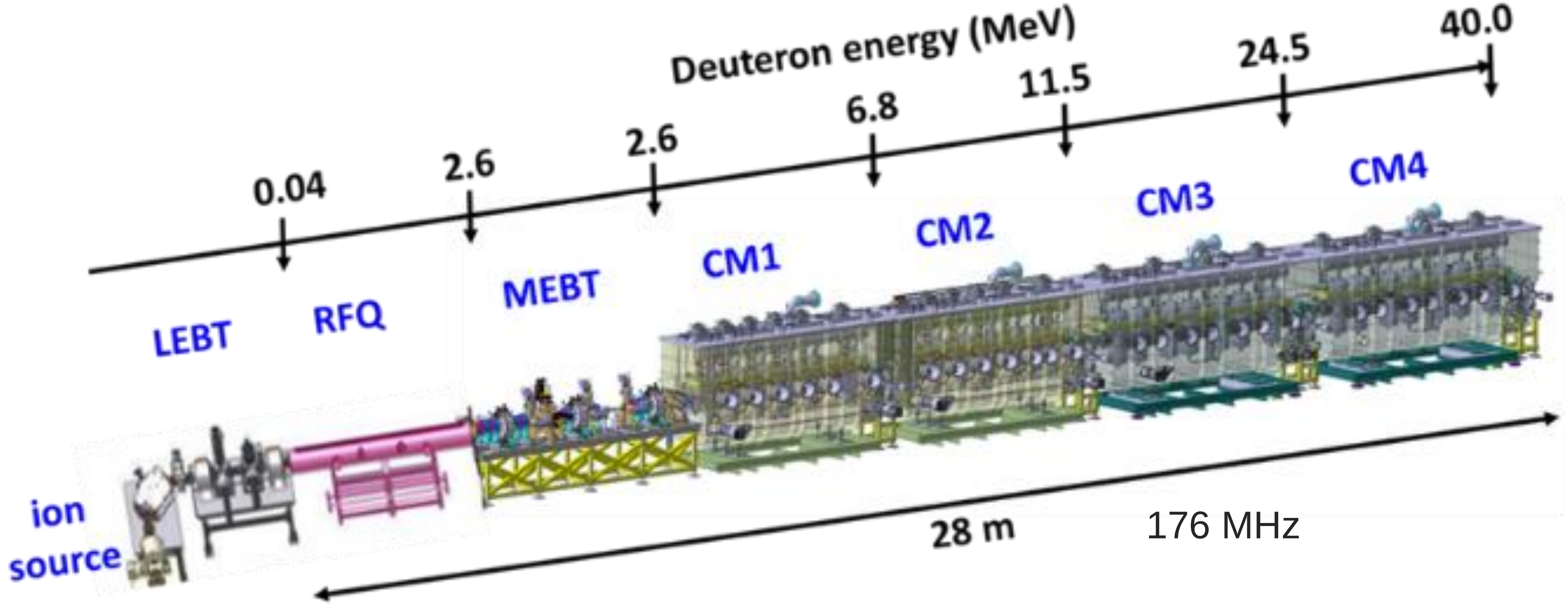
SARAF MEBT commissioning

CEA-IRFU - J. Dumas, N. Pichoff, A. Chance, F. Gougnaud, F. Senée, D. Uriot

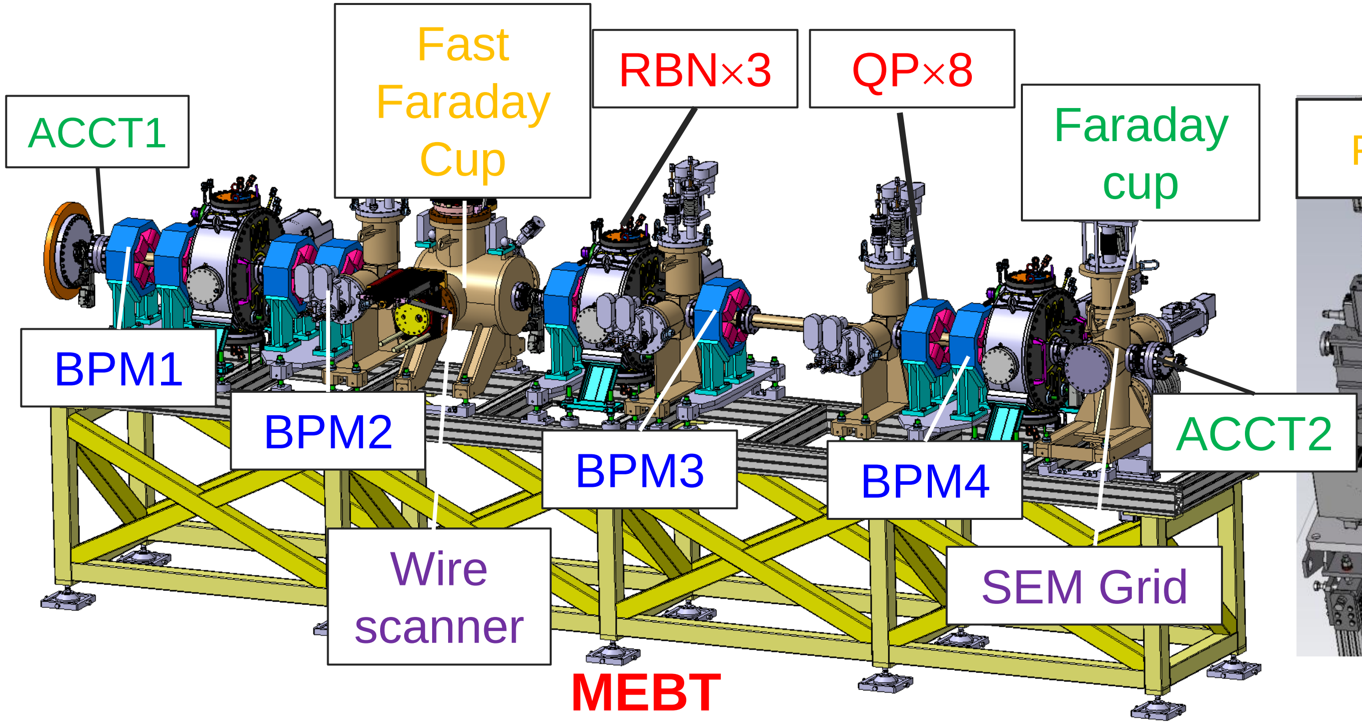
SNRC - A. Kreisel, J. Luner, A. Perry, E. Reinfeld, L. Weissman

The SARAF LINAC

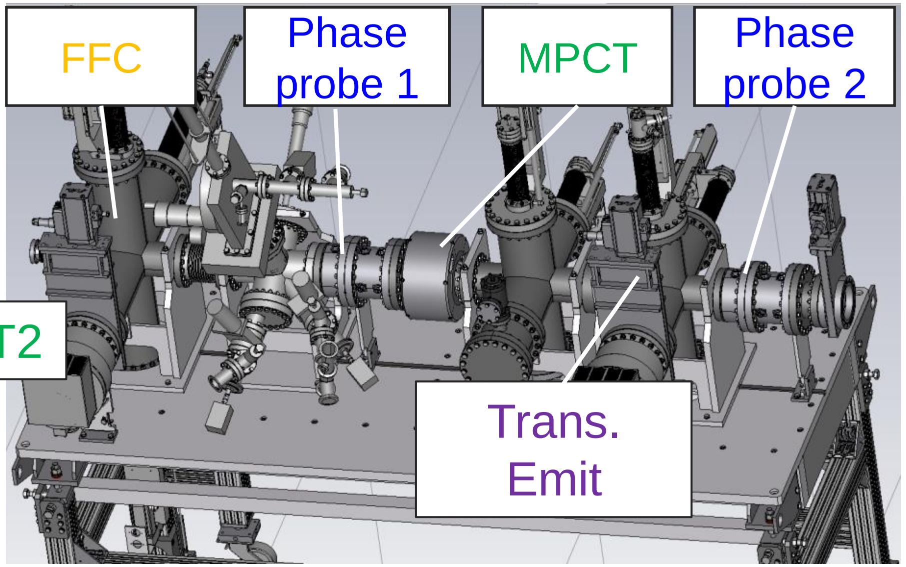
Ions	Protons/Deutons
Energy	1.3/2.6 – 35/40 MeV
Current	0.04 - 5 mA 100µs to CW



The SARAF MEBT



MEBT



DPLATE (from Phase 1)

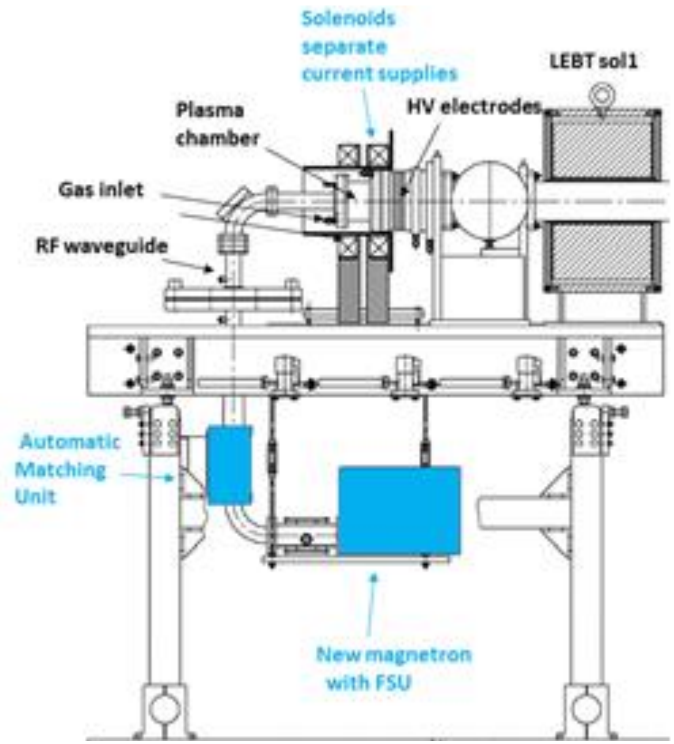
- Tests of Beam Diagnostics and Local Control System
- RFQ and MEBT transmission measurements
- Rebuncher calibration
- Longitudinal characterization (bunch length, emittance)
- Transverse characterization (bunch width, emittance)

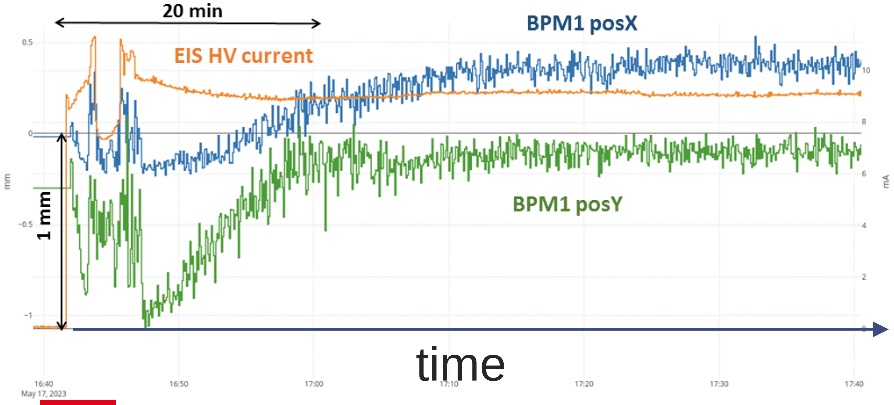
Contents

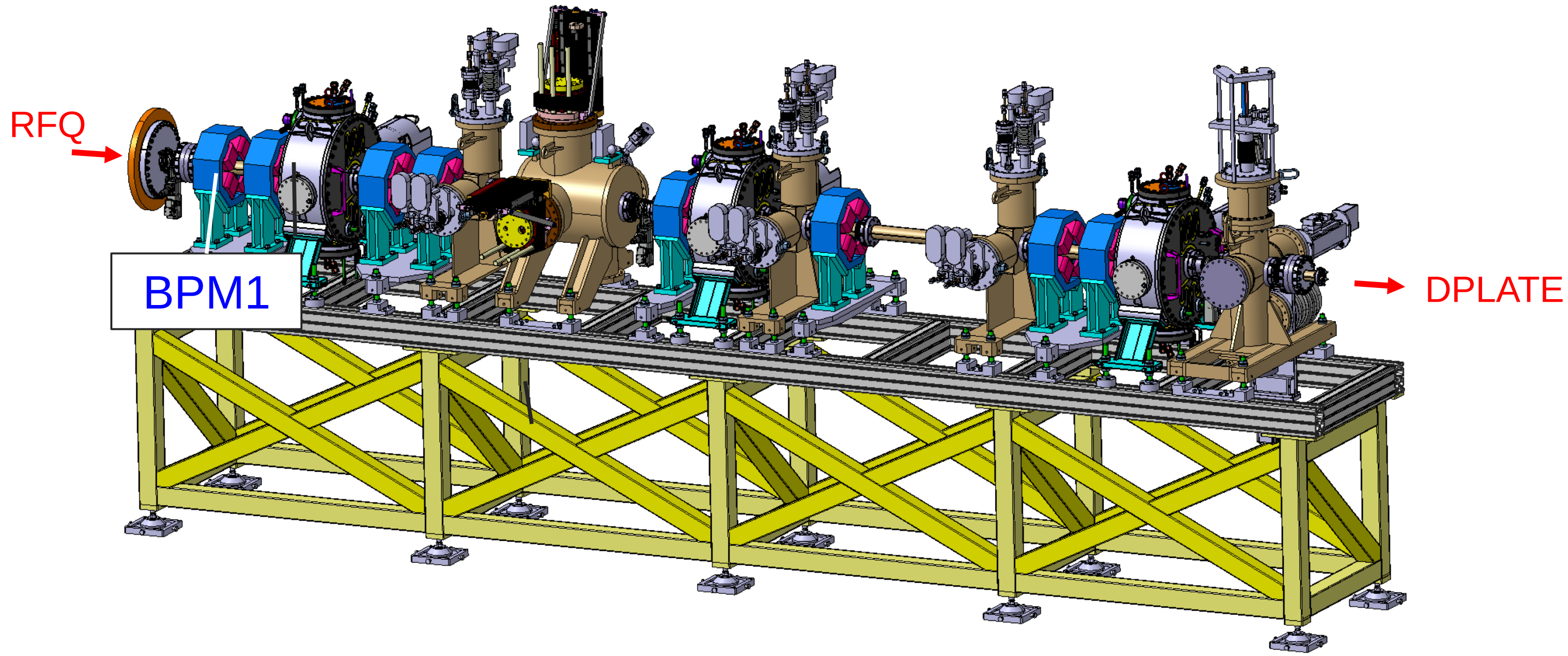
- The Machine tuning
- The Beam characterization in MEBT
- Machine learning philosophy…

■ Machine Tuning

EIS - Warm-up

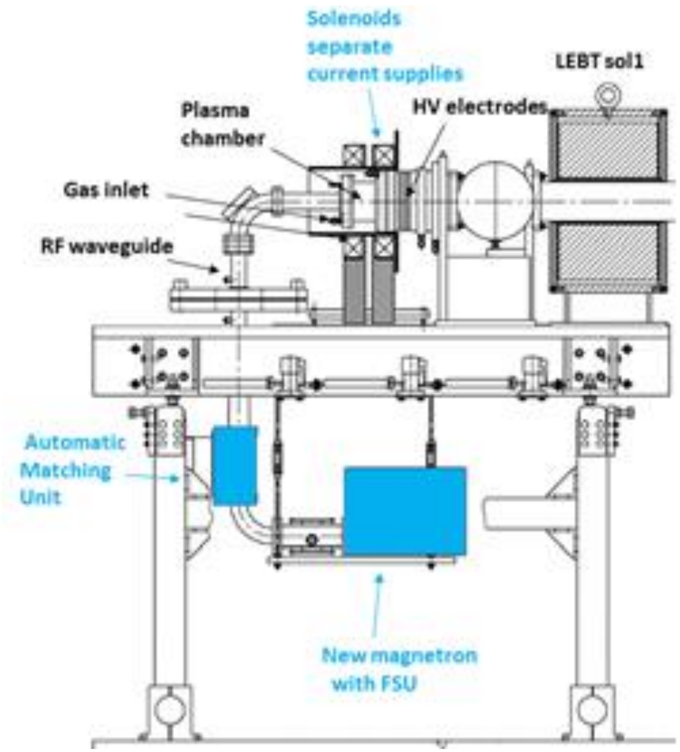


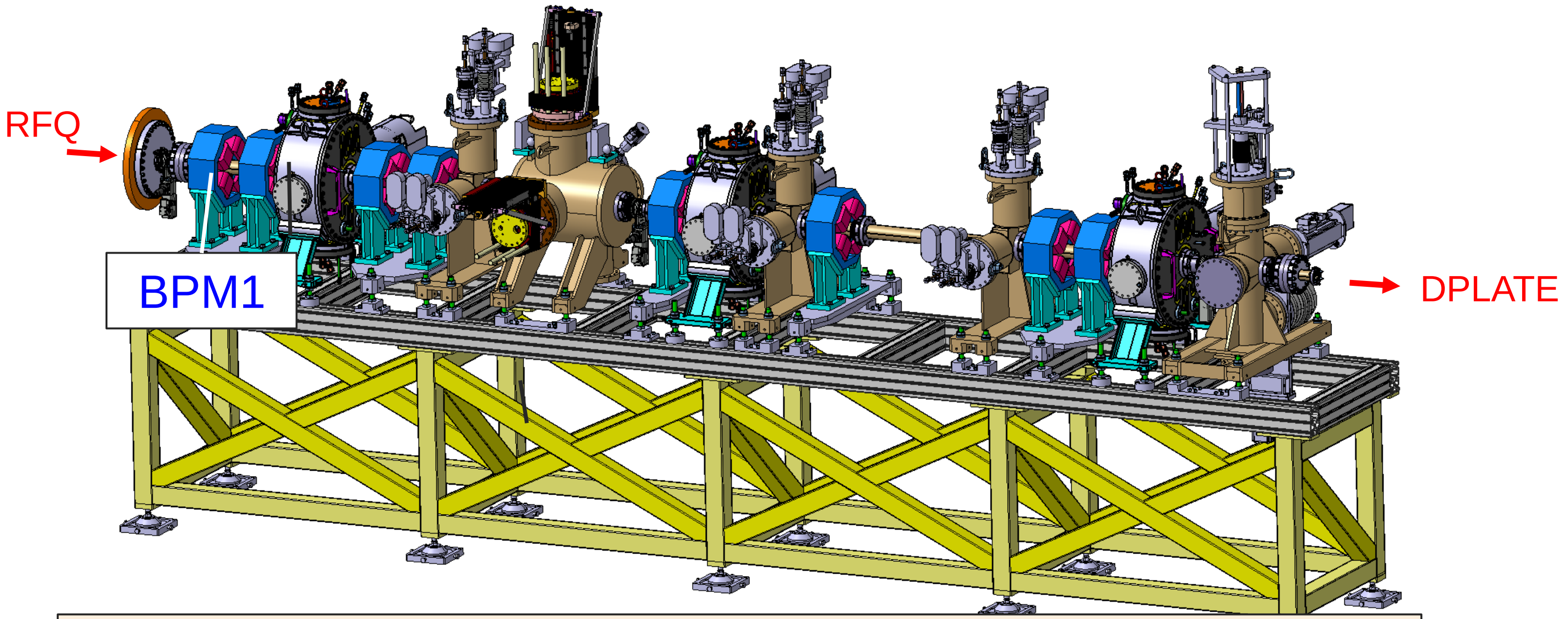




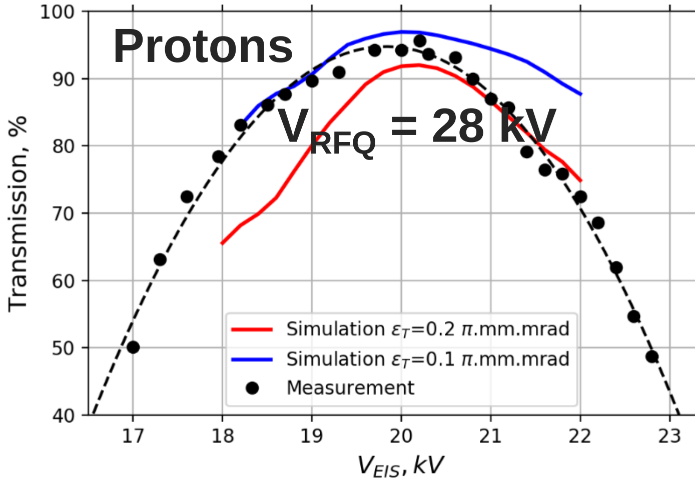
20 minutes are needed after EIS switch ON for a stable beam out of the RFQ

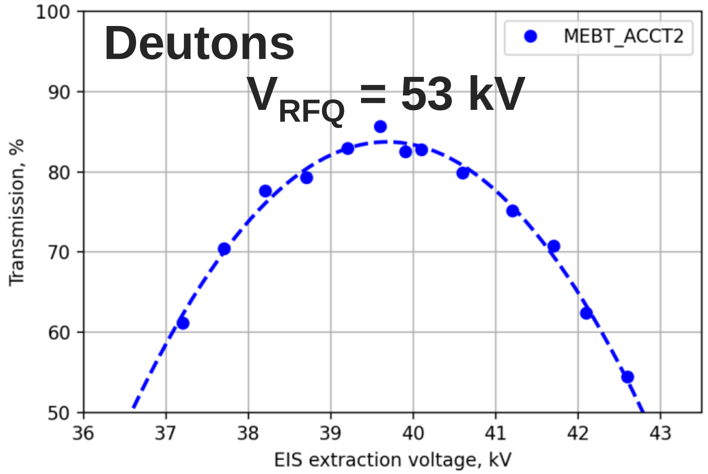
EIS - Voltage tuning (to RFQ)



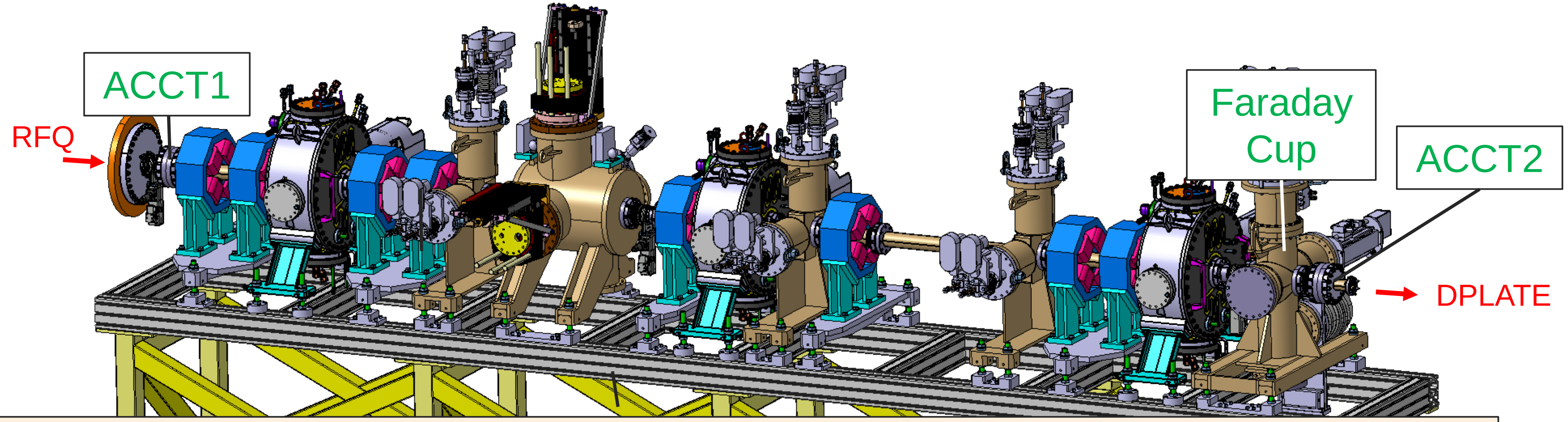


RFQ Transmission (/ACCT$_{LEBT}$), nominal optics

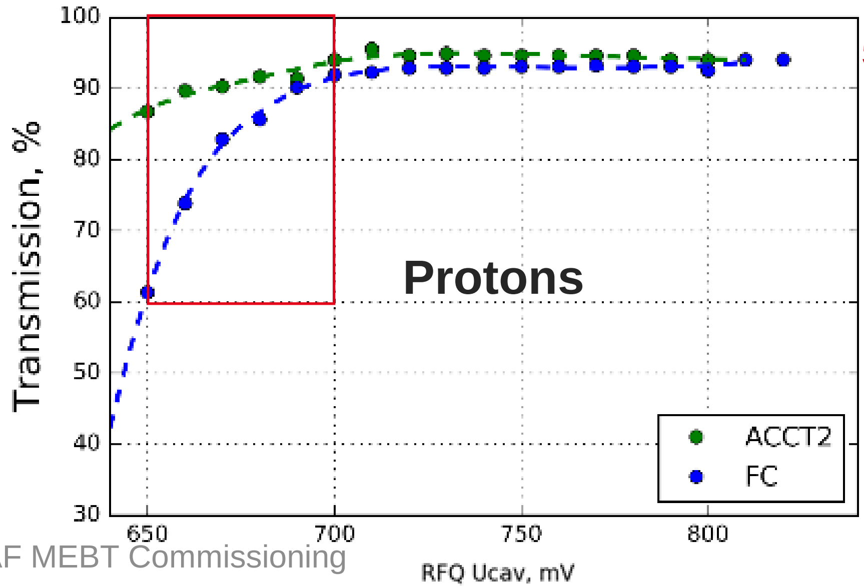




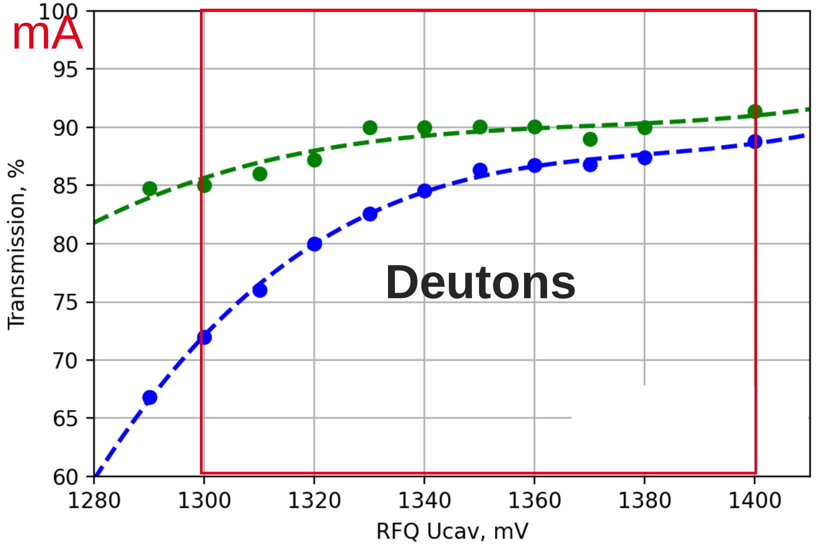
RFQ and MEBT transmission measurements



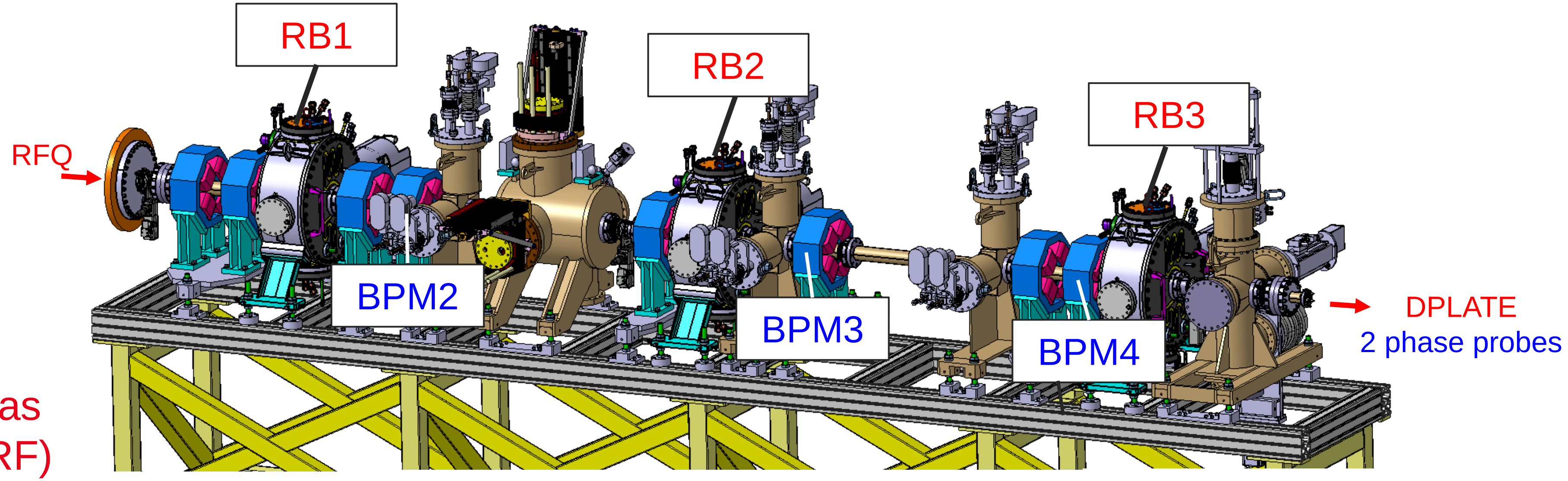
Transmission (/$ACCT_{LEBT}$), nominal optics



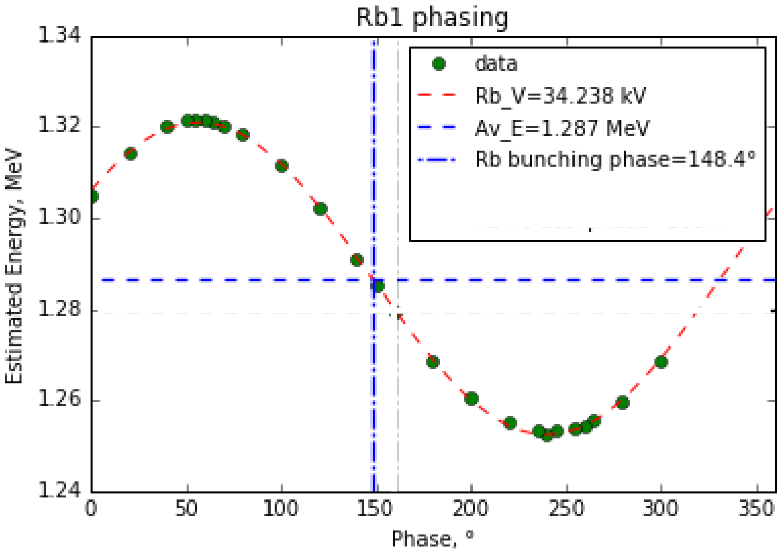
5 mA



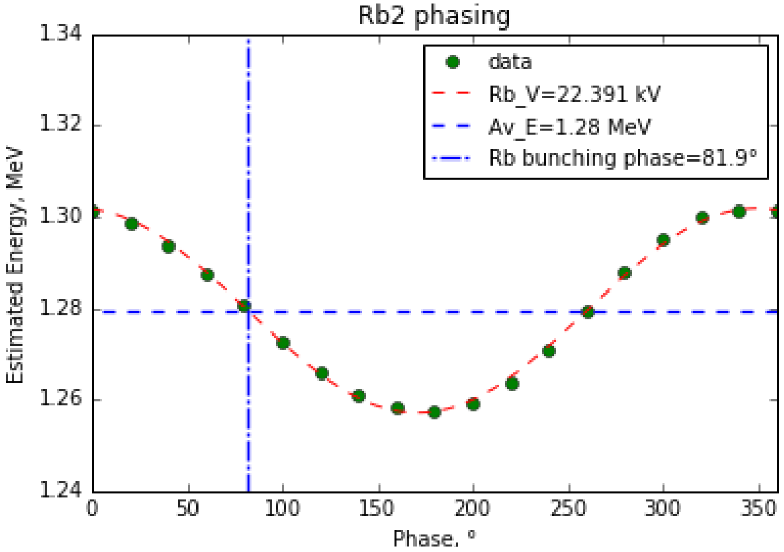
Rebuncher calibration (protons)



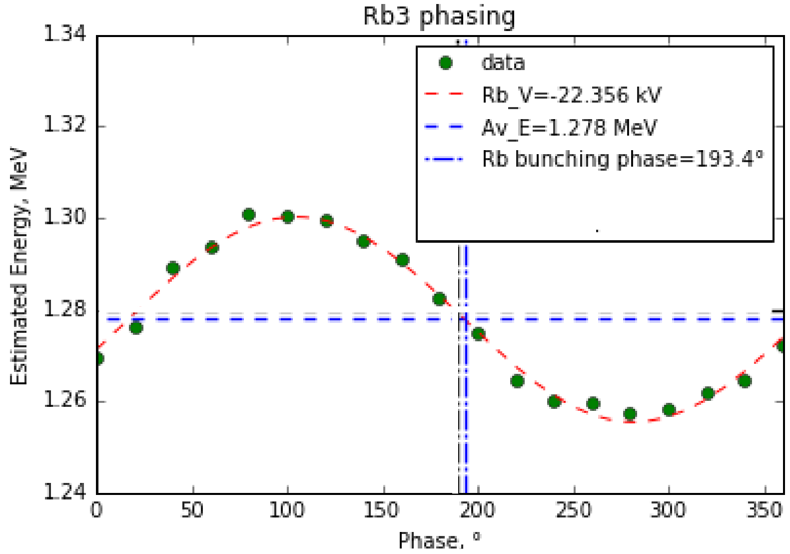
This discrepancy has been resolved (LLRF)



with BPM2-BPM3

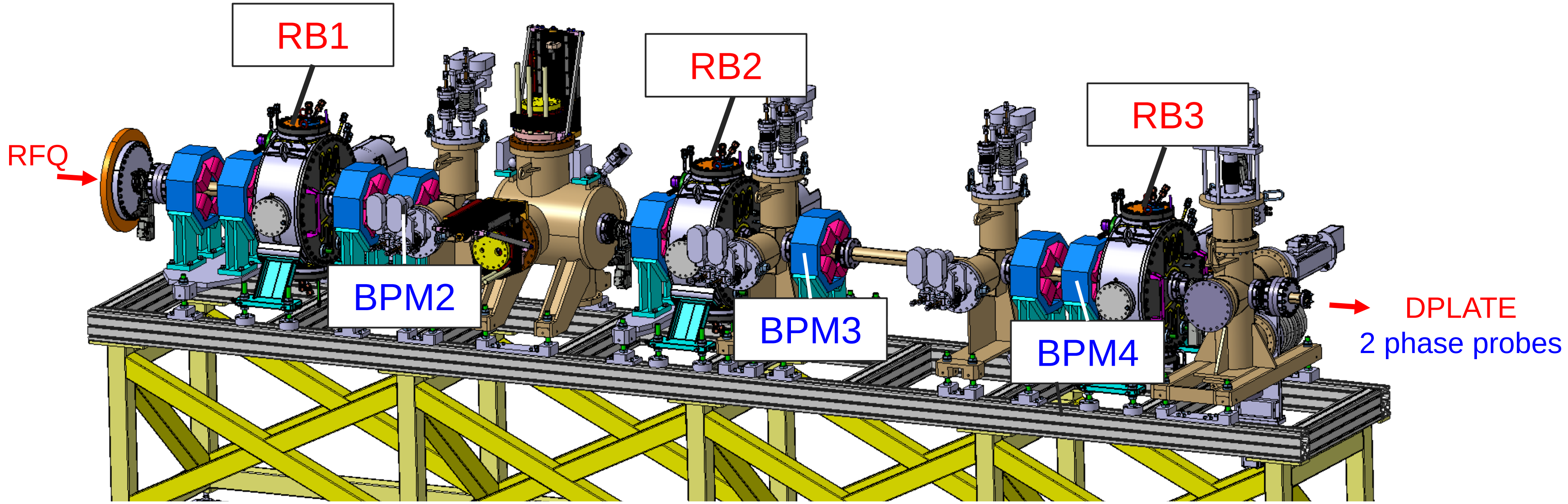


with BPM3-BPM4

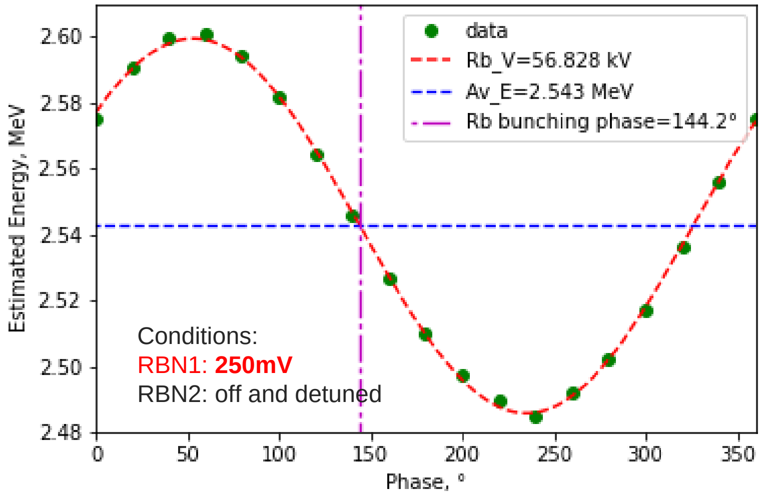


With phase probes in DPLATE

Rebuncher calibration (deutons)

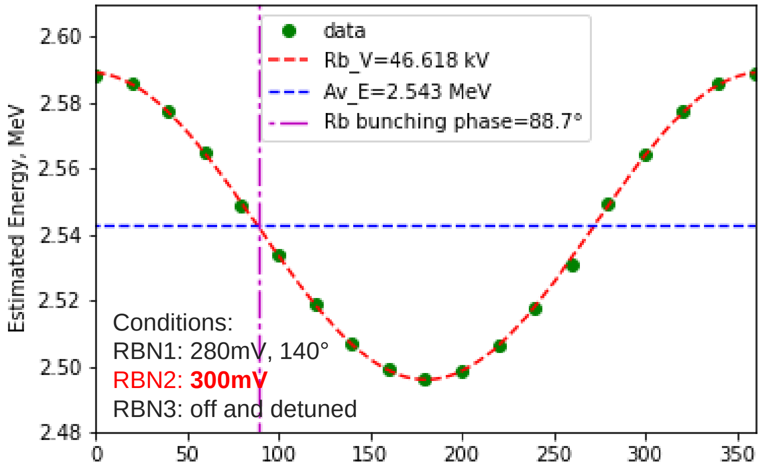


Phasing RBN1



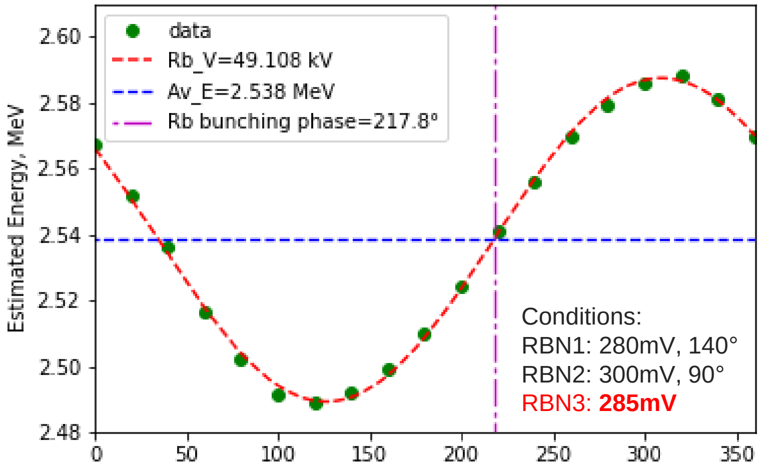
with BPM2-BPM3

Phasing RBN2



with BPM3-BPM4

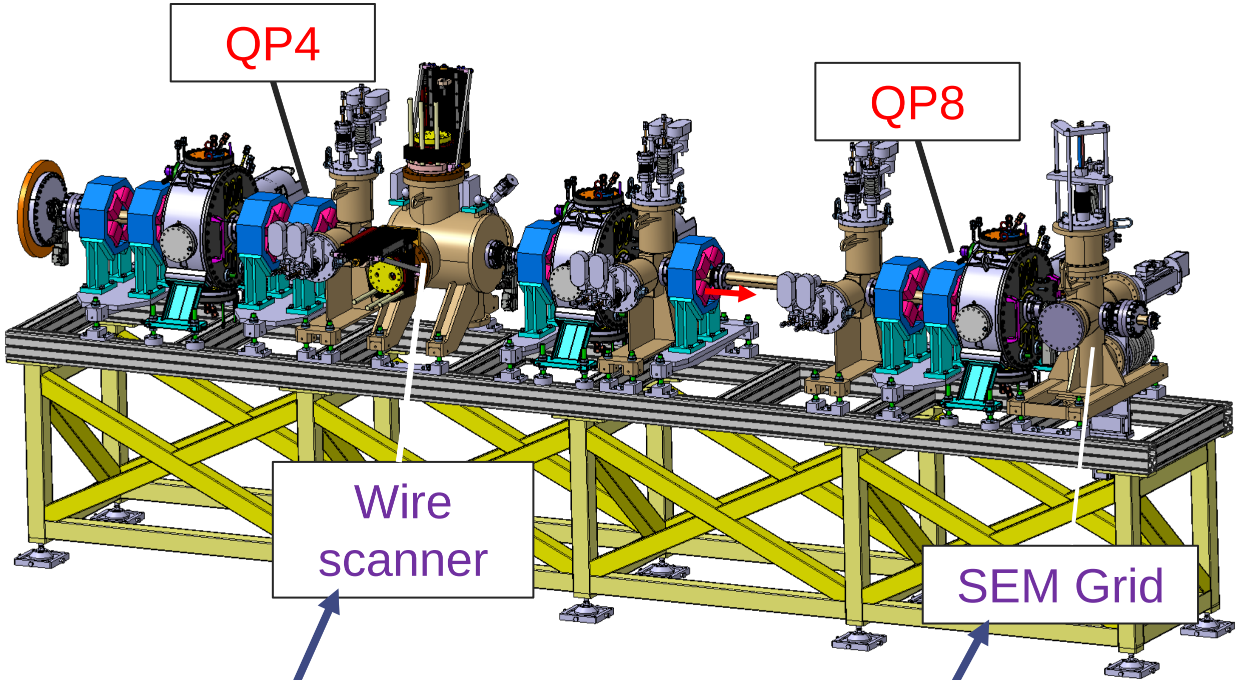
Phasing RBN3

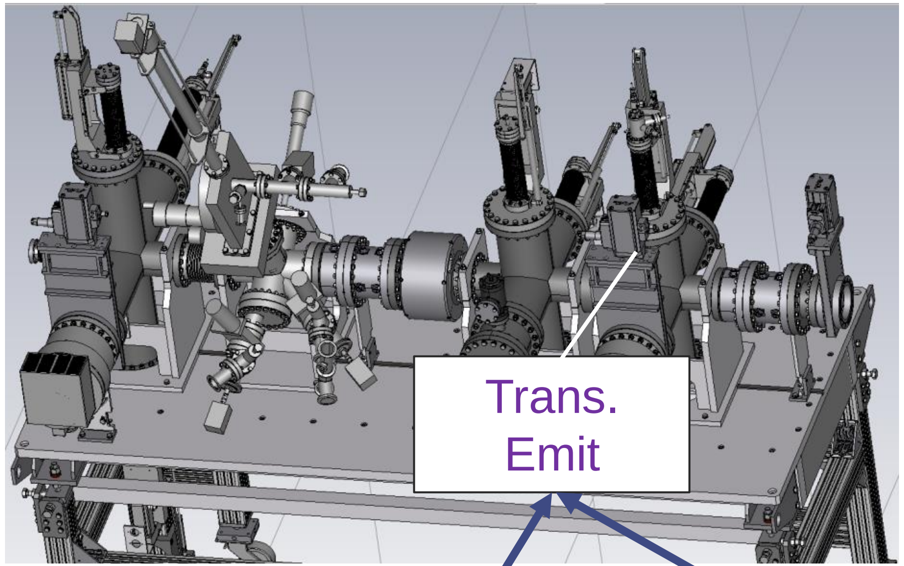


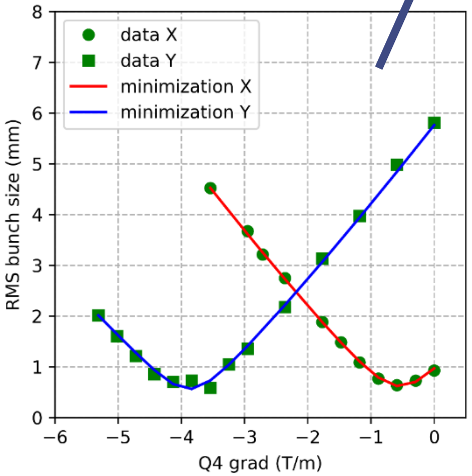
With phase probes in DPLATE

■ Beam characterization

Transversal characterization (protons)

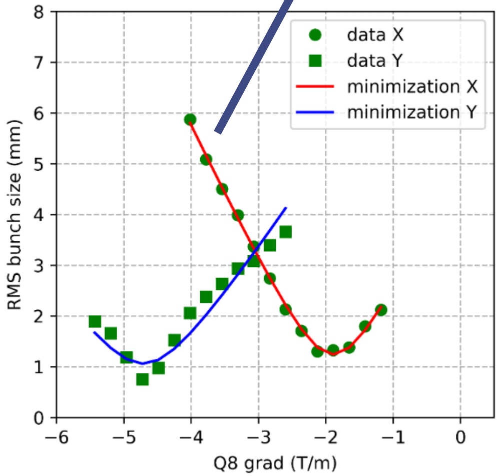






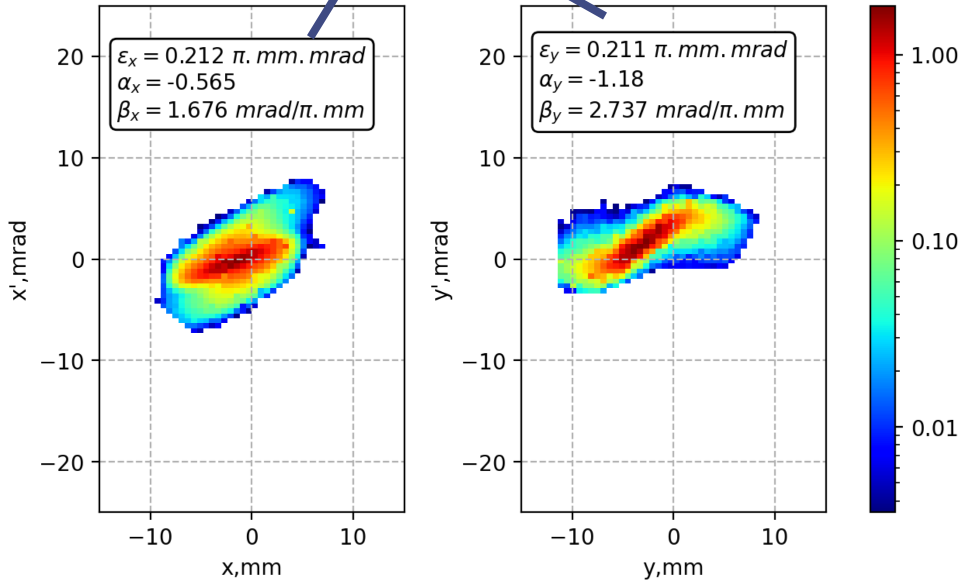
$\varepsilon_x = 0.202\ \pi.mm.mrad$
$\alpha_x = 0.343$
$\beta_x = 0.221\ mrad/\pi.mm$

$\varepsilon_y = 0.149\ \pi.mm.mrad$
$\alpha_y = -0.495$
$\beta_y = 0.167\ mrad/\pi.mm$

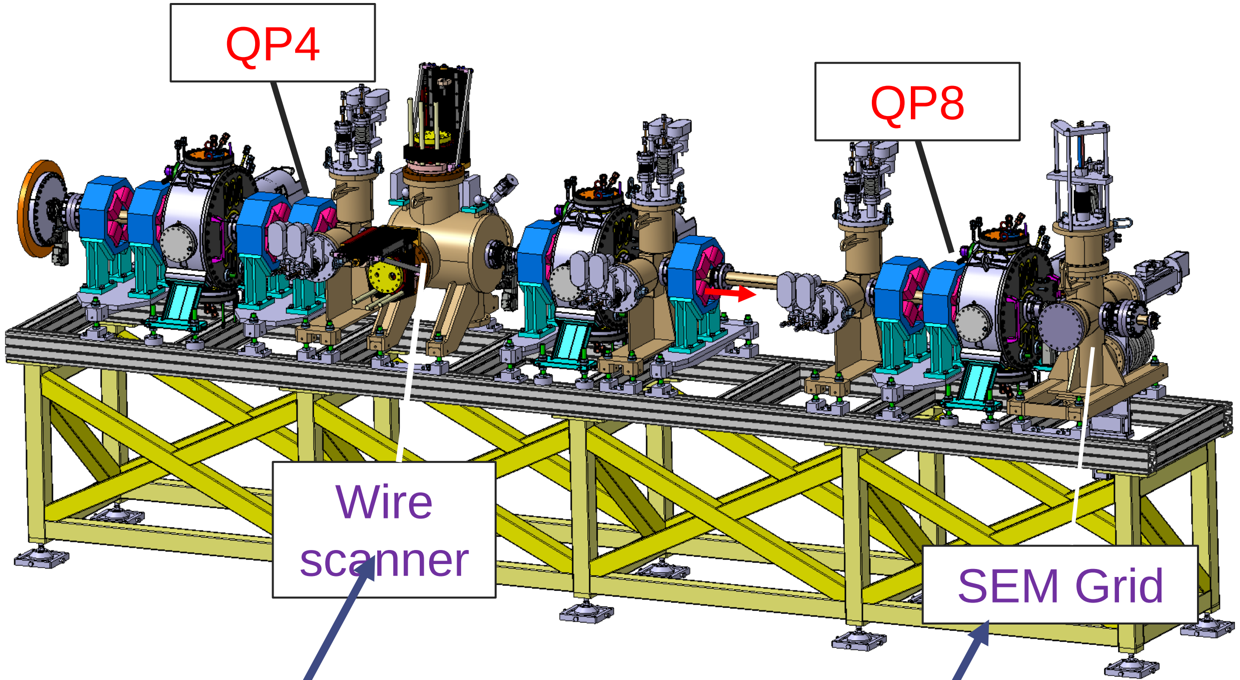


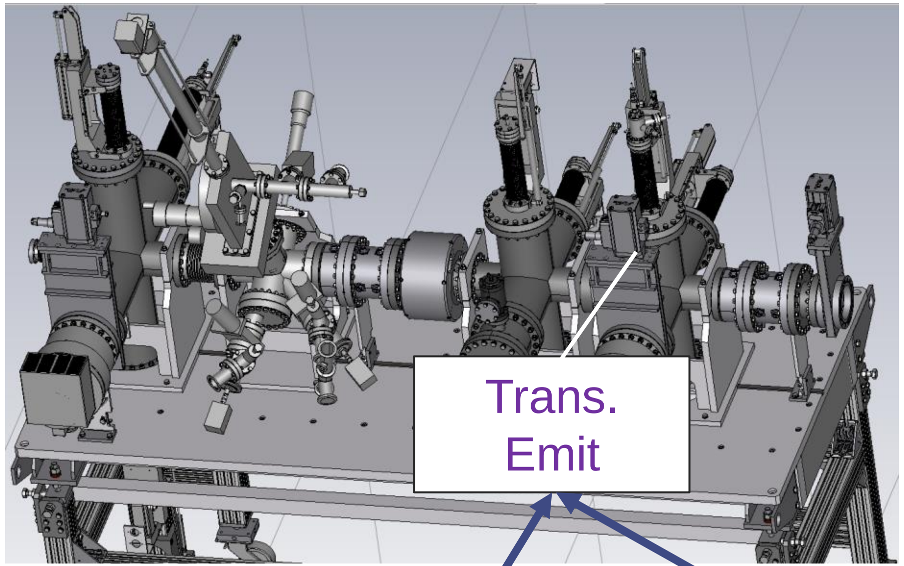
$\varepsilon_x = 0.454\ \pi.mm.mrad$
$\alpha_x = 0.5$
$\beta_x = 0.228\ mrad/\pi.mm$

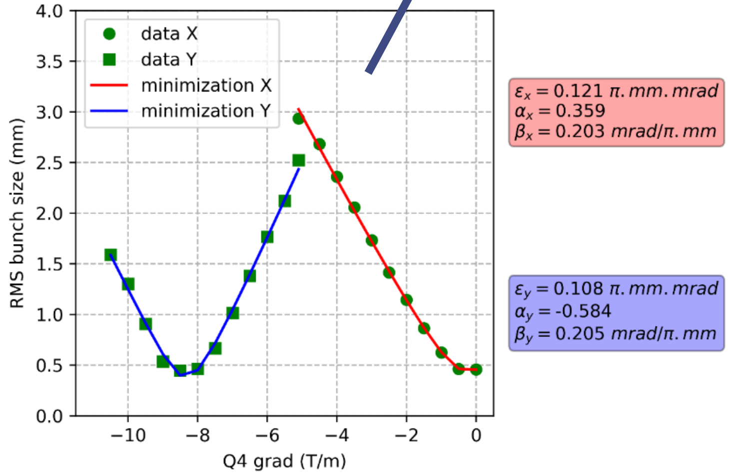
$\varepsilon_y = 0.408\ \pi.mm.mrad$
$\alpha_y = 0.003$
$\beta_y = 0.219\ mrad/\pi.mm$

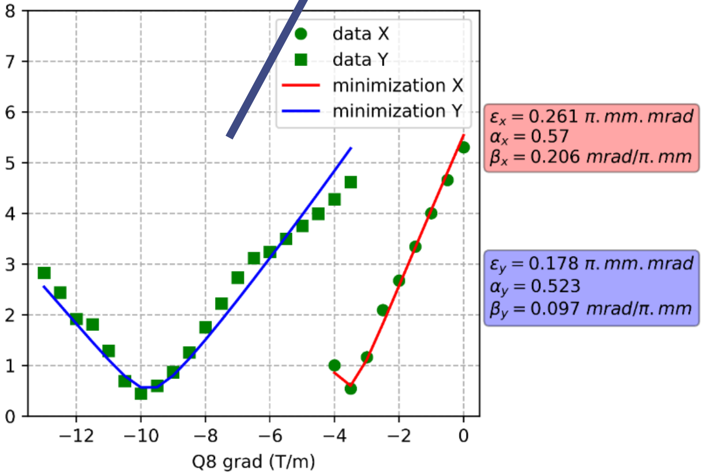


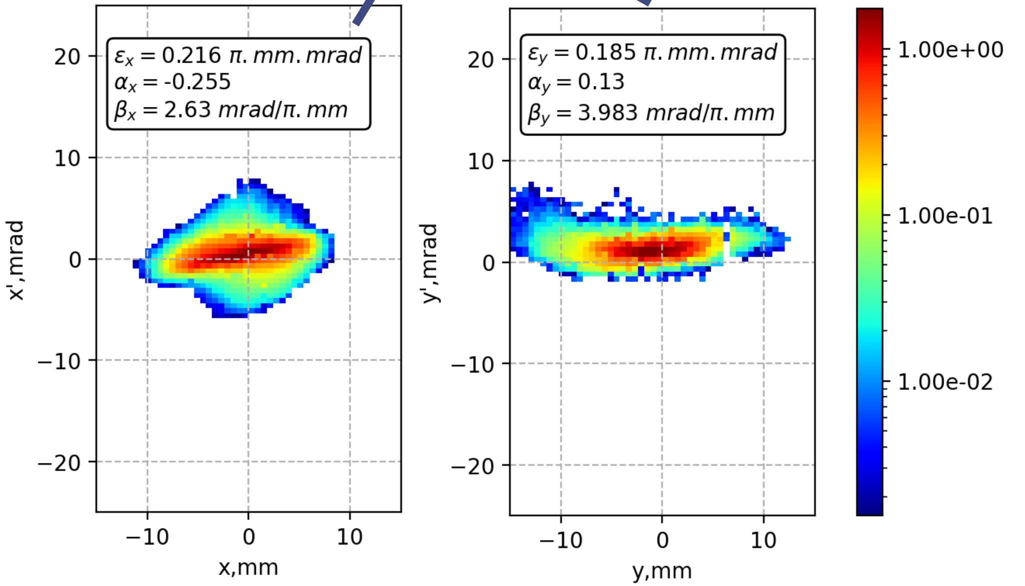
Transversal characterization (deutons)



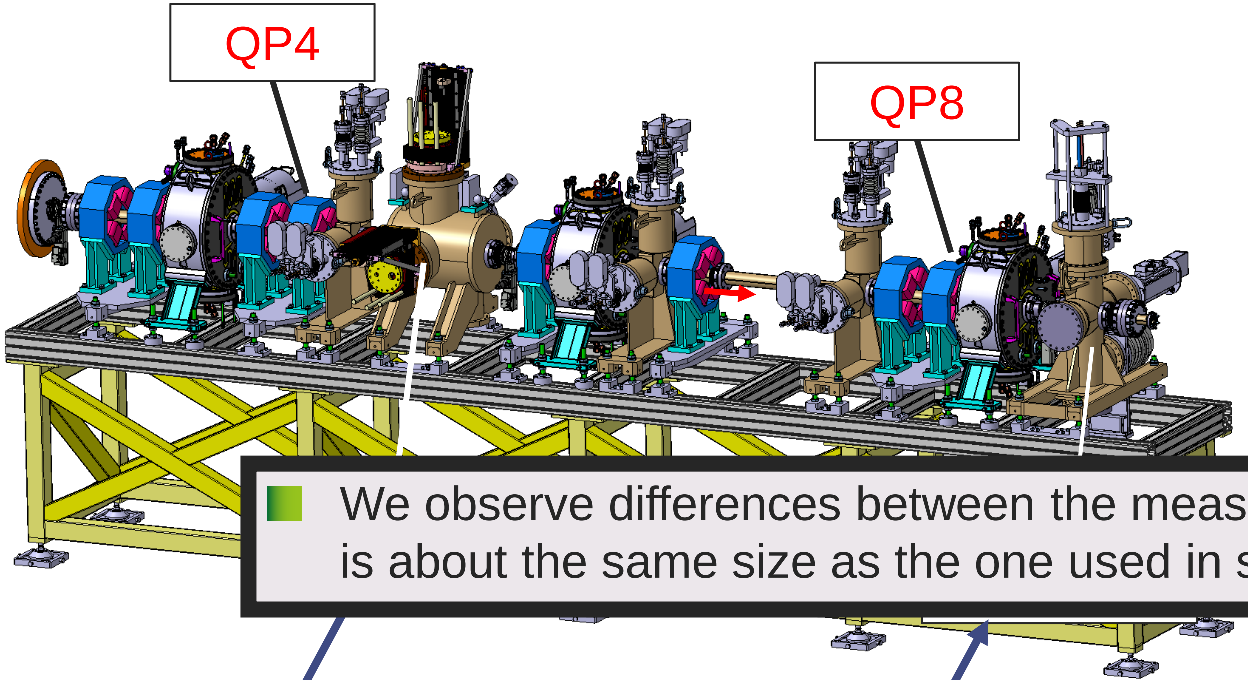


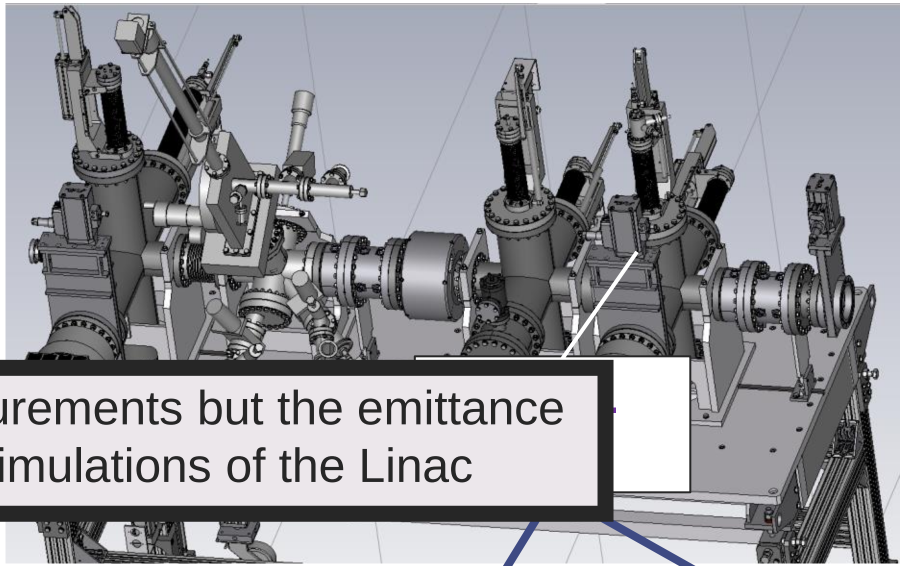




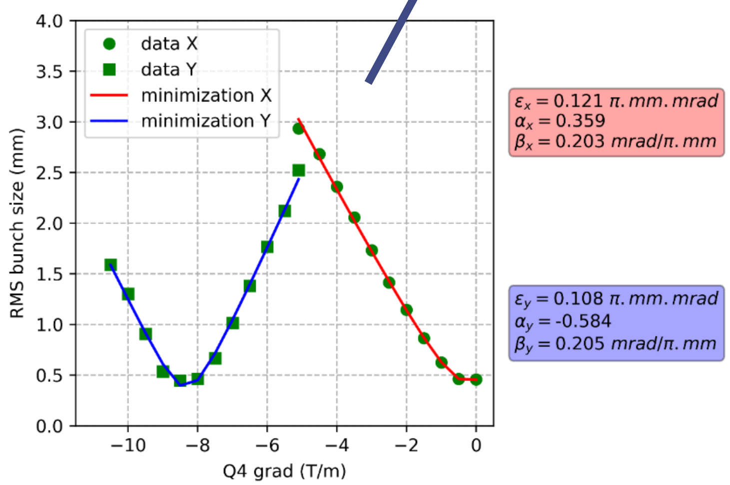


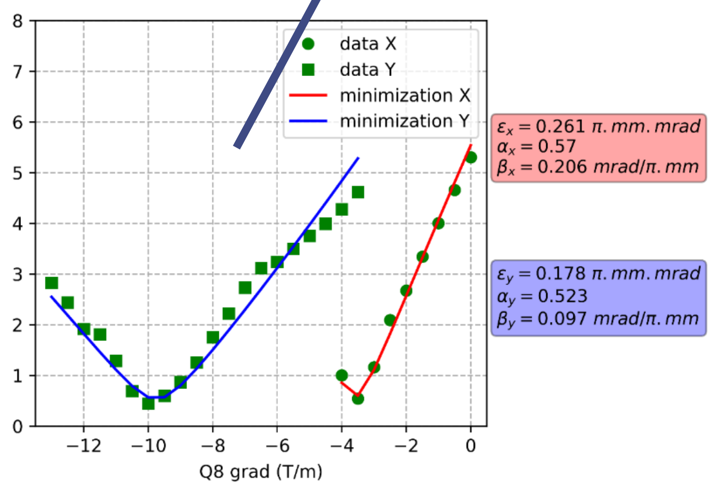
Transversal characterization (deutons)

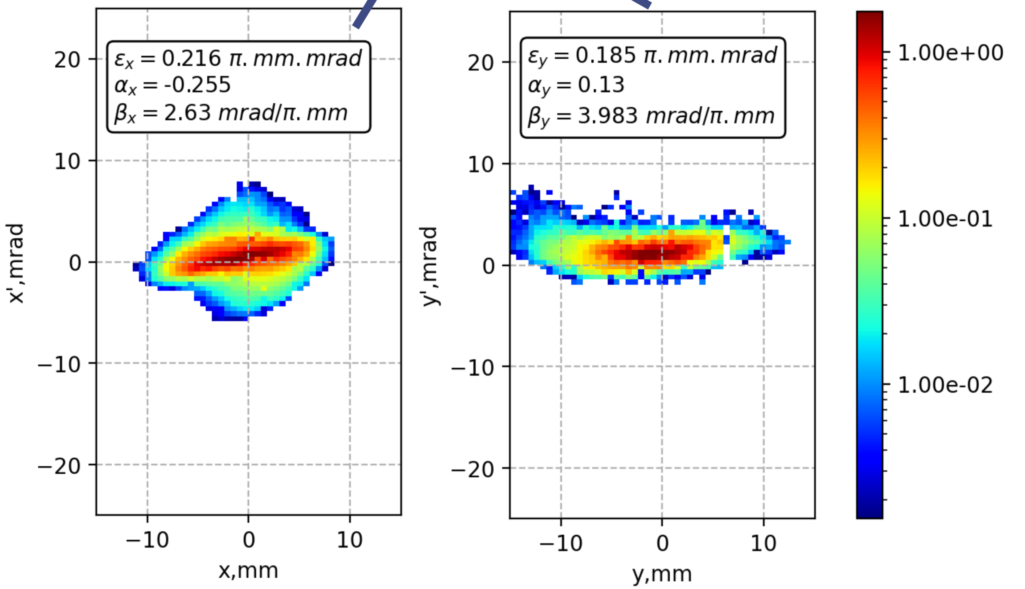




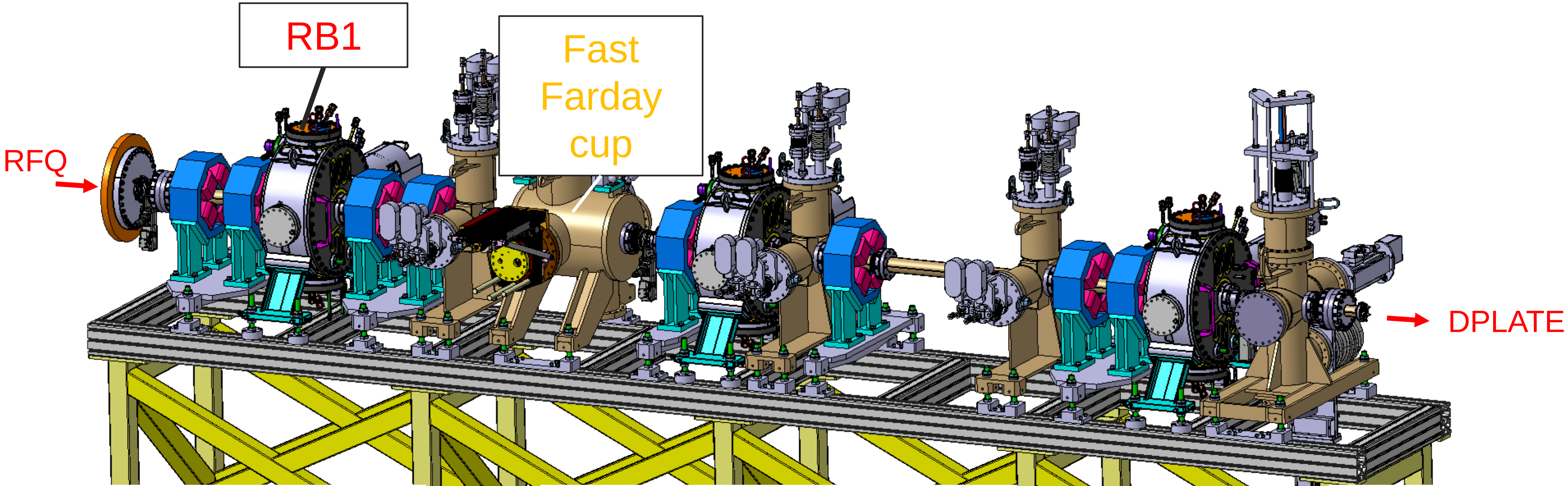
- We observe differences between the measurements but the emittance is about the same size as the one used in simulations of the Linac



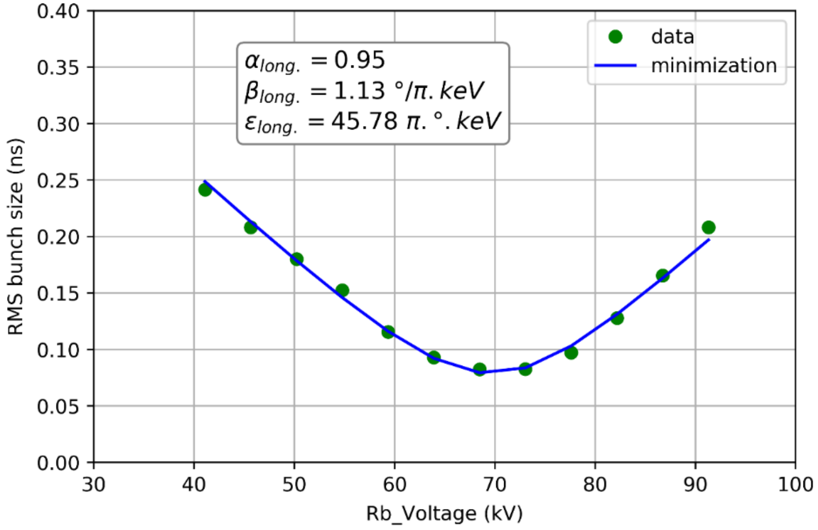




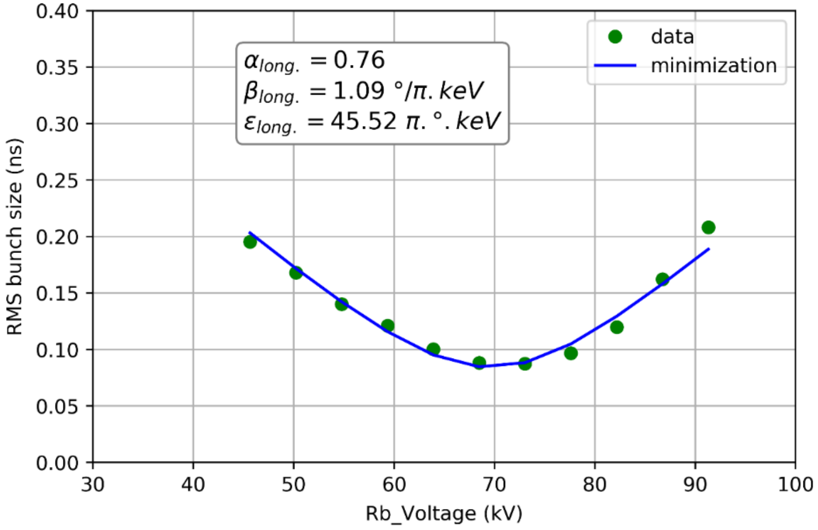
Longitudinal characterization in DB1 (protons)



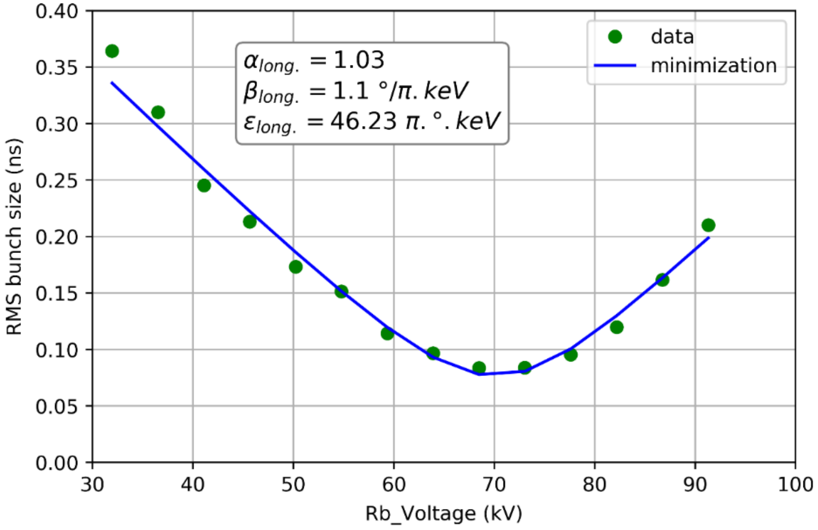
Feb. 21, 2023 at 14:24



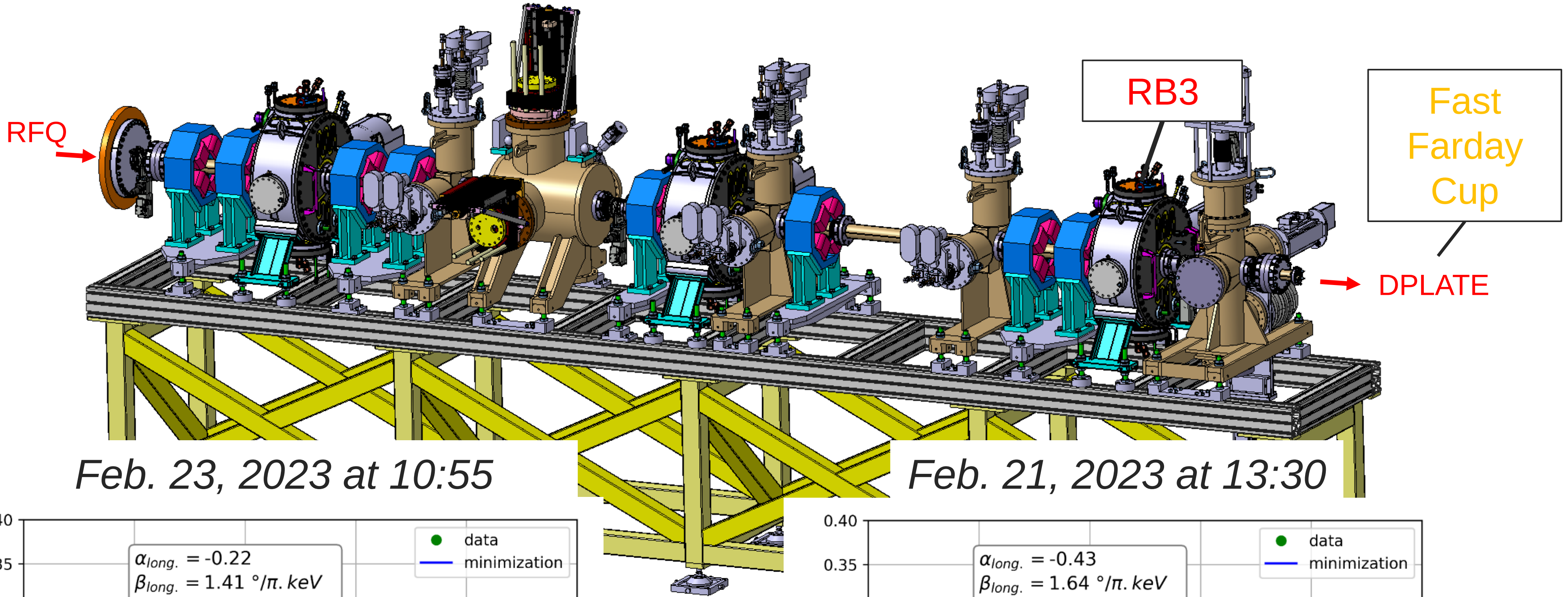
Feb. 21, 2023 at 17:26



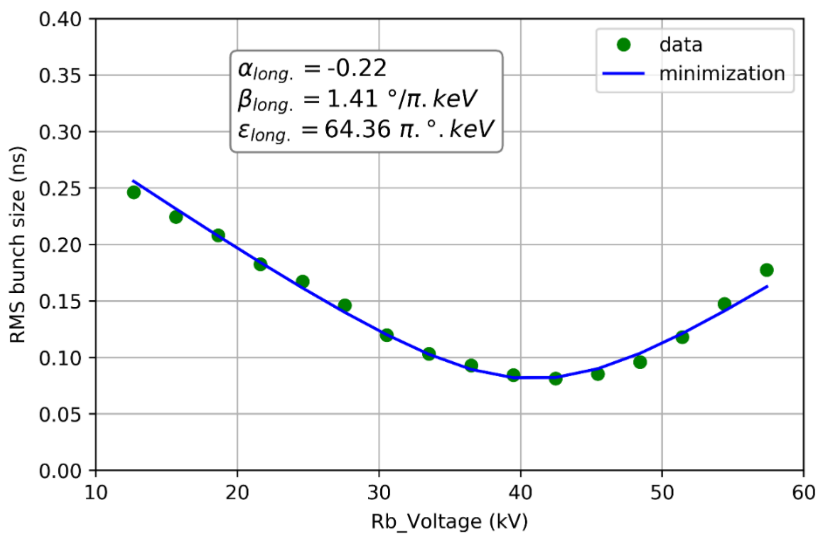
Feb. 23, 2023



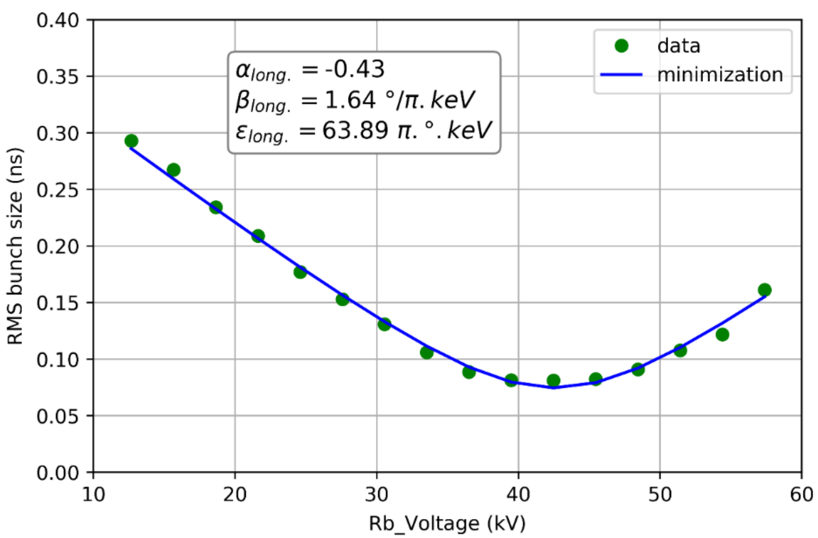
Longitudinal characterization in Dplate (protons)



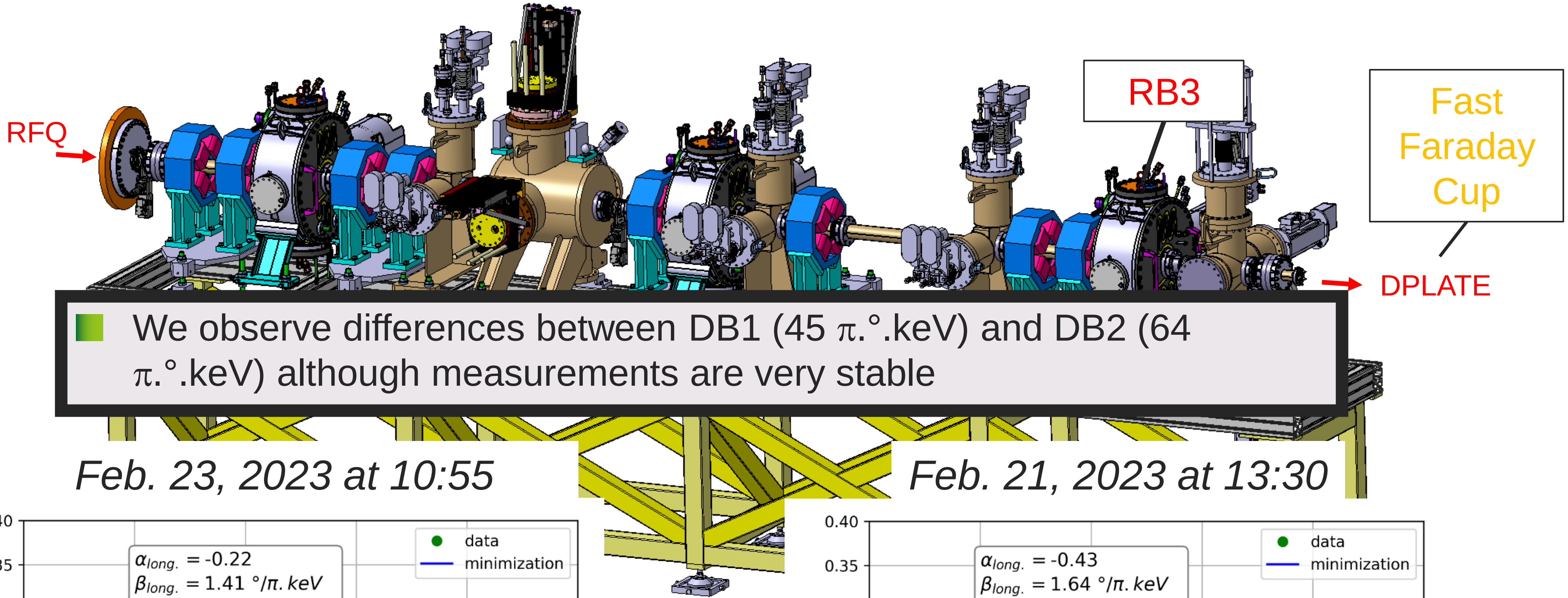
Feb. 23, 2023 at 10:55



Feb. 21, 2023 at 13:30

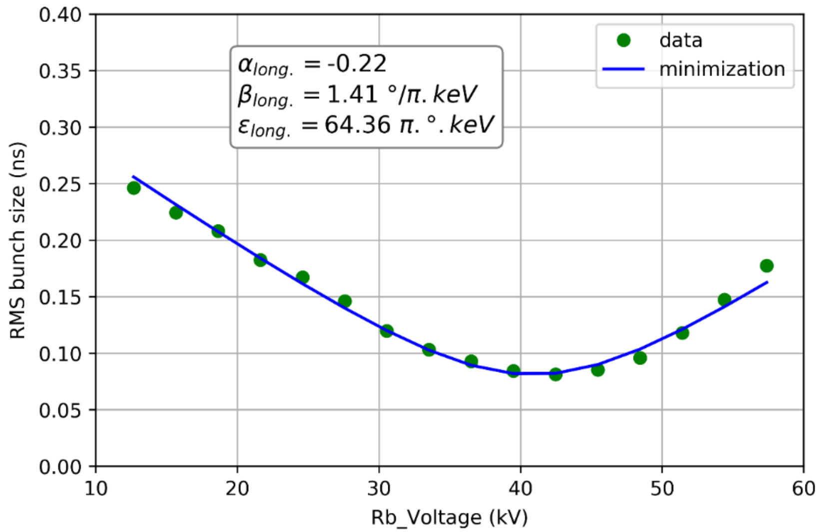


Longitudinal characterization in DB2 (protons)

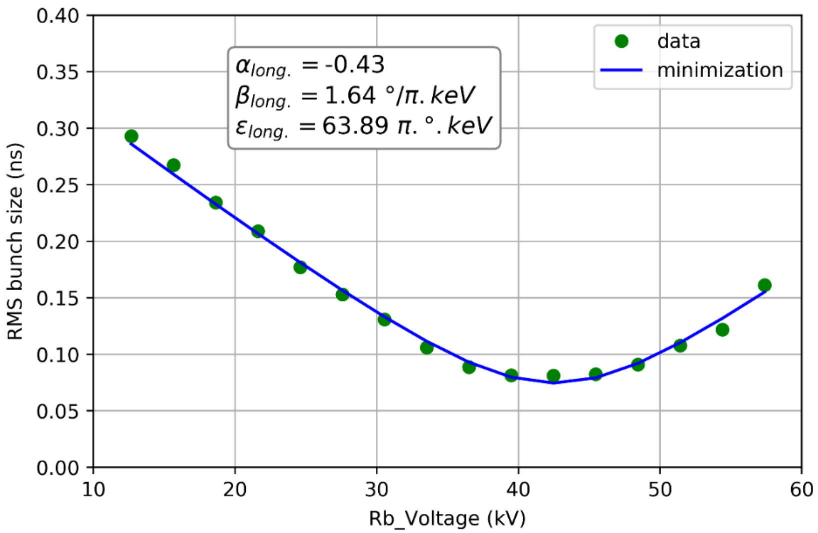


- We observe differences between DB1 (45 π.°.keV) and DB2 (64 π.°.keV) although measurements are very stable

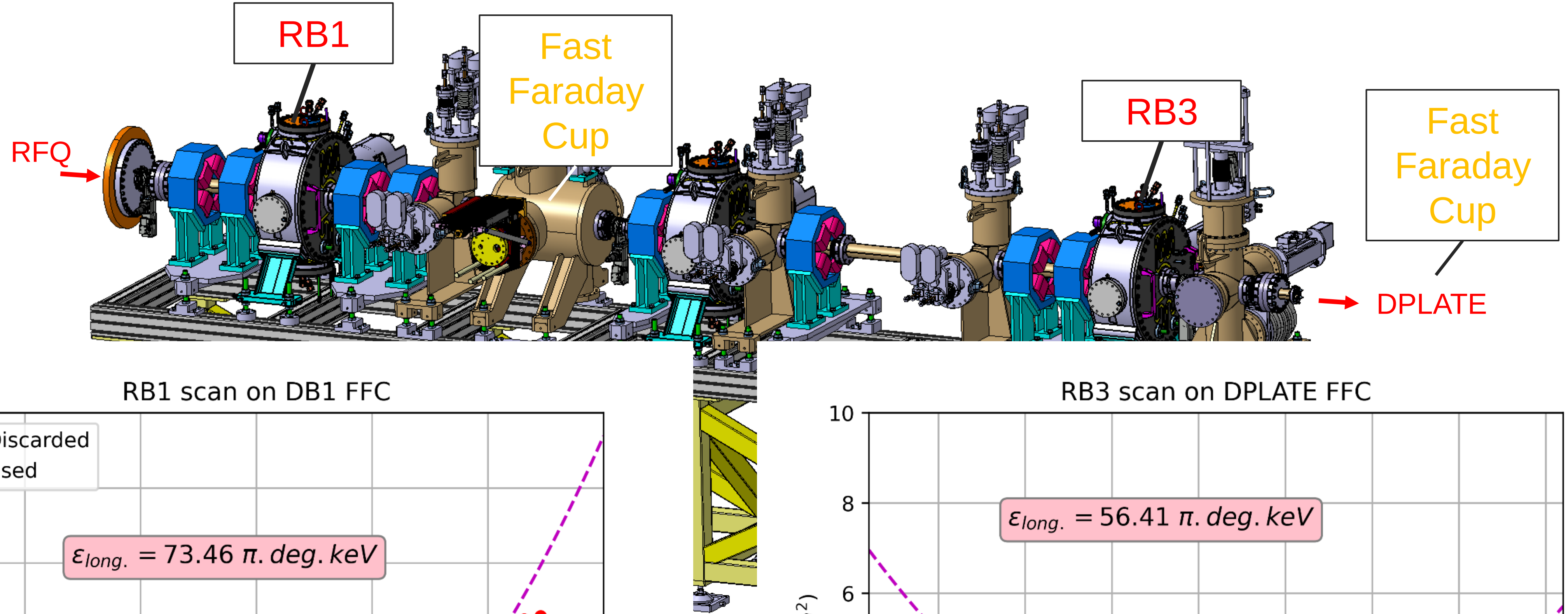
Feb. 23, 2023 at 10:55

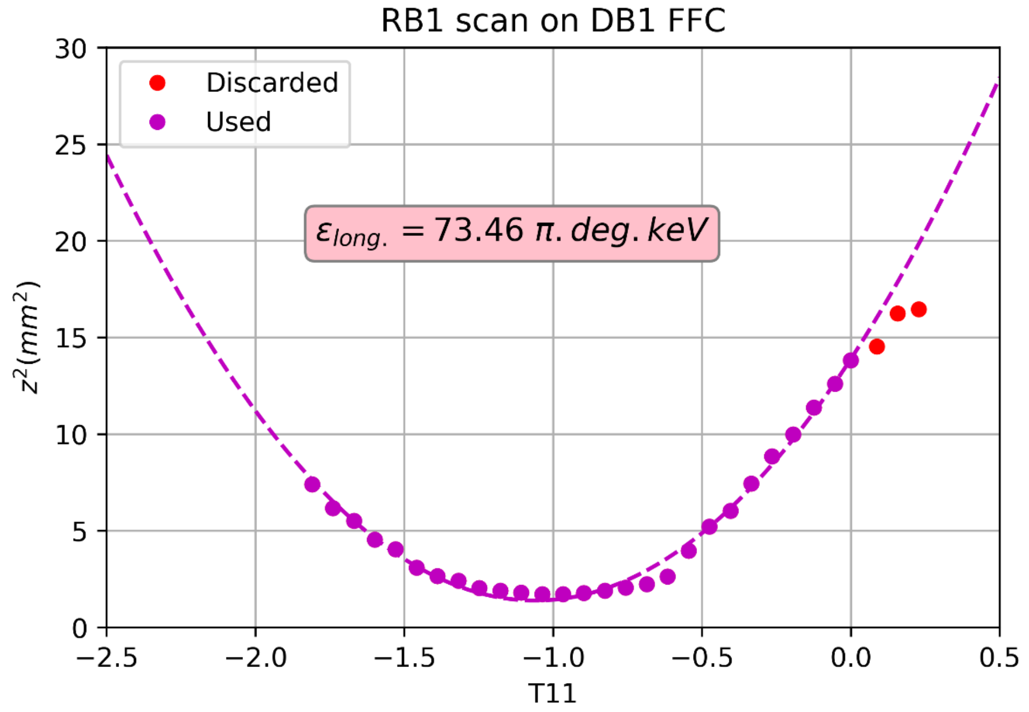


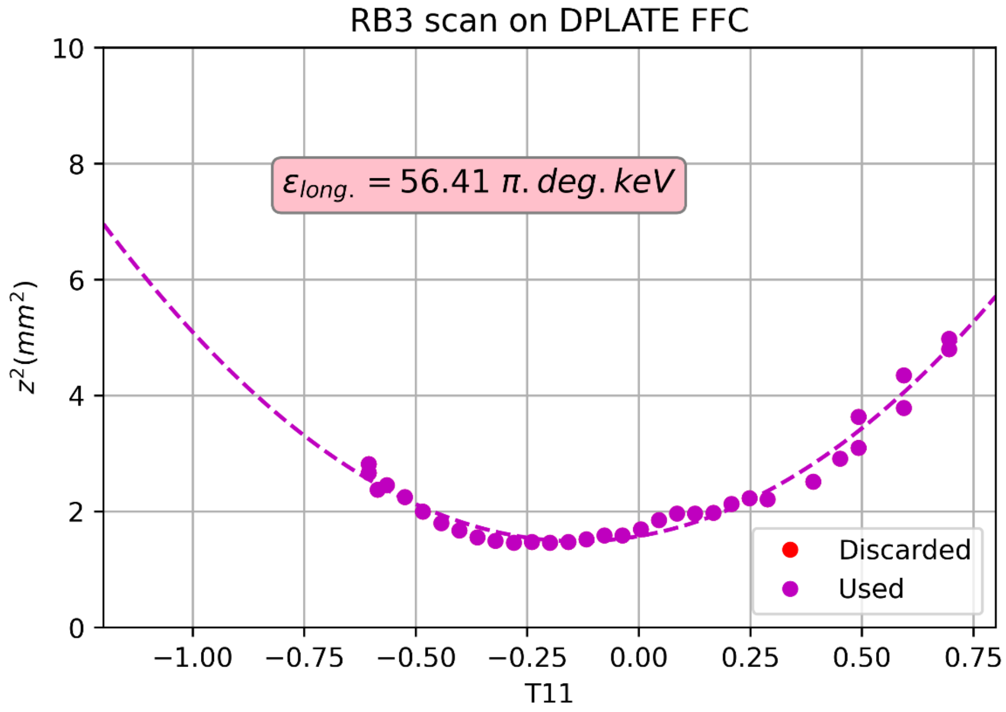
Feb. 21, 2023 at 13:30



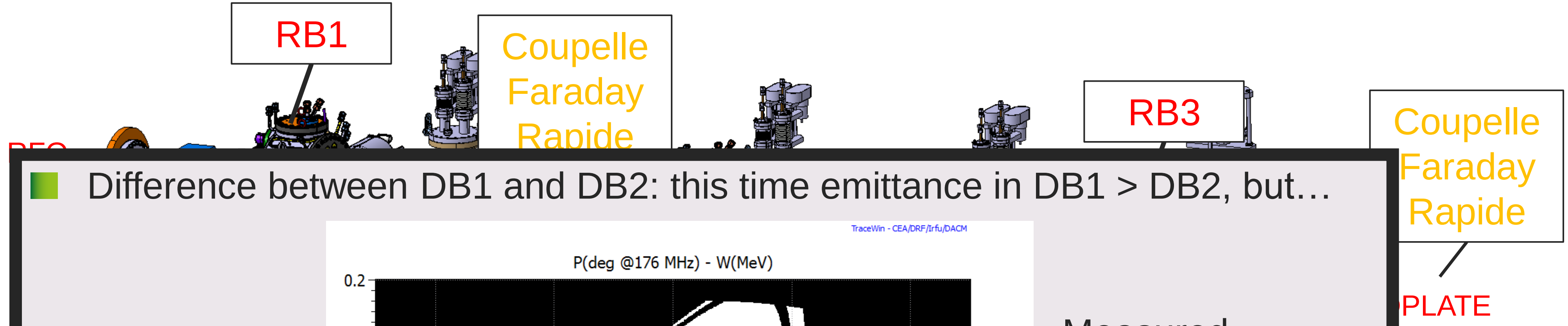
Longitudinal characterization (deutons)



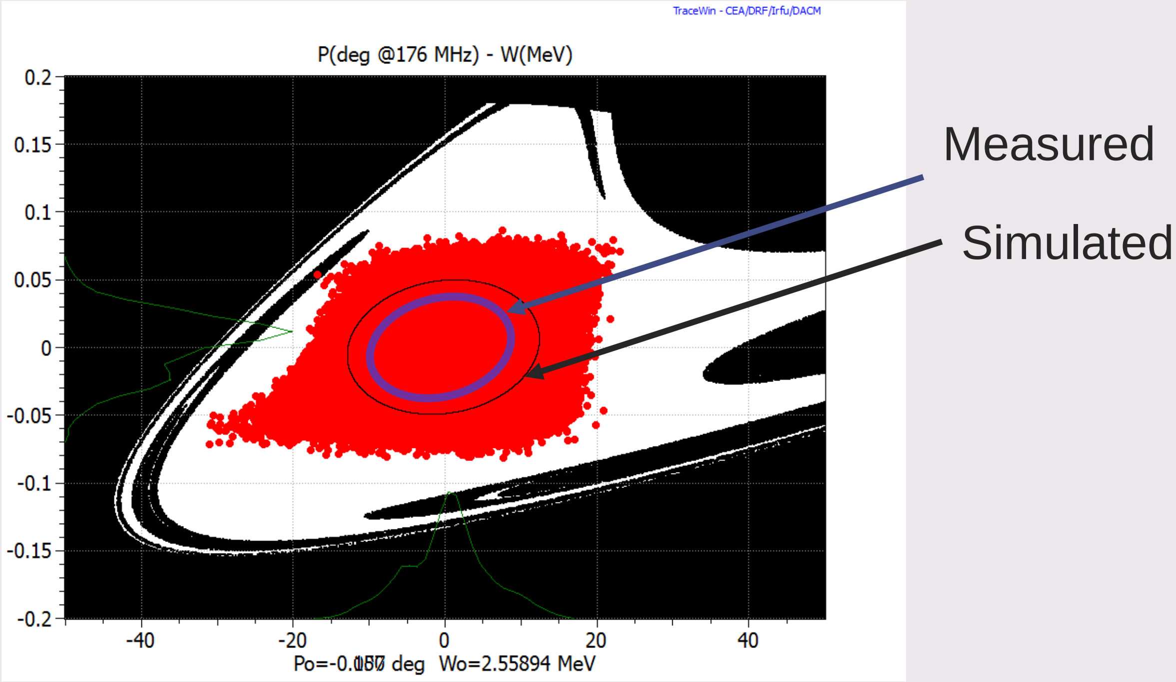




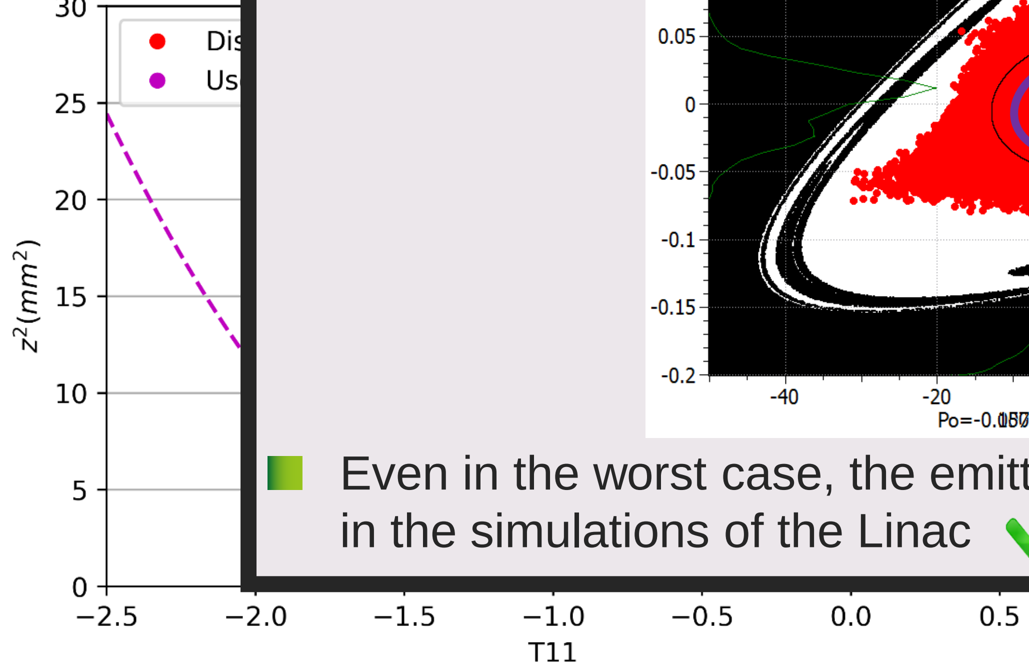
Caractérisation longitudinale (deutons)

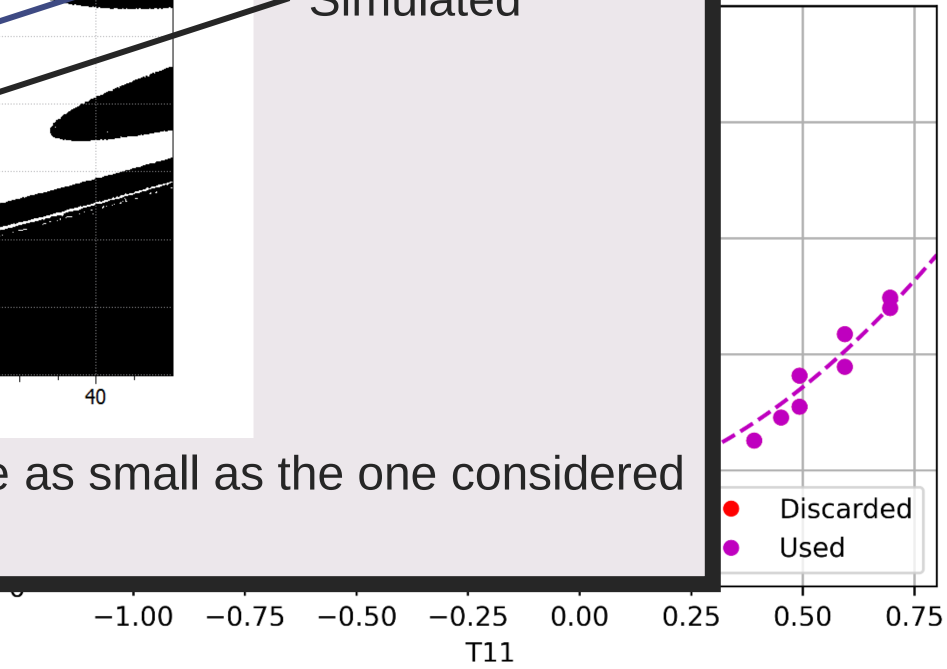


- Difference between DB1 and DB2: this time emittance in DB1 > DB2, but…

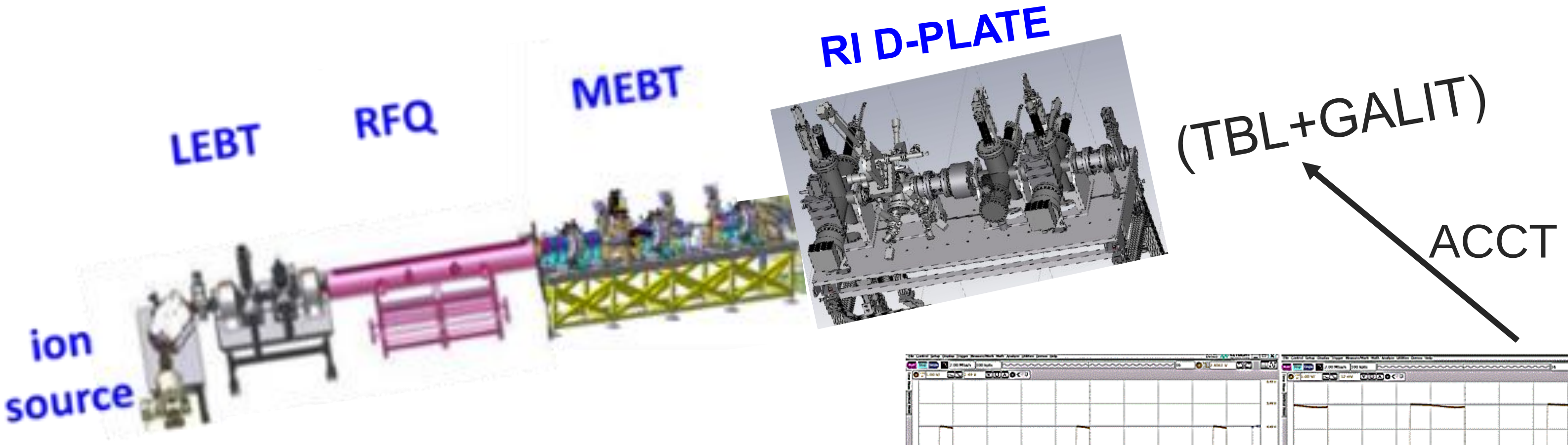


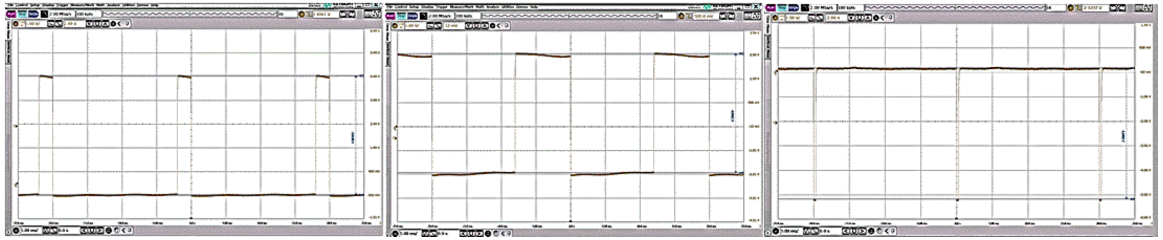
- Even in the worst case, the emittance is twice as small as the one considered in the simulations of the Linac ✔

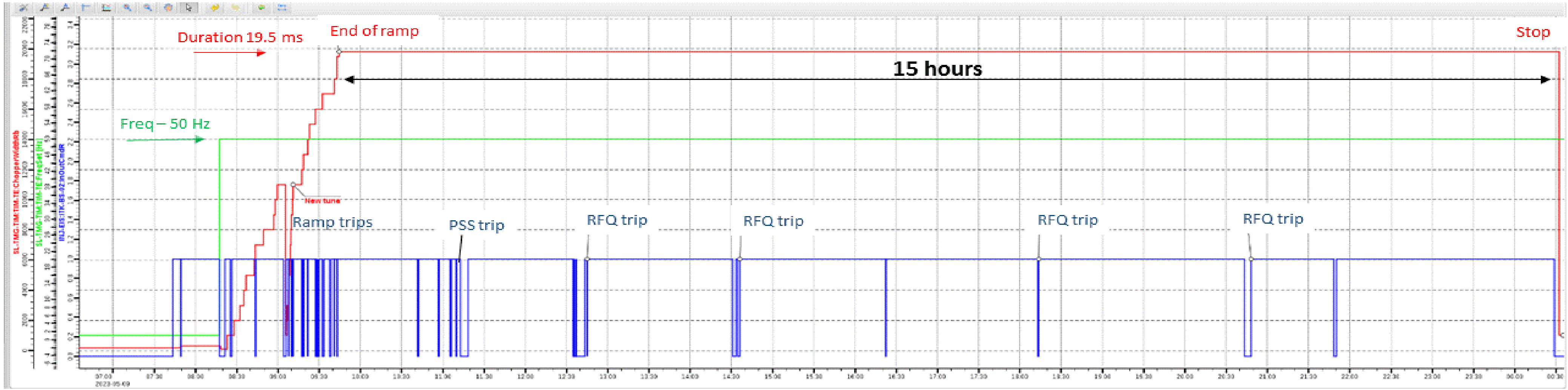




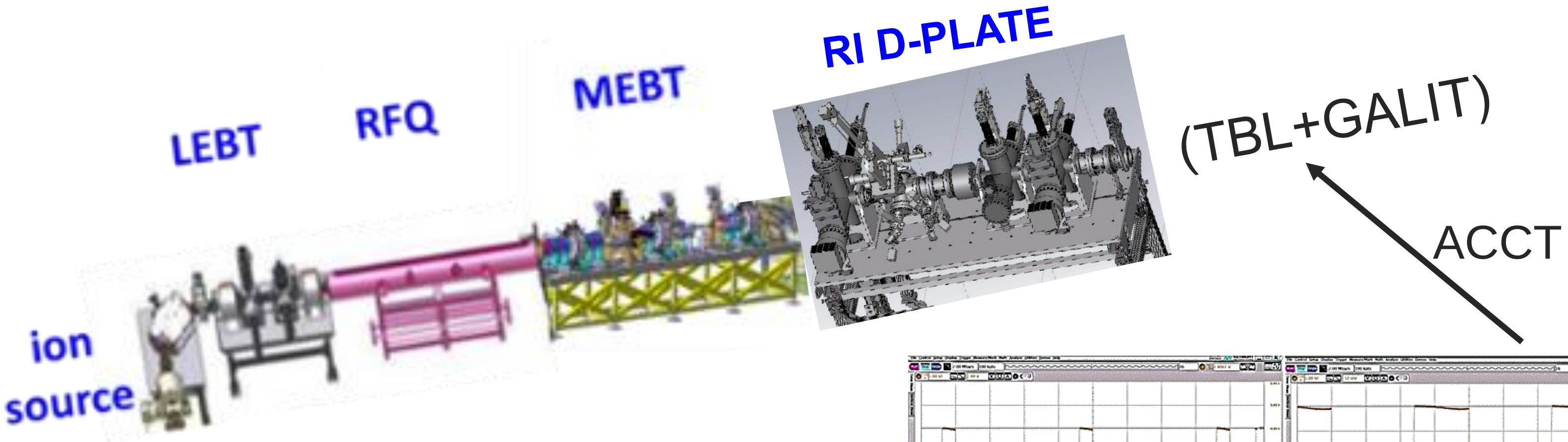
Power ramp up (protons)

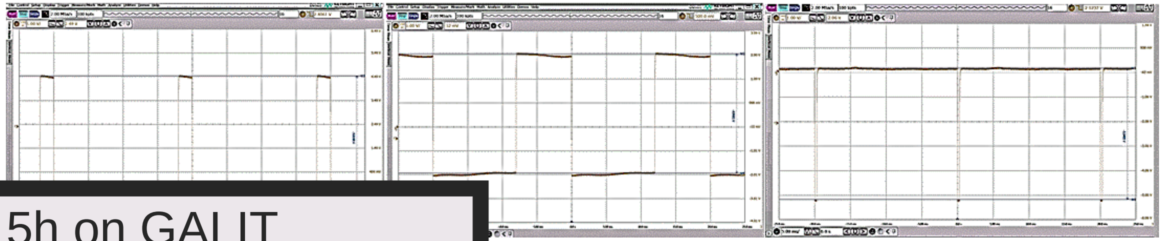




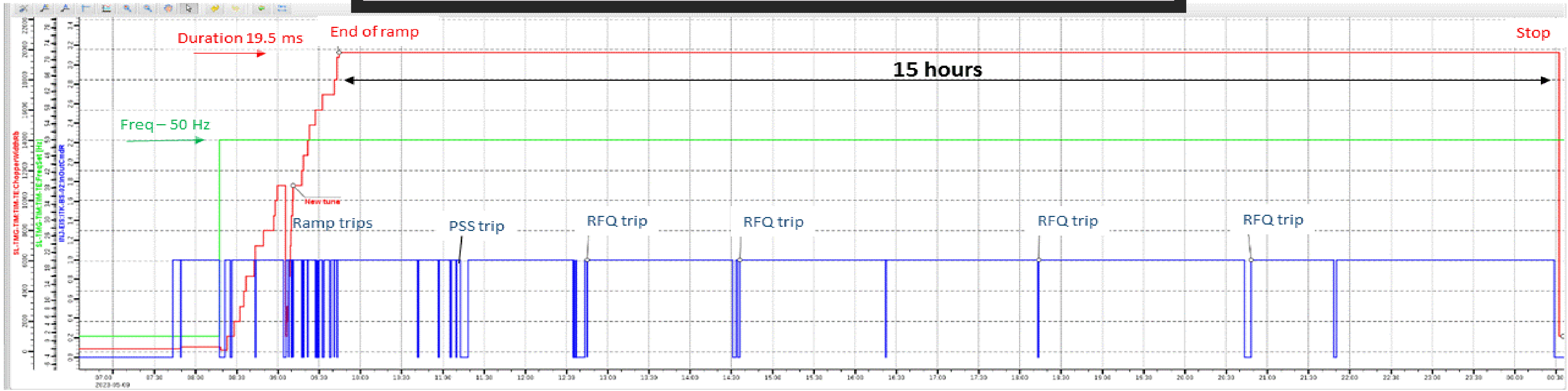


Power ramp up (protons)





- 97.5% of duty cycle for 15h on GALIT



■ Machine learning

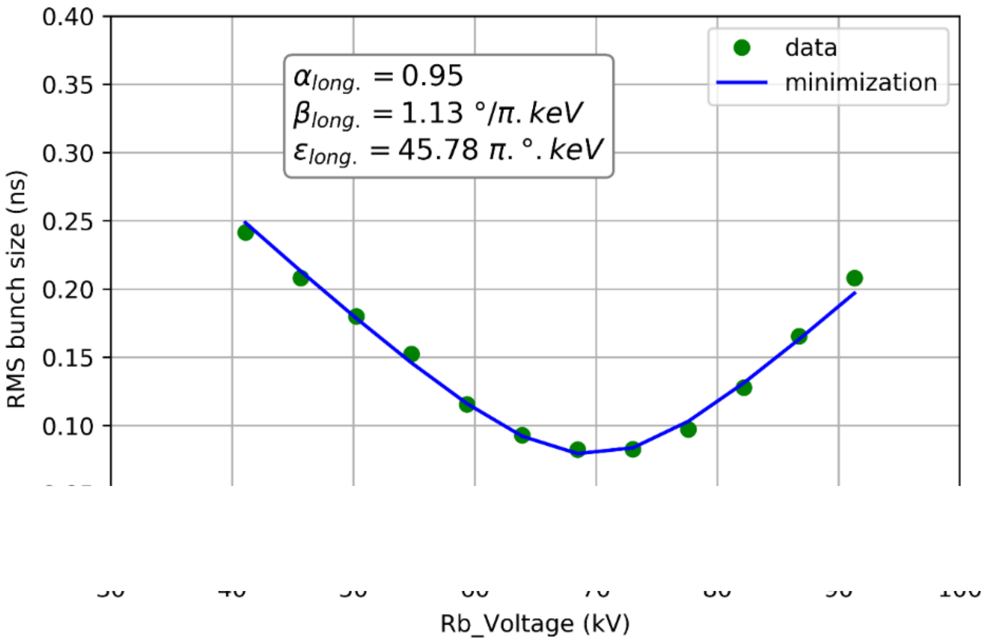
Usual data processing

The usual way to process the experimental data, is to consider "perfect" (possibly after device transfer function deconvolution) beam **measured properties**

Examples: Bunch length…

From these measured properties, one tries to access to other **deduced properties**

Examples: Longitudinal emittance…



Nevertheless :

- The final deduced properties (emittance) are **not exactly those of the beam** (measurement uncertainties)
- They are usually **uncompleted** (dimensions are missing, no correlation…)
- **How to use** the deduced properties to make predictions and associated uncertainties ?

Digital twin

Real world: The linac is operated according to:

- a set of **physical parameters**,
- a set of **control parameters** (IN/OUT Control-System variables).

Examples: Distances, Source voltage, RFQ-peak-up, Power supply currents…

Virtual world: A linac has been designed and is modeled with a **digital twin** made of:

- a **simulation tool** (TraceWIN),
- a set of **model parameters** (SARAF file description).

Examples: Input beam energy, RFQ-Voltage, MEBT-QP1 gradient…

Links between real and virtual worlds:

- The simulation tool models the physics (with possible bugs),
- Each model parameter is linked to one or more control parameters.

Examples: Qpole gradient $\leftrightarrow$ PS current…

Adjusting digital twin

During the design and at the start of the machine, links are “estimated” as measured individually on each components, with uncertainties.

*Example: QP1_G = k0 [±dk] * QP1_I, …*

We propose to adjust gradually, experiment after experiment, the links *(k…)* in order to improve the digital twin, using **Bayesian inference** technics (machine learning).

In order to do it, one should be able to:

- Store in a **database** each experimental result and associated machine configuration (installed devices+control parameters),
- **Simulate** the best as possible the results of the experiments,
- Calculate a “**distance**” between experimental and simulated measurements,
- **Adjusting** the best digital twin parameters minimizing the average weighted distance of all experiments and associated uncertainties.

Bayesian method

A : a set of experimental measurements

B : a theory or a set of parameters in the numerical Twin

Simulation of the experimental results

The probability of the parameters after the experiment

$$p(B/A) = \frac{p(A/B)}{p(A)} \times p(B)$$

The probability of the parameters before the experiment

The uncertainties of the experimental measurements

Leading to:

- The best set of parameter set B_{opt} (maximizing $p(B/A)$ or $B_{opt} = \frac{\int p(B/A) \times B \cdot dB}{\int p(B/A) \cdot dB}$)
- The uncertainties on the parameters : $V_B = \frac{\int p(B/A) \times B \times B^* \cdot dB}{\int p(B/A) \cdot dB}$

Bayesian method - incremental

A_n: a new set of experimental measurements (after A_{n-1})

$$p(B/A_n) = \frac{p(A_n/B)}{p(A_n)} \times p(B/A_{n-1})$$

$$\rightarrow \qquad p(B/A_n) = \prod_{i=1}^{n} \frac{p(A_i/B)}{p(A_i)} \times p_0(B)$$

- The numerical twin can then be « adjusted » experiment after experiment.

- If needed, all the experiments can be processed again.

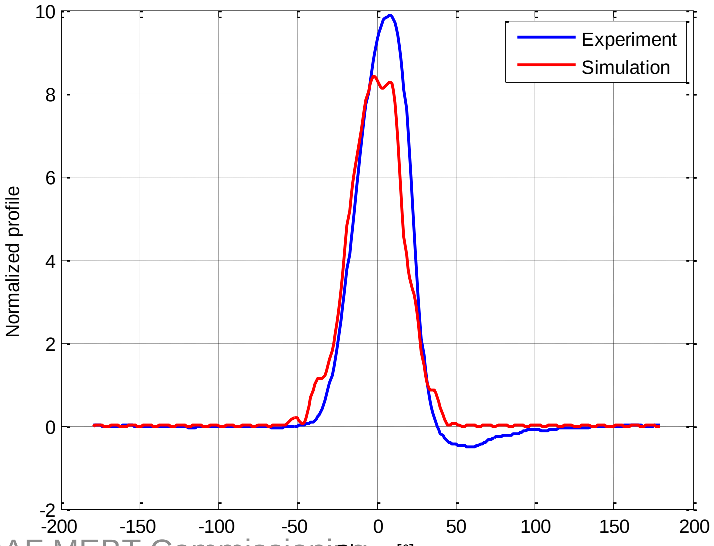
- New parameters can be added without losing what has been learned on other parameters.

- Analysing deviant experimental results, one can:
  - Either improve measurement understanding (badly simulated)
  - Or improve linac model (missing parameters)
  - …

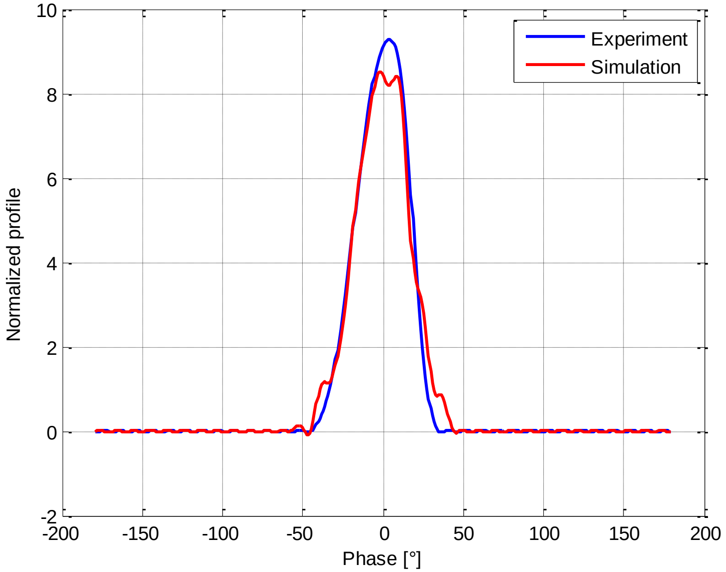
Longitudinal emittance : improving model

- FFC **pinhole** of 0.5 mm radius
  - → only a fraction of the beam is measured
- The profiles are noisy and experimental profiles have **negative "bounce"**
  - → This can be simulated or at least smoothed
- **Scope Bandwidth** of 6Ghz
  - → Possible resolution limitation → can be simulated

→ A simulation of the measurement is applied to the simulated beam
→ Experiment and simulated experiments can be compared

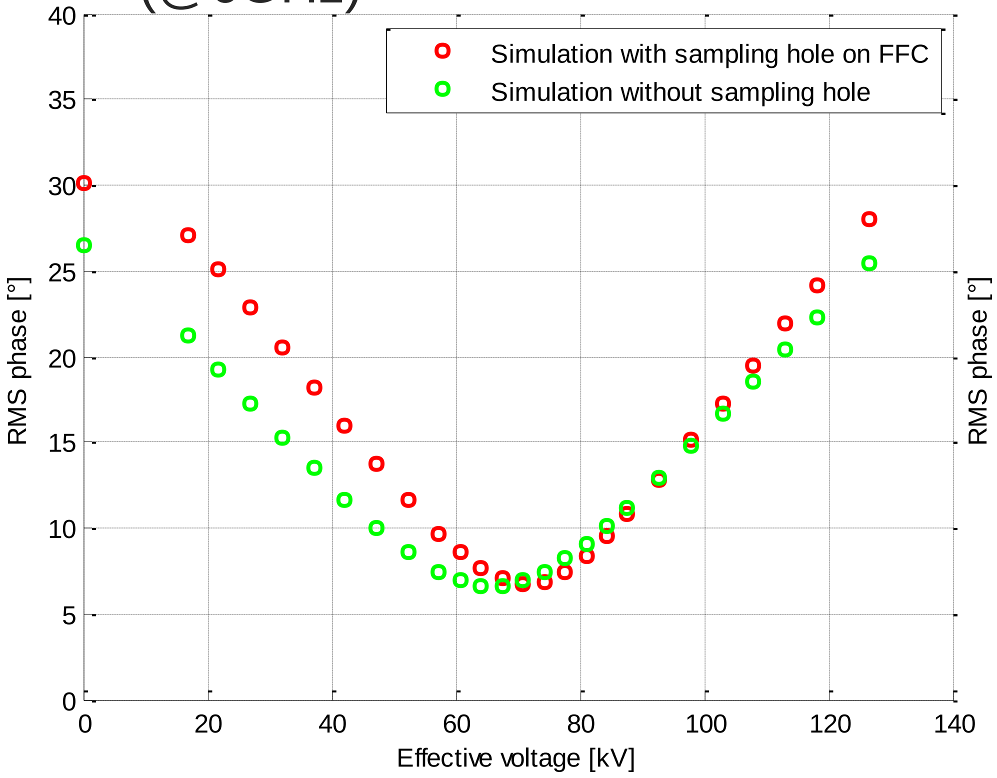


→

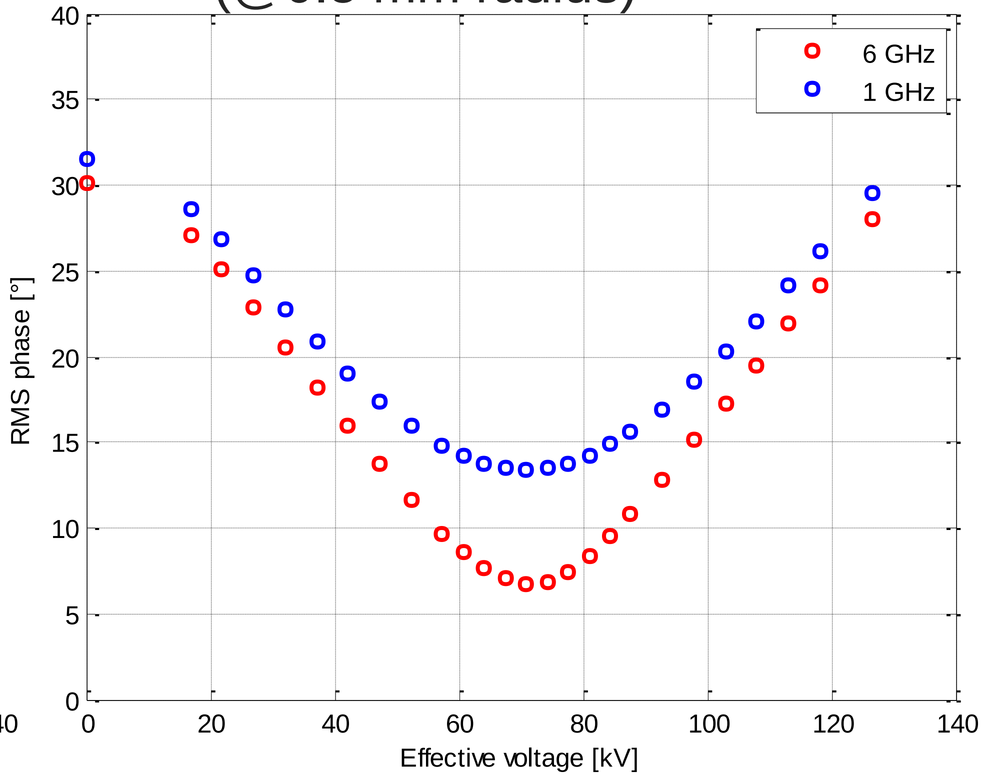


Example of exp. conditions simulation

- FFC pinhole of 0.5 mm radius (@6GHz)

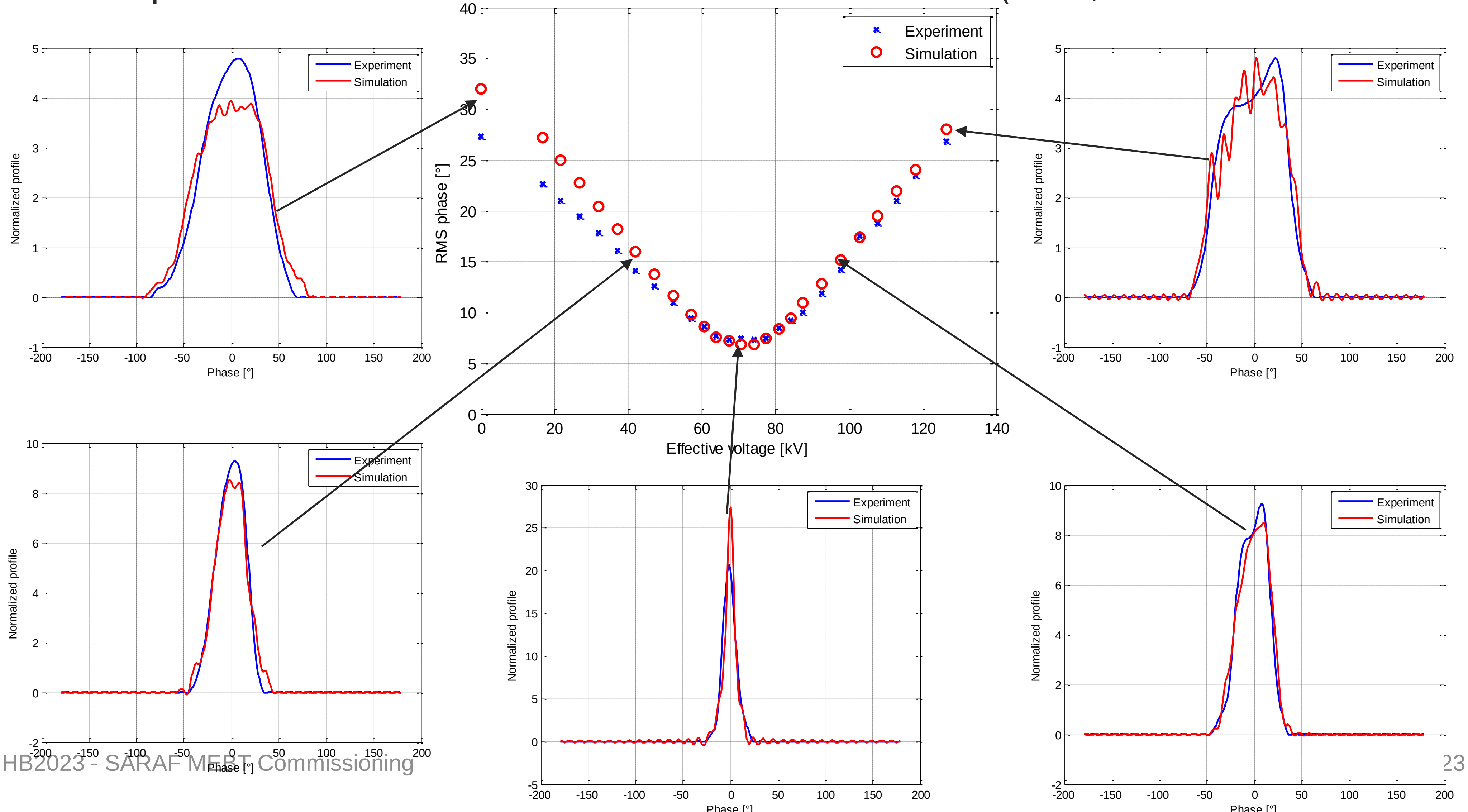


- Oscilloscope bandwidth (@0.5 mm radius)



Longitudinal emittance : Improving model

- Remarkable agreement between simulations (TraceWin) and experiments (no parameter change)
- Iterative process with new beam/beamline characterization (RFQ, transverse emittance…)



Little story

When doing **the transverse emittance measurements** (Quad scan) of the 5 mA proton beam, one remarked that the experiment results were **very different** from the numerical twin predictions.

<u>Strategy 1</u>: We could have kept the experiment result “as reality” and have considered that the beam transverse parameters were not “as expected”, trying to implement them in the code.

<u>Strategy 2</u>: Nevertheless, using this “machine learning” philosophy, we observed that the experimental results were much better reproduced by considering an increasing of the focusing force by about +20% (much more that estimated initial uncertainties of a few %).

→ Finally, checking the Control-System, one founds out that **there was a mistake on the G_QP/I_QP parameter by +18%** (wrong magnetic length was used) !

By using <u>strategy 1</u>, one could have **resolved the incoherence** between code and measurement by compensating two errors (one on the initial distribution, one in Qpole gradients). Nevertheless, this would have produced **new incoherence with other MEBT configurations (**deuterons, current…)

Using <u>strategy 2</u> allowed us to improve our machine knowledge **for all configurations**.