DE LA RECHERCHE À L'INDUSTRIE

Experience from IPHI

RFQ mini-workshop Cavity & Beam Dynamics & Strategies for Hiigher Current Commissioning

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Overview

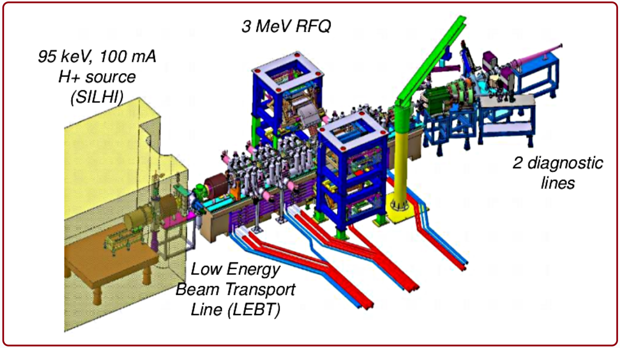
Overview

IPHI Main Parameters

A demonstrator of a 100 mA CW proton injector

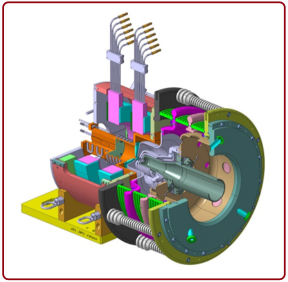
Main parameters

- ECR ion source and LEBT: 100 mA, 95 keV, pulsed or cw
- 4-vanes RFQ: 100 mA, 3 MeV, 352 MHz
- Power sources: 2 klystrons of more than 1 MW
- 2 beam lines: straight line with beam dump and a deflected line with dipole magnet.

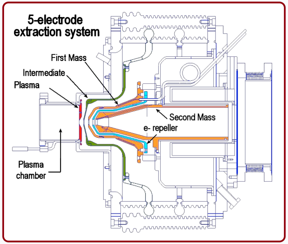


SILHI Ion Source Main Parameters

- Developed in Saclay since 1994
- 2.45 GHz ECR ion sources
- Particles: H^+, D^+, He^+
- Pulsed to c.w. beam
- Designed for 100 mA H^+ pulsed or c.w.
- SILHI-like source developped for IFMIF and FAIR proton linac



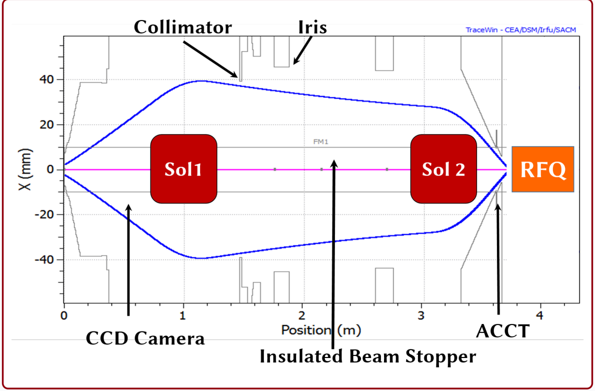
2.45 GHz SILHI ion source

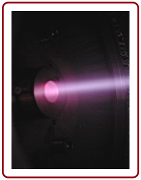


Low Energy Beam Transport (LEBT) Line

The IPHI LEBT:

- Dual solenoid focusing scheme
- Sterrers to correct beam misalignment
- Beam diagnostics (DCCT, ACCT, CCD Camera, Insulated Beam Stopper)
- Iris to control/limit beam size and intensity

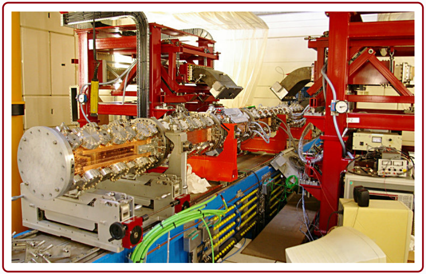


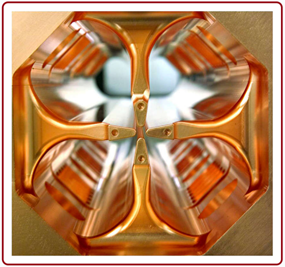


IPHI 4-Vanes RFQ

Parameter	*Value*
Particle	H^+
Max. Current [mA]	100
Frequency [MHz]	352
Input Energy [keV/u]	95
Output Energy [MeV/u]	3
RFQ length [m]	6
Duty Cycle [%]	cw

- R&D program for high intensity beams (CEA/CNRS/CERN)
- Segmented in 6 sections
- Mech. tolerances $\pm 30\ \mu m$
- Commissioned in 2016 in pulsed mode

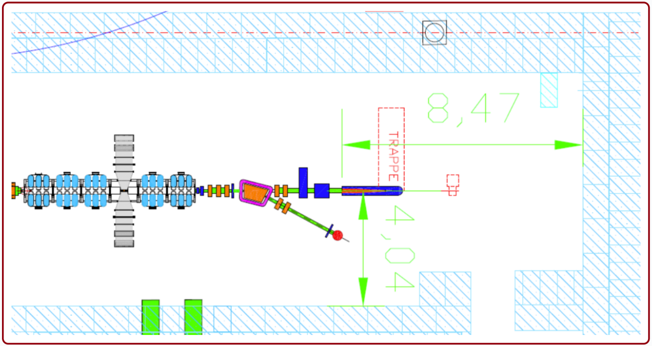




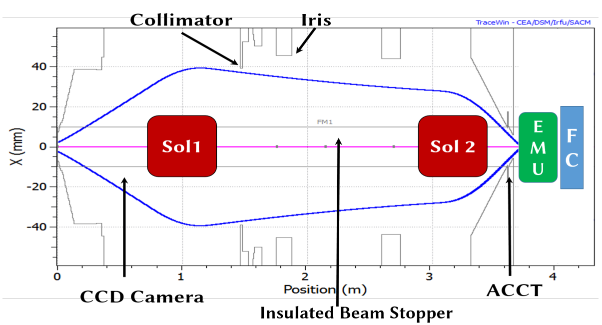
Medium Energy Beam Transport (MEBT) Line

Medium energy beam lines

- RFQ output section 1: 3 quadrupoles
- Dipole magnet 28.5°
- Straight section: 2 quadrupoles and 300 kW beam dump
- Deflected line: 2 quadrupoles and beam stopper or experiment



Overview



SILHI source & LEBT setup

- LEBT with 2 solenoids
- Total length: 3.5 m
- RFQ injection cone
- Emittancemeter (Allison scanner) and Faraday Cup at the end of the beam line

Simulation strategy

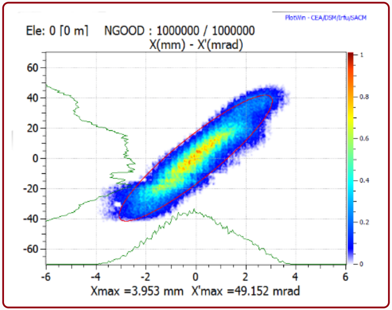
1. **Experiment: optimization** of the beam transmission through the cone. Solenoids values are fixed.
2. **Experiment: emittance** measurement.
3. **Simulation:** using TraceWin, **adjustment** of the beam initial conditions (α, β, ε) and degree of SCC to **fit** to the measured emittance.
4. **Simulation:** using TraceWin with the fitted parameters determination of **optimal solenoid values** for RFQ injection.
5. **Experimental validation:** Emittance measurement.

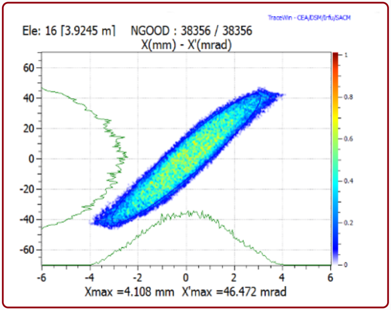
This method is simple and independent of:

- Self-consistent SCC simulations (time consuming)
- Ion source beam distribution simulation

- **PRO:** An empirical model that is easy to use
- **CONS:** Lack of physics in the model

I_{CF} = 30 mA

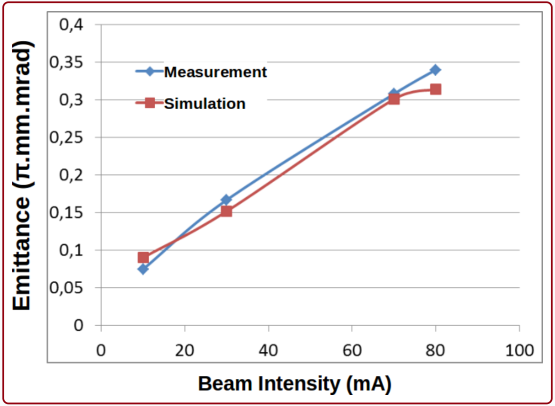




Experiment $\varepsilon = 0.17\ \pi$.mm.mrad

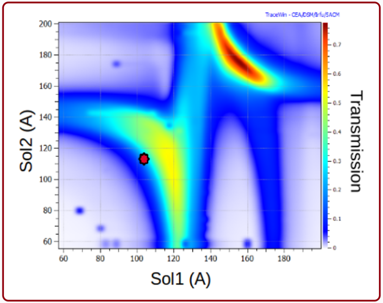
Simulation $\varepsilon = 0.15\ \pi$.mm.mrad

Simulation vs Experience
Emittance vs Beam Intensity

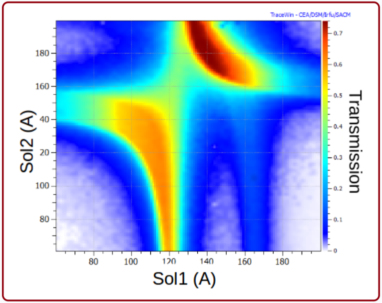


SILHI LEBT simulations

- Simulations give a quite good agreement with data
- Model has to be tested with a 100 mA beam
- Validation with SCC self consistent code (Warp) is needed



Experiment



Simulation

Beam intensity: 40 mA

- Reasonable agreement.
- Discrepancies: alignment and steerers.
- RFQ optimal injection $\neq$ Maximal LEBT transmission

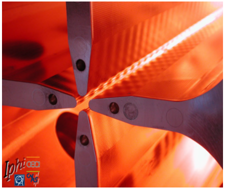
Overview

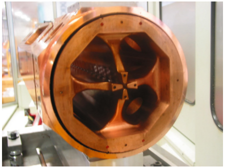
IPHI RFQ Commissioning

See Michel & Olivier's talk

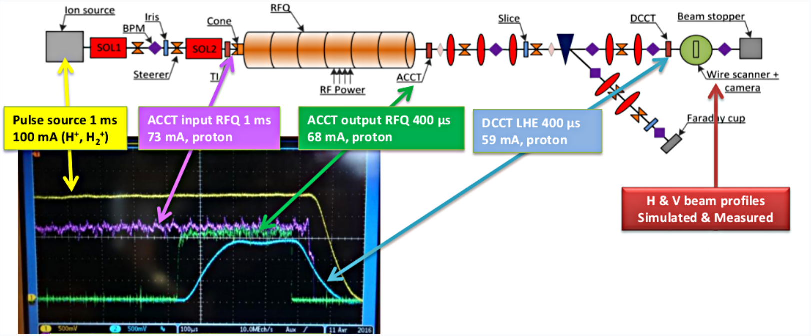
RF Conditioning

- Conditioning started in April 2015 limited by the cooling system of the RFQ (duty cycle limited to 1%)
- After technical issues, conditioning restarted in February 2016 until 1.2 MW peak with a duty cycle of 0.5%
- April 2016: first beam accelerated: Intensity = 60 mA at 0.4% d. c.
- Mid-2018: nominal voltage reached at 5% d. c.
- End 2018: RF platform upgrade (pulsed klystron, installation/test a new CW klystron), RFQ cooling system upgrade
- Mid-2019: RF tuners have been replaced
- September 2019: nominal voltage reached at 50% d. c.





April 2016: First Beam Accelerated

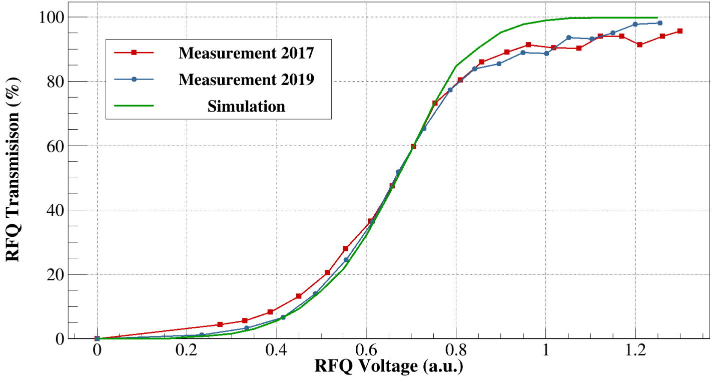


Results obtained

- Transmission through the RFQ in 2016: 93% – Now: 96%.
- Accelerated beam in 2016: Intensity = 60 mA at 0.4% duty cycle.
- Output beam energy (3 MeV) was checked with dipole magnetic field.
- October 2018: beam power of 7 kW was accelerated.

Transmission vs RFQ Voltage

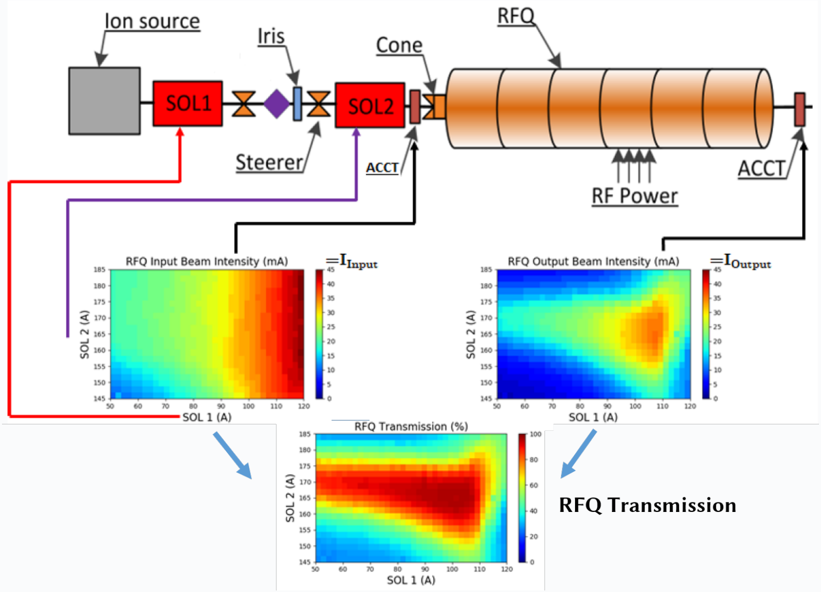
Low Beam Power



- Measurement performed for a ≈70 mA proton beam at the RFQ injection
- Two measurements: before (2017) and after (2019) tuner replacement

RFQ Transmission vs LEBT Solenoids Tuning

Experimental Setup



RFQ Transmission

RFQ Transmission vs LEBT Solenoids Tuning

Experimental conditions

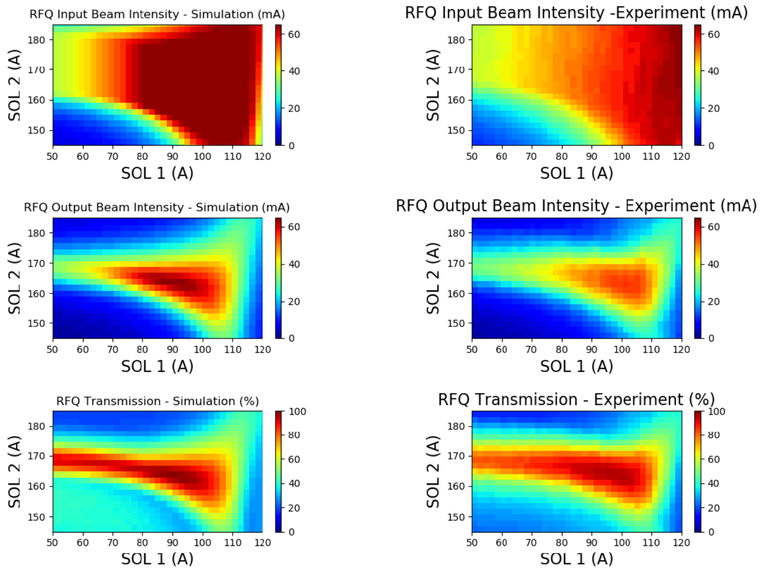
- 80 mA H^+ beam from the source (total extracted current $\approx$ 100 mA) then reduced by iris
- Duty cycle: 10^{-4} (100 µs at 1 Hz) ⟶ beam pulses achieved by RFQ (2 ms pulses from the source) – RFQ as a chopper...
- Data taken for several iris aperture

Simulation model

- Initial LEBT model established during LEBT commissioning + RFQ simulation
- The input Twiss parameters have been optimized (within 15%) and SCC (within 5%) to minimize the experimental/simulation spread
- It has been found that the solenoids magnetic field have to be increased by 8% to minimize the experimental/simulation spread
  ⟶ Solenoids field measurement is needed to confirm that.

RFQ Transmission vs LEBT Solenoids Tuning

Experiment vs Simulation for Iris aperture 90 mm



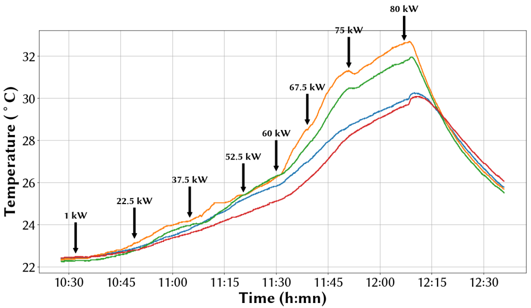
September - October 2019

- The extracted beam power was gradually ramped-up to 80 kW.
- Peak current at RFQ output: 50–55 mA.
- The duty cycle was increased from a few % to 50 %.
- The beam was sent to the beam dump (direct beam line).

Pulses: 7 ms @ 50 Hz

$I_{H^+} = 50\,\text{mA}$

Beam Power = 52.5 kW

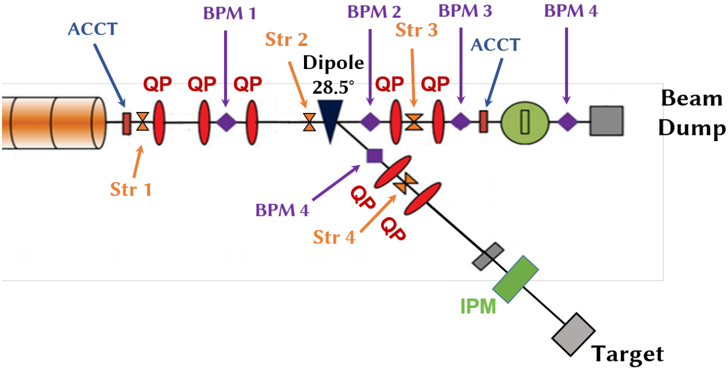


Overview

IPHI MEBT Setup

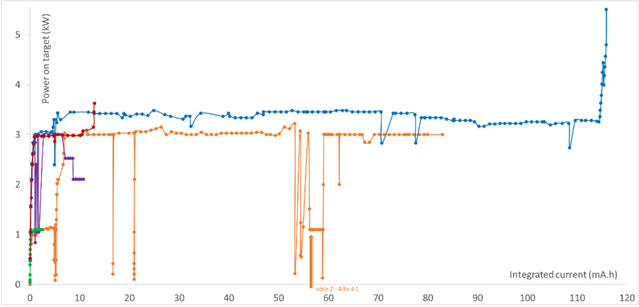
Two Beam Lines

- A straight line to a beam dump (300 kW)
- An experimental line (deflection 28.5°)



Target Tests for Neutron Production

- 21 mA pulsed beam: pulses of 2.85 ms @ 17 Hz
- 5 targets testes, 239 hours of beam on targets
- A target tested up to 115 mA.h, 5.5 kW
- Beam size: $\approx$ 11 mm RMS – $< P > max \approx 0.5\,\mathrm{kW\,cm^{-2}}$



Integrated Power on Targets

Toward a 30 kW Experiment 2021 – 2022

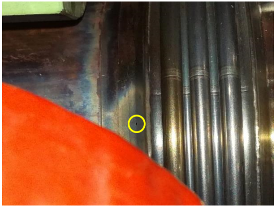
Goals

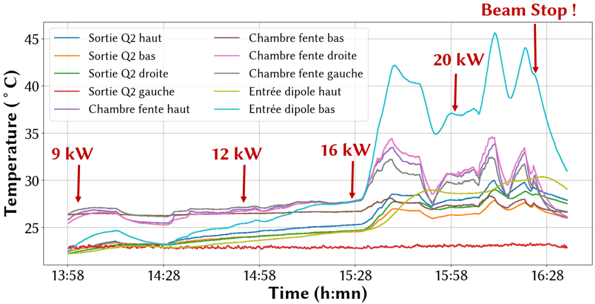
- Tests of a higher power neutron production target
- Required power on target: 30 kW
- Beam Intensity $\approx$ 30 mA
- Duty cycle: 10 ms pulses @33 Hz
- Beam on target during 100 hours
- Beam size on target: $\sigma_x = 15\,\text{mm}/\sigma_y = 20\,\text{mm}$

IPHI MEBT Commissioning @30 kW

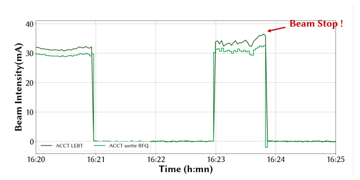
- Commissioning with a 30 kW beam transported in the experimental line (28.5°)
- Stability tests for ”long runs”

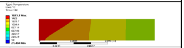
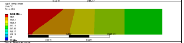
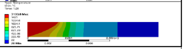
- Array of thermocouples along the beam line
- Power ramp-up to 30 kW to the beam dump (straight line)
- Several days later: a hole in the beam line @20 kW before Q3





- Small increase of beam current before hole (instability)
- BPMs signal remained stable
- Data archiving: 2 s resolution
- No signal on neutron beam loss monitors



Puissance uniforme	Diamètre x épaisseur	Temps pour fusion	Densité de puissance	Image modèle à l'instant de fusion de la face 2
165W	6mmx2mm	360 s	0.58kW/cm2	
200W	6mmx2mm	50.5s	0.71kW/cm2	
1000W	6mmx2mm	1.08s	3.54kW/cm2	

Thermal Calculations

- Beam "spot" around $\varphi 6$ mm on the beam pipe
- For 85 W power lost: 1 hour
- For 200 W power lost: 1 mn
- At 10 cm of the hot spot ≈ 45°C after 1 hour for 85 W power lost
- Difficult to record a sudden increase of beam beam loss (200 W) at more than 1 cm

Power Ramp-up Strategy

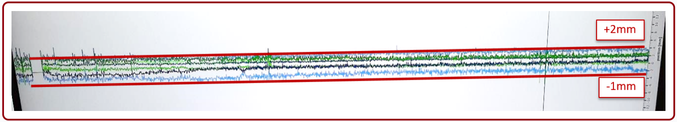
Beam Trajectory Correction

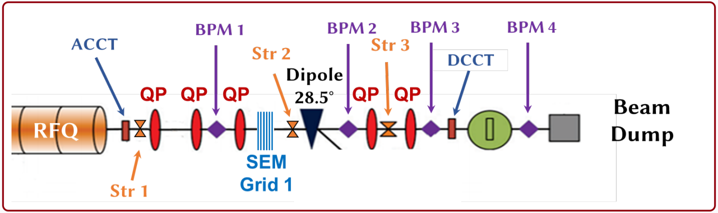
Secure the Beam Position at Low Duty Cycle

- Measurements at nominal intensity (35 mA) and 10^{-4} duty cycle
- Magnetic steerers field measurement (field maps were wrong !)
- Test of the BPMs with a new electronic + IPHI electronic calibration
- Cross check of the beam position measurements with a SEM grid
- Beam alignment in quad center to minimize dipolar kicks

Duty Cycle increase

- Keep the BPM signal constant with the duty cycle increase
- Thermal camera monitoring
- Keep the measured temperatures below 28℃





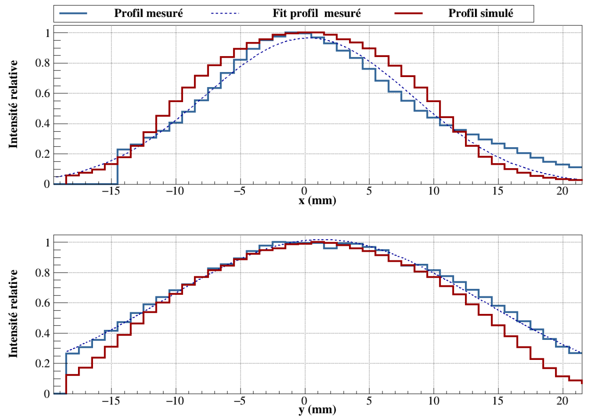
Beam Profile Measurements

- SEM grid from GANIL (44 tungsten wires with 1 mm step)
- Measurement on RF axis, before dipole
- Measurements at nominal beam intensity (35 mA) and 10^{-4} duty cycle ($\approx$ 10 W)

Beam Dynamics Simulation

- Input beam distribution coming from RFQ simulation
- Quadrupole field maps in agreement with field measurement

Beam Intensity: 34 mA – Quad triplet = 0 A

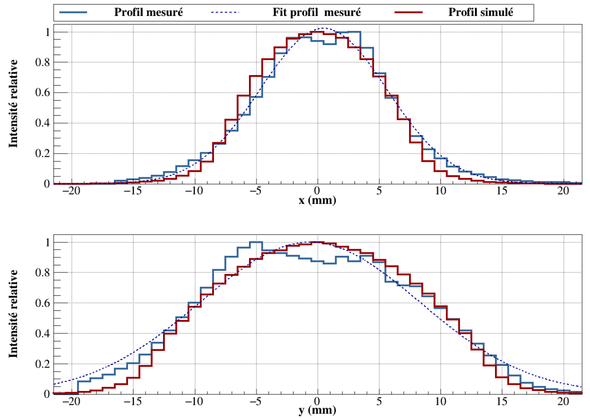


Measured Profile	Gaussian Fit	Simulation
$\sigma_x = 7.8\,\mathrm{mm}$	$\sigma_x = 8\,\mathrm{mm}$	$\sigma_x = 7.4\,\mathrm{mm}$
$\sigma_y = 9.6\,\mathrm{mm}$	$\sigma_y = 12.3\,\mathrm{mm}$	$\sigma_y = 9.0\,\mathrm{mm}$

Beam Transport

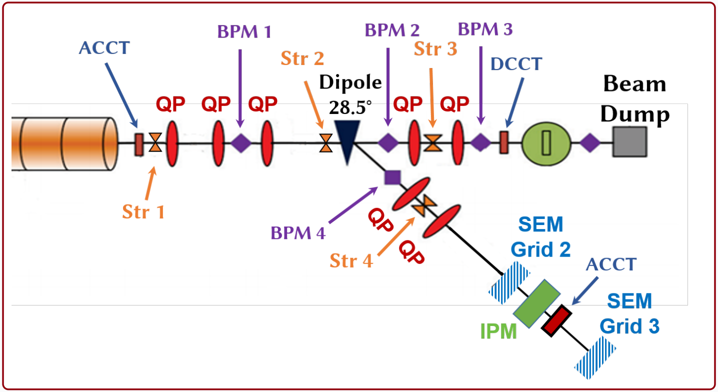
Measurements vs Simulation @ SEM Grid Position 1

Beam Intensity: 34 mA – Q1=−47 A / Q2=75 A / Q3=−45 A



Measured Profile	Gaussian Fit	Simulation
$\sigma_x = 5.3\,\mathrm{mm}$	$\sigma_x = 5.2\,\mathrm{mm}$	$\sigma_x = 4.7\,\mathrm{mm}$
$\sigma_y = 7.9\,\mathrm{mm}$	$\sigma_y = 8.9\,\mathrm{mm}$	$\sigma_y = 7.2\,\mathrm{mm}$

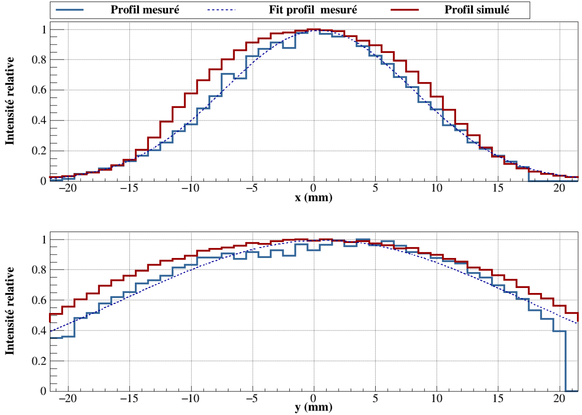
Measurements vs Simulation @ SEM Grid Position 2 and 3



Beam Profile Measurements

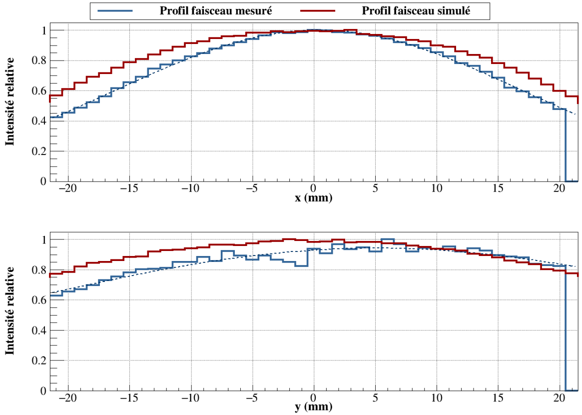
- Measurement with SEM 2 in the beam line (permanent position)
- Measurement with SEM 3 at target position

Beam Intensity: 34 mA – Q4=−3.7 A / Q5=11.2 A



Measured Profile	Gaussian Fit	Simulation
$\sigma_x = 7.2\,\text{mm}$	$\sigma_x = 7.7\,\text{mm}$	$\sigma_x = 7.7\,\text{mm}$
$\sigma_y = 10.8\,\text{mm}$	$\sigma_y = 16.3\,\text{mm}$	$\sigma_y = 12.0\,\text{mm}$

Beam Intensity: 34 mA – Q4=–3.7 A / Q5=11.2 A

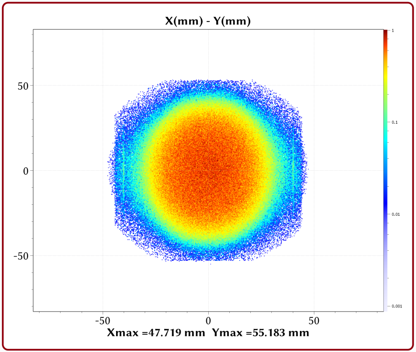


Measured Profile	Gaussian Fit	Simulation
$\sigma_x = 10.8\,\text{mm}$	$\sigma_x = 16.6\,\text{mm}$	$\sigma_x = 12.3\,\text{mm}$
$\sigma_y = 11.7\,\text{mm}$	$\sigma_y = 30.5\,\text{mm}$	$\sigma_y = 13.0\,\text{mm}$

Beam Transport

Measurements vs Simulation @ SEM Grid Position 3 (Target)

Beam Intensity: 34 mA – Q4=−3.7 A / Q5=11.2 A



Simulated Beam Distribution on Target

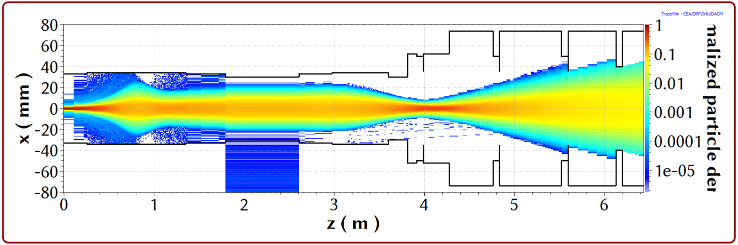
Simulated Beam Size on Target

$$\sigma_x = 15.8\,\mathrm{mm}$$
$$\sigma_y = 20\,\mathrm{mm}$$

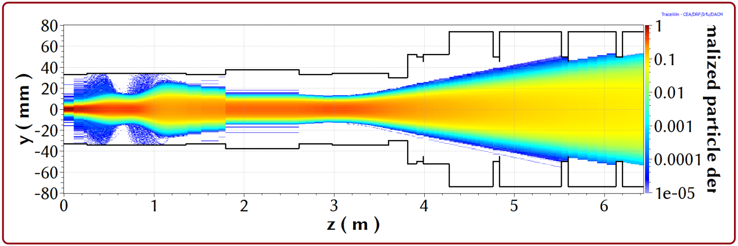
SEM grid measurement range (-19 mm – + 23 mm) is too small for the beam size...

Beam Transport

Simulation of Beam Transport in the MEBT Line



Beam density in X plane



Beam density in Y plane

Thermal Tests on Al Target

- 2 days of experiment at 30 kW (with a maximum @ 37 kW beam power)
- Final beam centring on target (temperature measurement)
- Thermomechanical calculations validation

Final Experiment with Be Target

- 10 days of experiment ($\approx$ 10 hours beam time per day)
- Average beam power around 27 kW (limitation due to the target)
- A few technical problems (power supply, control system) but no problem with the beam
- More than 100 hours of beam time integrated on target
- On the last day/night: 24 hours of beam without major stops (a few sparks at the ion source)

Overview

Conclusions and Perspectives

Conclusions

- IPHI beam commissioning has been done up to 80 kW beam power during a short time
- IPHI beam commissioning has been done up for a reliable operation with a 30 kW beam power
- The beam transport in the whole accelerator has been simulated
- A neutron production experiment has been performed with more of 100 hours of beam time on target

Lesson Learned and Perspectives

- We were too optimistic, at the beginning, with a high power beam
- Lack of interlock and MPS on IPHI (will be added)
- RFQ bead-pull measurement and tuning
- A 3 MeV emittancemeter (slit-grid) is under development
- Replacement of diagnostics (never enough diags...) is planned
- A chopper for the LEBT is under development

The Whole Team !

... *an those who are not on the picture:* C. Alba-Simionesco, B. Bolzon, R. Braud, J. Darpentigny, C. Doira, C. Deberles, R. Duperrier, G. Exil, Y. Gauthier , F. Gibert, E. Giner-Demange, A. Gomes, T. Hamelin, K. Jiguet, E. Jorgji, W. Josse, O. Kuster, R. Lautie, P. Lavie, A. Letourneau, A. Marchix, C. Marchand, A. Menelle, K. Paunac, P. Permingeat, E. Petit, O. Piquet, F. Porcher, B. Pottin, F. Prunes, O. Sineau, L. Thulliez, H. N. Tran, D. Uriot.

Thank you for your attention !