30 kW Beam Commissioning of the High-Intensity Proton Accelerator IPHI: Experiments, Simulations and Space Charge

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Overview

Overview

1. **The IPHI Facility, a High Intensity Proton Injector**
   - IPHI Overview
   - SILHI Ion Source
   - LEBT
   - RFQ
   - MEBT
2. LEBT Commissioning
3. RFQ Beam Commissioning
4. MEBT Commissioning and Experiments with IPHI
5. Conclusions and Perspectives

The Founding Fathers

A demonstrator of a 100 mA CW proton injector

IPHI, THE SACLAY HIGH-INTENSITY PROTON INJECTOR PROJECT

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Abstract

High-power accelerators are being studied for several projects based on high-flux neutron sources driven by proton or deuteron beams. Since the front end is the most critical part of such accelerators, it has been decided to build a High-Intensity Proton Injector (IPHI) designed to accelerate a cw 100 mA beam up to 11 MeV. The aim is

a compromise between the technical risk and the total cost of the project. A good compromise is difficult to achieve without a serious R&D program focused on the important issues mentioned above. Since rf linacs have emerged as the accelerators of choice for pulsed or cw beams above 5 MW, we have undertaken a comprehensive demonstration program for the low-energy part of such machines.

J.-M.Lagniel et al. (1997).
IPHI, the Saclay High-Intensity Proton Injector Project..
PAC 1997 Proceedings, Vancouver, B.C., Canada..

Initial Goals of the IPHI Project:

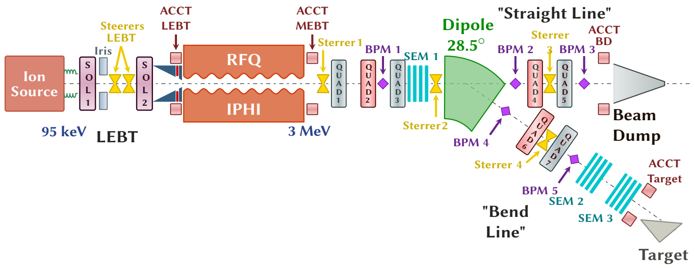
1. Development and validation of beam dynamics codes
2. Beam characterisation for future high power accelerators
3. Demonstration of technological choices
4. Reliability, availability tests and fast re-starting procedures
5. Increase the laboratory competences in high intensity/high power accelerator commissioning, tuning and operation

IPHI Main Parameters

A demonstrator of a 100 mA CW proton injector

Main parameters

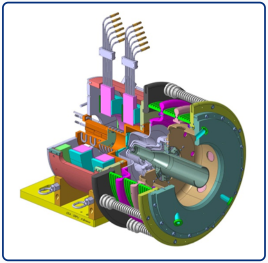
- ECR ion source and LEBT: 100 mA, 95 keV, pulsed or cw
- 4-vanes RFQ: 100 mA, 3 MeV, 352 MHz
- Power sources: 2 klystrons of more than 1 MW
- 2 beam lines: straight line with beam dump and a bend line with dipole magnet.



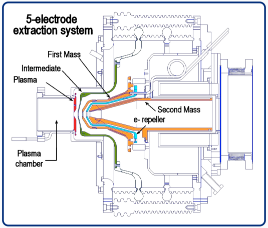
Light Ion Production
Ion Sources at CEA-Saclay

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



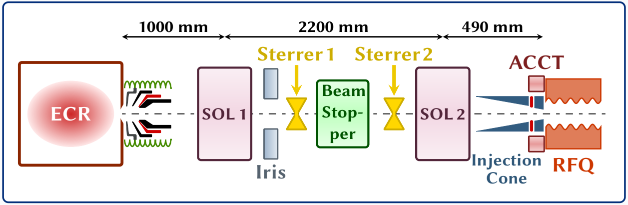
2.45 GHz SILHI ion source

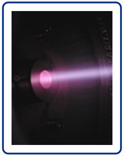


Low Energy Beam Transport (LEBT) Line

IPHI LEBT

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

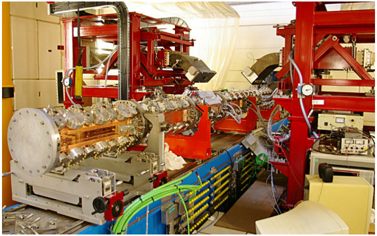


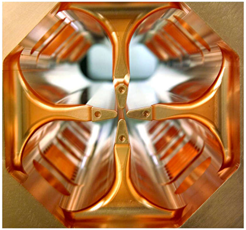


IPHI 4-Vanes RFQ

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

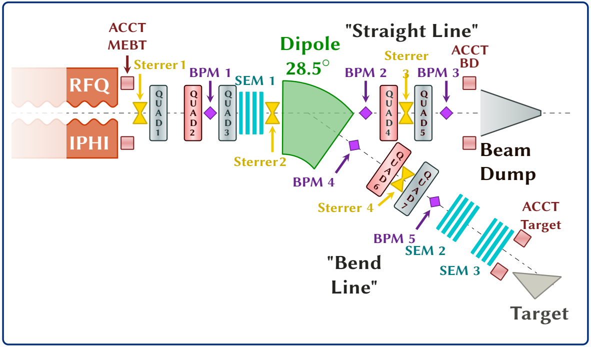




Medium Energy Beam Transport (MEBT) Line

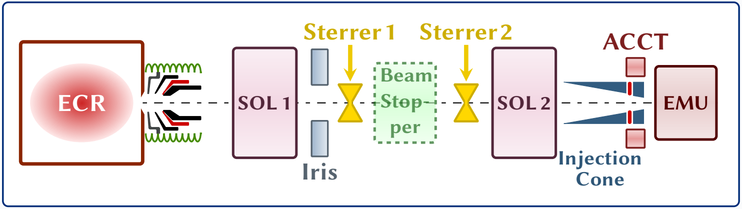
Medium Energy Beam Transport Lines

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



Overview

SILHI Source & LEBT
Experimental Setup for Beam Commissioning



SILHI source & LEBT setup

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

Self-Consistent LEBT Simulations

- Simulation of the beam interactions with the residual gas and beam pipes, diagnostics…
- Simulation of the dynamics of the beam and the secondary particle.
- Dedicated codes like Warp, Bender…
- **PRO:** A lot of physics.
- **CONS:** Very time consuming.

Grote, D. P., Friedman, A., Vay, J.-L., and Haber, I. (2005).
The Warp code: Modeling high intensity ion beams..
AIP Conference Proceedings, 749(1):55–58.

A few references

- D. Noll: HB 2016, Linac 2014.
- L. Bellan: Ph.D. thesis, Padova University (2017), ICIS 2018.
- F. Gardin: Ph. D. thesis, Paris-Saclay University (2017).

LEBT Simulations

State of the art – ”Gabovitch model”

So-called ”Gabovitch model”

- Semi-analytical model.
- Formlula (Igor Gabovich et al., 1975) to computation of the space charge compensatin degree along the LEBT.
- Useable with transport codes like TraceWIn.
- **PRO:** Fast computing time.
- **CONS:** Need some adjustements (presence of electric field).

D. Winklehner and D. Leitner (2015).
A space charge compensation model for positive DC ion beams..
Journal of Instrumentation **10** T10006..

A few references

- L. Bellan: LINAC 2022.
- D. Winklehner: Ph. D. thesis, MSU (2013).

A Semi-Empirical Model

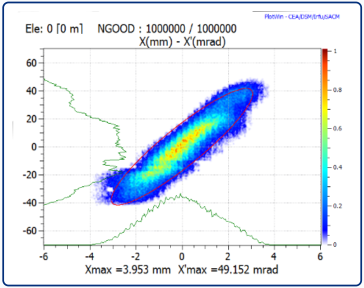
Method:

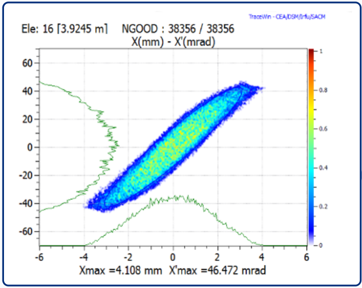
1. **Experiment:** **optimization** of the beam transmission through the cone. Solenoids values are fixed.
2. **Experiment:** **emittance** measurement.
3. **Simulation:** using TraceWin, **adjustment** of the beam initial Twiss parameters (α, β, ϵ) and SCC degree to **fit** to the measured emittance.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

- **PRO:** An empirical model that is easy to use
- **PRO:** Independent of ion source distribution simulation
- **CONS:** Lack of physics in the model

Simulation vs Experience
Emittance Measurement

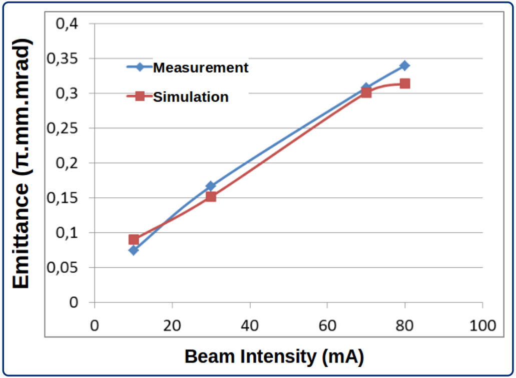
I_{CF} = 30 mA





Experiment ϵ = 0.17 π.mm.mrad

Simulation ϵ = 0.15 π.mm.mrad



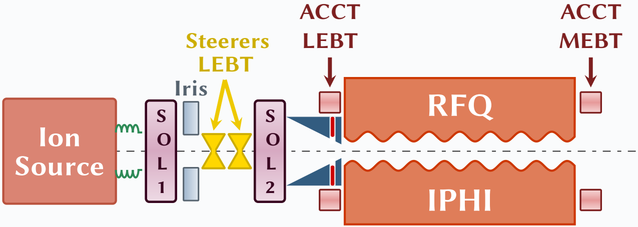
IPHI LEBT simulations

- Simulations give a quite good agreement with experimental data up to 70–80 mA.
- Model has to be tested for a proton beam in the 100 mA range.

Overview

1. The IPHI Facility, a High Intensity Proton Injector
2. LEBT Commissioning
3. RFQ Beam Commissioning
   - Beam Commissioning at Low Beam Power
   - Beam Commissioning at High Beam Power
4. MEBT Commissioning and Experiments with IPHI
5. Conclusions and Perspectives

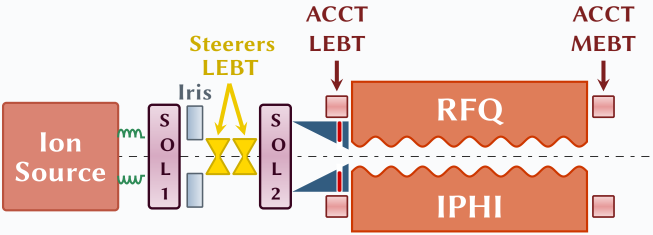
RFQ Transmission Experiments



Experimental Conditions

- RFQ transmission is measured using 2 ACCTs: one at the RFQ input, one at the output.
- 80 mA H^+ beam extract from the source (total extracted current $\approx$ 100 mA).
- Experiments with several iris apertures (different injected beam current).
- Beam duty cycle: 10^{-4} (100 µs at 1 Hz): beam pulses achieved by RFQ (2 ms pulses from the source) – RFQ as a chopper...

LEBT/RFQ Simulations

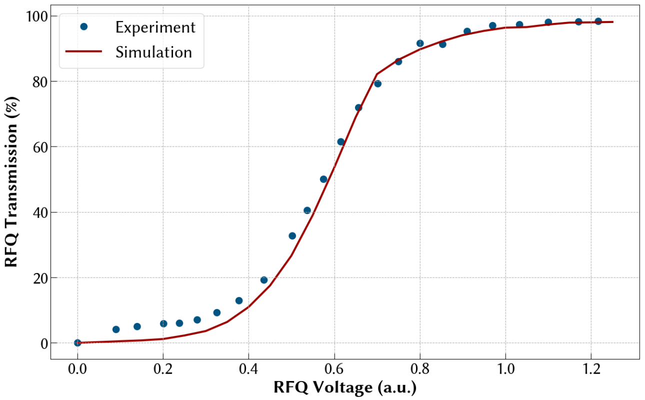


Simulation Conditions

- TraceWin/Toutatis are used.
- LEBT model with a constant current (80 mA). The injected beam current is adjusted with the iris, like the experiment.
- RFQ model build from a bead-pull measurement.

RFQ Transmission vs RFQ Voltage

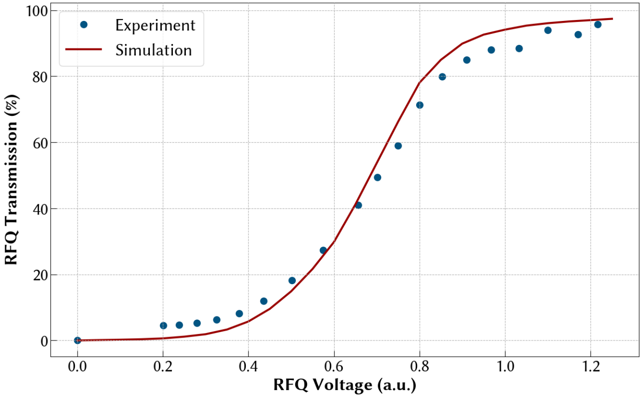
I_{H^+} = 30 mA – Low Beam Power



- Measurement performed for a 30 mA proton beam at the RFQ injection

RFQ Transmission vs RFQ Voltage

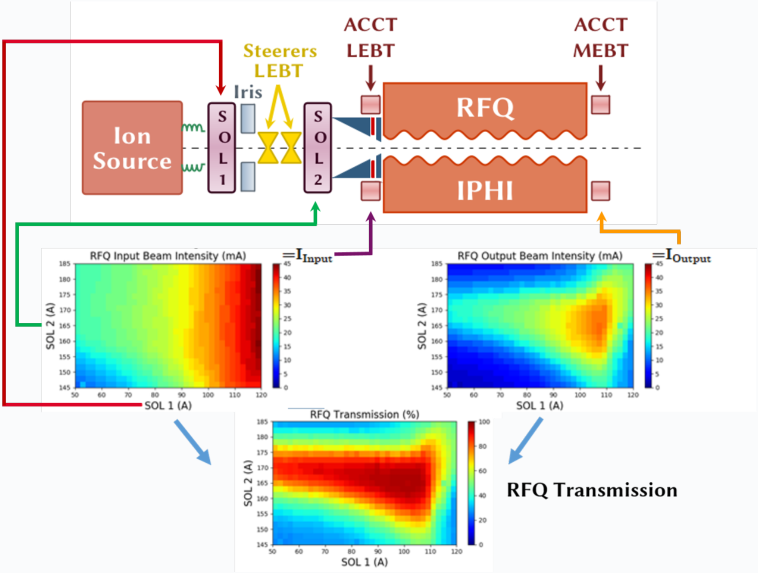
I_{H^+} = 60 mA – Low Beam Power



- Measurement performed for a 60 mA proton beam at the RFQ injection

RFQ Transmission vs LEBT Solenoids Tuning

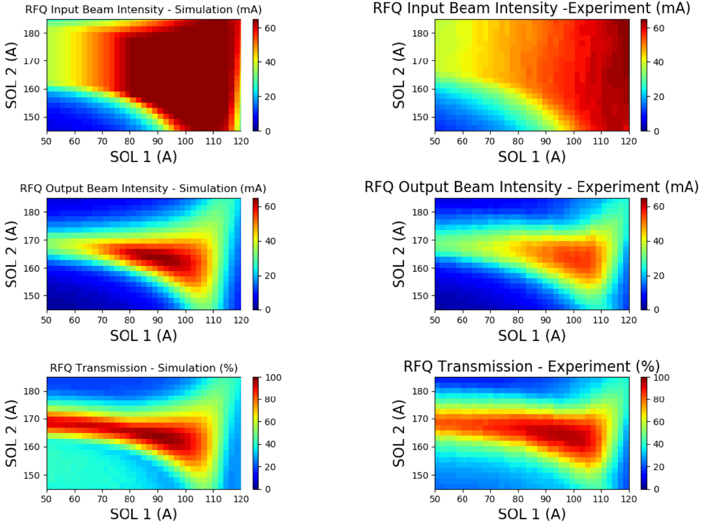
Experimental Setup



RFQ Transmission vs LEBT Solenoids Tuning

Experiment vs Simulation for iris aperture 90 mm (60 mA)

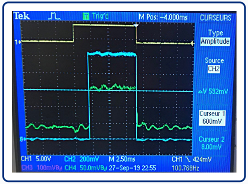
Simulations | **Experiment**



Beam Commissioning
Beam Power Ramp-up

End of 2019

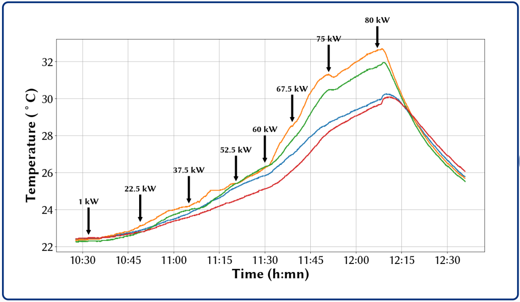
- The extracted beam power was gradually ramped-up to 80 kW.
- Peak current at RFQ output: 50–55 mA.
- The duty cycle was increased from a few % to 50 %.
- The beam was sent to the beam dump (straight line).



Pulses: 7 ms @ 50 Hz

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

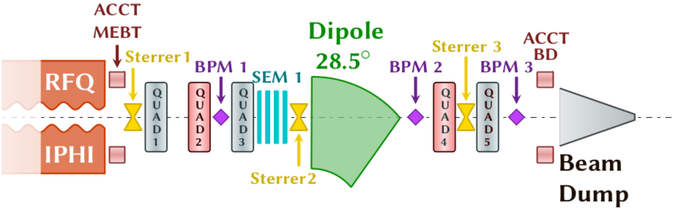
Beam Power = 52.5 kW



Overview

1. The IPHI Facility, a High Intensity Proton Injector
2. LEBT Commissioning
3. RFQ Beam Commissioning
4. **MEBT Commissioning and Experiments with IPHI**
   - IPHI MEBT "Straight Line"
   - IPHI MEBT "Bend Line"
   - The 30 kW Neutron Production Experiment
5. Conclusions and Perspectives

IPHI MEBT "Straight Line" Setup



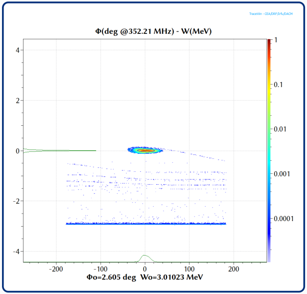
MEBT Measurements

- Dipole is switched off.
- Beam current measurement after RFQ and before beam dump (ACCTs): MEBT transmission.
- Beam profile with SEM grid 1
- SEM grid from GANIL (44 tungsten wires with 1 mm step)
- Measurements at nominal beam intensity (30 mA) and 10^{-4} duty cycle ($\approx$ 10 W)

MEBT "Straight Line" Transmission

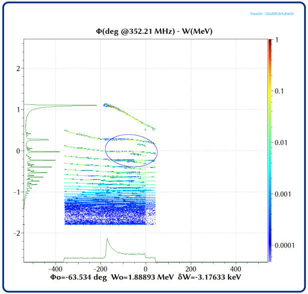
Measurements

- Nominal transmission ≈100%.
- MEBT Transmission measurement vs RFQ voltage.
- Transport simulation through the MEBT.



$V_{RFQ} = 1$

$< W_{Beam} >= 3\,\text{MeV}$



$V_{RFQ} = 0.8$

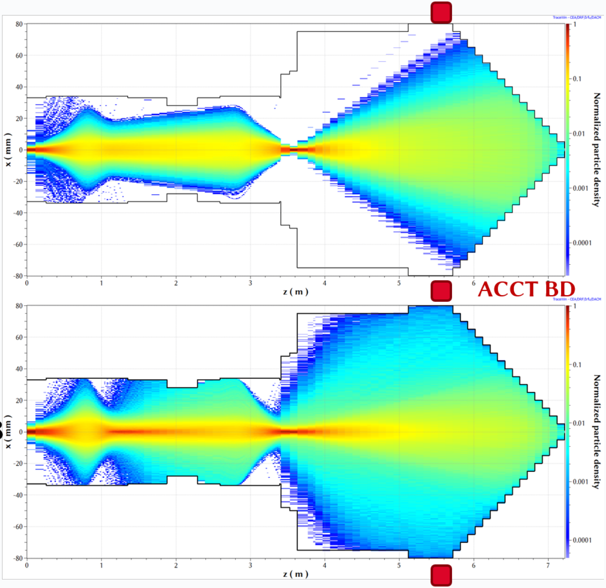
$< W_{Beam} >= 1.9\,\text{MeV}$

MEBT ”Straight Line” Transmission

Beam Transport for 2 RFQ Voltages

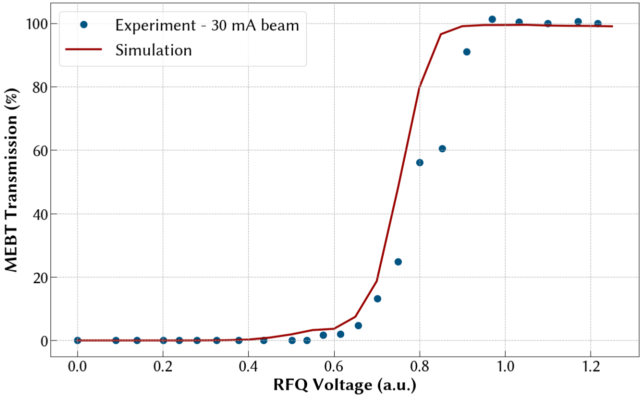
$V_{RFQ} = 1$

$V_{RFQ} = 0.8$



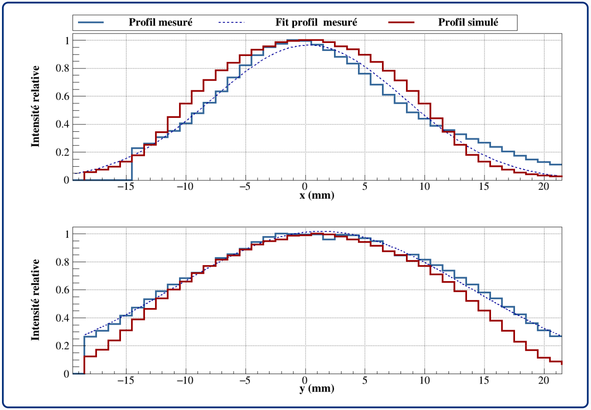
MEBT Transmission vs RFQ Voltage

I_{H^+} = 30 mA – Low Beam Power



- Measurement performed for a 30 mA proton beam at the RFQ injection

Beam Intensity: 34 mA – Quad triplet = 0 A

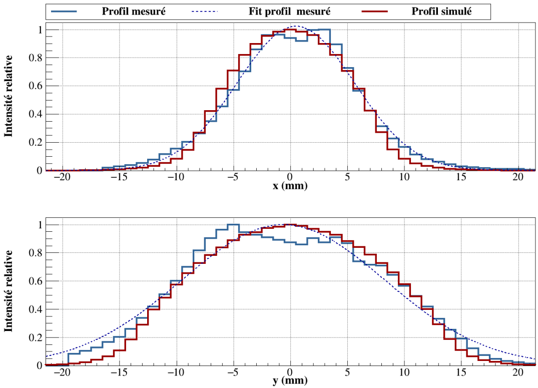


Measured Profile	Gaussian Fit	Simulation
$\sigma_x = 7.8\,\text{mm}$	$\sigma_x = 8\,\text{mm}$	$\sigma_x = 7.4\,\text{mm}$
$\sigma_y = 9.6\,\text{mm}$	$\sigma_y = 12.3\,\text{mm}$	$\sigma_y = 9.0\,\text{mm}$

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
$\sigma_x = 5.3\,\text{mm}$	$\sigma_x = 5.2\,\text{mm}$	$\sigma_x = 4.7\,\text{mm}$
$\sigma_y = 7.9\,\text{mm}$	$\sigma_y = 8.9\,\text{mm}$	$\sigma_y = 7.2\,\text{mm}$

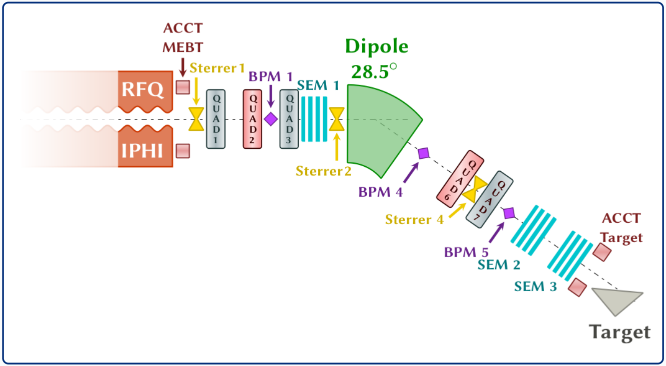
Toward a 30 kW Experiment
Beam Commissioning of the MEBT ”Bend Line”

Goals

- Tests of a high 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 bend line.
- Stability tests for ”long runs”.



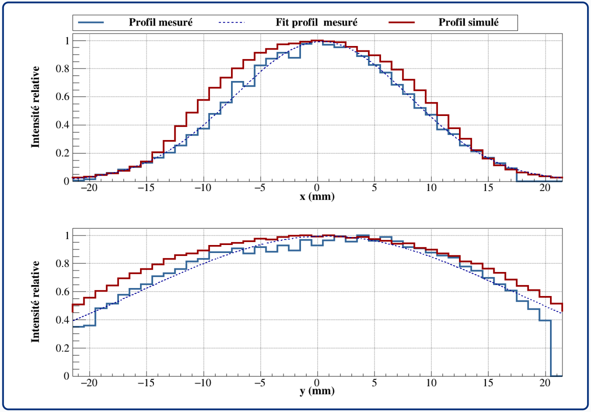
Beam Profile Measurements

- Measurement with SEM 2 and SEM 3.
- Measurements at nominal beam intensity (30 mA) and 10^{-4} duty cycle (≈ 10 W).

Beam Transport

Measurements vs Simulation @ SEM Grid Position 2

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

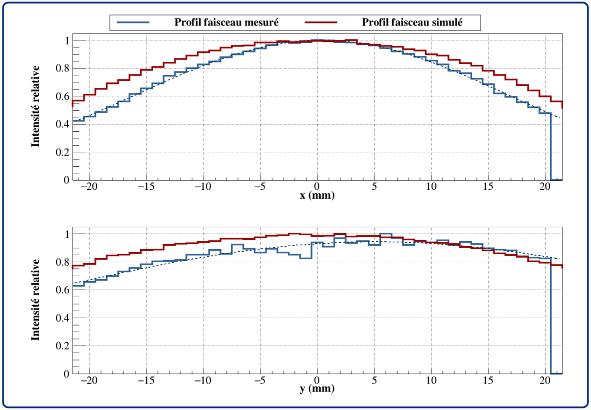


Measured Profile	Gaussian Fit	Simulation
$\sigma_x = 7.2\,\text{mm}$	$\sigma_x = 7.7\,\text{mm}$	$\sigma_x = 7.7\,\text{mm}$
$\sigma_y = 10.8\,\text{mm}$	$\sigma_y = 16.3\,\text{mm}$	$\sigma_y = 12.0\,\text{mm}$

Beam Transport

Measurements vs Simulation @ SEM Grid Position 3 (Target)

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

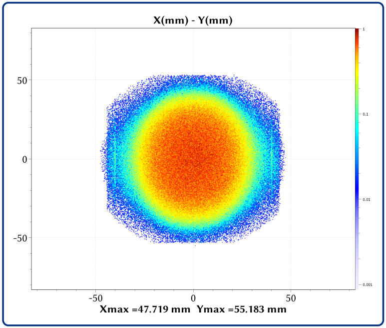


Measured Profile	Gaussian Fit	Simulation
$\sigma_x = 10.8\,\text{mm}$	$\sigma_x = 16.6\,\text{mm}$	$\sigma_x = 12.3\,\text{mm}$
$\sigma_y = 11.7\,\text{mm}$	$\sigma_y = 30.5\,\text{mm}$	$\sigma_y = 13.0\,\text{mm}$

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

$\sigma_x = 15.8\,\text{mm}$

$\sigma_y = 20\,\text{mm}$

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

Neutron Production Experiment
January/February 2022

Thermal Tests on Al Target

- 2 days of experiment at 30 kW (with a maximum @ 37 kW beam power)
- Final beam centering on target (temperature measurement)
- Thermomechanical simulations 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)
- More than 100 hours of beam time integrated on target.
- Integrated charge on target $\approx$ 3200 C
- 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 (E2E) has been simulated.
- A neutron production experiment has been performed with more of 100 hours of beam time on target.

Perspectives

- A 3 MeV emittancemeter (slit-grid) is under development
- RFQ bead-pull measurement and tuning
- A chopper for the LEBT is under development
- A design study for a CANS (20–30 MeV) at Saclay is about to start: ICONE Neutrons for Materials Sciences

The Team !

... *an those who are not on the picture (not exhaustive):* C. Alba-Simionesco, B. Bolzon, R. Braud, A.C. Chauveau, J. Darpentigny, C. Doira, C. Deberles, R. Duperrier, G. Exil, R. Ferdinand, Y. Gauthier , F. Gibert, E. Giner-Demange, R. Gobin, 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 !