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

**HB 2023, CERN, Geneva, Switzerland.**

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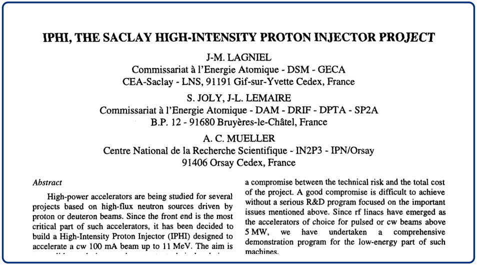
October 10, 2023

# Overview

# Overview

# 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:

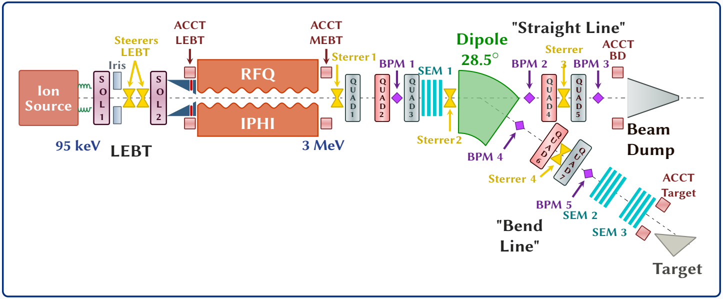
1. Development and validation of beam dynamics codes.
2. Beam characterization for future high power accelerators.
3. Demonstration of technological choices.
4. Reliability, availability tests and fast re-starting procedures.
5. Increase the laboratory competences in high intensity/high power accelerator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

# IPHI Main Parameters

A demonstrator of a 100 mA CW proton injector

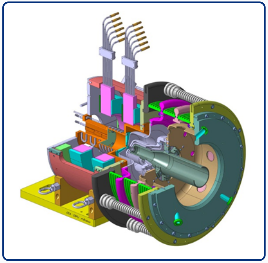
## Main parameters

- 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.

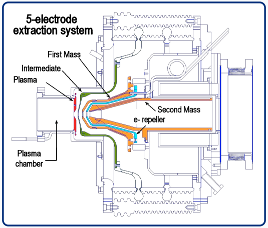


## SILHI Ion Source Main Parameters

- 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.



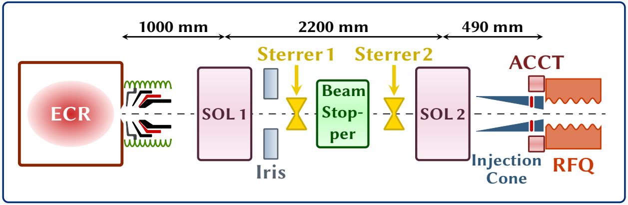
**2.45 GHz SILHI ion source**

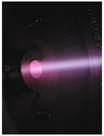


# Low Energy Beam Transport (LEBT) Line

## 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.

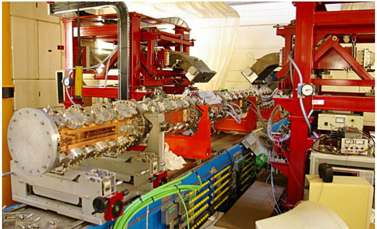


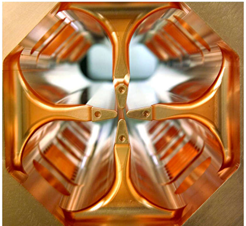



# IPHI 4-Vanes RFQ

| 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.

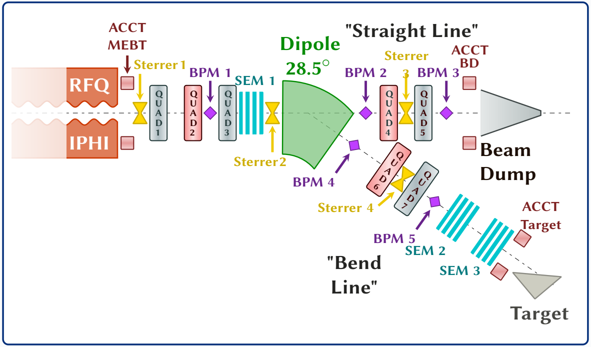




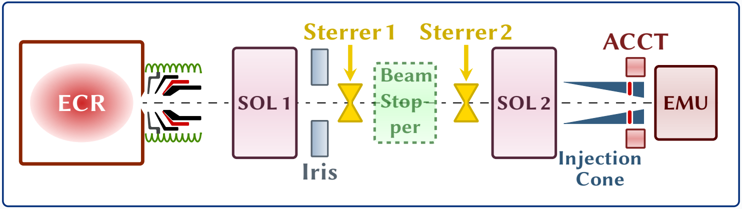
# Medium Energy Beam Transport (MEBT) Line

## 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 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. Gérardin: Ph. D. thesis, Paris-Saclay University (2017).

# LEBT Simulations

## State of the art – ”Gabovitch model”

### So-called ”Gabovitch model”

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

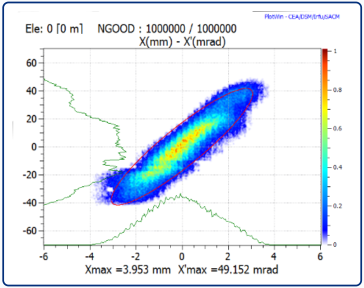
**Method:**

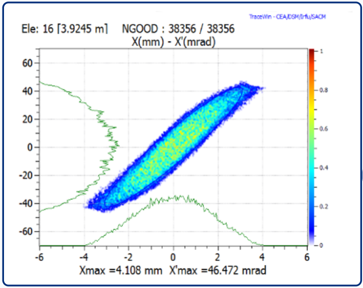
1. **Experiment:** **optimization** of the beam transmission through the cone. Solenoids values are fixed.
2. **Experiment:** **emittance** measurement.
3. **Simulation:** using TraceWin, **adjustment** of the beam initial Twiss parameters ($\alpha, \beta, \epsilon$) and SCC degree to **fit** to the 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**

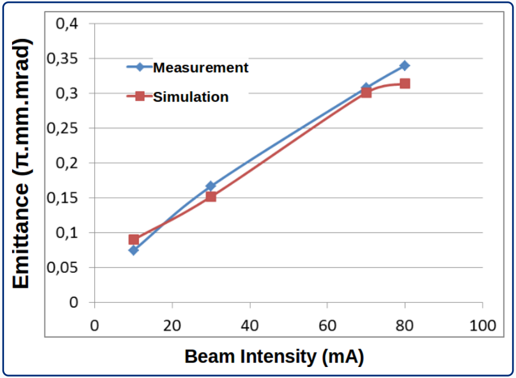



Experiment $\epsilon = 0.17\ \pi$.mm.mrad

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

# Simulation vs Experience
## Emittance vs Beam Intensity



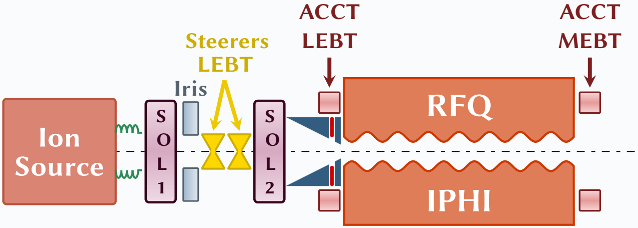

### IPHI LEBT simulations

- 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

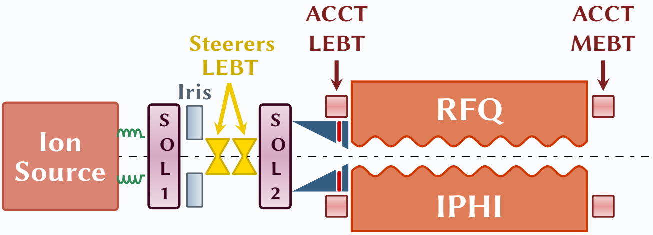
# RFQ Transmission Experiments




## 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

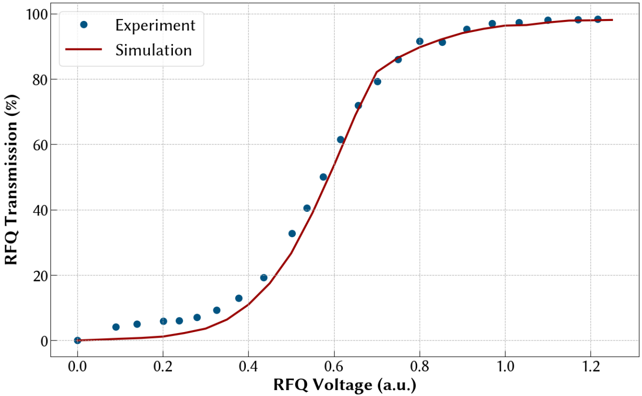



## Simulation Conditions

- 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

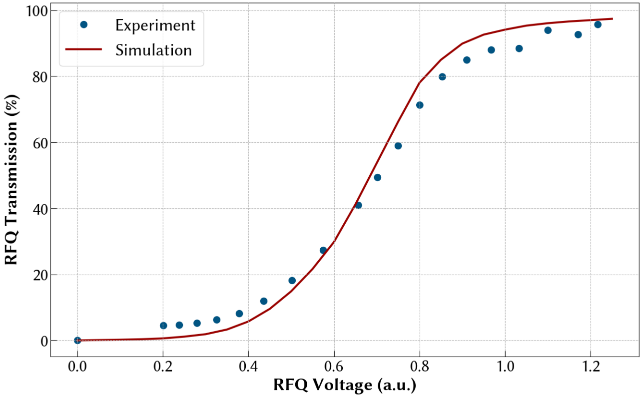
## $I_{H^+}$ = 30 mA – Low Beam Power




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

# RFQ Transmission vs RFQ Voltage

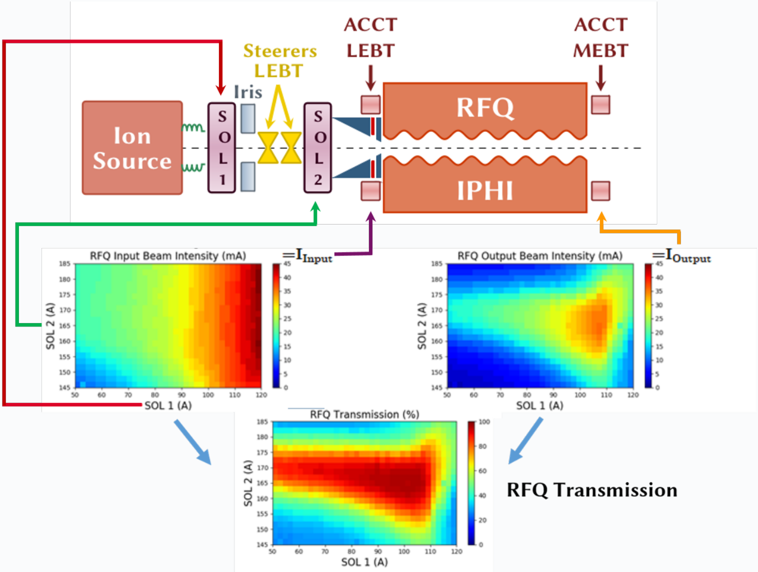
## $I_{H^+}$ = 60 mA – Low Beam Power




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

# RFQ Transmission vs LEBT Solenoids Tuning

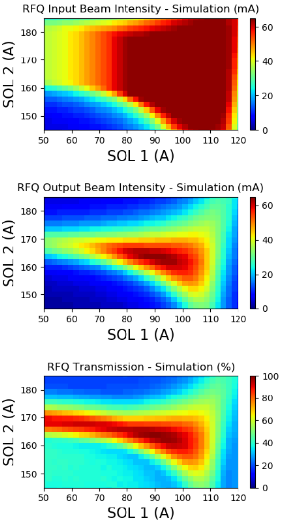
## Experimental Setup



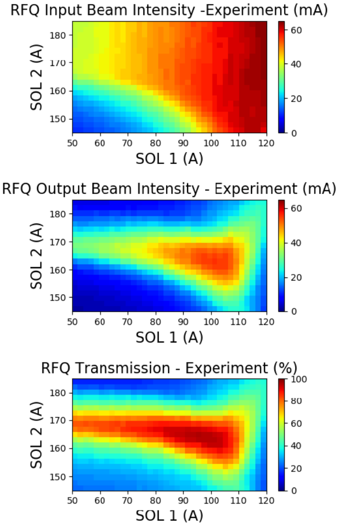
# RFQ Transmission vs LEBT Solenoids Tuning

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

### Simulations

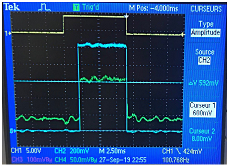



### Experiment



## End of 2019

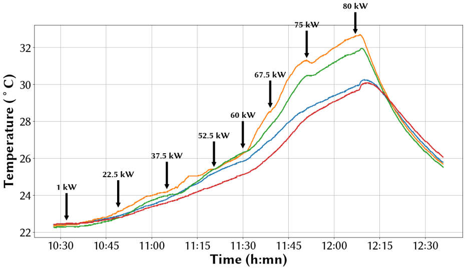
- The extracted beam power was gradually ramped-up to 80 kW.
- Peak current at RFQ output: 50–55 mA.
- The duty cycle was increased from a few % to 50 %.
- The beam was sent to the beam dump (straight line).




Pulses: 7 ms @ 50 Hz

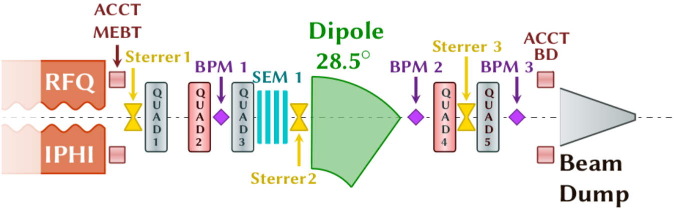
$I_{H^+} = 50\,\text{mA}$

**Beam Power = 52.5 kW**



# Overview

# IPHI MEBT "Straight Line" Setup



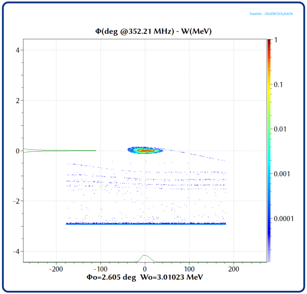

## MEBT Measurements

- 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)

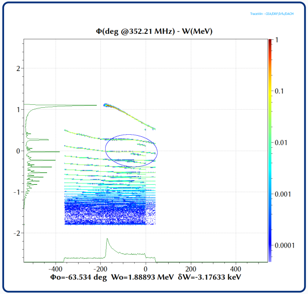
# MEBT "Straight Line" Transmission

## Measurements

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




$V_{RFQ} = 1$
$< W_{Beam} >= 3$ MeV



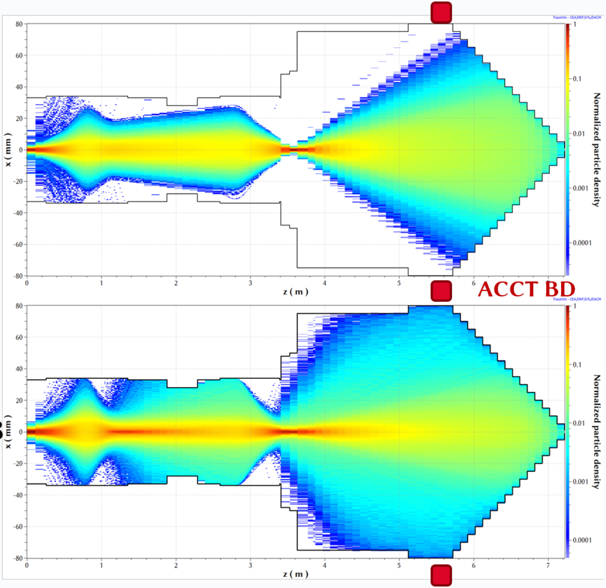

$V_{RFQ} = 0.8$
$< W_{Beam} >= 1.9$ MeV

# MEBT ”Straight Line” Transmission

## Beam Transport for 2 RFQ Voltages

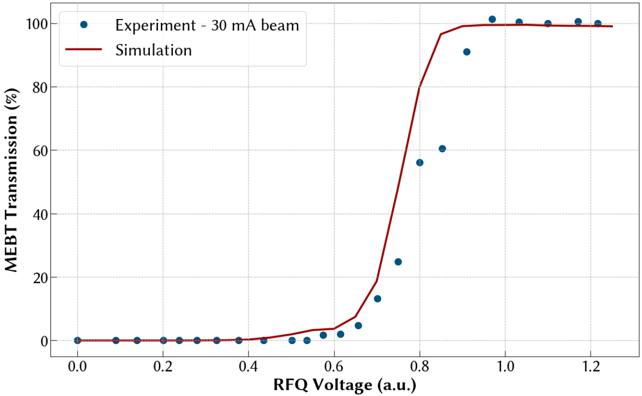
$V_{RFQ} = 1$

$V_{RFQ} = 0.8$



# MEBT Transmission vs RFQ Voltage

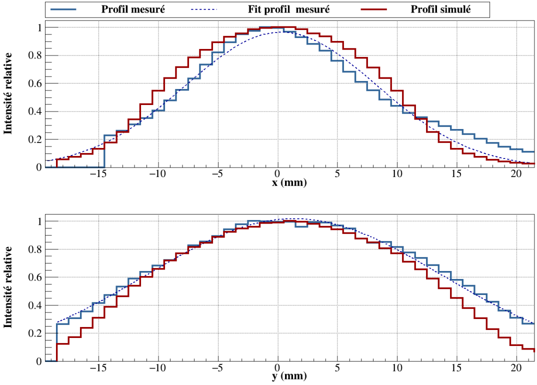
## $I_{H^+}$ = 30 mA – Low Beam Power




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

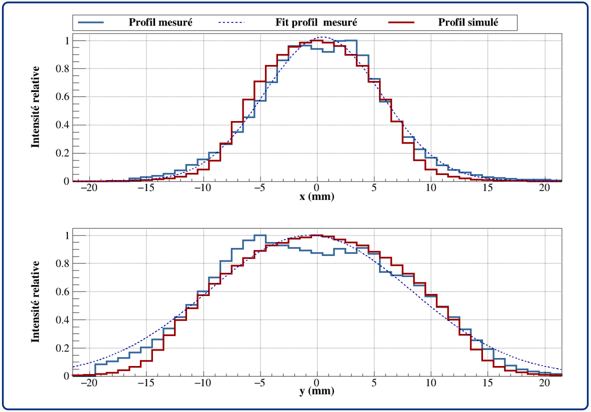
# Beam Transport
## Measurements vs Simulation @ SEM Grid Position 1

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




**Measured Profile**

$\sigma_x = 5.3\,\text{mm}$

$\sigma_y = 7.9\,\text{mm}$

**Gaussian Fit**

$\sigma_x = 5.2\,\text{mm}$

$\sigma_y = 8.9\,\text{mm}$

**Simulation**

$\sigma_x = 4.7\,\text{mm}$

$\sigma_y = 7.2\,\text{mm}$

# Toward a 30 kW Experiment

## Beam Commissioning of the MEBT ”Bend Line”

### Goals

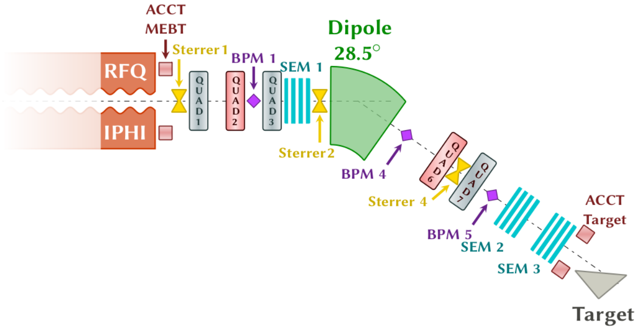
- Tests of a high power neutron production target.
- Required power on target: 30 kW.
- Beam Intensity $\approx 30\,\text{mA}$.
- Duty cycle: 10 ms pulses @33 Hz.
- Beam on target during 100 hours.
- Beam size on target: $\sigma_x = 15\,\text{mm} / \sigma_y = 20\,\text{mm}$.

### IPHI MEBT Commissioning @30 kW

- Commissioning with a 30 kW beam transported in the bend line.
- Stability tests for ”long runs”.

# Beam Transport

## Measurements @ SEM Grid Position 2 and 3



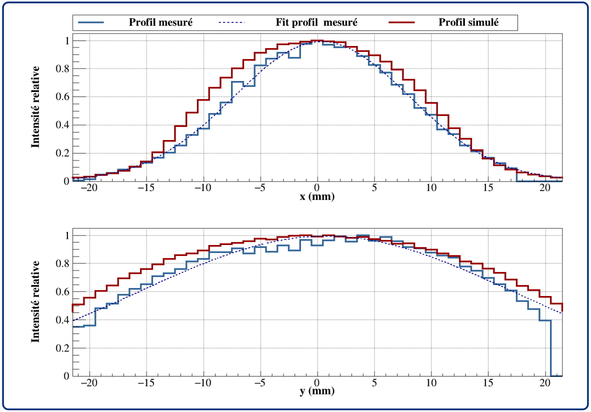

### Beam Profile Measurements

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

# Beam Transport

## Measurements vs Simulation @ SEM Grid Position 2

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

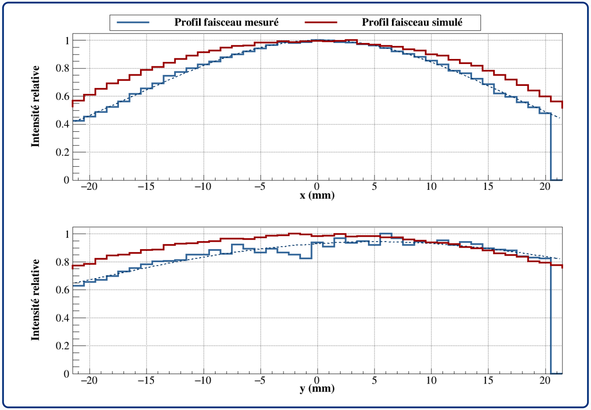



| Measured Profile | Gaussian Fit | Simulation |
|---|---|---|
| $\sigma_x = 7.2\,\text{mm}$ | $\sigma_x = 7.7\,\text{mm}$ | $\sigma_x = 7.7\,\text{mm}$ |
| $\sigma_y = 10.8\,\text{mm}$ | $\sigma_y = 16.3\,\text{mm}$ | $\sigma_y = 12.0\,\text{mm}$ |

# Beam Transport

## Measurements vs Simulation @ SEM Grid Position 3 (Target)

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

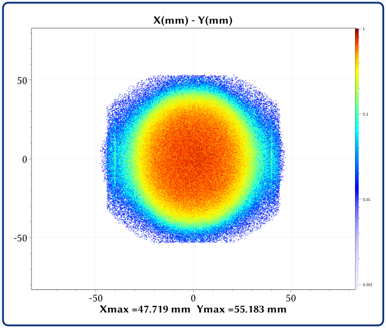



| Measured Profile | Gaussian Fit | Simulation |
|---|---|---|
| $\sigma_x = 10.8\,\text{mm}$ | $\sigma_x = 16.6\,\text{mm}$ | $\sigma_x = 12.3\,\text{mm}$ |
| $\sigma_y = 11.7\,\text{mm}$ | $\sigma_y = 30.5\,\text{mm}$ | $\sigma_y = 13.0\,\text{mm}$ |

# 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 !