IPHI, a high intensity proton accelerator for neutron production

UCANS VIII, Paris, France.

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Overview

1. **The IPHI Facility, a High Intensity Proton Injector**
   - IPHI Overview
   - SILHI Ion Source
   - LEBT
   - RFQ
   - MEBT
2. **IPHI Commissioning**
   - RFQ Commissioning
   - Beam Commissioning
   - Next steps for IPHI
3. **Neutron Production Experiments with IPHI**
   - Neutron Production Experiments Runs 1 & 2
   - Neutron Production Experiments Run 3
4. **Future Experiments: Toward 50 kW on Target**
5. **Conclusions and Perspectives**

Overview

IPHI Initial Goals

A demonstrator of a 100 mA CW proton injector

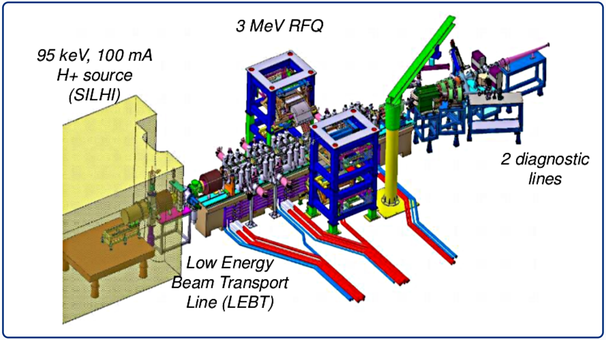
1. Development and validation of beam dynamics codes
2. Beam characterisation for future high power accelerators
3. Development and tests of beam diagnostics that can be used in the future high intensity accelerators
4. Reliability tests and fast re-starting procedures
5. Increase the laboratory competences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

The IPHI Radio-Frequency Quadrupole

IPHI Main Parameters

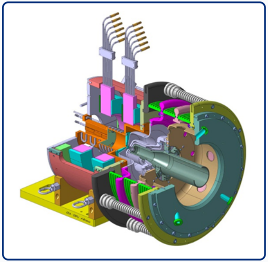
Main parameters

- 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.

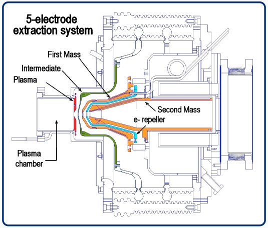


SILHI Ion Source Main Parameters

- 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.
- A "low current" version (SILHI 2, $\approx$ 50 mA) is commercially available (www.pantechnik.com)



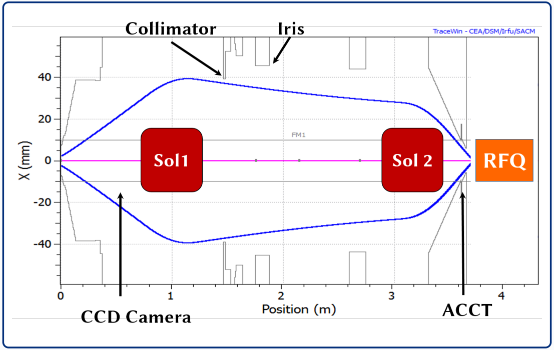
2.45 GHz SILHI ion source

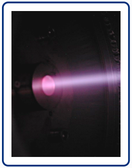


Low Energy Beam Transport (LEBT) Line

The role of a LEBT is to **transport and adapt** the beam to **optimize** its injection into the RFQ.

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

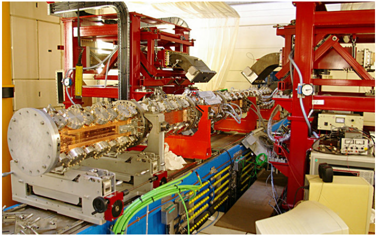


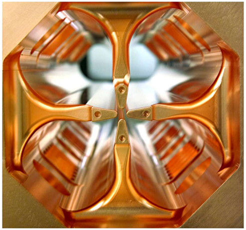


IPHI 4-Vanes RFQ

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

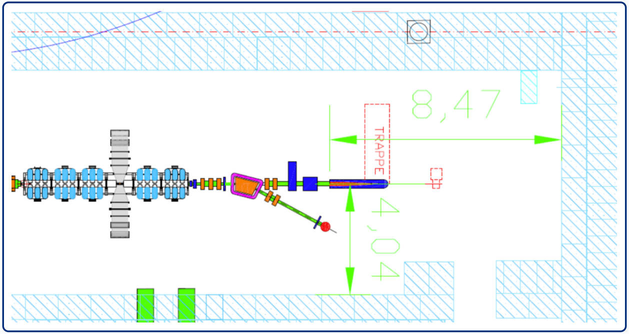




Medium Energy Beam Transport (MEBT) Line

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 low power beam stopper (several kW)

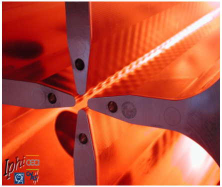


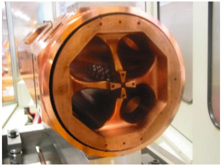
Overview

IPHI RFQ Commissioning

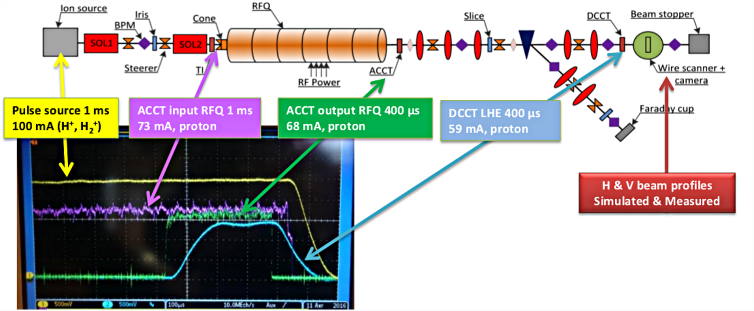
RF Conditioning

- 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% duty cycle.
- Mid-2018 nominal voltage reached at 5% duty cycle (R.F. pulses:3.6 ms 14 Hz.
- End 2018: RF platform upgrade (pulsed klystron, installation / test a new CW klystron), RFQ cooling system upgrade.
- Mid-2019: RF tuners have been replaced.





April 2016: First Beam Accelerated

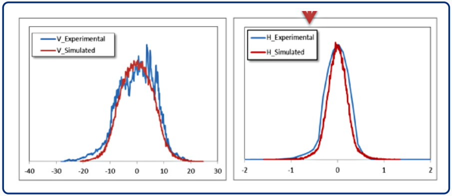


Results obtained

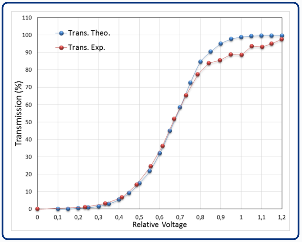
- Transmission through the RFQ in 2016: 93% – Now: 96%.
- Accelerated beam in 2016: Intensity = 60 mA at 0.4% duty cycle.
- Output beam energy (3 MeV) was checked with dipole magnetic field.
- October 2018: beam power of 7 kW was accelerated.

Beam Commissioning

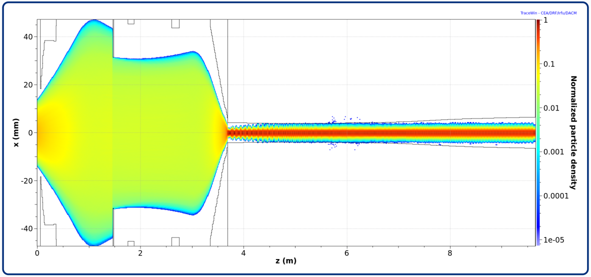
Experimental Results and Comparison to Simulations



Beam Profiles in MEBT

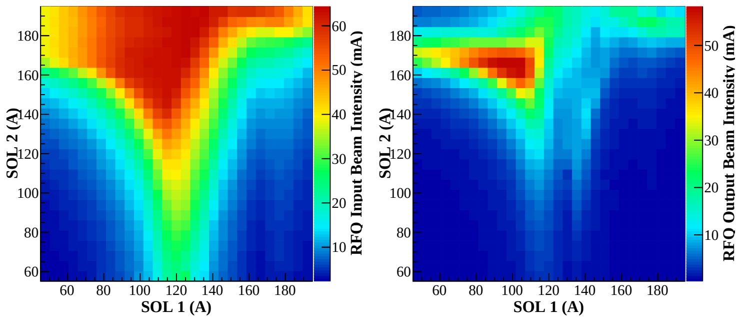


Transmission vs RFQ Voltage



Beam Commissioning
RFQ Transmission vs LEBT Solenoids Tuning

- Source duty cycle: 5 % (Total extracted current ≈ 100 mA)
- RFQ duty cycle: 0.1% (100 µs at 1 Hz)



ACCT end of LEBT

ACCT after the RFQ

Beam Commissioning
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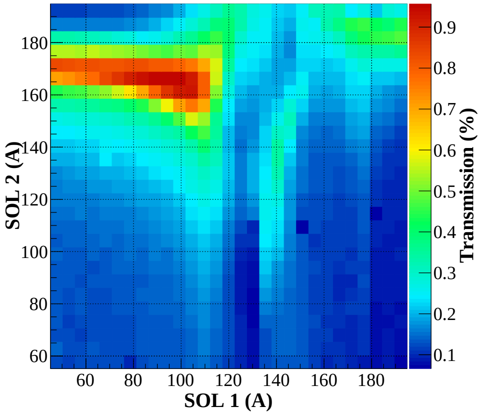


- Maximal transmission > 96 %
- Beam dynamics analysis is currently performed.

IPHI: Next Steps

- Conditioning to reach nominal voltage at 30% duty cycle (and above ?).
- Accelerate beam at 30% duty cycle.

- **Trans National Access to IPHI (or to the 352 MHz RF power amplifiers) is foreseen in the ARIES project framework**: 12 x 3 weeks in the mid-2017 – mid-2021 period.
- Experiments on IPHI should be discussed **in advance** (technical feasibility, radioprotection issues, responsibility for activated parts...)


EUROPEAN COMMISSION HORIZON 2020

HORIZON 2020

H2020- INFRAIA-01-2016-2017: Integrating and opening research infrastructures of European interest

Integrating Activity: Research and Innovation Action

Physical Sciences – Advanced Communities – Particle Accelerators

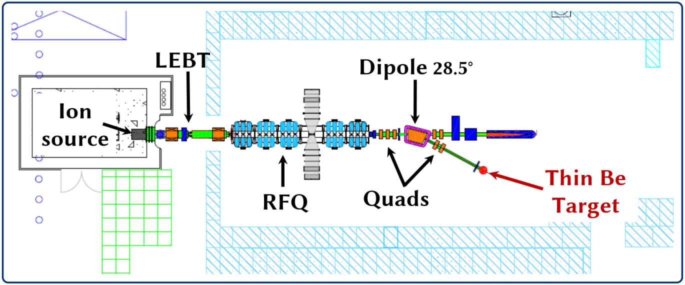
Title of proposal: Accelerator Research and Innovation for European Science and Society

Short name: ARIES

Overview

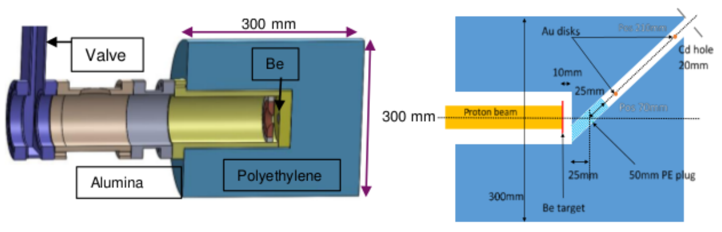
Experimental Conditions

- Proton Beam: 3 MeV, 1 Hz, 100 µs, 10 mA to 50 mA
- Thin Be target with polyethylene moderator
- Experiment on IPHI deflected beam line
- Run 1: July 2017 – Run 2: January 2018



Run 1 & 2 Experimental Setup

Neutron Production Experiment – Run 1
Experimental Setup

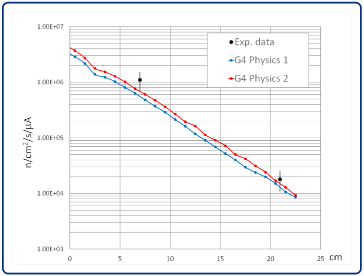


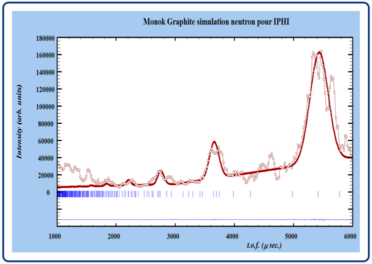
- Au foils
- Gamma detectors
- At 8.4 m: ^{3}He detectors with ToF acquisition system (triggered with accelerator)

Neutron Production Experiment – Run 1

Experimental Results

Power on target: 10 W





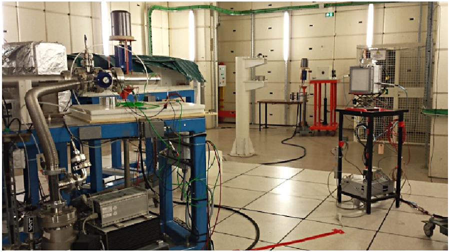
Gold disks measurements inside the moderator (dots)
GEANT4 Monte Carlo simulations (lines)

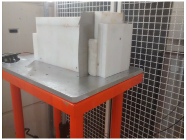
TOF measurements at 8 m (dots)
Graphite crystal
Full proof fit (line)

Run 2 – Experimental Setup
Detectors

Main goals

- Fast neutrons emissions
- Background



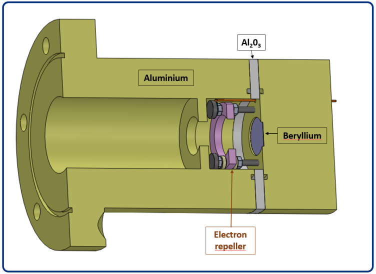


^{3}He detector + PE shielding + B4C shielding (looking at the target at 8m)

Available detectors

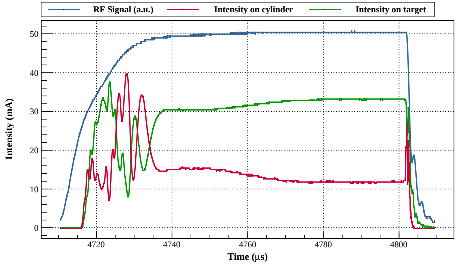
- Bonner sphere
- ^{3}He detector on lift table
- ”Fast neutrons” detector CEA - DEDIP (Ion. Chamb. + Micromegas)
- ”Thermal neutron” detector CEA - DEDIP (Ion. Chamb. + Micromegas)
- Gamma chambers
- Gamma NaI spectrometer

Run 2 – Beam Intensity Measurement

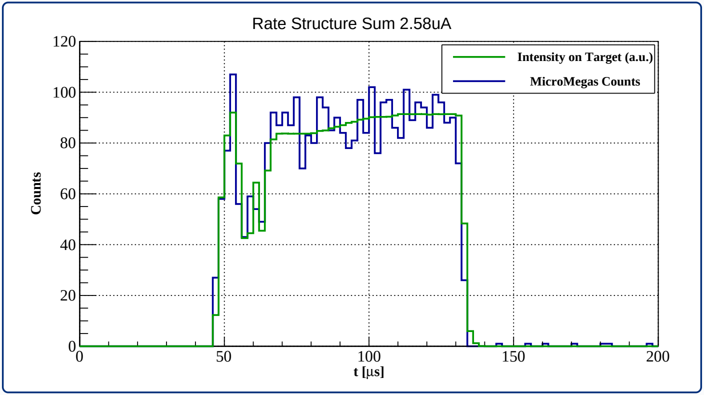


Beam Intensity Measurement

- Insulated Be target
- Electron repeller
- Insulated cylinder



Run 2 – Beam Intensity on Target and Fast Neutrons Detection



Beam Intensity on Target

Signal integrated by fast neutrons detector

Goals

- Increase the proton beam power on target, up to several kW.
- Characterize the beam on target.
- R & D on solid targets.

Experiments

- Preliminary tests on an Al target.
- Neutron production with a solid Be target, ϕ 50 mm.
- New moderator and shielding.
- Several weeks of experiment, first semester 2019.

For detailed consideration on the solid Be target, see Burkhard ANNIGHÖFER's talk, *A Solid Beryllium Target for Sonate.*

Neutron Production Experiments Run 3
Goals and Experimental Conditions

Goals

- Increase the proton beam power on target, up to several kW.
- Characterize the beam on target.
- R & D on solid targets.

Experiments

- Preliminary tests on an Al target.
- Neutron production with a solid Be target, ϕ 50 mm.
- New moderator and shielding.
- Several weeks of experiment, first semester 2019.

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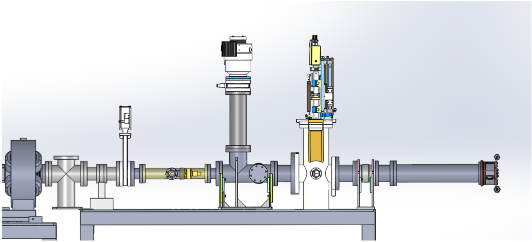
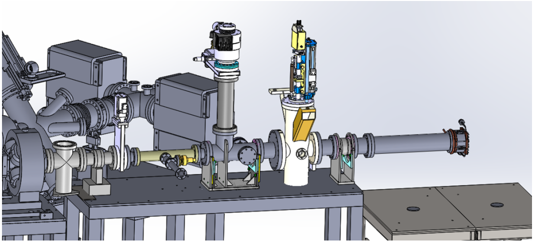
New beam line between quadrupole doublet and target

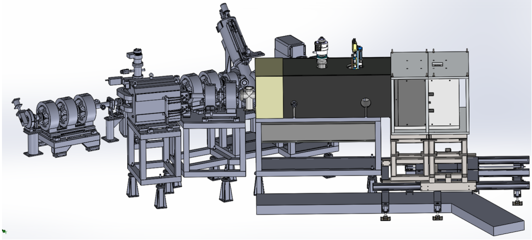


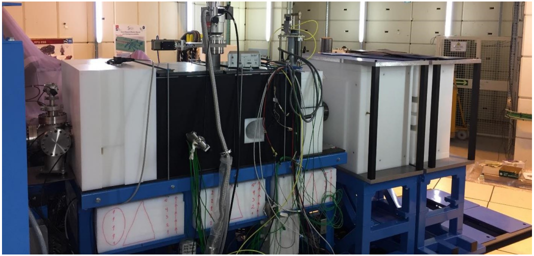


Neutron Production Experiment Run 3

Experimental Setup

New moderator/reflector and shielding for beam power increase.

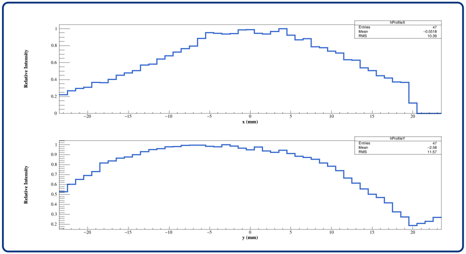




Run 3 – Beam Diagnostics on Target
SEM grid profiler

Secondary Emission Monitor

- Design and electronics by GANIL
- 48 wires spaced by 1 mm in 2 planes



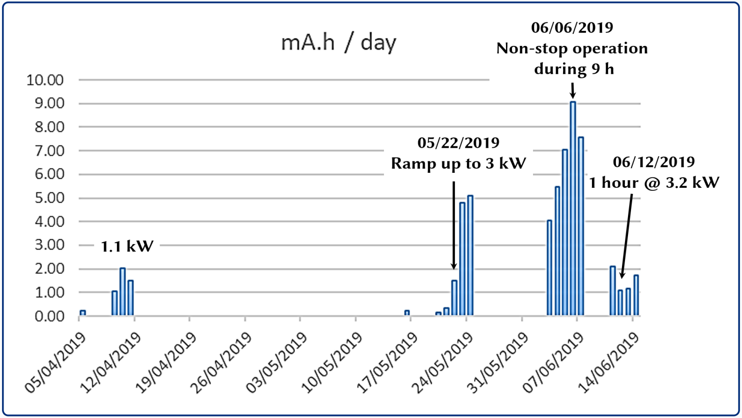
$\sigma_x = 10.4\,\text{mm} - \sigma_y = 11.6\,\text{mm}$

- Reliable measurement
- Can be used for beam tuning
- Measurement only at low duty cycle and low current (20 mA at 0.1%)

Run3 – Integrated Beam Time

Experiment with 3 kW beam power on a Be target

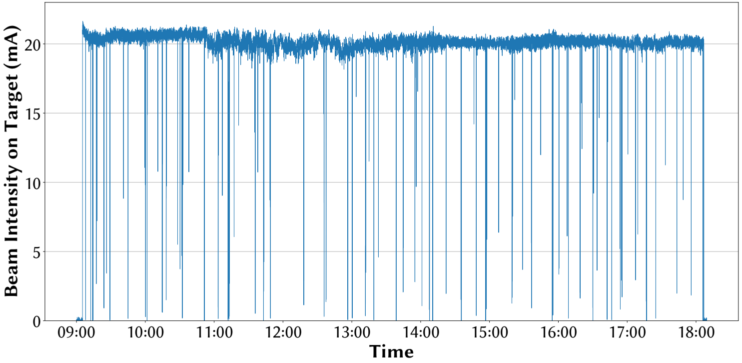
Beam during 19 days, 97 runs



- 62 hours with more than 1 kW beam power
- Total charge : 56.2 mA h
- 47.7 hours with more than 3 kW beam power
- 1.7×10^{20} protons/cm^2

Run 3 – Non-Stop Operation During One Day

Non-stop 9 hours run – 3 kW beam power on target



- Beam pulse: 2.85 ms
- Repetition rate: 17 Hz
- ECR source very stable
- a few sparks in the RFQ

Overview

Beam power of 50 kW on target →

Intensity 50 mA – duty cycle: 30%

Several challenges to increase the beam power

- RFQ commissioning at 30% duty cycle at full voltage
- Optimization of beam dynamics
- Improve the beam line
- New beam diagnostic to monitor the beam
- New target design
- Power density on target ¡ 500 W cm^{-2}

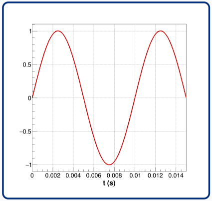
How to Limit the Beam Density on Target?

Beam rastering: several solutions

- Change beam density distribution (non-linear optics: hexapoles, octupoles)
- Moving target (mechanical rastering)
- **Target tilting by an angle α** (density decrease $\propto \sin\alpha$)
- **Beam deflection with sweeping magnet**

Target tilt by 20° in one plane.

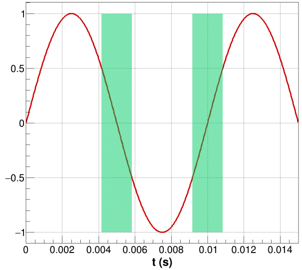
Target size increase $\approx$ factor of 3.



Magnetic sweeping in the other plane

$B \propto \sin(2\pi f_{sweep}\, t + \varphi)$

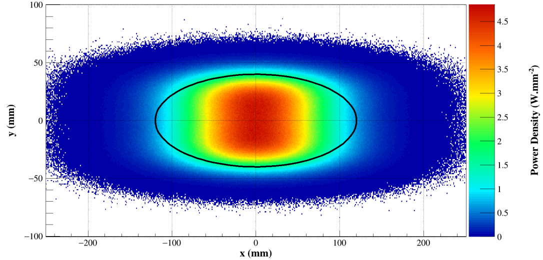
Beam Rastering with Sweeping Magnet
Synchronization



Sweeping signal for magnet

- Sweeping frequency : 100 Hz – Deviation angle ≈ 6.6 mrad (0.38°).
- Beam has to be synchronized with the sweeping signal: the linear part of the sinusoidal signal is used, 30 % of the time.
- Beam repetition rate: 200 Hz.

Beam Rastering with Sweeping Magnet
Beam density simulation results



Beam density on target. Maximum density ¡ 500 W cm^{-2}.

- Gaussian beam on target: $\sigma_x = 20$ mm – $\sigma_y = 10$ mm, balayé dans un plan (vertical).
- Tilted target in the horizontal plane ($\approx 19.5°$).
- Beam intensity: 51 mA, 30 % duty cycle – 51 kW beam power.

Overview

Conclusions and Perspectives

Conclusions

- IPHI beam commissioning has been done up to 7 kW beam power.
- IPHI is reliable enough to perform experiments of neutron production.
- Experiment with a 3 kW beam power on solid a Be target (56.2 mA h).
- Promising experimental results.

Perspectives

- Ramp-up IPHI duty cycle to 30 %.
- Experiment with a 50 kW beam power on target is foreseen.
- A lot of challenges are ahead of us: beam dynamics, diagnostics, target development, neutron simulations...
- Detailed accelerator design for SONATE.

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The Whole Team !

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