Space charge for LIPAc IPMs

LIPAc: Linear IFMIF Prototype Accelerator

J. Egberts, *J. Marroncle*

J. Egberts's PhD thesis defended on September 25th, 2012 at Orsay (France)

"IFMIF-LIPAc Beam diagnostics: Profiling and Loss Monitoring System"

http://irfu.cea.fr/Documentation/Theses/

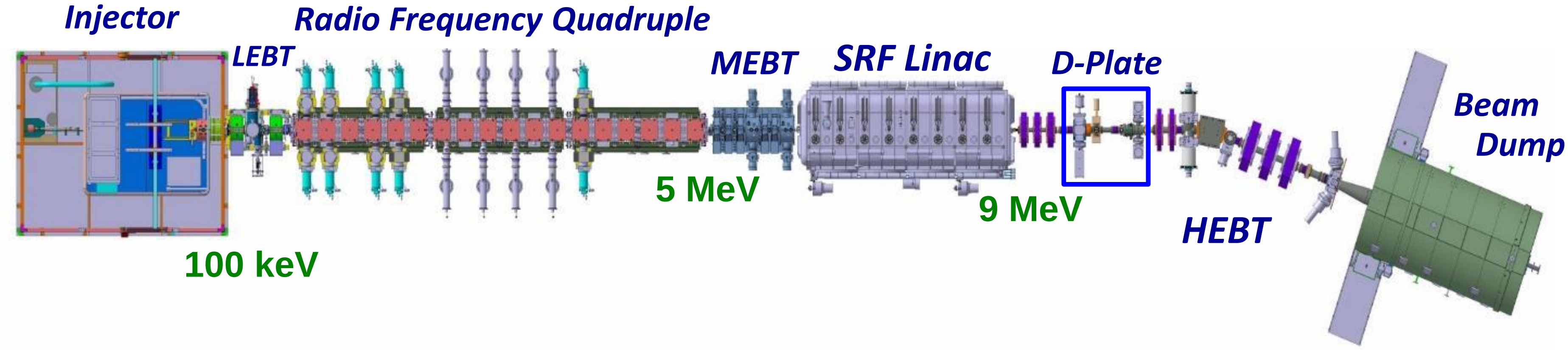
Presently working in d-fine group (consulting)

Overview

- LIPAc: a quick overview
- IPM prototype
  - Electric field homogeneity:
    - Design
    - tests at GSI
- Space Charge
  - Technique proposed for LIPAc:
    - SC algorithm
    - tests of the algorithm at CEA Saclay
- Summary

Accelerator: LIPAc

Linear IFMIF Prototype Accelerator



Rokkasho (Japan)

Deuteron beam

- → 9 MeV
- → I=125 mA cw
- → 1.125 MW
- → RF = 175 MHz (5.7 ns)

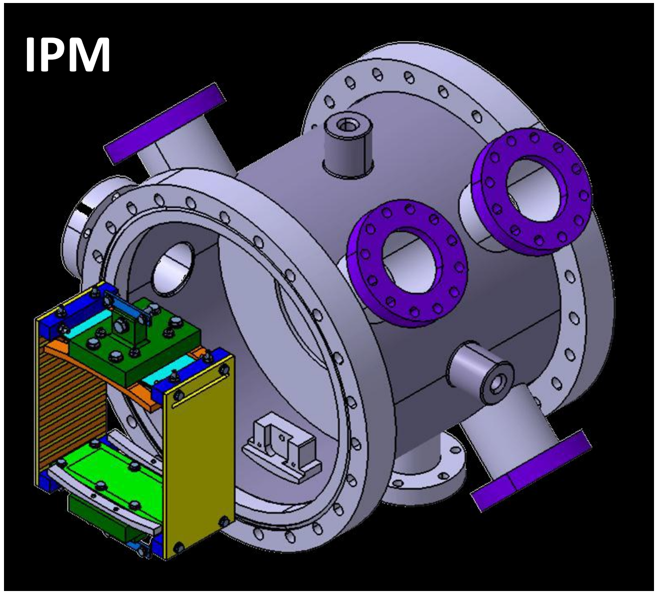
Present status of the commissioning

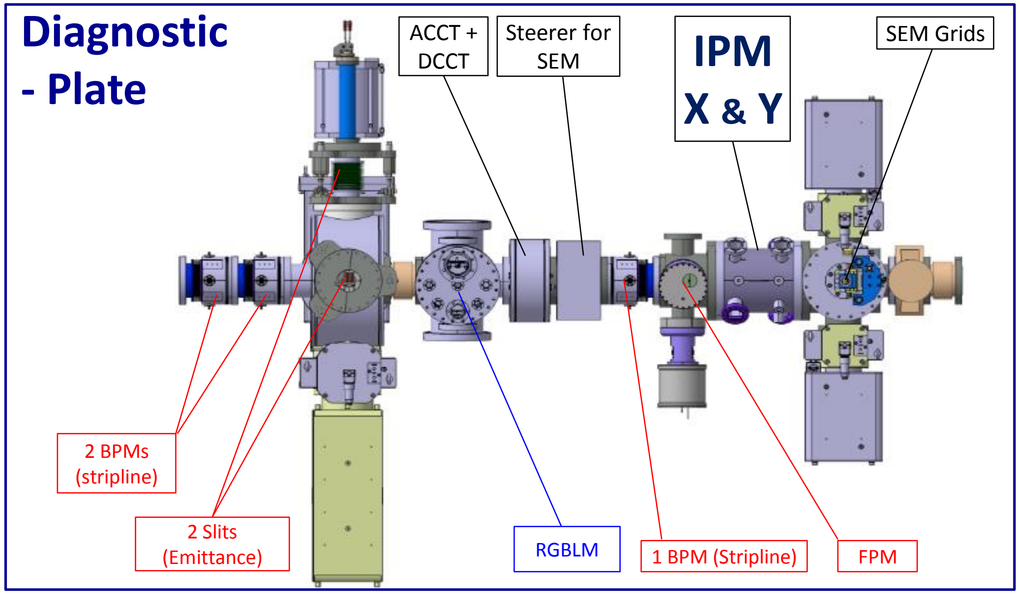
Proton & Deuteron injector commissioning: done

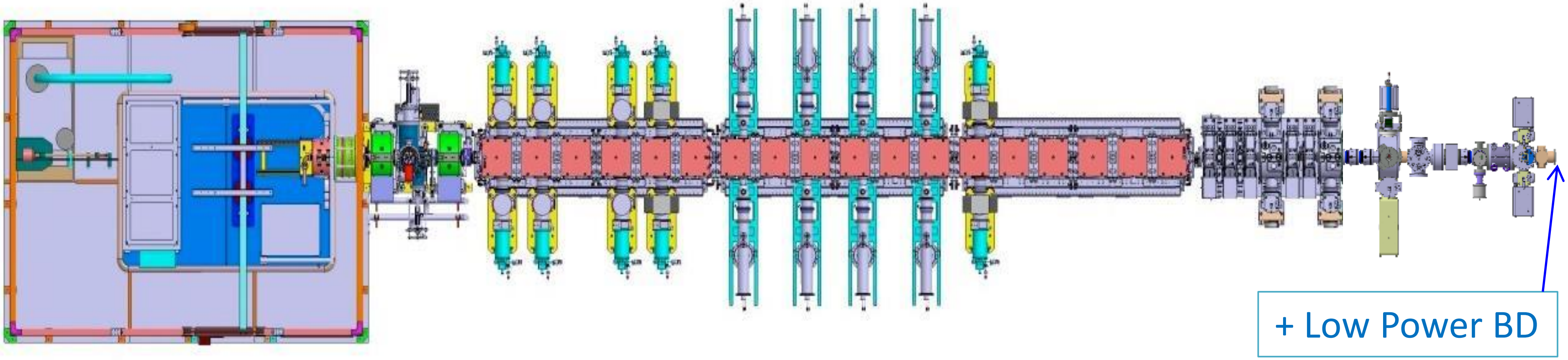
RFQ commissioning: starting in May 2016

→ IPM X&Y will be used in semester 2016 (5 MeV)

RFQ commissioning







SC processing for LIPAc

Hypothesis

- ionization by-products submitted to 2 electric field contributions
  1. IPM electric field applied on the IPM cage
  2. Space charge Electric field due to the beam contribution

Correction process

- transversal beam shapes describe by Generalized Gaussian distribution
- particle tracking in a realistic electric field IPM cage → generating profile distortions

→ Effect of distortions are determined and original profile can thus be reconstructed.

➔ roadmap of the presentation

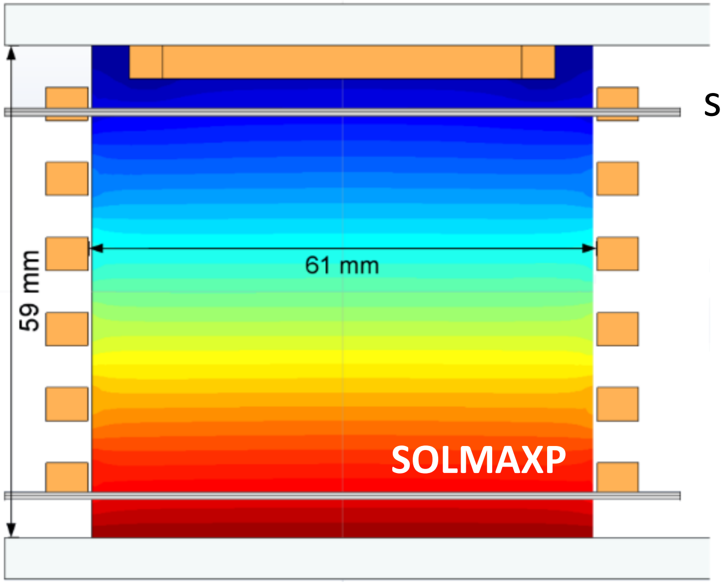
- electric field uniformity
- SC correction

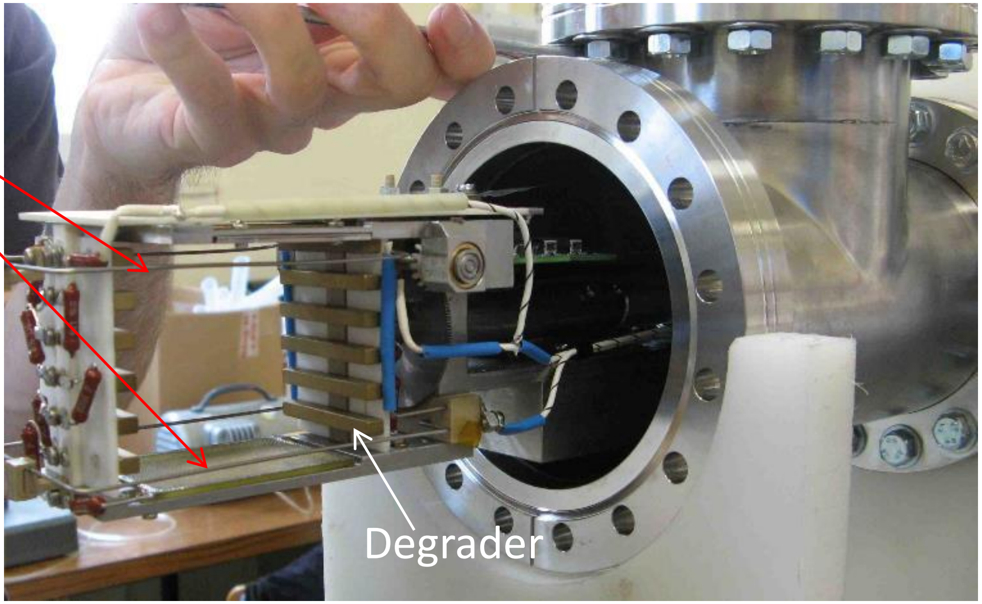
Electric field uniformity

IPM

"Small" prototype (aperture: 61 × 59 mm^2 - depth 40 mm)

- 32 strips for charge collection (pitch = 1.25 mm ➞ 40 mm active width)
- electric field uniformity ➞ Electric field simulation by FEM (SOLMAXP)
- lateral degraders (150 MΩ) + 1 spire on top and bottom to reinforce the E-field homogeneity
- movable slits in longitudinal direction for monitoring the active length of strips
- typical applied voltage ~ 5 kV ⇒ E = 833 V/cm





Electric field: FEM simulation

Finite Element Method

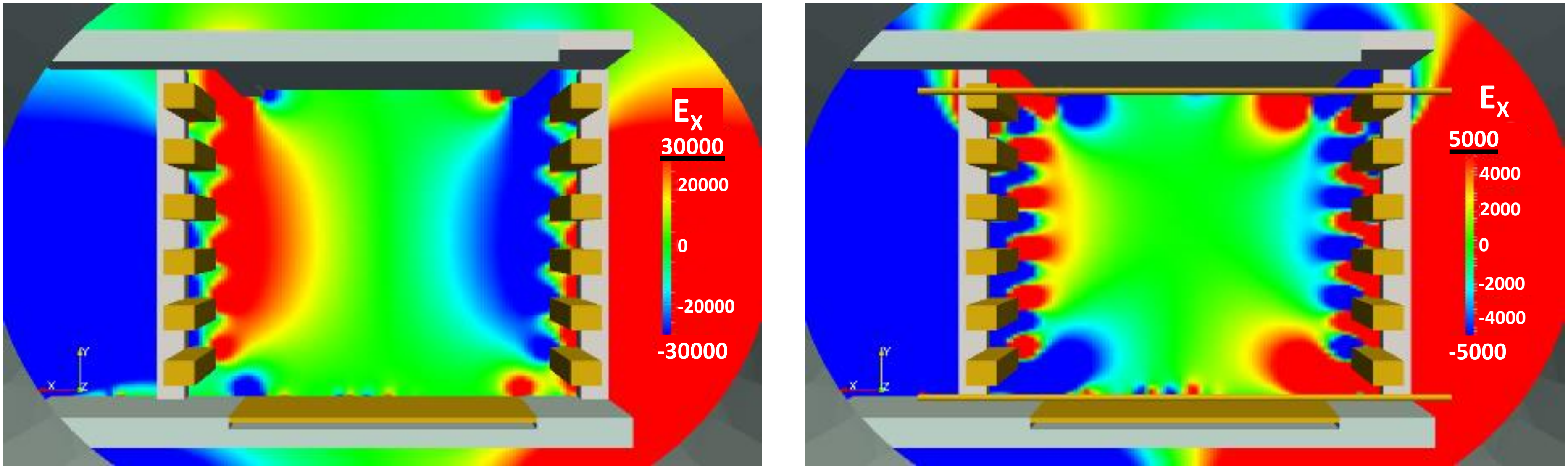
- SOLMAXP (R. Duperrier, CEA Saclay, Irfu/SACM)

E_x component (V/m) in the transverse plane of the IPM

- no spire ➞ inhomogeneity < 30%
- spire (copper loop) ➞ inhomogeneity < 3%

inhomogeneity < 30%

inhomogeneity < 3%

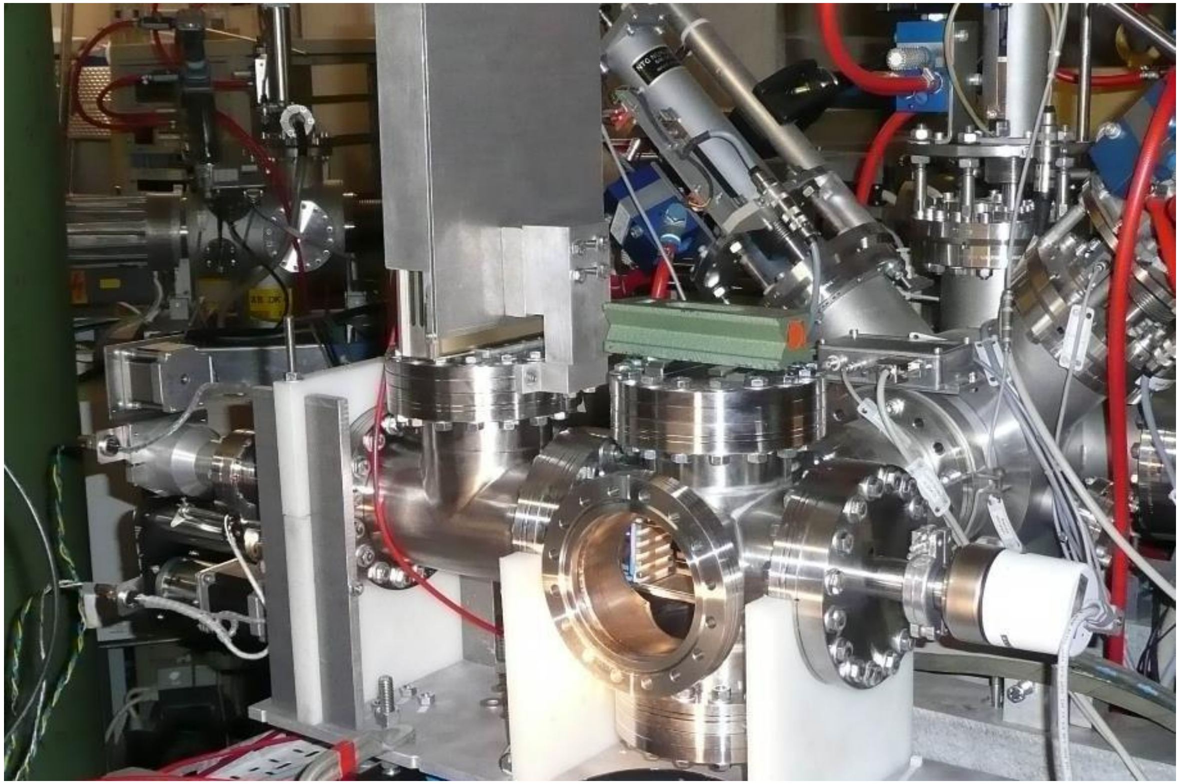


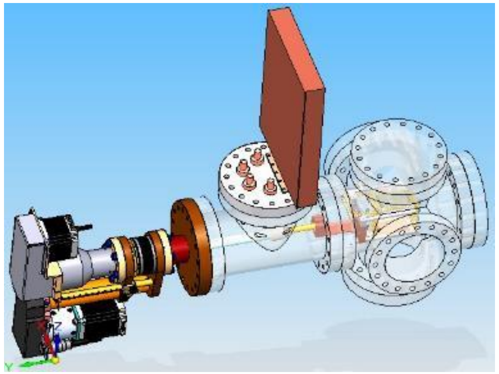
J. Egberts – April 2010

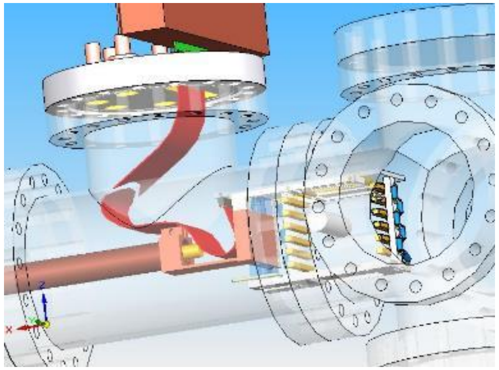
GSI test

Tests on the UNILAC of GSI (X2 branch devoted to GSI diagnostic team)

- ➞ May and November 2010
- ➞ examples of beam conditions:
  - 33 µA $^{48}\mathrm{Ca}^{10+}$ at 4.6 MeV/A @ 5ms/s
  - 1.6 mA $^{238}\mathrm{U}^{28+}$ at 4.8 MeV/A @ 100 µs/s
- ➞ Residual gas: adjustable pressure from 5 10^{-7} mbar to 5 10^{-5} mbar







Electric field uniformity (1)

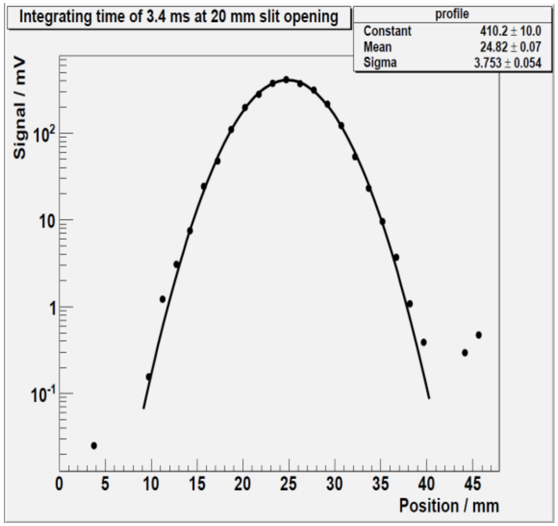
Beam conditions are kept frozen

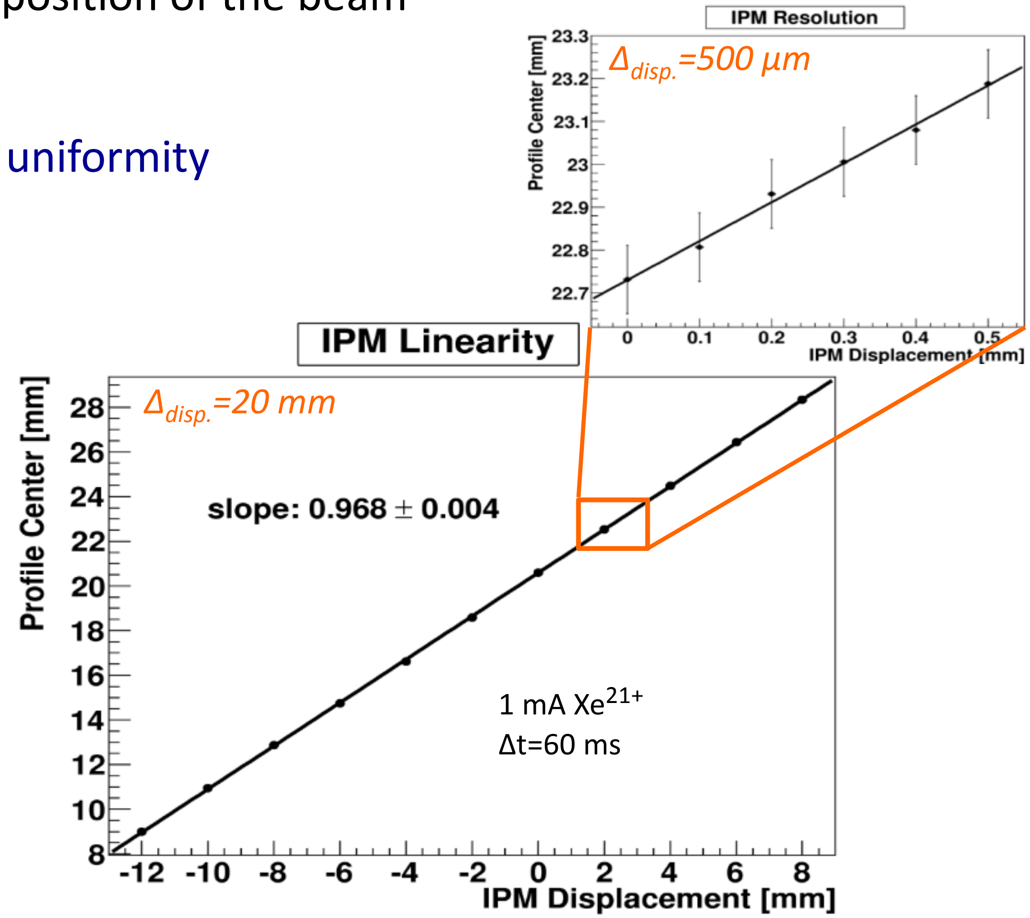
- Stepper motor → accurate transversal displacement of the IPM
- IPM → calculation of the central position of the beam

Very good linearity (slope ~ 1)

⇒ Good electric field uniformity

Beam profile measured with the IPM



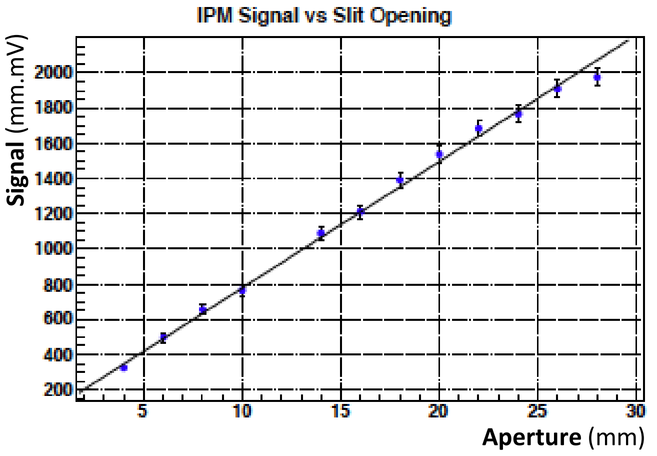


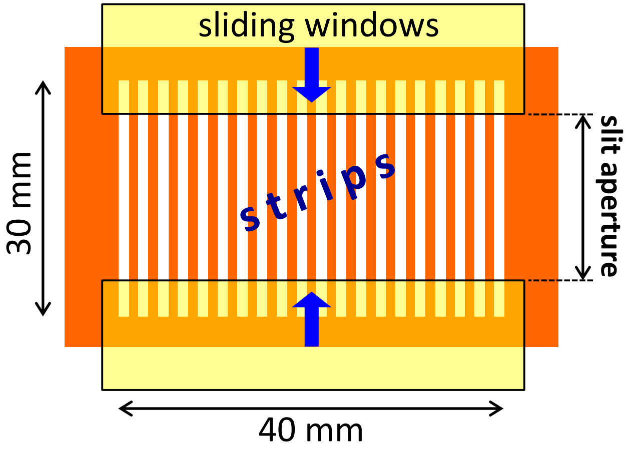
Electric field uniformity (2)

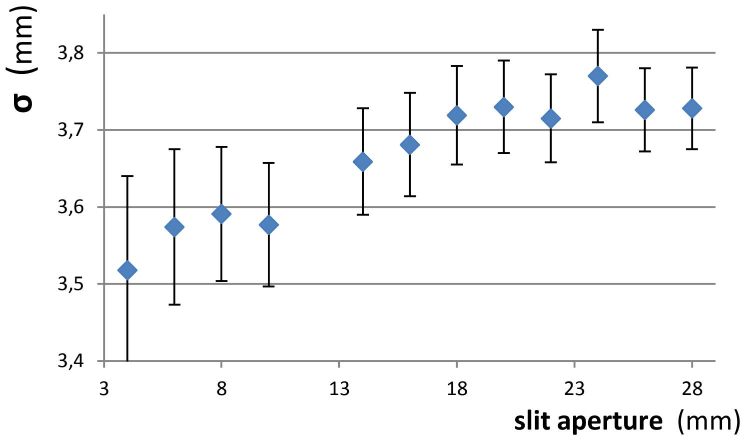
Aperture variation of the sliding window

- strip current rises linearly
- weak σ enlargement

  ⇒ due to field inhomogeneity or to tilted strips?







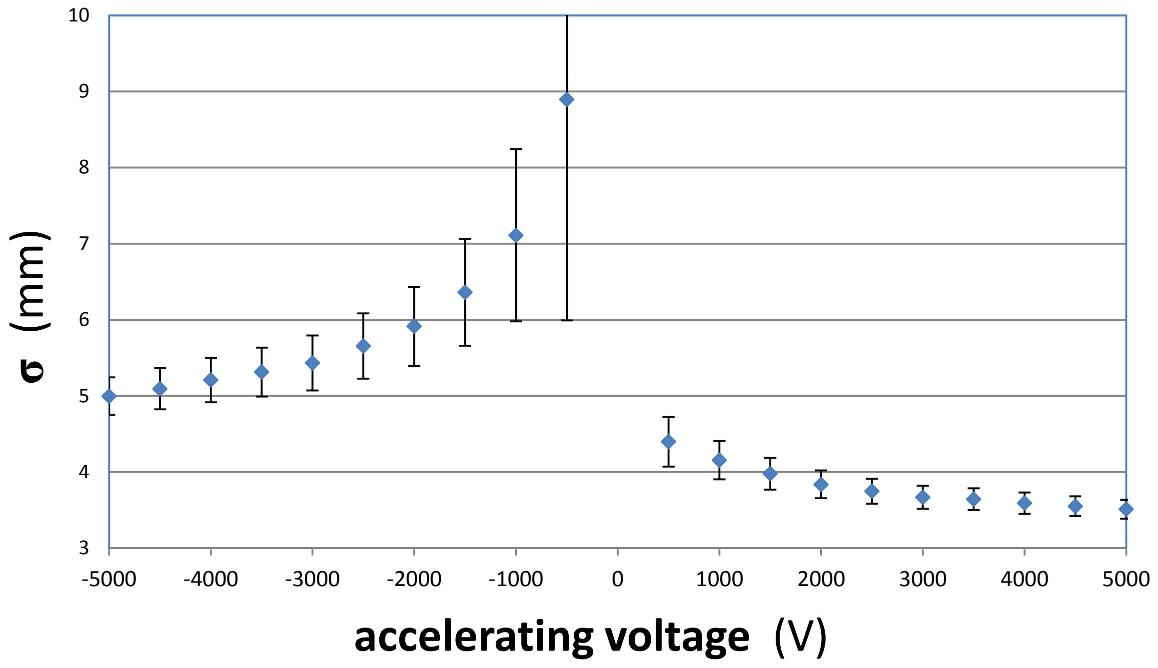
Conclusion: E field uniformity seems to be quite good on “inner” transverse plane

Profile width: electrons/ions

Accelerating Field

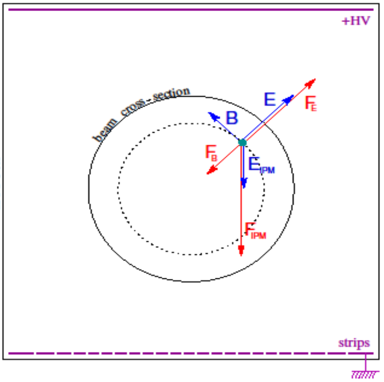
Profile width

- electron profile much broader than ion profile
- profile width decrease with higher voltages



Space Charge

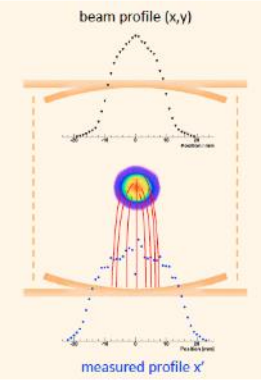
Space Charge effect → LIPAc



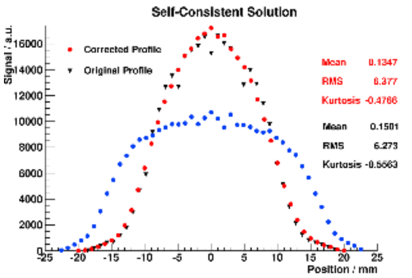
Ionization products experienced

- IPM electric field
- Beam electric field: **Space Charge**
  - ➞ GSI: low I ⇒ negligible effect
  - ➞ IPHI: high I, low E ⇒ big effect (profile distortion)

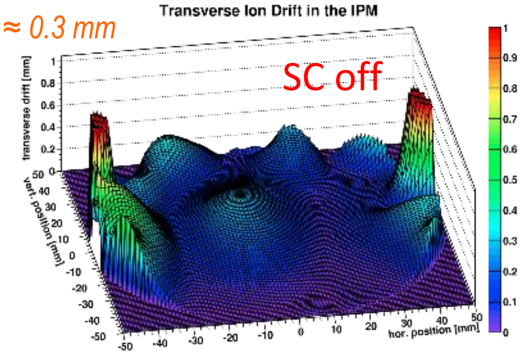
Theoretical



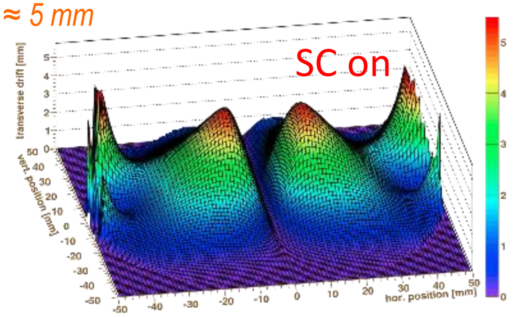
Profile reconstruction with an algorithm



$\Delta_{max} \approx 0.3$ mm



$\Delta_{max} \approx 5$ mm



How to counteract SC

- magnetic field for guidance ➞ no space available
- increasing the electric field ➞ limitation due to deviation
- applying correction with an algorithm (developed by Jan Egberts)

Space Charge Algorithm (1)

1- Hypothesis

- D^+
- round beam
- beam charge distribution described by a Generalized Gaussian Distribution (GGD) with no RF structure → Maxwell Gauss equation to evaluate $\vec{E}$(r)

2- Approach

- $\vec{\mathrm{P}}_{\mathrm{corrected}} = \mathrm{M} \otimes \vec{\mathrm{P}}_{\mathrm{measured}}$
- Matrix components M_{ij} represent the probability that an ion collected on strip j has been create at the position i

➞ beam distribution (GGD) & ions trajectories

- Set of matrices computed for various parameter combinations

  I_{beam}: 1 to 125 mA ➞ 35

  σ: 5 to 15 mm ➞ 21

  β: -0.25 to 0.25 ➞ 3

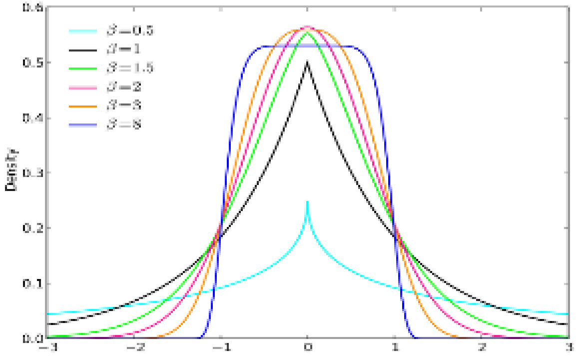
  HV: 1

  total matrices: 2205

Generalized Gaussian distribution

- μ: profile center
- Two degrees of freedom
  - σ: 2nd moment
  - β: kurtosis, 4th moment

$$p_{\alpha,\beta,\mu}(x)=\frac{\beta}{2\alpha\,\Gamma(1/\beta)}e^{-\left(\frac{|x-\mu|}{\alpha}\right)^{\beta}}$$

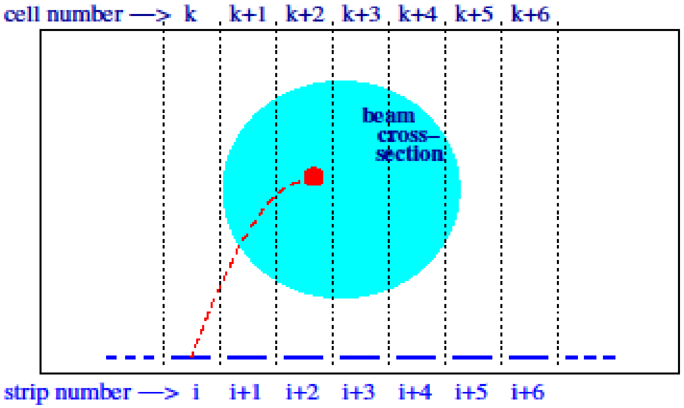


Note: Gaussian for β=2, with σ=α/2

Note

the drift of the ions in the electric field is simulated for evaluating the probability components of the Matrix.

$M_{k+2,i}$: probability that an ion emitted in k+2 cell is detected in i cell



Space Charge Algorithm (2)

3- First parameter to initiate iteration process

- fit of the experimental profile using a GGD to **extract**

  ➞ $\sigma_0 = \sigma_{exp}$
  ➞ $\beta_0 = \beta_{exp}$

  where I_{beam} is given by Current Transformers

- iterations

$$\vec{P}_1 = M(\sigma_{exp}, \beta_{exp}) \cdot \vec{P}_{Measured} \Rightarrow \sigma_1 \text{ and } \beta_1 \text{ extraction from } \vec{P}_1 \text{ fit}$$

$$\vec{P}_2 = M(\sigma_1, \beta_1) \cdot \vec{P}_1 \Rightarrow \sigma_2 \text{ and } \beta_2 \text{ extraction from } \vec{P}_2 \text{ fit}$$

…

$$\vec{P}_n = M(\sigma_{n-1}, \beta_{n-1}) \cdot \vec{P}_{n-1} \Rightarrow \sigma_n \text{ and } \beta_n \text{ extraction from } \vec{P}_n \text{ fit}$$

  until parameters converge ($\sigma_n \approx \sigma_{n-1}$; $\beta_n \approx \beta_{n-1}$) ➞ self consistent solution

- process is not a direct matrix product due to

  ➞ experimental fit quality
  ➞ σ and β are discrete quantities
  ➞ 2 variables

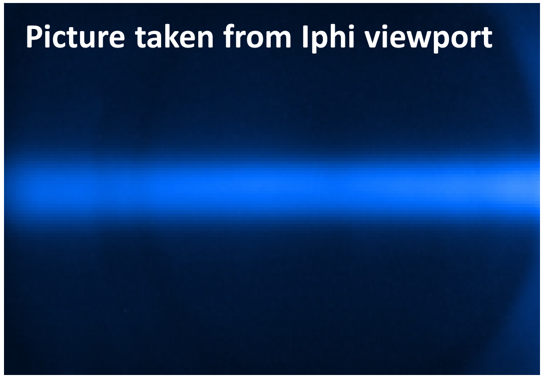
  but, iterating process is under control because the smaller σ_{final} the larger is σ_{exp} and anyway σ_{final} is always smaller than σ_{exp}

Algorithm test

Silhi source of Iphi (CEA Saclay)

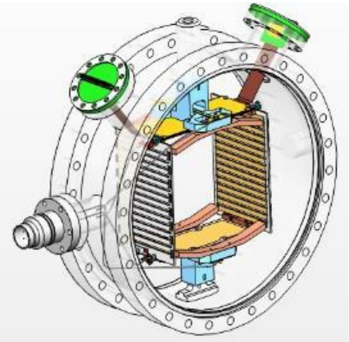
- protons
- dc: few 10^{-3} up to cw
- E_{max} = 95 keV
- I_{max} = 100 mA
- P ~ 6 10^{-5} Torr

Silhi: Source of Light Ions at High Intensity
Iphi: Injector of Protons at High Intensity



Picture taken from Iphi viewport

IPM was able to handle CW beam up to 21 mA.



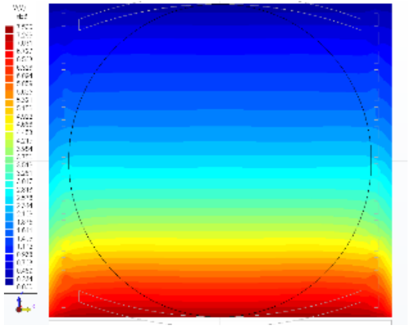
Large aperture: 15 × 15 cm^2

Degraders (16×2): 230 MΩ

➞ Lorentz-3D for electric field uniformity

FEE based on integrators; rate ≈ 10 Hz

HV_{max} = 16 kV



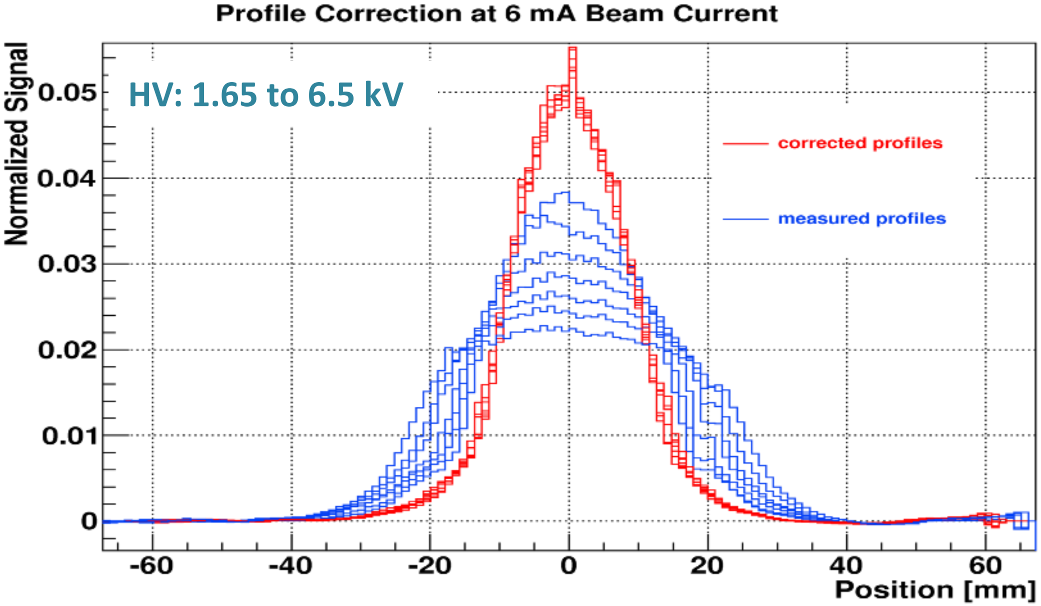
Algorithm test (2)

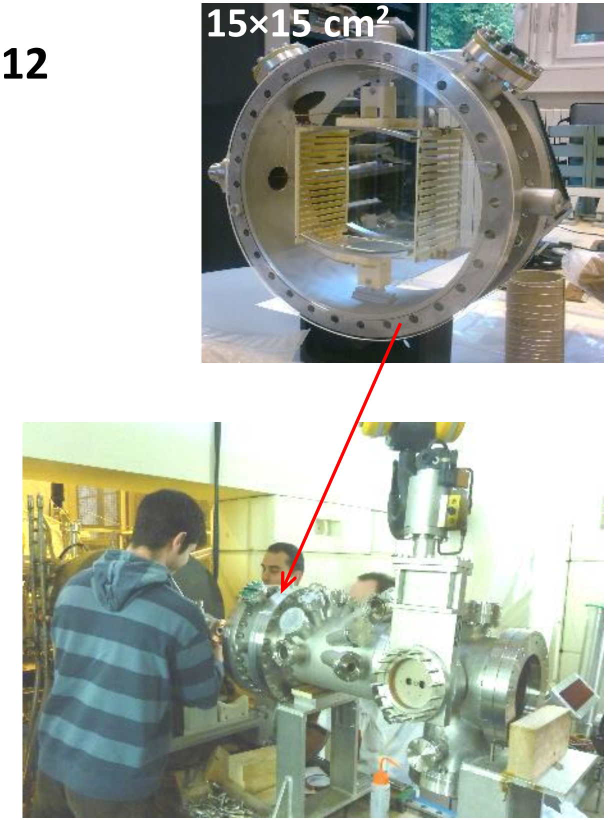
Tests done at Saclay on SILHI source: Dec. 2011 - Feb. 2012

proton $E_{max} = 90$ keV, $I_{max} = 6$ mA

Main test: SC algorithm

- frozen beam characteristics (conditions)
- only variation of extracting field





Summary

Good electric field uniformity was achieved for LIPAc IPMs

SC effect

an algorithm to correct SC was developed and tested with promising results

Nevertheless, mathematical algorithm like the one developed by Cyrille would be the solution firstly foreseen for ESS IPMs

Question: electrons or ions → simulation to reproduce beam size?

Thanks to:

CEA Saclay colleagues

P. Abbon, J.F. Denis, ***J. Egberts***, J.F. Gournay, F. Jeanneau, J.P. Mols, T. Papaevangelou, H. Przybilski

GSI diagnostics group and UNILAC GSI people

SILHI – IPHI group at CEA Saclay

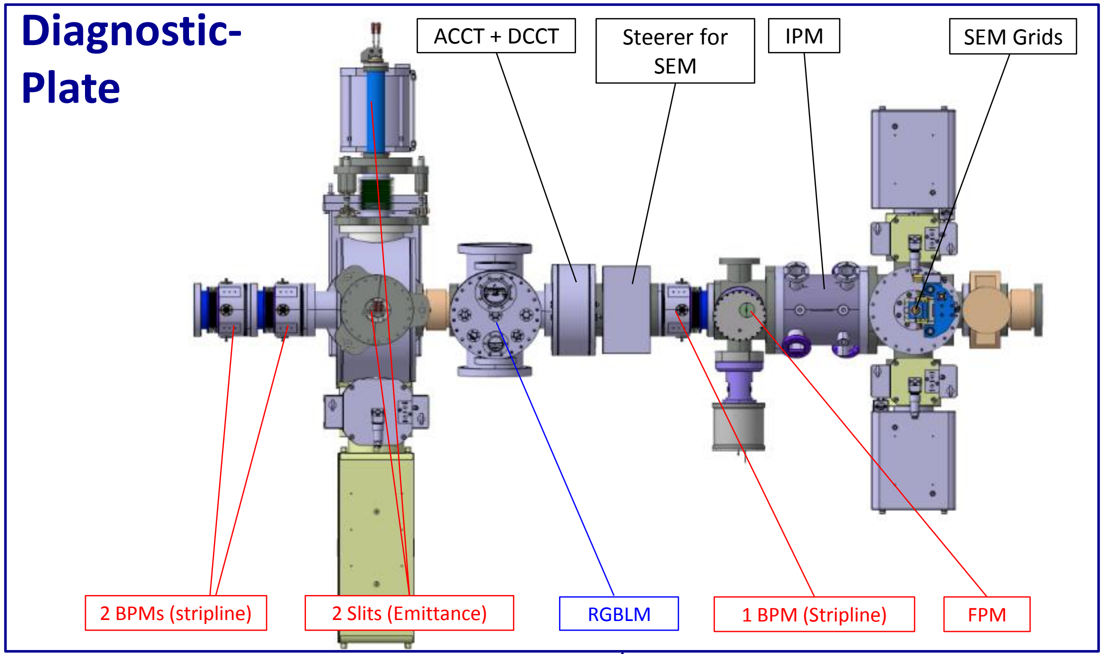
Thank your for your attention

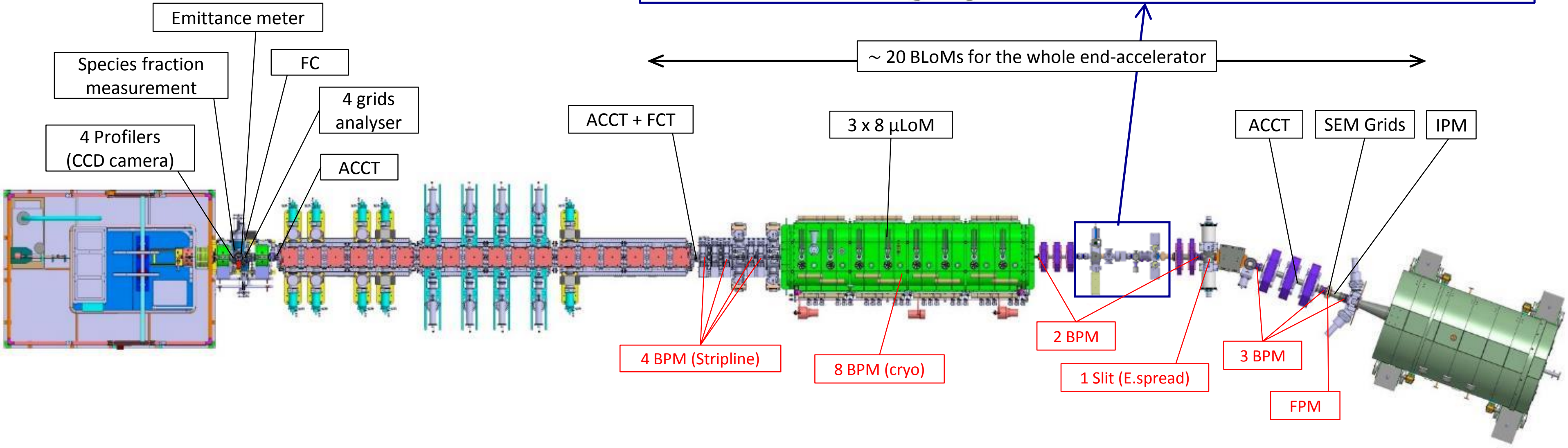
Extra slides

LIPAc diagnostics

<u>Glossary:</u>

ACCT: AC Current Transformer
BLoM: Beam Loss Monitor
RGBLM: Residual Gas Bunch Length Monitor
BPM: Beam Position Monitor
DCCT: DC Current Transformer
FC: Faraday Cup
FFC: Fast Faraday Cup
FCT: Fast Current Transformer
IPM: Ionization Profile Monitor
FPM: Fluorescence Profile Monitor
µLoM: Micro Loss Monitor





IFMIF

$E_{deuteron}$ = 40 MeV

I_{beam} = 2 × 125 mA

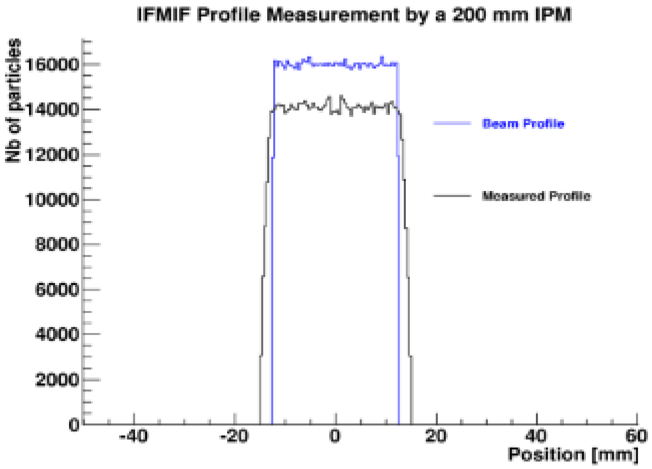
HV = 12 kV

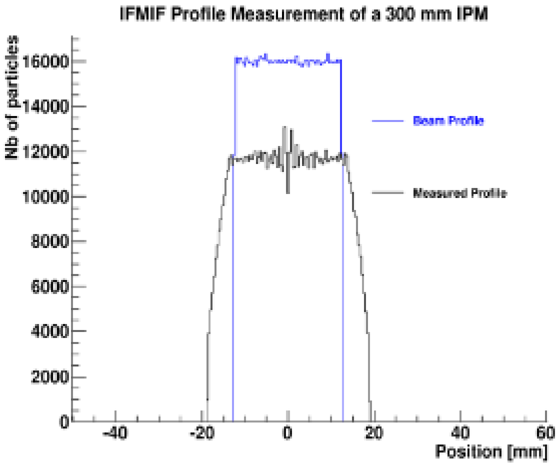
Assumption:

- perfect electric field uniformity ➞ IPM with a large depth
- beam cross section: 25 × 100 mm^2

⇒ Space charge effect for IPM aperture:

- 200 mm (left)
- 300 mm (right)

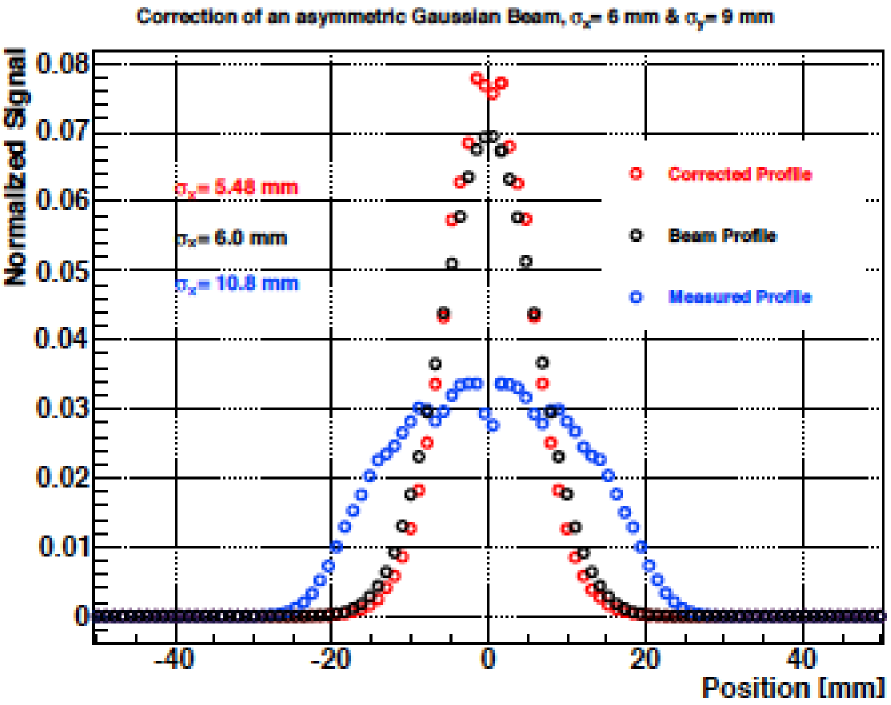

IFMIF Profile Measurement by a 200 mm IPM


IFMIF Profile Measurement of a 300 mm IPM

SC for Asymmetric beam

σ_x = 6 mm - σ_y = 9 mm

Search algorithm find profile with a $\sigma_x^{reconstructed}$ = 5.5 mm



Profile comparison IPM / FPM

Extracted from « GSI SCIENTIFIC REPORT 2010 »

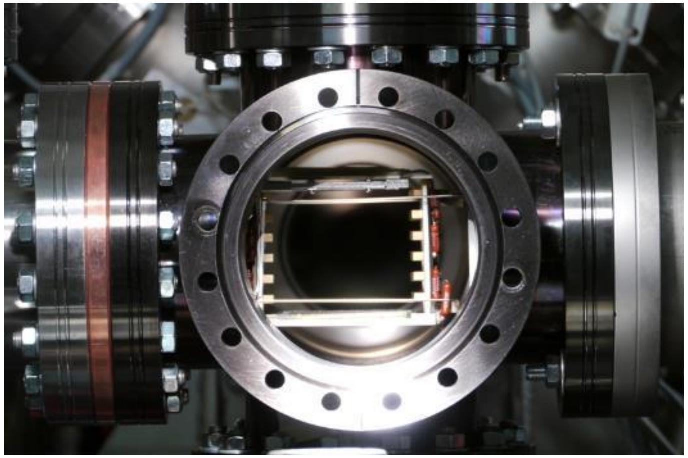
Characterization of a Non-Intensified Ionization Profile Monitor @ UNILAC

F. Becker[1], C. Andre[1], T. Giacomini[1], P. Forck[1], B. Walasek-Höhne[1], P. Abbon[2], J. Egberts[2], F. Jeanneau[2], J. Marroncle[2], J.-P. Mols[2], T. Papaevangelou[2]
[1]GSI, D-64291 Darmstadt, Germany; [2]Centre CEA de Saclay, F- 91191, France

At the same location (cross):

- IPM on 1 port
- FPM or BIF on a port at 90°

Note, walls were blackened to avoid reflection for CCD



FPM: Fluorescence Profile Monitor
BIF: Beam Induced Fluorescence

Comparison of BIF and IPM Profiles in Different Gases