Beam Diagnostics for the IFMIF / LIPAc Accelerator

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Outline

- IFMIF / LIPAc Accelerators
- Beam Loss
    - Ionization Chamber
    - CVD Diamond
- Transverse Beam Profiling
    - Ionization Profile Monitor
- Conclusion

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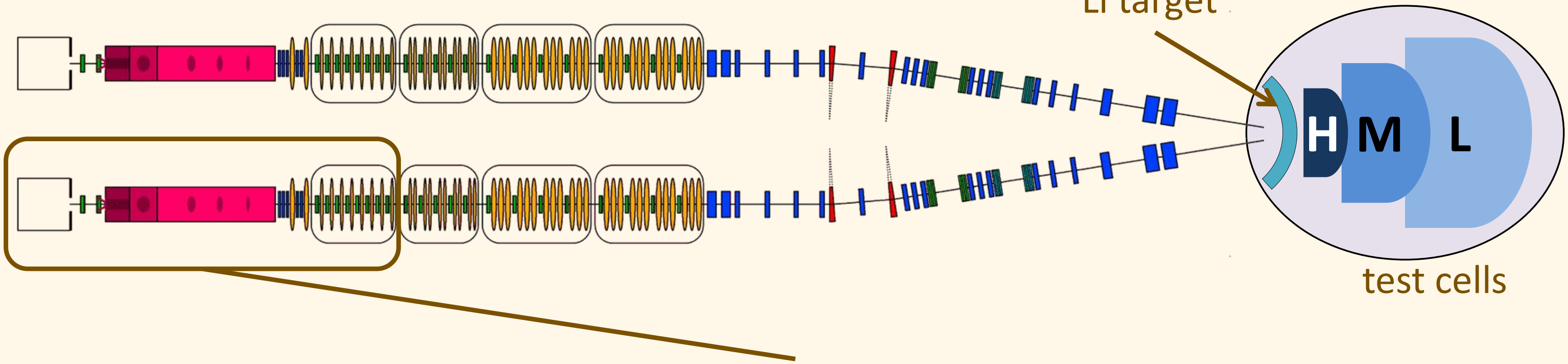
LIPAc: *Linear IFMIF Prototype Accelerator*

IFMIF: *International Fusion Material Irradiation Facility*

IFMIF:

- Beam current: **2 x 125 mA** cw deuterium
- Energy: **40 MeV**
- Beam power: **2 x 5 MW**



LIPAc: Prototype limited to **1 x 125 mA** cw @ **9 MeV, 1.125 MW**

Diagnostics developed by **CIEMAT Madrid, INFN Legnaro, and CEA Saclay**

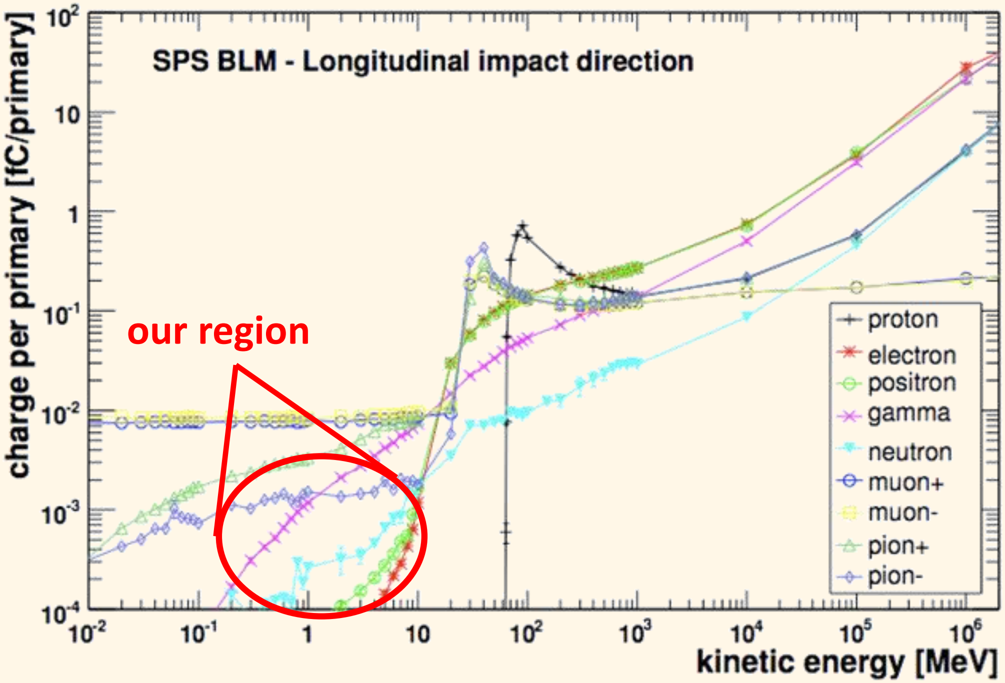
Beam Loss - Ionization Chamber (IC)

Designed for LHC:

- high sensitivity at high energies
- low sensitivity at low energies

Approach to tune IC:

- neutron capture by Boron 10
- replace fill gas by BF3
- wrap IC with CH2 to thermalize neutrons



GEANT4 simulation performed at CERN by Markus Stocker

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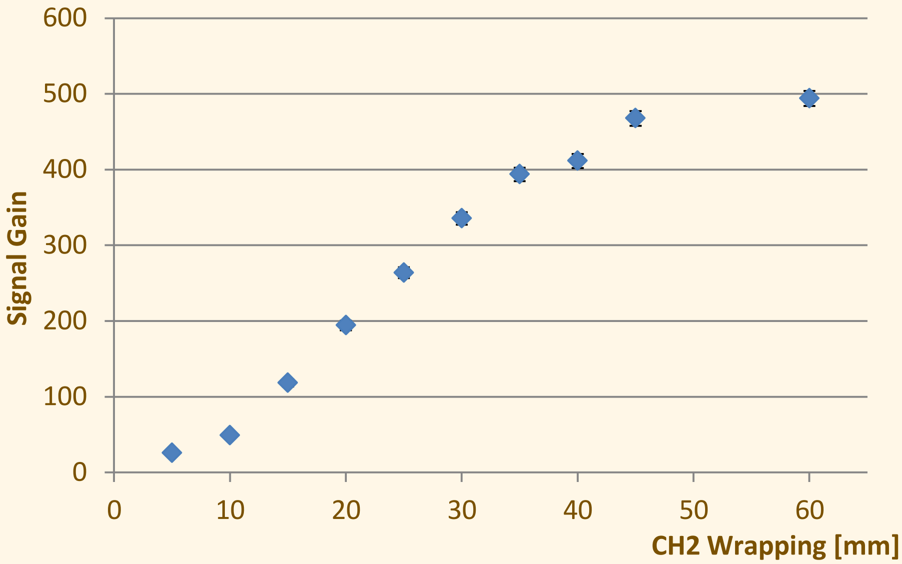
Beam Loss - Ionization Chamber (IC)

Geant4 simulation results:

- BF3 works well for low energy neutrons
- IC signal increased with CH2 wrapping
- potential signal gain: ~ 100 ☺ ☺ ☺



Issues:

- BF3 is highly toxic… ☹
- BF3 is corrosive… ☹ ☹
- bad combination… ☹ ☹ ☹

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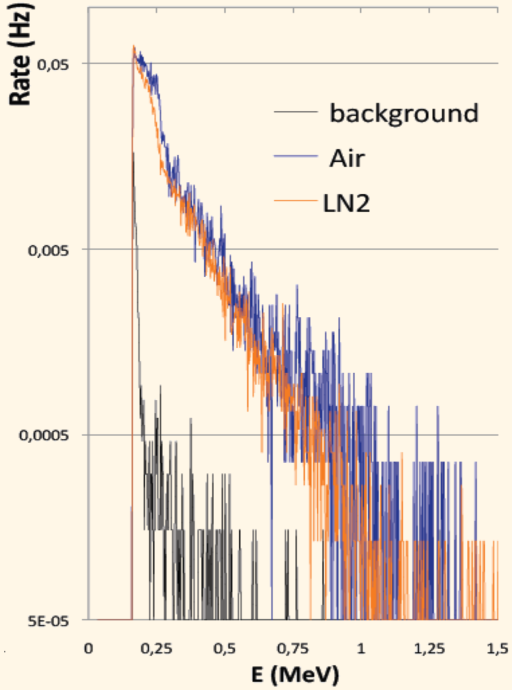
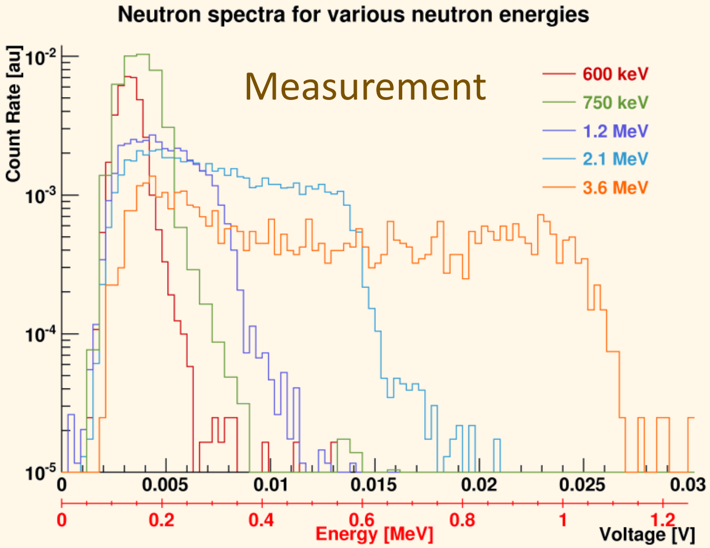
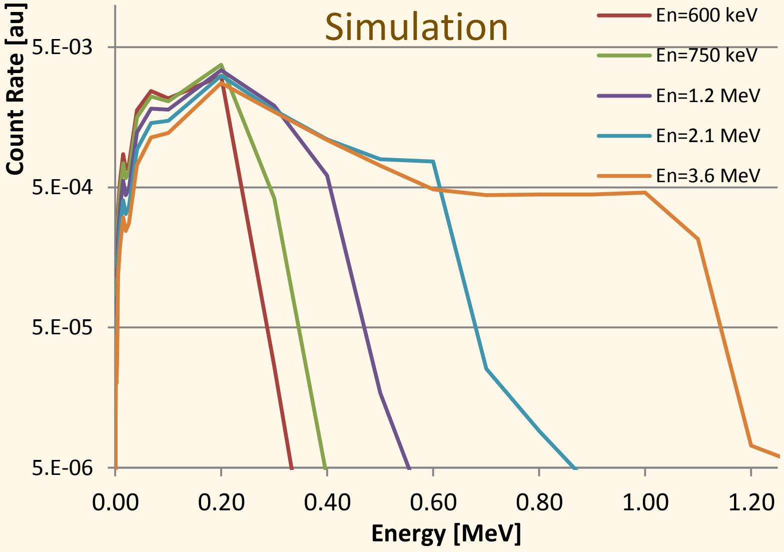
Beam Loss – CVD Diamond

- sCVD diamonds to be placed in the cryostat
- Tested at liquid nitrogen and helium
- Calibrated at ambient temperature for neutrons







Simulation done by Anthony Marchix, CEA Saclay

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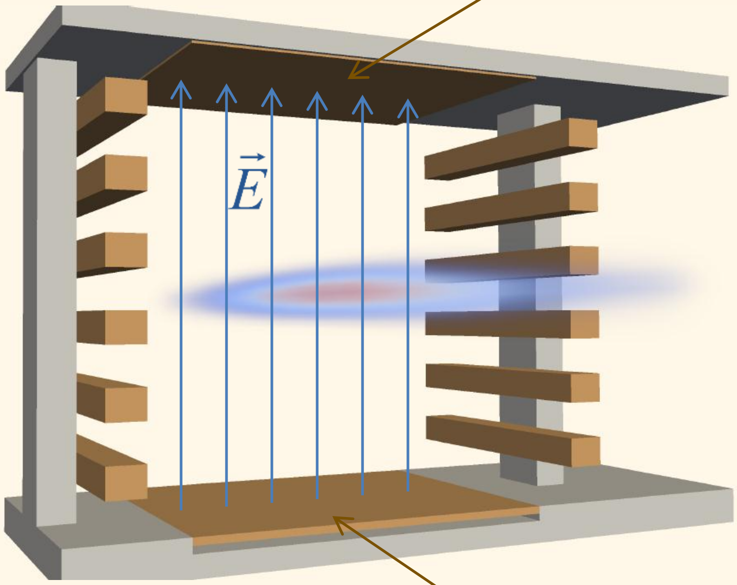
Transverse Profiling - IPM

Principle of Operation:

- Beam ionizes residual gas
- Electrons / ions are extracted by E-field
- Beam profile derived from ionization current



Intrinsic issue:

- Ionization must NOT change its profile
  ⇒ **Uniform extraction Field required!**

LIPAc Challenges:

- Limited space
  ⇒ Compact design (wrt. large aperture)
- High background radiation (~7 kSv/h close to the beam dump)

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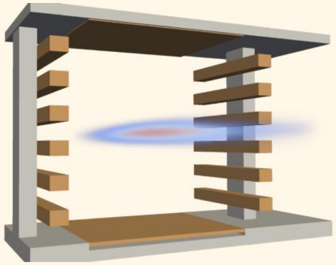
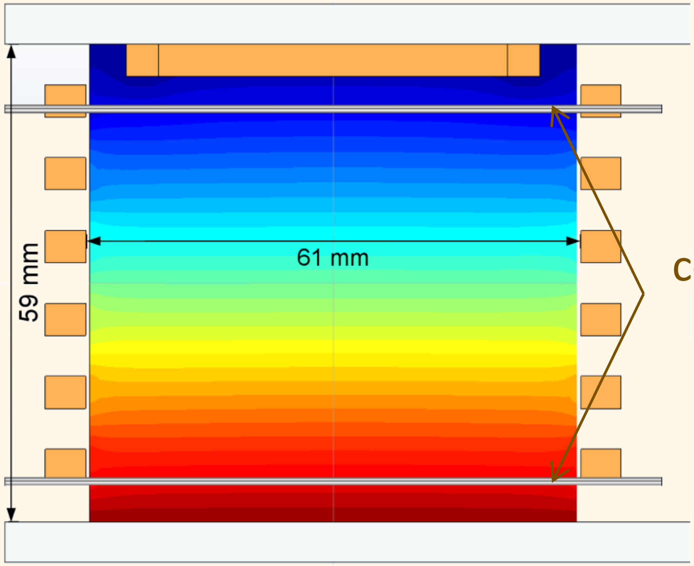


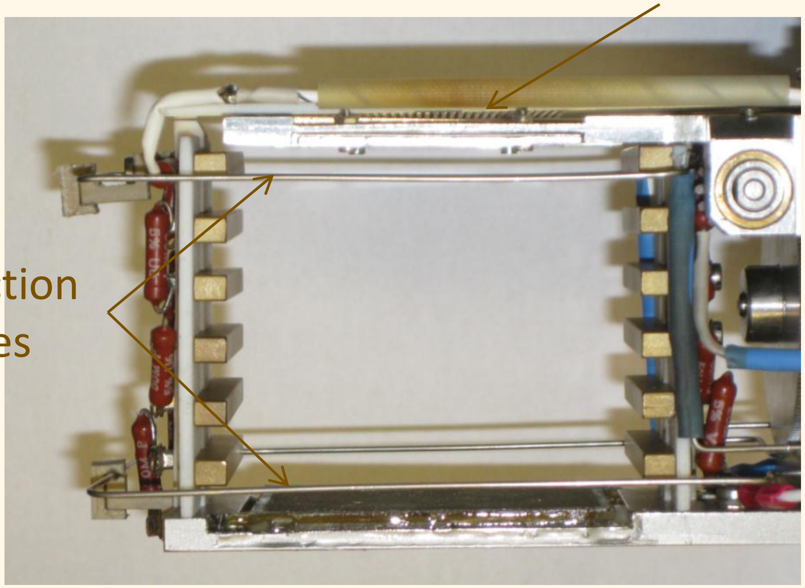
IPM Prototype Design

- Charge collected on 32 strips with 1.25 mm pitch
- Prototype designed based on FEM E-field simulations*
- Internal dimensions: 61 mm x 59 mm x 40 mm
- Voltage applied: 5000 V (E = 833 V/cm)
- Tested at GSI and CEA Saclay



correction wires

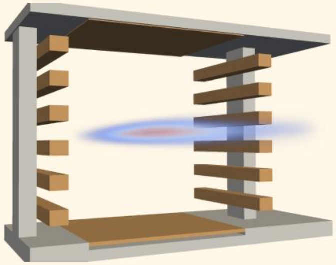
read-out strips



*Lorentz-E Particle Trajectory Solver Copyright © 1998 - 2010 Integrated Engineering Software Sales Inc.

Transverse Profiling - IPM

BIF Comparison

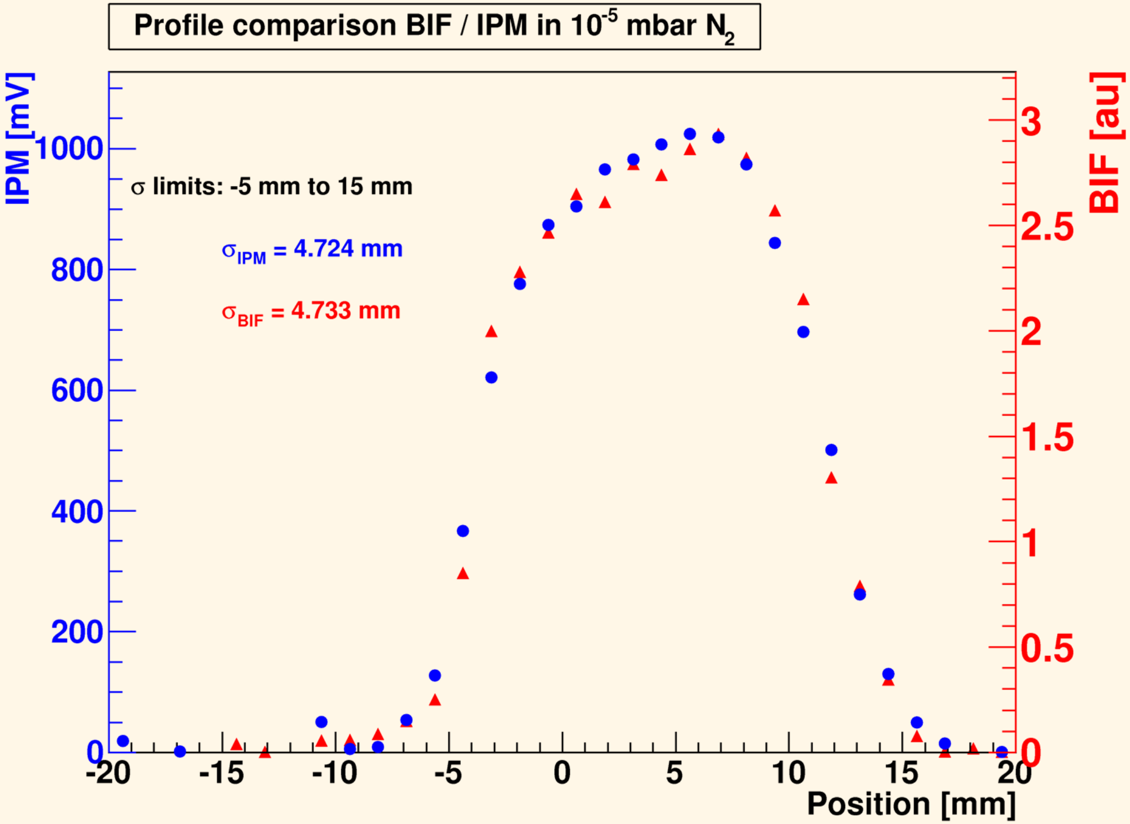


10^{-5} mbar N_2

BIF: Beam Induced Fluorescence

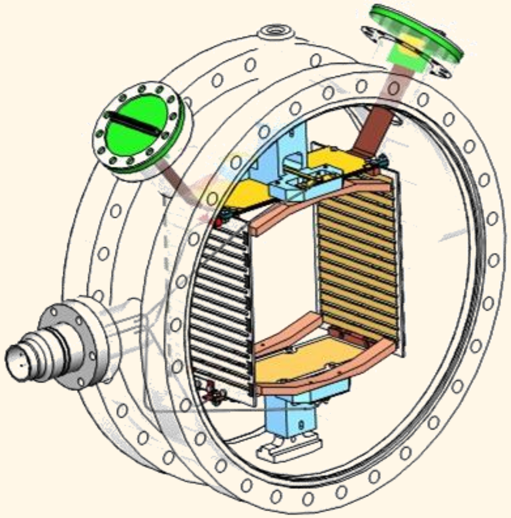
BIF Monitor based on light emitted by atoms excited by the beam

BIF profiles acquired by *Frank Becker, GSI*



Beam: 1 mA Xe^{21+}

Transverse Profiling - IPM

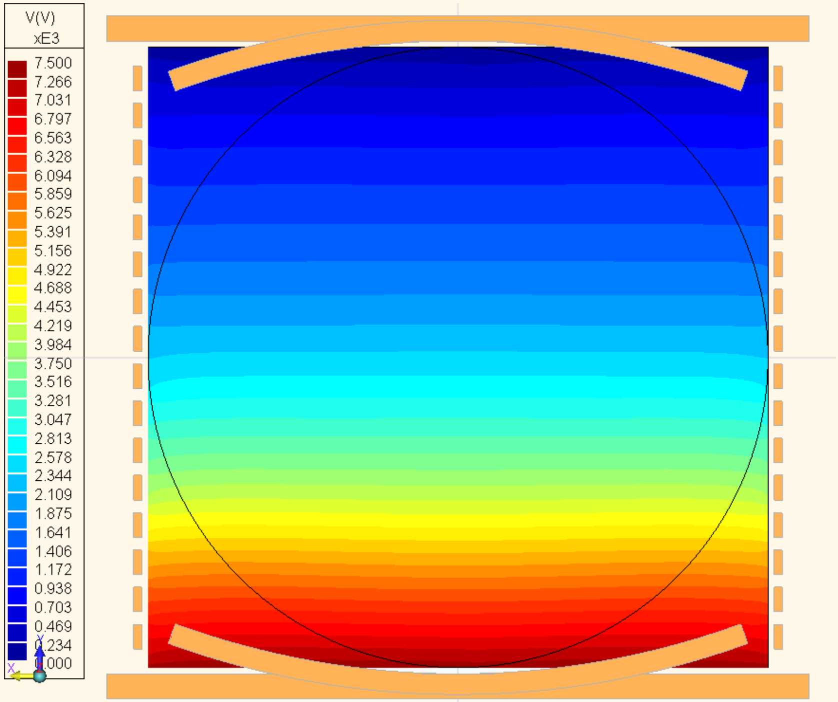


Final Design Challenges:

- ❖ High radiation level ⇒ radiation hard components exclusively
- ❖ Lack of space ⇒ very compact design required

Design results:

- ❖ Depth of 100 mm with an aperture of 150 mm
- ❖ E-field uniform within ~ 3%



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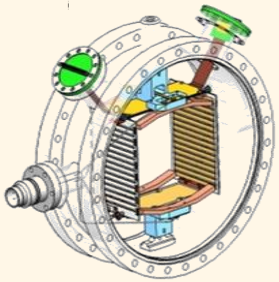
Particle Tracking – Ion Displacement



Neglecting Space Charge Effect!

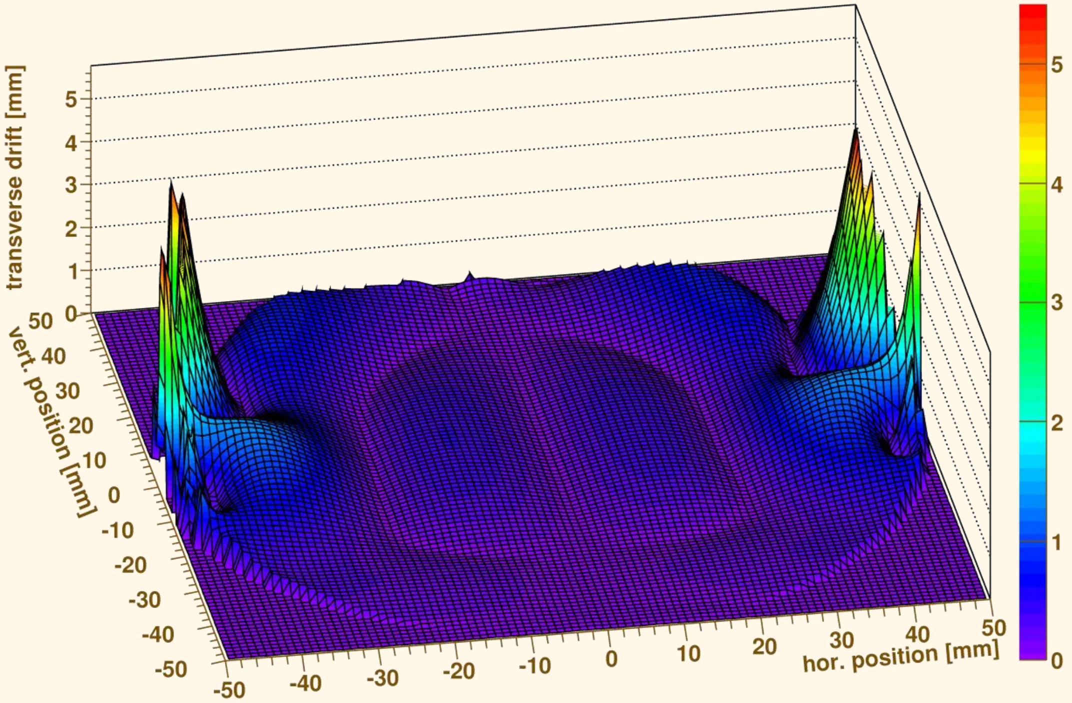
Particle Tracking:

Transverse displacement during ion drift versus starting position

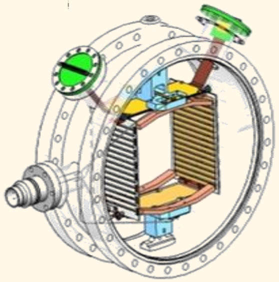
In beam region:

Displacement < 500 µm

Simulation of the Transverse Ion Drift in the el. Field



Particle Tracking – Ion Displacement



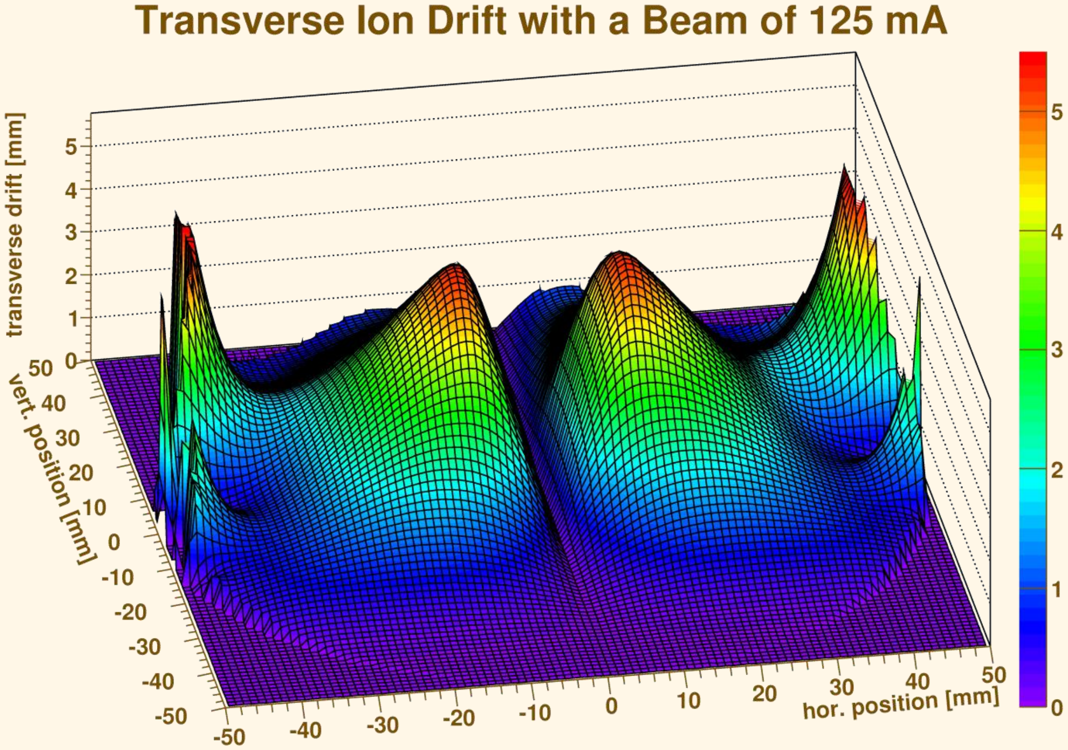
Space Charge for 125 mA Beam

Particle Tracking:

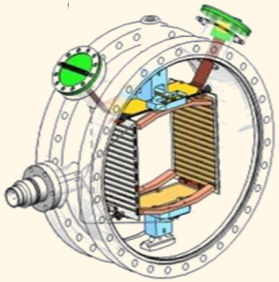
Transverse displacement during ion drift versus starting position

With space charge of 125 mA:

Displacement > 5 mm



Transverse Profiling - IPM



Simulation beam profile measurement:

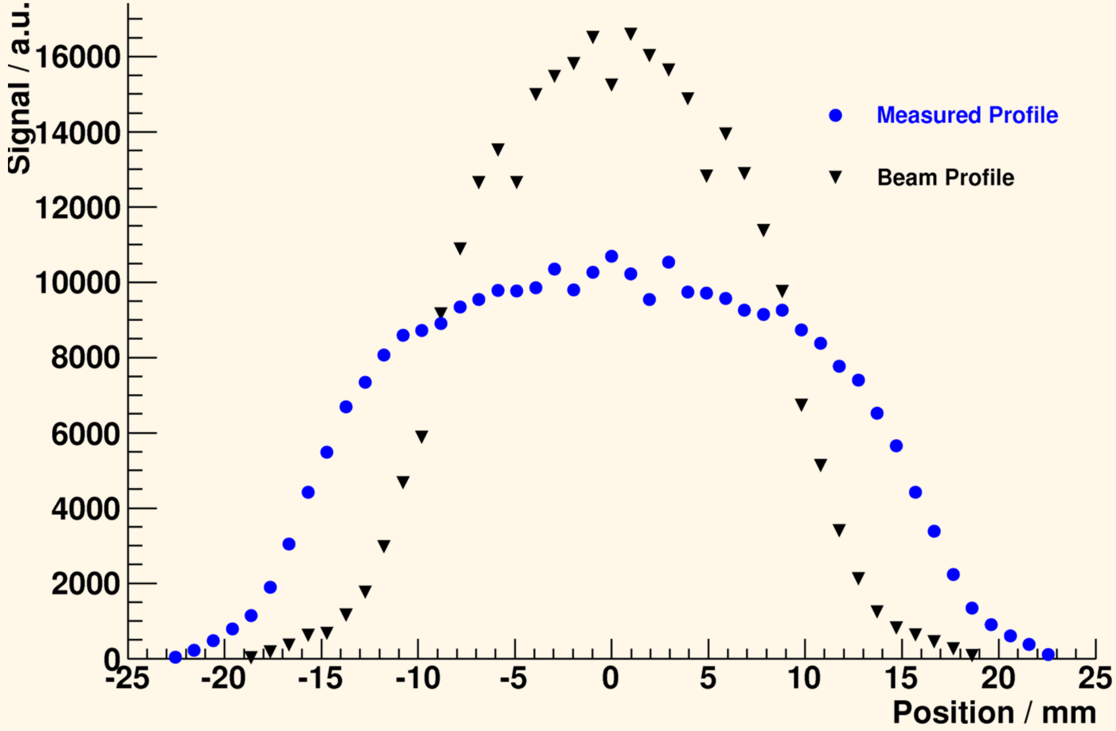
Resulting Profile:

Strong Distortions due to

Space Charge

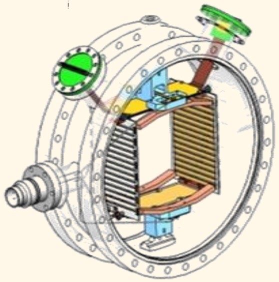
original beam profile

measured profile (simulation)



Approach: Correction Algorithm to compensate Space Charge…

Transverse Profiling - IPM

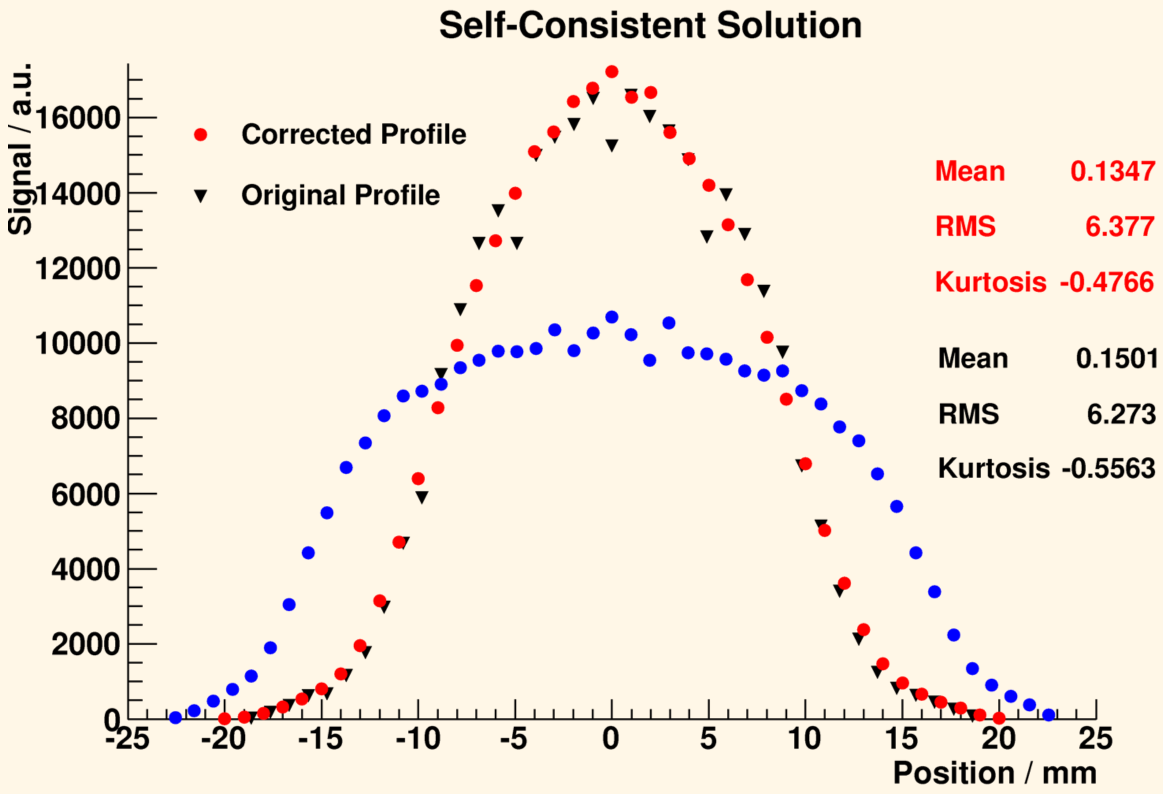


Example of a self-consistent solution:

corrected beam profile

original beam profile

measured profile (simulation)



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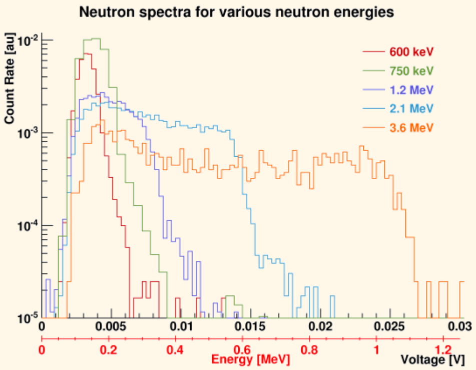
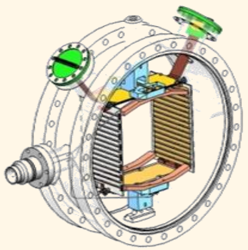
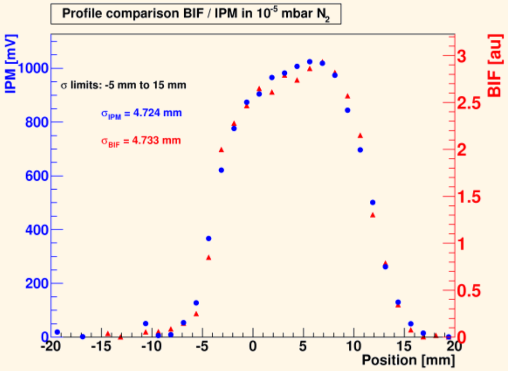
Conclusion

- LHC IC as beam loss monitor
    - Possibility to increase IC neutron sensitivity, if necessary
- CVD diamond in Cryostat
    - Tested at cryogenic temperatures
    - Calibrated for neutrons
- IPM as transverse profiler
    - Tested at GSI
    - Tested at CEA Saclay
    - Algorithm for space charge compensation

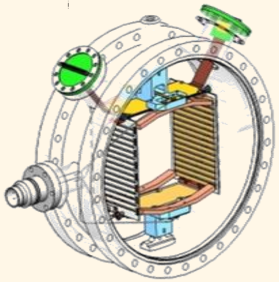






Backups

Particle Tracking – Ion Displacement



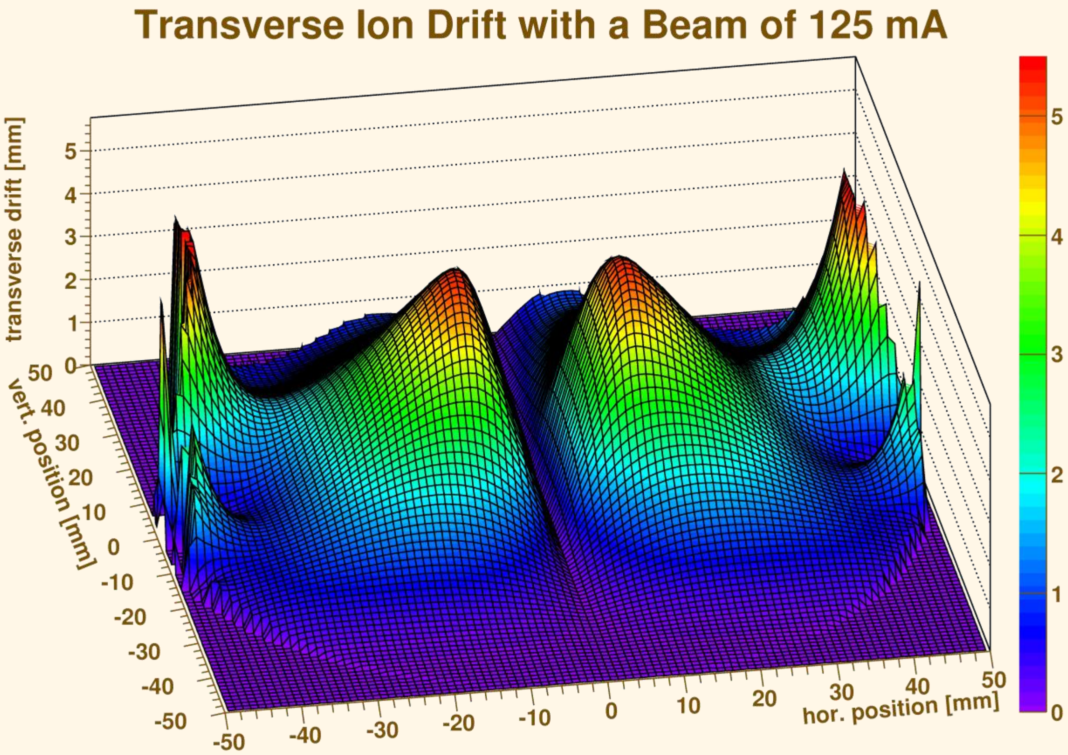
Space Charge for 125 mA Beam

Particle Tracking:

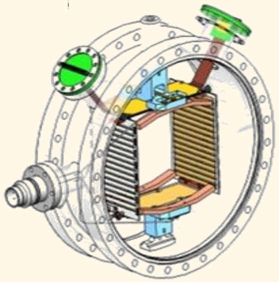
Transverse displacement during ion drift versus starting position

With space charge of 125 mA:

Displacement > 5 mm



Particle Tracking – Ion Displacement

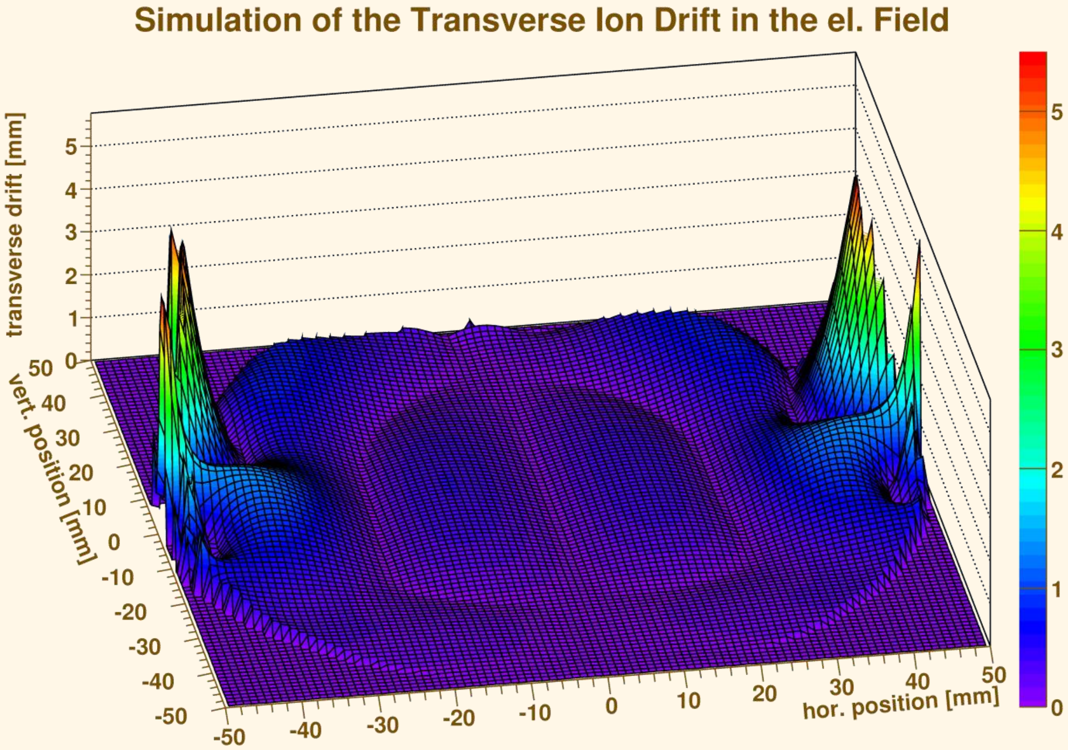


Neglecting Space Charge Effect!

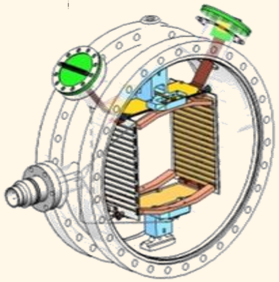
Particle Tracking:

Transverse displacement during ion drift versus starting position

Tracking w/o space charge in same scale!!!



Correction Algorithm



How to find the proper beam distribution?

Idea:

Vary test distribution until self-consistent solution is found!

Possible criteria for self-consistency:

- ~~Beam position (1. distribution moment)~~ unaffected by space charge
- *RMS (2. distribution moment)* ☺☺☺
- ~~Skewness (3. distribution moment)~~ expected to be zero
- *Kurtosis (4. distribution moment)* ☺☺☺

→ <u>two</u> degrees of freedom!

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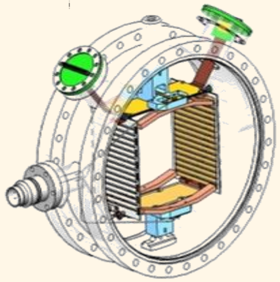
Correction Algorithm



What could be a proper test distribution?

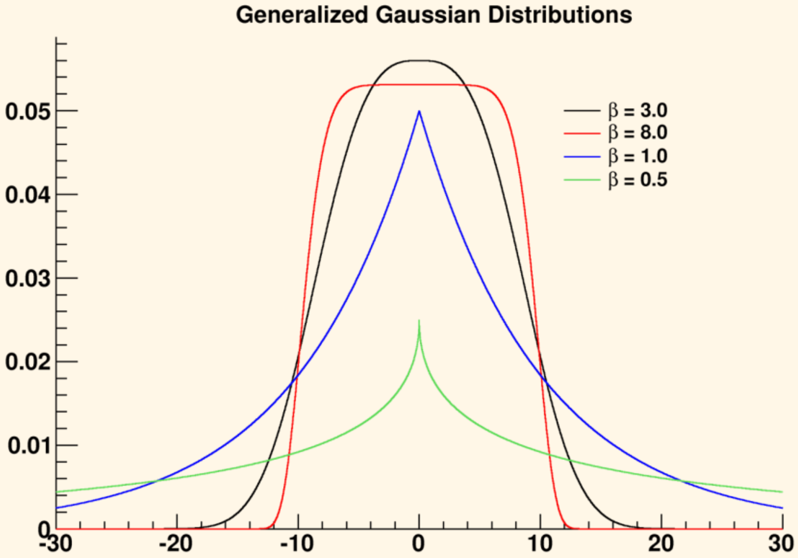
Candidate for test distribution: Generalized Gaussian

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

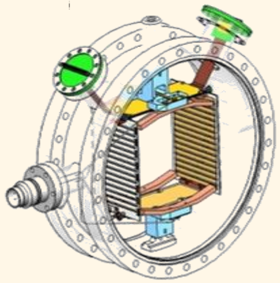
μ given by profile center

→ <u>two</u> degrees of freedom!

Cover any shape ranging from peaked Gaussian to rectangular distributions!



Transverse Profiling - IPM



Example of a self-consistent solution:

Parameters of test distribution:

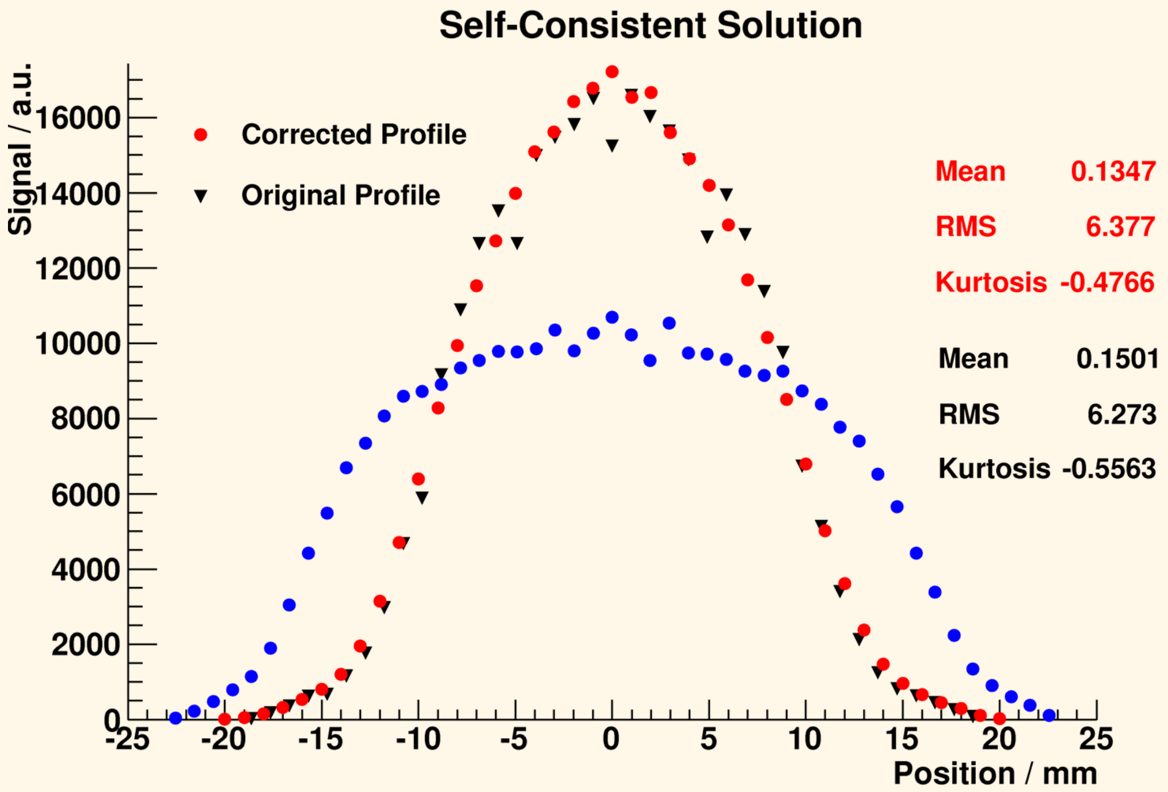
RMS: **6.30** mm
Kurtosis: **-0.50**

Consistent with:

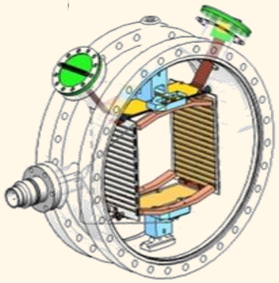
RMS: **6.38** mm
Kurtosis: **-0.48**

Original beam profile:

RMS: 6.27 mm
Kurtosis: -0.56



Correction Algorithm



*Example of a **not** self-consistent solution:*

Parameters of test distribution:

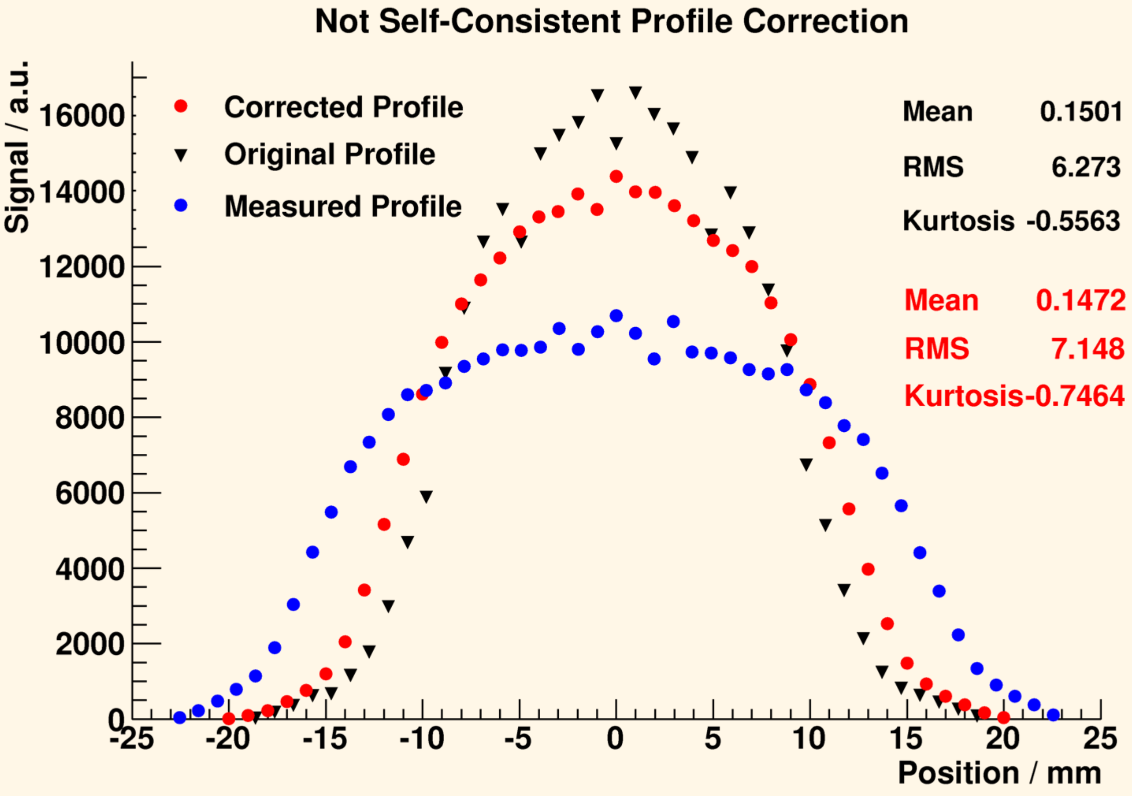
RMS: **8.72** mm
Kurtosis: **-0.81**

<ins>**Not**</ins> consistent with:

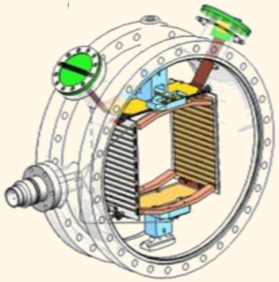
RMS: **7.15** mm
Kurtosis: **-0.75**

Original beam profile:

RMS: 6.27 mm
Kurtosis: -0.56



Correction Algorithm - Conclusion



Advantages:

- Good correction results according to simulations
- Generalized Gaussians grant wide range of possible profile shapes
- Cheap - no additional hardware components required
- Option to correct for other well-known distortions

Disadvantages:

- Still in a very preliminary phase!
- Not yet practically tested!
- No correction possible for profiles that cannot be approximated by generalized Gaussians!

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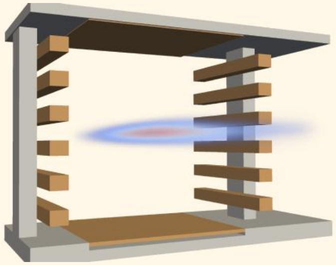
Prototype Test at GSI

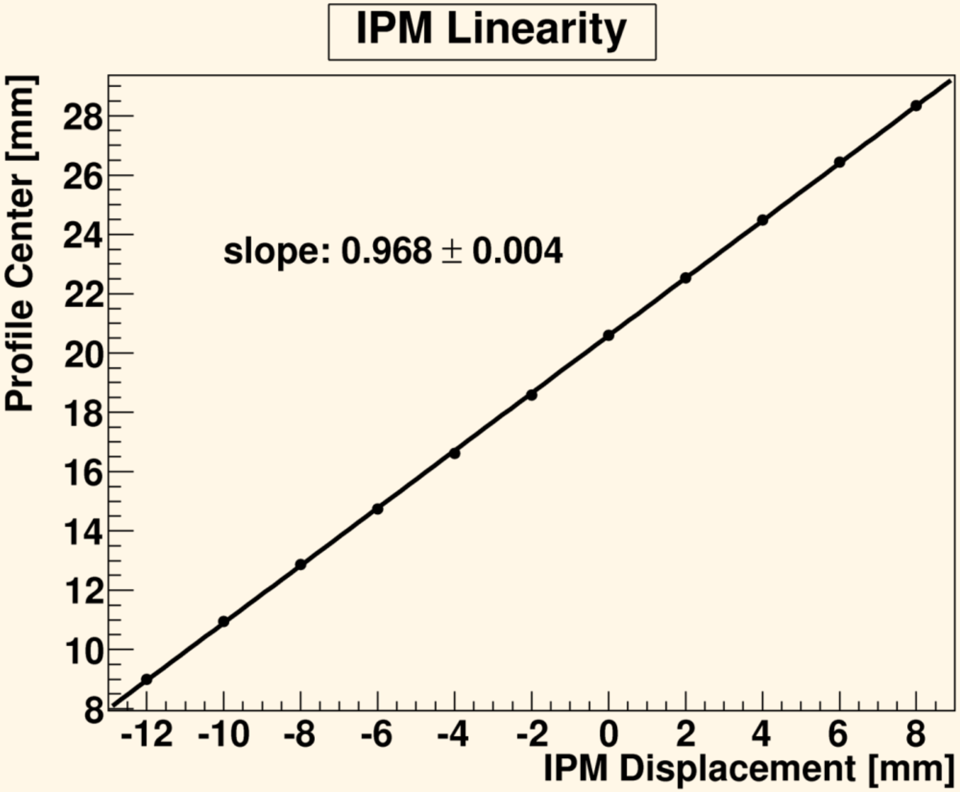
Field Uniformity Test



- Move IPM in 2 mm steps perpendicular to the beam
- Plot profile center versus IPM position

- Linear response over all active area

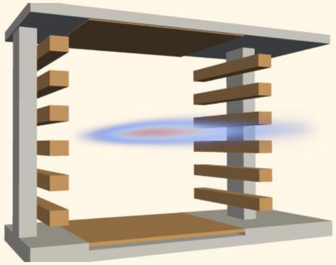
Good field uniformity



Beam: 30 µA Ca^{10+}

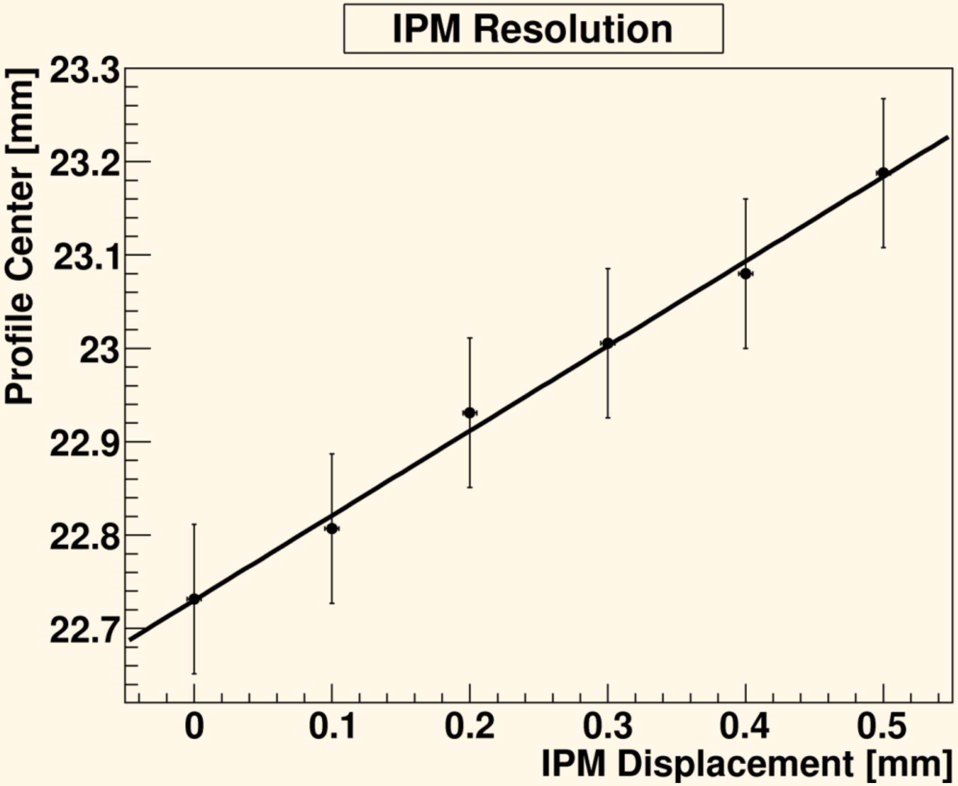
Prototype Test at GSI

Position Resolution



- Move IPM in 100 µm steps perpendicular to the beam
- Plot profile center versus IPM position

- Can resolve 100 µm beam shifts



Beam: 120 µA Xe^{21+}

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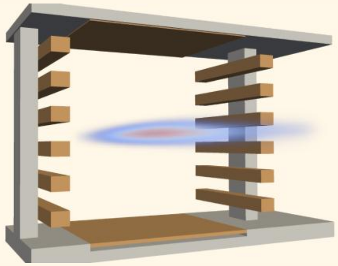
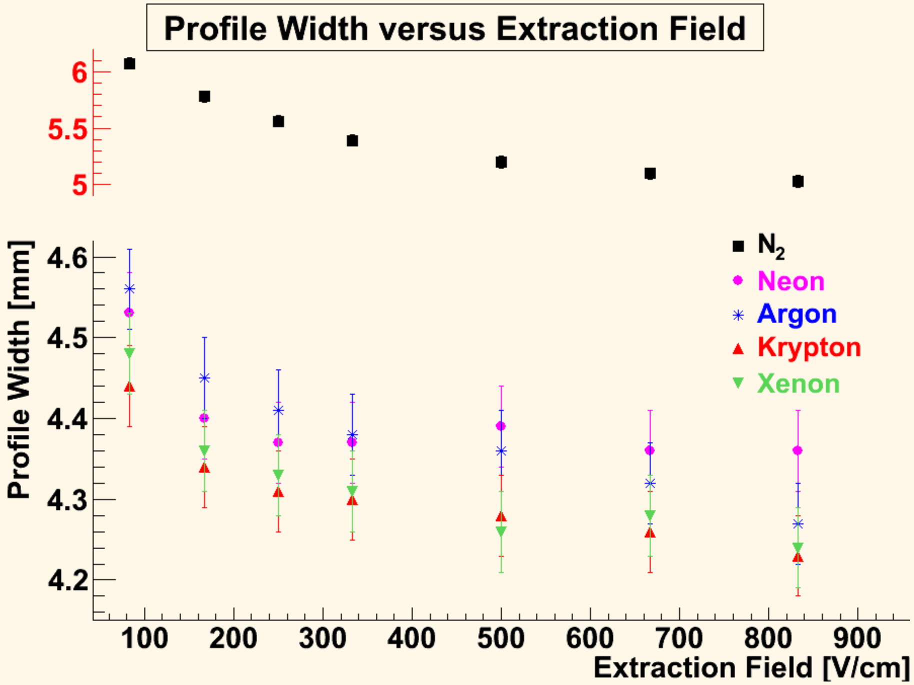
Electric Field Strength



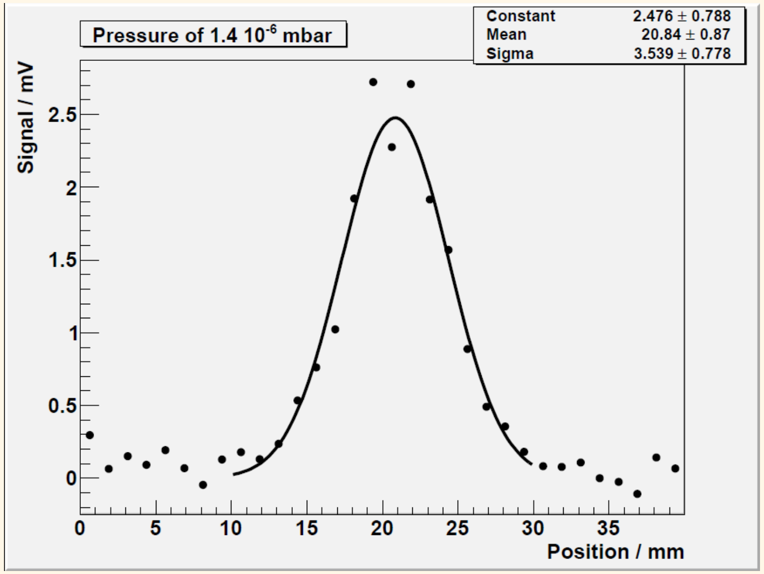
- Profile width decreases with higher extraction fields
- Plateau at a few kV
- Effect stronger for molecular N_2 than for atomic noble gases



E-field dominant at 500 - 1000 V/cm

Beam: 1 mA Xe^{21+}

lowest current measurable at IFMIF:



❖measurable for 30 µA $^{48}\mathrm{Ca}^{10+}$ at $1.4 \cdot 10^{-6}$ mbar

❖Z^2 dependence of ionization cross section:

$$30\ \mu\mathrm{A}\ ^{48}\mathrm{Ca}^{10+} \Leftrightarrow 300\ \mu\mathrm{A}\ \mathrm{D}^{+}$$

❖ pressure scaling:

$$300\ \mu\mathrm{A} \cdot (1.4 \cdot 10^{-6}\ \mathrm{mbar} / 10^{-8}\ \mathrm{mbar}) = 42\ \mathrm{mA\ at}\ 10^{-8}\ \mathrm{mbar},$$

or

$$300\ \mu\mathrm{A} \cdot (1.4 \cdot 10^{-6}\ \mathrm{mbar} / 10^{-7}\ \mathrm{mbar}) = 4.2\ \mathrm{mA\ at}\ 10^{-7}\ \mathrm{mbar}$$

High Current Test

IPHI: Injecteur de Protons à Haute Intensité (I < 100 mA; E = 95 keV)

- Test at IPHI source
  - Low energy ⇒ high ionization cross section
  - No collimation ⇒ IPM is irradiated by beam
- IPM operational up to 10 mA cw (SC and I_{ioniz} comparable to LIPAc)
  - For I > 10 mA: tripping power supply probably due to primary or secondary particle bombardment
- IPM tested up to 20 mA in 10 % duty cycle

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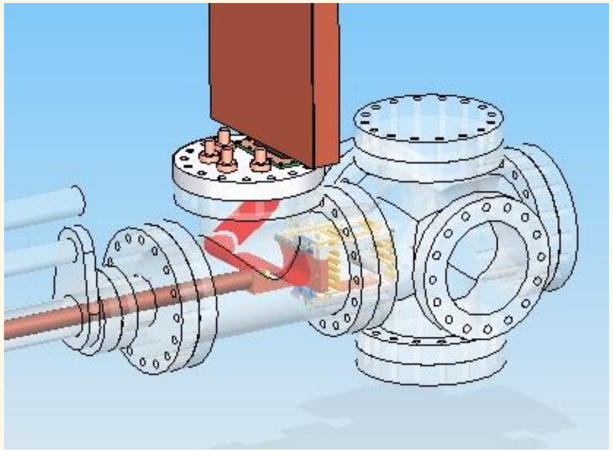
Data Readout

Front-End (FE) electronics:

- FE electronics mounted on the beam pipe
  - Transimpendance card / logarithmic card:
    - Continuous multiplexed output every ≈ 2 µs
  - Integrating card:
    - Integration time between 81 µs and 64 ms - or even more…



Data Acquisition:

- Acqiris Card:
  - 8 bit ADC
  - 1 GHz sampling rate with 2MB memory depth
  - 2133 acquisitions per profile – up to 800 profiles per data transfer