Challenges for the LIPAc Ionization Profile Monitor (IPM)

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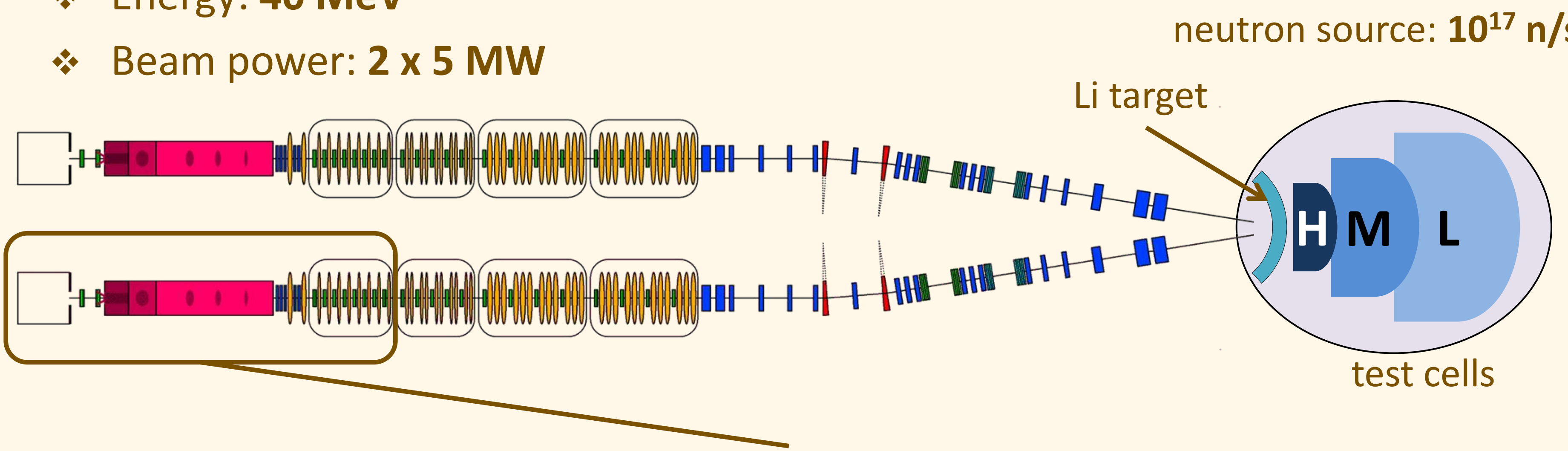
Outline

- LIPAc Accelerator (IFMIF - EVEDA)
- IPM – Characteristics
- Challenges
  - Background Radiation
  - High Beam Current
- Conclusion

IFMIF: International Fusion Material Irradiation Facility

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

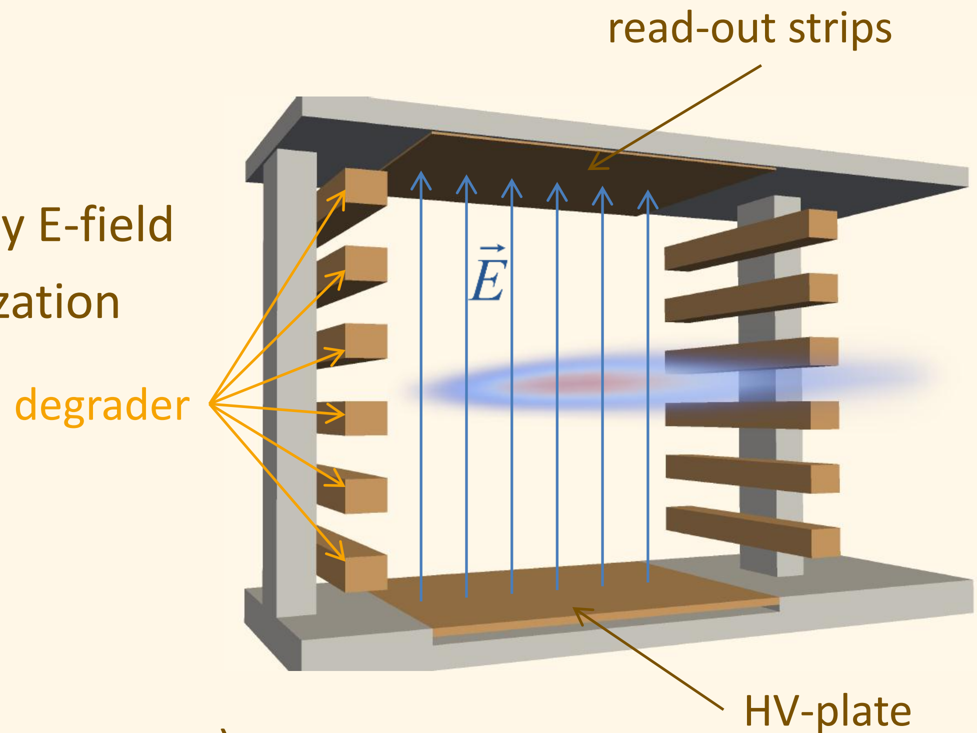


LIPAc: Linear IFMIF Prototype Accelerator

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

Principle of Operation:

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



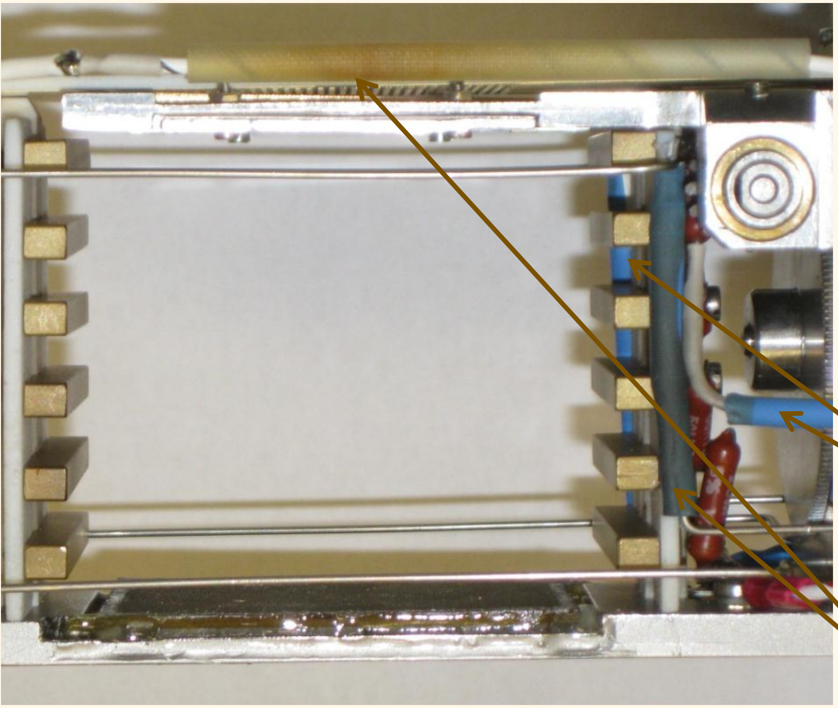
LIPAc Challenges:

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

Radiation Hard IPM Design

Mainly radiation hard materials used, like:

metals, ceramics, epoxy glass, indium joints…

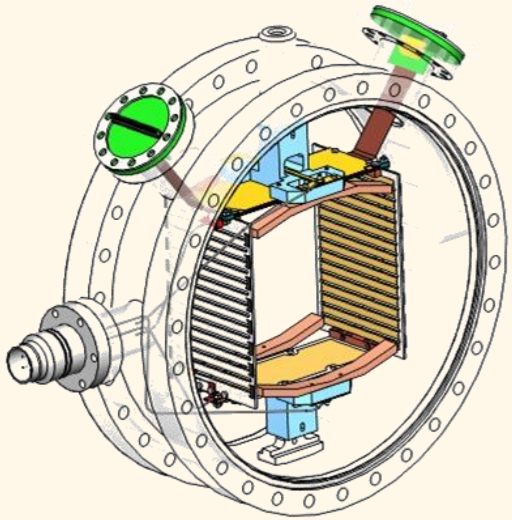


For radiation weak materials:

- Front-end electronics at remote distance and shielded
- Resistors are well shielded
- Flat resistors used to minimize irradiation

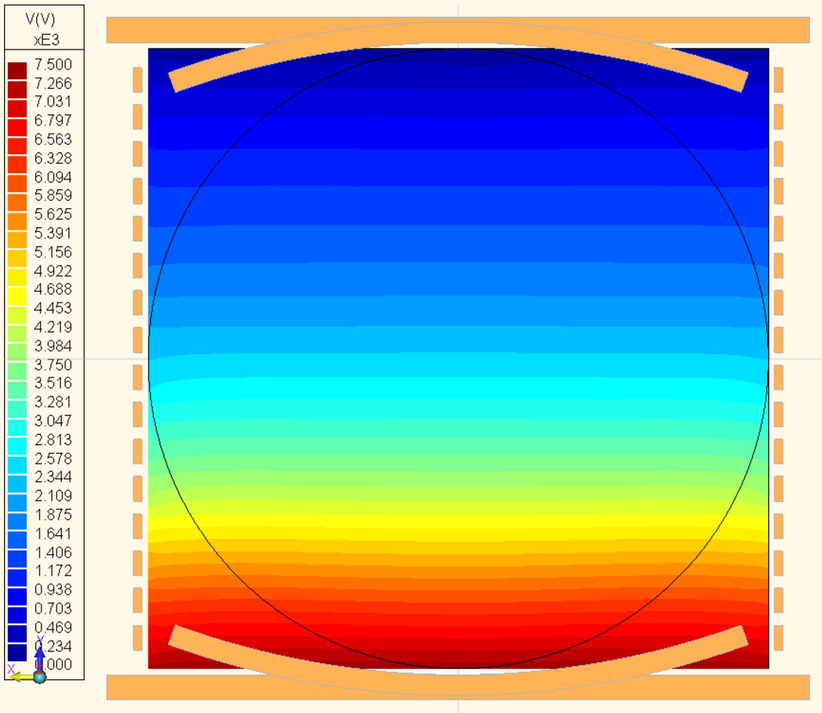
Virtually no radiation effects on plastics that were shielded by the beam pipe / the IPM

Strong radiation effects on plastics of the IPM prototype after tests at GSI



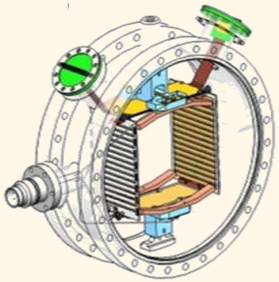
Final Design Challenges:

- ❖ Lack of space ⇒ very compact design required
- ❖ High radiation level ⇒ radiation hard components exclusively
- ❖ Large aperture of 150 mm



Design results:

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



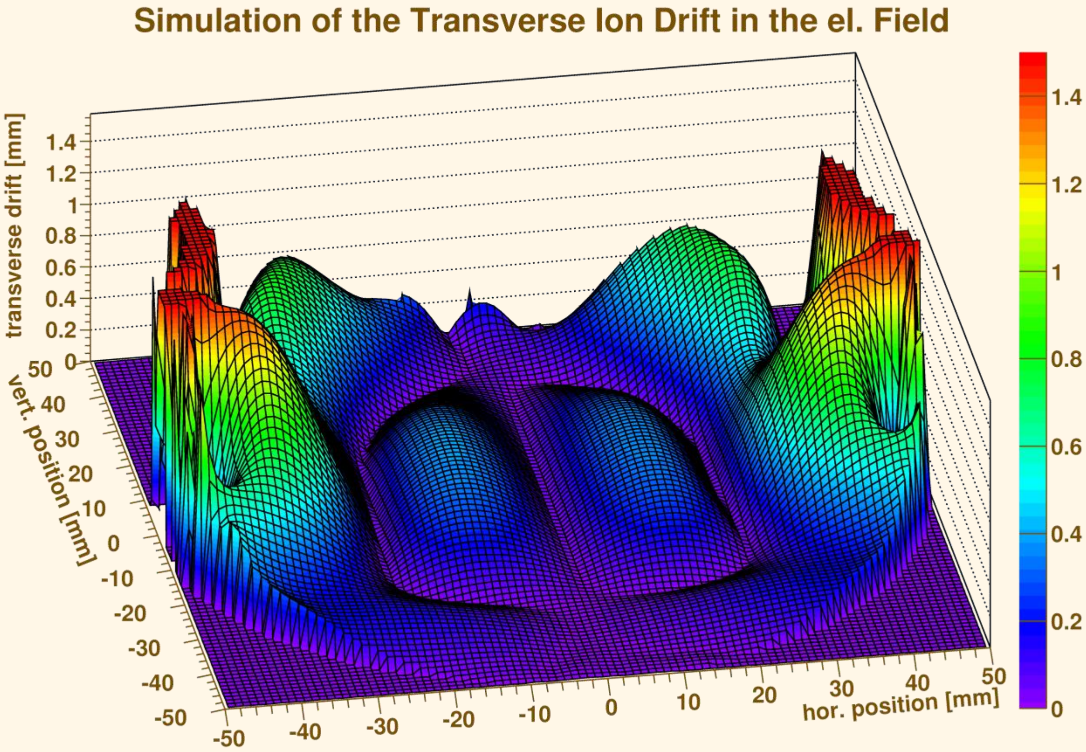
Neglecting Space Charge Effect!

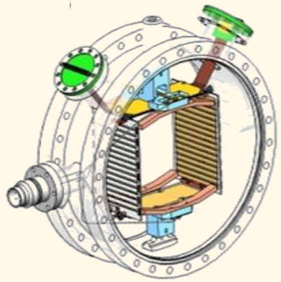
Particle Tracking:

Transverse displacement during ion drift versus starting position

In beam region:

Displacement < 500 µm

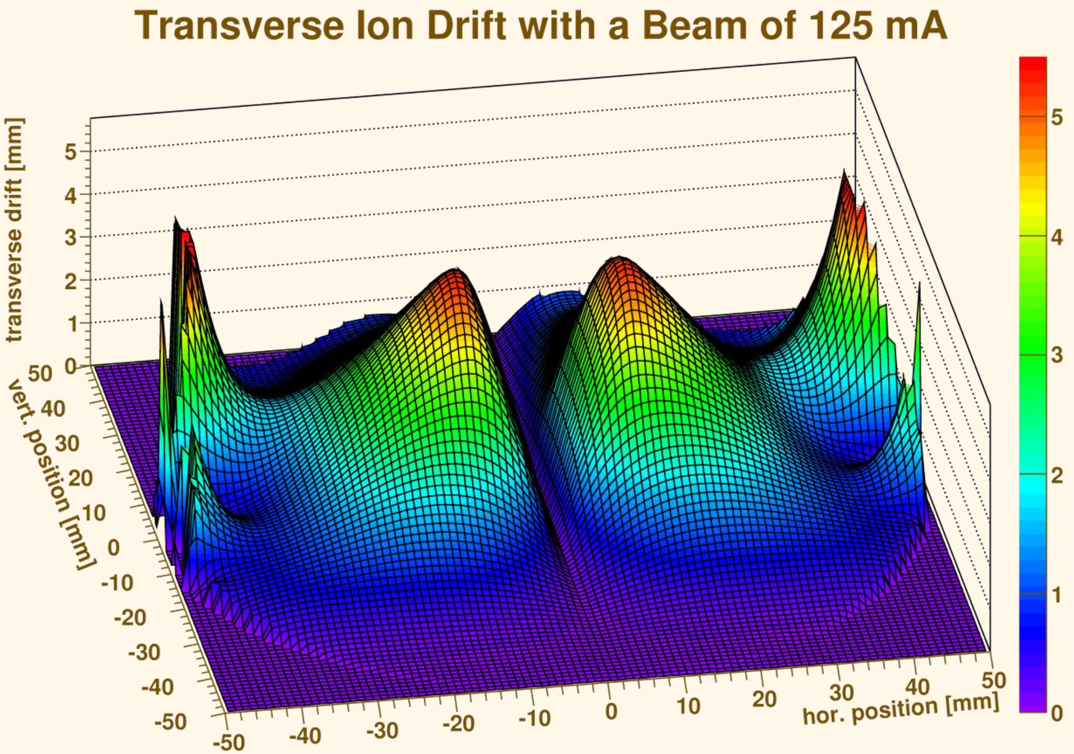




Space Charge for 125 mA Beam

Particle Tracking:

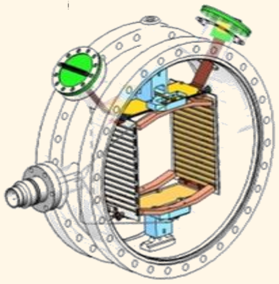
Transverse displacement during ion drift versus starting position



With space charge of 125 mA:

Displacement > 5 mm

Particle Tracking – Ion Displacement



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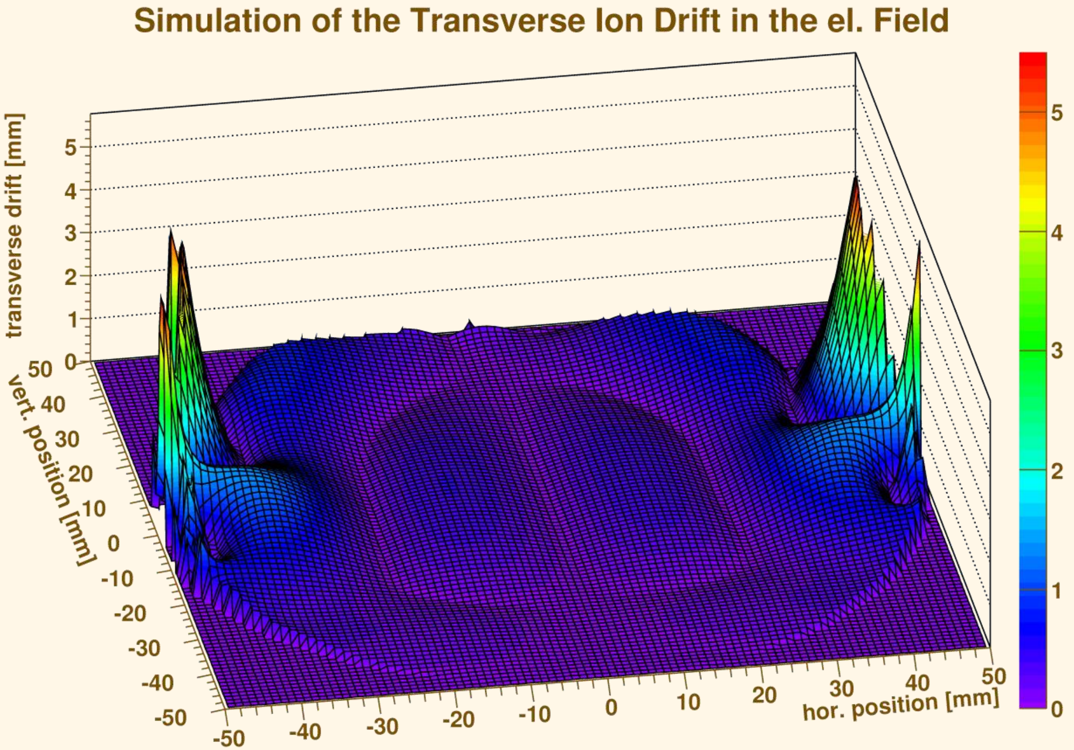
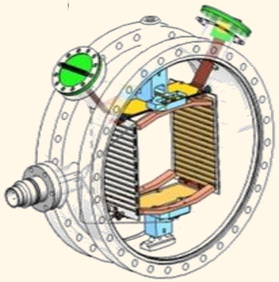
Transverse displacement during ion drift versus starting position



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

Particle Tracking – Resulting Profile

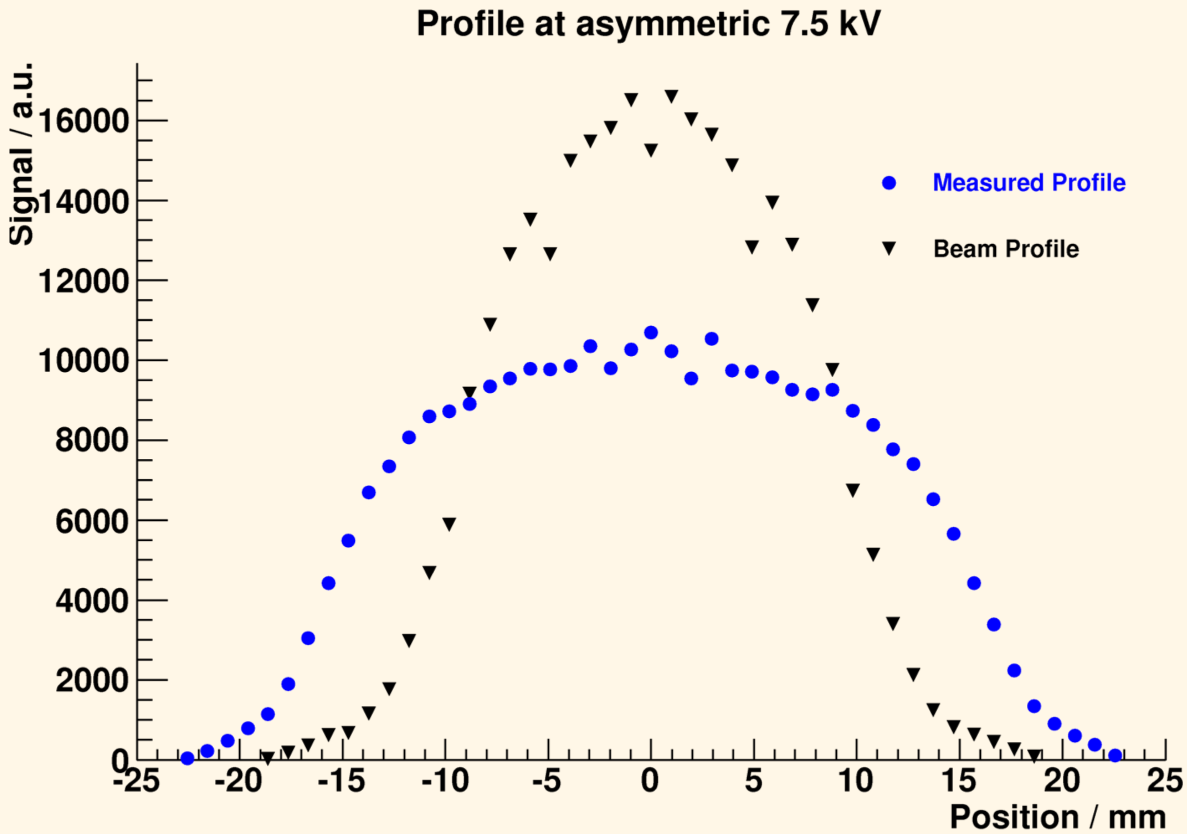


Resulting Profile:

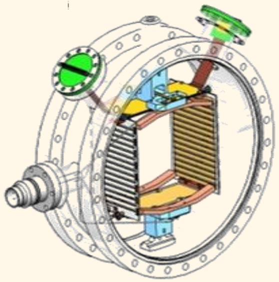
Strong Distortions due to space charge

original beam profile

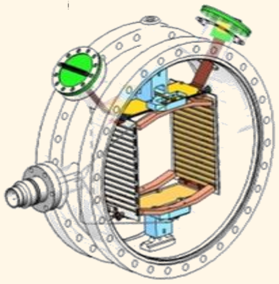
measured profile (simulation)



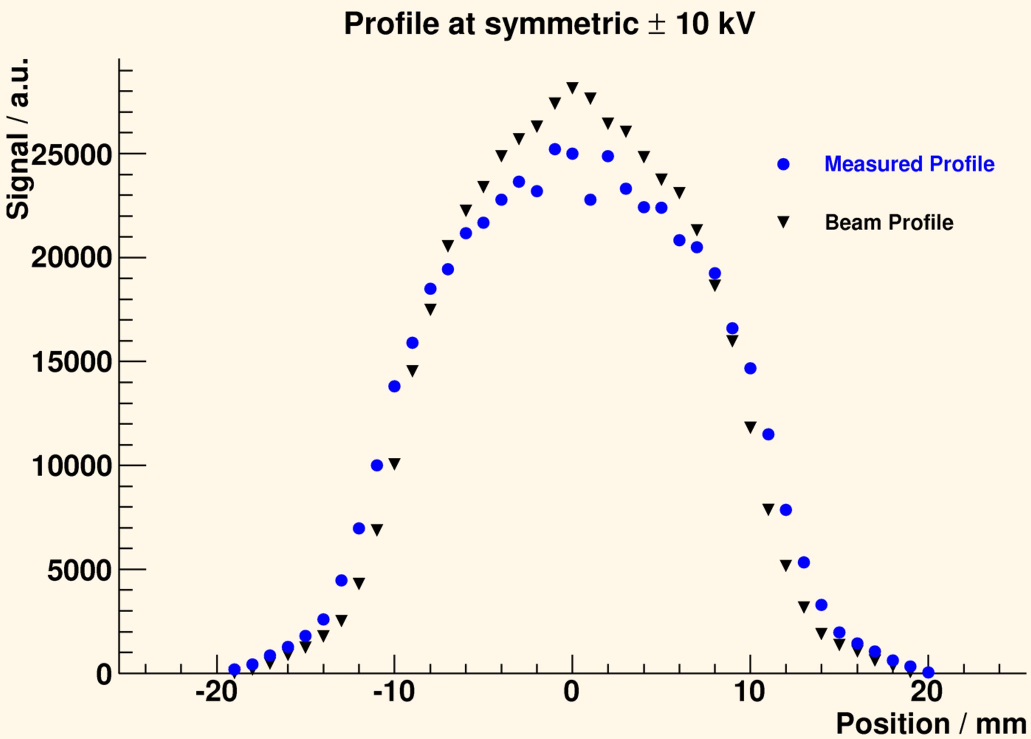
Space Charge Effect – Possible Solutions



- ***Increase electric field***
- ***Use magnetic field guidance***
- ***Apply correction algorithm***

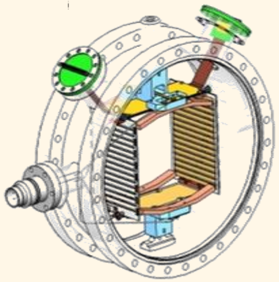


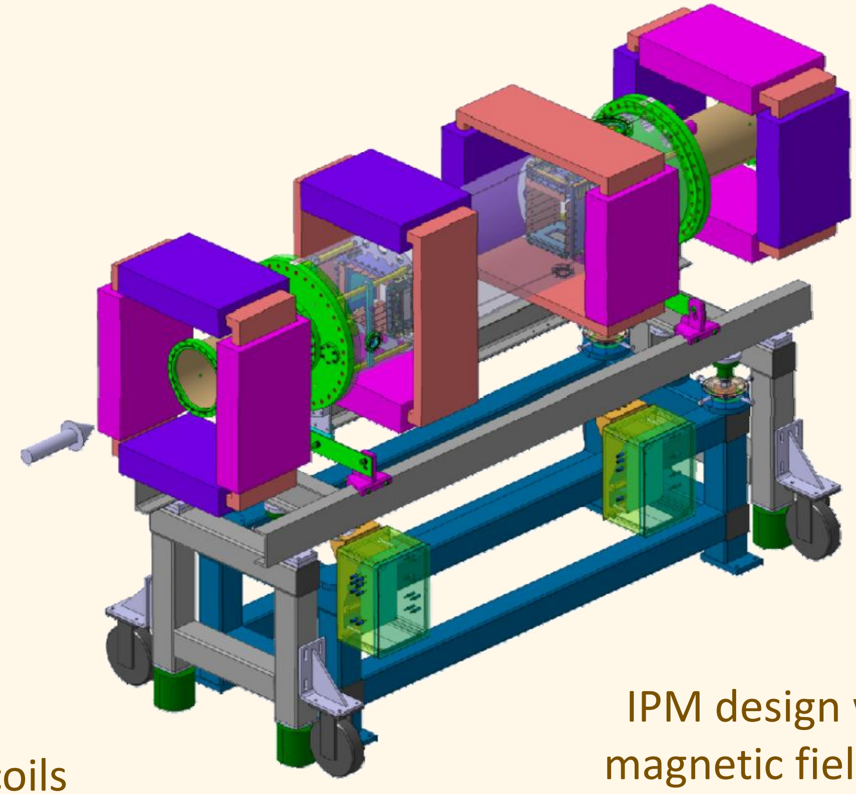
- ***Increase electric field***
  - Just minimizing effects
  - Limited voltage applicable
- ***Use magnetic field guidance***
- ***Apply correction algorithm***



Electric field generated by ± 10 kV instead of 7.5 kV

Space Charge Effect – Magnetic Field

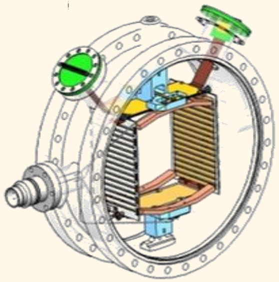


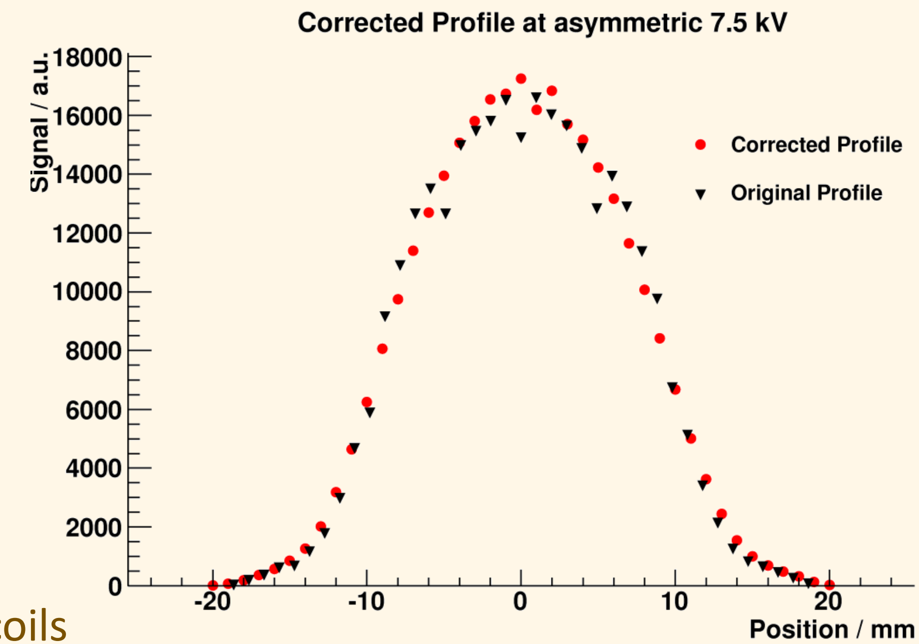


IPM design with magnetic field by Tino Giacomini, GSI

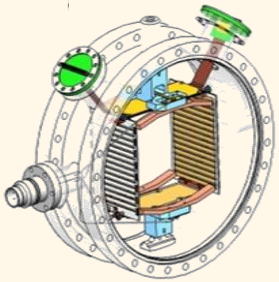
- ***Increase electric field***
  - Just minimizing effects
  - Limited voltage applicable
- ***Use magnetic field guidance***
  - Space consuming due to:
    - Magnetic field compensation coils
    - Higher demands on electric field uniformity
- ***Apply correction algorithm***

Space Charge Effect – Correction Algorithm





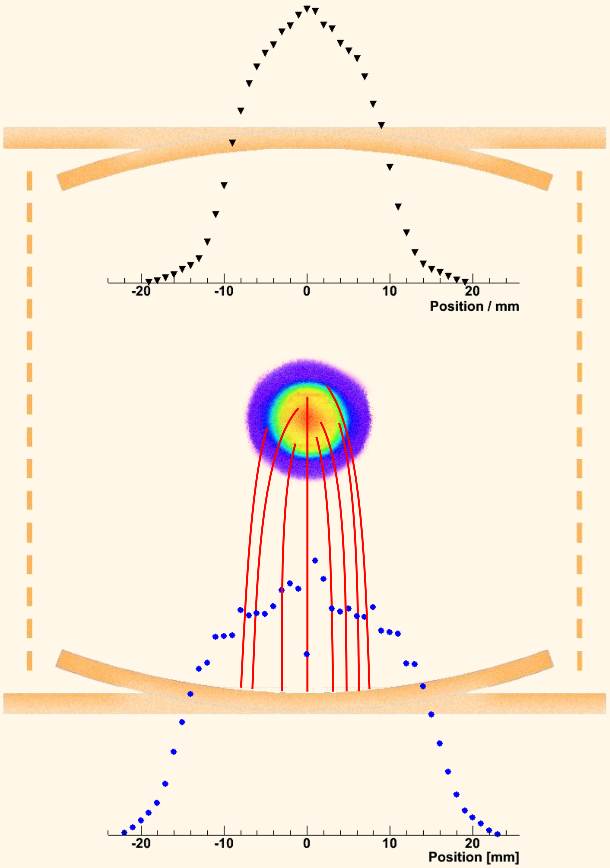
- ***Increase electric field***
  - Just minimizing effects
  - Limited voltage applicable
- ***Use magnetic field guidance***
  - Space consuming due to:
    - Magnetic field compensation coils
    - Higher demands on electric field uniformity
- ***Apply correction algorithm***
  - Risk of distortions in case of malfunctioning



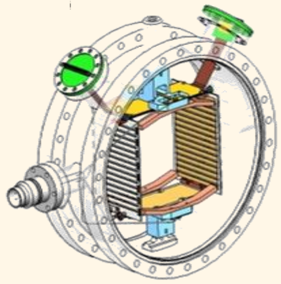
Idea:

- Calculate space charge force
- Determine ion displacement at each position
- Correct the profile

beam profile (x,y)



measured profile x’



Idea:

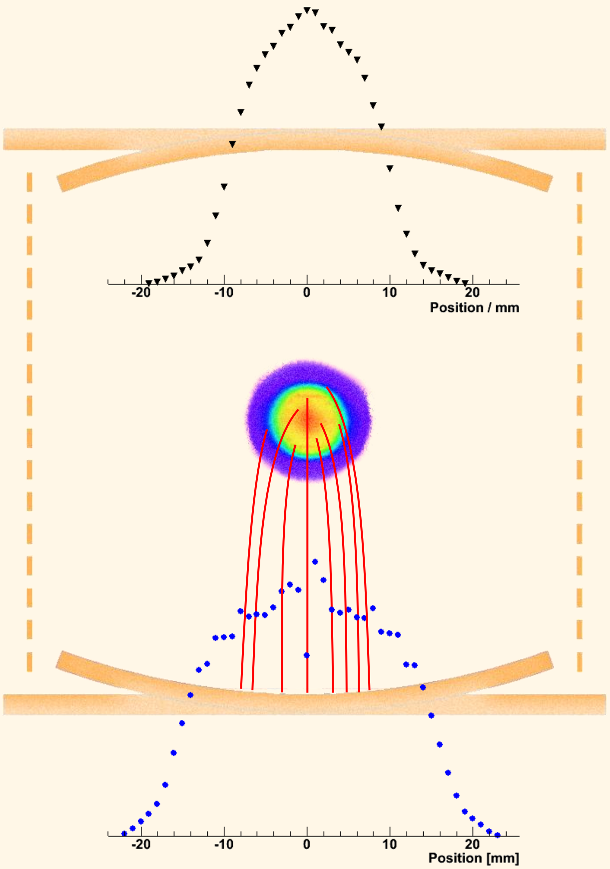
- Calculate space charge force
- Determine ion displacement at each position
- Correct the profile

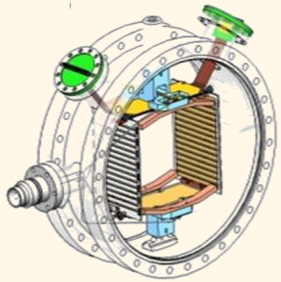
Problem:

Beam particle distribution required to calculate space charge force

Approach:

Assume *beam distribution*….





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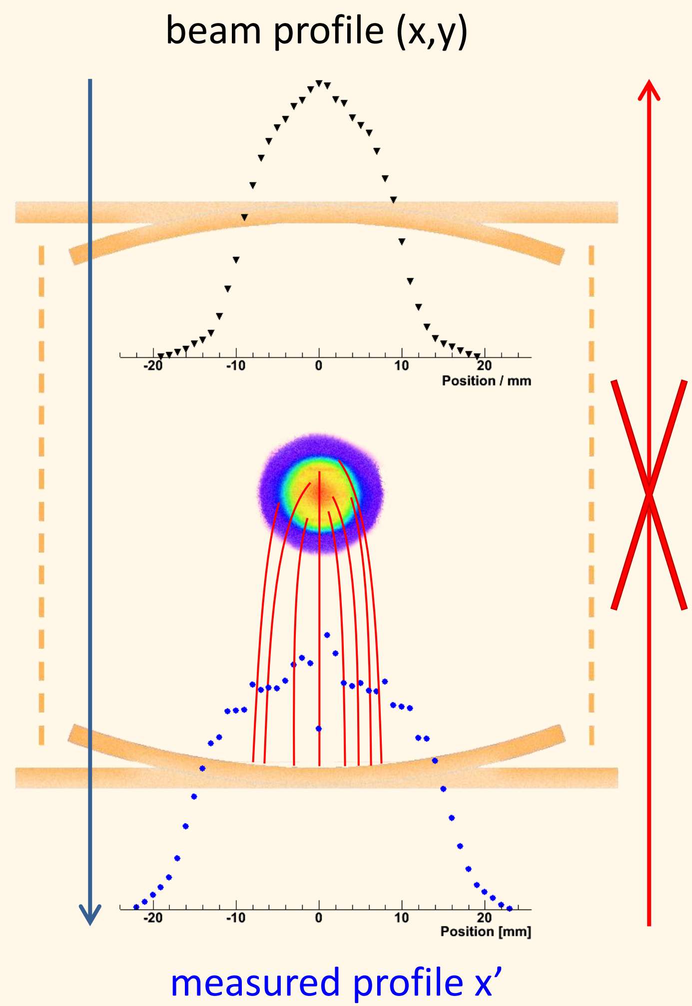


Problem:

Beam particle distribution required to calculate space charge force

Approach:

Assume *beam distribution*….

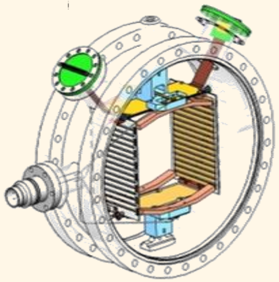
Problem:

No bijective mapping between (x,y) and x'

Approach:

Apply statistics: $g(x') = \Sigma\, p_{x'}(x,y)\cdot(x,y)$

$p_{x'}(x,y)$ is given by *beam distribution*….



How to find the proper beam distribution?

Idea:

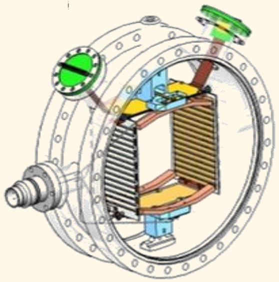
Vary test distribution until self-consistent solution is found!

Possible criteria for self-consistency:

- *RMS (2. distribution moment)*

  → Gauss

  → strong distortions for non-Gaussian beams 😐😐😐



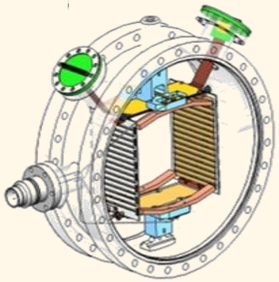
How to find the proper beam distribution?

Idea:

Vary test distribution until self-consistent solution is found!

Possible criteria for self-consistency:

- Beam position (1. distribution moment)
- *RMS (2. distribution moment)*



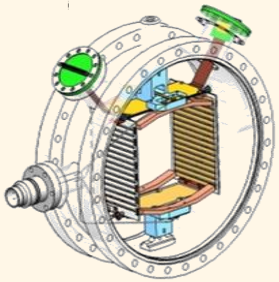
How to find the proper beam distribution?

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)



How to find the proper beam distribution?

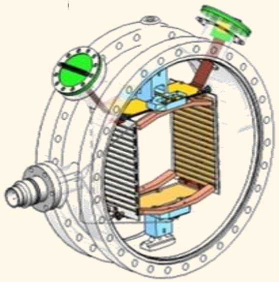
Idea:

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!



What could be a proper test distribution?

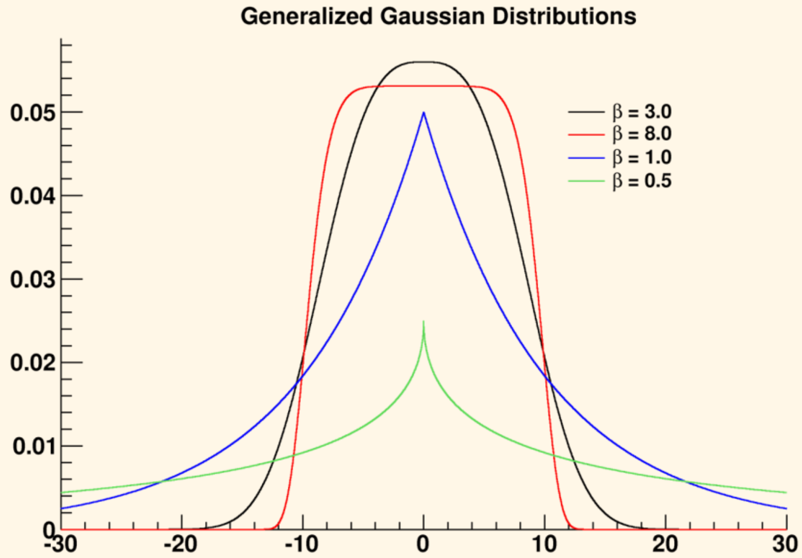
Candidate for test distribution: Generalized Gaussian

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

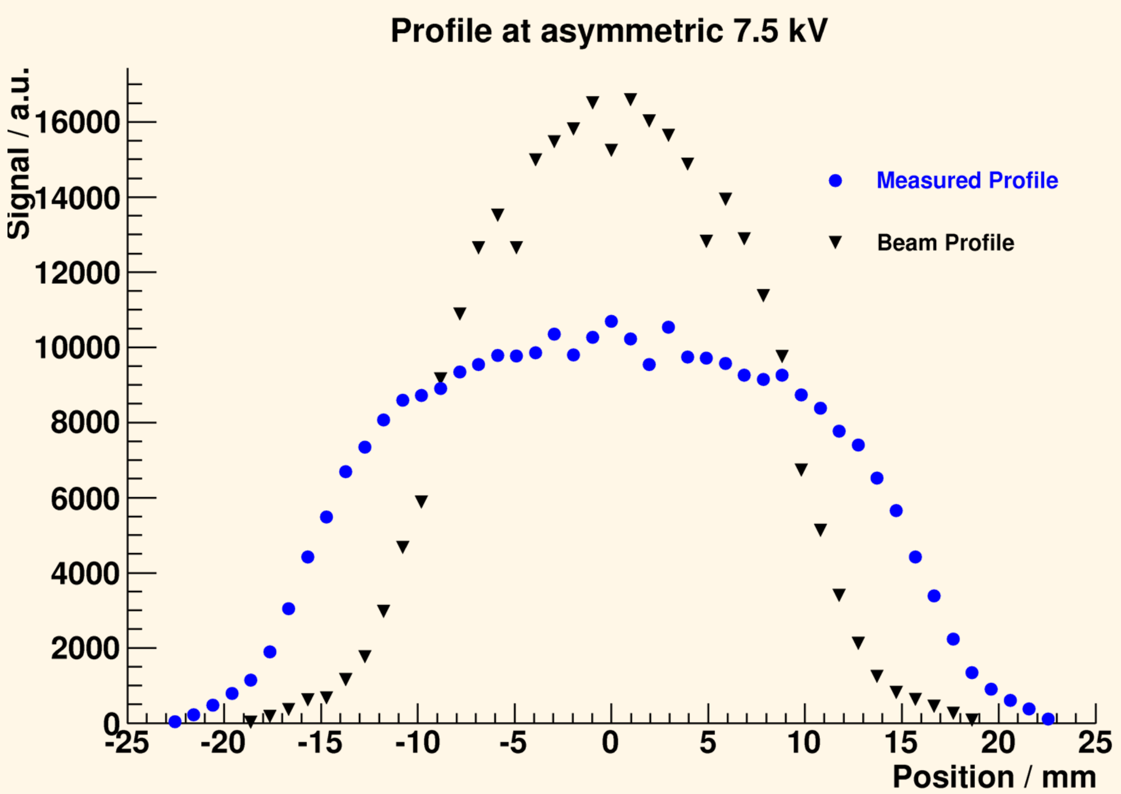
μ given by profile center

→ <u>two</u> degrees of freedom!

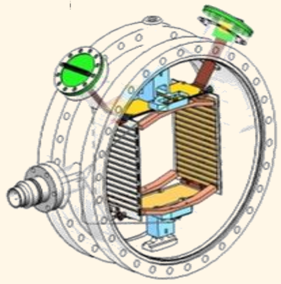
Cover any shape ranging from peaked Gaussian to rectangular distributions!



Simulation beam profile measurement:



Example of a self-consistent solution:



Parameters of test distribution:

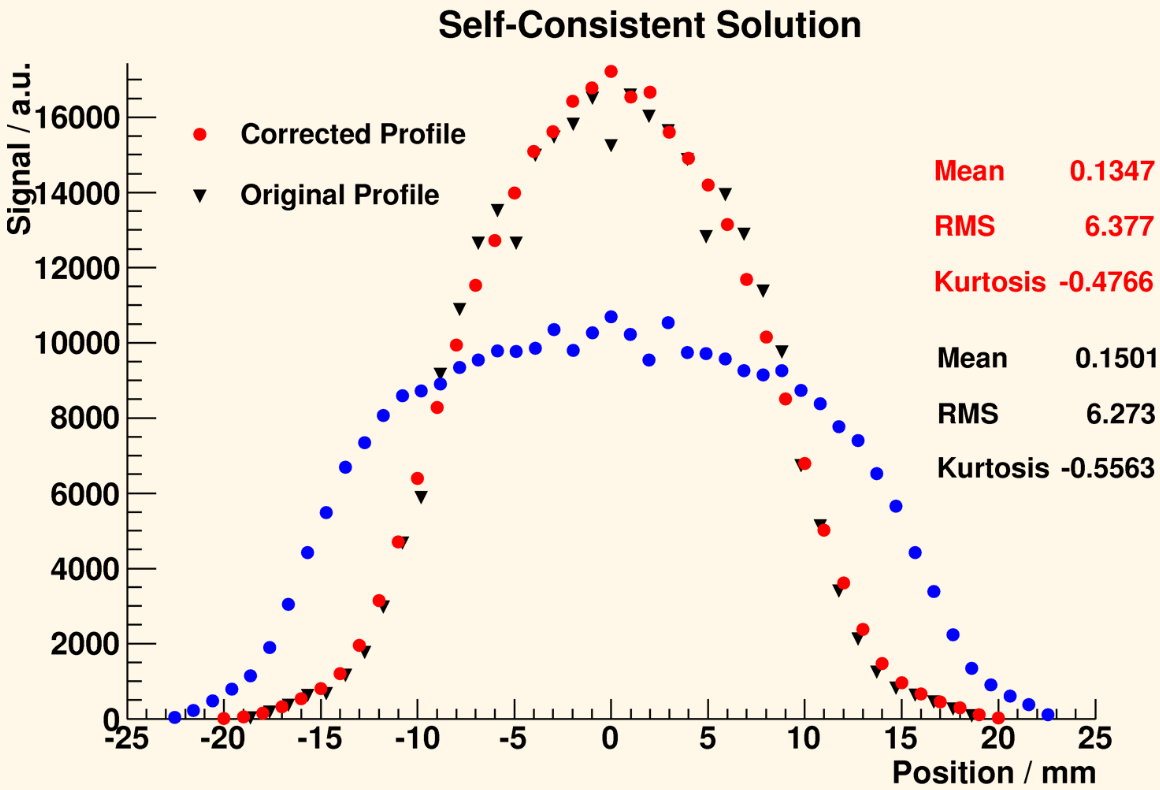
RMS: 6.30 mm
Kurtosis: -0.50

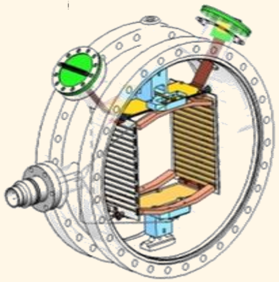
Consistent with:

RMS: 6.38 mm
Kurtosis: -0.48

Original beam profile:

RMS: 6.27 mm
Kurtosis: -0.56





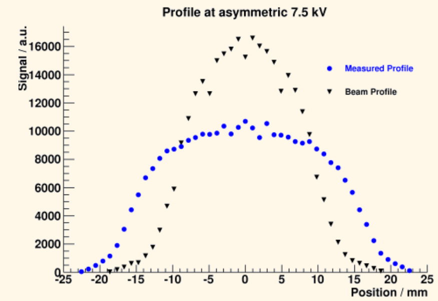
__Advantages__:

- 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

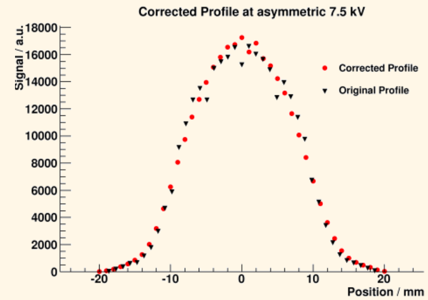
__Disadvantages__:

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

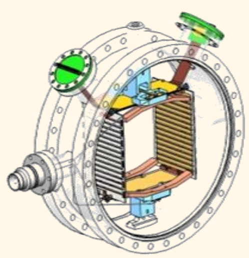
Conclusion



- IPM works well at low charge density beams
- IPM designed to withstand high radiation background

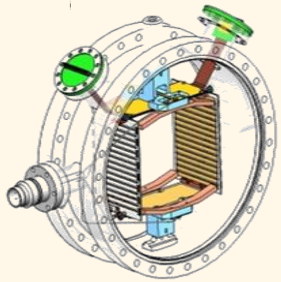


- Three options for space charge compensation:
  - Magnetic field
  - Increased electric field
  - Correction algorithm
- Magnetic field solution hardly feasible due to lack of space
- Proposed Solution:



Correction algorithm with increased electric field to reduce effects of potential algorithm failure

Backups



Example of a not self-consistent solution:

Parameters of test distribution:

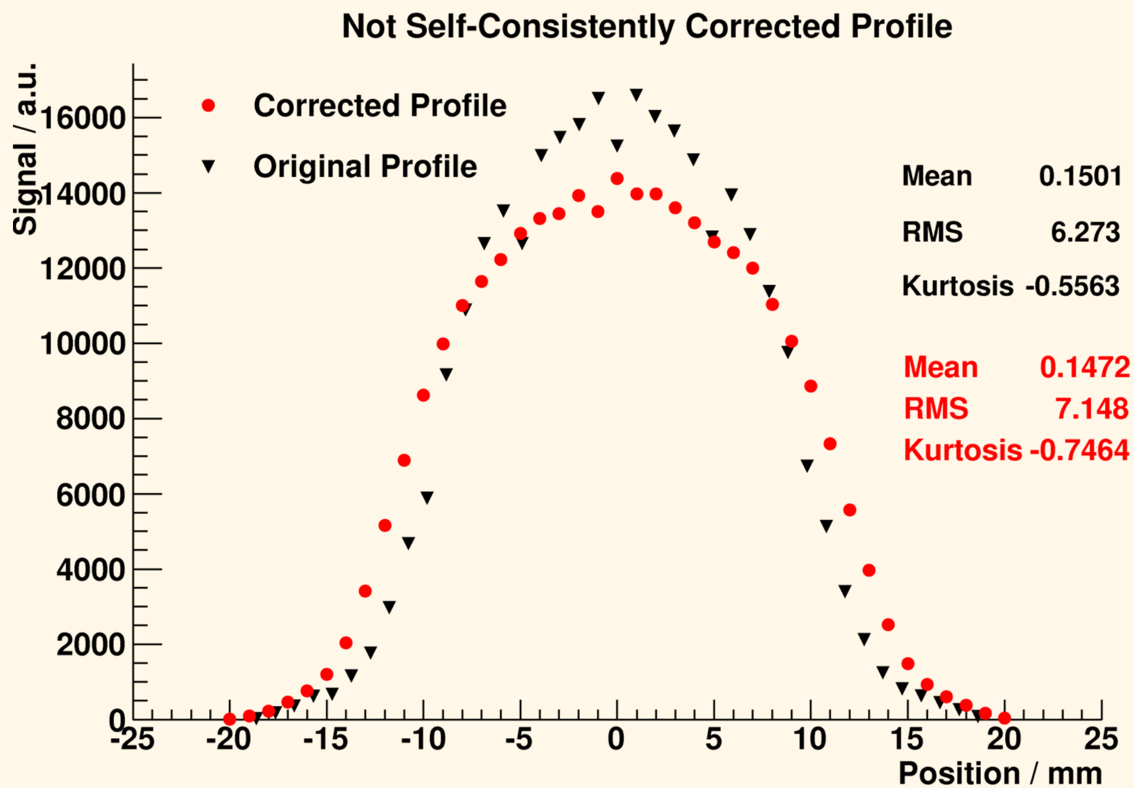
RMS: 8.72 mm
Kurtosis: -0.81

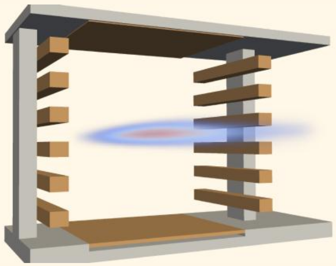
Not consistent with:

RMS: 7.15 mm
Kurtosis: -0.75

Original beam profile:

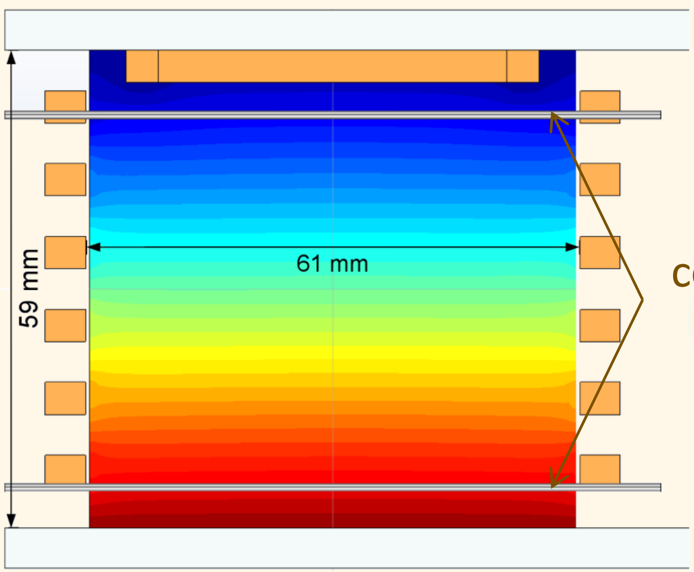
RMS: 6.27 mm
Kurtosis: -0.56

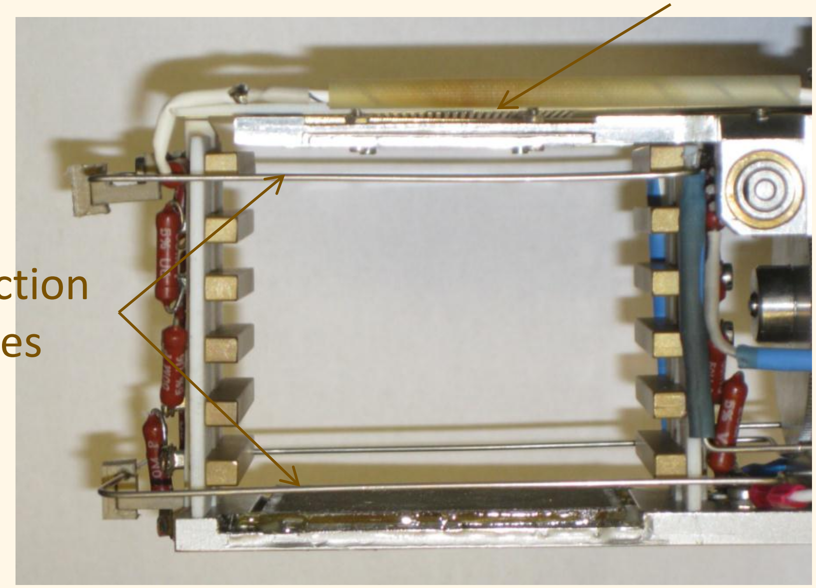




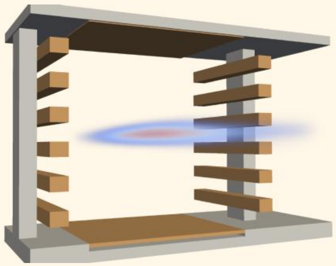
IPM Prototype Design

- Charge collected on 32 strips with 1.25 mm pitch
- Uniform electric field required to conserve beam profile
- 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)





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

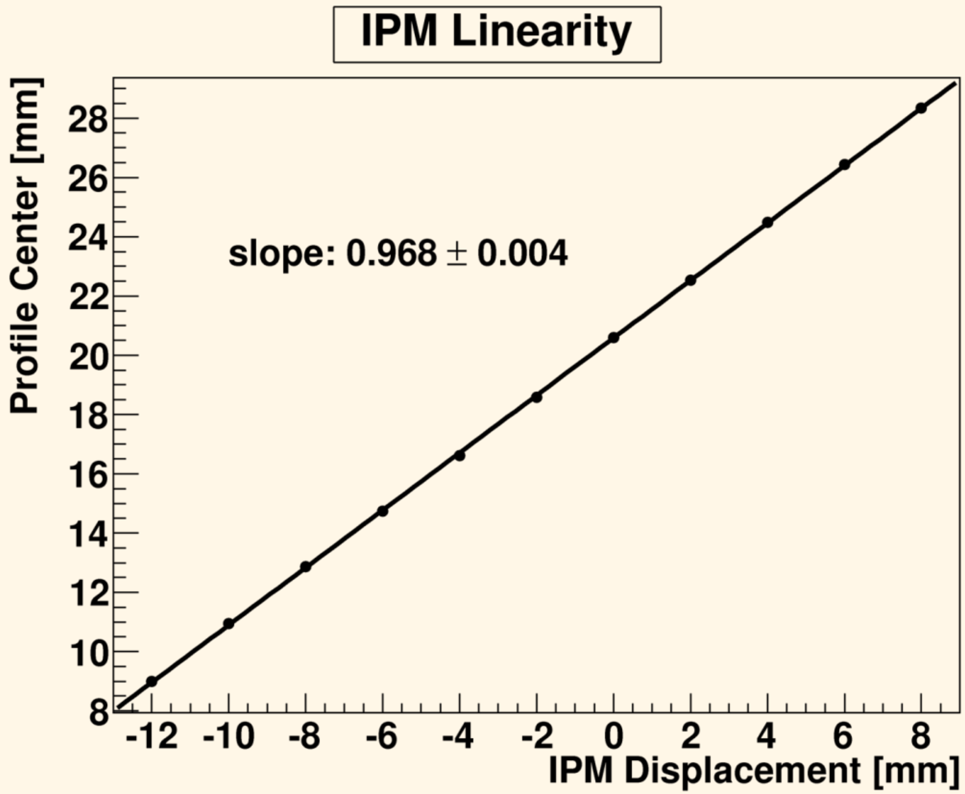


Field Uniformity Test

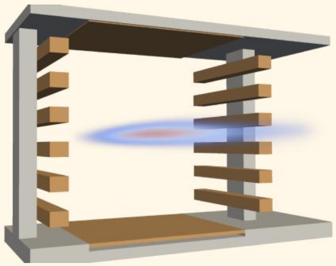
- ❖ Move IPM in 2 mm steps perpendicular to the beam
- ❖ Plot profile center versus IPM position

- ❖ Linear response over all active area

Good field uniformity

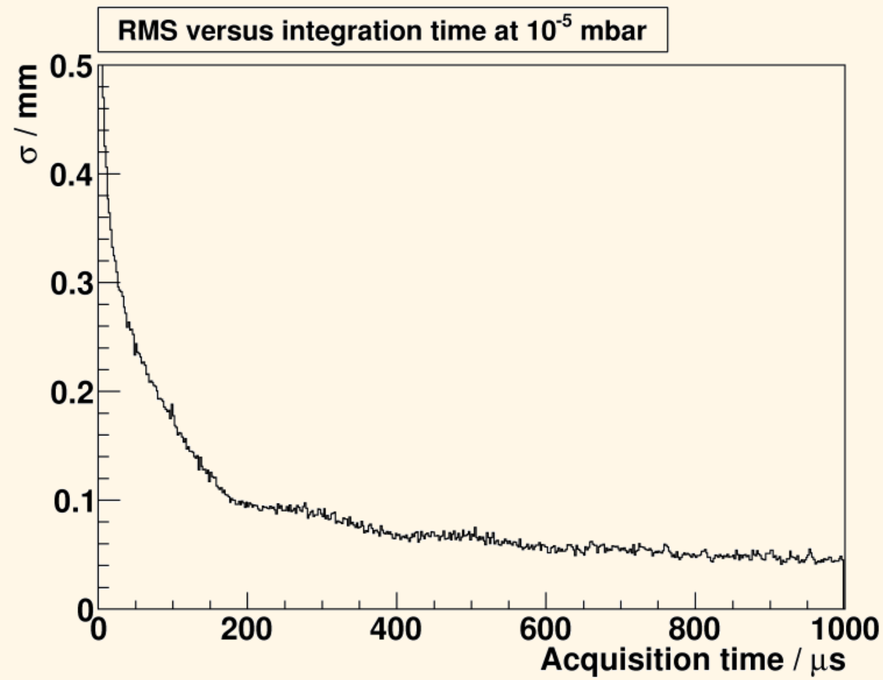


Beam: 30 µA Ca^{10+}



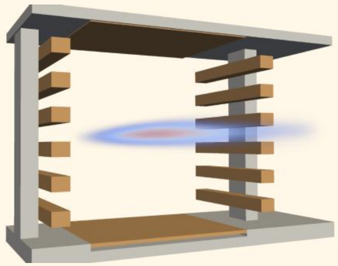
Position Resolution

- Fluctuation of beam center versus data acquisition time
- 120 µA Xe^{21+}, 10^{-5} mbar N_2
- Plateau of < 100 µm at ~1kHz



Beam: 1 mA Xe^{21+}

BIF Comparison

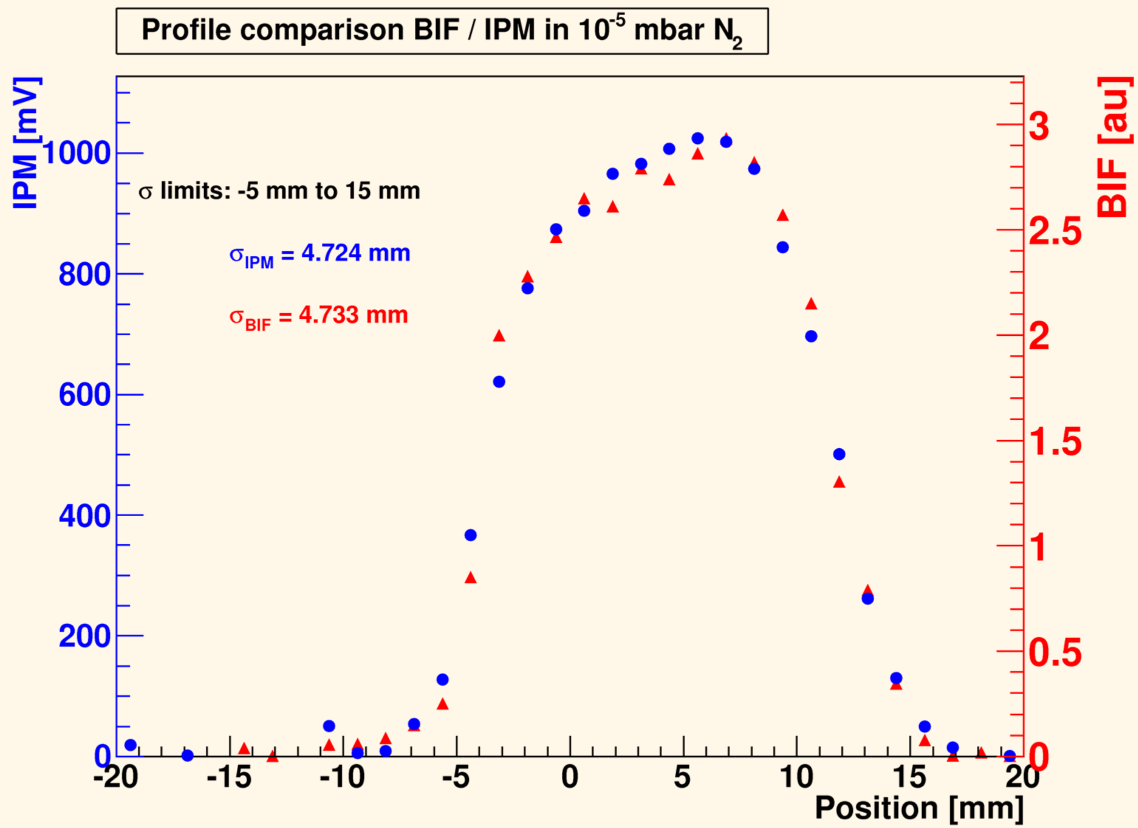


10^{-5} mbar N_2

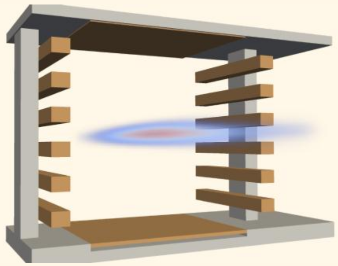
BIF: <u>B</u>eam <u>I</u>nduced <u>F</u>luorescence

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

BIF profiles acquired by *Frank Becker, GSI*

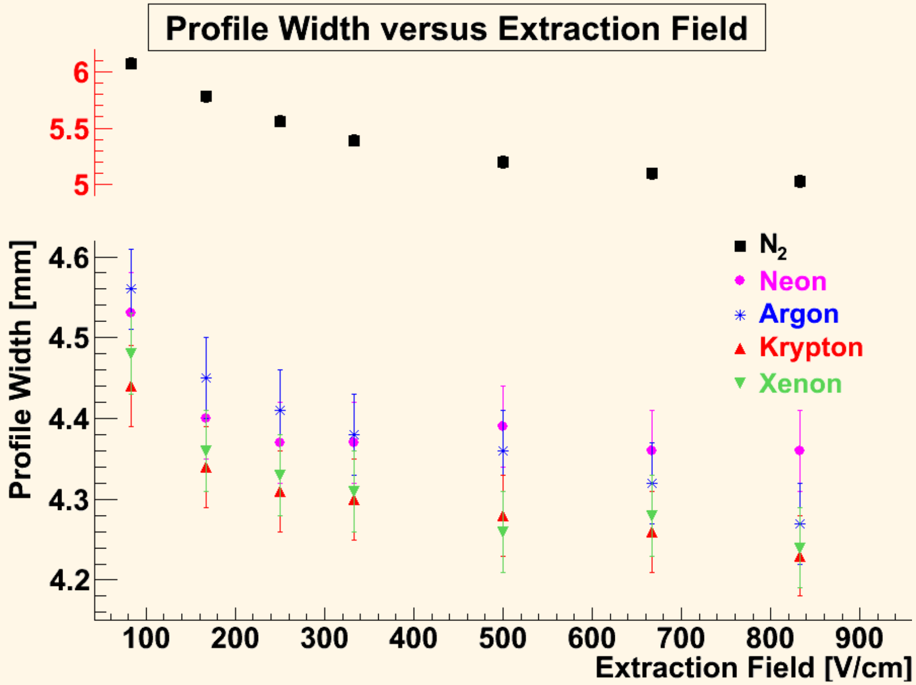


Beam: 1 mA Xe^{21+}



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

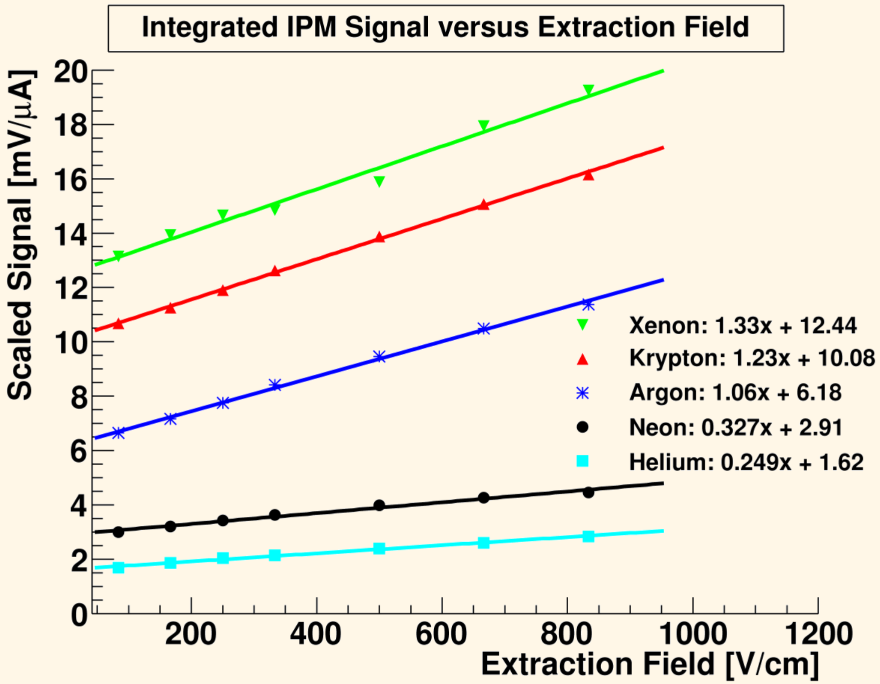
Beam: 1 mA Xe^{21+}

Signal Amplification

- Total strip current plotted versus extraction voltage
- Signal rises linearly

***Hypothesis*: Secondary electron emission during ion collection**

- $\left|\vec{E}\right| \propto E_{KIN} \propto SEM$



Beam: 1 mA Xe^{21+}

Secondary Electron Yield Comparison

	Magnuson [1]	Carlston [2]	Zalm [3]	Baragiola [4,5]	IPM
He	---	---	---	0.39	1.28
Ne	0.25	0.3	0.35	---	0.92
Ar	0.21	0.33	0.29	0.28	1.01
Kr	0.2	0.3	0.29	0.25	0.69
Xe	0.14	0.2	0.19	---	0.53

Secondary Electron Emission from IPM measurements and literature

Oxidation layer on read-out strips may increase SEE yield

1. **Magnuson, et al.** *"Electron ejection from metals due to 1- to 10-keV noble gas ion bombardment. I. Polycrystalline Materials",* 1963, Physical Review, Vol. 129, pp. 2403-2409
2. **Carlston, et al.** *"Electron ejection form single crystals due to 1- to 10-keV noble gas ion bombardment",* 1965, Physical Review, Vol. 139, pp. A729-A736
3. **Zalm, P.C. and Beckers, L.J.** *"Ion-induced secondary electron emission from copper and zinc",* 1985, Journal of Surface Science, Vol. 152, pp. 135-141
4. **Baragiola, et al.** *"Electron emission from clean metal surfaces induced by low-energy light ions",* 1979, Physical Review B, Vol. 19, pp. 121-129
5. **Baragiola, et al.** *"Ion-induced electron emission from clean metals",* 1979, Journal of Surface Science, Vol. 90, pp. 240-255

Secondary Electron Yield Comparison

	Magnuson [1]	Carlston [2]	Zalm [3]	Baragiola [4,5]	IPM
He	---	---	---	1.47	1.47
Ne	1.14	0.97	1.13	---	1.06
Ar	0.95	1.06	0.94	1.06	1.15
Kr	0.91	0.97	0.94	0.94	0.79
Xe	0.64	0.64	0.61	---	0.61

Secondary Electron Emission normalized on mean of Ne, Ar and Kr

Good agreement with literature values for normalized yields

1. **Magnuson, et al.** “*Electron ejection from metals due to 1- to 10-keV noble gas ion bombardment. I. Polycrystalline Materials”,* 1963, Physical Review, Vol. 129, pp. 2403-2409
2. **Carlston, et al.** “*Electron ejection form single crystals due to 1- to 10-keV noble gas ion bombardment”,* 1965, Physical Review, Vol. 139, pp. A729-A736
3. **Zalm, P.C. and Beckers, L.J.** “*Ion-induced secondary electron emission from copper and zinc”,* 1985, Journal of Surface Science, Vol. 152, pp. 135-141
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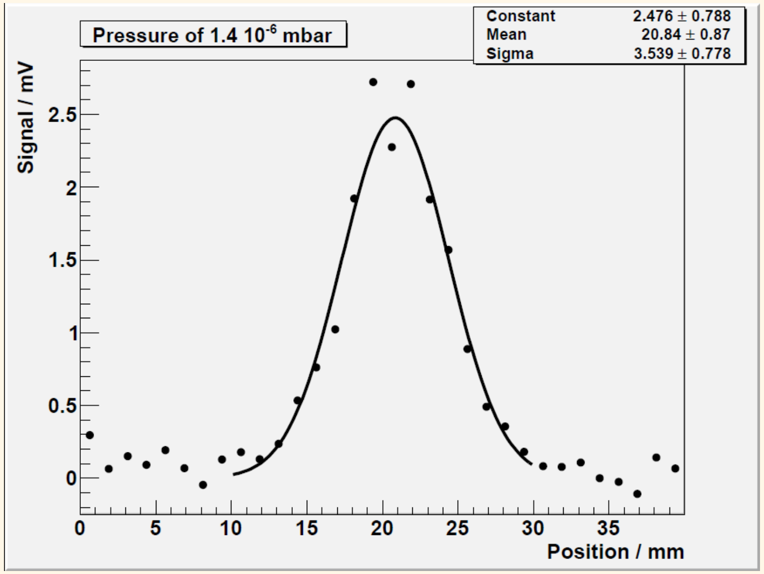
High Current Test

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

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

lowest current measurable at IFMIF:



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

❖Z^2 dependence of ionization cross section:

30 μA $^{48}Ca^{10+}$ ⇔ 300 μA D^+

❖ pressure scaling:

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

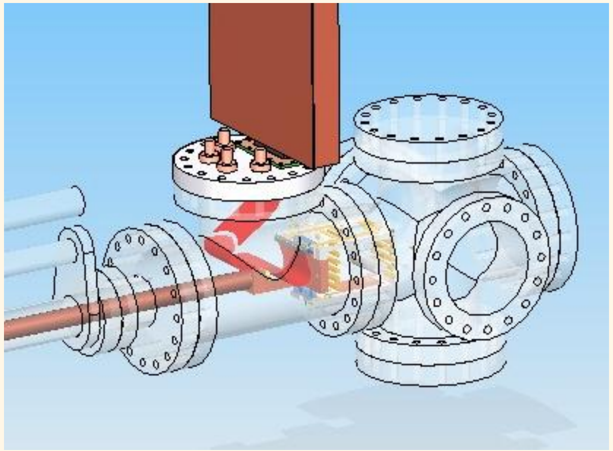
or

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

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