Ionization Profile Monitors at GSI

Darmstadt, 22nd of November 2018

Peter Forck

Gesellschaft für Schwerionenforschung (GSI)

IPM development, realization, DAQ, simulation, analysis by:

Tino Giacomini: Complete technical realization

Mariusz Sapinski: Supervising code *Virtual-IPM*, experiences from CERN

Rahul Singh: Experimental data analysis

Dominik Vilsmeier: Complete work on *Virtual-IPM*

(Mariusz Sapinski, Rahul Singh, Dominik Vilsmeier: machine learning)

Andreas Reiter, Timo Milosic & Thomas Sieber: CRYRING IPM

BID-Group: Technical realization, DAQ

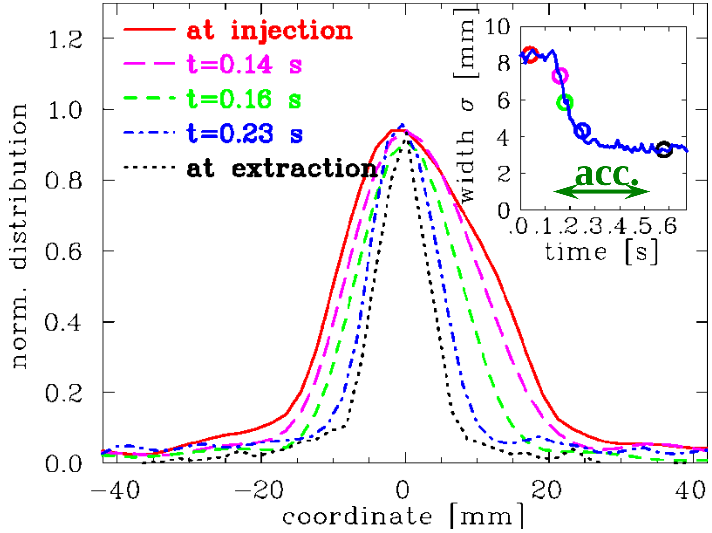
Users & operators: Proposal for improvements

Wish list for Profile Measurements

Ideal profile measurements at a synchrotron should fulfill:

- Completely non-destructive for the beam
- Direct measurement to ensure reliability
- High spatial resolution e.g. $\approx \sigma_{beam}$ /5
- Emittance evaluation via $\sigma_{beam} = \sqrt{\varepsilon \cdot \beta}$
- High time resolution e.g. down to one turn of ≈ 1 μs
- Reliable data reduction to display relevant information
- Online data presentation without time delay
- Easy-to-use GUI for operation
- Available from accelerator commissioning to regular operation

Example: Accel. at SIS18 for C^{6+} from 6.7→ 600 MeV/u



Outline of the talk:

- Principle of Ionization Profile Monitors IPM
- Technical realization at ESR, SIS18 and for FAIR
- Some basic & advanced measurements
- Requirements for magnetic field, realization at SIS18 and for SIS100
- Simulations for disturbing effects
- IPM at CRYRING and BIF at UNILAC
- Conclusion

Ionization Profile Monitor: Principle

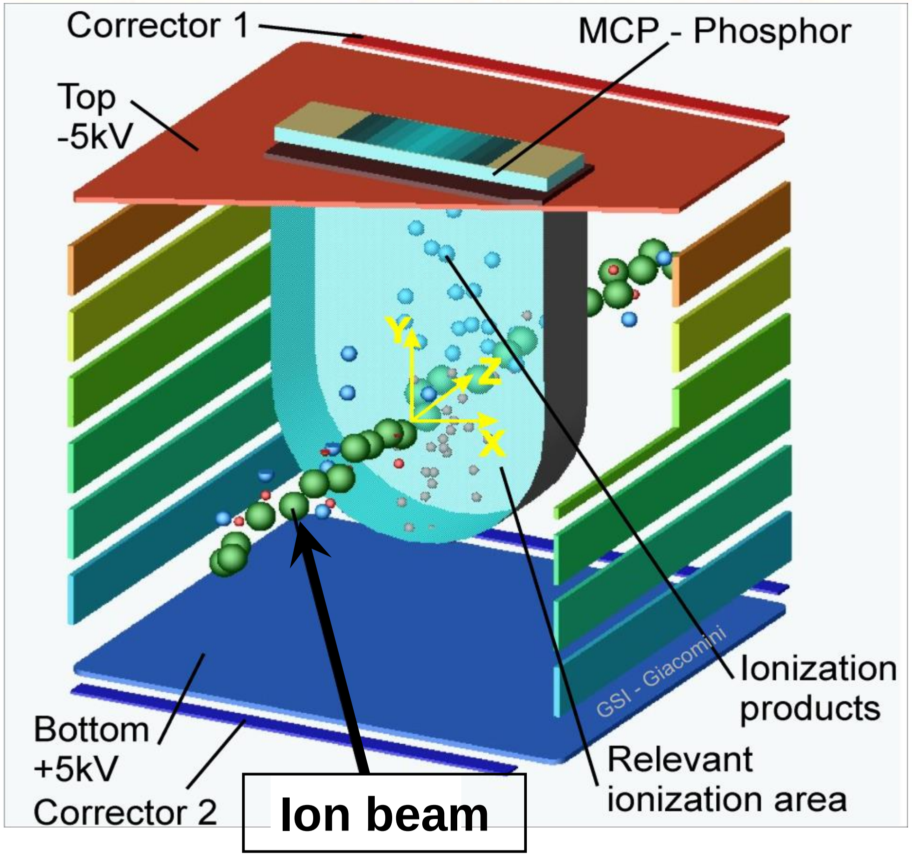
Idea: Ionization of residual gas
& spatial resolved detection

Detection scheme:

- Secondary e⁻ or ions accelerated by E-field electrodes & side strips E≈ 50… 300 kV/m

⇒ **'4π-detection scheme'** for as ions or electrons

- Single particle detection



Typical vacuum pressure:

Transfer line: $\boldsymbol{p} = 10^{-7}$ mbar

$\Leftrightarrow \quad \rho_{gas} = p/k_B T = 3 \cdot 10^{9}$ cm^{-3}

Synchrotron: $\boldsymbol{p} = 10^{-11}$ mbar

$\Leftrightarrow \quad \rho_{gas} = 3 \cdot 10^{5}$ cm^{-3}

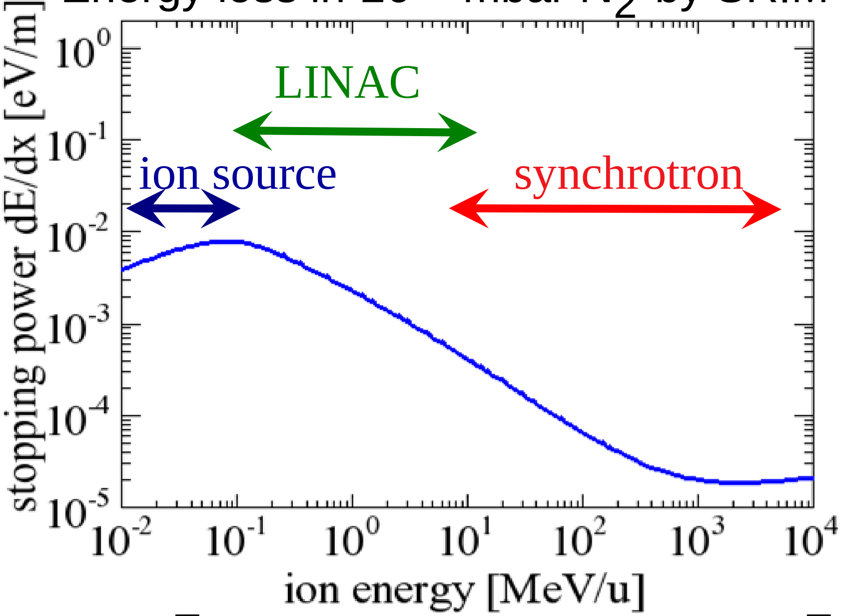
'Typical' beam density at SIS18:

10^{10} ions, de-bunched, $\sigma_{beam} = 3$ mm $\Rightarrow \rho_{beam} = 1.3 \cdot 10^{6}$ cm^{-3} (equivalent KV-distribution)

Courtesy T. Giacomini (GSI)

Expected Signal Strength for IPM and BIF-Monitor

Physics:
Energy loss of ions in gas *dE/dx*
⇒ Profile determination from residual gas
➢ Ionization:
in average roughly ≈ 100 eV/ionization



Ionization probability proportional to *dE/dx* by Bethe-Bloch formula:

$$-\frac{dE}{dx} = \text{const} \cdot \frac{Z_t \cdot \rho_t}{A_t} \cdot Z_p^{\,2} \cdot \frac{1}{\beta^2} \cdot \left[\ln\left(\text{const} \cdot \frac{\gamma^2 \beta^2}{W_{max}} \right) - \beta^2 \right]$$

Target electron density:
Proportional to vacuum pressure
⇒ Adaptation of signal strength

∝ 1/E_{kin} (for E_{kin} > 1GeV nearly constant)

Expected Signal Strength for IPM and BIF-Monitor

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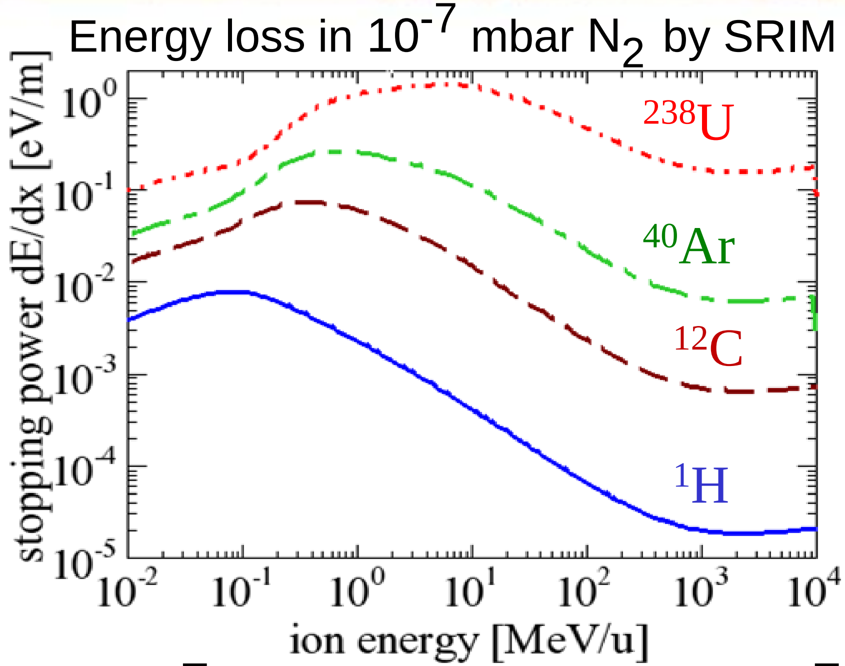

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Target electron density:
Proportional to vacuum pressure
⇒ Adaptation of signal strength

$\propto 1/E_{kin}$ (for $E_{kin} >$ 1GeV nearly constant)

Strong dependence on projectile charge for ions $Z_p^{\,2}$

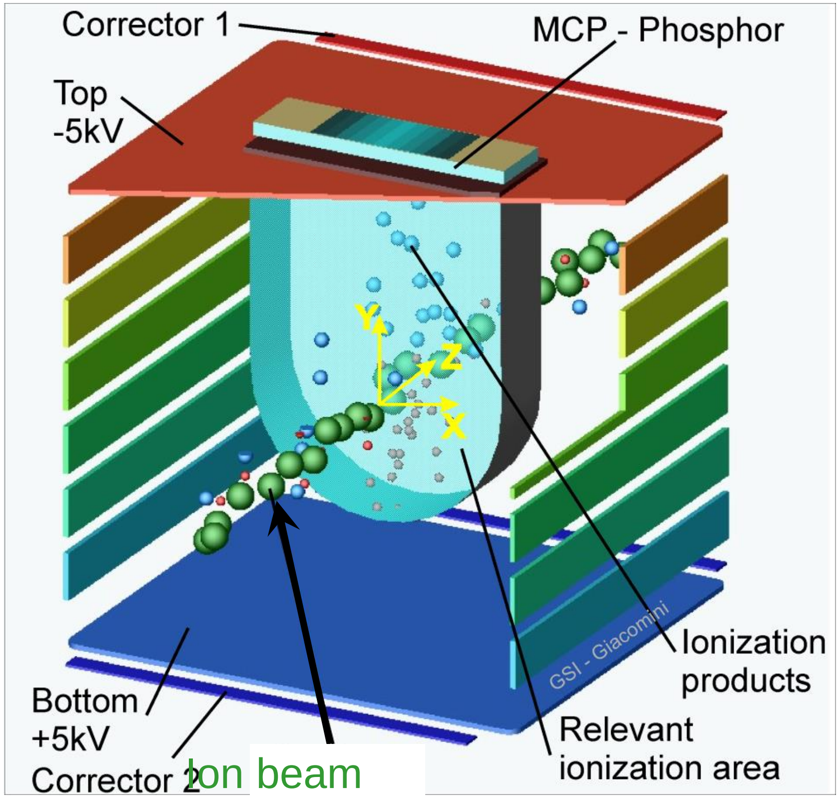
Modification proton ↔ ions: $Z_p(E_{kin})$. Charge equilibrium is assumed for *dE/dx*

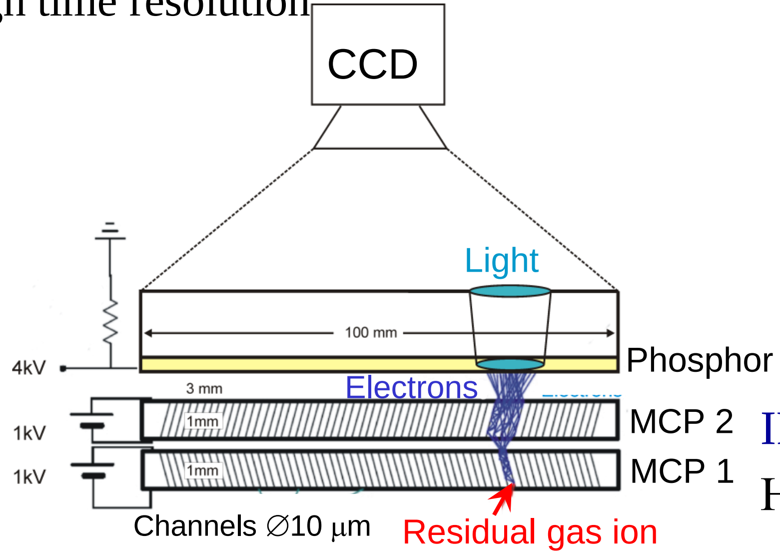
Ionization Profile Monitor: Principle

Advantage: '4π-detection scheme' for ionization products

Detection scheme:

- Secondary e⁻ or ions accelerated by E-field electrodes & side strips E≈ 50… 300 kV/m
- MCP (Micro Channel Plate) electron converter & 10^6-fold amplifier
- *either* Phosphor screen & CCD
  → high spatial resolution of 100 μm
- *or* wire array down to 250 μm pitch
  → high time resolution





IPMs are installed in nearly all synchrotrons

However, no 'standard' realization exists!

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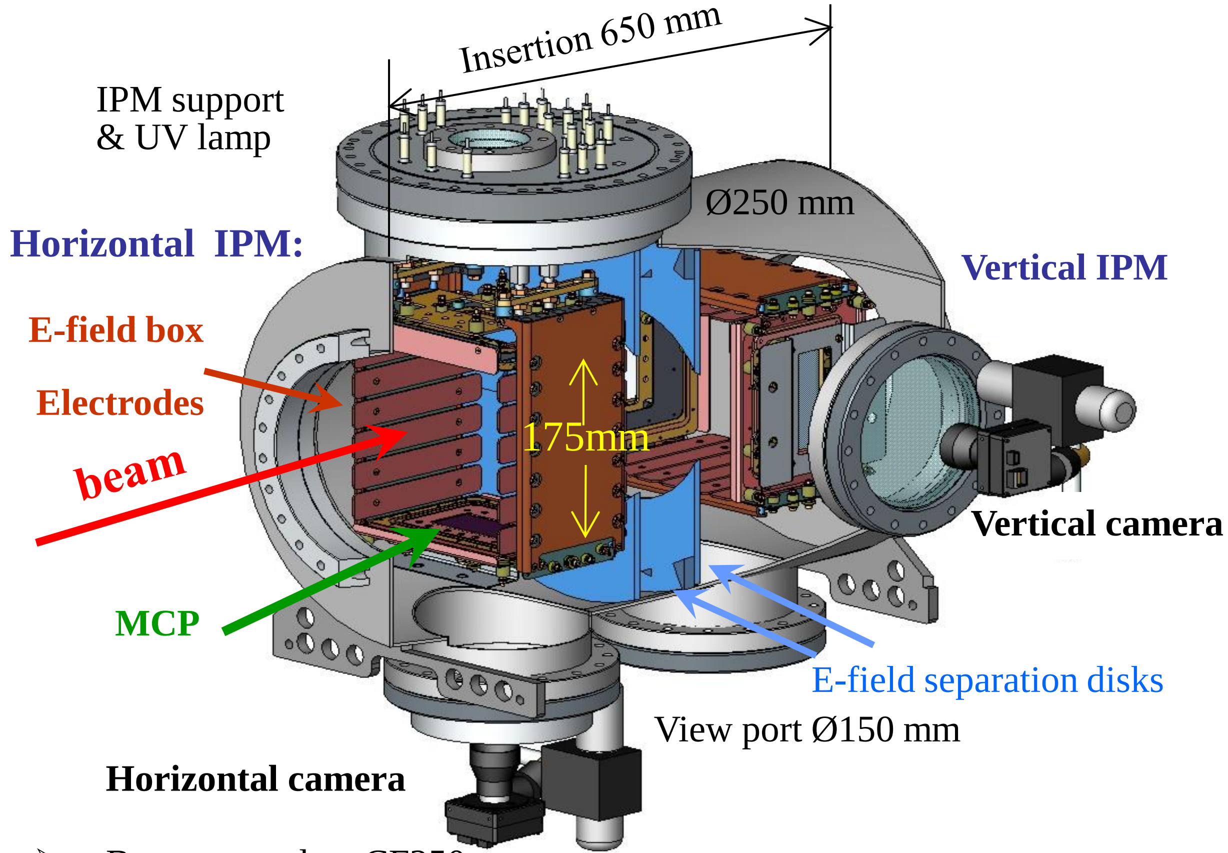
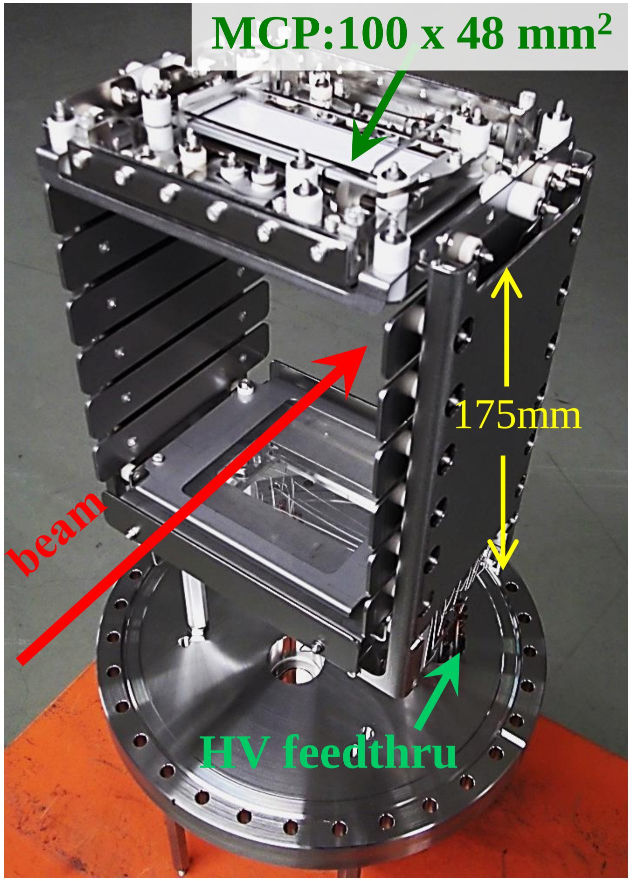
Ionization Profile Monitor Realization at ESR

The detector hardware at ESR:

Realization at ESR:



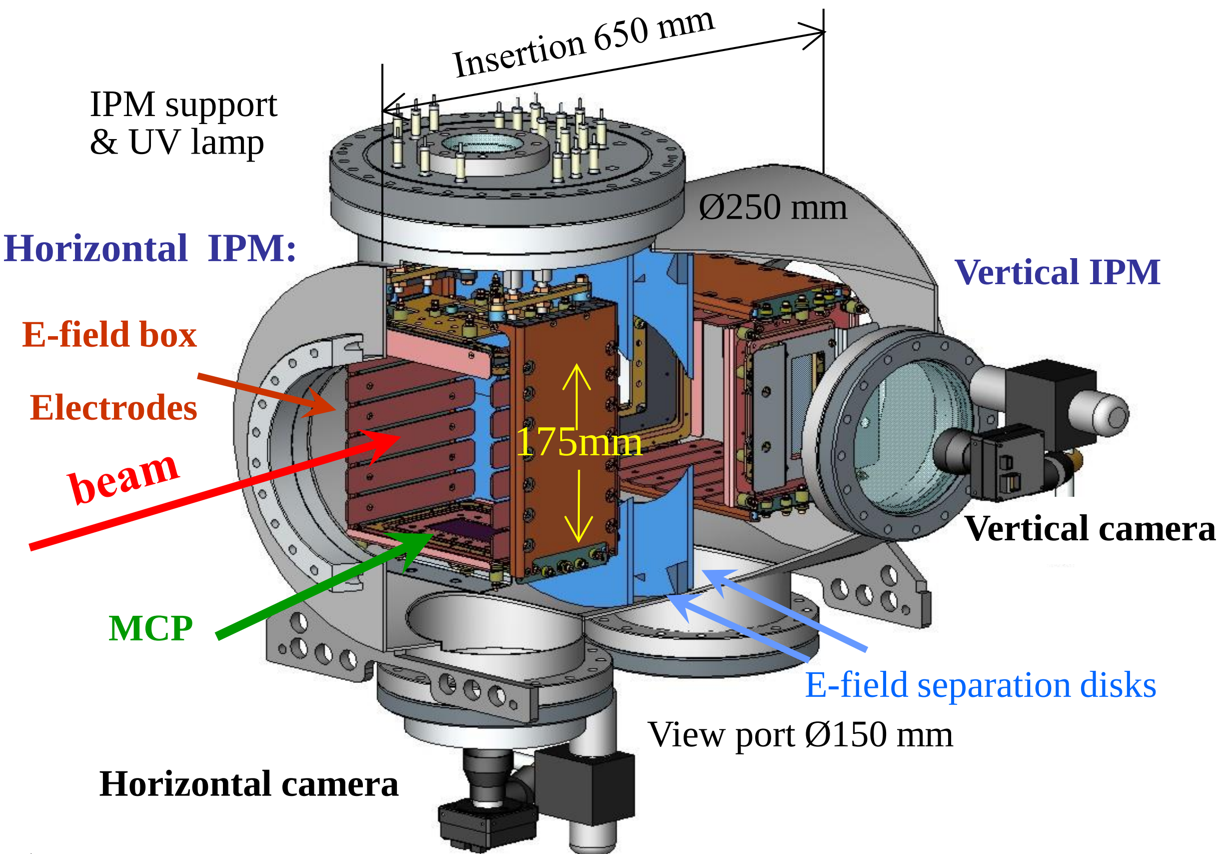


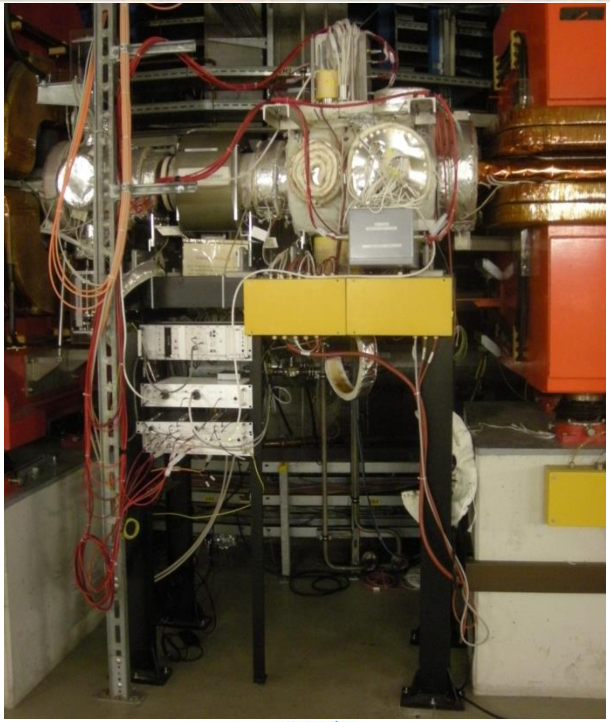
- Box mounted on CF250
- Readout by camera through CF100 viewport
- MCP size : 100 x 48 mm^2
- E-field 0.65 kV/cm (6 kV at both sides)

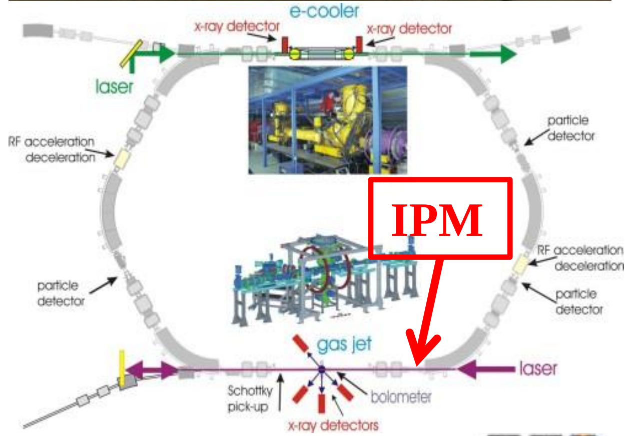
Care: For low energies, significant kick to the beam

Ionization Profile Monitor Realization at ESR

The detector hardware at ESR:







- Box mounted on CF250
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- MCP size : 100 x 48 mm^2
- E-field 0.65 kV/cm (6 kV at both sides)

Ionization Profile Monitor Realization at ESR: DAQ

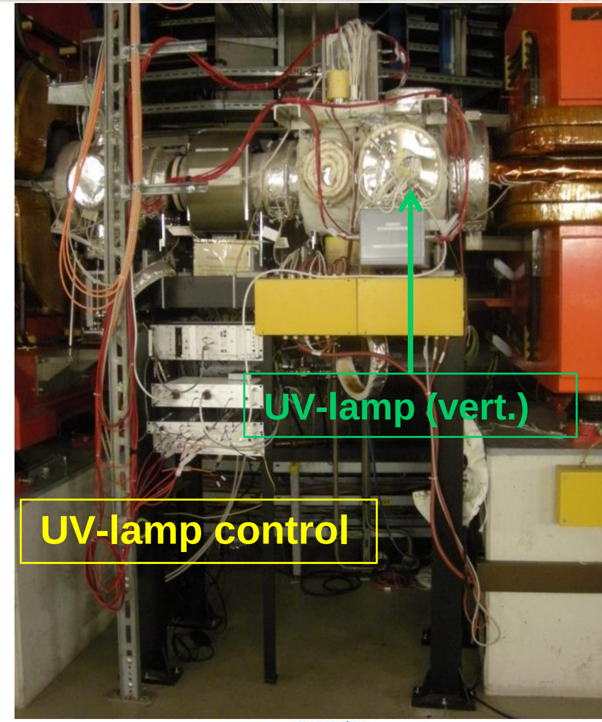
The DAQ realization at ESR at GSI:

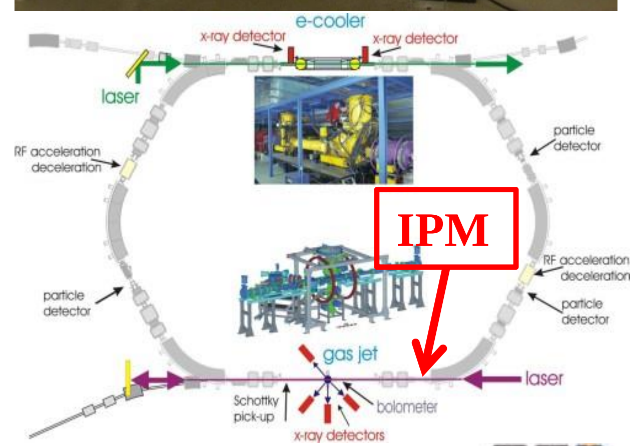
- Camera with GigE IDS µEye (CMOS)
  typical readout rate 5 frames/s for online observation
- Digitalization in PC
- High voltage supplier
- Control of voltages, UV lamp

Front-end slow control & UV-lamp

PC with GigE card

HV power supplier

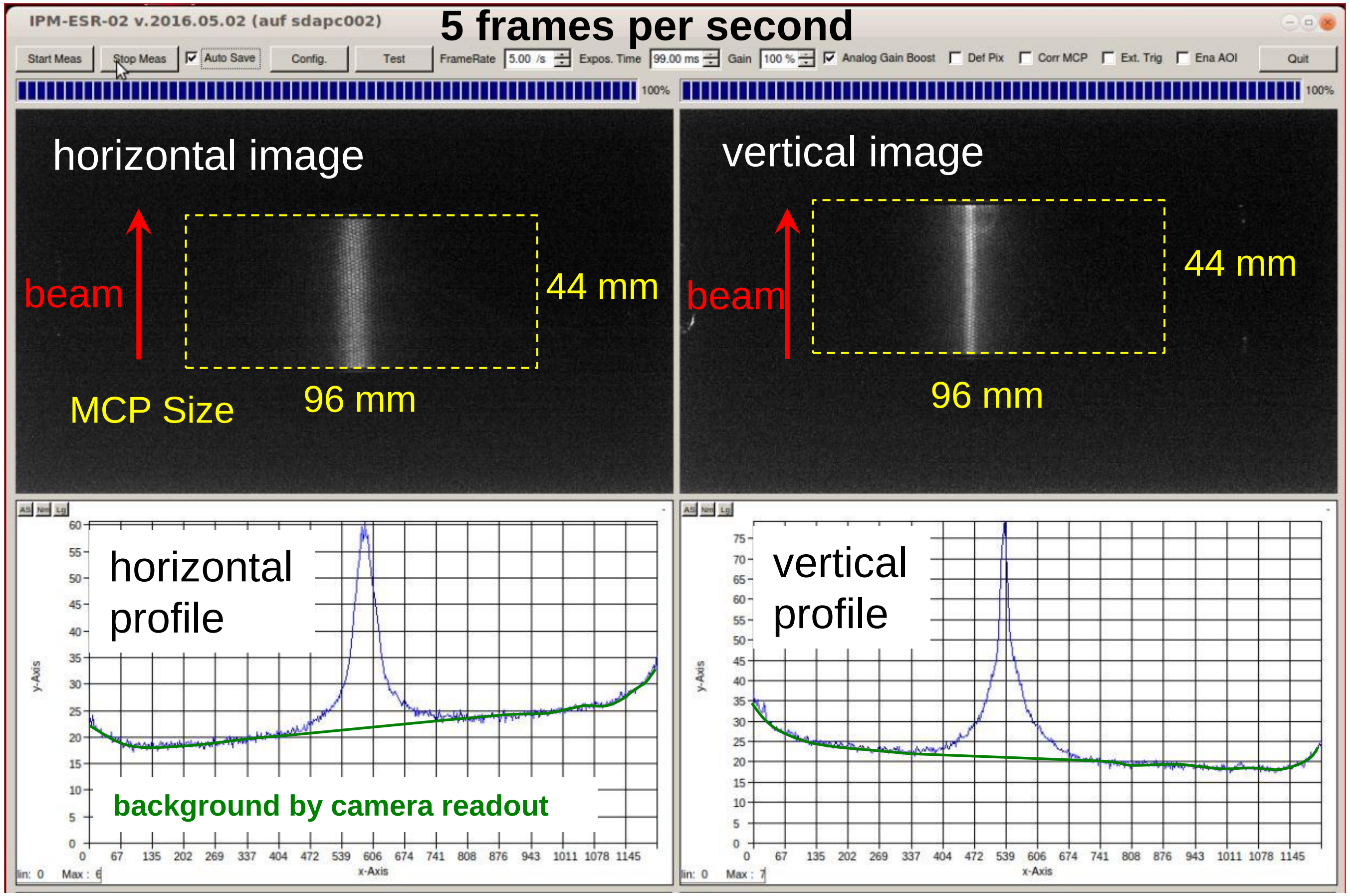




Courtesy T. Giacomini (GSI)

Ionization Profile Monitor Realization at ESR: Result

Camera readout, actual max. 8 frames/s, usage with typically 1 frame/s for cooling observation



Beam:
U @ 300 MeV/u

Status: ➢ Hardware completely installed and tested
➢ FESA DAQ started, but not GUI
➢ Can be used for profile observation (slow readout) with Qt-based software

Ionization Profile Monitor at SIS18

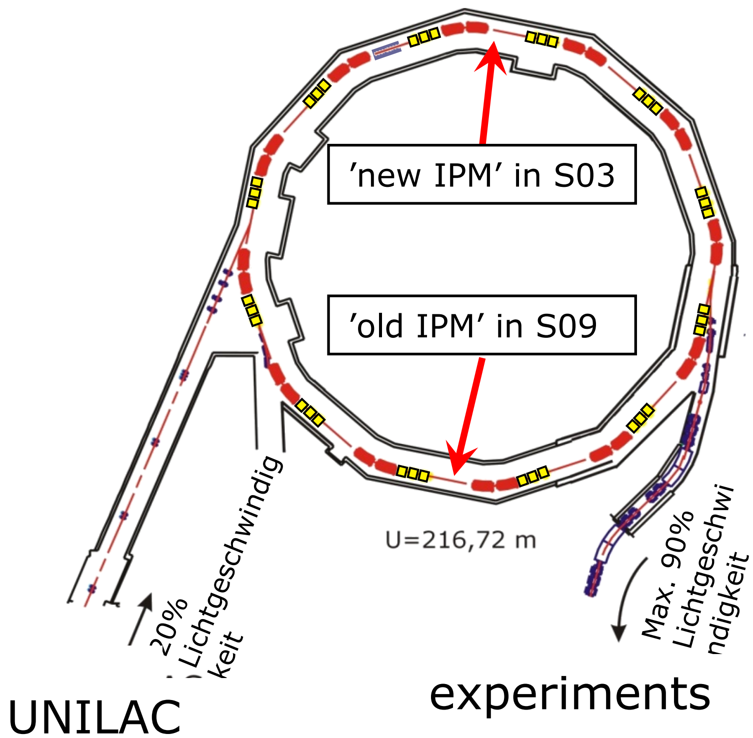
The realization at SIS18,'**old** IPM' at S09:

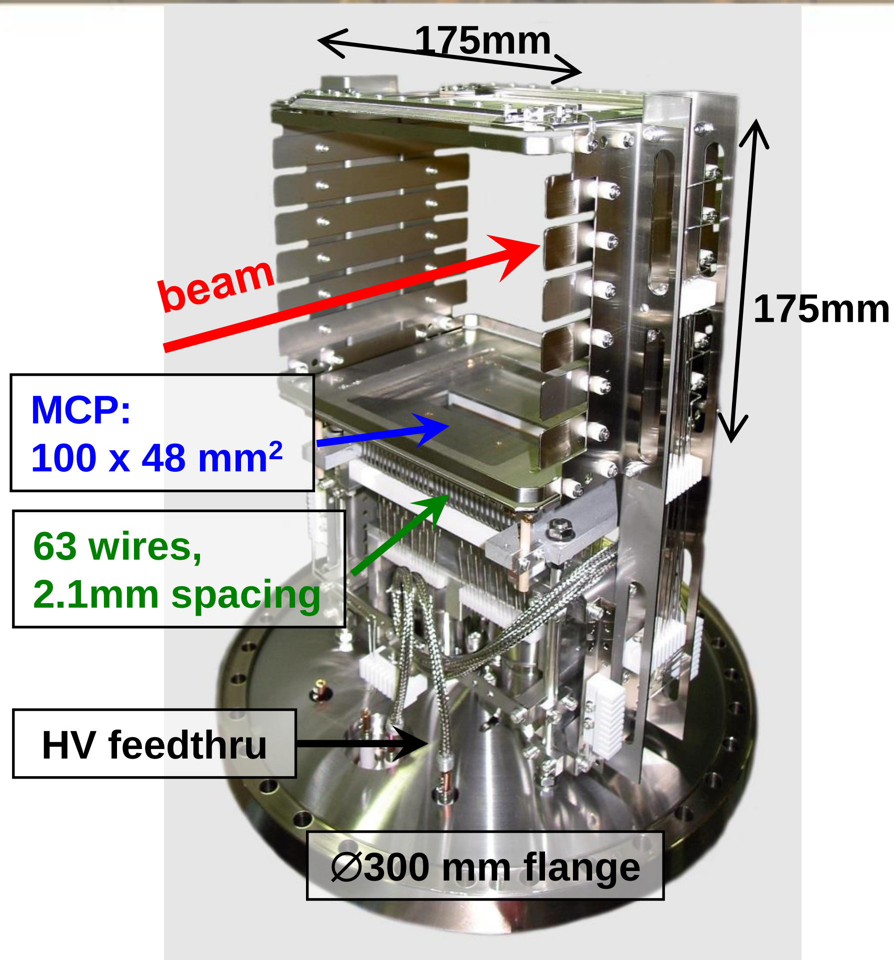
Electric field: 0.68 kV/cm (6 kV both sides)

MCP size: 100 x 48 mm^2

Wire array: ∅ 0.6 mm wires, 2.1 mm pitch

Electronic readout: I/U converters for each wire





Ionization Profile Monitor at SIS18

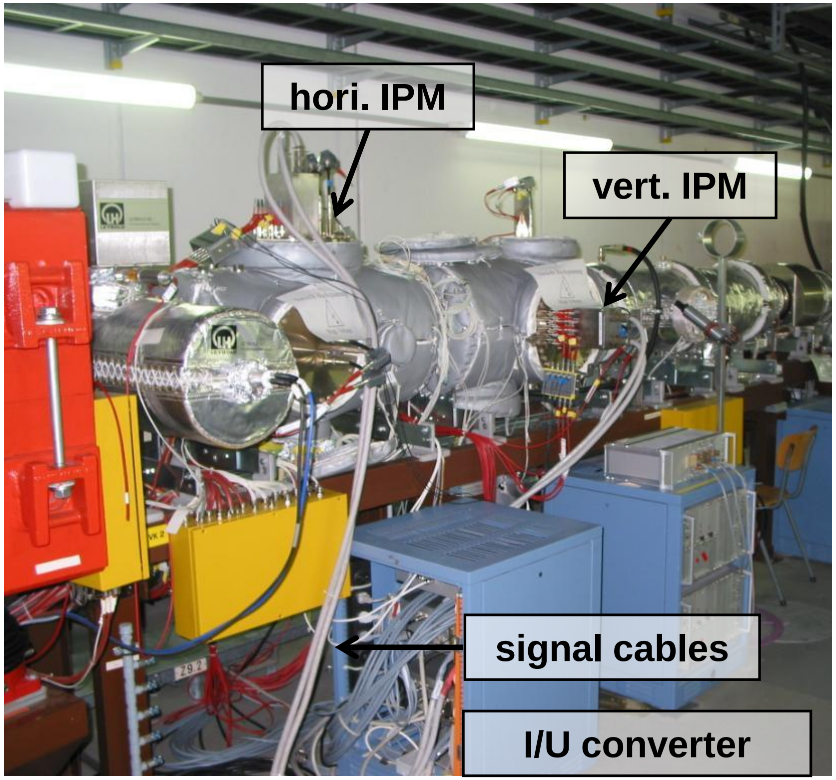
The realization at SIS18 ‘**old** IPM’ in S09:

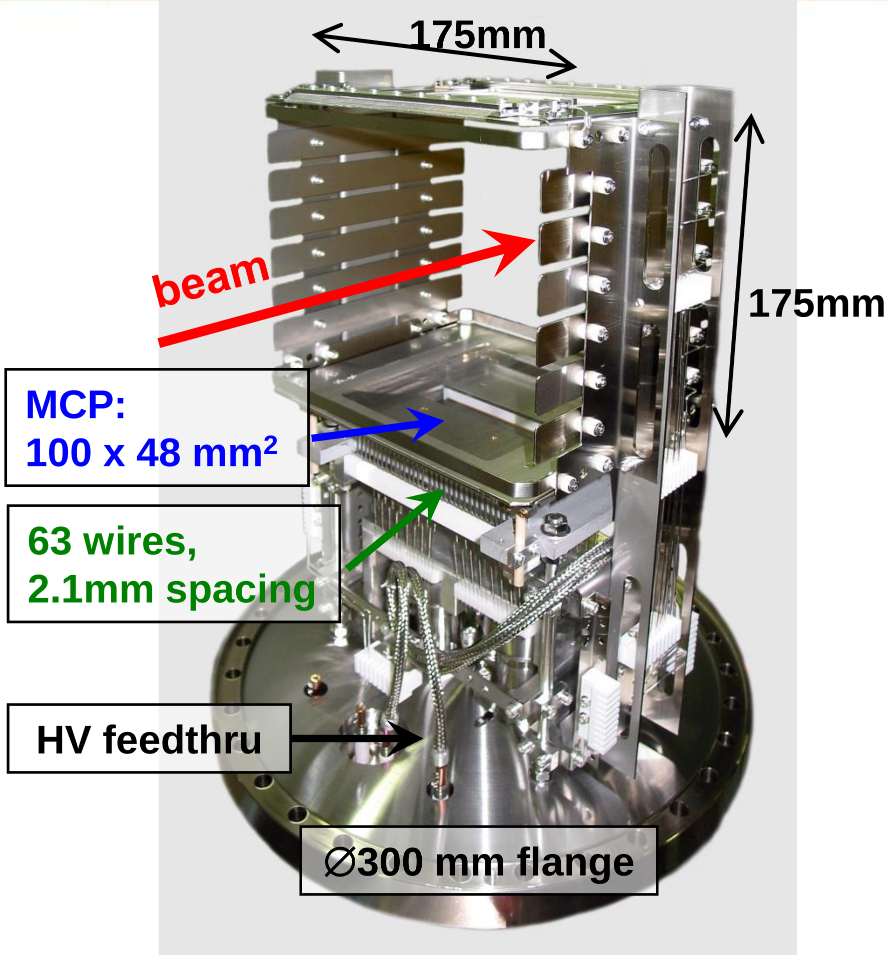
Electric field: 0.68 kV/cm (6 kV both sides)

MCP size: 100 x 48 mm^2

Wire array: ∅ 0.6 mm wires, 2.1 mm pitch

Electronic readout: I/U converters for each wire





Ionization Profile Monitor at SIS18: DAQ

The realization at SIS18 ‘**old** IPM’ in S09:

Electric field: 0.68 kV/cm (6 kV both sides)

MCP size: 100 x 48 mm^2

Wire array: ∅ 0.6 mm wires, 2.1 mm pitch

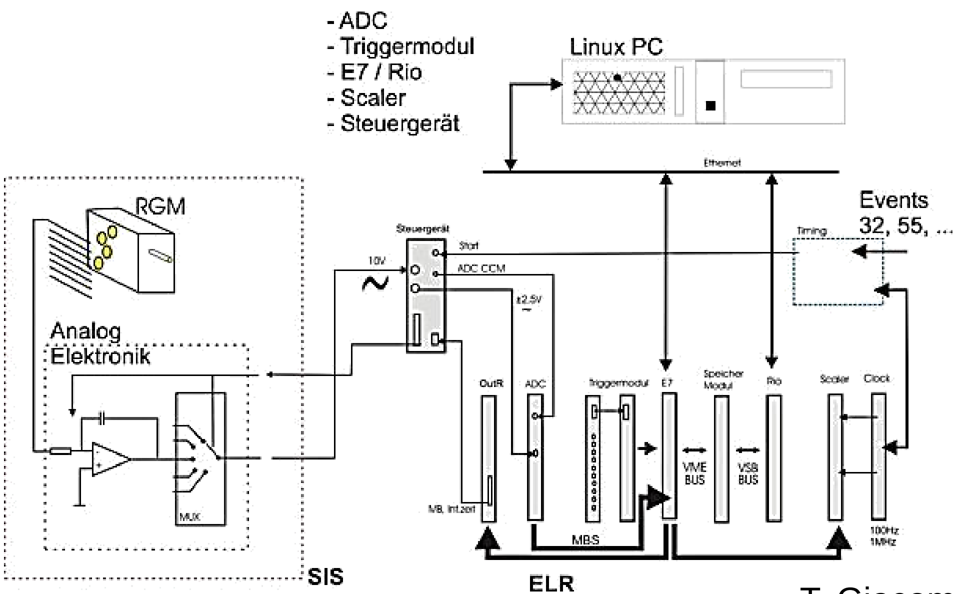
Electronic readout: I/U converters for each wire

Digitalization: VME ADC by (outdated) MBS

Readout performance: 100 profiles/s

⇒ **stable operation with reasonable time resolution**

⇒ **but limited spatial resolution**



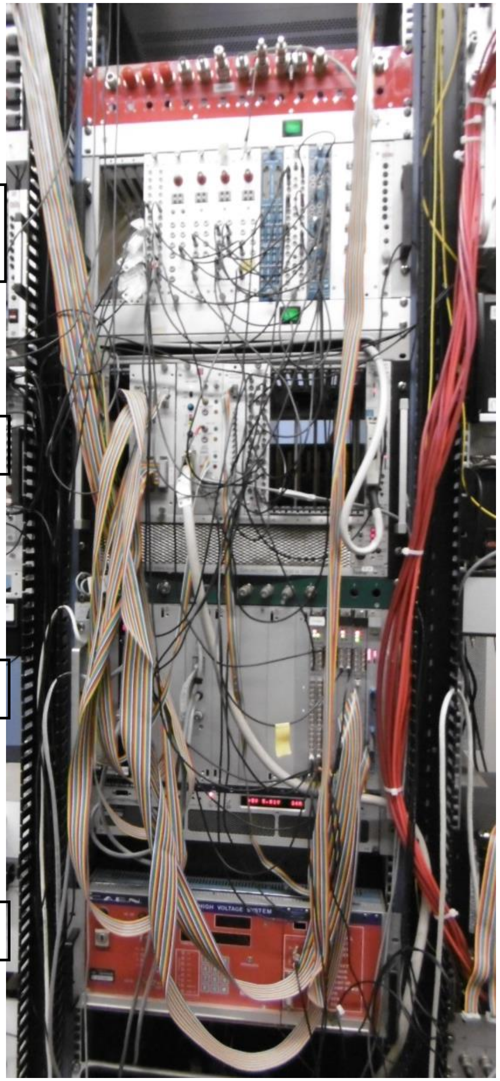
T. Giacomini et al., DIPAC 2011

Timing
installed ≈15 years ago

Control of front-end I/U

VME with ADC

HV power supplier



Ionization Profile at SIS18: Control

The realization at SIS18 ‘**old** IPM’ in S09:

Electric field: 0.68 kV/cm (6 kV both sides)

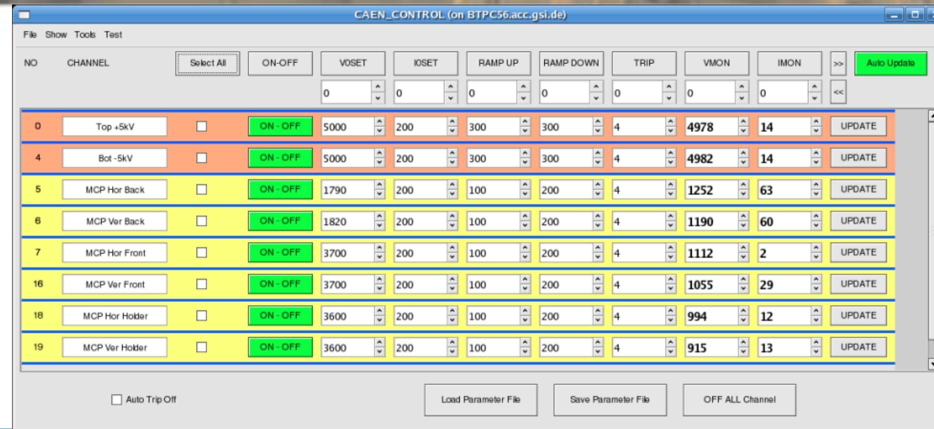
MCP size: 100 x 48 mm^2

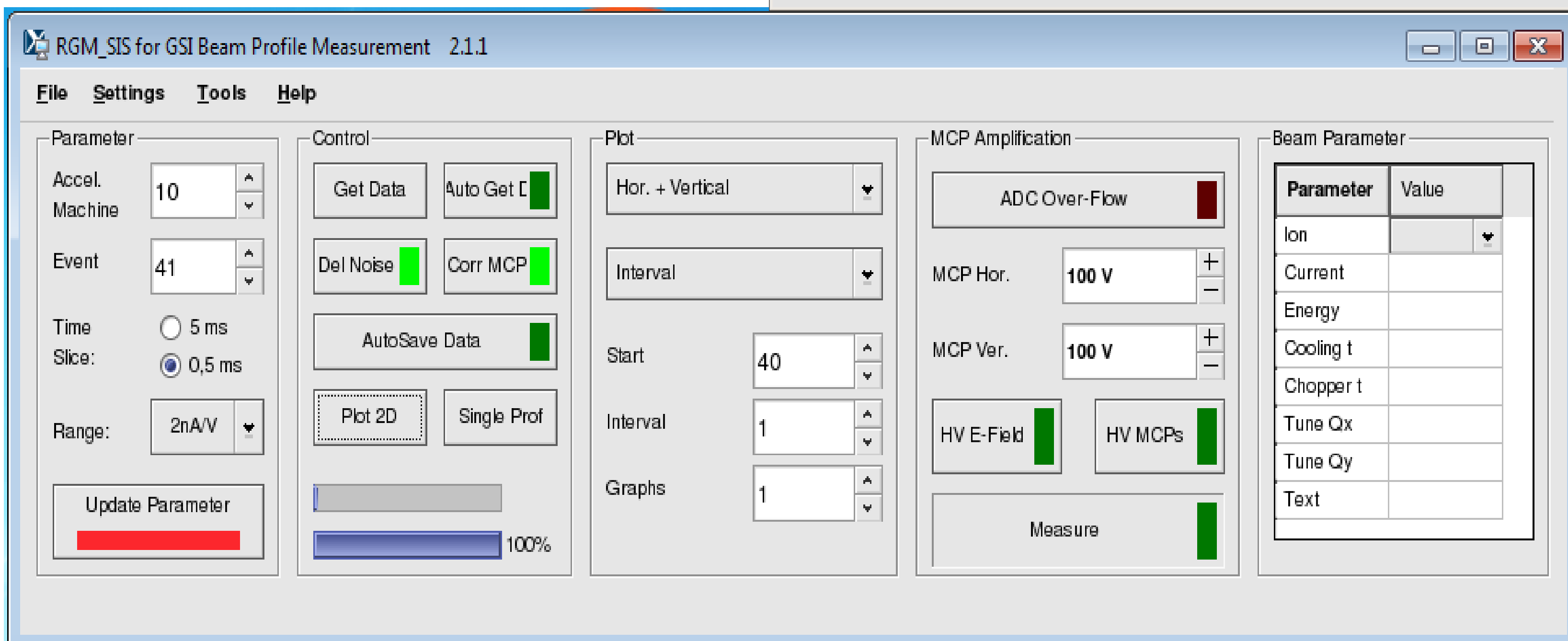
Wire array: ∅ 0.6 mm wires, 2.1 mm pitch

Electronic readout: I/U converters for each wire

Digitalization: VME ADC by (outdated) MBS

Readout performance: 100 profiles/s





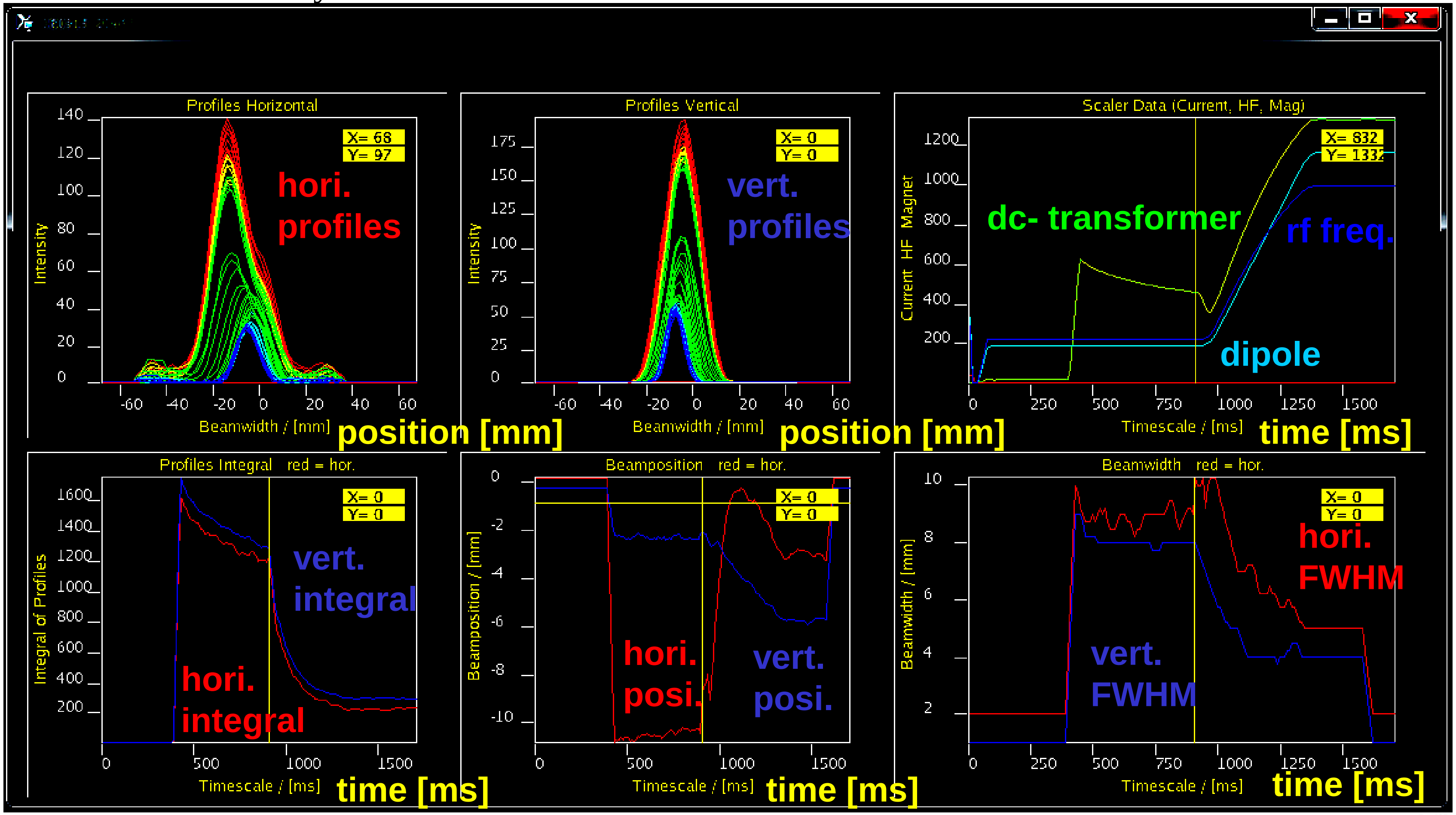
Ionization Profile at SIS18: Data Presentation

The GUI for SIS18 '**old** IPM':

Example for:
- 7.8 ·10^9 Ar^{18+} ions
- 11.4 → 350 MeV/u
- 1.7 s cycle

Status:
- Operational since many years
- Presently some network problems for MBS

⇒ Can be used by operators



Courtesy T. Giacomini (GSI)

Ionization Profile Monitor Realization at SIS18 'new IPM'

The realization at SIS18 '**new** IPM':

Electric field: 0.88 kV/cm (8 kV each side)

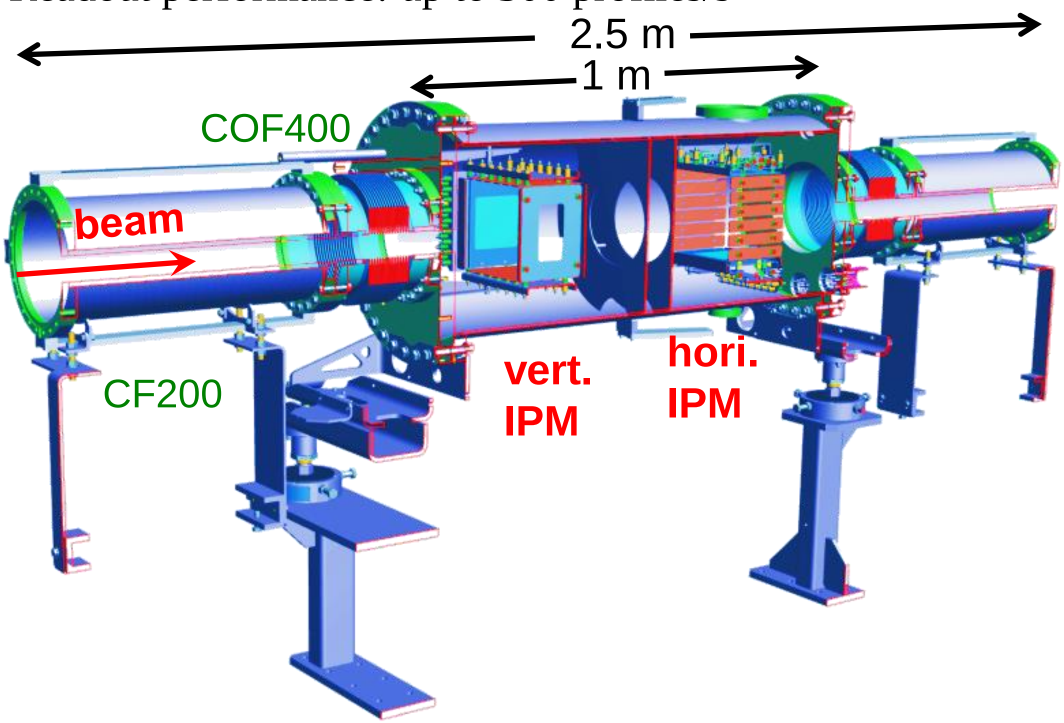
MCP size: 100 x 48 mm^2

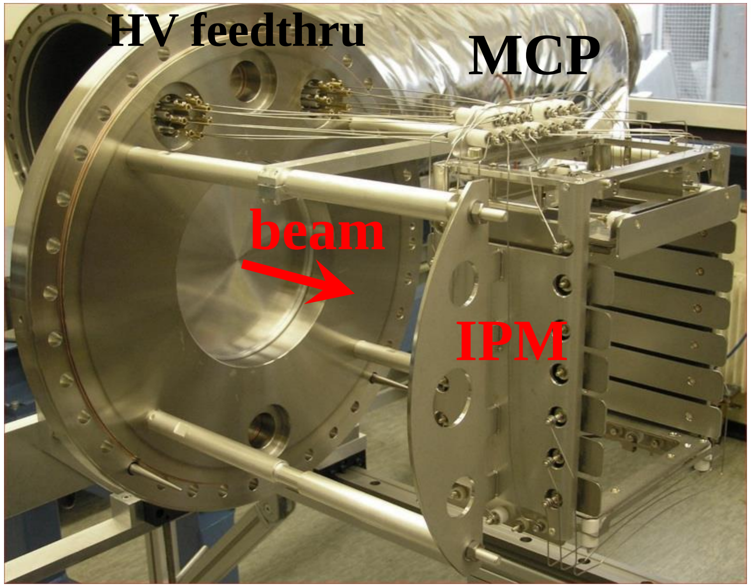
Phosphor: P47, $\tau \approx$ 100 ns decay time, blue emission

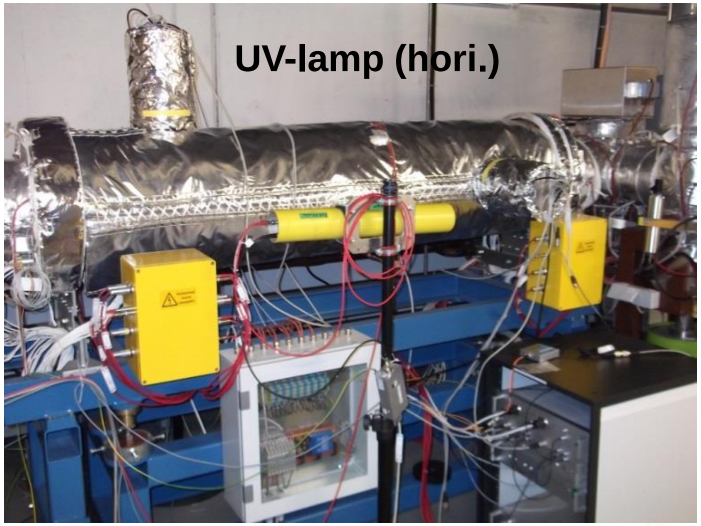
Digitalization: GigE camera AVT Mako G030

Interface to FESA

Readout performance: up to 300 profiles/s







Courtesy T. Giacomini (GSI)

Ionization Profile Monitor Realization at SIS18: DAQ

The realization at SIS18 ‘**new** IPM’:

Electric field: 0.88 kV/cm (8 kV each side)

MCP size: 100 x 48 mm^2

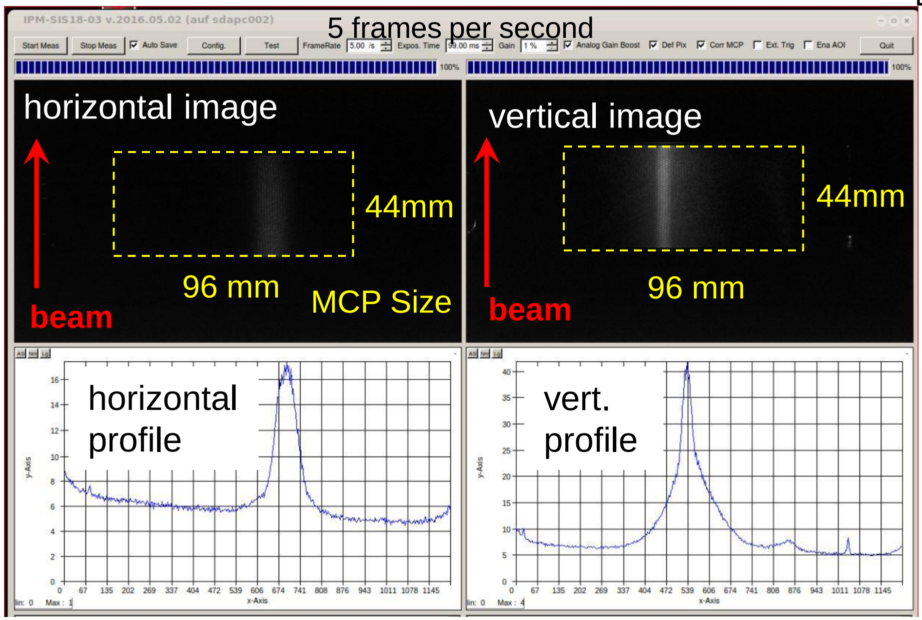
Phosphor: P47, $\tau \approx$ 100 ns decay time, blue emi.

Digitalization: GigE camera AVT Mako G030

Interface to FESA

Readout performance: up to 300 profiles/s

⇒ **high spatial resolution of 0.2 mm**



Beam: $^{238}U^{73+}$ at 300 MeV/u

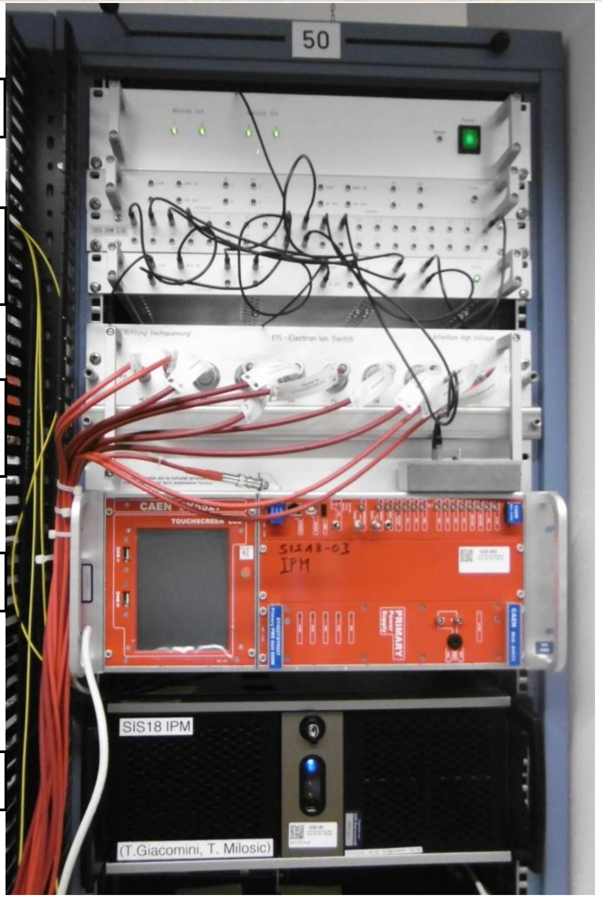
12 & 24 V power

Front-end slow control & UV-lamp

HV connection and switch ion to e⁻ detection

HV power supplier

PC with GigE card



Status:

- Hardware installed, but some problems
- 1st version of FESA DAQ produced, but no GUI
- Awaiting installation of magnets
- **Serves as prototype for SIS100**

Multi Channel Plate MCP

MCP are particle detectors with secondary electron multiplication

A MCP is:

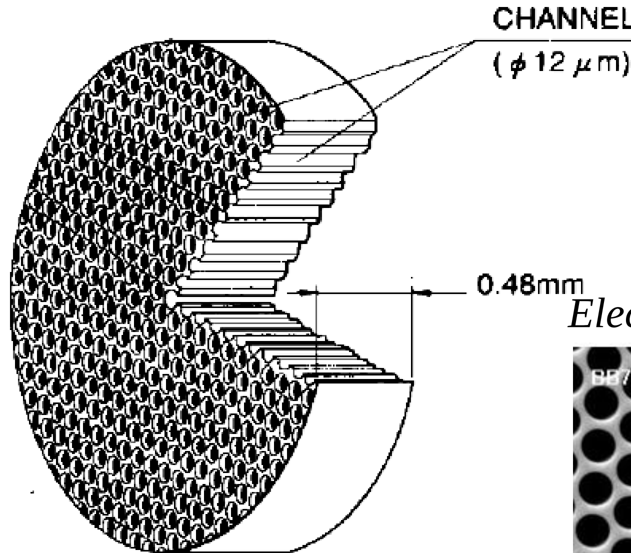
- 1 mm glass plate with ≈10 μm holes
- thin Cr-Ni layer on surface
- voltage ≈1 kV/plate across

→ e^- amplification of ≈ 10^3 per plate.

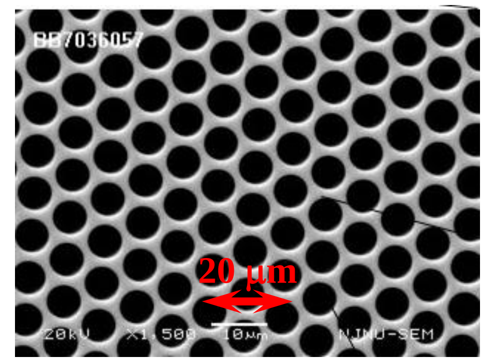
→ resolution ≈ 0.1 mm (2 MCPs)

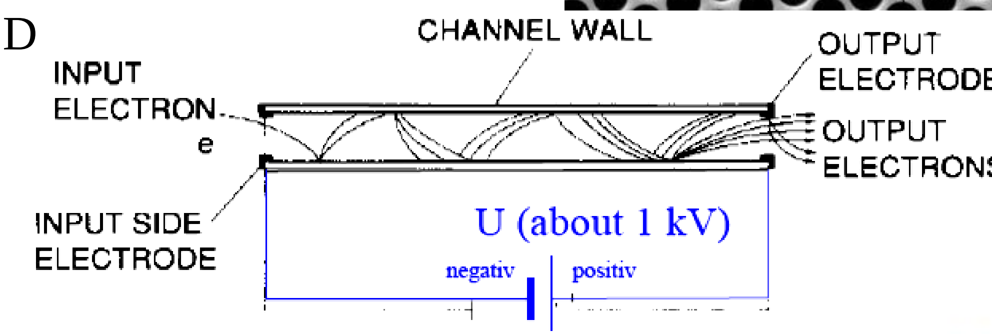
Anode technologies:

- **SIS18:** Grid 2.1 mm spacing
  → fast electronics readout possible
- **ESR & SIS18:** phosphor screen + CCD
  → high resolution, but slow timing
  → fast readout by photo-multipliers
- **CRYRING:** single particle detection
  → for low beam current.



Electron microscope image:

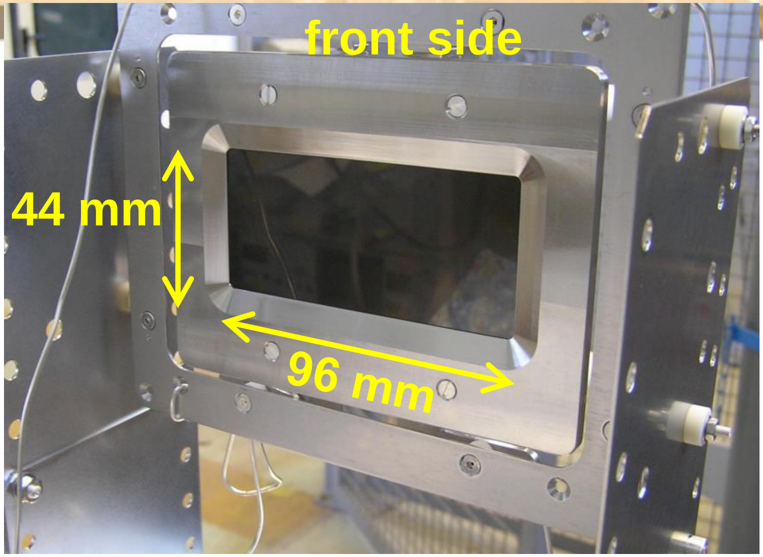


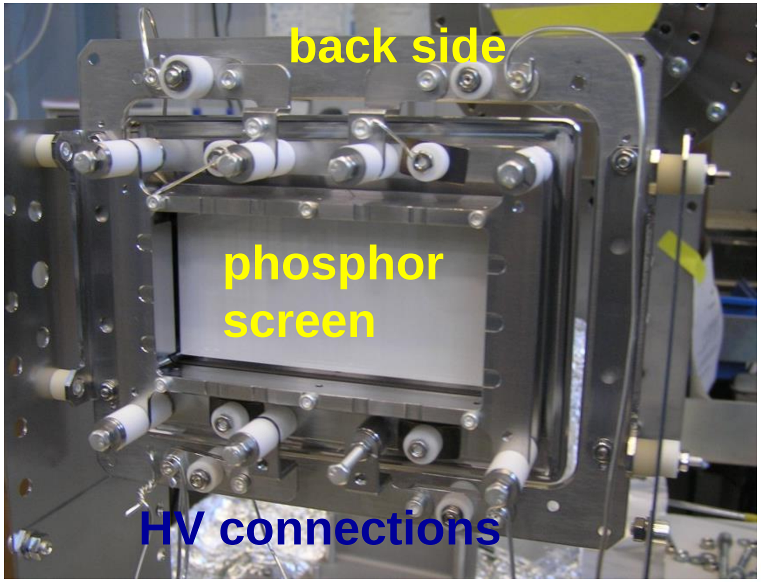


IPM: Multi Channel Plate MCP for ESR & SIS18

MCP Module with Phosphor screen:

- Two MCPs 100 x 48 mm^2
  ⇒ single particle detection
- P47, ≈ 100 ns decay time
  ⇒ turn-by-turn observation possible
- CMOS camera with GigE interface
- Future extension:
  fast readout with photo-detectors
  Photomultiplier or solid state SiPMT





Courtesy T. Giacomini (GSI)

MCP Inhomogeneity & Aging

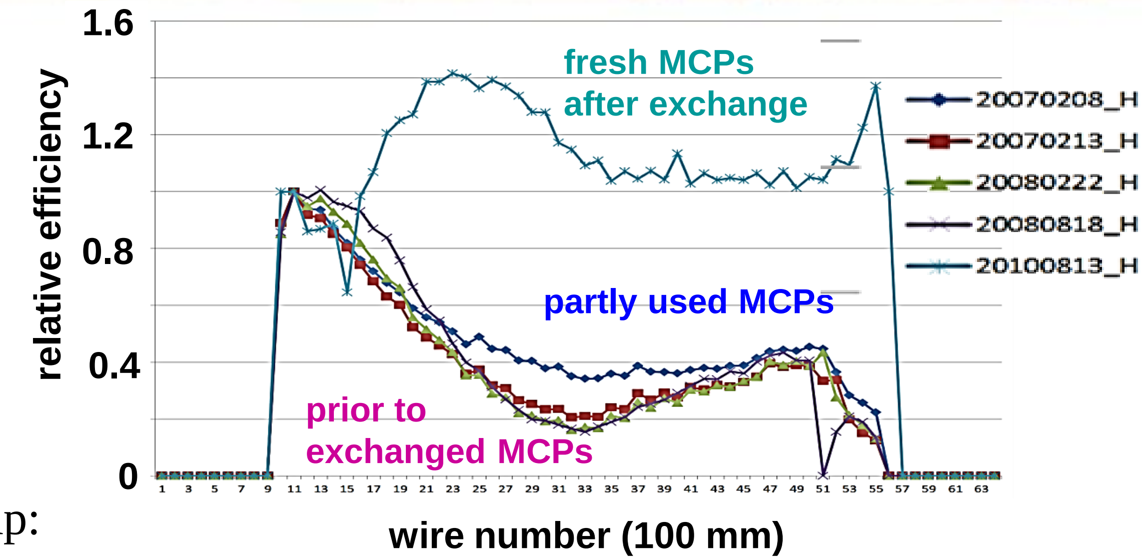
- **MCP efficiency:**

Inhomogeneity typically ±20 %

- **'MCP aging':**

Destruction of coating at MCP exit by electron bombardment

→ **exchange when reaching 30 %**

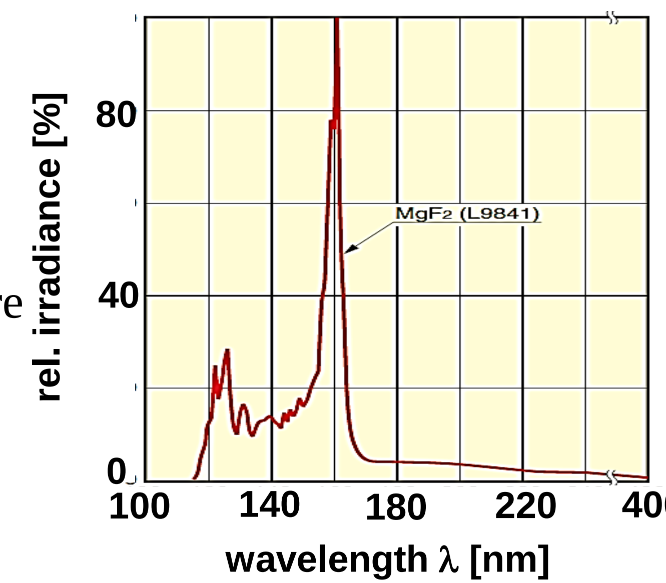


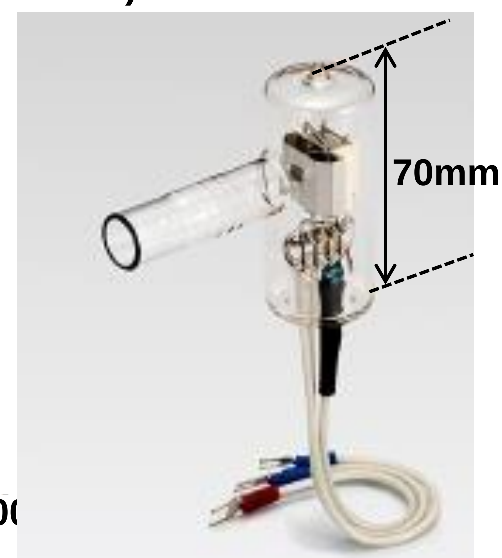
Cure → calibration:

Check of inhomogeneity by UV-lamp:

- Hamamatsu L2D2 lamp, wavelength down to λ = 115 nm
- Mounted outside of vacuum
- Regular calibration

⇒ Efficiency correction via software





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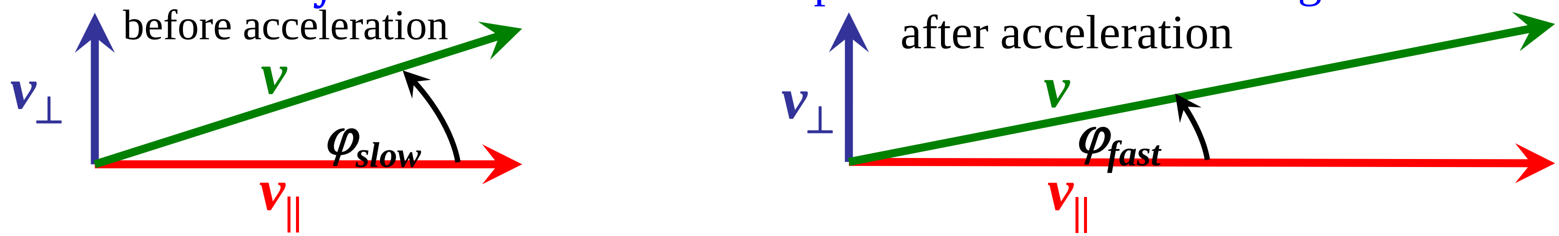
'Adiabatic' Damping during Acceleration

The emittance $\varepsilon = \int dx dx'$ is defined via the position deviation and angle in **lab-frame**



After acceleration the longitudinal velocity is increased $\Rightarrow$ angle φ is smaller

$\Rightarrow$ normalized emittance $\varepsilon_{norm} = \beta\gamma\cdot\varepsilon$ is preserved (Lorentz factor γ & velocity $\beta = v_\parallel/c$)

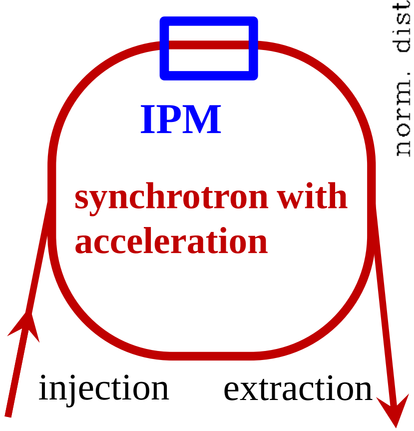
Example: Acceleration in SIS18 of C^{6+}

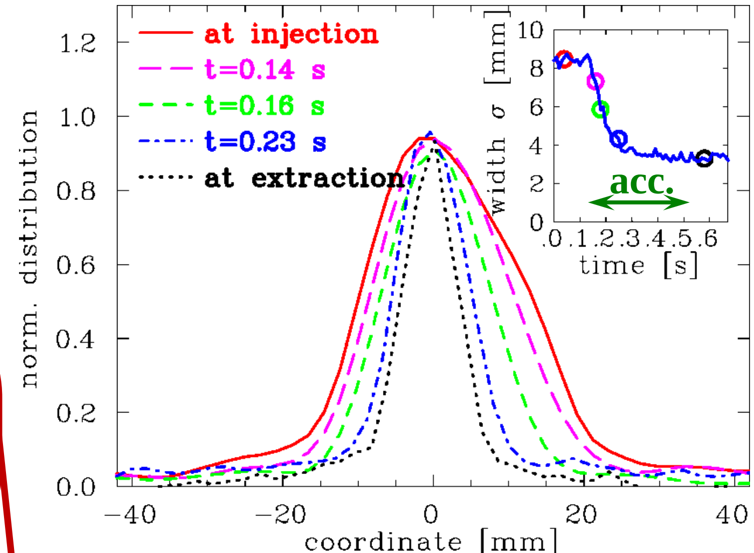
6.7 → 600 MeV/u (β = 12 → 79 %) observed by IPM

theoretical width: $\sigma_f = \sqrt{\frac{\beta_i \cdot \gamma_i}{\beta_f \cdot \gamma_f}} \cdot \sigma_i$

$= 0.33 \cdot \sigma_i$

measured width: $\sigma_f \approx 0.37 \cdot \sigma_i$





Emittance 'Control' via Chopped Injection

For a multi-turn injection the emittance can be controlled by beam chopping

Bumper magnet action:

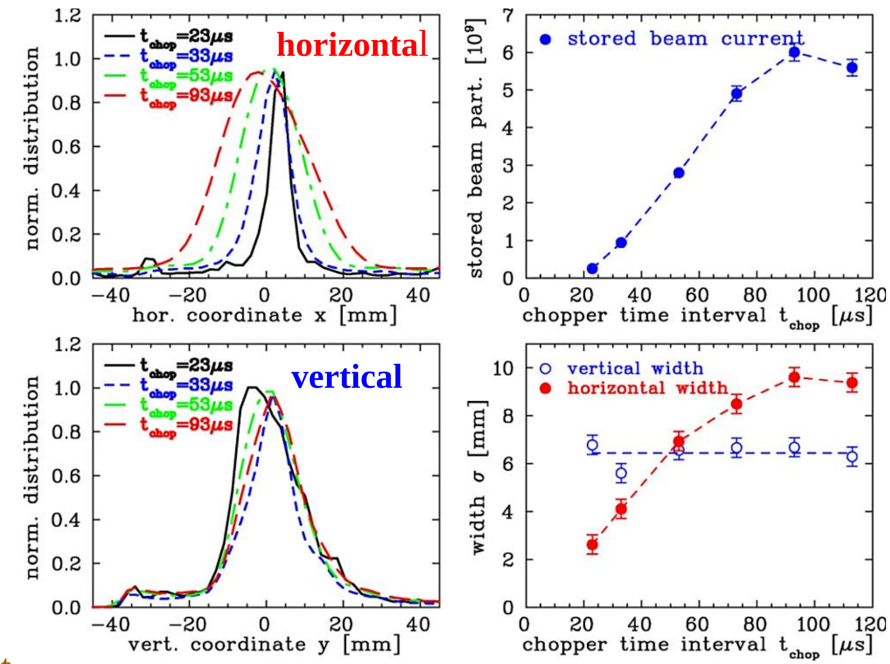
- First beamlet injected on central path
- Successive filling of 'outer' phase space

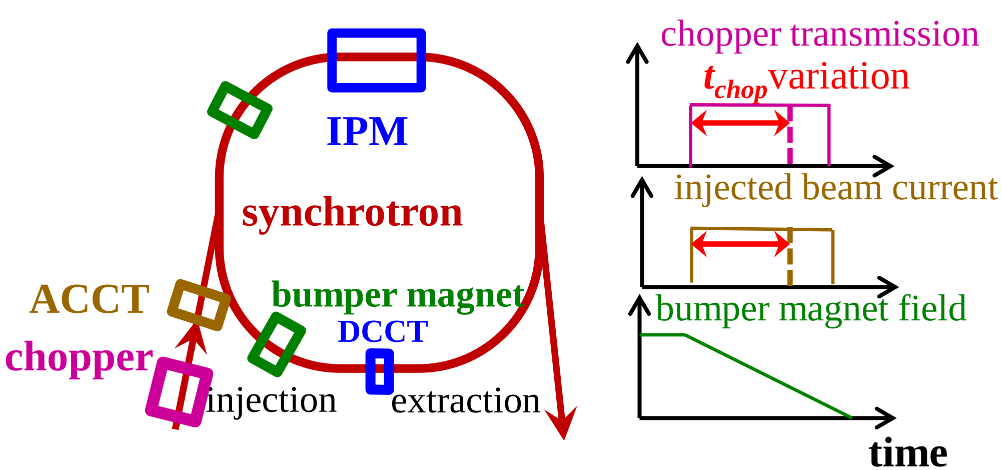
$\Rightarrow$ stored horizontal emittance varies

$\Rightarrow$ vertical emittance un-changed

$\Rightarrow$ injected current increase for longer t_{chop}

Example: C^{6+} at 6.7 MeV/u, up to $6\cdot10^9$ ions per fill with multi-turn injection at GSI synchrotron, 5µs/turn





Emittance Enlargement & hollow Beam by Injection Mis-steering

Emittance conservation requires precise injection matching

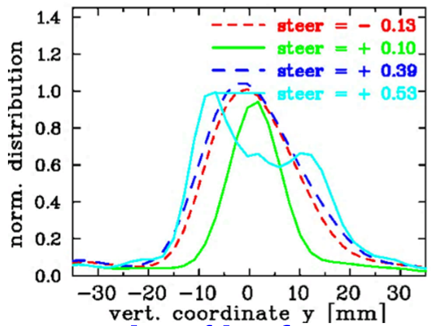
Wrong angle of injected beam:

- ➢ injection into outer phase space → large β-amplitude i.e. large beam
- ➢ might result in 'hollow' beam

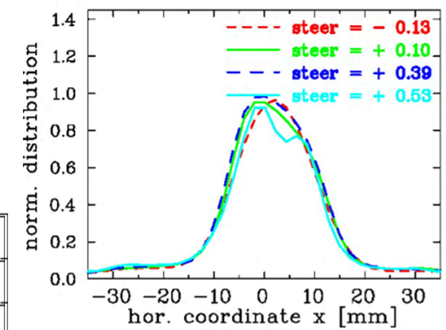
⇒ larger emittance after accel.

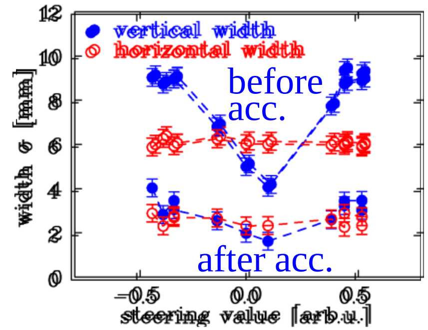
Example: Variation of vertical injection angle by magnetic steerer
Beam: C^{6+} at 6.7 MeV/u acc. to 600 MeV/u, up to $6\cdot10^{9}$ ions per fill
with multi-turn injection, IPM integration 0.5 ms i.e. ≈ 100 turns

Vertical profile **at** injection:

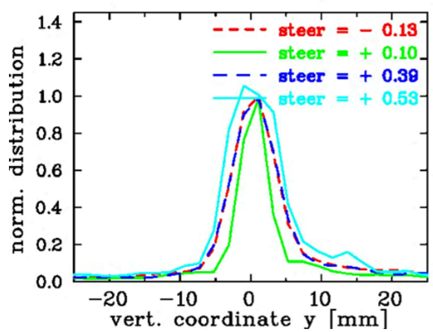


Horizontal profile **at** injection:

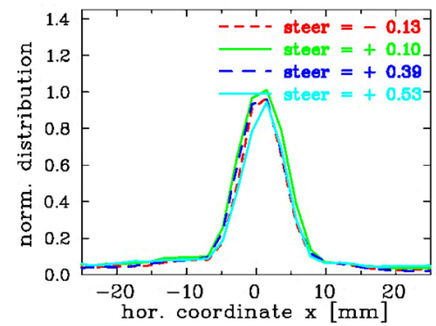


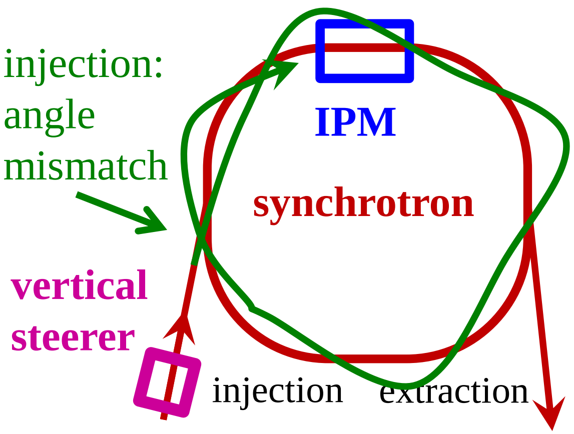


Vertical profile **after** acc.:

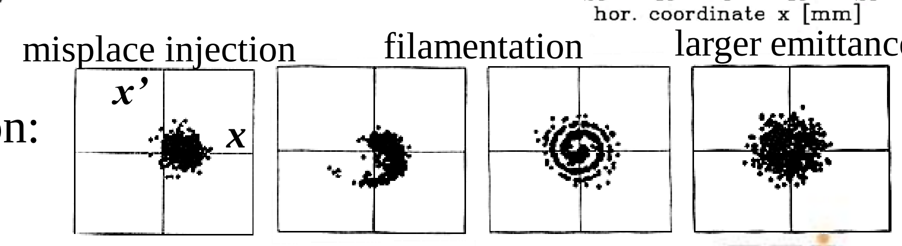


Horizontal profile **after** acc.:





Schematic simulation:
Courtesy M. Syphers

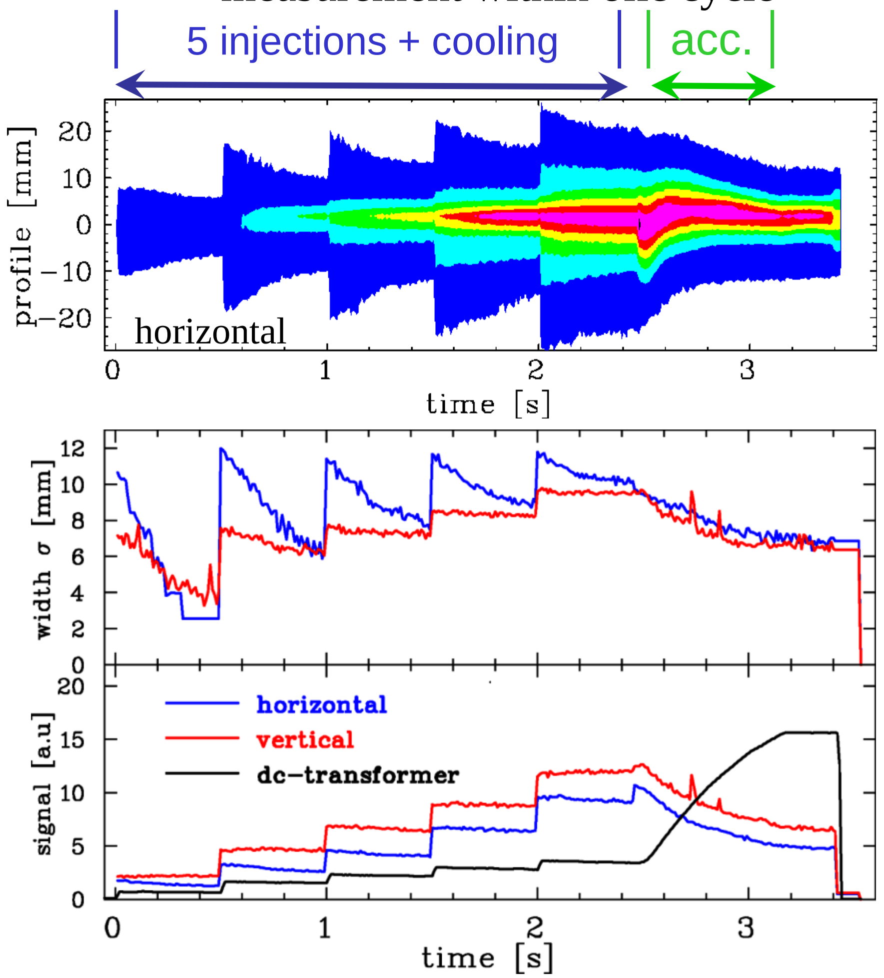


IPM: Observation of Cooling and Stacking

Example:
U^{73+} beam at GSI for intensity increase
stacking by *electron cooling*
and acc. 11.4 → 400 MeV/u

Task for IPM:
- Observation of cooling
- Emittance evaluation during cycle

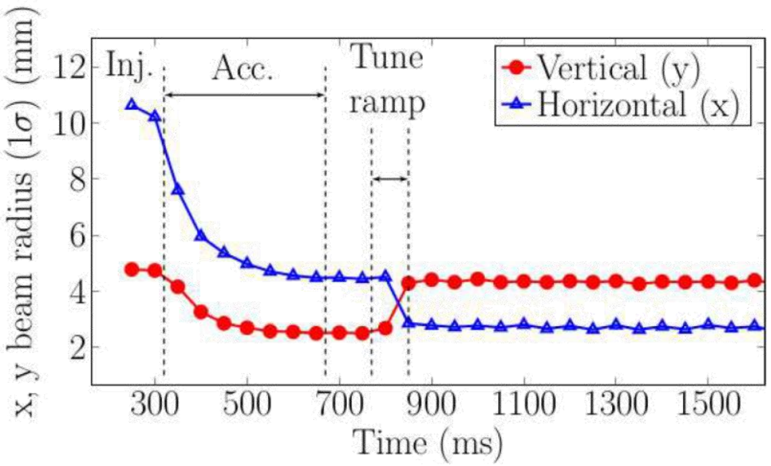
IPM: Profile recording every 10 ms
measurement within **one** cycle

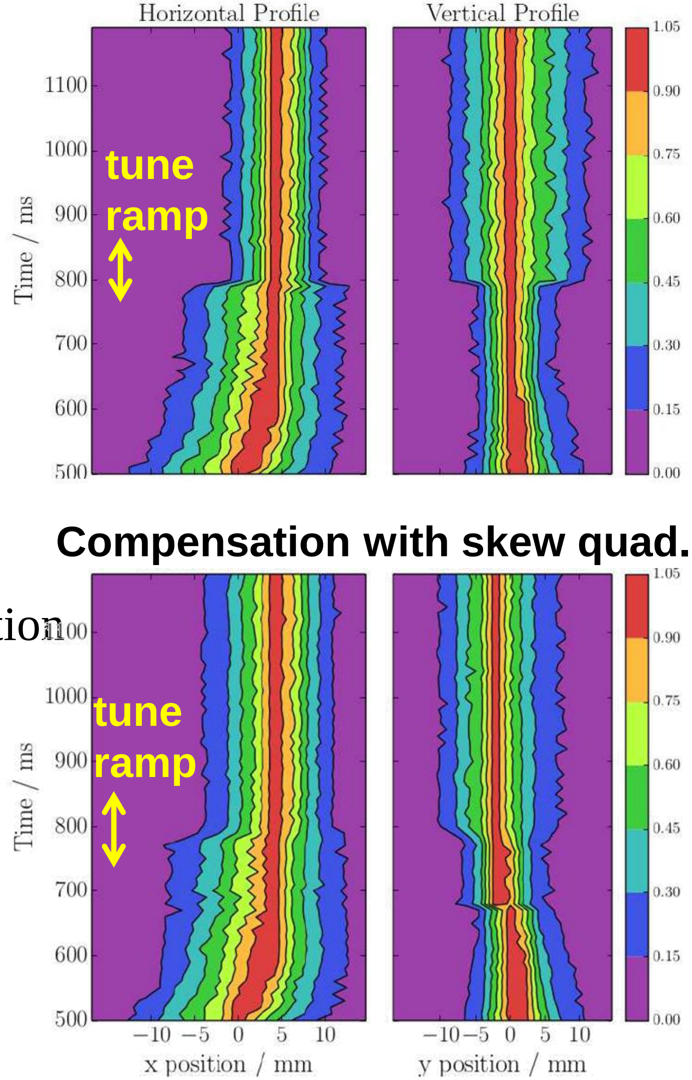


Effect of horizontal-vertical Coupling Resonance

Horizontal ↔ vertical coupling if $Q_x = Q_y$

Example for tune crossing $Q_x = 4.16 \rightarrow 4.33$:





Beam: 10^{10} N^{7+} after acceleration, before slow extraction

hori. $Q_x = 4.16 \rightarrow 4.33$ within 0.1s, vert: $Q_y = 3.29$

$\Rightarrow$ coupling when $Q_x = Q_y$

Tune measurement by transverse Schottky spectrum

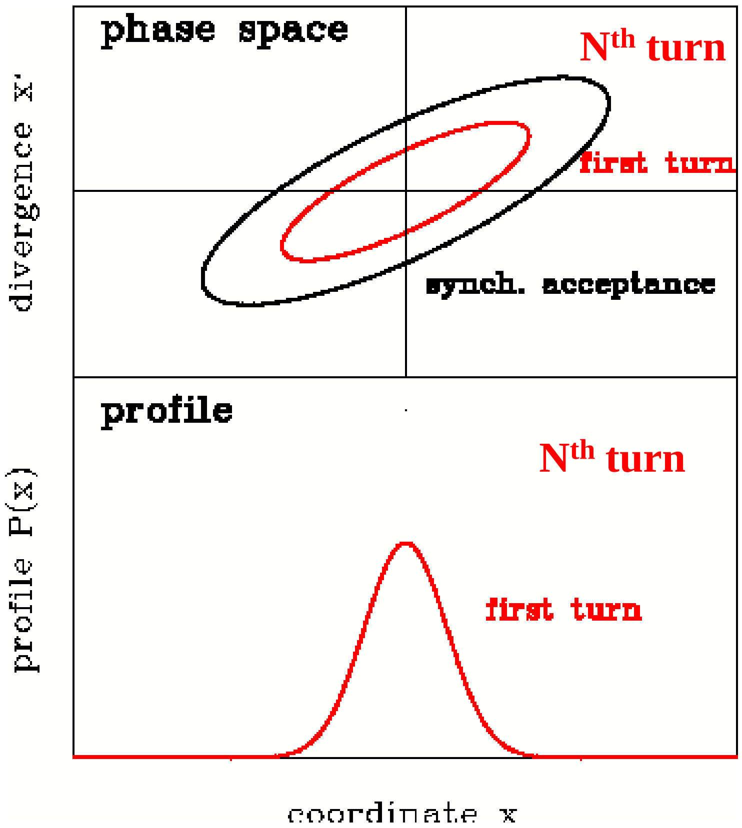
Partly compensation of coupling resonance with skew quadrupoles to control emittances

R. Singh et al., GSI-Annual Report 2014, p. 488

Injection Matching into a Synchrotron: Phase Space Mismatch

Ideal case of injection matching:

Orientation of injected beam matches
phase space as given by synchrotron
Twiss parameters α, β, and γ i.e. 'machine emittance'
⇔ no change after each turn ⇔ stable storage



Injection Matching into a Synchrotron: Phase Space Mismatch

Ideal case of injection matching:

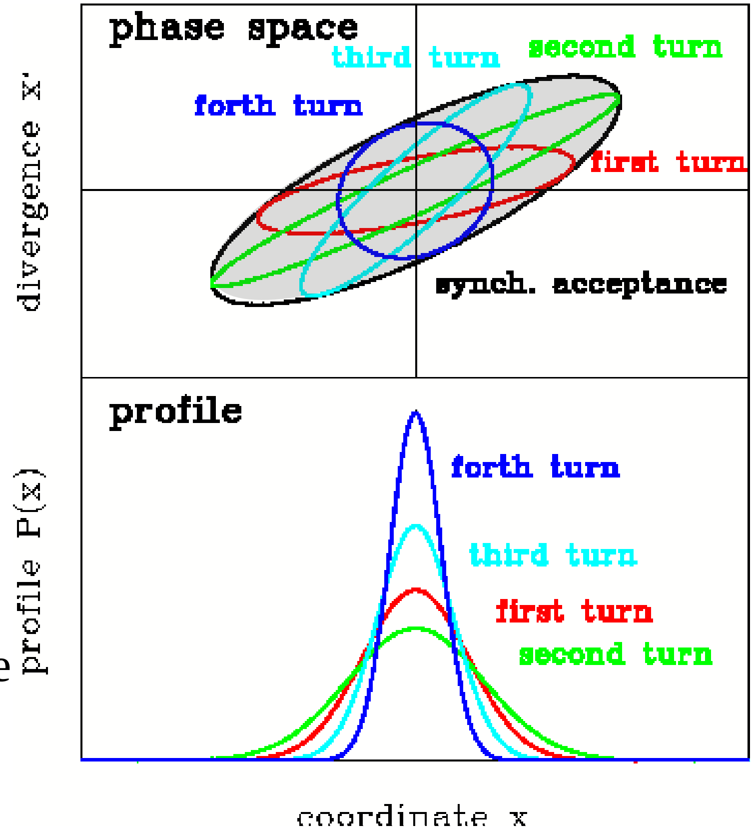
Orientation of injected beam matches phase space as given by synchrotron Twiss parameters α, β, and γ i.e. 'machine emittance'
⇔ no change after each turn ⇔ stable storage

Mis-matched case:

- The beam ellipse $\boldsymbol{\sigma}_{beam}$ has different orientation as machine ellipse at injection point for N=0 i.e.
- Transformation after one turn

$$\boldsymbol{\sigma}_{beam}(N=1) = \mathbf{M}\boldsymbol{\sigma}_{beam}(N=0)\,\mathbf{M}^T \neq \boldsymbol{\sigma}_{beam}(N=0)$$

i.e. rotation in phase space by the tune
Depictive argument: Always particle on both ellipse
Observable quantity: Beam profile oscillates



After many turns:

Particle have different tunes e.g. by longitudinal momentum deviation and chromaticity $\frac{\Delta Q}{Q_0} = \xi \cdot \frac{\Delta p}{p_0}$

⇒ Entire transverse phase space is filled i.e. beam with enlarged emittance

Injection Matching into a Synchrotron: Phase Space Mismatch

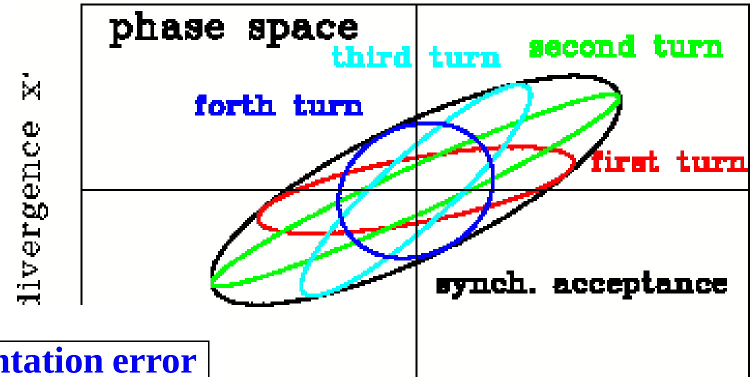
Mis-matched injection into a synchrotron:

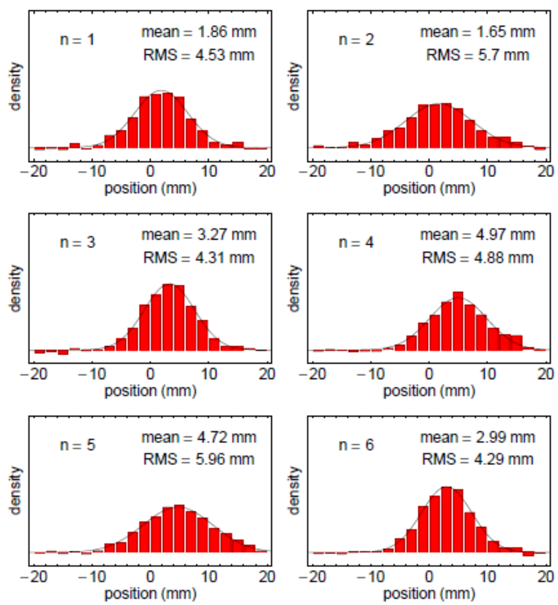
Can be monitored by beam profile measurement:

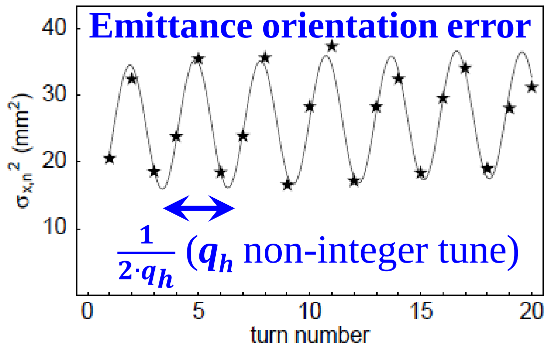
Example: Injection of a 80 ns bunch of protons into CERN PS at 1.4 GeV/u (2.2 μs revolution time)

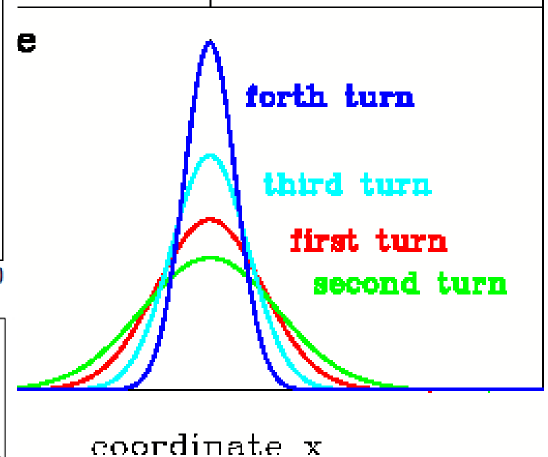
Profile measurement by SEM-Grid

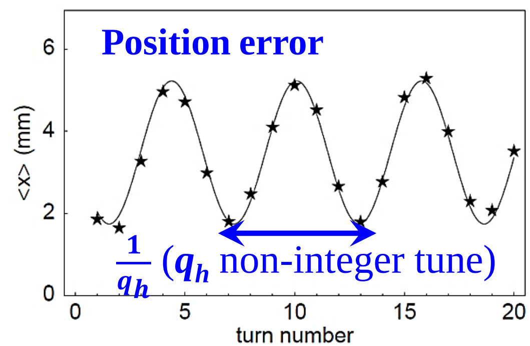
- Turn-by-turn profile variation related to tune
- Used for improvement of injection parameters











From M. Benedikt et al., DIPAC 2001

IPM: Turn-by-Turn Measurement

Important application:

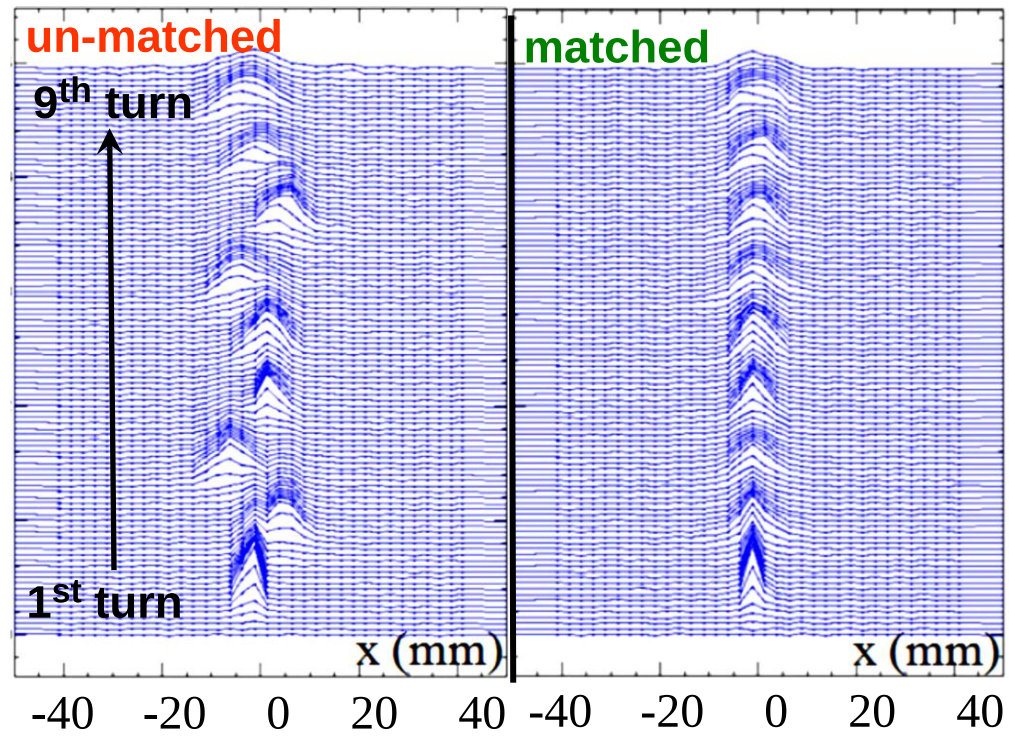
- Injection matching
  to prevent for emittance enlargement
- Observation during 'bunch gymnastics'

⇒ turn–by-turn measurement

Required time resolution ≈ 100 ns

Turn-by-turn IPMs at
BNL, CERN, FNAL etc.
Not realized at GSI yet
but nice-to-have for SIS100!

Example: Injection to J-PARC RCS at 0.4 GeV
Anode: wire array with 1mm pitch



H. Hotchi (J-PARC), HB'08, A Satou (J-PARC) et al., EPAC'08

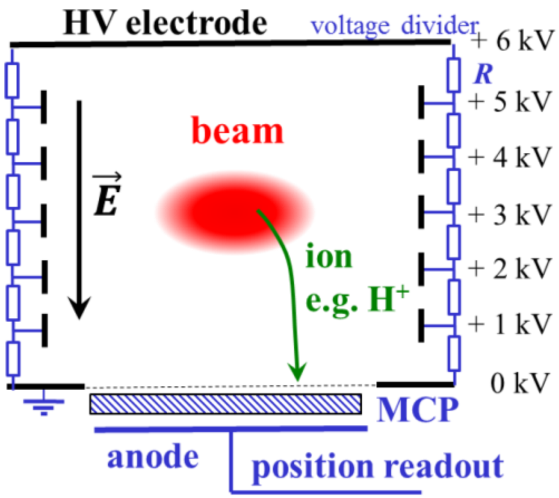
Outline of the Talk

Outline of the talk:

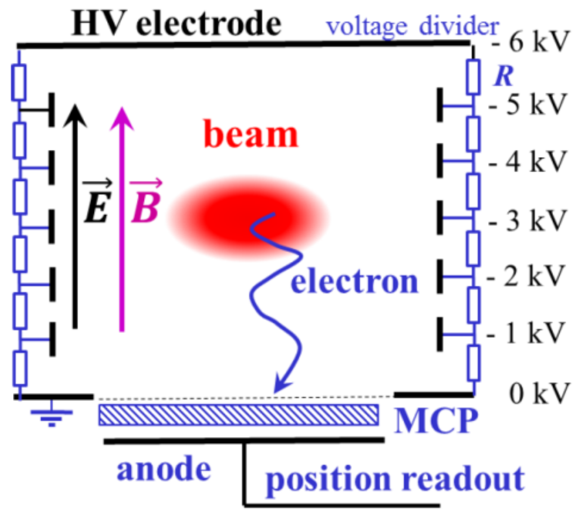
- Principle of Ionization Profile Monitors
- Technical realization at ESR, SIS18 and for FAIR
- Some basic & advanced measurements
- **Requirements for magnetic field, realization at SIS18**
- Simulations for disturbing effects
- IPM at CRYRING and BIF at UNILAC
- Conclusion

Electron Detection and Guidance by Magnetic Field

Ion detection mode:

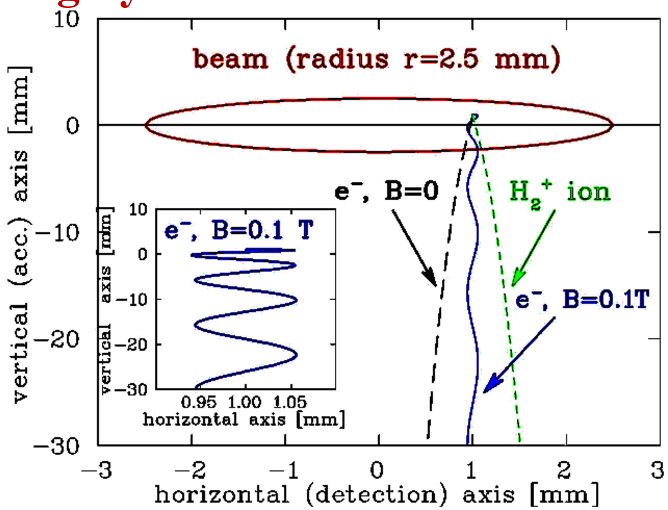


Electron detection mode:



⇒ broadening by beam's electric field

$7\cdot 10^{10}$ charges per 10 m bunch



e^- detection in an external magnetic field

→ cyclotron radius $r_C = \frac{mv_\perp}{eB}$

for $E_{kin,\perp} = 10$ eV & $B = 0.1$ T ⇒ $r_c \approx 100$ µm

E_{kin} from atomic physics, ≈100 µm resolution of MCP

Time-of-flight: ≈1 - 2 ns ⇒ 2 - 3 cycles.

B-field: Dipole with large aperture

→ IPM is expensive & large device!

Broadening due to the Beam's Space Charge: Ion Detection

Influence of the residual gas ion trajectory by :

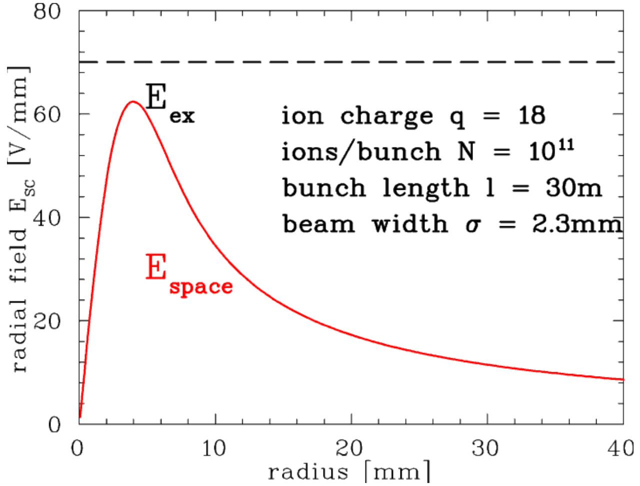
- External electric field $\boldsymbol{E_{ex}}$
- Electric field of the beam's space charge $\boldsymbol{E_{space}}$

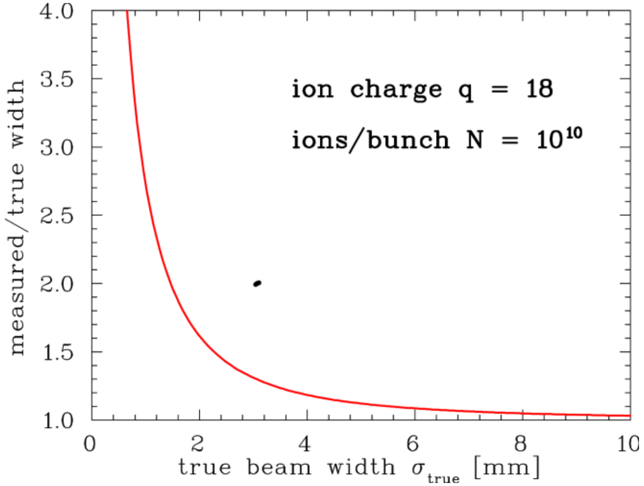
e.g. Gaussian density distribution for round beam: $E_{space}(r) = \frac{1}{2\pi\varepsilon_0} \cdot \frac{qeN}{l} \cdot \frac{1}{r} \cdot \left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right]$

Estimation of correction: $\sigma^2_{corr} \approx \frac{e^2 \ln 2}{4\pi\varepsilon_0 \sqrt{m_p c^2}} \cdot \frac{qN}{l} \cdot d_{gap} \cdot \sqrt{\frac{1}{eU_{ex}}} \propto N \cdot d_{gap} \cdot \sqrt{\frac{1}{U_{ex}}}$

With the measured beam width is **roughly approximated** by convolution: $\sigma^2_{meas} = \sigma^2_{true} + \sigma^2_{corr}$

Example: Space charge Ar^{18+}, 10^{11} per 30 m bunch, with $\boldsymbol{\sigma_{true}}$ = 2.3 mm





Example for Space Charge Broadening

Example for SIS18: 11 MeV/u → 500 MeV/u with typical SIS18 parameters

H_2^+ detection:

Inj.: σ_{long} = 110 ns

σ_{trans} = 5 mm

Extr.: σ_{long} = 25 ns

σ_{trans} = 2.3 mm

t_{drift} = 220±15 ns

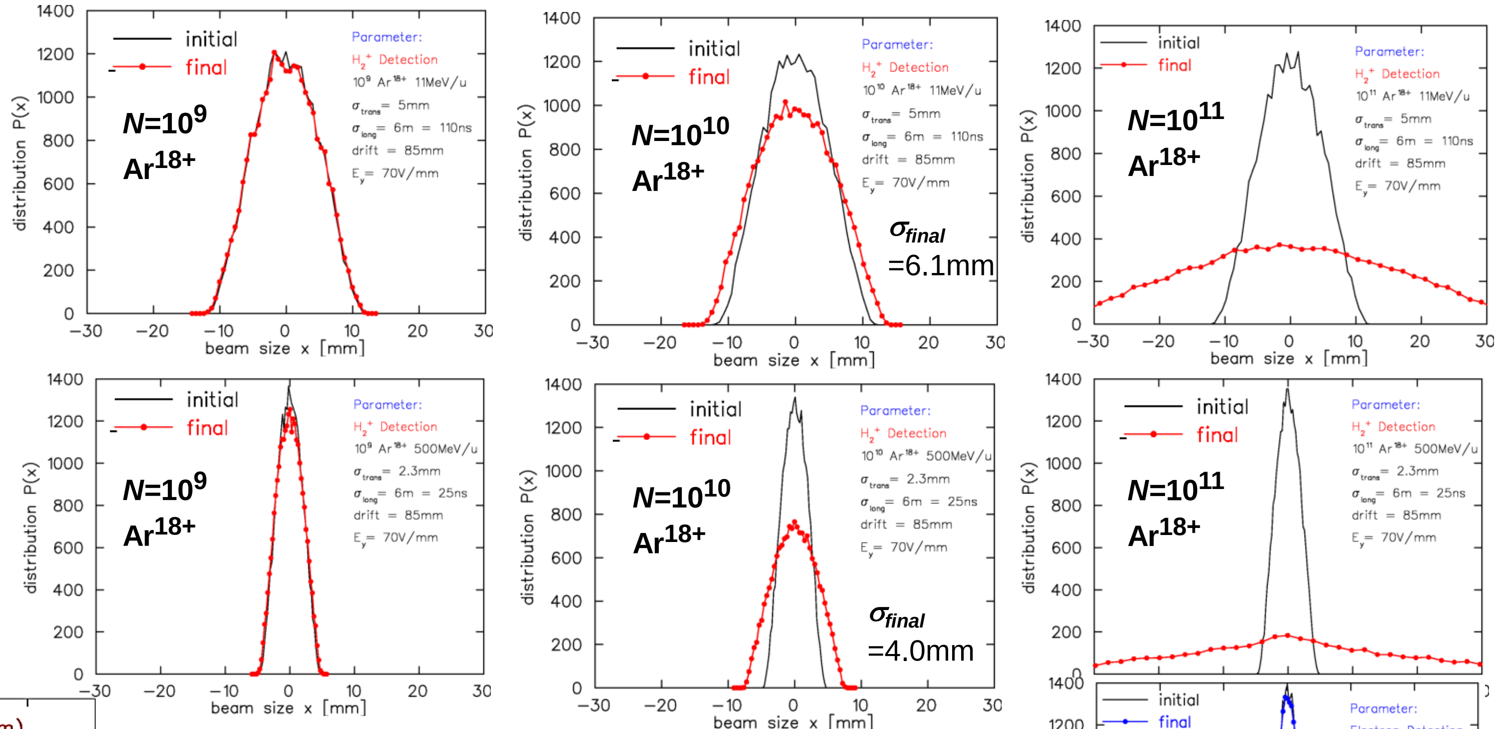
⇒ broadening for

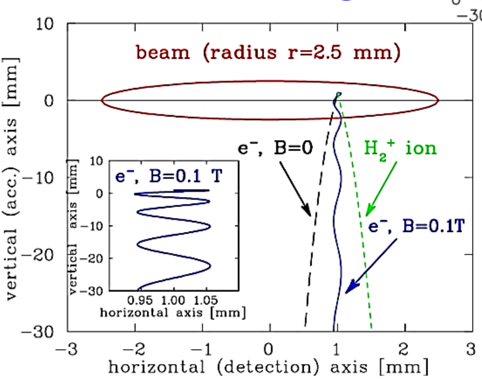
***N* > 10^10/bunch**

e⁻ detection:

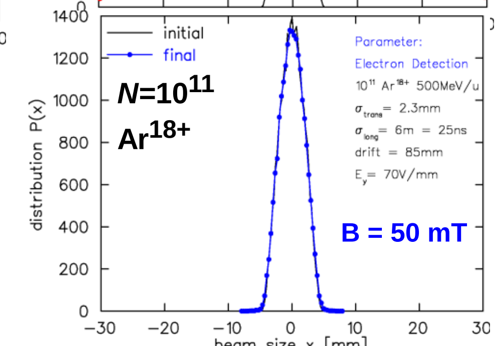
t_{drift} = 4.5±1 ns

⇒ no broadening





⇒ high currents needs guiding magnetic field



Simulation code by: P. Forck, M. Herty, S. Udrea (GSI)

IPM Magnet Design for SIS18 & SIS100

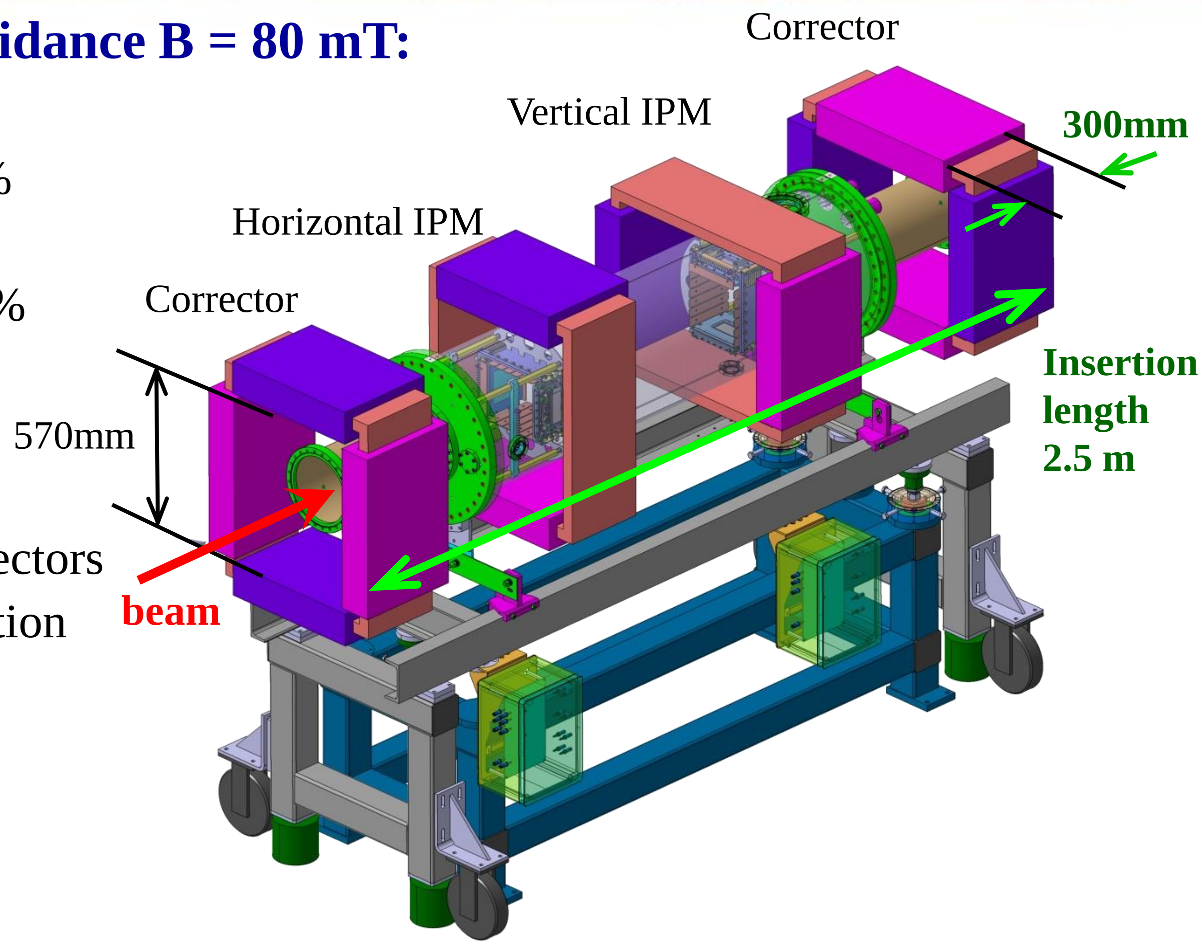
Magnetic field for electron guidance B = 80 mT:

Maximum image distortion:

5% of beam width ⇒ $\Delta B/B <$ 1 %

Challenges:

- High ***B***-field homogeneity of 1%
- Clearance 540 mm
- Correctors compensating beam steering
- Insertion length 2.5 m incl. correctors
- Changeable from e^- to ion detection



IPM: Magnet Design

Magnetic field for electron guidance:

Maximum image distortion:

5% of beam width $\Rightarrow$ $\Delta B/B < 1\,\%$

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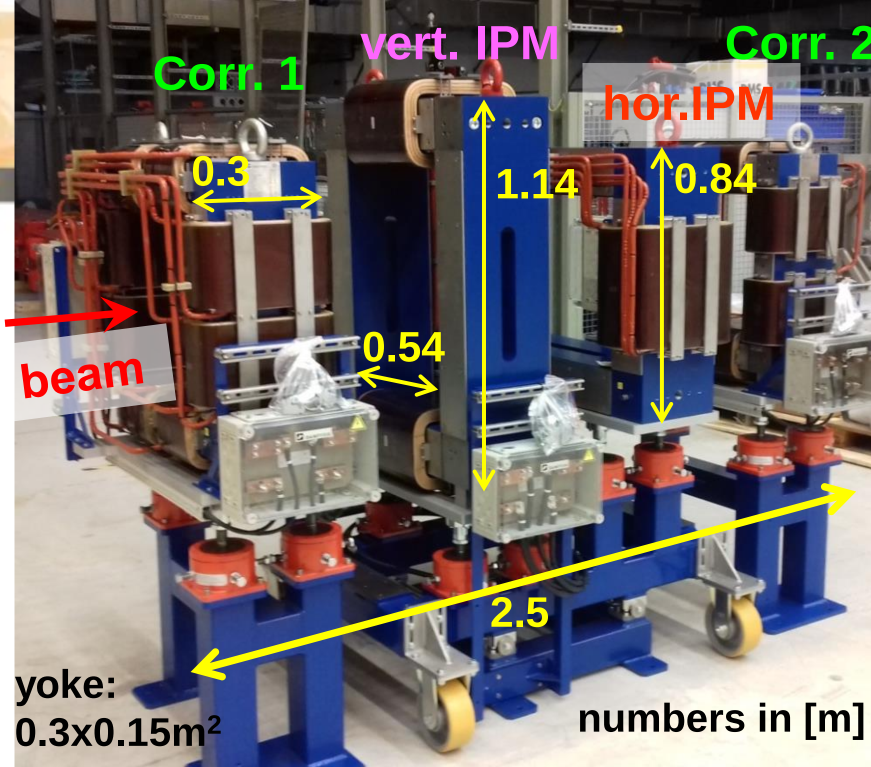
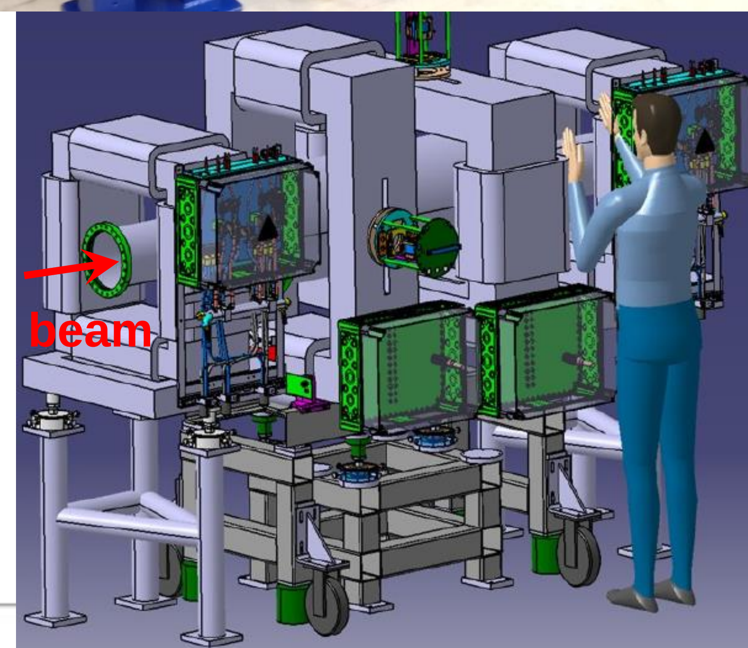




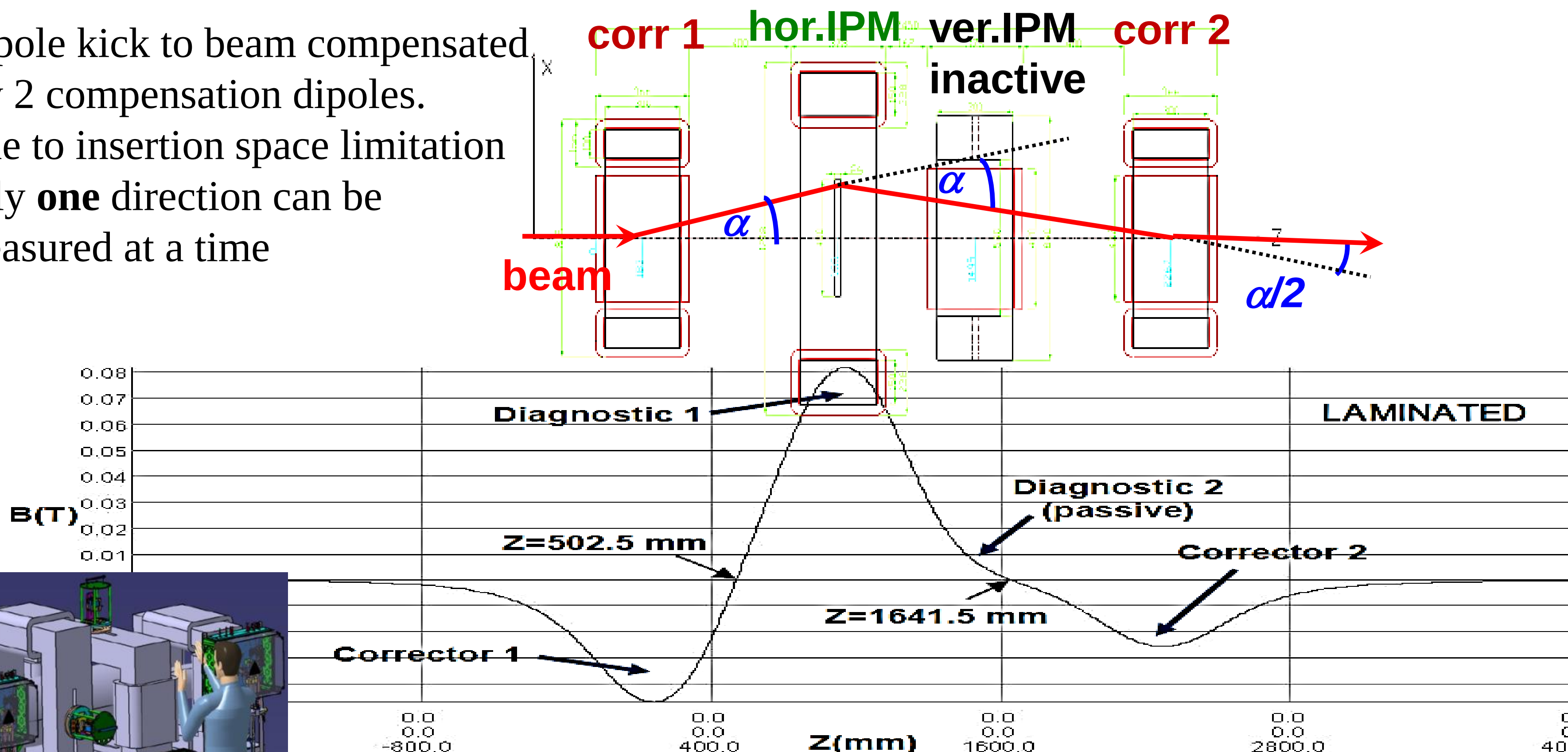
Status:

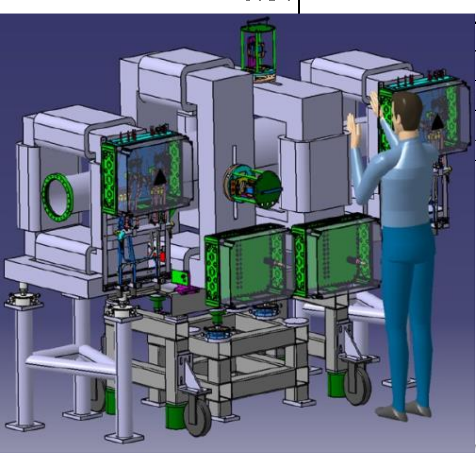
- Magnets delivered, power suppliers in production
- Problems during production, required revision
- Field mapping planned for ≈ May 2019
- Vacuum chamber delivery in April 2019
- Installation planned for begin 2020

IPM Magnet Design: Bump Compensation

Magnetic field for electron guidance B = 80 mT:

- Dipole kick to beam compensated by 2 compensation dipoles.
- Due to insertion space limitation only **one** direction can be measured at a time





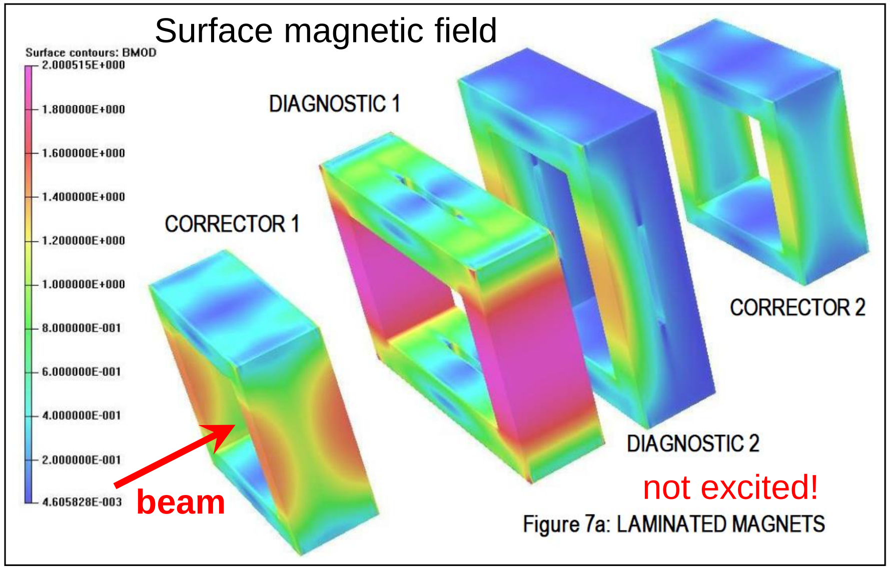
Integrated, on-axis dipole field $\int B_y(z)\, dz = 0.83$ mTm (!)

Courtesy G. de Villiers (iThemba Labs)

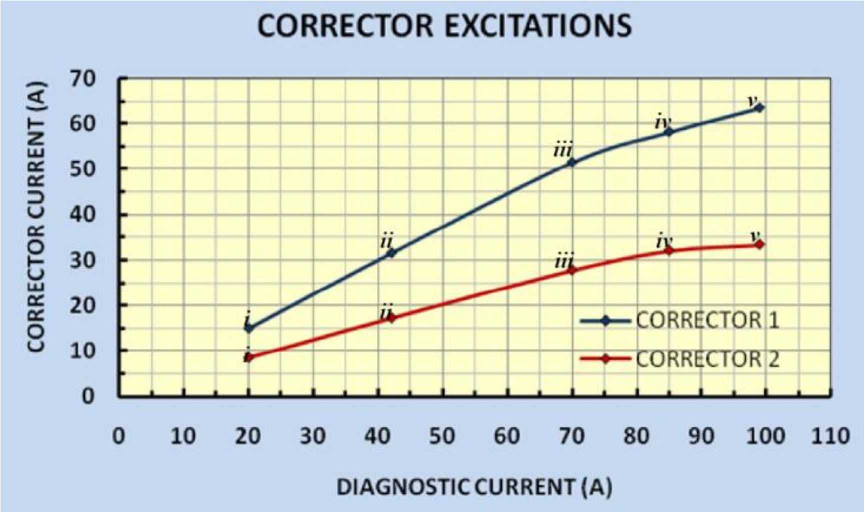
IPM Magnet Design: 'Cross Talk' by neighboring Magnetization

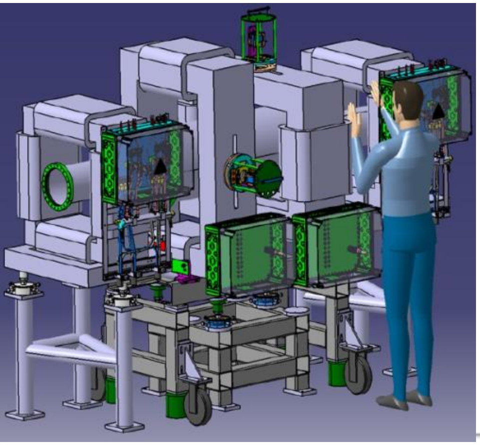
Magnetic field for electron guidance B = 80 mT:

- ➢ Larger aperture (570 mm) than length (300 mm)
- ⇒ Large stray field
- ⇒ Magnetization of neighboring yoke
  - ⇔ 'cross talk' of magnets
- ⇒ Field mapping requires entire magnet string



Courtesy G. de Villiers (iThemba Labs)





IPM Magnet Design: Sextuple Compensation

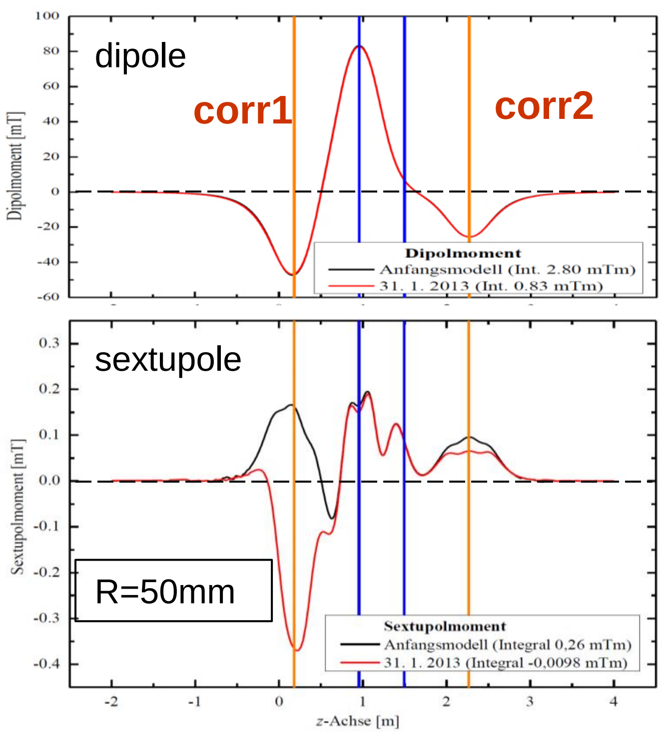
Magnetic field for electron guidance B = 80 mT:

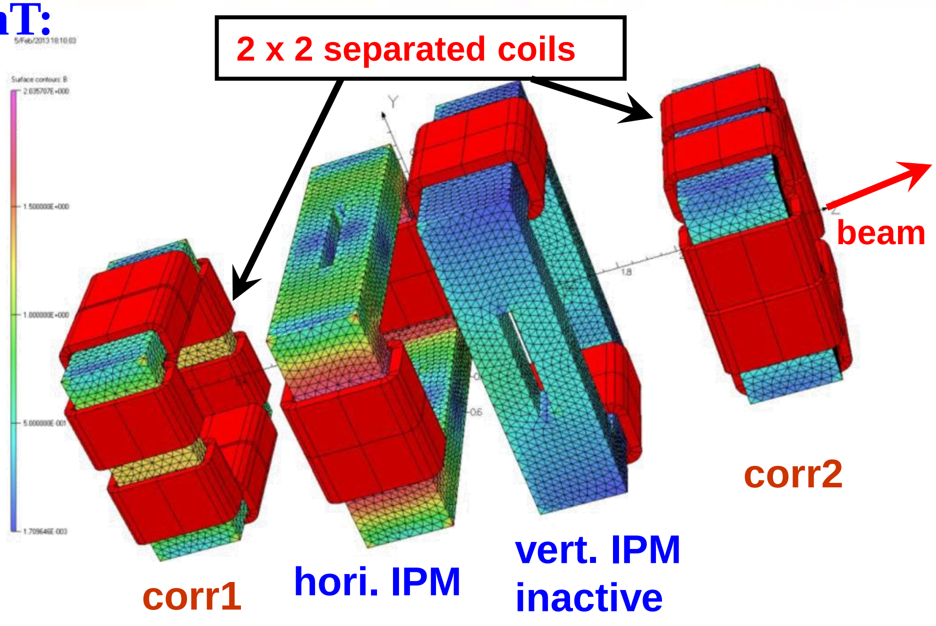
- Larger aperture (570 mm) than length (300 mm)

⇒ Large sextupole components

Idea: 2x2 separated coils of corr.-magnets create 'bad' dipole field

⇒ comp. sextupole effect





Normalized sextupole strength for 11 MeV/u & ***m/q***= 2:

- $k_2 \cdot L \approx 0.3\ m^{-2}$ **before** optimization
- $k_2 \cdot L \approx -0.007\ m^{-2}$ **after** optimization

(slow extraction $k_2 \cdot L \approx 0.2\ m^{-2}$)

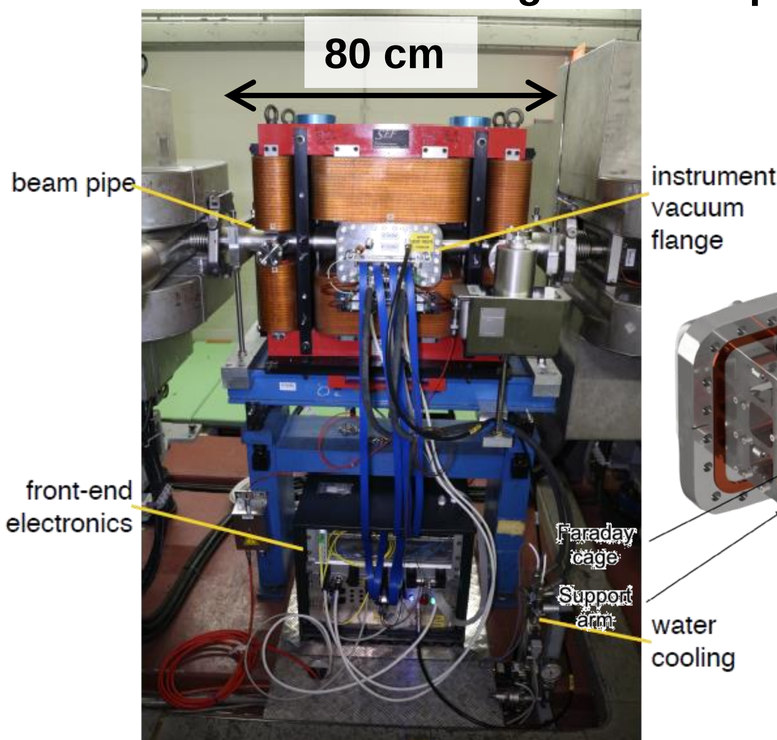
P. Rottländer (GSI) et al., internal report

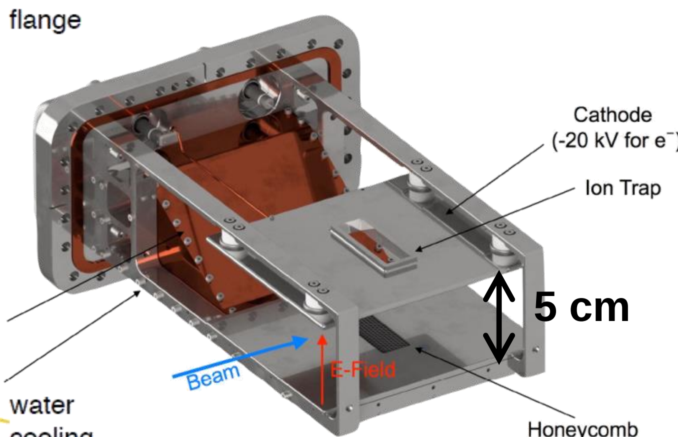
Magnet Design at CERN-PS & J-PARC

J-PARC Main Ring:
- diagnostics magnet gap 220 mm
- Diagnostics field B = 250 mT, corrector B = 130 mT
- Profile with 32 strips of 2.5 mm width

Courtesy K. Satou et al. J-PARC

CERN-PS: Hori. IPM magnet & comp.





CERN-PS:
- Diagnostics magnet B = 200 mT
- Profile with silicon detector (TimePix3)
- File cage of 50 mm height

Courtesy J. Storey, S. Levasseur et al. CERN

Outline of the Talk

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Simulation of Space Charge Effects: General Behavior for Ions

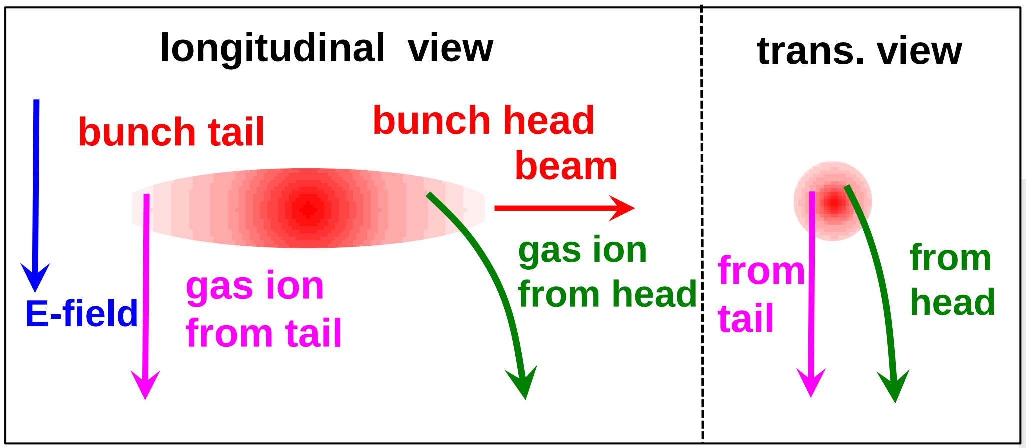
Space-charge effects: Beam's space charge can be comparable to external homogeneous E- field

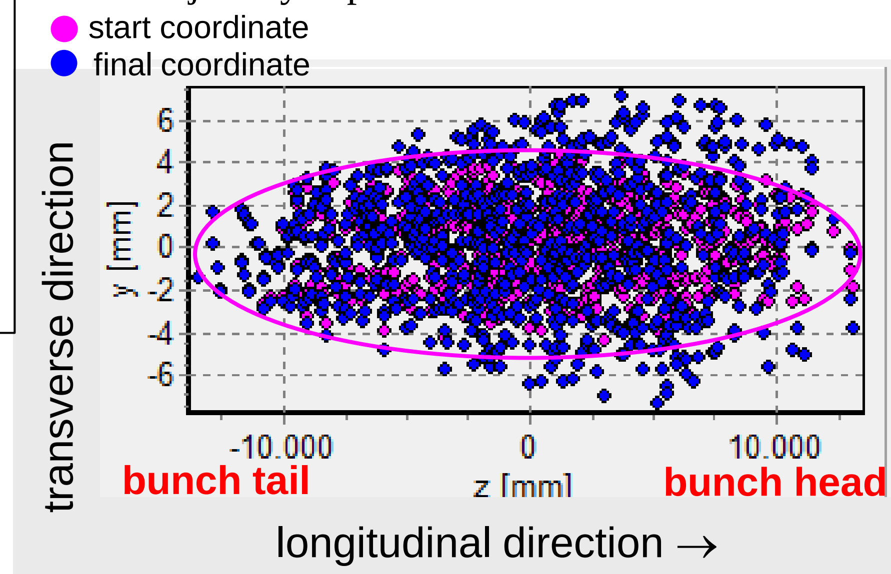
Numerical calculation:
- Ion or e^- created with realistic velocity distribution
- Trajectory in field of **moving** bunches
- Distribution at barrier of MCP

Example: 10^{10} Ar^{18+} @ 500 MeV/u (β = 75 %)

σ_{long} = 25 ns, σ_{trans} = 2.3 mm (SIS18 parameter)

⇒ **ion** trajectory dependence on bunch movement





Features:

⇒ 3dim calculation required

⇒ Relativistic Lorentz-transformation for fields required

Simulation of Space Charge Effects: General Behavior for Electrons

Space-charge effects: Beam's space charge can be comparable to external homogeneous E- field

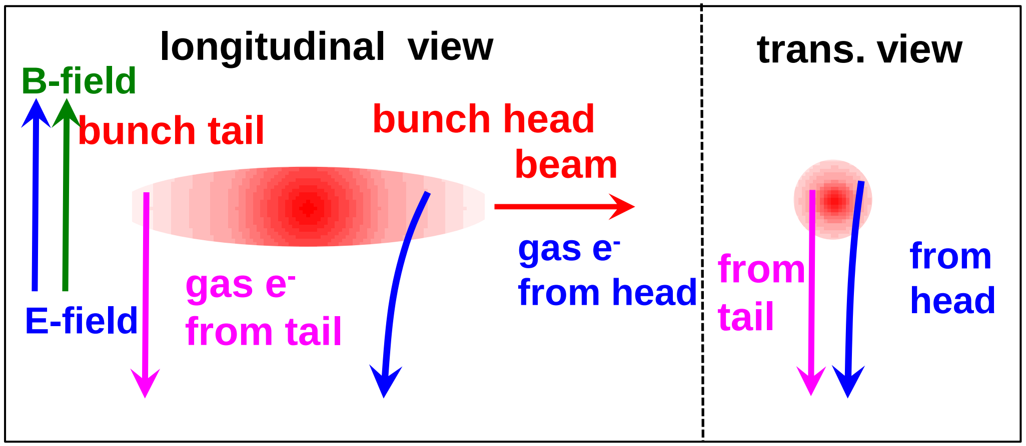
Numerical calculation:
- Ion or e⁻ created with realistic velocity distribution
- Trajectory in field of **moving** bunches
- Distribution at barrier of MCP

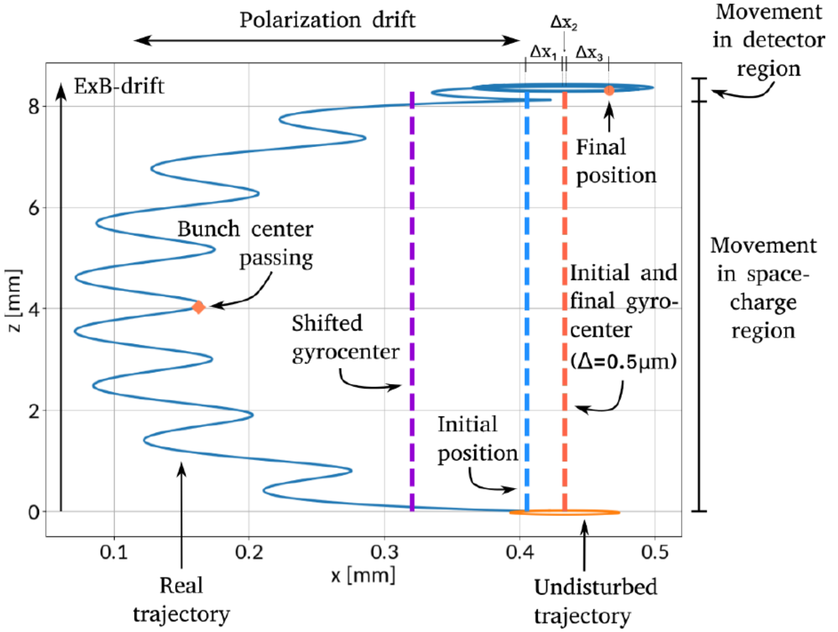
Example: LHC parameter, 2×10^{11}/bunch

$\sigma_{long} = 0.3$ ns, $\sigma_{trans} = 0.3$ mm

Start at $x = 1.5\sigma_{trans}$ & $z = 2\sigma_{long}$, $v_0 = 10^6$ (-1,0,1) m/s

$B = 0.2$ T, $E = 0.47$ kV/cm,





Features:

⇒ 3dim calculation required

⇒ Relativistic Lorentz-transformation for fields required

⇒ For electron detection and intense beams:

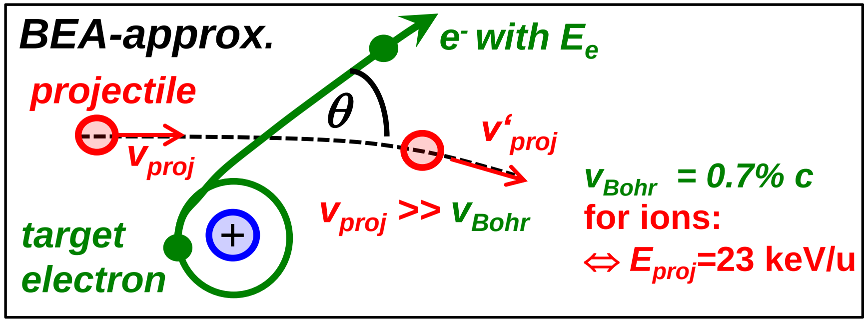
complex trajectory due to gyration on external B-field

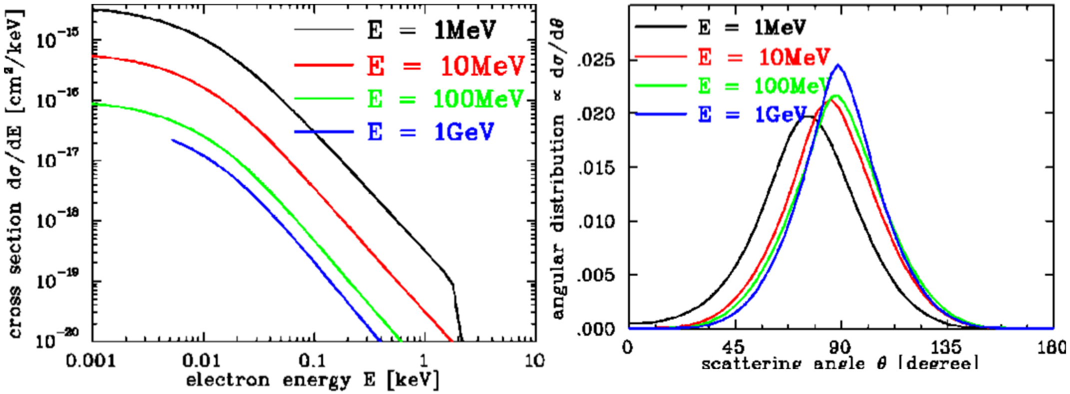
D. Vilsmeier et al., in preparation for PRAB

Electron Energy & Angular Distribution

Collision of the fast projectile with target electrons leads to 'initial' cyclotron radius:

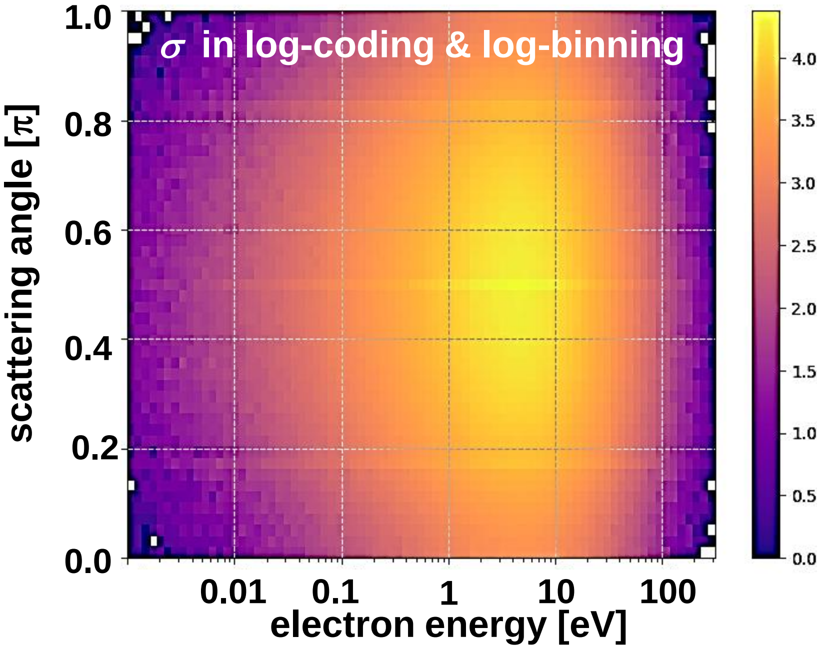
Single differential cross section for p on H_2 gas with 'Binary Encounter Approximation':





Analytical quantum mechanical approach:

Double diff. cross section for 500 MeV/u Ar^{18+} on atomic hydrogen with **Voitkiv-formula (1999)**



Results:
- Comparable shape of energy distribution
- ≈ 55 % below 10 eV, 93 % below 100 eV, 99.5 % below 1 keV
- Peaked at angle $\theta \approx 90^0$
- SIS18: no significant influence for profile broadening but e.g. for LHC as σ≈ 0.2 mm beam size

Courtesy M. Krämer (GSI)

Courtesy D. Vilsmeier (GSI)

Code ‘*Virtual-IPM*’ by D. Vilsmeier and M. Sapinsky

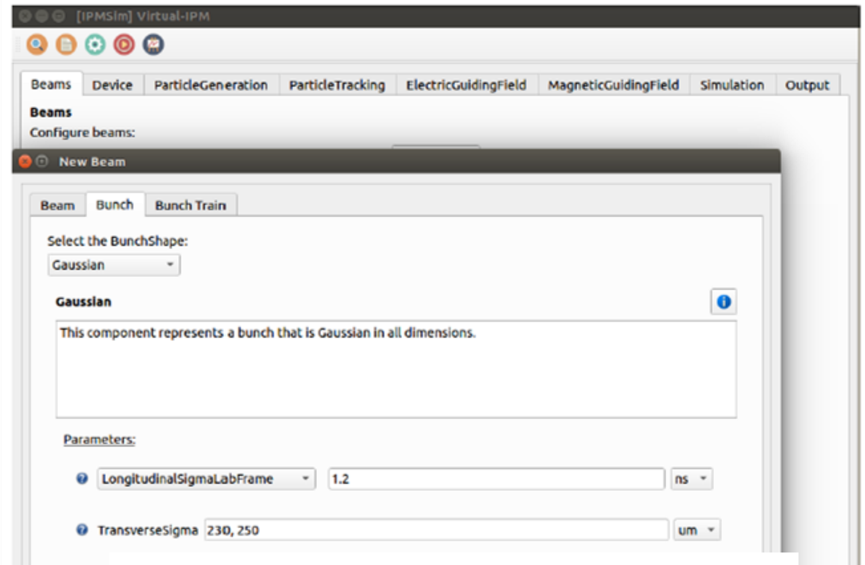
Virtual-IPM: Code for **<u>all</u>** beam parameters with advanced Python programming:

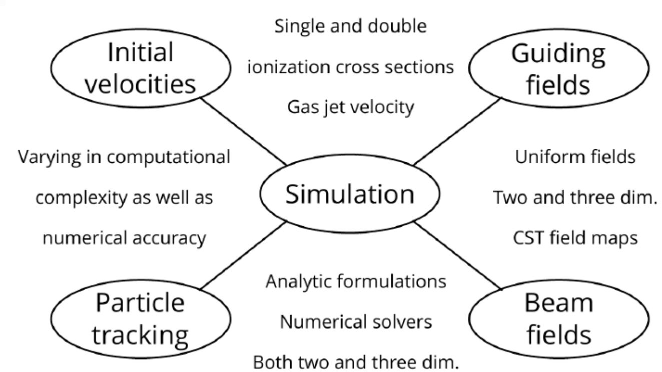
Situation: Each laboratory has its own code with special application & restriction

⇒ ‘All-in-one’ code developed and published on https://gitlab.com/IPMsim/Virtual-IPM

Code includes:

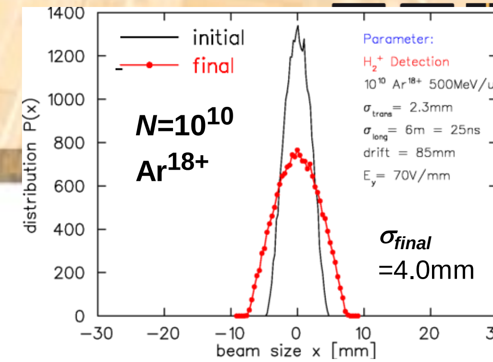
- Application for **LINACs**
  e.g. short bunches, non-relativistic
- Application for **synchrotrons**
  e.g. long bunches, relativistic
- Homogeneous $\vec{E}$ & $\vec{B}$ fields ***or*** input CST maps
- Realistic e⁻ generation $\frac{d^2\sigma}{dE \cdot d\theta}$
- Accurate numeric for particle tracking
- Meaningful GUI
- **Usable for IPM, BIF, gas jets, multiple beams....**





See M. Sapinski et al., IBIC 2016
D. Vilsmeier et al., IBIC 2017 and reference therein

Some Results using *Virtual-IPM*



- Estimation of profile deformation of ion detection of intense beams:
  → example shown for 10^{10} Ar@500 MeV/u
- Estimation of required magnetic field strength for e^- detection:
  For intense beams the electron's trajectory is significantly deformed by bunch field, e.g at LHC
  → **Which B-field is required ?**

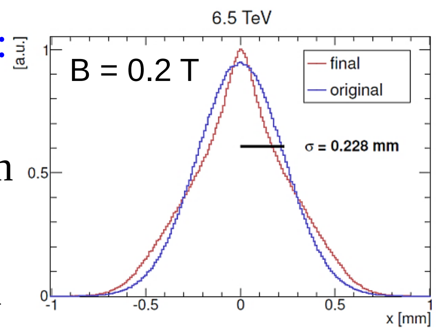
LHC parameter:

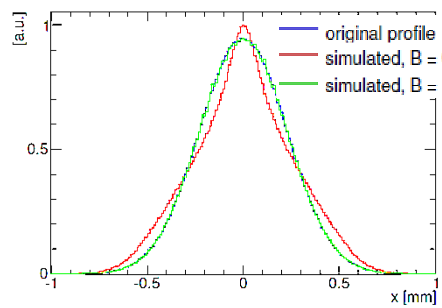
$\boldsymbol{E_{kin}}$ = 6.5 TeV

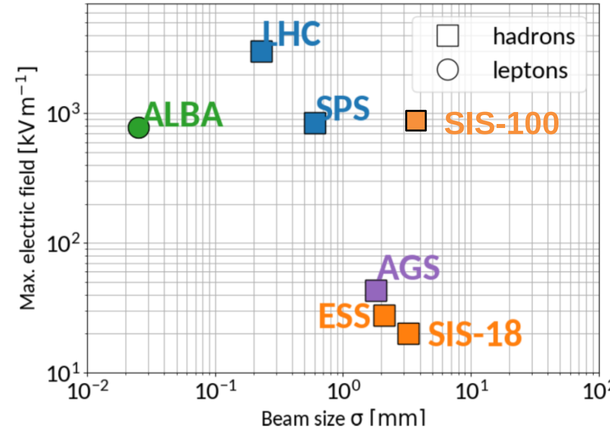
1.3 x 10^{11}/bunch

$\boldsymbol{\sigma_{long}}$ =0.6 ns

$\boldsymbol{\sigma_{trans}}$ =0.29 mm







- Required B-field for SIS100 ?

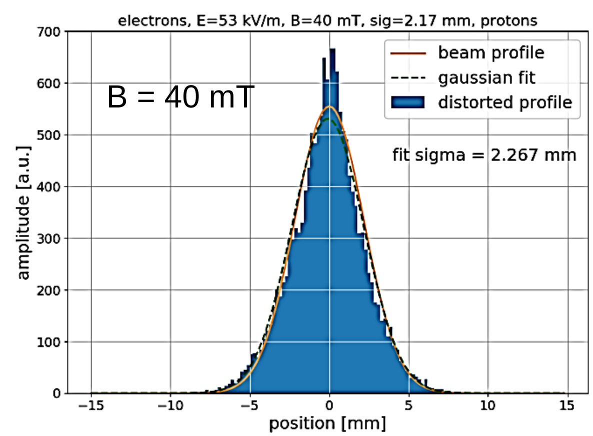
  $\boldsymbol{E_{kin}}$ = 30 GeV

  2 x10^{13}/bunch

  $\boldsymbol{\sigma_{long}}$ = 15 ns

  $\boldsymbol{\sigma_x}$ = 2.17 mm, $\boldsymbol{\sigma_y}$ = 4.4 mm

⇒ **SIS100 magnet design is OK!**



- Multiple beams:
  LHC electron lens project
  (hollow e^--beam as collimator)
  controlled by
  Beam Induced Fluorescence Monitor

D. Vilsmeier et al., HB 2014   M. Sapinski et al., HB 2018   D. Vilsmeier et al., in preparation for PRAB

Machine Learning for Image Reconstruction

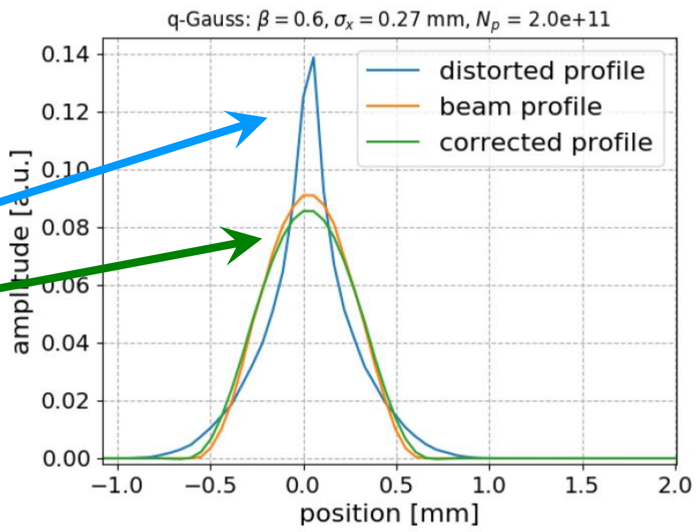
Machine Learning:
'A numerical algorithm that improves its performance at a given talk based on experiences'

Idea:

- Distorted profiles calculated by *Virtual-IPM* for various input parameters
- Training of neural network
- Reconstruction of **measured profile** to approximate real **beam profile**

One results: Training with Gaussian shapes can reconstruct non-Gaussian shapes!

Example for ML validation



Actual subject within accelerator science, novel method for IPMs

Discussed by M. Sapinski at GSI Acc. Seminar 16th Aug. 2018 & publications

M. Sapinski et al., HB 2018 & IPAC 2018, R Singh et al., IBIC 2017

Outline of the Talk

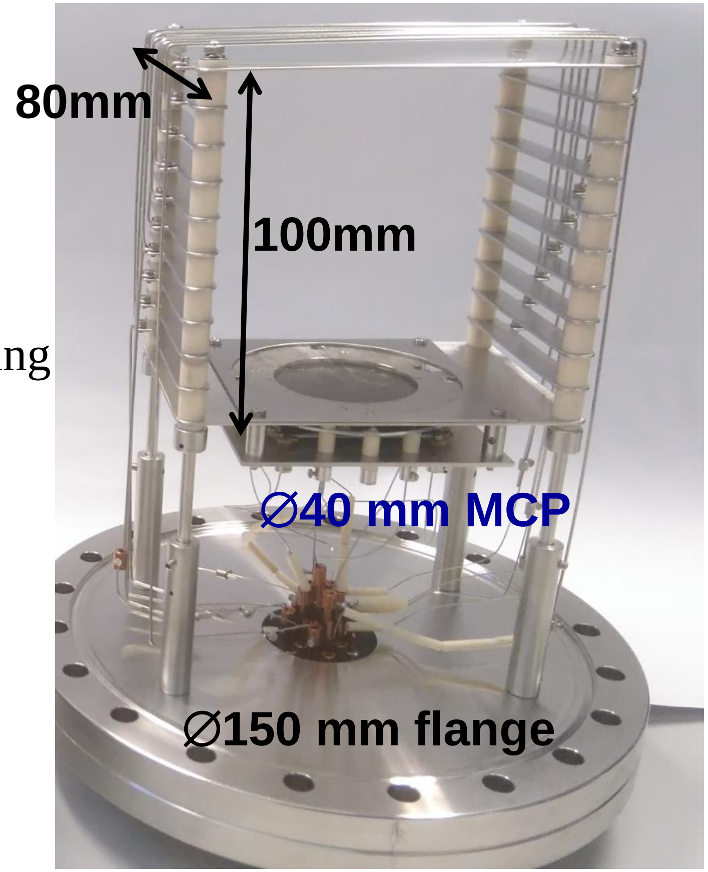
Outline of the talk:

- Principle of Ionization Profile Monitors
- Technical realization at ESR, SIS18 and for FAIR
- Some basic & advanced measurements
- Requirements for magnetic field, realization at SIS18
- Simulations for disturbing effects
- **IPM at CRYRING and BIF at UNILAC**
- Conclusion

IPM at CRYRING: Hardware of Field-Box

IPM design by MSL-team in 1990th:

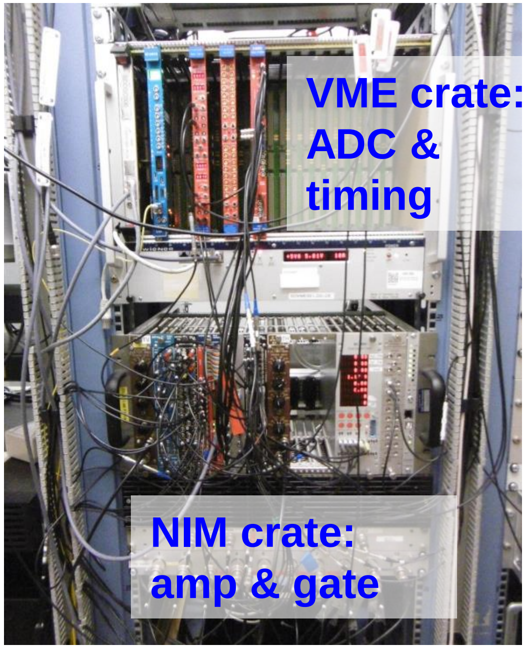
- Field cage: 100 mm , 80 mm depth
- Chevron type (stack of 2 MCPs, 40 mm diam.)
- Resistive anode
- Charge-sensitive pre-amplifiers
- Resolution: $\sigma \approx 130$ µm due to single event counting
- Maximum MCP digitalization rates ~5×10^4 Hz
- For 300 keV/u injection correction required
- At GSI: Operation without corrector

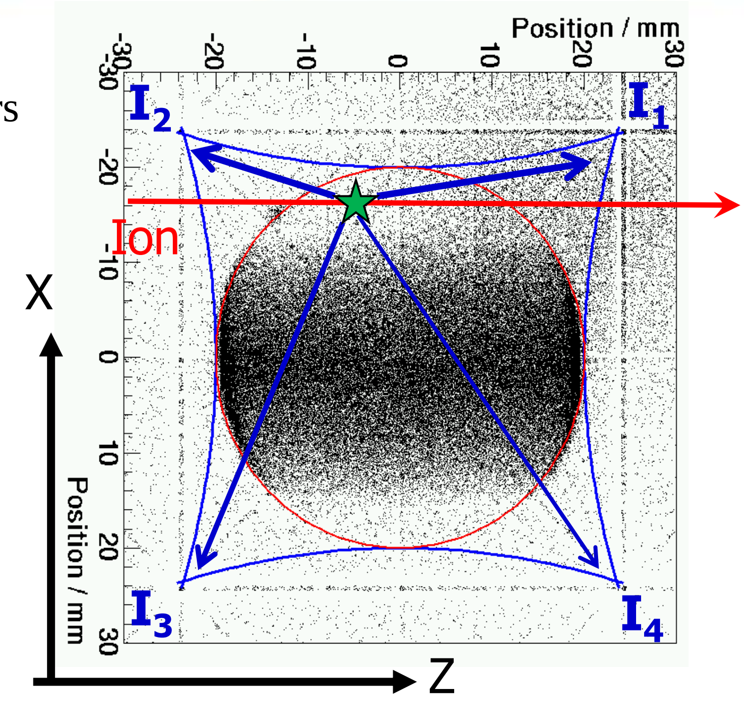


IPM at CRYRING: Electronics

Signal processing and DAQ:

- Charge-sensitive pre-amplifiers & spectroscopy amplifiers
- DAQ: VME peak-sensing ADC, 20 kHz readout
- Position (***x,y***) of each event via charge division





- Charge readout at corners
- Detection of peak values

Position calculation based on asymmetry

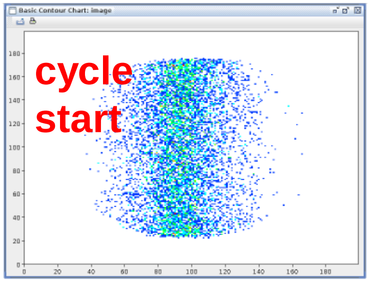
$$x/r = \frac{(I_1+I_2) - (I_3+I_4)}{\sum I_i} \qquad z/r = \frac{(I_1+I_4) - (I_2+I_3)}{\sum I_i}$$

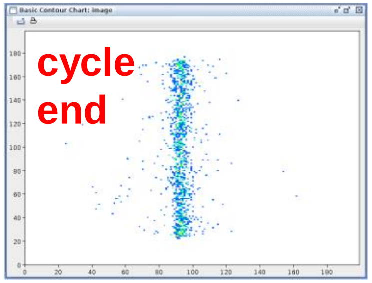
IPM at CRYRING: Results

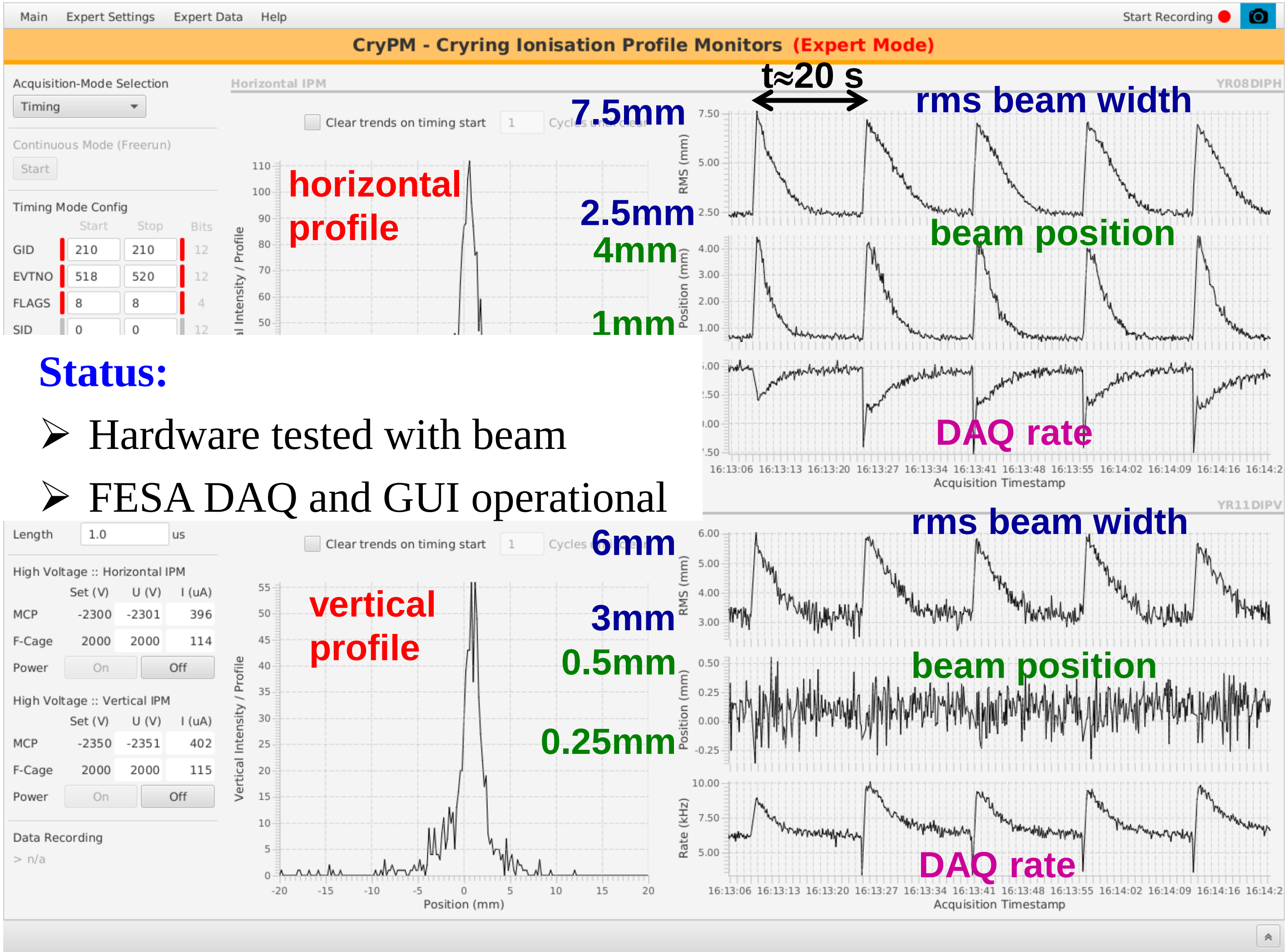
FESA DAQ and GUI used at November 2018 beam time during electron cooling

Features:

- Permanent oper., here t_{aver} =125 ms
- Good signal-to-noise
- used for alignment of electron cooler







Status:

- Hardware tested with beam
- FESA DAQ and GUI operational

Beam Induced Fluorescence (BIF) Monitor: Principle

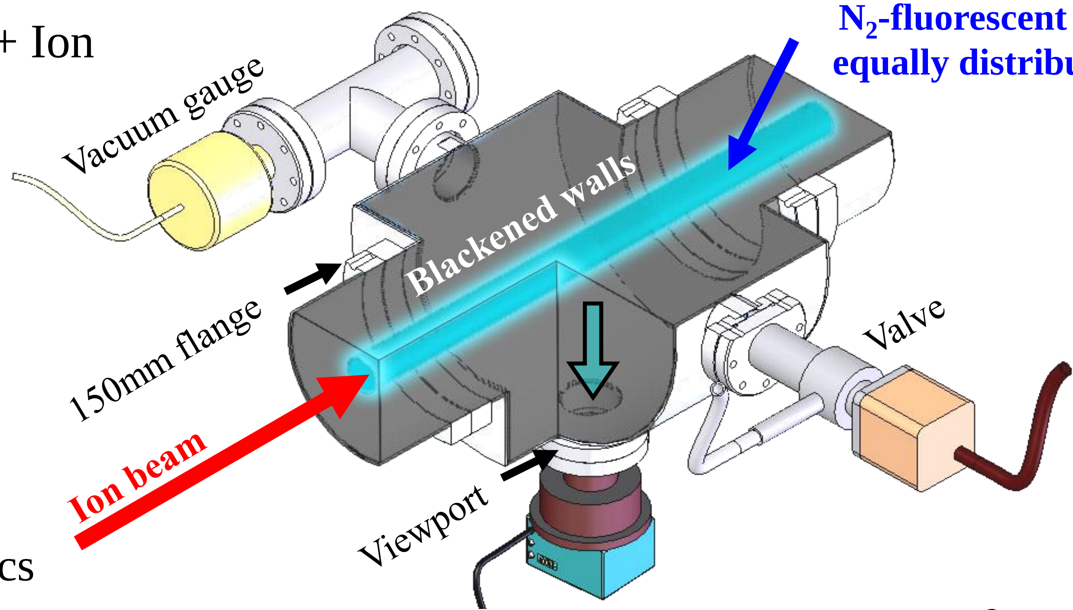
Detecting ***photons*** from residual gas molecules, e.g. Nitrogen

N_2 + Ion → $(N_2^+)^*$+ Ion → N_2^+ + γ + Ion

390 nm< λ< 470 nm

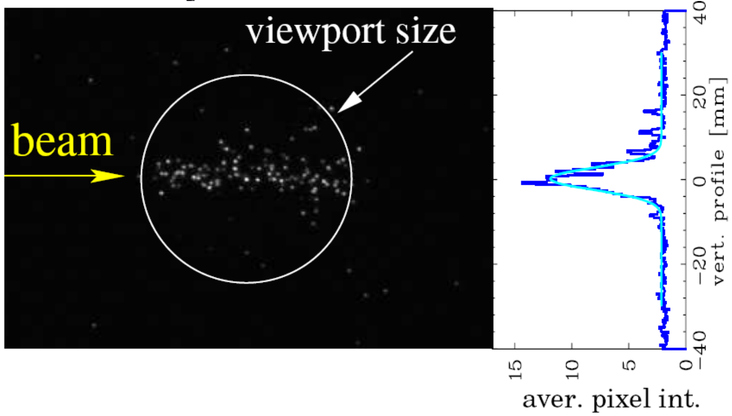
emitted into solid angle Ω to camera

single photon detection scheme



Features for UNILAC:

- Single pulse observation possible down to ≈10 μs time resolution
- High resolution (here 0.2 mm/pixel) can be matched to application by optics
- Commercial Image Intensifier
- Pressure pump up to 10^{-6} mbar possible



Remark concerning European Spallation Source:

- BIF foreseen at normal-conducting LINAC $E_{kin} \leq 90$ MeV
- IPM foreseen at super-conducting LINAC
- Space charge broadening investigated

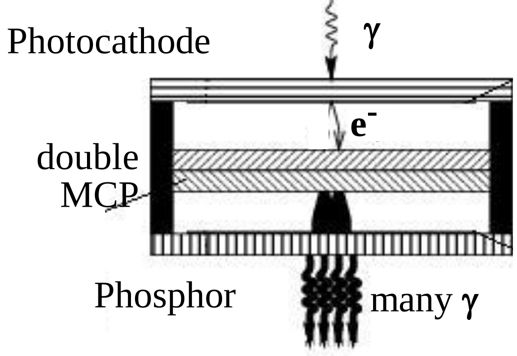
F. Becker et al., DIPAC'11

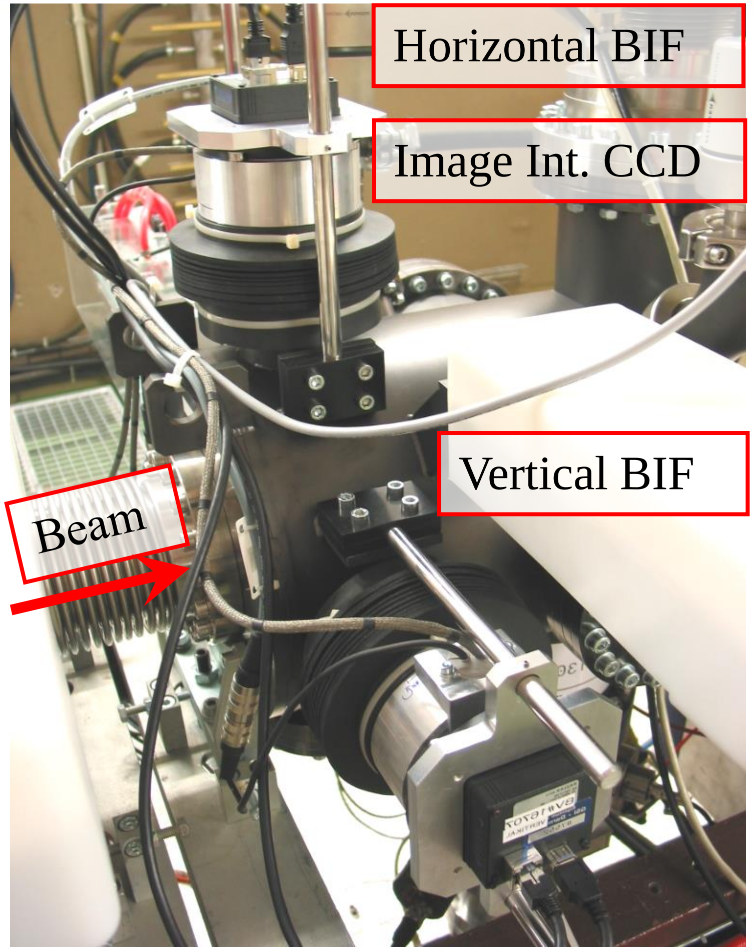
Beam: Ar^{10+} at 4.7 MeV/u, I=2.5 mA, 10^{11} ppp, p=10^{-5} mbar

BIF-Monitor: Technical Realization at UNILAC

Example: BIF station at UNILAC:

- Insertion length 25 cm
- 2 x image intensified CCD cameras
- Optics with reproduction scale 0.2 mm/pixel
- Gas inlet + gauge, pneumatic actuator for calibration
- presently installed at 7 locations
- **Advantage:** compact insertion, resolution adaptable of-the-shelf components
- **Disadvantage:** less signal ≈ 10^{-5}...10^{-4} of IPM





C. Andre (GSI) et al., Proc. IBIC 2014

Courtesy Ch. Andre (GSI)

Dedicated Workshops on IPM Developments

1[st] IPM workshop 3[rd] - 4[th] of February **2016** at CERN:

'Ionization Profile Monitor Simulation kick-off Workshop'

17 participants

2[nd] IPM workshop 22[nd] - 24[th] of May **2017** at GSI:

'Simulation, Design & Operation of Ionization Profile Monitors'

(Within the frame of European ARIES-ADA)

33 participants

3[rd] IPM workshop 18[th] - 20[th] September **2018** at J-PARC:

'International workshop on non-invasive Beam Profile Monitors for Hadron Machines and its related Techniques'

27 participants

⇒ **active community to realize complex beam instrument**

Summary and Outlook

Ionization profile monitors well suited for GSI rings:

- Direct measurement of profile during entire cycle
- Sufficient signal for time resolution ≈ 3...100 ms in dependence on beam current and vacuum pressure
- Spatial resolution of 2 mm for ‘old IPM’ SIS18 and ≈ 0.2 mm for other IPMs → mostly sufficient
- Operational monitors with complex technical realization (as common to IPMs at other institutes)
- Concept for profile distortions established by advanced simulation code, used for further applications

IPM at CRYRING:

- Used during beam time, design by MSL, GSI FESA-DAQ & GUI operational, good spatial resolution

IPM at ESR:

- Hardware well functional, 1st version of FESA DAQ, but GUI pending

‘Old IPM’ at SIS18:

- Used frequently during machine experiments, usage during operation could be more intense
- Appropriate GUI, presently some network problems

‘New IPM’ at SIS18 (serves as prototype for SIS100)**:**

- Vacuum hardware must be improved (some reflection), 1st version FESA DAQ, but GUI pending
- Modifications **were** required for magnets, final field mapping in Q2/19, installation begin of 2020.

IPM at FAIR-HEBT:

- Simplified IPM for max. 15 location for long-term profile observation considered

Thank you for your attention!