Non-Invasive Transverse Profile Measurement Methods

Randy Thurman-Keup

68th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams

October 9-13, 2023

Introduction

- Non-Invasive
  - No significant alteration of the beam phase space or intensity
  - No damage to the instrument
- No synchrotron radiation (only exists in LHC now?)
- Interaction of the beam with a gas
  - Either via ionization or fluorescence
  - Using either residual or injected gas
- Electron/ion probe beams
- Laser-induced photoionization (unique for H-)

Residual Gas Ionization

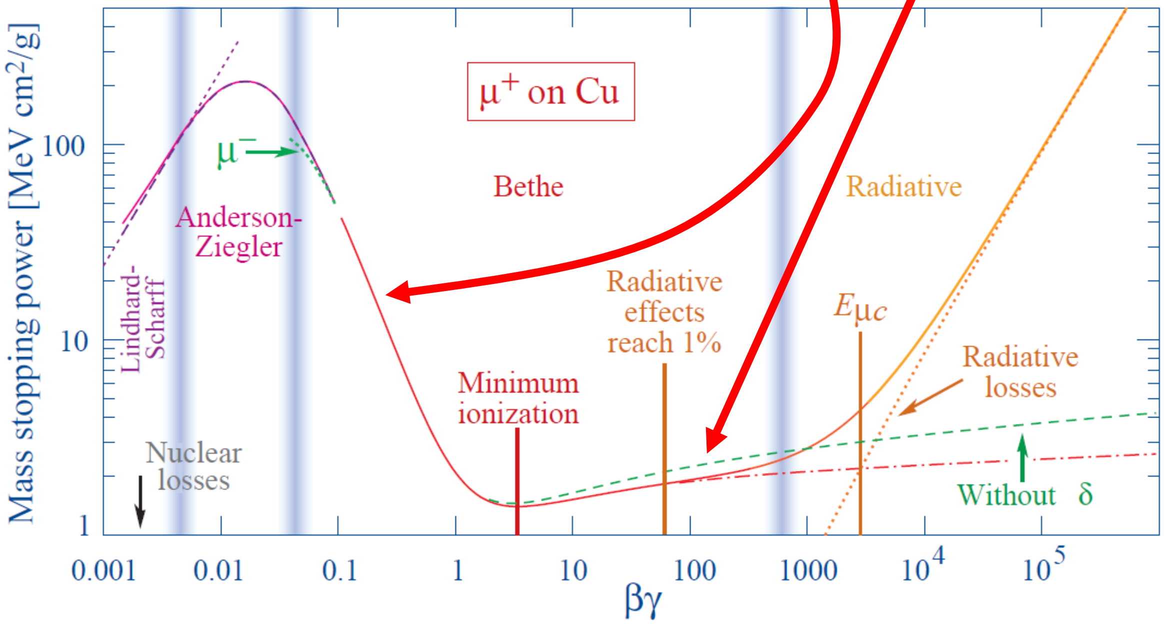
- Utilize beam-induced ionization of residual gas in the beampipe

$$N_2 + p \rightarrow N_2^+ + e^- + p$$

- Ionization rates determined by Bethe equation

$$\left\langle -\frac{dE}{dx} \right\rangle = \left(\frac{e^4 N_A}{4\pi\varepsilon_0^2 m_e c^2} \right) \rho z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

ρ = gas density
z = beam charge



$$n_e = d \cdot \sigma_{ion} \cdot N \cdot P \cdot \frac{N_A}{RT}$$

Distance $\mathcal{O}(10^{-2})$

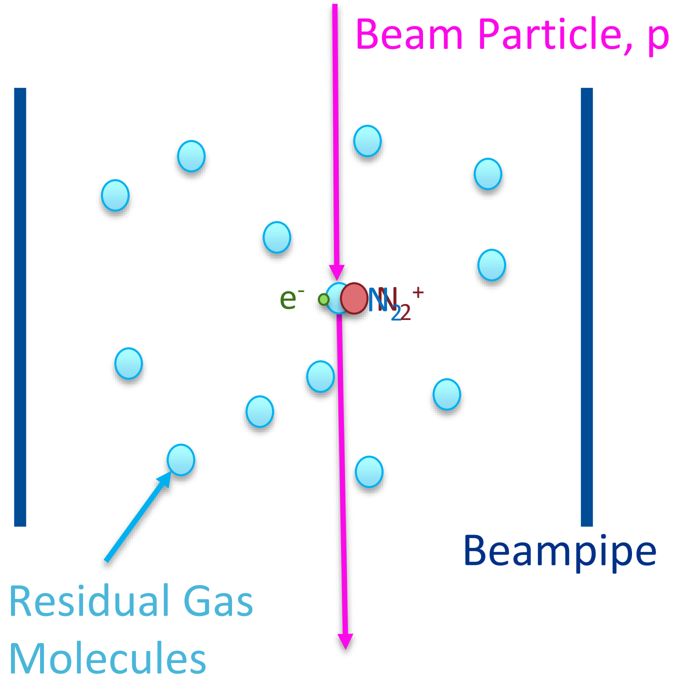
Cross Section $\mathcal{O}(10^{-23})$

# of beam particles $\mathcal{O}(10^{11})$

Pressure $\mathcal{O}(10^{-6})$

Gas Stuff $\mathcal{O}(10^{20})$

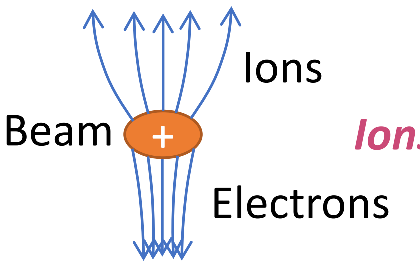
= 1



Residual Gas Ionization

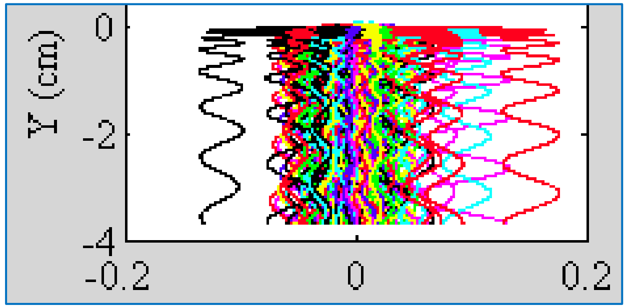
Typically called an Ionization Profile Monitor, IPM (but also RGM, BGI, …)

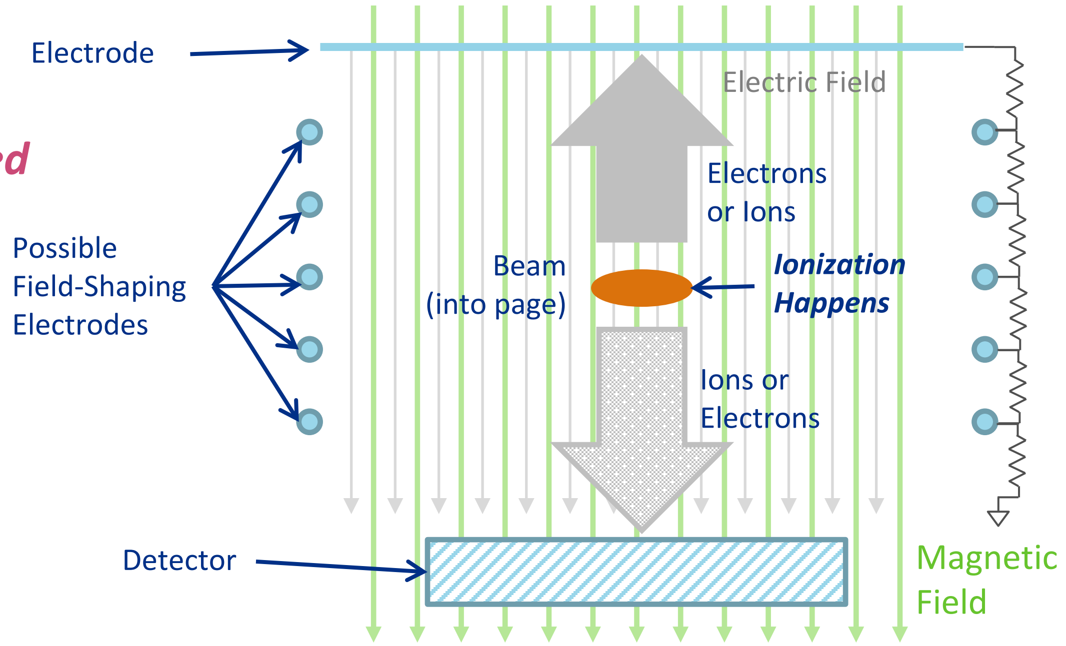
- Use an electric field to separate the ionization products
  - Typically in a range of 100 – 300 kV/m
- Want to preserve ion/electron starting positions during trip to detector
  - Trajectories may be impacted by space charge of the beam *V. Shiltsev, NIMA 986 (2021) 164744*
- Can use a magnetic field parallel to electric field to constrain electron trajectories if collecting electrons

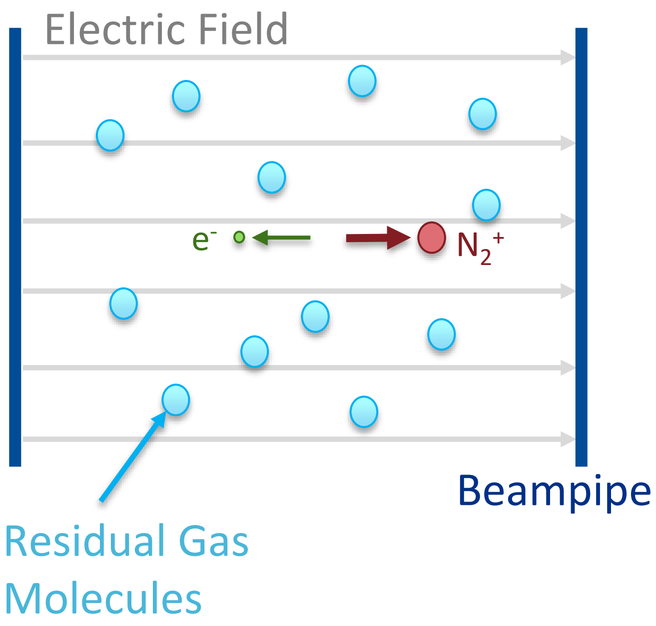


Ions less impacted

Electrons spiral with Larmor radius







IPM – Signal collection

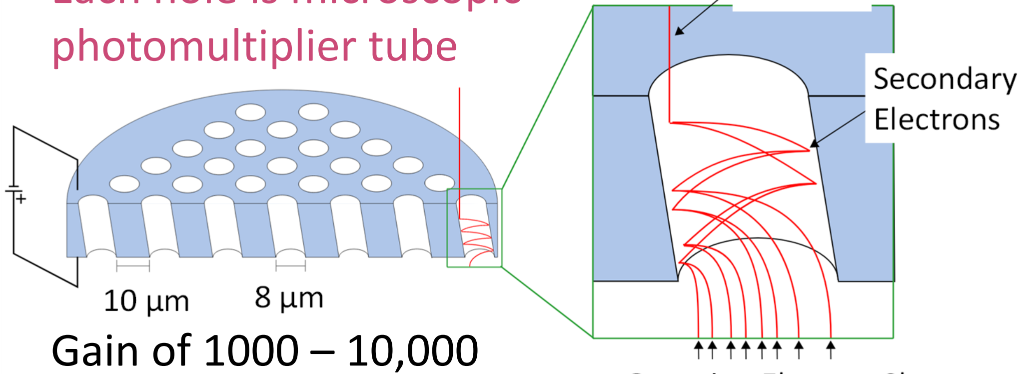
- Signal is typically small – A few per bunch to hundreds per bunch
  - Requires low-noise amplification or low-noise data acquisition
- Microchannel Plate → Phosphor Screen → Imaging System
- Phosphor Screen → Intensified Imaging System
  - Microchannel plates are outside the vacuum
- Microchannel Plate → Copper Strips or Wires → Data Acquisition
- Pixel Detector → Data Acquisition

Better **spatial** resolution

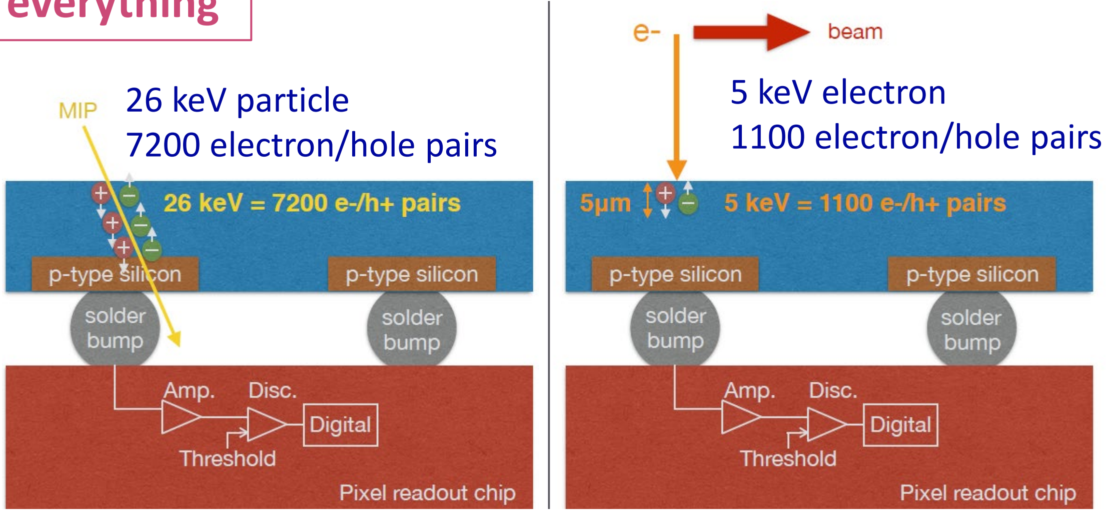
Better **time** resolution

Better **everything**

Each hole is microscopic photomultiplier tube



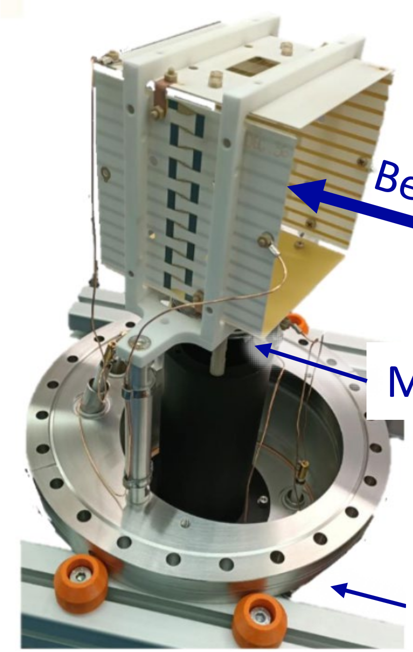
Gain of 1000 – 10,000



IPM – Signal collection

MCP / Phosphor Screen

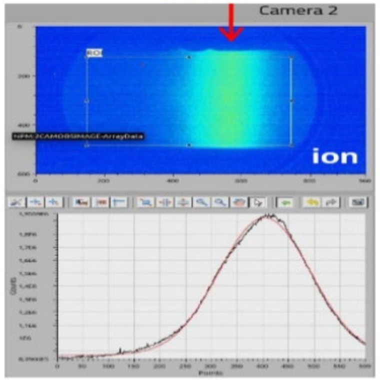
J. Marroncle et al.
IBIC2023, WEP001

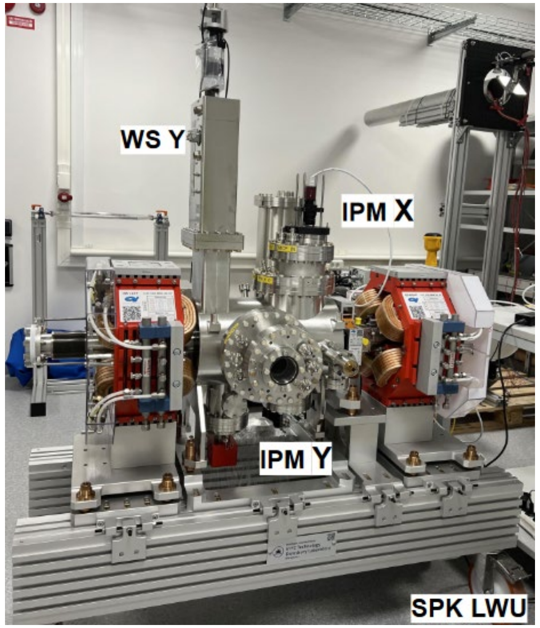


Beam
MCP/Phosphor
Camera

ESS

beam





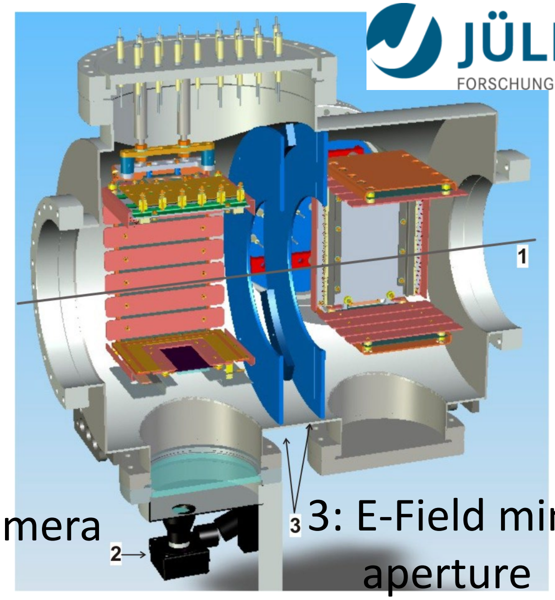
- 5 IPMs between cryomodules
- Ion collection

C. Böhme, IPM Workshop 2018, JPARC

COSY / GSI

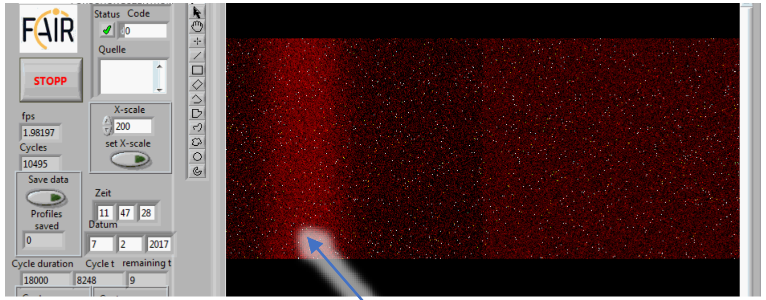
Ion collection

200 fps



1: Beam
2: Camera
3: E-Field minimizing aperture

Picture by T. Giacomini, GSI

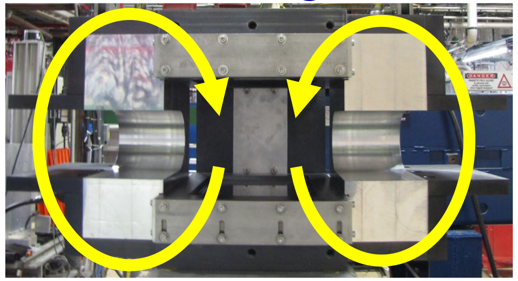


Beam Image

IPM – Signal collection

MCP / Conductive Strips

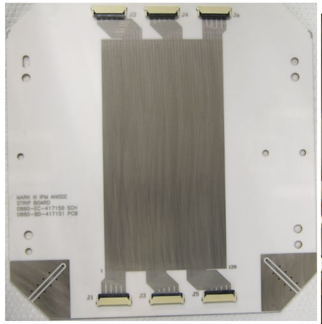
Permanent Magnet ~ 1 kG



All electron collection with magnet

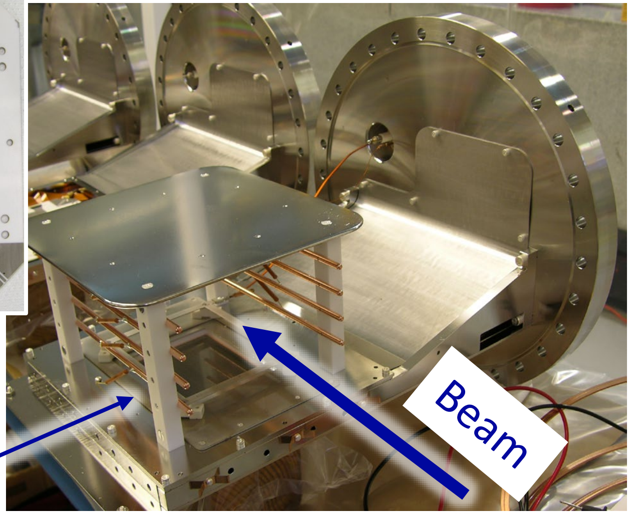
FNAL MI/RR

~1 MHz Bandwidth



Conductive Strips 0.5 mm pitch

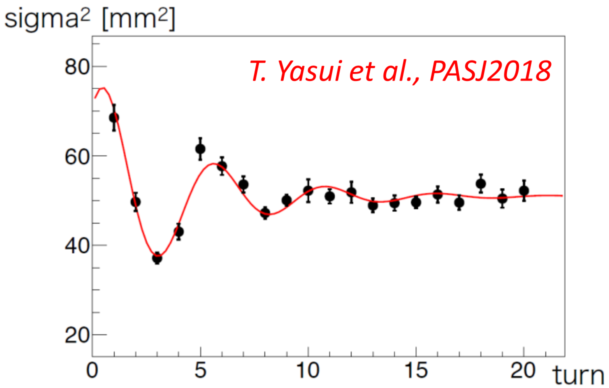
MCP / Strips



JPARC MR

2.5 mm pitch

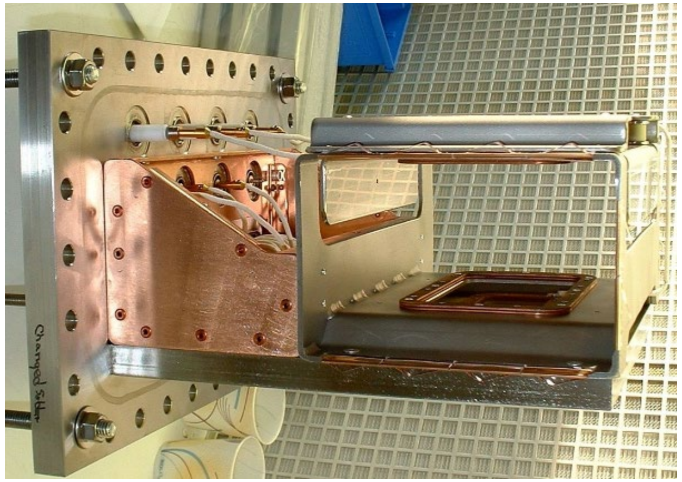
K. Satou, 3rd IPM Workshop

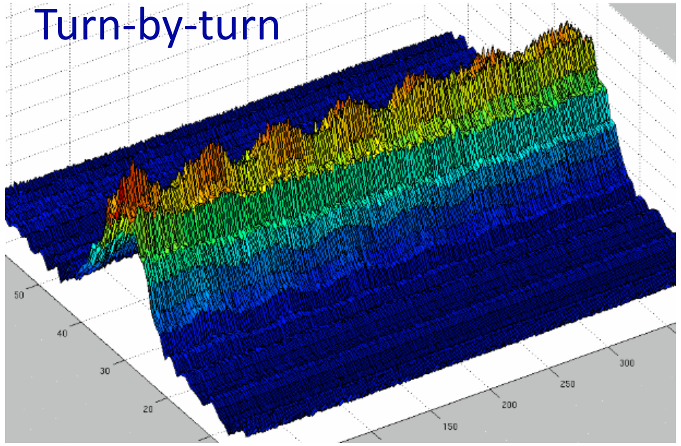


R. Connolly et al., BNL-102439-2013-TECH

BNL AGS

0.53 mm pitch

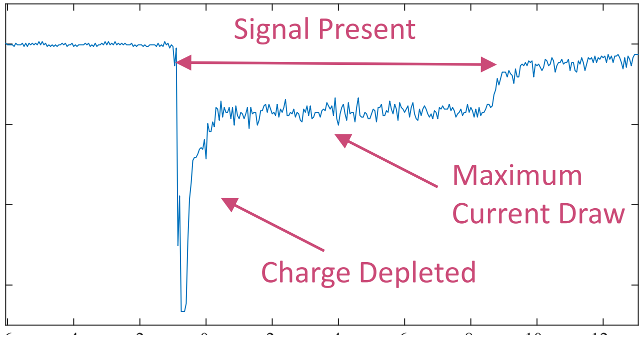




Microchannel Plate Features

- Short-term drop in gain for large current draw
  - $\mathcal{O}$(1 ms) charging time
- Gradual drop in gain due to aging
  - Function of current drawn from the MCP (>1 C/cm^2)
- Fast initial gain drop due to 'scrubbing'
  - Adsorbed gasses must be removed after exposure to air

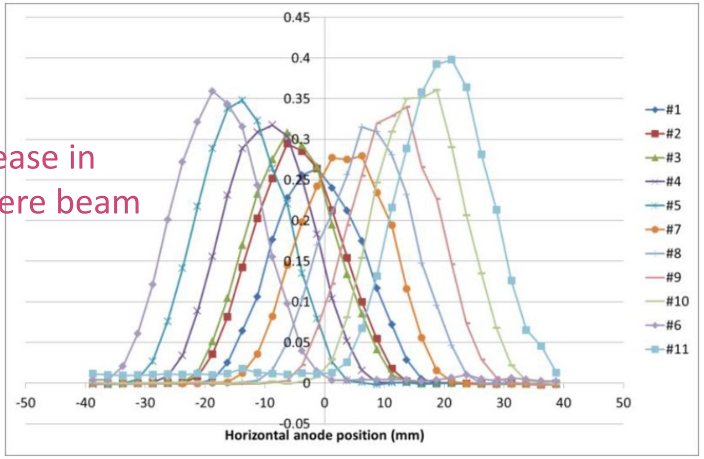
Photomultiplier Tube Example

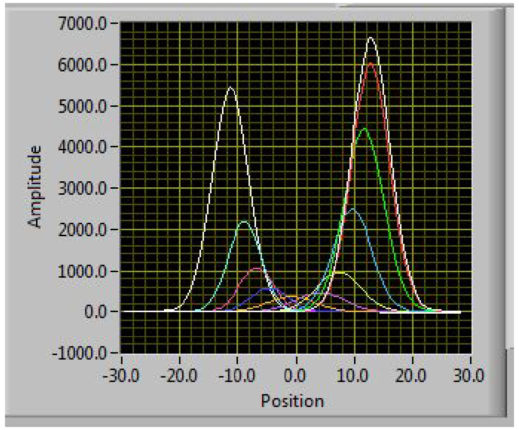


K. Satou, 3rd IPM Workshop

Gain decrease in center where beam is located

JPARC

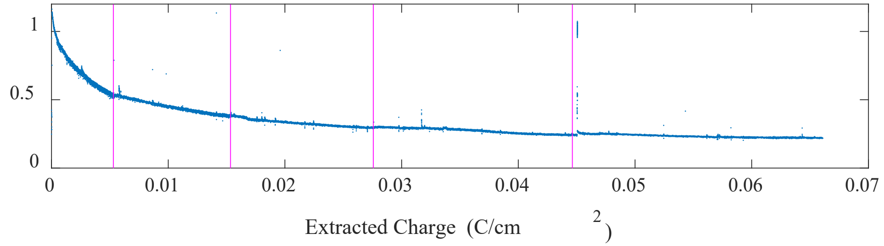




FNAL Scan: Typically seen after just a couple of years of intermittent use

FNAL

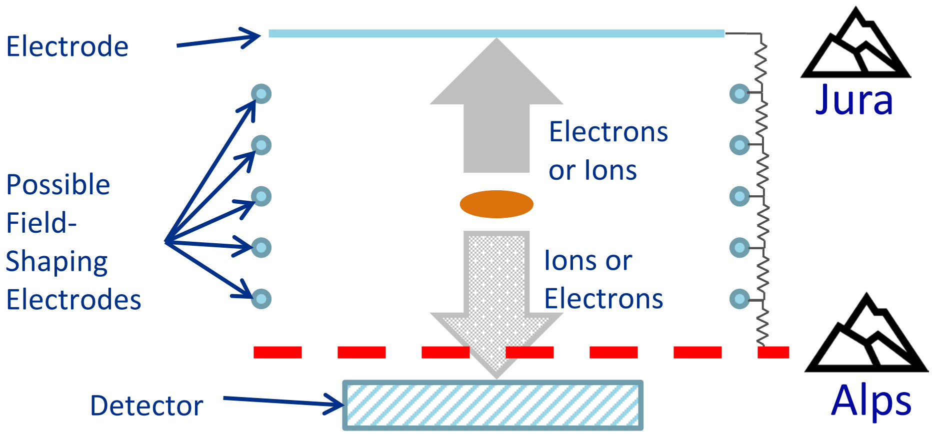
MCP Gain (arb. units)

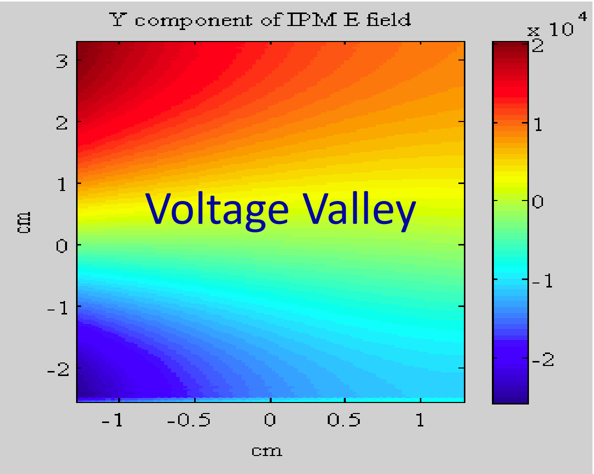


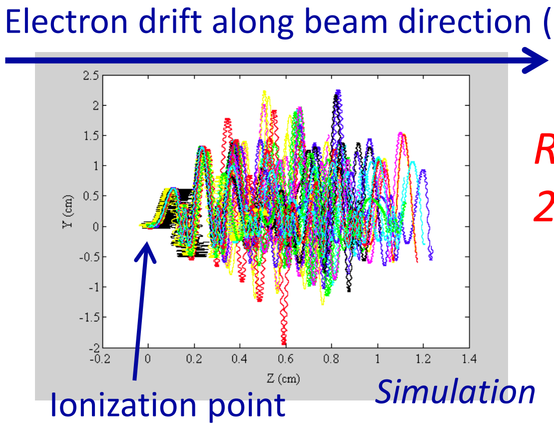
Calibrate gain: UV lamp, step the beam

Gating the IPM

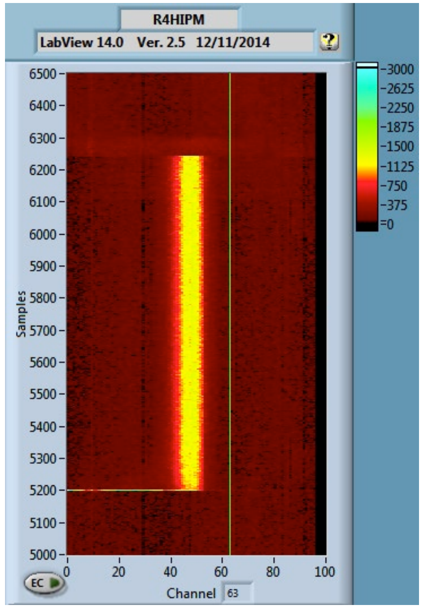
- Include an additional electrode in the path of the detected particles

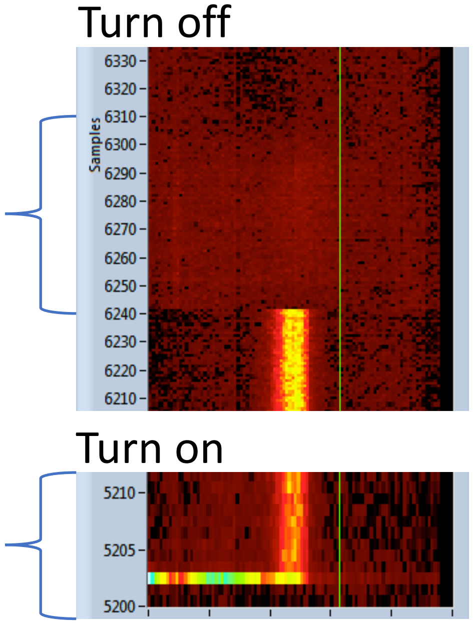






R. Thurman-Keup
2nd IPM Workshop





FNAL MI/RR

J. Zagel, 2nd IPM Workshop

See also R. Connolly et al., BNL-102439-2013-TECH
and K. Satou, IBIC2019, TUPP020

IPM – Signal collection

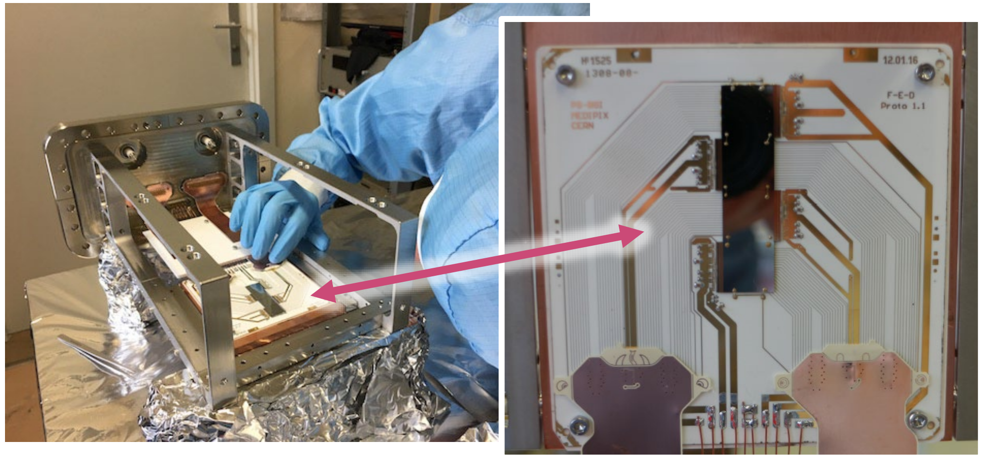
S. Levasseur et al., IBIC2021

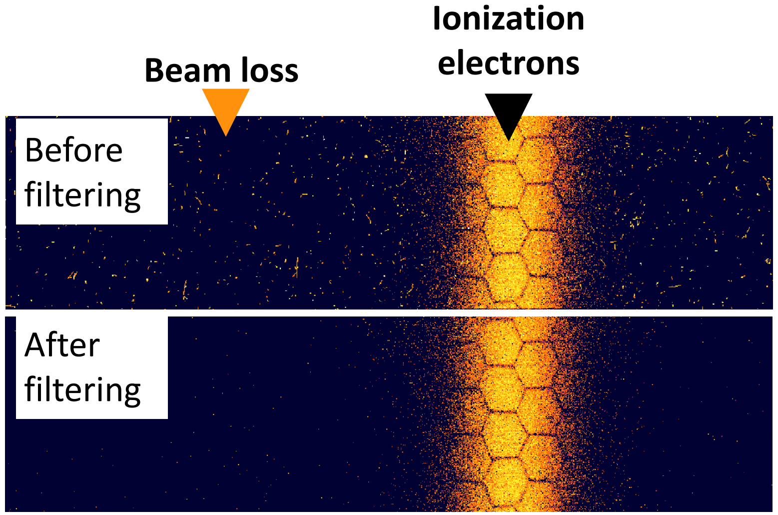
J. Storey, 20th Anniversary Timepix Symposium; BI Day 2017

Pixel Detector

Electron collection with magnet

CERN PS - Timepix





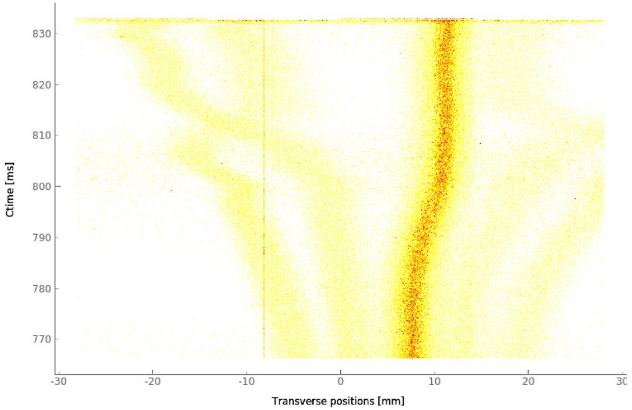
Timepix3 characteristics:

- **Detector resolution = 55 μm**
- **Time resolution = 1.56 ns**

Performance limitations:

- Dead time per pixel > 475 ns
- Output bandwidth < 80 MEvents/s

Multi-turn extraction showing transverse beamlets

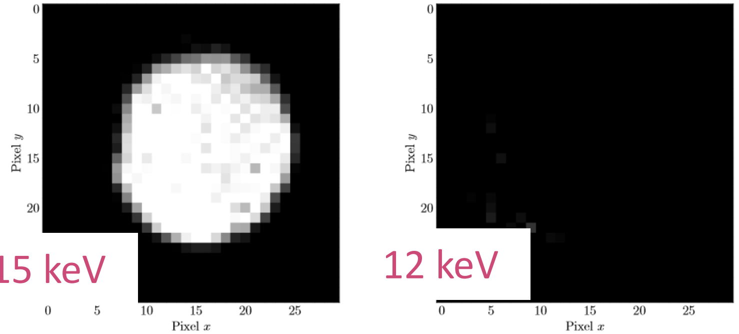


F. Benedetti et al. ANIMMA2019

ESS Test with ions

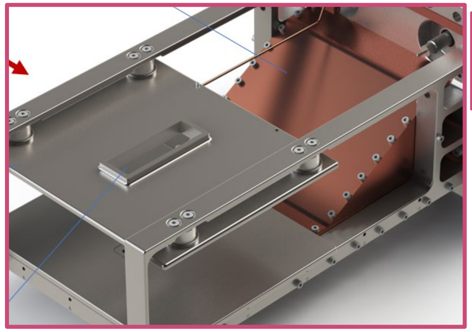
Test of Timepix with H_2^+ ions

Very sensitive to energy

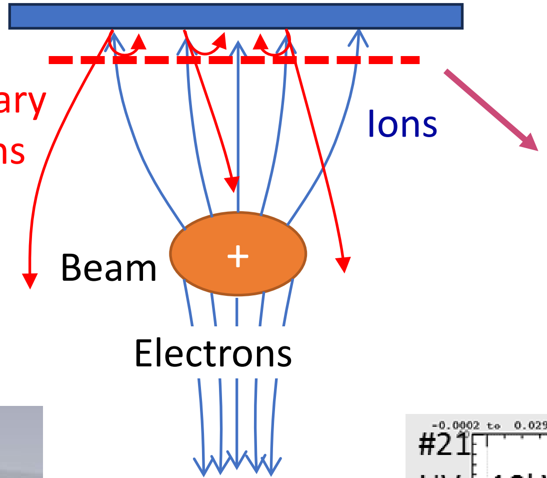


IPM – Ionization Remnants

- For electron detection, ions must not produce secondary electrons
  - Grid with more negative voltage
  - Ion capture chamber



CERN

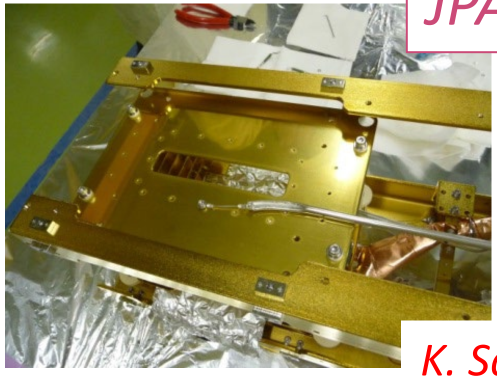


FNAL

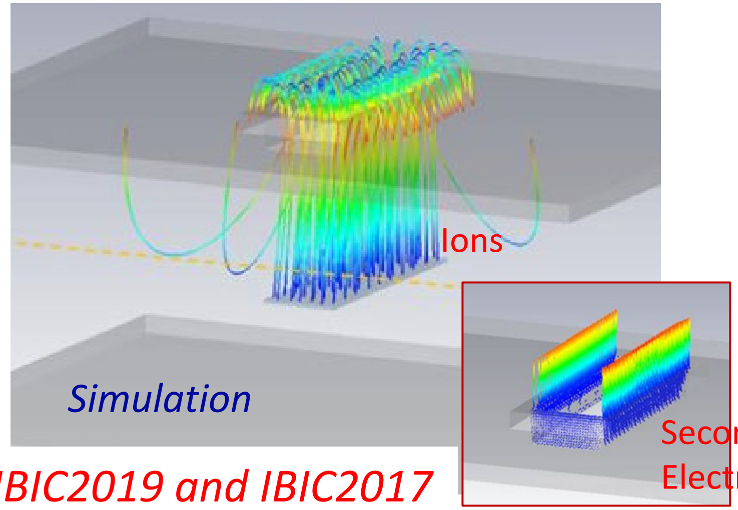
Grid to contain secondaries

60% clearance

JPARC

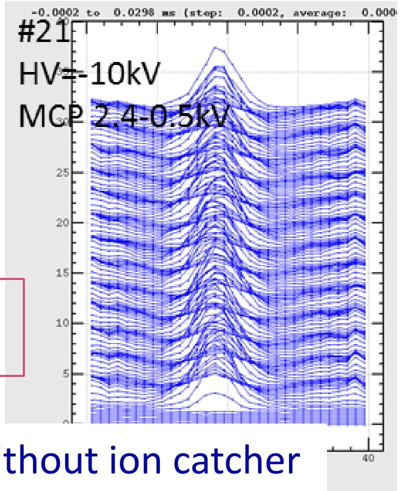


Ions go through hole and curve to top side of electrode

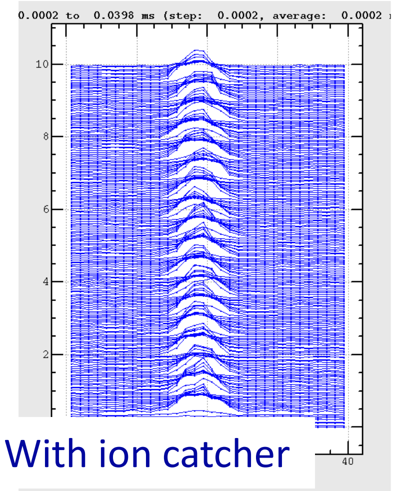


K. Satou, IBIC2019 and IBIC2017

JPARC



Without ion catcher



With ion catcher

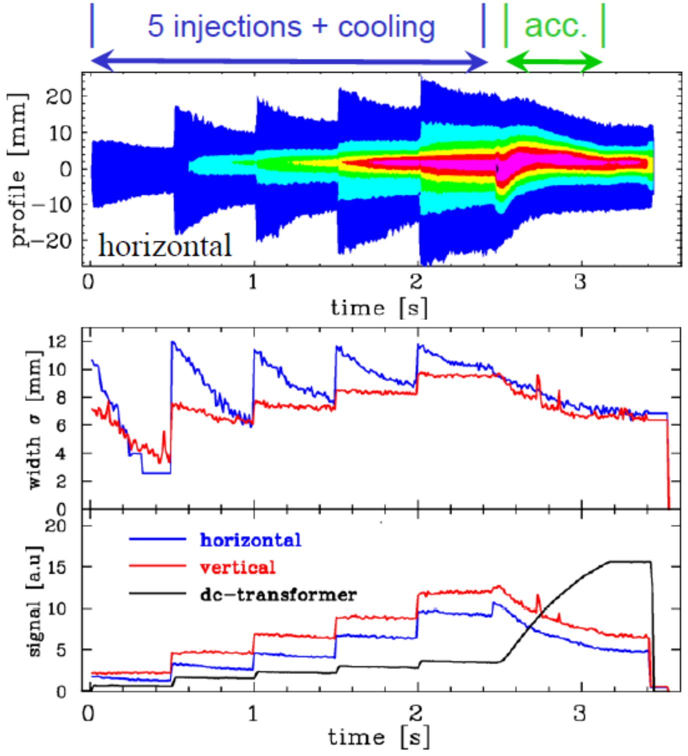
IPM Examples

P. Forck, IPAC2010

U^{73+} beam stacked
with electron cooling

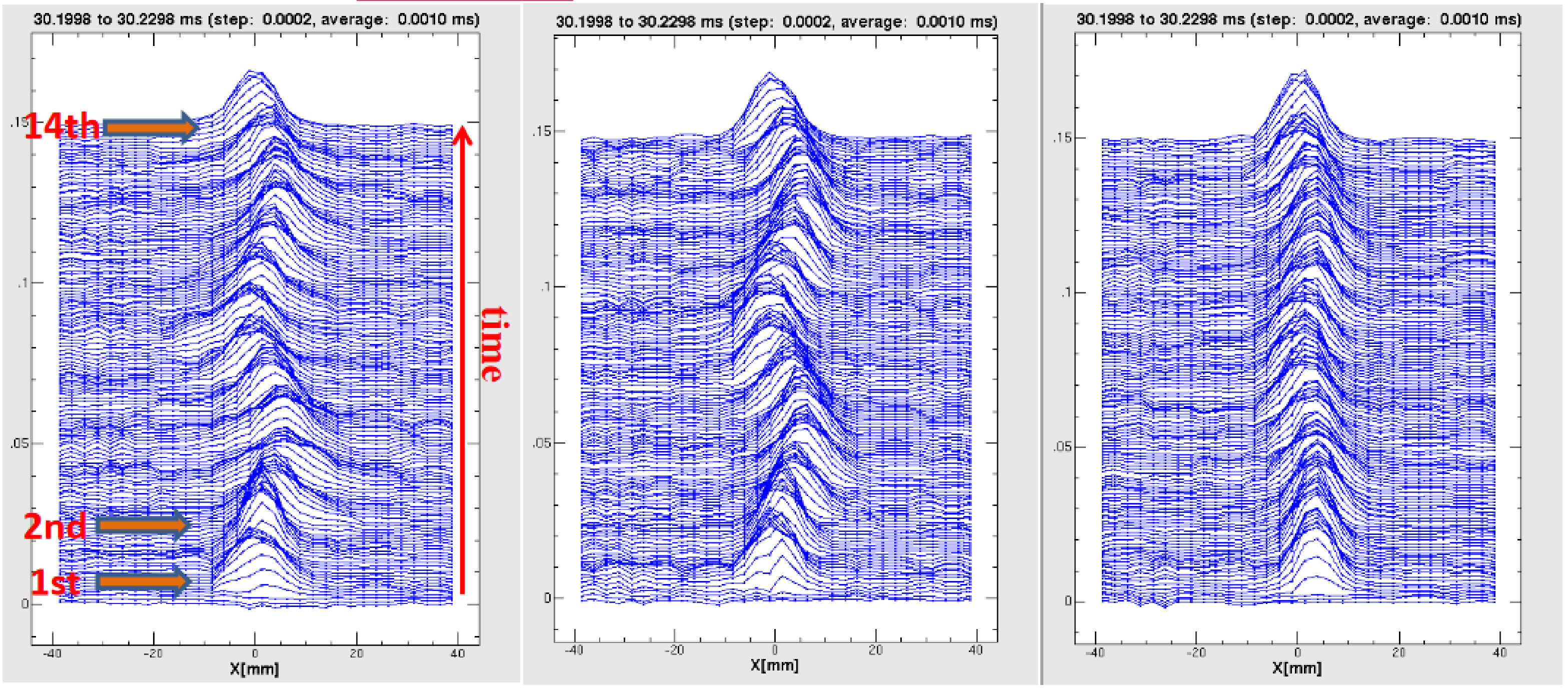
GSI

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



JPARC

K. Satou, IBIC2017



Injection miss-match
Q mode + D mode

After Q mode tuning
D mode remains

After Q and D mode tuning

Residual Gas Fluorescence

- Similar to beam-induced ionization, except less energy transferred

$$N_2 + p \rightarrow (N_2^+)^* + e^- + p \rightarrow N_2^+ + \gamma + e^- + p$$

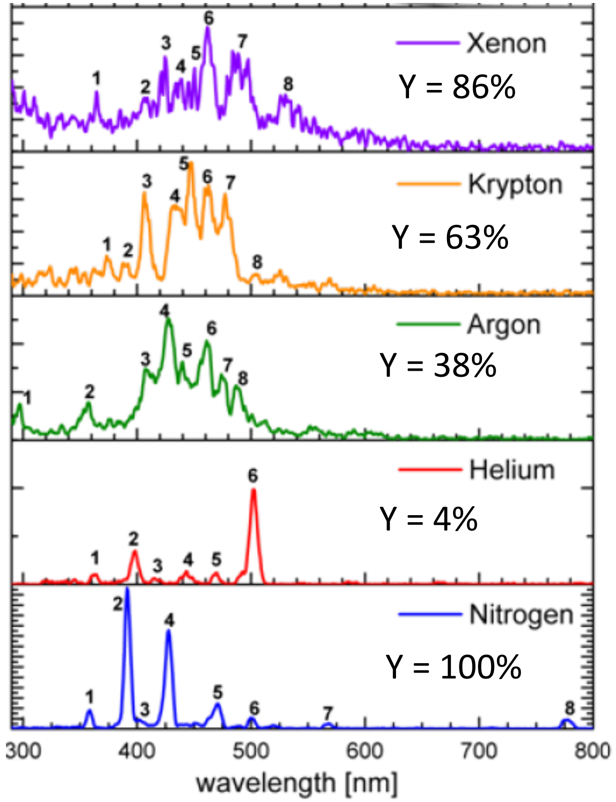
$$Xe + p \rightarrow (Xe)^* + p \rightarrow Xe + \gamma + p$$

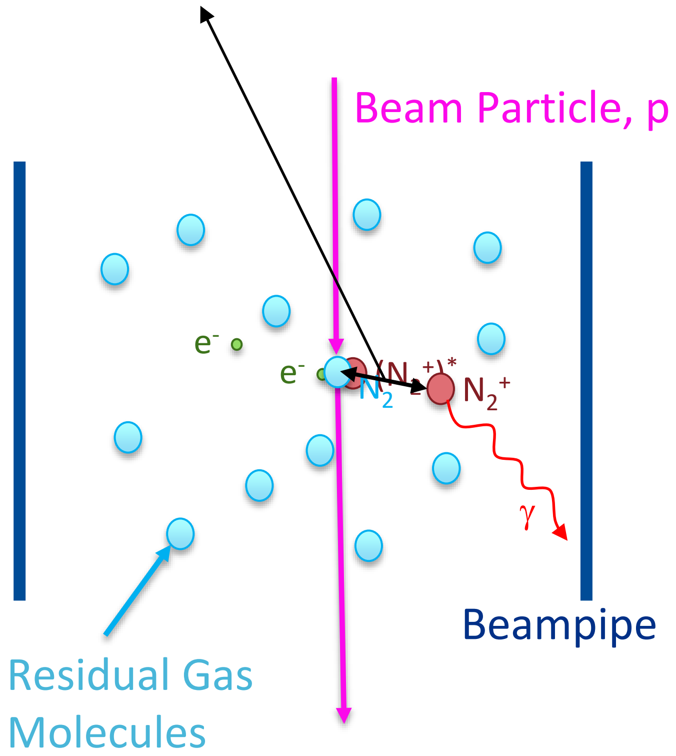
- Movement of excited molecule before emission
  - Determined by lifetime of excited state and energy of molecule
- Changes origination position of beam interaction

$\tau(N_2)$ = 60 ns $\tau(Xe)$ = 6 ns
Distance from *kT* motion
N_2 = 25 μm   Xe < 1 μm

Y = Relative Fluorescence Yield

F. Becker et al. DIPAC2009

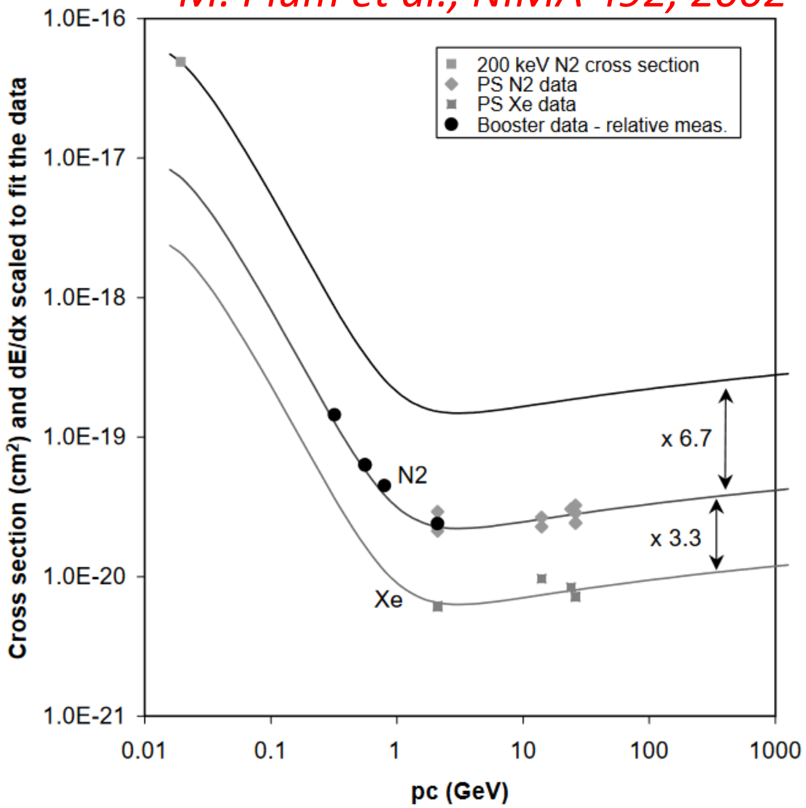




Residual Gas Fluorescence

- Behavior with beam energy shown to follow dE/dx expections
- Signal relative to ionizations
  - Number of primary ionizations for N_2
    - ~20 in 2 cm of atmospheric pressure
      F. Sauli, CERN 77-09
  - Number of photons from N_2
    - ~1.2 in 2 cm of atmospheric pressure
      M. Friend, 3rd IPM Workshop
      M. Plum et al., NIMA 492, 2002
  - ~16 times fewer photons than ion pairs
  - 4π angular collection of ions
  - 45-degree half-angle cone is only ~$\pi/2$
  - Total is factor of 100 fewer photons
- Use gas injection to offset small number of photons

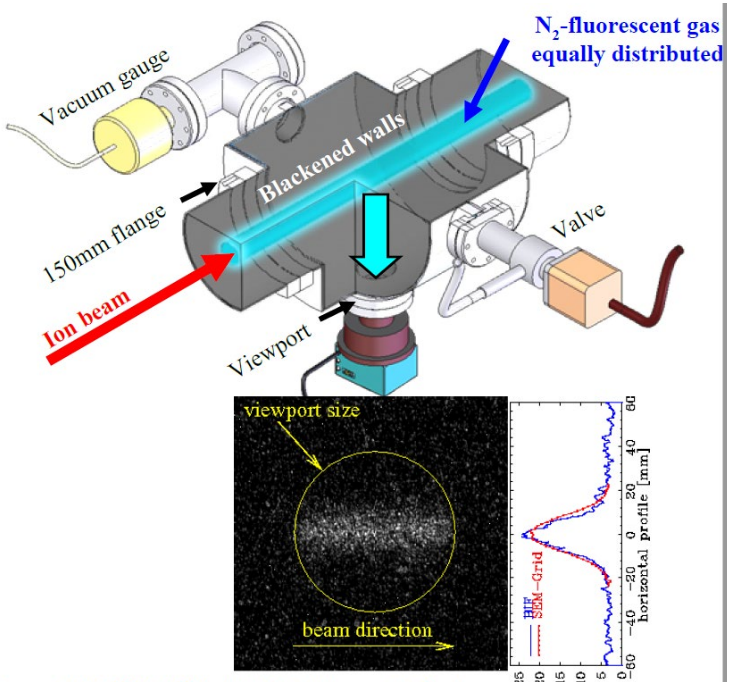
M. Plum et al., NIMA 492, 2002



Residual Gas Fluorescence

GSI

F. Becker et al., DIPAC2007



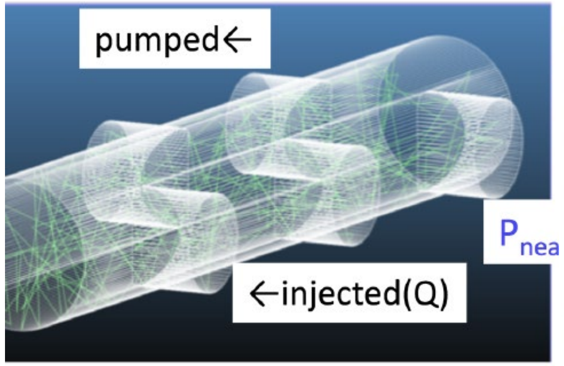
Beam: 4×10^{10} Xe^{48+} at 200MeV/u, $p=10^{-3}$ mbar

JPARC Neutrino Beamline

S. Cao, IBIC2020

Need significant increase in pressure → simulations with Molflow

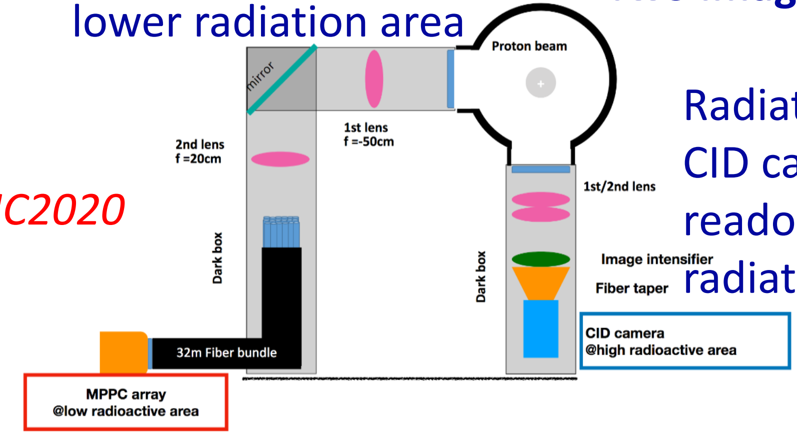
Molflow:
Monte Carlo simulation
for vacuum system

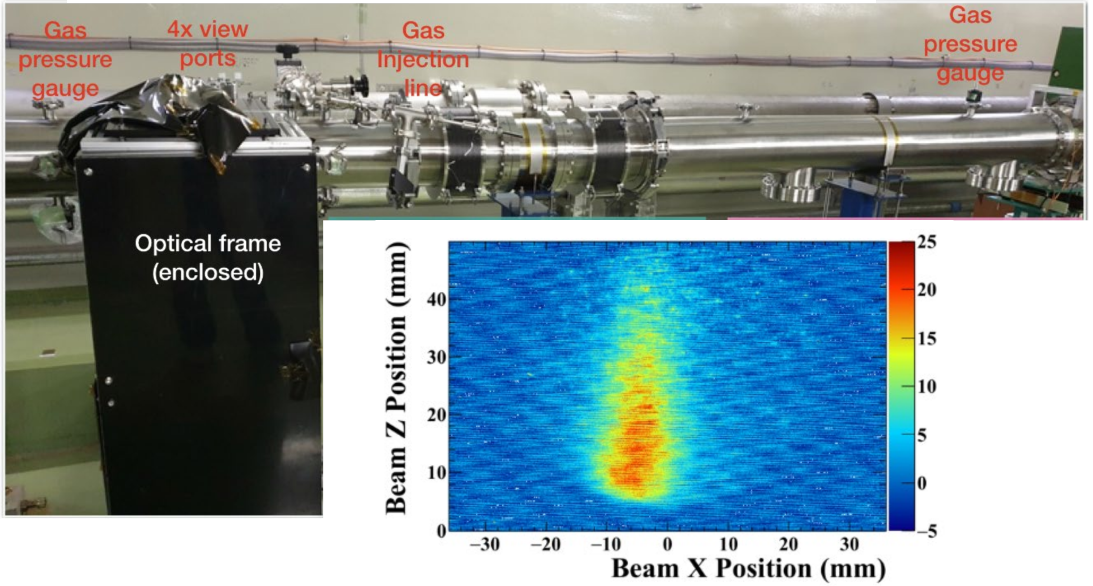


Fiber transport to lower radiation area

Two imaging paths

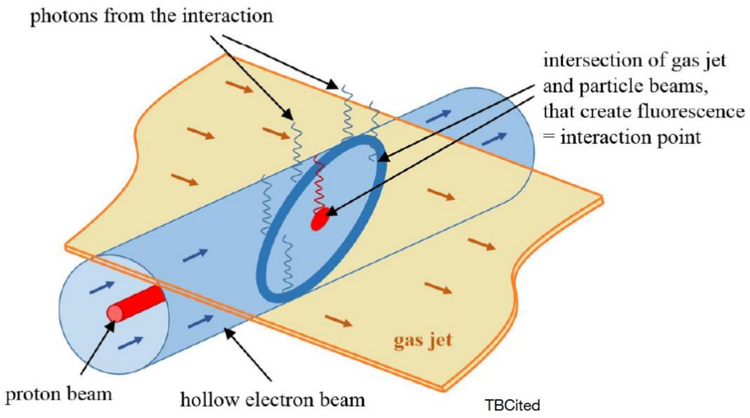
Radiation tolerant CID camera for readout in high radiation area



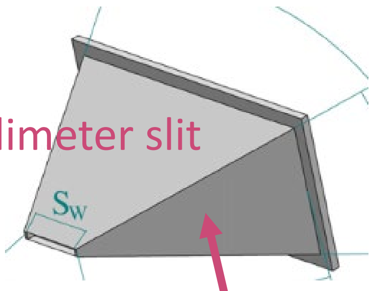


Gas Jets

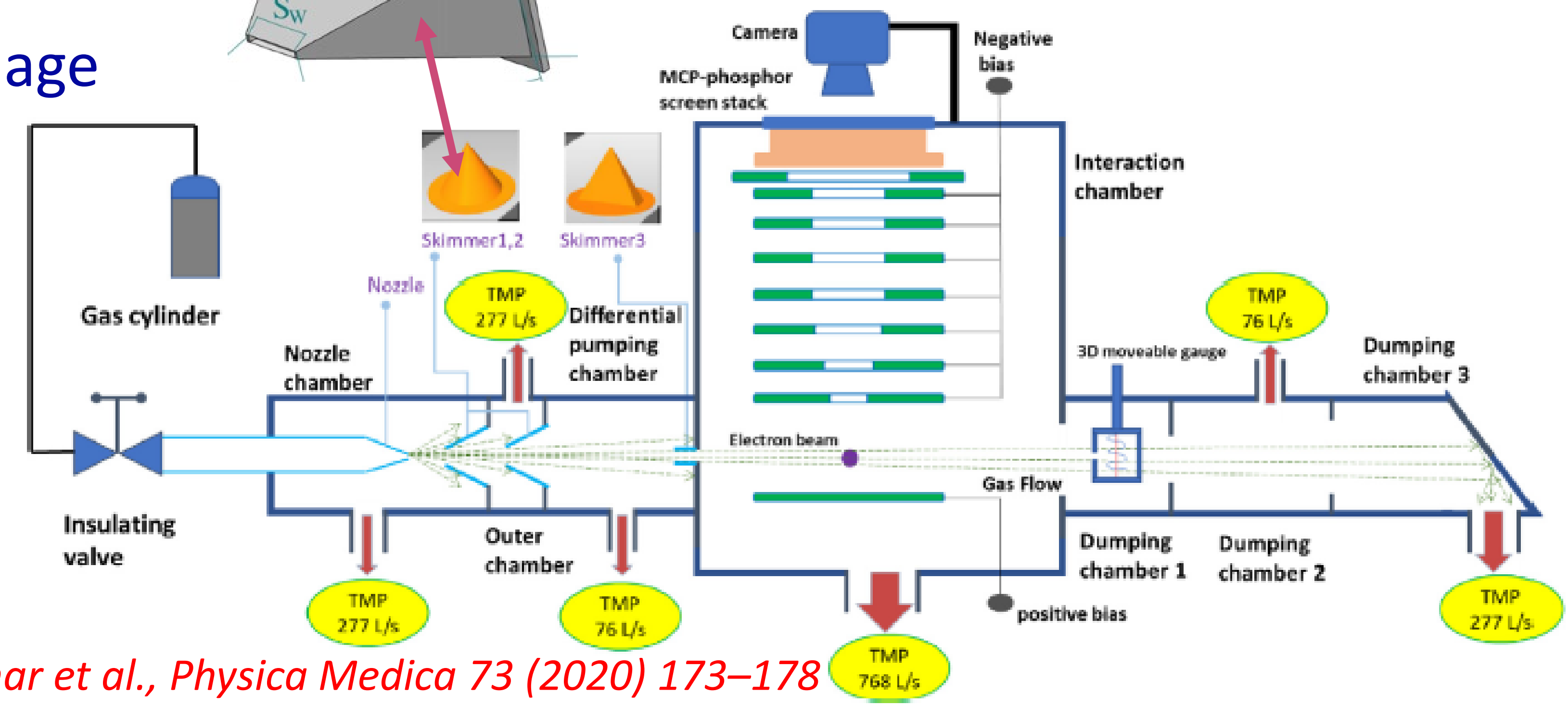
- Sheet of high velocity gas molecules created instead of using residual gas
  - $\mathcal{O}$(1-10) times kT velocity which is 400 m/s for N_2
- Can collect ions or photons
- Two-dimensional beam image
  - Sheet thickness is resolution contribution



TBCited



M. Putignano and C.P. Welsch NIMA 667 (2012)



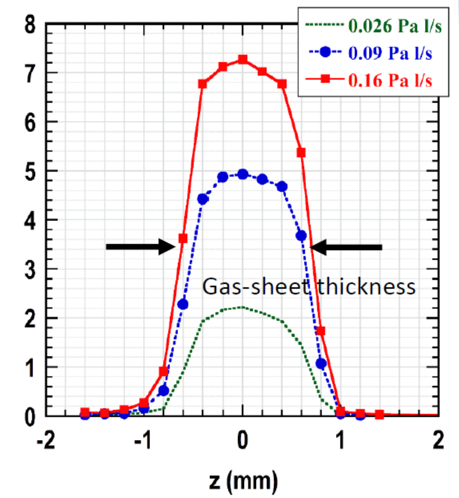
N. Kumar et al., Physica Medica 73 (2020) 173–178

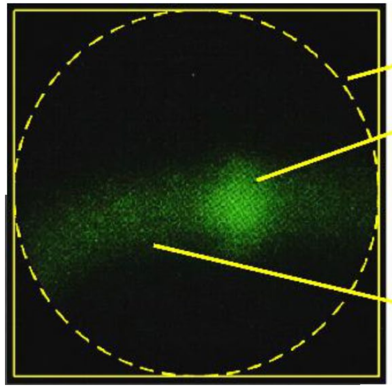
Gas Jets

JPARC LINAC

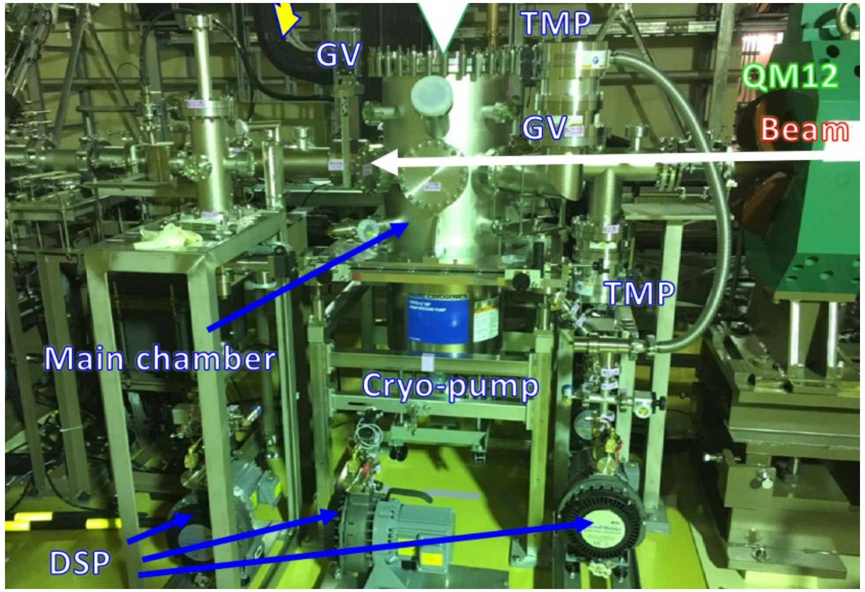
Collects ions

Sheet Thickness

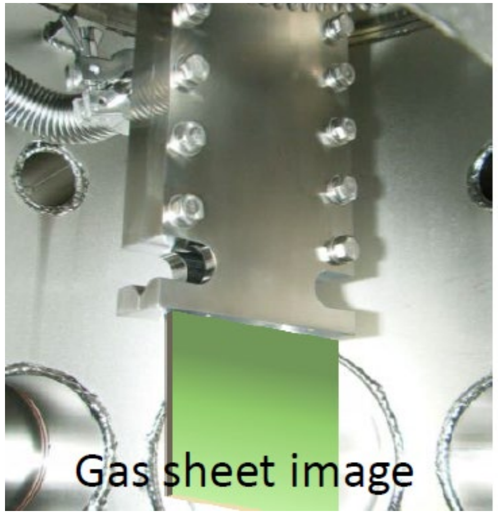


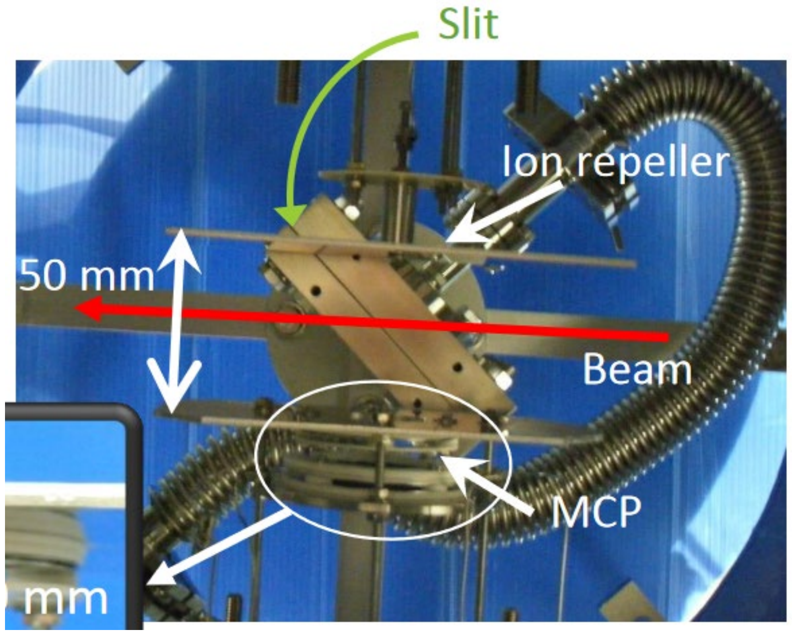


J. Kamiya, 3rd IPM Workshop



Sheet generating chamber
No skimmers



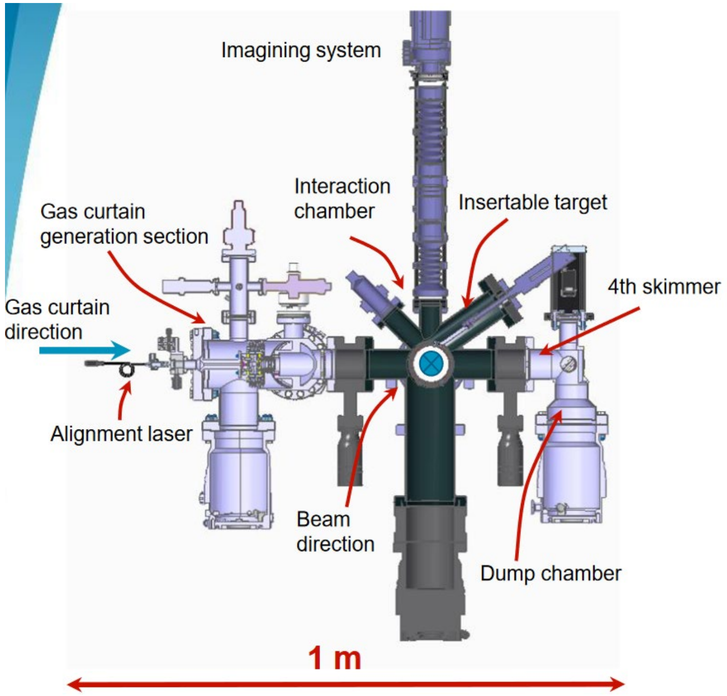


Gas Jets

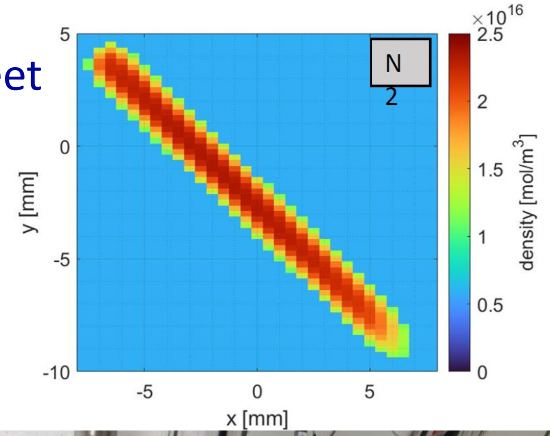
CERN LHC

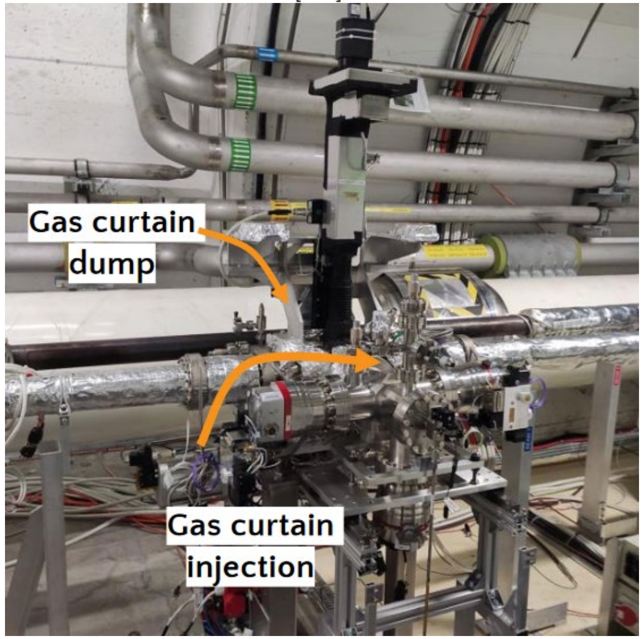
Collects Photons

O. Sedlacek, IBIC2023



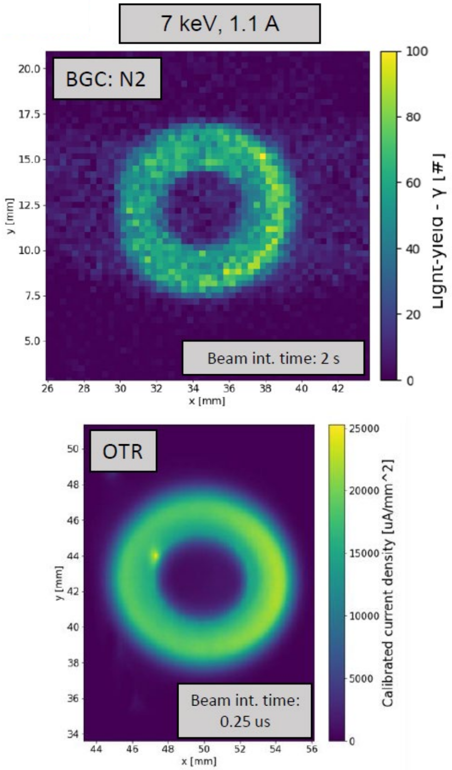
Gas Sheet Profile



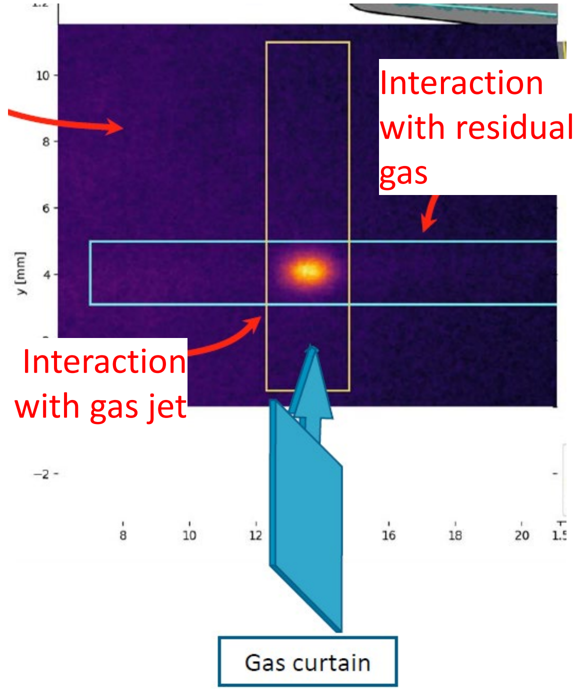


Used for overlapping beams of protons and electrons of electron lens

Electron Lens Beam



LHC 6.8 TeV Beam

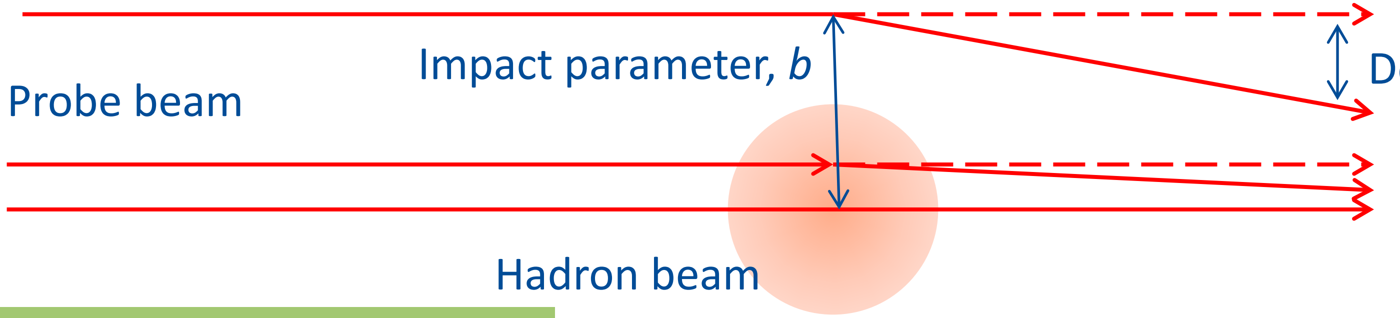


Deflection of Probe Beam

- Determine the profile of a hadron beam by using the deflection of a probe beam

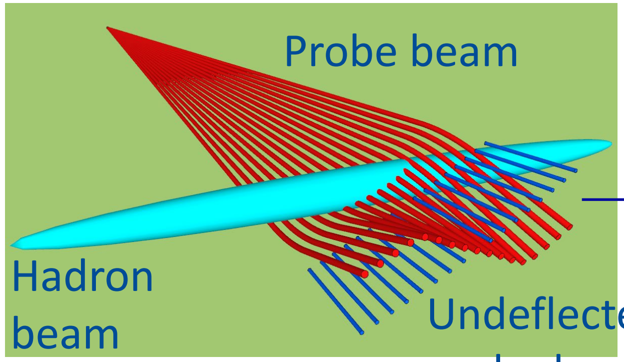
Assume $\gamma \gg 1$, no magnetic field, $\rho \neq f(z)$, deflection is very small such that $\vec{r} \approx \{b, vt\}$, $\vec{p} \approx \{0, p\}$, and $\theta \approx \frac{|\Delta\vec{p}|}{|\vec{p}|}$

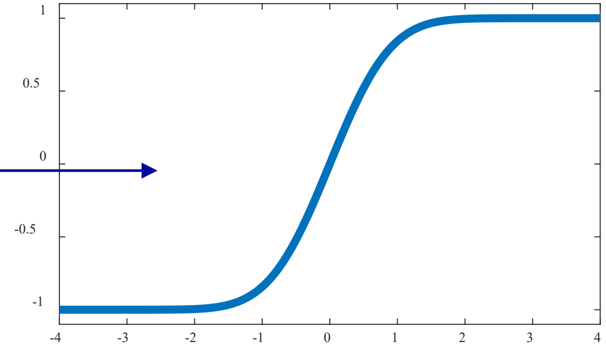
Probe beam is deflected by electric and magnetic fields of the hadron beam



$$\vec{F}(\vec{r}) \propto \int d^2\vec{r}'\rho(\vec{r}')\frac{(\vec{r}-\vec{r}')}{|\vec{r}-\vec{r}'|^2}$$

$$\Delta\vec{p} = \int_{-\infty}^{\infty} dt\ \vec{F}(\vec{r}(t))$$

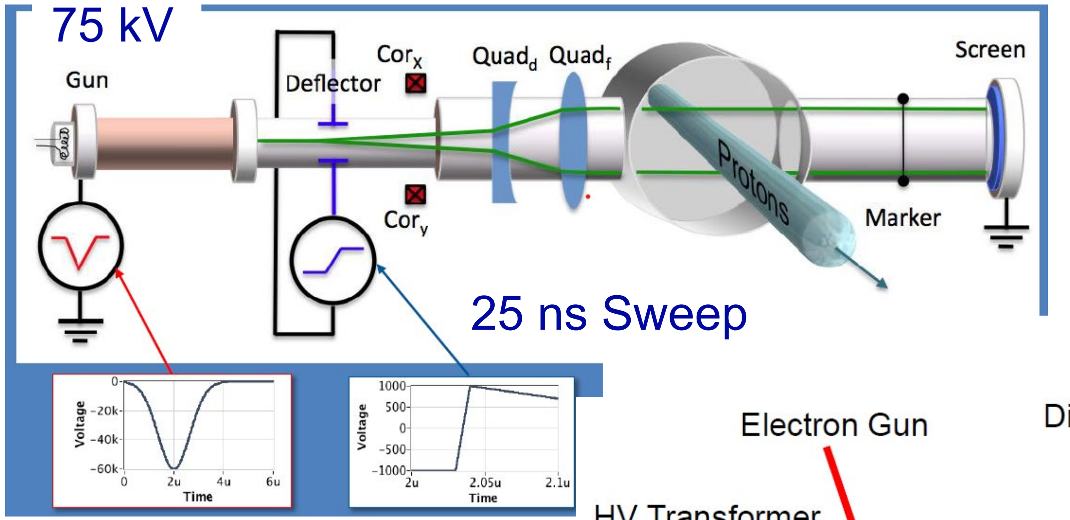




$$\frac{d\theta(b)}{db} \propto \int_{-\infty}^{\infty} dy'\,\rho(b, y')$$ ← x profile

$$\xrightarrow{gaussian\ beam} \boldsymbol{\theta(b) = erf(b)}$$

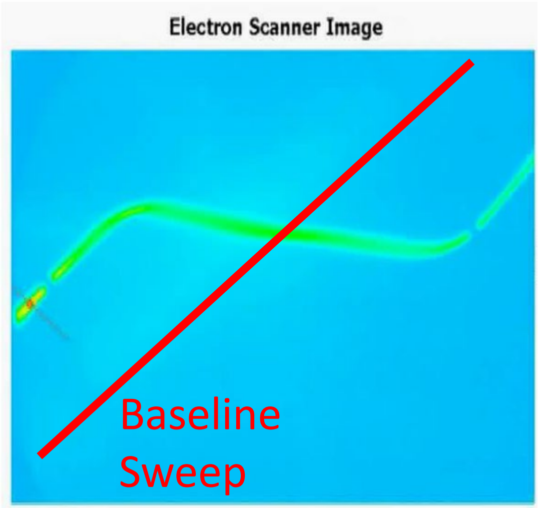
Electron Beam Profiler

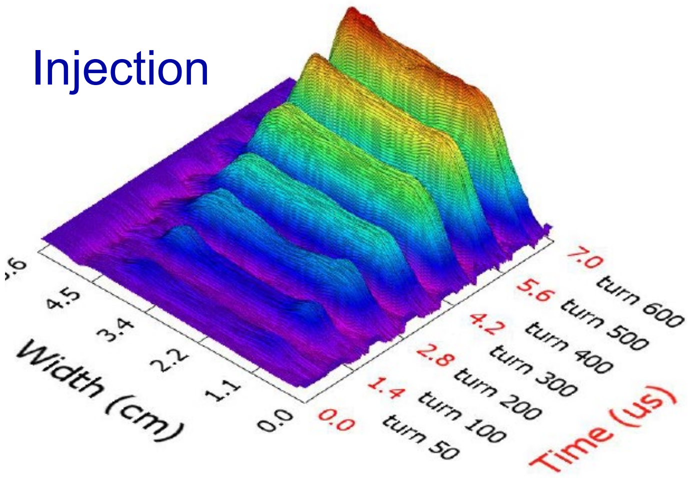


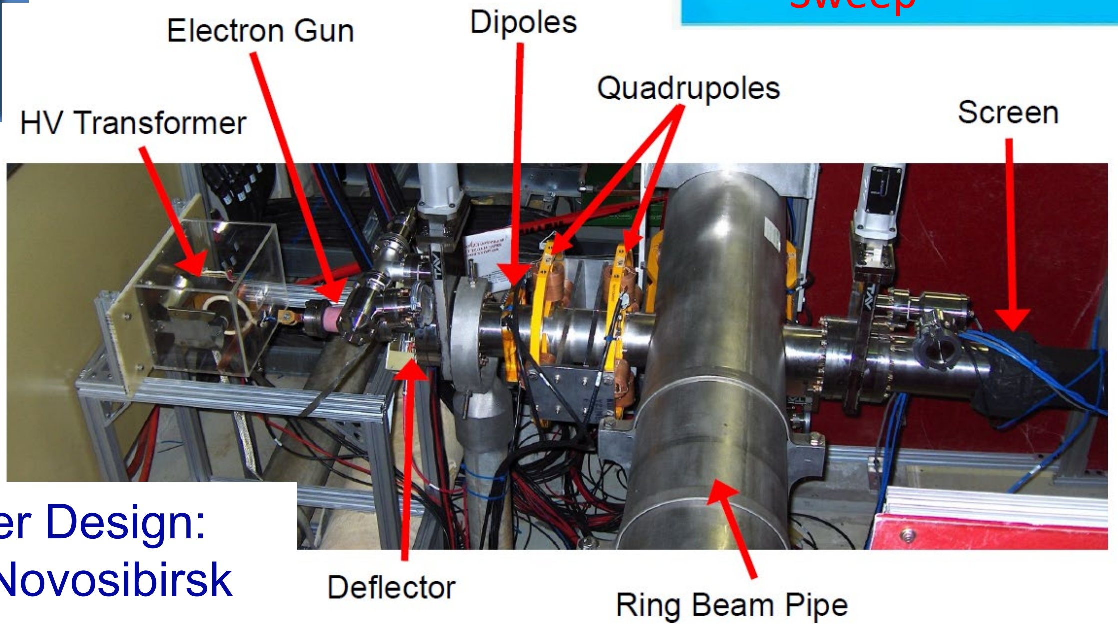
SNS

600 ns bunch length
Single bunch in ring, h=1

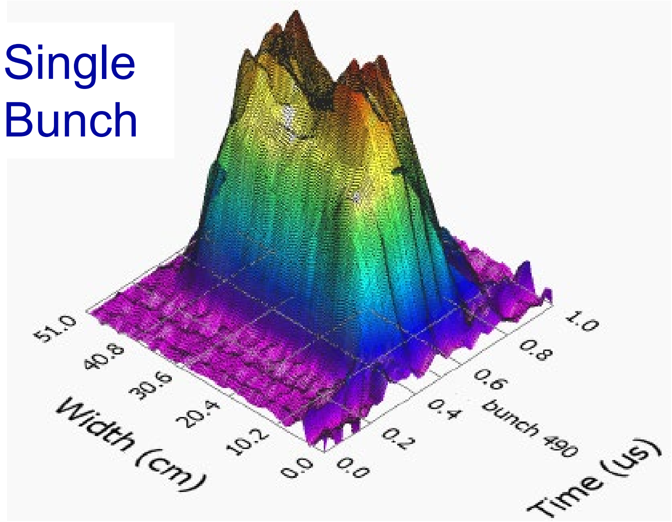
W. Blokland, 9th DITANET







Scanner Design:
BINP, Novosibirsk

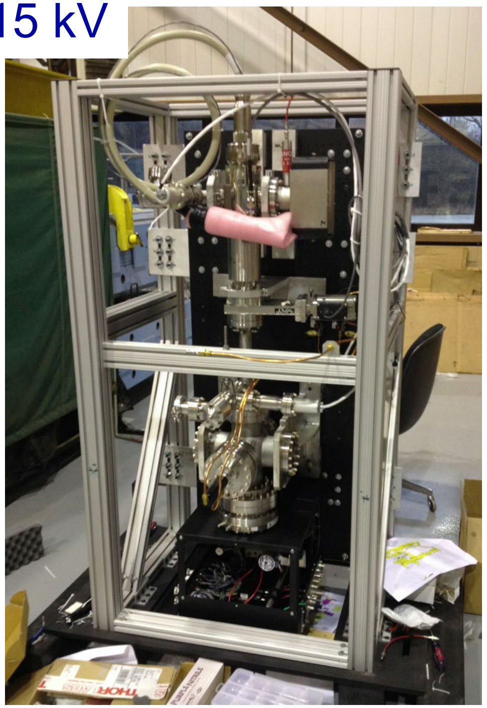


Electron(Ion) Beam Profiler

FNAL MI

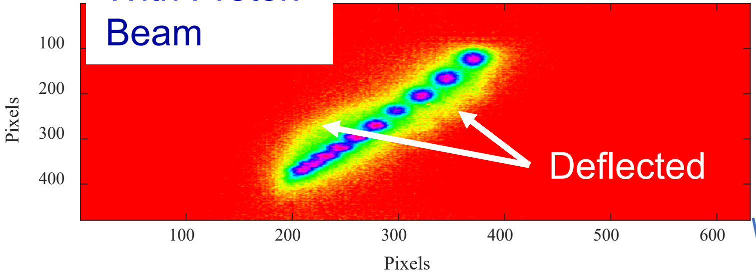
~10 ns bunch length

15 kV

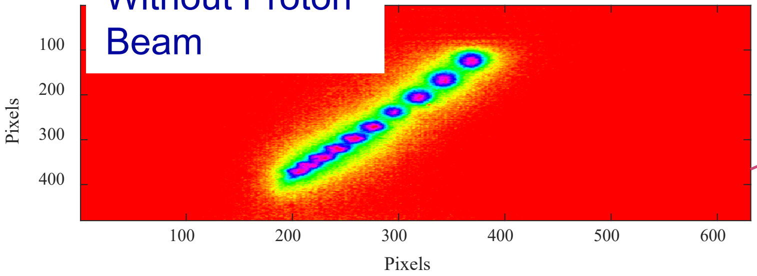


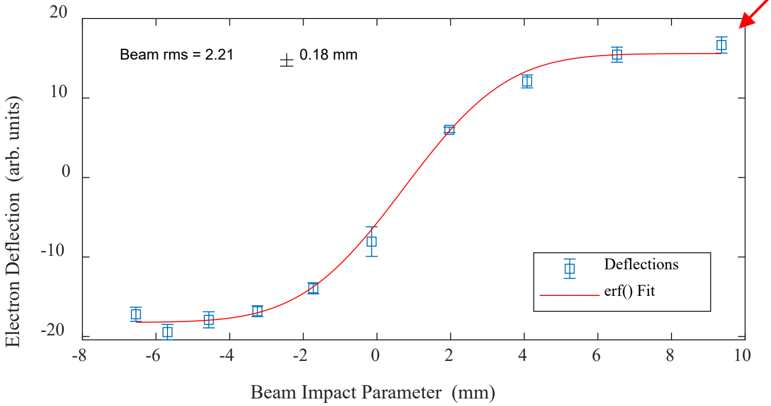
R. Thurman-Keup, IBIC2023

With Proton Beam



Without Proton Beam

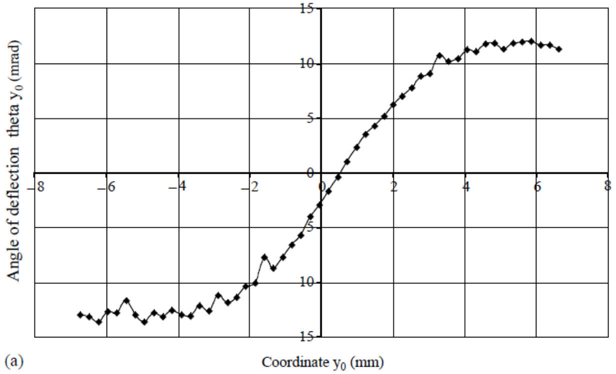


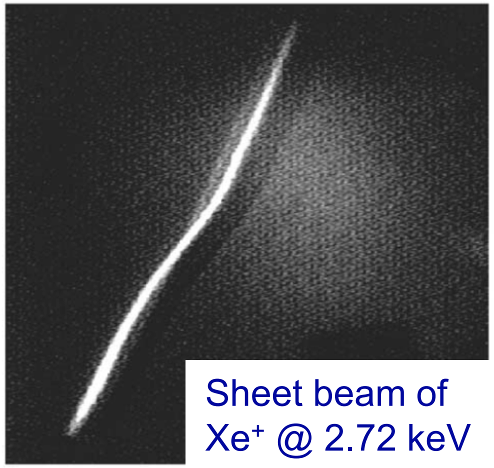


- Discrete steps of electron beam
  - 25 ns sweep time too long
  - Electrons move through too rapidly and see the gaps between bunches
- Use low energy ions
  - Slow ion deflection averages bunch structure

CERN SPS

J. Bosser et al., NIMA 484 (2002)





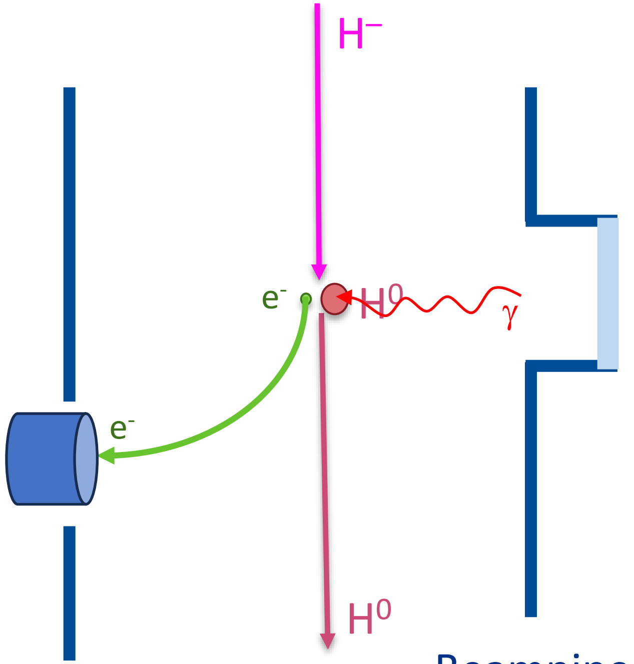
Sheet beam of Xe^+ @ 2.72 keV

Photoionization of H^- by Laser

- A photon with enough energy (1064 nm is sufficient) can ionize the 'loose' electron on the H^- ion which has a binding energy of 0.75 eV

$$\mathrm{H}^- + \gamma \rightarrow \mathrm{H}^0 + e^-$$

- Electron is collected via magnetic field and detector
- Laser is stepped through the beam to obtain profile
- Additionally, H^0 can be detected downstream to obtain divergence and thus emittance
  - Beam must be bent by magnet to isolate the H^0
- For laser pulse lengths < bunch length, can measure bunch length



Photoionization of H^- by Laser

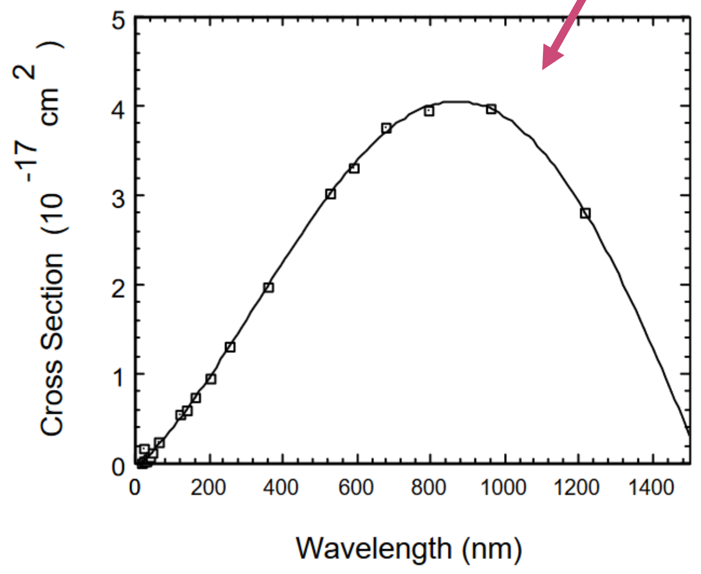
- Number of ionizations for laser perpendicular to beam

$$dn = c\sigma_I(\tilde{\lambda}_l) I_l I_b \, dtdxdydz \qquad \tilde{\lambda}_l = \lambda_l\sqrt{1-\beta^2}$$

Bunch density

Lorentz-transformed laser wavelength

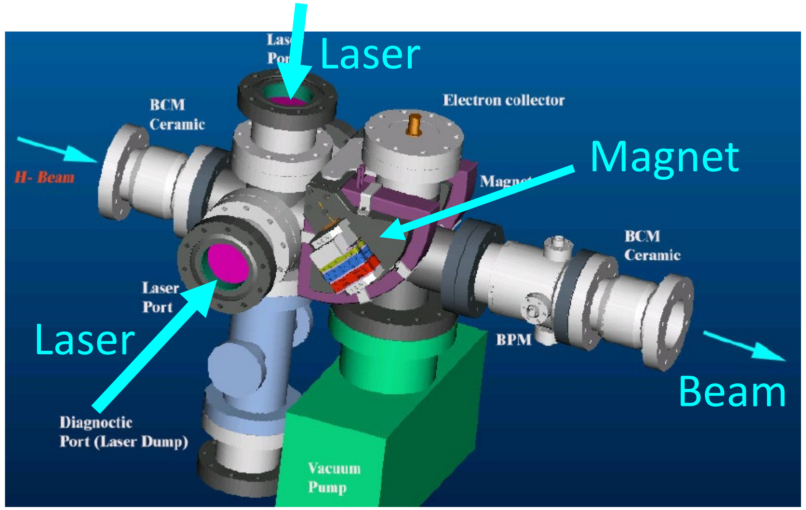
Laser density



Data from Broad and Reinhardt, Phys . Rev. A14 (1976)

- For a 30 mJ, 10 ns laser pulse on a 30 ps bunch with 1 x 10^8 ions
  - Expect a few percent of the beam to be ionized
    → 1 pC of H^0/e^- pairs
  - Laser is usually 1064 nm due to commercial availability
- Called a Laserwire

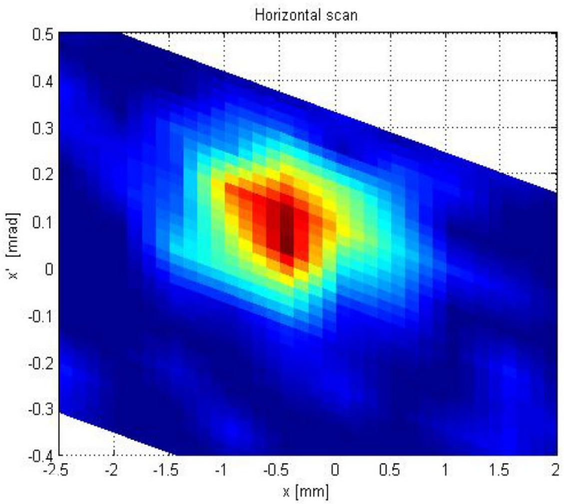
Photoionization of H^- by Laser



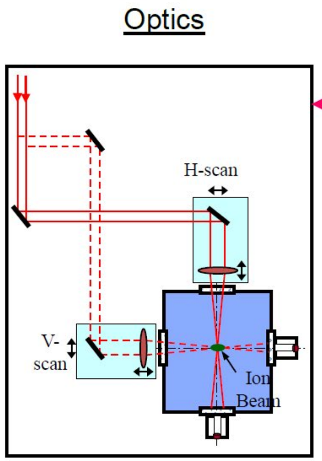
SNS

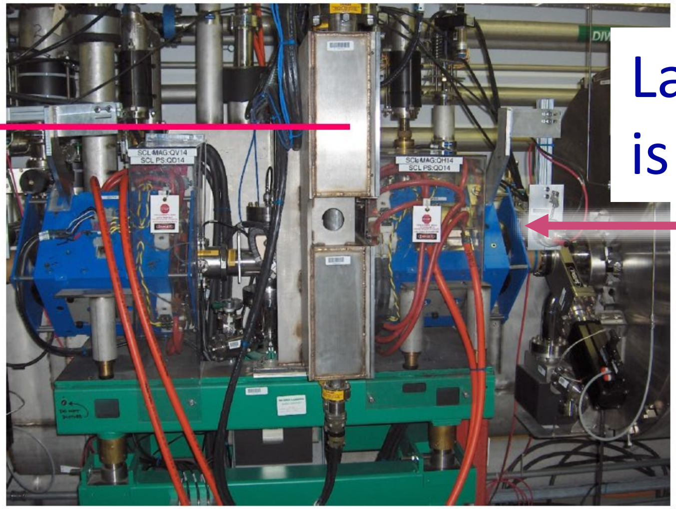
9 Laserwires
200 MeV – 1 GeV
Laser: 50 mJ / 10 ns / 30 Hz
Detect e^-

Phase space measurement using H^0 at end of Linac



Profile measurements along the SRF cryomodules

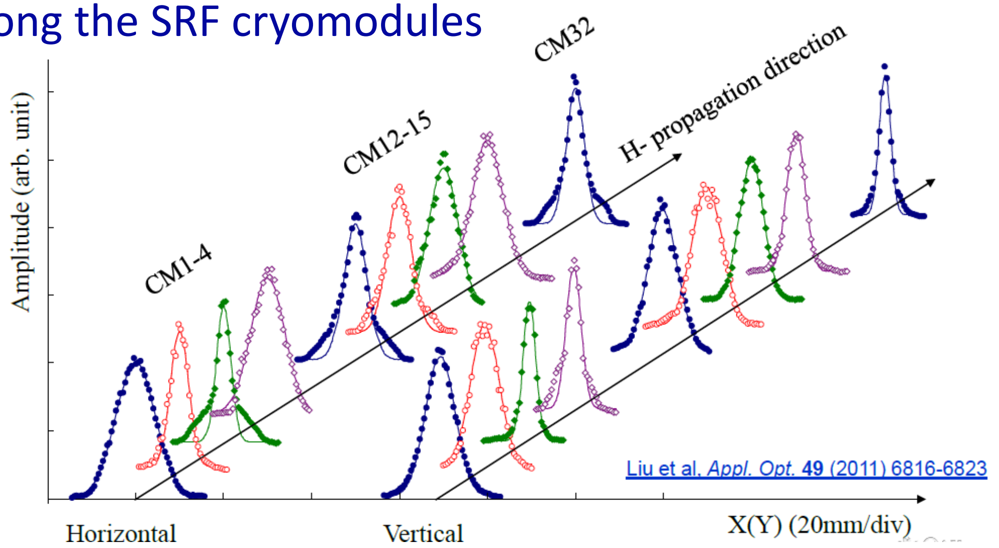




Laser transport is free space

Beam

Y. Liu, NAPAC2011

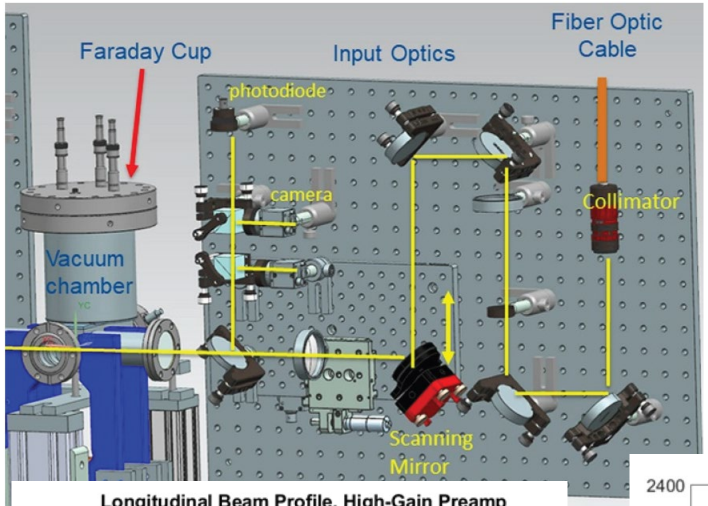


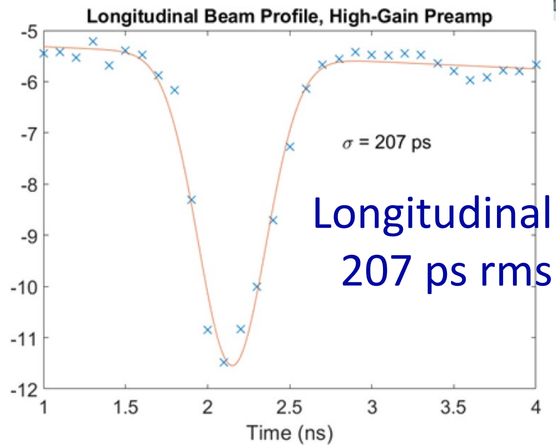
Photoionization of H^- by Laser

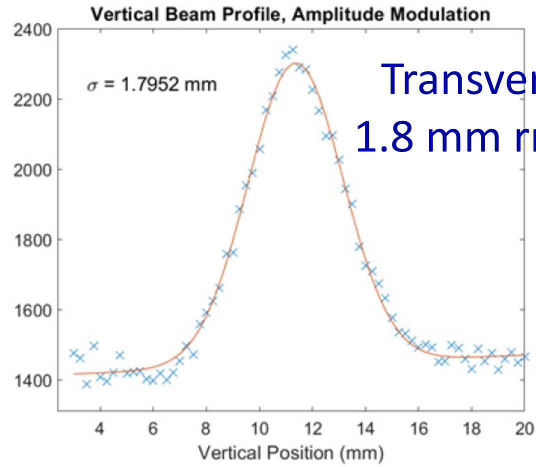
V. Scarpine, IBIC2021

FNAL PIP2IT

1 Laserwire
2.1 MeV Beam
Laser: 6 nJ / 12 ps / 162.5 MHz
Detect e^-



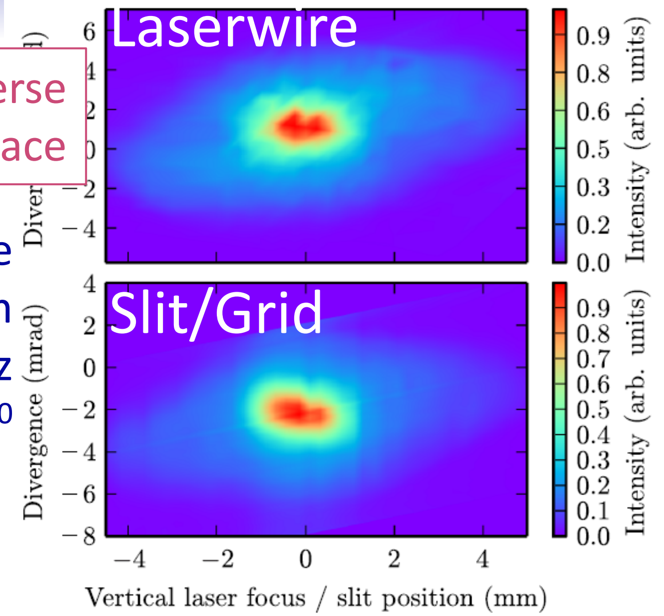




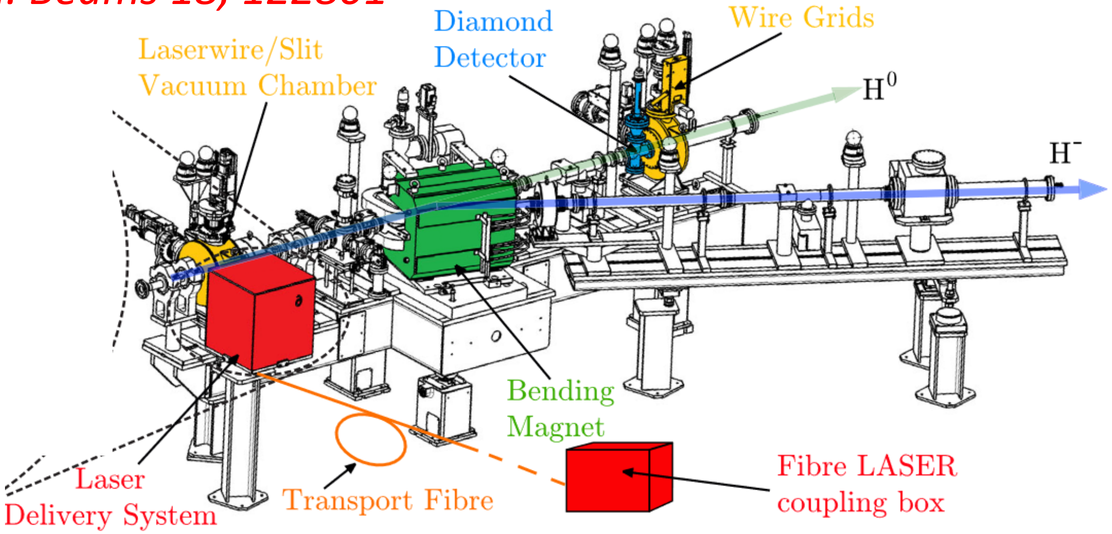
CERN LINAC4

1 Laserwire
3 MeV Beam
Laser: ½ mJ / 80 ns / 60 kHz
Detect H^0

Transverse Phase Space



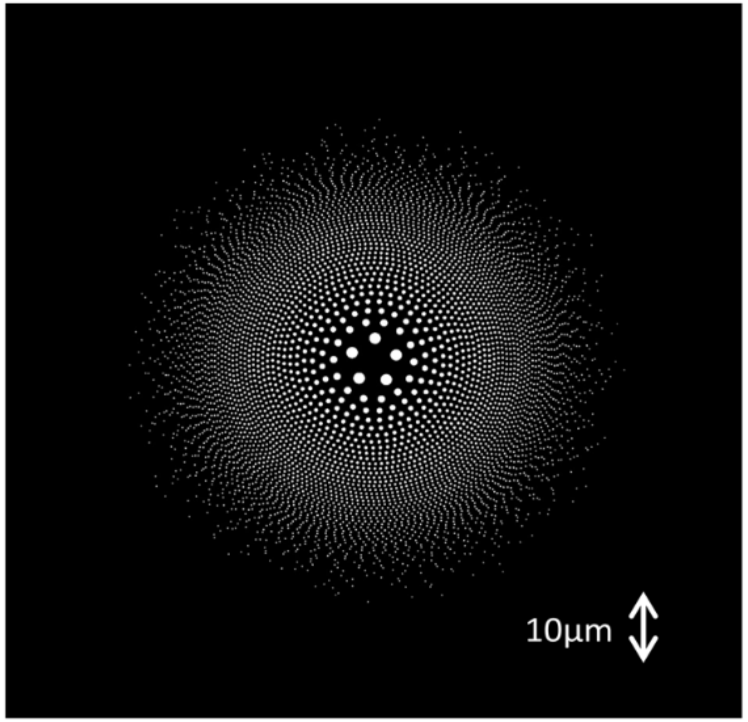
T. Hofmann, Phys. Rev. ST Accel. Beams 18, 122801



Future?

- Pixel Detectors (already here!!)
- Quantum gas jets!!
  - N. Kumar, IPAC2021
  - Can make pencil beams

Atomic Sieve



Further Reading

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3rd IPM Workshop, JPARC, 2018, https://conference-indico.kek.jp/event/55/
CERN BGI(IPM) website, https://bgi.web.cern.ch/

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