Minimal Invasive Beam Profile Monitors for High Intense Hadron Beams

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Basics on physics, recent technical realizations and some applications for:

- Detection of residual gas products: IPM and BIF
- Laser 'wire' and electron beam scanners
- Photon emission for relativistic beams: OTR and SRM

Comparison as a summary

Remark: Examples are presented from different laboratories.
An extended list of existing installations is given in the written proceedings.

Profile Measurement Demands

Non-invasive diagnostics $\Rightarrow$ undisturbed observation of beam parameters

- Transfer line: Observation of same beam at different locations, variation during pulse
- Synchrotron: Observation of variation during acceleration and any further manipulations
- Large beam power: Destruction of intersecting material as wire scanner, screen, SEM-Grid

Diagnostics with small impact on beam ***and*** instrument $\Rightarrow$ high sensitivity

Typical beam parameter:

- Beam width σ: 0.3 mm to 10 mm (sometimes non-Gaussian)
- Beam current I_{beam}: Pulsed LINAC up to 100 mA, synchrotron up to 10 A

Physical basis for detection:

- Electronic Stopping Power ***dE/dx***: Ionization Profile Monitor **IPM**
  Beam Induced Fluorescence **BIF** Monitor
- Photo-detachment for H^- beams: Laser 'Wire' Scanner **LWS**
- Deflection in beam's space charge: Electron Beam Scanner **EBS**
- Transition radiation for rel. beams *E>10* GeV: **OTR** Screens ('minimal invasive' method)
- Synchrotron radiation for rel. beams *E*>100 GeV: Synchrotron Radiation Monitor **SRM**

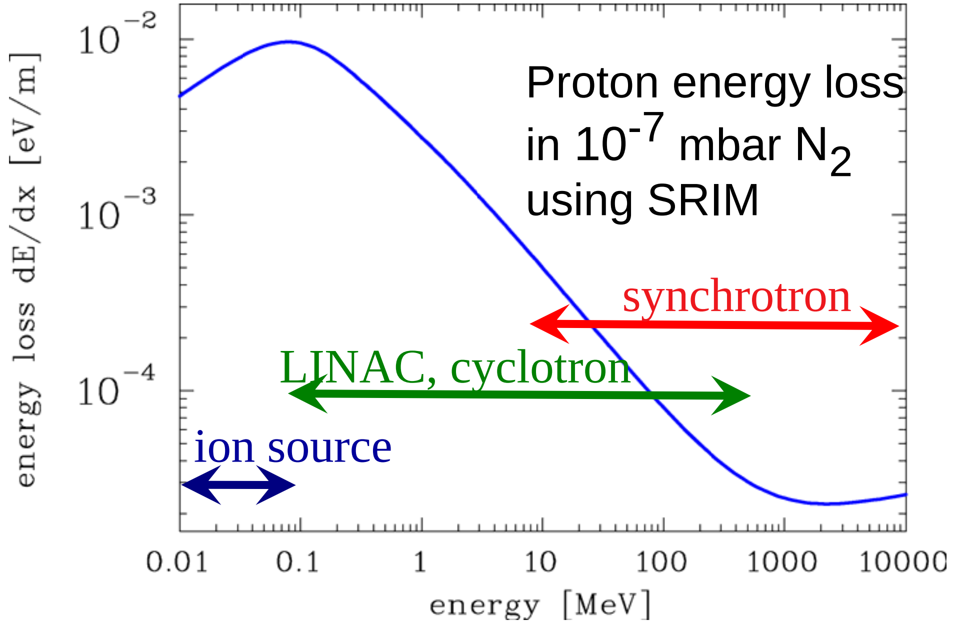
Signal Strength for IPM and BIF-Monitor

***Physics*:**

Energy loss of hadrons in gas ***dE/dx***

$\Rightarrow$ Profile determination from residual gas

- **Ionization:** about 100 eV/ionization
- **Excitation + photon emission:** about 3 keV/photon



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
$\Rightarrow$ Adaptation of signal strength

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

Strong dependence on projectile charge for ions A^{Zp}

Ionization Profile Monitor

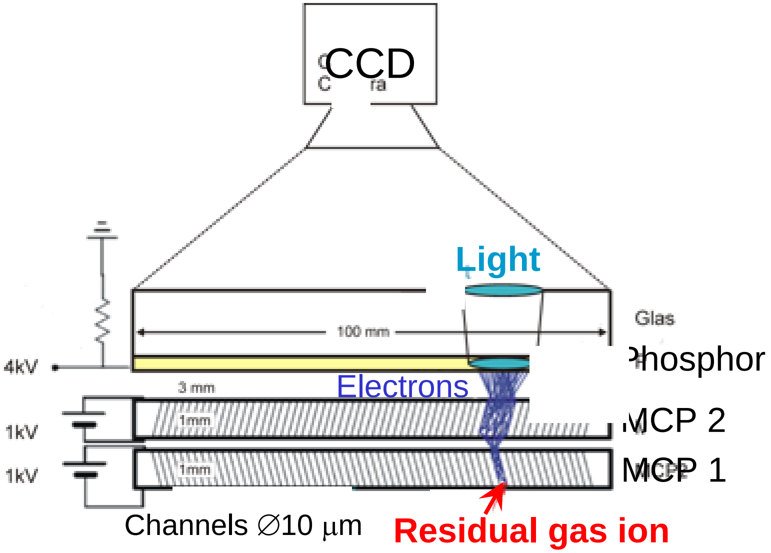
Main application: Synchrotrons and transfer lines for all beams

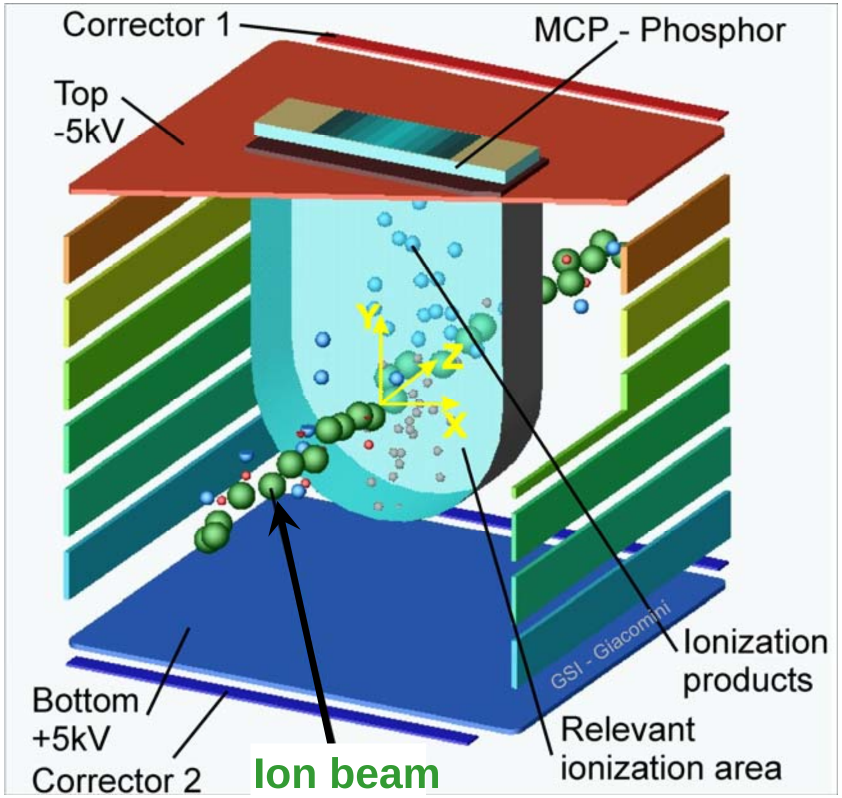
Ionization Profile Monitor: Principle

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

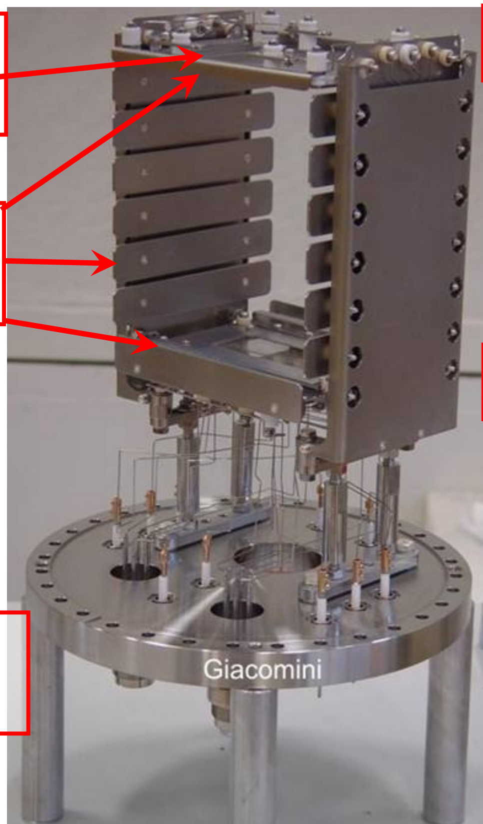
However, no 'standard' realization exists!

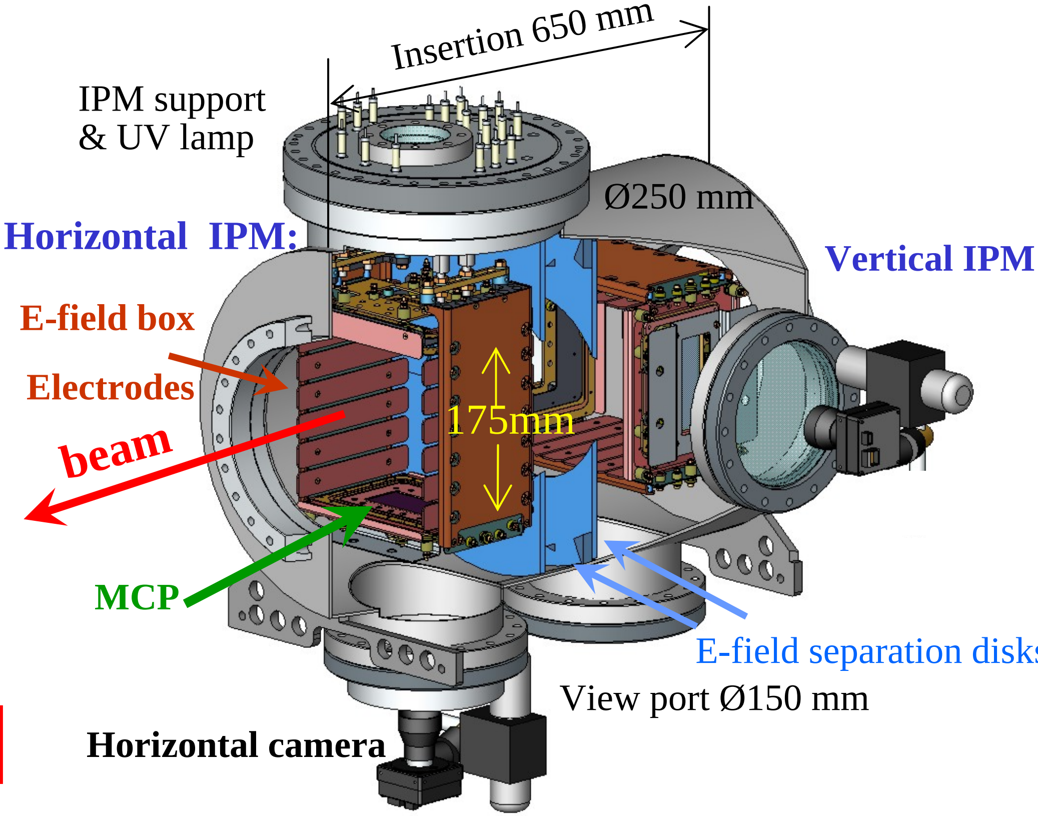
Ionization Profile Monitor: Realization at GSI and FZJ

Example: Installation at GSI and FZJ

➢ Electric potential ±6 kV⇒E=70 kV/m
electrodes ⇒ 1% homogeneity

E-field box 175x175mm^2



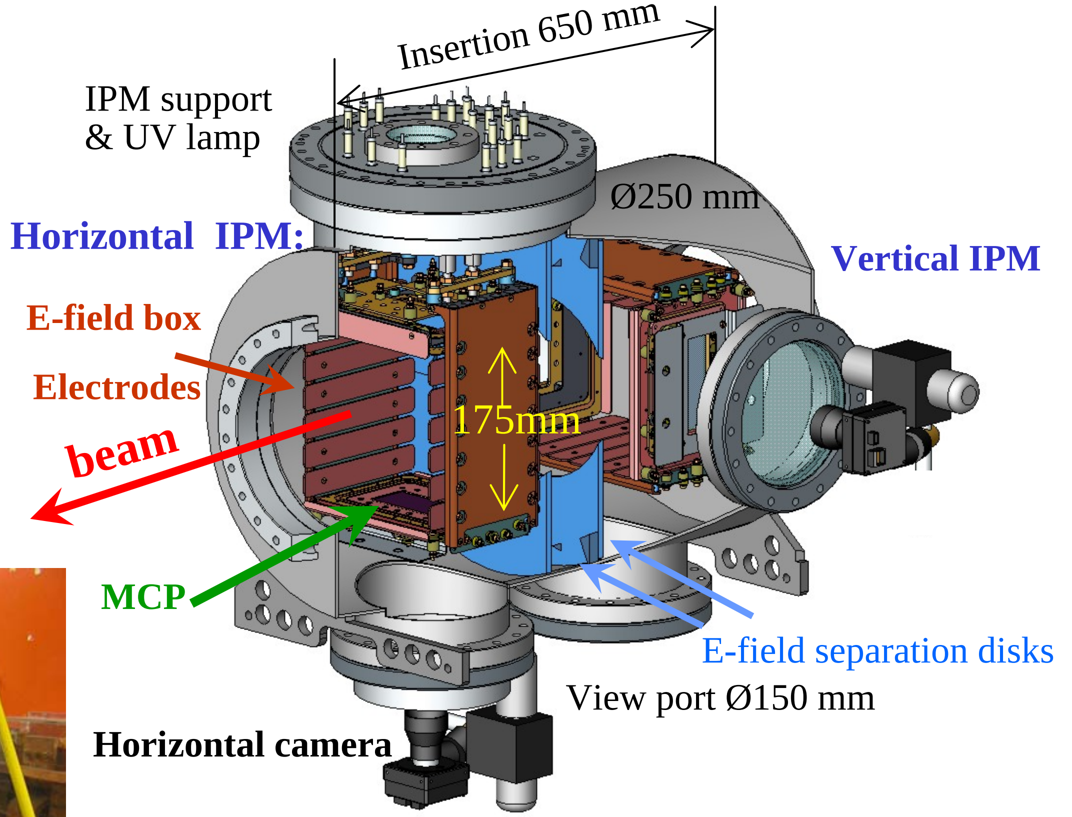


C. Böhme (FZJ), T Giacomini (GSI) et al, DIPAC'09

Ionization Profile Monitor: Realization at GSI and FZJ

Example: Installation at GSI and FZJ

- Electric potential ±6 kV⇒E=70 kV/m electrodes ⇒ 1% homogeneity
- MCP for single particle detection & phosphor for light spot, 100x50 mm^2
- Readout by camera with 200 fps
- UV lamp:
  calibration of MCP sensitivity



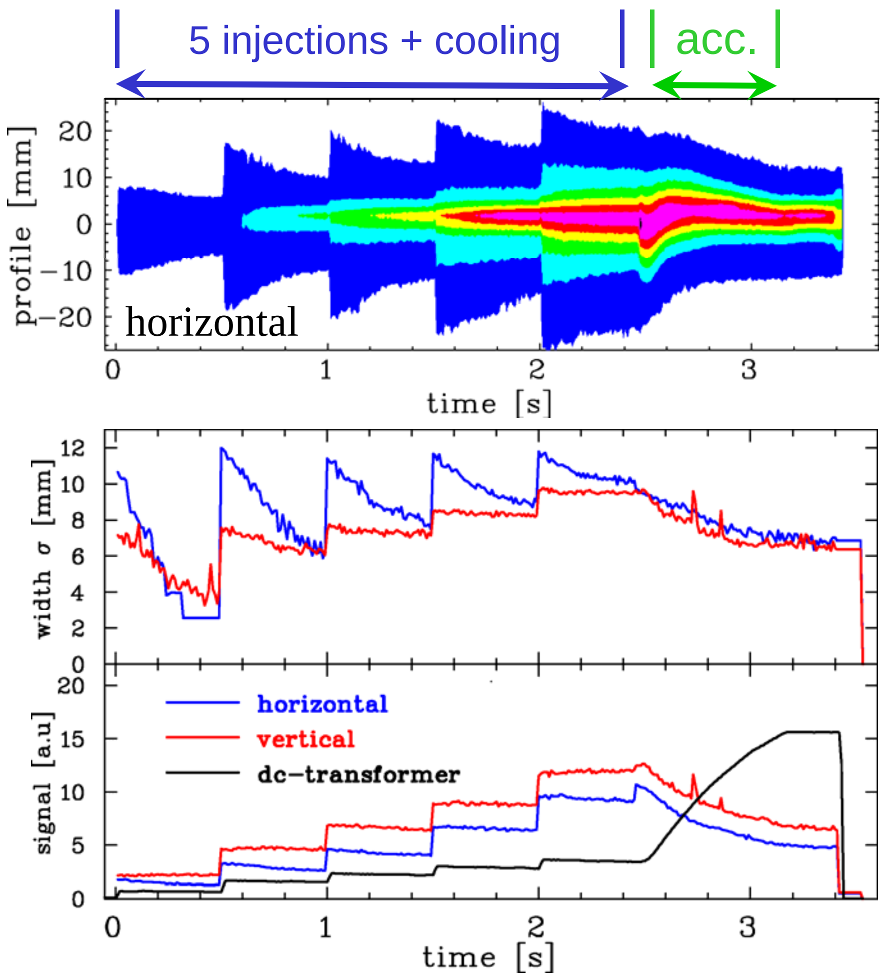
Installation at FZJ-COSY: insertion 650mm

C. Böhme (FZJ), T Giacomini (GSI) et al, DIPAC'09

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

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



Task for IPM:

- Observation of cooling
- Emittance evaluation during cycle

see poster: V. Kamerdzhiev (FZJ) et al., MOPD093

P. Forck (GSI) et al., DIPAC'05

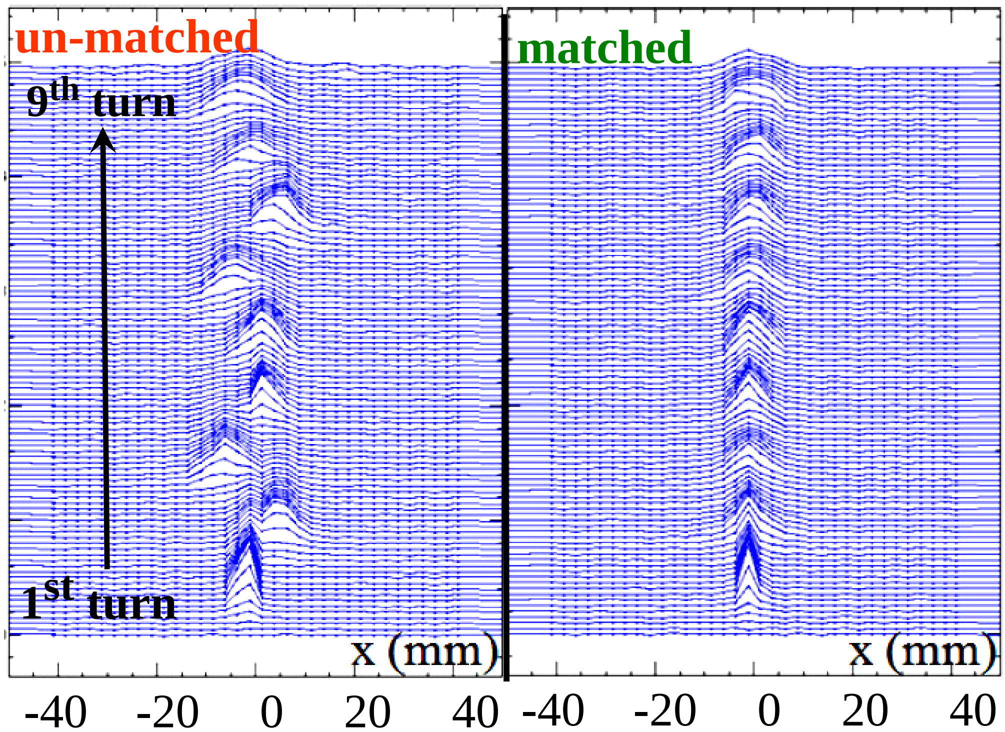
IPM: Turn-by-Turn Measurement

Important application:

Injection matching

to prevent for emittance enlargement
⇒ turn–by-turn measurement
Required time resolution 100 ns

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



Further advanced turn-by-turn IPMs at BNL, CERN, FNAL etc.

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

IPM: Space Charge Influence for Intense Beams

Ion detection: For intense beams
$\Rightarrow$ broadening due to space charge

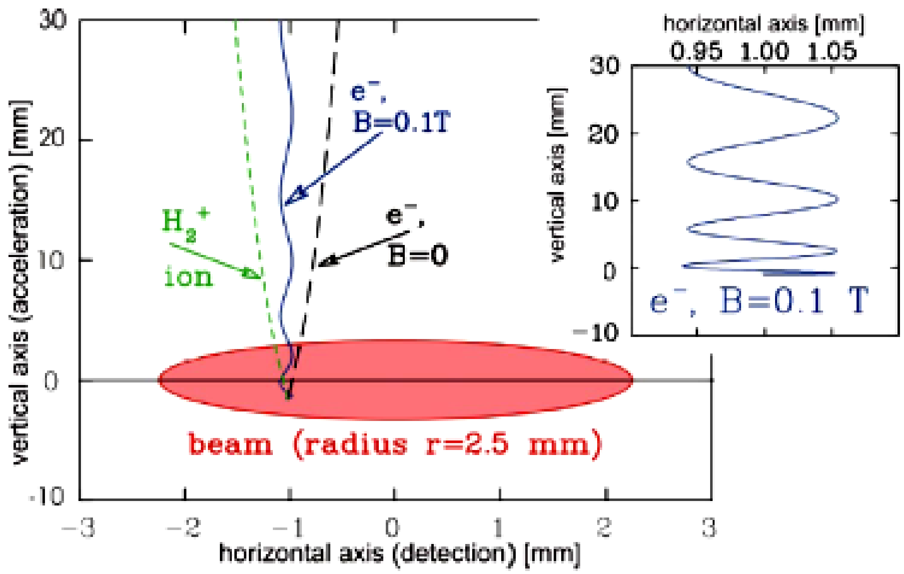
Electron detection:

B-field required for e$^-$ guidance toward MCP

Effects: 3-dim start velocity of electrons

$E_{kin}(90\%) < 50$ eV, $\theta_{max} \approx 90^0$

$\Rightarrow$ $r_{cyl} < 100$ µm for **B** $\approx$ 0.1 T



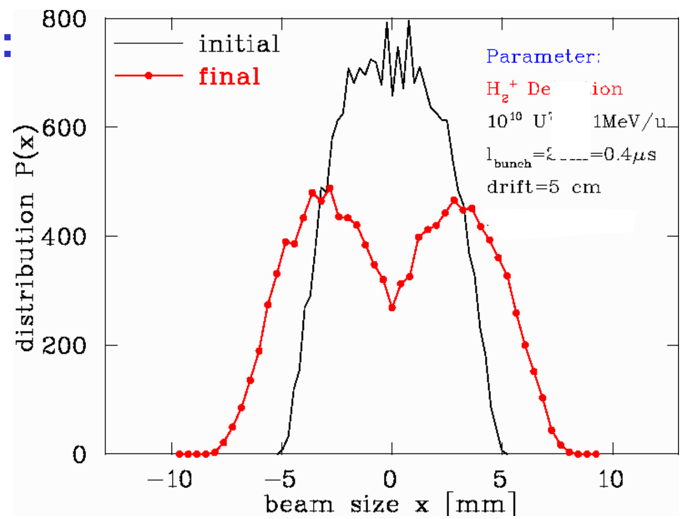
Monte-Carlo simulation:

Ion versus e$^-$ detection

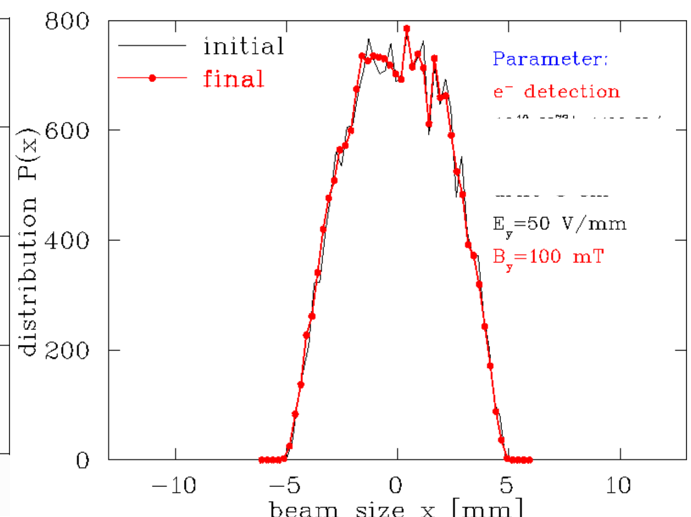
10^{12} charges

$\Rightarrow$ Only e$^-$ scheme
gives correct image

ion detection



B-field & electron detection



IPM: Magnet Design

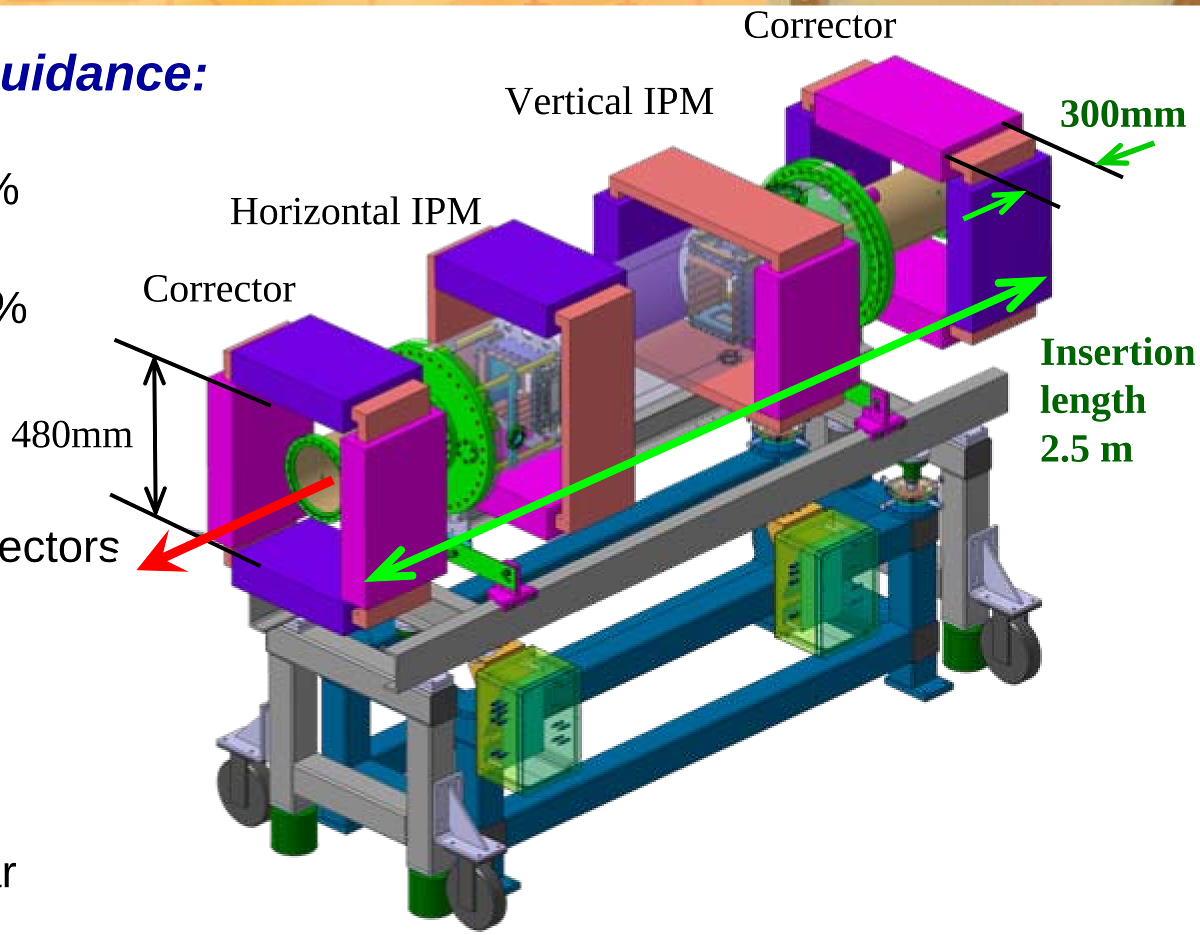
Magnetic field for electron guidance:

Maximum image distortion:

5% of beam width ⇒ **ΔB/B** < 1 %

Challenges:

- High **B**-field homogeneity of 1%
- Clearance up to 500 mm
- Correctors required
  to compensate beam steering
- Insertion length 2.5 m incl. correctors



For MCP wire-array readout
lower clearance required

At transfer line:

Vacuum pressure up to 10^{-5} mbar
IPM without MCP realized
→ much less mechanical efforts

Design by G. de Villiers (iThemba Lab), T. Giacomini (GSI)

Further types of magnets e.g. K.Satou (J-PARC) et al., EPAC'08, J.Zagel (FNAL) et al., PAC'01, R.Connolly (RHIC) et al., PAC'01, C. Fischer (CERN) et al. BIW'04

Beam Induced Fluorescence Monitor

Main application: Transfer lines for all beams

Beam Induced Fluorescence Monitor: Principle

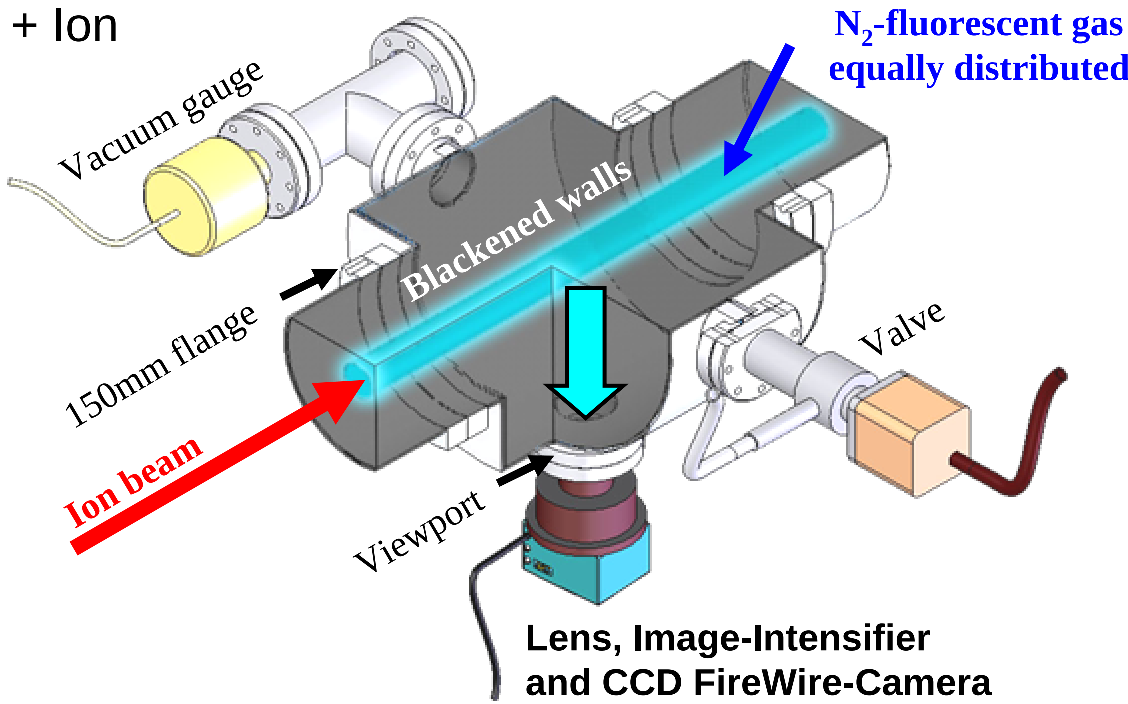
Detecting ***photons*** from residual gas molecules, e.g. Nitrogen

$N_2 + \text{Ion} \rightarrow (N_2^{+})^{*} + \text{Ion} \rightarrow N_2^{+} + \gamma + \text{Ion}$

390 nm< λ< 470 nm

emitted into solid angle Ω to camera

single photon detection scheme



F. Becker (2007) et al., Proc. DIPAC'07

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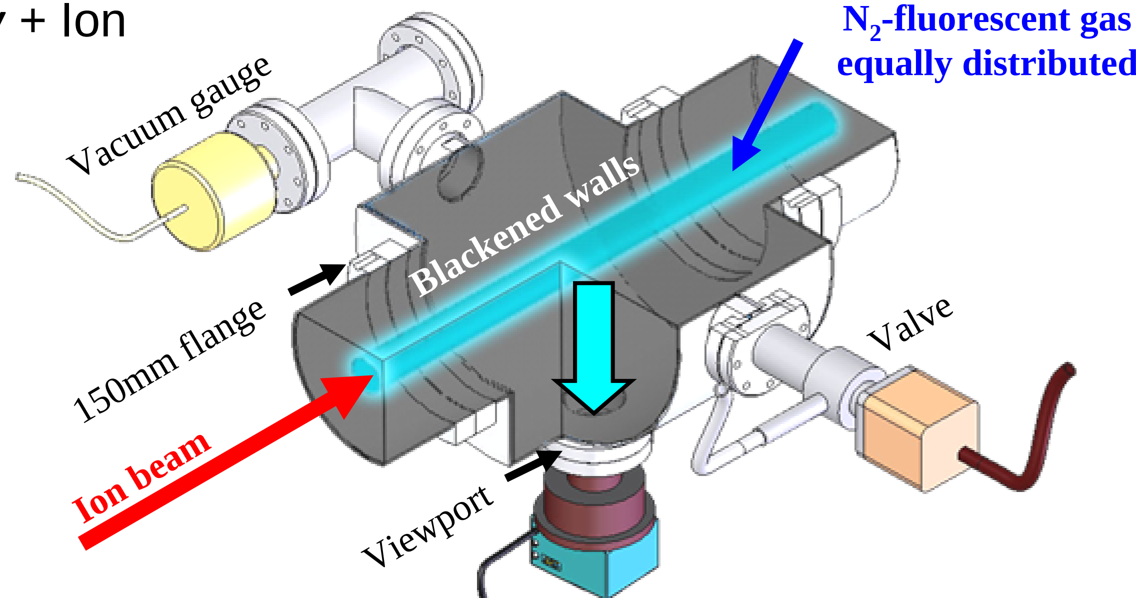
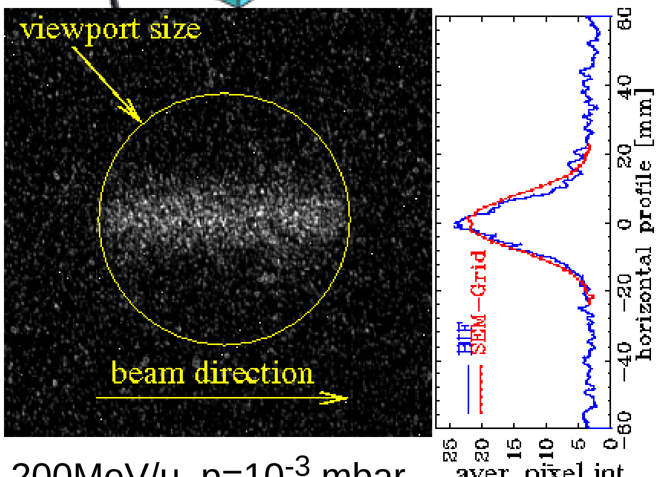


Features:

- Single pulse observation possible
  down to ≈10 µs time resolution
- High resolution (here 0.2 mm/pixel)
  can be matched to application
- Commercial Image Intensifier
- Less installations inside vacuum as for IPM

See poster Y. Hashimoto (J-PARC) et al., MOPE014



F. Becker (2007) et al., Proc. DIPAC'07

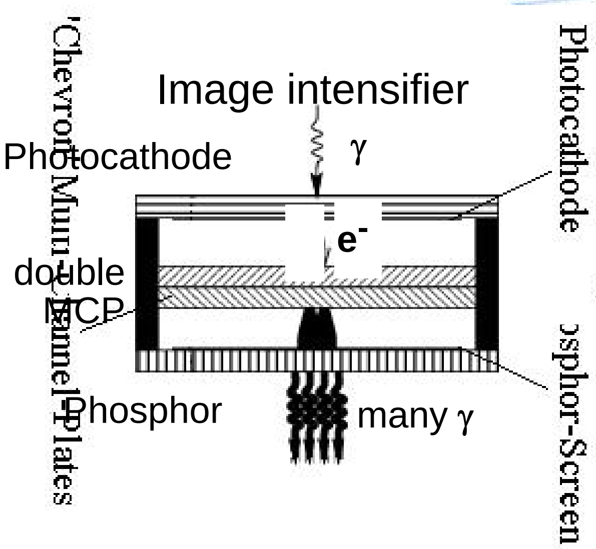
Beam: 4×10^{10} Xe^{48+} at 200MeV/u, p=10^{-3} mbar

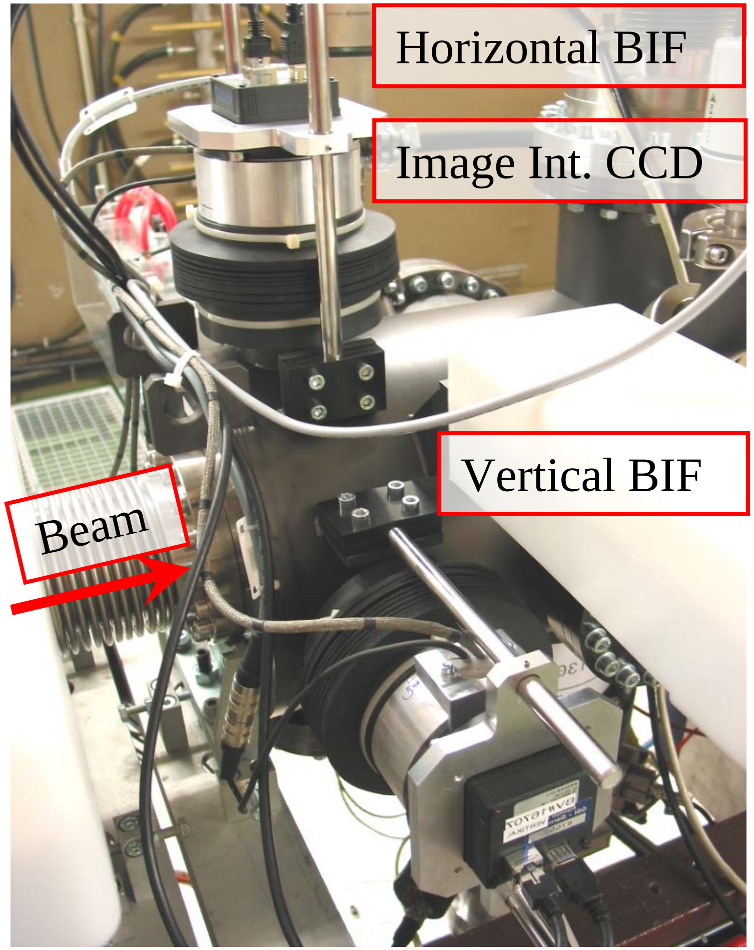
BIF-Monitor: Technical Realization

Example **BIF station at GSI-LINAC:**

- Insertion length 25 cm
- 2 x image intensified CCD cameras
- Optics with reproduction scale 0.2 mm/pixel
- Gas inlet + gauge
- Pneumatic feed-through for calibration

Realization at other labs (e.g.BNL, CERN, FZJ):
Segmented photomultiplier, CID or emCCD





P. Forck (GSI) et al., Proc. DIPAC'05 and F. Becker (GSI) et al., DIPAC'07

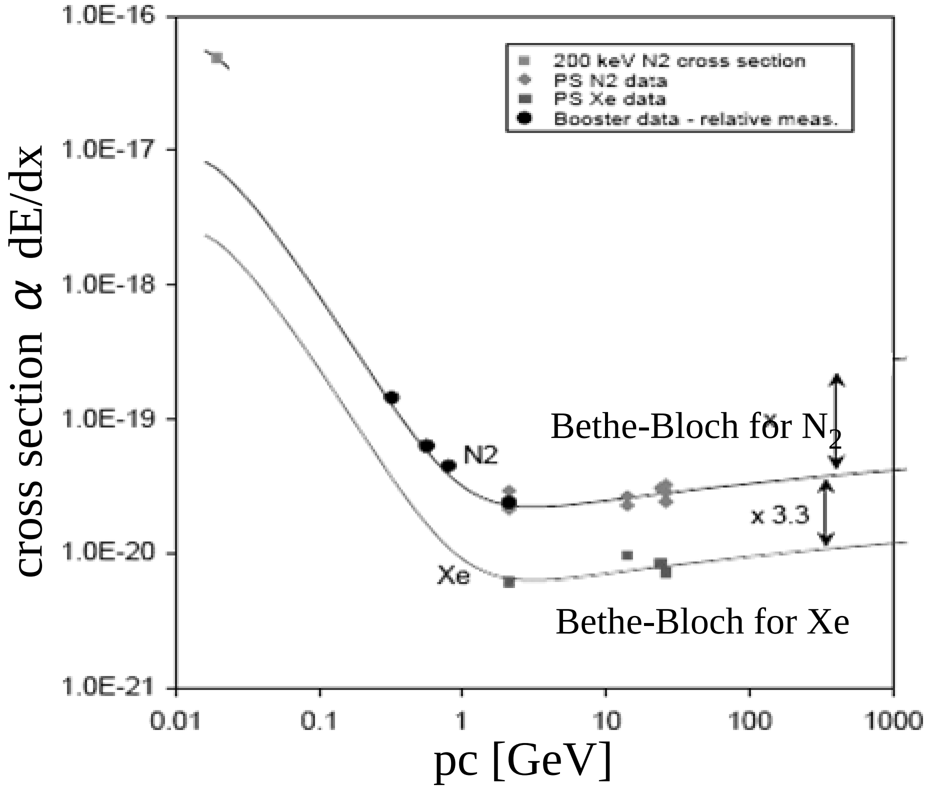
BIF-Monitor: Signal Scaling

Scaling of fluorescence yield:

Experiments at CERN-synchrotrons and
GSI HEBT behind synchrotron

$\Rightarrow$ yield scales like Bethe-Bloch equation

Example: CERN-PS for p in N_2 and Xe



Further results:

- Excited transitions independent of energy
- Fluorescence yield proportional to vacuum pressure
- Profile width independent of pressure tested for 10^{-6} to 10^{-1} mbar
- Lifetime independent on energy $\approx$60 ns for $\mathbf{N_2}$ and $\approx$6 ns for **Xe**

M. Plum (LANL&CERN) et al., NIM A (2002), F. Becker (GSI) et al, Proc DIPAC'07

BIF-Monitor: Spectroscopy – Fluorescence Yield

Results of detailed investigations:

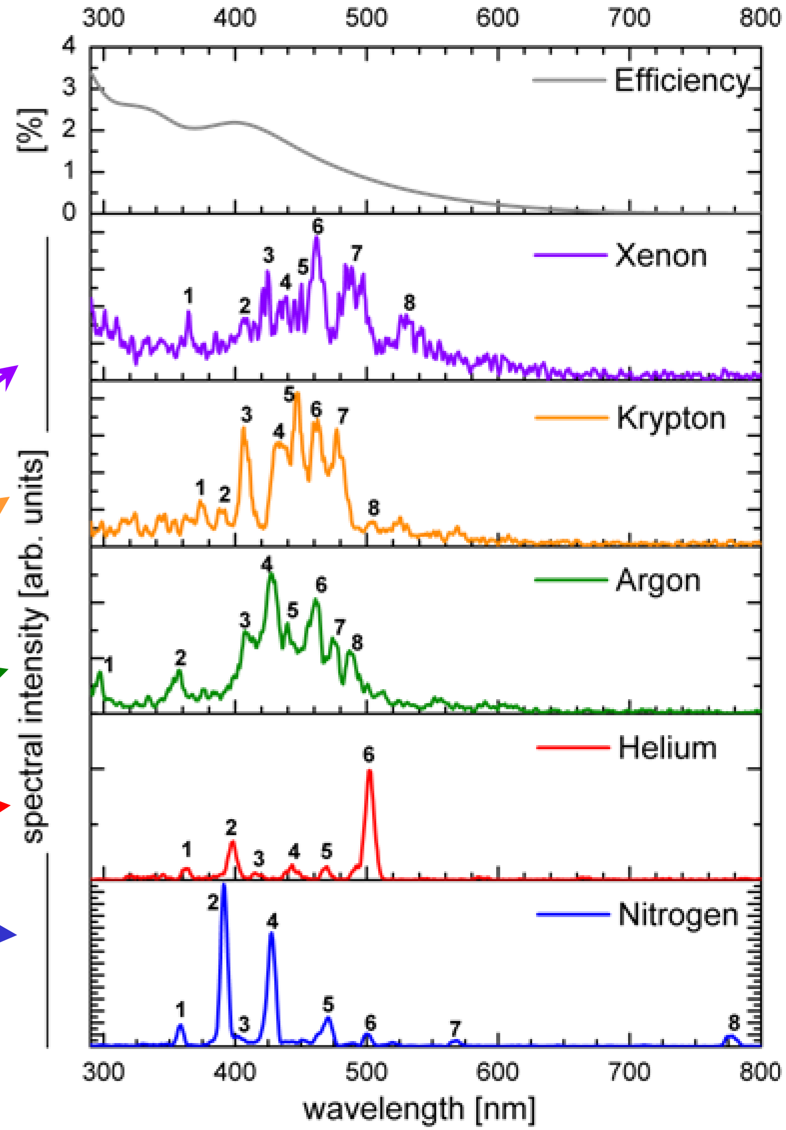
- Rare gases and $\mathbf{N_2}$: green to near-UV
- Compact wavelength interval for $\mathbf{N_2}$
- Fluorescence yield: $\mathbf{N_2}$ ≈4x higher as rare gases

⇒ N_2 and Xe are well suited !

Relative fluorescence yield ***Y*** (all wavelength):

gas	*Y* for *p*	*Y* for p/n_e
Xe	86 %	22 %
Kr	63 %	25 %
Ar	38 %	30 %
He	4 %	26 %
N_2	100 %	100 %

Beam: S^{6+} at 5.16 MeV/u, p_{N2} =10^{-3} mbar



$\boldsymbol{n_e}$: gas electron density ∝ energy loss ⇔ beam influence

F. Becker (GSI) et al., Proc. DIPAC'09

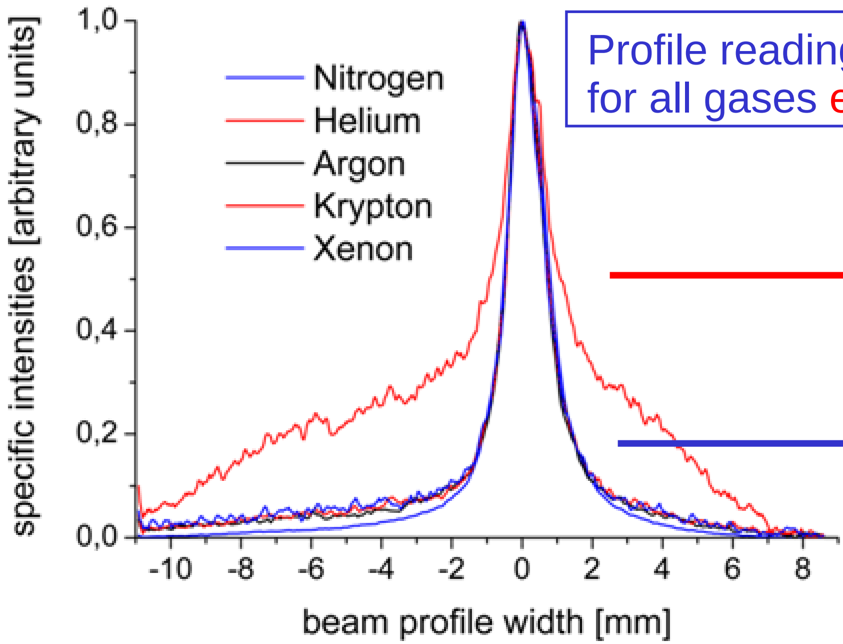
BIF-Monitor: Spectroscopy – Profile Reading

Results of detailed investigations:

- Rare gases and N_2: green to near-UV
- Compact wavelength interval for N_2
- Fluorescence yield: N_2 ≈4x higher as rare gases
- Same profile reading for all gas except He

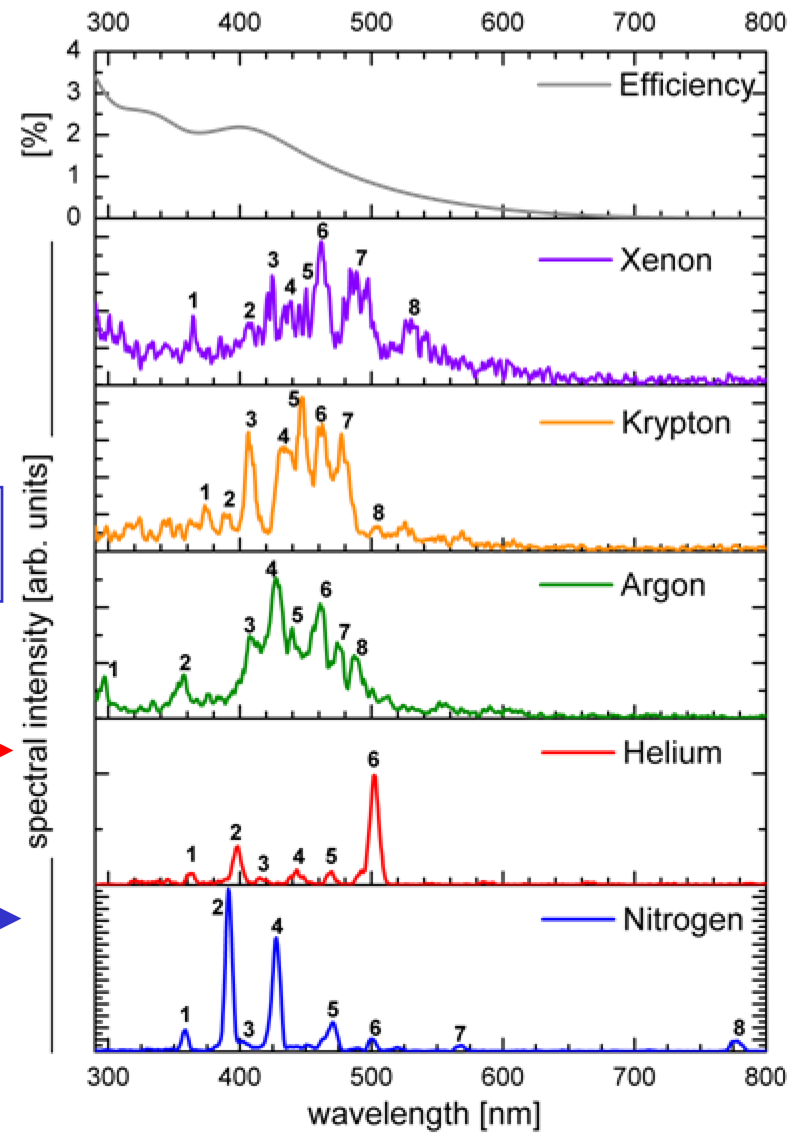
⇒ N_2 *and Xe are well suited !*

Normalized profile reading for all λ:



Profile reading equal for all gases except He

Beam: S^{6+} at 5.16 MeV/u, p_{N2} =10^{-3} mbar



F. Becker (GSI) et al., Proc. DIPAC'09

Laser 'Wire' Scanner

Main application: Transfer lines H^- beams only

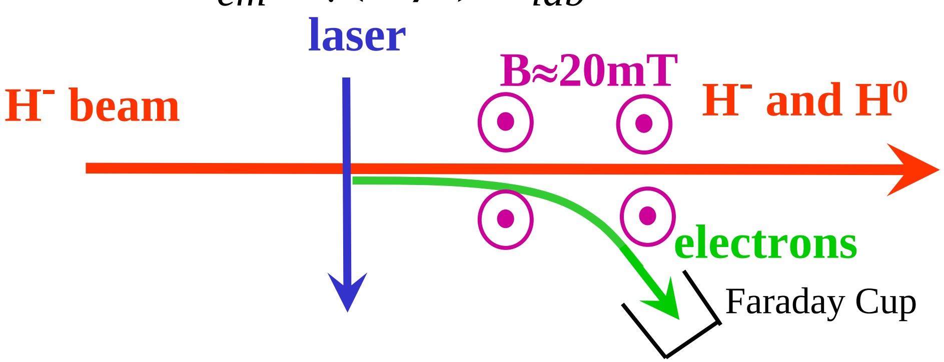
Laser Scanner: Principle for H^- Beams

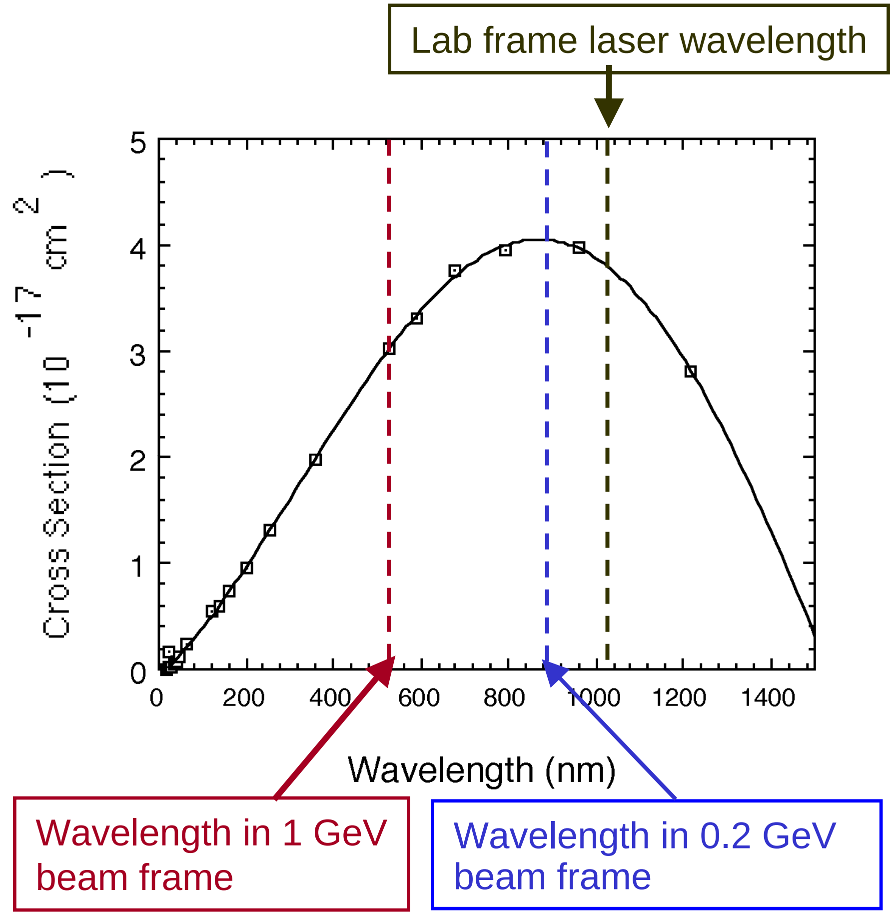
Photo-detachment: **$H^- + \gamma \rightarrow H^0 + e^-$** binding energy E=0.75 eV $\leftrightarrow$ λ=1670 nm

Photo-detachment maximal at λ=830 nm

Doppler shifted photon energy in rest-frame:

$$E_{cm} = \gamma(1-\beta)\cdot E_{lab}$$





Example: super-cond. SNS-LINAC 0.2 $\rightarrow$ 1GeV

Nd:YAG laser: λ_{lab}=1064 nm, 50-200 mJ
7 ns pulse length, 30 Hz rep.
$\Rightarrow$ detachment: $\approx$3 % of H^-

Dipole: Separation of e- having $\beta_e = \beta_H$

Faraday Cup: e^- detection

See poster Y. Liu (SNS) et al., MOPE101

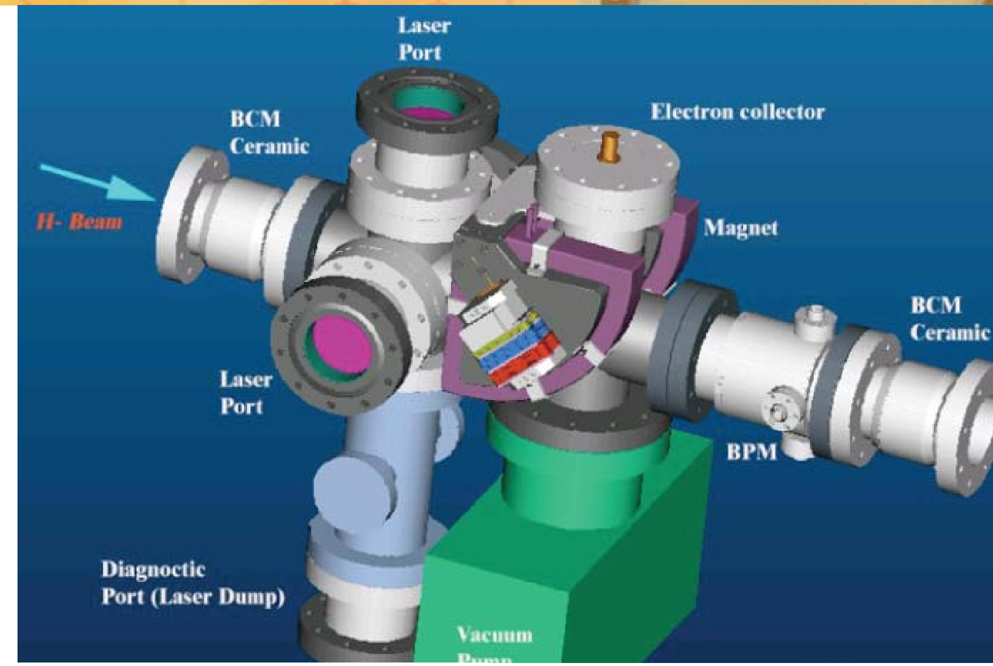
Y. Liu (SNS) et al., NIM **A** 238, 241 (2010) , R.Connolly et al., Proc. LINAC'02

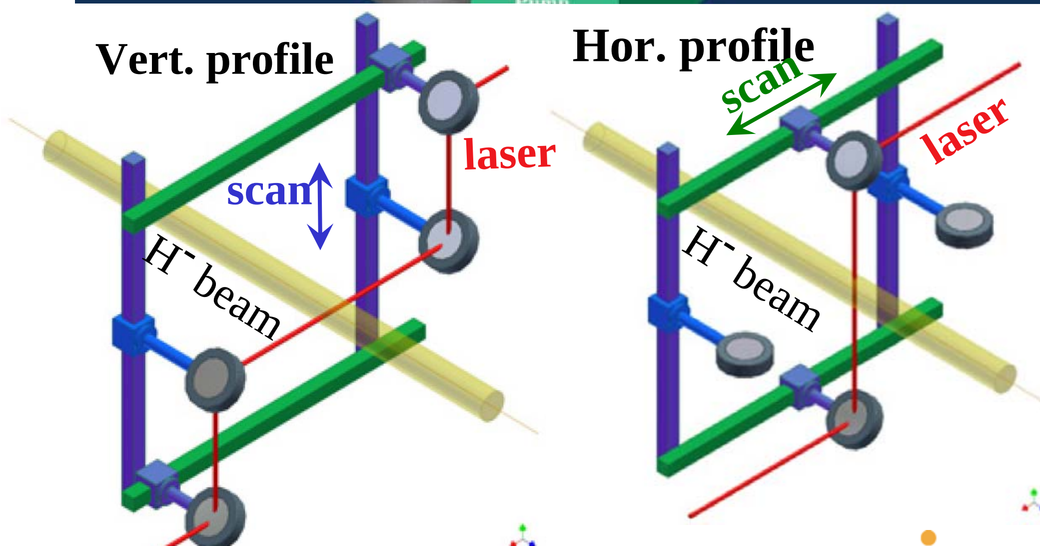
Laser Scanner: Detection Scheme for H^- at SNS-LINAC

SNS installation:

Nd:YAG (50-200 mJ, 7ns) in laser room

- One of 9 stations is served at a time
- Laser with spot size: 10 to 50 µm





Y. Liu (SNS) et al., NIM **A** 238, 241 (2010),
D.A. Lee (RAL) et al., EPAC '08,
R. Connolly (BNL) et al. BIW'10

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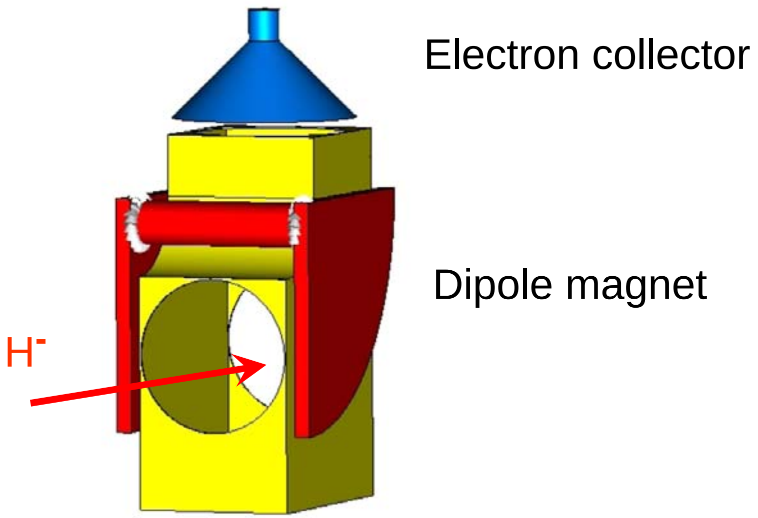
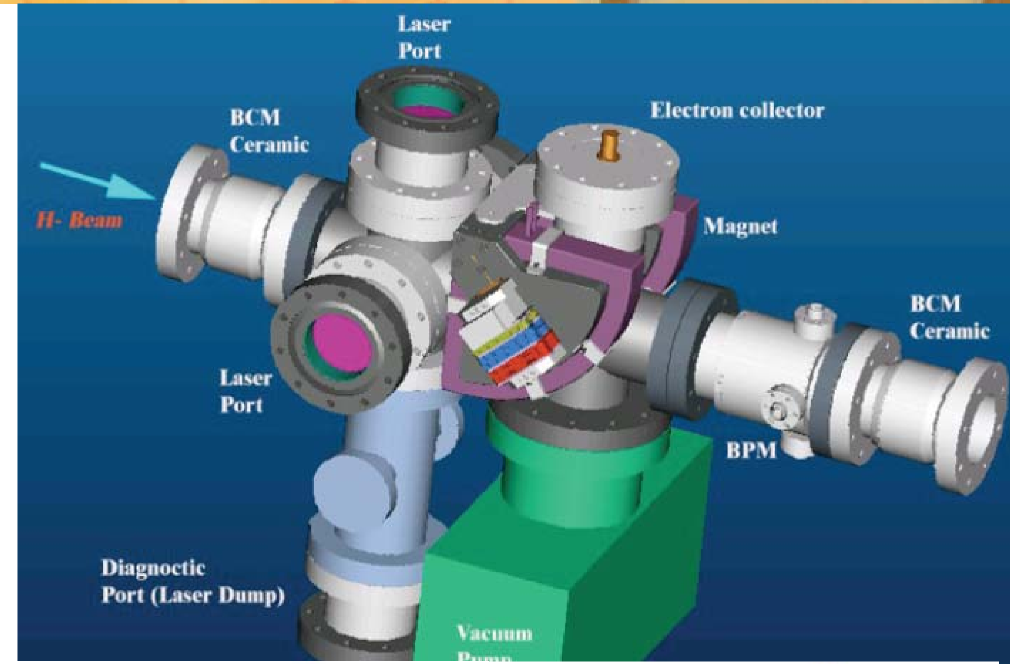
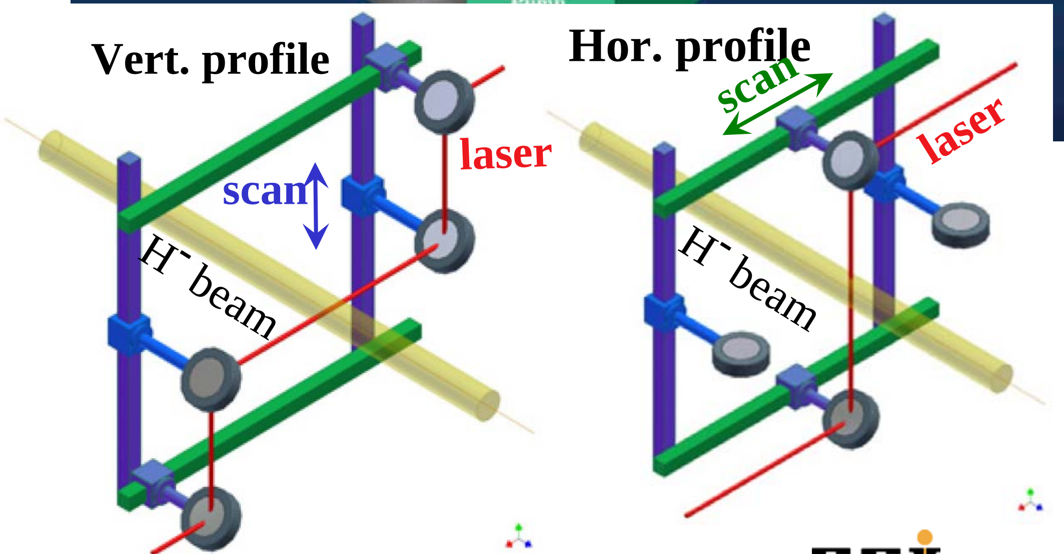
- e^- separation by **B**≈20 mT (β-dependent)
- Detection with Faraday Cup







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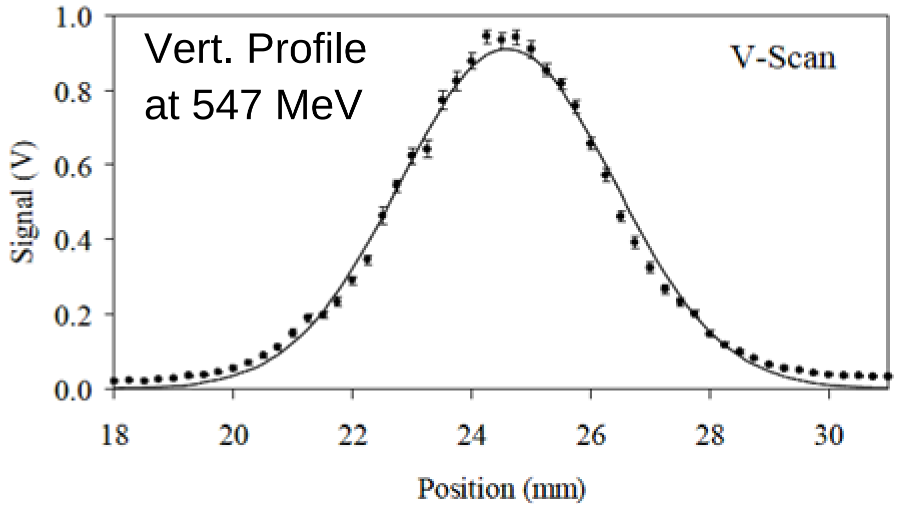
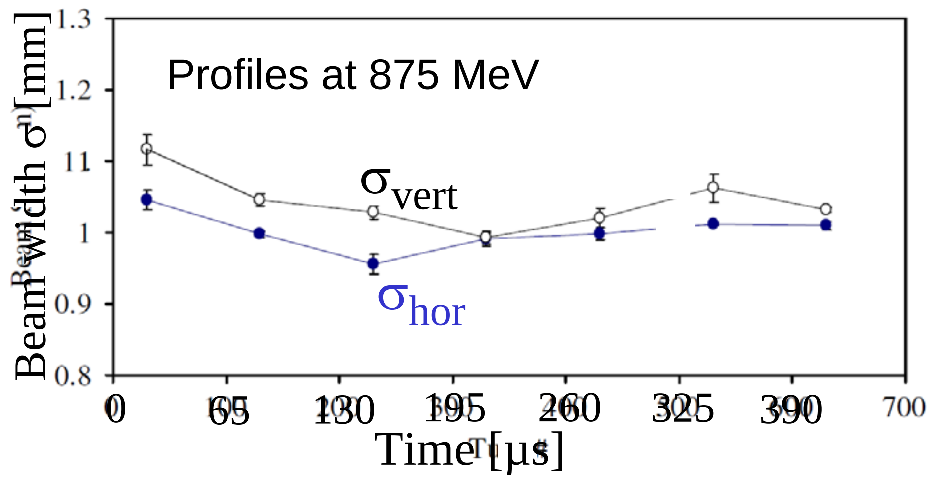
- Laser with spot size: 10 to 50 µm
- e^- separation by **B**≈20 mT (β-dependent)
- Detection with Faraday Cup
- ***Example:*** Profile measurement at SNS
- **Advantage:** Time resolution ≈30 ns
  - ⇒ variation during macro-pulse





- Compact installation with local laser possible
- Spatial resolved detection of separated H^0
  - → emittance determination
- Long. bunch shape measurement possible
- Applicability considered for 70 keV at RAL

Y. Liu (SNS) et al., NIM **A** 238, 241 (2010),
D.A. Lee (RAL) et al., EPAC ‘08,
R. Connolly (BNL) et al. BIW’10, J. Pogge (SNS) et al., Proc. BIW ‘08

Electron Beam Scanner

Main application: Synchrotrons for all beams

Electron Beam Scanner: Principle

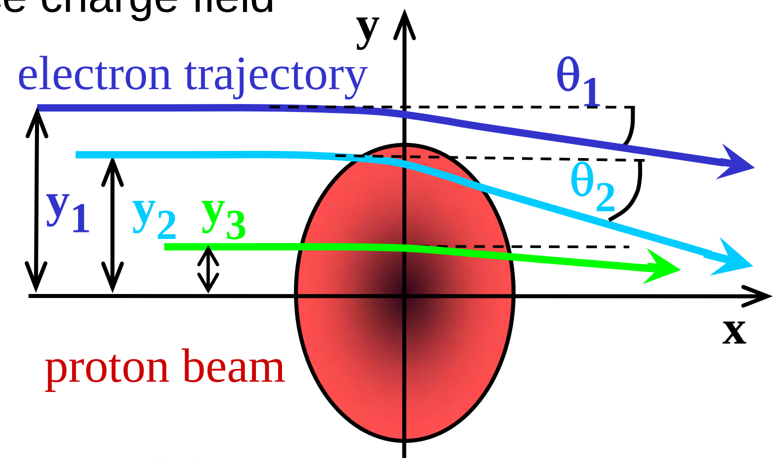
Physics: Deflection of electrons by the beam's space charge field

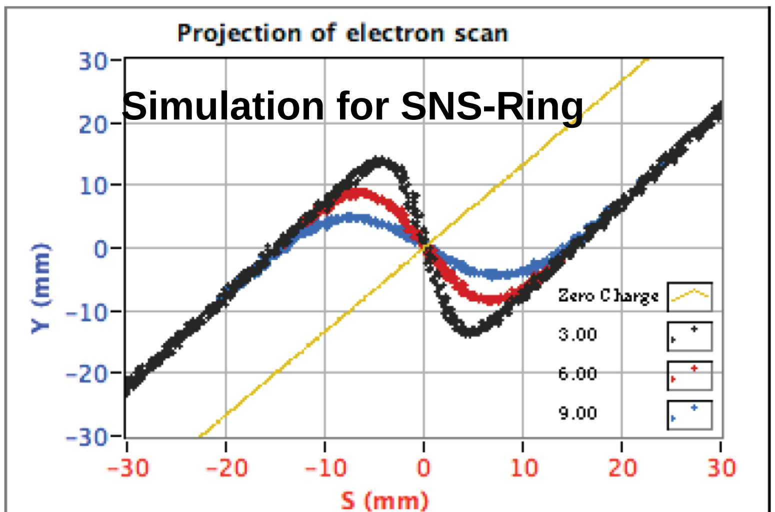
Assumptions:

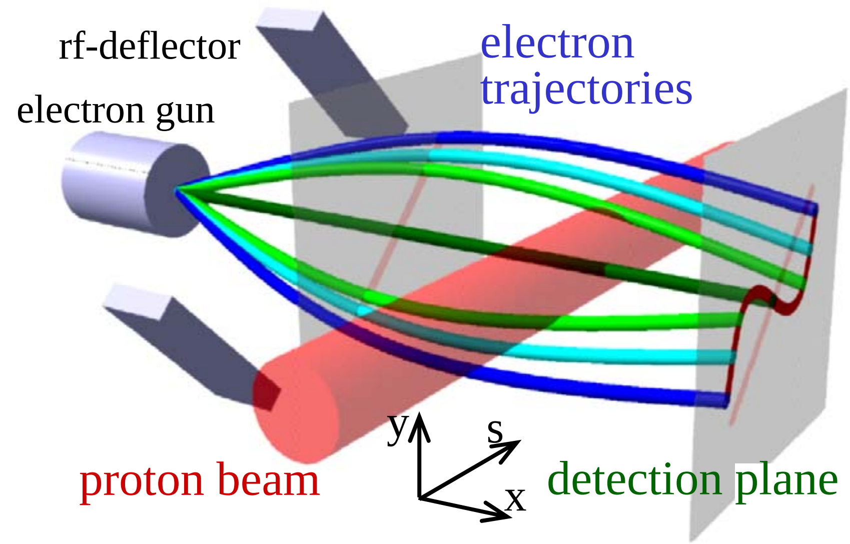
- Diameter: $d_{ele} << d_{bunch}$
- Time: $t_{ele} << t_{bunch}$
- Electron velocity: $v_\perp << v_\parallel$

$\Rightarrow$ deflection angle for vertical profile:

$$\frac{d\theta}{dy} = \frac{1}{\varepsilon_0} \cdot \frac{e}{m v_\perp} \int_{path} \rho(x,y) \cdot dx$$







Scan in y and s, recording of electron trace $P(y)$

$\Rightarrow$ Profile $\propto \dfrac{dP(y)}{ds}$

W. Blokland (SNS) et al., Proc. DIPAC'09

Electron Beam Scanner: Installation at SNS-Ring

Installation for horizontal profile

Parameter for SNS:

- Total length: 1.5 m
- Electron energy: max. 75 keV
- Electron current: max. 5 mA
- Repetition rate: 5 Hz
- Phosphor observation with camera
- Scan duration: 20 ns

Requirements:

- Optimal electron energy depends on ion current
- Shielding against external B-fields

Phosphor & camera

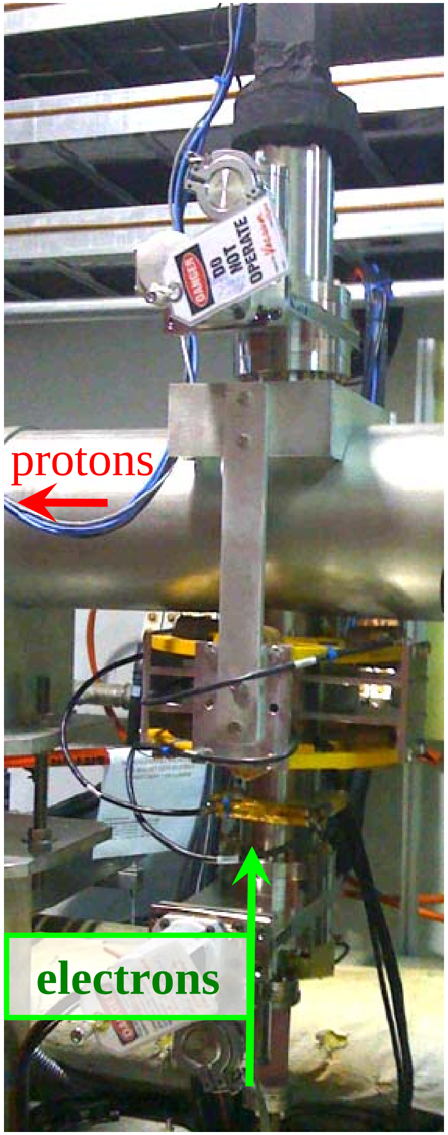
beam pipe

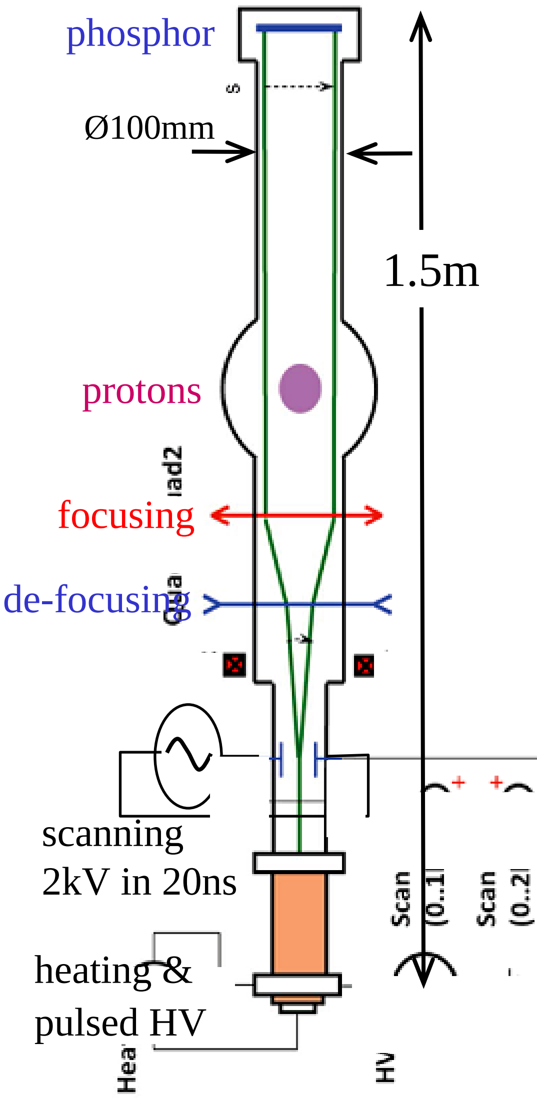
Ø250mm

quadrupoles

rf deflector

electron gun





Scanner Design: BINP, Novosibirsk

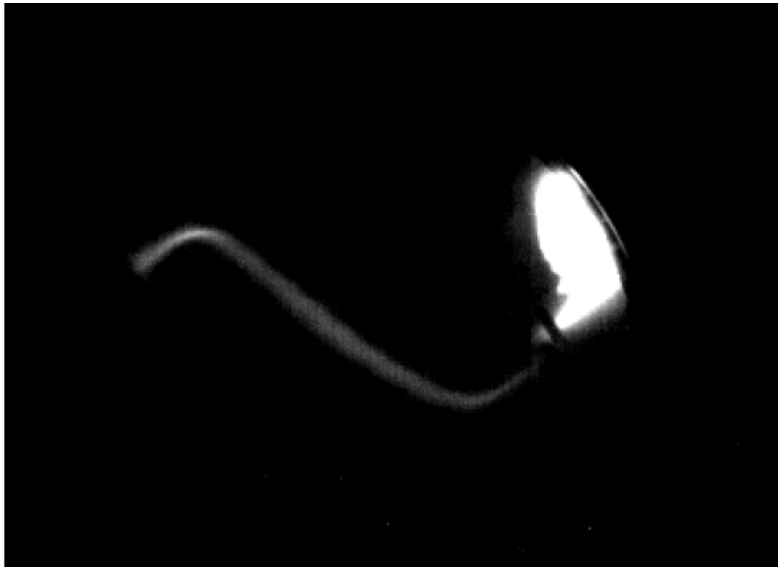
W. Blokland (SNS) et al., Proc. DIPAC'09

Electron Beam Scanner: Results

Example:

Raw data:

horizontal defection for 5 µC at SNS Ring



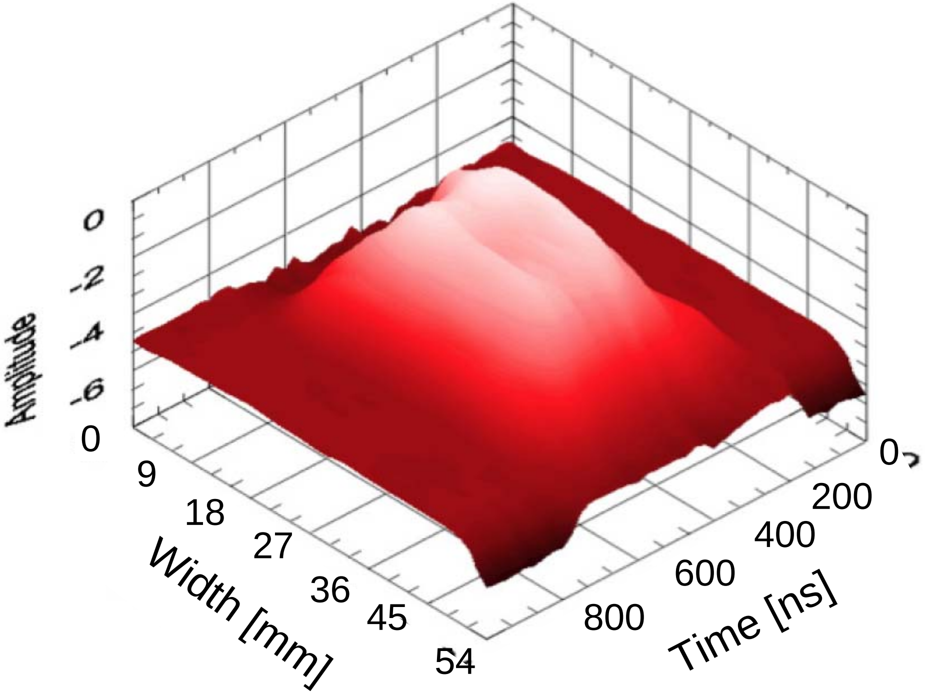
- Device tested with 7.7 keV/u K^+
  P.K. Roy (LBNL) et al. (2005)
- **Ion** beam scanner
  tested with p at 50 MeV and 150-450 GeV
  J. Bosser (CERN) et al., (2002)

Sliced profile:

Proton beam 4 µC filling

20 ns scan one bunch at a turn 343

(recorded at consecutive ring fillings)



Advantage:

Sliced profile recording

with 20 ns resolution!

W. Blokland (SNS) et al., Proc. DIPAC'09

Optical Transition Radiation Screen

Main application: Synchrotrons and Transfer lines for *E* > 10 GeV

Optical Transition Radiation Monitor: Principle

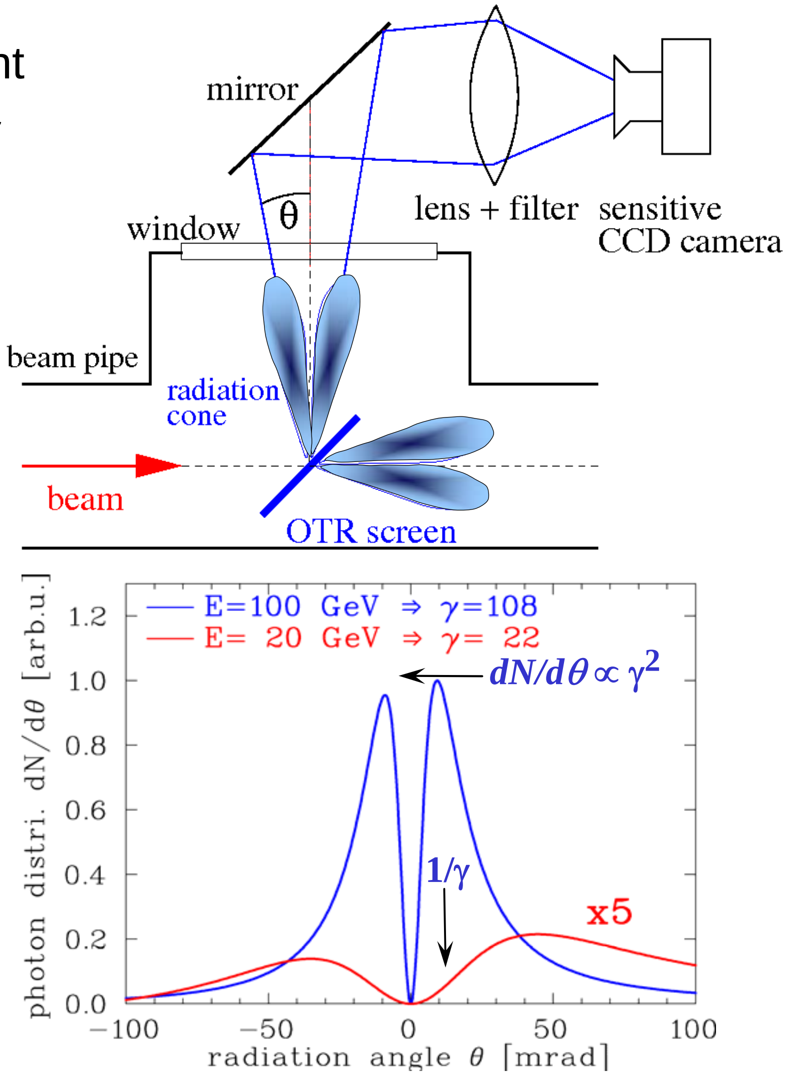
Physics: Boundary with different dielectric constant

→ Emission of photons within cone centered at **1/γ**

maximum scaling $\boldsymbol{dN/d\theta} \propto \gamma^2$

Practical usage **only** for ***E*** >10 GeV

Surface phenomena ⇒ thin foil possible



OTR screens operational at FNAL, CERN, J-PARC…

OTR-Monitor: Technical Realization

Physics: Boundary with different dielectric constant

→ Emission of photons within cone centered at **1/**γ

maximum scaling $dN/d\theta \propto \gamma^2$

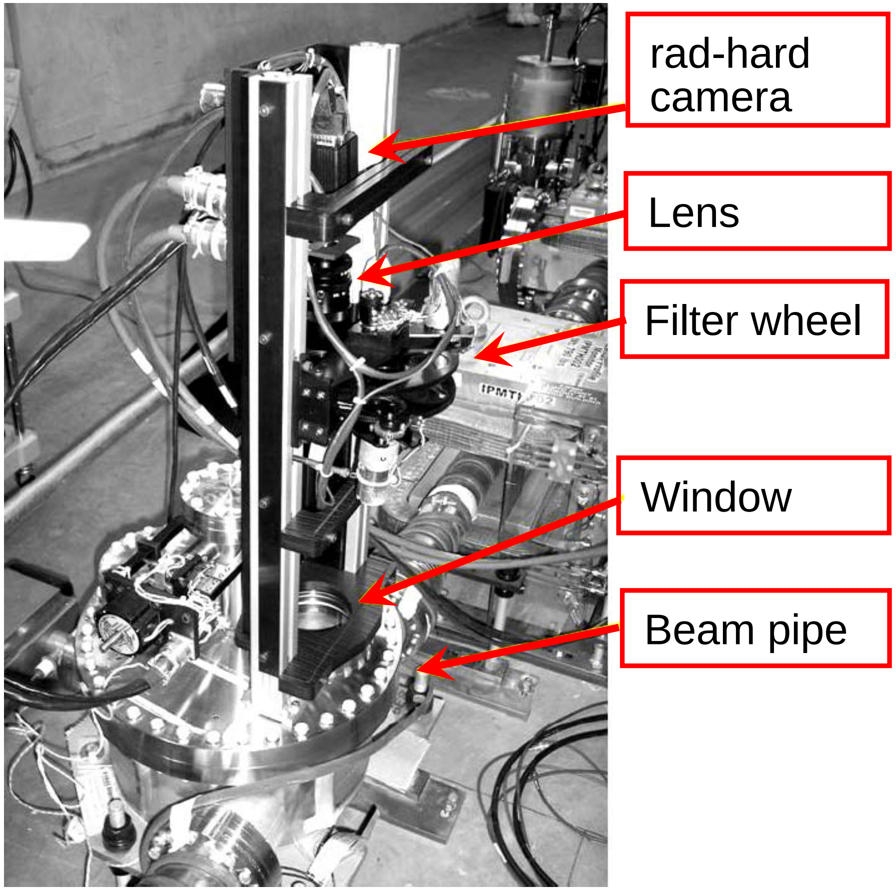
Practical usage **only** for ***E*** >10 GeV

Surface phenomena ⇒ thin foil possible

Example of realization at TERATRON:

- Insertion of foil
  e.g. 5 μm Kapton coated with 0.1μm Al
- Invasive diagnostics but thin foil
  allows for observation of several turns
- **Advantage:**
  thin foil ⇒ low heating & low straggling
  2-dim image visible

Installation at FNAL-TEVATRON



V.E. Scarpine (FNAL) et al., BIW'06

OTR-Monitor: Results

Physics: Boundary with different dielectric constant
→ Emission of photons within cone centered at **1/**γ
maximum scaling $dN/d\theta \propto \gamma^2$
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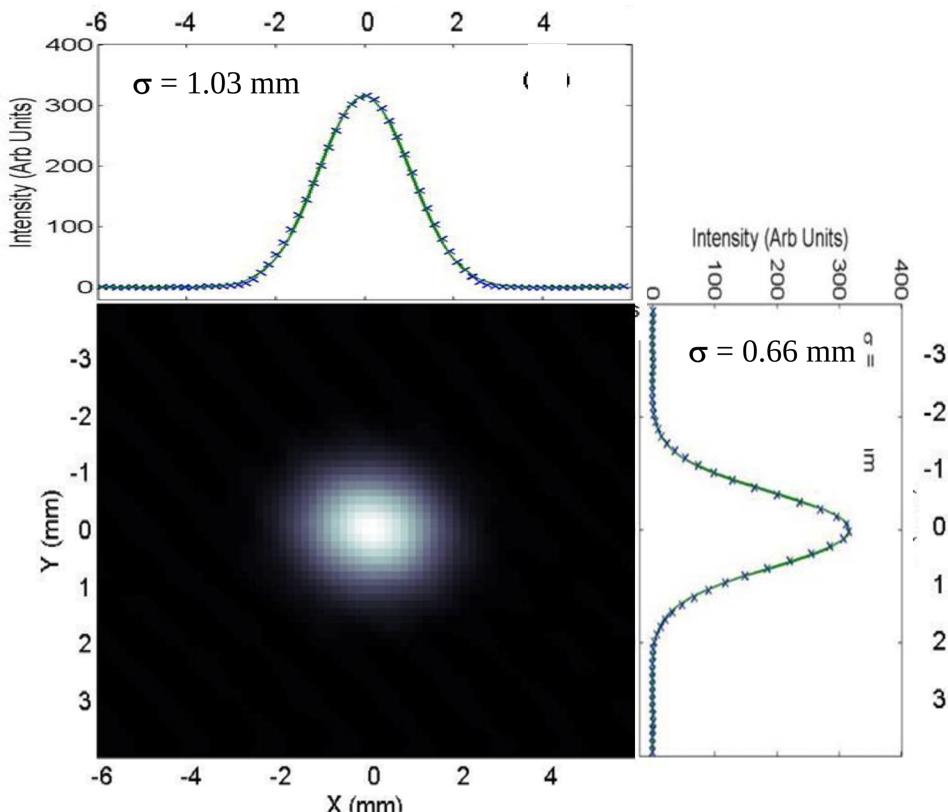
Measurement at FNAL-TEVATRON



Example of results: Single proton bunch at 150 GeV with turn-by-turn resolution
2-dim image: x-y coubling visible e.g. effect on e.g. skew quadupoles

V.E. Scarpine (FNAL) et al., BIW'06

OTR-Monitor: Results

***Example* for target diagnostics at FNAL:**

Insertion of OTR in front of NuMI target

120-150 GeV protons for neutrino physics

Online profile observation possible

Radiation hardness test at FNAL:

$7 \cdot 10^{19}$ protons in 70 days

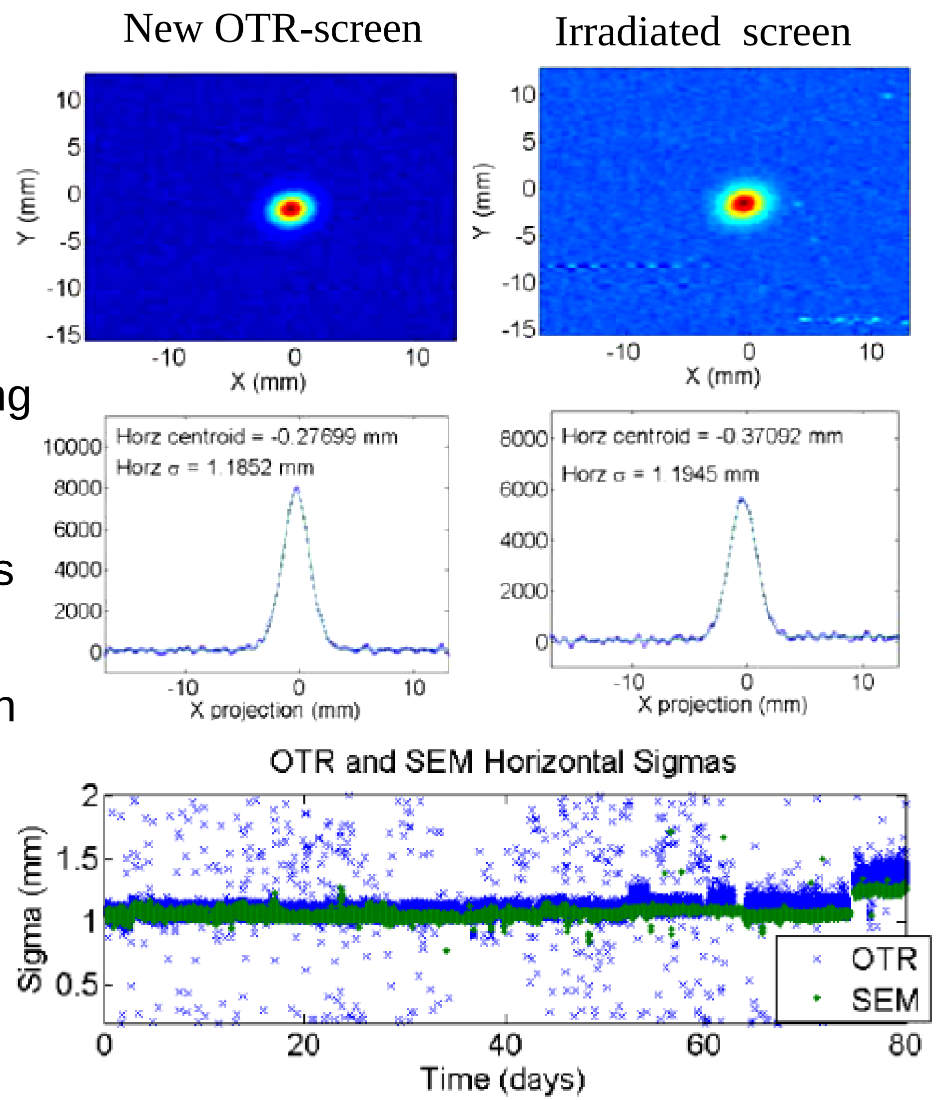
→ half signal strength but ***same*** width reading

Application: Target → online diagnostics

Synchrotron → injection studies

Further studies: Coherent OTR

Optical Diffraction Radiation



V.E. Scarpine (FNAL) et al., PAC'07

Synchrotron Radiation Monitor

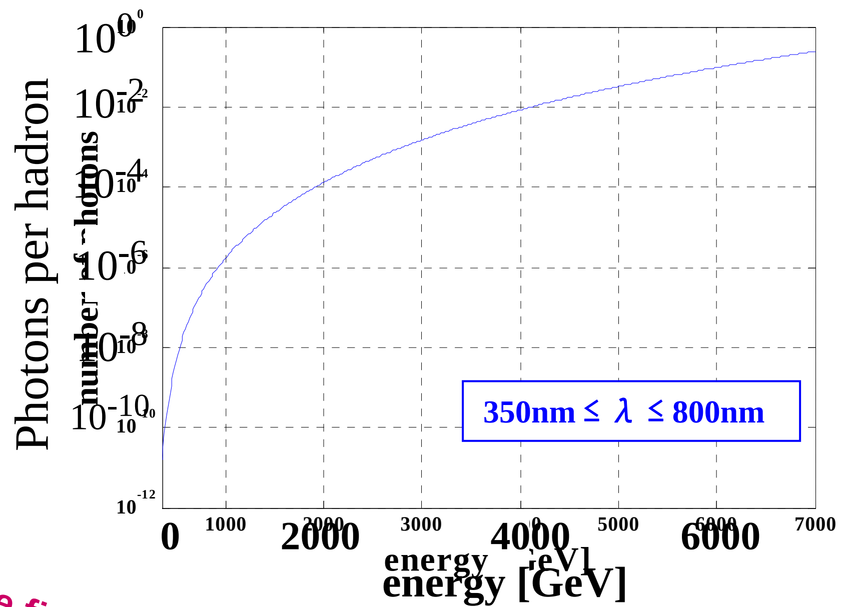
Main application: Synchrotrons for *E* > 100 GeV

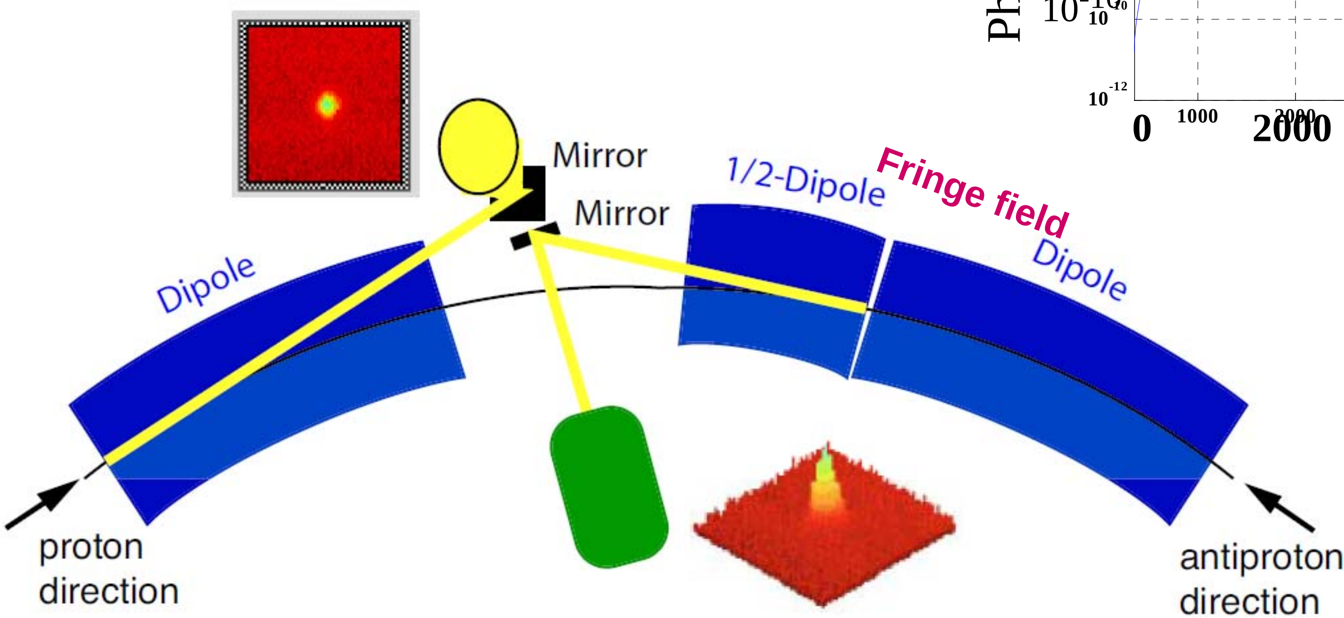
Synchrotron Radiation Monitor: Principle

Physics: Emission of radiation by charges on bent trajectory

For a dipole: $P \propto \frac{\gamma^4}{\rho^2}$ and $\lambda_c \propto \frac{\rho}{\gamma^3}$

- Dipole of ρ = 1km, γ=1000 $\Rightarrow$ $\lambda_c \approx$ 4µm
- Radiation from dipole-fringe field: shorter λ_c
- Undulator for 100 to 500 GeV





H.W.K. Cheung (FNAL) et al., PAC'03, R. Thruman-Keup (FNAL), BIW'06, G. Kube (DESY) et al., BIW'06

Synchrotron Radiation Monitor: Technical Realization

Physics: Emission of radiation by charges on bent trajectory

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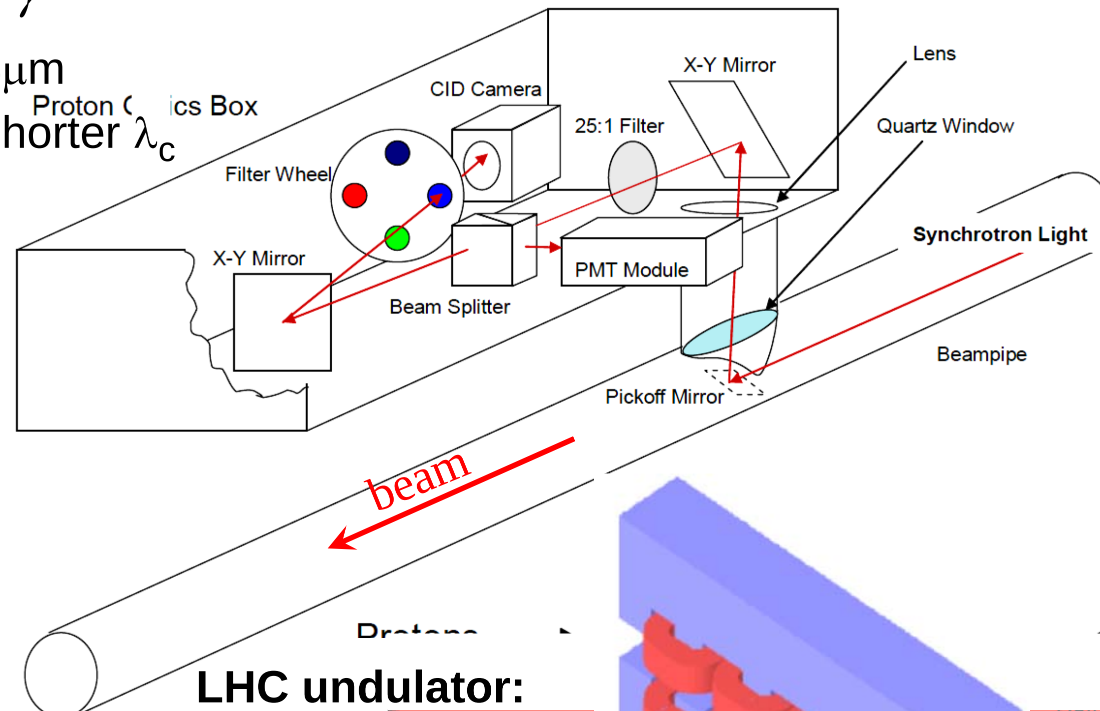
- Dipole of ρ = 1km, γ=1000 $\Rightarrow$ $\lambda_c \approx$ 4µm
- Radiation from dipole-fringe field: shorter λ_c
- Undulator for 100 to 500 GeV

Example for realization at Tevatron:

Optical table with intensified CID

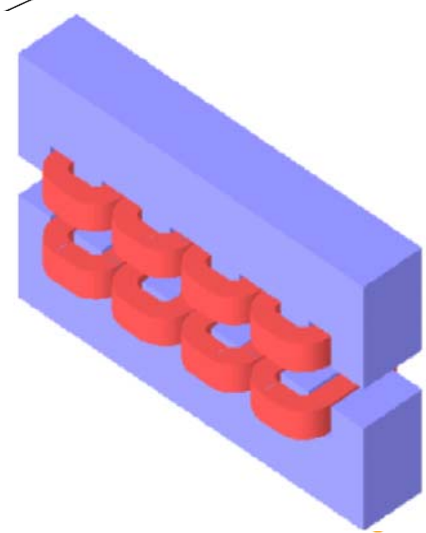


Example for realization at LHC:

- Undulator 0.45→1.2 TeV,
- Dipole edge: 1.2→3 TeV
- Dipole center 3 to 7 TeV

LHC undulator:

2 periods of 280mm
Pole gap 60 mm
Max. field 5T
$\Rightarrow \lambda_c$= 640 nm

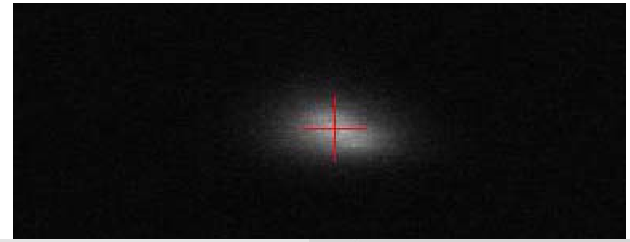


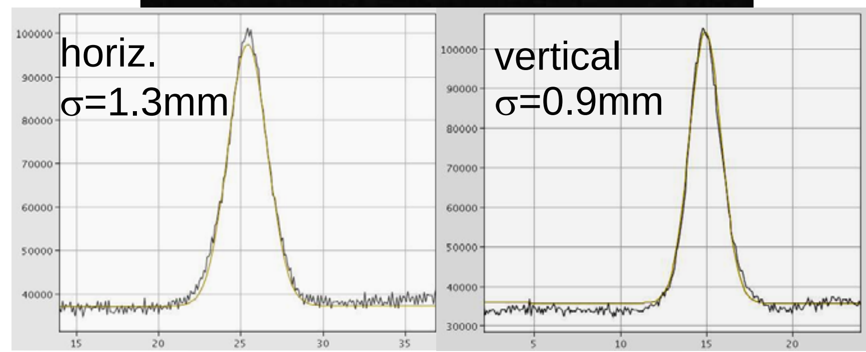
R. Thruman-Keup (FNAL), BIW'06, T. Lefevre (CERN) et al., IPAC'10, R. Maccaferi

Synchrotron Radiation Monitor: Results

Physics: Emission of radiation by charges on bent trajectory

For a dipole: $P \propto \dfrac{\gamma^4}{\rho^2}$ and $\lambda_c \propto \dfrac{\rho}{\gamma^3}$





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- Radiation from dipole-fringe field: shorter λ_c
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Example for realization at Tevatron:

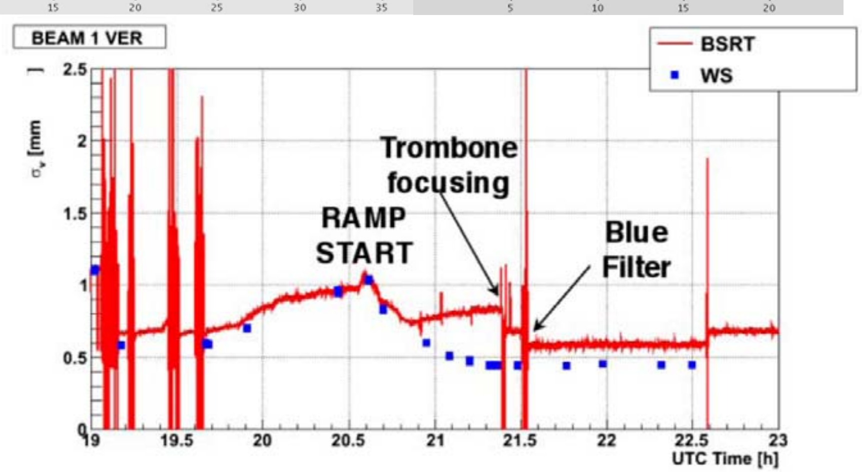
Optical table with intensified CID

Example for realization at LHC:

- Undulator 0.45→1.2 TeV,
- Dipole edge: 1.2→3 TeV
- Dipole center 3 to 7 TeV

Example from LHC acceleration:

- Radiation from undulator for 0.45 TeV
- Online display every 20 ms
- Turn-by-turn readout in preparation



See poster T. Lefevre et al., MOPE057, WEPEB072

T. Lefevre (CERN) et al., IPAC'10, R. Jones (CERN), BIW'10

Comparison of minimal invasive Profile Diagnostics

Very simplified comparison between the minimal invasive methods

	IPM	BIF	EBS	LWS	OTR	SRM
Physics	Energy loss	Energy loss	Space charge defl.	Photo-detachment	Transition radiation	Sycnhrotron light
Beam precaution	None	None	None	H^-	*E*>10 GeV	*E*>100 GeV
Profile display	Projection	Projection	Projection	Projection	2-dim	2-dim
Imaging meth.	Continuous	Continuous	Scan 10 Hz	Scan 30 Hz	Continuous	Continuous
Signal strength	Medium	Low	High	High	Medium	Low
Time resolution	100 ns	1 μs	10 ns	10 ns	1 μs	10 μs
Spatial resolution	100 μm	30 μm	100 μm	30 μm	10 μm	100 μm
Complexity	High	Low	Medium	High	Low	Very high
Main application	Synchr. & Trans. line	Trans. line	Synchr.	Trans.line	Synchr.& Trans. Line	Synchr. only

Negative ion beam sheet: see poster K. Shinto (JAEA) et al., MOPE016

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Thank you for your attention!