Presentation for IBIC17, **WE3AB2**
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Simulation and Progress in Ionization Profile Monitors for High Intensity Proton Beam

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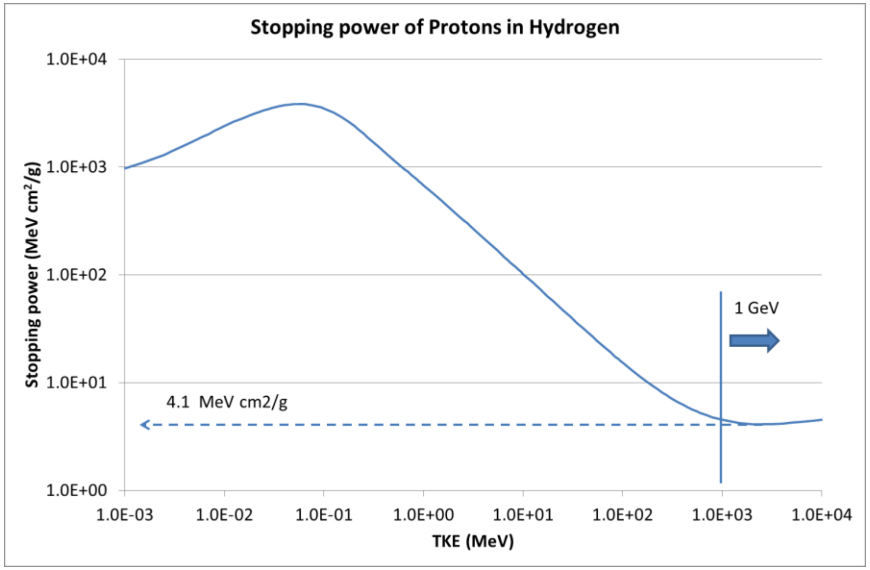
Outline

- Introduction
  - What is IPM?
  - Particle detection
  - J-PARC system
- Two mode operations
  - Ion collection mode, w.o. magnetic guiding field
  - Electron motion in electric and magnetic guiding field
- New simulation code of IPM, IPMsim3D
- Recent progresses of IPM
  - New IPM for the CERN-PS
  - Gated IPM system in FNAL
- IPM workshop
- Summary

What is IPM ?

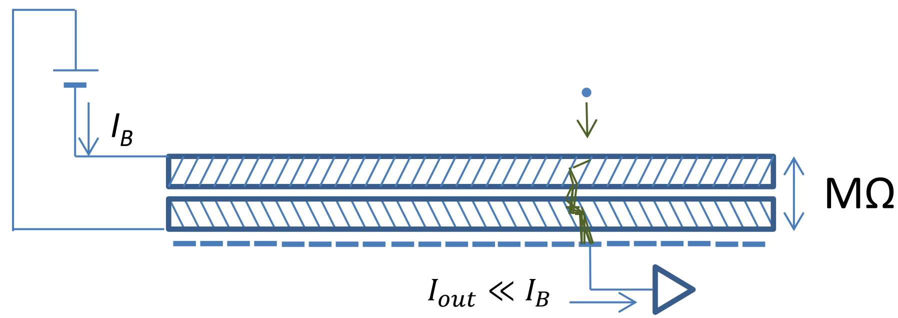
- **I**onization **P**rofile **M**onitor (**IPM**)
- **Non-destructive** 1D profile monitor
- 1D profile monitor based on the **beam induced ionizations**
- Charged particle produced by the ionization
  - **Residual gas,** gas inlet (Supersonic gas jet, gas chamber)
  - **Charged particle detection,** Gas fluorescence
- Two mode operations: Ion w.o. Bg or electron w Bg
  - Low intensity and DC beam : Ion collection mode
  - High intensity bunched beam : E collection mode
- There are long history, since 1966, however it is **hard to say that this is a well established technique because of its complexity on particle motion and contamination issue**
  - **The first IPM**
    - **V. Dudnikov, "The intense proton beam accumulation in storage ring by charge-exchange injection method", Ph.D. Thesis, Novosibirsk INP, 1966.**
    - **G. Budker, G. Dimov, and V. Dudnikov, in proceedings of the international symposiumon electron and positron storage rings, Saclay, France, 1966 (Saclay, Paris, 1966), Article No. VIII-6-1.**

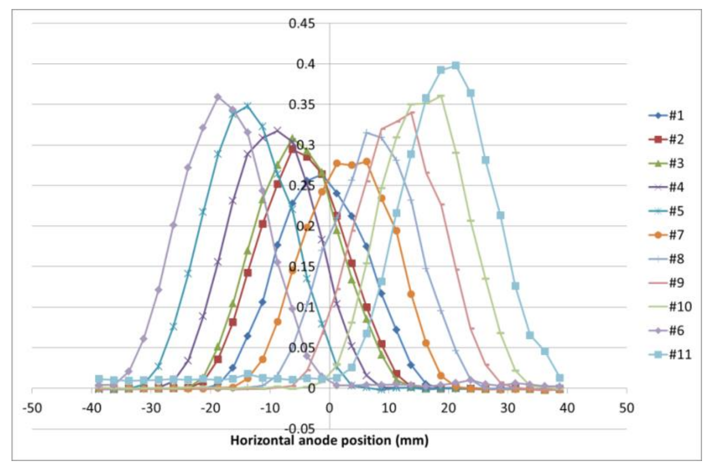
Particle detections



Signal multiplier is basically needed

- Rectangular MCP with multi-anode
- Rectangular MCP with phosfer screen





Local gain change for long time usage

Signal estimate in case of J-PARC MR

Beam intensity, Nb: 4E11~13 ppb
Proton Energy: 3-30 GeV
Pressure, P: 5E-7 Pa
Gas: Hydrogen
Stopping power, dE/dx : 4.3 MeV cm²/g
W value: 36 eV
Density, ρ: 8.99E-5 g/cm³/atm
l. Detector size, dZ: 2 cm

Number of ion-electron pairs : N

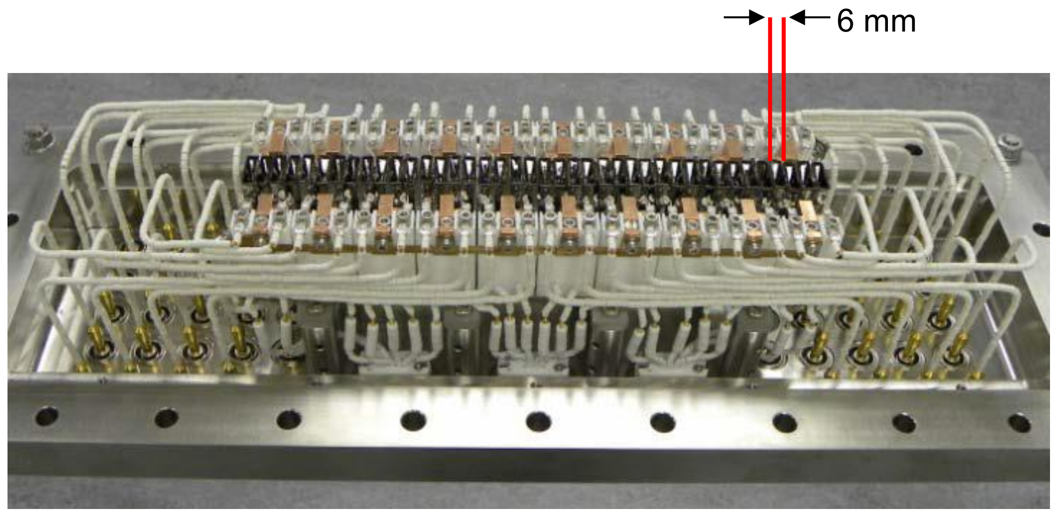
$$N = N_b\, \rho\, \frac{P}{10^5}\, {dE}/{dx}\, \frac{1}{W}\, dZ = \mathbf{43{\sim}4300\ per\ bunch}$$

Calibration method is required

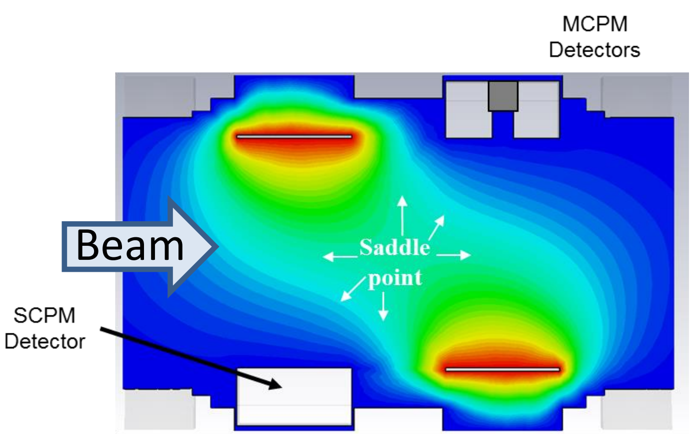
- Beam based, Thin wire, EGA, EV light

Channeltron system (ISIS/RAL IPM)
Courtesy by Mr. Wilcox

A single channeltron



The 40 channeltron array used to measure beam profile



Longitudinal electric potential distribution created by the two drift field electrodes

Profile measured by the multi-channeltron detector
Gain calibration can be made using movable single channeltron detector

J-PARC IPM: Components and two mode operations

- A set of electrodes to generate electric field to collect charged particle
- High voltage to collect charged particle against a strong space charge electric field of the high intensity bunched beam
  - Space charge E field
    - **2MV/m** for MR ext. beam
- 3-pole magnet system to generate guiding field to collect electrons against space charge electric field

Ideally the E and B field doesn't make any force

- MCP to multiply the signal
- Multi strip anode to read out the charge from MCP
- Electron source, EGA (Electron generator arrays), to check gain aging of the MCP -> Will be removed this summer

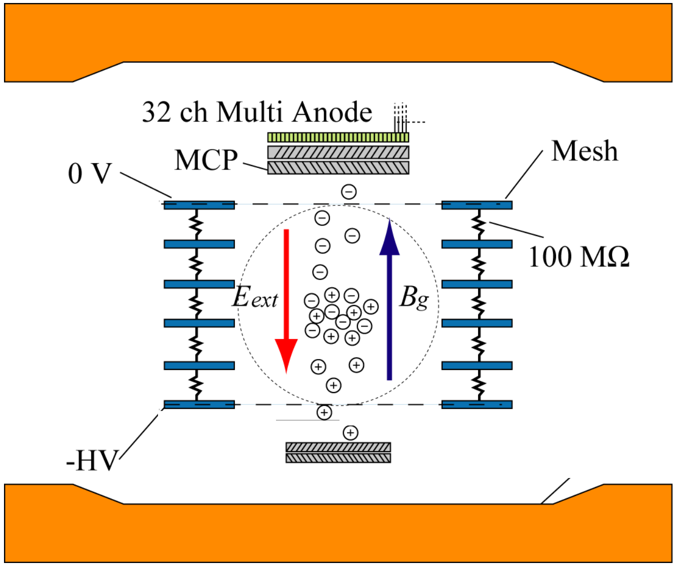
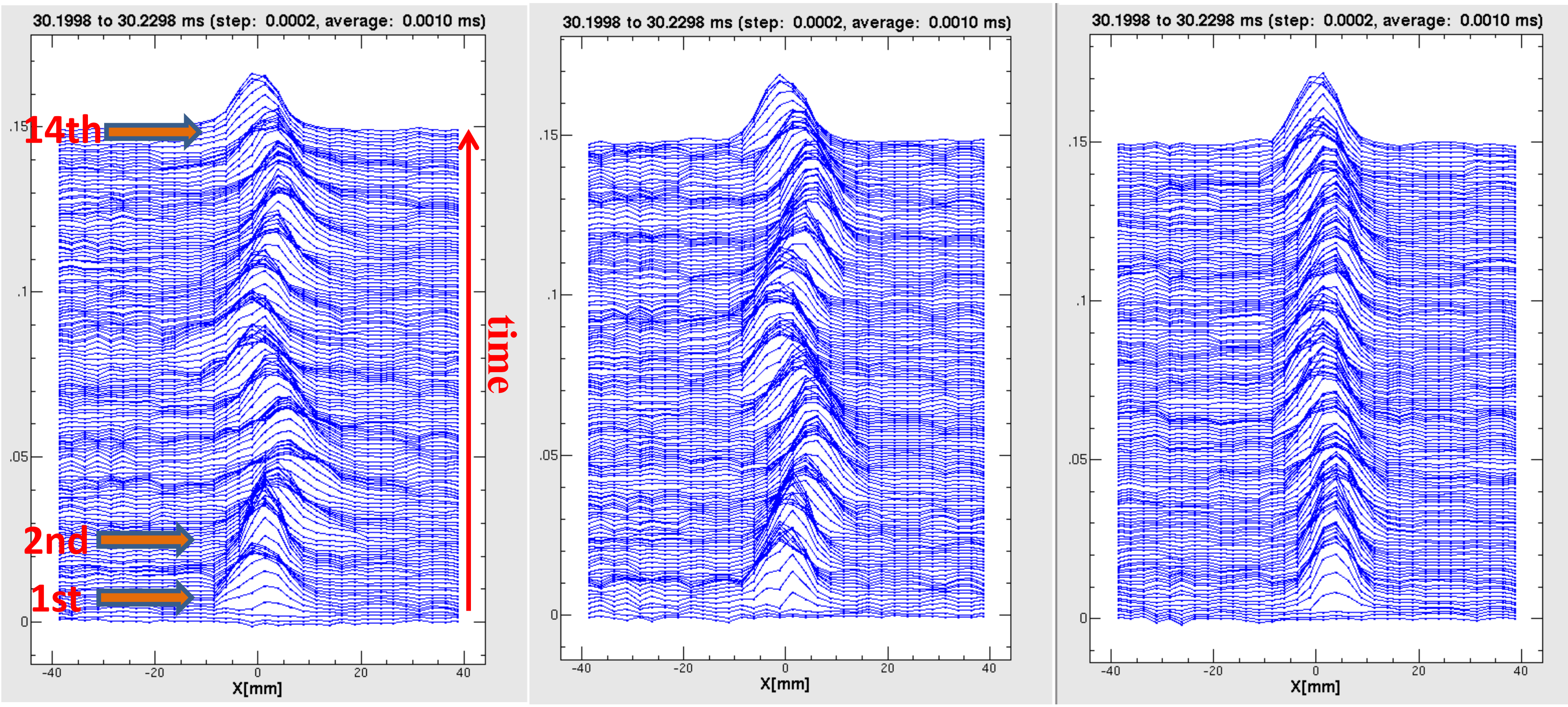


Photo of IPM

Turn by turn profile measurements
Ion collection, Inj. beam

From 1st turn to 14th turn profile measured at J-PARC IPM



Injection miss-match
Q mode + D mode

After Q mode tuning
D mode

After Q and D mode tuning

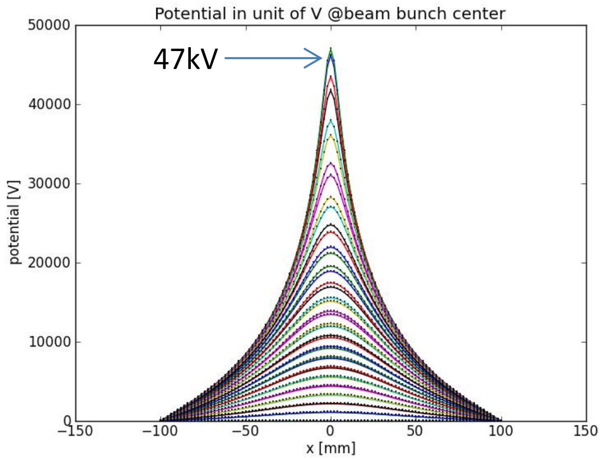
Ion collection without B?

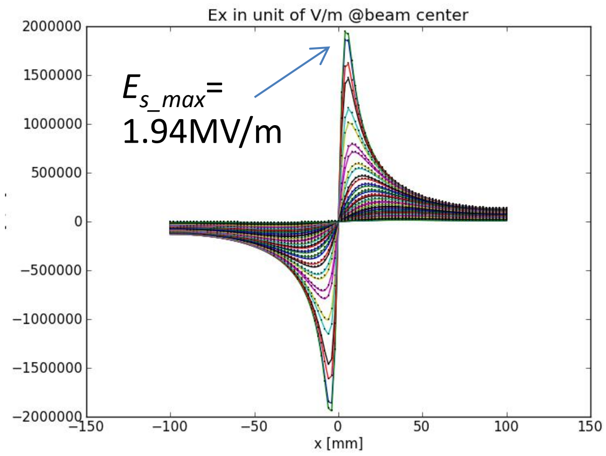
Beam parameters of J-PARC MR
・Injection (3 GeV)
σ_t=40ns(600ns interval), σ_x=7.6mm, σ_y=12.3mm
・Extraction (30 GeV)
σ_t= 10ns(588ns interval), σ_x= 2.7mm, σ_y= 4.4mm

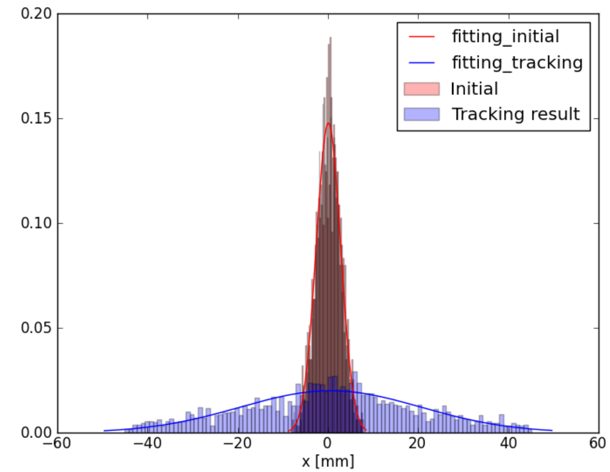
Calculated space charge E field is
Potential_max=47kV, Es_max≈2MV/m
required HV to overcome the Es is,
2MV/m*130mm=260kV!!

Even if we can apply the 260 kV DC between the electrodes (130mm gap), the profile will be,,,,

Profile: ion w.o. B, 260 kV

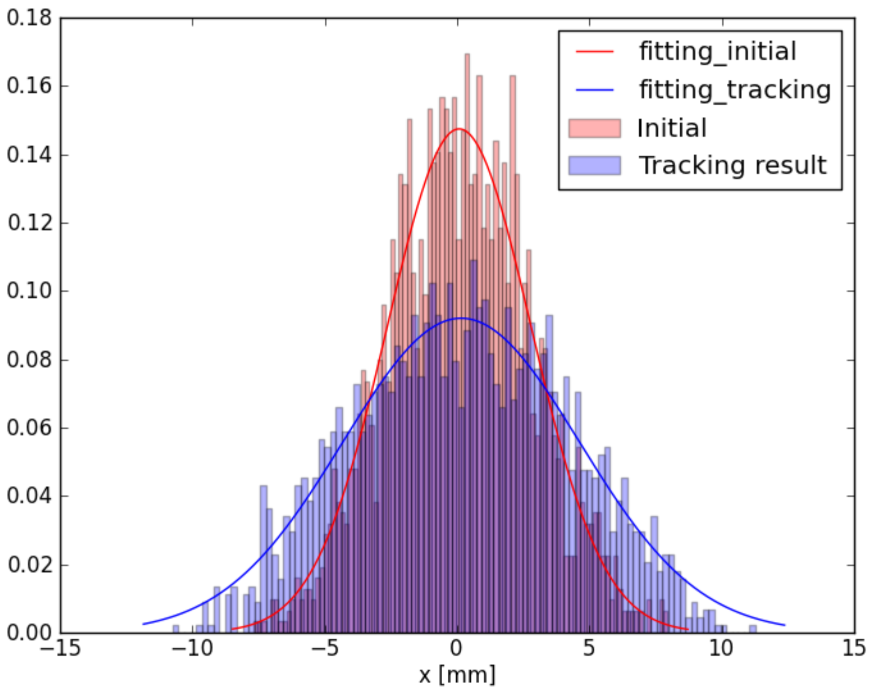




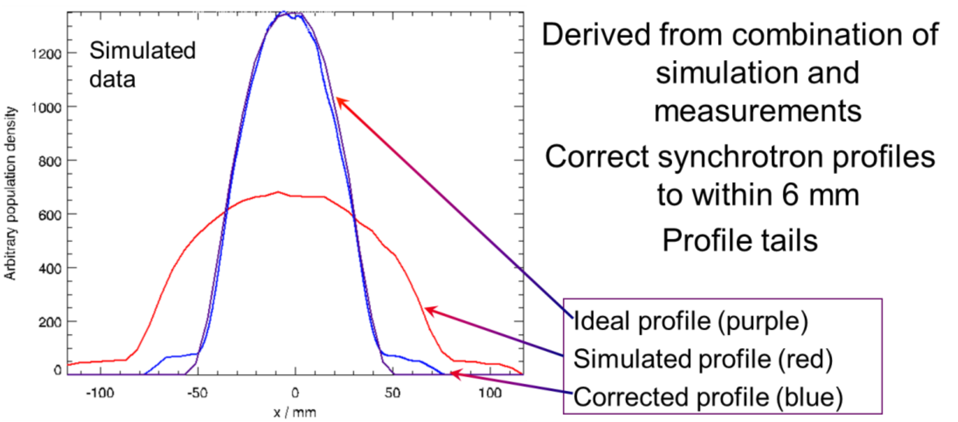


Ion collection w.o. B

If the beam intensity is 1/10, the profile will be,,,



Model based reconstruction method can be applied



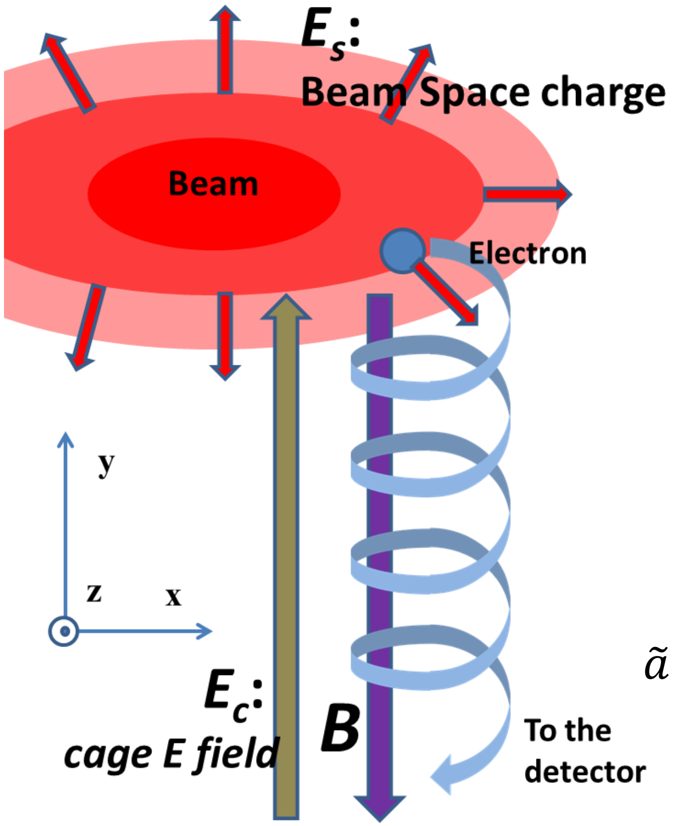
Reconstructed beam profile
From proceedings of EPAC08, Genoa, Italy, TUPC109
Courtesy by Mr. Wilcox (ISIS/RAL)

Similar methods is planned at
- ISIS/RAL
- ESS
- IFMIF EVEDA
- 、、、

Electron collection mode w. Bg: IPM for high intensity proton accelerators

Electron motion acting with Ec, Es, and Bg
Position resolution estimate for simple case, const. fields.

Electron motion in E(=const.) and B(=const.) field



Equation of motion

$$\vec{a} = -\frac{e}{m}(\vec{E} + \vec{v} \times \vec{B})$$

where,

$$\vec{E} = \overrightarrow{E_c} + \overrightarrow{E_s} = (E_x, E_y, E_z)$$

$$\vec{B} = (B_x, B_y, B_z) \approx (\theta_x, 1, \theta_z)B$$

$$\theta_x, \theta_z \ll 1$$

Imaginary variable
$\tilde{a} = a_x + ia_z, \tilde{v} = v_x + iv_z, \tilde{\theta} = \theta_x + i\theta_z, \ldots$

$$\tilde{a} = i\omega \frac{\widetilde{E \times B}}{B^2} - \frac{e}{m} E_y \tilde{\theta} - \frac{e}{m} \widetilde{v \times B} \approx -i\omega\tilde{v} - \omega\frac{\tilde{E}}{B} - i\omega^2 \frac{E_y}{B}\tilde{\theta}t$$

1st : Rotation along By, 2nd : $E \times B$ motion, 3rd : *$E \times B$ motion but along Bx and Bz*

Integration should be made along the trajectory, the fields depend on positions, so the pass integral can not be analytically obtained.

-> const. fields are assumed here

Position displacement

$$\tilde{\Delta} = \Delta_x + i\Delta_z$$

$$\approx \frac{i}{\omega}\widetilde{v_0}\underbrace{\left(e^{-i\omega t}-1\right)}_{\textit{Larmor rotation}} + \frac{\tilde{E}}{B}\left\{\frac{1}{\omega}\left(e^{-i\omega t}-1\right) + \underbrace{it}_{E\times B\ \text{drift}}\right\} + i\frac{E_y}{B}\tilde{\theta}\left\{\frac{1}{\omega}\left(e^{-i\omega t}-1\right) + it\right\} - \frac{1}{2}\frac{eE_y}{m}t^2(\approx FL)\tilde{\theta}$$

Larmor rotation

Initial velocity term

$E \times B$ drift

Ex, By -> drift to Z dir.

Ez, By -> drift to X dir.

Error field, $E_x + iE_z$, term
E_s and E_c

B error, $B_x + iB_z$, term
Modulation due to B error

Geometrical term

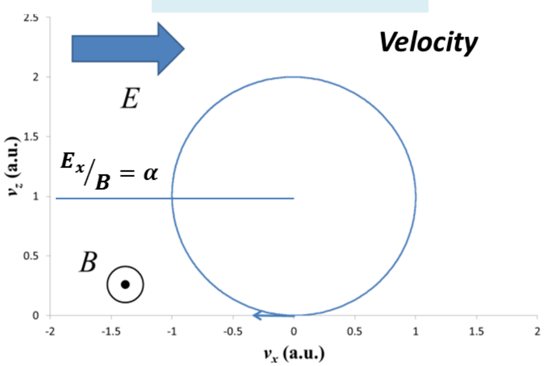
- **Relativistic beam**
- **Longitudinal length > detector size**

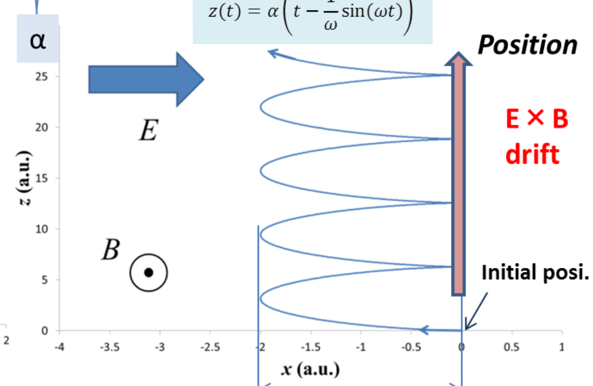
Es is essentially transverse and only Esx will cause distortion

$$\frac{E\times B}{B^2} = i\frac{E_x}{B} = \text{const.}$$

$$v_x(t) = -\alpha sin(\omega t)$$
$$v_z(t) = \alpha(1 - cos(\omega t))$$

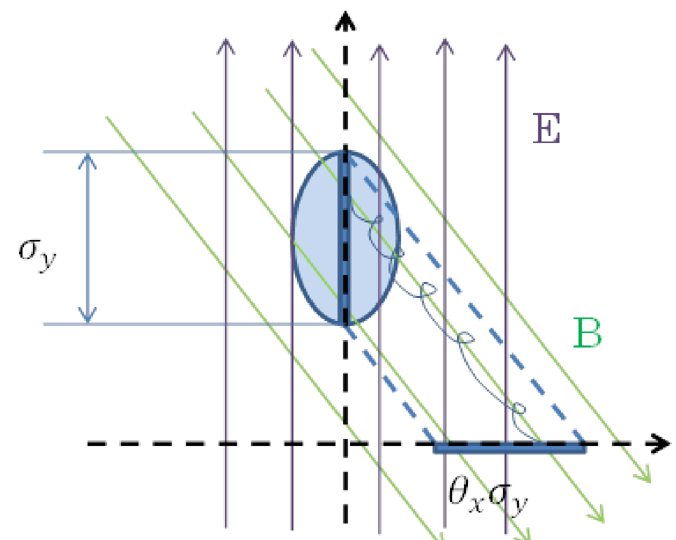
$$x(t) = \alpha\frac{1}{\omega}(\cos(\omega t) - 1)$$
$$z(t) = \alpha\left(t - \frac{1}{\omega}\sin(\omega t)\right)$$





$2\frac{\alpha}{\omega}$**: H position shift**

- Gyro-motion around B
- Constant velocity of Ex/B for guiding center
  ⇒well known as **E × B drift**



Geometrical shift

Why we need strong B?

Merit of a strong B field is clear!!

$$\frac{i}{\omega}\widetilde{v_0}\left(e^{-i\omega t}-1\right)+\frac{\tilde{E}}{B}\left\{\frac{1}{\omega}\left(e^{-i\omega t}-1\right)+it\right\}+i\frac{E_y}{B}\tilde{\theta}\left\{\frac{1}{\omega}\left(e^{-i\omega t}-1\right)+it\right\}-\frac{1}{2}\frac{eE_y}{m}t^2(\approx FL)\tilde{\theta}$$

Δx by Initial velocity term (Larmore rotation):

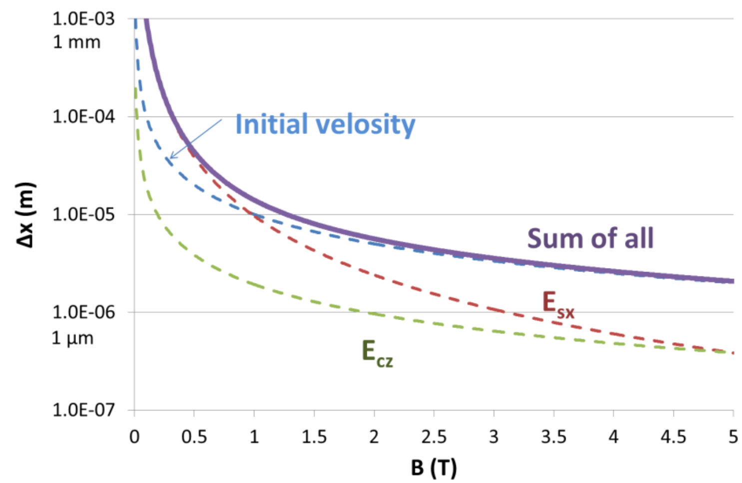
$$\Delta x=\frac{v_0}{\omega}=\frac{mv_0}{e\boldsymbol{B}}=\frac{10^{-5}}{B}\ [\mathrm{m}]$$ In case of TKE=10eV

Δx by Error field, E_{sx} (Larmore rotation):

$$\Delta x=2\frac{\alpha}{\omega}=2\frac{E_{sx}/B}{\omega}=\frac{E_{sx}m}{e\boldsymbol{B}^2}=\frac{0.5\times10^{-10}}{B^2}E_{sx}\ [\mathrm{m}]$$

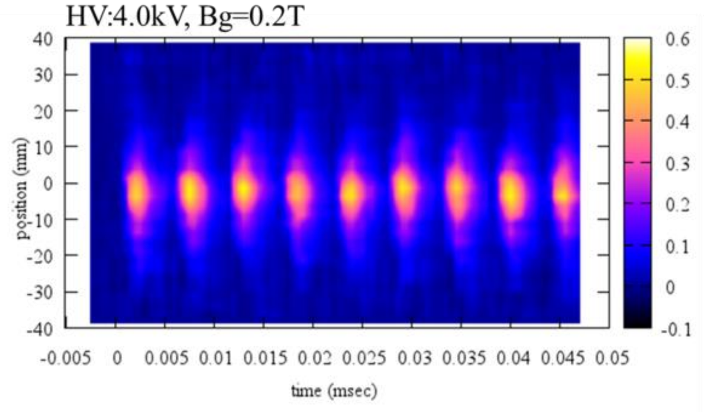
Δx by Error field, E_{cz}, E ×B drift:

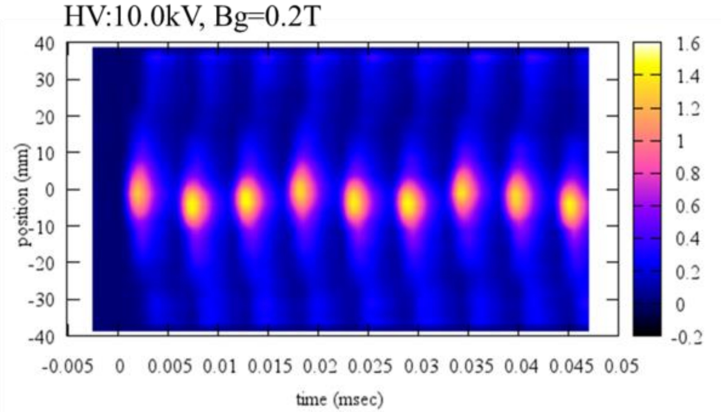
$$\Delta x=\frac{E_{cz}}{\boldsymbol{B}}\times TOF=10^{-9}\frac{E_{cz}}{\boldsymbol{B}}$$ In case of TOF=1 ns

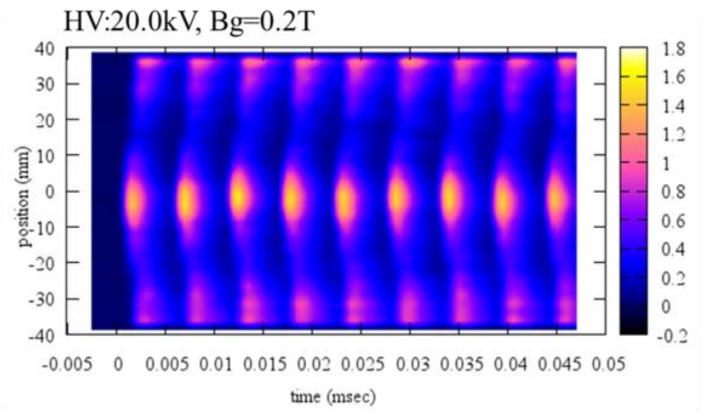


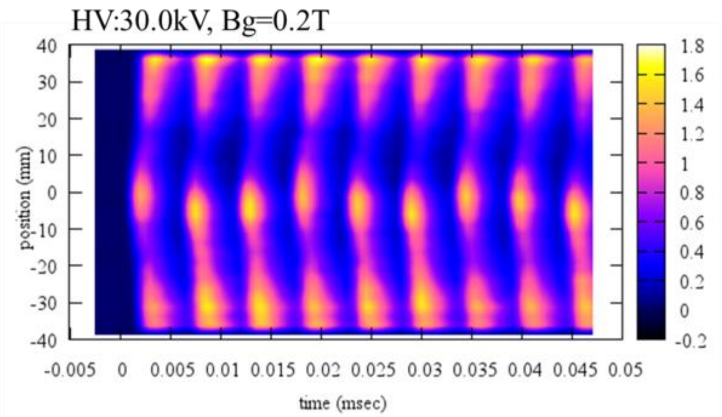
These fields depend on the cage and magnet design and Es is depend on the beam profile ⇒ 3D simulation code

Is it possible to collect electrons only from the ionization process?: Contamination issue



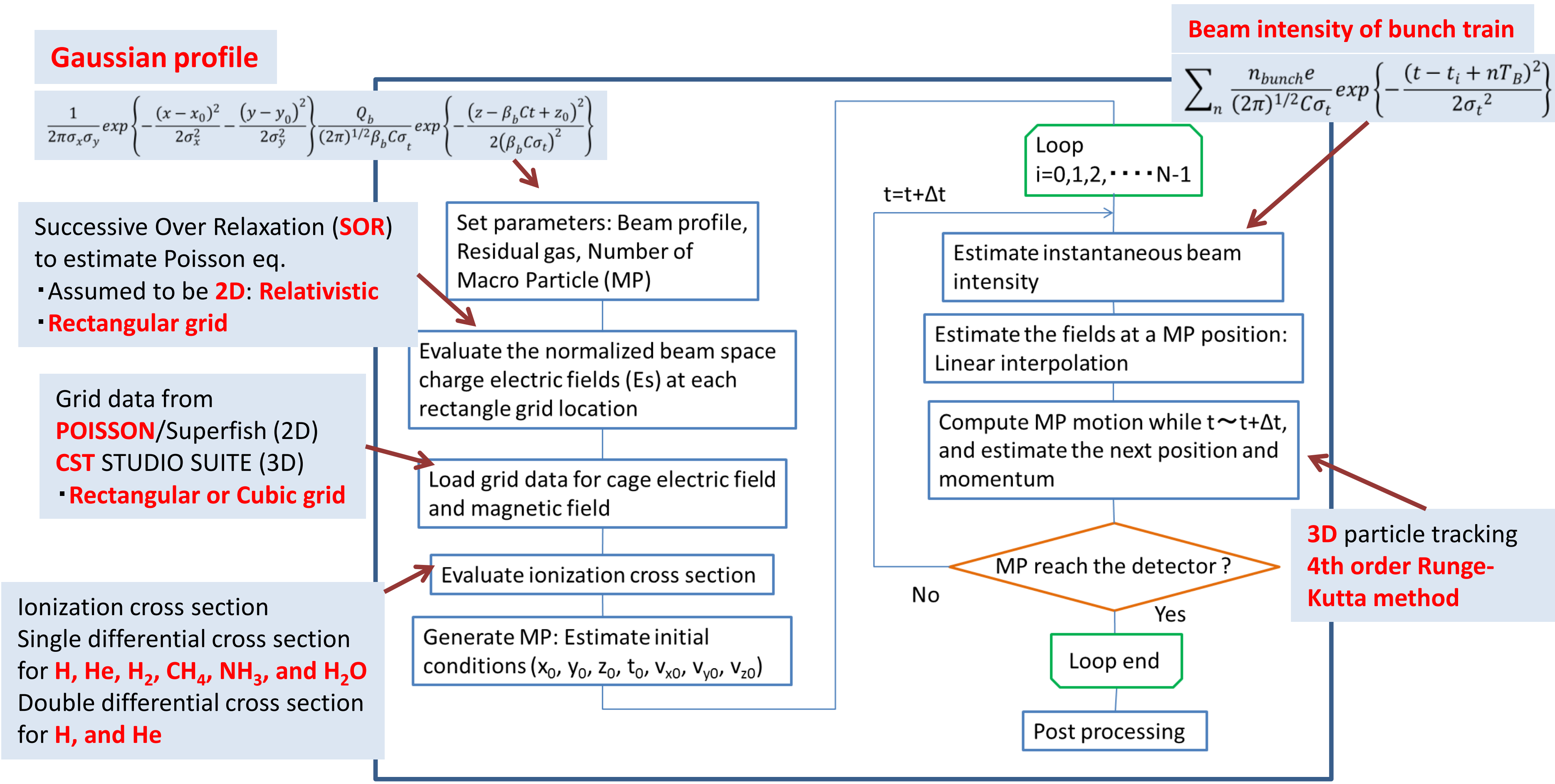






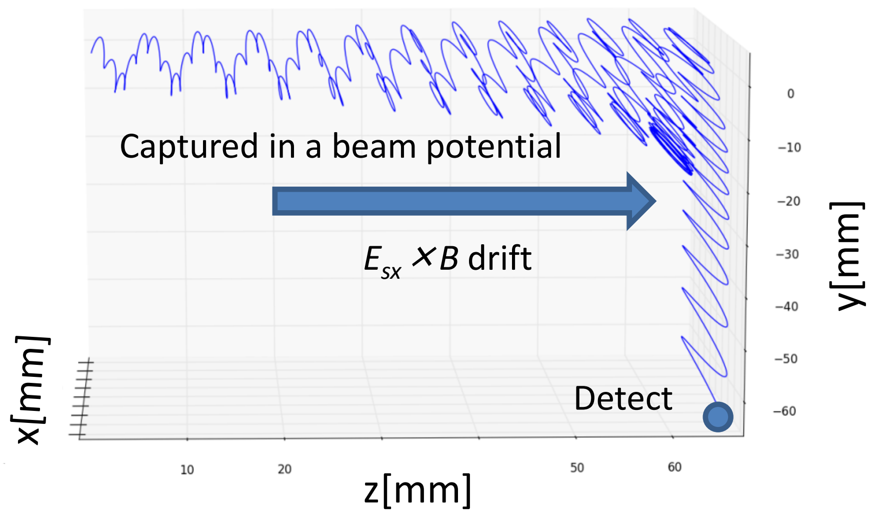
- The turn by turn profile showed beam induced contamination, and it depends on Ec, Bg fields as well as beam parameters
- The contaminant electrons appeared ~1.5 μs after the beam passage
- Mechanism of this contamination issue is **now under investigation**
- **Simulation not only for electrons gene. in the cage but also electrons gene. outside of the cage**

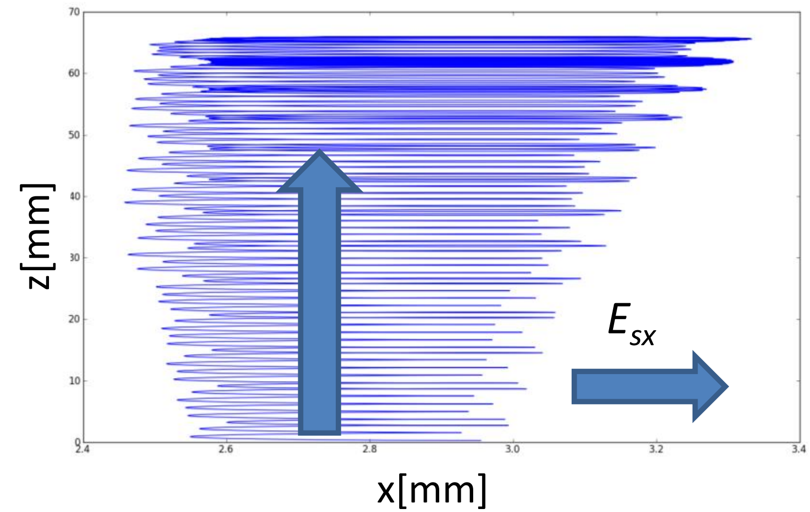
Python based 3D particle tracking code
Profile simulator for IPM design: IPMsim3D

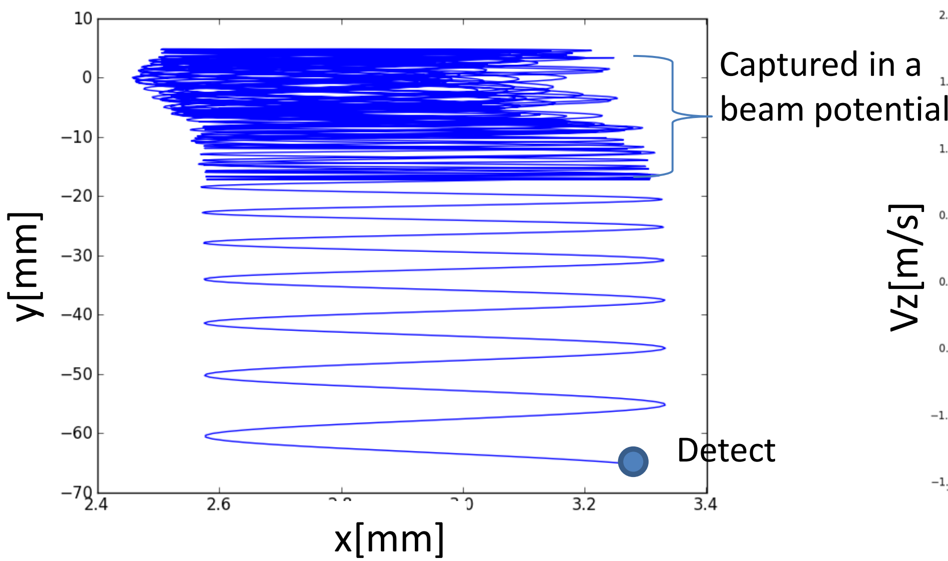


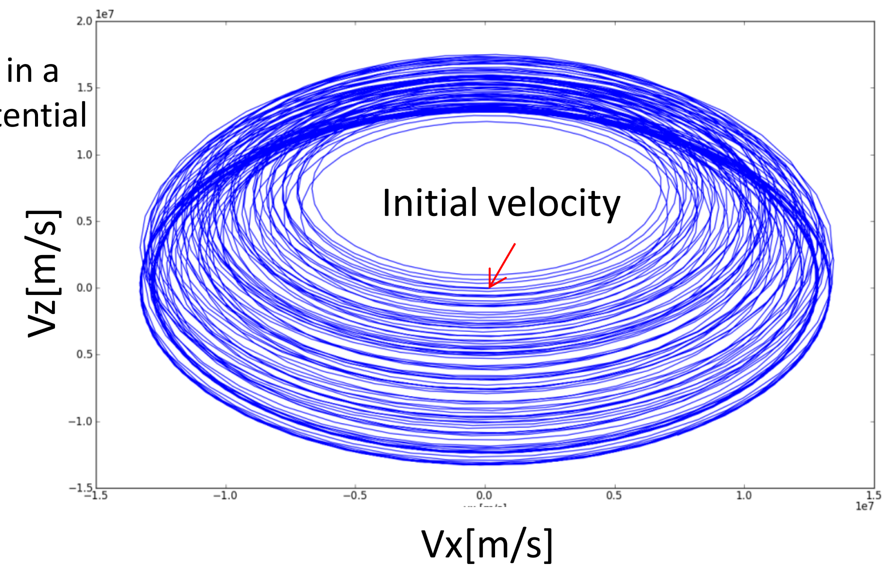
Flow chart of the simulator

Electron trajectory in strong Es

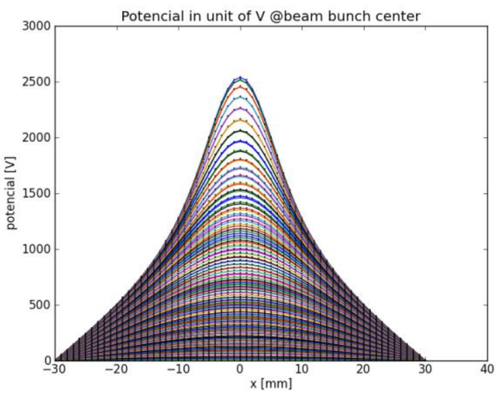




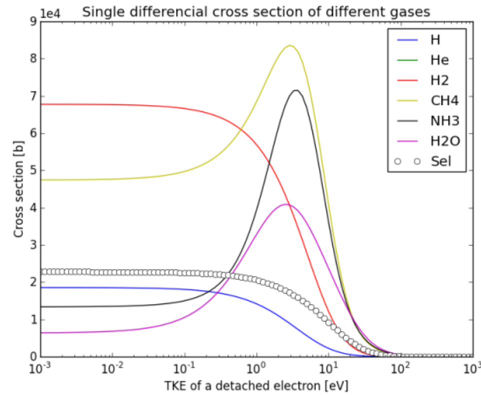




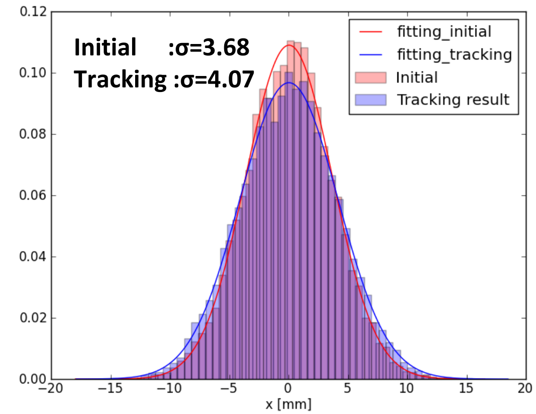
An example of calculated profile



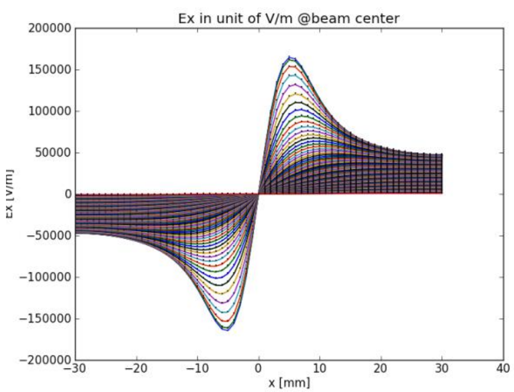
Potential



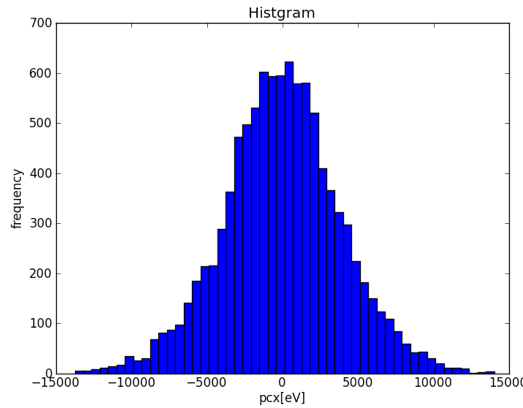
SDCS



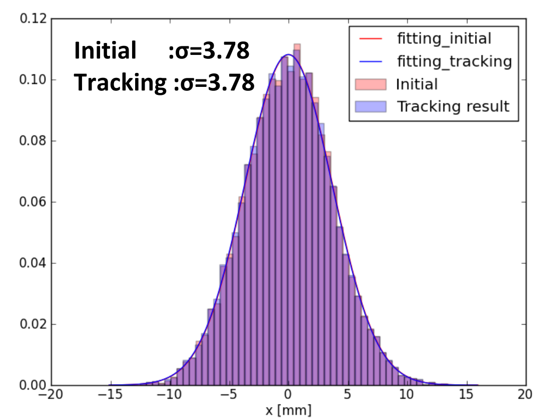
Profile, B=0.02T



Ex



CPx [eV]



Profile, B=0.2T

Existing simulation codes for IPM

Table 1: The Current Simulation Codes. See Text for the Details.

Name/Lab	Language	Ionization	Guiding field	Beam shape	Beam field	Tracking
GSI code	C++	simple DDCS	uniform E,B	parabolic 3D	3D analytic relativ.	numeric R-K 4th order
PyECLOUD-BGI /CERN	python	realistic DDCS	uniform E,B	Gauss 3D	2D analytic relativ. only	analytic
FNAL	MATLAB	simple SDCS	3D map E,B	arbitrary	3D numeric relativ. (E and B)	num. MATLAB rel. eq. of motion
ISIS	C++	at rest	CST map E only	arbitrary (CST)	2D numeric (CST) non-relativ.	numeric Euler 2nd order
IFMIF	C++	at rest	Lorenz-3E map E only	General. Gauss	numeric (Lorenz-3E) non-relativ.	
ESS	MATLAB	at rest	uniform E,B	Gauss 3D	3D numeric (MATLAB) relativ.	numeric MATLAB R-K
IPMSim3D /J-PARC	python	realistic DDCS	2D/3Dmap E, B	Gauss 3D	2D numeric (SOR) relativ. only	numeric R-K 4th order

From Proc. of IBIC16, TUPG71, M.Sapinski *et. al.*

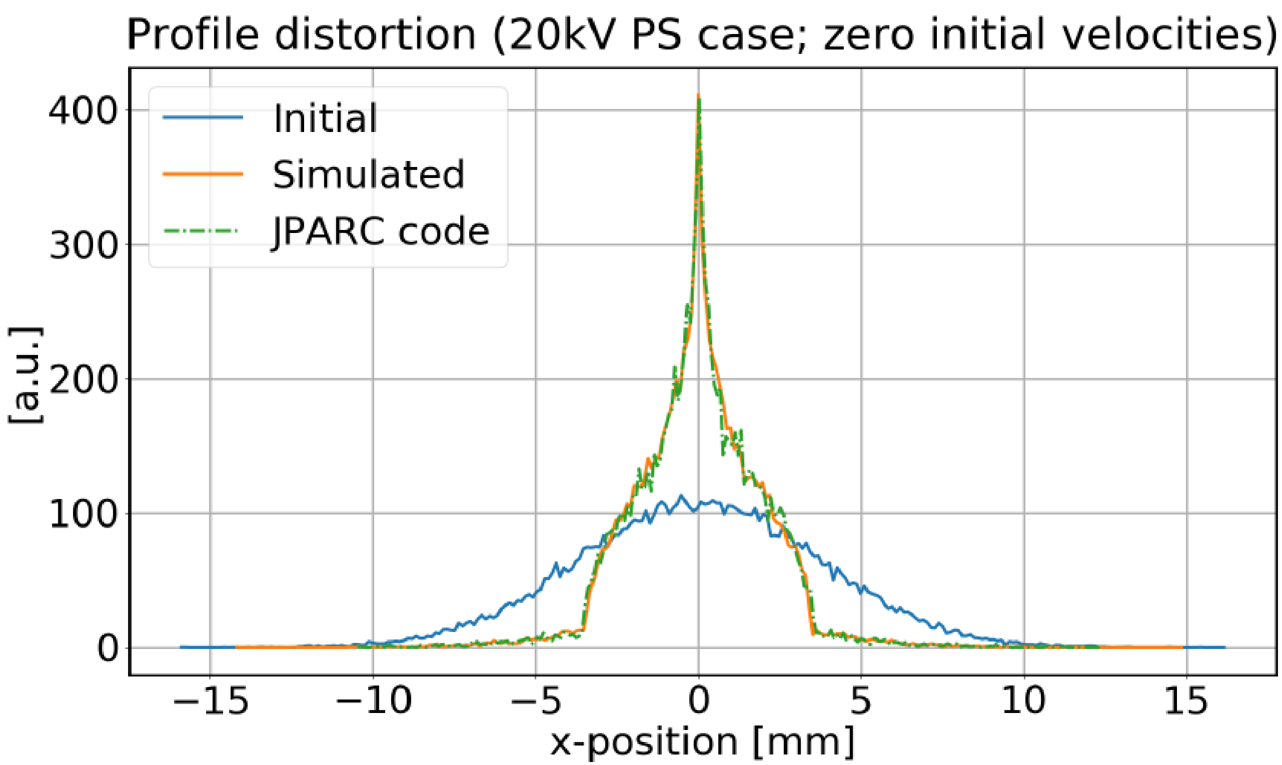
Courtesy of Dr. M.Sapinski (GSI)

New IPM simulation code by D. Vilsmeier, P. Forck and M. Sapinski (GSI)

Poster presentation: **WEPCC07**

New modules are added: **Beam gas interactions -> Beam Induced Fluorescence Monitors (BIF) simulation**

Cross checking



New GSI code vs. IPMsim3D

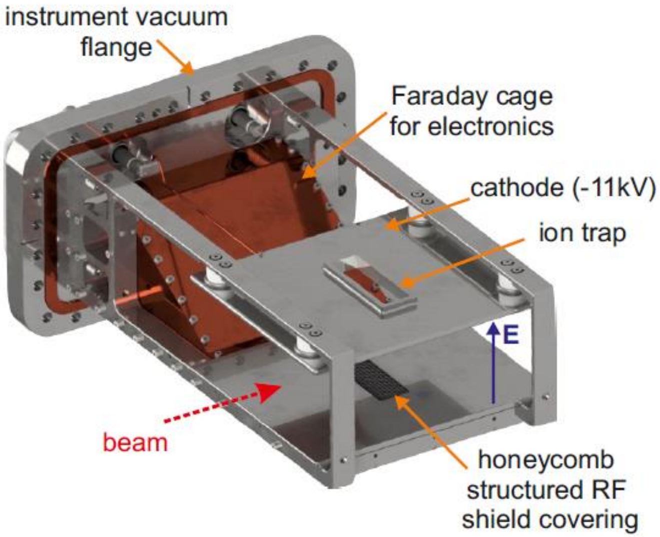
Courtesy of Mr. D. Vilsmeier (GSI)

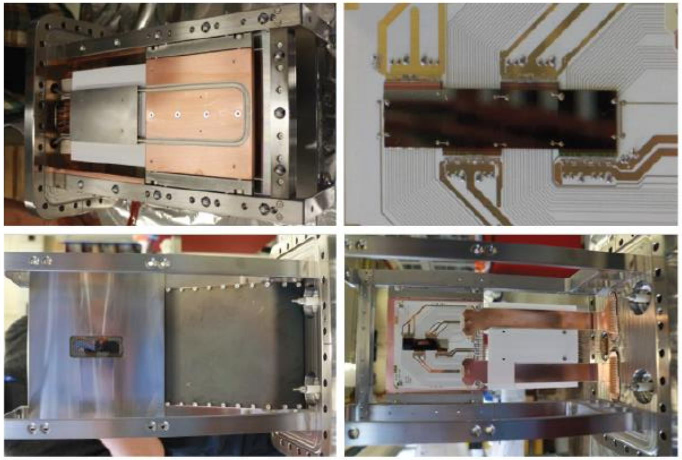
Recent progresses of IPM

- CERN PS IPM
- Gated IPM system(FNAL)

New IPM for CERN PS

- Simple cage design
  - Field estimate using CST
  - Optimized by using the IPMsim3D code
- Ion trap
  - Suppress electron contamination originating from ion collision on a electrode
- Multi-pixel Si detector system
  - 55 µm × 55 µm silicon sensor pixels (65,536 pixels)
  - Fast responce
  - Good position resolution
- [Oral presentation: WE2AB5, J.W.Story et. al.]

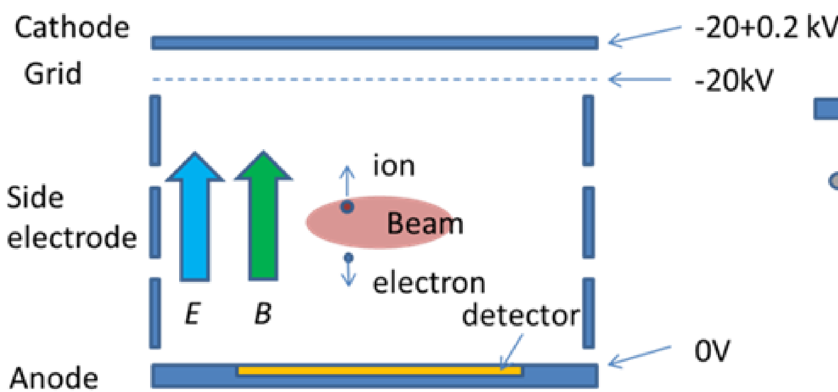


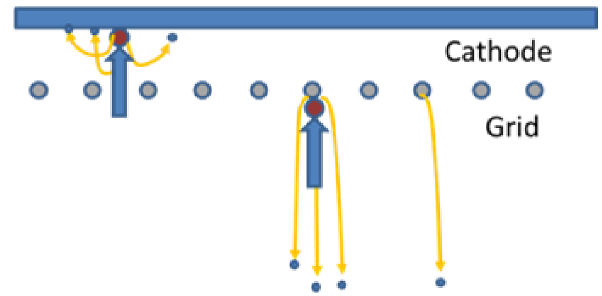


Courtesy by Dr. J.W. Storey (CERN)

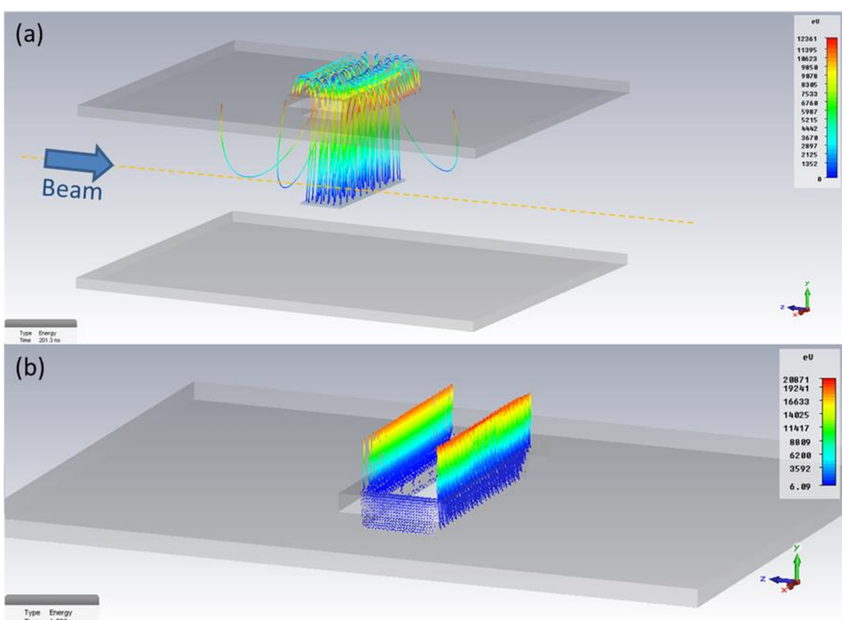
CERN PS IPM//Ion trap

Suppress secondary electron contamination





Simple solution



a)Ion motion

1)Accelerate to the cathode

2)Pass through the slot

3)Stop at the point between the slot and the chamber wall

4)Accelerate again to the cathode and captured on the cathode

b)Secondary electron motion

1)The ion bombardment results in secondary electrons

2)Escaped electrons from the wall **goes to the chamber wall**

3)And finally **these are completely captured**

Gated IPM system (FNAL)

- **Issue on a charged particle detector, Micro Channel Plate (MCP)**
- **Local gain degradation after the long-term operation of 9 years, in case of J-PARC MR IPM**
  - **MCP is used as a charged particle detection and signal amplification devise and its gain uniformity is essential for the profile measurement**
  - **The local gain decrease with increase the integrated output charge, and thus it is severe at the center area**
  - **MCP devise is expensive and cannot be replaced easily**

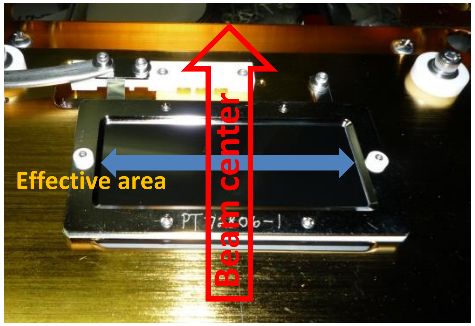
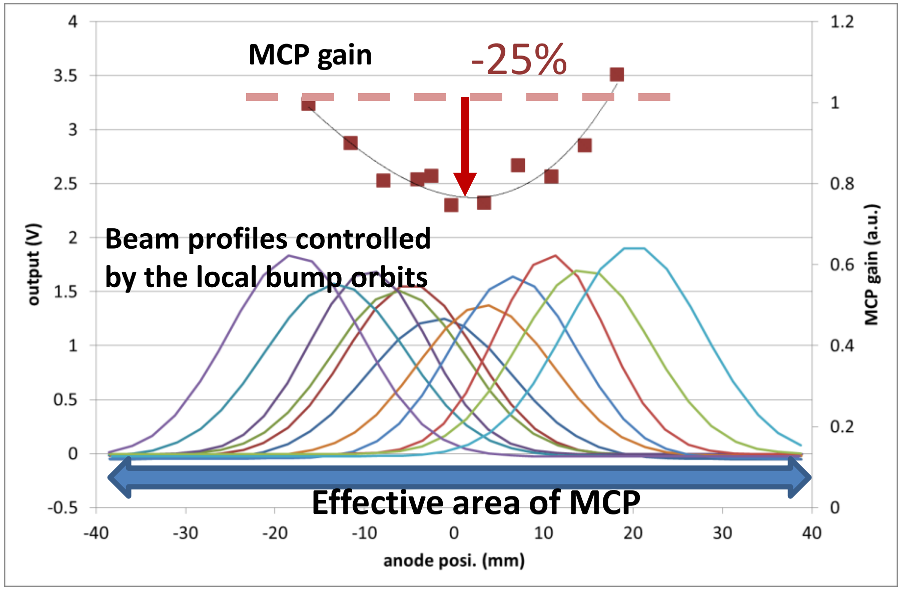


Photo of the detector, MCP



Solution: HV DC -> Pulse mode operation

Local gain decrease can be expressed as

Integrated output charge

Beam center fluctuation

Integrated time of measurement

Beam on ratio

$$\Delta \mathbf{G}(x) \propto Q(x) \propto G_0(V_{bias}) \cdot \underbrace{\tilde{\rho}\left(x - f_{x0}(x)\right)}_{\text{Averaged profile measured}} \cdot \tilde{I_0} \cdot T \cdot D_{beam} \cdot \boldsymbol{D_{IPM}}$$

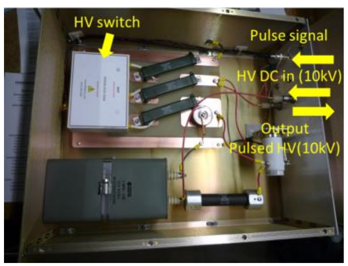
Local gain change

MCP gain set

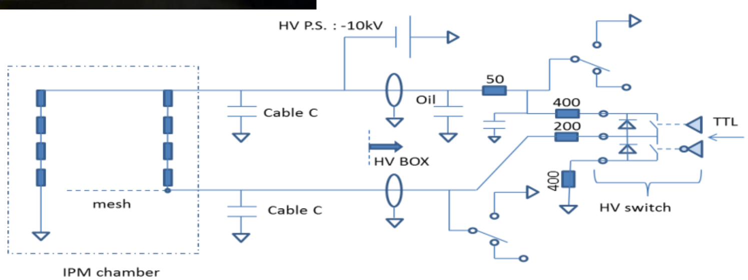
Averaged intensity

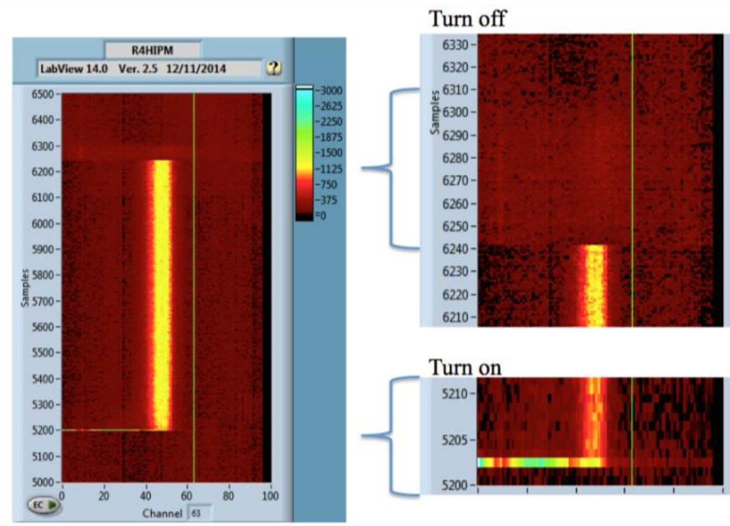
Duty of IPM operation

Gated IPM system can optimize this parameter



Courtesy of James R Zagel: Photo and block diagram of the HV switching module for FANL IPM





Courtesy of Randy Thurman-Keup (FNAL), profile measured by the IPM @ FNAL with pulsed HV: From the presentation file of US/Japan monitor meeting at FNAL, 2015.

When 100Hz 1% duty switching operation is used ($D_{IPM}: 1 \rightarrow 0.01$), only 20 turn profiles will be selected for each pulse. MCP life will be extended to 100 times longer than that in the case of non-gated system.

IPM workshop

- The intercommunication framework, IPM workshop, was established.
- First workshop at CERN
  - 3-4 March 2016
  - During the last 40 years numerous codes were written to address various aspects of the electron/ion transport in IPMs, however none of these codes is publicly available, maintained, well documented nor completed.
  - In this workshop an inter-laboratory collaboration with goal to create, benchmark and maintain such a code will be discussed and planned.
  - https://indico.cern.ch/event/491615/
- Second workshop at GSI (ARIES)
  - 21-24 May 2017
  - To share the experience in design and operation of Ionization Profile Monitors
  - Benchmarking and discussion about the IPM codes
  - http://indico.gsi.de/event/5366/

Group photo: First IPM workshop

Group photo: Second IPM workshop

Present issues: We are interested in,,,

From discussions at 2nd IPM workshop

- Light reflection issue in optical IPMs: Experience, cures, coating
- Gas dynamics-Thermal effects
- MCP/Phosphor : aging effect and gain decrease
- How to setup optimal gains in MCP-Phosphor-Camera system?
- How to estimate ionization process?
- Cross checking of the simulation codes, reproducibility check with measured data
- Profile reconstruction problem : Model based, Neural network, CEA method,,,,
- Alternative to MCP? Silicon pixel detector
- Rf-shielding : Rf noise shield, Rf heating problem
- **Electron contamination issues**

Plan!!

Next 3rd IPM workshop: J-PARC, Japan

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Summary

- Residual gas IPM is a non-destructive profile monitor which can be applied for the high intensity proton accelerator
- However, detector system, calibration system, electron contamination issues are still of utmost concern
- Some of the simulation codes are now available, and some codes are now being cross-checking : IPMsim3D(J-PARC,CERN), ESS code, GSI code, PyEcloud based code (CERN)
- Recent progress was presented
  - CERN PS IPM: Ion trap, Si multi pixel detector (Timepix 3)
  - Gated IPM system
  - Ion trap and gated IPM system for J-PARC is now designing
- IPM workshop is being opened since 2016, as an inter communication frame for IPM researcher (designer)
  - 3rd workshop will go to J-PARC/Japan, 2018 (plan)
  - kenichirou.satou@j-parc.jp
- Presentations on IPM in this conference
  - Oral: WE2AB5: J.W.Story *et.al.*: "First results from the operation of a rest gas ionization profile monitor based on a hybrid pixel detector
  - Poster:WEPCC06: R. Singh *et.al.*: "Simulation supported profile reconstruction with machine learning"
  - Poster: WEPCC07: D.M.Vilsmeier: "A modular application for IPM simulations"
  - Poster: WEPCC13: J. He *et. al.* : "Preliminary study on ionization profile monitor for ADS injector I"