



An analytic Tracking Code with many Restrictions used at GSI

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Original analytic solution in year 2000: P. Strehl, M. Dolinska, R.W. Müller

Realization of code in year 2004: M. Herty (supervision P. Forck)

IPM Workshop CERN, March 3rd, 2016

Outline of the talk:

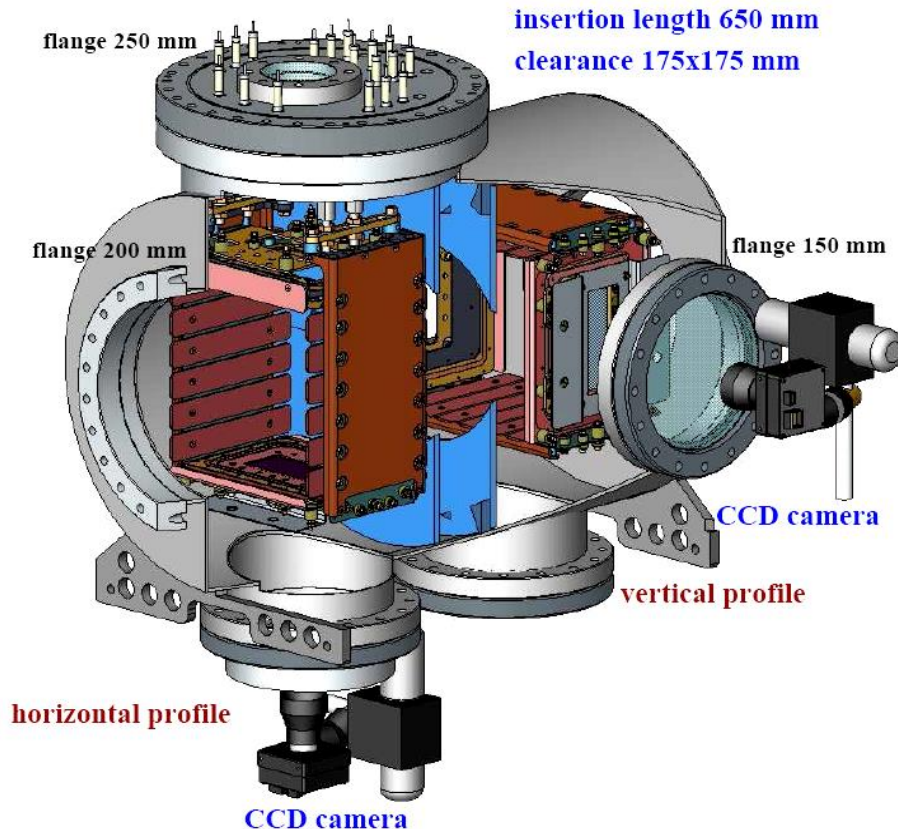
- Applications at GSI
 - for IPM, Beam Induced Fluorescence and Bunch Shape Monitor
- Example of code input and results
- Conclusion

Ionization Profile Monitor at GSI Synchrotron SIS

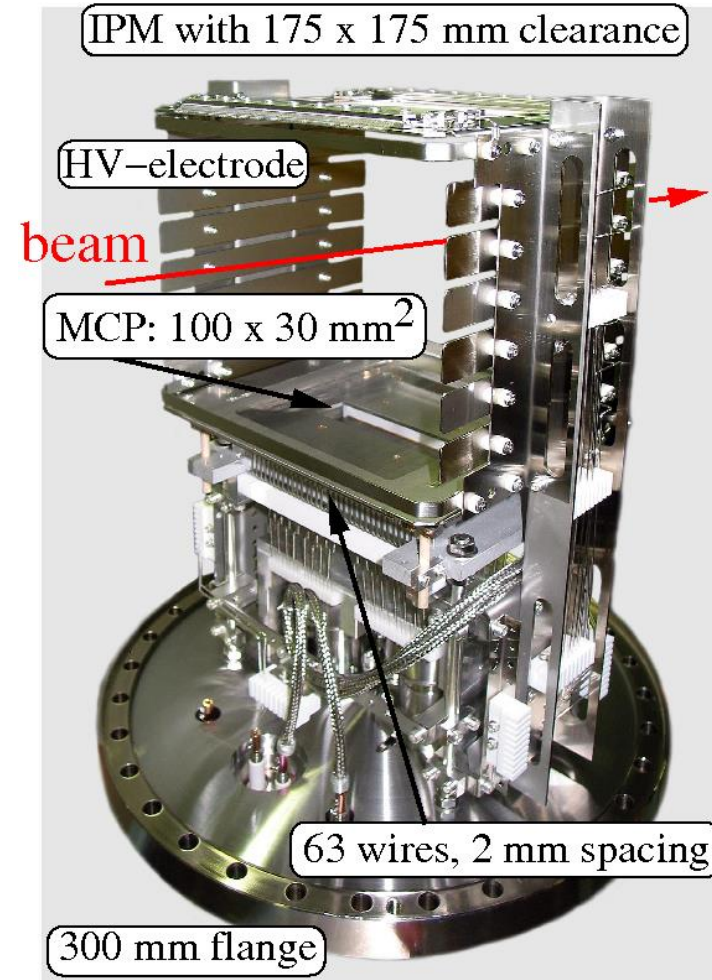


IPMs at GSI:

- Large clearance 175 x 175 mm²
- Ion detection by E -field ≈0.5 kV/cm, Chevron MCP
- ‘Old’ SIS18 IPM wire readout, installed in 2000
- ‘New’ SIS18 and ESR IPM phosphor readout
- Vacuum pressure $p \approx 10^{-11}$ mbar



Realization at GSI synchrotron:



'New' IPM for SIS18 : Magnet Design



Magnetic field for electron guidance:

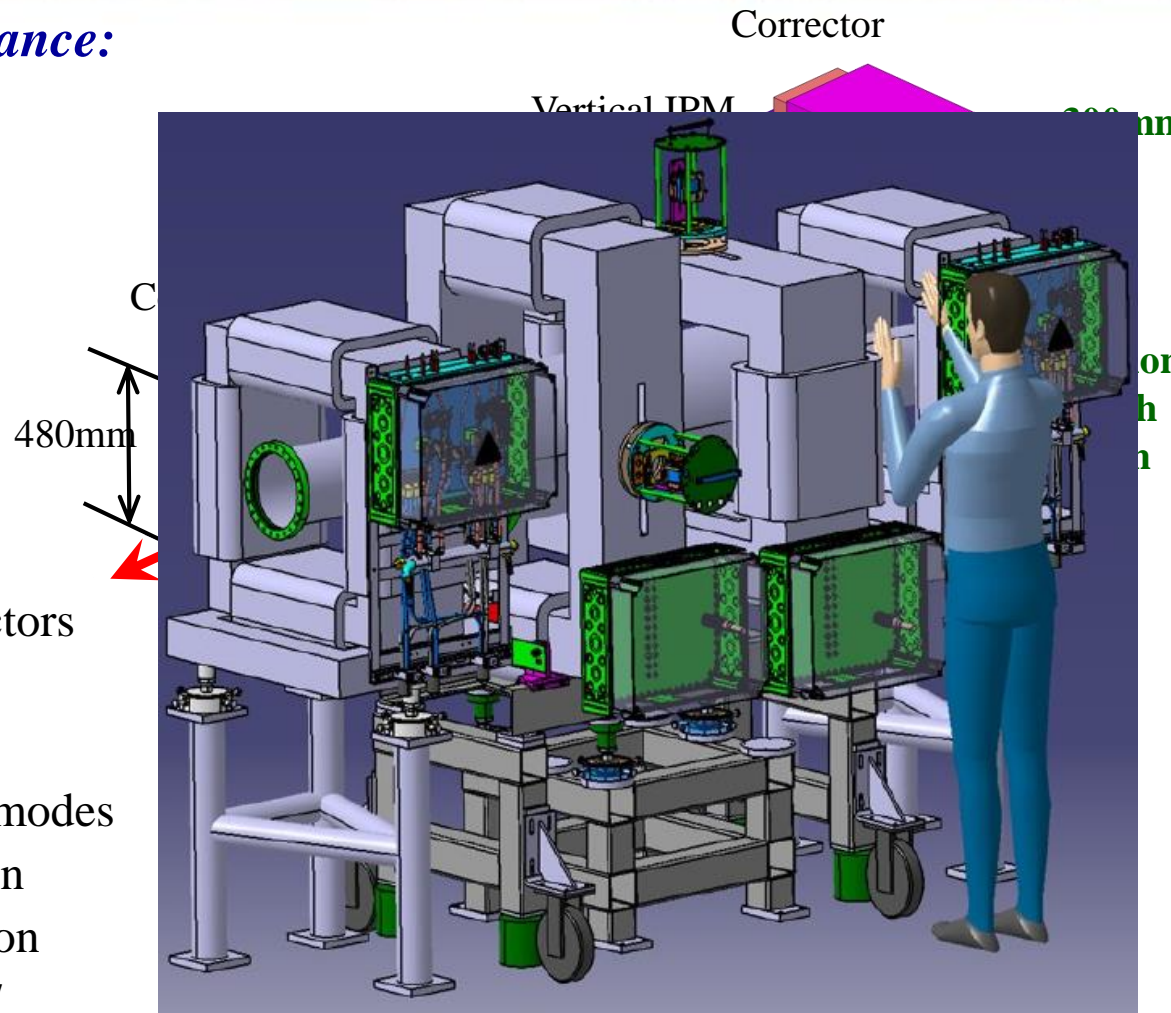
Maximum image distortion:

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

Challenges:

- High B -field homogeneity of 1%
- Clearance of 480 mm
- Design for $B = 30$ mT
- Correctors required to compensate beam steering
- Insertion length 2.5 m incl. correctors
- in production phase

For MCP phosphor readout for two modes
slow with ≈ 10 ms for high resolution
fast turn-by-turn with lower resolution
Installation without magnets in 2017



Magnetic field required for GSI-parameters



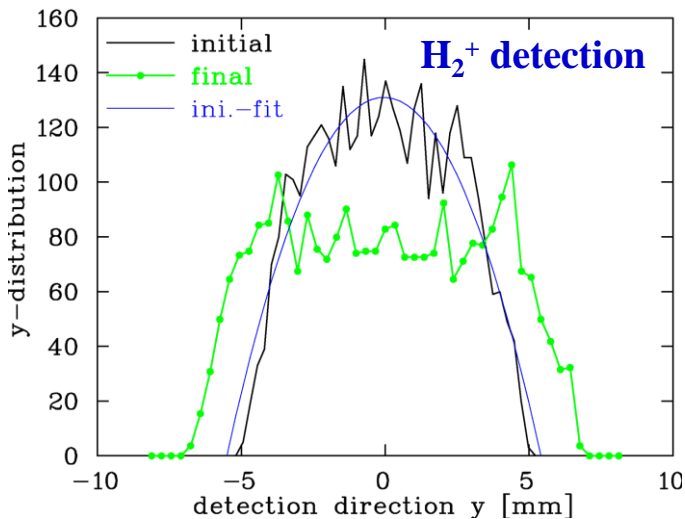
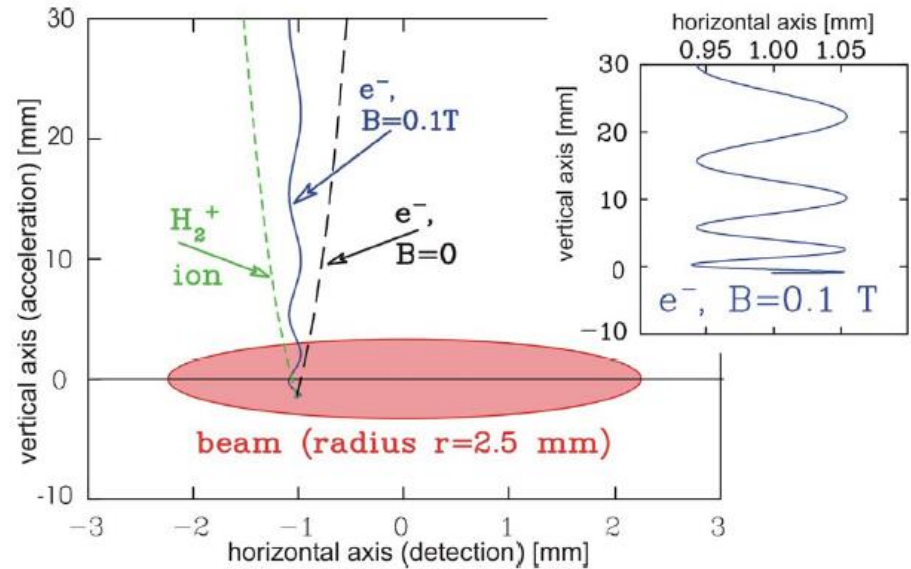
Ion detection: For intense beams
 \Rightarrow broadening due to space charge

Simplified estimation for electron detection:
 B-field required for e^- guidance toward MCP.

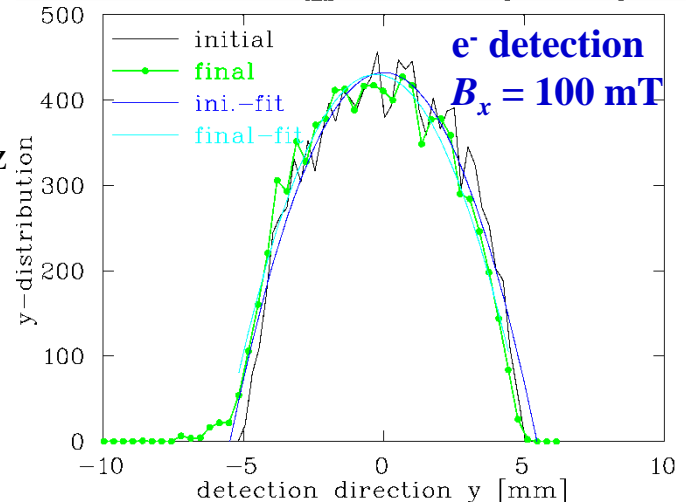
Effects: 3-dim start velocity of electrons

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

$$\Rightarrow r_{cyl} < 100 \text{ } \mu\text{m} \text{ for } B \approx 0.1 \text{ T}$$



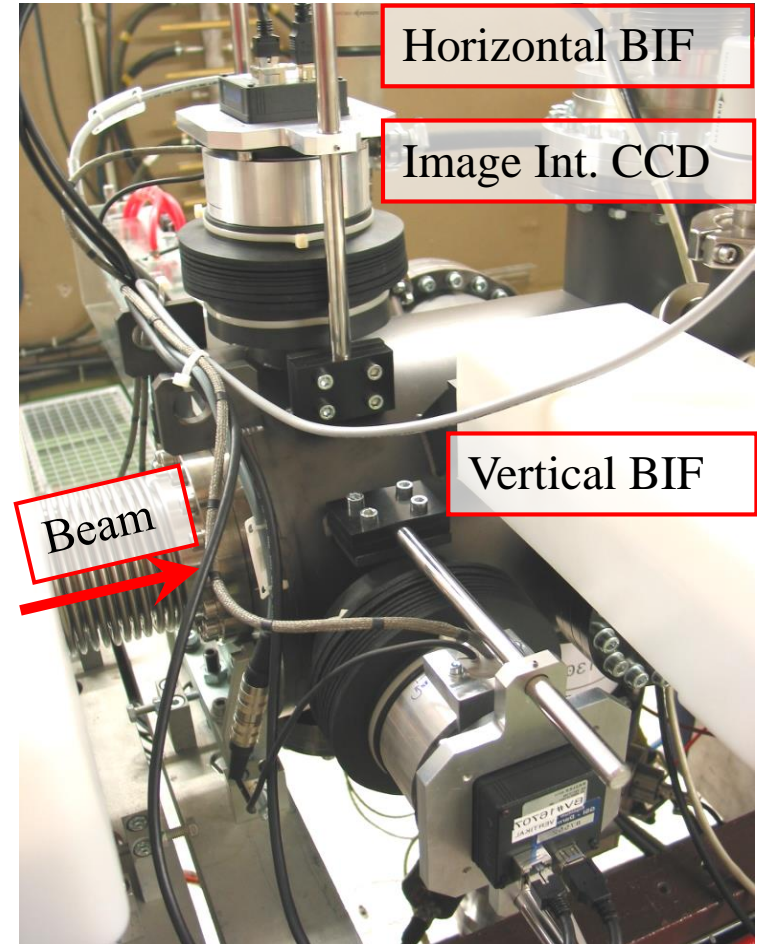
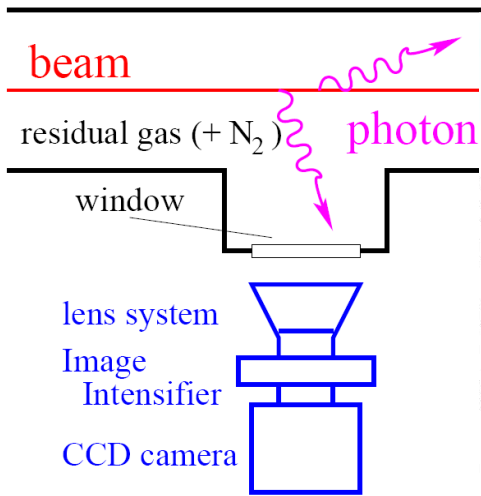
Beam:
 10^9 U^{73+} per bunch
 $\beta = 15\%$, 0.8 MHz
 bunch length: 25 m
IPM:
 Border at 5 cm
 $E_x = 500 \text{ V/cm}$



BIF-Monitor: Technical Realization at GSI LINAC

Six BIF stations at GSI-LINAC (length $\approx 200\text{m}$):

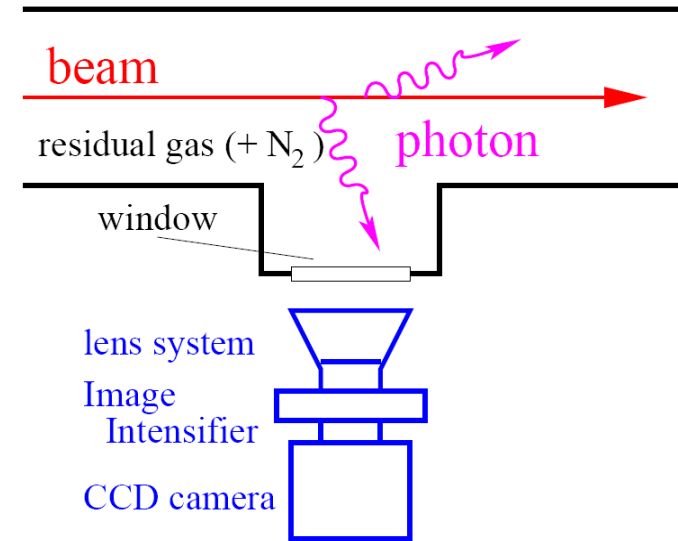
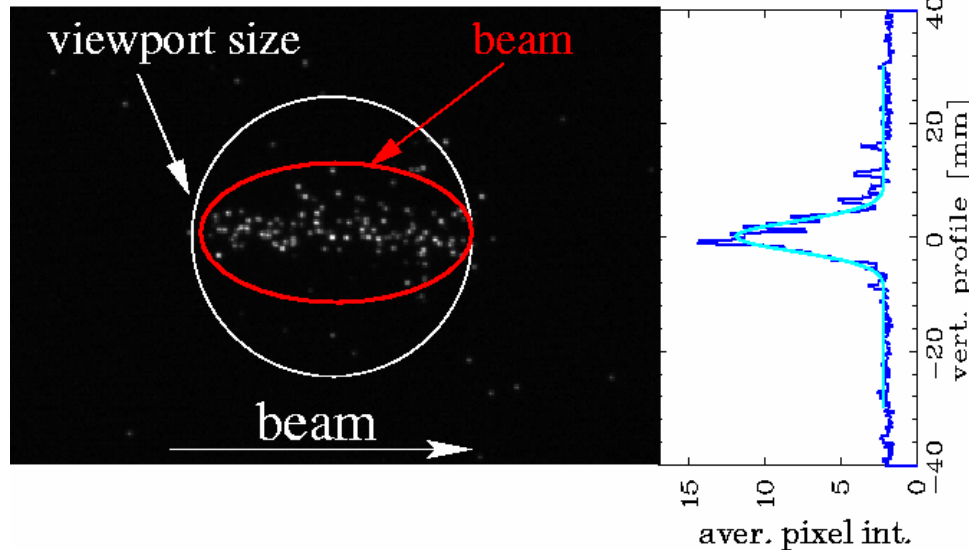
- 2 x image intensified CCD cameras each
- double MCP ('Chevron geometry')
- Optics with reproduction scale 0.2 mm/pixel
- Gas inlet + vacuum gauge
- Pneumatic actuator for calibration
- Insertion length 25 cm for both directions only
- **Advantage:** single macro-pulse observation



Beam Induced Fluorescence Monitor BIF: Image Intensifier



‘Single photon counting’:



Example at GSI-LINAC:

4.7 MeV/u Ar¹⁰⁺ beam

I=2.5 mA equals to 10¹¹ particle

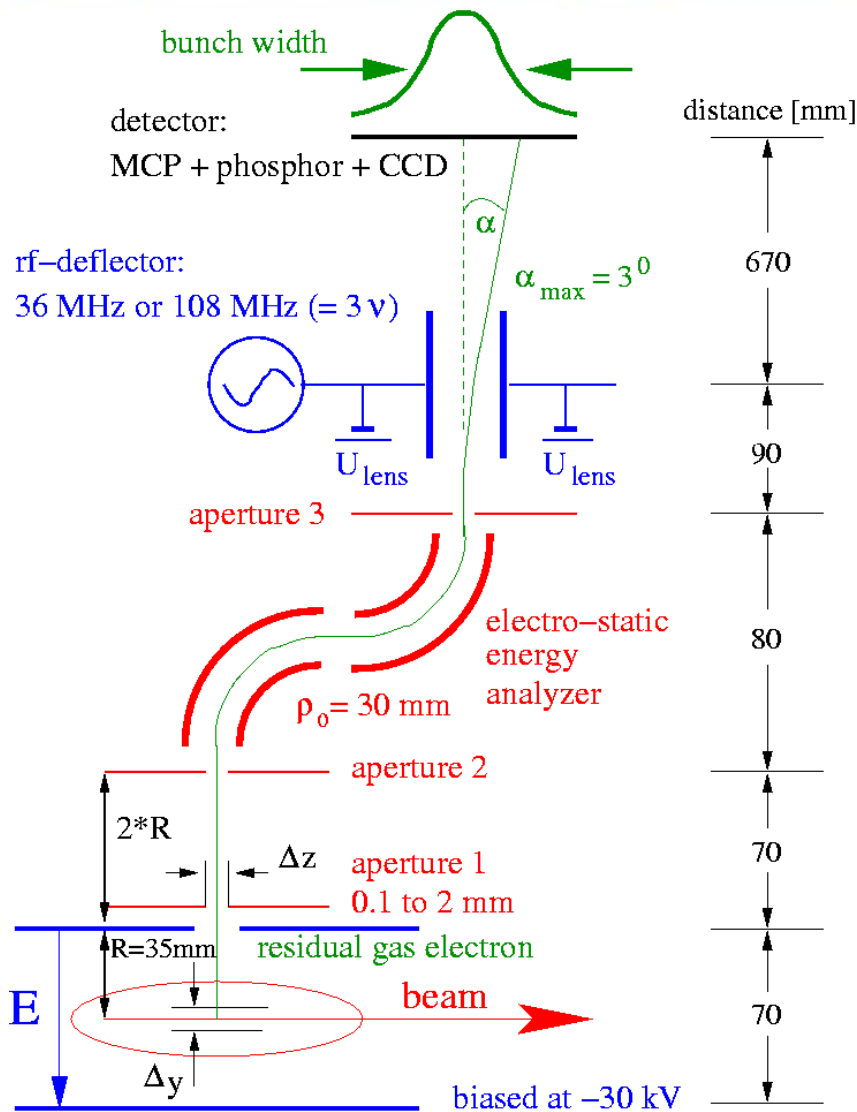
One single macro pulse of 200 μs

Vacuum pressure: p=10⁻⁵ mbar (N₂)

Parameter of BIF Monitor:

- Single photon detection by image intensifier
- N₂ working gas
- Observation of transition of N₂⁺ lifetime ≈ 60 ns
⇒ N₂⁺ is influenced by space charge

Non-intercepting Bunch Shape Measurement

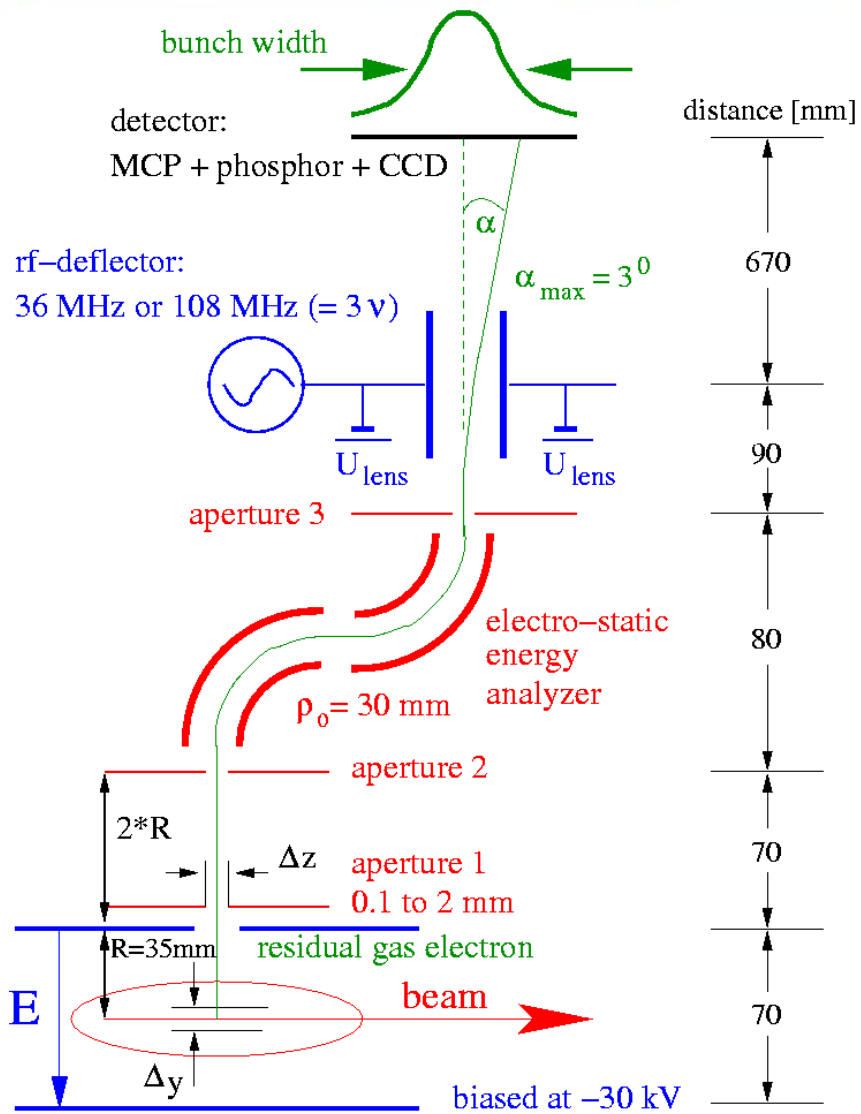


Scheme for non-destructive device:

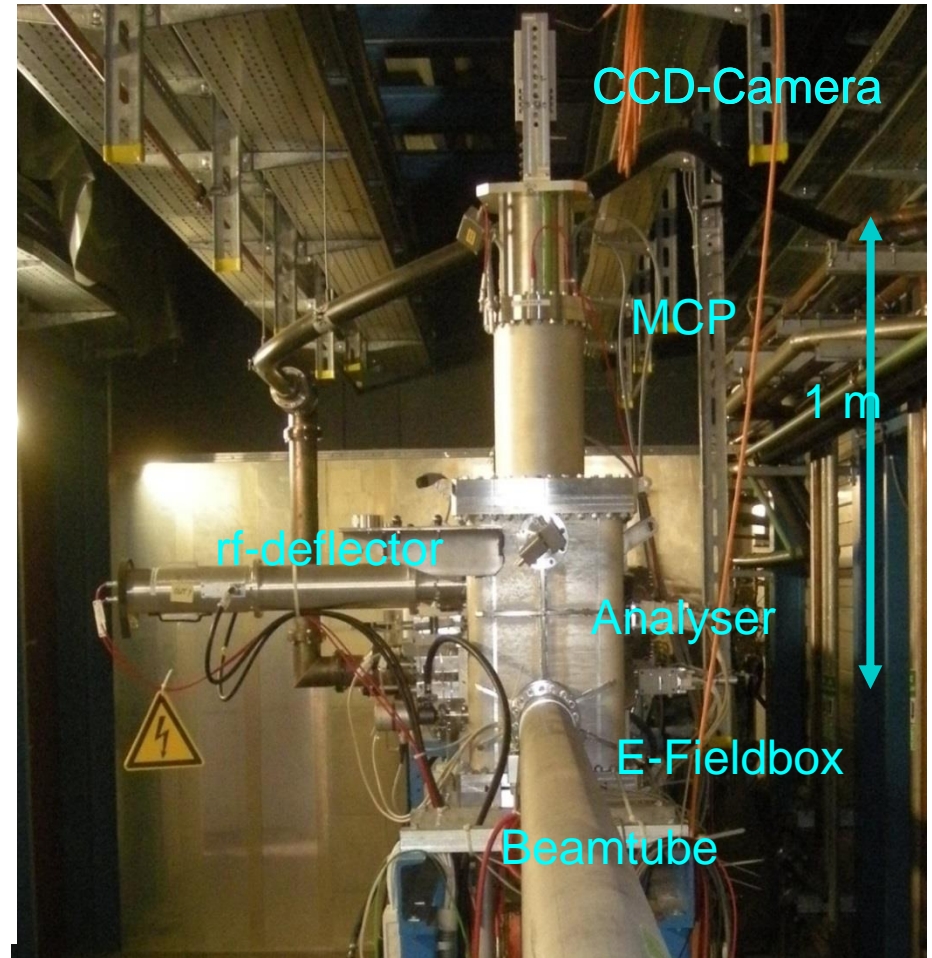
- Secondary electrons from **residual gas**
- Acceleration by electric field
(like for Ionization Profile Monitor)
- Target localization by apertures and electro-static analyzer
($\Delta y = 0.2$ to 2 mm, $\Delta z = 0.2$ to 1 mm)
- rf-resonator as ‘time-to-space’ converter
 $\lambda/4$ resonator, $Q_0 \approx 300$, $P_{in} = 50$ W max.
- Readout by MCP + Phosphor + CCD
- Measurement within several macro-pulses

With courtesy of B. Zwicker

Non-intercepting Bunch Shape Measurement



realization of non-intercepting monitor at GSI:
Installation in transfer line UNILAC to SIS:



Simulation of Space Charge Effects: General Behavior



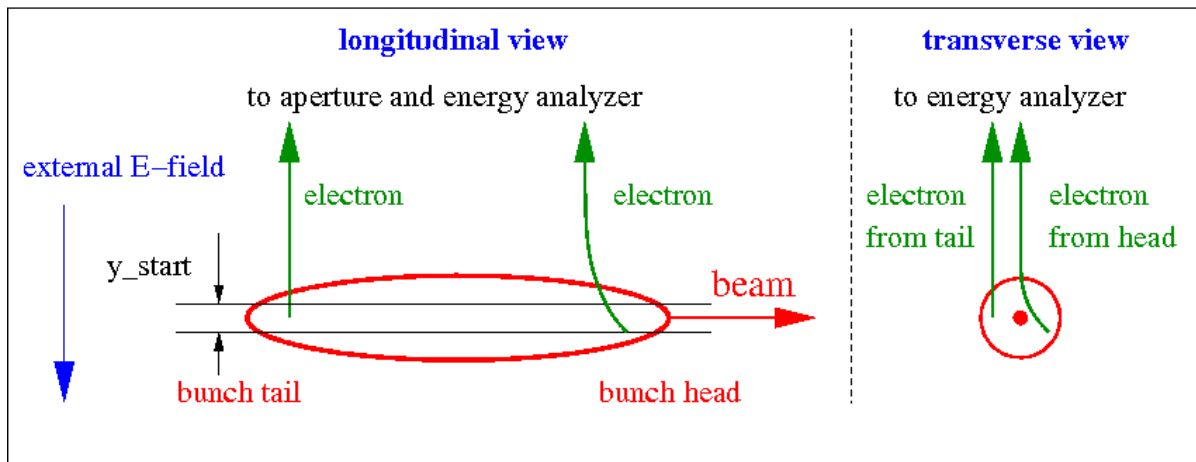
Space-charge effects:

Beam's space charge ↔ external homogeneous E- field (larger effect as for biased wire)

Numerical calculation: e^- created with realistic velocity distribution by atomic collision (δ -rays)

e^- trajectory in field of moving bunches of parabolic distribution

linear optics for energy analyzer up to rf-deflector

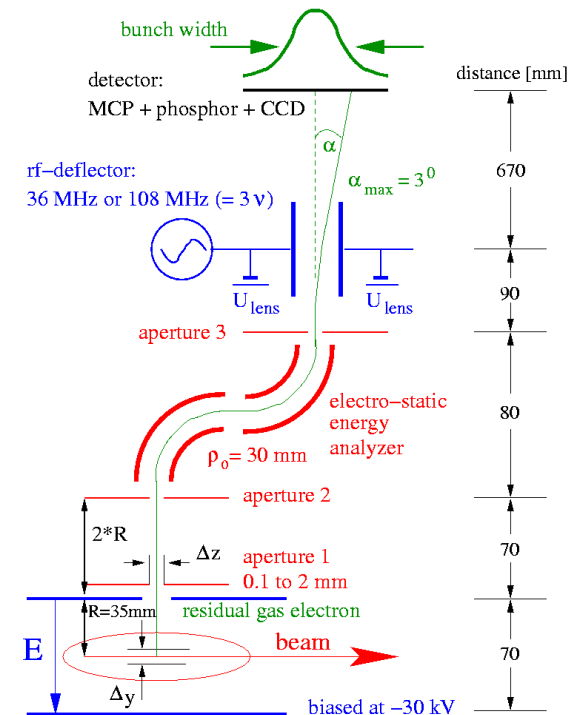


Beam parameters for test case:

transverse ± 5 mm root points

Longitudinal ± 0.6 ns root point

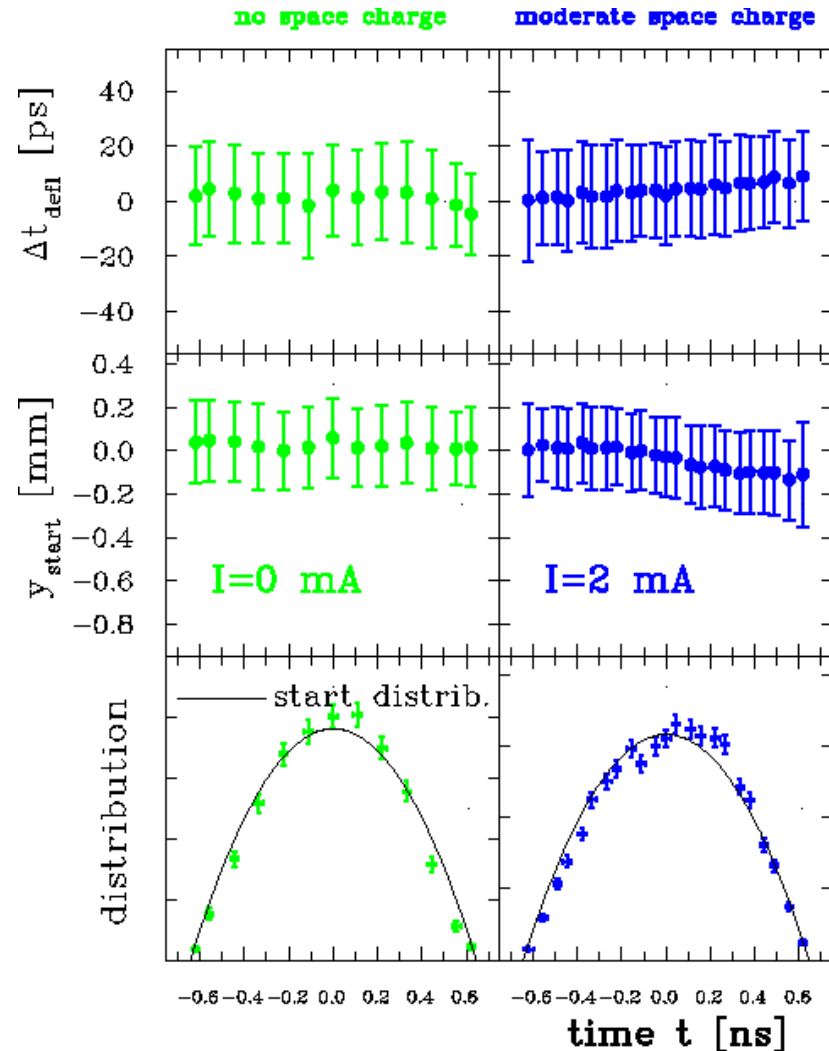
E-field 420 V/mm (30kV total)



Simulation of Space Charge Effect: Results



Beam's space charge \leftrightarrow external homo. E - field:



Parameter like for measurement
Features:

- Arrival time at deflector is sufficient constant, $\Delta t < 40$ ps compared to reference particle
- Cut through bunch is sufficient stable $\Delta y < 0.8$ mm (root-points are ± 5 mm here)
- **But** for high current:
 - # e^- vary along the bunch
 - (bunch head pulls e^- toward center)
 - \Rightarrow lower space charge by transverse defocusing of beam
 - \Rightarrow guidance of e^- by B-field
 - \Rightarrow further investigations required

Simulation Code: General Idea



Idea of the simulation code:

- Homogenous external electric and magnetic fields
- Analytical description of bunch charge density $\rho(\vec{x})$
- Bunch $\vec{E}(\vec{x})$ -field via **analytical** solution of Poisson $\Delta\phi(\vec{x}) = -\frac{\rho(\vec{x})}{\epsilon_0}$ in free space
- Movement of bunches each time step, multiple bunches can be defined
- Monte Carlo based selection of initial start coordinates and velocities
- Trajectory with Runge-Kutta tracking in moving bunch field and external fields
- Storage of initial and final coordinates, velocities and arrival time for each particle

History: Code produced by a (clever) student in 2004

Language: C++ for the core; GUI in C++ with specifics of outdated Borland compiler, which is **not** available anymore, , maintenance difficult

Should be usable for LINAC and synchrotron beams $1 \text{ MeV/u} < E_{kin} < 30 \text{ GeV/u}$

Simulation Code: Input Consideration



Analytical description of bunch fields:

- Horizontal x equals vertical y size (rotational symmetric), longitudinal extension free parameter, but trans. size R larger than bunch length L
- Density: homogeneous $\rho(\vec{x}) = \text{const}$ **or** parabolic $\rho(r, z) \propto \left(1 - \frac{r^2}{R^2} - \frac{z^2}{L^2}\right)$
Formulas see: P. Strehl Internal publication, partly in book Springer Verlag based on transformation to elliptical coordinates & solution of Poisson Equation
- Solution of bunch field using elliptical coordinates i.e. non-linear transformation
- No boundary condition (i.e. free space = ‘open boundary’ is assumed)
- Movement of bunches, originally non-relativistic
→ Lorentz-Transformation of fields for relativistic case might be wrong
- Only homogeneous external E and B -fields
- Too simple, maybe unrealistic electron start velocities (?)

Advantage: Bunch can be described with few parameters, fast calculation

Code Input

Modes of usage:

- ***E* & *B* field at location *x***
- **Single particle trajectory**
- **IPM mode: Boundary dependent**
- **BIF-mode: Time dependent**

Actual parameter:

- H_2^+ ion detection
- $E_x = 1$ kV/cm
- Bunch 1 m length = 22 ns
- 1 cm trans. extension
- parabolic density
- 10^{11} charges
- $\beta = 15\%$, 1 MHz acc.

The screenshot shows the 'Settings' window of the IPM simulation code. The window has a menu bar with 'Settings', 'Single Point Calculations', 'Multiple Point Calculations', 'About', and 'Quit'. The main area is divided into several sections:

- Parameters:**
 - Simulate:** Radio buttons for 'Single Particle', 'Static Point', and 'Multiple Points' (selected).
 - Time Options:** 'Simulation time [ns]' (300) and 'Steps [1/ns]' (1).
 - Coordinate [mm]:** 'transversal' (X0: 1,0000, Y0: 0,0000) and 'longitudinal' (Z0: 0,0000).
 - Velocity [mm/ns]:** 'transversal' (VX0: 0,0000, VY0: 0,0000) and 'longitudinal' (VZ0: 0,0000).
- Variables of residual gas:** 'Mass [1=Proton]' (2,00), 'Charge' (1), and 'Electron' checkbox (unchecked).
- External El. Field [V/mm]:** 'Switch on/off' checkbox (checked), and fields for EX (100,0), EY (0,0), and EZ (0,0).
- External Magn. Field [mT]:** 'Switch on/off' checkbox (unchecked), and fields for BX (0), BY (0), and BZ (0).
- Variables of Bunches:**
 - Beta [v/c] (0,1500), Rep. Rate [MHz] (1,0), Number of Bunches (5), Particles per Bunch (1,0E10).
 - Bunch Shape:** Radio buttons for 'Sphere' and 'Ellipsoid' (selected).
 - Radius [mm] (10,00), long half axis a[mm] (500,00), trans half axis b[mm] (5).
 - Charge Distribution:** Radio buttons for 'Homogeneous' and 'Parabolic' (selected).
 - Charge per Particle (10).
 - 'Calculation with relativistic effects' checkbox (unchecked).

Code Input

Bounding box
& number of trajectories

Actual parameter:

- H_2^+ ion detection
- $E_x = 1$ kV/cm
- Bunch 1 m length
- 1 cm trans. extension
- parabolic density
- 10^{11} charges
- $\beta = 15$ %, 1 MHz acc.

Boundary Hit Algorithm

Simulation Type Charts Return

Simulates the path of a cloud of particles starting in the box and hitting the barrier.

Coordinates Of The Box [mm]

	Minimum Values	Maximum Values
x Coordinates	-12	12
y Coordinates	-12	12
z Coordinates	-600	600

Offset Of The Bunches [mm] 0

x-Coordinate Of The Barrier [mm] 50

Further Inputs

Maximum Time [ns] 300

Steps per ns 5

#Simulation Points (Shape) 3000

#Simulation Points (Charge) 10

Distance Between Two Bunches [mm] 8994

Height Of Bunches [mm] 5

Length Of Bunches [mm] 100.00

Status: Finished.

Debugplot

Simulation

Code Output

Actual parameter:

- H_2^+ ion detection
- $E_x = 1$ kV/cm
- Bunch 1m length = 22ns
- 1 cm trans. extension
- parabolic density
- 10^{11} charges
- $\beta = 15\%$, 1 MHz acc.

Boundary Hit Algorithm

Simulation Type Charts Return

⇒ broadening for ion detection

⇒ differences for head ↔ tail

Barrier position [mm] Total points

#Intervals Reached barrier

Offset Of The Bunches [mm]

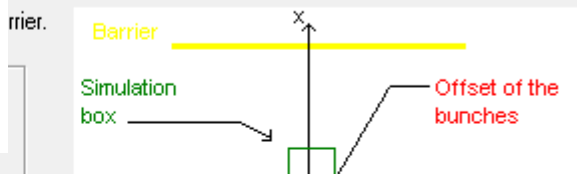
x Coordinates

y Coordinates

z Coordinates

Offset Of The Barrier [mm]

x-Coordinate Of The Barrier [mm]

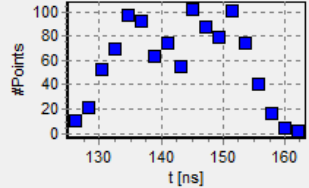
Barrier. 

Results Of The Bdry Hit Algorithm

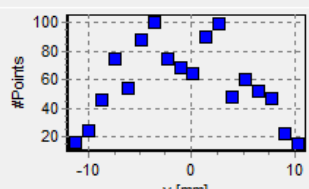
Barrier position [mm] Total points

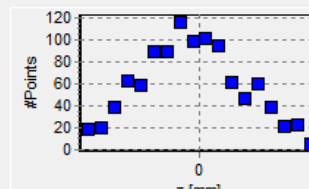
#Intervals Reached barrier

Histogram of the distribution of final positions

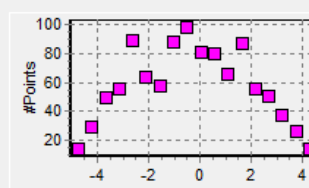


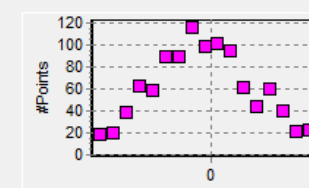
(x,y) in one of these plots means that y points have a property inside the interval [x, x+val] where val is the value in the box below the plot





Distribution of the initial values



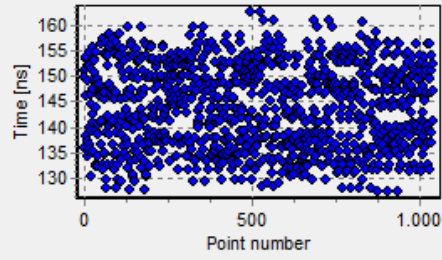


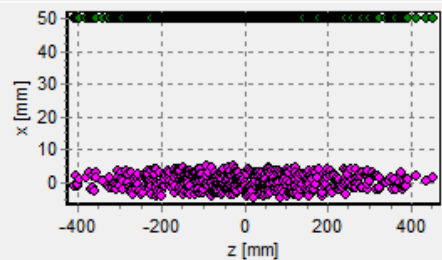
Form11

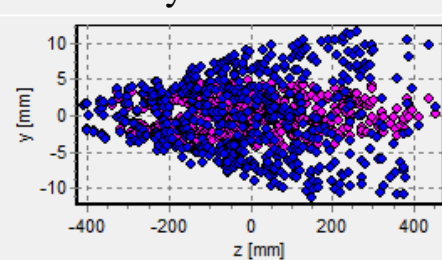
◆ initial coordinate

◆ final x coordinate

◆ final y coordinate







Online Output

Actual parameter:

- electron detection
- $v_{ini} = 0$
- $B_x = 100$ mT
- $E_x = 1$ kV/cm
- Bunch 1 m length
- 1 cm trans. extension
- parabolic density
- 10^{11} charges
- $\beta = 15$ %, 1 MHz acc.

Boundary Hit Algorithm

Simulation Type Charts Return

Simulates the path of a cloud of particles starting in the box and hitting the barrier.

⇒ no broadening for e⁻ detection

x Coordinates:

y Coordinates:

z Coordinates:

Offset Of The Bunches [mm]:

x-Coordinate Of The Barrier [mm]:

Further Inputs

Maximum Time [ns]:

Steps per ns:

Barrier

Simulation box

Height

Width

Offset of the bunches

Moving direction

Results Of The Bdry Hit Algorithm

Barrier position [mm]: Total points:

#Intervals: Reached barrier:

Histogram of the distribution of final positions

#Points vs t [ns]

Clear

Draw

[x,y] in one of these plots means that y points have a property inside the interval [x, x+val] where val is the value in the box below the plot

#Points vs y [mm]

0,4765923872

#Points vs z [mm]

0,5458777

50,6010964

Distribution of the initial values

#Points vs y [mm]

#Points vs z [mm]

Form11

Time [ns] vs Point number

Clear points

x [mm] vs z [mm]

y [mm] vs z [mm]

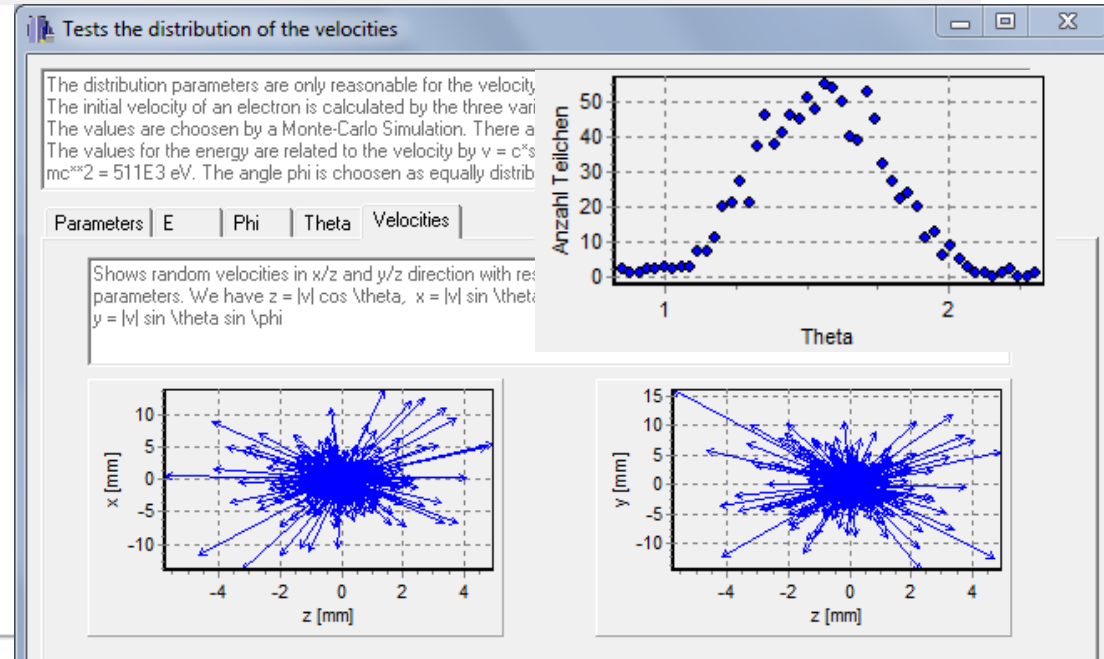
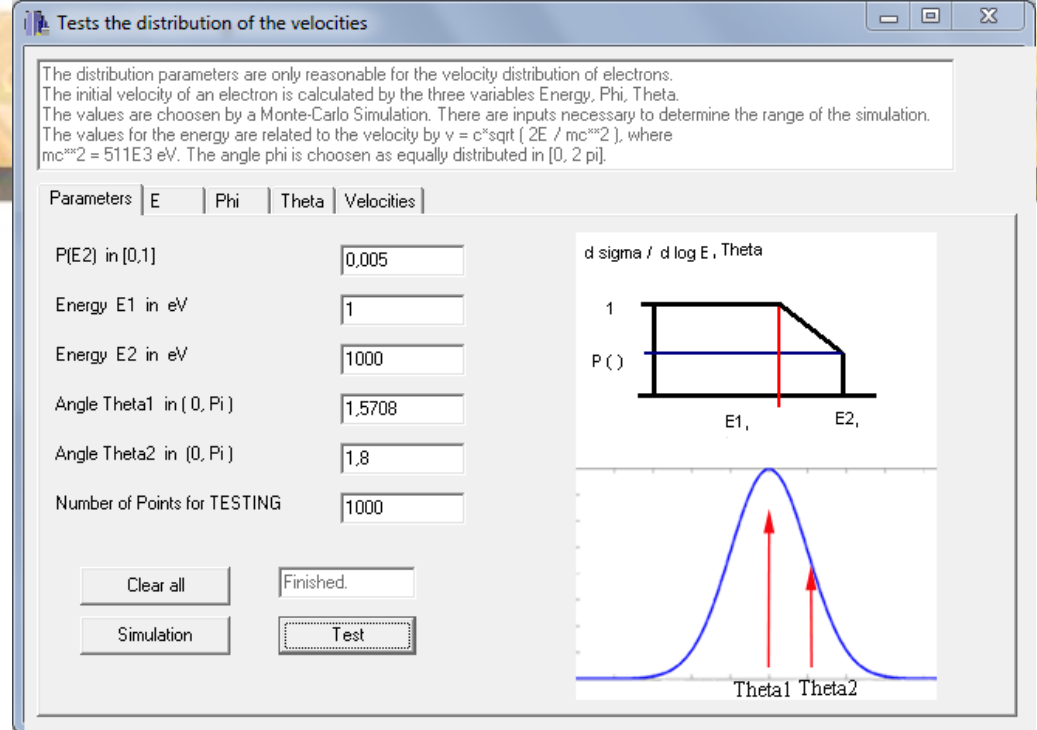
Usage of e^- Distribution

Actual parameter:

- electron detection
- $B_x = 100$ mT
- $E_x = 1$ kV/cm
- Bunch 1 m length
- 1 cm trans. extension
- parabolic density
- 10^{11} charges
- $\beta = 15\%$, 1 MHz acc.

Electron parametrization: with 'separated' Ansatz:

- energy $d\sigma/dE$
 - constant value $\theta < E < E_1$
 - linear decay $E_1 < E < E_2$
 - $\sigma = 0$ for $E > E_2$
- angular $d\sigma/d\theta$
 - Gaussian with center θ_1
 - and width θ_2



Usage of e^- Distribution

Actual parameter:

- electron detection
- $B_x = 100$ mT
- $E_x = 1$ kV/cm
- Bunch 1 m length
- 1 cm trans. extension
- parabolic density
- 10^{11} charges
- $\beta = 15$ %, 1 MHz acc.

⇒ no significant difference compared to $v_{ini} = 0$ for **this** case

Tests the distribution of the velocities

The distribution parameters are only reasonable for the velocity distribution of electrons. The initial velocity of an electron is calculated by the three variables Energy, Phi, Theta. The values are chosen by a Monte-Carlo Simulation. There are inputs necessary to determine the range of the simulation. The values for the energy are related to the velocity by $v = c \cdot \sqrt{2E / mc^2}$, where $mc^2 = 511E3$ eV. The angle phi is chosen as equally distributed in $[0, 2\pi]$.

Parameters | E | Phi | Theta | Velocities

P(E) in [0,1]

Energy E1 in eV

d sigma / d log E, Theta

Number of Points for TESTING

Clear all Finished.

Simulation Test

Results Of The Bdry Hit Algorithm

Barrier position [mm] Total points

#Intervals Reached barrier

Histogram of the distribution of final positions

0,5148297983

52,0763287

0,5106008

Distribution of the initial values

Form11

Clear points

Simulation Code: General Idea

BIF type evaluation:

Actual parameter:

- H_2^+ ion detection
- Bunch 1 m length
- 1 cm trans. extension
- parabolic density
- 10^{11} charges
- $\beta = 15\%$, 1 MHz acc.

H_2^+ fluorescence

→ position after 100 ns

Simulation Code: General Idea

BIF type evaluation:

Actual parameter:

- N_2^+ ion detection
- Bunch 1 m length
- 1 cm trans. extension
- parabolic density
- 10^{11} charges
- $\beta = 15\%$, 5 MHz acc.

N_2^+ fluorescence

→ position after 100 ns

Time Dependent Evolution

Simulations Charts Return

Simulation of the time evolution of a given box

Coordinates Of The Box [mm]

	Minimum Values	Maximum Values
x,y Coordinates	-12	12
z Coordinates	-600	600

Offset Of The Bunches [mm] 0

Other Inputs

Stopp Time [ns] 100

Steps per ns 1

#Simulation Points (Shape) 3000

#Simulation Points (Charge) 10

Distance Between Two Bunches [mm] 4.497E4

Height Of Bunches [mm] 5

Length Of Bunches [mm] 500.00

Initial Velocity For All Particles In The Box [mm/ns] 0

Show Velocities

Output

Progress

Charts

Valid Points 1153

Begin: red

End: blue/green

x [mm]

z [mm]

y [mm]

z [mm]

Simulation box

Offset of the bunches

Height

Width

Distance between two bunches

Moving direction of the bunches

EM-Field Transformation



Present status: Wrong transformation of E and B field → will be corrected

The electrostatic field of the bunch is calculated in its rest frame according to the charge distribution and then transformed to the laboratory frame

- Field vectors are properly transformed
- Longitudinal bunch size is **not** transformed:
 - ⇒ same size is assumed in the laboratory frame and the rest frame of the bunch
- Time and coordinates are also not properly transformed,
 - ⇒ fields have the wrong geometry and a too large longitudinal extension

$$\mathbf{E}' = \gamma (\mathbf{E} + \mathbf{v} \times \mathbf{B}) - (\gamma - 1) (\mathbf{E} \cdot \hat{\mathbf{v}}) \hat{\mathbf{v}}$$

$$\mathbf{B}' = \gamma \left(\mathbf{B} - \frac{\mathbf{v} \times \mathbf{E}}{c^2} \right) - (\gamma - 1) (\mathbf{B} \cdot \hat{\mathbf{v}}) \hat{\mathbf{v}}$$

Analytical Solution of electric Potential



The electrostatic field of elongated bunches is calculated by means of the Poisson equation and a transformation to curvilinear coordinates

New coordinates ξ and η via

$$z(\xi, \eta) = c \cdot \xi \cdot \eta \quad \text{and} \quad r(\xi, \eta) = c \cdot \sqrt{(\xi^2 - 1)(1 - \eta^2)}$$

$$-1 \leq \eta \leq 1 \quad \text{and} \quad 1 \leq \xi \leq \infty \quad \text{with the normalization } c = \sqrt{L^2 - R^2}$$

The Poisson equation is solved analytically for the considered charge distributions

$$\Delta\phi(\xi, \eta) = \frac{1}{c^2(\xi^2 - \eta^2)} \left[\frac{\partial}{\partial \xi} (\xi^2 - 1) \frac{\partial \phi}{\partial \xi} + \frac{\partial}{\partial \eta} (1 - \eta^2) \frac{\partial \phi}{\partial \eta} \right] = \rho(\xi, \eta)$$

Problems appear in the numerical implementation when the longitudinal bunch size is much larger than the transversal size i.e. $L \gg R$

problems are expected if $L > 10^5 R$, but it seems to appear for lower values of L

Not evident presently: *Is it a numerical or analytical problem?*

\Rightarrow solution is pending

Simulation Code: Conclusions



Restrictions:

- Horizontal x equals vertical y extension, longitudinal extension free parameter
- Density: $\rho(\vec{x}) = \text{const}$ (i.e. transversal KV-distr., longitudinal ‘air-bag’) used for tests
or parabolic $\rho(r, z) \propto \left(1 - \frac{r^2}{R^2} - \frac{z^2}{L^2}\right)$
- No boundary conditions (i.e. free space = ‘open boundary’ is assumed)
- Long bunches with $L \gg R$ **might be wrong**
possible reason related to elliptical coordinates i.e. non-linear transformation
- Relativistic case **is wrong**, but could hopefully be corrected
- Only homogeneous external E and B -fields,
- Too simple, maybe unrealistic electron start velocities

⇒ **Usage:** could be used as a first approximation for IPM, BIF & BSM

Advantage: Bunch can be described with few parameters, fast calculation, good GUI

Code language: C++ for the core, GUI using outdated Borland compiler

History: Production in 2004 by a student, never benchmarked against other codes !