An analytic Tracking Code with many Restrictions used at GSI

Peter Forck, Serban Udrea, GSI & Uni Frankfurt

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

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

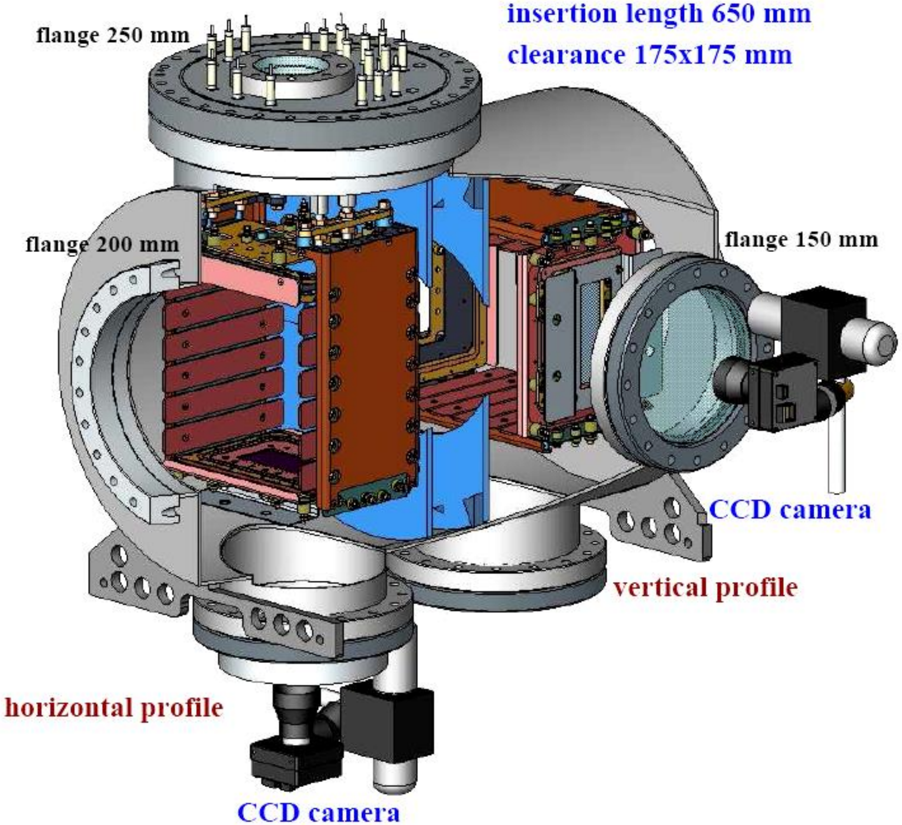
IPM Workshop CERN, March 3rd , 2016

Outline of the talk:

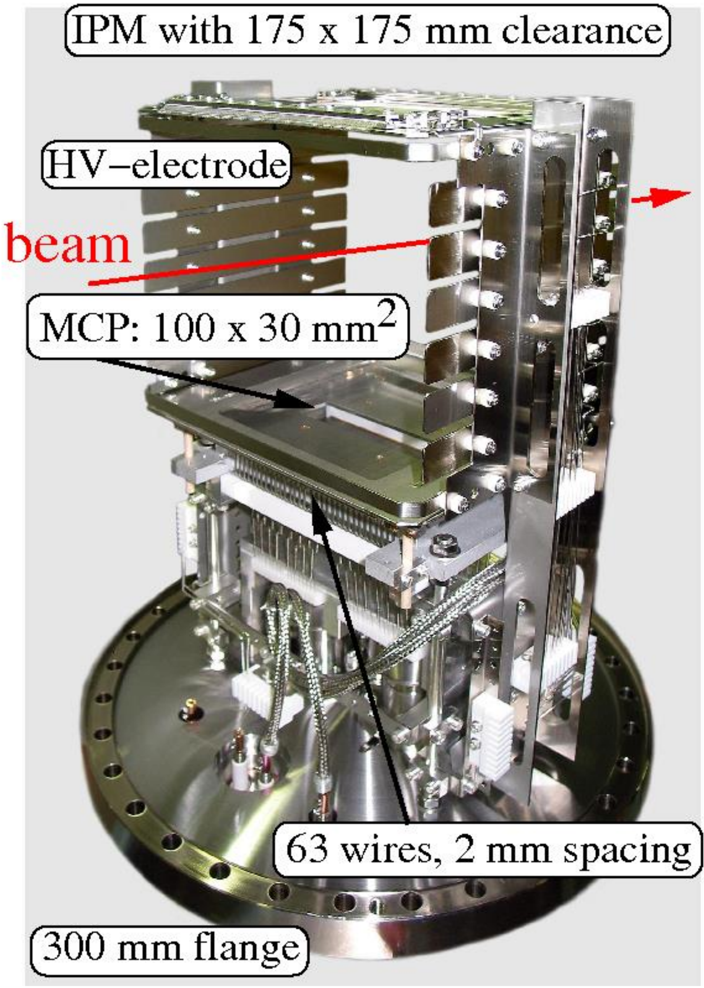
- Applications at GSI
  for IPM, Beam Induced Fluorescence and Bunch Shape Monitor
- Example of code input and results
- Conclusion

IPMs at GSI:

- Large clearance 175 x 175 mm^2
- 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 $\boldsymbol{p} \approx 10^{-11}$ mbar



Realization at GSI synchrotron:



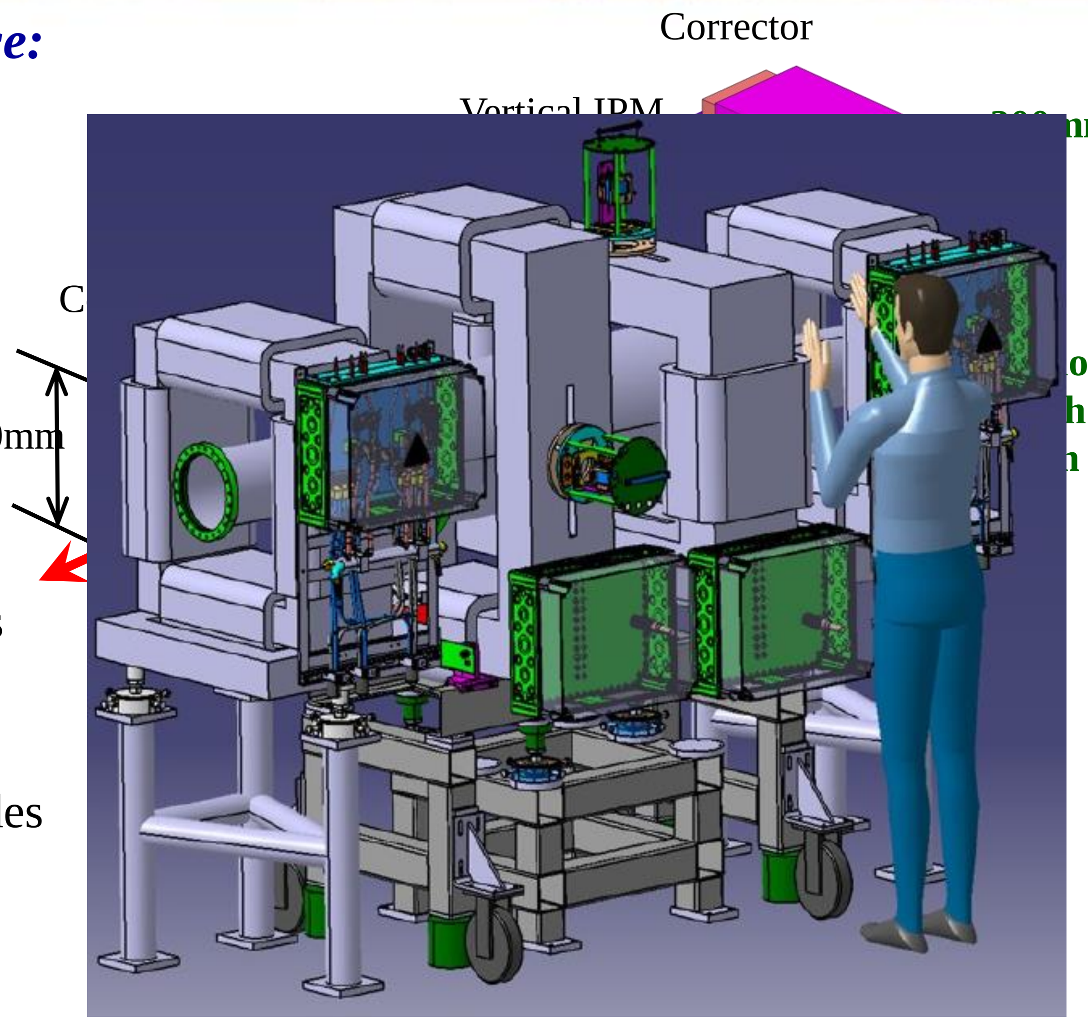
Magnetic field for electron guidance:

Maximum image distortion:

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

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
⇒ broadening due to space charge

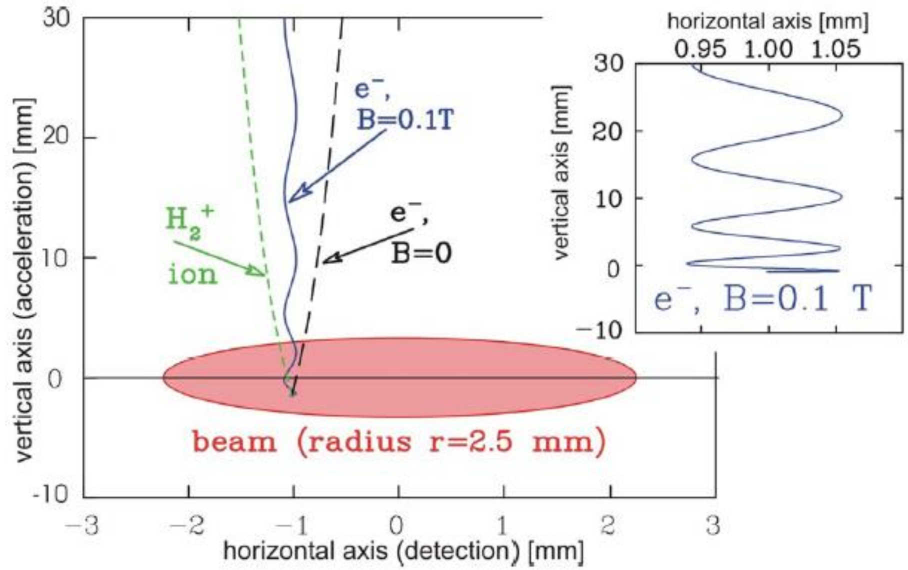
Simplified estimation for electron detection:

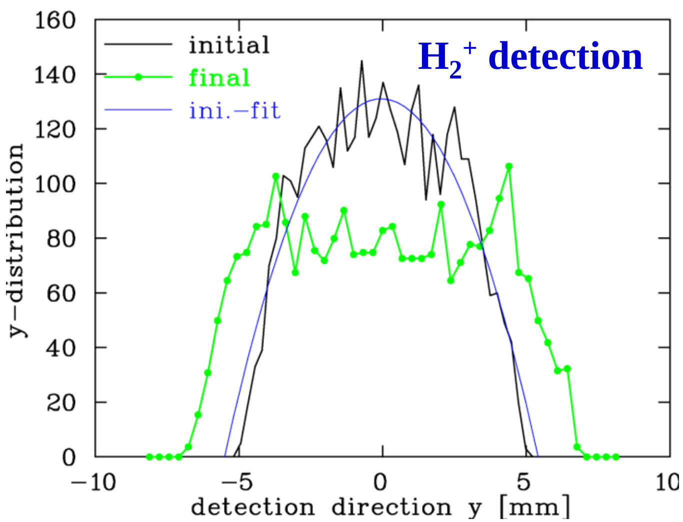
B-field required for e^- guidance toward MCP.

Effects: 3-dim start velocity of electrons

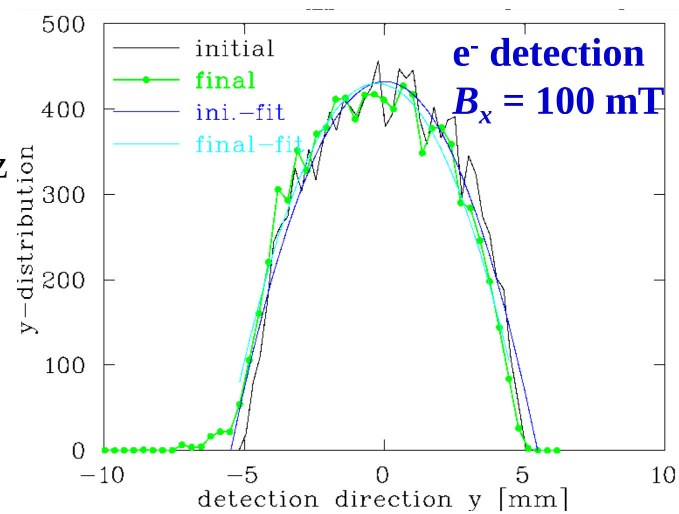
$E_{kin}(90\%) < 50$ eV, $\theta_{max} \approx 90^0$

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





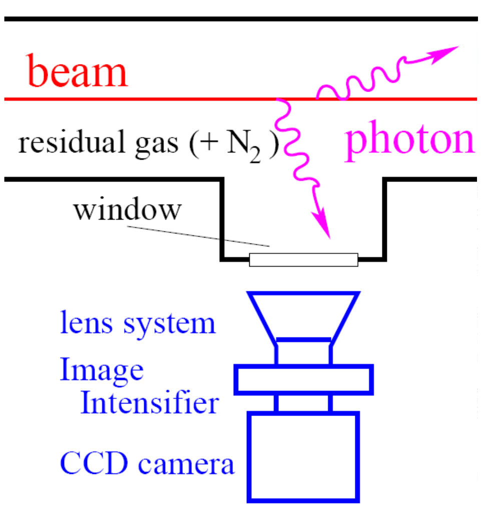
Beam:
10^9 U^{73+} per bunch
β = 15 % , 0.8 MHz
bunch length: 25 m
IPM:
Border at 5 cm
E_x = 500 V/cm

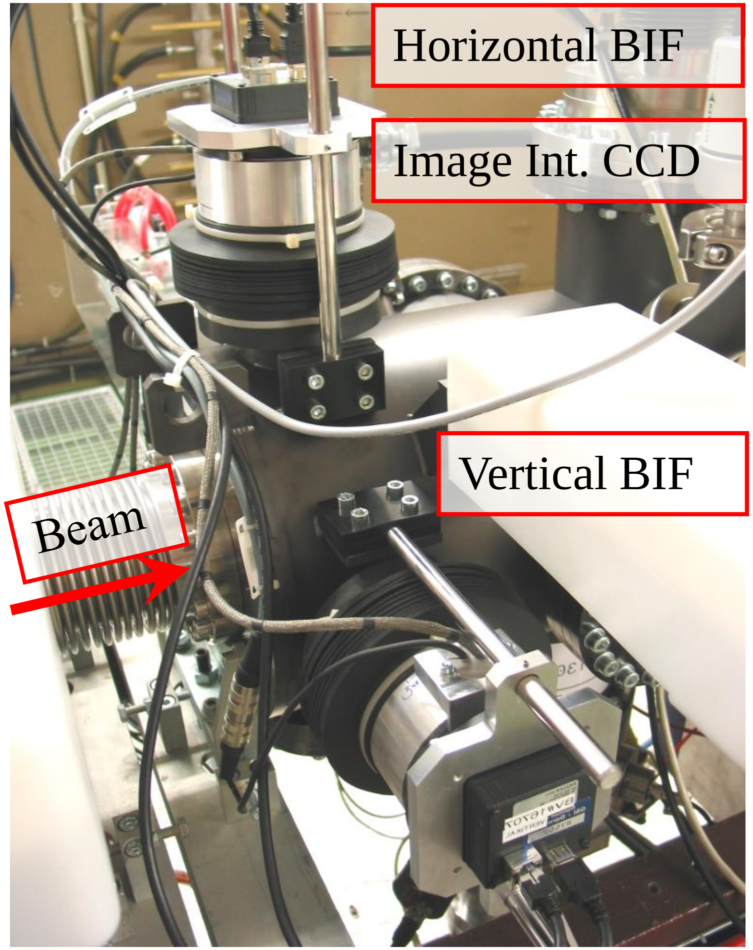


BIF-Monitor: Technical Realization at GSI LINAC

Six BIF stations at GSI-LINAC (length ≈ 200m):

- 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

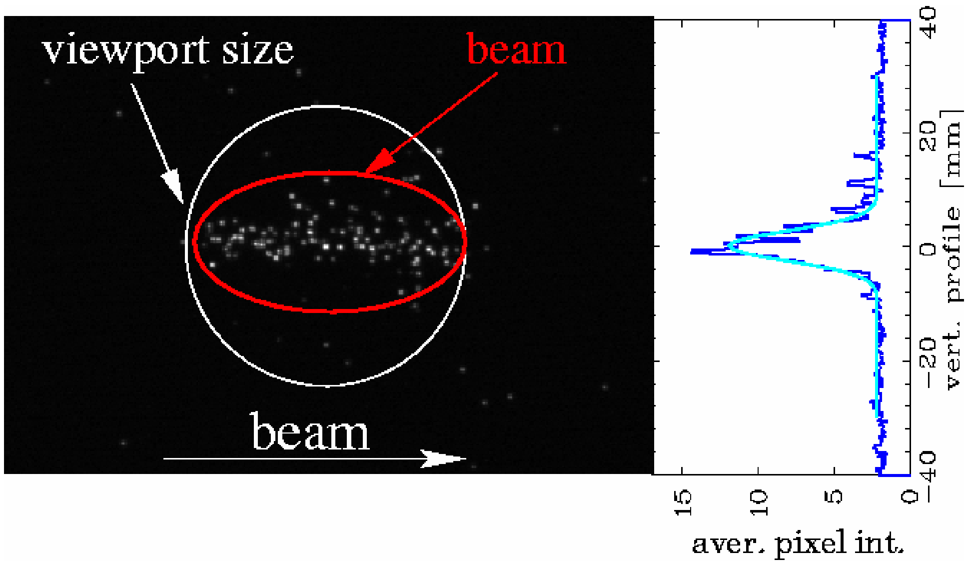


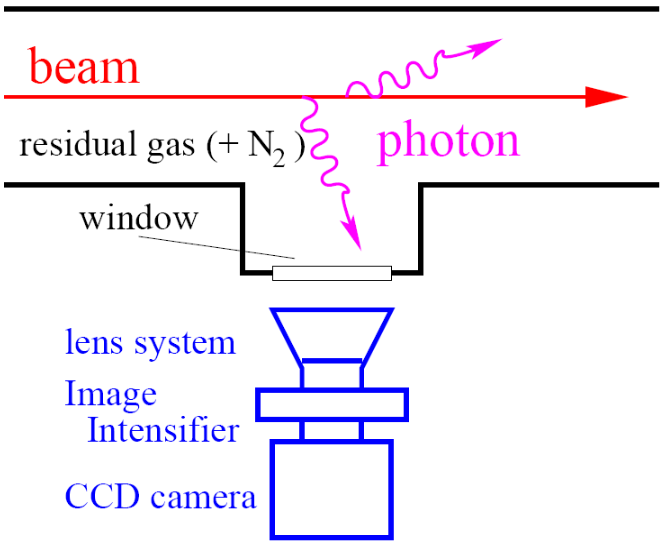


F. Becker (GSI) et al., Proc. DIPAC'07, C. Andre (GSI) et al., Proc. DIPAC'11

Beam Induced Fluorescence Monitor BIF: Image Intensifier

'Single photon counting':





Example at GSI-LINAC:

4.7 MeV/u Ar $^{10+}$ beam

I=2.5 mA equals to 10^{11} particle

One single macro pulse of 200 μs

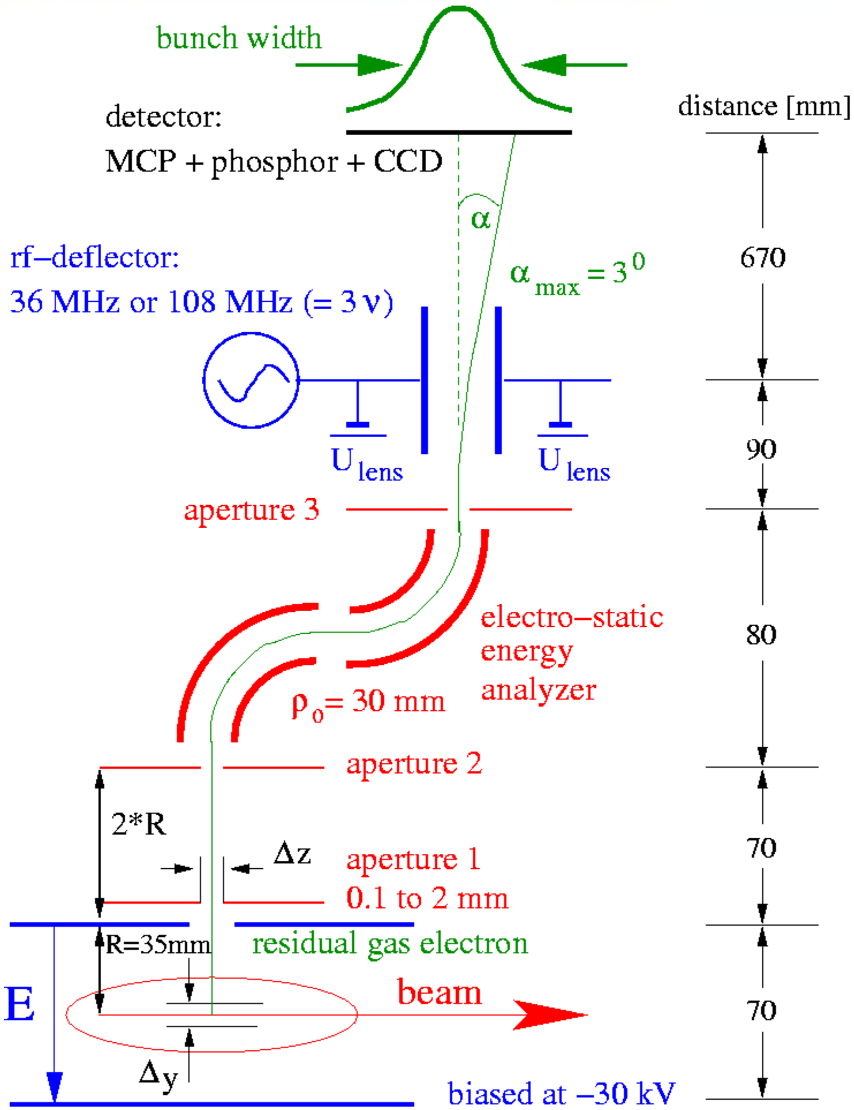
Vacuum pressure: p=10^{-5} mbar (N_2)

Parameter of BIF Monitor:

- Single photon detection by image intensifier
- N_2 working gas
- Observation of transition of N_2^+ lifetime ≈ 60 ns

  ⇒ N_2^+ is influenced by space charge

Non-intercepting Bunch Shape Measurement

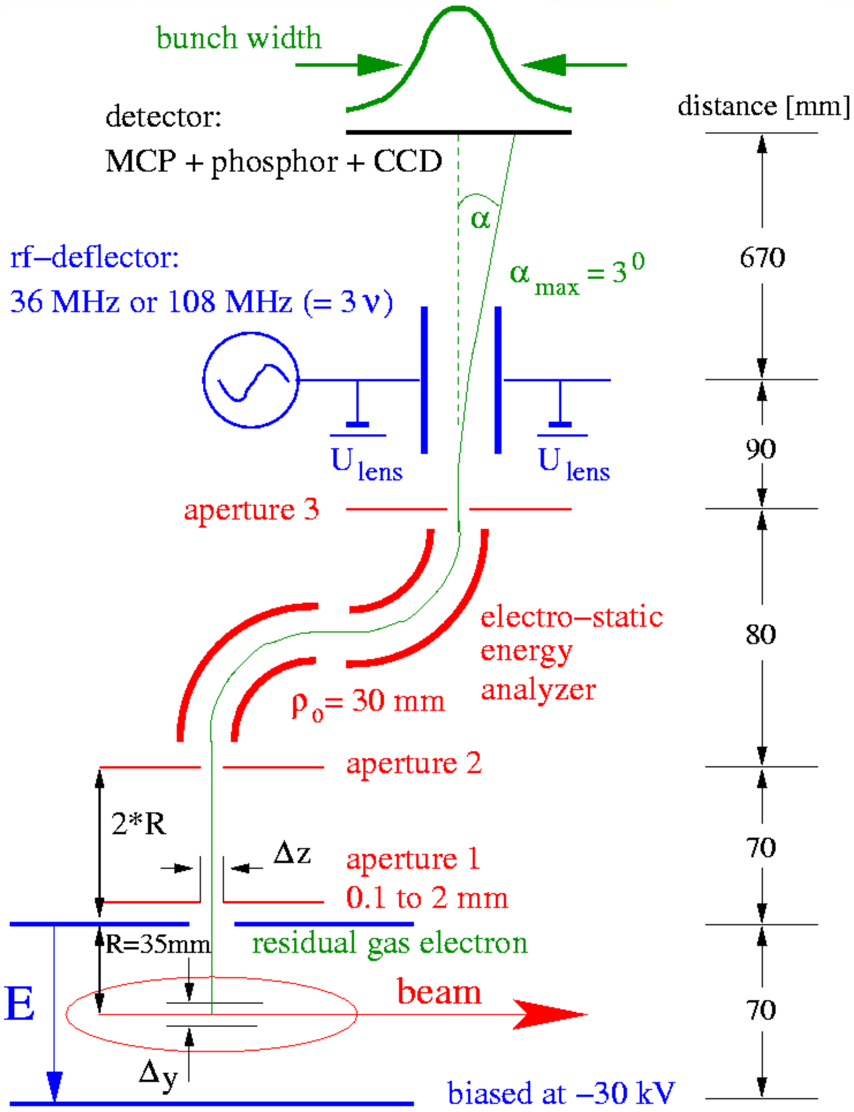


Scheme for non-destructive device:

- Secondary electrons from **residual gas**
- Acceleration by electric field
  (like for Ionization Profile Monitor)
- Target localization by apertures and electro-static analyzer
  (Δy = 0.2 to 2 mm, Δz=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

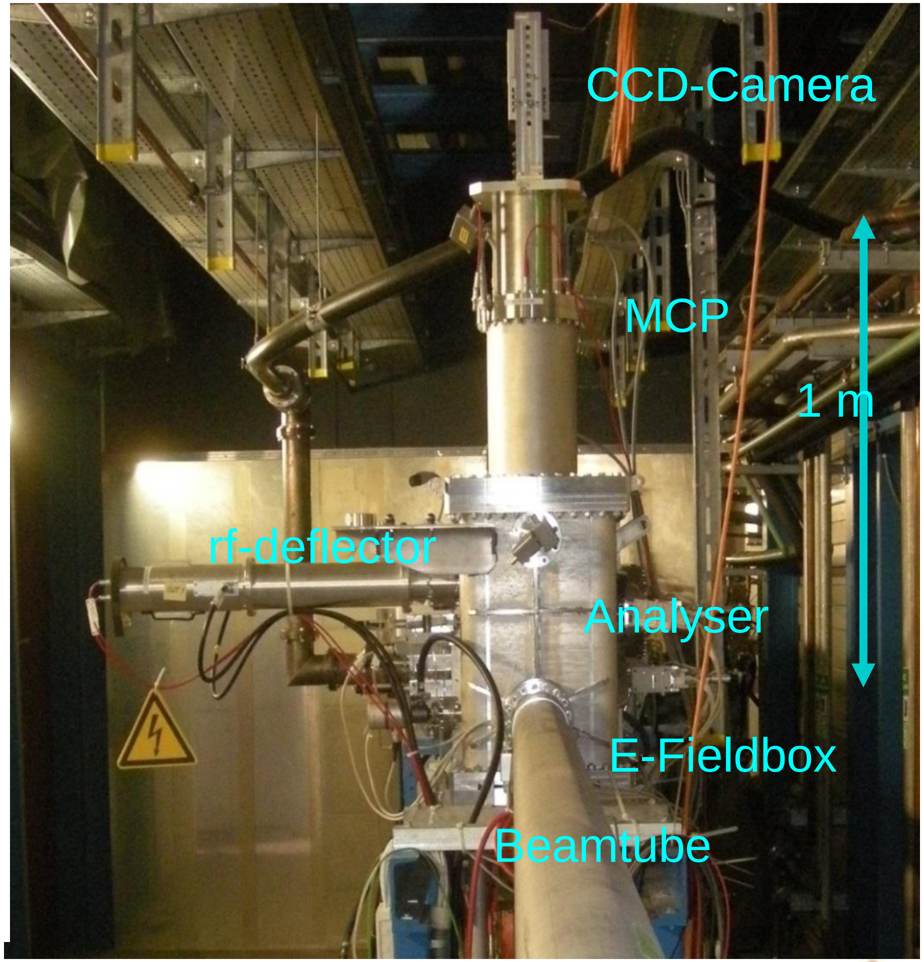
With courtesy of B. Zwicker

Non-intercepting Bunch Shape Measurement



ealization of non-intercepting monitor at GSI:

Installation in transfer line UNILAC to SIS:



Simulation of Space Charge Effects: General Behavior

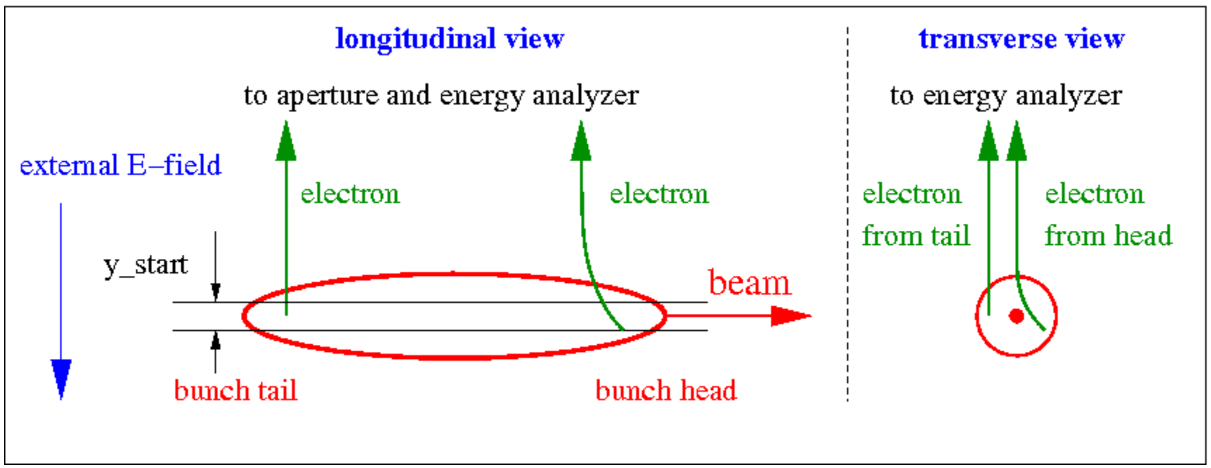
Space-charge effects:

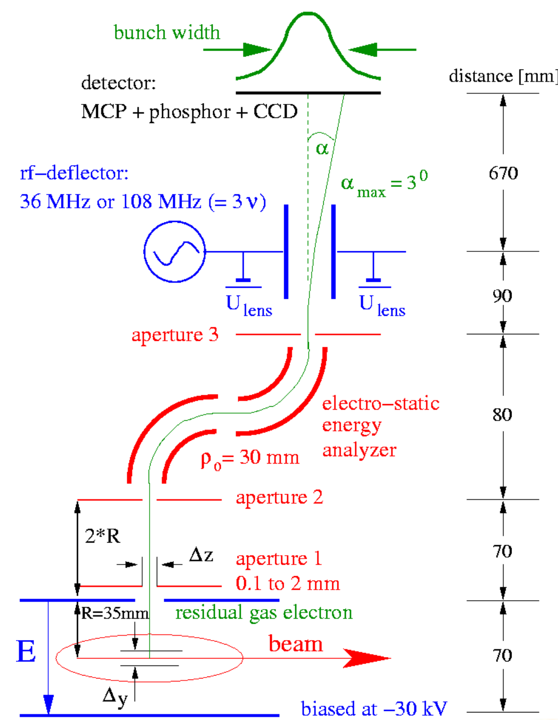
Beam's space charge ↔ external homogeneous E- field (larger effect as for biased wire)

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:

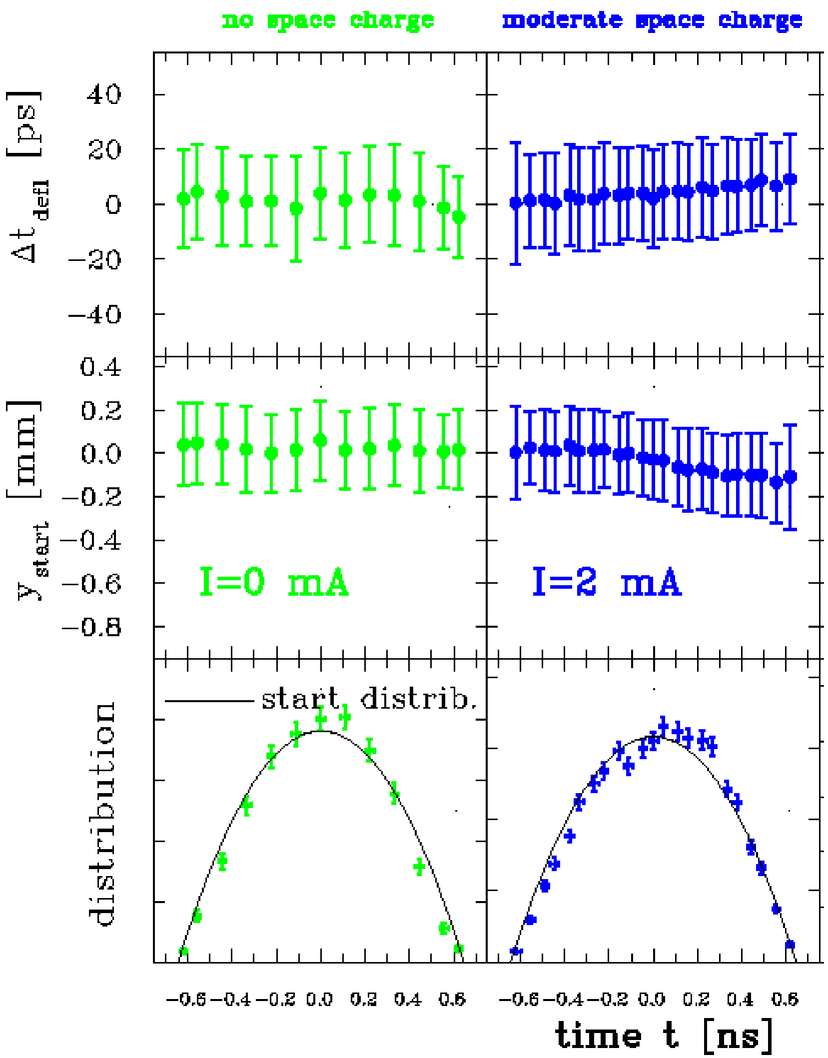
transverse ±5 mm root points

Longitudinal ±0.6 ns root point

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

Simulation of Space Charge Effect: Results

Beam's space charge ↔ external homo. ***E***- field:



Parameter like for measurement

Features:

- Arrival time at deflector is sufficient constant, Δt < 40 ps compared to reference particle
- Cut through bunch is sufficient stable Δy < 0.8 mm (root-points are ±5 mm here)

- **But** for high current: #e⁻ vary along the bunch

(bunch head pulls e⁻ toward center)

⇒ lower space charge by transverse defocusing of beam

⇒ guidance of e- by B-field

⇒ 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 $\Delta\phi(\vec{x}) = -\frac{\rho(\vec{x})}{\varepsilon_0}$ 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 inn C++ with specifics of outdated Borland compiler, which is **not** available anymore, , maintenance difficult

Should be usable for LINAC and synchrotron beams 1 MeV/u < E_{kin} < 30 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 $\rho(\vec{x}) = const$ **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

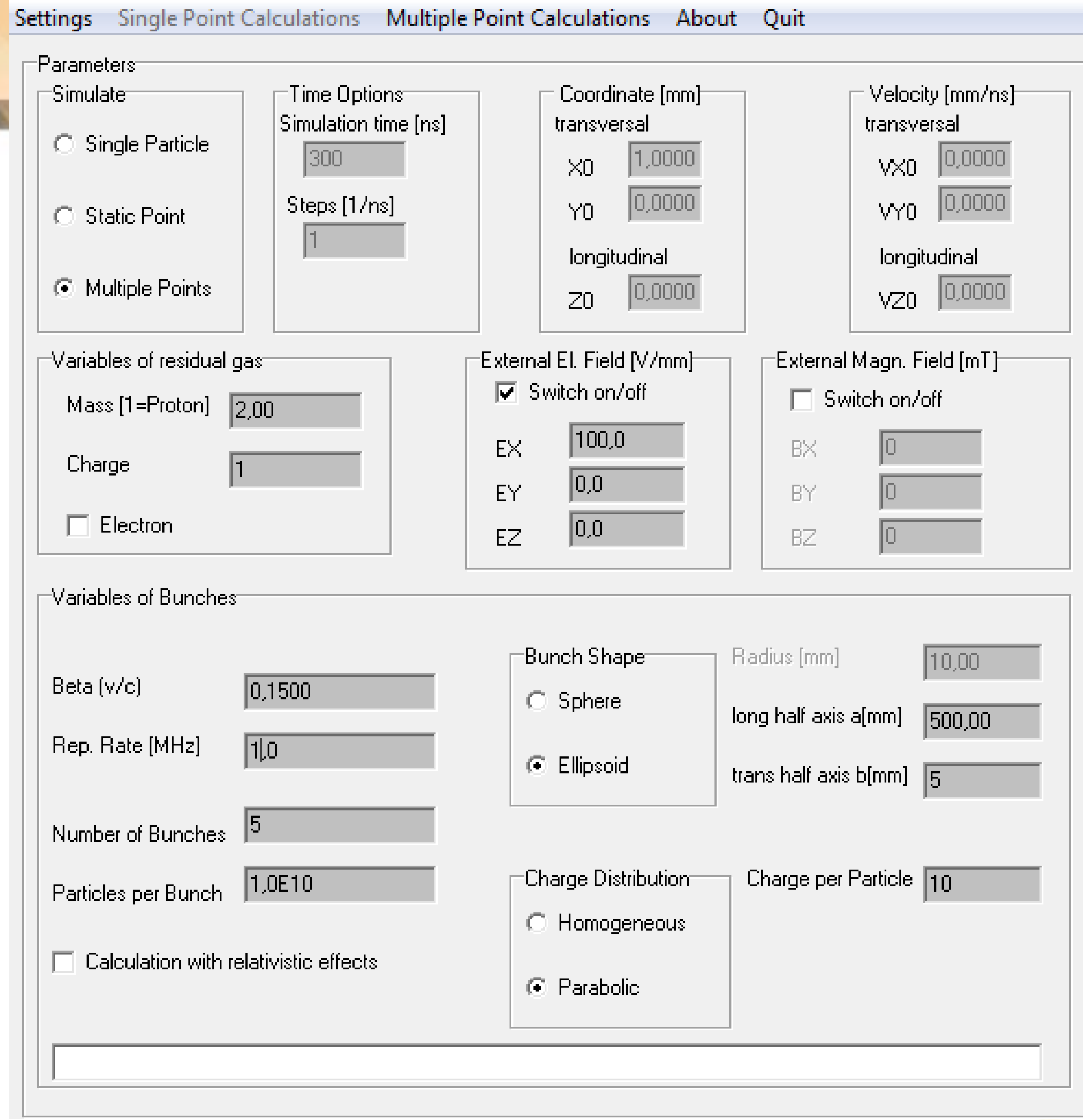
Code Input

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
- β = 15 %, 1 MHz acc.



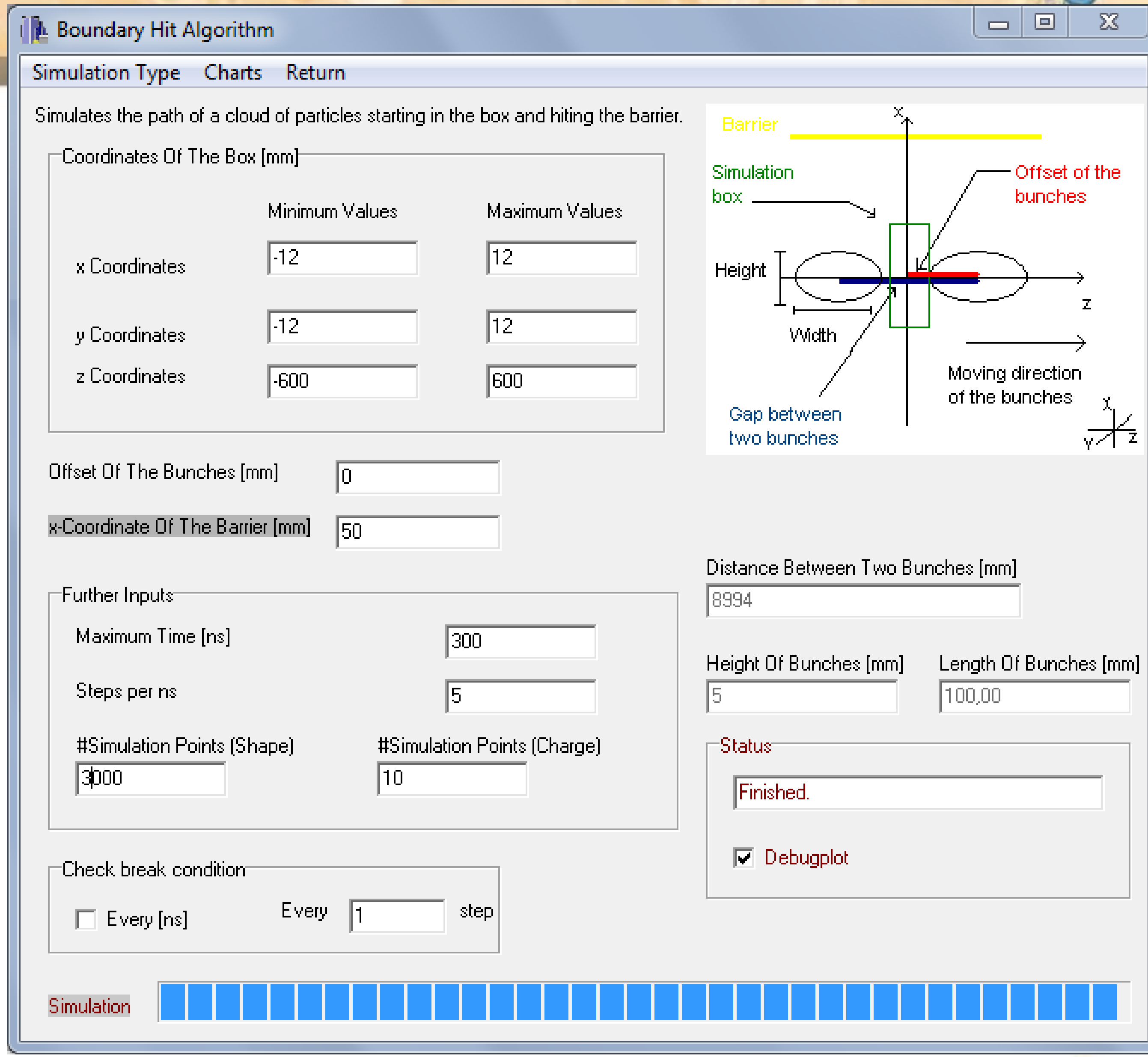
Code Input

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
- β = 15 %, 1 MHz acc.



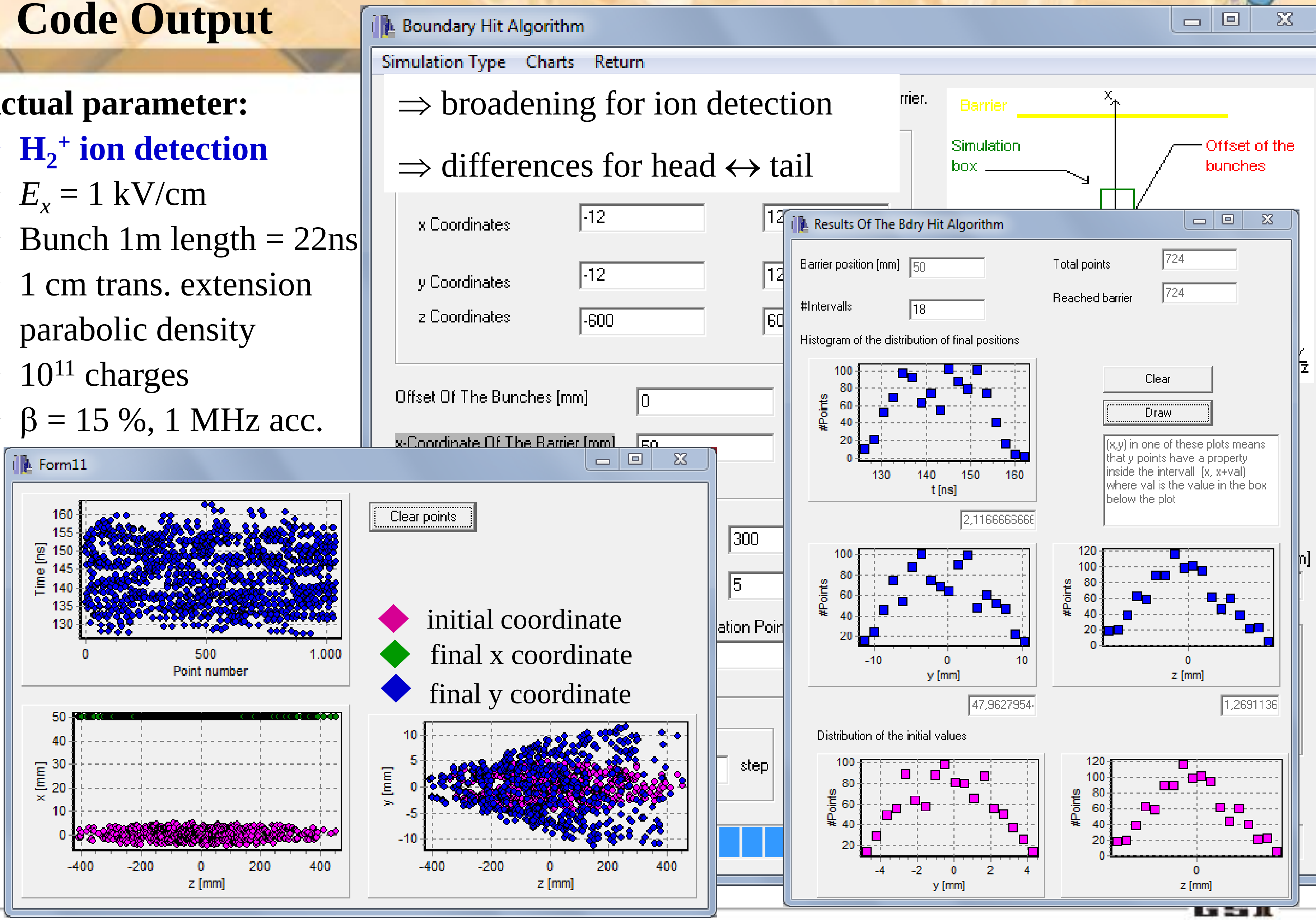
Code Output

Actual parameter:

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

⇒ broadening for ion detection

⇒ differences for head ↔ tail

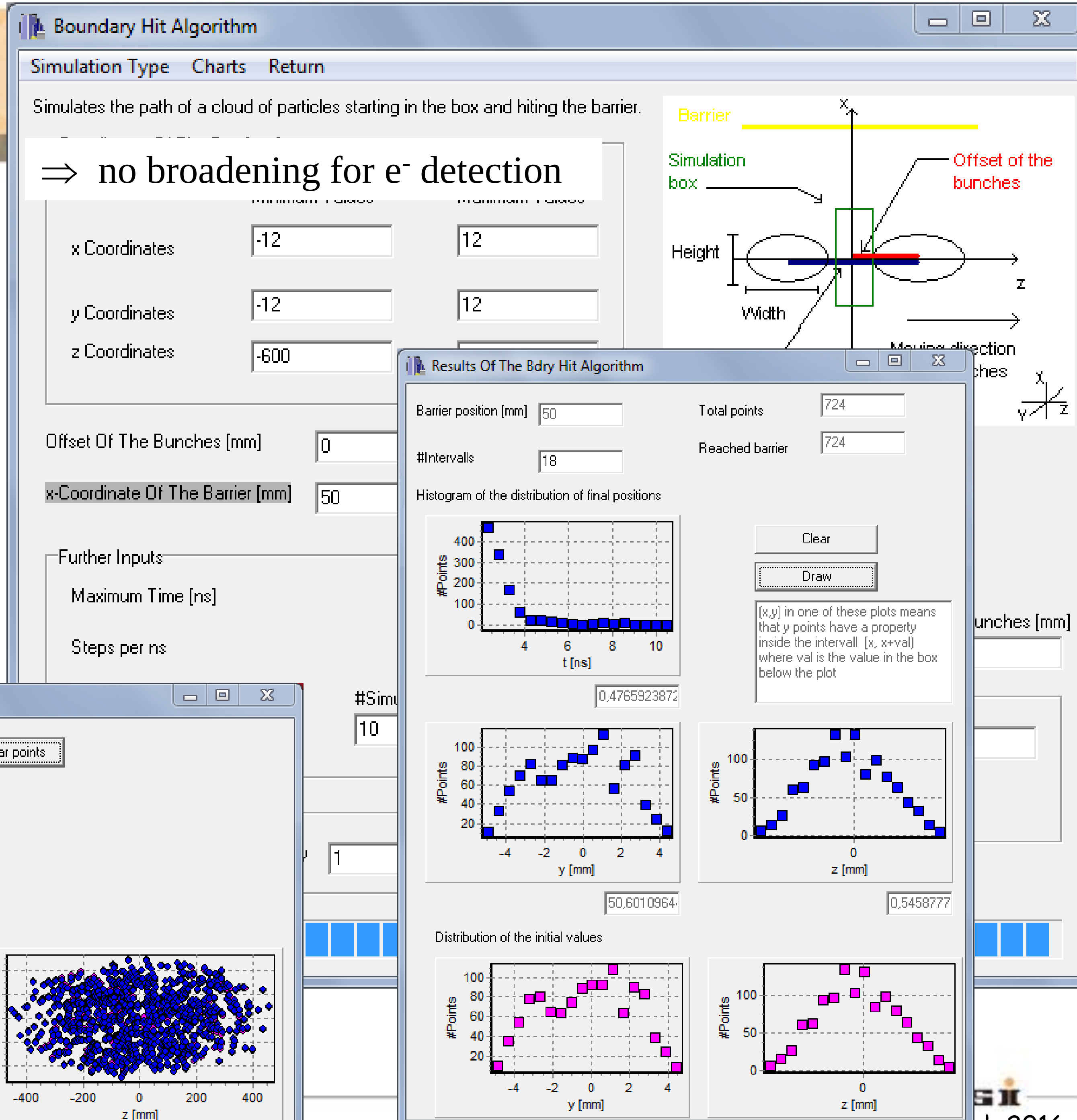


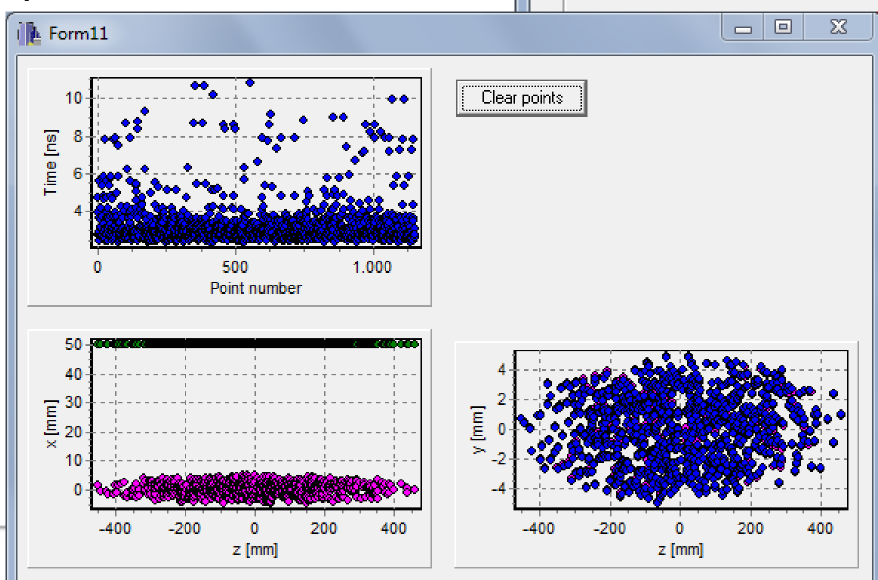
Online Output

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
- β = 15 %, 1 MHz acc.

⇒ no broadening for e⁻ detection





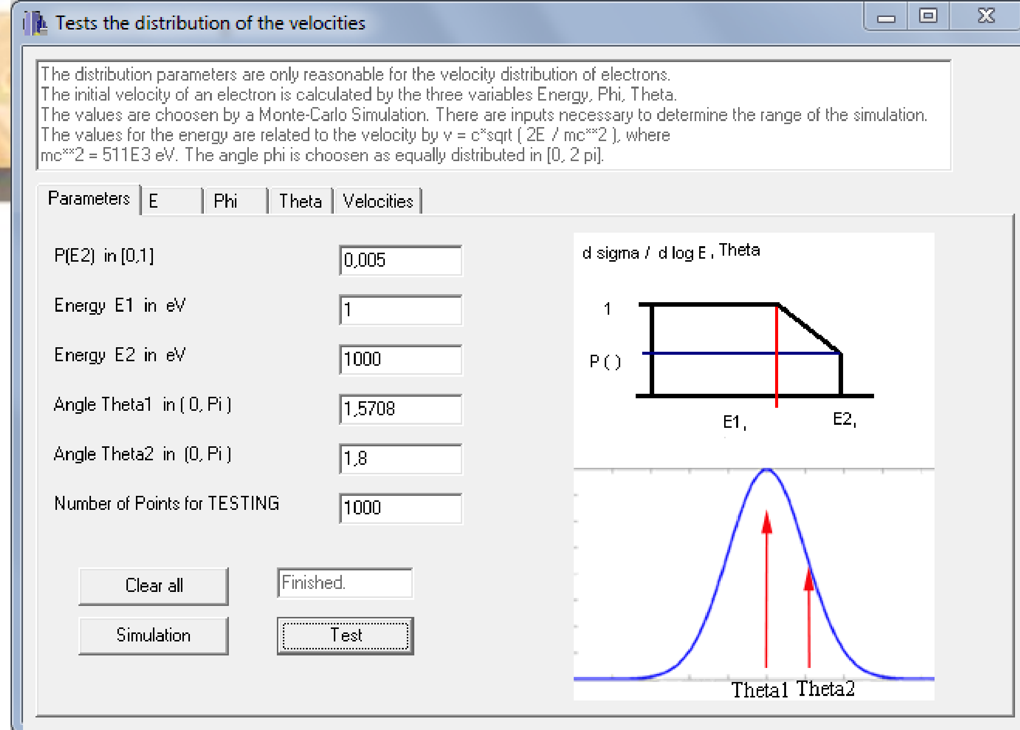
Usage of e$^-$ Distribution

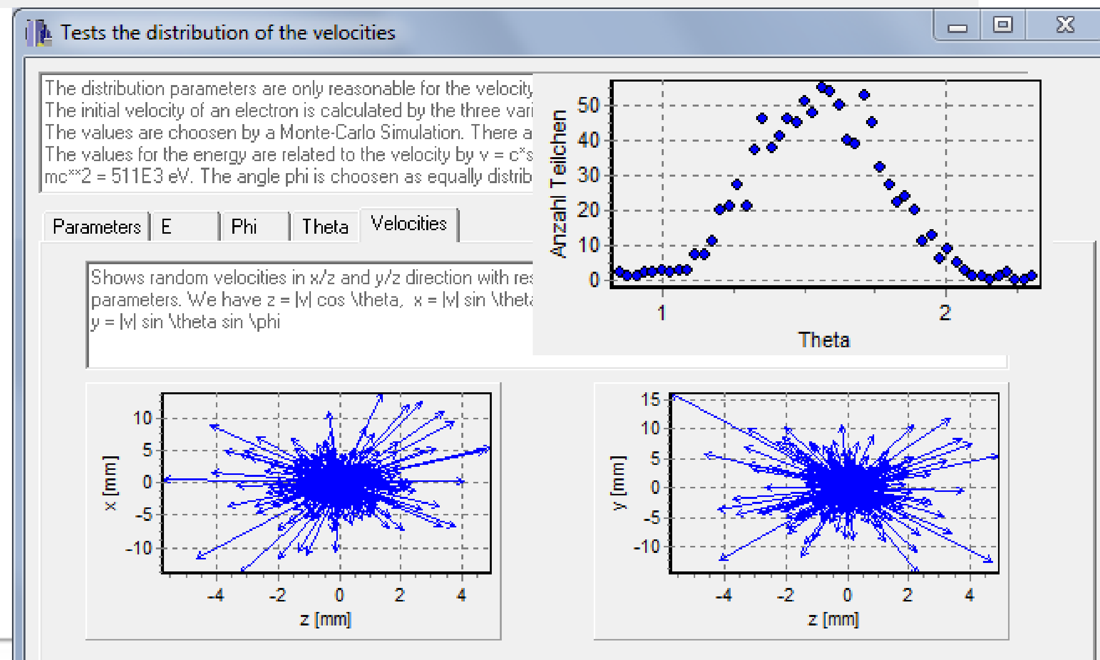
Actual parameter:

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

Electron parametrization: with 'separated' Ansatz:

- energy $\mathbf{d}\boldsymbol{\sigma}/\mathbf{d}\boldsymbol{E}$
  constant value $\boldsymbol{0 < E < E_1}$
  linear decay $\boldsymbol{E_1 < E < E_2}$
  $\boldsymbol{\sigma = 0}$ for $\boldsymbol{E > E_2}$
- angular $\mathbf{d}\boldsymbol{\sigma}/\mathbf{d}\boldsymbol{\theta}$
  Gaussian with center $\boldsymbol{\theta_1}$
  and width $\boldsymbol{\theta_2}$



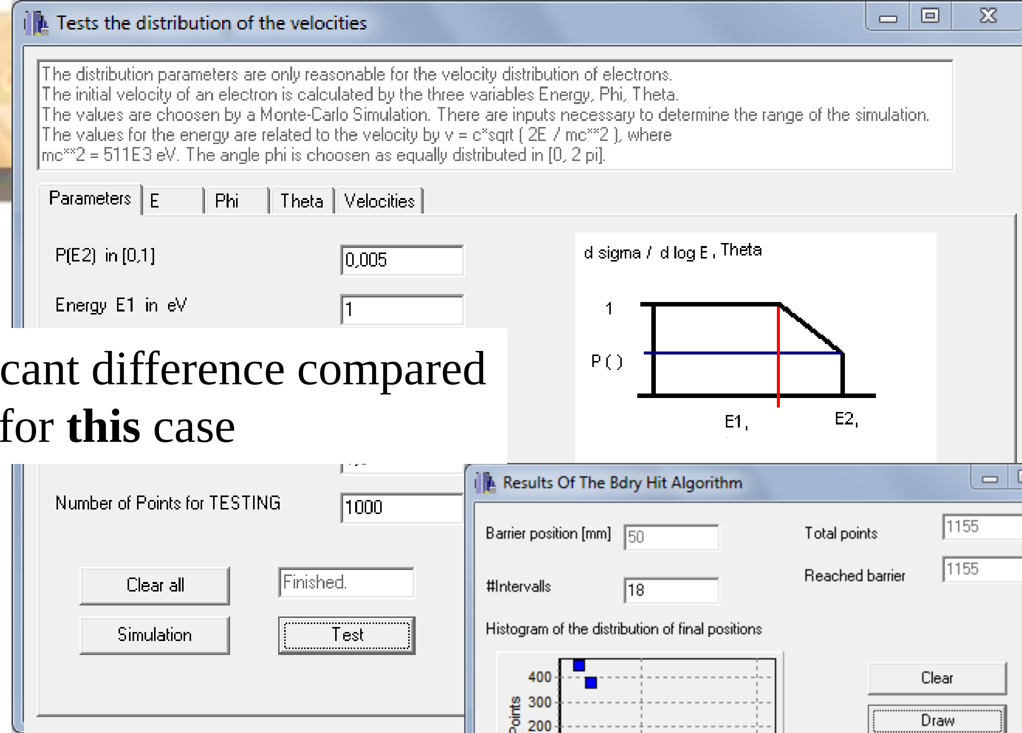


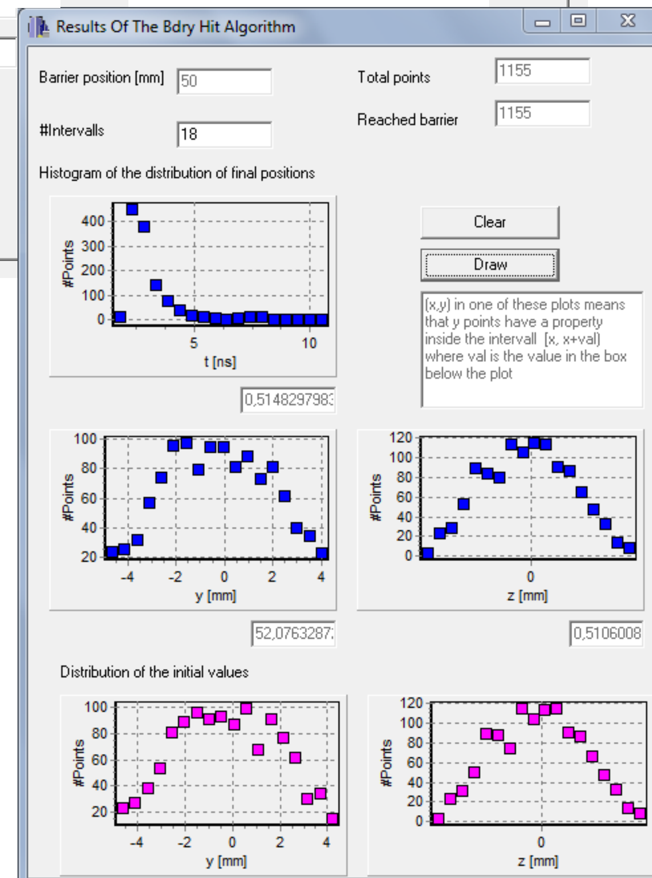
Usage of e⁻ Distribution

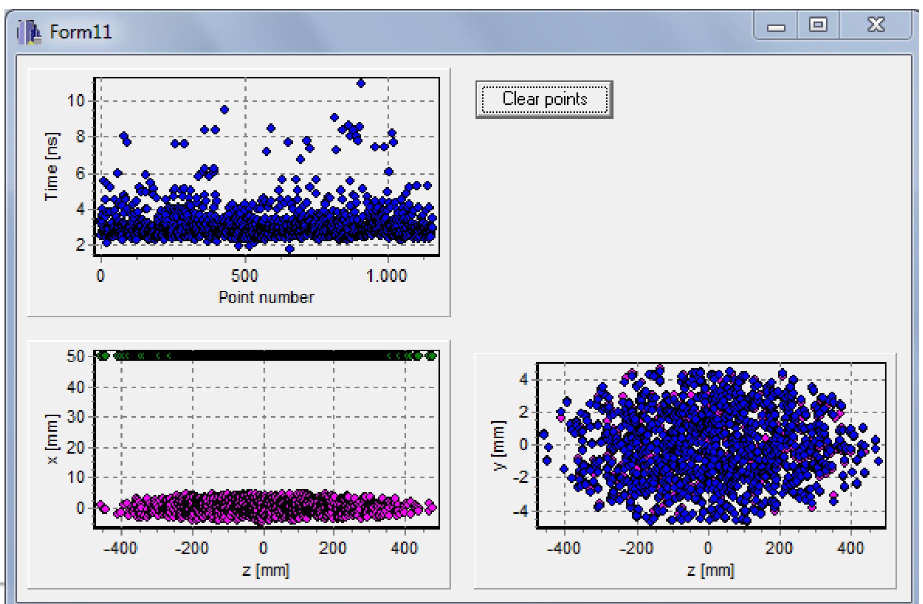
Actual parameter:

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

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







Simulation Code: General Idea

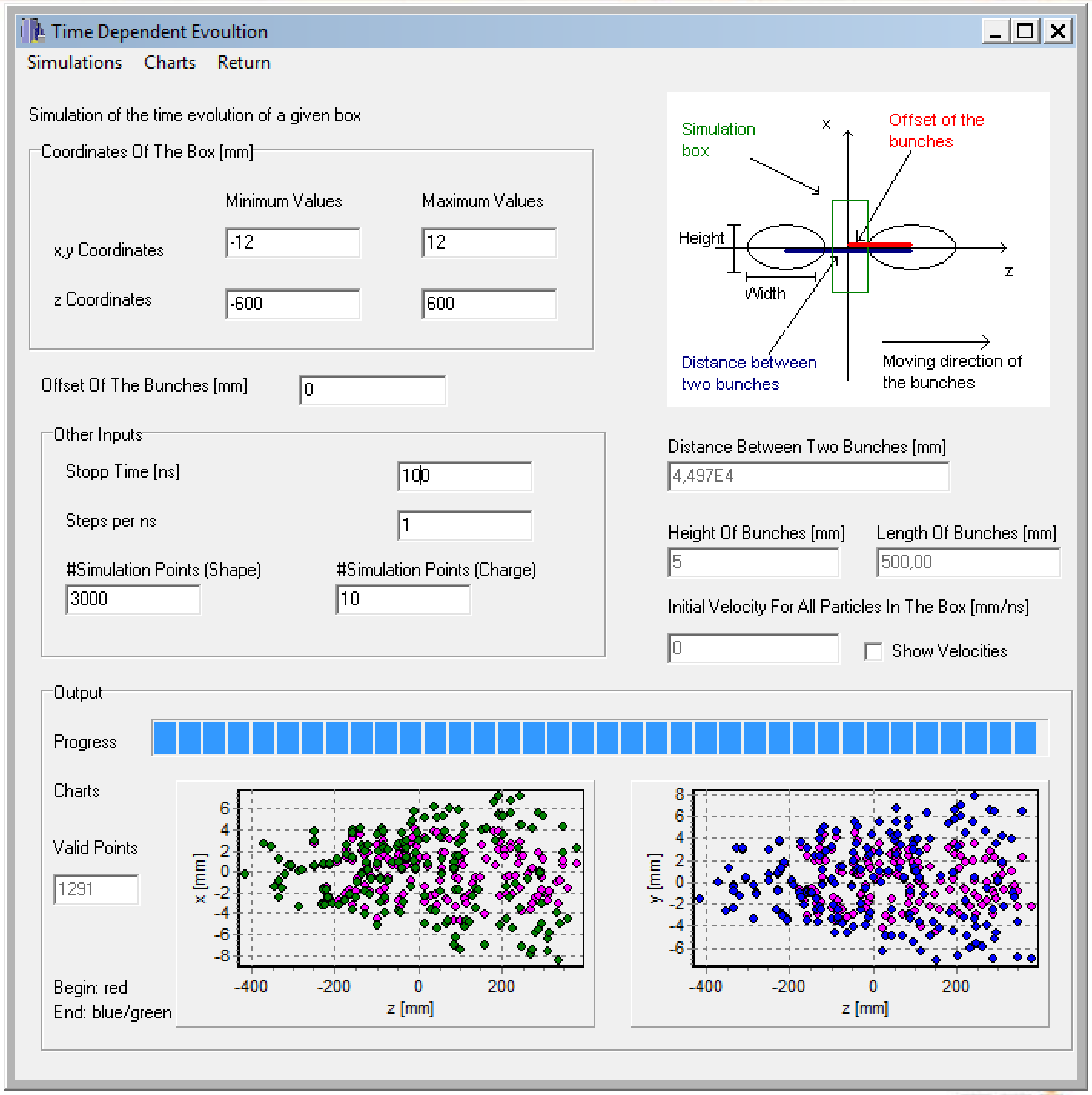
BIF type evaluation:

Actual parameter:

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

H_2^+ fluorescence

→ position after 100 ns



Simulation Code: General Idea

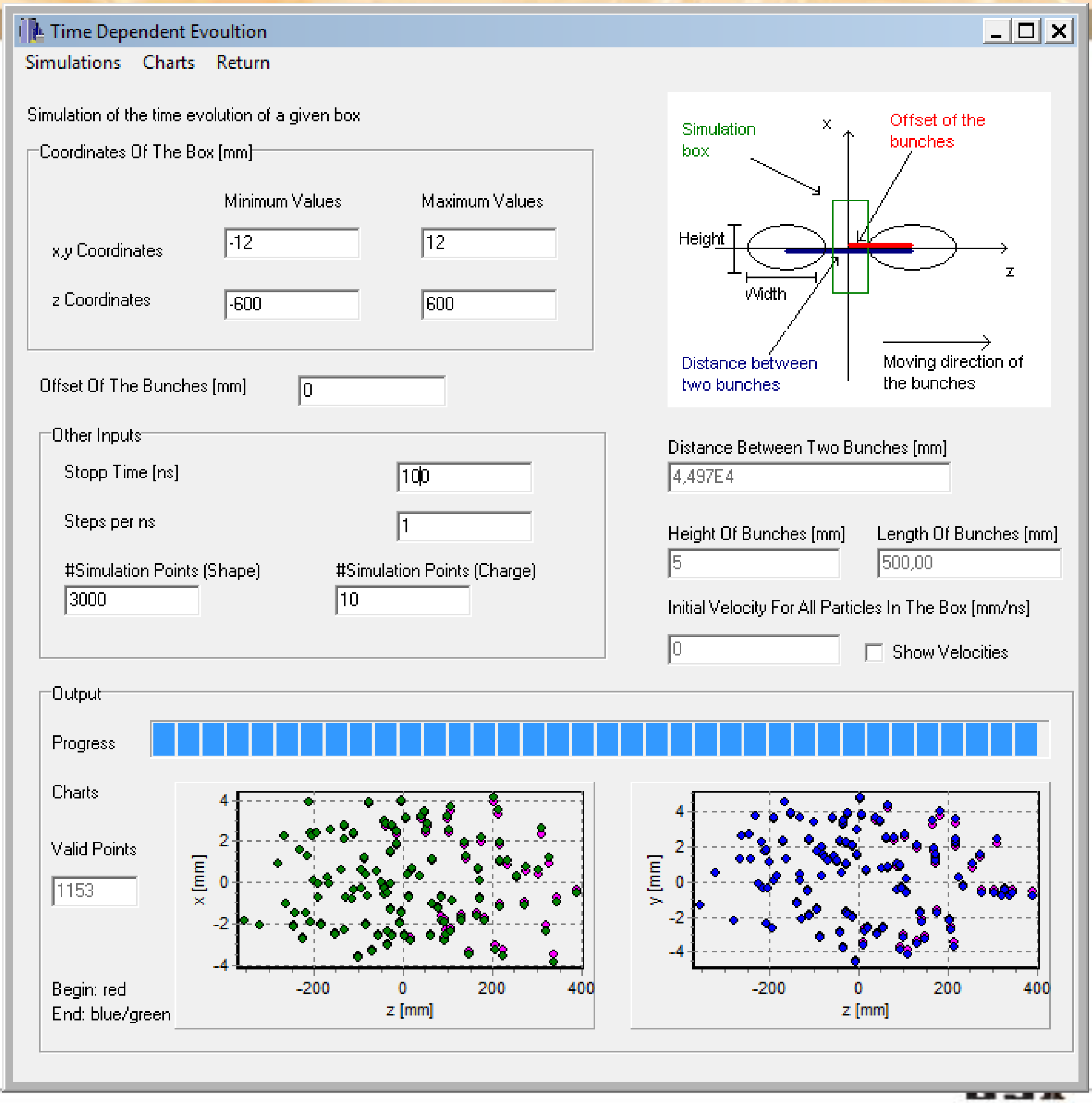
BIF type evaluation:

Actual parameter:

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

N_2^+ fluorescence

→ position after 100 ns



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

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

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

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

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

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

The Poisson equation is solved analytically for the considered charge distributions

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

Problems appear in the numerical implementation when the longitudinal bunch size is much large than the transversal size i.e. ***L*** >> ***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?*

⇒ **solution is pending**

Simulation Code: Conclusions

Restrictions:

- Horizontal ***x*** equals vertical ***y*** extension, longitudinal extension free parameter
- Density: $\rho(\vec{x}) = const$ (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*** >> ***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 !