# OPAL Simulation for PSI Medical Cyclotron COMET


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# Motivation

- OPAL is a simulation tool developed at PSI
- COMET is a real machine operating at PSI
- Need to improve the simulation for COMET
- For OPAL, new features need to be implemented in order to simulate COMET
- A win-win cooperation

# Focus of Talk

- New features in OPAL
  - Applying multiple field maps
  - Introducing more general collimators

- Simulation for the central region of COMET
  - Chimney and puller
  - Fixed phase slit

# Object Oriented Parallel Accelerator Library

**OPAL is a tool for charged particle optics in accelerators and beam lines**

- Including 3D space charge
- Exemplifying the importance of high performance computing
- Written in C++ and easy to be extended
- Using MAD language
- Running on largest clusters as well as on laptop

**OPAL flavours**

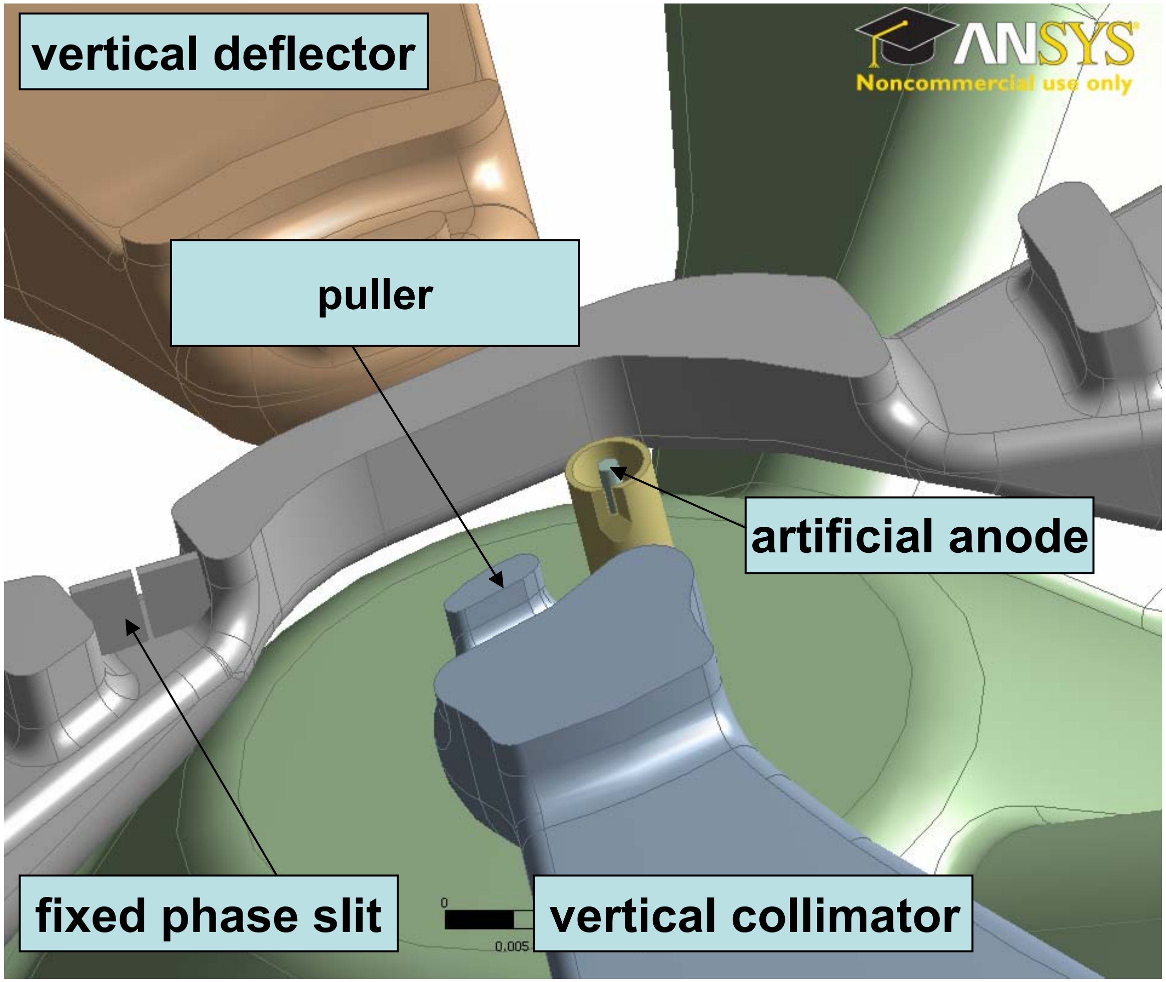
- OPAL-T
- OPAL-MAP
- OPAL-CYCL
  particle tracking in cyclotrons such as PSI Inj-II, PSI Ring, etc.
  3D space charge including neighbouring turns
  time as independent variable

  acceleration through simple straight gap
  collimator physics in low energy region not tested

# PSI Medical Cyclotron COMET

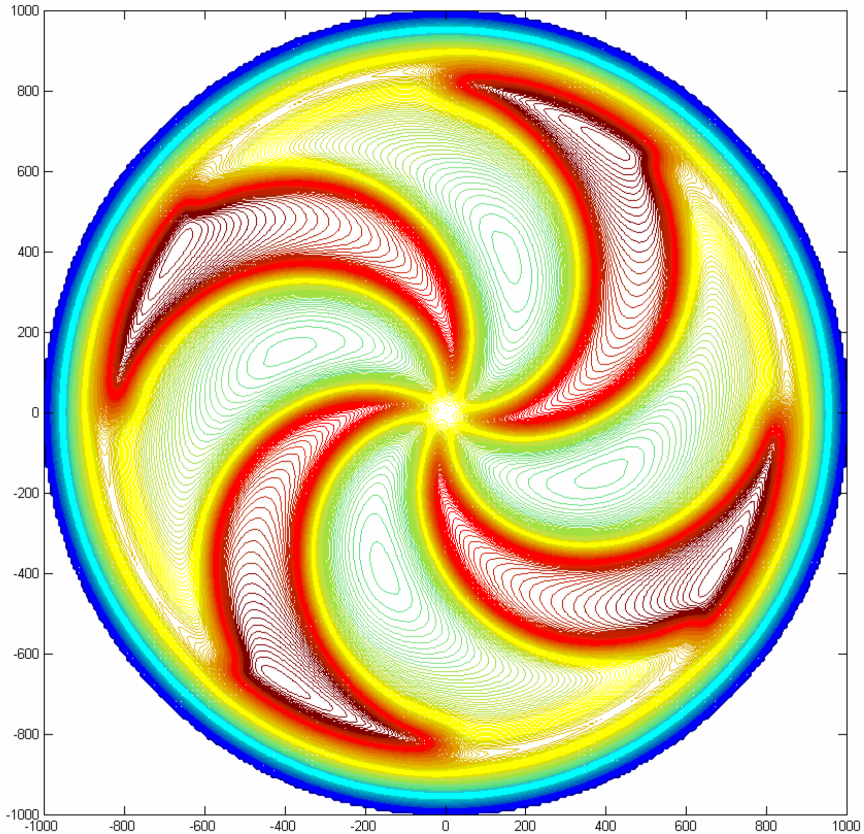

- Beam energy: 250 MeV
- Beam current: 500 nA
- Superconducting coils
- Magnetic field: 2.4 – 3 T
- Dee in spiral form
- RF frequency: 72.8 MHz
- Harmonic number: 2

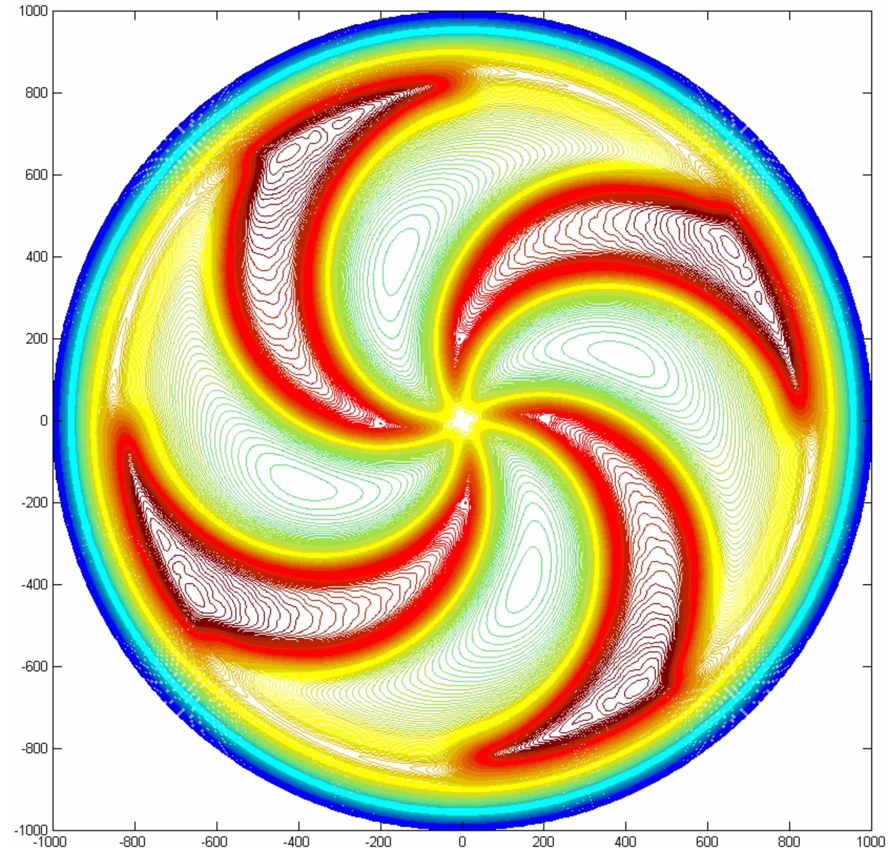
# Central Region




- Ion Source
  Chimney: 0 V
  Opening: 0.5×5 mm²
- Artificial anode: +50 kV
  Helps to produce right shape of zero potential surface
- Puller
  Peak voltage: ca 80 kV
  Frequency: 72.8 MHz
- Fixed phase slits
  Opening: 0.2 mm
  Thickness: 1 mm
- Vertical deflector on D3
- Vertical collimator on D1

# Magnetic Field Maps



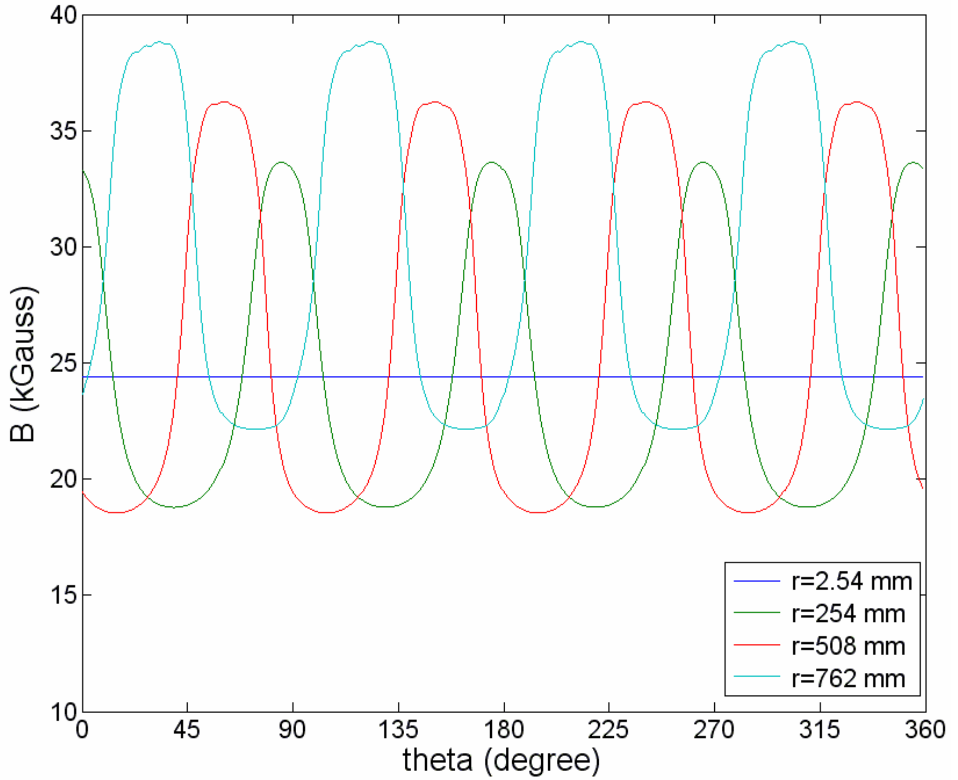



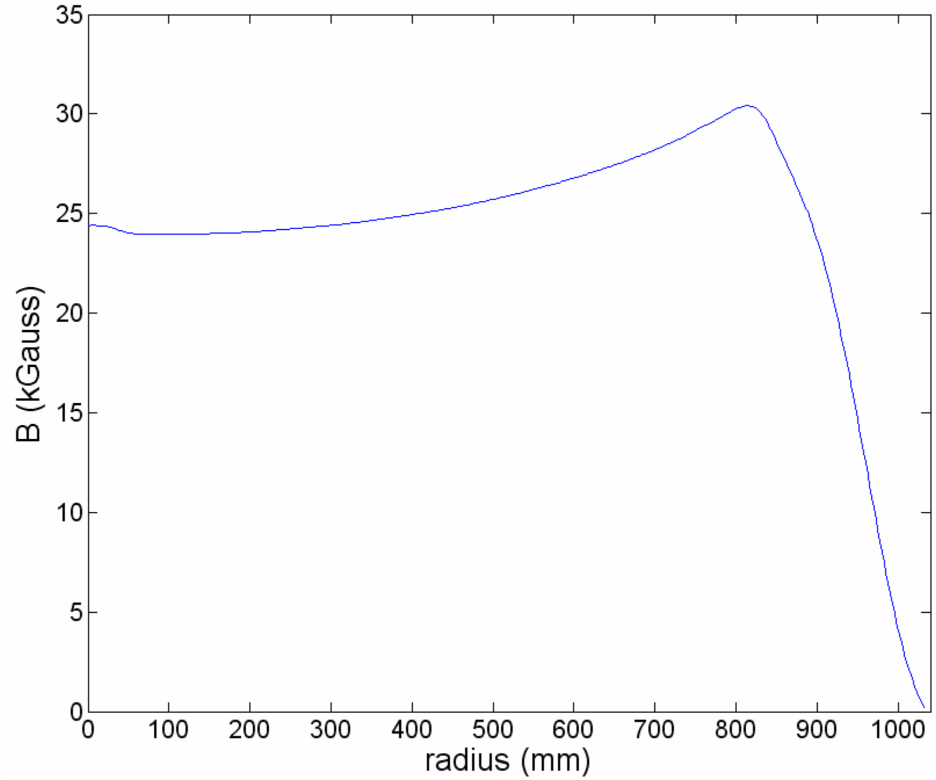

**Left: Magnetic field in median plane from TOSCA simulation**

**Right: Magnetic field from measurement mirrored about x-axis**

**Tracking only in anticlockwise direction**

# Magnetic Field

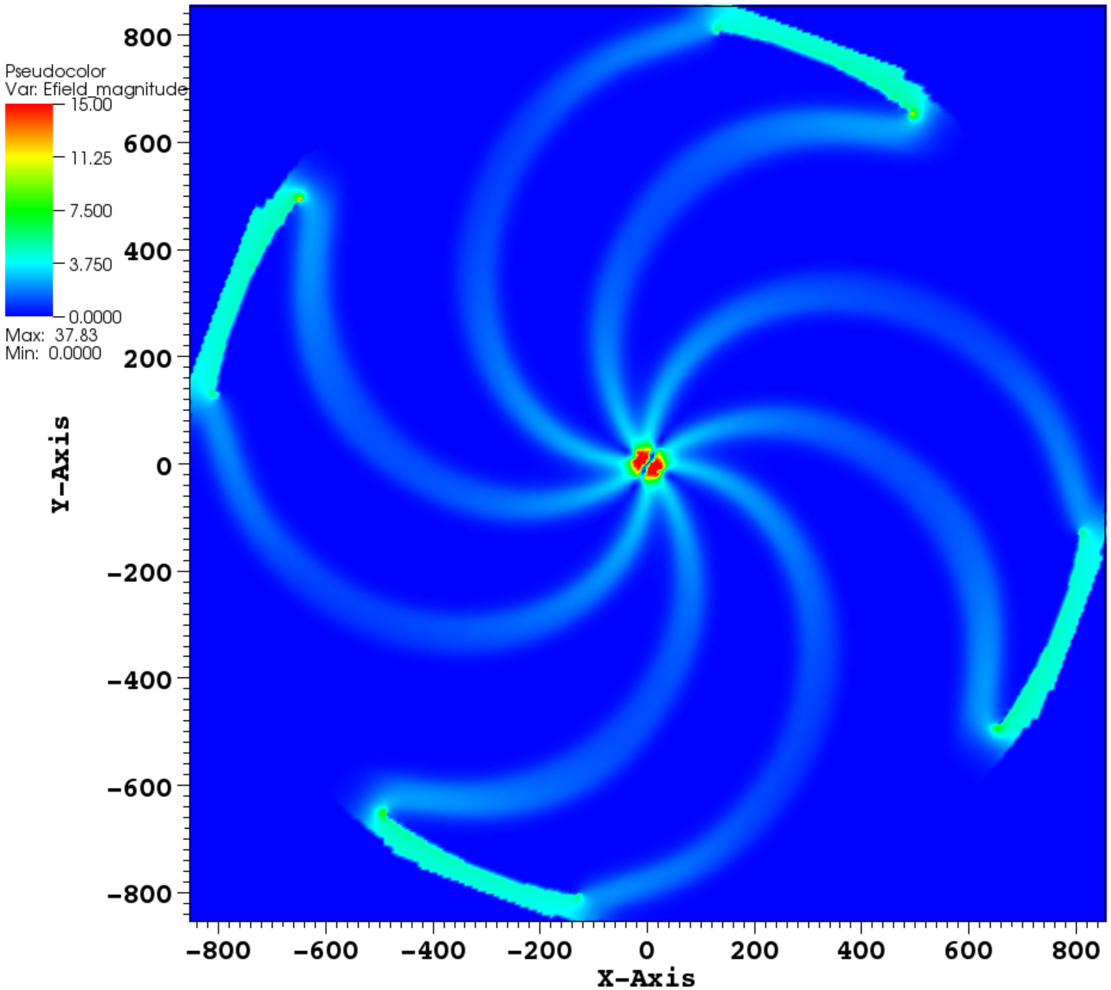



**Left: Azimuthal variation of B field at r = 2.54, 254, 508, 762 mm**

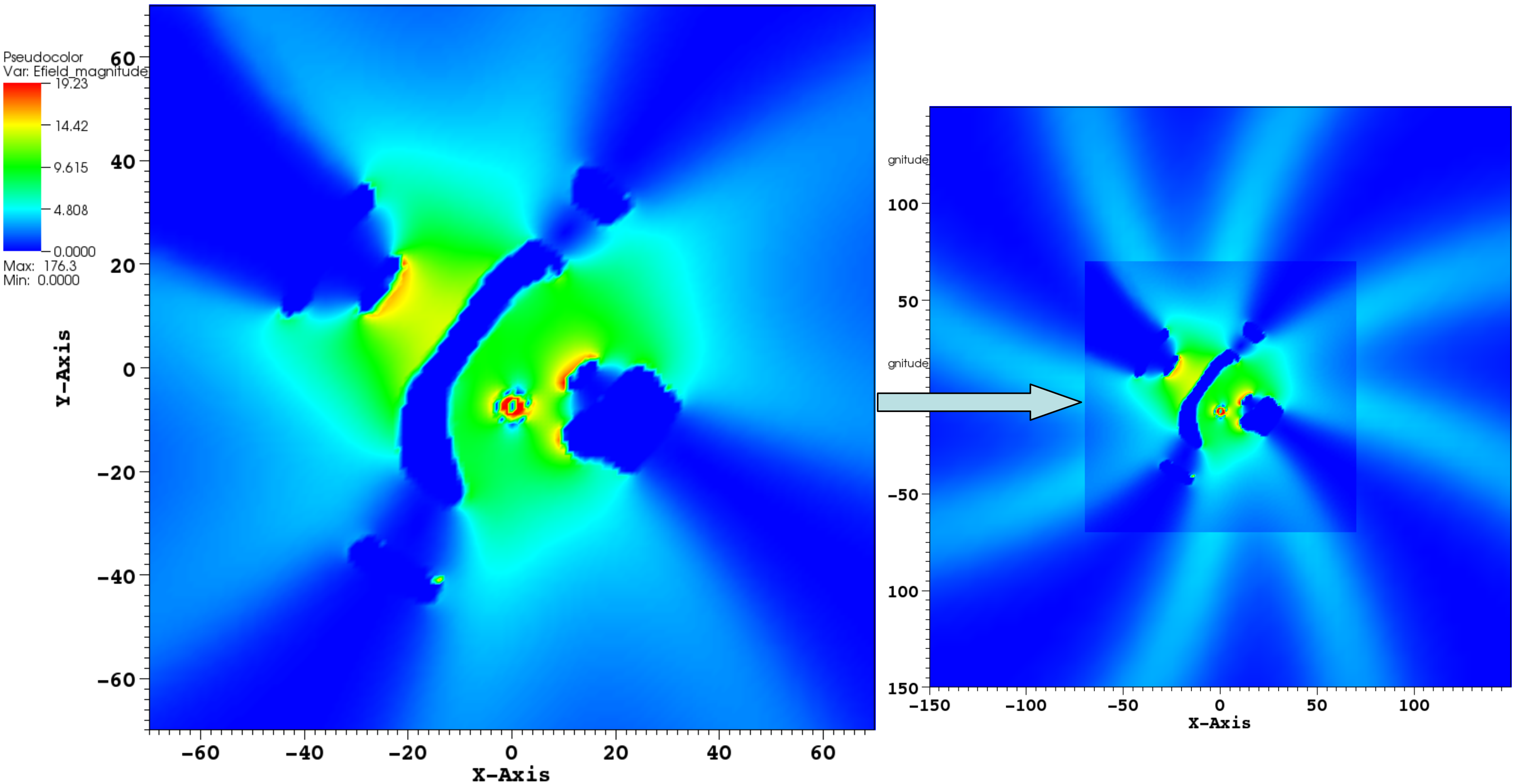
**Right: Radial variation of average B field**

# RF Field Map




- ANSYS simulation from Lukas Stingelin
- Grid size 5×5×5, field region (-855 -855 -5) to (855 855 5), all in mm

# Electric Field in Central Region




- Electrostatic simulation, modulated with RF frequency
- Grid size 1×1×2.5, field region (-70 -70 -10) to (70 70 10), all in mm

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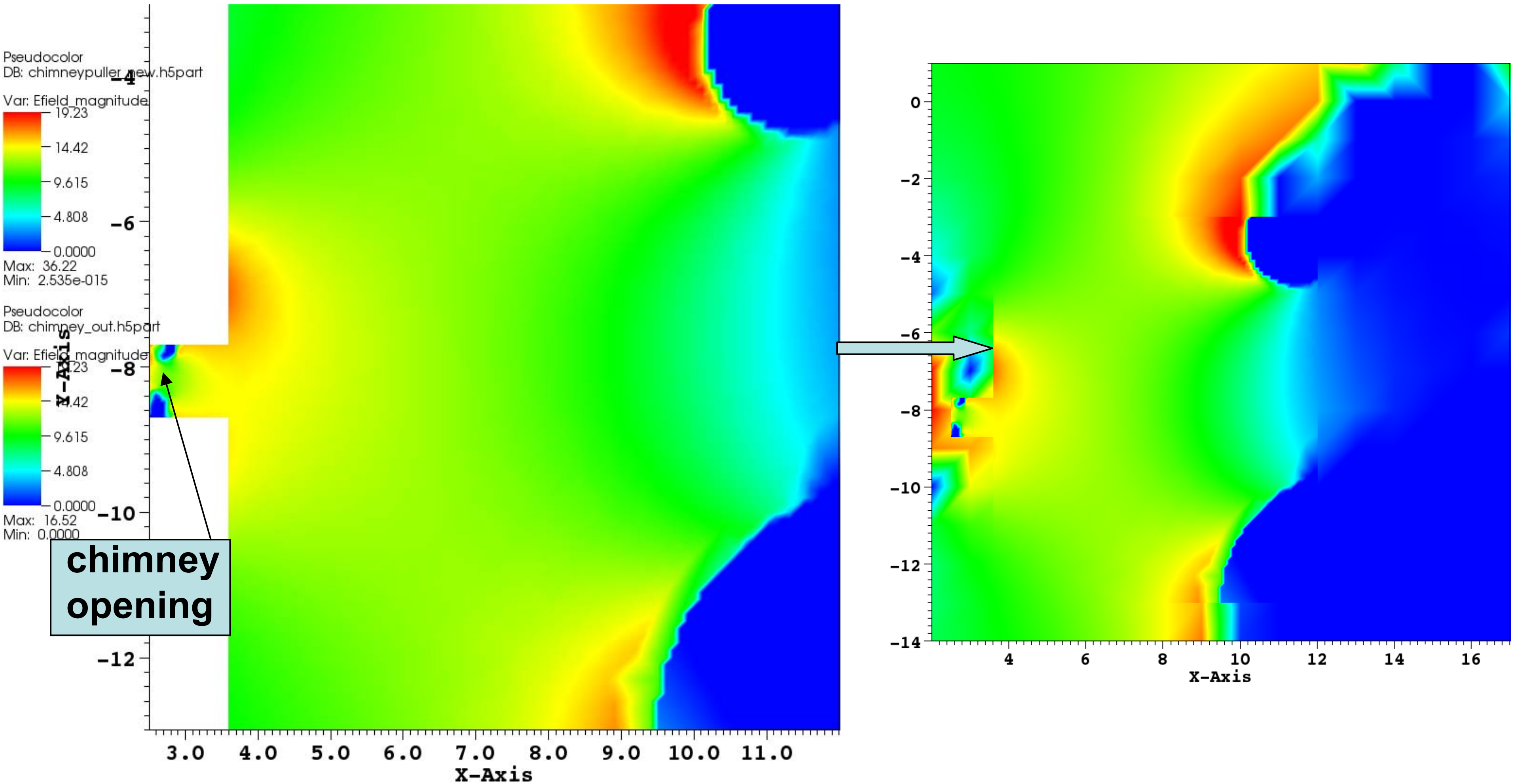
# Electric Field near Chimney and Puller




**Chimney: grid size 0.05×0.05×0.05, region (2.5 -8.7 -3) to (3.6 -7.7 3), in mm**

**Puller: grid size 0.1×0.1×0.1, region (3.6 -13 -5) to (12 -3 5), in mm**

# New Features in OPAL for COMET

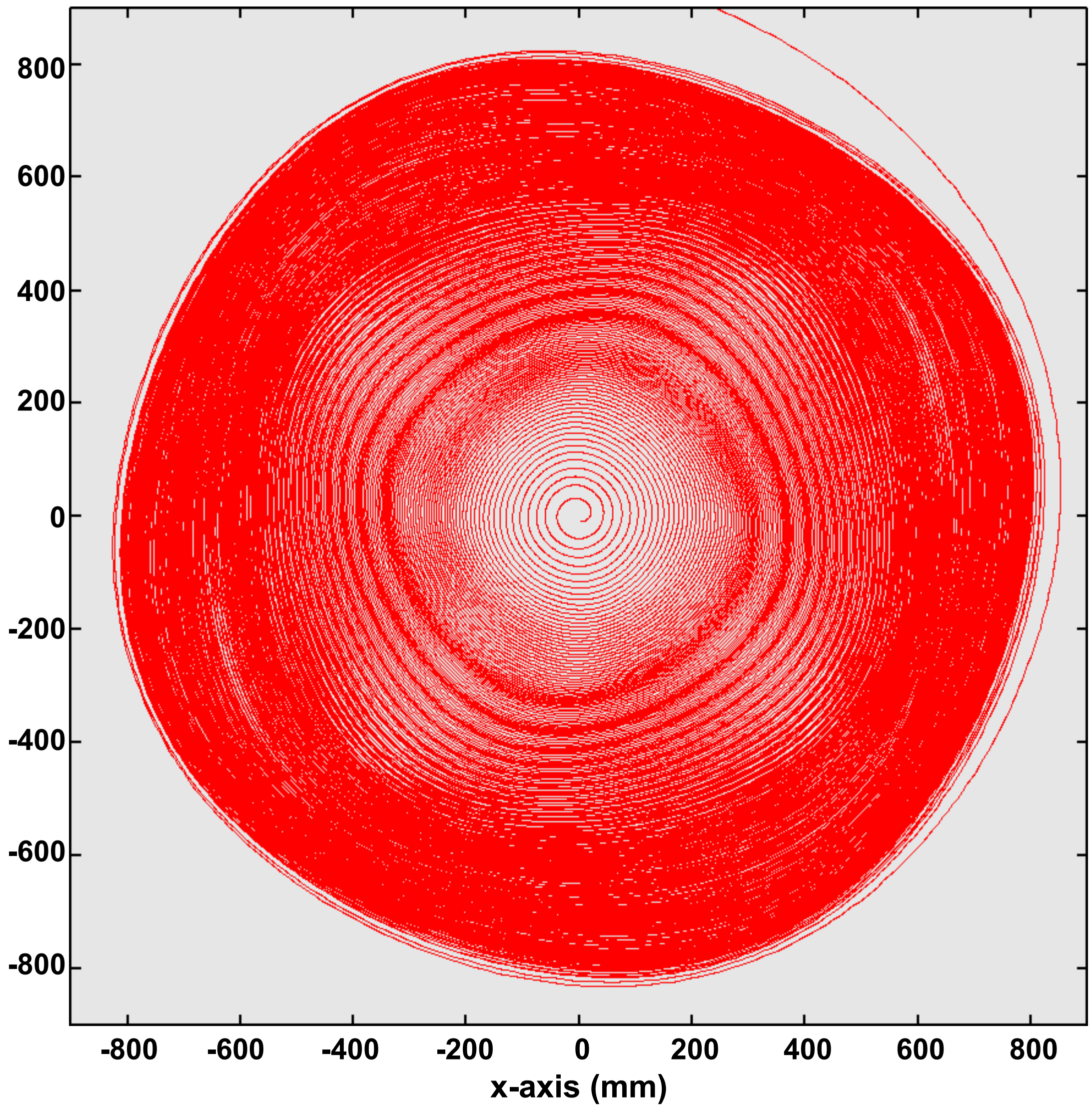
- Dee in spiral is far different from simple straight gap
  Applying 3D field map

- Detailed field maps necessary in central region
  Implementing multiple field maps

- Phase slit in central region crucial for beam product
  Implementing low energy collimation

- Other features in vision
  Vertical deflector
  Collimators with different shapes other than rectangular
  Trim rods

# Single Particle Tracking



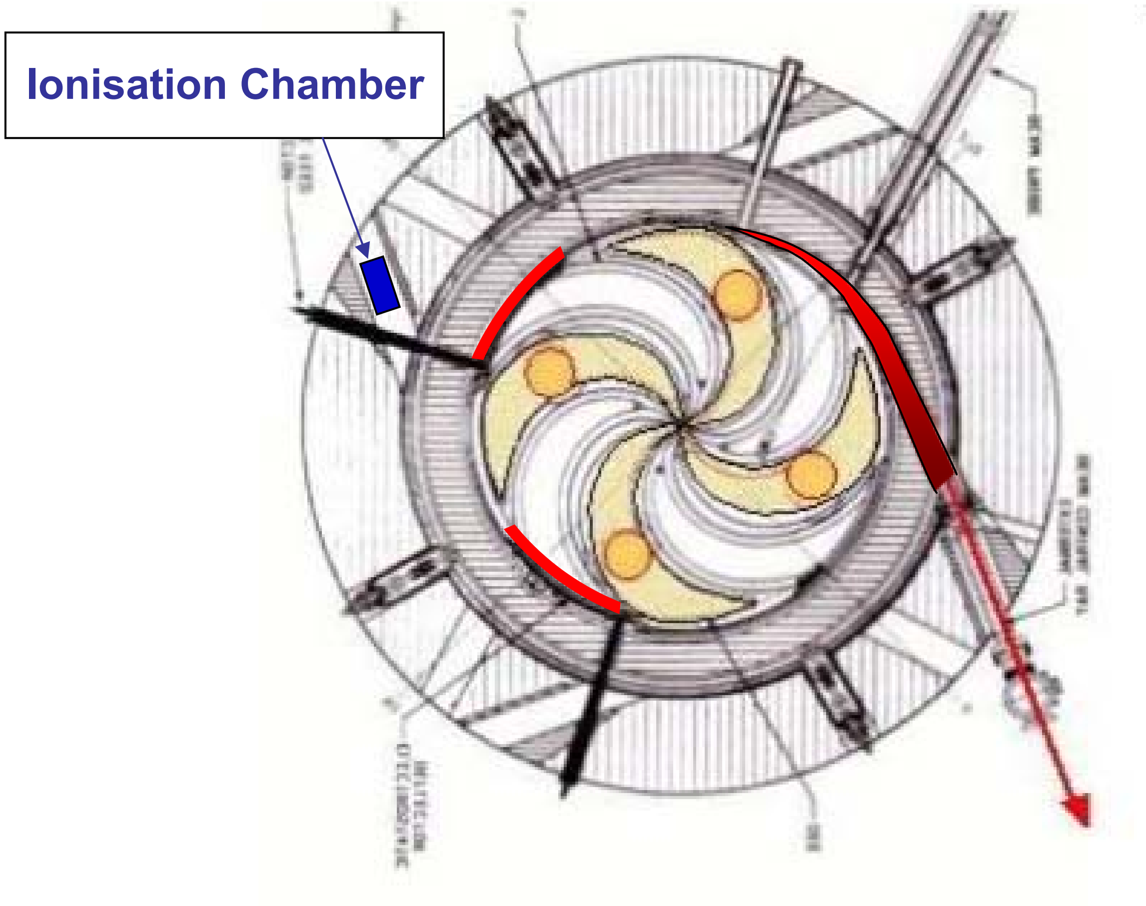

(1) Get R(x, y, z)
(2) Pick a field map
(3) Get $E_0(x, y, z)$
(4) Calculate E

$$E = E_0\cos(\omega t + \varphi_0)$$

(5) Calculate B(x, y, z)
(6) Calculate Lorentz force
(7) Calculate next R(x, y, z)

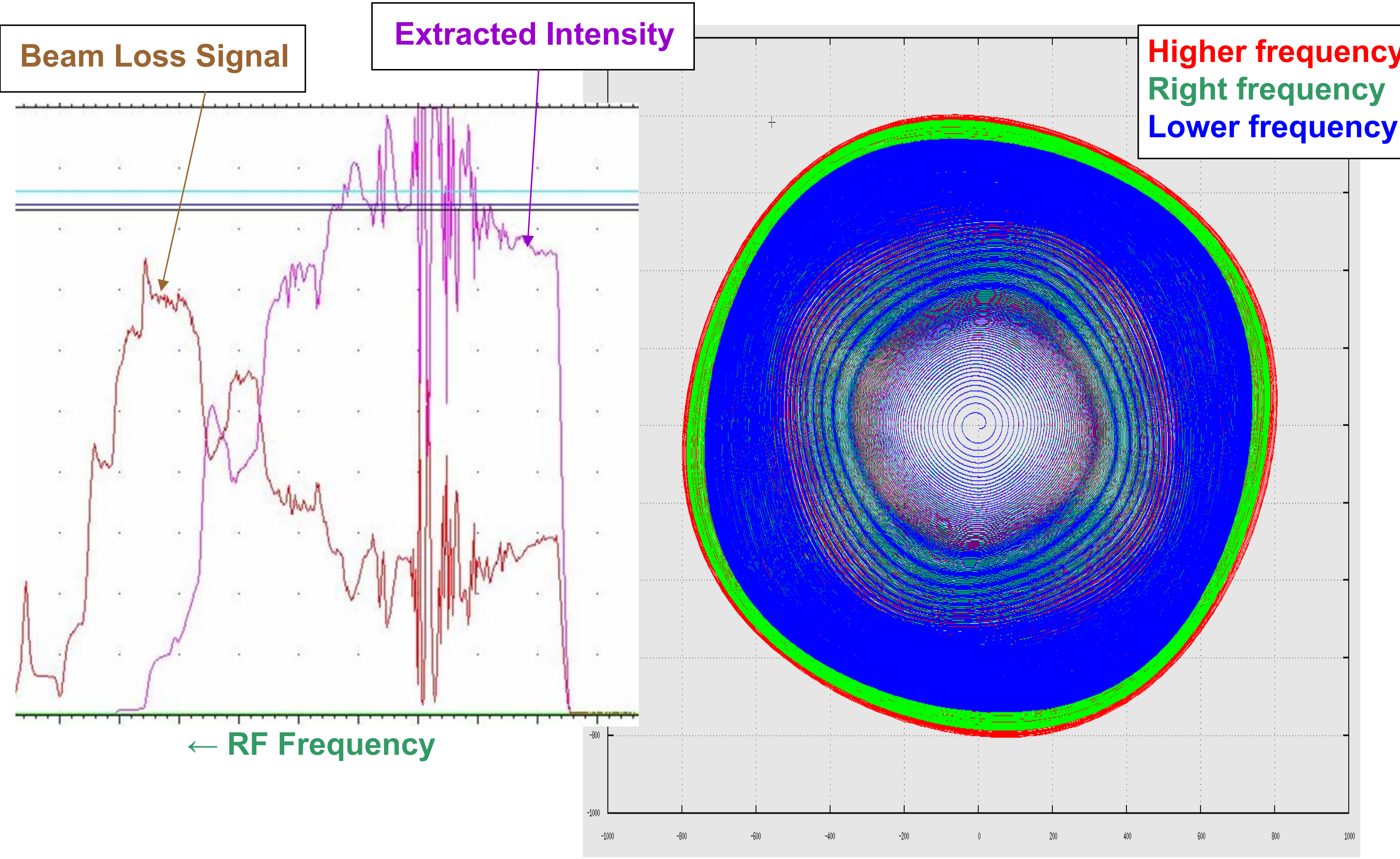
**Independent variable t**
**One field map at one position**
**$\varphi_0$ same for all maps**

# Where are the Beam Losses?

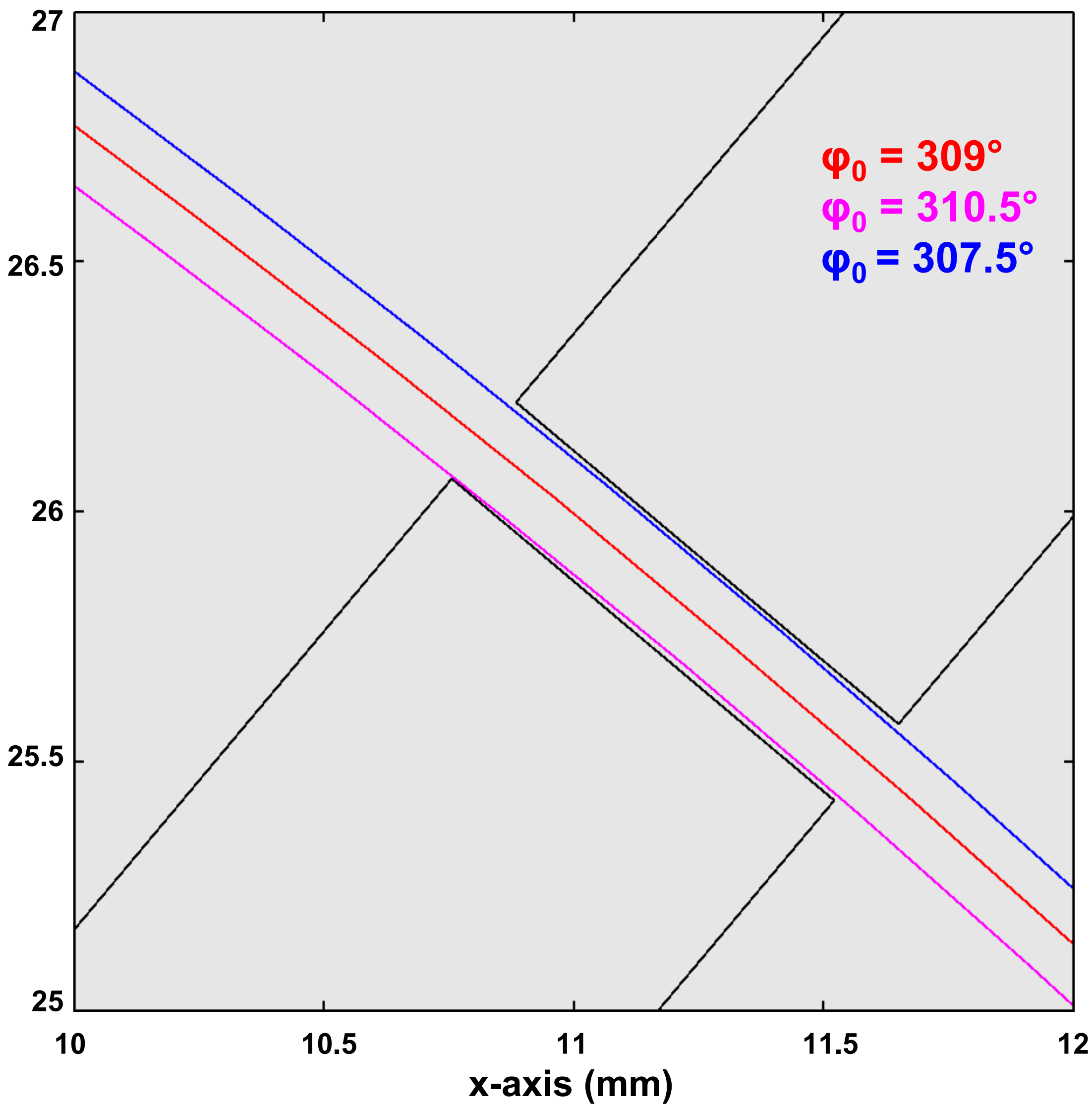



Only sensitive to losses at extractor

# Where are the Beam Losses?



# Initial RF Phase




**Fixed phase slit**

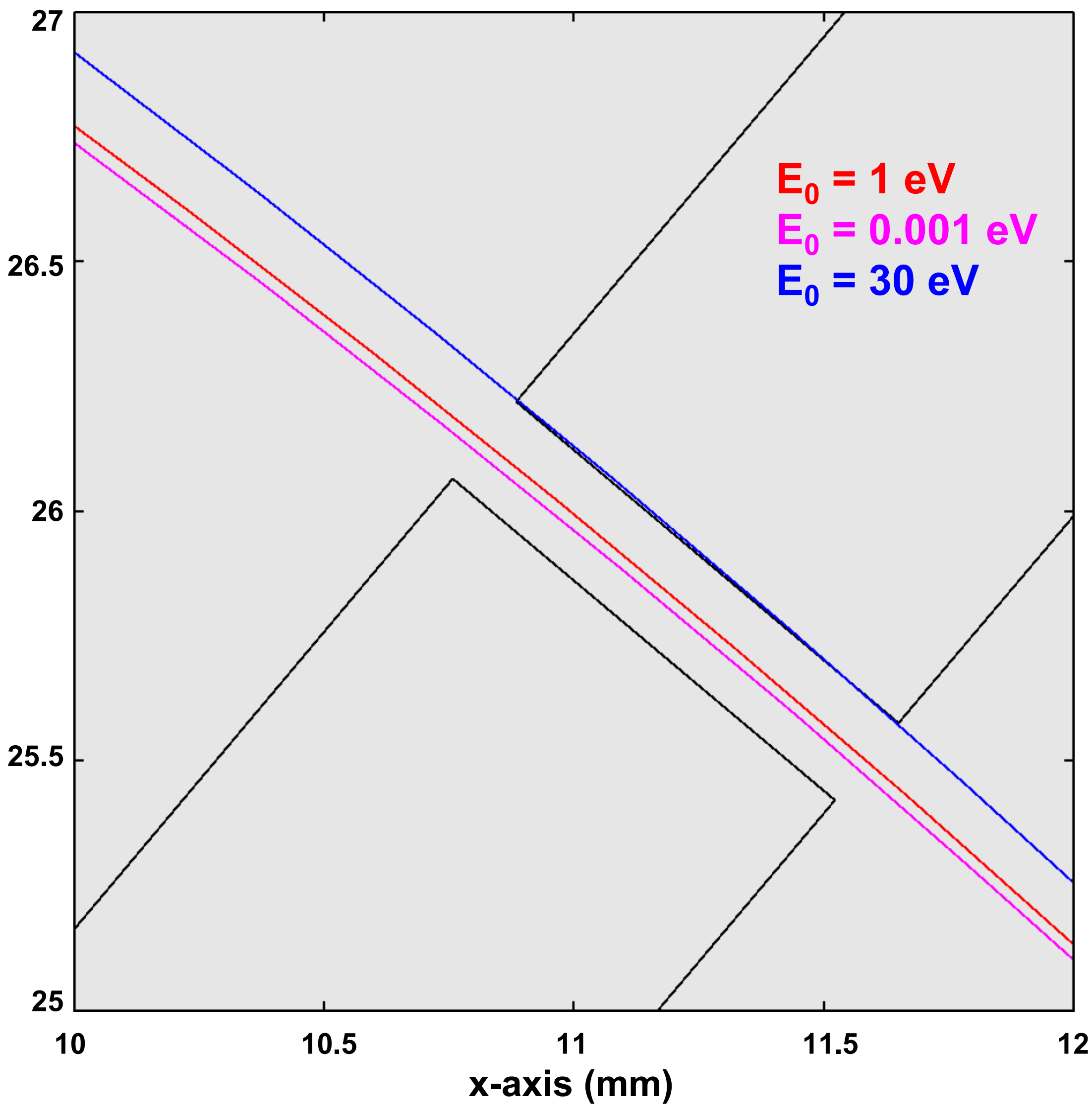
- Opening: 0.2 mm
- Thickness: 1 mm
- Plotted as black lines

**Initial conditions**

- Position: centre of opening
- Energy: 1 eV
- Radial momentum: 0

- Optimal phase $\varphi_0 = 309°$
- Phase deviation $\Delta\varphi = 1.5°$
- $\varphi_0$ and $\Delta\varphi$ dependent on puller voltage

# Initial Energy




Initial position: center of chimney opening

Initial RF phase: 309°

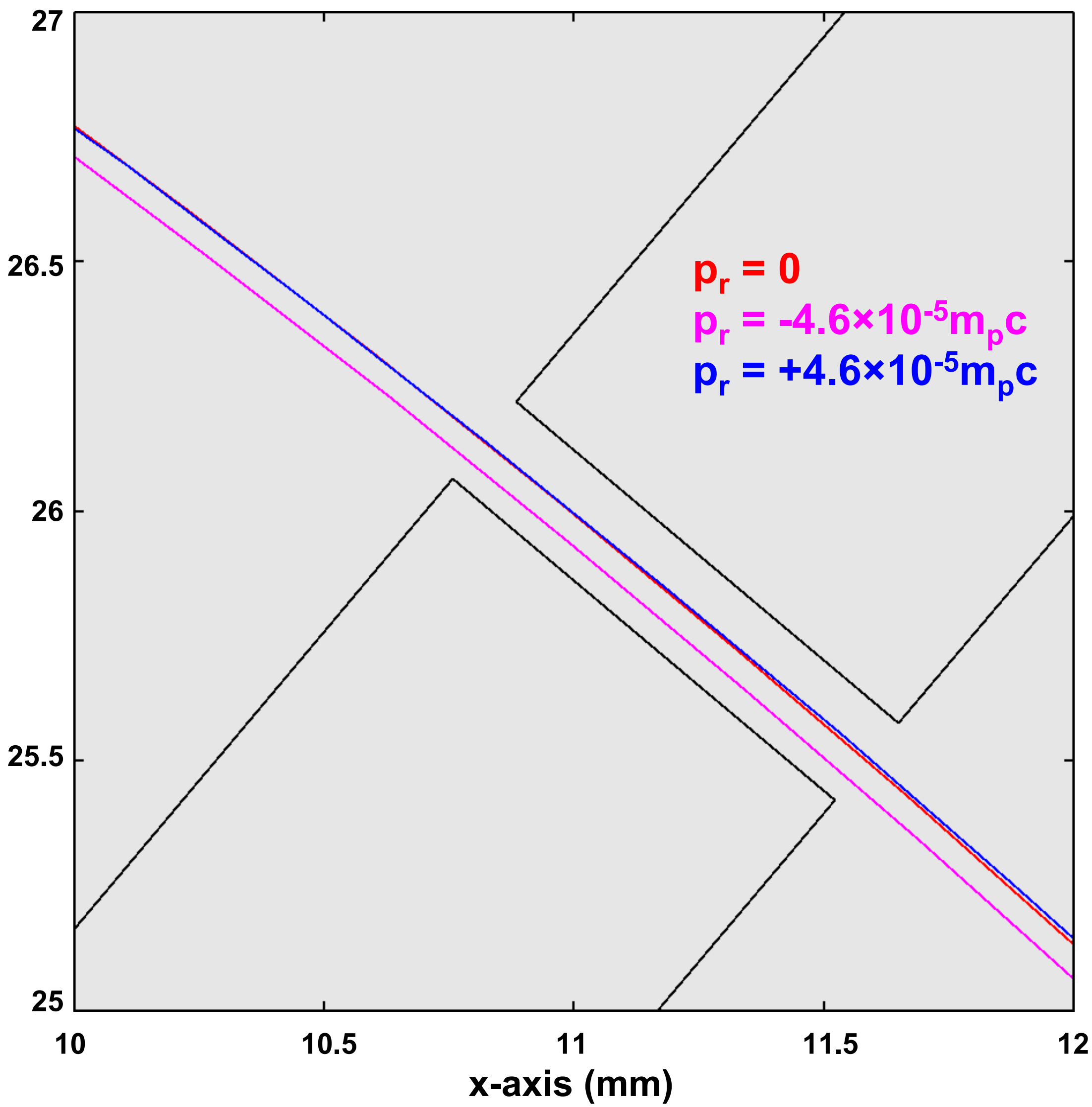
Radial momentum: 0

Initial energy:

- $E_0$ = 1 eV
- $E_0$ = 0.001 eV
- $E_0$ = 30 eV

**A wide range of low energy protons may pass through phase slit for a given RF phase**

# Initial Radial Momentum




Initial position: center of chimney opening

Initial RF phase: 309°

Initial energy: 1 eV

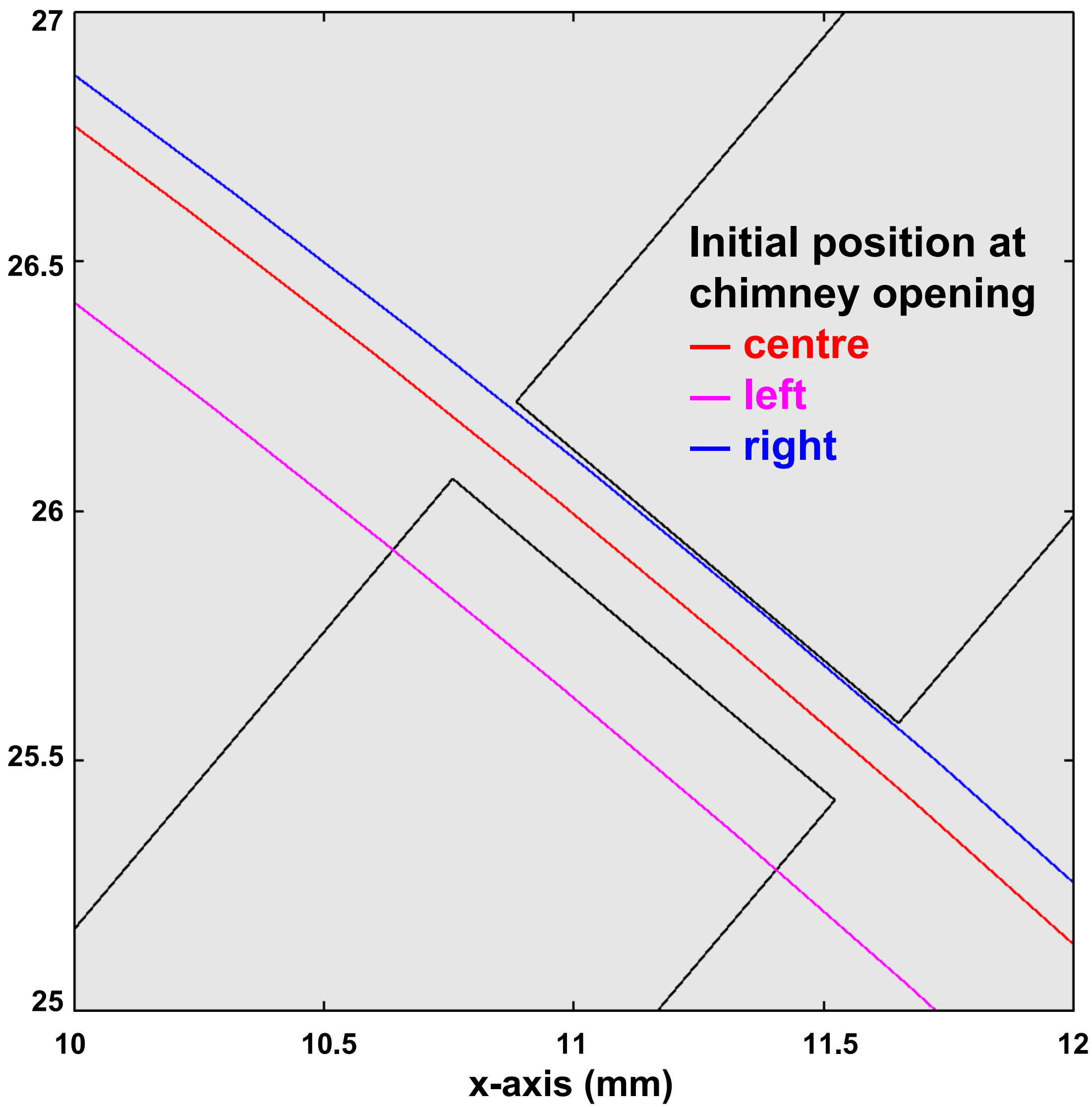
$p_0$: $4.6169\times10^{-5} m_p c$

Initial radial momentum:

- $p_r = 0$
- $p_r/p_0 = 0$
- $p_r = -4.6\times10^{-5} m_p c$
- $p_r/p_0 = -0.996$
- $p_r = +4.6\times10^{-5} m_p c$
- $p_r/p_0 = +0.996$

**Initial radial momentum spread not critical at all**

# Initial Position: Horizontal

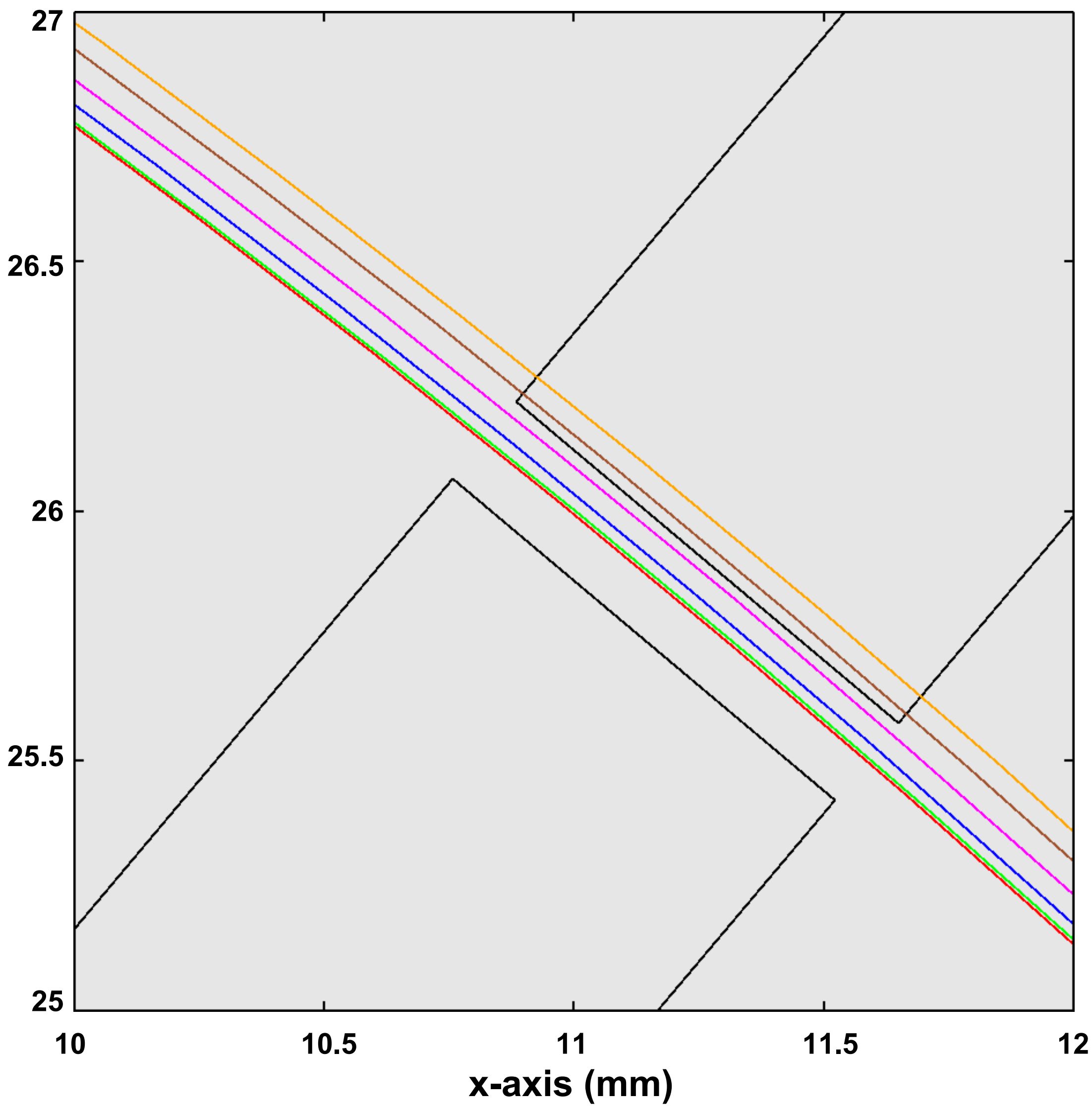



Initial RF phase: 309°
Initial energy: 1 eV
Radial momentum: 0

Initial horizontal position:
Centre of chimney opening
Left side of chimney opening
Right side of chimney opening

Left side more critical

# Initial Position: Vertical




Initial RF phase: 309°

Initial energy: 1 eV

Radial momentum: 0

Initial vertical position:

$z_0$ = 0

$z_0$ = 0.5 mm

$z_0$ = 1.0 mm

$z_0$ = 1.5 mm

$z_0$ = 2.0 mm

$z_0$ = -2.0 mm

**Initial vertical position less critical as horizontal one**

# Summary for Single Particle Tracking

- OPAL simulation for COMET applying multiple field maps

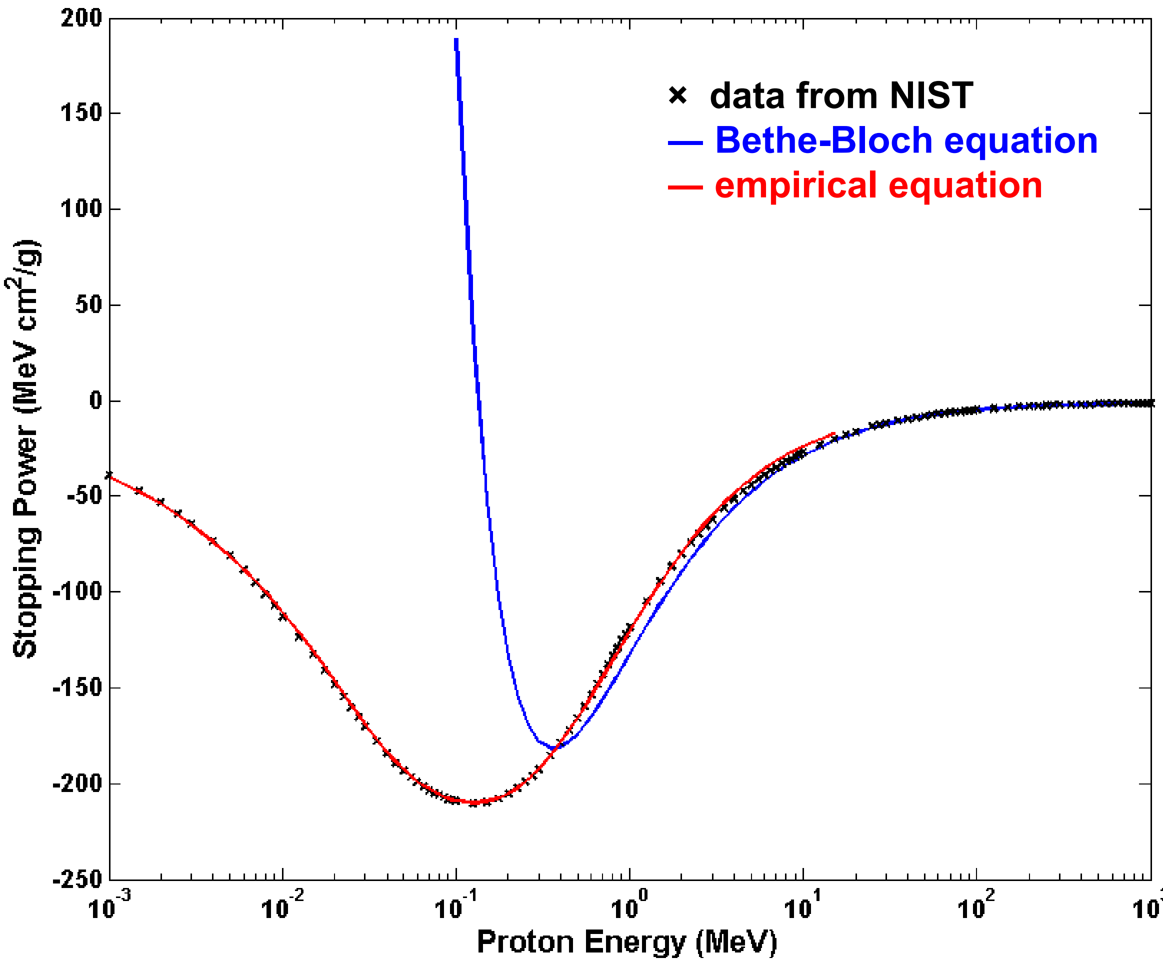
  Simulation fits well with experimental beam loss pattern

- Single particle tracking

  Puller voltage crucial for optimal RF phase and phase acceptance

  Particles from left side of chimney opening critical

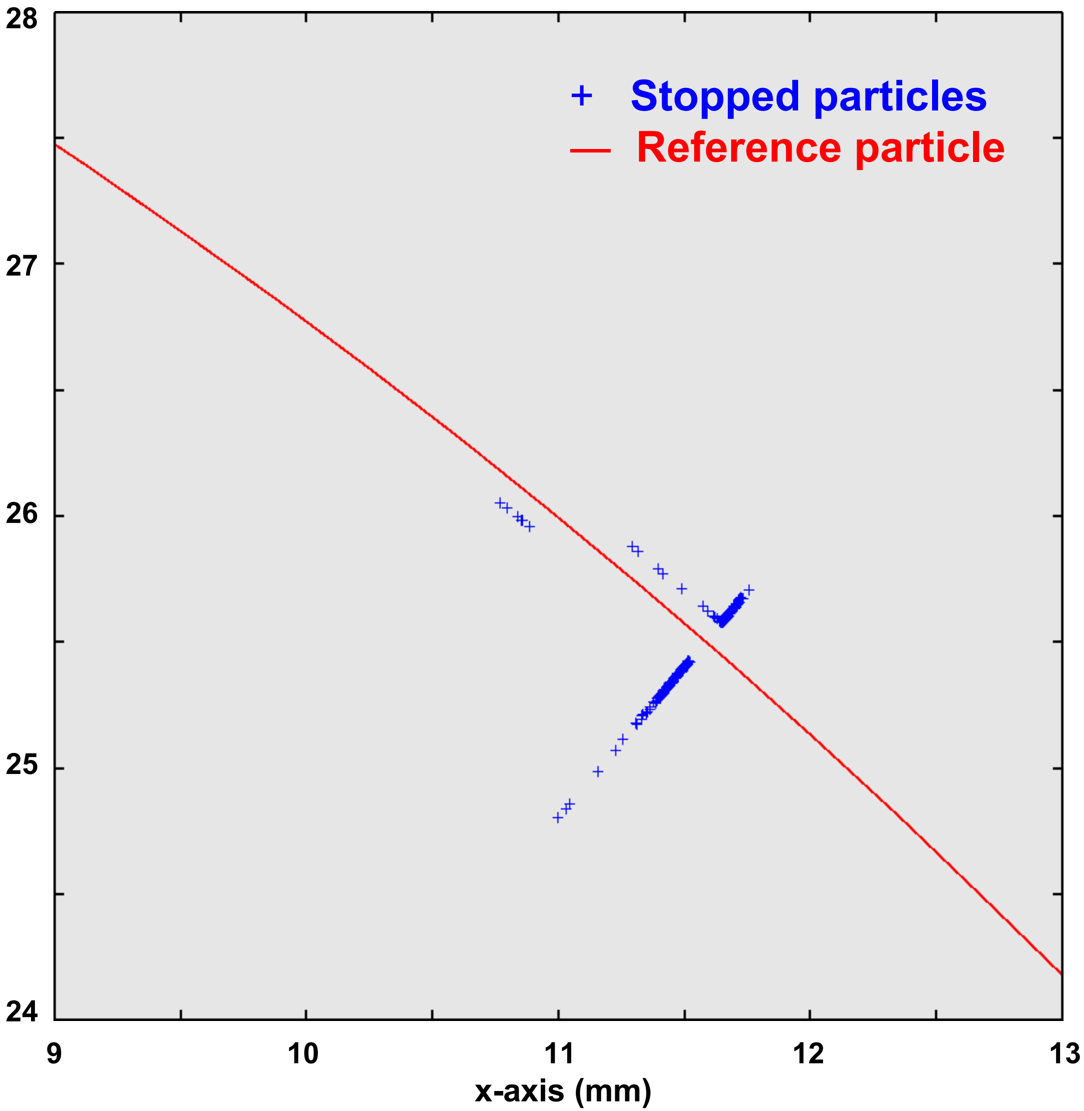
# Collimation in Low Energy Region




**Proton Stopping Power in Cu Target**

- The well-known Bethe-Bloch equation is inapplicable in low energy region
- An empirical equation has to be applied to calculate the stopping power in low energy region
- For proton in Cu collimator low energy means E < 1 MeV
- Beam energy at fixed phase slit: ~ 0.2 MeV
- Right physics and right geometry lead to right collimation in COMET central region

# Collimation by Phase Slit




Reference particle started from the centre of chimney opening

$E = 1$ eV

$p_r = 0$

$\varphi_0 = 309°$

1000 particles in Gaussian distribution started near chimney opening

$\sigma_x = 0.08$ mm, $\sigma_{px} = 0.5$ eV/c

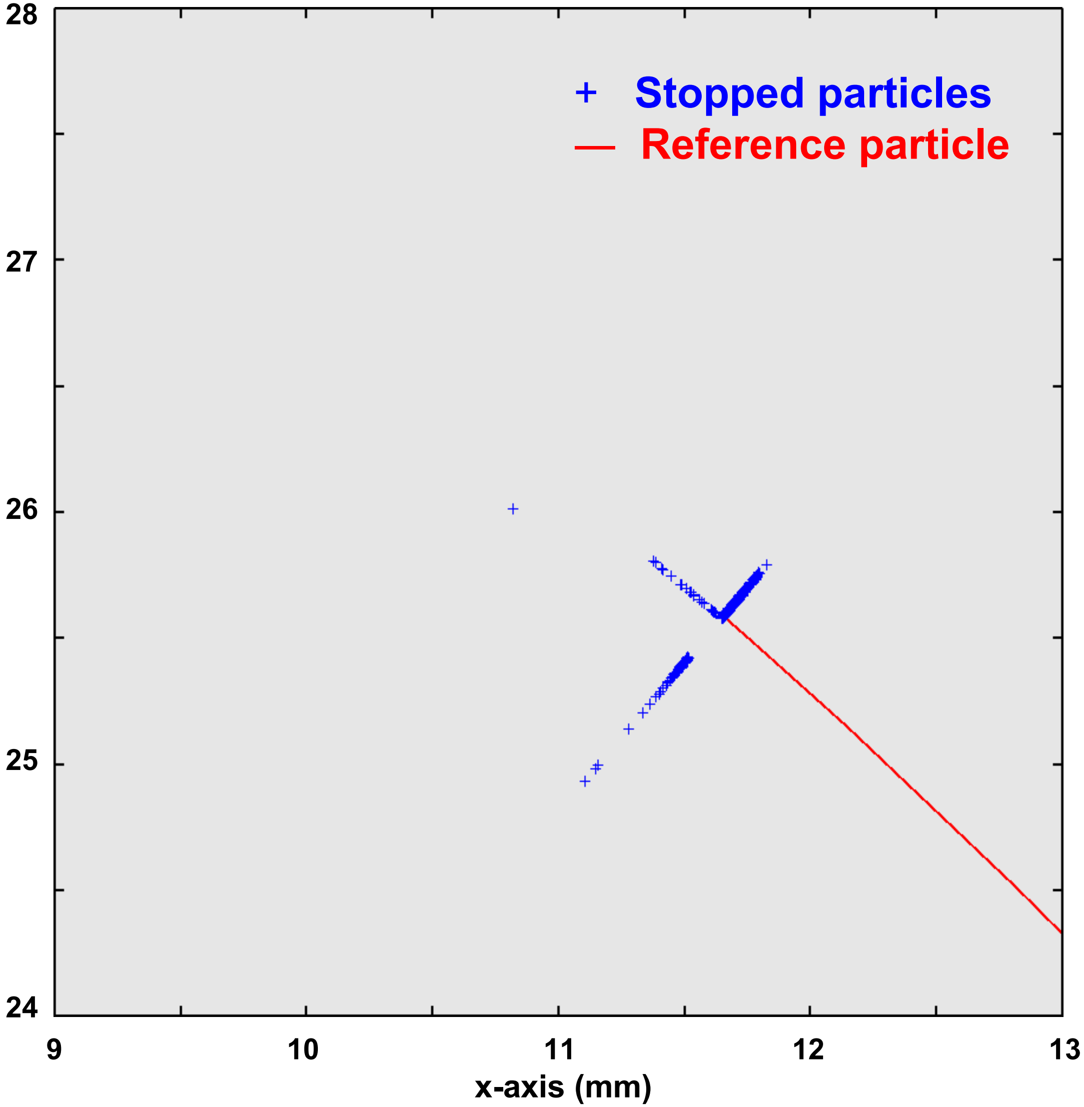
$\sigma_y = 0.00$ mm, $\sigma_{py} = 0.5$ eV/c

$\sigma_z = 0.80$ mm, $\sigma_{pz} = 0.5$ eV/c

651 particles passing through

Transmission: 65%

# Collimation by Phase Slit




Reference particle started from the centre of chimney opening

$E = 1$ eV

$p_r = 0$

$\varphi_0 = 307°$

1000 particles in Gaussian distribution started near chimney opening

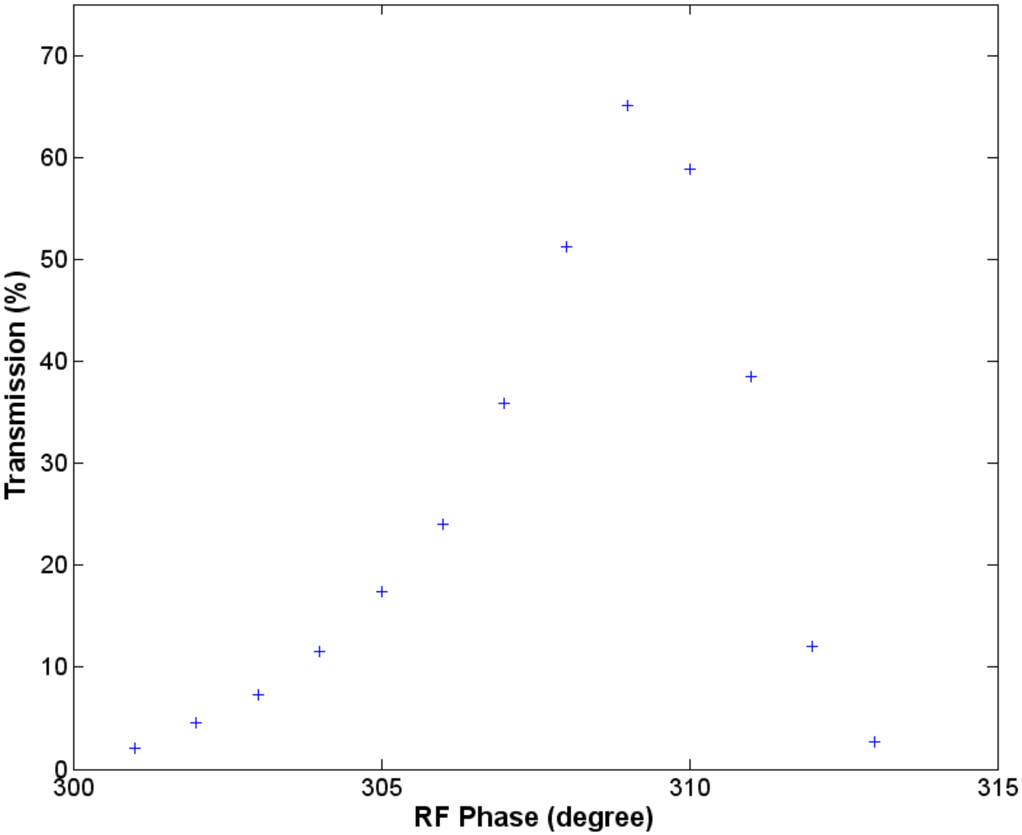
$\sigma_x = 0.08$ mm, $\sigma_{px} = 0.5$ eV/c

$\sigma_y = 0.00$ mm, $\sigma_{py} = 0.5$ eV/c

$\sigma_z = 0.80$ mm, $\sigma_{pz} = 0.5$ eV/c

**Transmission: 36%**

# Collimation by Phase Slit



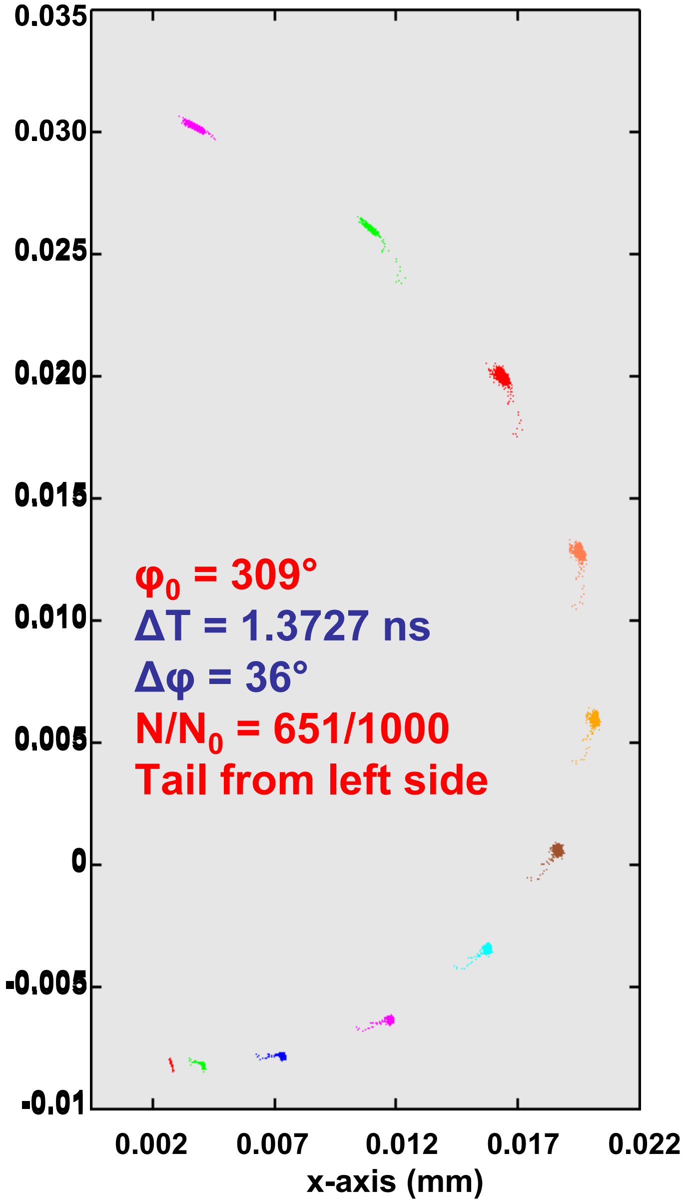

A maximal transmission at $\varphi_0$ ~309.5°

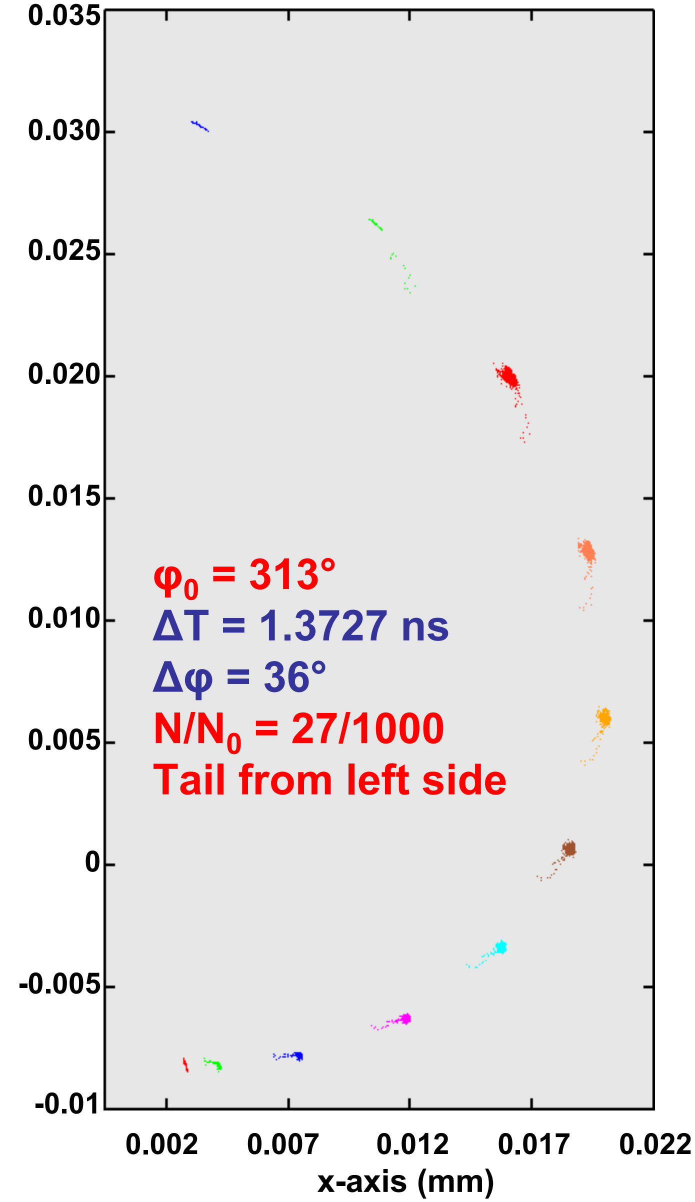
The transmission drops rather faster on higher RF phases

The acceptance of phase slit is around 10 degree of RF phase

Puller voltage crucial

# Bunch Development



# Summary and Outlook

- OPAL simulation for COMET applying multiple field maps
  Simulation fits well with experimental beam loss pattern
- Single particle tracking
  Puller voltage crucial for optimal RF phase and phase acceptance
  Particles from left side of chimney opening more critical
- Multiple particle tracking
  Beam collimation in low energy region
  Phase acceptance of the fixed phase slit around 10°
  Beam tail from left side of chimney opening

- Introduce vertical deflector, vertical collimators, and phase slit in special form
- Better specification of the initial beam
- Trim rods
- Extraction

# Acknowledgement

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