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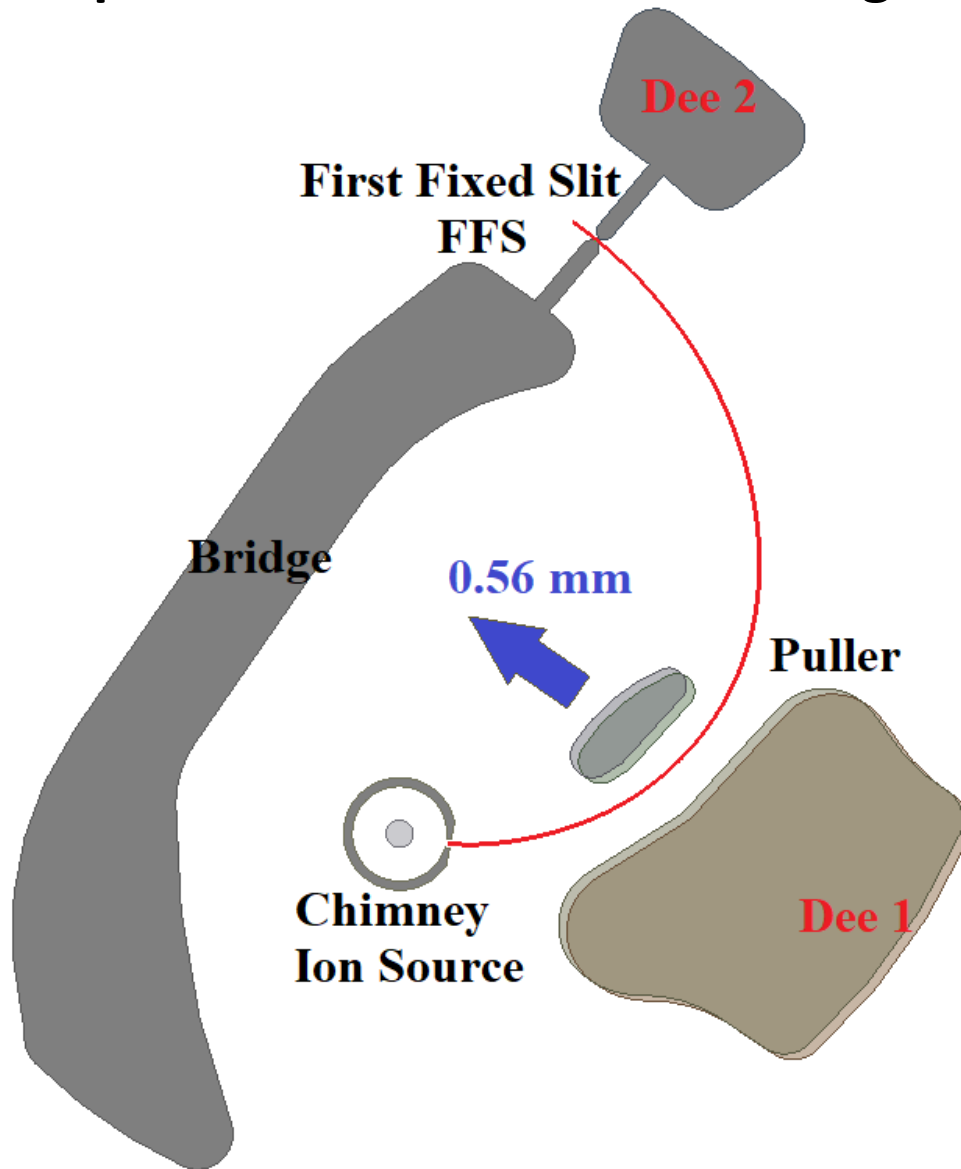
Ch. Baumgarten, P. Frey, M. Hartmann, R. Kan, M. Kostezzer, A. Muelhaupt,
M. Schippers, A. Schmidt, J. Snuverink, H. Zhang(Speaker) :: Paul Scherrer Institute

OPAL Simulation on the Beam Transmission in the Central Region of Medical Cyclotron COMET

December 7, WEA001, CYC2022, Beijing, China

- Introduction
- OPAL Simulation
 - Model of COMET Central Region
 - Field Maps
 - Initial Conditions
 - Simulation Results
- Experiment
- Summary

Top View of COMET Central Region



It was reported by Varian Medical Systems Particle Therapy GmbH, Germany

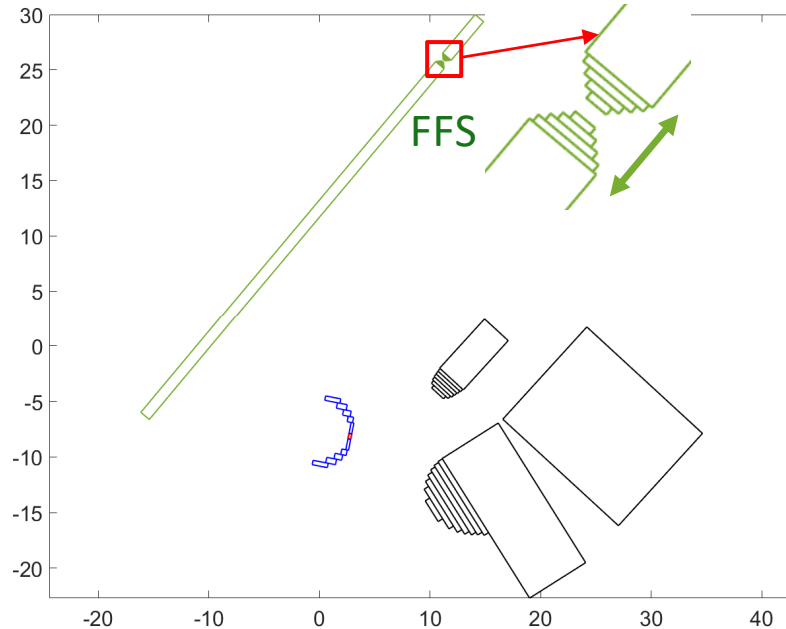
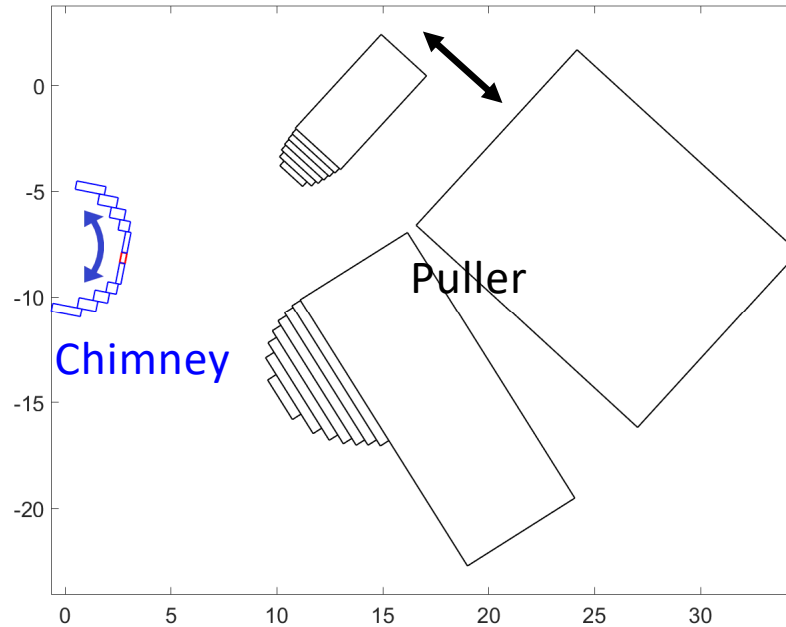
- Puller shifted 0.56 mm towards the center
- Beam intensity passing the FFS increases from 2500 nA to 4000 nA
- 60% improvement
- Configuration could be further optimized

- A high FFS transmission is an important step towards an extracted beam of high intensity
- Desirable for FLASH proton therapy.
- Simulation may be helpful to quantify the factors correlated with FFS transmission.
- Simulation may shed more light on further improvement

- OPAL is a parallel open source tool developed at PSI for charged particle optics in accelerators and beam lines.
- In OPAL simulation, a particle can only cycle anticlockwise inside a cyclotron.
- In medical cyclotron COMET, protons cycle clockwise.
- The model in this simulation is a mirror image of the real machine.

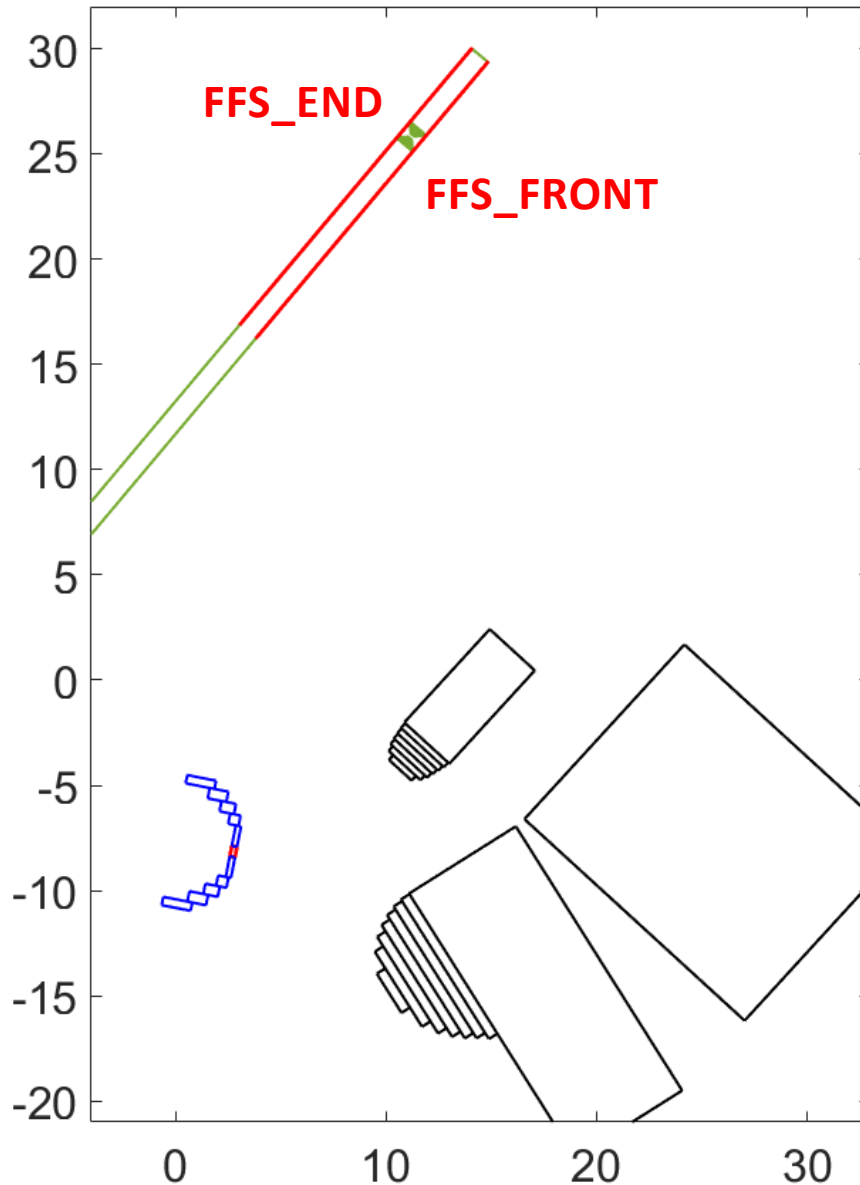
- Particle tracking starts from the chimney opening at $t = 0$.
- ϕ_0 is the initial RF phase at $t = 0$.
- $V_{\text{puller}} = -V_0 \cos(\omega t + \phi_0)$
- $\omega = 2\pi f$, $f = 72.61$ MHz, $V_0 \approx 80$ kV

OPAL Model for COMET Central Region



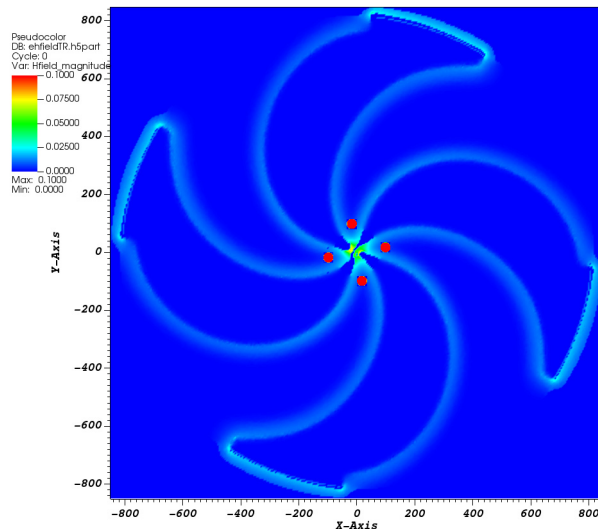
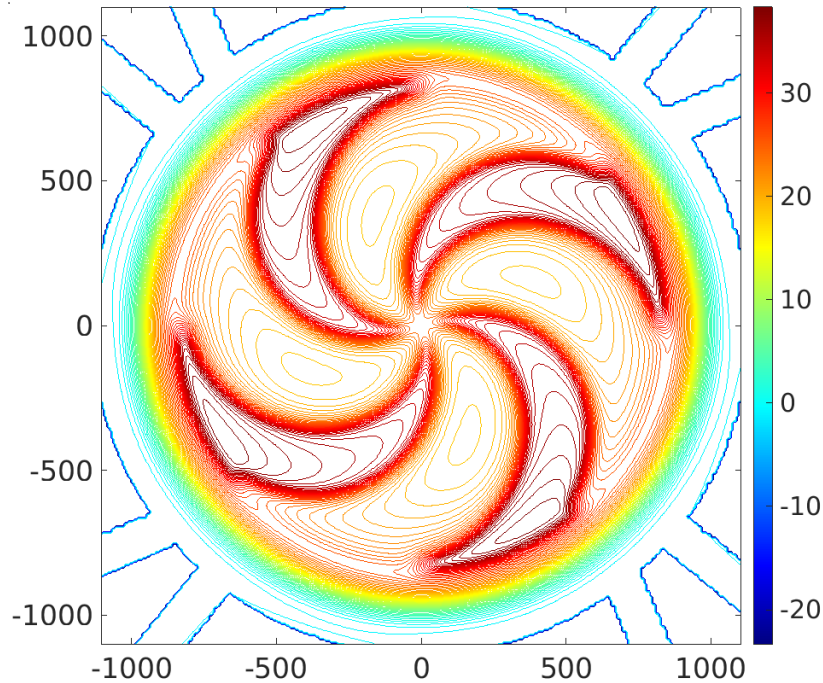
- OPAL uses only rectangular collimator blocks in a cyclotron
- Chimney is modeled by 12 rectangular collimator blocks
- Opening 0.5 mm wide and 3 mm high
- Chimney rotation is implemented
- Puller is modeled by 16 rectangular collimator blocks
- Puller shift is implemented
- FFS is modeled by 10 rectangular collimator blocks
- Shifting, opening and closing of FFS are implemented

Radial PROBEs FFS_FRONT & FFS_END



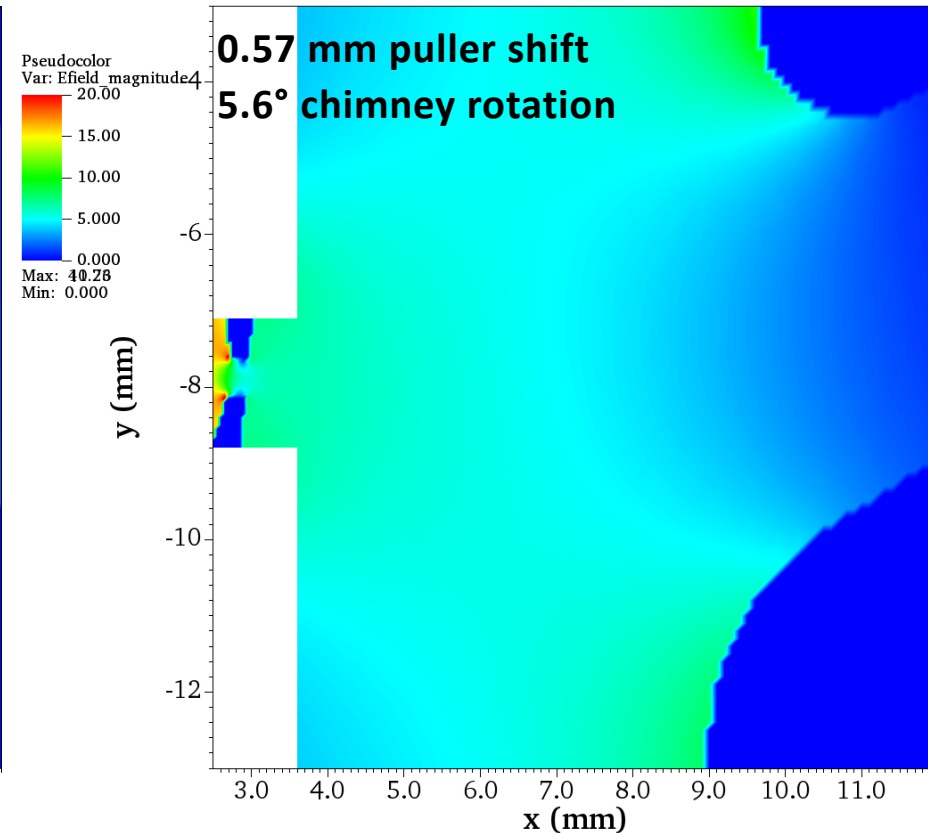
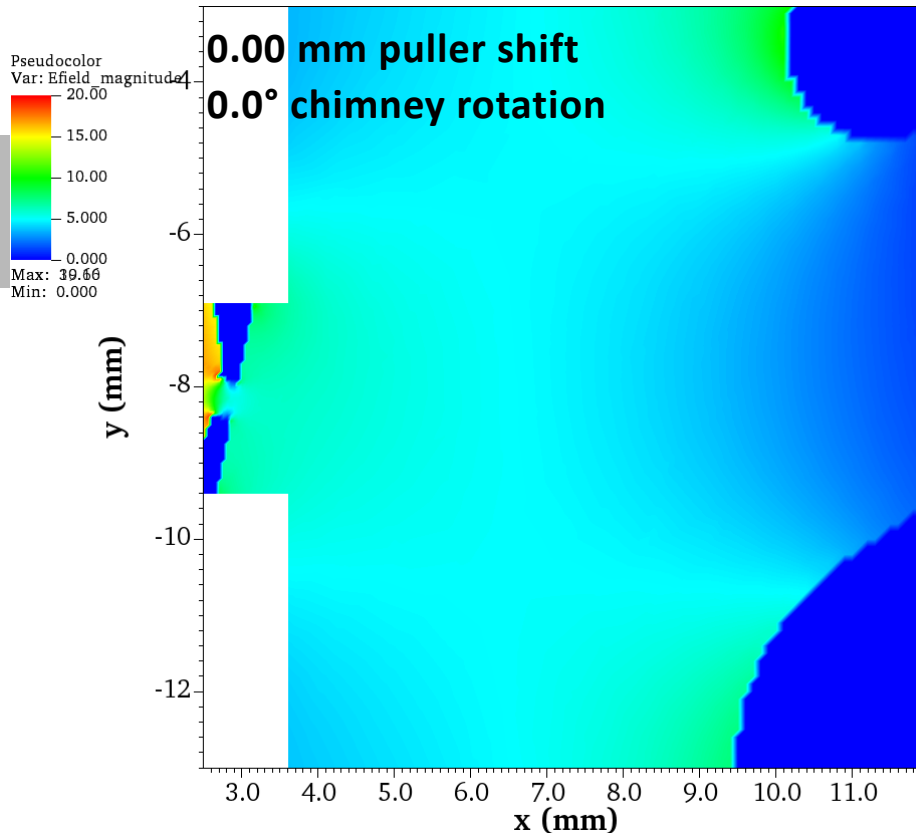
- PROBE in OPAL is a rectangular plane defined by its two corners (xstart, ystart, zstart) and (xend, yend, zend)
- PROBE has no effect on a passing particle
- PROBE registers the state of a particle upon passing the probe
(x, y, z, p_x, p_y, p_z)
- Two PROBEs are created
- **FFS_FRONT** just in front of FFS
- **FFS_END** just behind FFS

Particle Tracking in Electromagnetic Fields



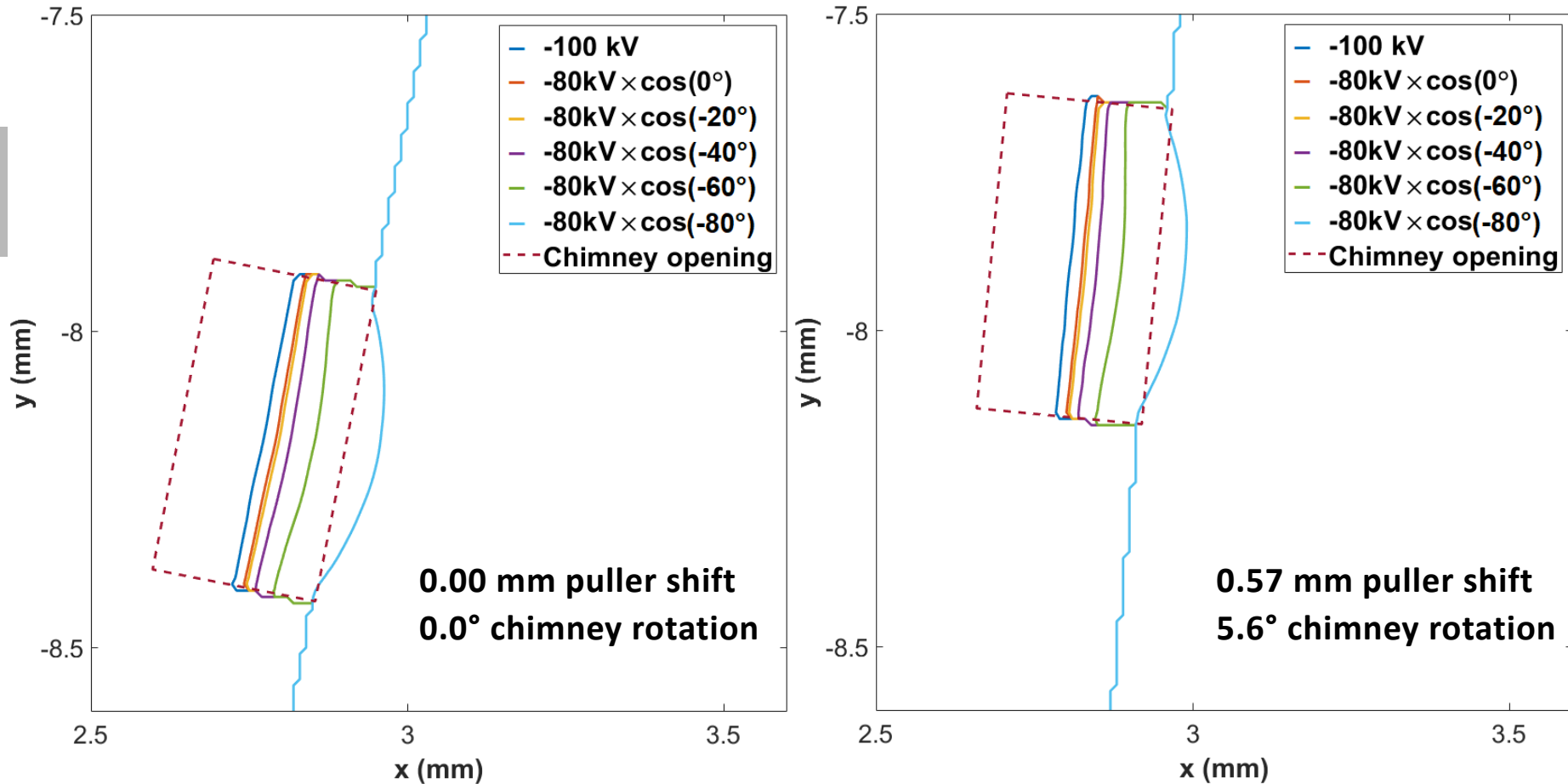
- OPAL features particle tracking through electromagnetic field maps
- 2D/3D, static/RF, separated/overlapped
- 2D static magnetic field map in the median plane from TOSCA simulation
- Unit: mm & kGauss
- ~2.4 T in the central region
- ~3 T near extraction
- 3D E-component of RF field
1700×1700×30 mm³ from ANSYS RF simulation
- Unit: mm & MV/m
- 250 MeV in ~650 turns
- Four maps for four inner trim rods
- Hard edge and uniform
- Important for beam centering

E-Field in Central Region from ANSYS



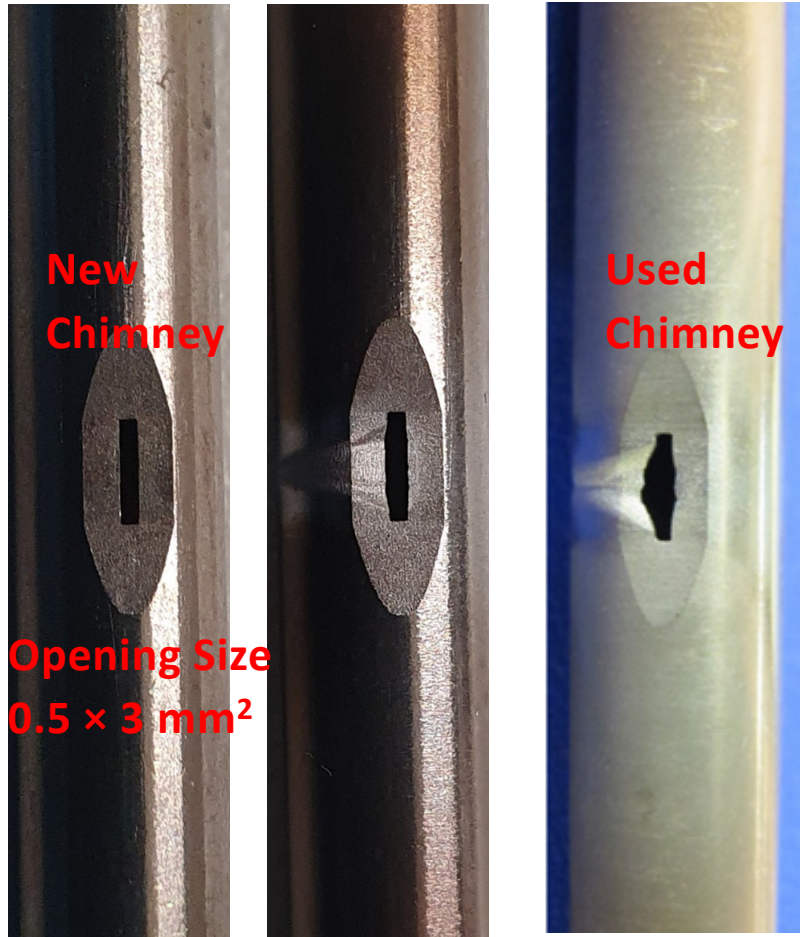
- Field map for a specific puller shift/chimney rotation calculated by ANSYS electrostatic field analysis
- Chimney grounded, Dee 1/3 (Puller) at $-80\cos(\phi_0)$ kV, Dee 2/4 at $+80\cos(\phi_0)$ kV
- $\phi_0 = -85:5:-75^\circ, -74:1:-49^\circ, -50:5:-25^\circ$, 33 ϕ_0 points
- ϕ_0 from -75° to -50° important for FFS transmission

Zero Potential Line Shifting with Puller Voltage



- Zero potential lines are determined also after applying $\pm 80 \cos(\phi_0)$ kV on Dees and 0 on chimney
- Zero potential lines shift and bend outwards when ϕ_0 decreasing from 0 to -80°
- For ϕ_0 around -80° , zero potential lines bend partially outside of chimney opening

Initial Conditions for Particle Tracking



New
Chimney

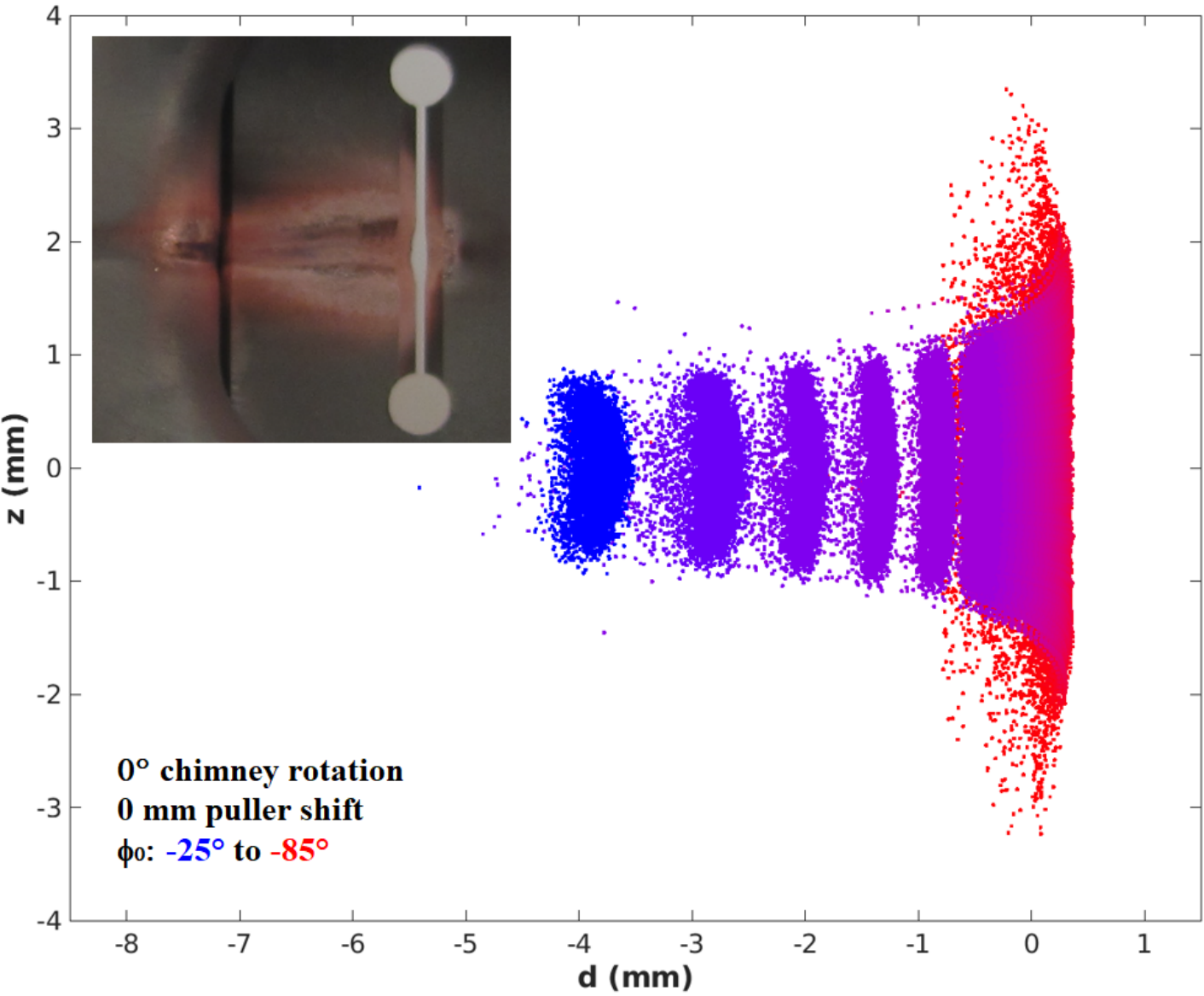
Opening Size
 $0.5 \times 3 \text{ mm}^2$

Used
Chimney

Left side more eroded

- Reference particle starts at the center of zero potential line
- $E_0 = 1 \text{ eV}$, $p_0 = 4.33E4 \text{ eV}/c$
- 10000 protons are generated from a Gaussian distribution
- $\sigma_x = 0.5/2/3 = 0.083 \text{ mm}$
- $\sigma_z = 3/2/3 = 0.5 \text{ mm}$
- σ_y may be set to 0
Protons start on zero potential surface approximately
- $\sigma_{px} = \sigma_{py} = \sigma_{pz} = 3.06E4 \text{ eV}/c$
Equivalent to $\sigma_{Ex} = \sigma_{Ey} = \sigma_{Ez} = 0.5 \text{ eV}$

Particle Distribution on FFS Front Surface



0 mm puller shift
0° chimney rotation
 ϕ_0 : -85° to -25°
right to left
 $\Delta\phi_0$: 5°

Similarity between simulation and photo

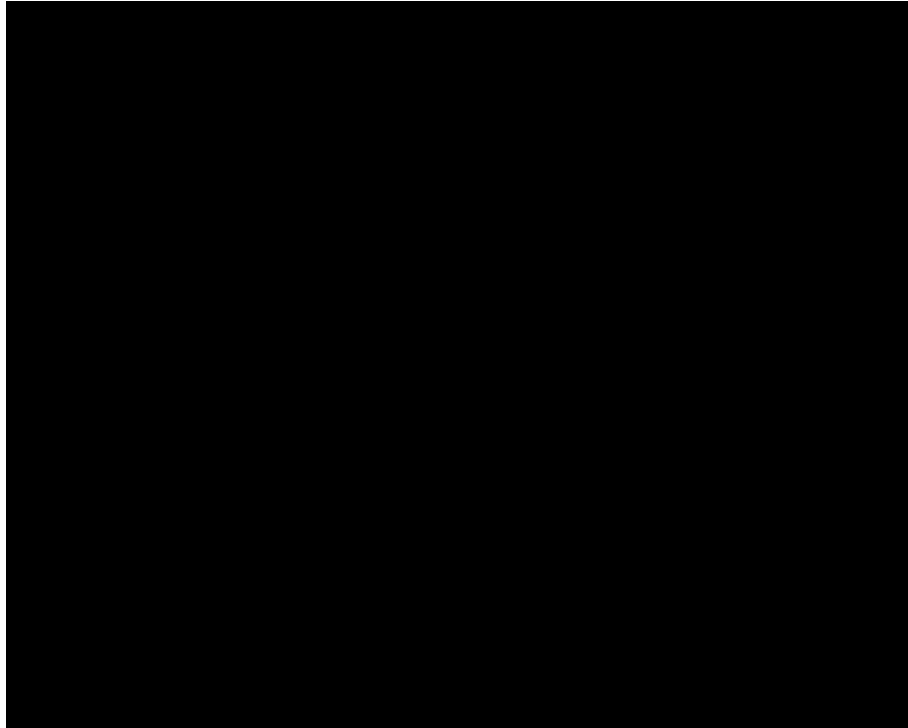
d-axis: intersection between the FFS front surface and the median plane

d: distance to the center of FFS slit projected on d-axis

d-Histogram after 0.57 mm Shift/5.6° Rotation

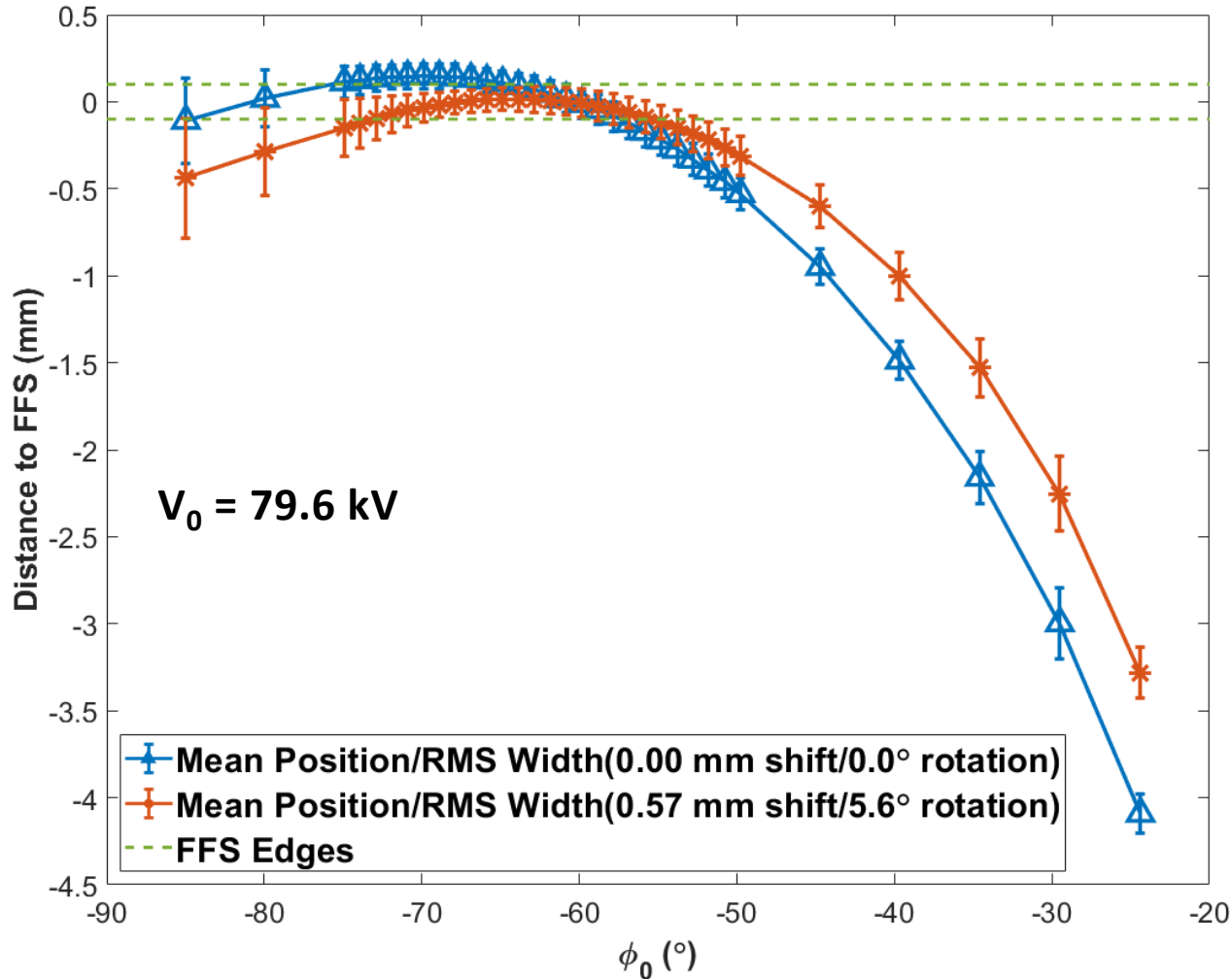
0.57 mm Puller Shift/5.6° Chimney Rotation

$V_0 = 79.6$ kV



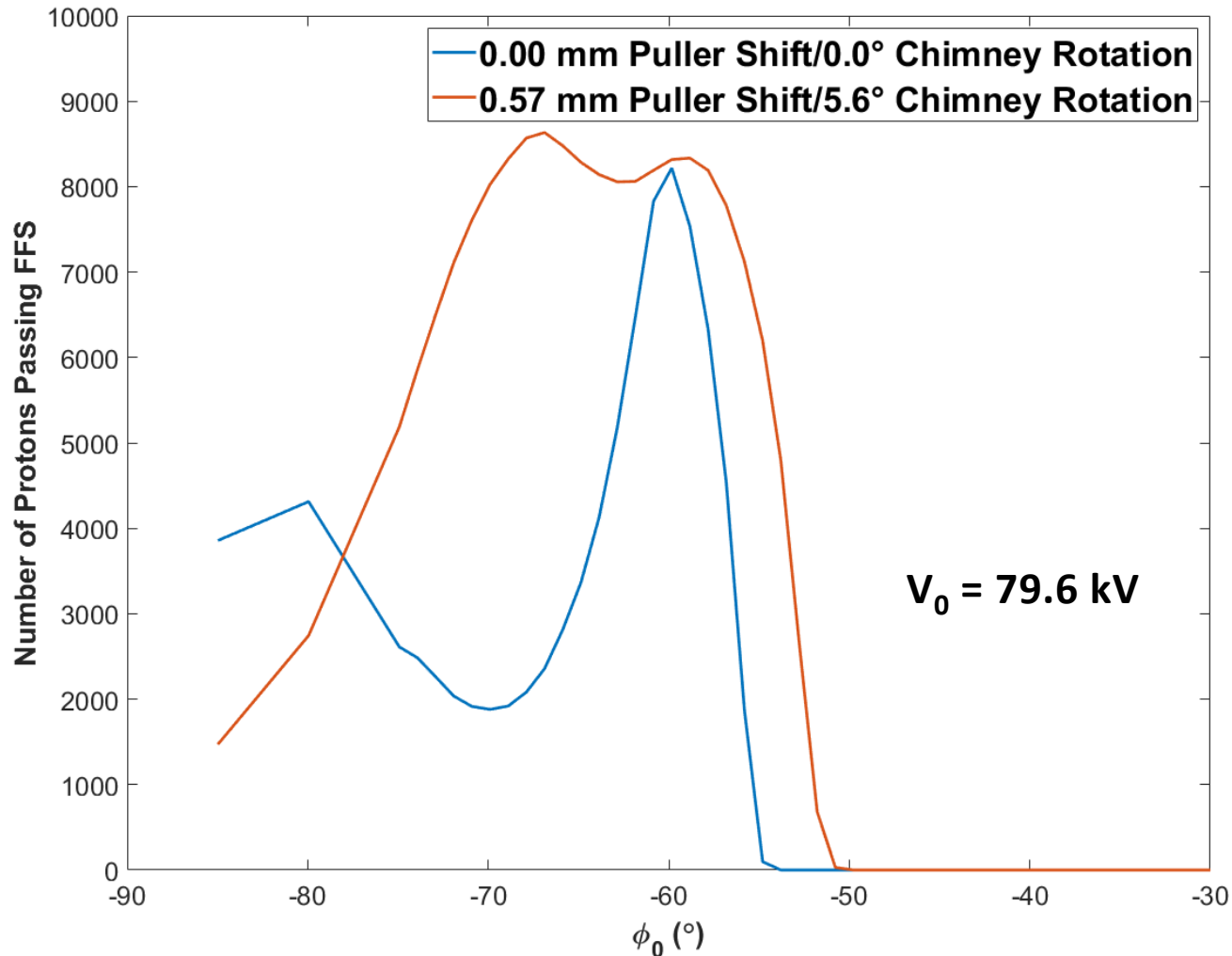
- Higher FFS transmission requires basically narrower beam closer to FFS over a wider range of RF phase
- FFS transmission depends on many factors
- Position and aperture of FFS, puller position, chimney orientation, peak puller voltage, etc.

\bar{d} and σ_d on FFS Front Surface vs. ϕ_0



Mean beam position \bar{d} and RMS width σ_d can be derived for each RF initial phase ϕ_0
 The plot shows that the beams from the modified configuration fit better to FFS at $V_0 = 79.6 \text{ kV}$

Number of Protons Passing FFS vs. ϕ_0



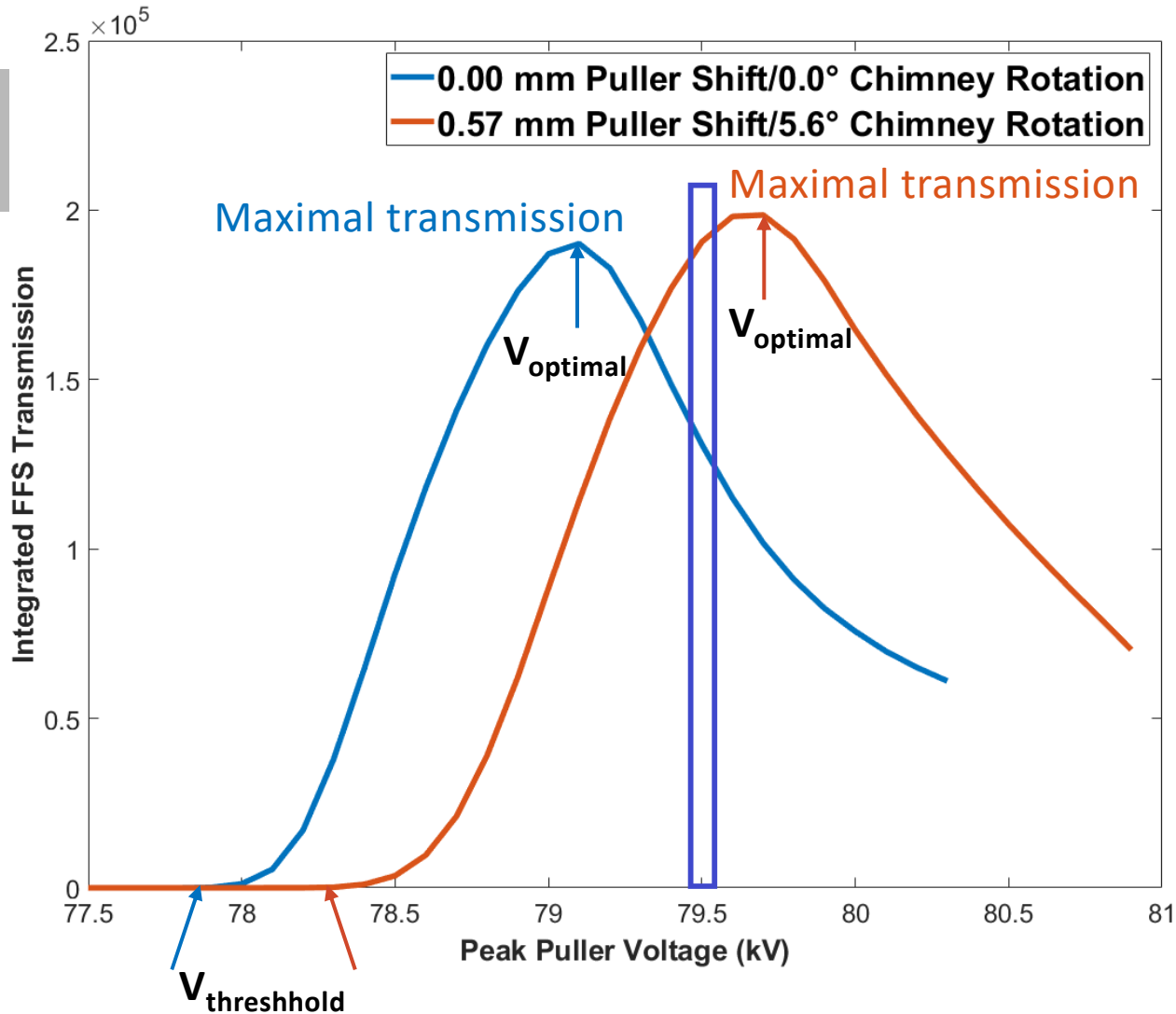
Number of protons passing FFS N can be derived by particle tracking for a chosen ϕ_0

N plotted against ϕ_0 for **original** and **modified** chimney/puller configurations

FFS transmission may be derived from an integral over ϕ_0 , equivalent to time t

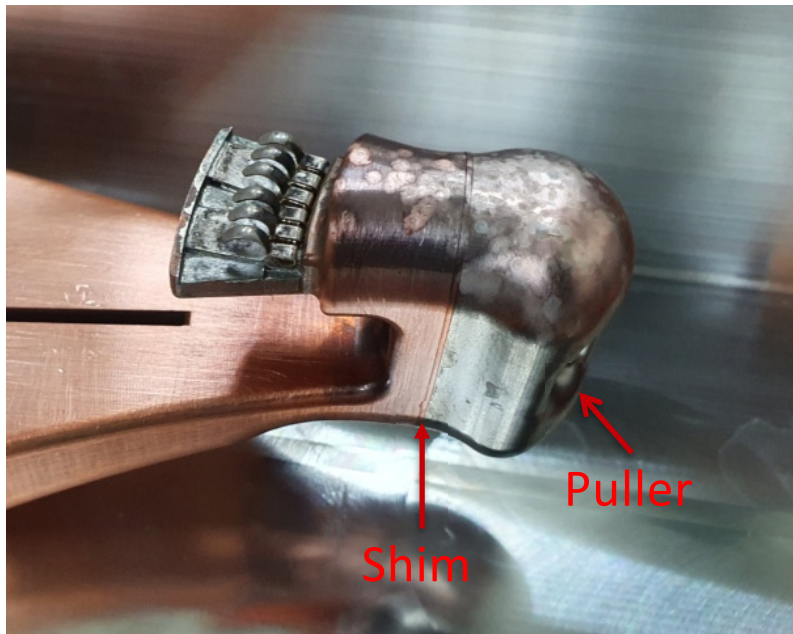
The ratio between FFS transmission from **modified/original** configuration is around 1.7

Integrated FFS Transmission vs. V_0



- $V_0 < V_{\text{threshold}}$, 0 transmission
- $V_0 > V_{\text{threshold}}$, transmission increases
- $V_0 = V_{\text{optimal}}$, maximal transmission
- $V_0 > V_{\text{optimal}}$, transmission decreases
- $V_0 \sim 80$ kV, transmission significantly higher after puller shift/chimney rotation

Experiment in COMET Cyclotron

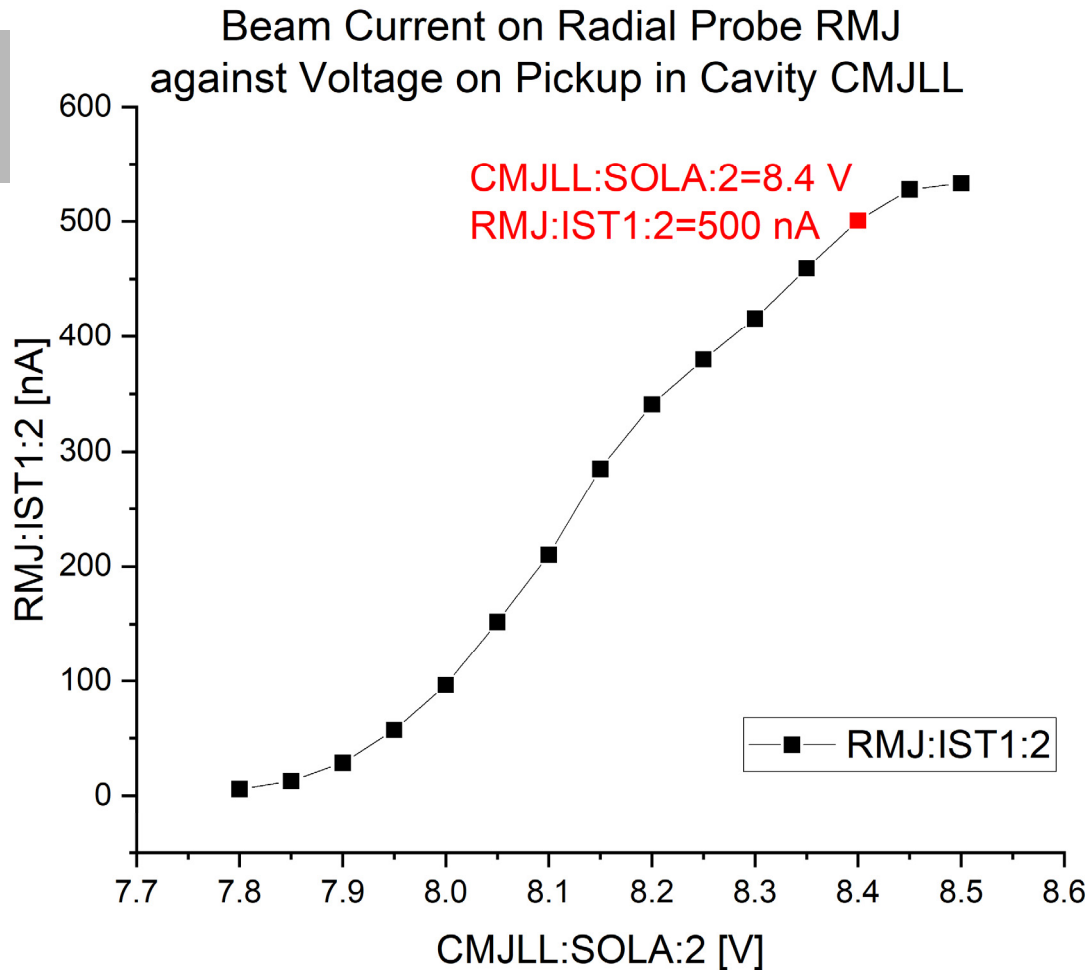


- Thickness of shim: 0.57 mm
- Clockwise chimney rotation: 5.6°
- FFS aperture: 0.16 mm before
0.20 mm after
- Radial probe 310 mm from center
- No obstacle in between
- Higher output on radial probe

	Arc current	Output
before	80 mA	368 nA
after	80 mA	1310 nA

- **FFS transmission 2.8 times higher**

Beam on Radial Probe vs. Voltage on RF Pickup



0.57 mm Puller Shift/5.6° Chimney Rotation

After modification

- Beam current on radial probe RMJ was measured as the function of the voltage on pickups in Dees CMJLL.
- The measured curve looks similar with the simulated curve of FFS transmission vs. V_0 .
- Operation point CMJLL = 8.4 V, RMJ = 500 nA, near maximum.
- The modified configuration is almost optimal for FFS transmission.
- CMJLL = 8.4 V corresponds to $V_0 = 79.6$ kV

- The simulated particle distribution on the FFS front surface looks similar to a photo of the front side of a FFS plate.
- Both simulation and the measurement indicate that the FFS transmission can be significantly improved after a 0.57 mm puller shift and a 5.6° chimney rotation.
- The simulated curve of FFS transmission vs. V_0 fits well with the measured curve of the beam current on the radial probe vs. the average voltage on the pickups inside Dees, which indicates that the peak voltage on the puller is ~79.6 kV for the routine operation.
- The configuration of the central region can be further optimized to get higher FFS transmission.
- The beam acceleration and extraction after the modification will be further verified through a combination of simulation and experiment.

Thank you for your attention!

My thanks go to

- All my co-authors for excellent team work.
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