Ongoing Injection Studies of Electrons from E-gun to Permanent Magnet

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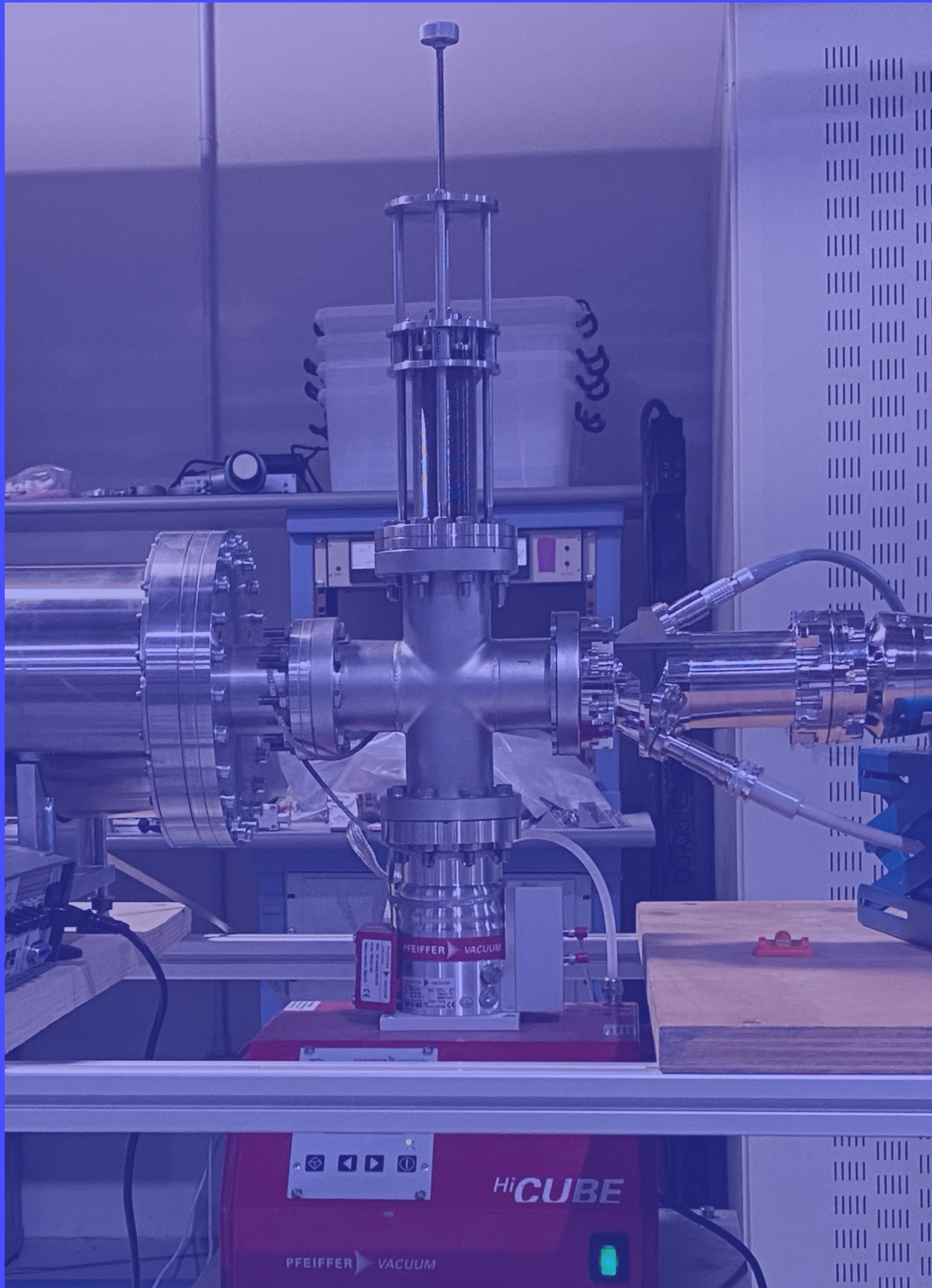
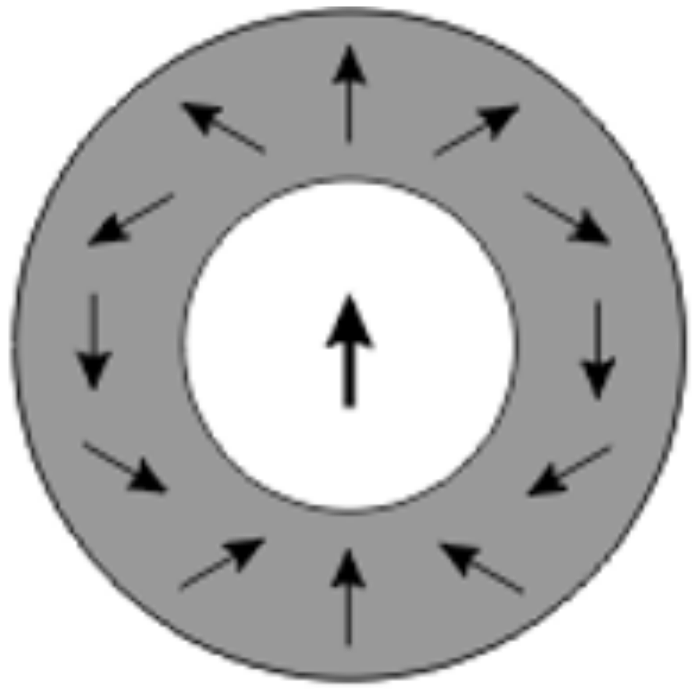
Outline

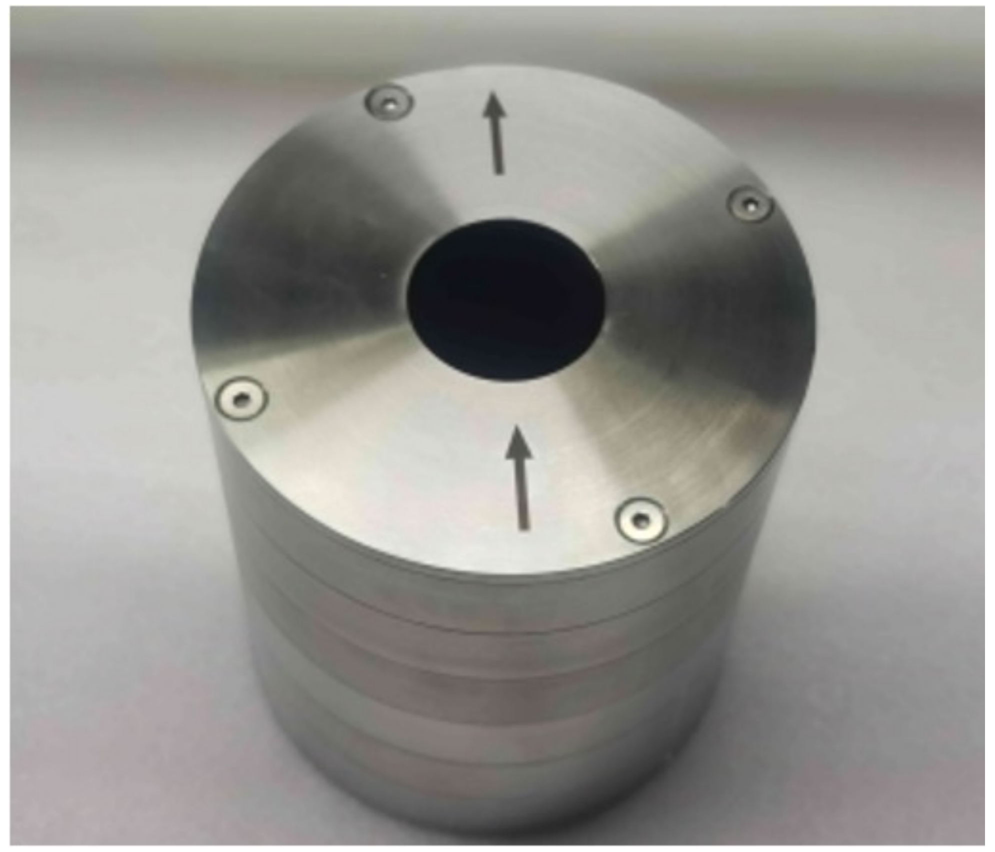
- ❏ Proposes
- ❏ Characterization of permanent magnet
- ❏ 1st setup: the perfect source for RF calibration
- ❏ 2nd setup: how to enter and get out in 1 T field
- ❏ E-gun setup state of art
- ❏ Prospectives & Next steps

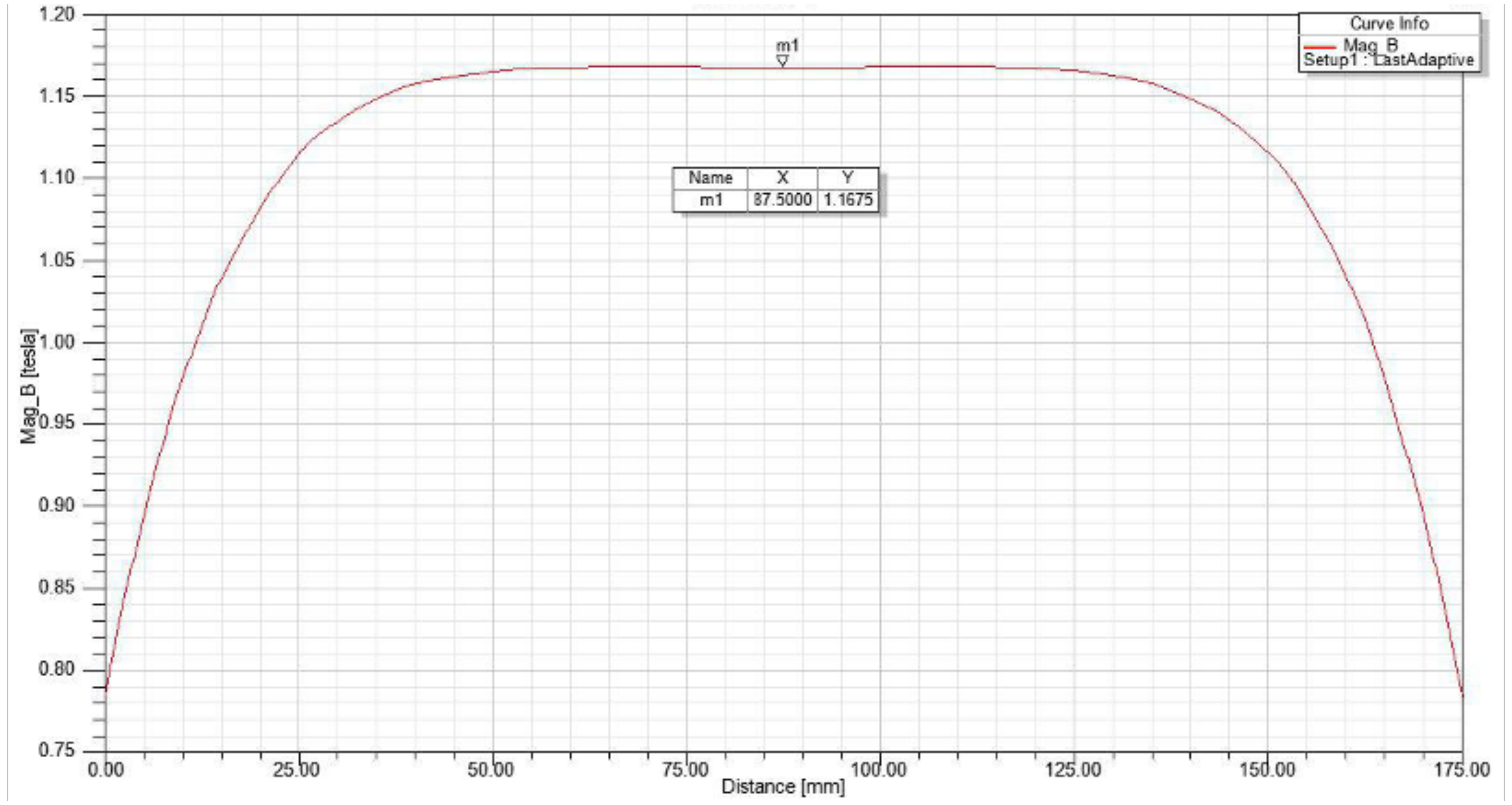


A Compact Powerful Magnet @ LNGS

- Magnet in LNGS:
  - Halbach cylinder permanent magnet
  - 185 mm length, 170 mm external ⌀, 50 mm internal ⌀
  - 1 T uniform magnetic field in *limited region inside*
  - Only z profile of B module from producers
  - Field lines difficult to simulate
    (field produced by array of magnets)



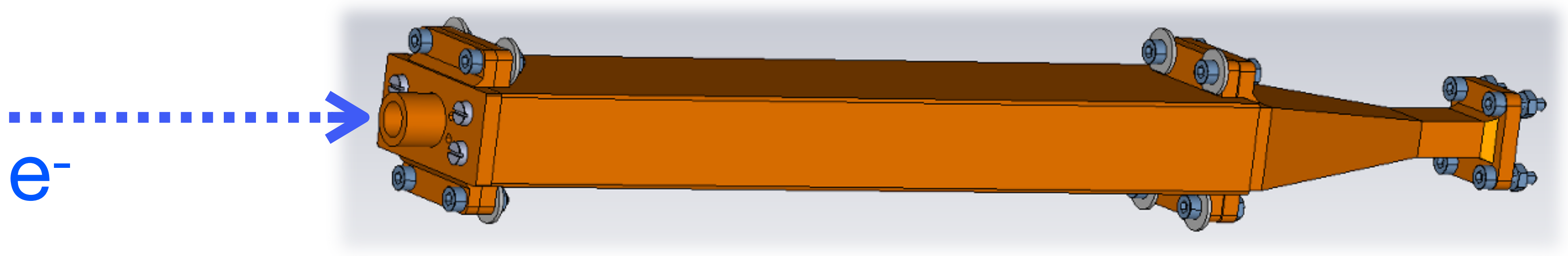




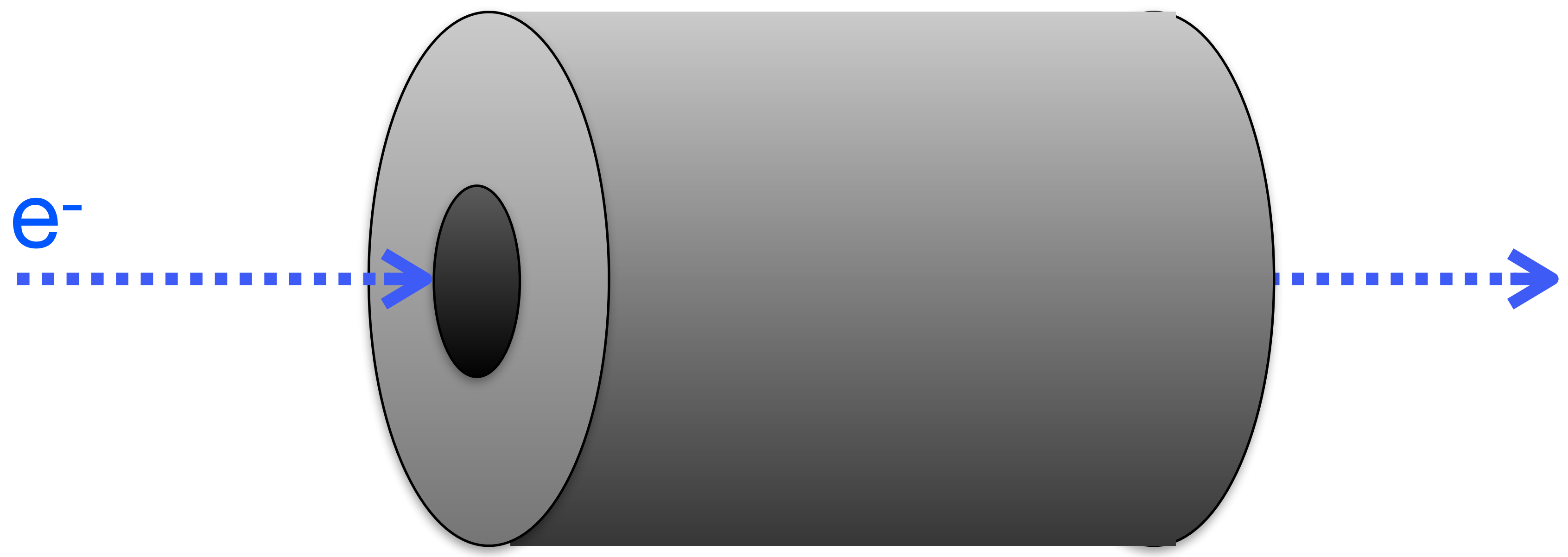
- Actual usage: RF detection setup with ^{83m}Kr gas injected directly into trap

E-gun + Magnet: Two Possible Measurements

- 1st setup: injection of beam electrons in actual RF region setup in LNGS (F. Virzi talk)
  - Now: ^{83m}Kr injection → 30.4 keV e^- (L line) produced in random point of trap
  - With e-gun:
    - ✓ 18.6 keV electrons
    - ✓ More control on electron initial distribution
    - ✓ More electrons (e-gun current till mA!)



- 2nd setup: passage of electrons trough 1 T magnetic field proof-of-principle
  - Bottle effect breaking demonstration
  - Become familiar with same drift exploited in filter



B MAP NEEDED!

Exploiting Laplace Equation for Scalar Potential

- Aim: know magnetic field behavior **outside** magnet to simulate e^- injection
- No sources in region of interest ⟶ governing laws:
- Procedure:
  1. Solve Laplace equation with **Neumann boundary conditions** = $B_\perp$ on infinte plane
  2. Derive B from ϕ_m
  3. Outcome = magnetic field lines
- Only need to measure $B_\perp$ on "infinite" plane

- **Gauss's Law for Magnetism:**

$$\nabla \cdot \mathbf{B} = 0 \quad \text{(No monopoles)}$$

- **Ampère's Law (Static, No Currents):**

$$\nabla \times \mathbf{B} = 0 \quad \text{(Field is curl} - \text{free)}$$

- **Implications:**
  - Existence of a scalar potential:

$$\mathbf{B} = -\nabla \phi_m$$

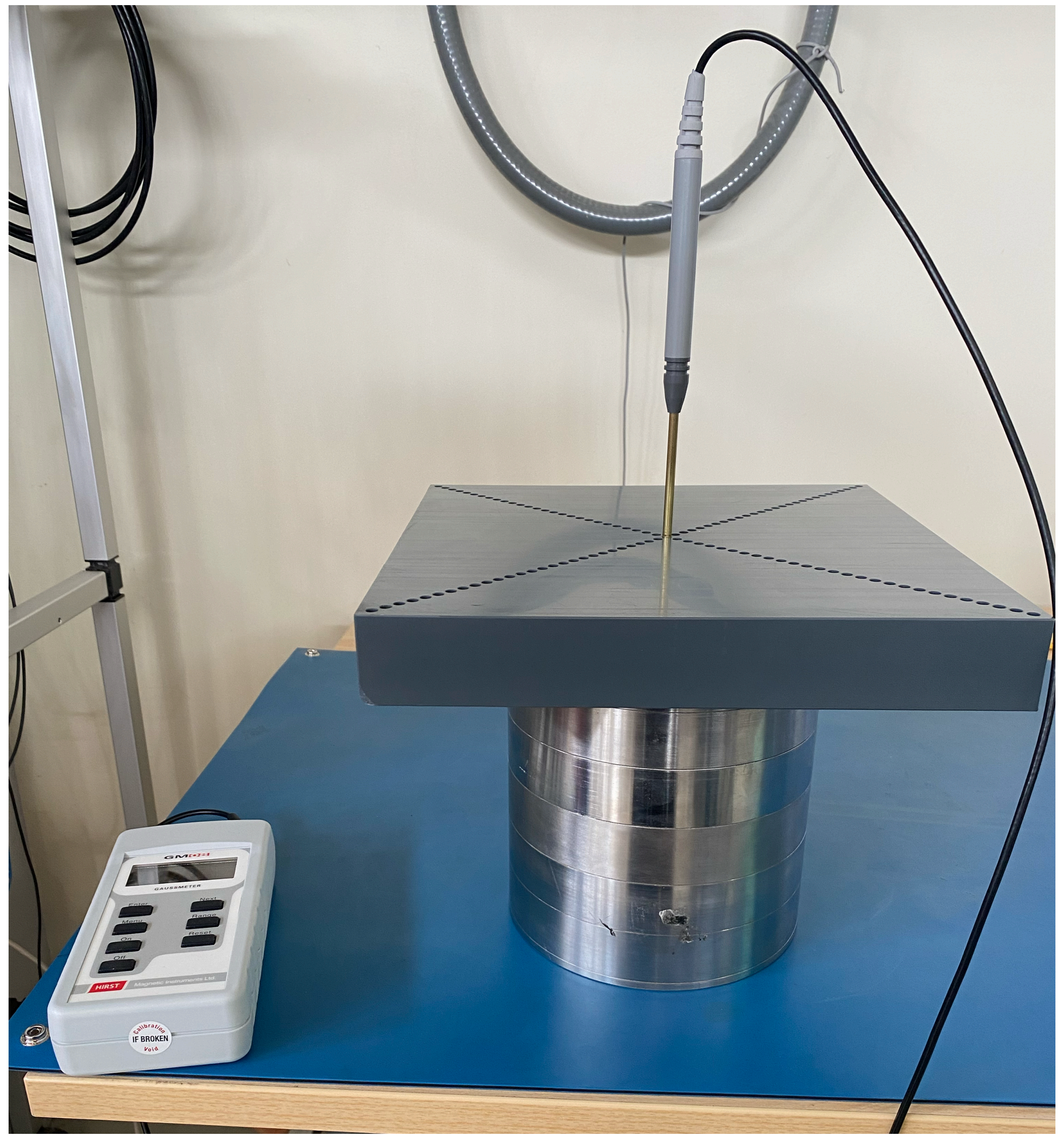
  - Laplace's Equation for ϕ_m:

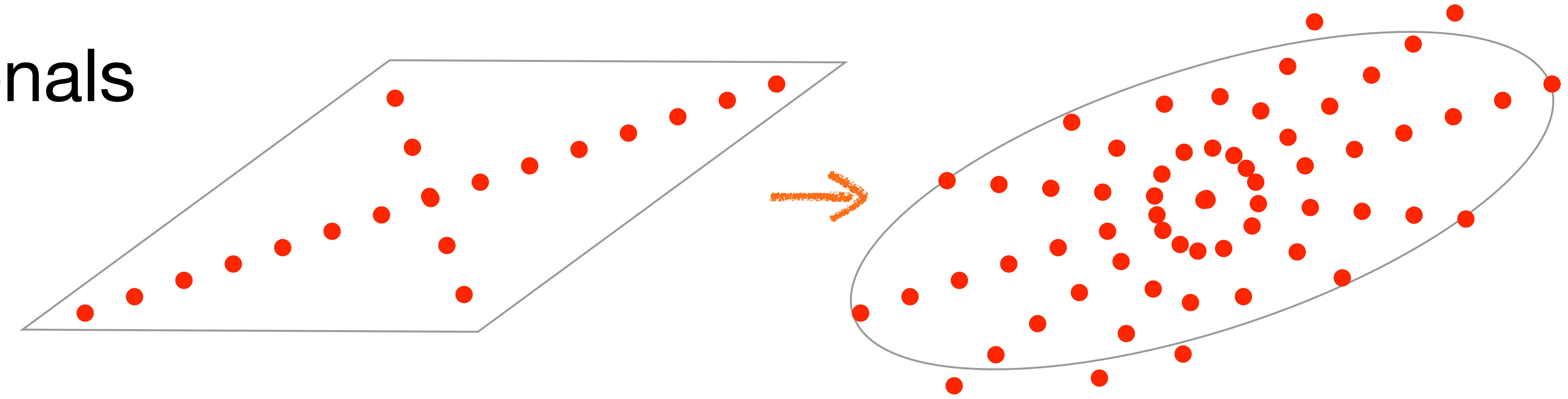
$$\nabla^2 \phi_m = 0$$

Measurement of Boundary Conditions

- Aim:
  measure $B_\perp$ on infinite plane outside magnet
  - plane // to cylinder face, 3 mm from it

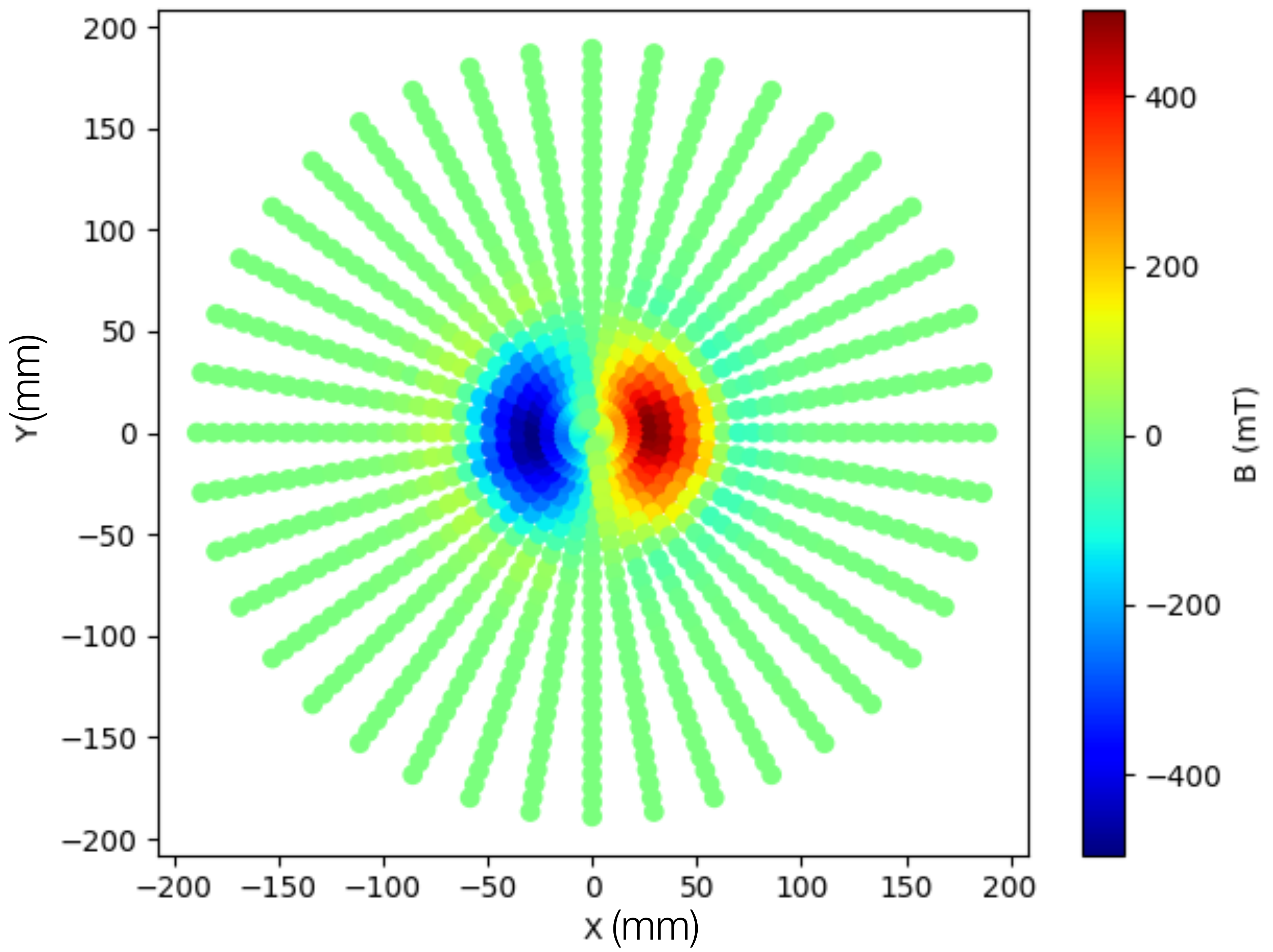
- Setup:
  - Halbach magnet dismounted from RF setup
  - Hirst GM08 Gaussmeter
  - cap by LNGS Mechanics Workshop with slots for inserting probe 7 mm apart on both diagonals



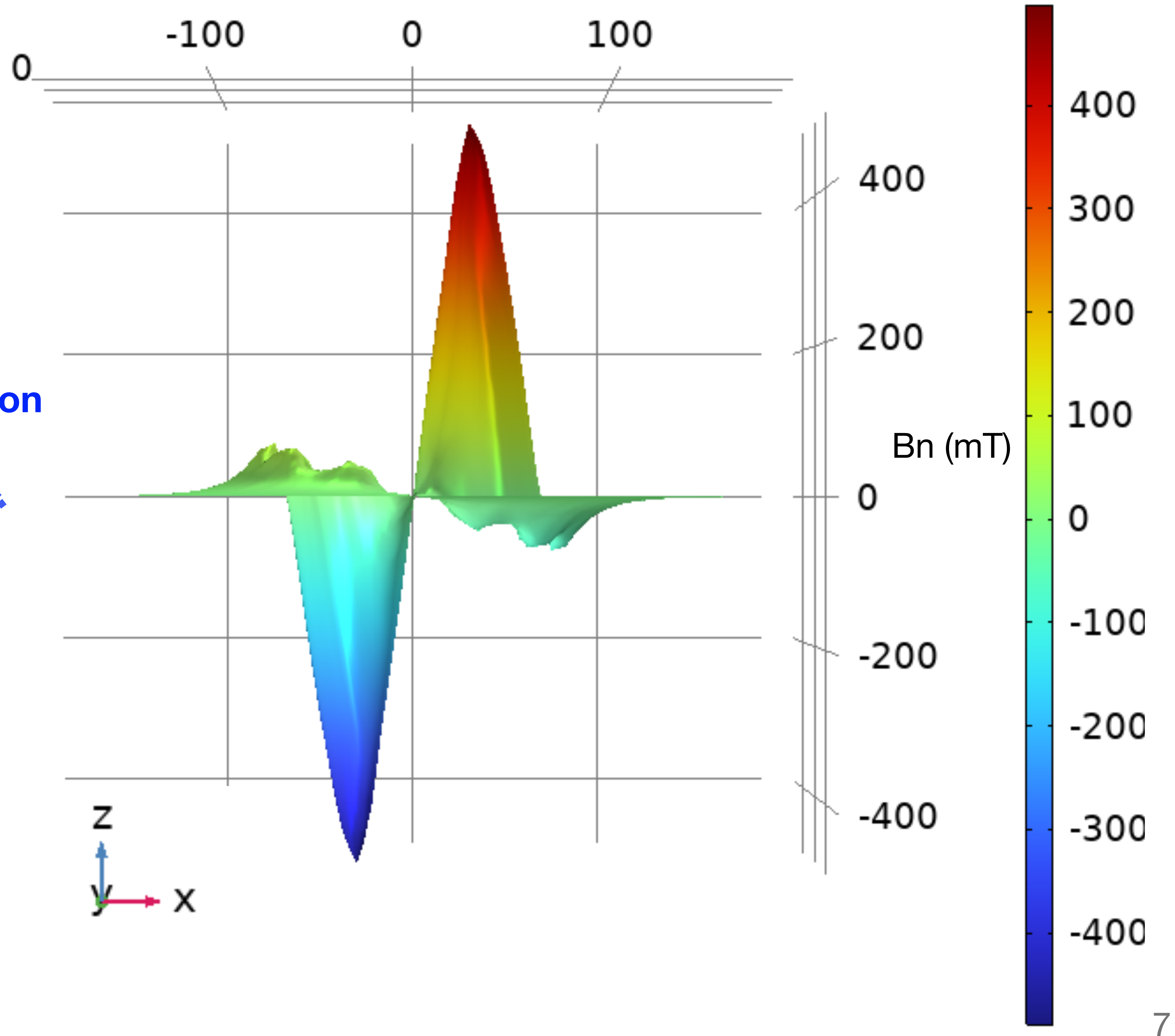


Behavior Showing Two Poles

- 54 points each diagonal, repeated every 9°
- Total: 1080 points covering a r $\simeq$ 20 cm circle area

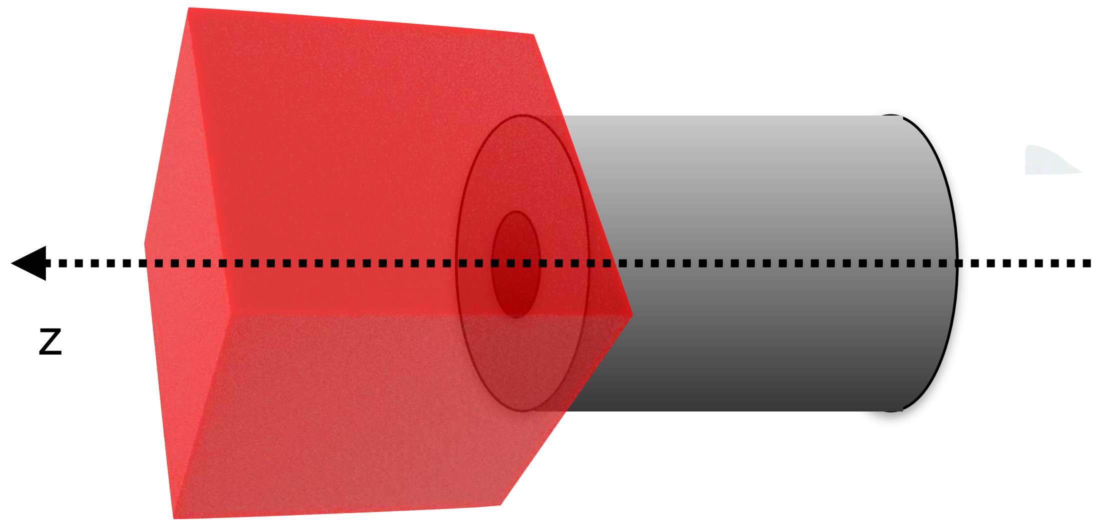


COMSOL Map Interpolation



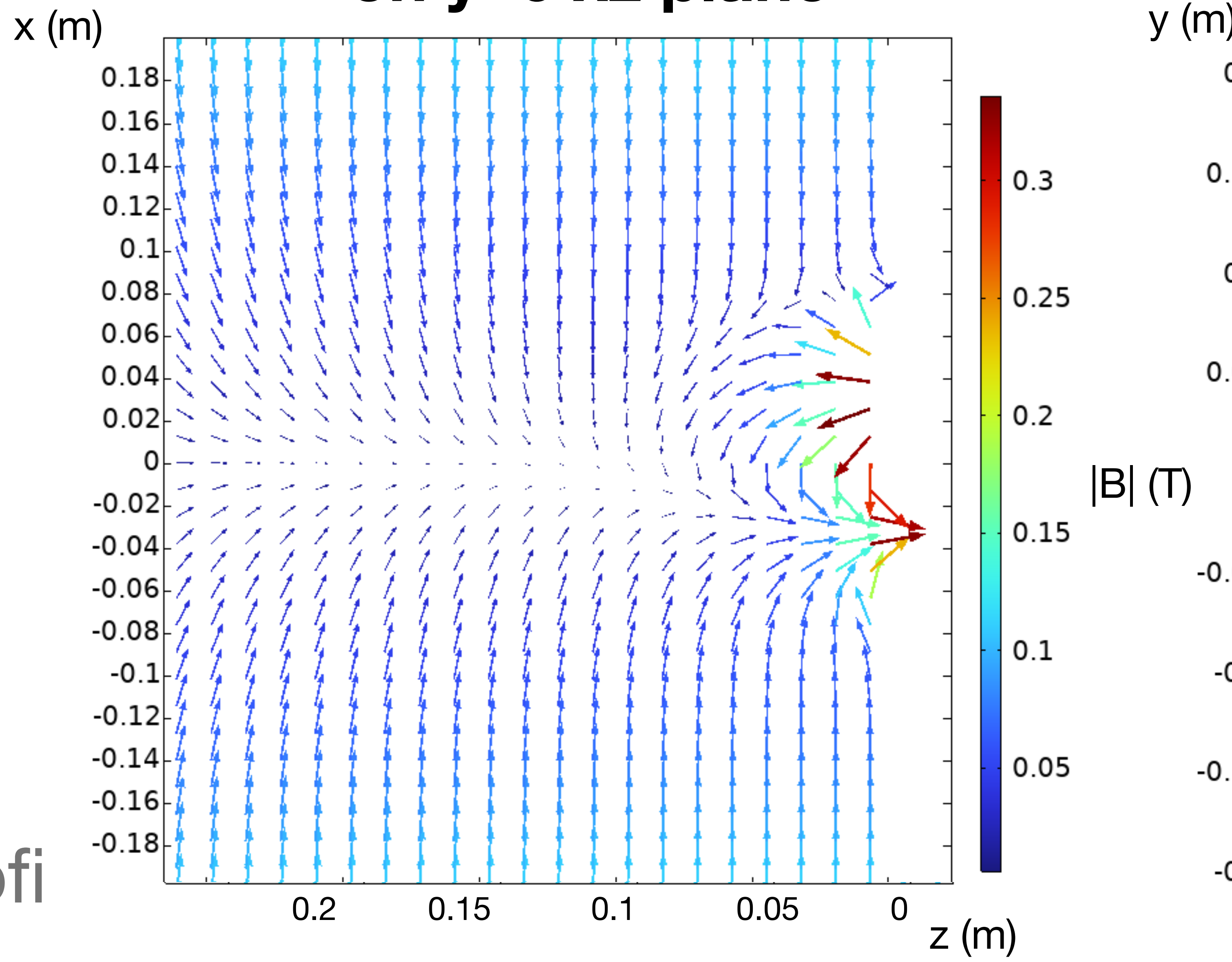
COMSOL Computed Field

- Given boundary conditions → solution of Laplace equation
  - using **COMSOL simulation software** based on advanced numerical methods *(collab with dr. C.Rizza from UnivAq)*
    - Field computed in a 35 cm side cubic volume

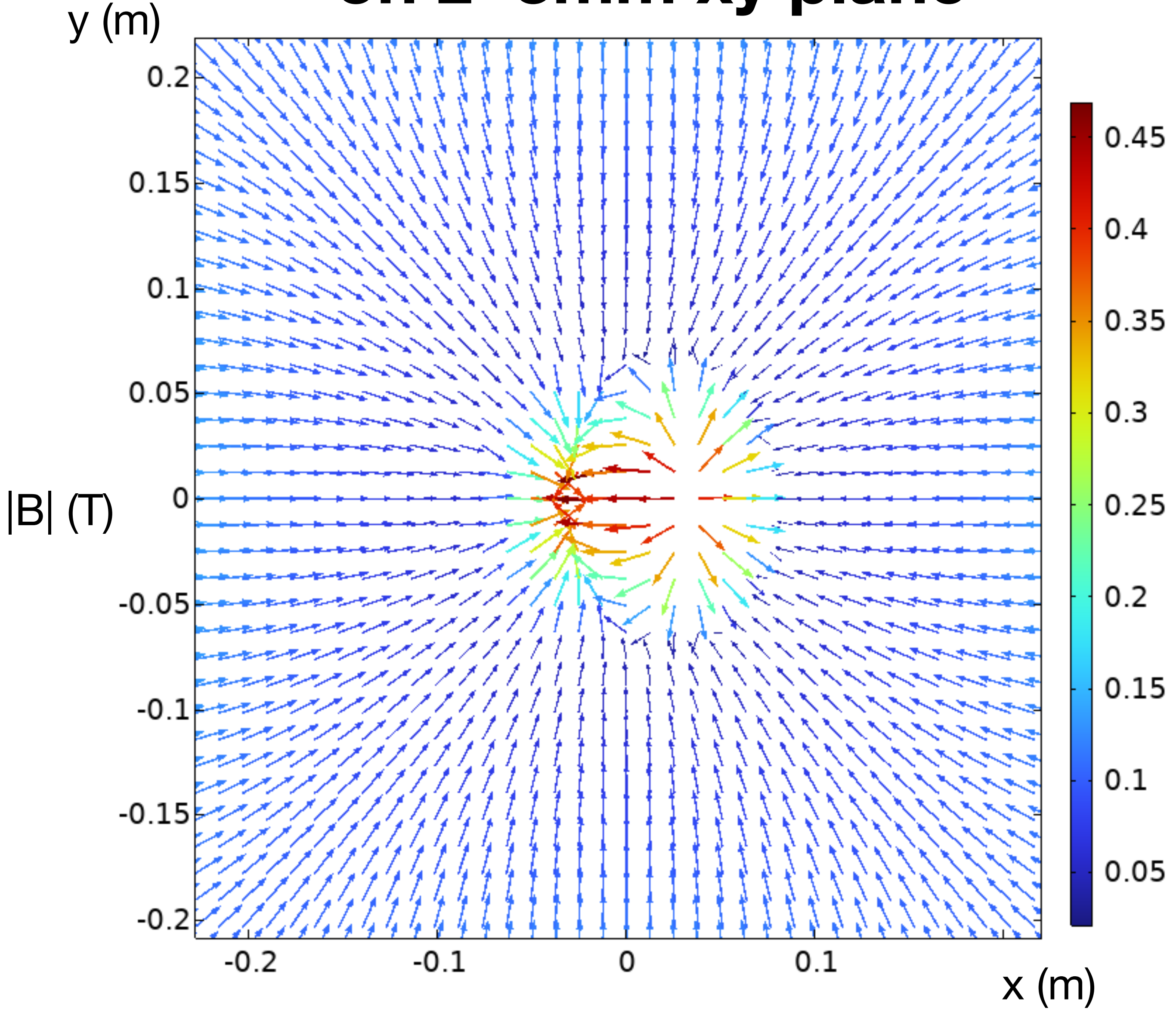


- Two examples of arrow plots from field obtained:

on y=0 xz plane



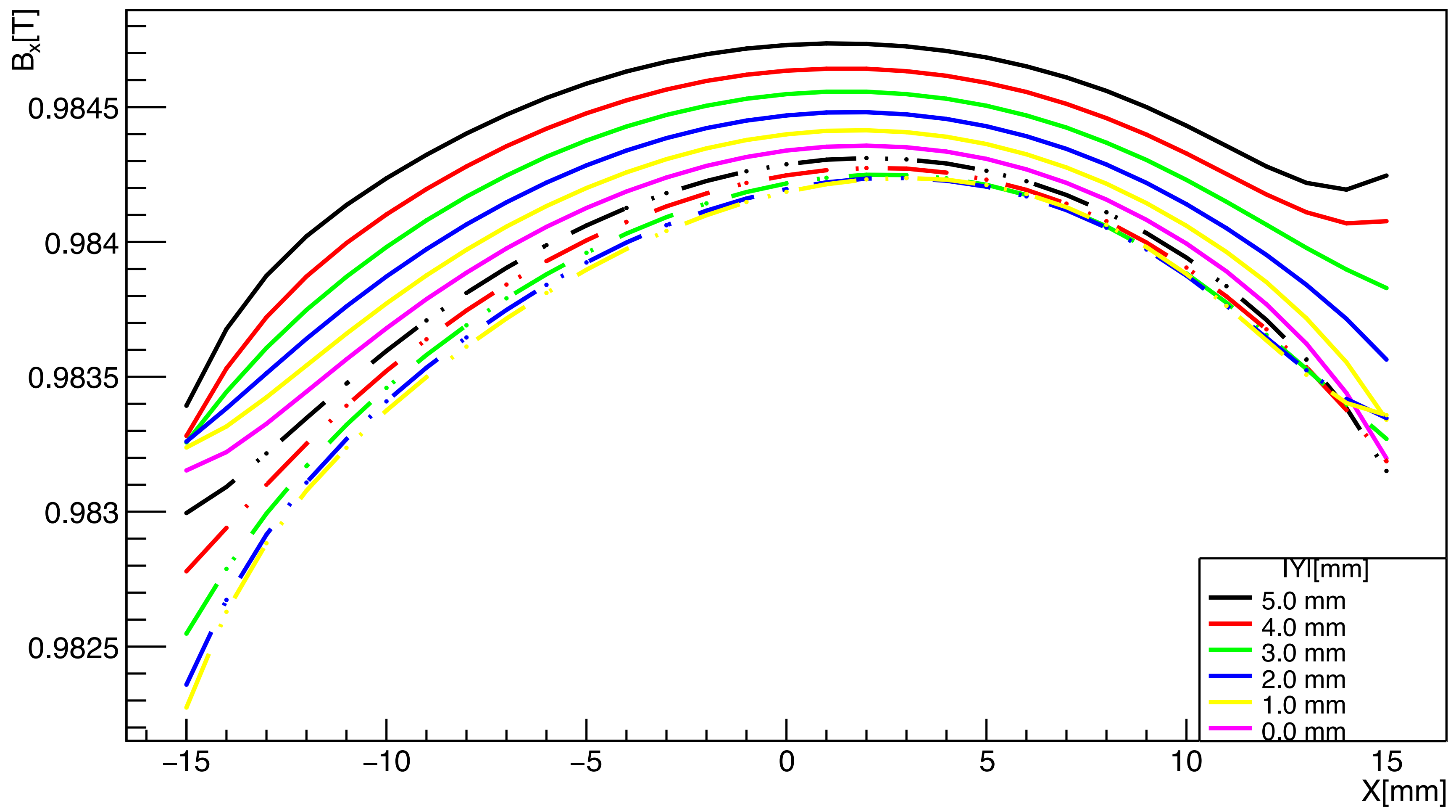
on z=3mm xy plane

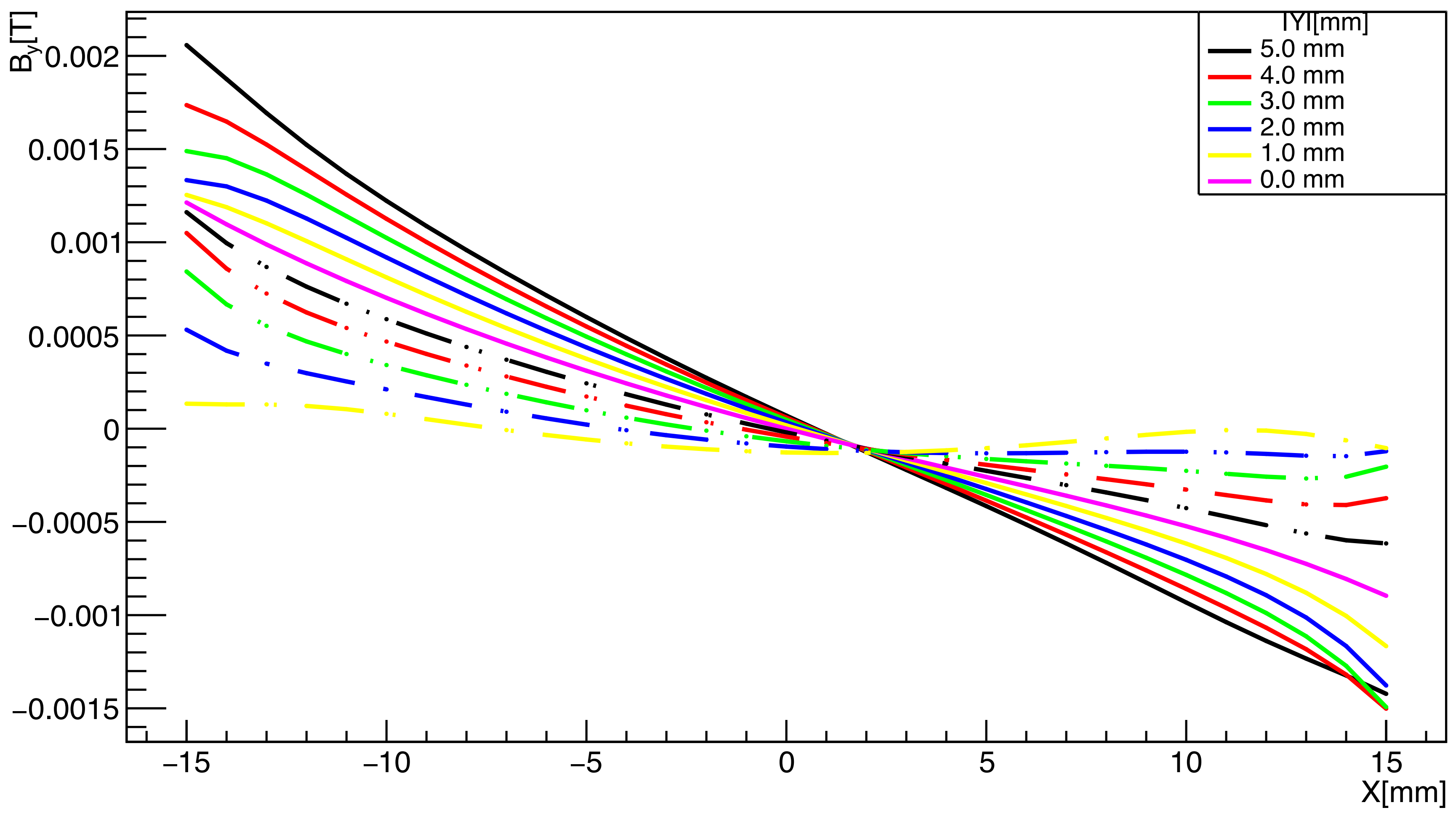


Agreement with measured $B_\perp$ along a diagonal @ 3 cm distance from magnet face!

Internal Field: Measurements + CERN Maps

- From CERN Magnet characterization: Bx & By profiles as function of x & y, <u>mediated in z</u>

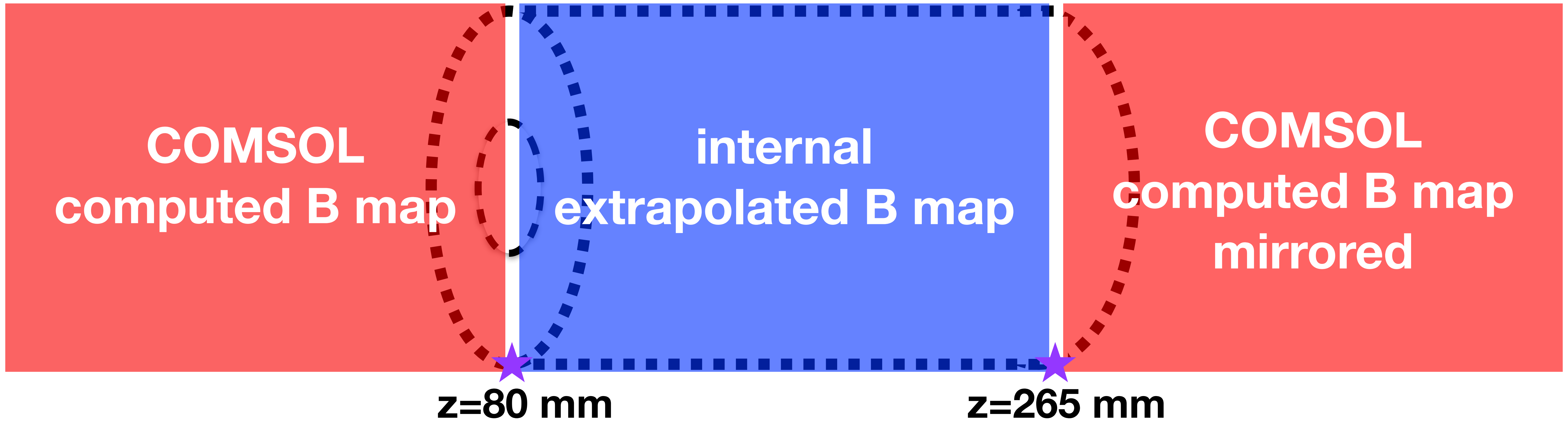




- To get z profiles:
  - Bx measurement for x,y=0 varying z through Gaussmeter *(by Federico)*
  - Scale of Bx, By for every z according to the measured profile
  - Bz scaled linearly from the values on face to the Bz=0 point (~2 cm far) → to be improved!

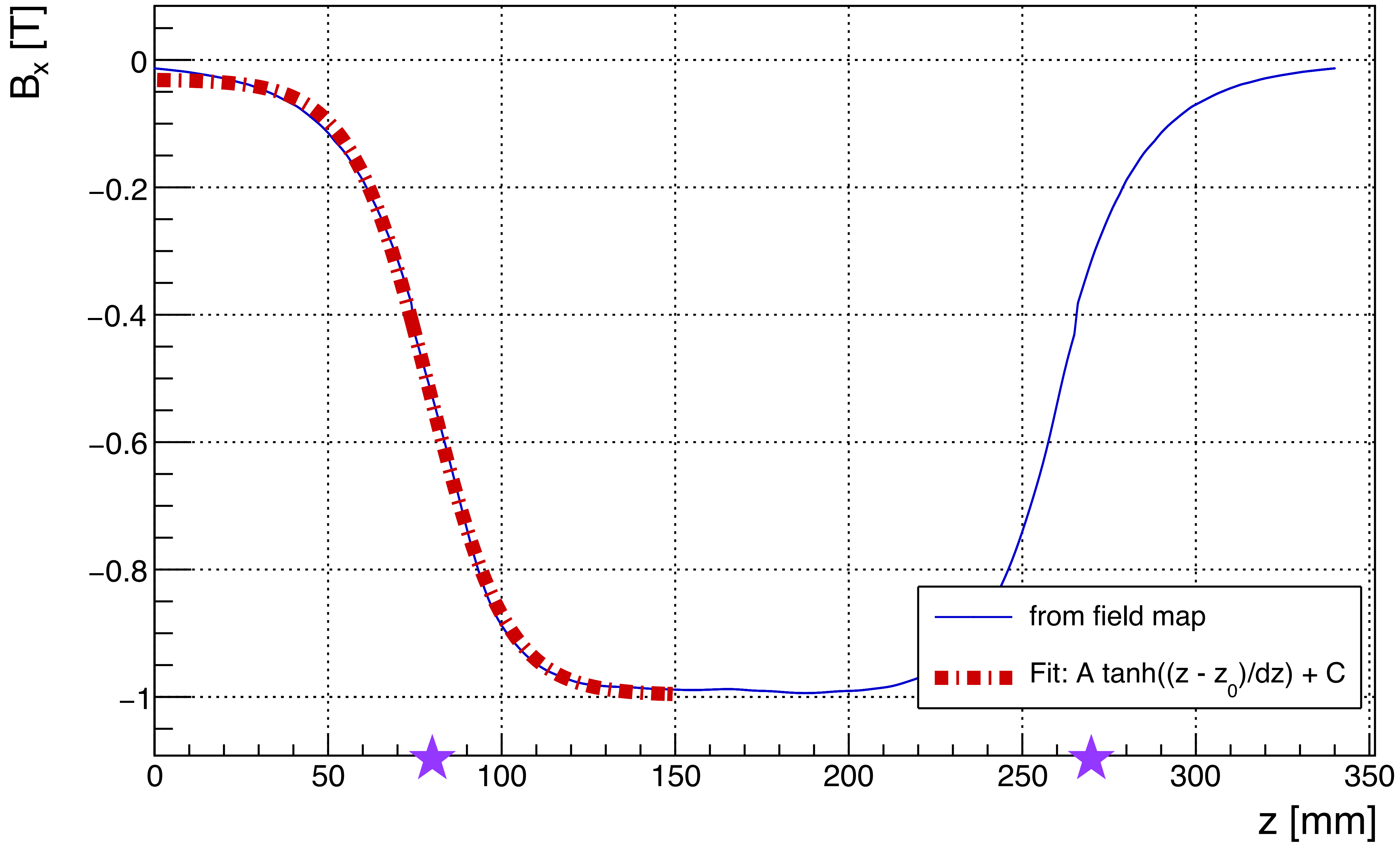
Very Steep Bx Profile

- Merging of



Field Map used for CST & Lorentz4 simulations!

- Let's have a look to Bx(x,y=0) vs z profile:
  - Good matching of different B maps
  - very steep magnitude increase: from 0 to 1 T in ~15 cm
  - Sigmoidal shape, fitted with *tanh*



A Compact Simple version of Accelerator Filter

GSSI

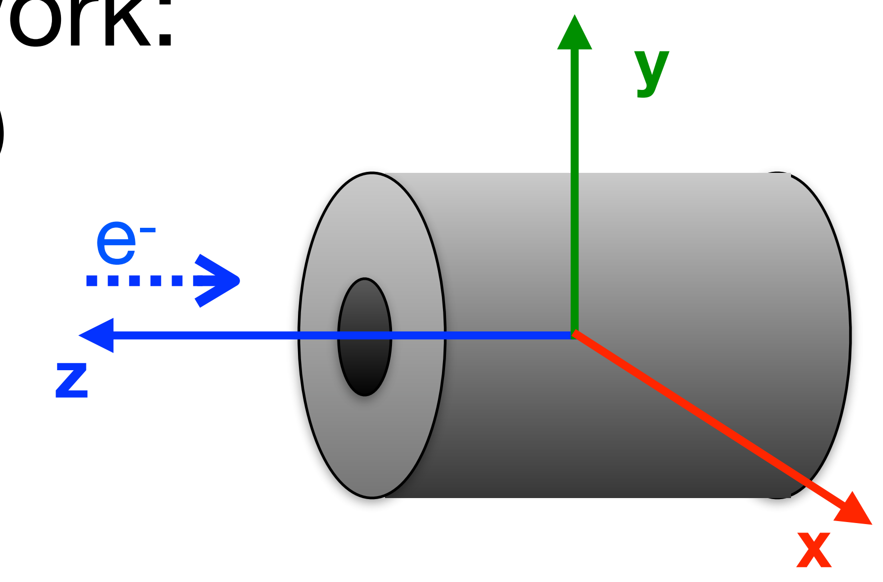
- Preliminary injection geometry: 5 sets of electrodes (2 bouncing + 1 top + 1 bottom each) to create very compact *single channel accelerator filter*

- Lot of things to take into account

1. Limited space in **xy**
   - Tube for vacuum inside magnet cavity with ⌀ < 50 mm
   - For RF: rigid space constraints to match with RF electrodes into trap (15 mm height x 37 mm width)
2. **B** field limit
   - Too low B → too large Larmor radius; too high B → problems with electrons ejection
3. Electron energy (**E_e**) limit
   - Too low E → limit in e-gun performances; too high E → too large Larmor radius

Quick Drifts Recap during Injection

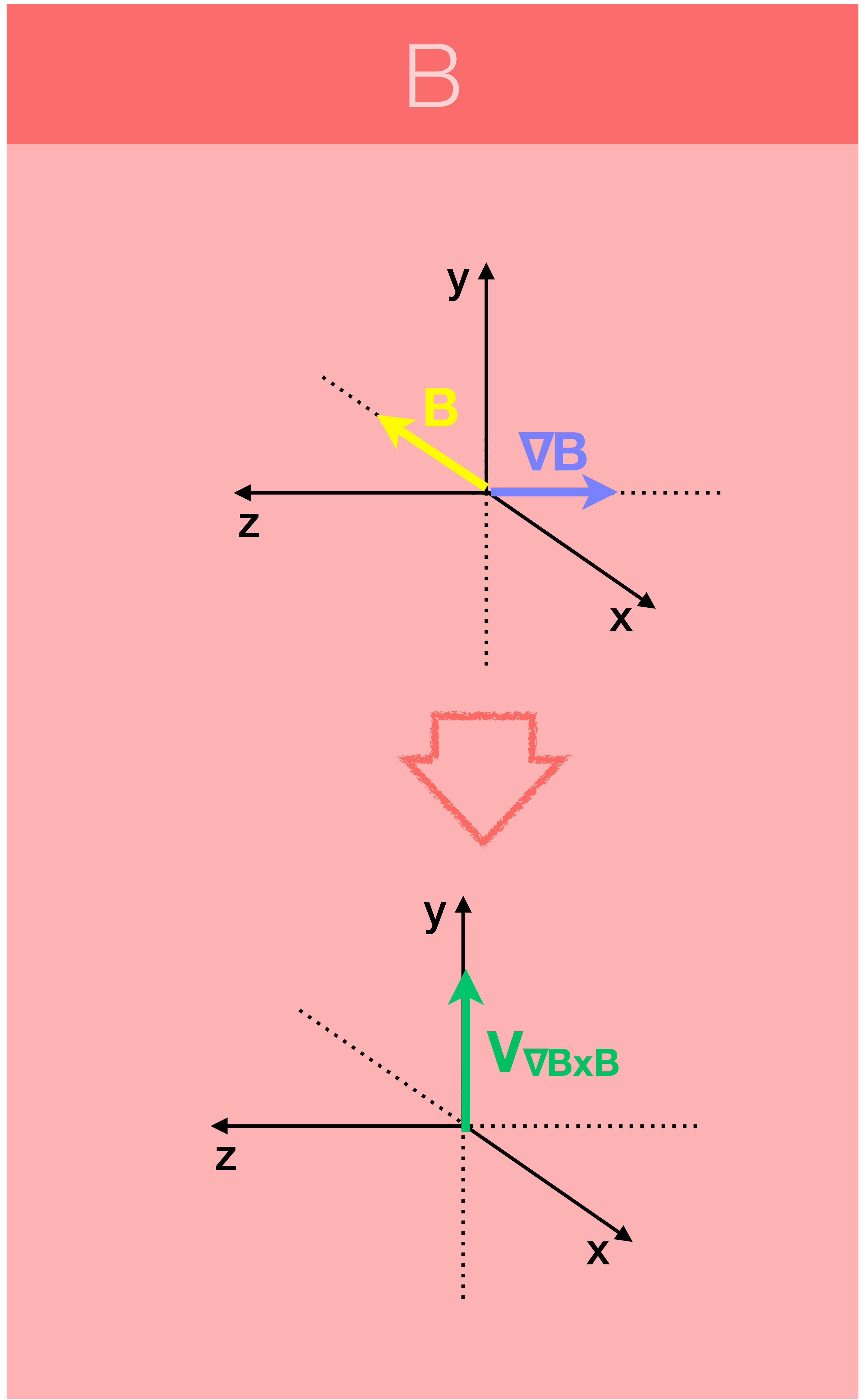
- Framework:
  (sorry)

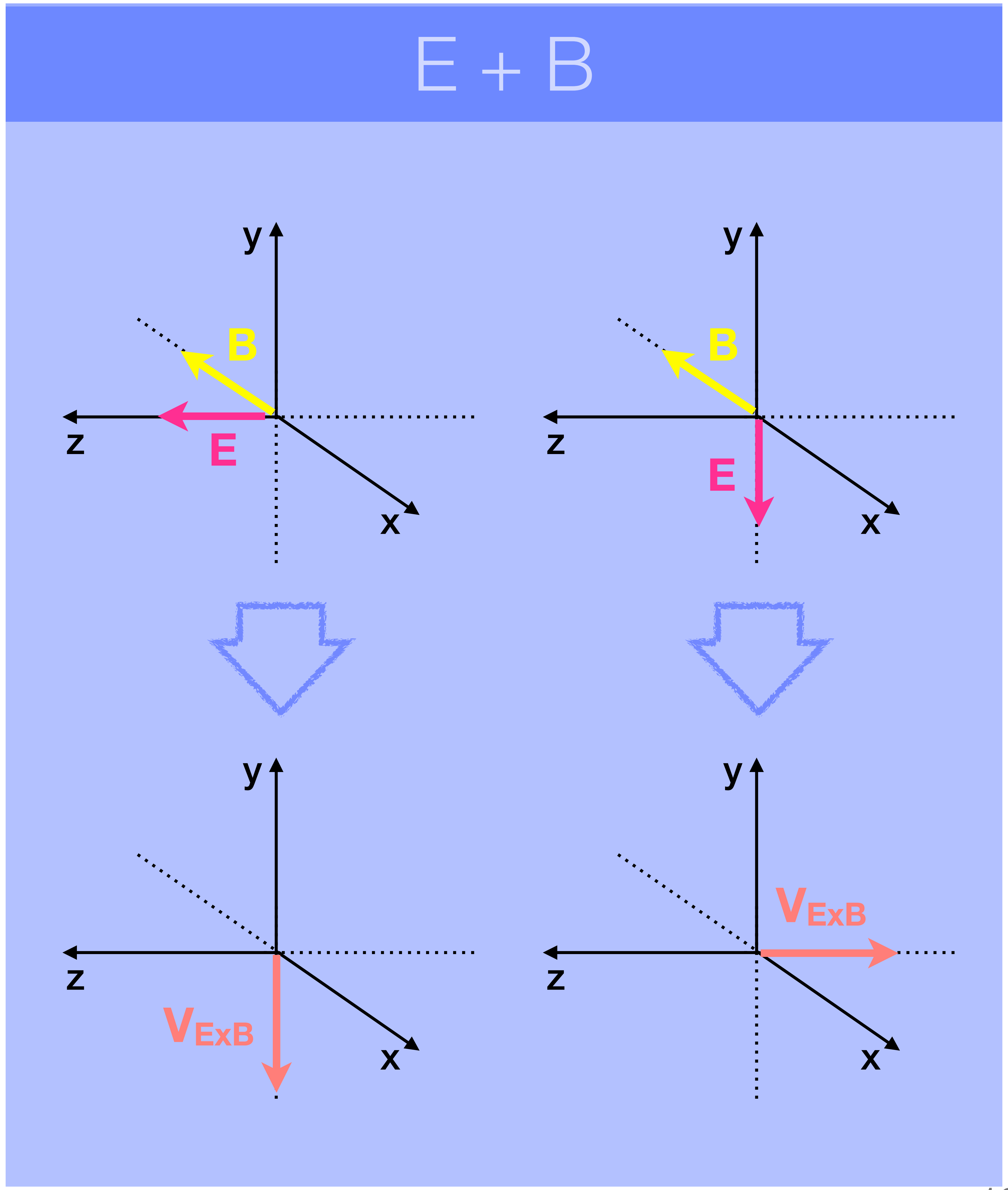


- Bx increase in -z direction
  → drift in +y direction

- To compensate it:
  E in +z direction needed

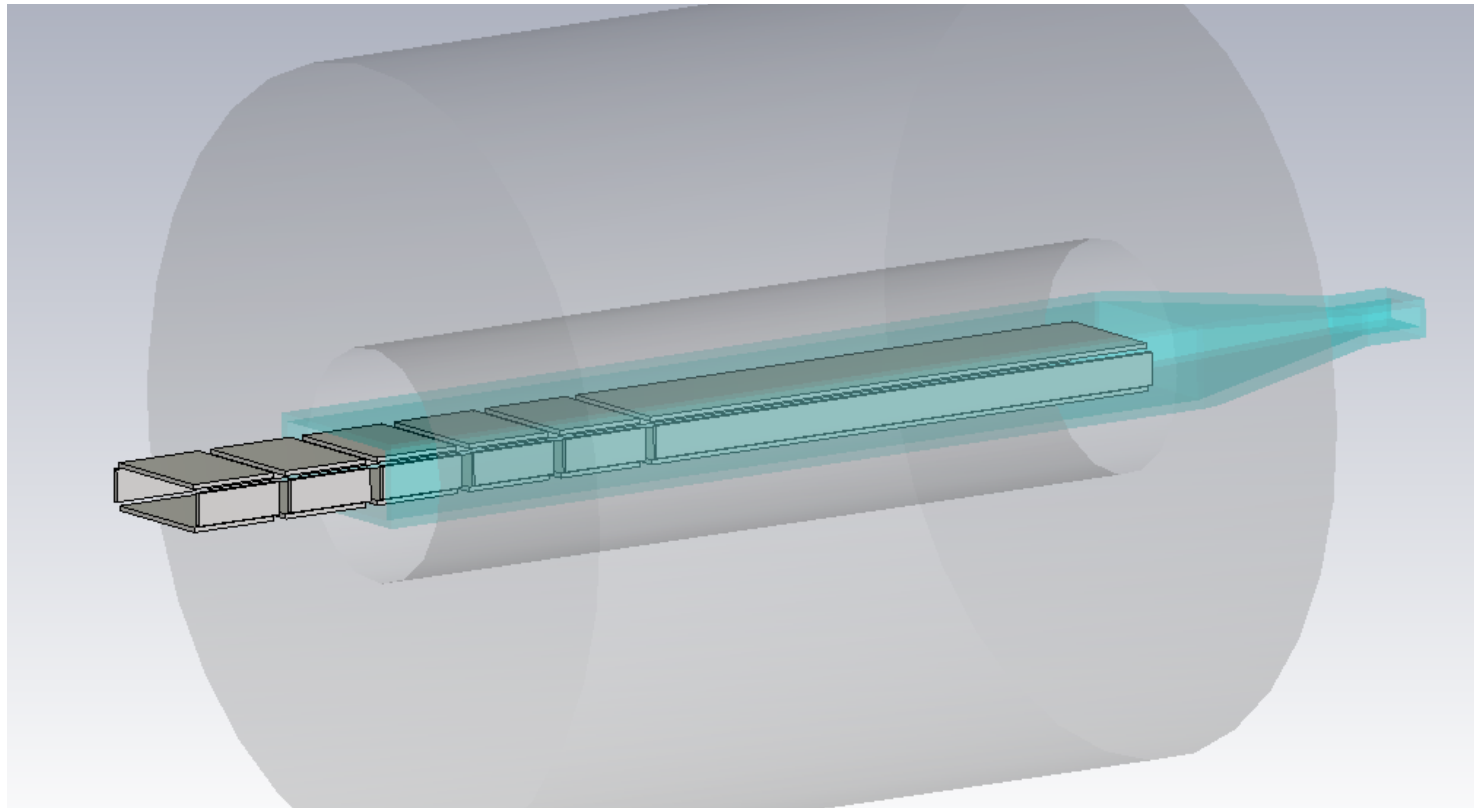
- To let electrons drift along z:
  E in -y direction needed

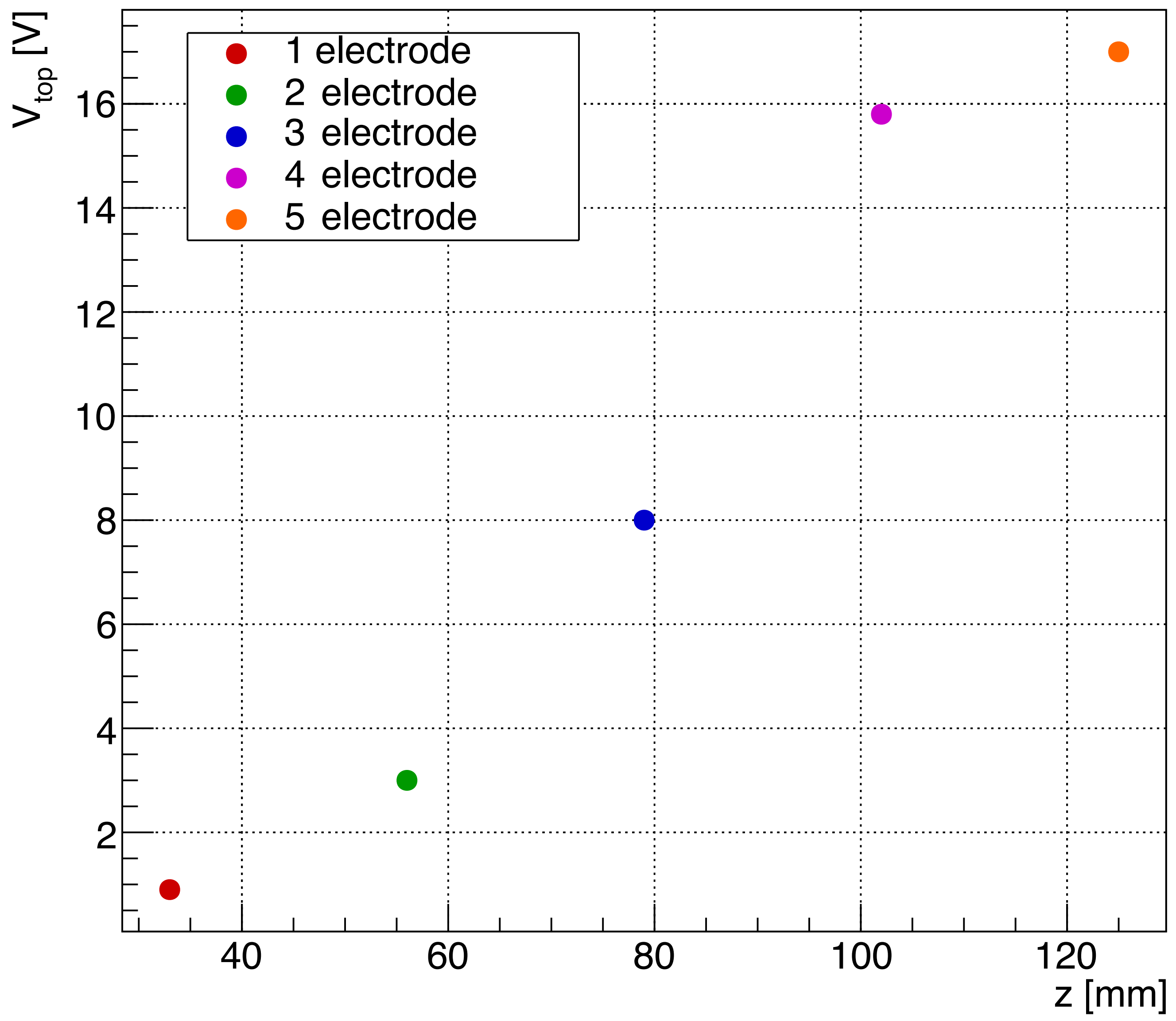




RF Setup: Injection & Slowdown Strategies

- Electrodes setup:
  - 5 electrodes’ sets of 2 cm length + RF ones
  - dimensions matching with RF:
    - ➢ 8.2 mm distance in y,
    - ➢ 30 mm in x

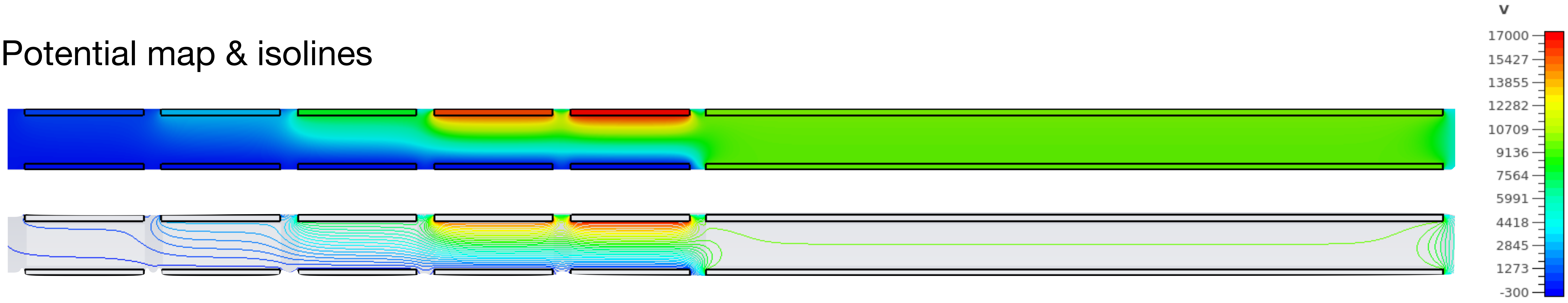




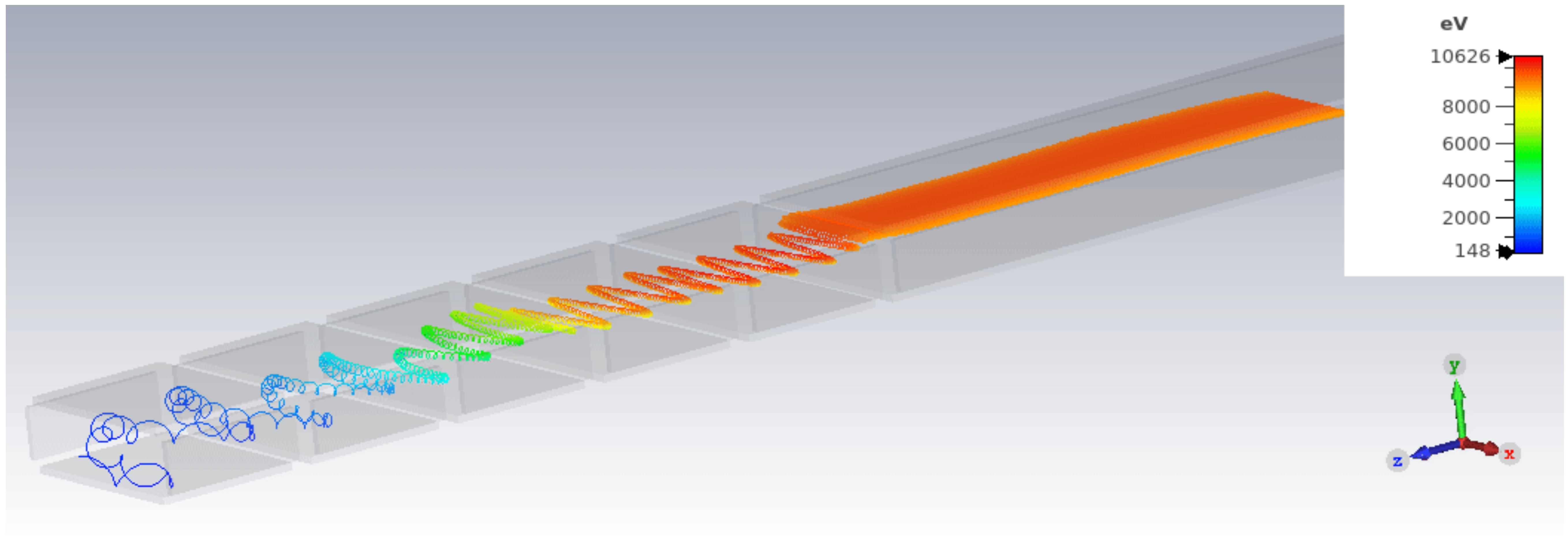
- Voltages applied:
  - top injection electrodes following a sigmoidal (smoother) profile
  - grounded injection bottom electrodes
  - RF electrodes to minimize z-drift (still to optimize!)

RF Setup: Injection & Slowdown Strategies

- Potential map & isolines

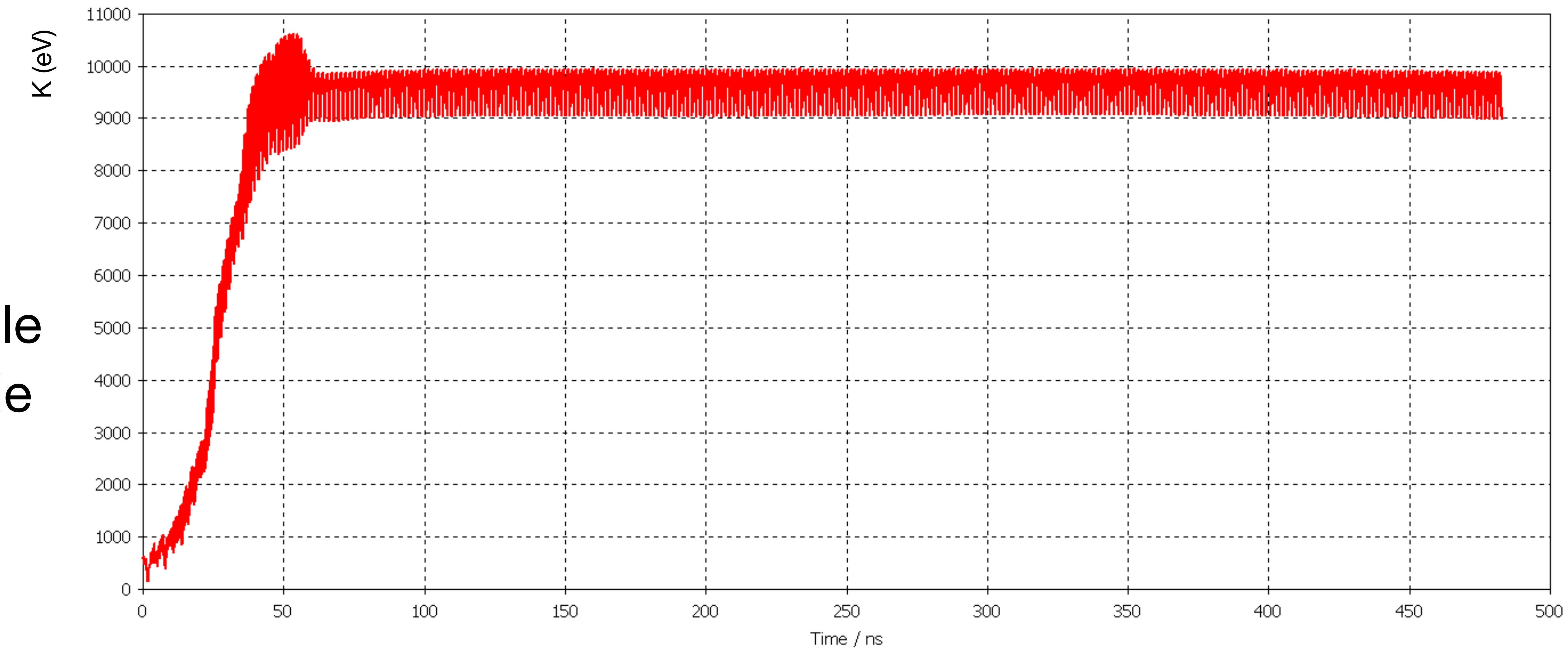


- Particle source
  - B field - Energy compromise:
    - ✓ 600 eV electron
    - ✓ 6 cm far from magnet (Bx= 38 mT)
  - Pitch angle of 50°
  - Centered in xy plane



Minimum Detectable Energy, Still Too Fast

- Preliminary CST results:
  - ✓ 1T region reached
  - from 600 eV to ~10 keV
  - → RF power ~0.7 fW → in principle detectable
  - 50 ns to reach RF region, 450 ns to travel 5 cm of it



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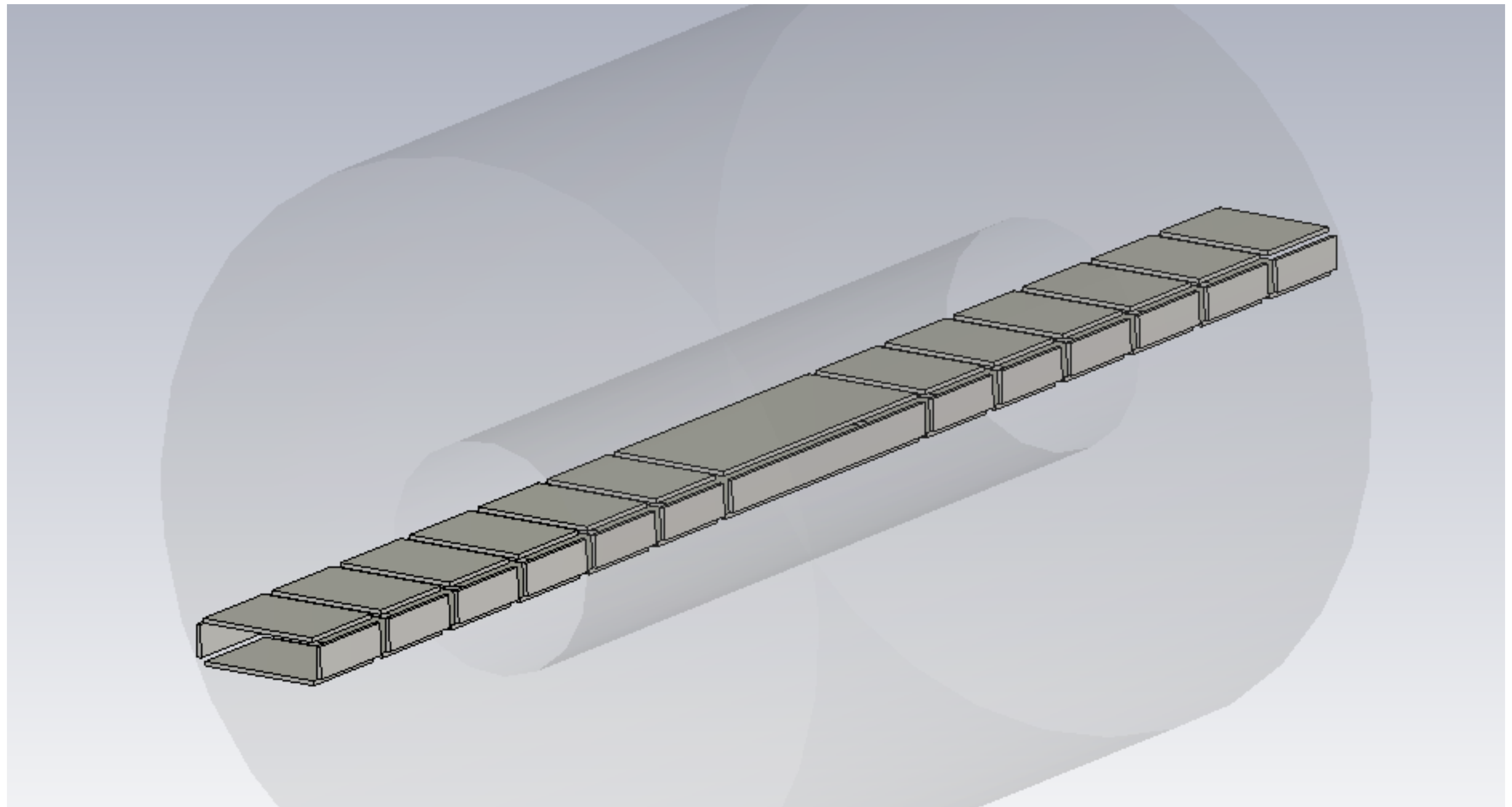
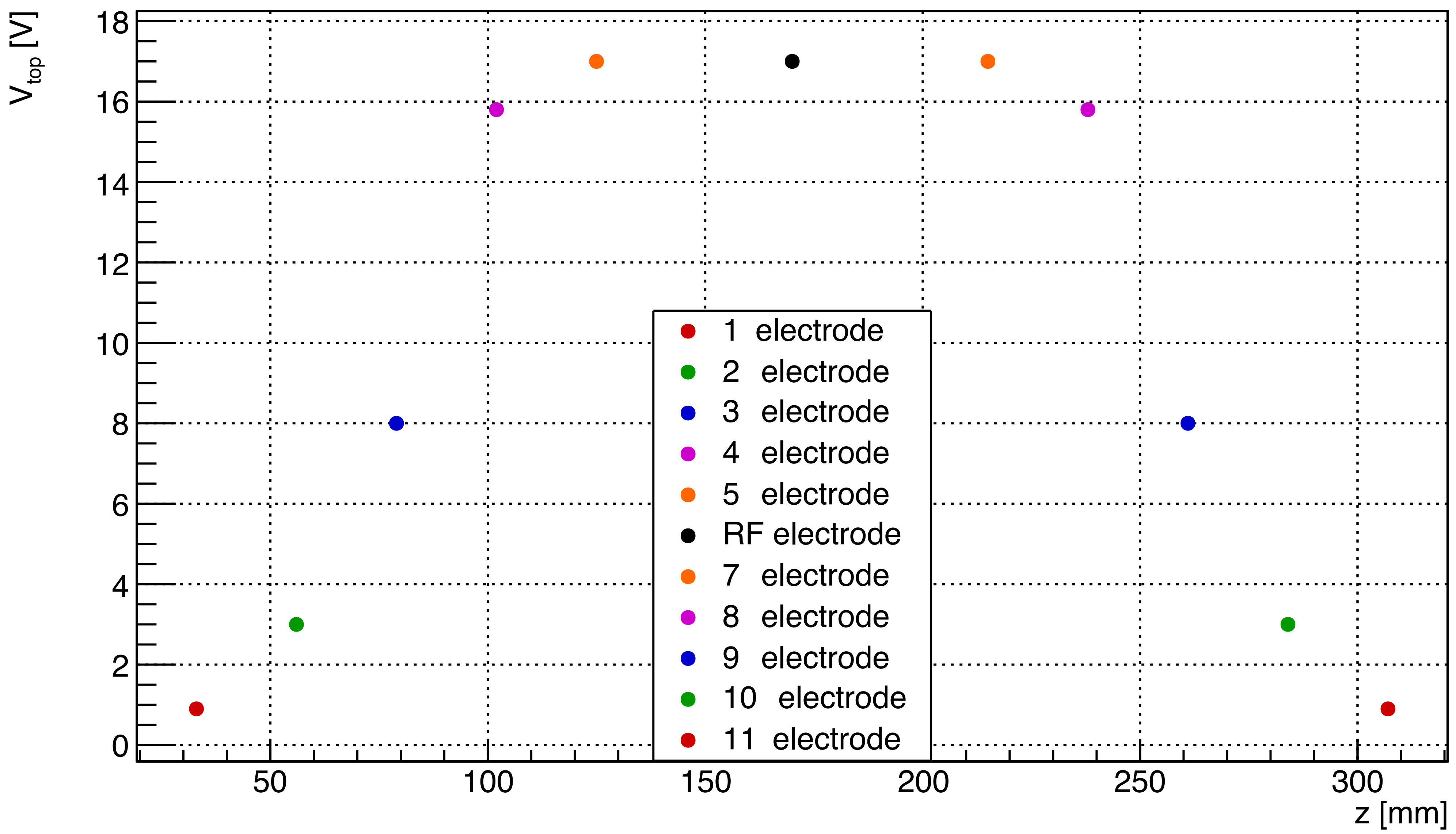
good slowdown, still not enough to be detectable (minimum 30 μs needed)

- Next steps:
  - find right RF voltages to keep e- @ same altitude (now too close to top electrode)
  - Deeper result analysis with *Lorentz4* *(see N.Rossi talk)*

From RF to Magnet Crossing Setup

- Preliminary electrodes setup:
  - Symmetric geometry:
    - ➢ 5 injection electrodes' sets,
    - ➢ "RF electrodes" (reduced in length)
    - ➢ 5 ejection electrodes' sets
  - dimensions still matching with RF (not needed!)

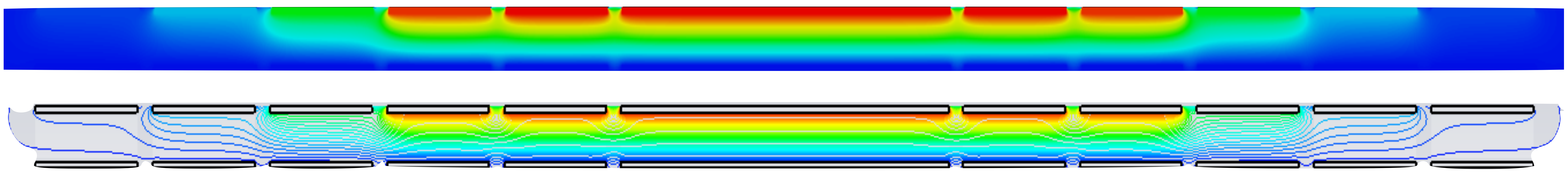


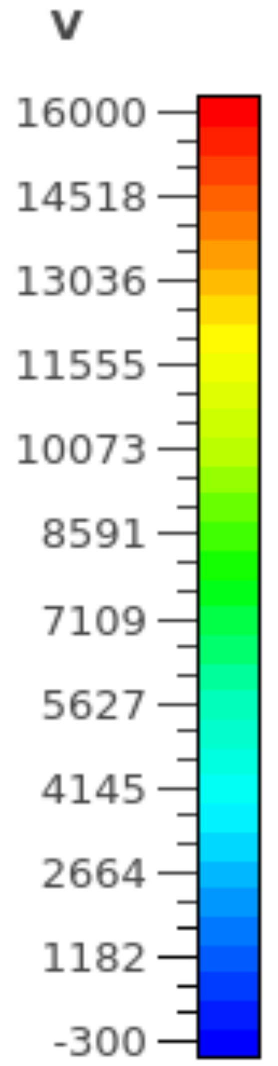


- Voltages applied:
  - Injection as previous setup
  - RF voltages matching 5th electrodes' ones
  - Ejection with mirrored voltages wrt center (∇B inversion → E in -z direction to compensate!)

From RF to Magnet Crossing Setup

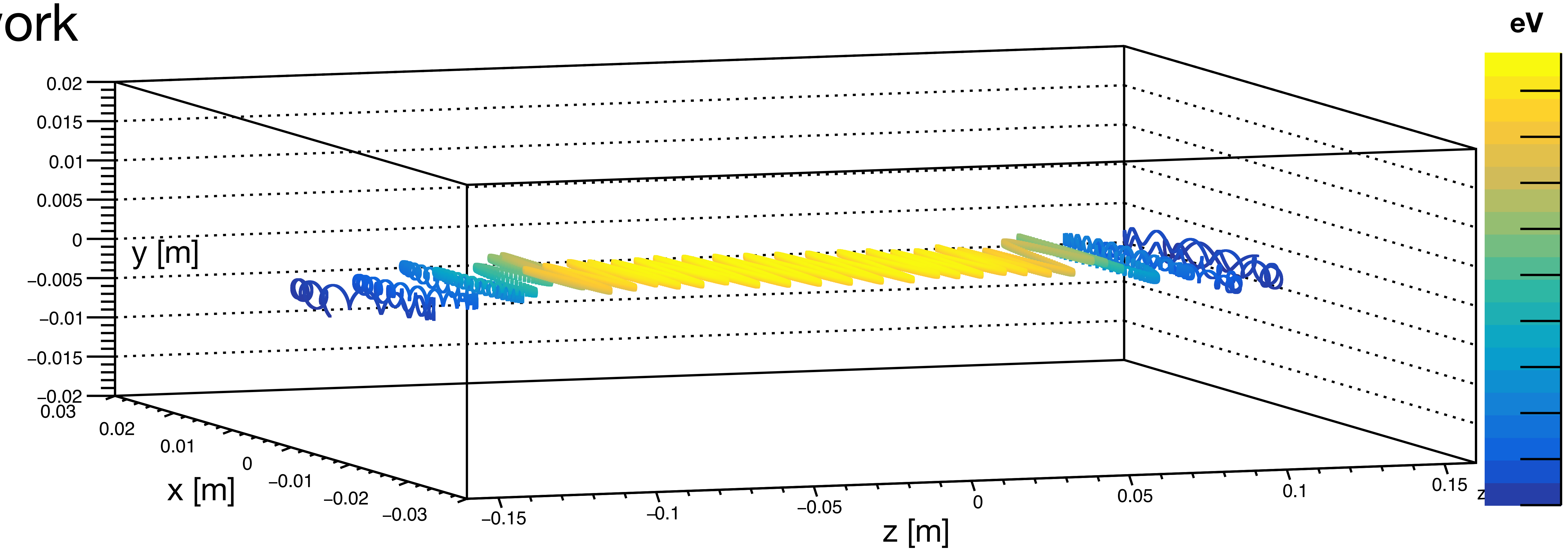
- Potential map & isolines





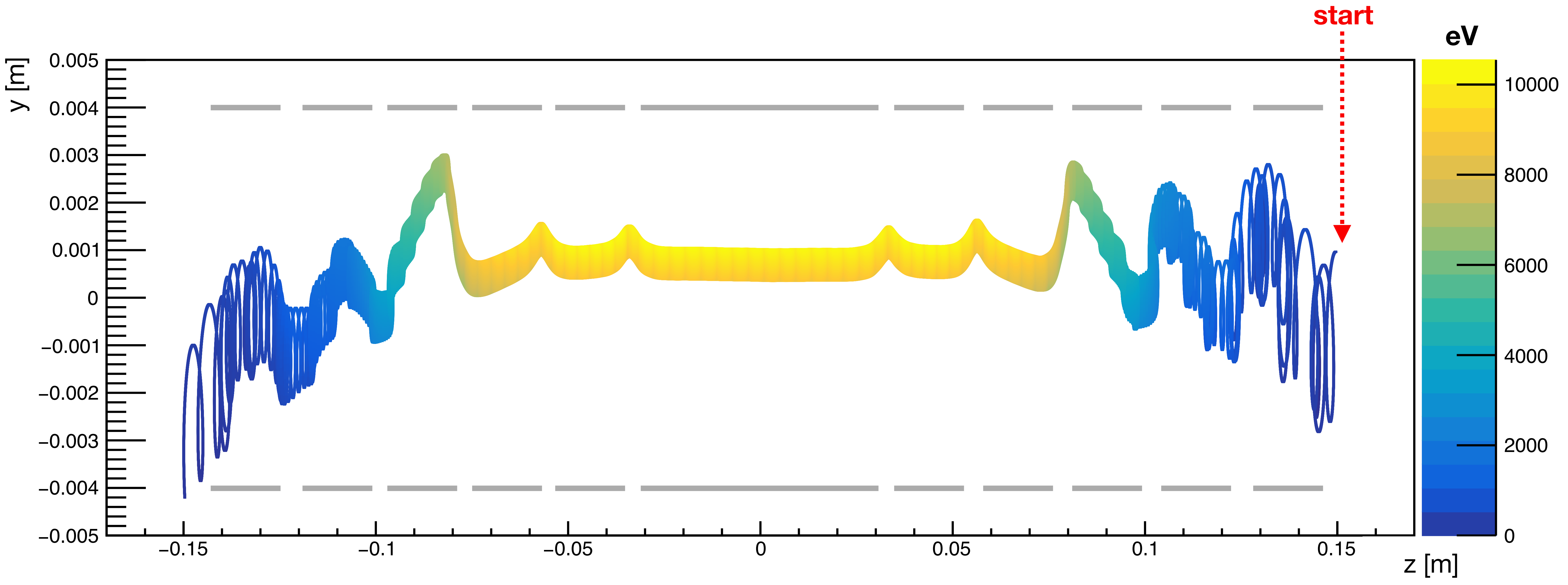
- Same particle source: 600 eV e[-] 6 cm far from magnet, 50° pitch angle

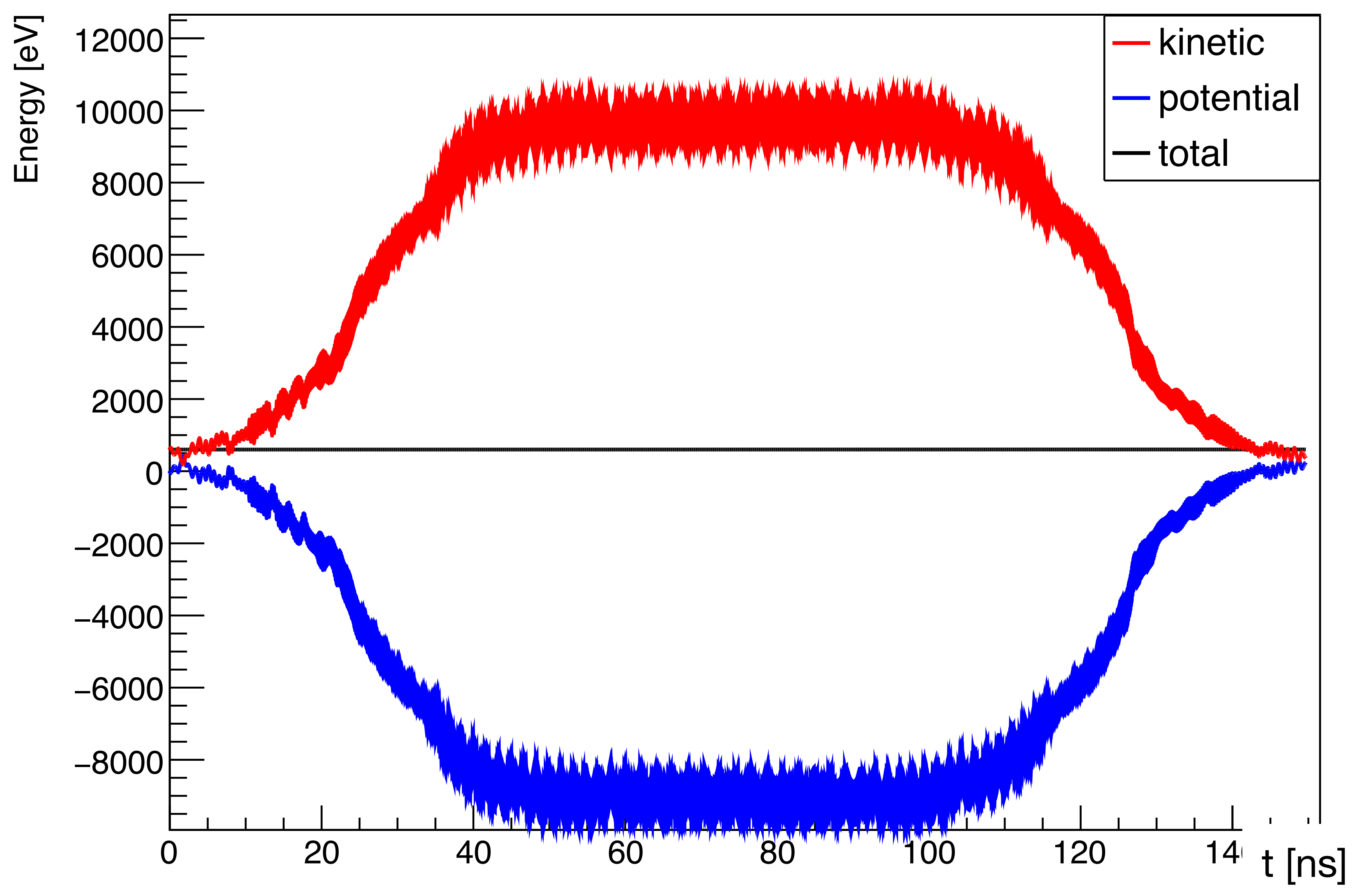
- New trajectory simulation framework = *Lorentz4*
  - takes as input CST field maps
  - reduced simulation time
  - customizable post-processing



Kinetic into Potential Energy Transformation

- yz trajectory projection showing **drifts balance**
  - +y (-y) drift along electrodes
  - -y (+y) drift along gaps
- asymmetries reflecting B field ones





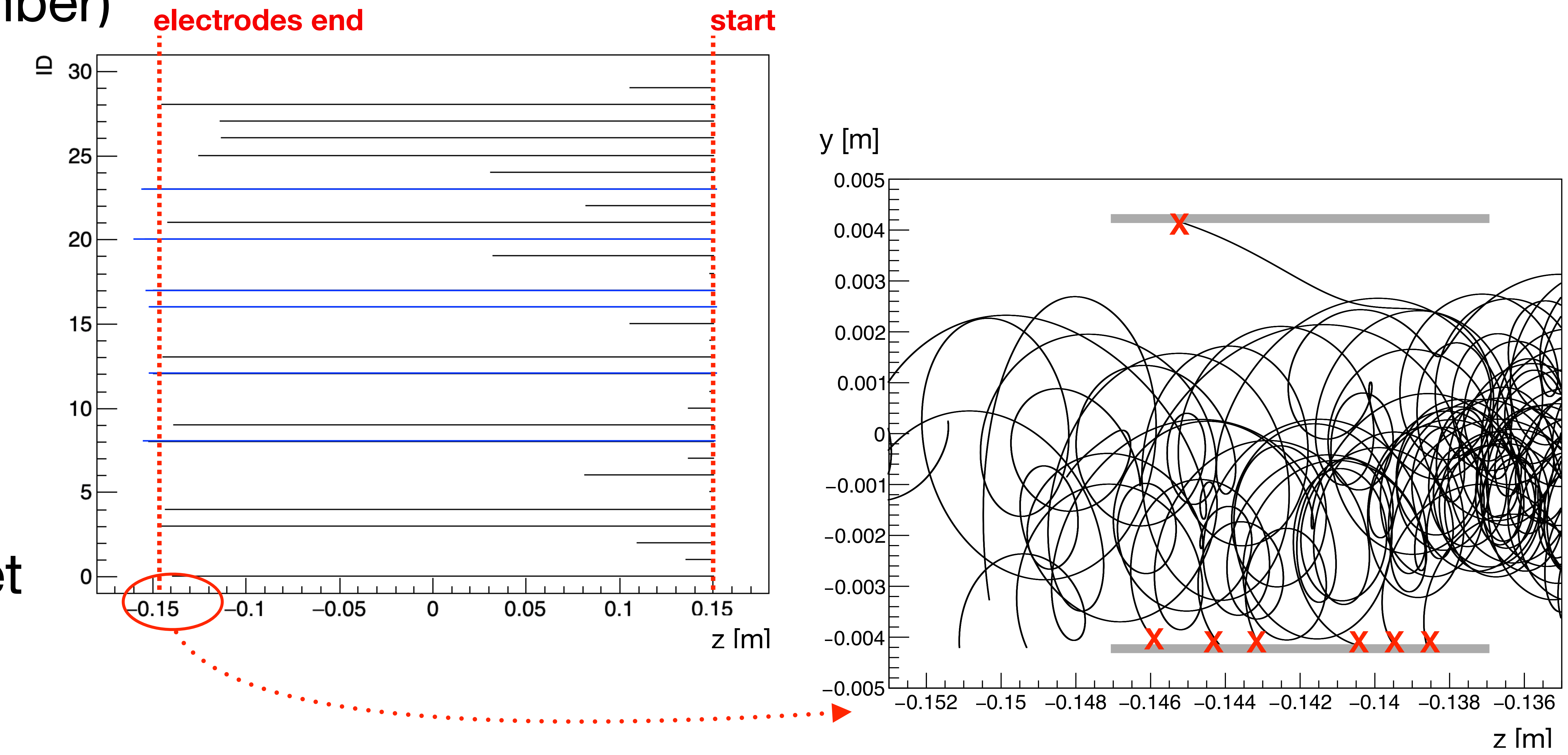
✓ Electron coming out from electrode system

✓ Good trajectory control despite poor segmentation

✓ Kinetic energy from 600 eV to ~ 10 keV and viceversa in ~ 30 cm!

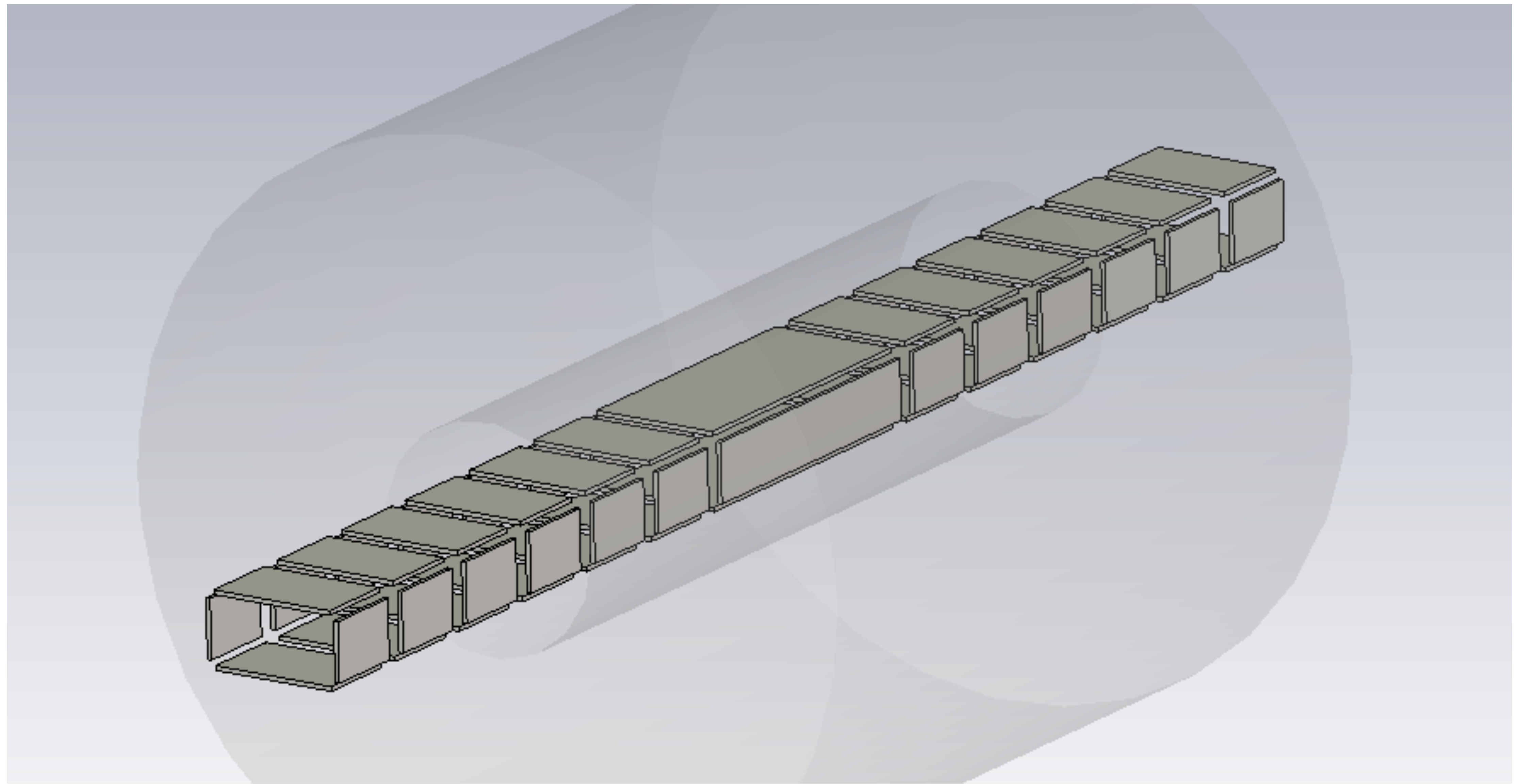
Efficiency Strongly Limited by Y-Dimension

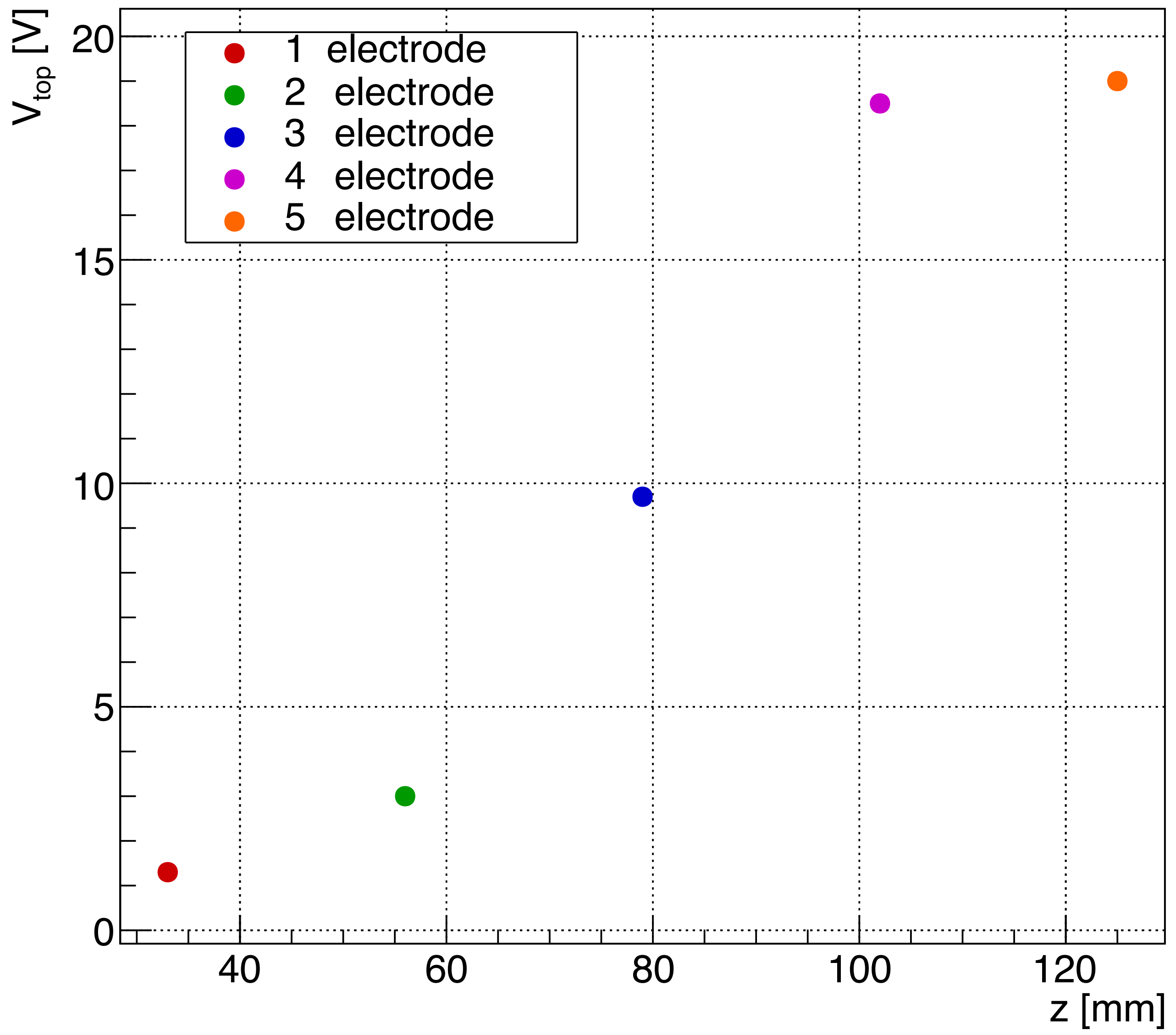
- Lorentz for (small) Montecarlo to simulate a real electron source features (e-gun ones)
  - 2 mm diameter spot (pessimistic number)
  - 5° angle spread
- Result: 6 over 30 potentially detectable
- Lot of electrons lost in last electrodes set by hitting top or bottom one
  - Still using dimensions matching trap constraints! Not needed for this setup
  - Can enlarge a bit x-y dimensions (still ⌀ < 50 mm constraint)



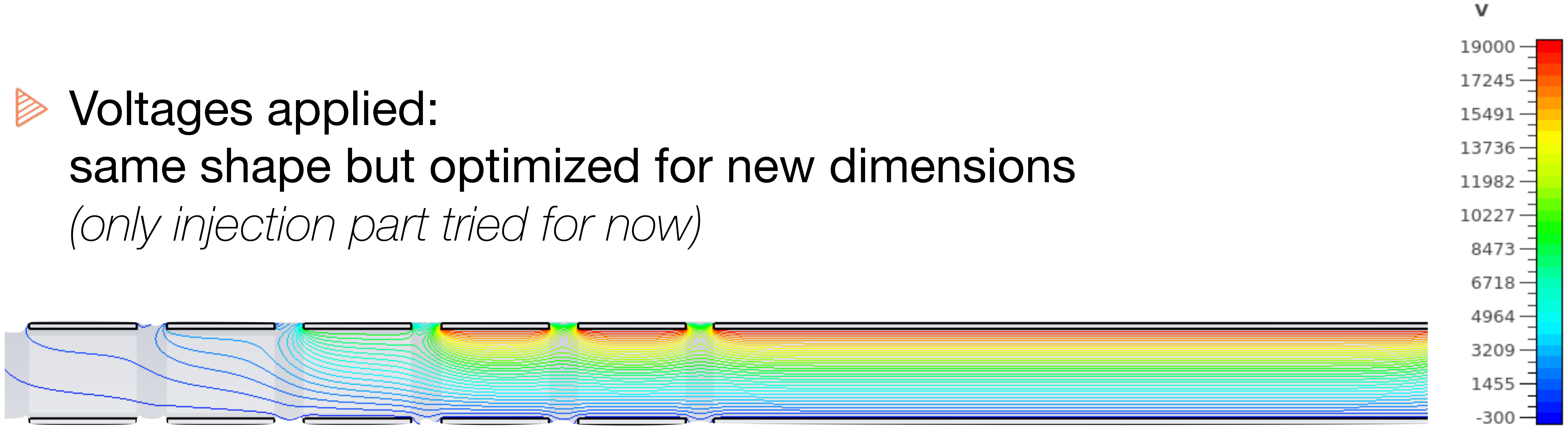
Road to Magnet Crossing Setup Optimization

- Dimensions changing:
  - ✓ y distance from 8.2 to 15 mm
  - x distance from 30 to 35 mm
    → higher y/x → less field uniformity ✗
  - electrode length from 20 to 18 mm





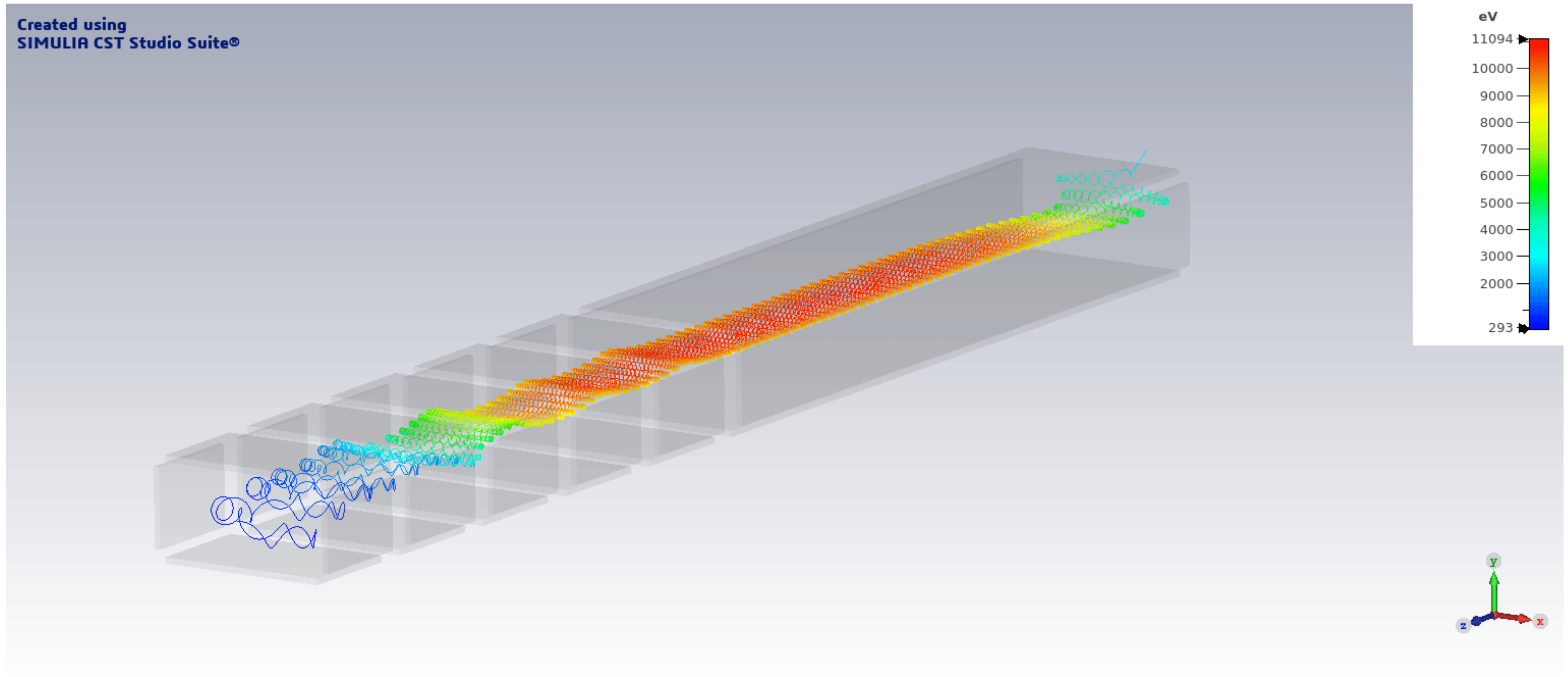
- Voltages applied:
  same shape but optimized for new dimensions
  (only injection part tried for now)

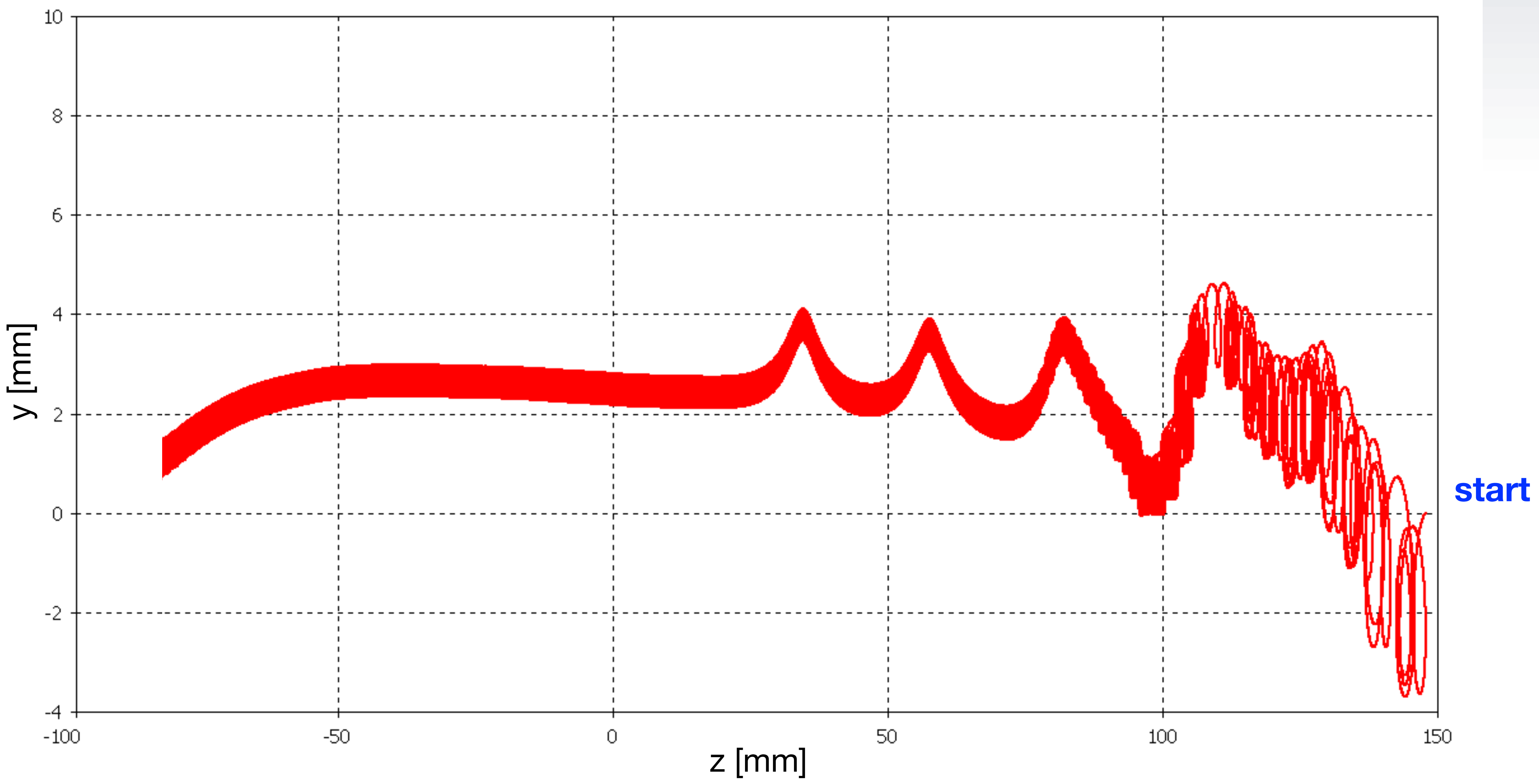


Promising Preliminary Results

- Particle source: **700 eV** e^- (better for e-gun!)
  6 cm far from magnet, 50° pitch angle

- Just a quick partial trial before coming here





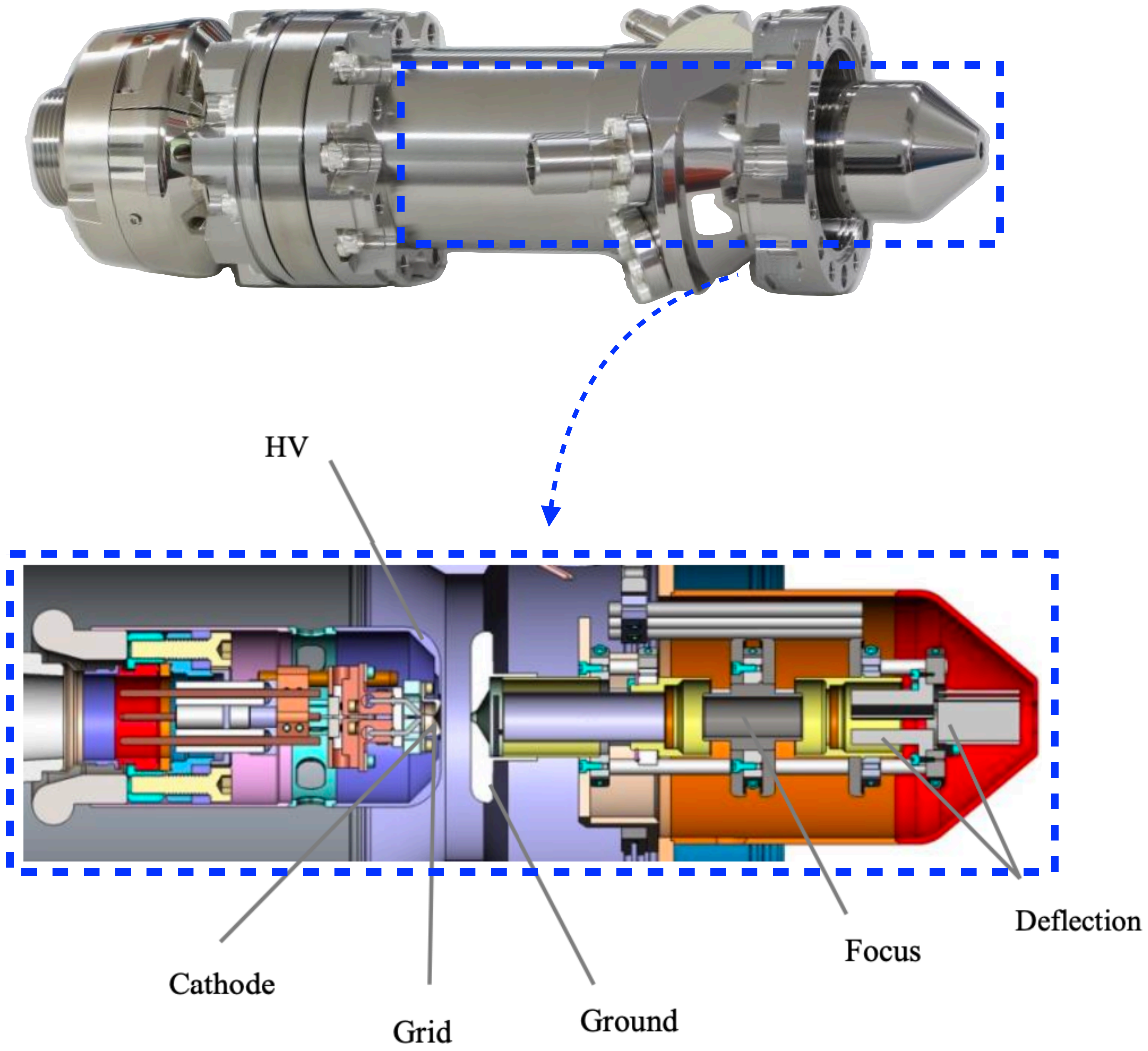
- Promising features:
  - electron altitude kept farer from electrodes
  - smaller Larmor radius/y distance ratio

Our Electron Gun: Features & Critical Points

KIMBALL PHYSICS
Excellence in Electron and Ion Optics

EMG-4212 / EGPS-3212
ELECTRON SOURCE / POWER SUPPLY

- Features:
  - Ta disk = grounded Anode
  - HV to accelerate electrons up to -20 kV
  - Wehnelt
  - Focus system (Einzel lens)
  - X/Y deflection plates



- Critical points:
  - Performances guaranteed from 1 to 20 keV
    → *need to be tested @ 600/700 eV*
  - Minimal working distance = 10 cm
    → *μ-metal tube till setup starting point ?*

How the Full Setup Looks Like: Some Upgrades

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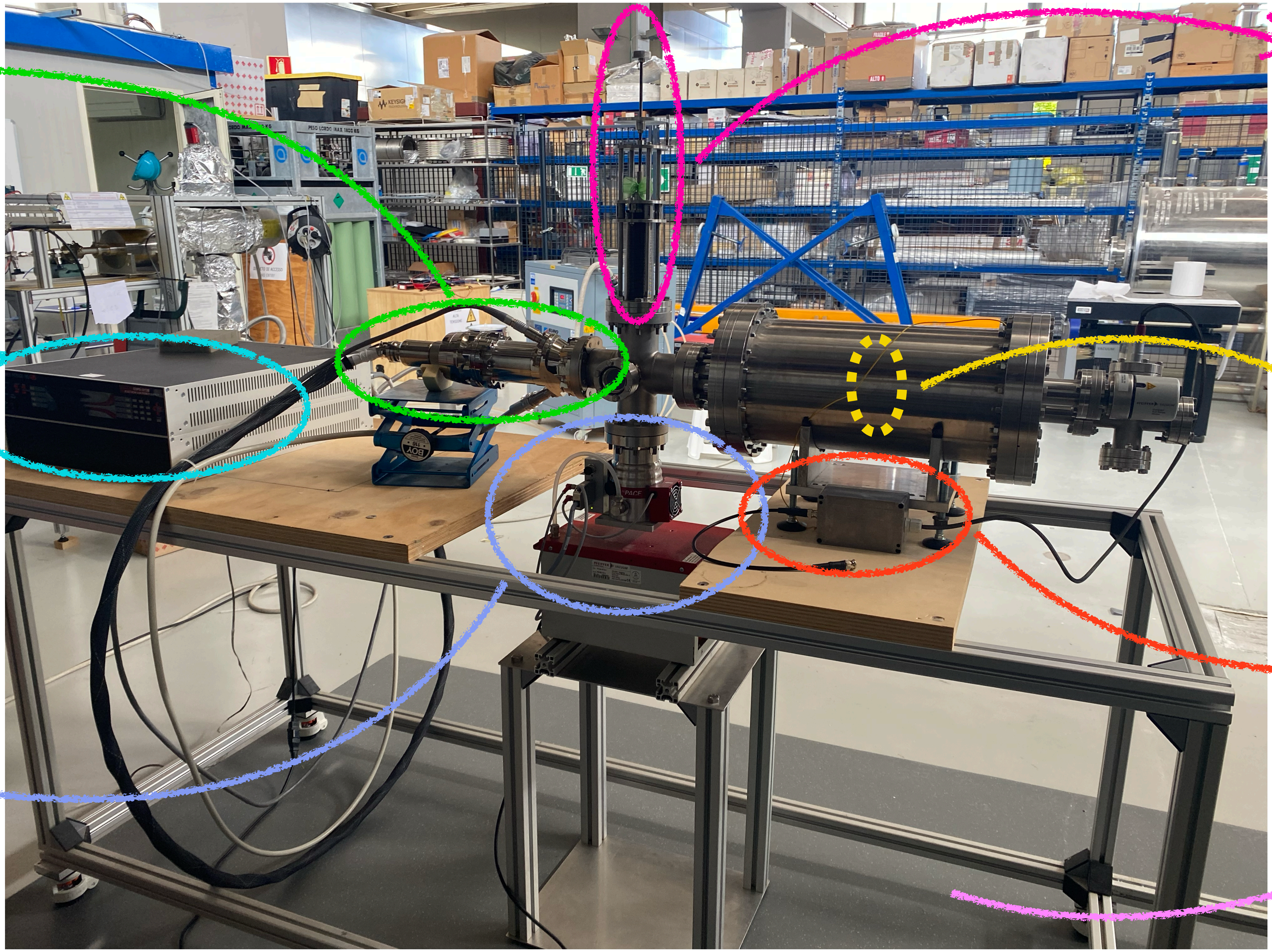
ELECTRON GUN
(E-GUN)

POWER SUPPLY

VACUUM PUMP
with primary pump separated to reduce vibrations
NEW



FEEDTHROUGH
+ (INSIDE)
Faraday Cup (FC)
coated with colloidal graphite NEW
&/or
phosphorous
screen

MICRO CHANNEL PLATE
(INSIDE)

RESISTIVE CIRCUIT
To connect 8.5 digits multimeter NEW

ANTISTATIC FLOOR
NEW

Recap & Next Steps

✓ Toy setup with only 5 injection electrodes sets worked → good starting point!

- Time to
  - Increase segmentation (e.g. 1 cm electrodes) → more trajectory control
  - optimize parameters (almost everything)

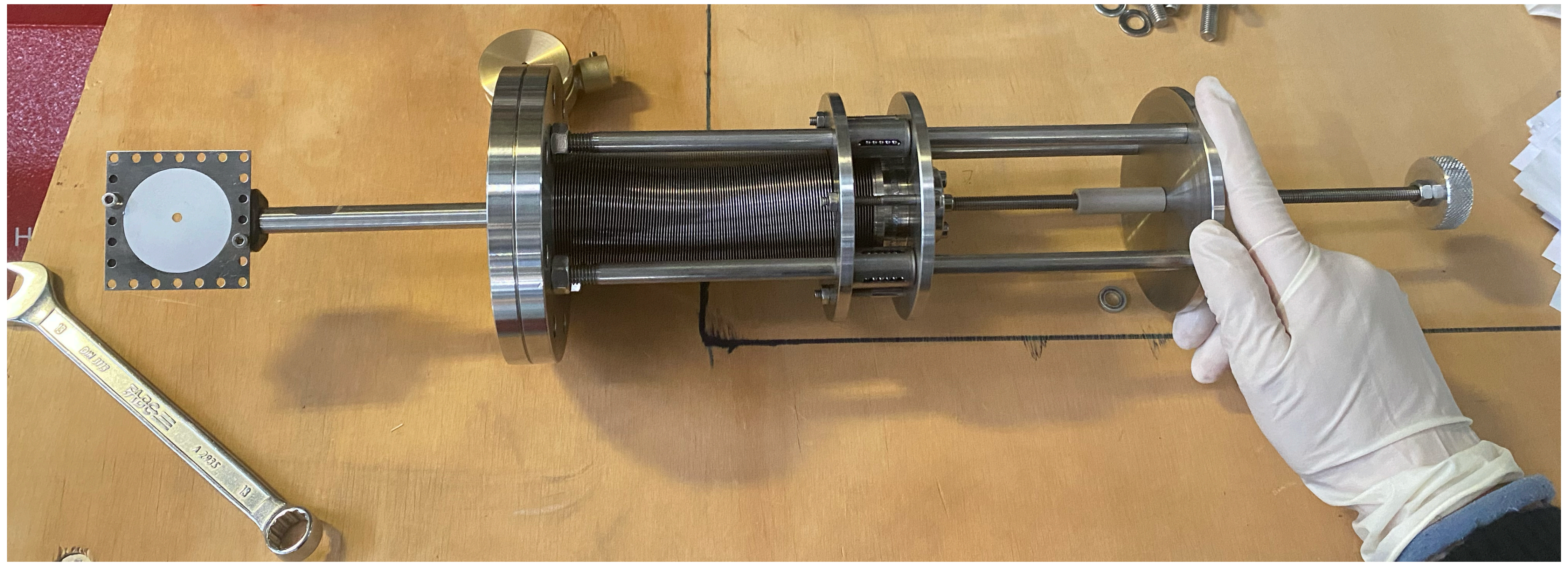
- Aims for each setup:
  - RF: acceleration system till 18.6 keV + slowdown till 30 μs in RF region
  - Magnet Crossing: maximize efficiency + possible detection setup

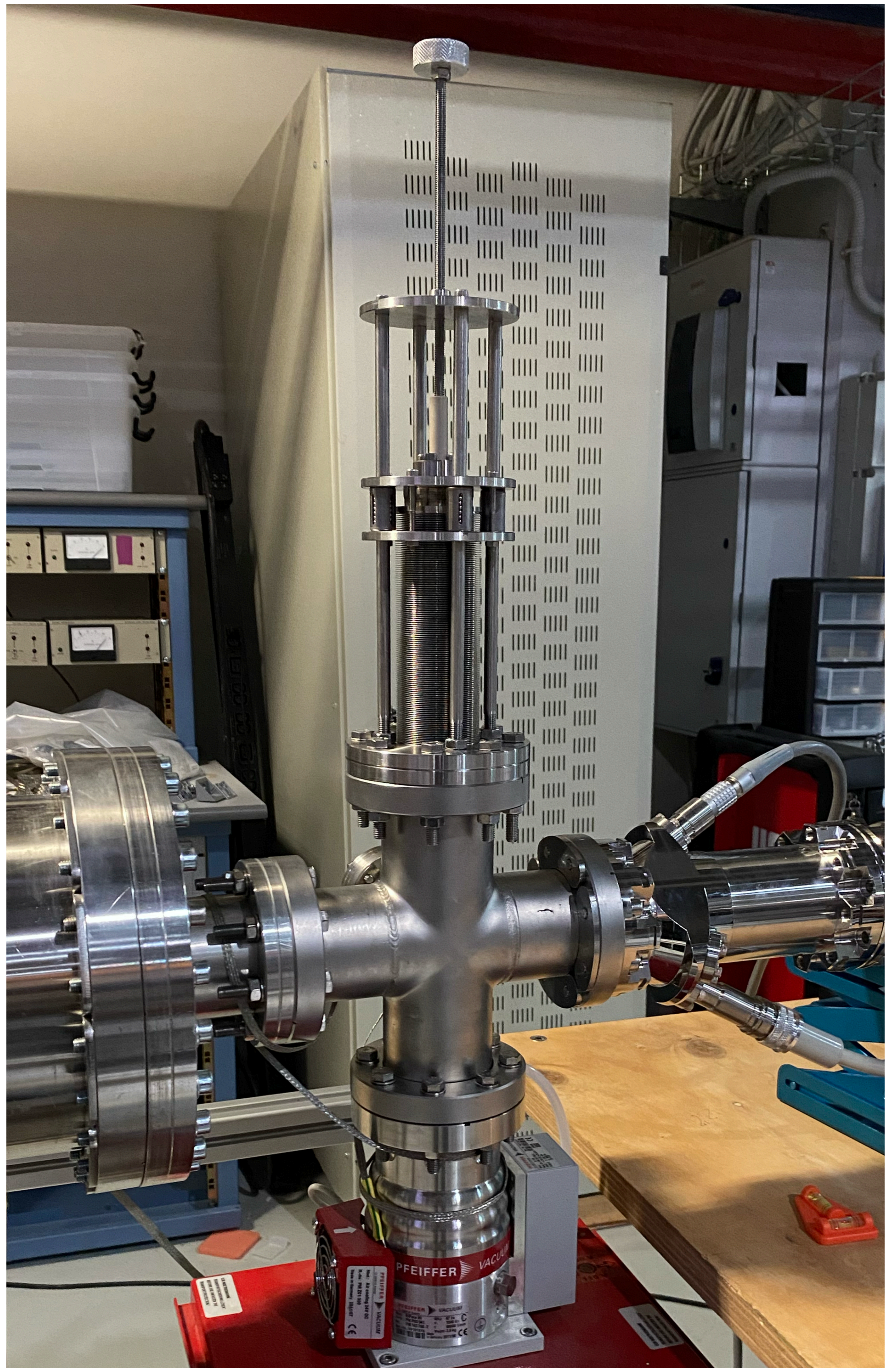
- To Do:
  - Better measurement of B field inside magnet (eg. Bz profile)
  - E-gun characterization @ 600/700 eV

BACKUP SLIDES

A Versatile Setup

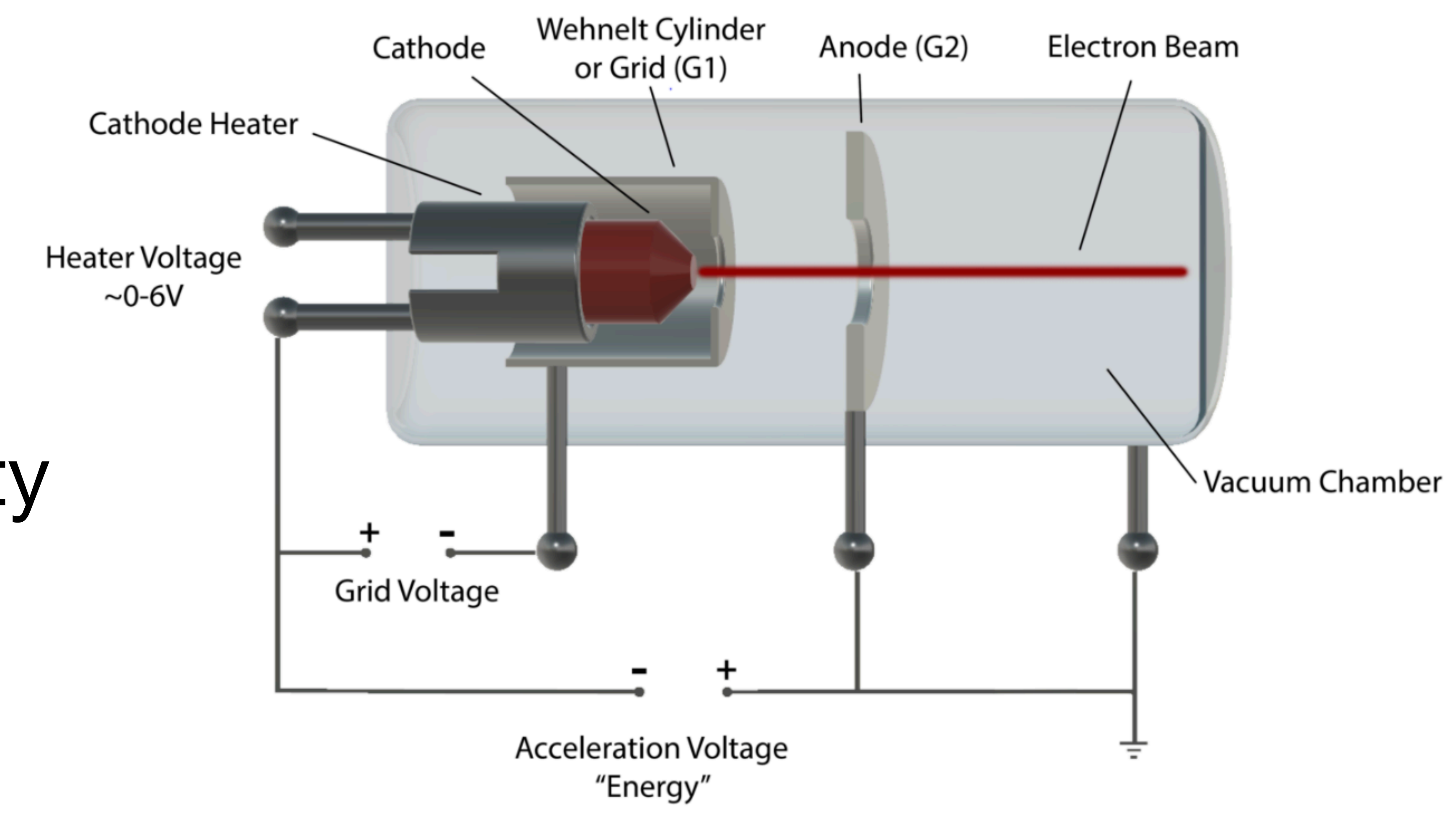
- Faraday cup &/or phosphor screen mounted on a feedthrough
  - ✓ Custom-made, in collaboration with LNGS Mechanics Workshop
  - ✓ Allows shifts on y-axis with sub-mm precision
  - ✓ Allows to completely remove beam monitoring unit from beam path





Wehnelt as a Beam Intensity Filter

- What is?
  - Tubular housing for cathode with fixed aperture
  - Negative bias → secondary electric field in cathode proximity



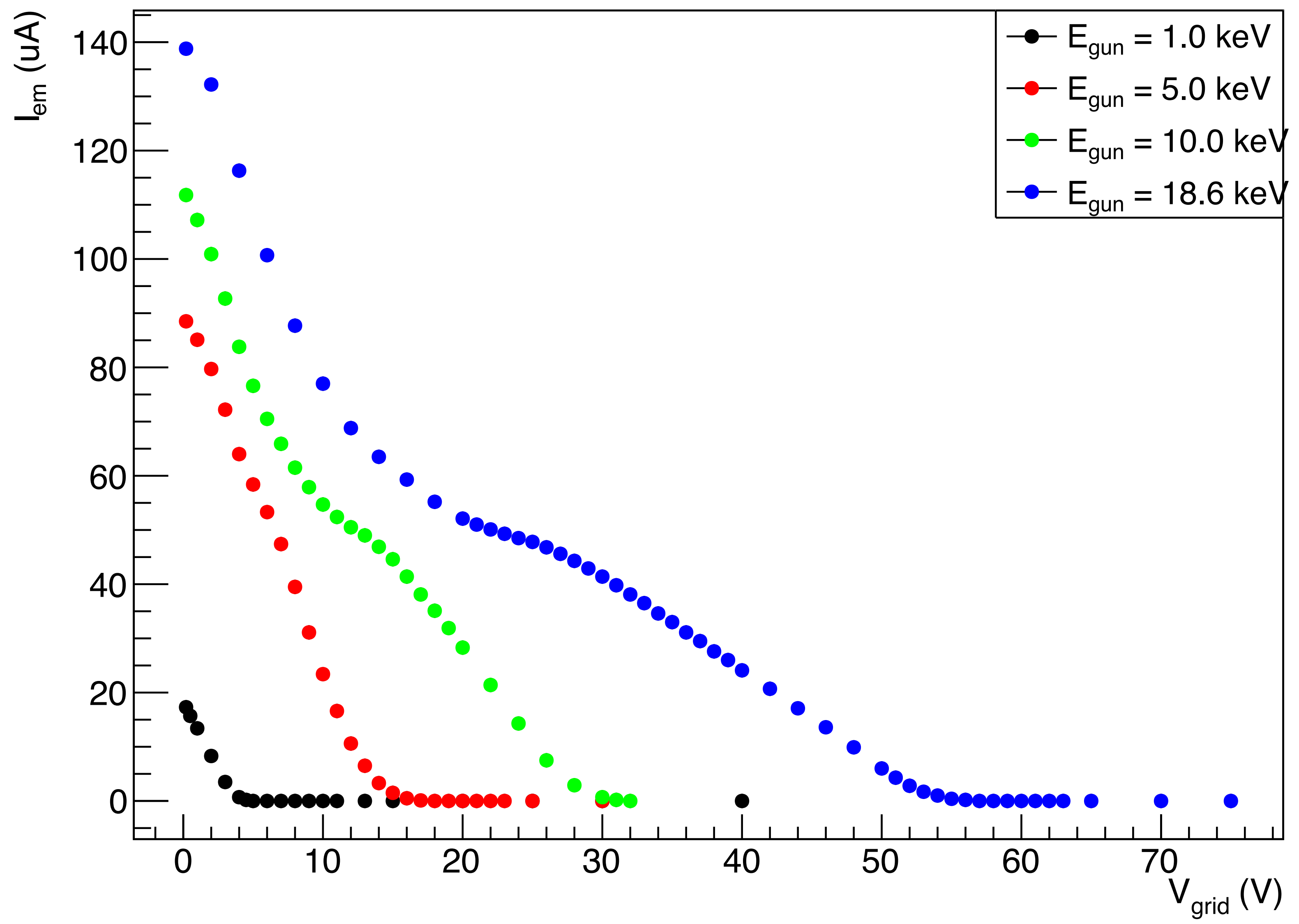
- How can be employed?
  - Mid-range voltage → adjust beam divergence & uniformity → beam characterization (spot size, I-V curve etc.)
  - High voltage → reduce electron emission from cathode edges till complete beam suppression

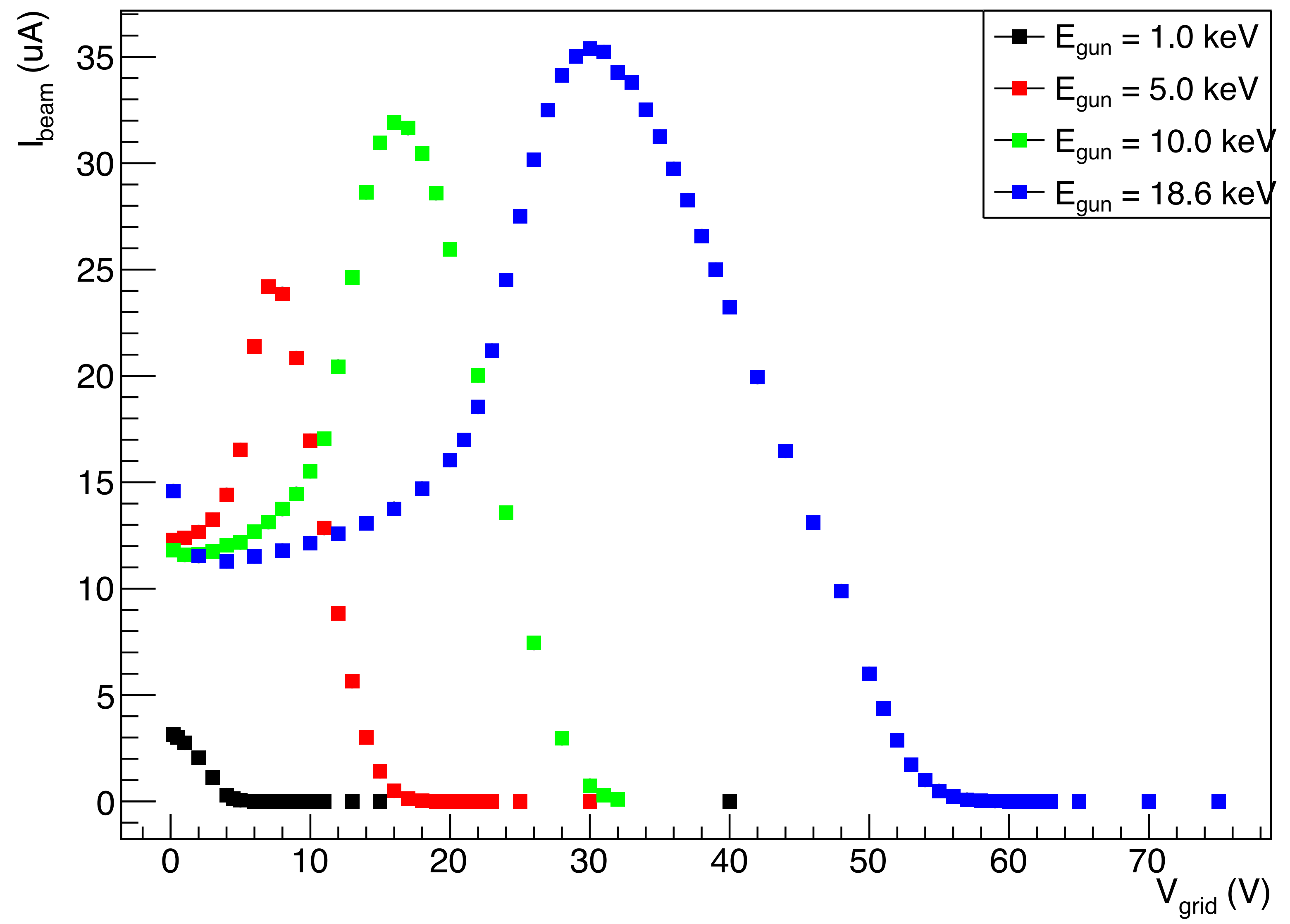
→ **Beam Intensity Filter**

possible needing for future usage as *electron trap calibration source*

Beam Current Optimized by Wehnelt

- Setup:
  - Keithley 2450 SourceMeter + double Faraday cup
  - Beam electron energy: 1 keV, 5 keV, 10 keV, 18.6 keV
  - Source voltage (V_{source}) set to 1.521 V
  - Focusing & deflection voltages optimized through Phosphor screen for each energy
  - Base pressure: 10^{-7} mbar
- Results:
  - Similar behaviors, different V_{grid} optimizing beam current
  - Better I_{beam}/I_{em} ratio for lower electron energies



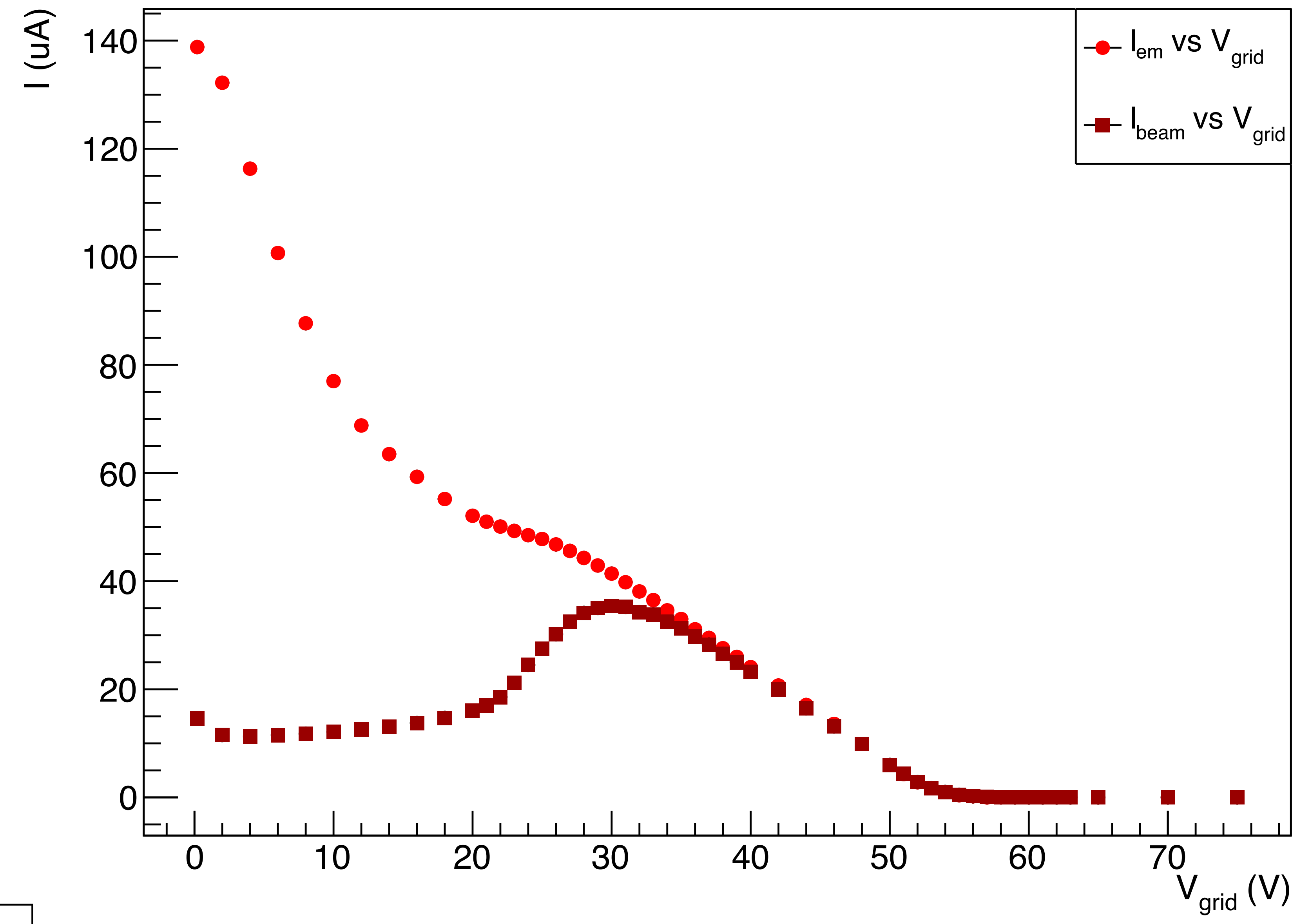


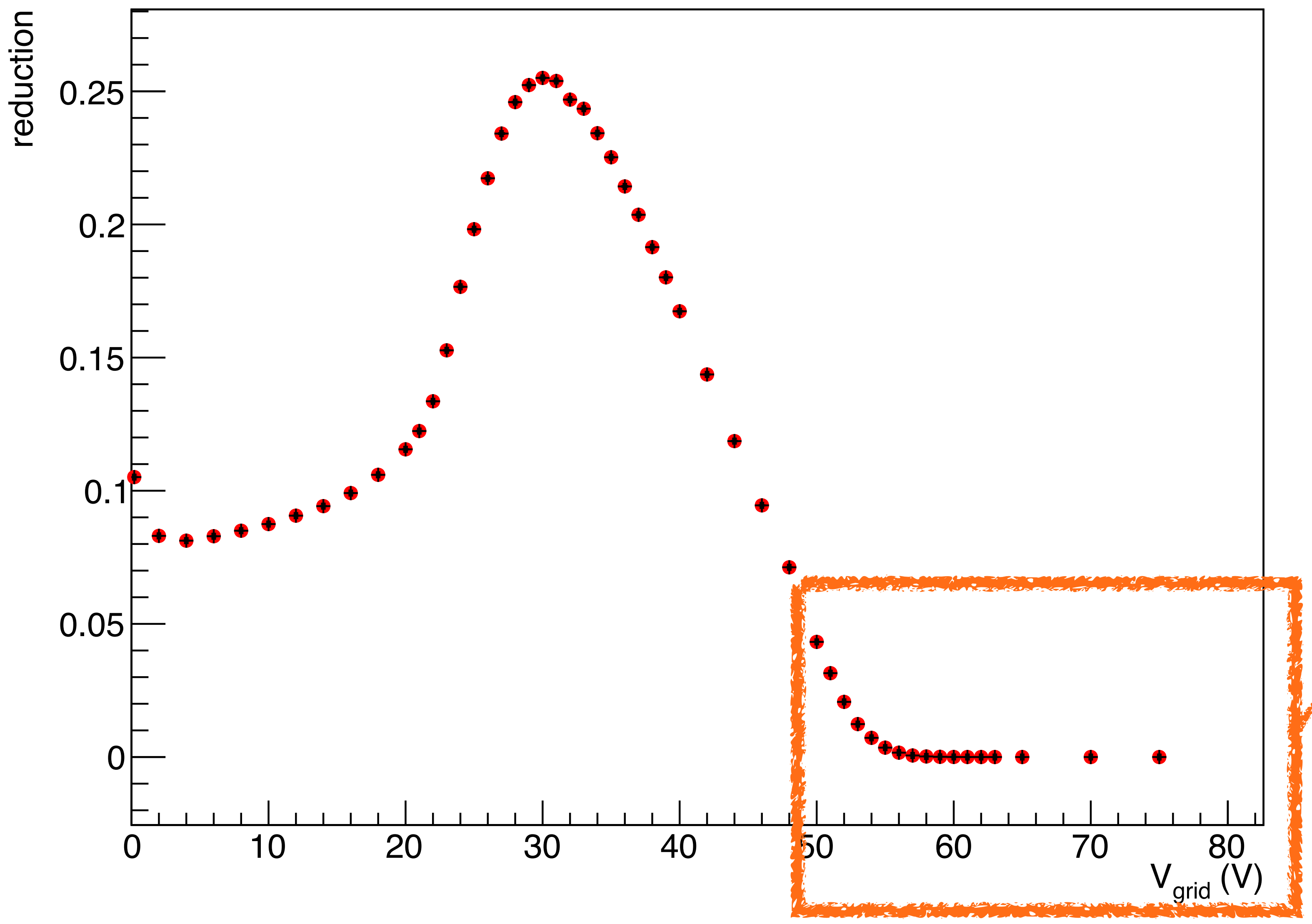
Up to 10^{-4} Reduction Factor

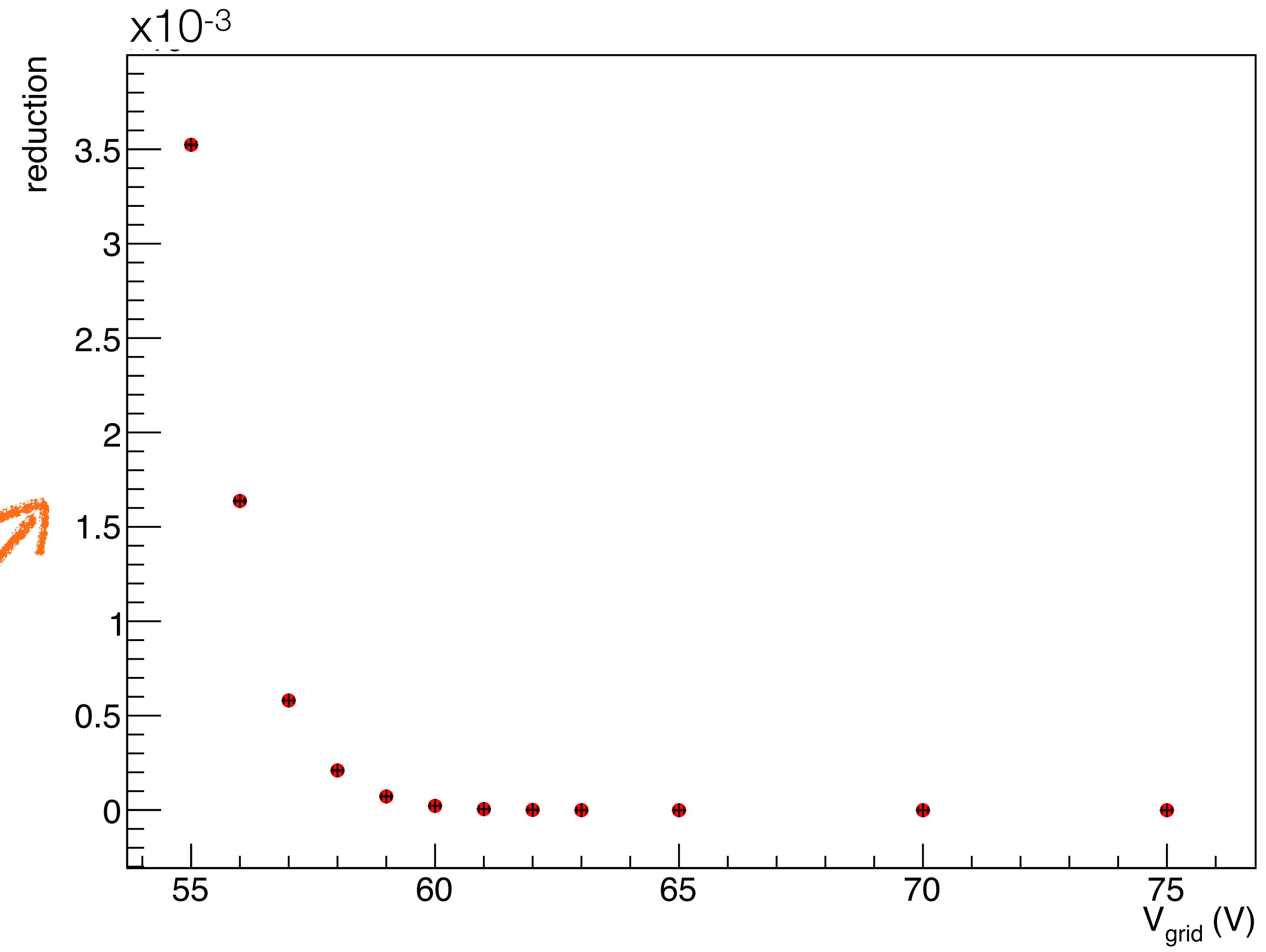
- Let's define: - "collection" efficiency $\epsilon = I_{beam}/I_{em}$
  - reduction factor $r = I_{beam}/I_{em}(V_{grid} = 0V)$

- Focusing on run @ 18.6 keV:
  - beam current I_{beam} maximized for V_{grid} = 30 kV
  - ϵ from 11% to ~100% for V_{grid} > 45 kV
  - $r > 10^{-4}$ for V_{grid} > 57 kV

from 140 μA to 700 pA!
not able to read
higher reduction
for instrumental limit







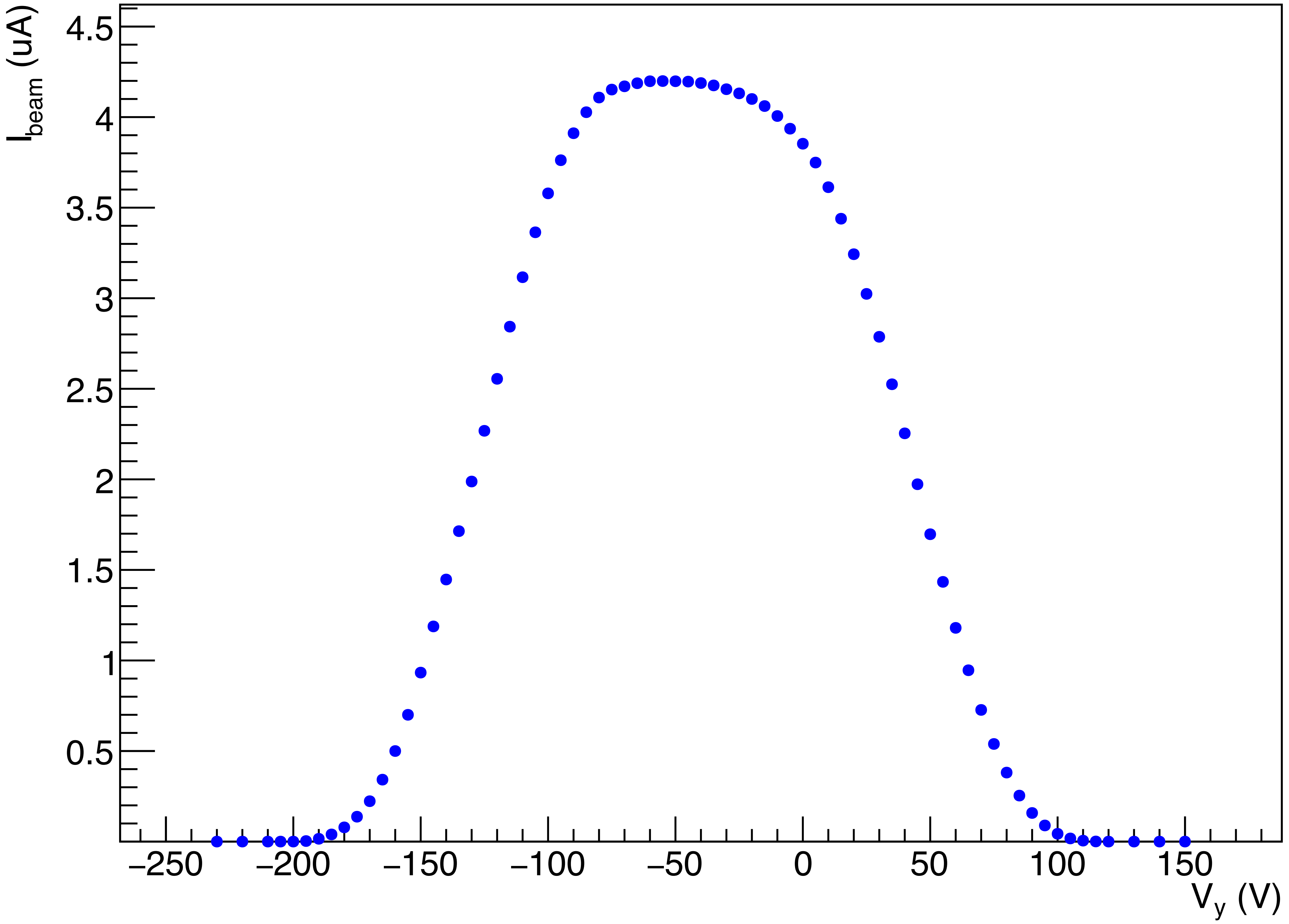
Preliminary Estimate of Beam Size

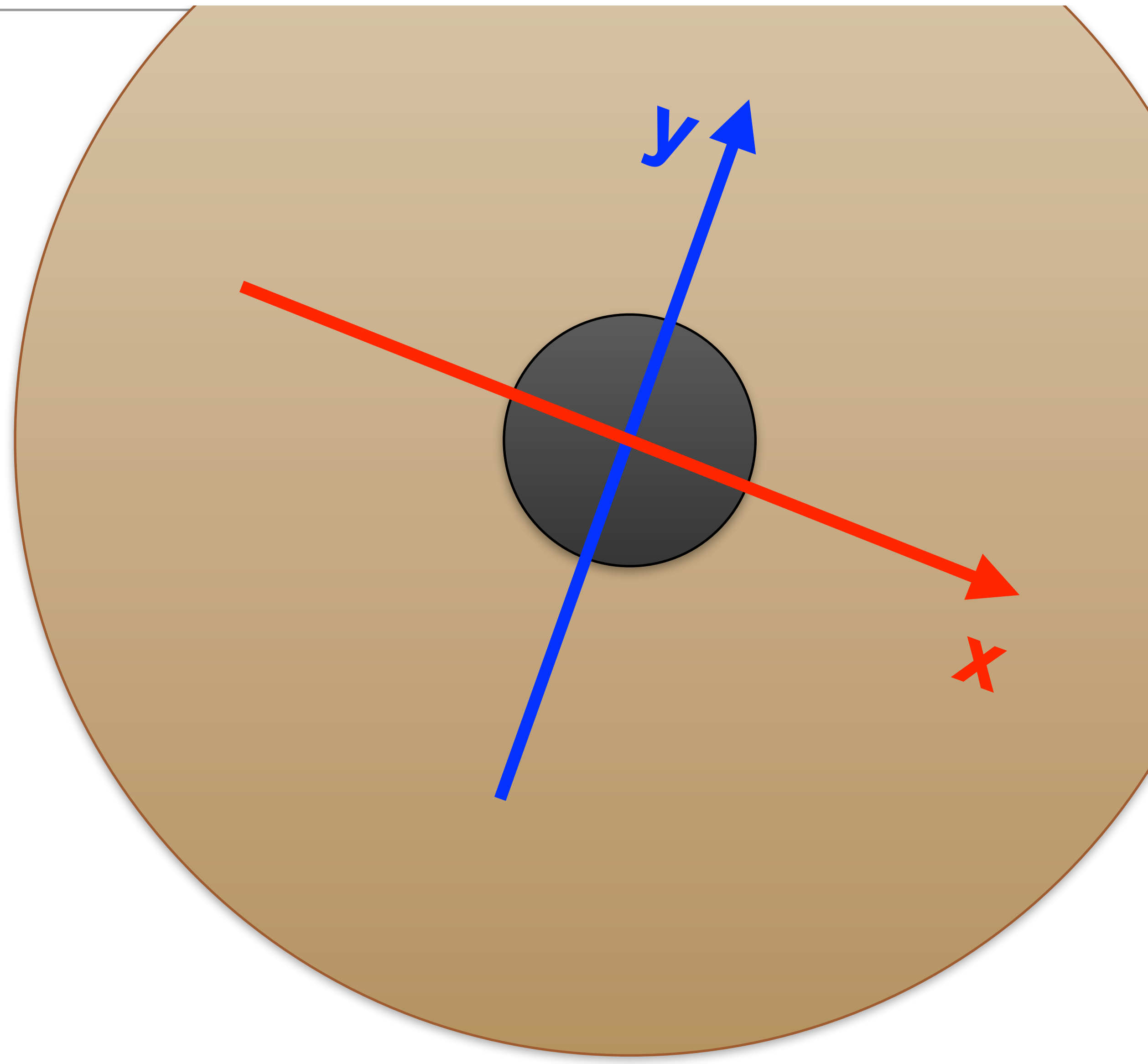
- Aims:
  estimate beam size + find correlation deflection voltage - position shift

- Scan of 3 mm Faraday cup hole moving beam with deflection voltages

  - I_{em} fixed to 5 uA
  - V_y from -240 V to 150 V
    with 5 V steps

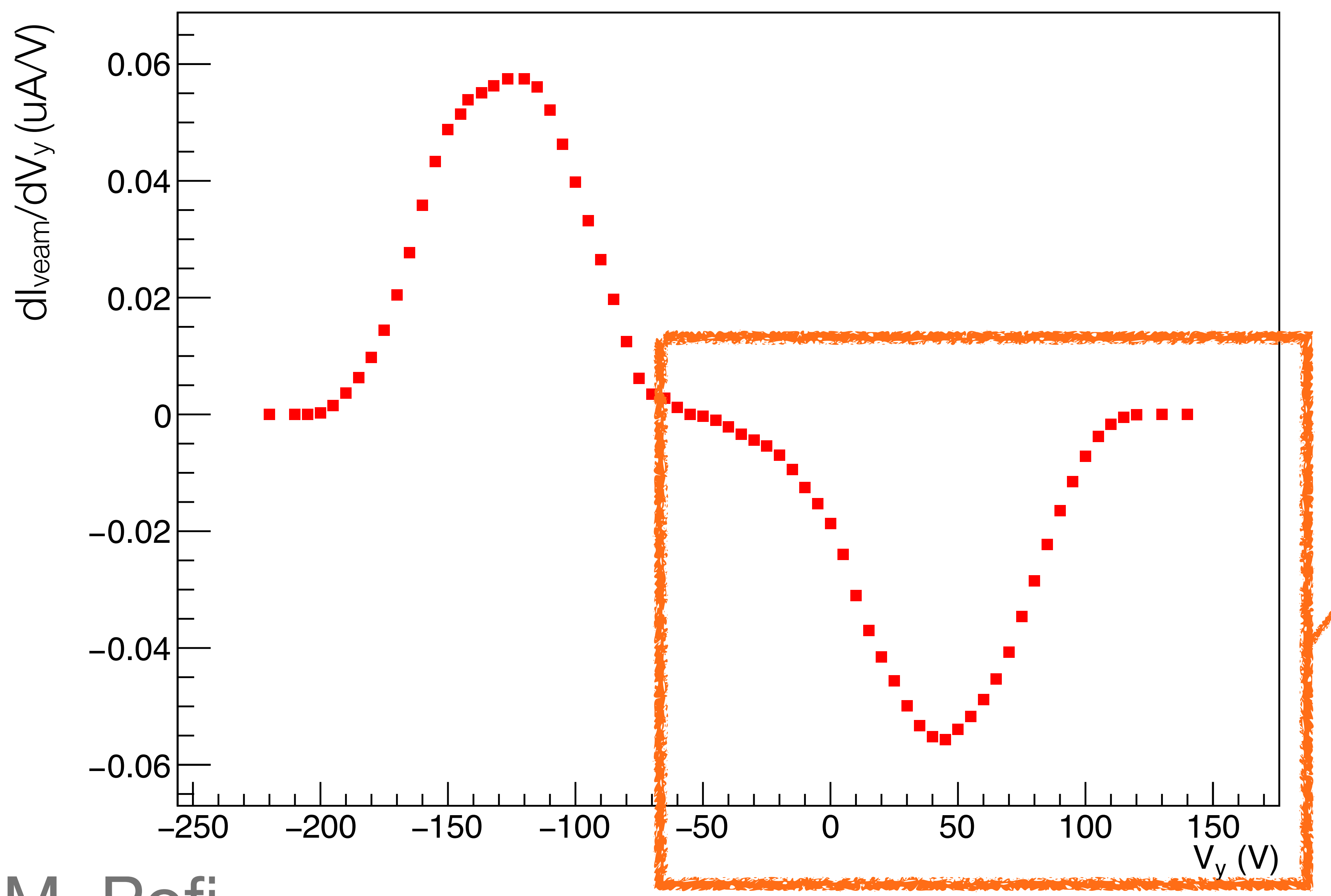
Result = convolution of
- gaussian
(e-gun spatial current distrib)
- step function (FC hole)

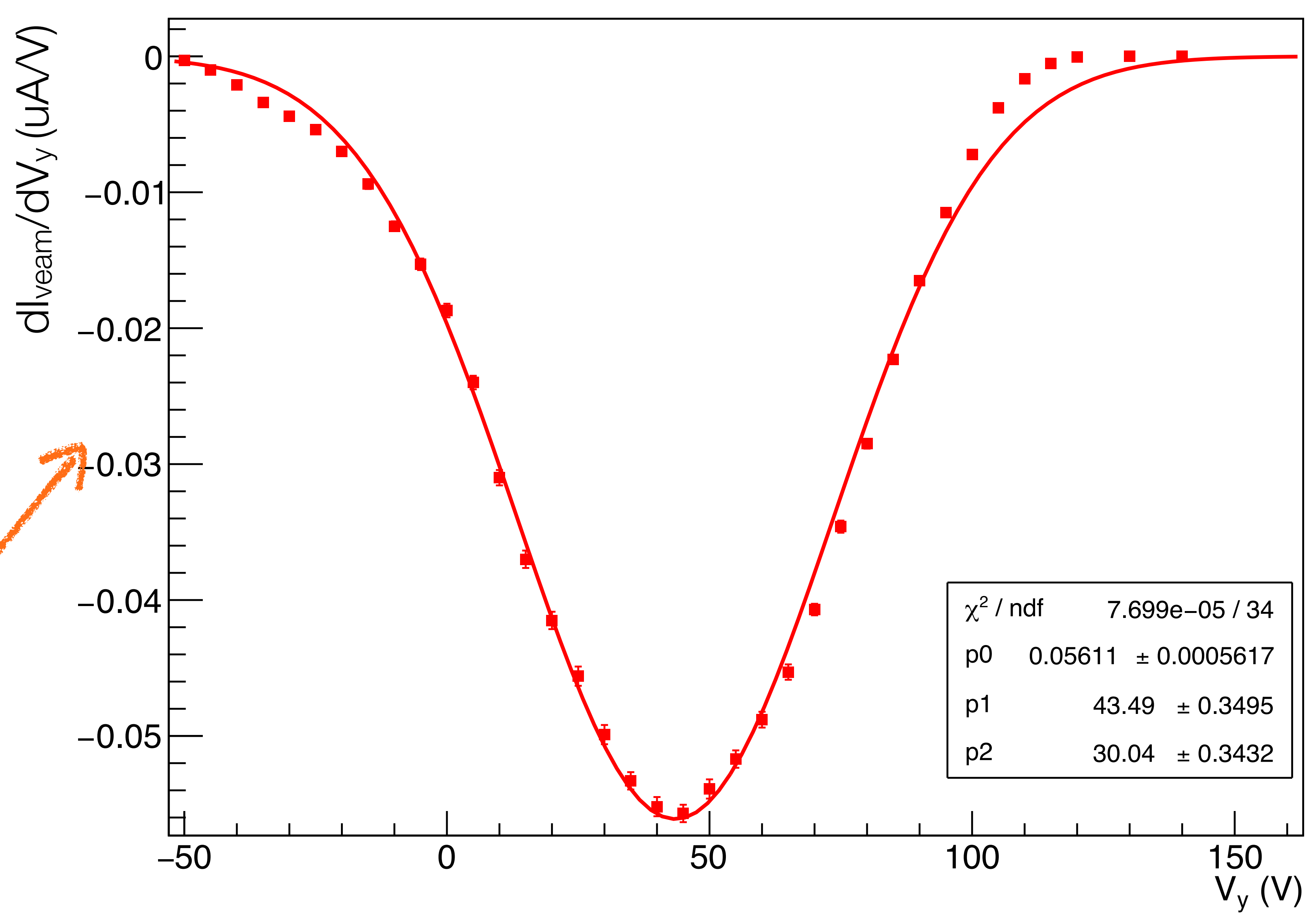




Sub-mm Spot Size

- From 1st derivative of I_{beam} vs V_y points (computed as $I_{beam}(V_y^i) - I_{beam}(V_y^{i-1}) / V_y^i - V_y^{i-1}$)
  - Gaussians reflecting beam spatial distribution with
    - Distance (peak to peak) ≃ 170 V = FC hole diameter = 3 mm → 1 V = 0.0176 mm
    - σ = 30 ± 0.3 V (fitted from 2nd gaussian) → σ = 0.53 mm





Recap & Next Steps

✓ Beam Current with reduction factor 10^{-4} exploiting Wehnelt grid

✓ 1st beam size estimate of ~0.5 mm
+ correlation deflection voltage - position shift

✓ I vs V from 0.1 μA to 180 μA

✓ Setup to measure $B_{\perp}$ on extended plane ready

TO DO

Beam Current with femtoammeter
to probe higher reduction

Estimate using manual shift via
feedthrough
+ optimize focusing voltage

Curve down to pA (or fA)

Measurement, COMSOL solution,
File Upload, Geometry implementation,
Multiparticle Simulation

Helmholtz coils cage