Expected performance of the IDEA dual-readout calorimeter

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Physics Benchmark

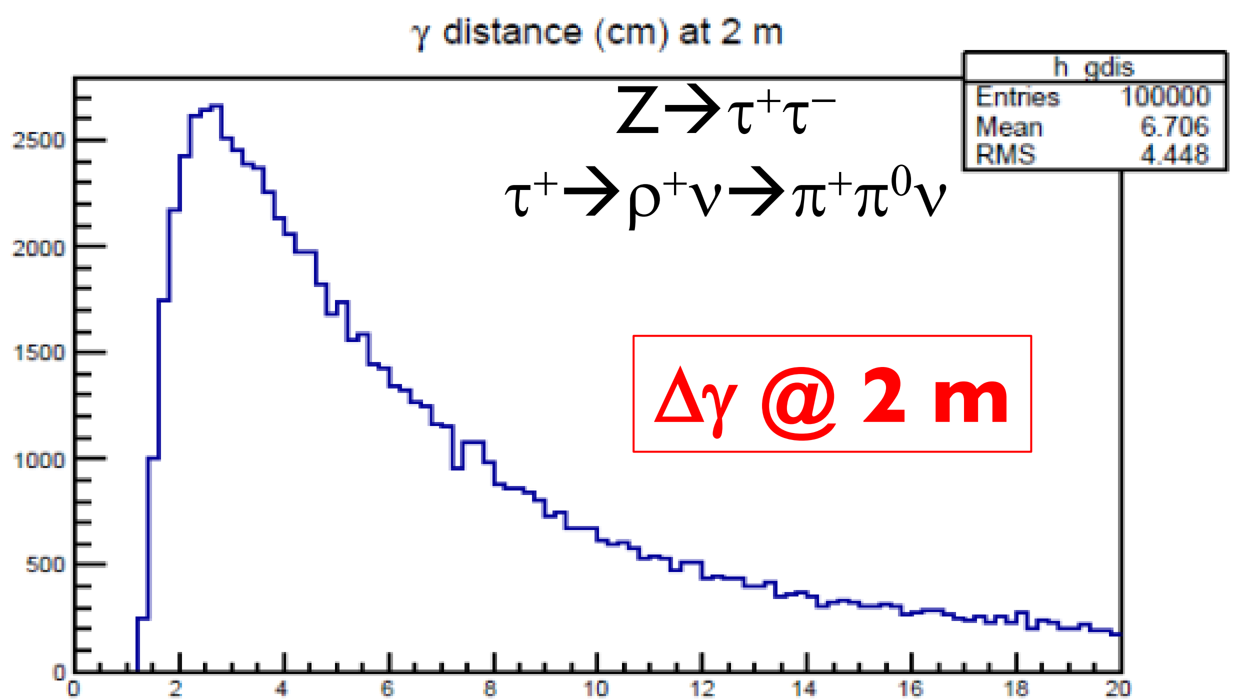
e+e- →HZ physics constraints

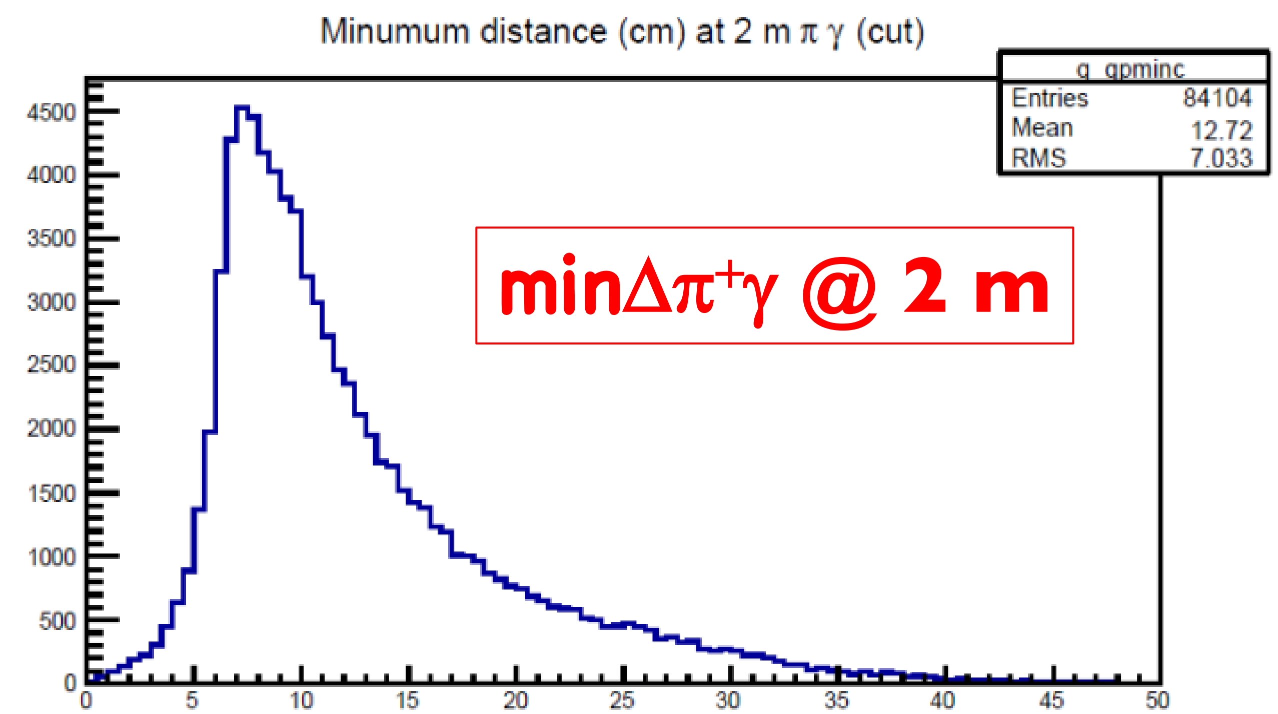
- H→ $\gamma\gamma$ → ECAL resolution
  - As good as possible – at least 20%/$\sqrt{E}$ + 1%
- H→ qq, VV → ECAL+HCAL resolution
  - As good as possible – at least 3-4% on jets from W,Z decay

e+e- → Z/WW physics constraints

- Additional EW physics drivers:
  - High precision acceptance determination
  - Good e/γ/π^0 discrimination

Other drivers

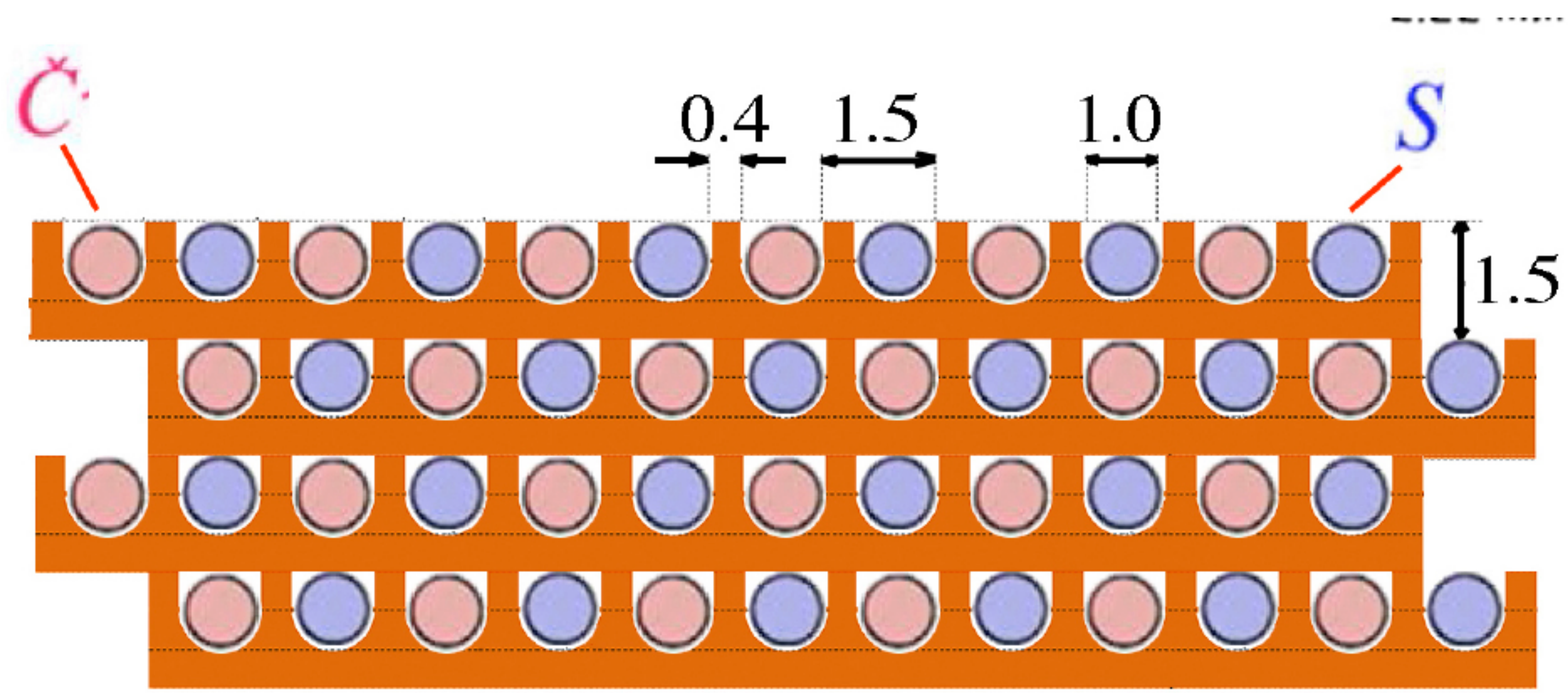




- π^0 important in tau and HF physics
  - No π^0: 35% $\tau \rightarrow$ 1 (e, μ) $\nu\nu$ + 20% $\tau \rightarrow (1,3)\pi^{\pm}$ $\iota\nu$
  - 1 π^0: 28% $\tau \rightarrow (1,3)$ $\pi^{\pm}\pi^0 l\nu$
  - 2 –3π^0: 10% $\tau \rightarrow \pi^{\pm}(2,3)$ $\pi^0 l\nu$
- High granularity/Pre-shower → π^0 identification
- Overlap with π^+ may require longitudinal segmentation

Dual Readout Calo: Basic configuration

- Alternate clear and scintillating fibers in metal matrix
- Scintillating fibers sensitive to all charged particles
- Clear fibers sense only Cherenkov light
  - Mostly electrons and positrons



Fiber pattern ***RD52***

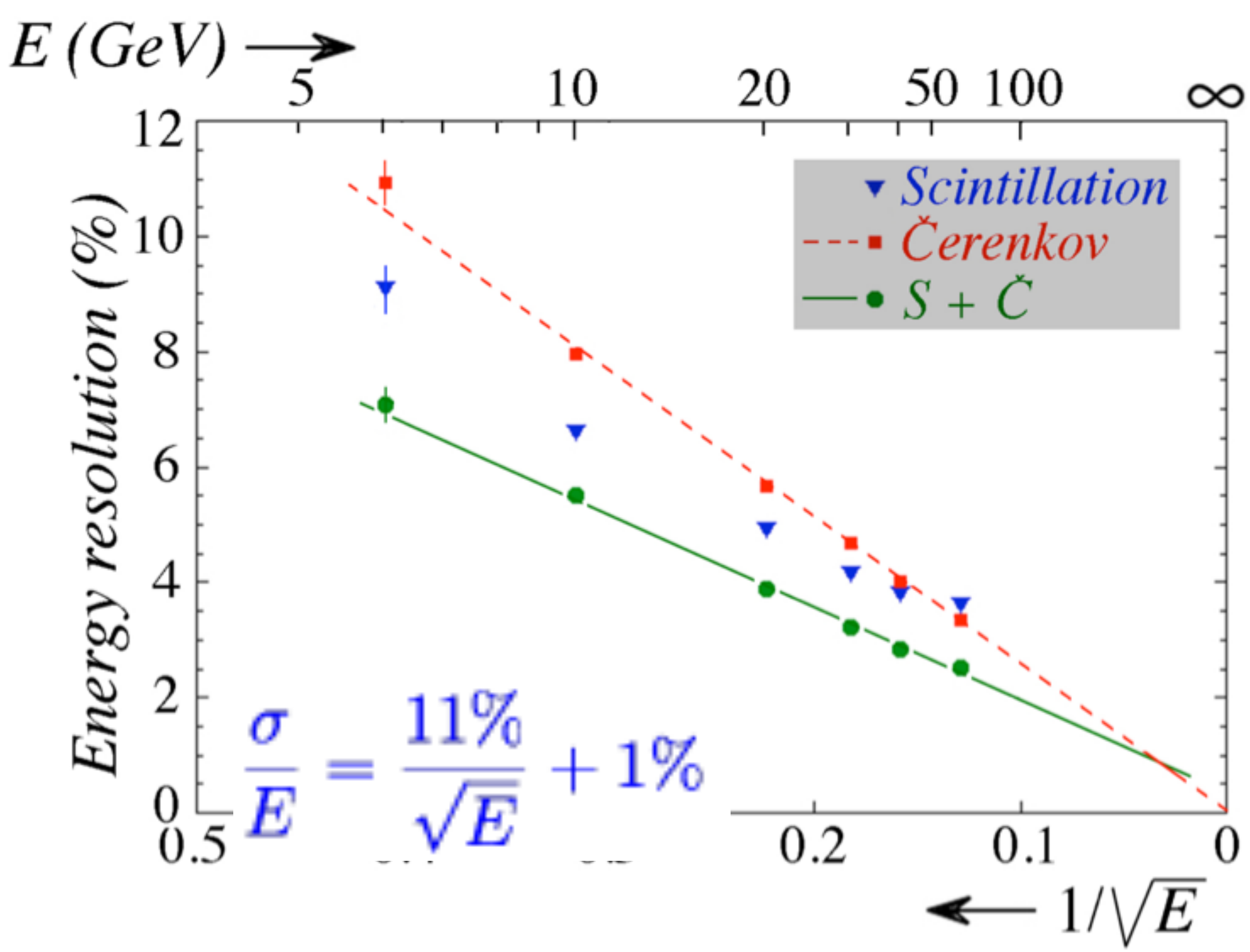
Dual Readout calorimeter

- Dual Readout Calorimeters main features
  - Designed to optimize EM, hadronic and jet resolution
    - Large sampling fraction for good EM resolution
    - Event by event correction for EM fluctuations in showers and jets
  - Intrinsic transverse granularity up to 1-2 mm
  - Potential for longitudinal segmentation with timing or specific fiber geometries
  - Particle ID capabilities
  - Fast detector response
  - All electronics in the back simplifies cooling and access

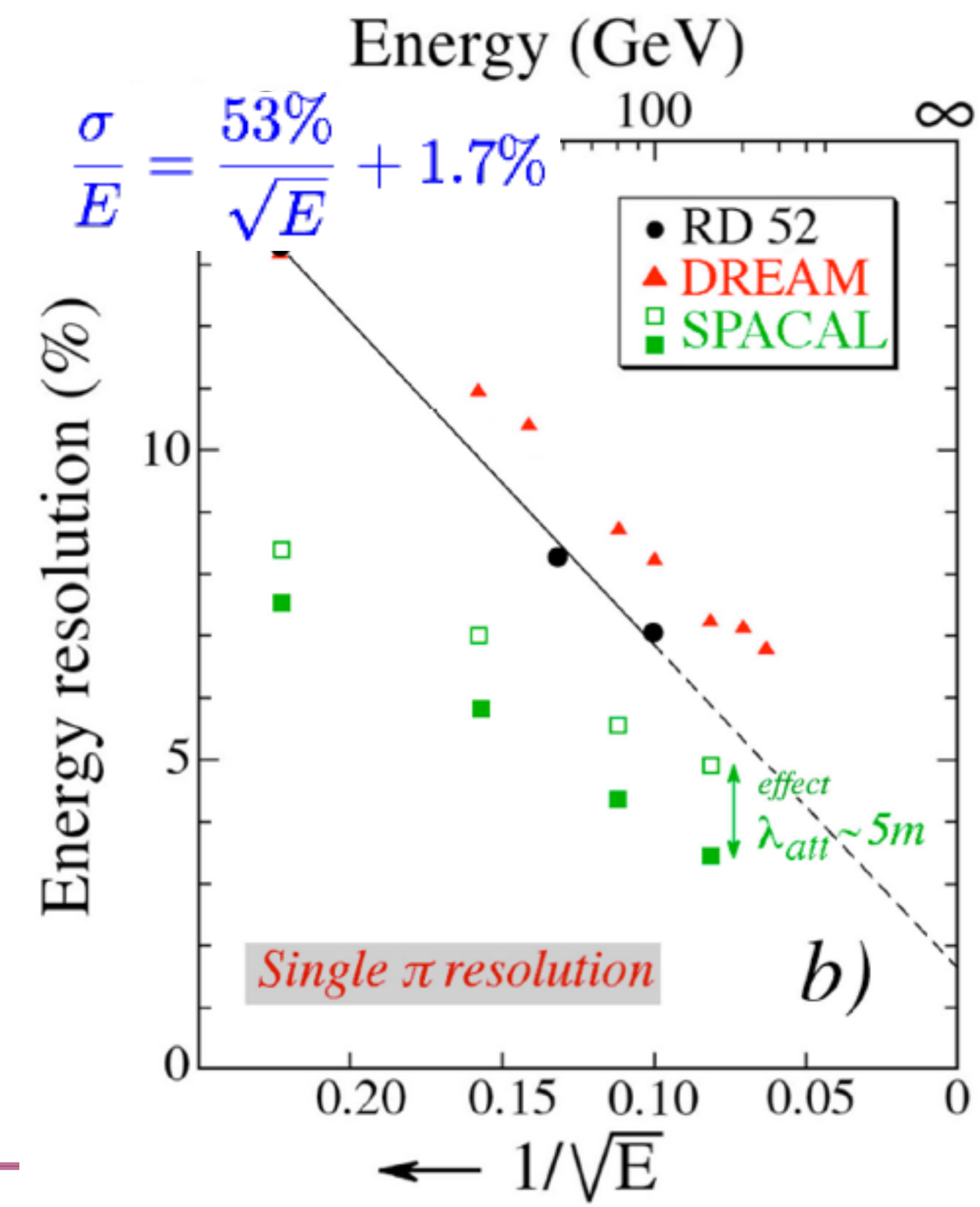
Prototypes performance

- Copper dual readout calorimeter
  - Demonstrated EM resolution
  - Observed Had resolution dominated by lateral leakage (~6%)

Courtesy of DREAM/RD52

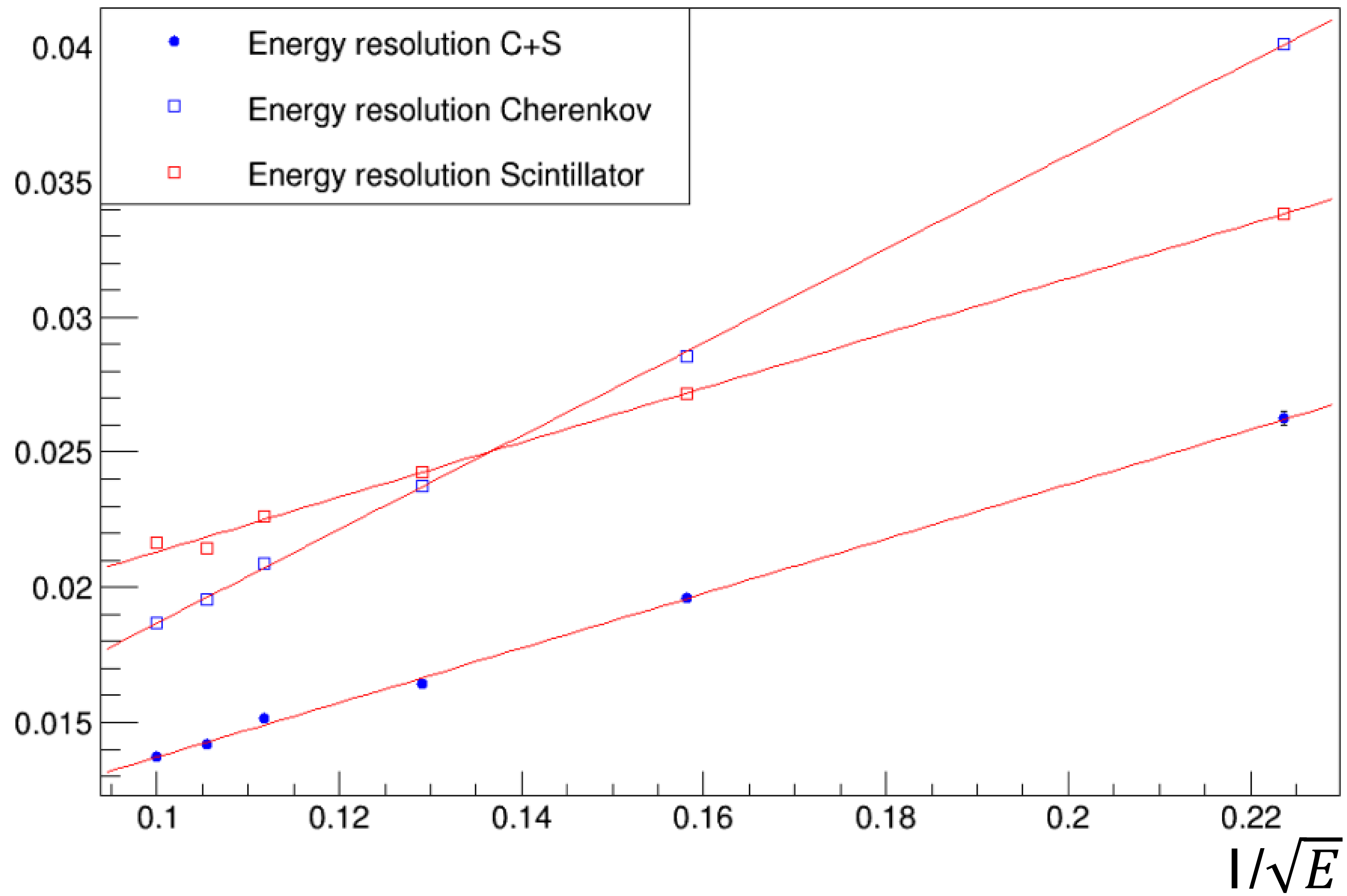


Cu



EM Performance

Simulation



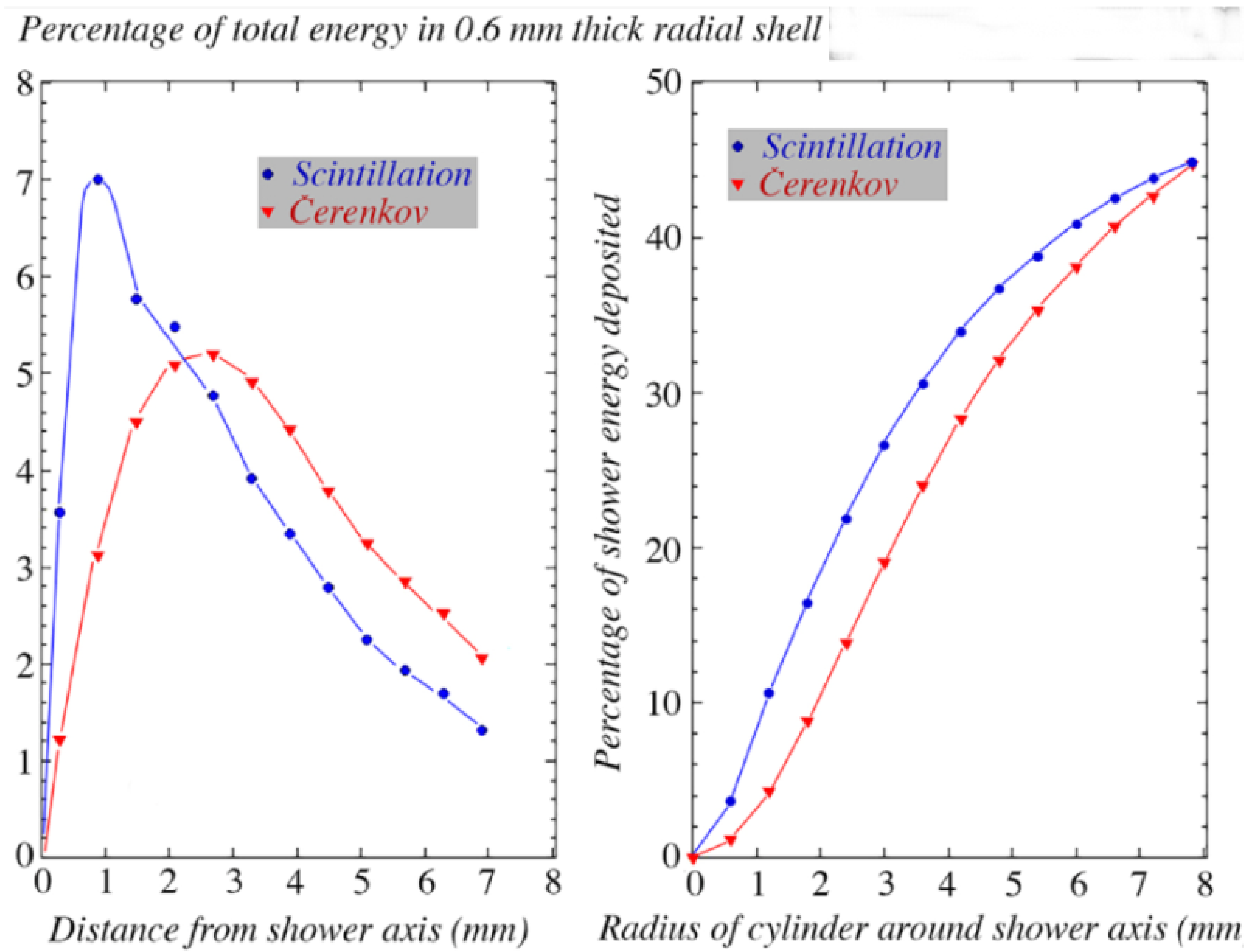
S-only: 10.5/√E+1.1 (%)

Č-only: 17.9/√E (%)

(unweighted) average: 10.3/√E+0.3 (%)

Radial shower profile

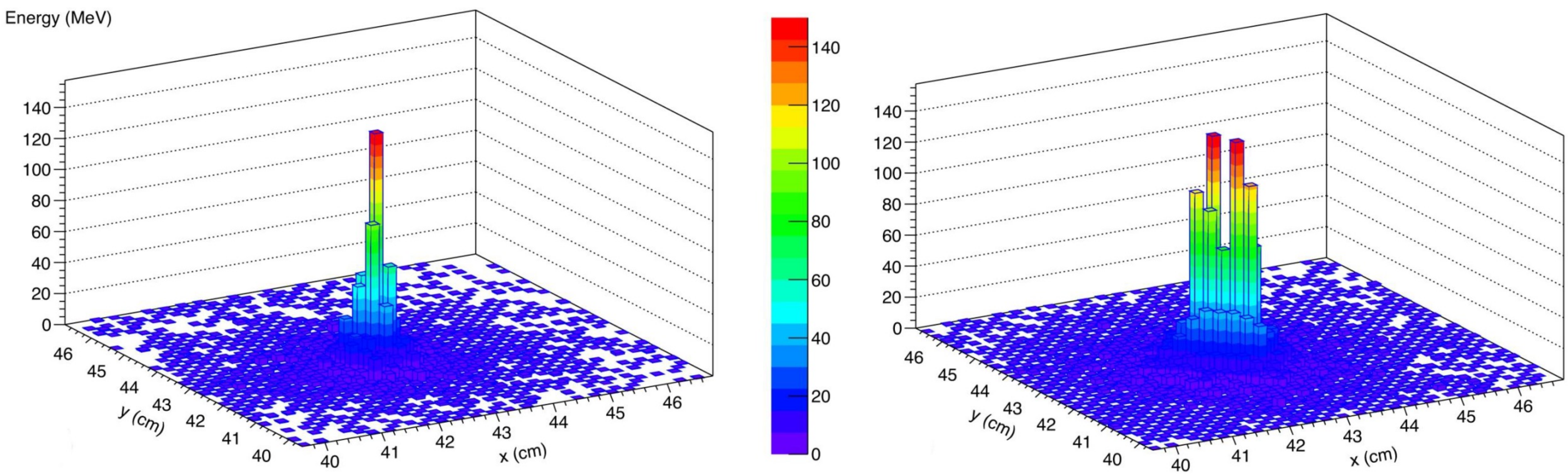
Test beam data



Radial shower profile

50 GeV electrons

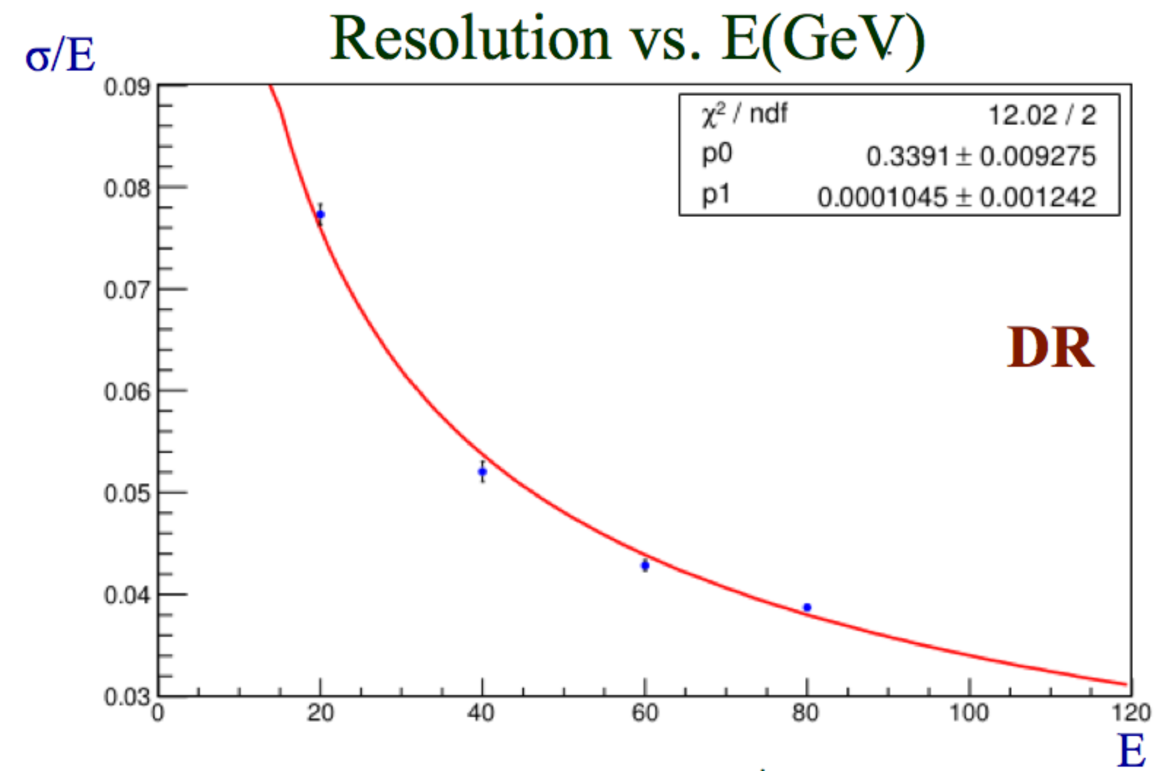
100 GeV π^0

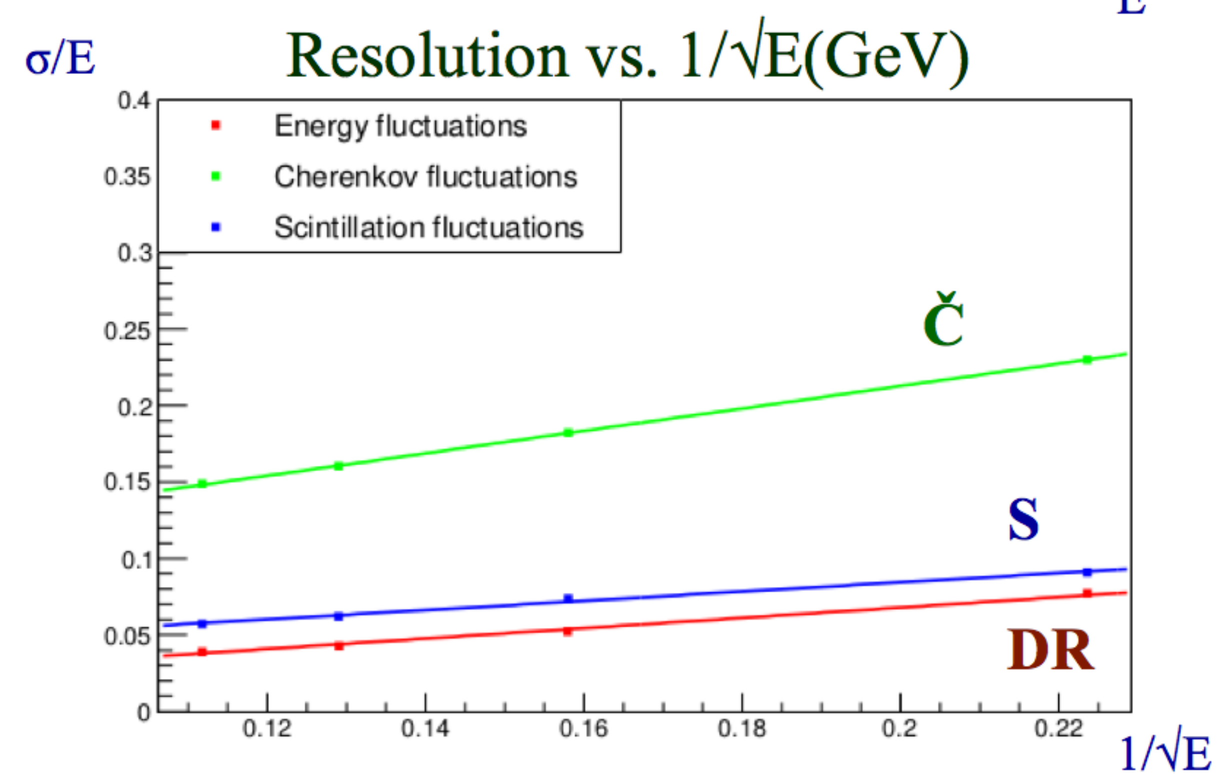


Test beam tuned simulation

HAD Performance

- Use test beam data to tune simulation
- Use simulation to correct for lateral leakage
- 81 and 91 GeV jet separation





$\check{C}$: $\sim 73/\sqrt{E} + 6.6$ (%)

S: $\sim 30/\sqrt{E} + 2.4$ (%)

DR: $\sim 34/\sqrt{E}$ (%)

HAD Performance

- Use test beam data to tune simulation
- Use simulation to correct for lateral leakage
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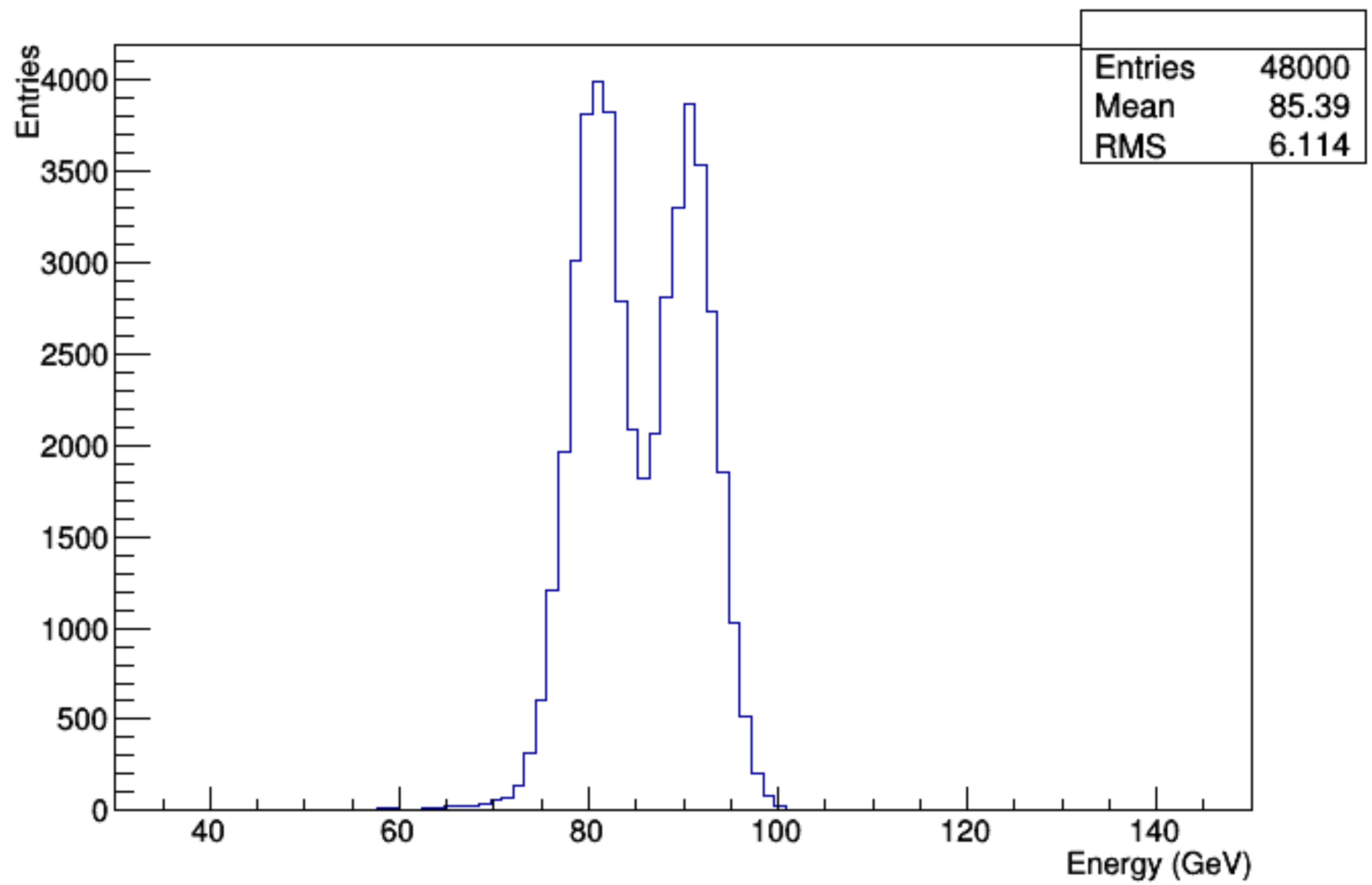
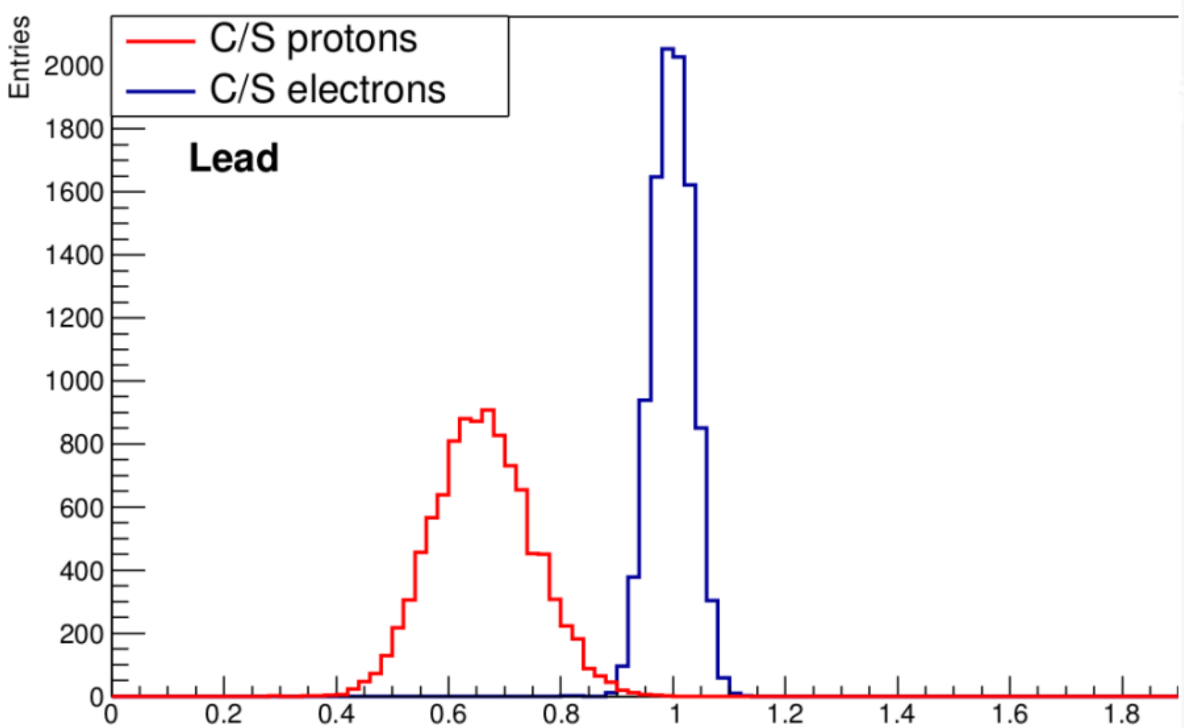
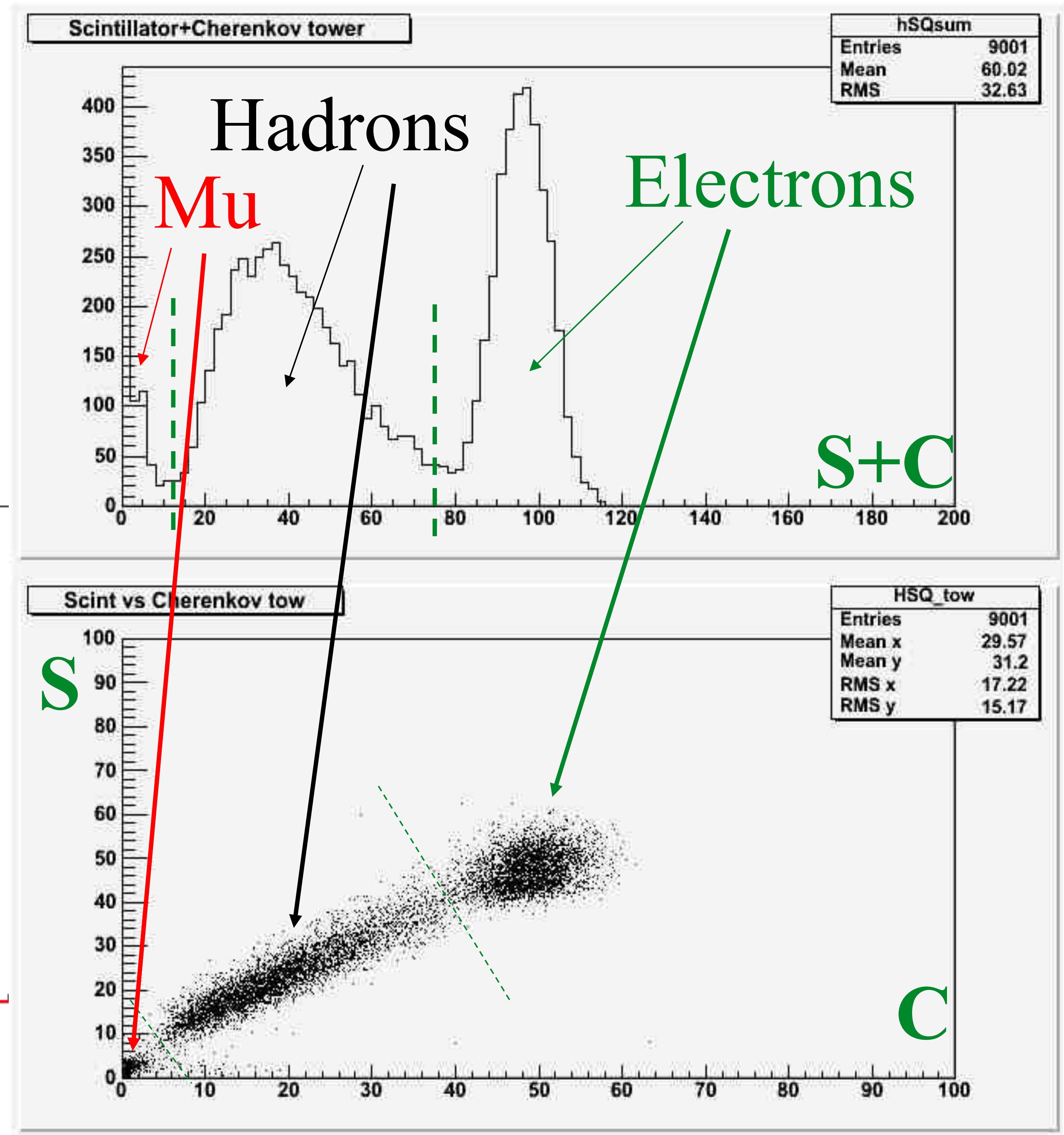


Particle ID

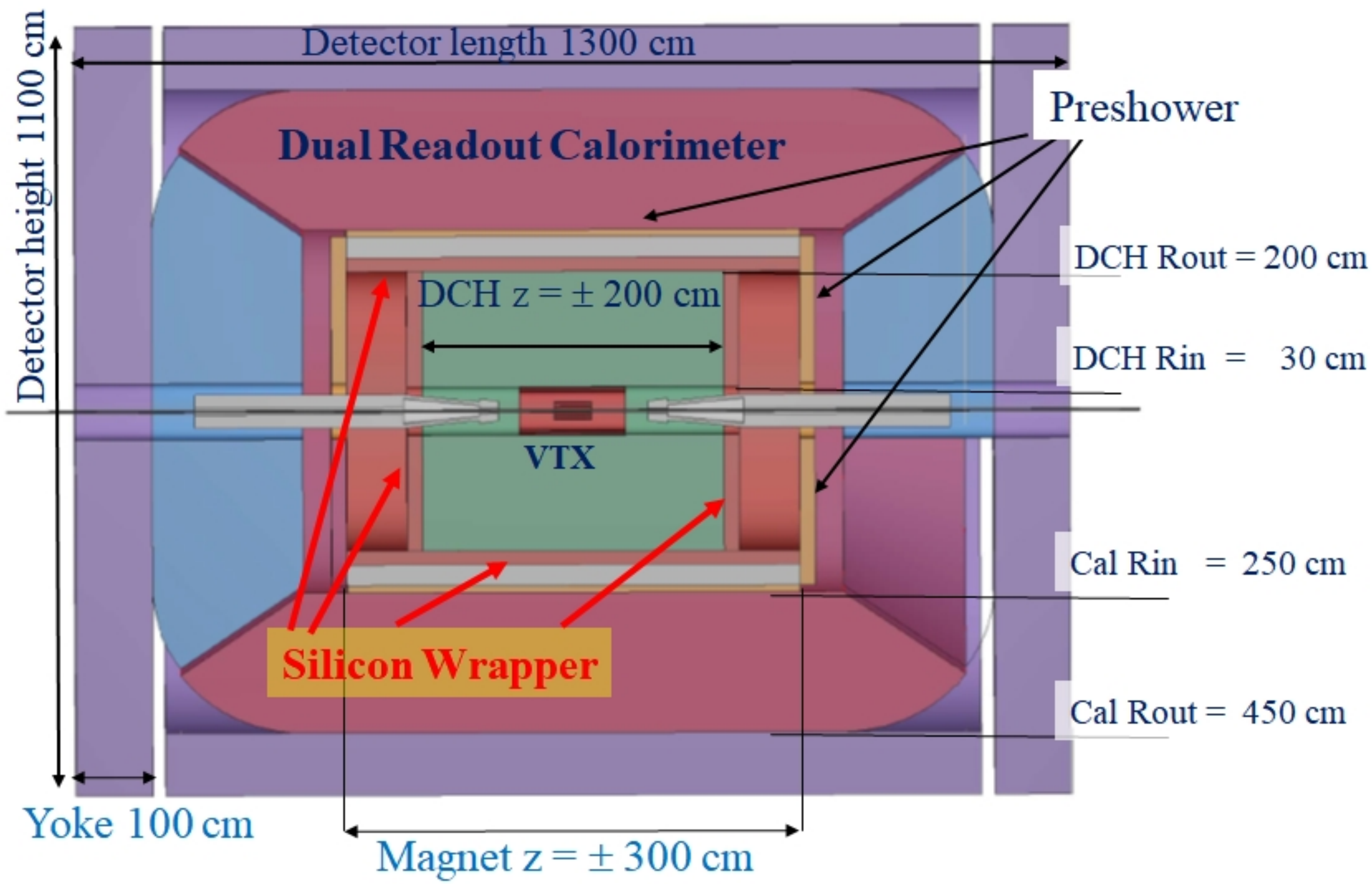
- Test beam
- 80 GeV electron/proton separation
  - Rejection power 600 @ 98% efficiency

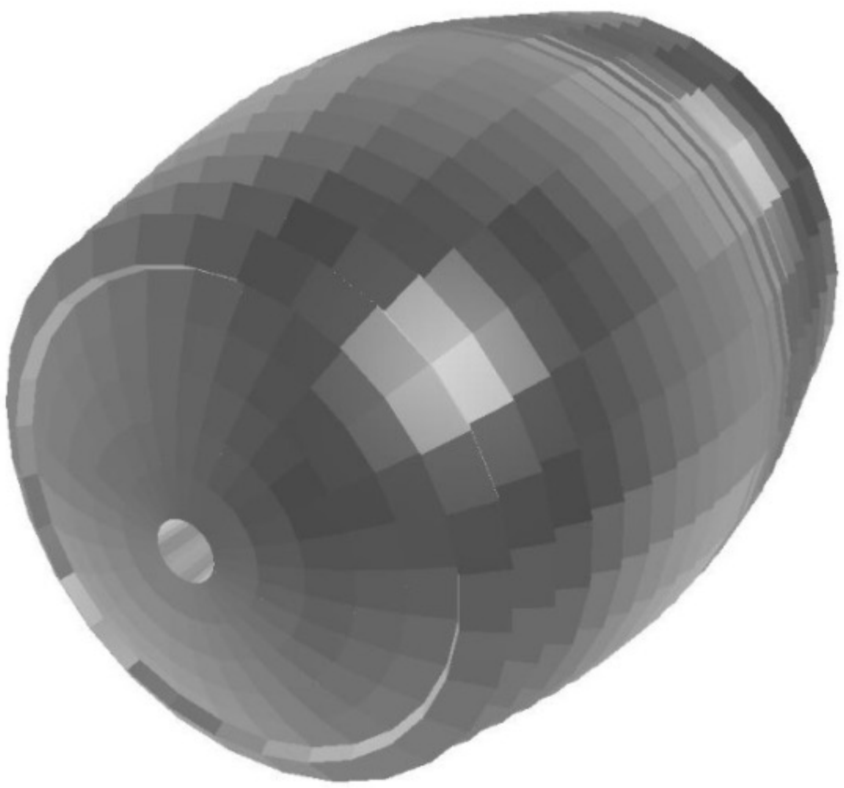


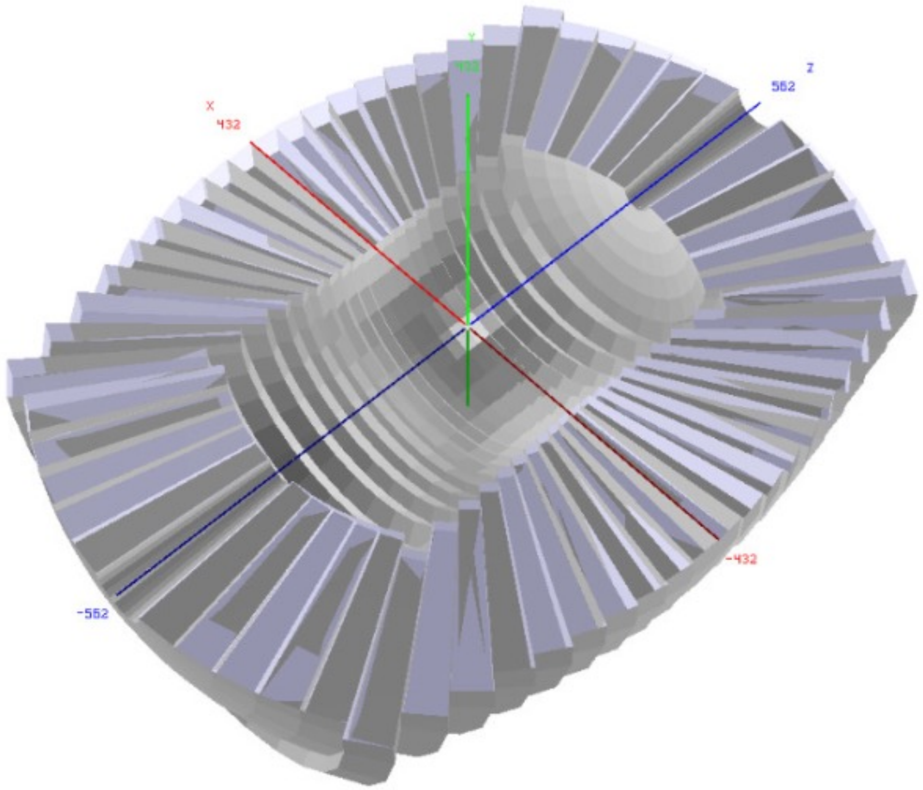


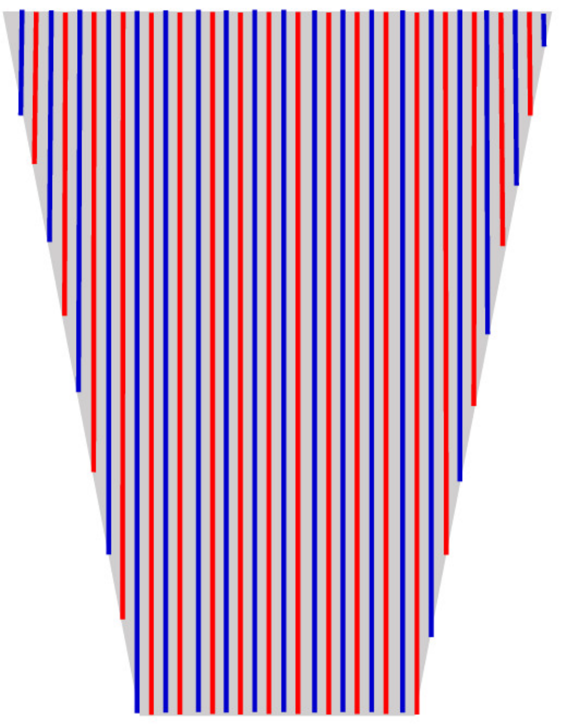
IDEA implementation

- Calorimeter outside thin coil
- Pre-shower in front
  - Improve π^0 ID
  - Improve acceptance determination







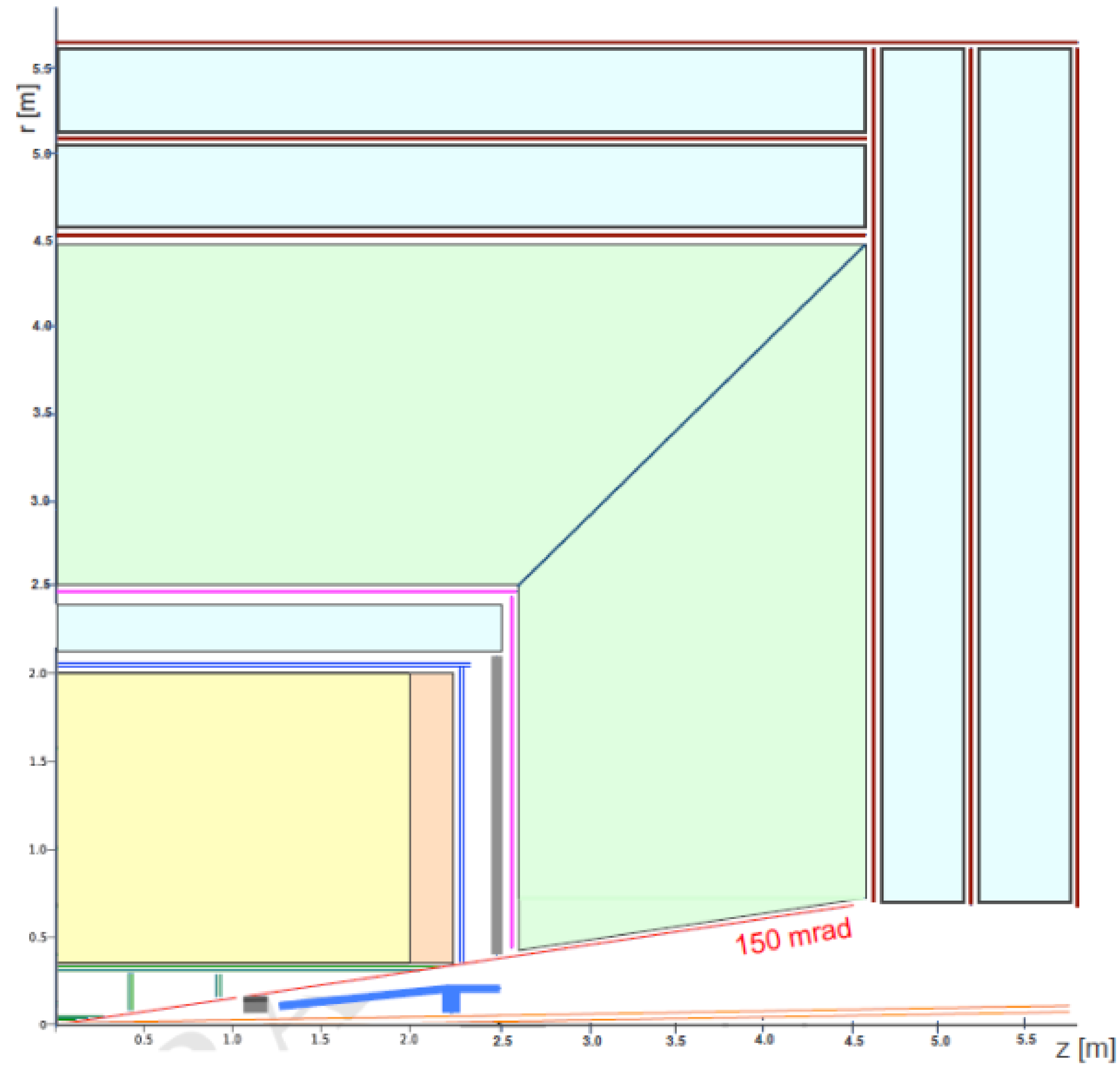


- Projective geometry
- Full coverage
- Wedge geometry

Optimization studies on the calorimeter mechanics ongoing

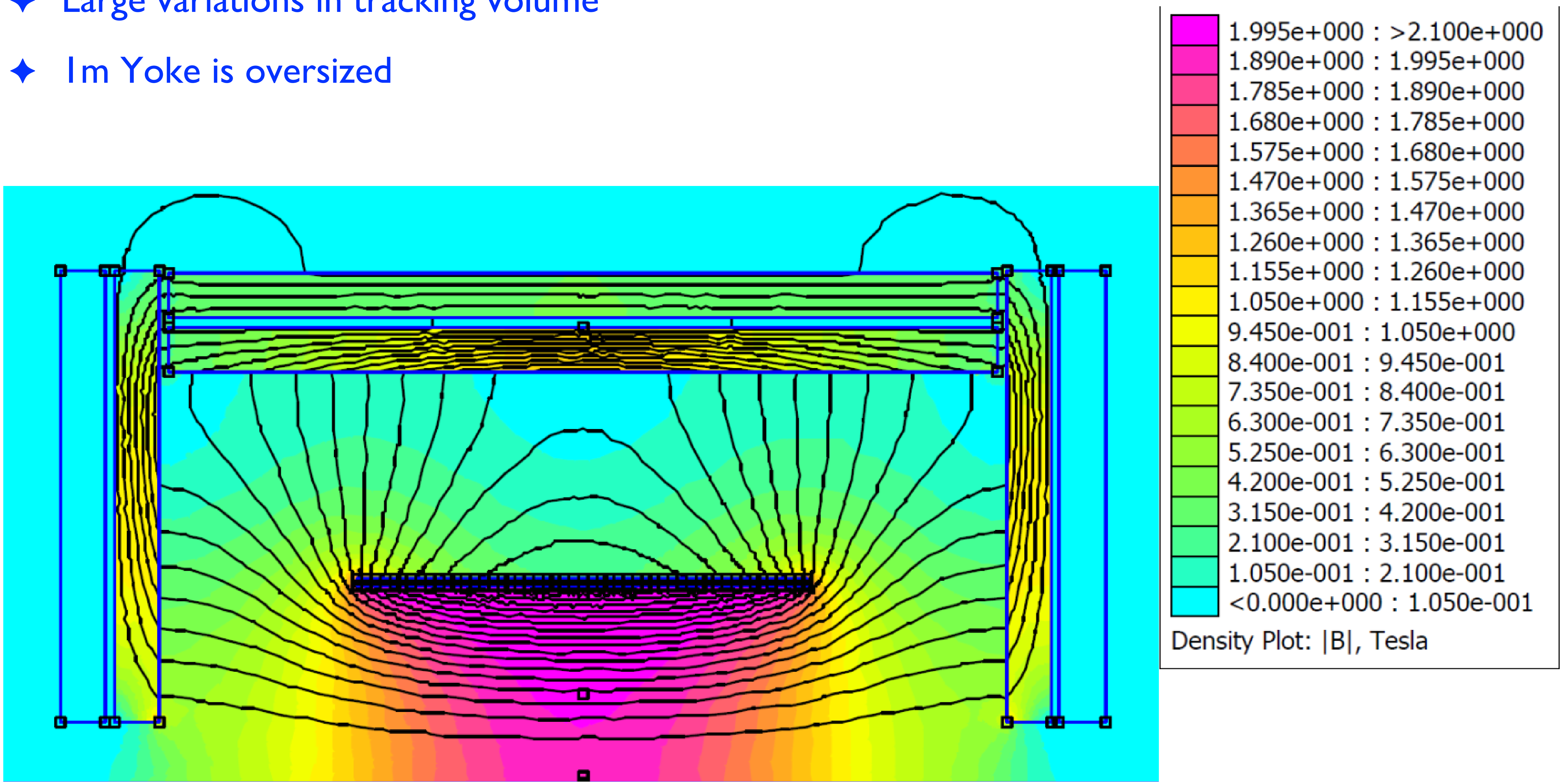
Solenoid parameters

- Coil center radius 2.25 m
- Coil length 5.0 m
- Goal field 2 Tesla



Simulation results: field map

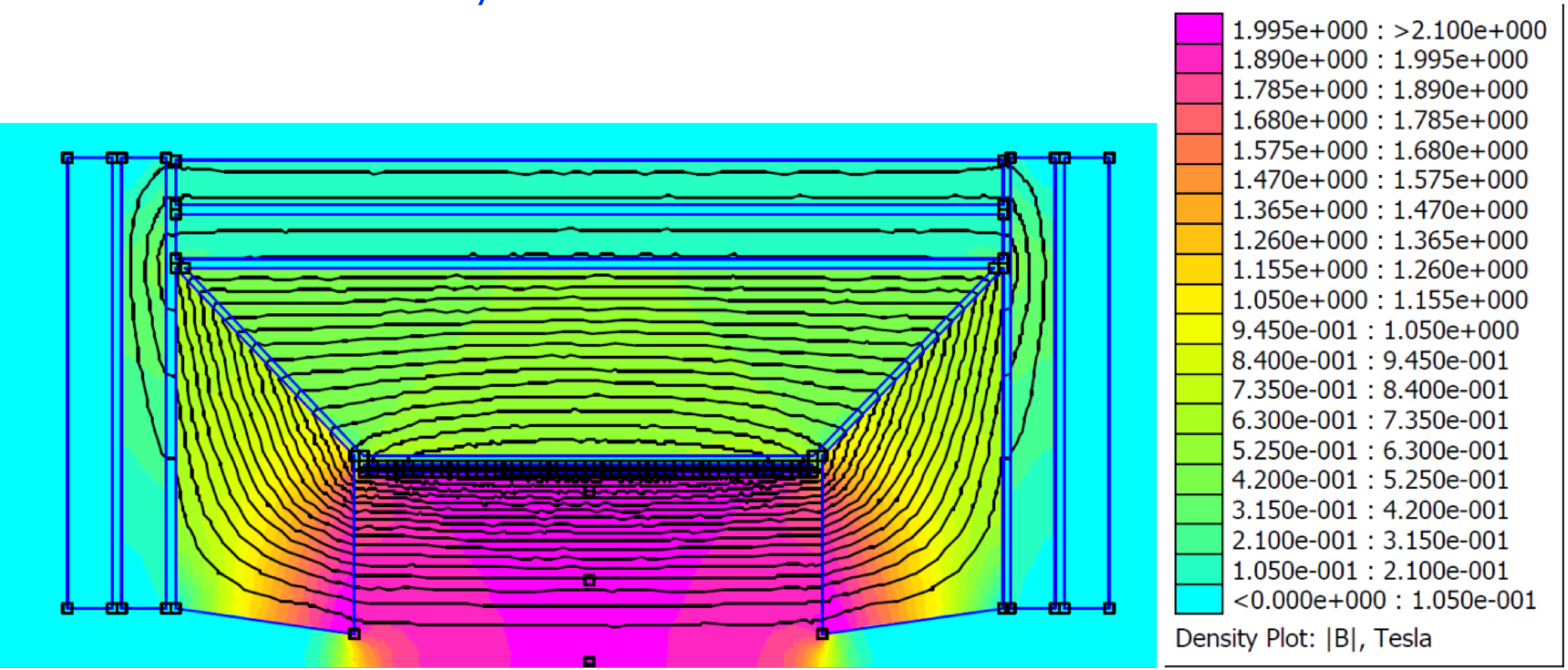
- Large variations in tracking volume
- 1m Yoke is oversized



Femm study

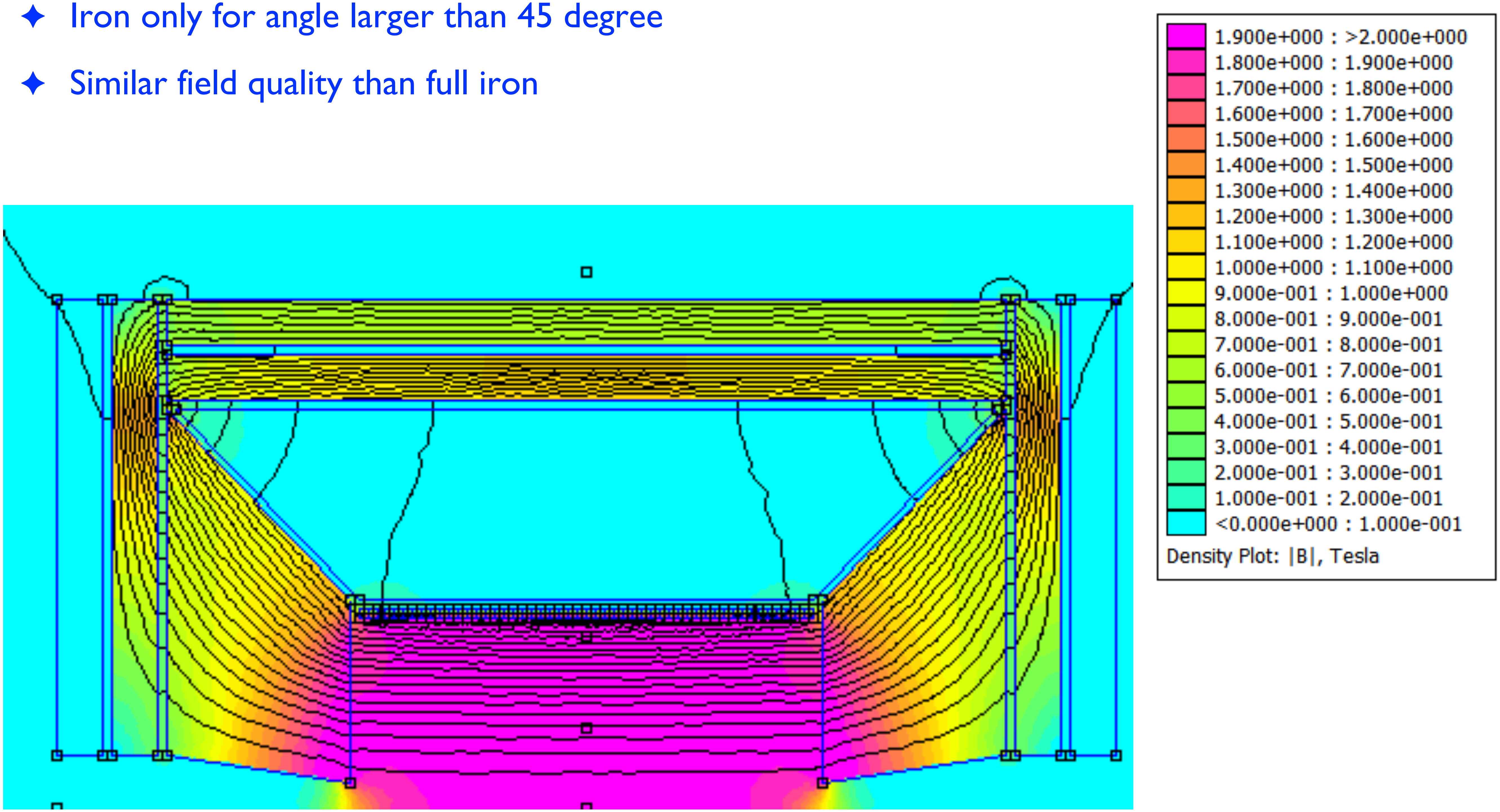
Iron calorimeter

- Much nicer!
- Almost no need for yoke

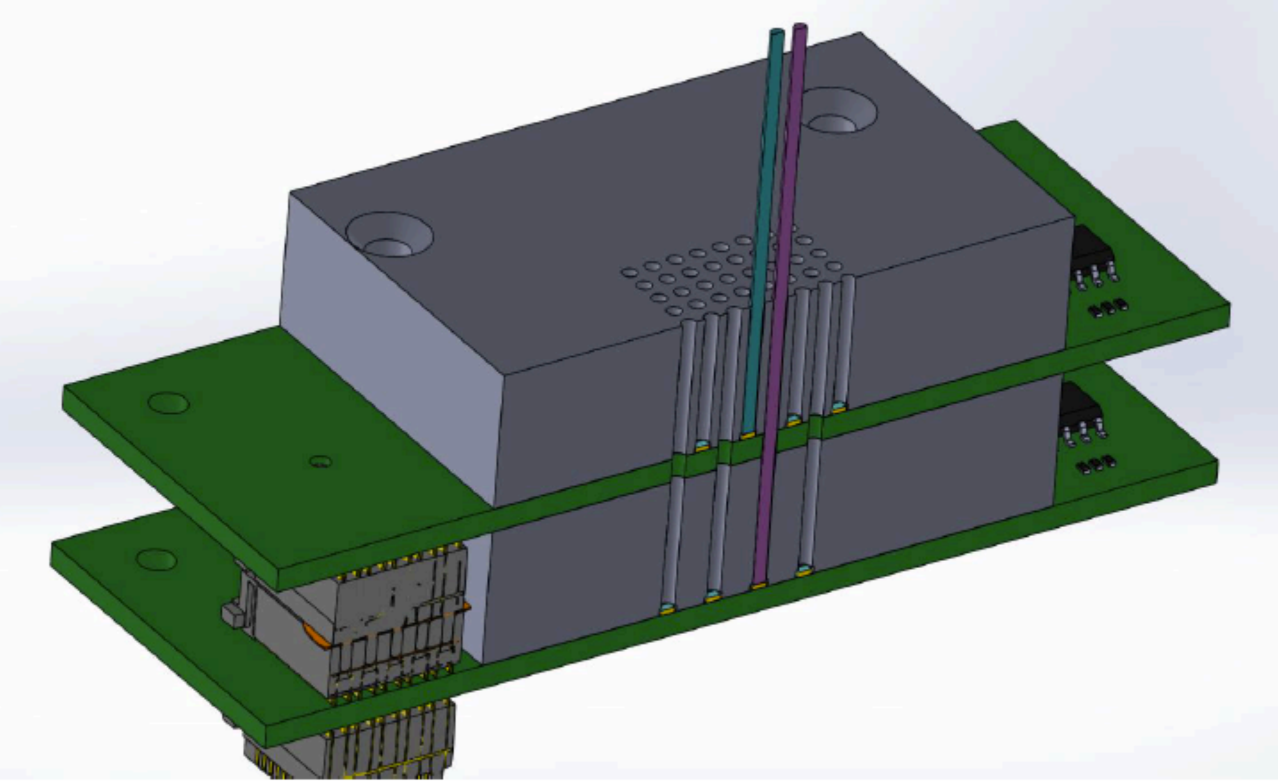


Forward iron calorimeter

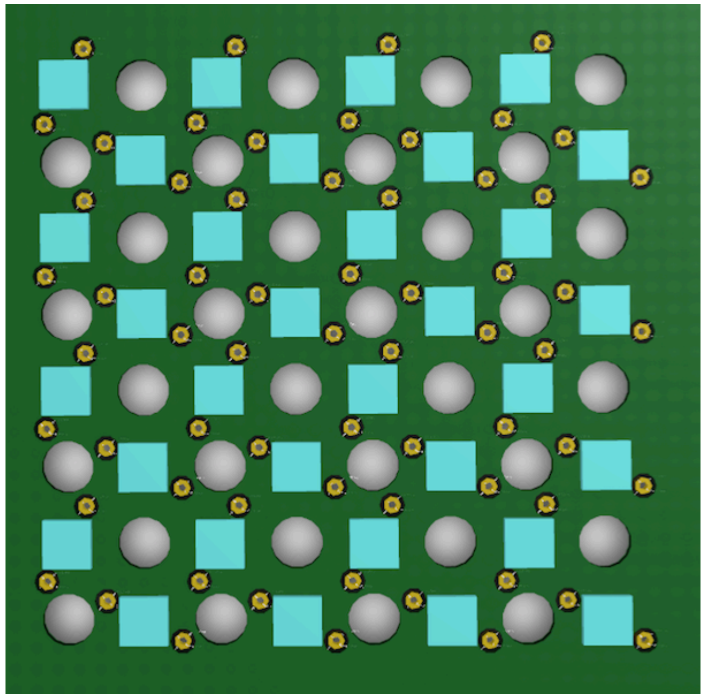
- Iron only for angle larger than 45 degree
- Similar field quality than full iron



SiPM Readout



- Dual layer SiPM readout
  - Avoids optical cross-talk
- Saturation studied with dedicated test beams
  - 25 μm pixels OK for Cherenkov
  - Need 10 μm for Scintillator
- Analogical signal grouping to reduce number of channels
  - Critical to be in linear regime (not possible to apply correction on summed channels)
  - Achievable with
    - Use of yellow filter to reduce scintillation light
    - Reduce sensor cell dimensions (from 25 μm to 5 μm)



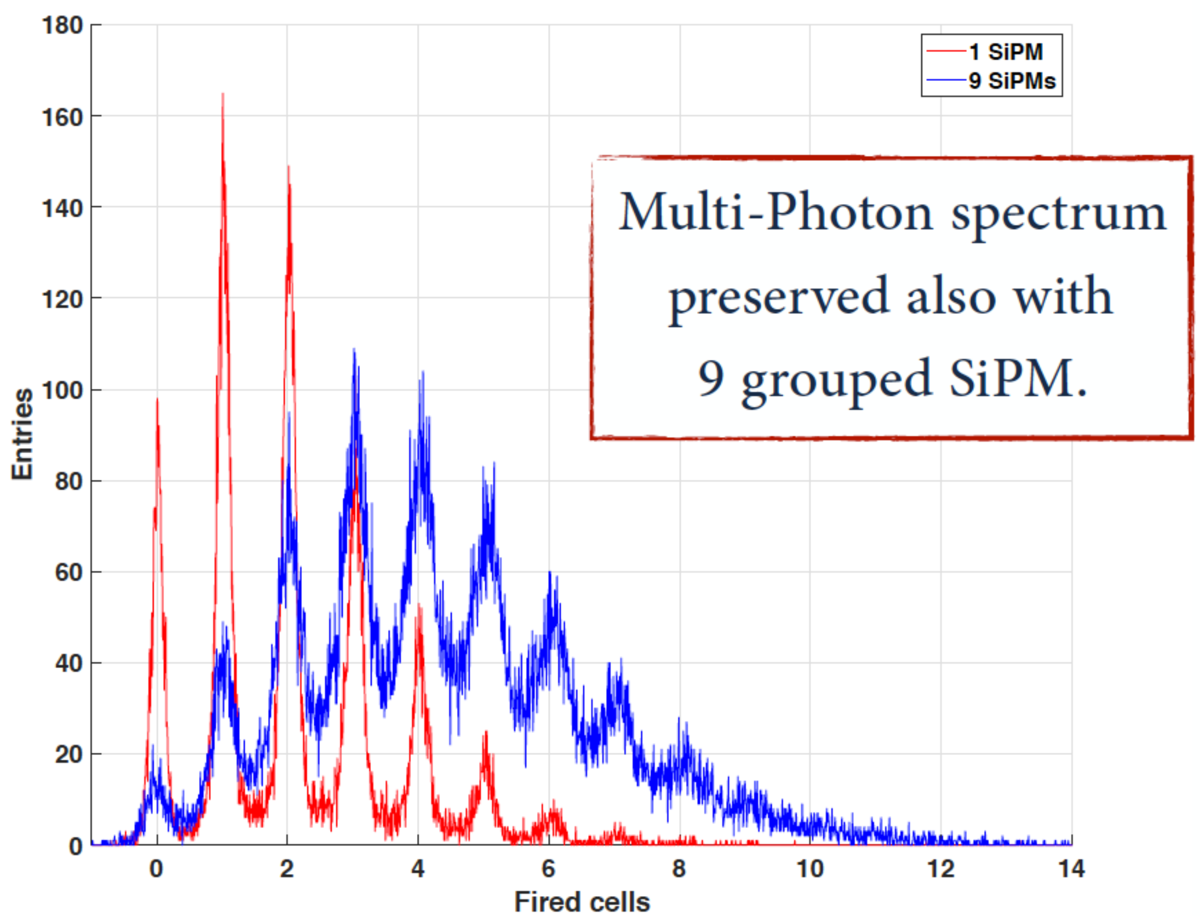
Signal grouping

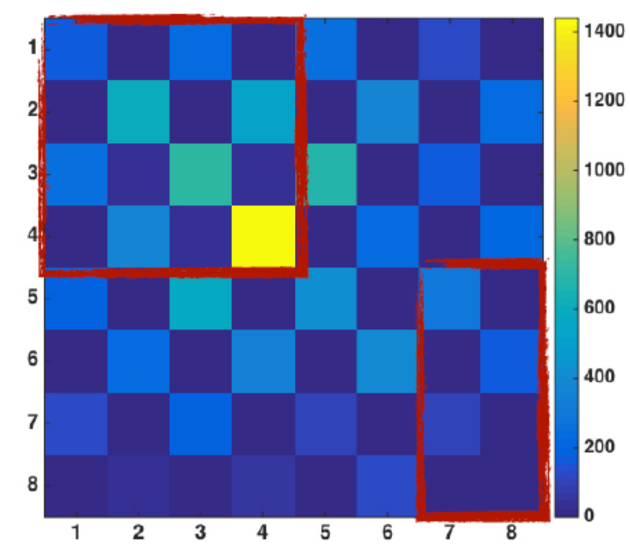
M. Antonello et al, NIM A (2018)
https://doi.org/10.1016/j.nima.2018.10.169

In a full scale module, the number of ***readout channels*** will be of the order of ***10^8***.

The possibility to **sum up the analog output** is under study:

- Number of SiPM that can be grouped guarantying the ***Multi-Photon spectrum***.
- SiPM *dynamic range*: sensors have to operate in a ***linear regime***.





SiPM number	1	4	8
Space granularity (mm^2)	4.5	18	36

Signal linearity results

* Values already corrected for the sensor non linearity response

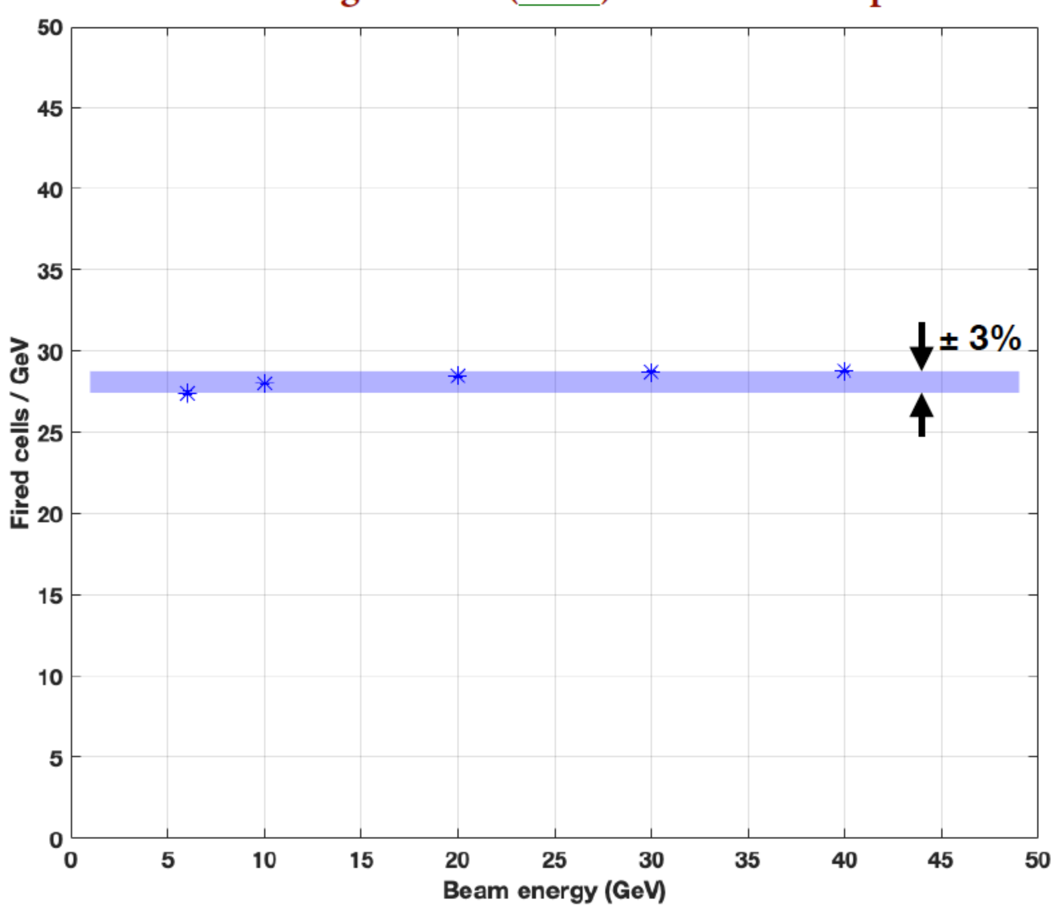
Measurement conditions (containment correction not applied):

$V_{op} = 5.5\ V_{ov}$ (57.5 V) and **PDE_C ~ 25% (440nm) - PDE_S ~ 20% (556nm)**

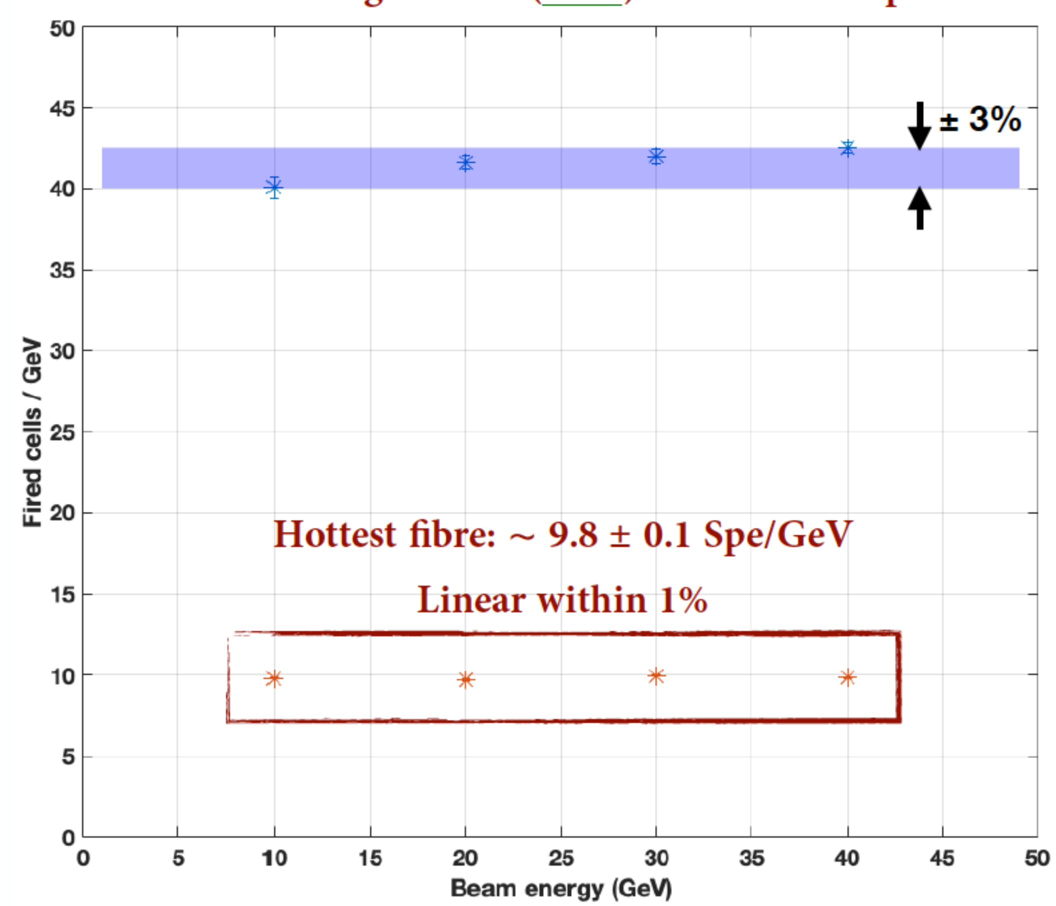
Temperature stability correction:

$\Delta T < 0.5°C$ during a single run (negligible) || $\Delta T \sim 1°C$ during the full scan (considered)

Cherenkov Light Yield (*2017*) ~ 28.6 ± 0.4 Cpe/GeV



Scintillation Light Yield (*2018*) ~ 41.9 ± 0.3 Spe/GeV



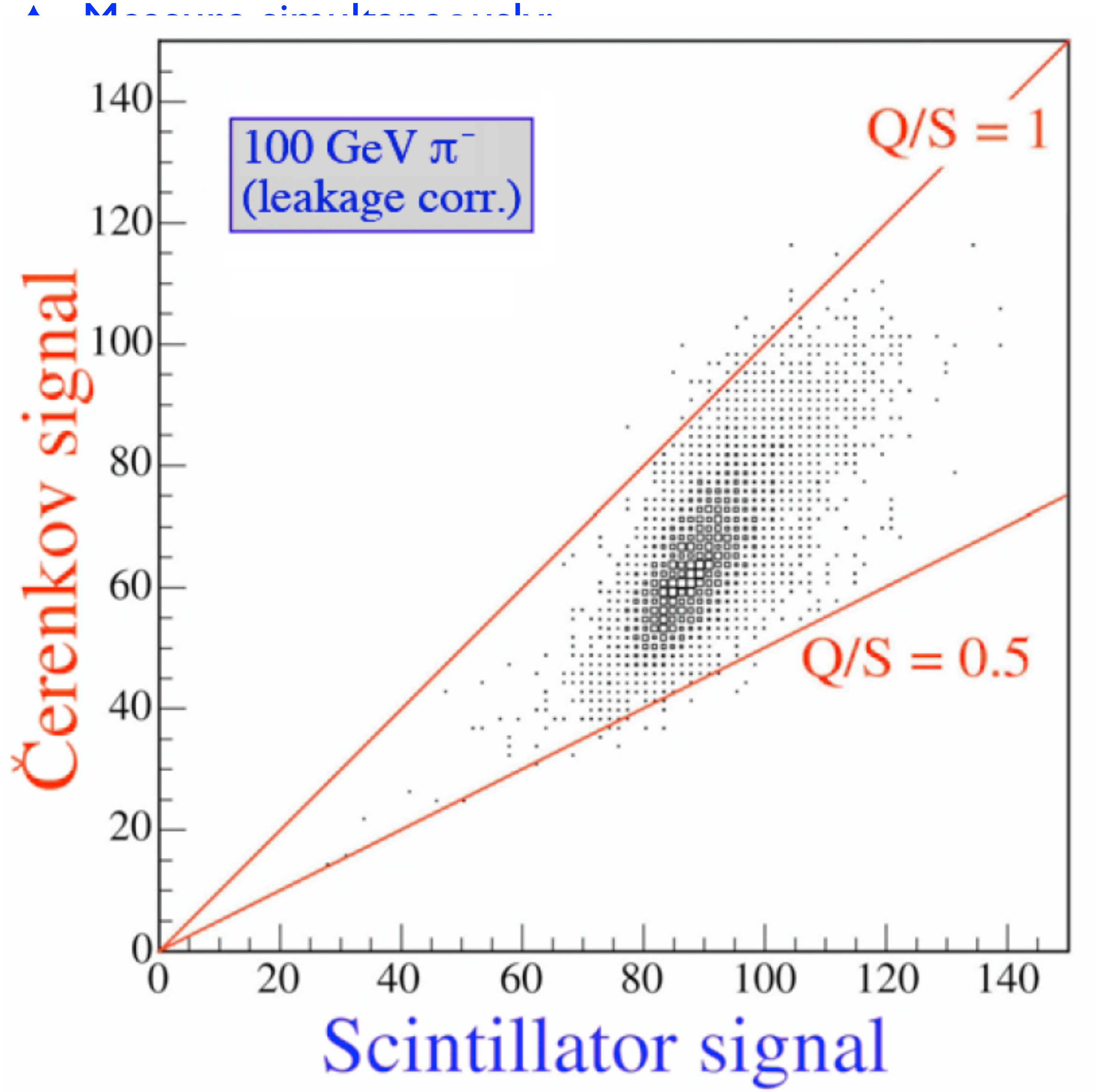
Conclusions

- Dual readout calorimetry is a well understood technology
  - Excellent EM and HAD resolution in a single package
  - Intrinsic high transverse granularity
  - Particle ID on isolated tracks
- Performance on prototype shown to be adequate
- Still a (quite) long list of optimization is needed to get the detector design ready for the experiment
  - Mechanical structure
  - Electronics readout

Backup

BACKUP

Working principle



$$S = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_S}(1 - f_{\mathrm{em}})\right]$$

$$Q = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_Q}(1 - f_{\mathrm{em}})\right]$$

$$\boxed{E = \frac{S - \chi Q}{1 - \chi}}$$

with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

Particle ID (e/had separation)

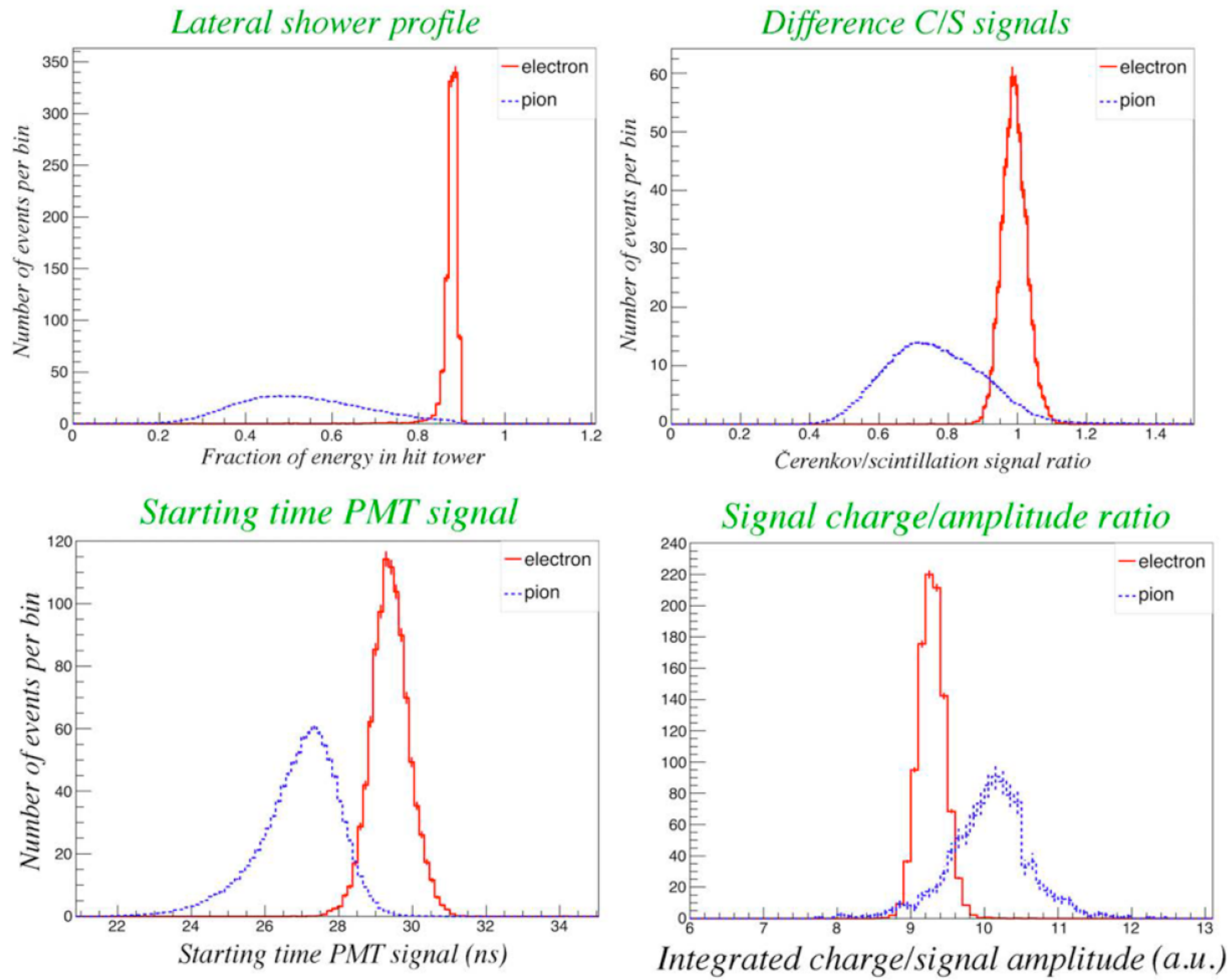
RD52 lead calorimeter

(60 GeV) e^- vs. π^-

$\varepsilon(e^-) > 99\%$
$R(\pi^-) \sim 500$

NIM A 735 (2014) 120

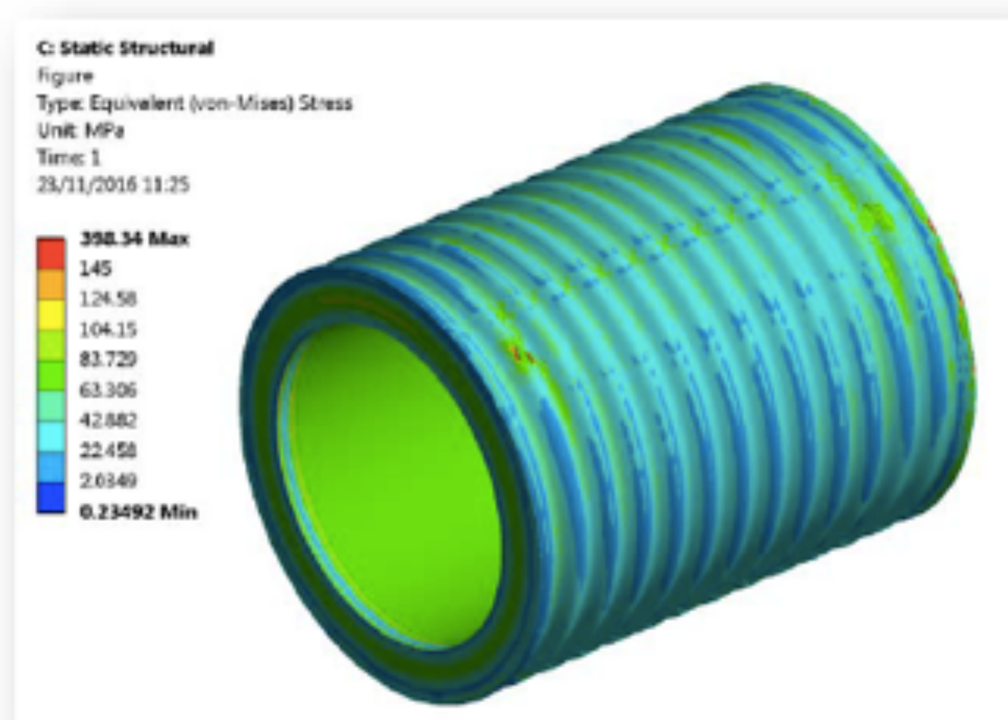
Methods to distinguish e/π in longitudinally unsegmented calorimeter



2T solenoid

- Two options:
  - Large bore (R=3.7 m) – calorimeter inside
  - Smaller bore (R=2.2 m) – calorimeter outside
    - Preferred: simpler/ Extreme EM resolution not needed
      - Thick calorimeter
    - Thin (30 cm): total = 0.74 X_0 (0.16 λ) at θ = 90°

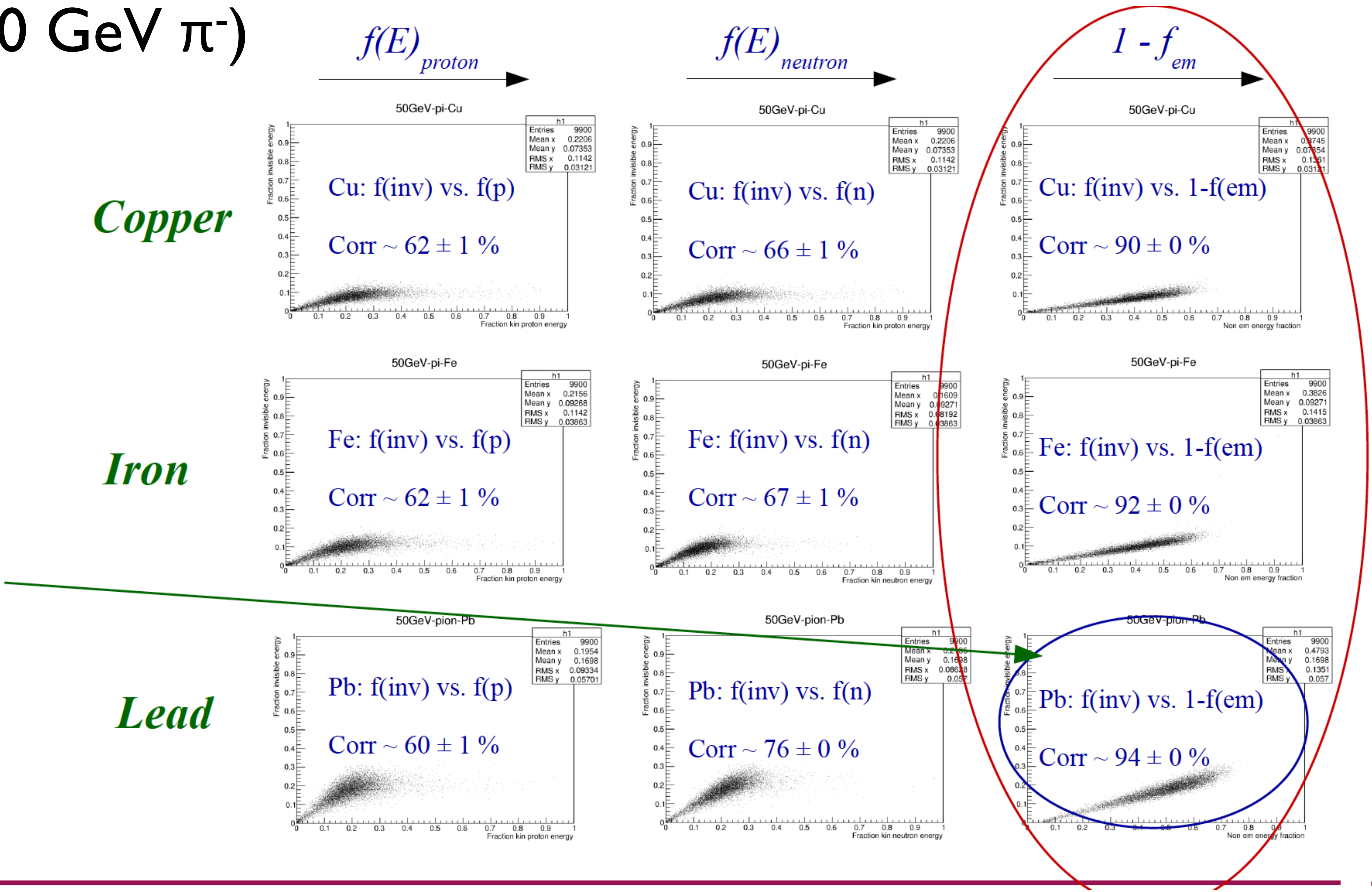
Property	Value
Magnetic field in center [T]	2
Free bore diameter [m]	4
Stored energy [MJ]	170
Cold mass [t]	8
Cold mass inner radius [m]	2.2
Cold mass thickness [m]	0.03
Cold mass length [m]	6



Courtesy of H. ten Kate et al.

Invisible Energy correlations

(50 GeV π^-)



Yellow filter effect

In the scintillation fibres the emitted light can be reabsorbed.
Light attenuation causes the signal dependence on where the fibres are hit by the shower particles and it is a phenomenon that is mainly important for hadron showers.

Response uniformity improved of ***30%***
Attenuation = ***77 times***

C: 69 Cpe/GeV $\rightarrow \epsilon_{Combined} \sim 16.0\,\%$
S: 93 Spe/GeV $\rightarrow \epsilon_{Combined} \sim 14.8\,\%$
$\epsilon_{C+S} = 10.9\,\%$

Attenuation effect

Error from sampling fluctuations:

$$\epsilon_{Sampling} \sim 10.5\,\%$$

Relative error of signal:

$$\epsilon_{N_{FC/GeV}} = \frac{1}{\sqrt{N_{FC/GeV}}}$$

Combined error for each channel:

$$\epsilon_{Combined} = \sqrt{\epsilon^2_{Sampling} + \epsilon^2_{N_{FC/GeV}}}$$

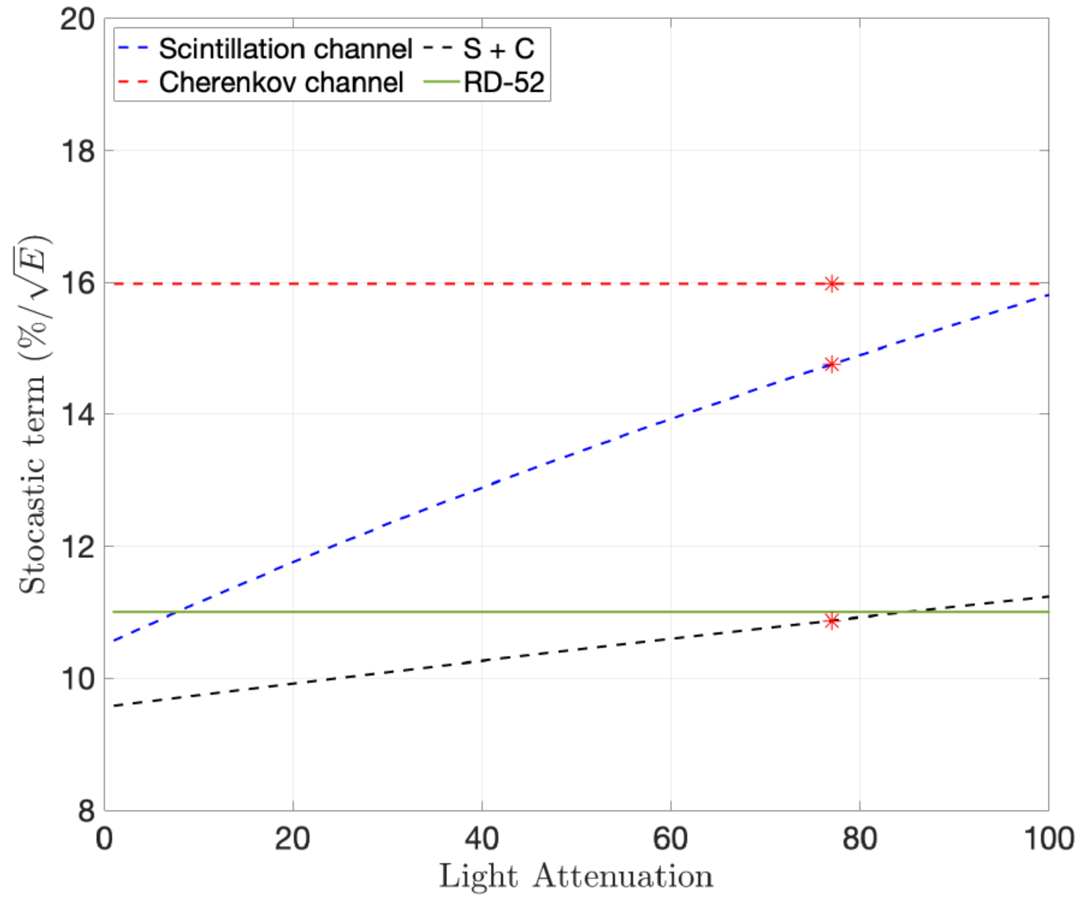
Stochastic term in e.m. resolution:

$$\epsilon_{C+S} \sim \frac{\sqrt{\epsilon^2_{Combined}(S) + \epsilon^2_{Combined}(C)}}{2}$$

C: 69 Cpe/GeV $\rightarrow \epsilon_{Combined} \sim 16.0\,\%$

S: 93 Spe/GeV $\rightarrow \epsilon_{Combined} \sim 14.8\,\%$

$$\epsilon_{C+S} = 10.9\,\%$$

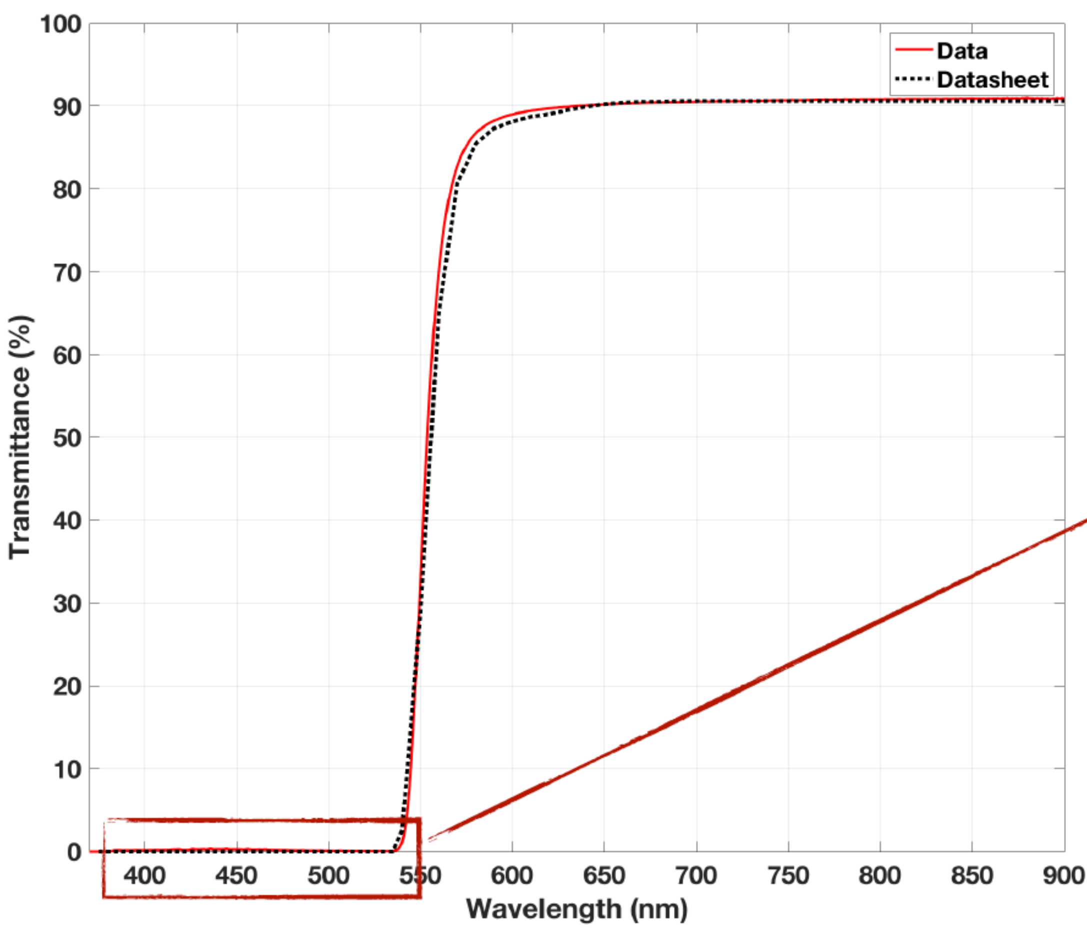


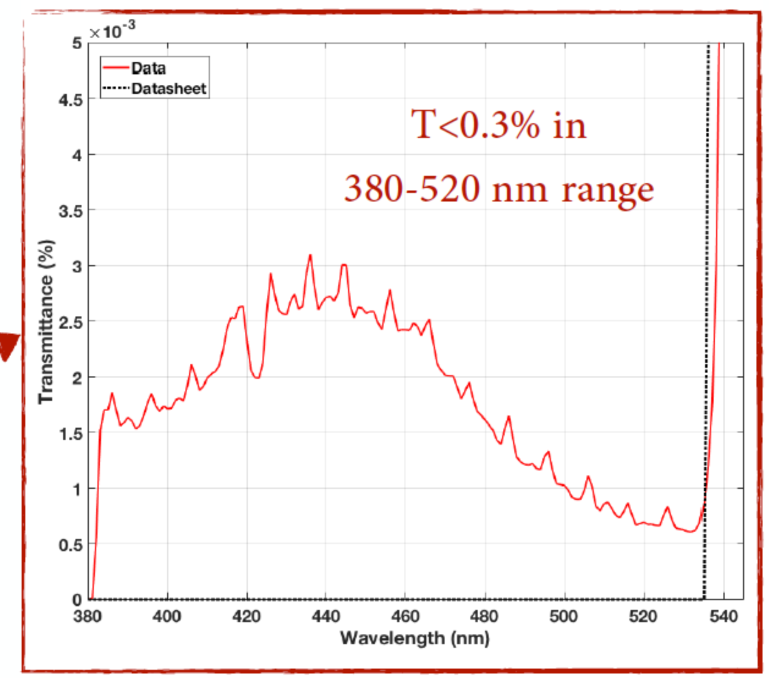
Yellow filter

Lab measurement of transmittance spectra (with spectrophotometer).

Good agreement between measurement and Datasheet.

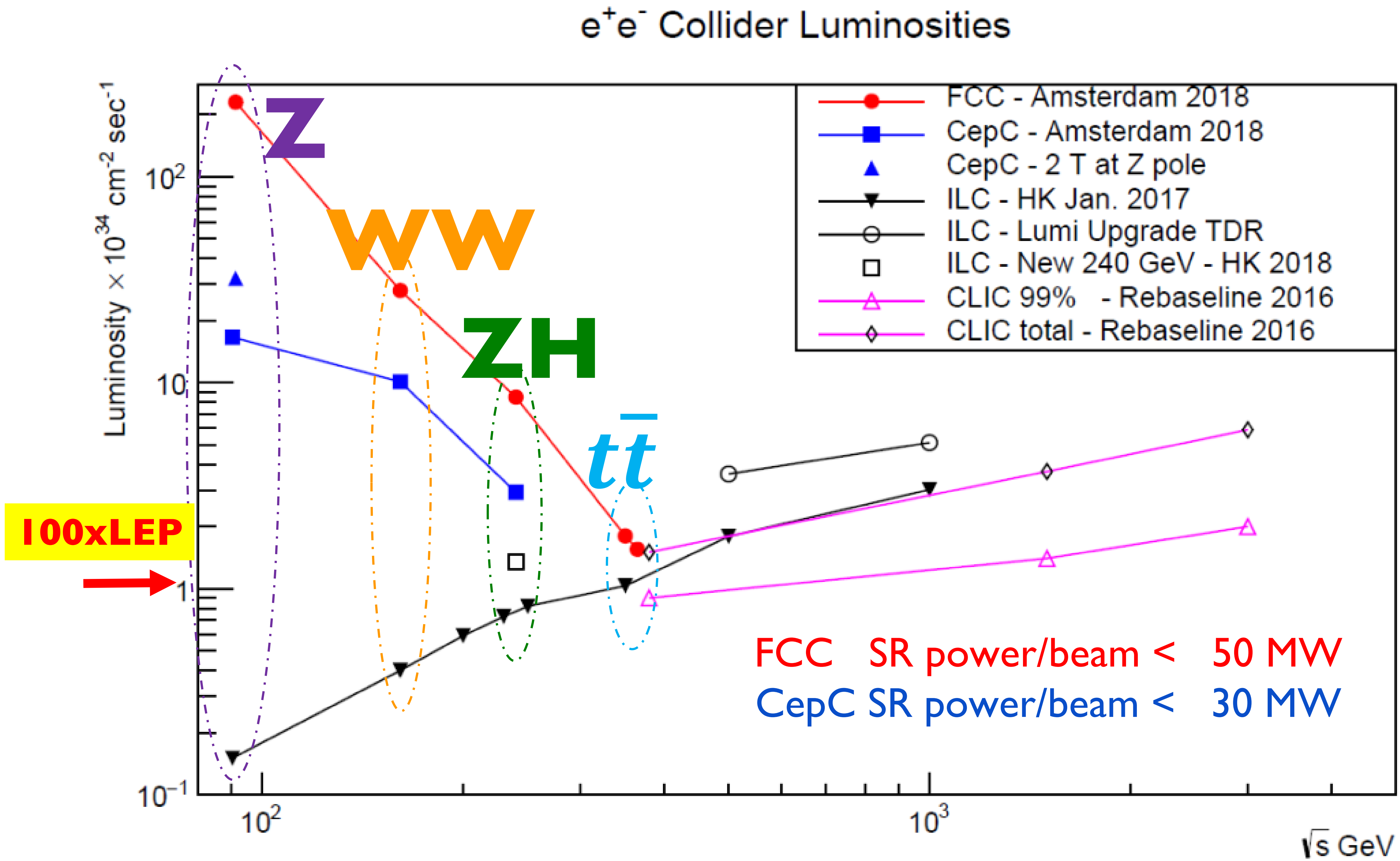
***Kodak Wratten 21 gelatine filter*.**





CepC, FCC, ILC, CLIC

luminosity comparison



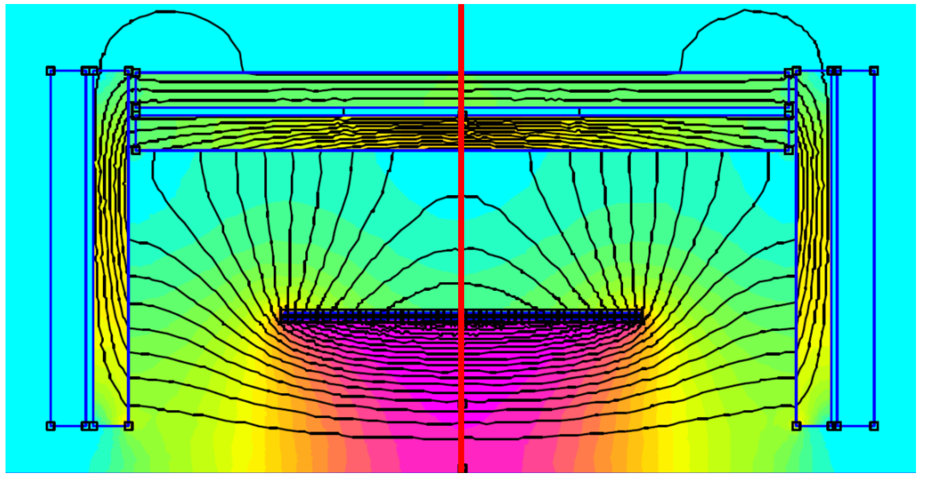
e+e- operation modes

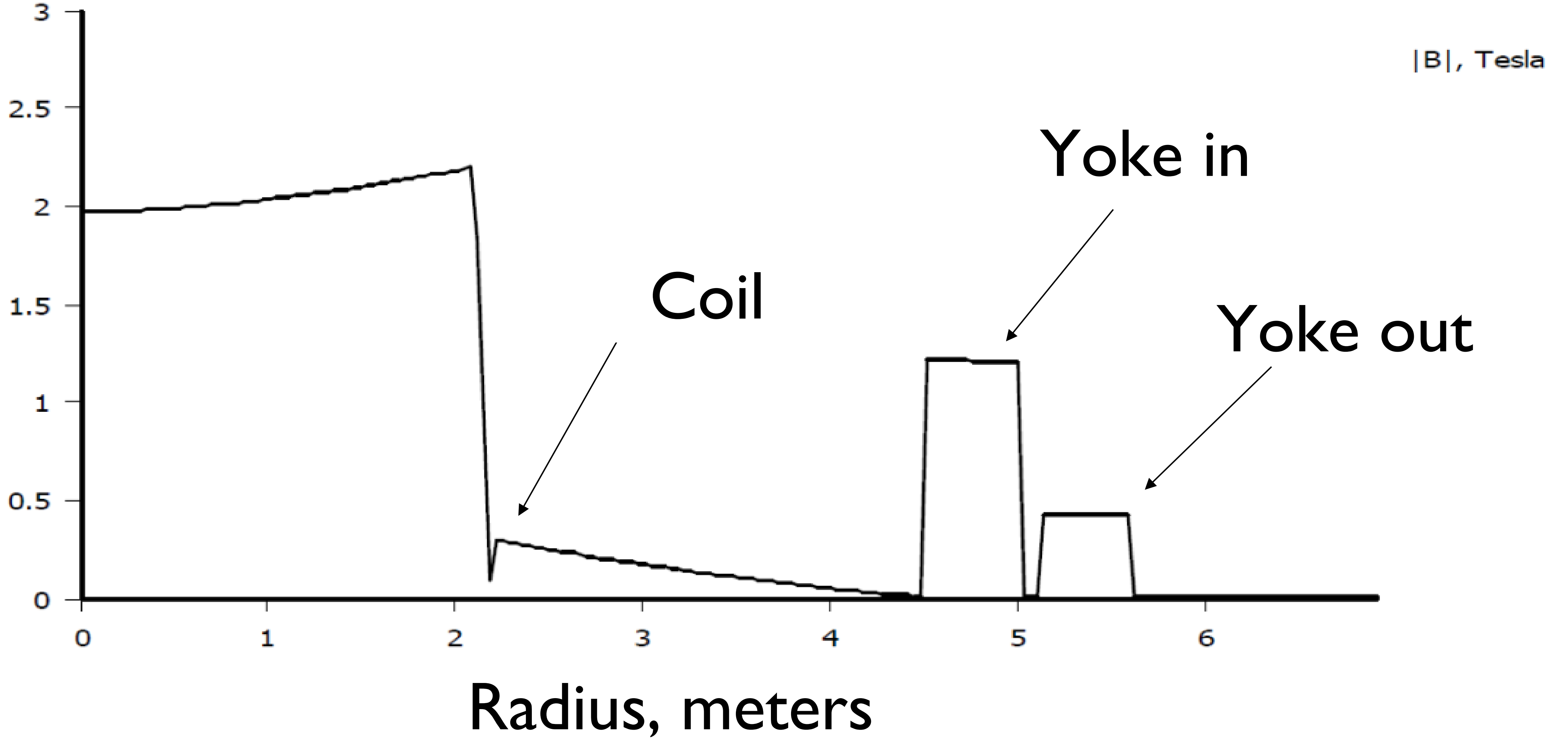
- Wide range of running conditions at CepC
  - Z pole (90 GeV):
    - ~ 10 ns between beam crossing
    - High luminosity O(10^{35})
  - ZH (250 GeV):
    - ~ 1 μs between beam crossing
    - Moderate luminosity - O(10^{34})

Simulation results: projections (R)

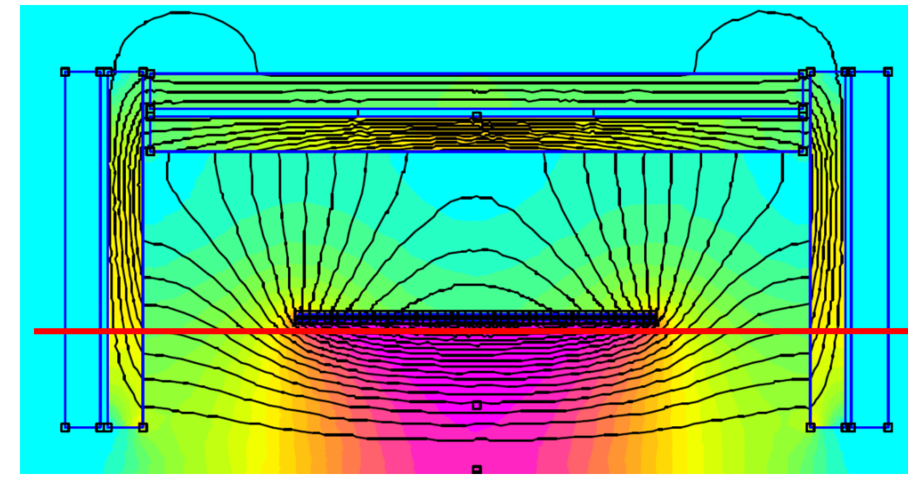
Radial field variation:

interaction vertex till after yoke



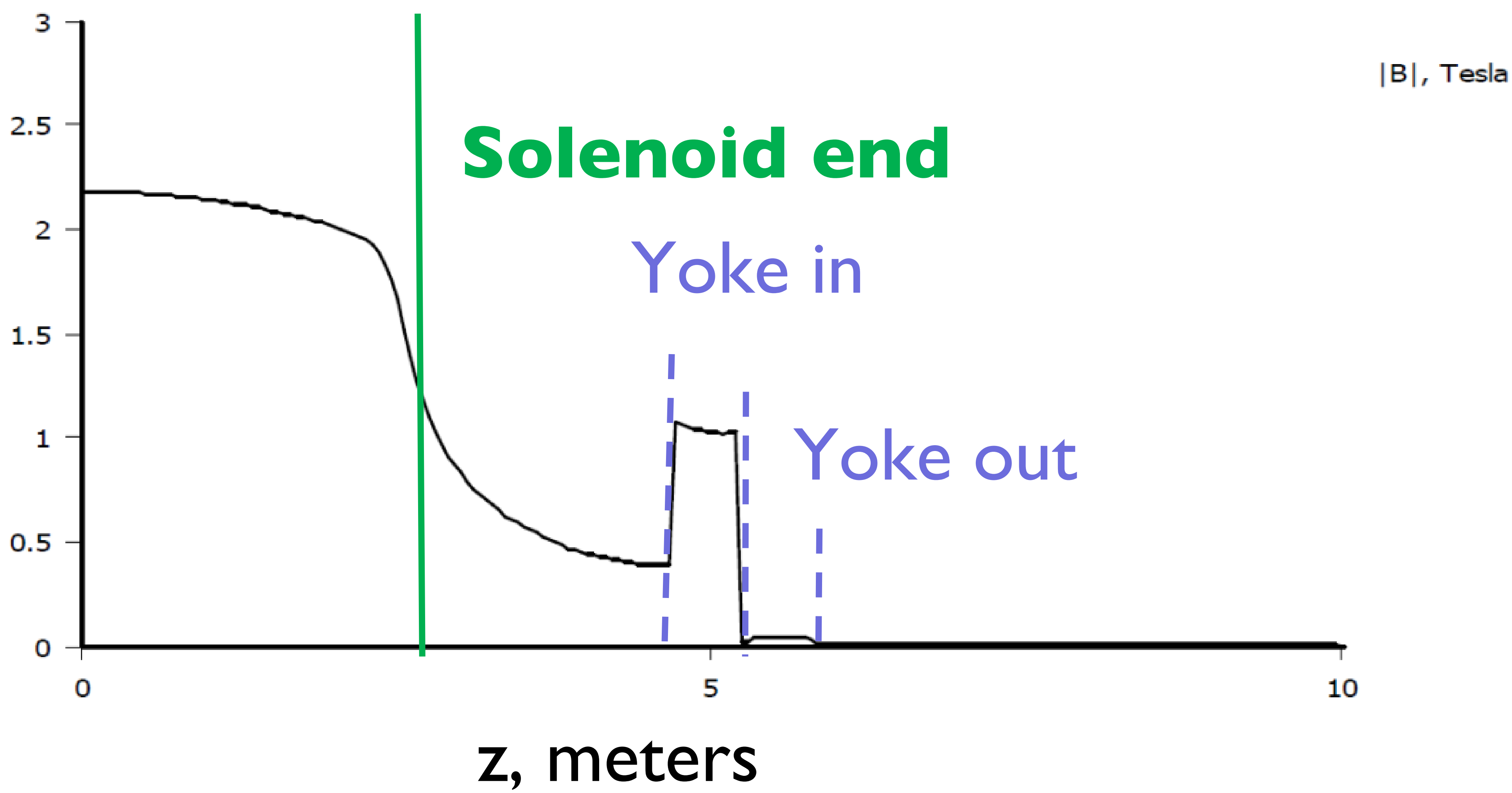


Simulation results: proj. (R = 2.0 m)



Longitudinal field projection

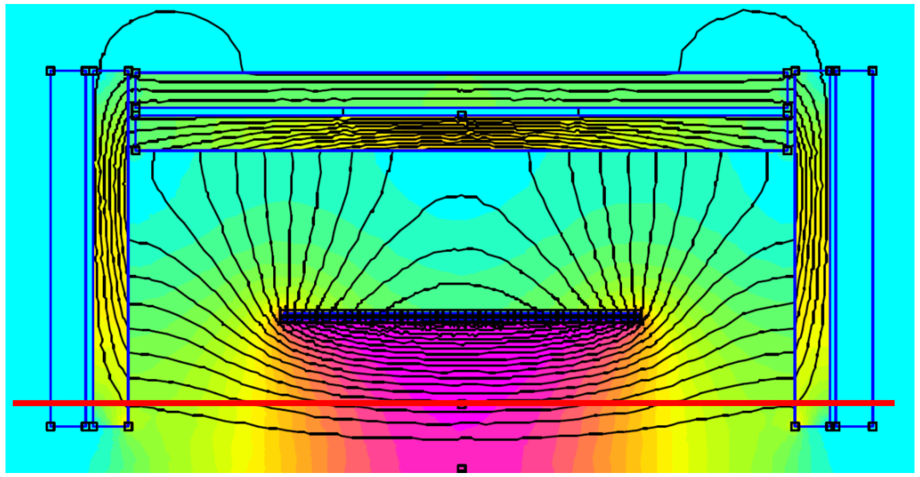
@ R = 2.0 m

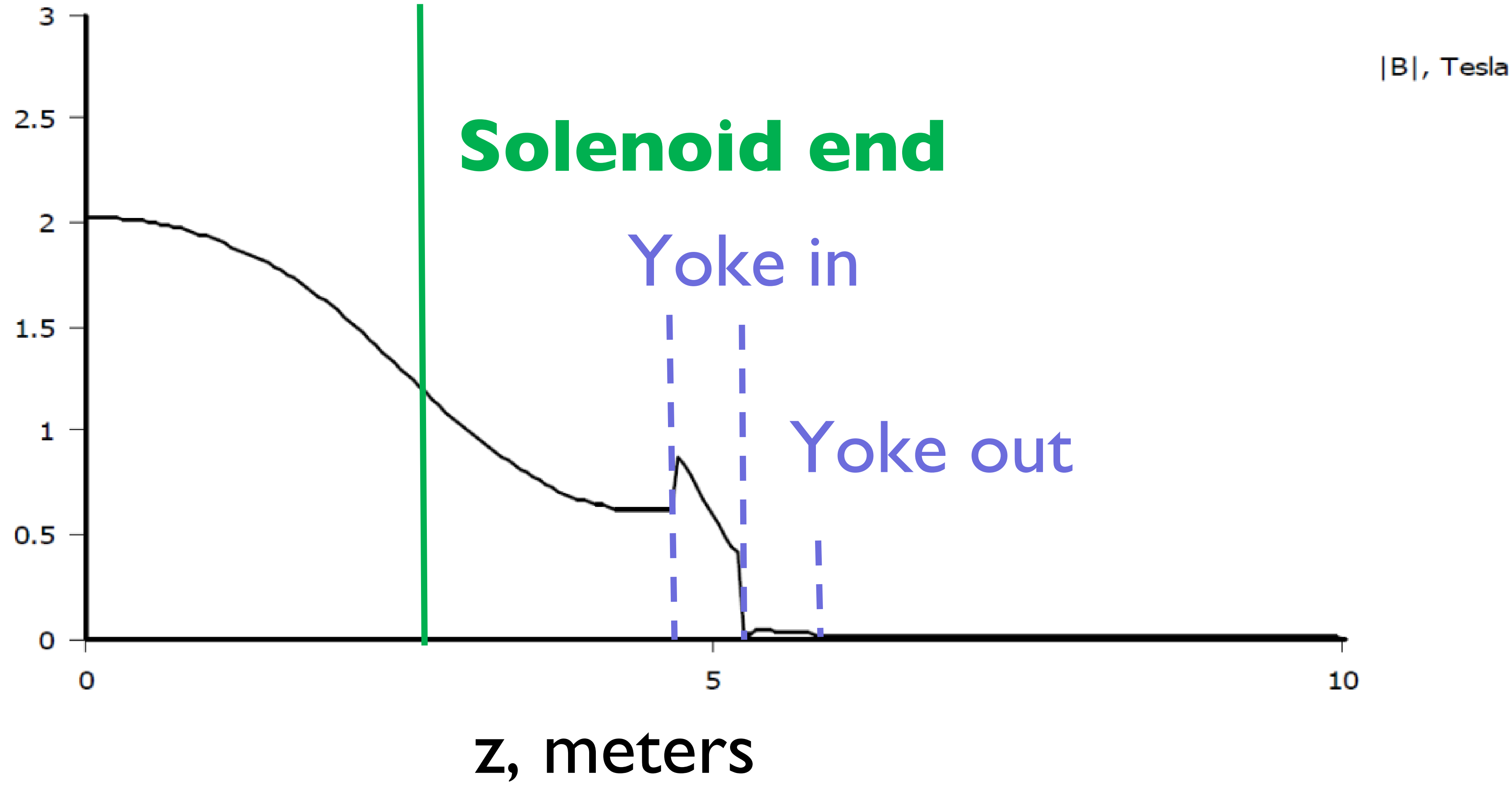


Simulation results: proj. (R = 1.0 m)

Longitudinal field projection

@ R=1.0 m

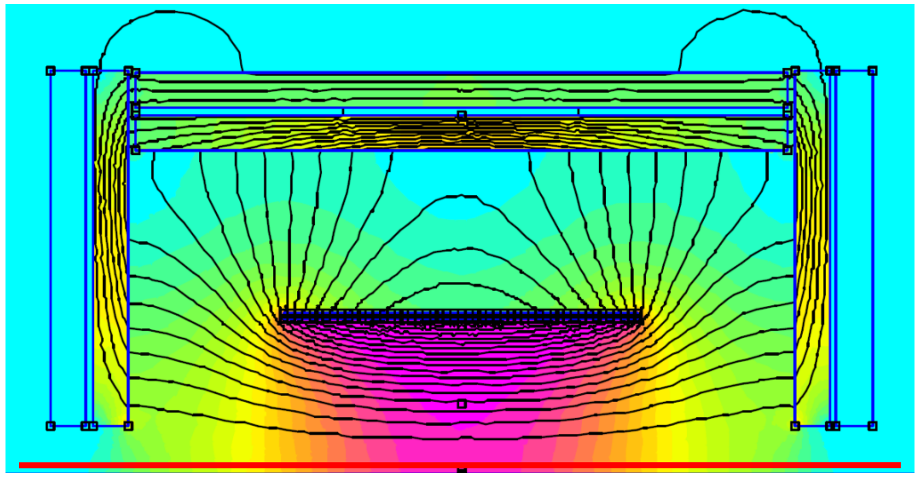


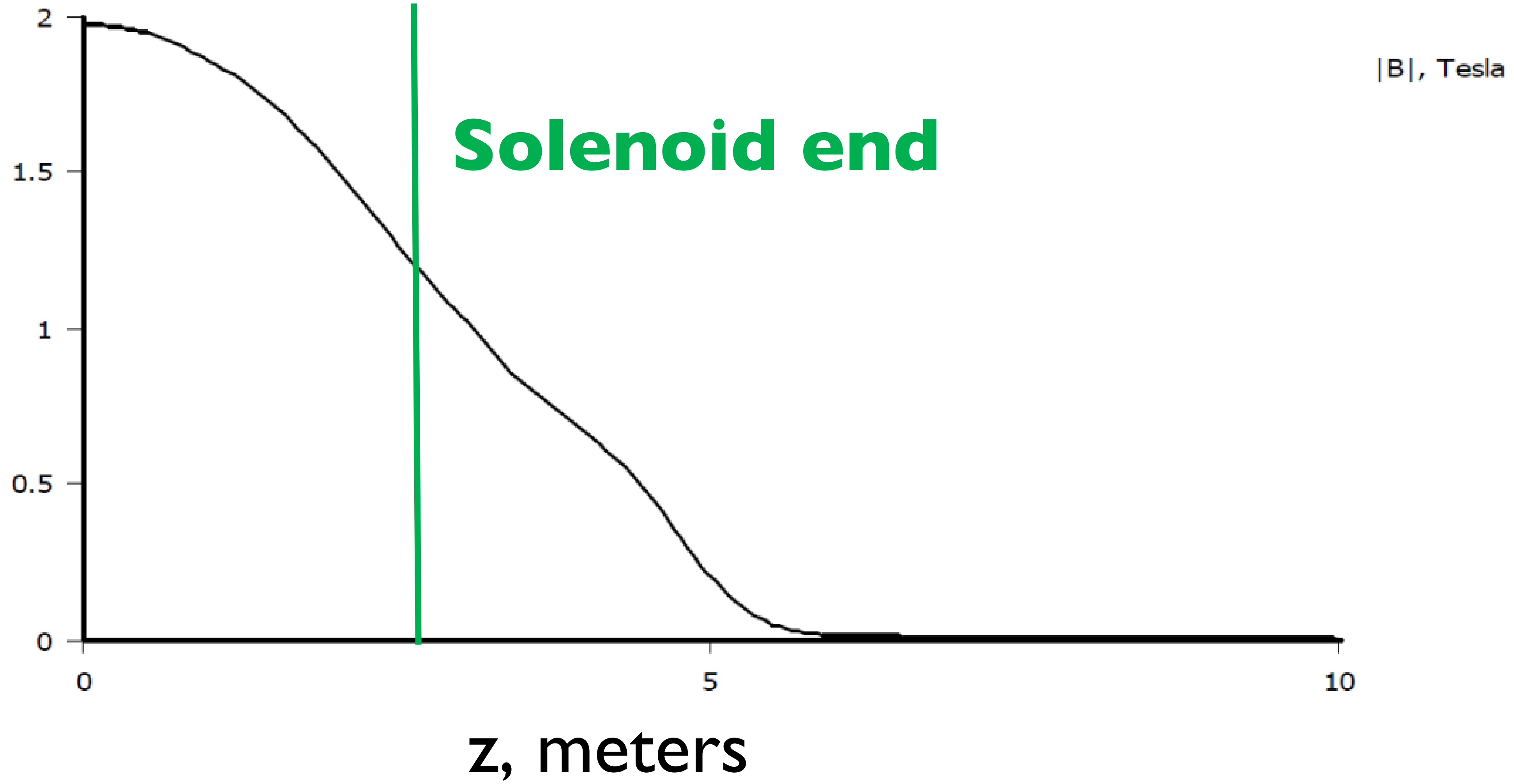


Simulation results: proj. (R = 0.1 m)

Longitudinal field projection

@ R=10 cm

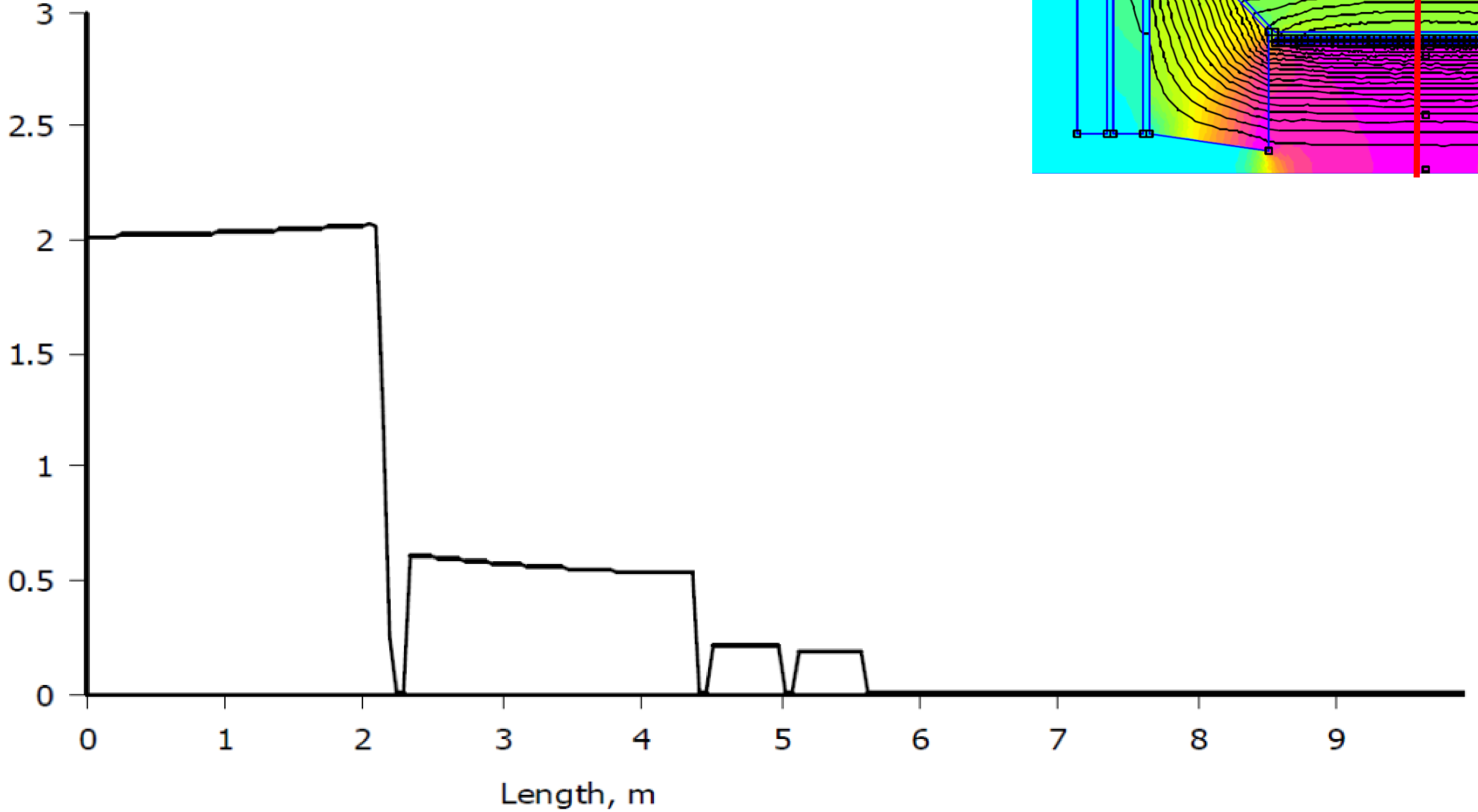


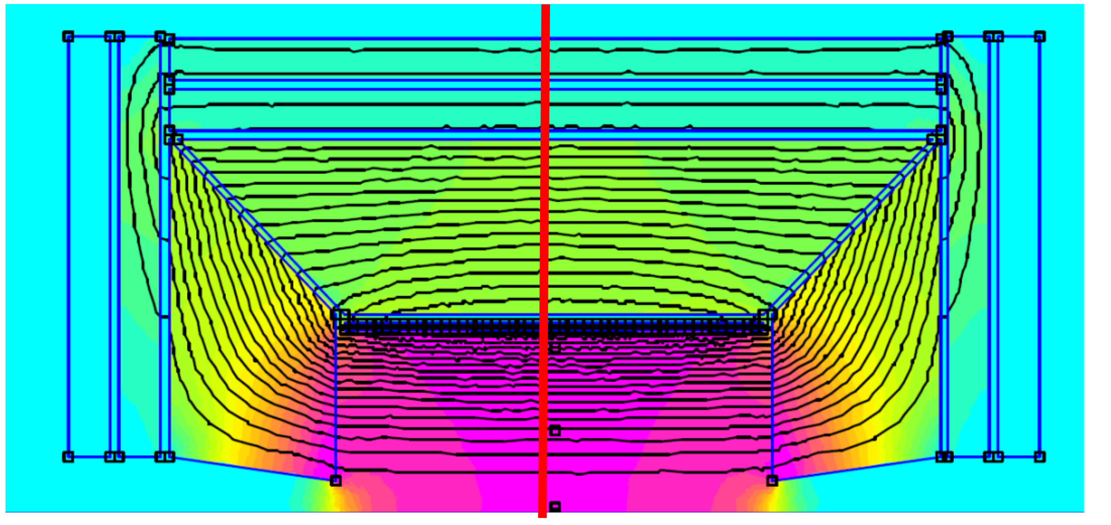


Iron calorimeter

Radial field variation:

interaction vertex till after yoke

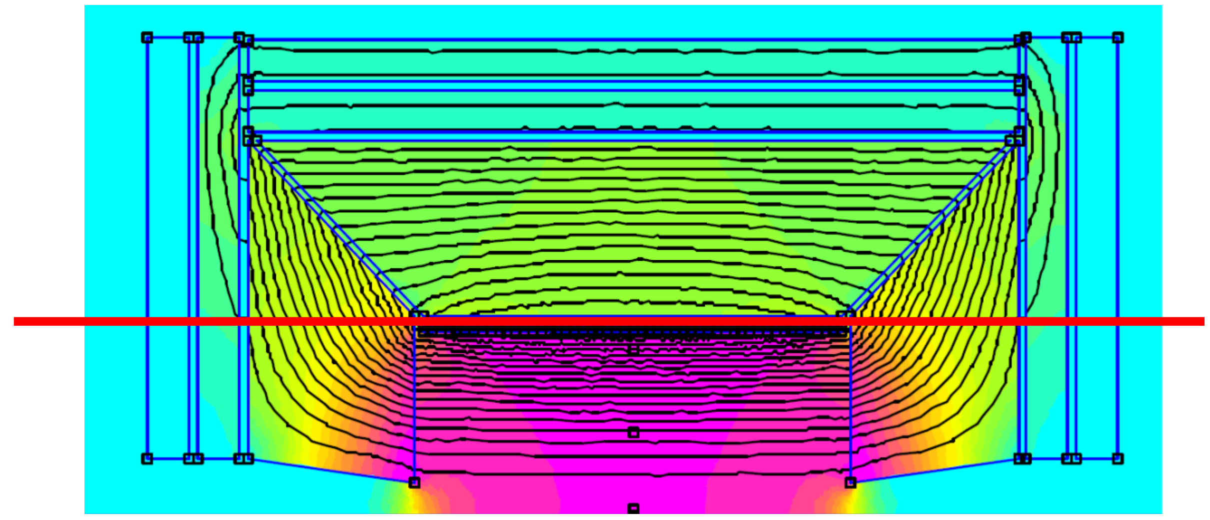


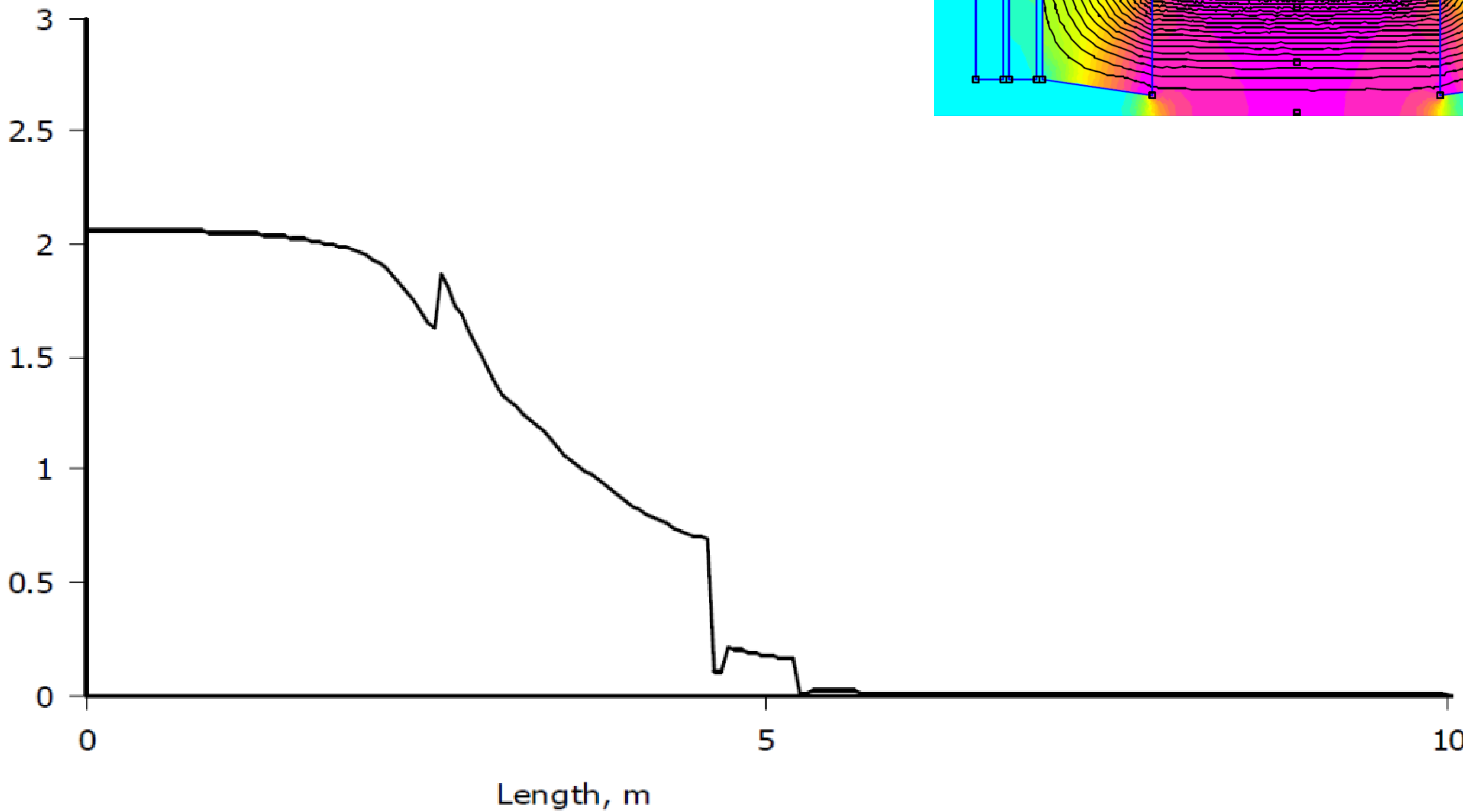


Iron calorimeter

Longitudinal field projection

@ R = 2.0 m

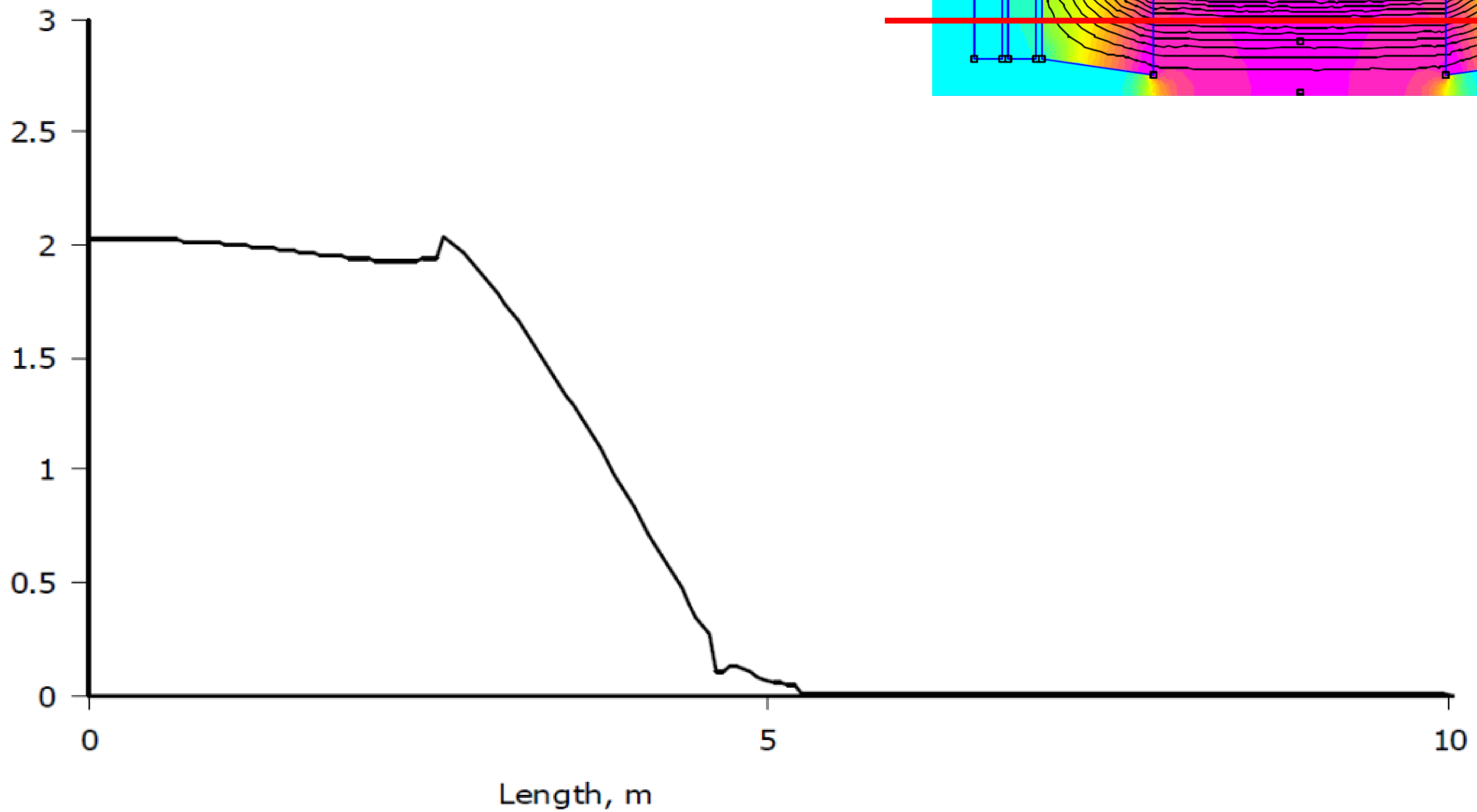


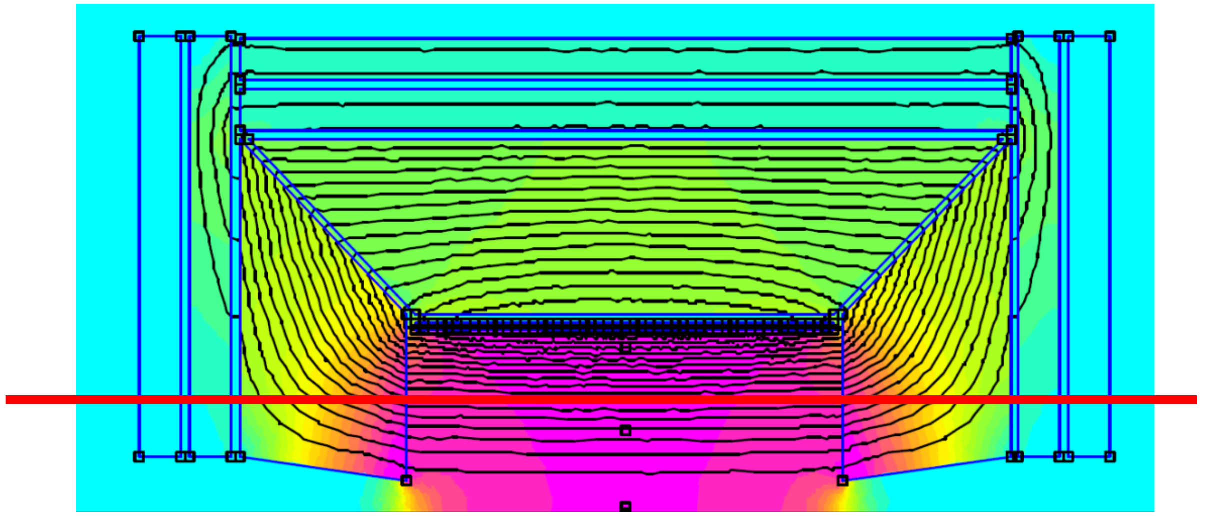


Iron calorimeter

Longitudinal field projection

@ R = 1.0 m

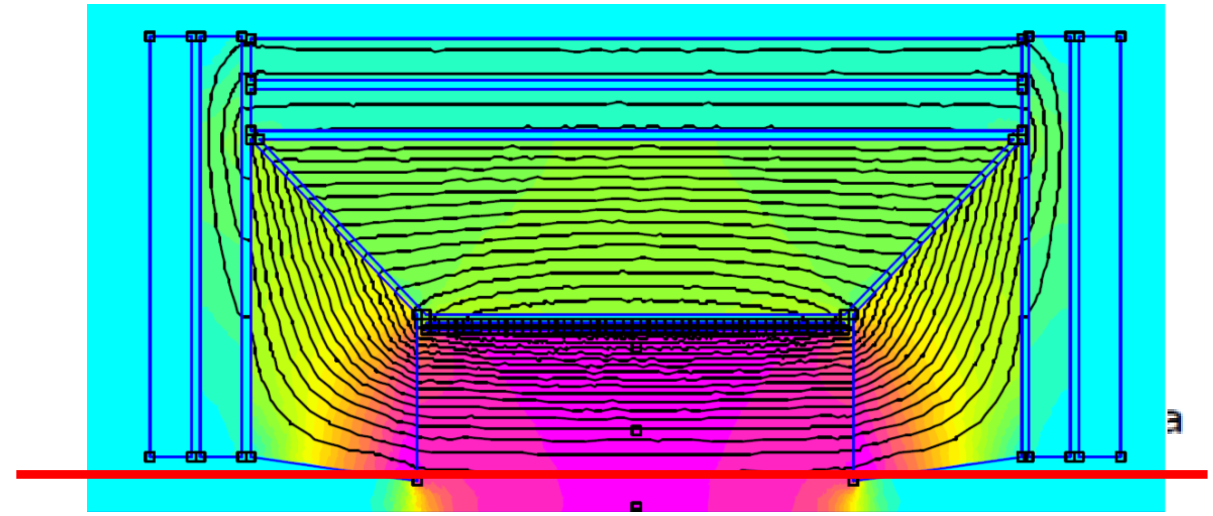


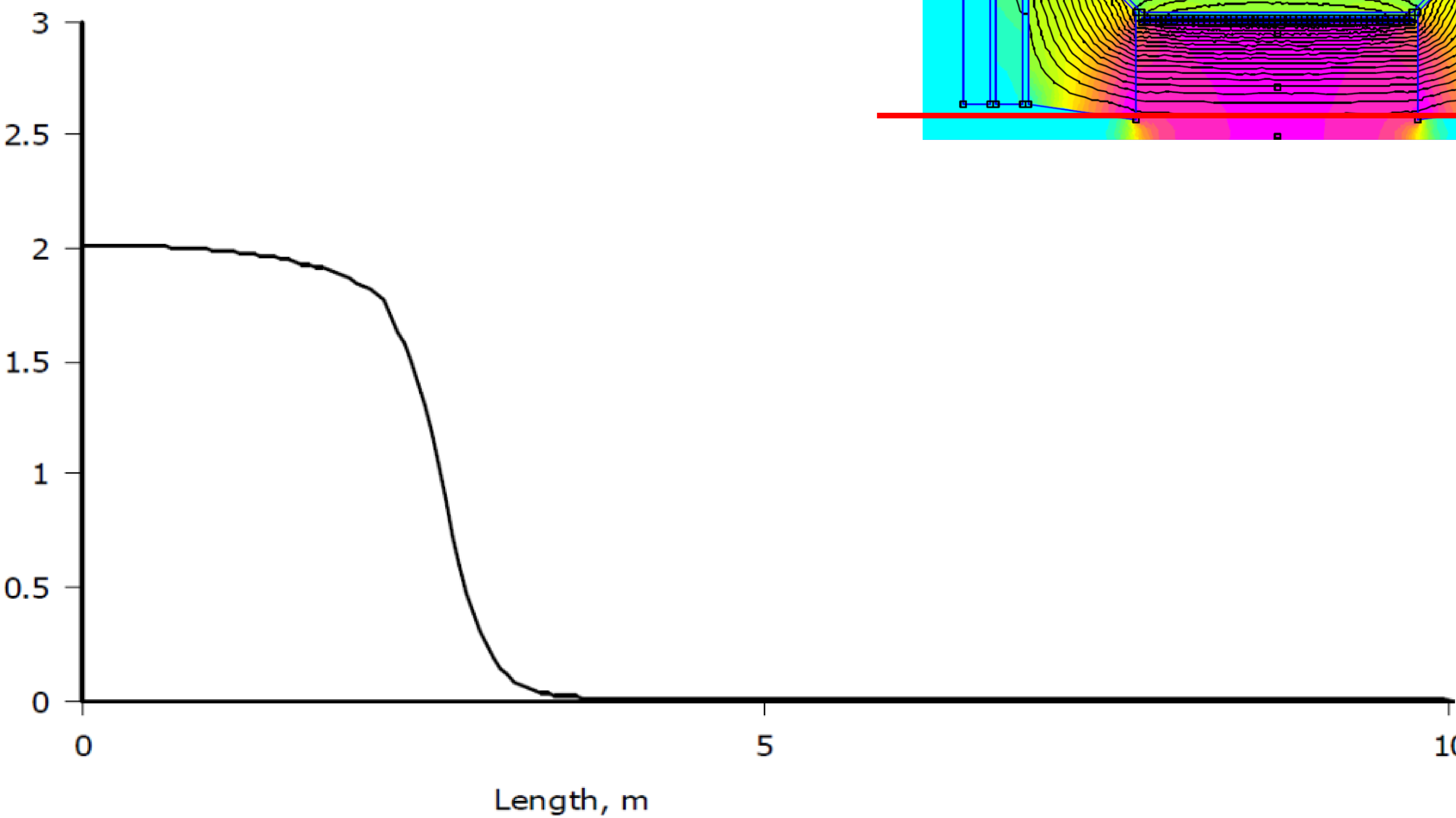


Iron calorimeter

Longitudinal field projection

@ R = 0.1 m

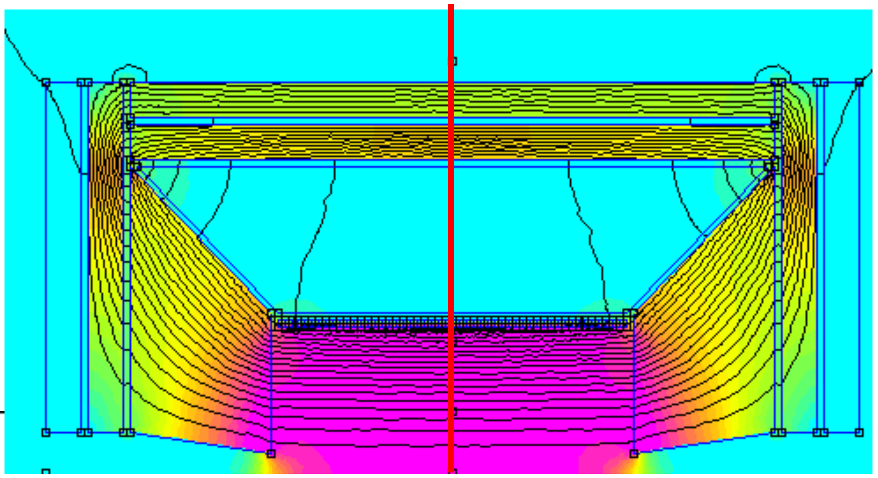


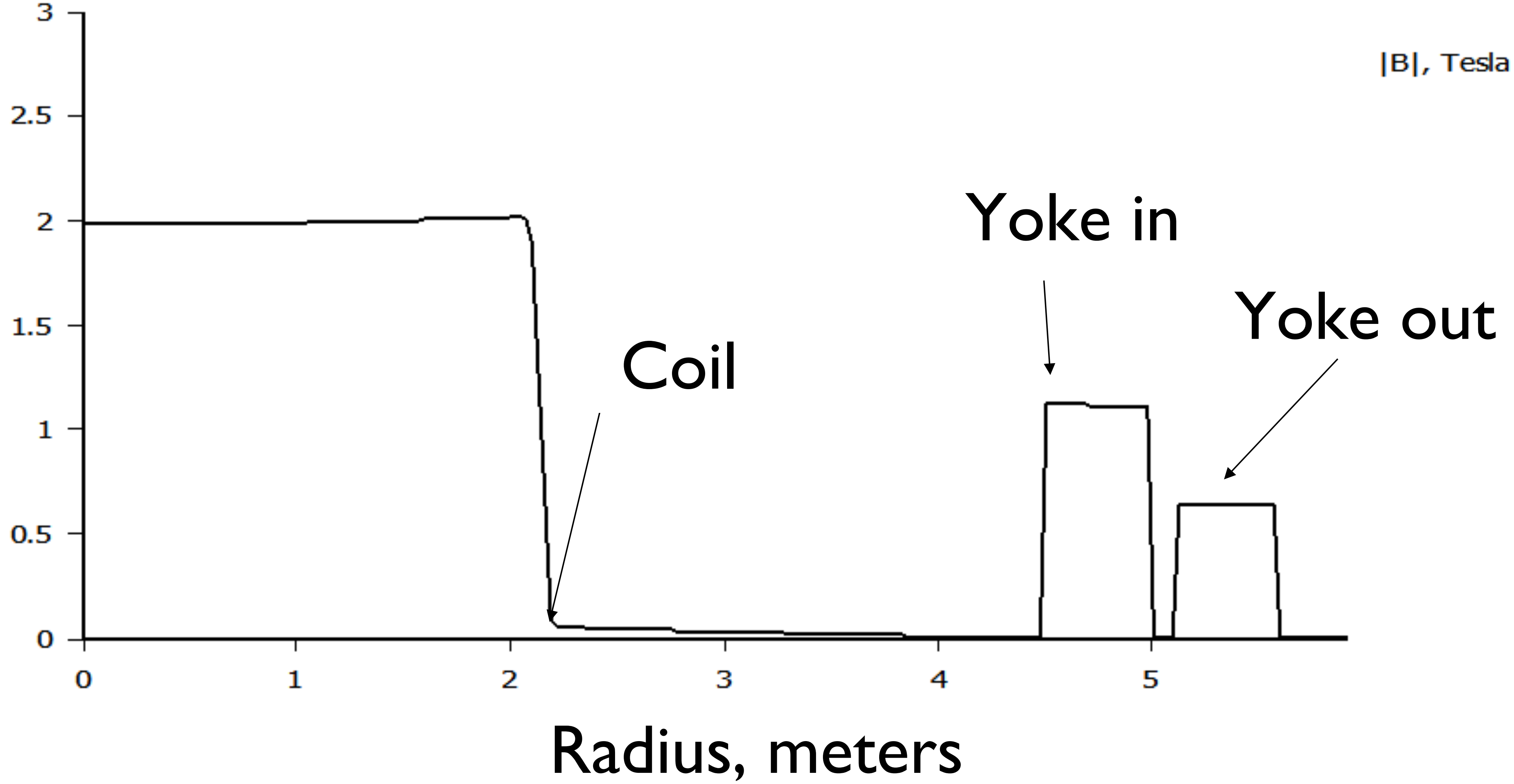


Forward iron calorimeter

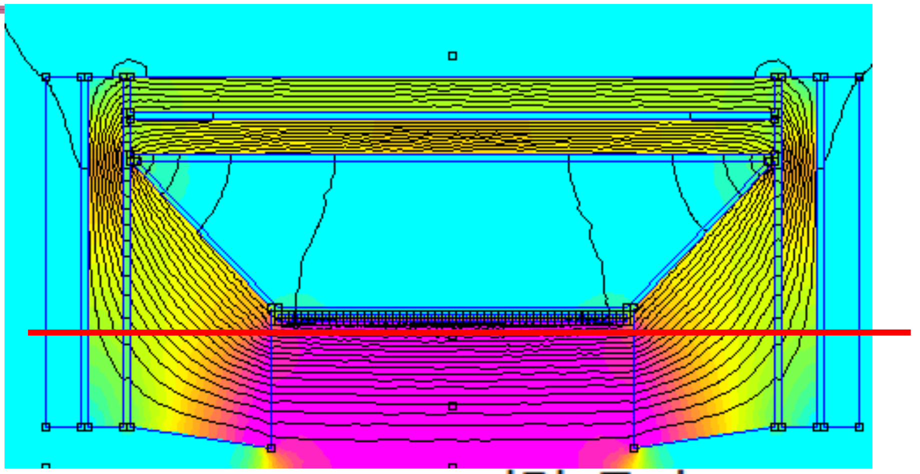
Radial field variation:

interaction vertex till after yoke





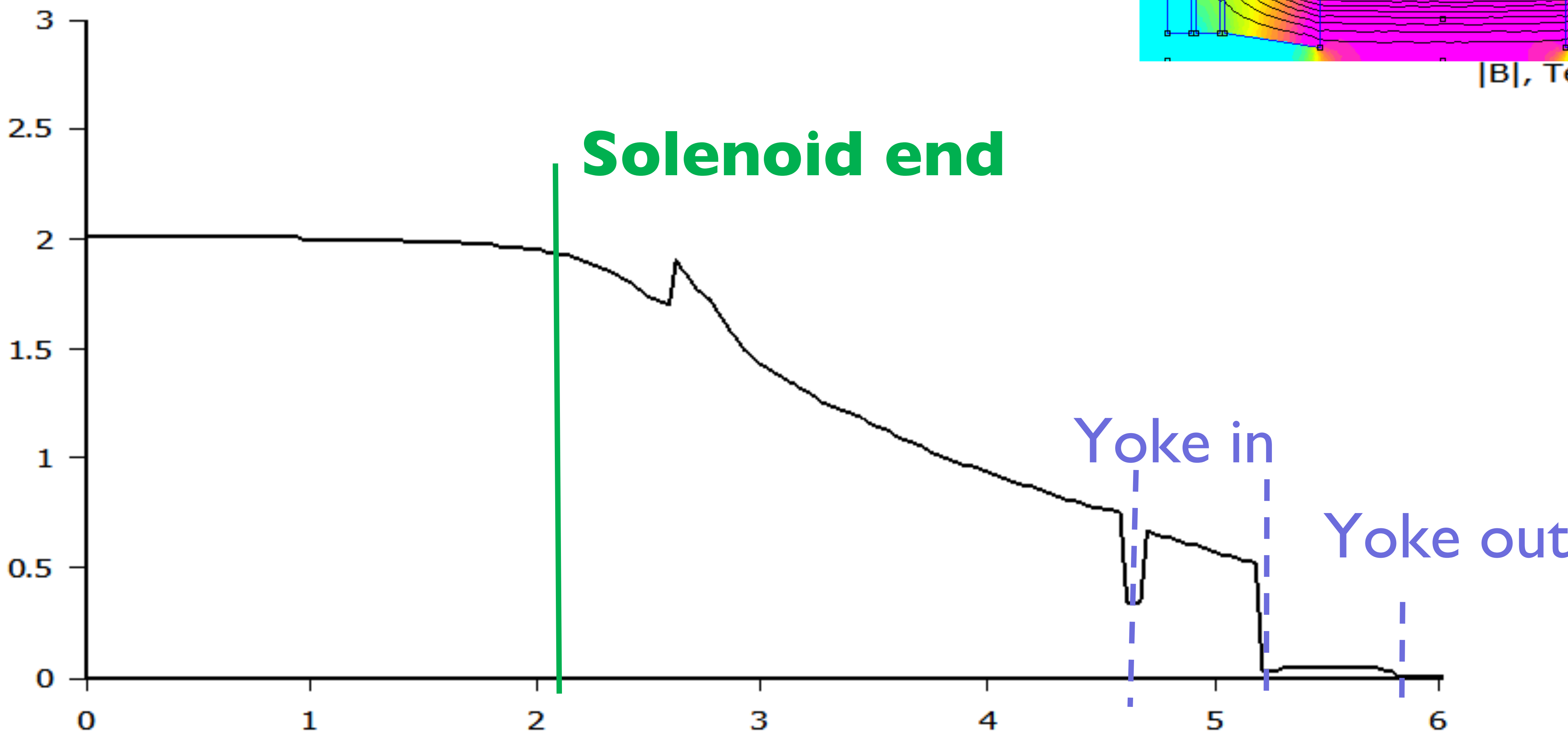
Forward iron calorimeter



|B|, Tesla

Longitudinal field projection

@ R = 2.0 m

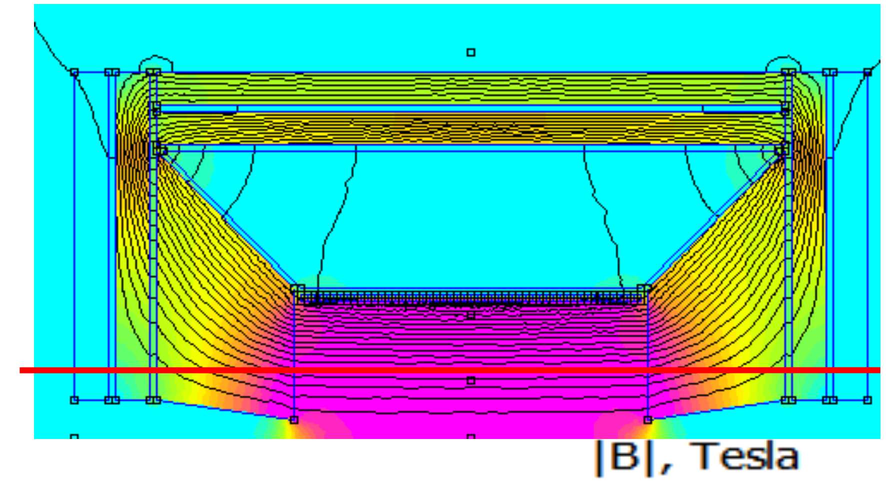


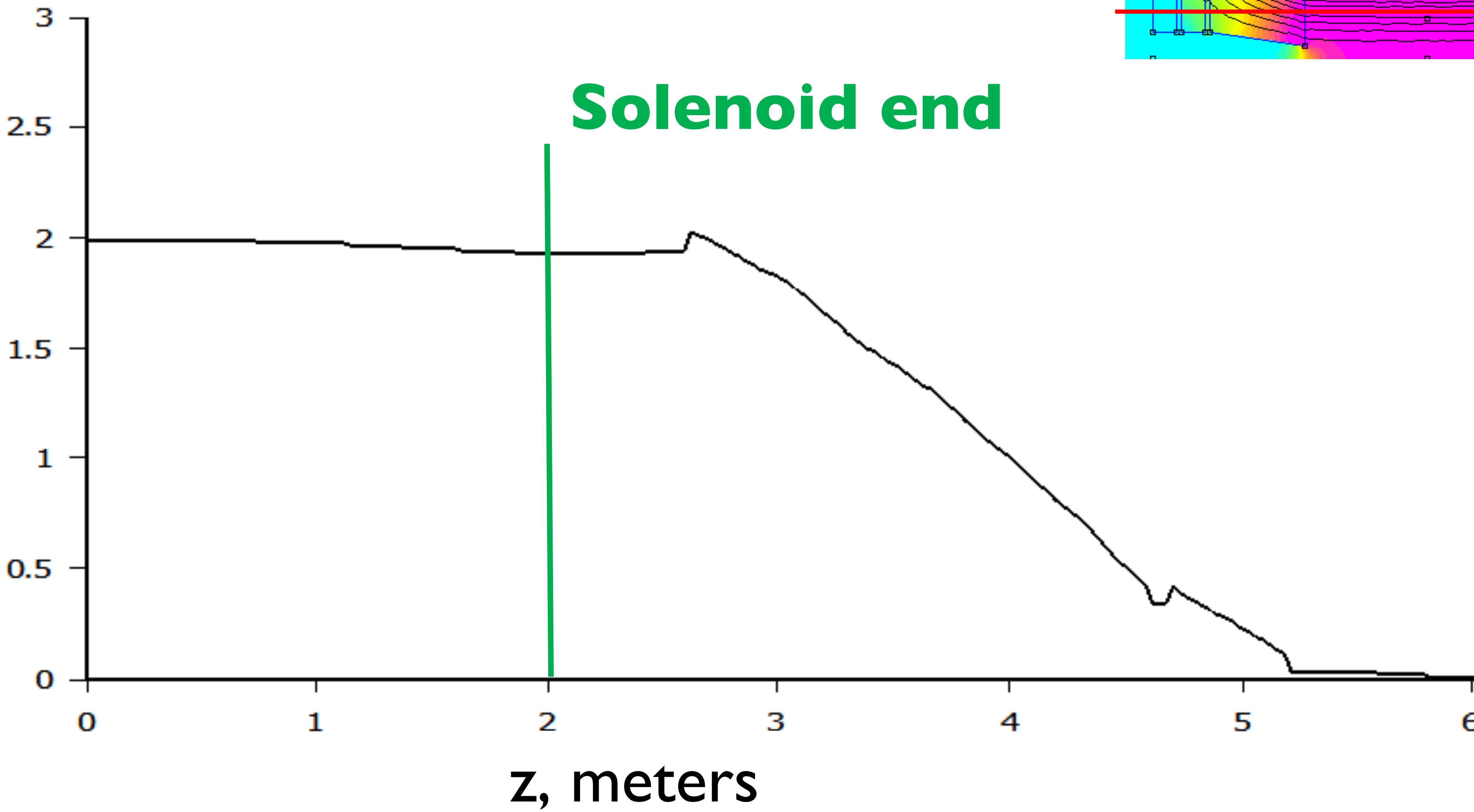
z, meters

Forward iron calorimeter

Longitudinal field projection

@ R = 1.0 m

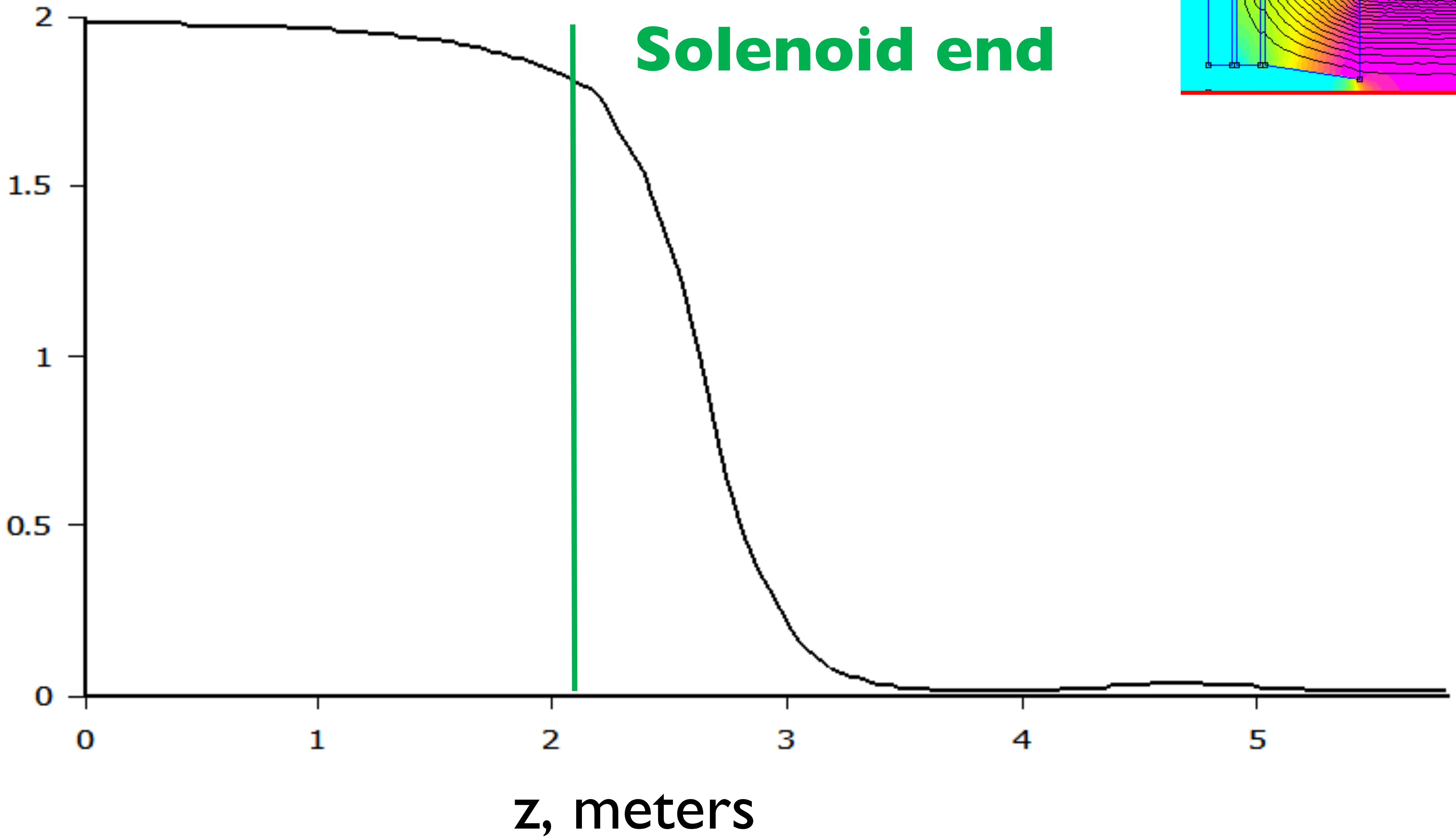


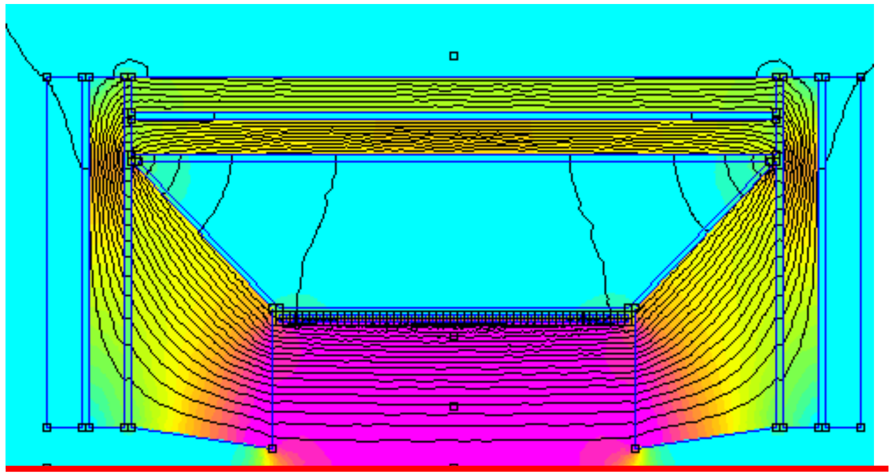


Forward iron calorimeter

Longitudinal field projection

@ R = 0.1 m





Future work

- Physics benchmarks with full simulation
- Mechanics:
  - Metal matrix technology
  - Fast module assembly
  - Calorimeter support
- Electronics
  - SiPM readout optimization (pixel size and x-talk)
  - Define readout chain
    - ASIC selection or development
    - Signal processing on detector
    - Readout and back-end design
  - Explore timing for longitudinal information