An Innovative Positron Spectrometer to Search for the Lepton Flavour Violating Muon Decay with a Sensitivity of 10^{-13}

(μ粒子のフレーバ非保存崩壊を10^{-13}の感度で探索する高感度陽電子分光計の開発)

西口 創 (高エネルギー加速器研究機構・素粒子原子核研究所)

2009年3月28日, 日本物理学会 第64回年次大会 (於立教大学)

CONTENTS

$\mu \rightarrow e\gamma$ Decay

Muon Decay in SM (1)

Decay Mode	Branching Ratio
$\mu \to e\nu\nu$ (Michel)	~ 100 %
$\mu \to e\nu\nu\gamma$ (Radiative)	1.4 % (E_γ>10MeV)
$\mu \to e\nu\nu + e^+e^-$	3.4×10^{-5}
$\mu \to e\gamma$	$<1.2\times10^{-11}$ (MEGA, 1999)

Muon Decay in SM (2)

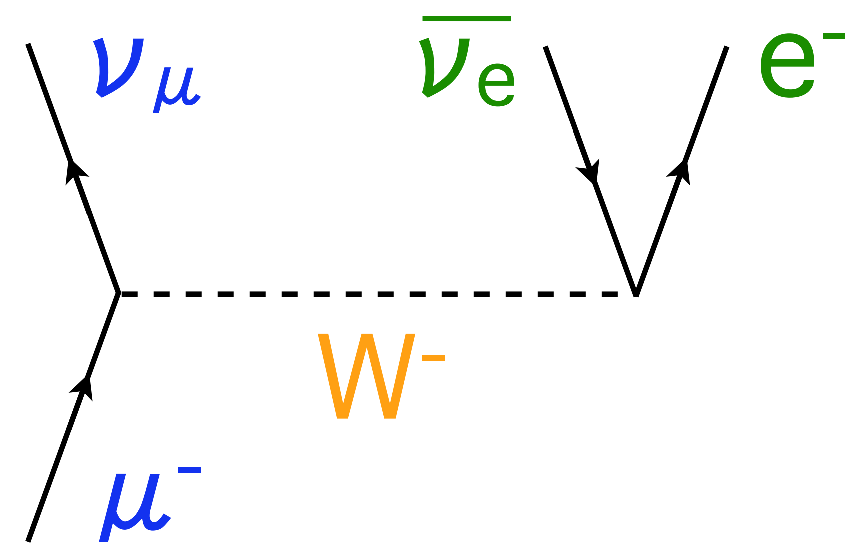
- Michel Decay : $\mu^- \to e^- \nu_\mu \overline{\nu}_e$ / $\mu^+ \to e^+ \overline{\nu}_\mu \nu_e$

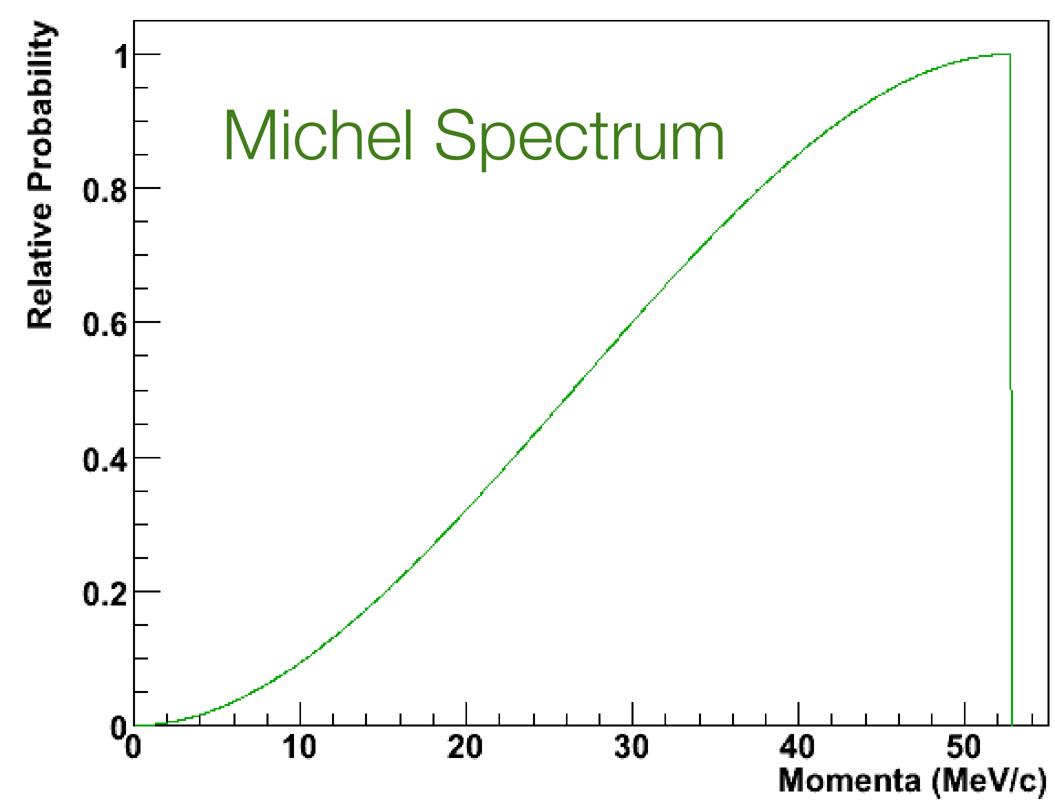
$$\mathcal{M} = -\frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \epsilon,\mu=R,L}} g^{\gamma}_{\epsilon\mu} \langle \bar{e}_\epsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle (\bar{\nu}_\mu)_m | \Gamma_\gamma | \mu_\mu \rangle$$

$$\frac{d^2\Gamma}{dx\,d(\cos\theta)} = \frac{m_\mu}{4\pi^3} W^4_{e\mu} G_F^2 \sqrt{x^2 - x_0^2} \times \left[\mathcal{F}_{IS}(x) + P_\mu \cos\theta_e \mathcal{F}_{AS}(x)\right] \times \left[1 + \vec{P}_e(x, \theta_e) \cdot \hat{\zeta}\right]$$

$$\mathcal{F}_{IS} = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x),$$

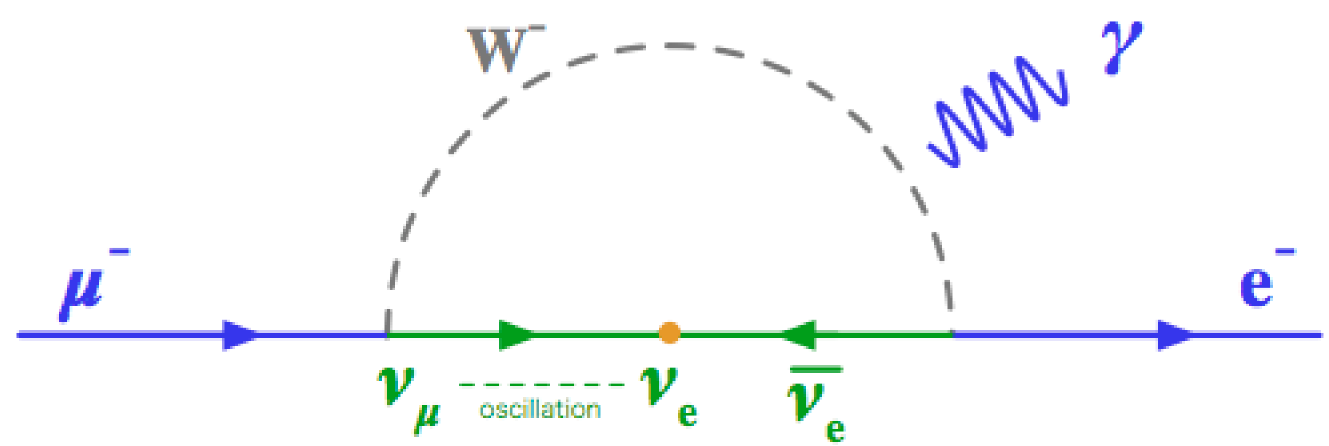
$$\mathcal{F}_{AS} = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 3 - \left(1 - \sqrt{1 - x_0^2}\right)\right)\right]$$





Muon Decay in SM (3)

- Lepton Flavour Violation (LFV)
  - Lepton Family Number Conservation in SM
  - Neutrino-Oscillation
  - Charged Lepton ???

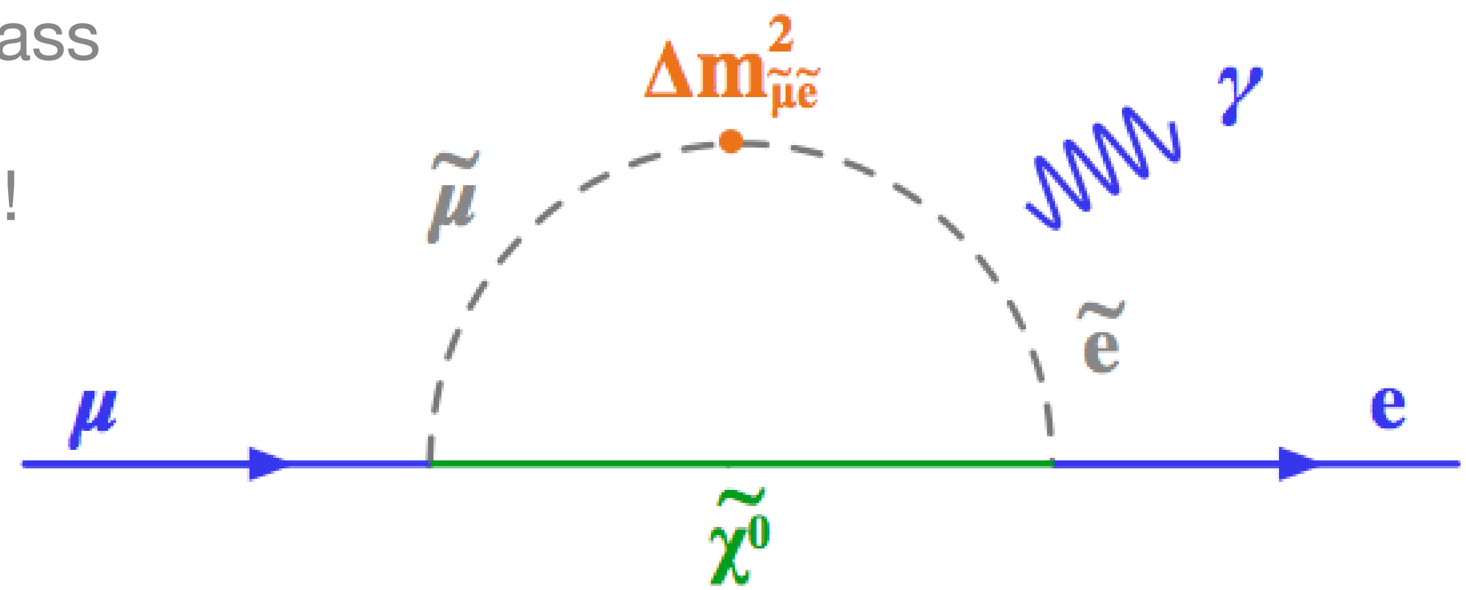


- Muon Rare Decay Search
  - *e.g.* $\mu \to e\gamma$ Decay

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{m^2_W} \right|^2 \Rightarrow \boxed{10^{-50} \text{ !!}}$$

$\mu \to e\gamma$ in SUSY (1)

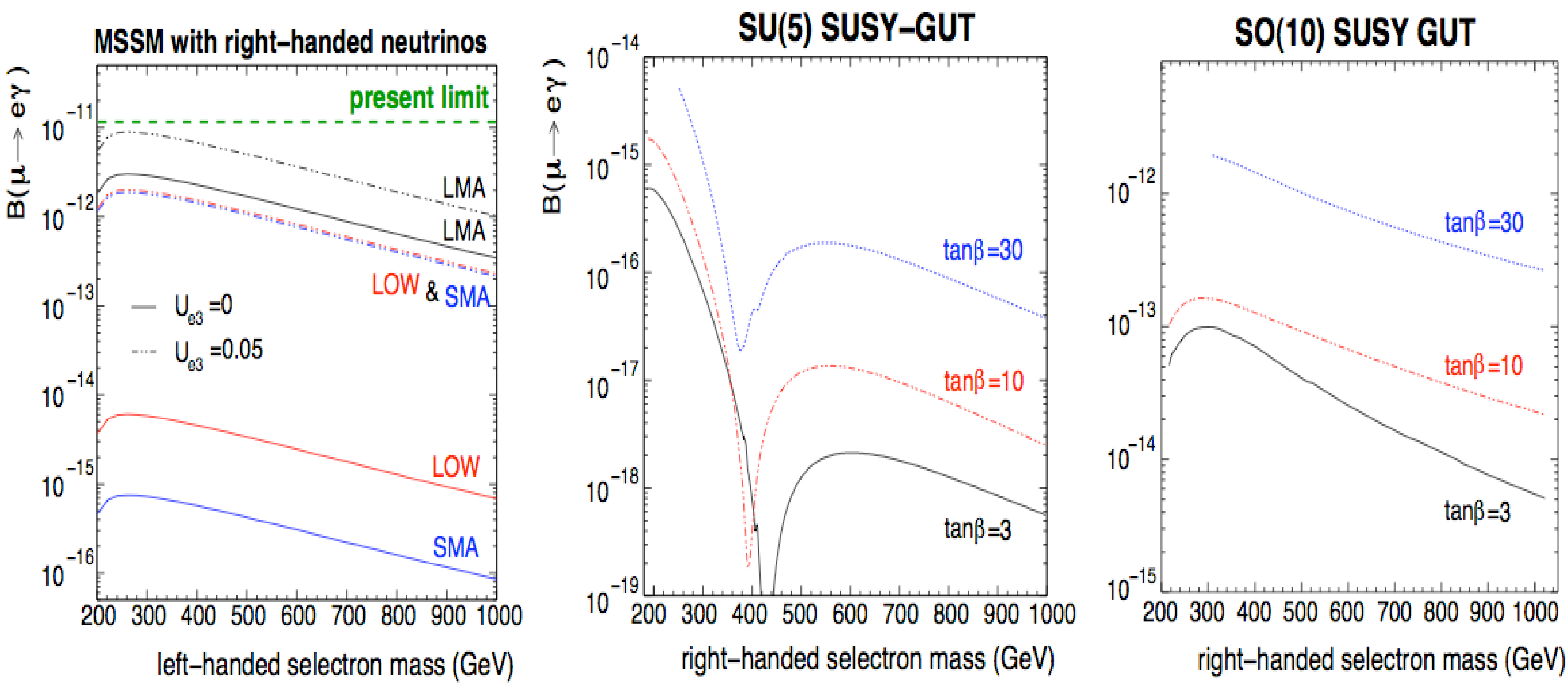
- LFV is expected to be enhanced by SUSY !!
    - Brand-New Candidate of LFV Source
    - Without Suppression by ν-mass
    - The First Evidence of SUSY !!
- Muon is Suitable Probe
    - *e.g.* $\mu \to e\gamma$ Decay



$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{\alpha^3 \pi \theta^2_{\tilde{e}\tilde{\mu}}}{G_F^2 \tilde{m}^4} \Rightarrow \boxed{10^{-15} \sim 10^{-11} \text{ !!}}$$

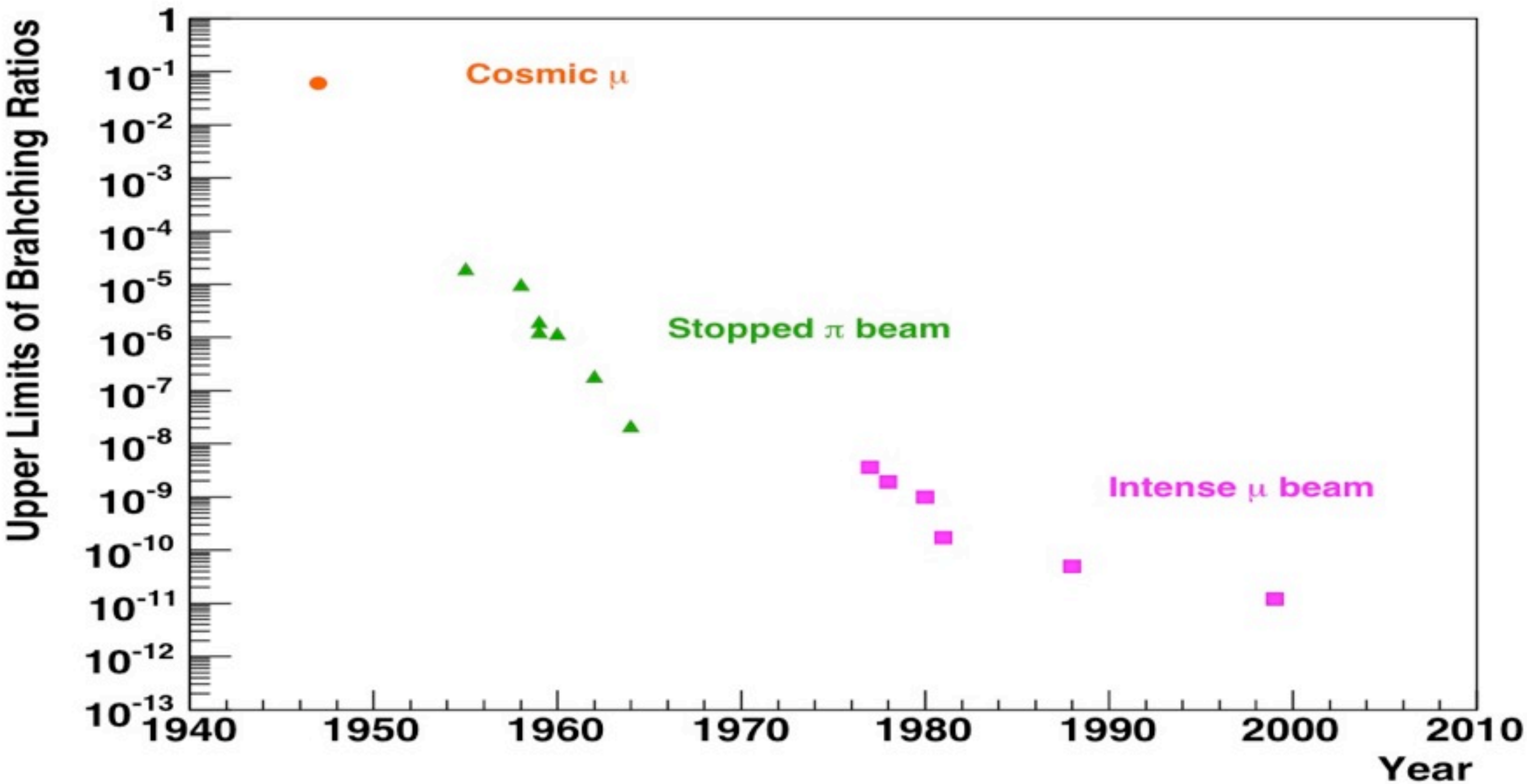
$\mu \to e\gamma$ in SUSY (2)

- Many SUSY-based models predict large B($\mu \to e\gamma$) !!



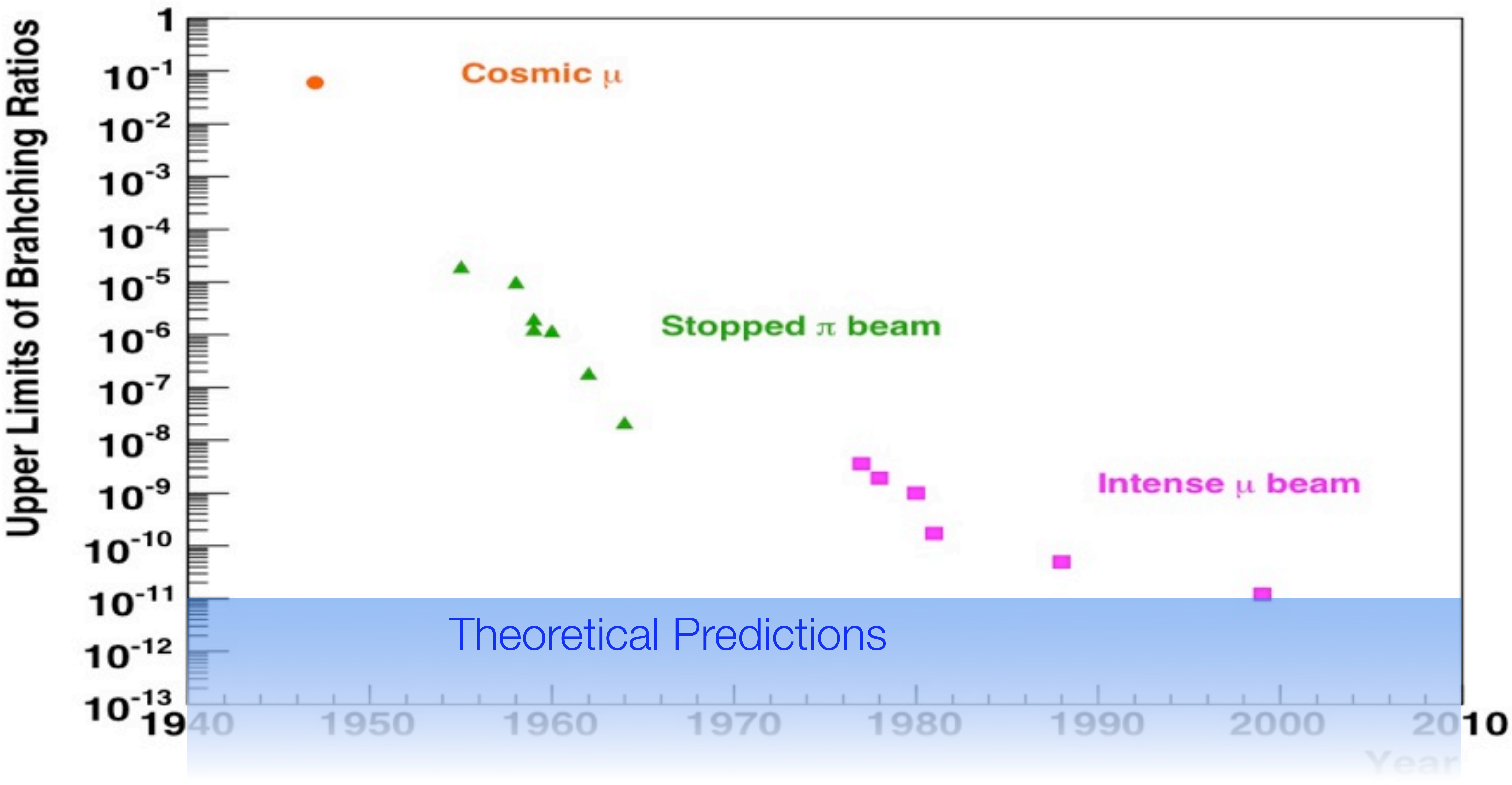
$\mu \to e\gamma$ Search Experiment

- $\mu \to e\gamma$ Search Experiment has 60-years history



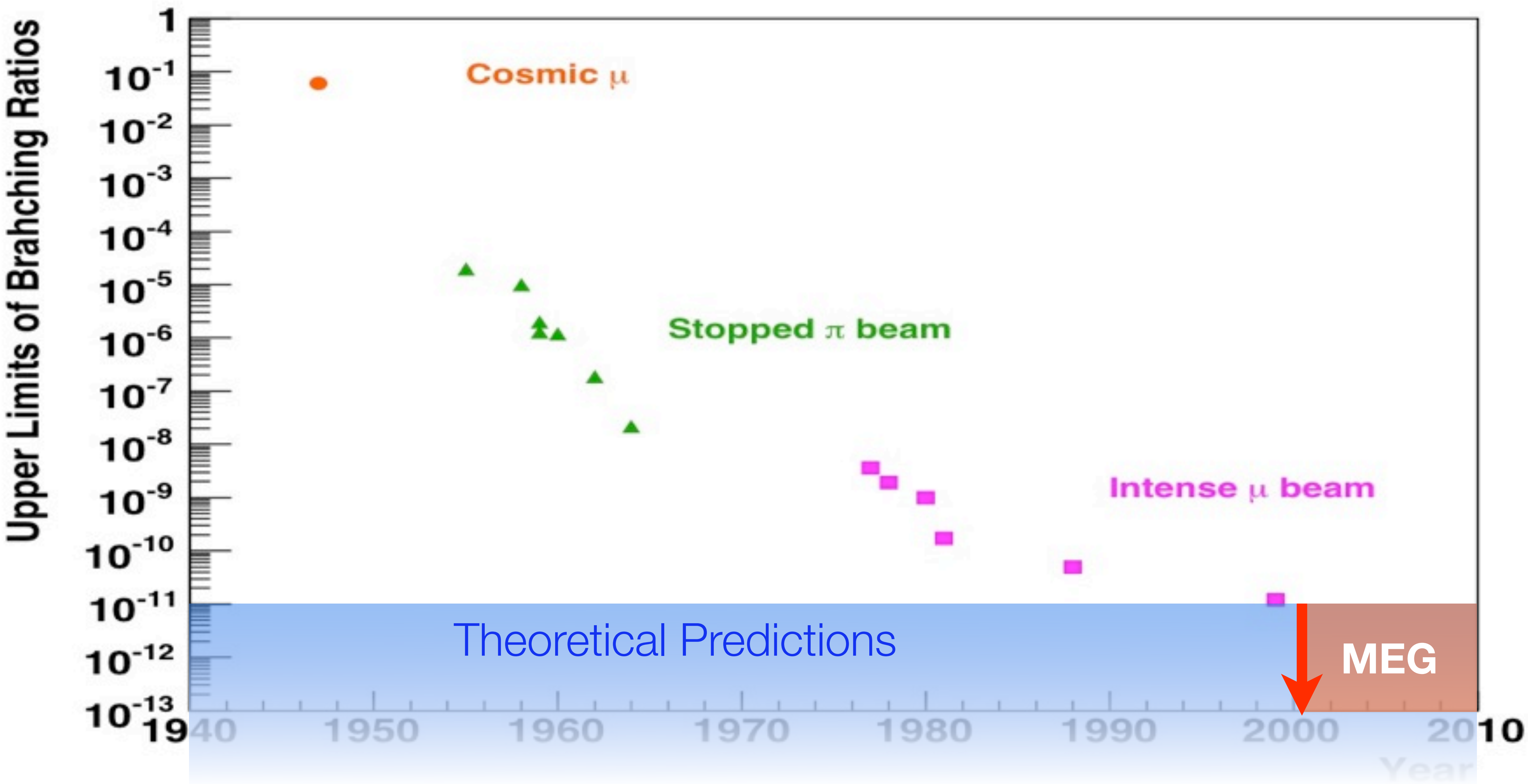
$\mu \to e\gamma$ Search Experiment

- $\mu \to e\gamma$ Search Experiment has 60-years history



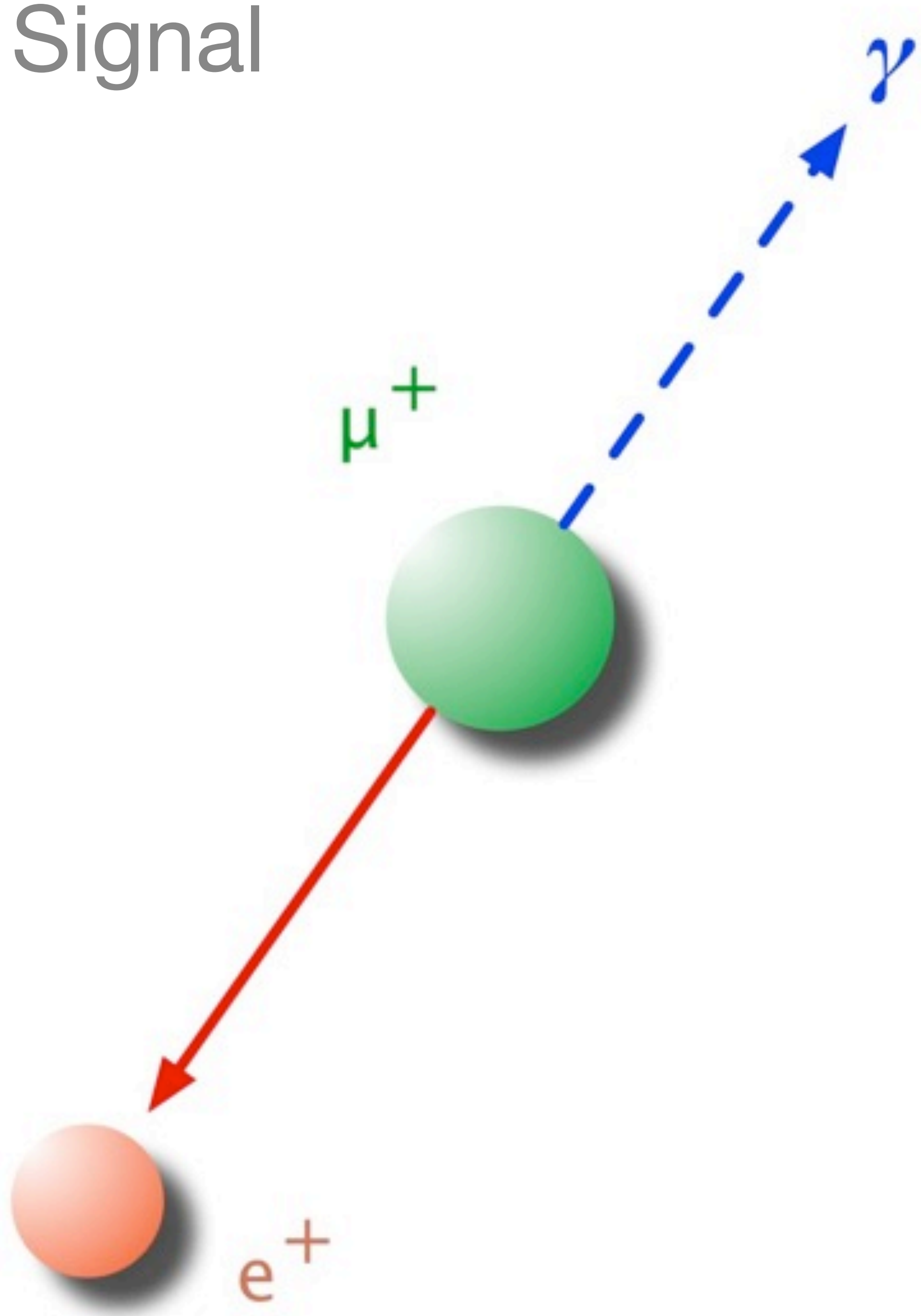
$\mu\to e\gamma$ Search Experiment

- $\mu\to e\gamma$ Search Experiment has 60-years history



$\mu \to e\gamma$ Signature & Background (1)

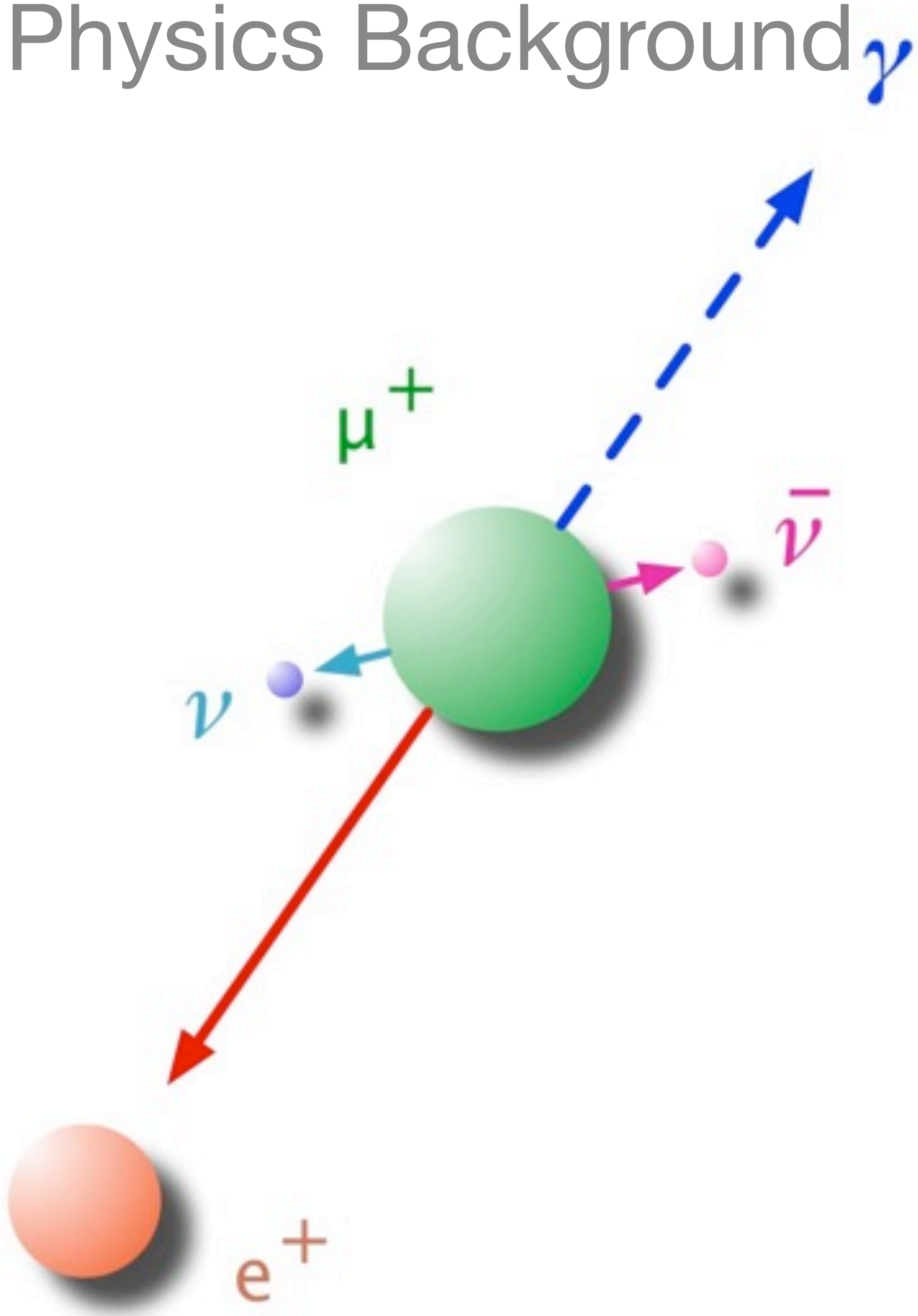
- Signal



- $E_e = E_\gamma$ = 52.8 MeV ($=m_\mu/2$)
- e^+ and γ coincidence ($\Delta t=0$)
- Back-to-Back ($\theta_{e\gamma}=\pi$)

$\mu\to e\gamma$ Signature & Background (2)

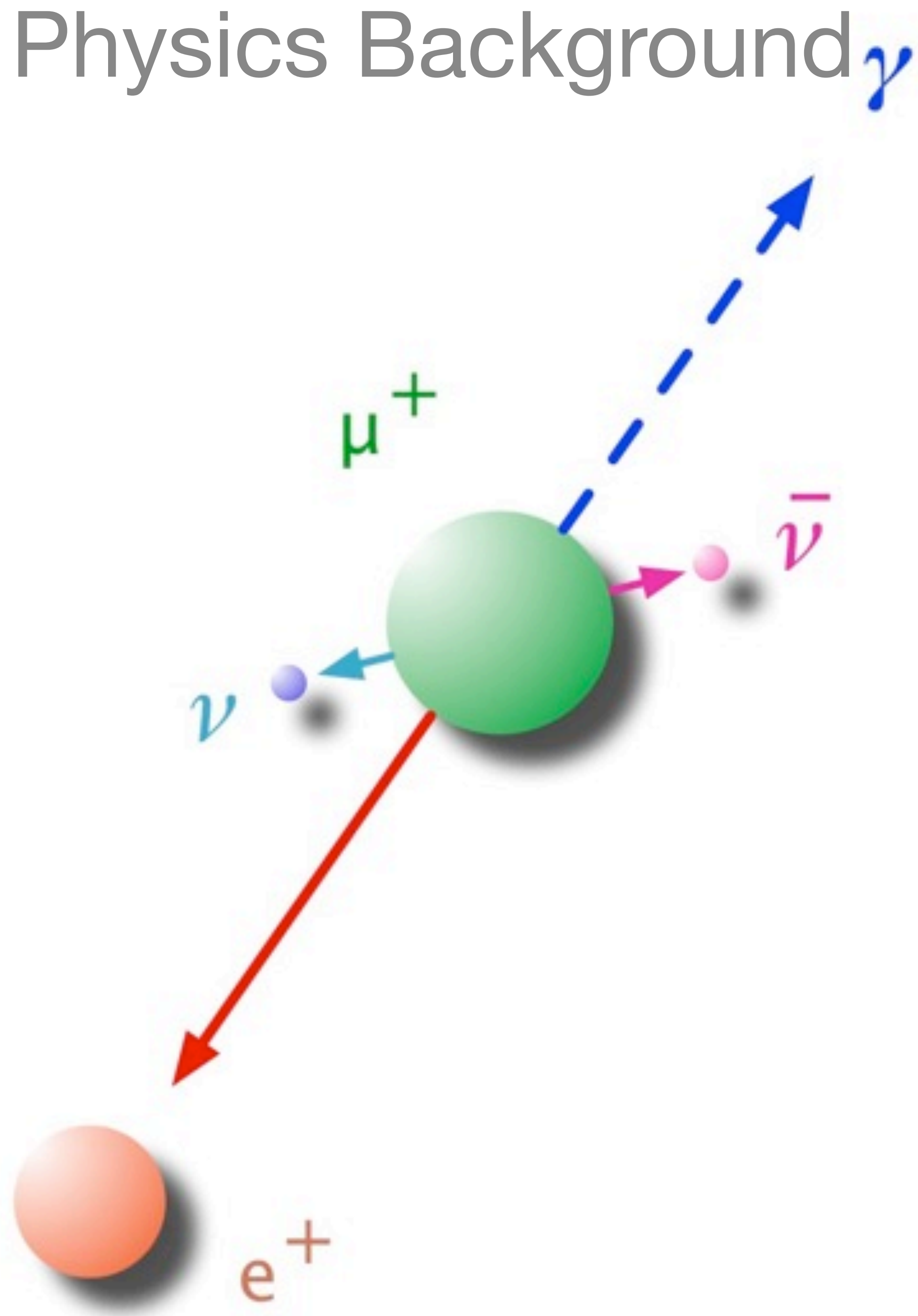
- Physics Background



- Radiative Muon Decay
- Back-to-Back e^+ and γ
- very small ν-mass

$\mu \to e\gamma$ Signature & Background (2)

- Physics Background

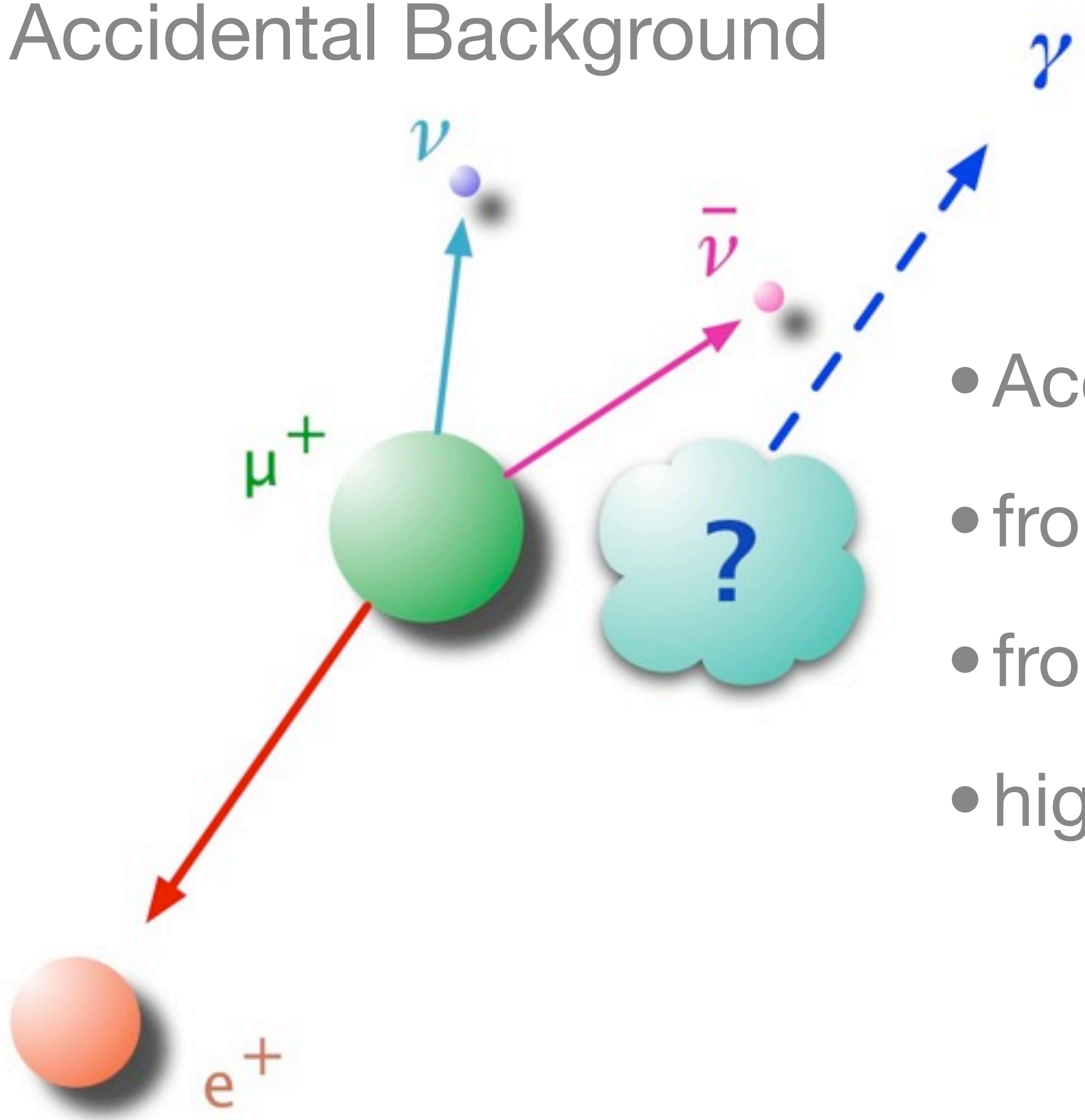


- Radiative Muon Decay
- Back-to-Back e^+ and γ
- very small ν-mass

good σ_E and σ_θ

$\mu \to e\gamma$ Signature & Background (3)

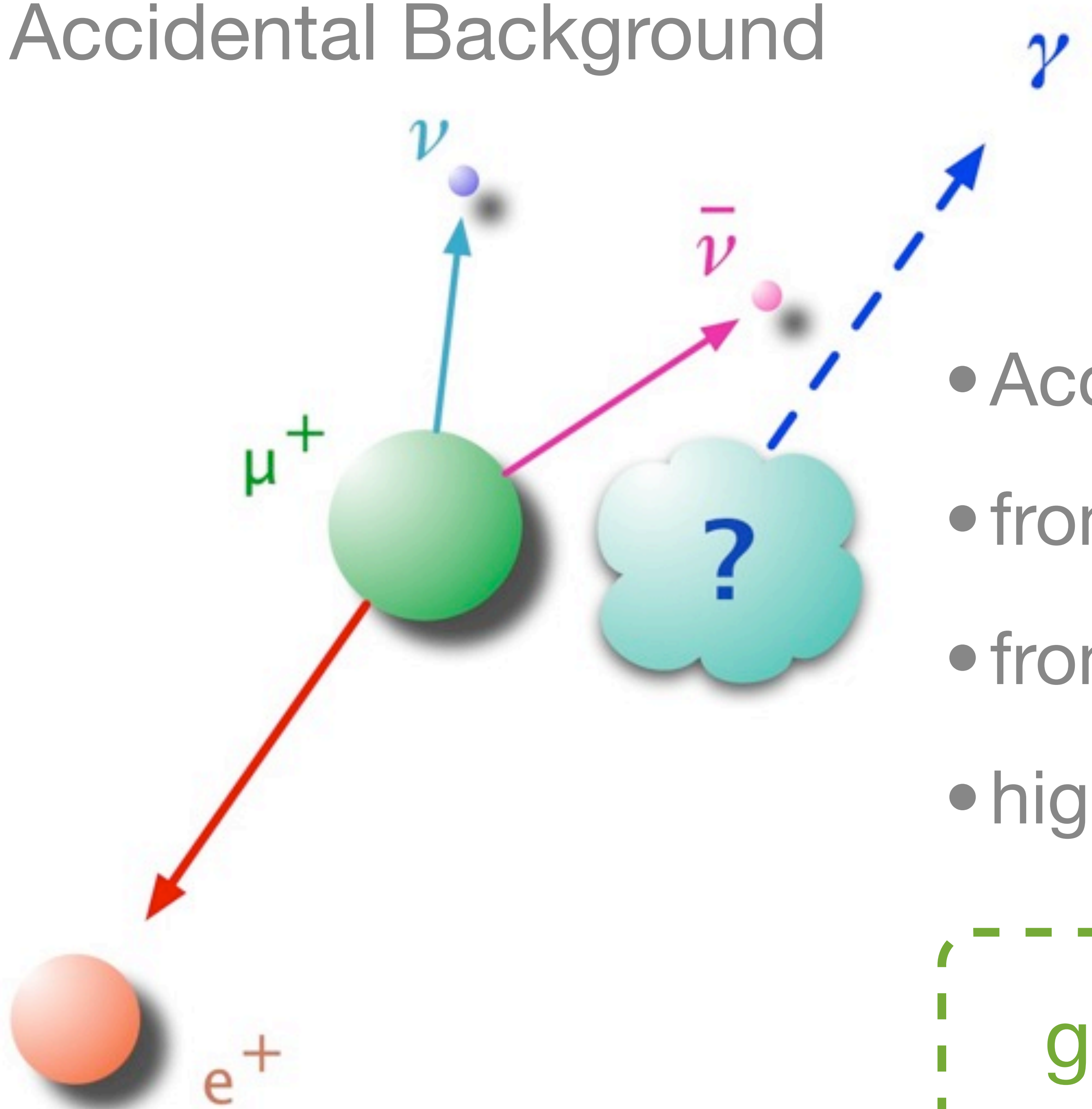
- Accidental Background



- Accidental Coincidence
- from Radiative Muon Decay
- from AiF of Michel e^+
- high rate e^+

$\mu \to e\gamma$ Signature & Background (3)

- Accidental Background

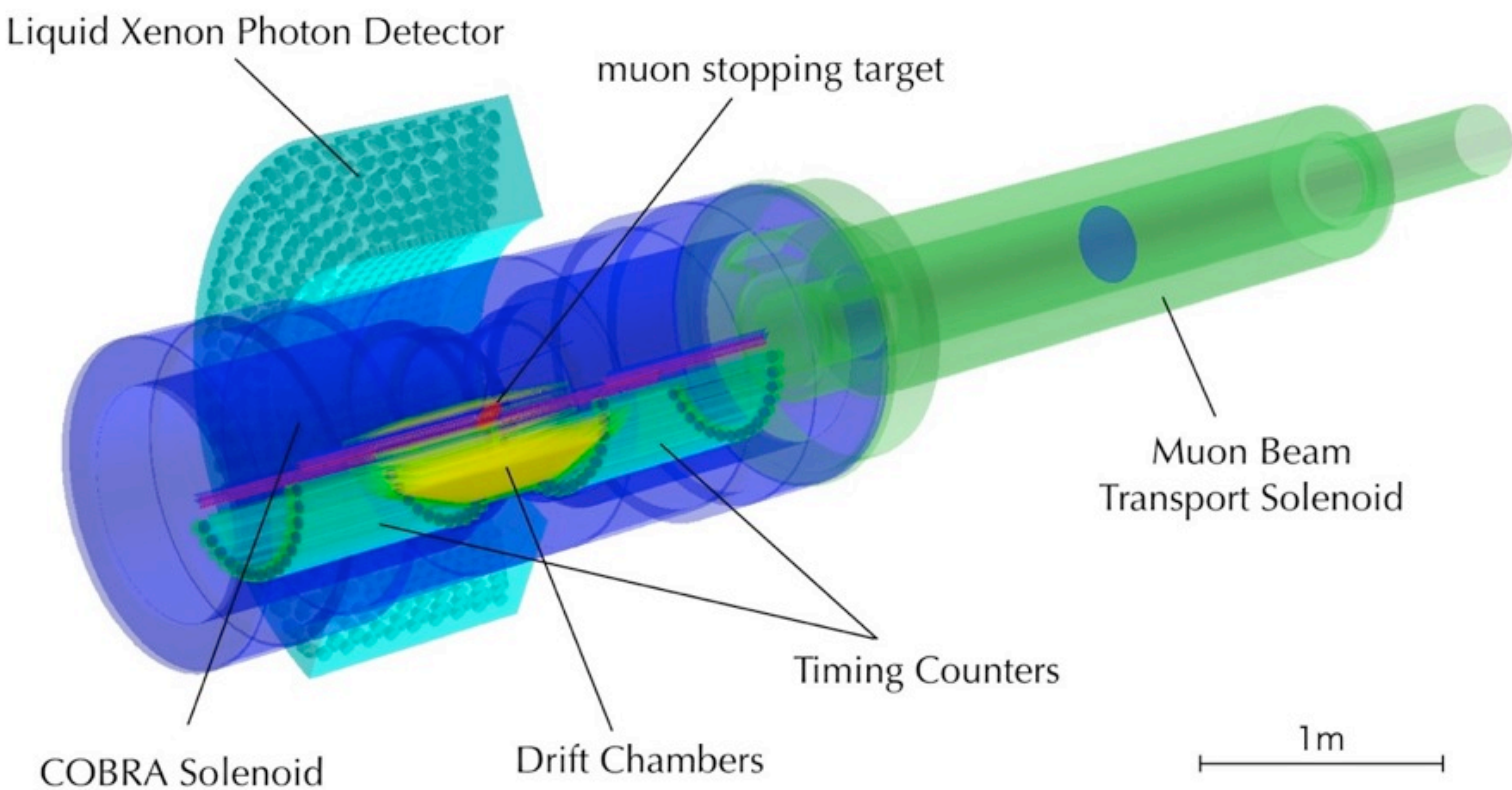


- Accidental Coincidence
- from Radiative Muon Decay
- from AiF of Michel e^+
- high rate e^+

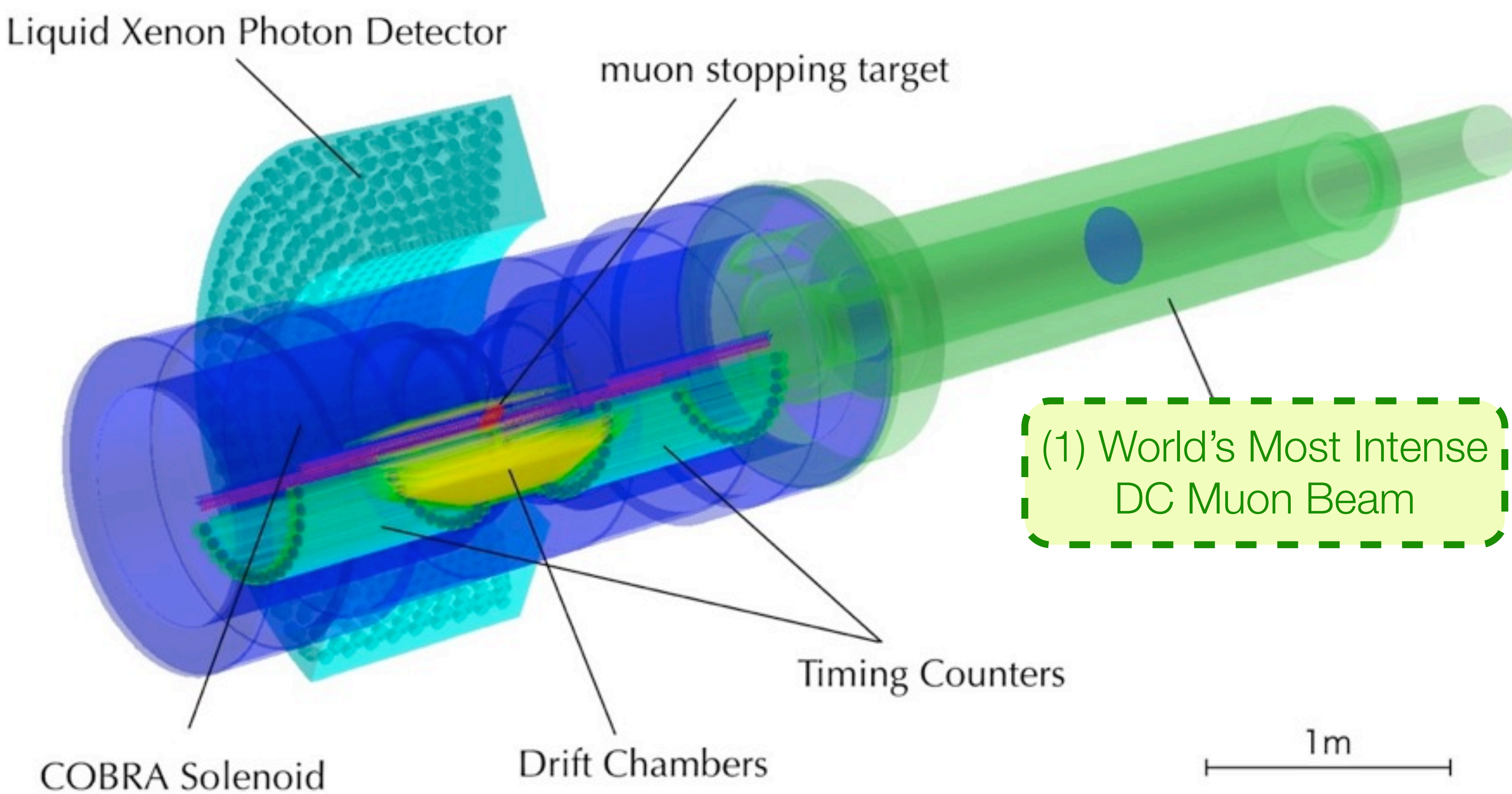
good Resolutions

MEG Experiment

MEG Experiment

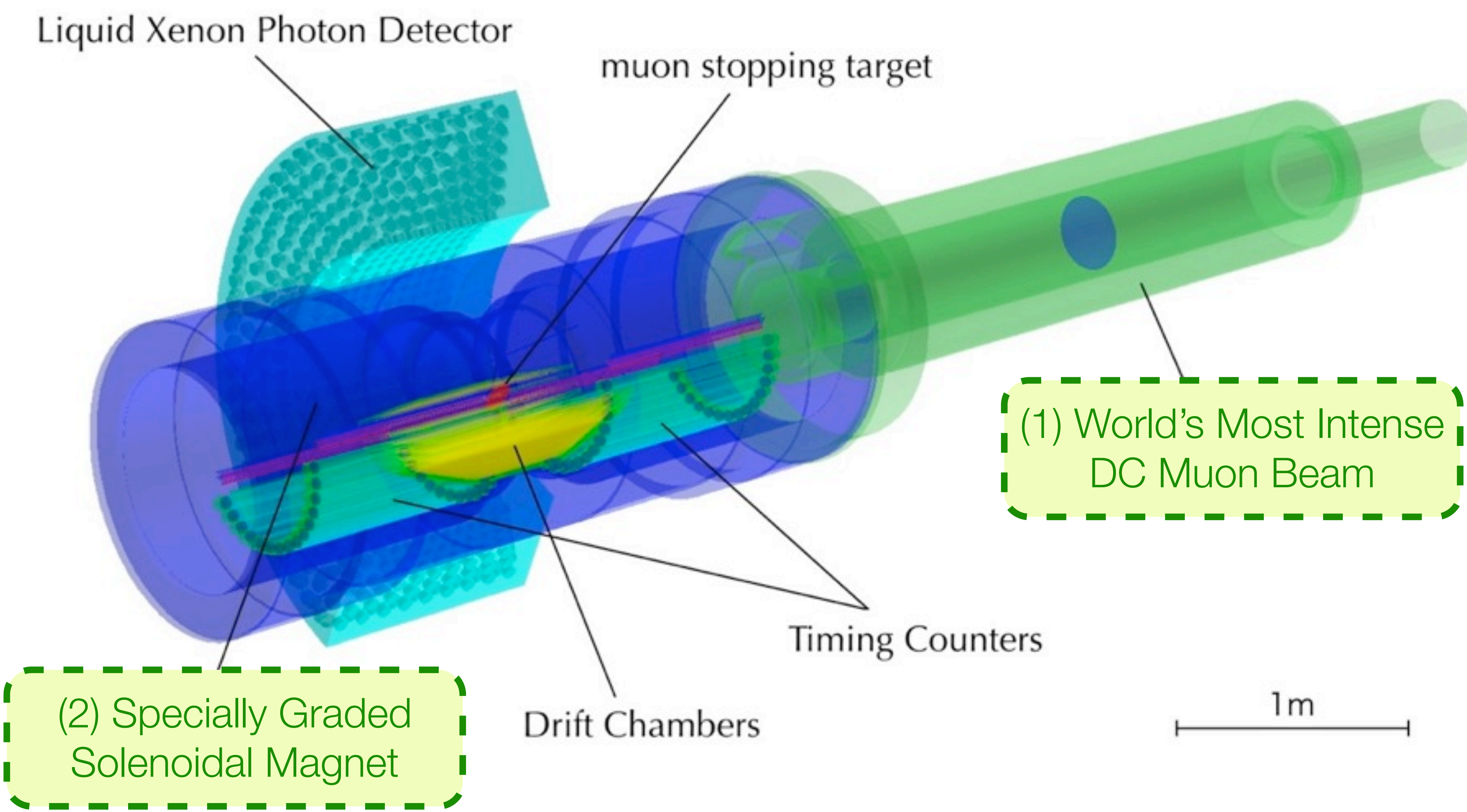


MEG Experiment

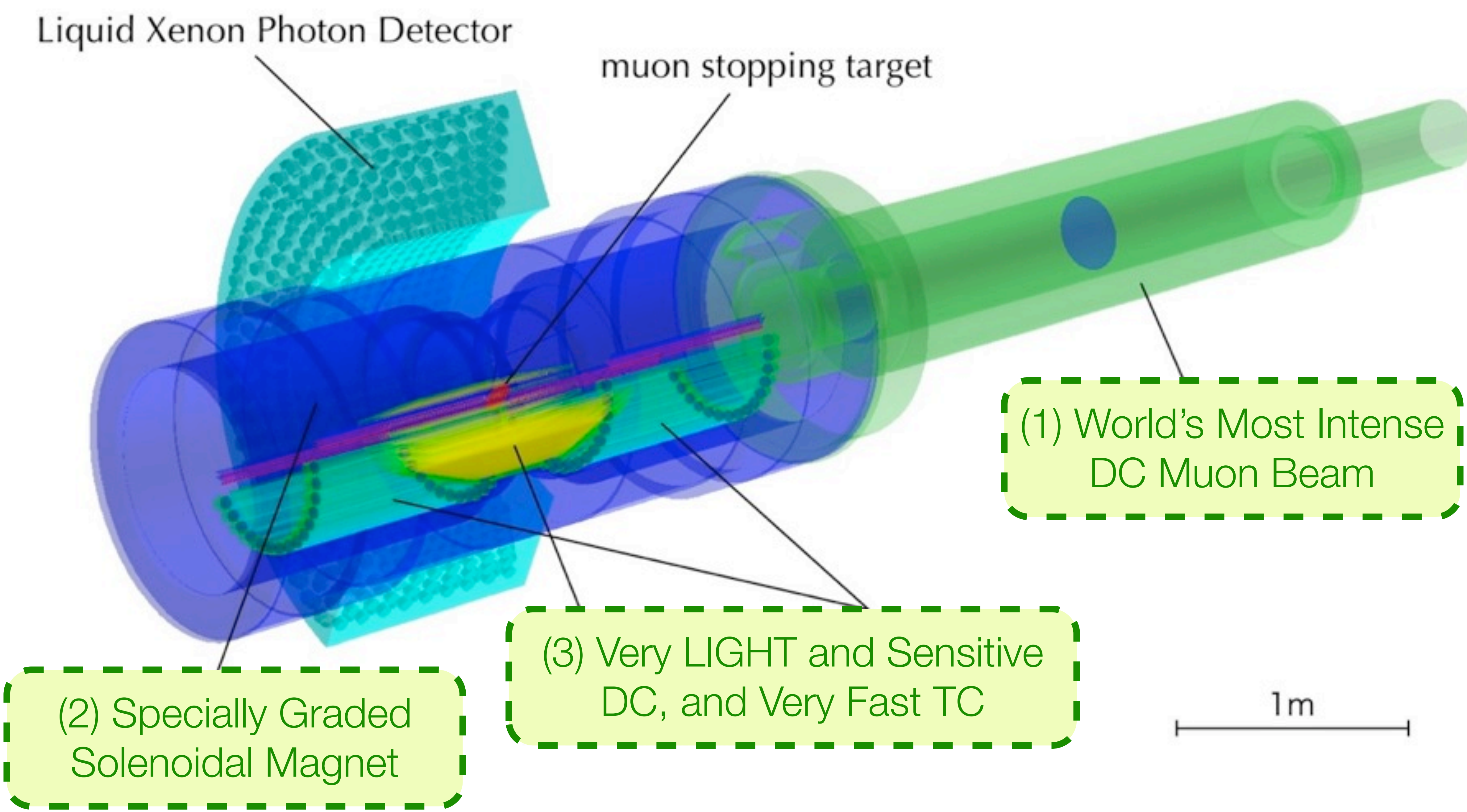


(1) World's Most Intense DC Muon Beam

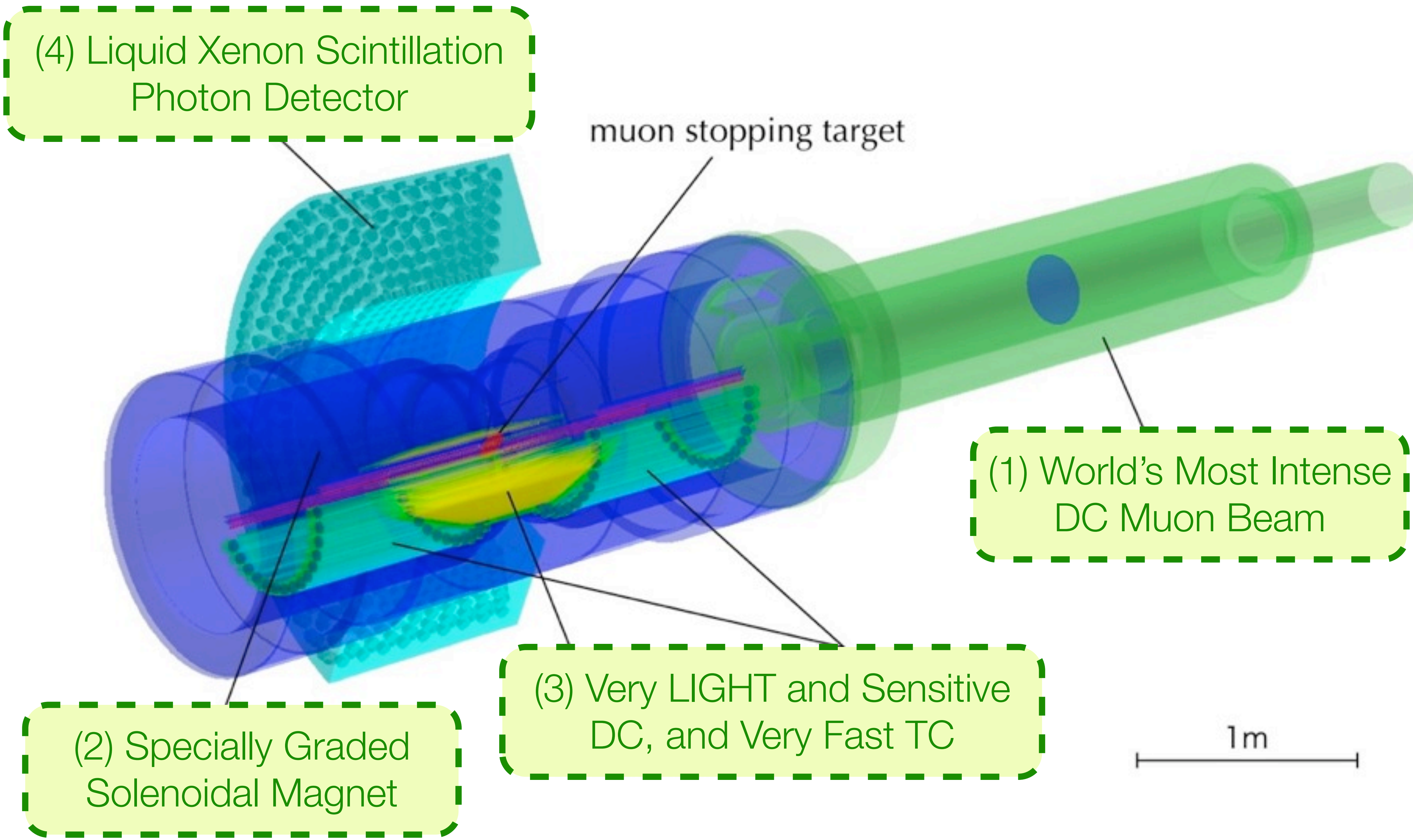
MEG Experiment



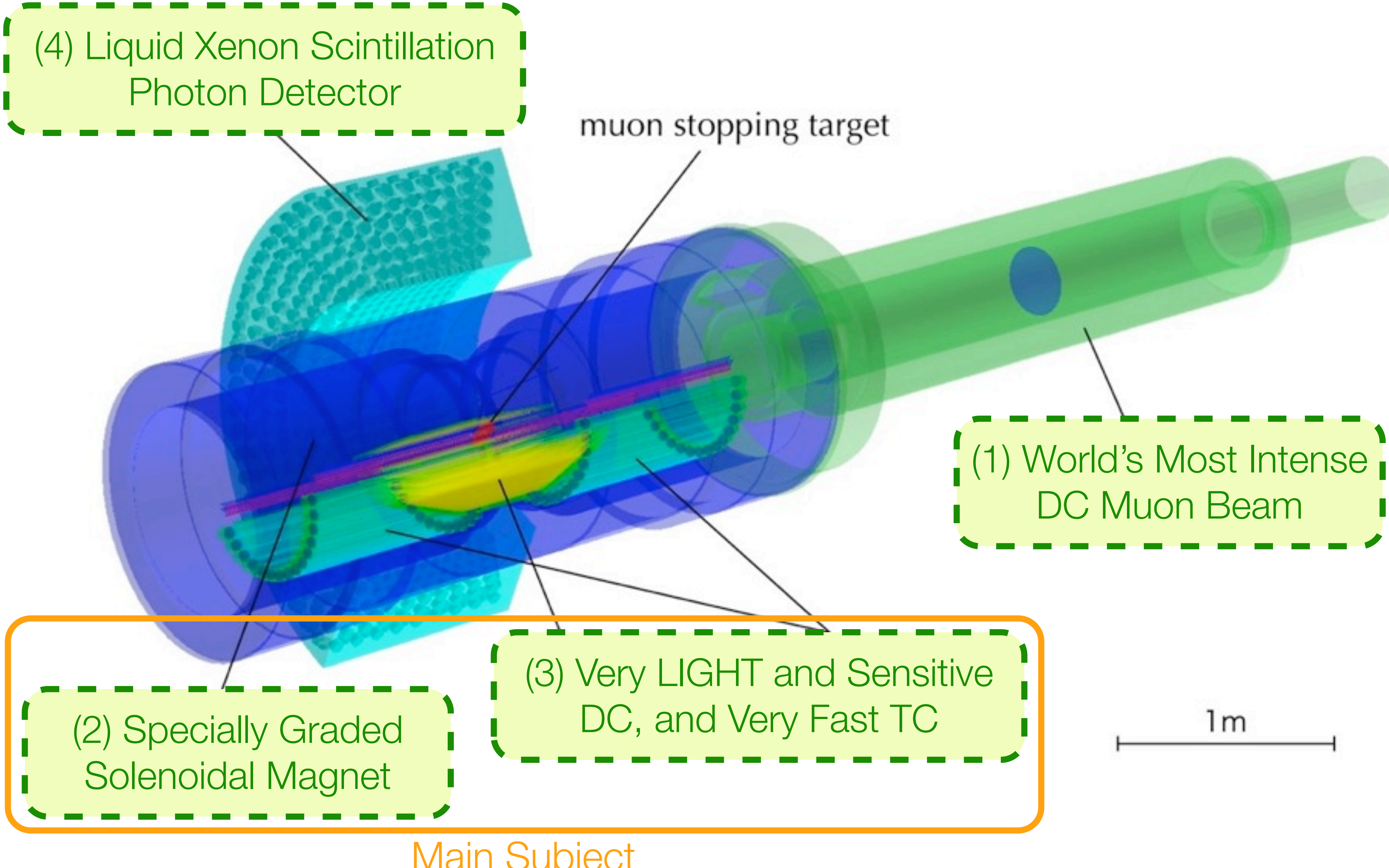
MEG Experiment



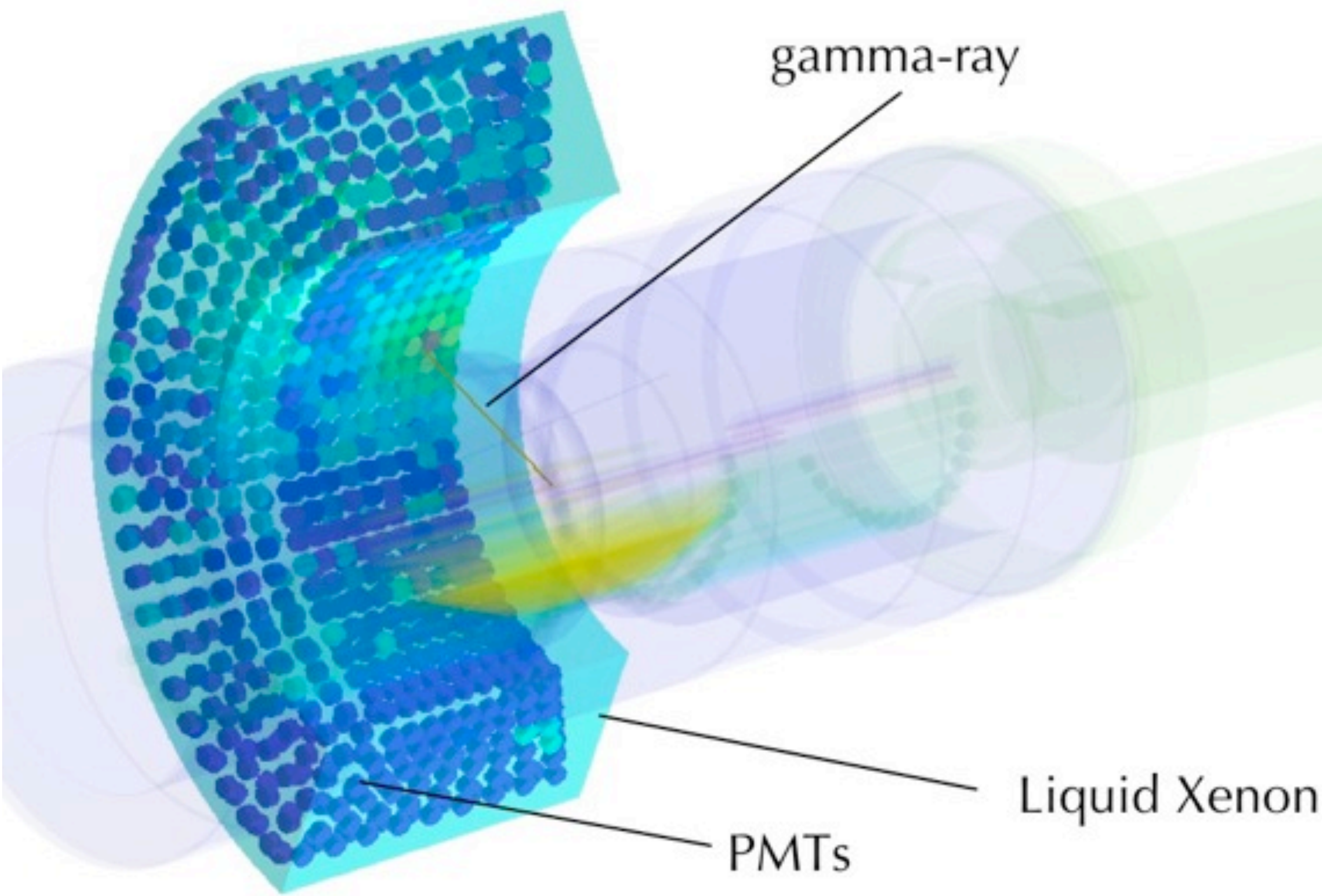
MEG Experiment



MEG Experiment



Photon Detector



- Liquid Xenon Scintillation Photon Detector
- Very Heavy (2.98g/cc)
- High Light Yield (80% NaI)
  - Good Resolutions (E, x)
- Fast Decay Time
  - Good Timing Resolution
  - Operational @ High Rate
- Liquid
  - Uniform, Easy Design

Trigger and DAQ (1)

- Trigger based on FADC and FPGA

Type-1 board
(100MHz FADC, Q and T reconstruction)

PMTs @ LXe (216+160)
PMTs @ TC (60)
APDs @ TC (64)

Anodes @ DC (32+32)
APDs @ NaI (9)
PMTs @ Cosmic-counter

Type-2 board
(Online reconstruction for Trigger)

MEG :	$Q(Xe)_{high}$ &	θ_{narrow} &	T_{narrow}	**4 Hz**
MEG-q :	$Q(Xe)_{low}$ &	θ_{narrow} &	T_{narrow}	**6 Hz**
MEG-d :	$Q(Xe)_{high}$ &	θ_{wide} &	T_{narrow}	**20 Hz**
MEG-t :	$Q(Xe)_{high}$ &	θ_{narrow} &	T_{wide}	**10 Hz**
RD-narrow :	$Q(Xe)_{low}$ &	&	T_{narrow}	**40 Hz**
RD-wide :	$Q(Xe)_{low}$ &	&	T_{wide}	**70 Hz**

Ancillary Triggers (calibration for sub-detectors)

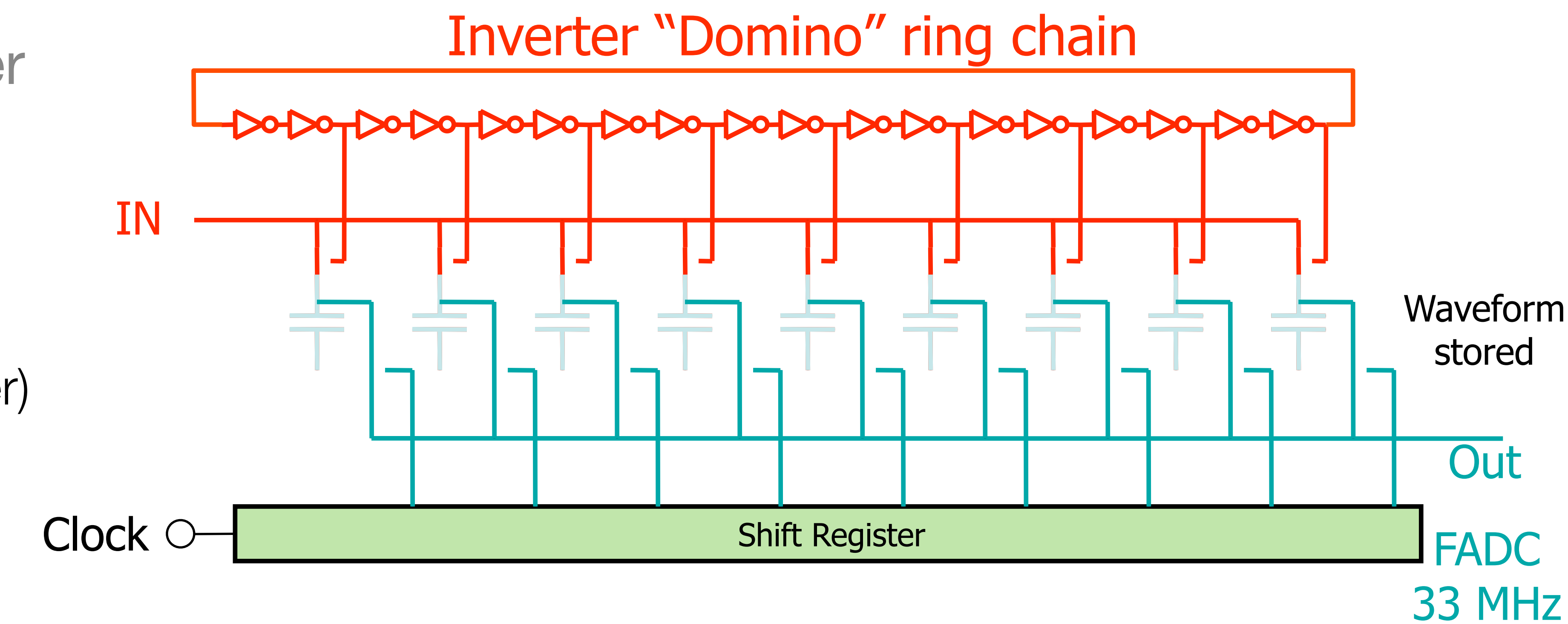
- All PMTs and APDs (LXe and TC) are sampled with 100MHz by Type-1 board and converted to Charge and Timing information.
- Type-2 receives Q/T from Type-1 and completes reconstruction. Energy / Angle / Time.
- $\mu \rightarrow e\gamma$ Trigger is provided by "Q(LXe)" && "e^+-γ Direction" && "e^+-γ Coincidence"
- In the engineering run 2007, expected trigger rate has been confirmed.

Trigger and DAQ (2)

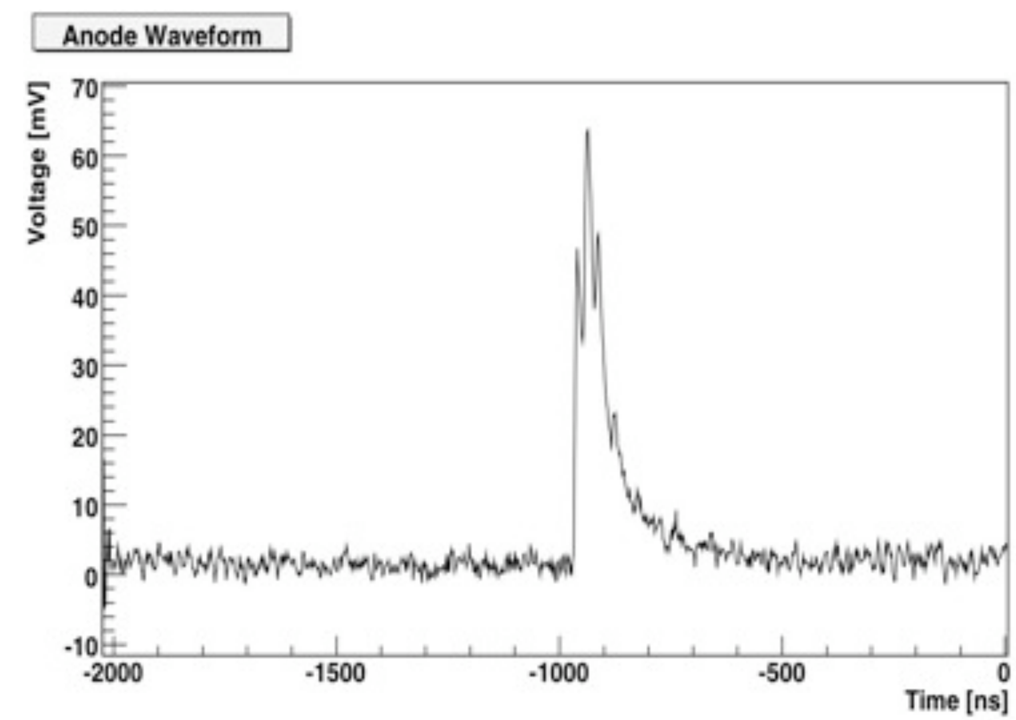
- Waveform Digitizer

DRS

(Domino Ring Sampler)



- ALL OUTPUTS are Recorded in Sampler
- 1024 capacitive sampling cells
- 1024 cells SCA
- 0.5 - 4 GHz sampling is available
- 1.8GHz for Xenon/TC and 500MHz for DC



Positron Spectrometer

Requirements

- **Very high counting rate**
- the most intense DC muon beam in the world
- muon stopping rate : 3×10^7 muon/sec

- **Good momentum/position/timing resolution**
- aiming excellent sensitivity
- 0.4-1% momentum resolution, 500μm position resolution for both direction(r,z) and 40 ps timing resolution

- **Low-mass material**
- 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
- γ background generation should be suppressed as much as possible

Requirements

- **Very high counting rate**
- the most intense DC muon beam in the world
- muon stopping rate : 3×10^7 muon/sec

→ Special B-field

- **Good momentum/position/timing resolution**
- aiming excellent sensitivity
- 0.4-1% momentum resolution, 500μm position resolution for both direction(r,z) and 40 ps timing resolution

- **Low-mass material**
- 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
- γ background generation should be suppressed as much as possible

Requirements

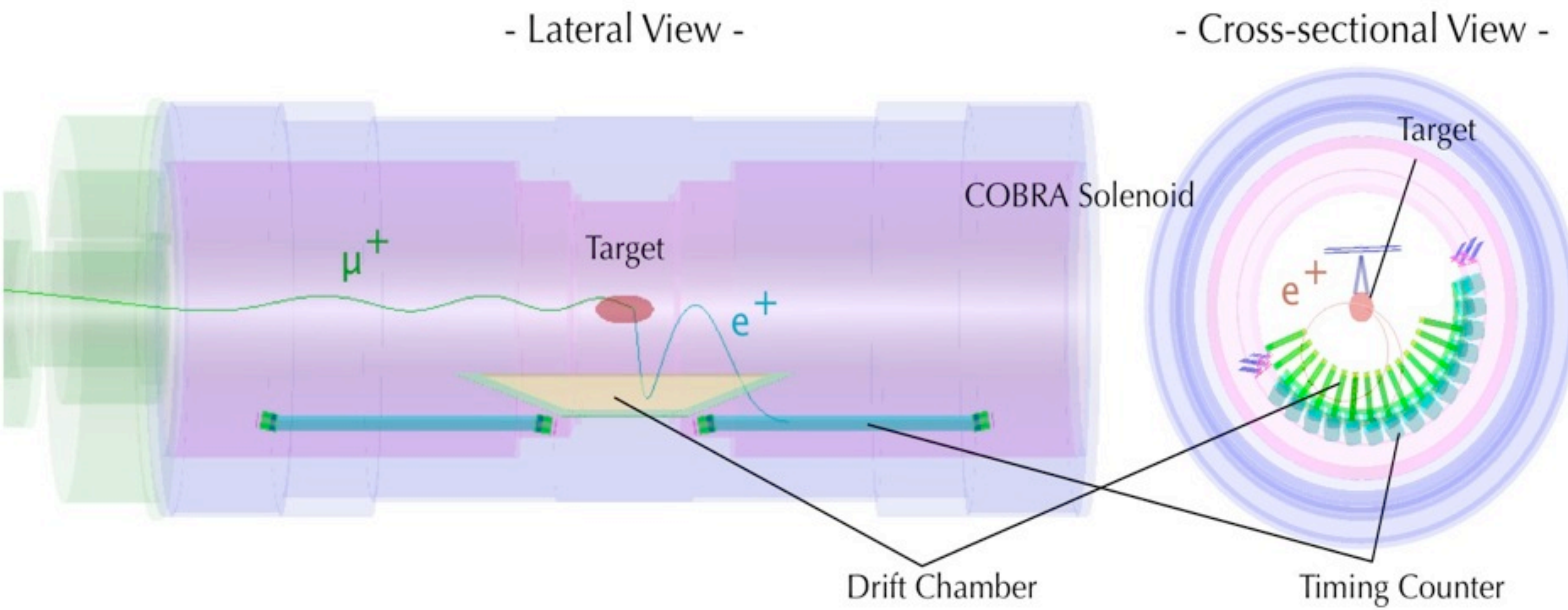
- **Very high counting rate**
- the most intense DC muon beam in the world
- muon stopping rate : 3×10^7 muon/sec

→ Special B-field

- **Good momentum/position/timing resolution**
- aiming excellent sensitivity
- 0.4-1% momentum resolution, 500μm position resolution for both direction(r,z) and 40 ps timing resolution
- **Low-mass material**
- 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
- γ background generation should be suppressed as much as possible

→ new sensitive & light DC

COBRA Spectrometer



Solenoid

superconducting solenoid
gradient B-field (0.5-1.7 T)
very thin conductor and cryostat wall ($0.2X_0$)

Drift Chamber

segmented radially (16 sectors)
helium:ethane (50:50)
opened-frame
very thin cathode foil with pads

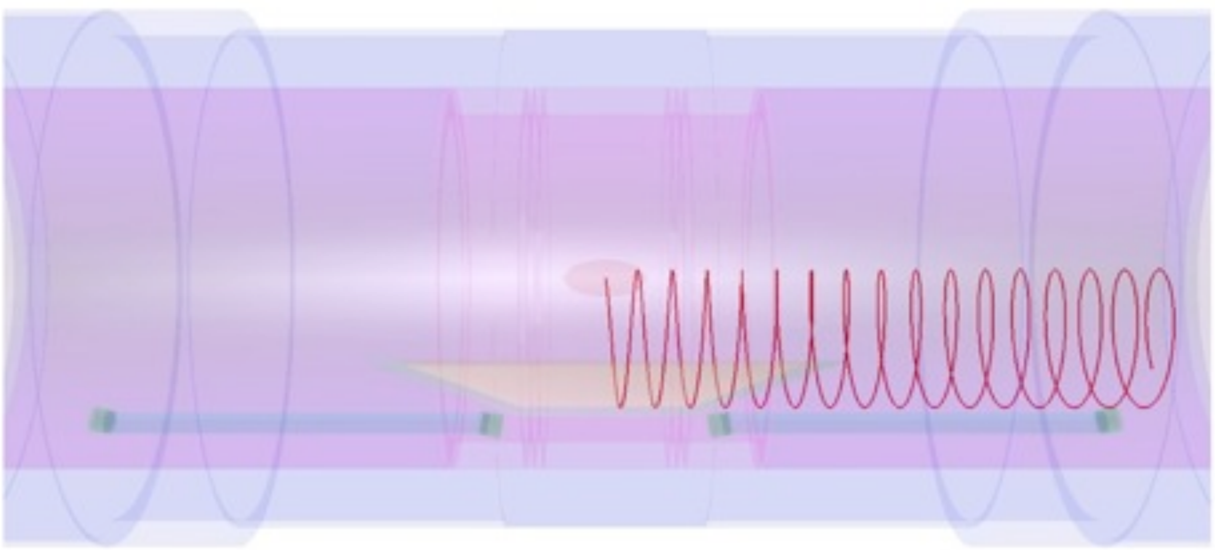
Timing Counter

2-layers of scintillators
- scintillator bars (outer)
- scintillator fibres (inner)

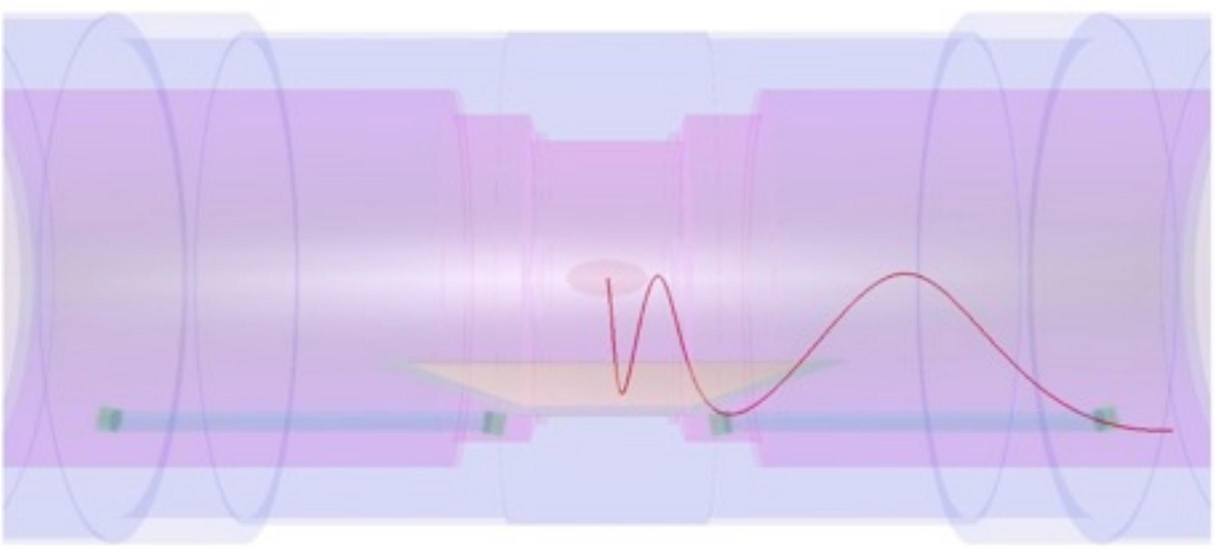
COBRA Concept (1)

COBRA Concept (1)

Uniform Field

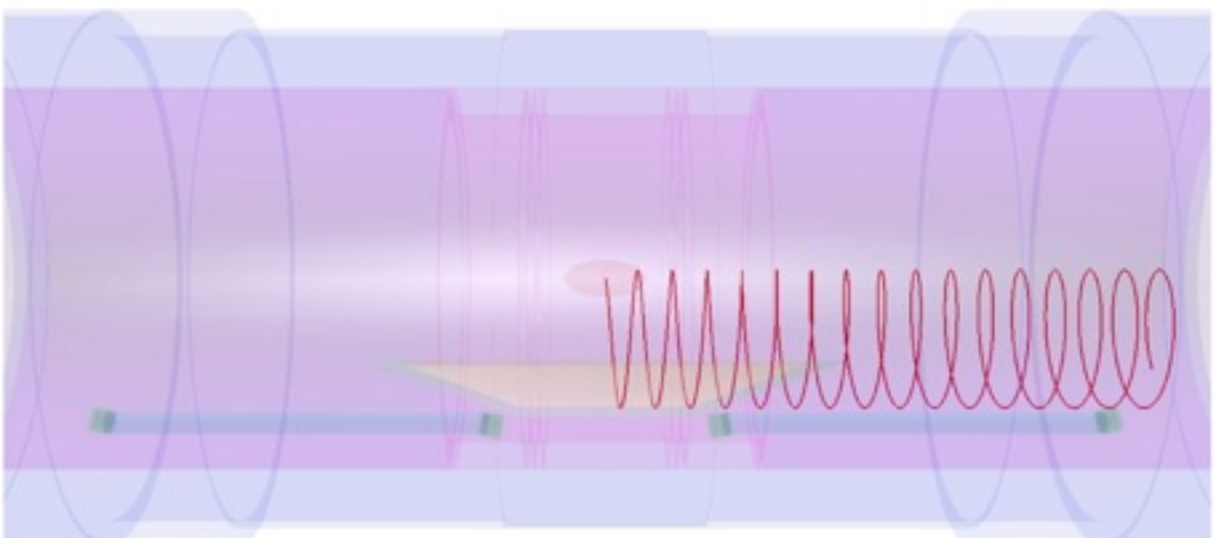


COBRA Field

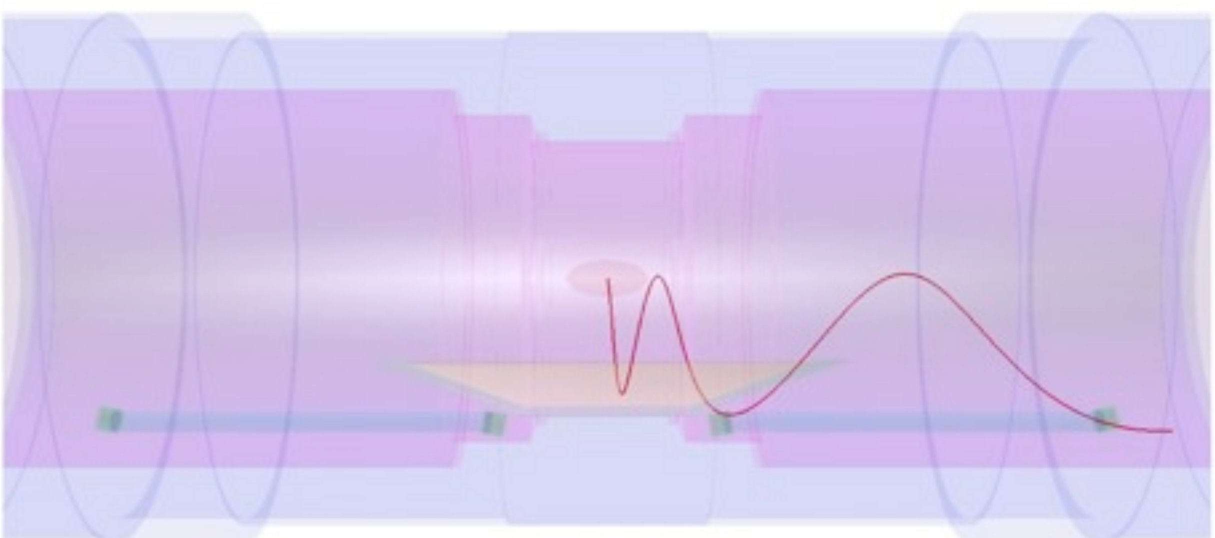


COBRA Concept (1)

Uniform Field



COBRA Field

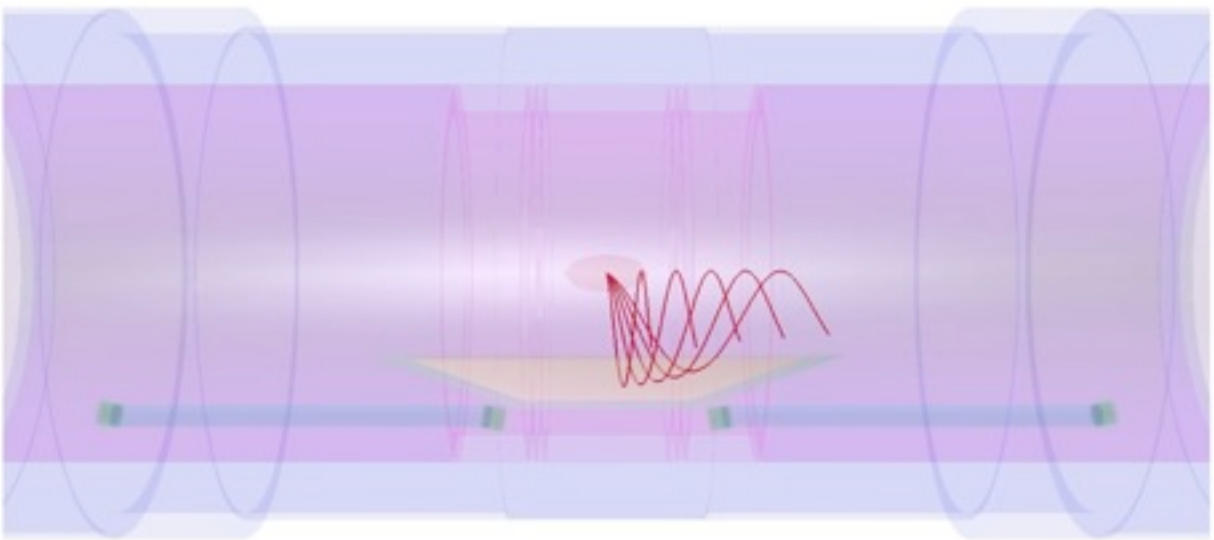


- Michel e^+ can be swept away very quickly
- Wire-chamber based tracker is operational

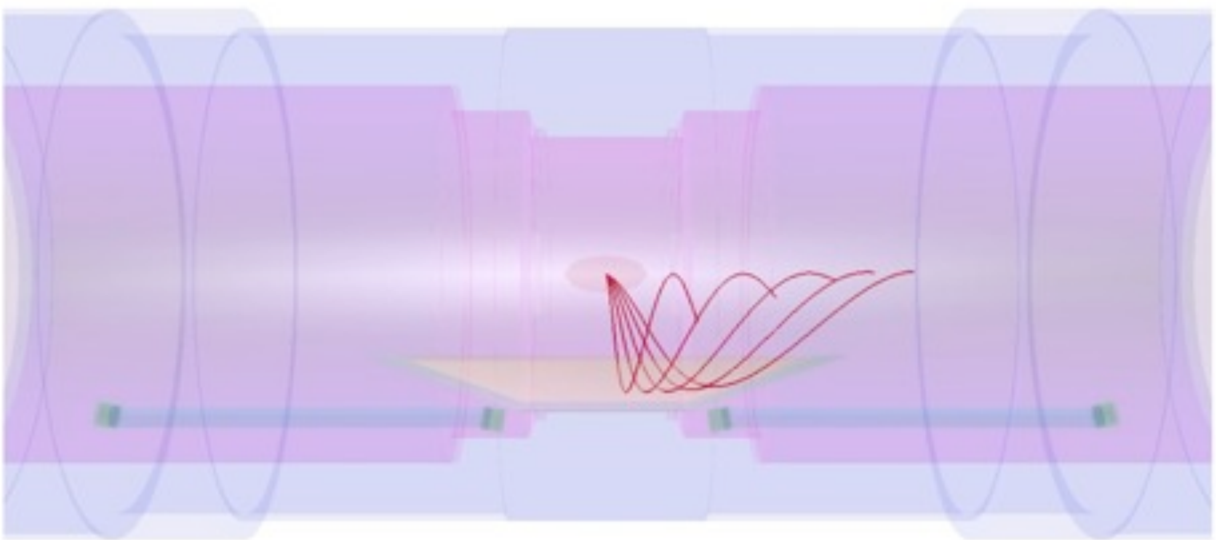
COBRA Concept (2)

COBRA Concept (2)

Uniform Field

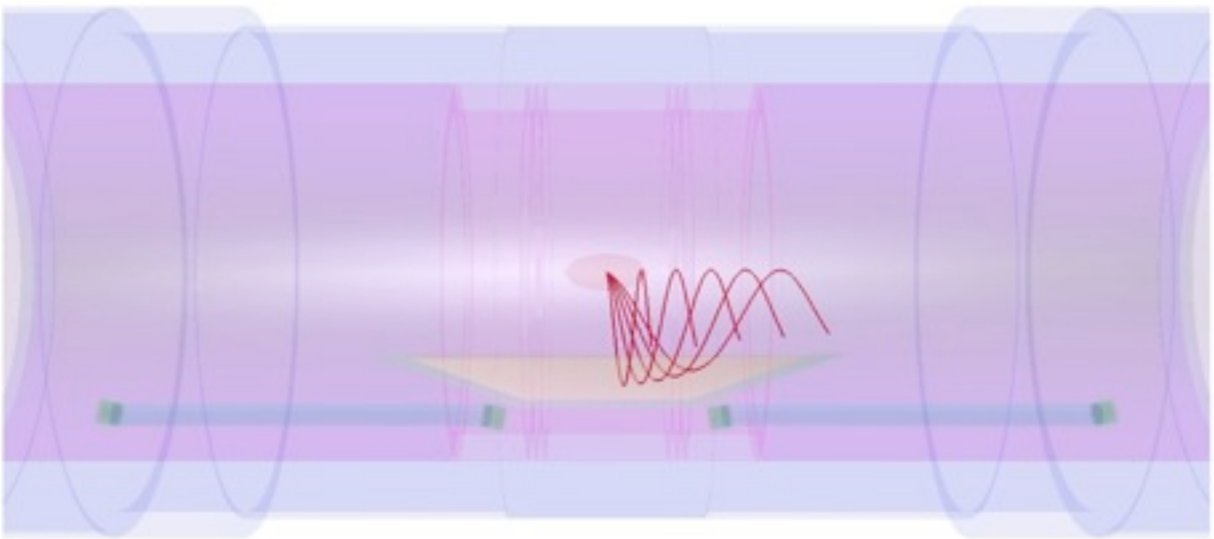


COBRA Field

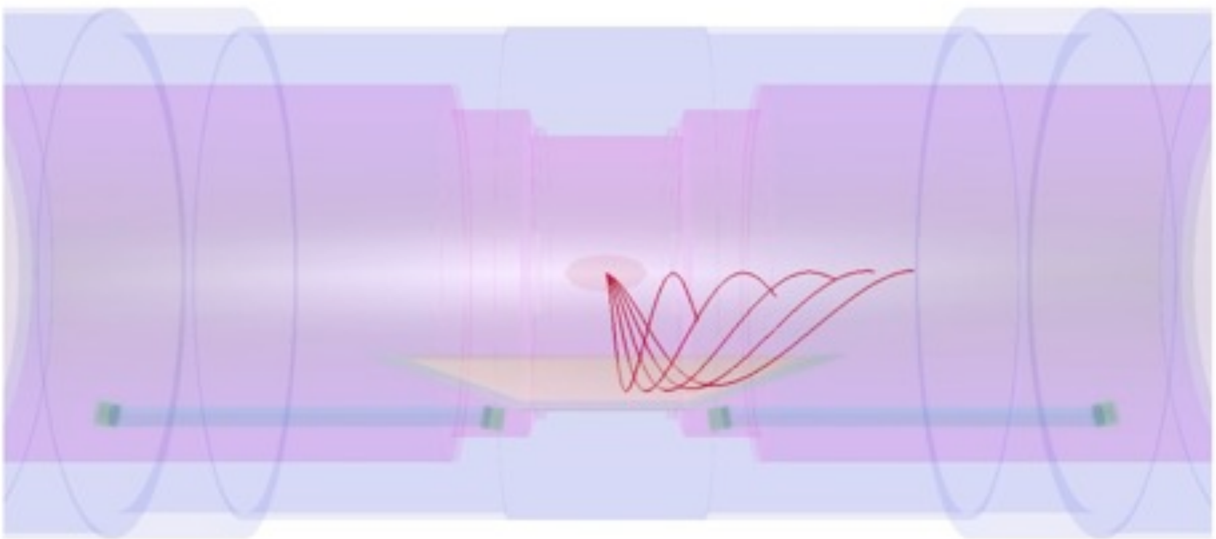


COBRA Concept (2)

Uniform Field

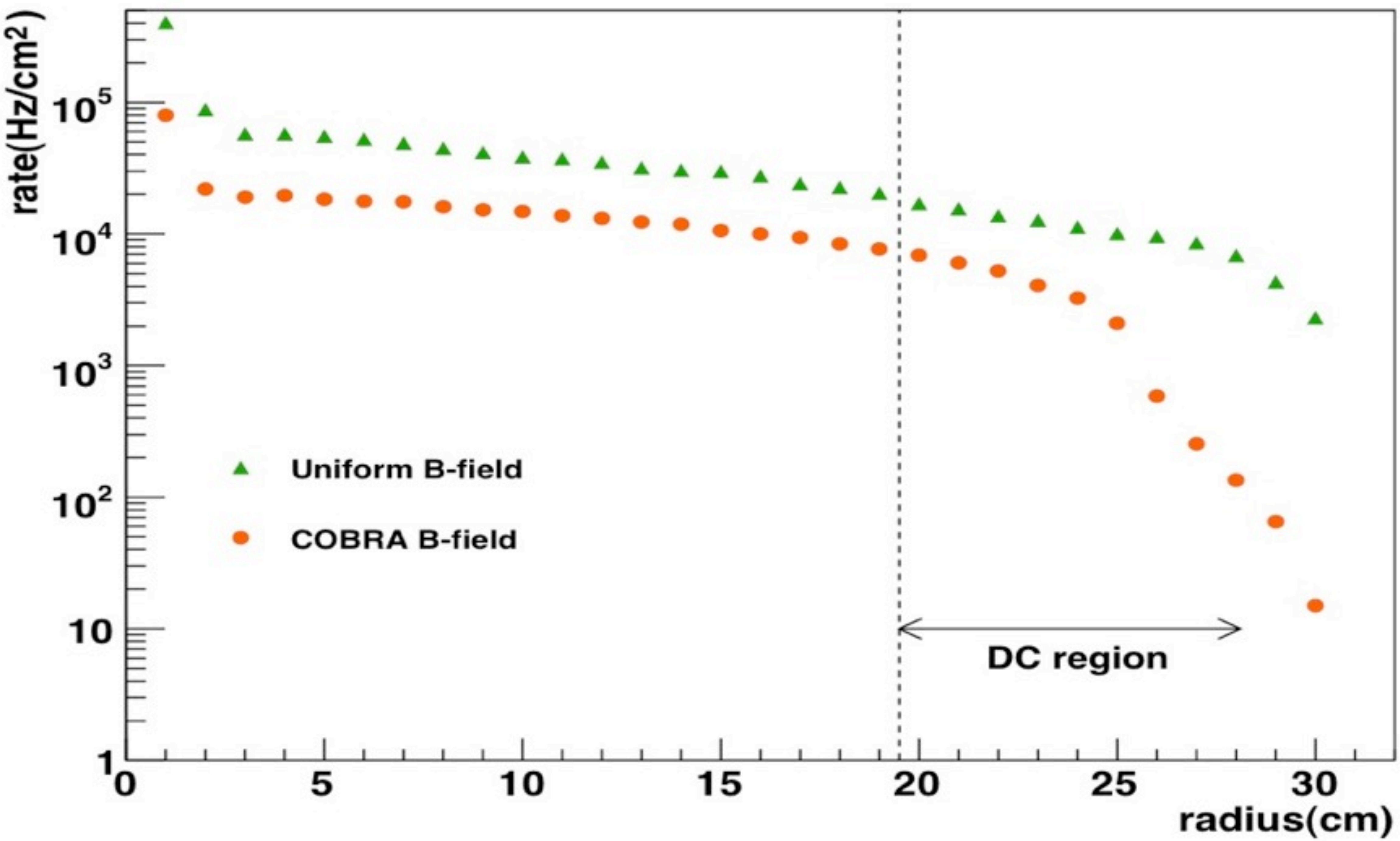


COBRA Field

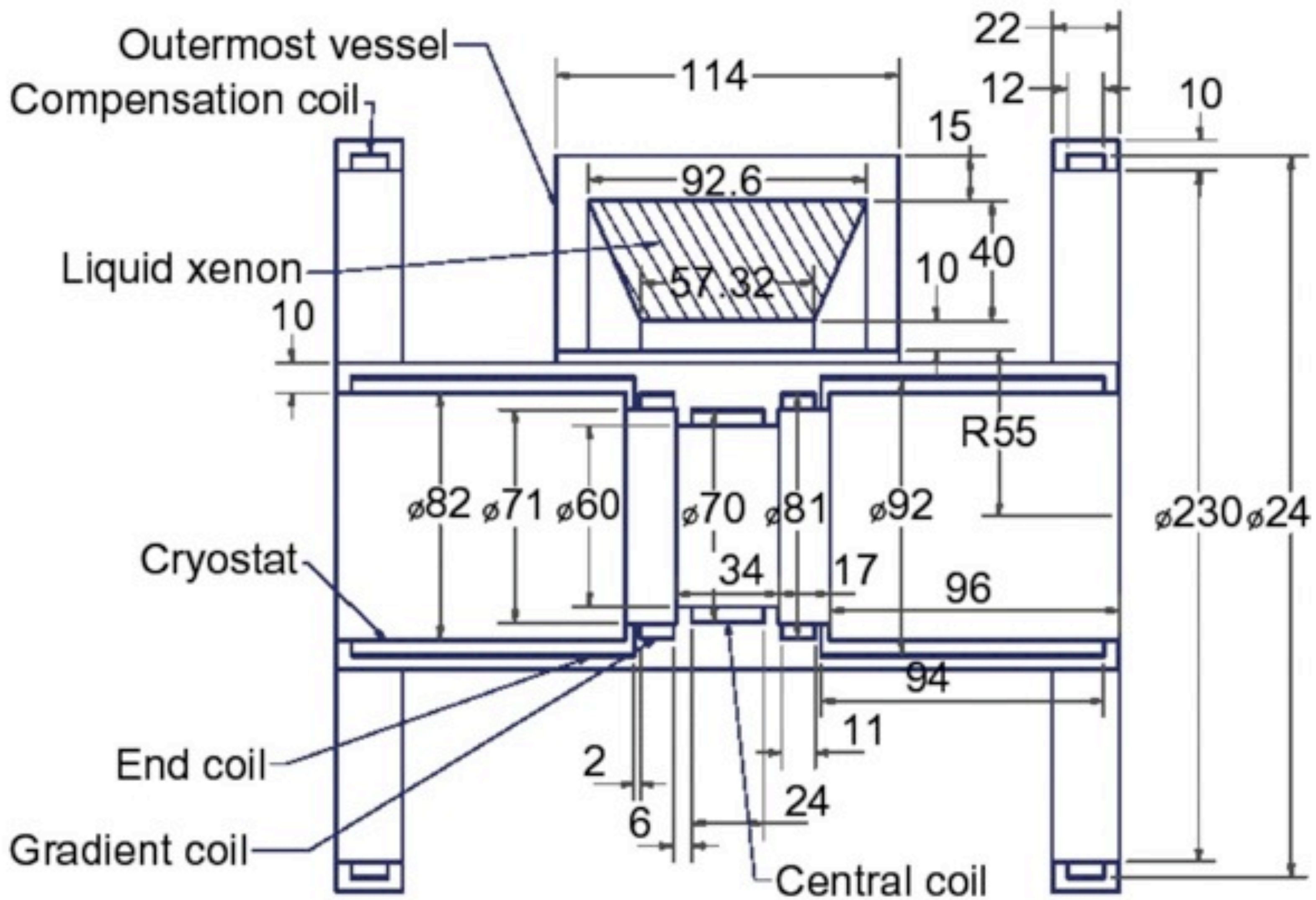


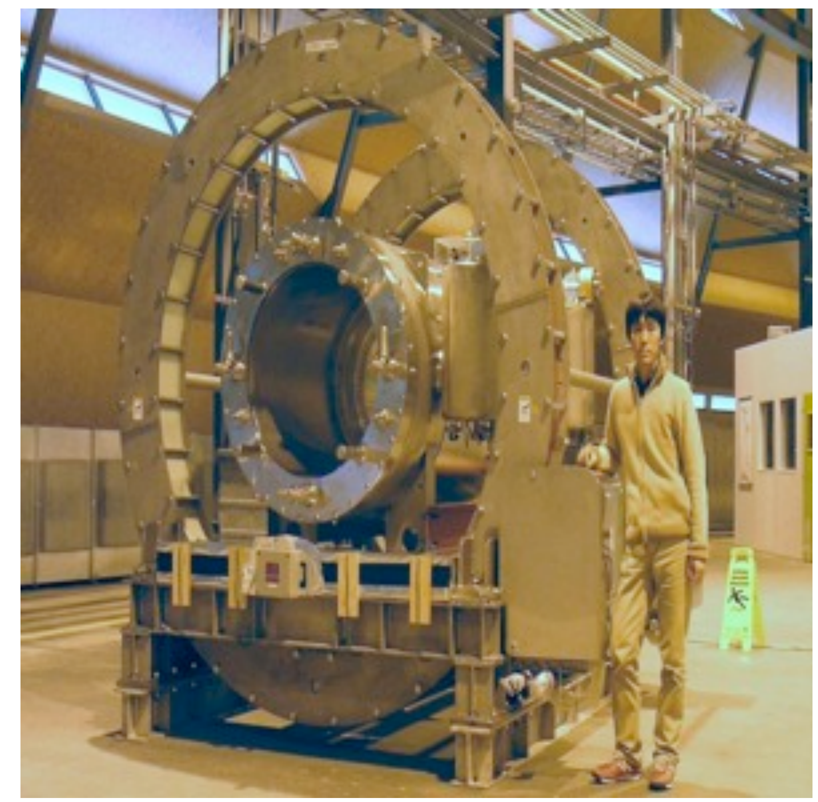
- COnstant Bending RAdius is Possible
- DC is placed at larger-radii region only
- DC is sensitive to high-p region only, blind to most of Michel e^+

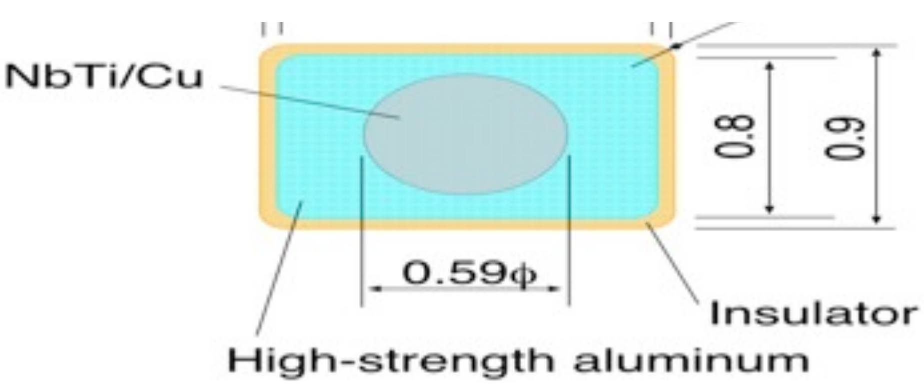
COBRA Concept (3)

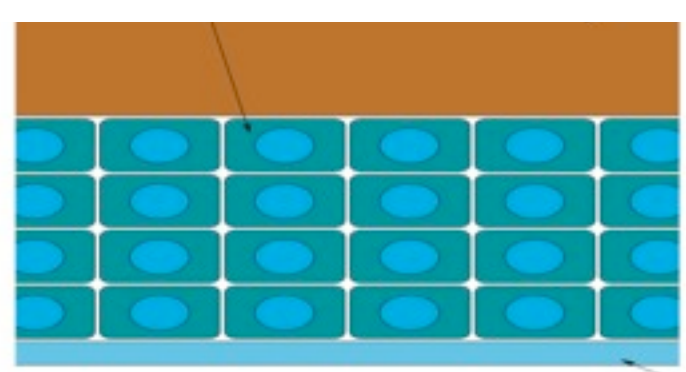


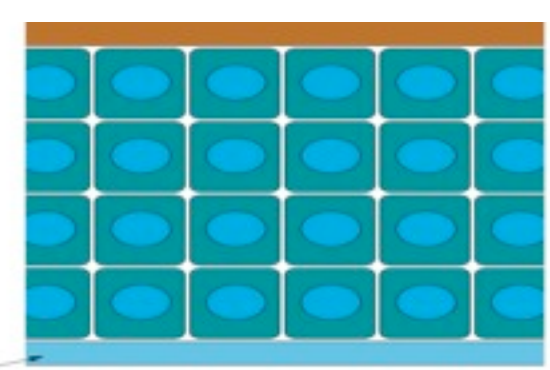
COBRA Magnet



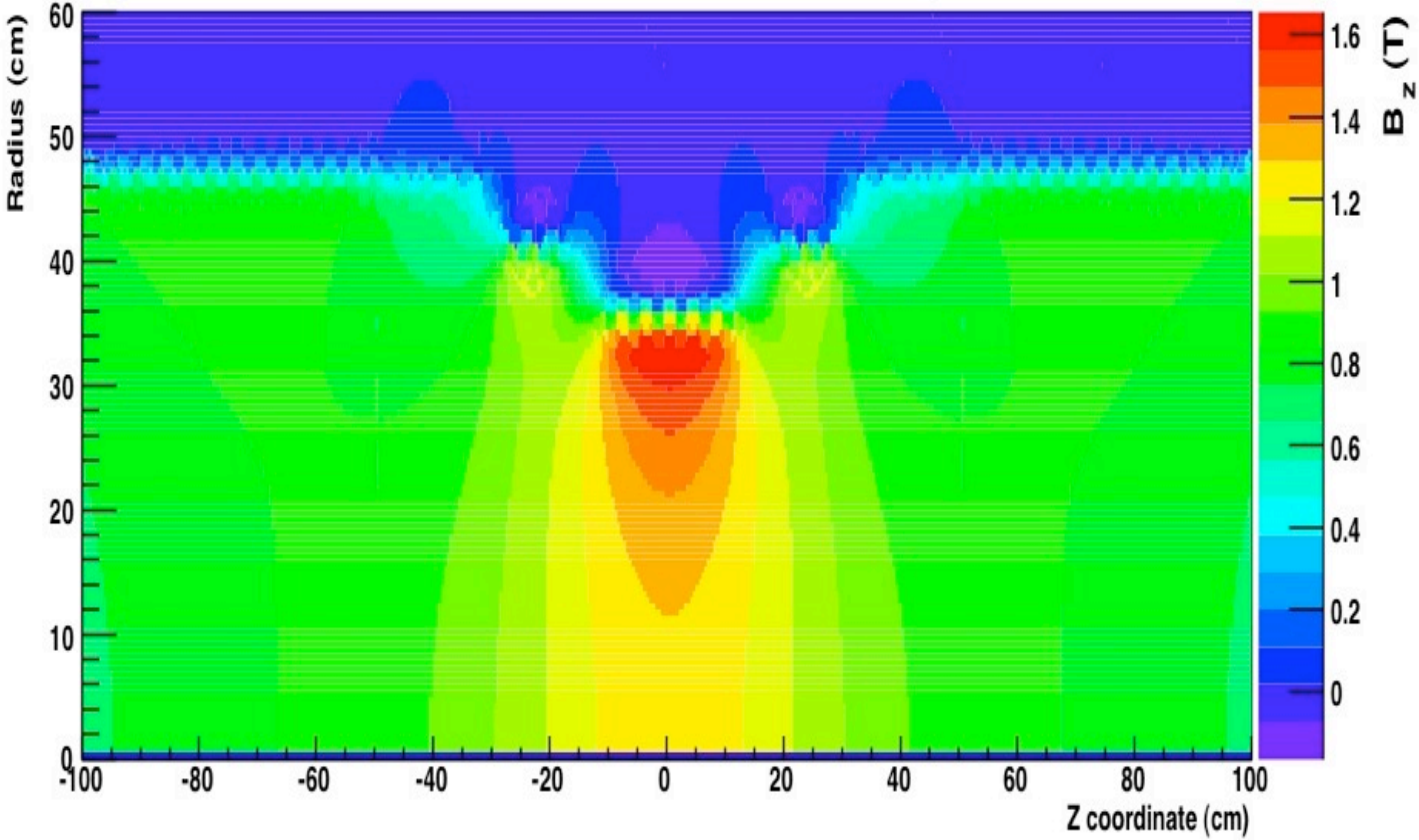




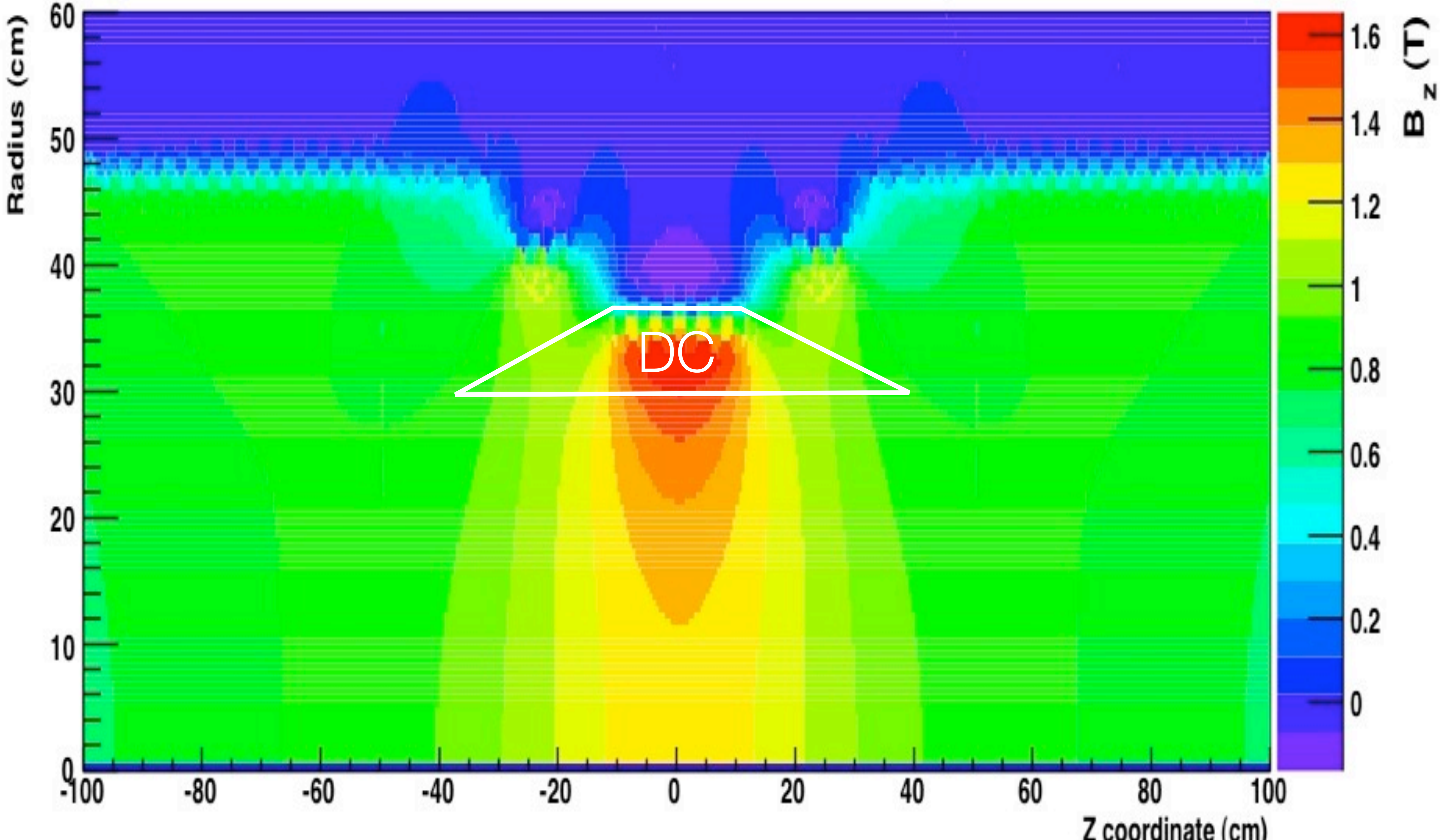




COBRA Field

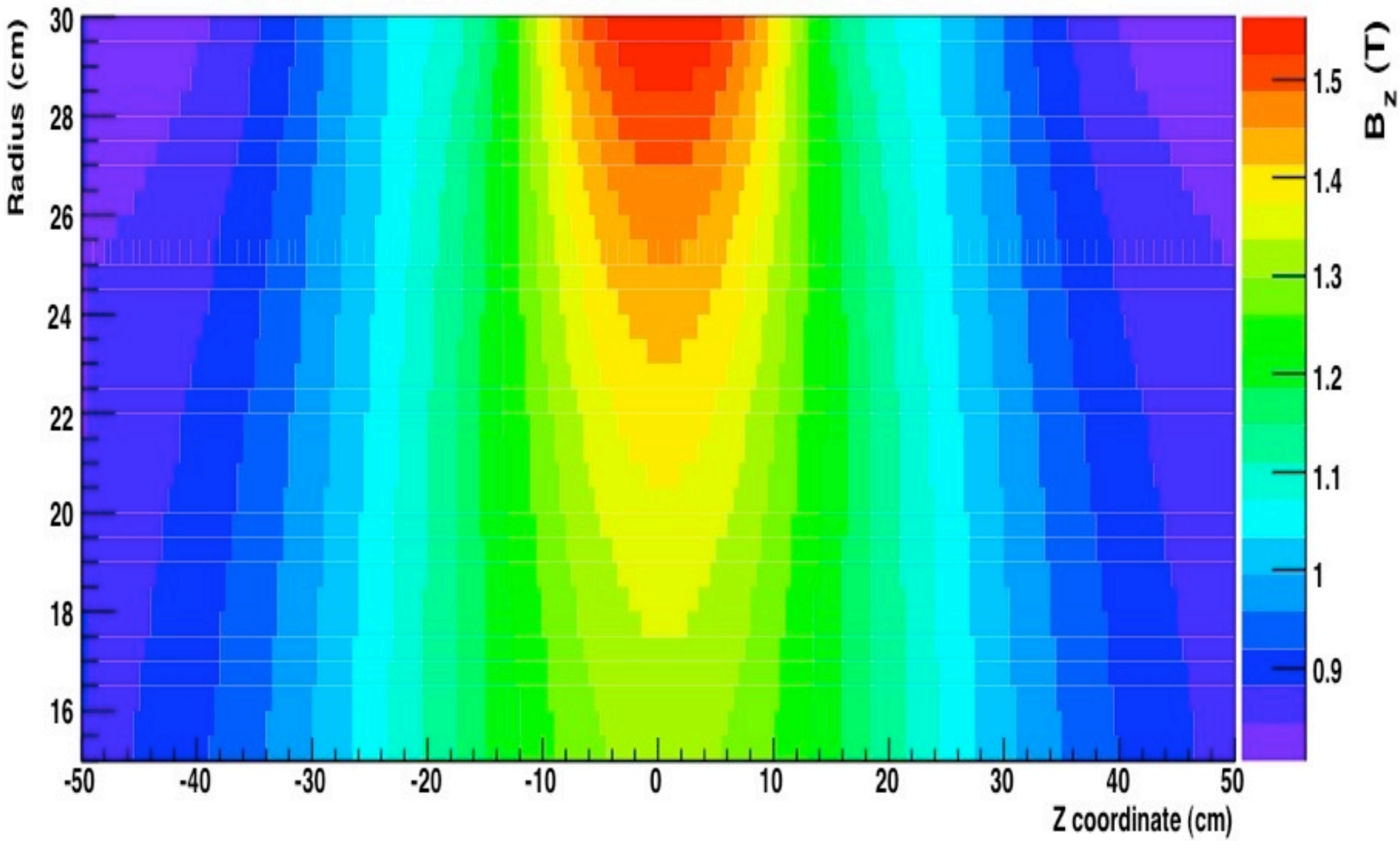

Radius (cm)
60
50
40
30
20
10
0
-100
-80
-60
-40
-20
0
20
40
60
80
100
Z coordinate (cm)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
B_z (T)

COBRA Field



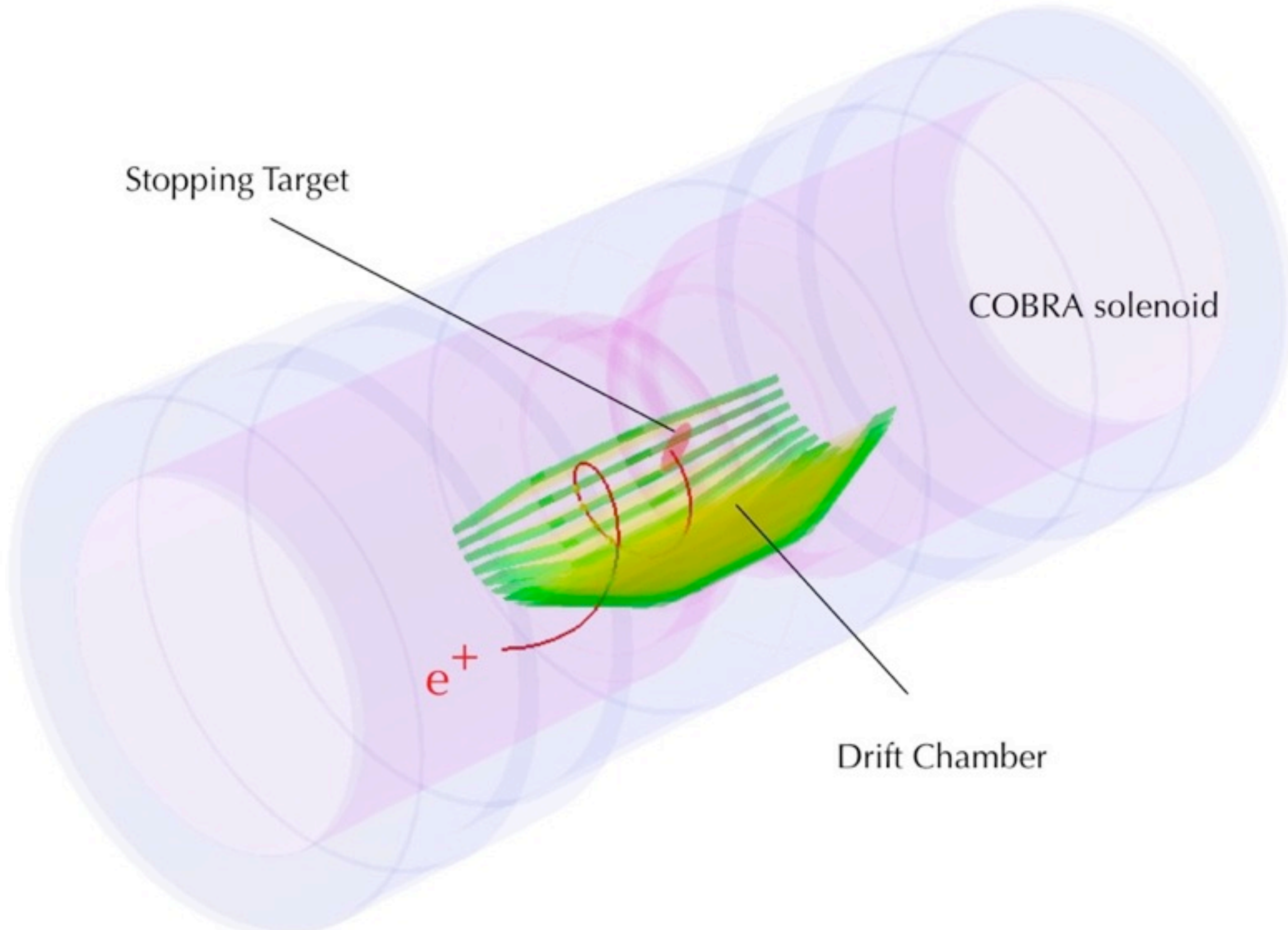
Radius (cm)
60
50
40
30
20
10
0
-100
-80
-60
-40
-20
0
20
40
60
80
100
Z coordinate (cm)
DC
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
B_z (T)

COBRA Field

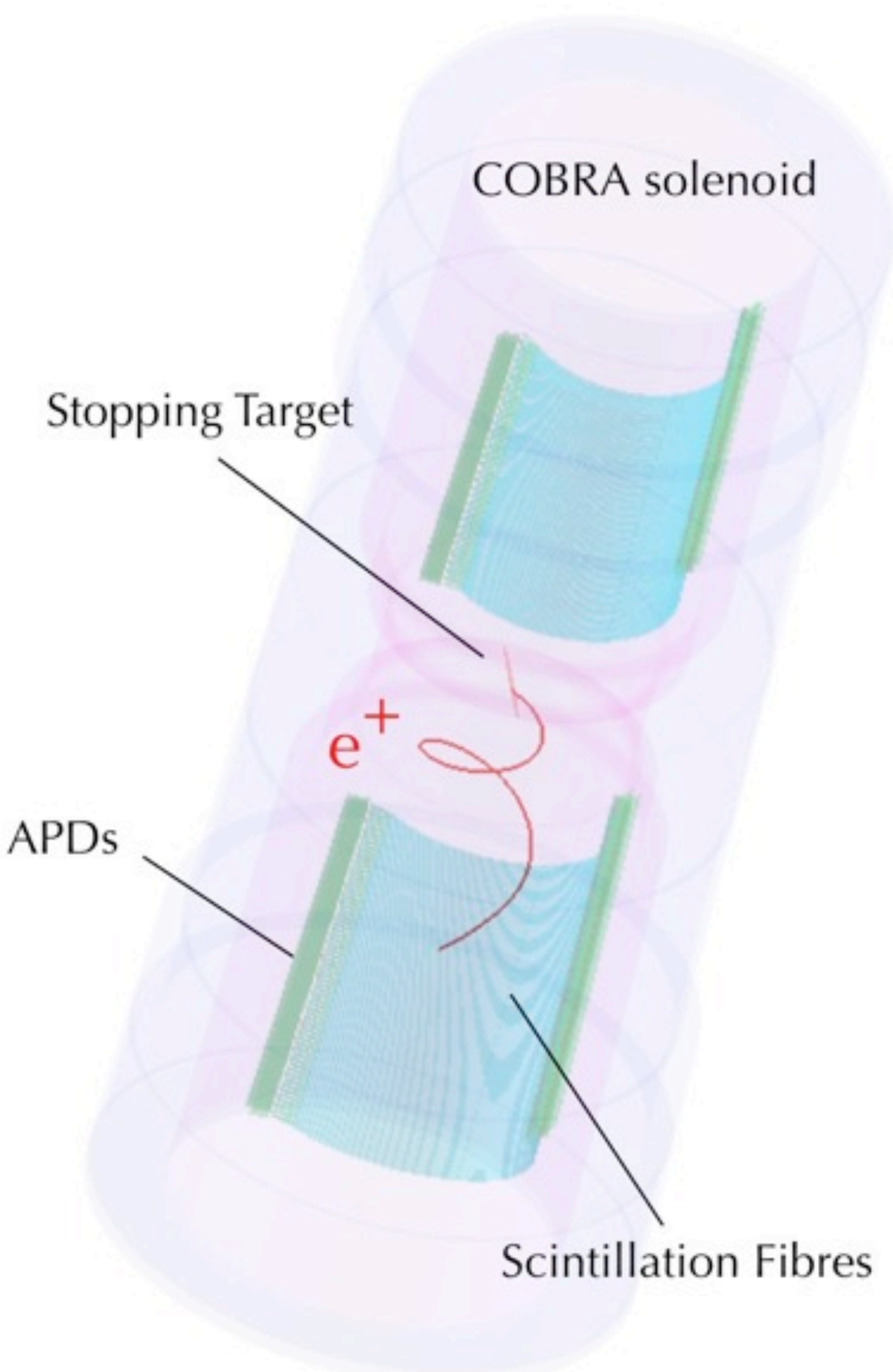


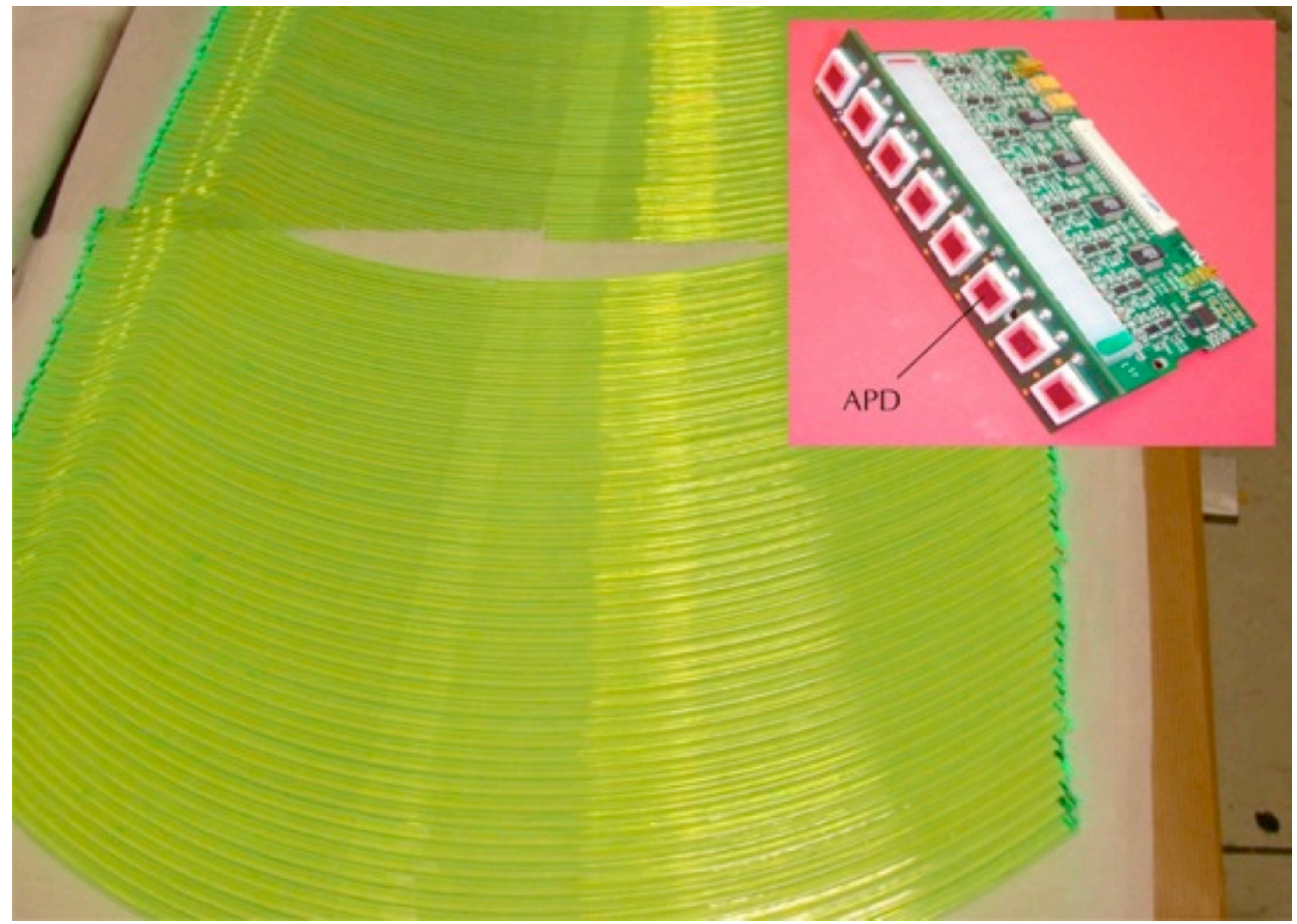
Radius (cm)
30
28
26
24
22
20
18
16
-50
-40
-30
-20
-10
0
10
20
30
40
50
Z coordinate (cm)
1.5
1.4
1.3
1.2
1.1
1
0.9
B_z (T)

Positron Detection (DC)



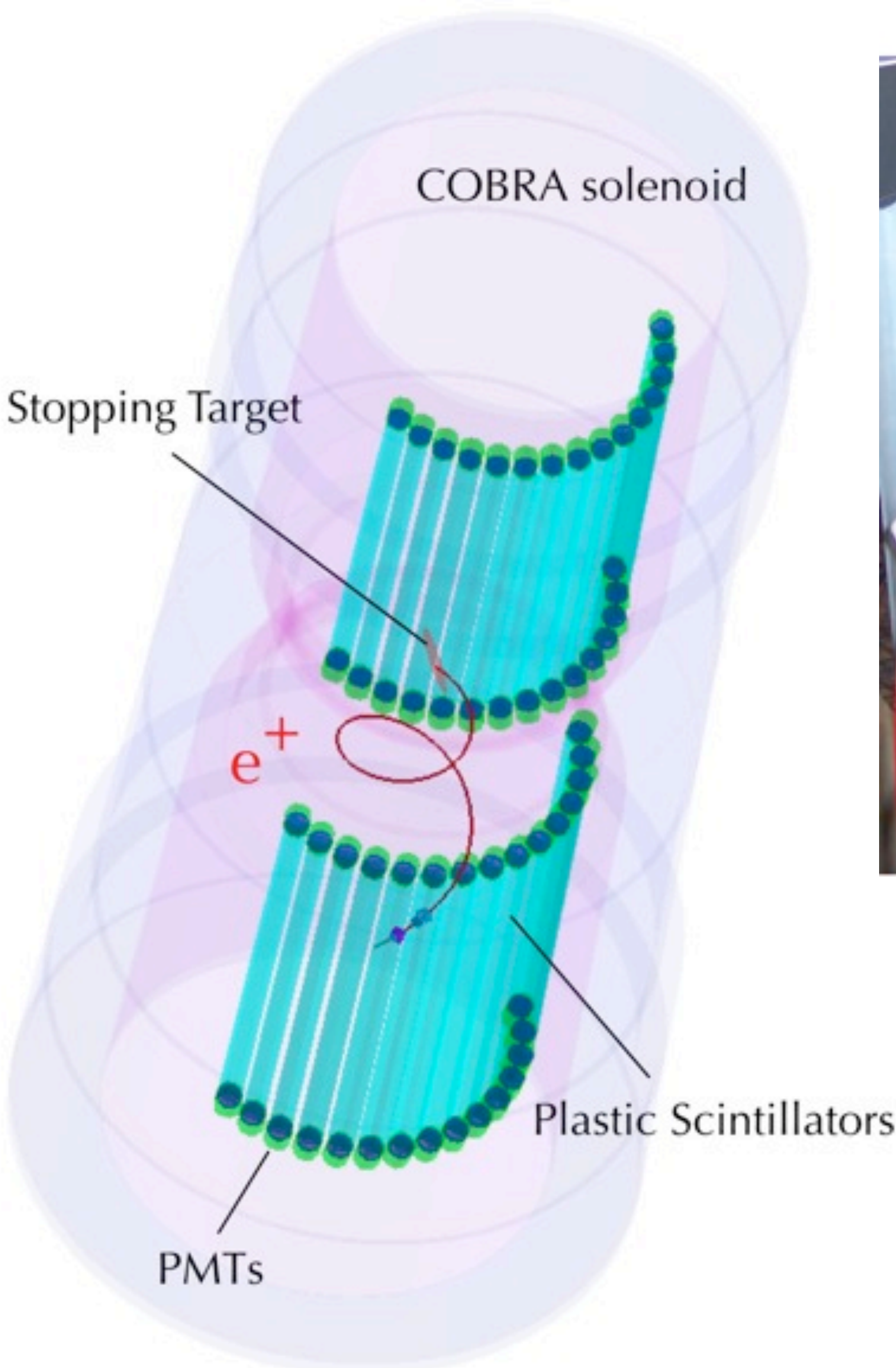
Positron Detection (TC, Inner)

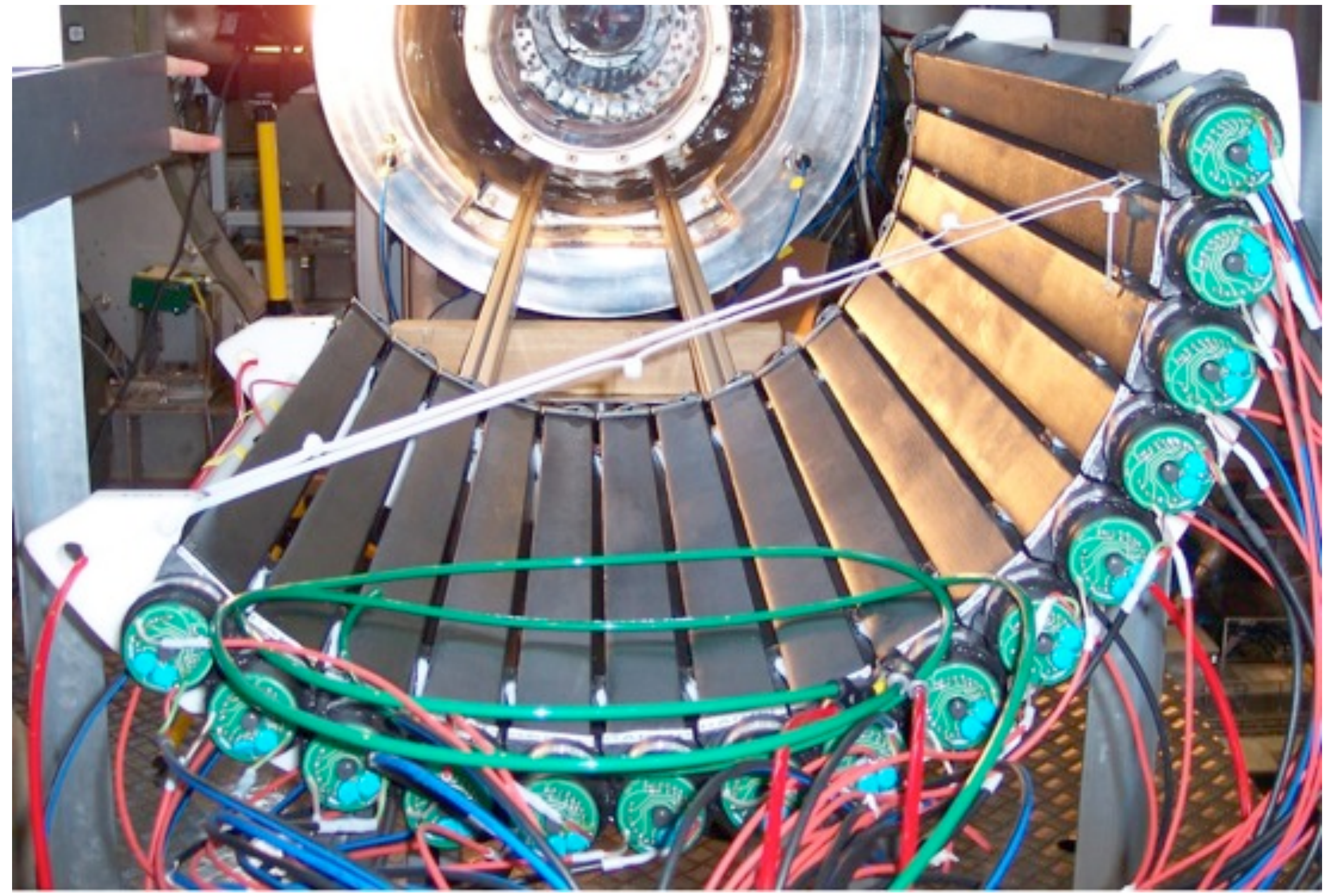




- 256 Plastic Scintillation Fibres (6x6mm^2, BCF-20)
- Both-end APDs (S8664-55), called z-counter
- Used for z-trigger

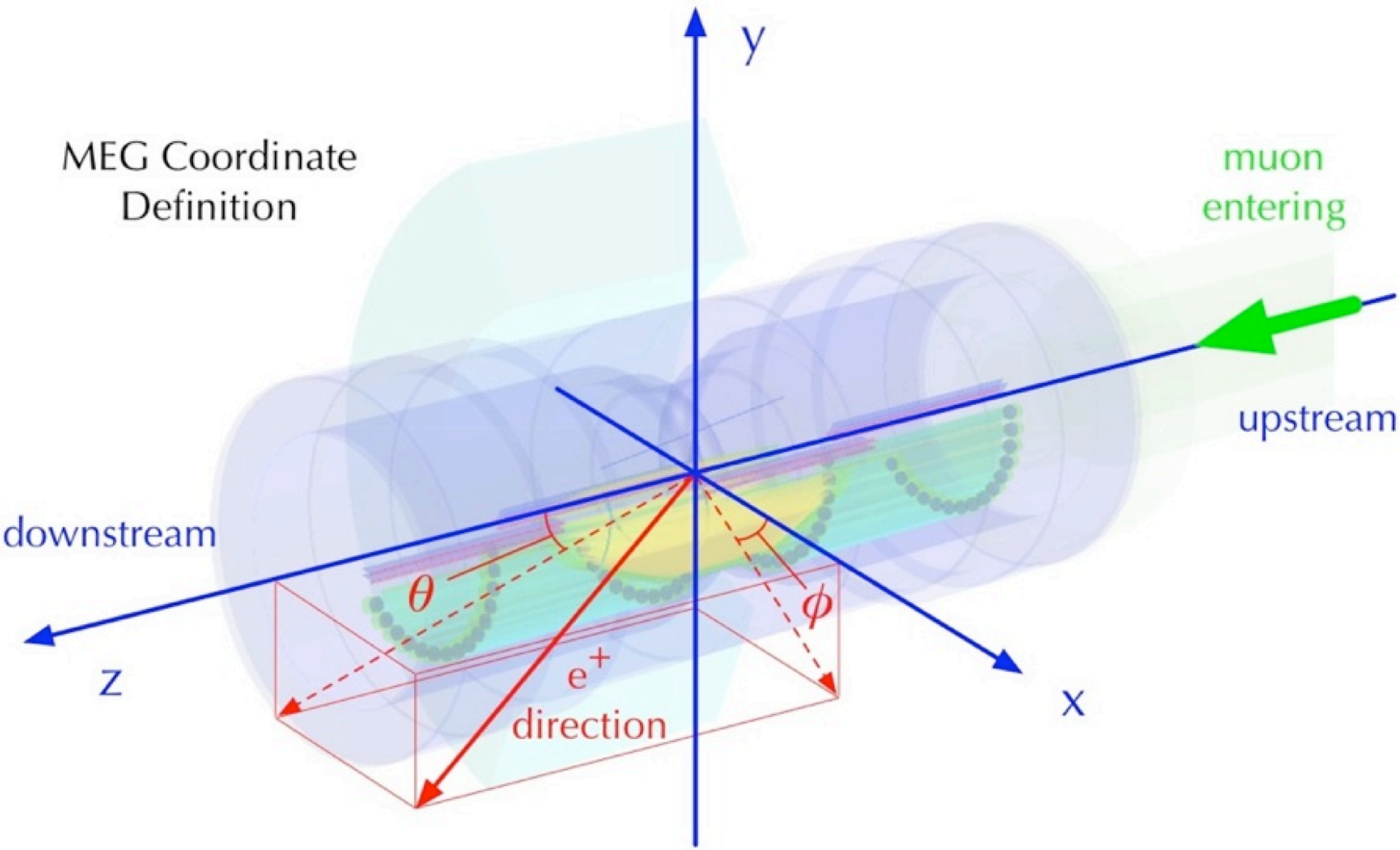
Positron Detection (TC, Outer)





- 30 Plastic Scintillator Bars (4x4x90cm^3, BC404)
- Both-end PMTs (R5924), called phi-counter
- Used for Trigger and Timing Measurement

Global Coordinate System



Drift Chamber

Requirements

- **Very high counting rate**
  - muon stopping rate : 3x10^7 muon/sec

- **Good Spacial Resolution without Increasing Mass**
  - 500μm position resolution for both direction, R and Z
  - 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
  - γ background generation should be suppressed as much as possible

Requirements

- **Very high counting rate**
  - muon stopping rate : 3×10^7 muon/sec

→

- COBRA field
- restricted region
- small cell

- **Good Spacial Resolution without Increasing Mass**
  - 500μm position resolution for both direction, R and Z
  - 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
  - γ background generation should be suppressed as much as possible

Requirements

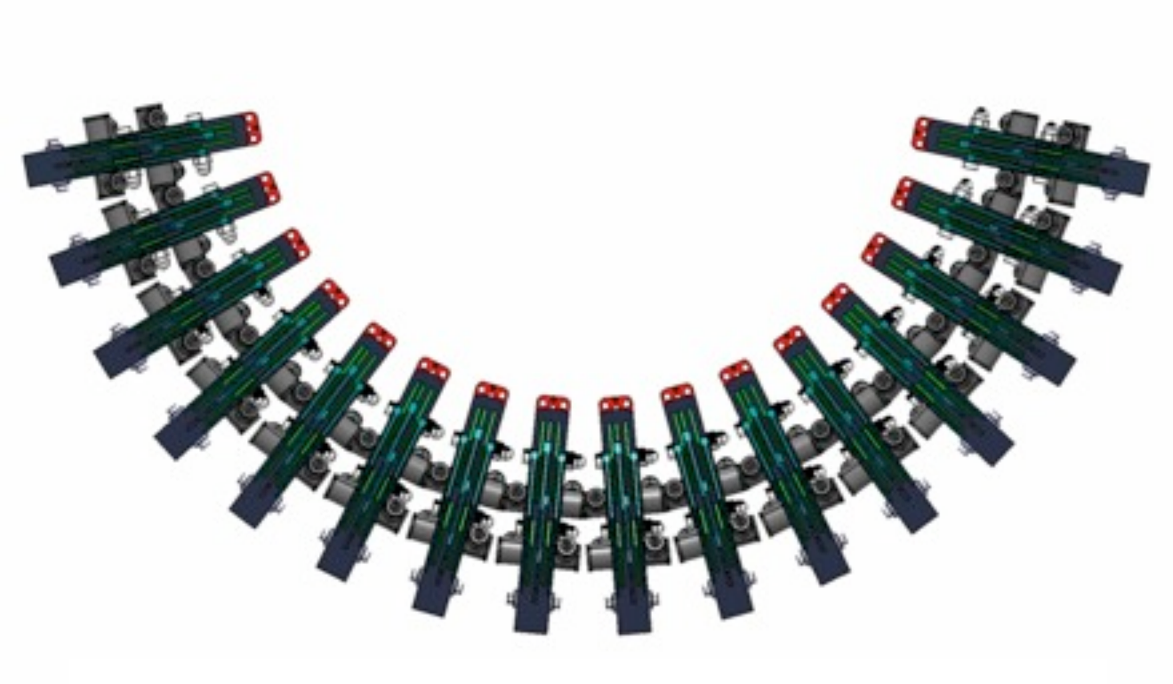
- **Very high counting rate**
    - muon stopping rate : 3×10^{7} muon/sec

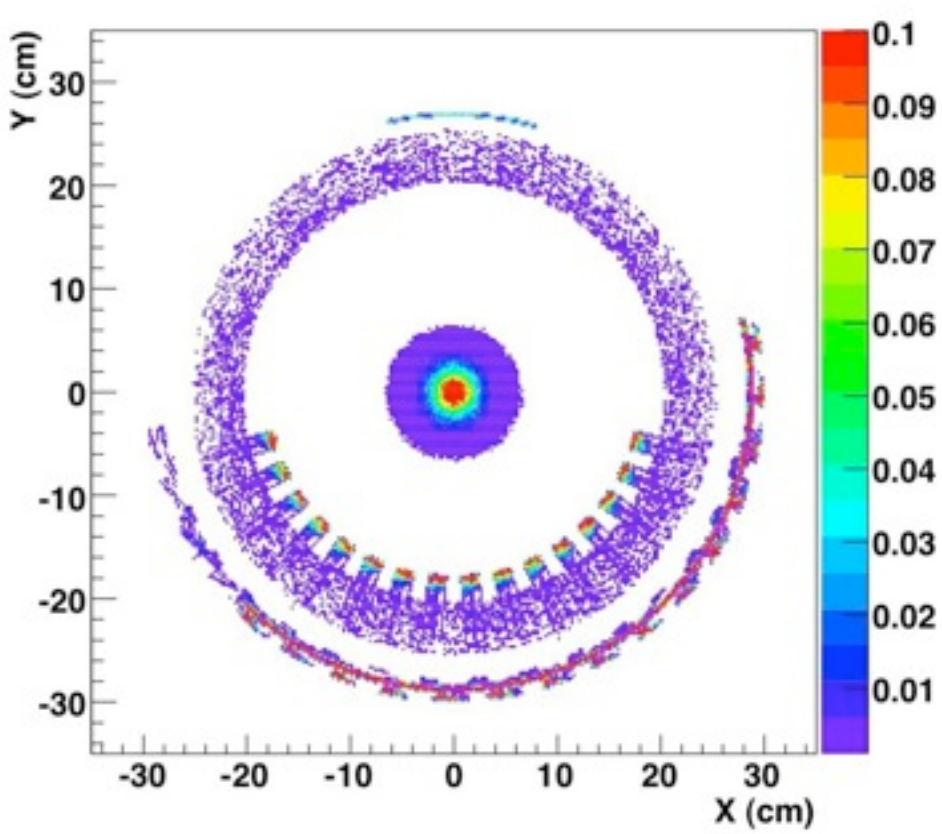
- COBRA field
- restricted region
- small cell

- **Good Spacial Resolution without Increasing Mass**
    - 500μm position resolution for both direction, R and Z
    - 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
    - γ background generation should be suppressed as much as possible

- Ultimate-Low-mass
- Thin-cathode foil with Vernier pads
- Min.- readout channel

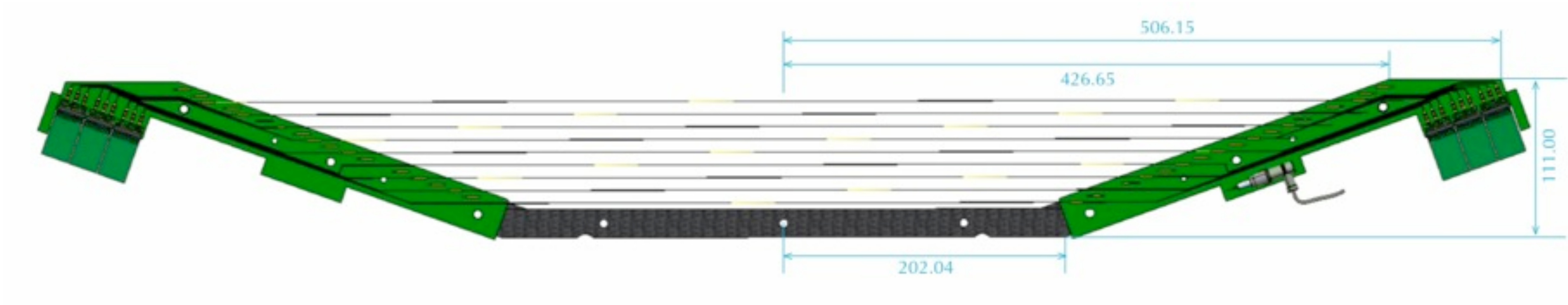
Overview

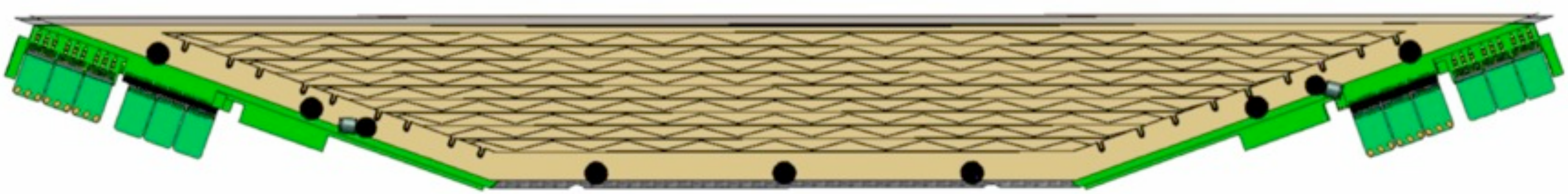


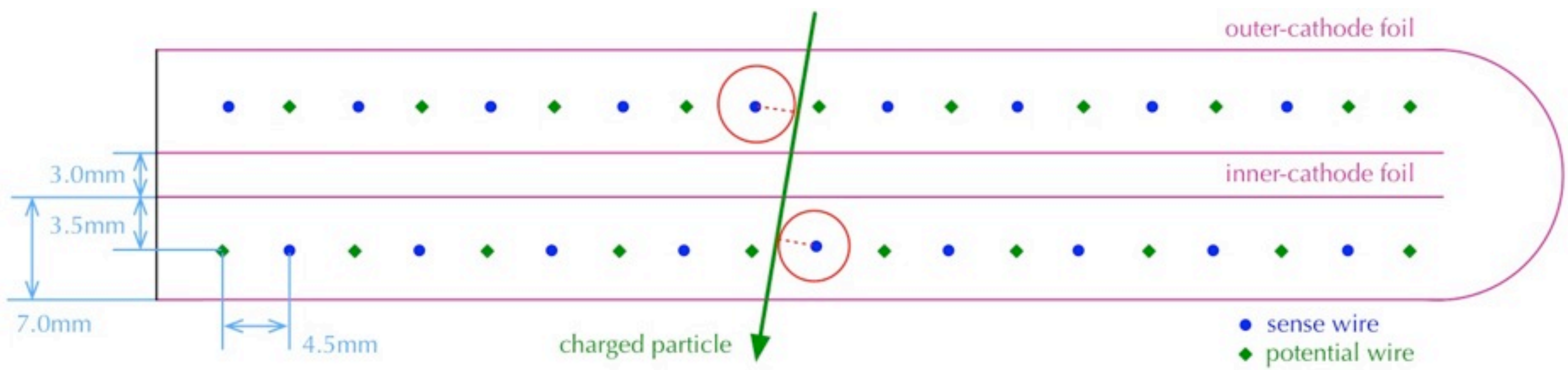


- 16 Segmented Module Structure
- Helium-Ethane gas mixture
- 2 Layers of axial wires
  - staggered sense and potential
  - without stereo wire
- carbon-fibre frame
  - open-structure
  - trapezium shape
- ultra-thin cathode foil
  - vernier-pad mechanism

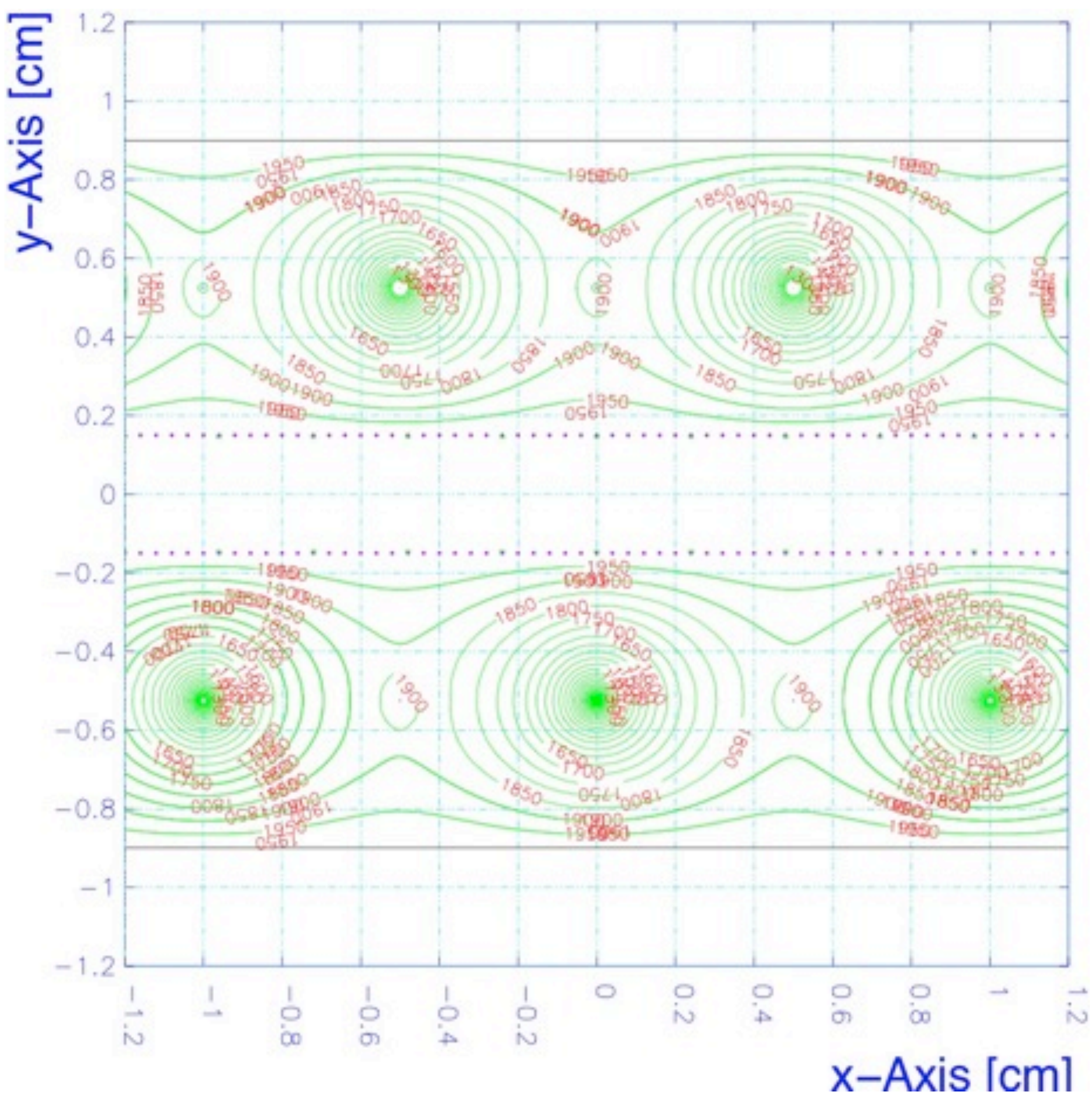
Chamber Design (1)

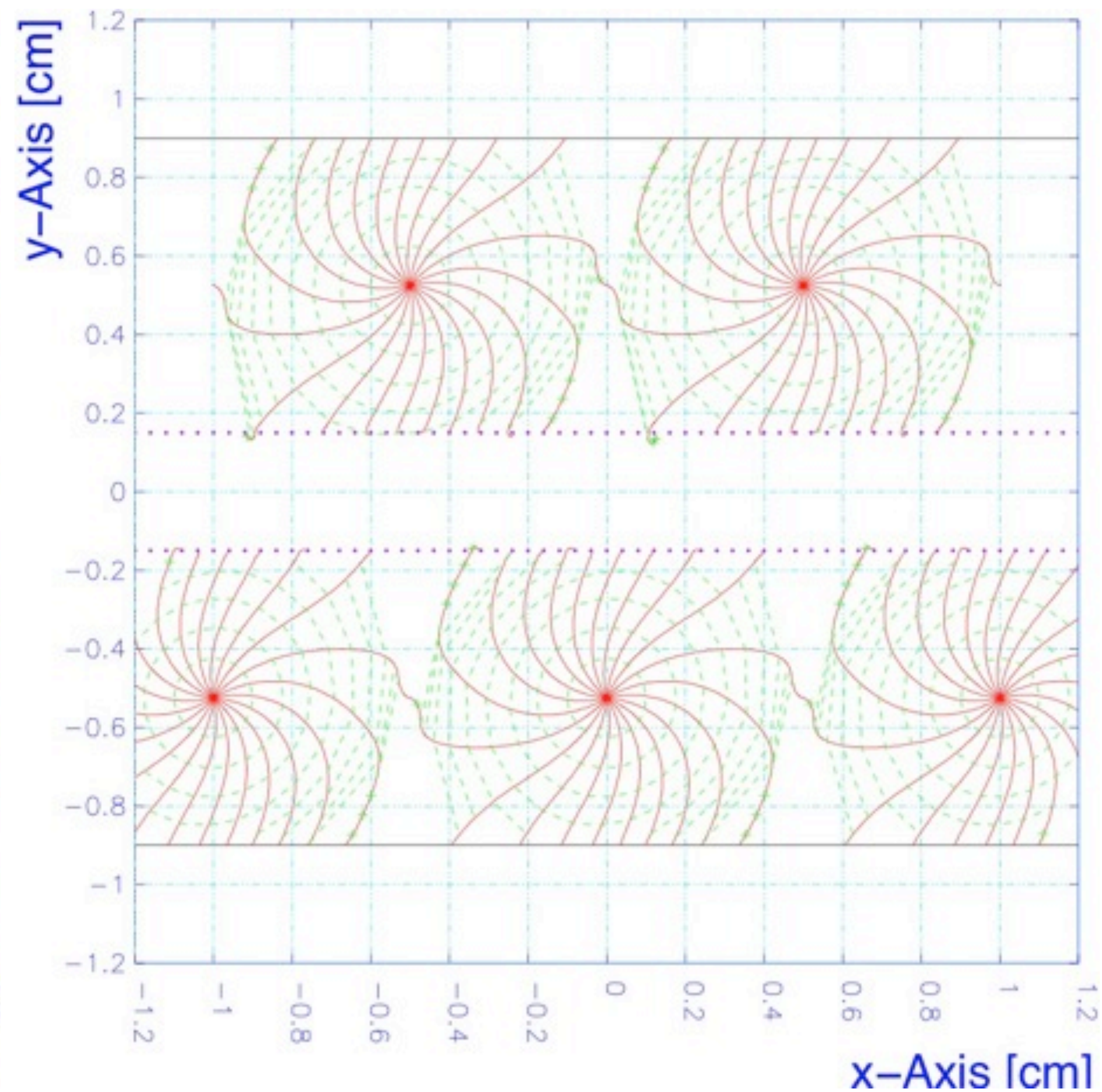




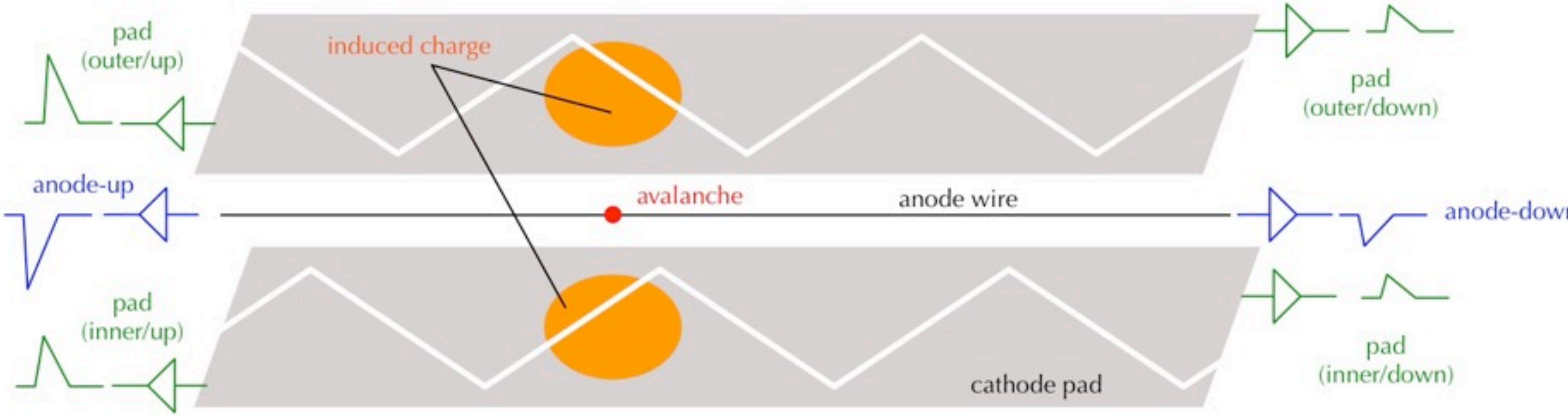


Chamber Design (2)

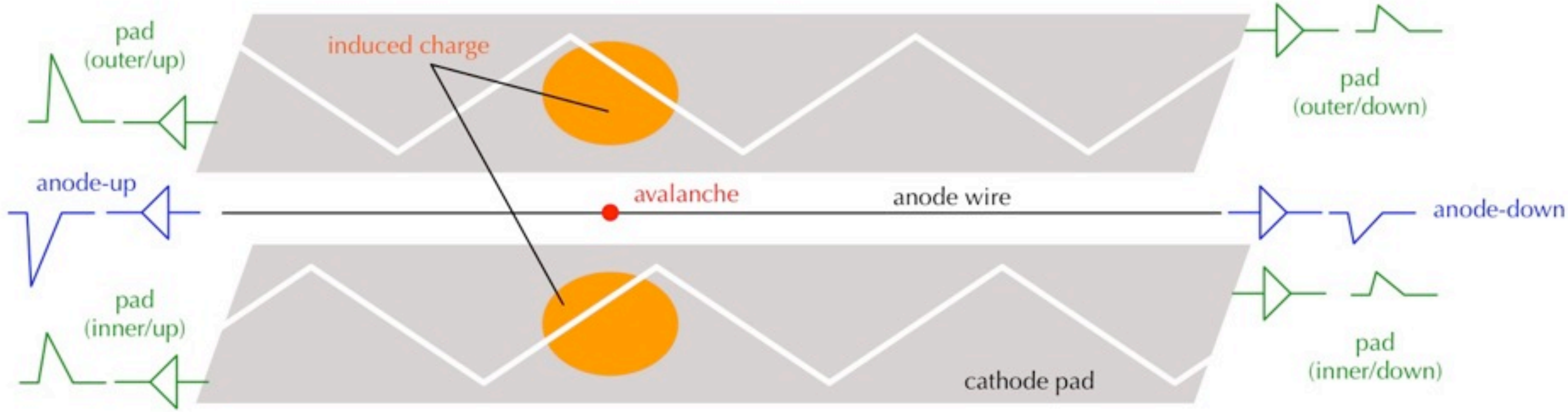




Vernier Pad


pad
(outer/up)
induced charge
pad
(outer/down)
anode-up
avalanche
anode wire
anode-down
pad
(inner/up)
cathode pad
pad
(inner/down)

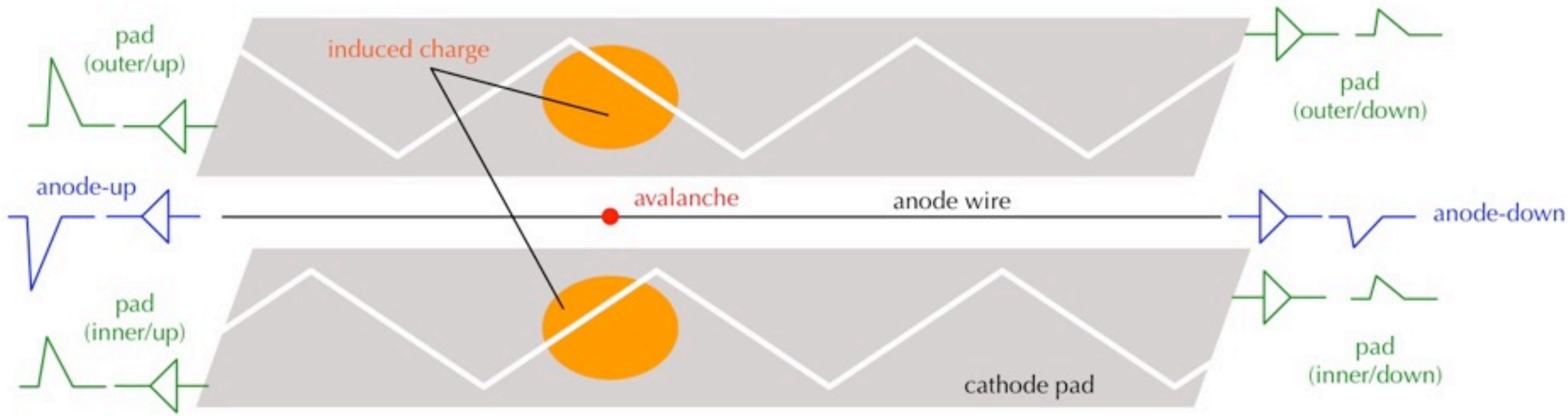
Vernier Pad



$$\varepsilon_1 = \frac{Q_{iu} - Q_{id}}{Q_{iu} + Q_{id}}$$

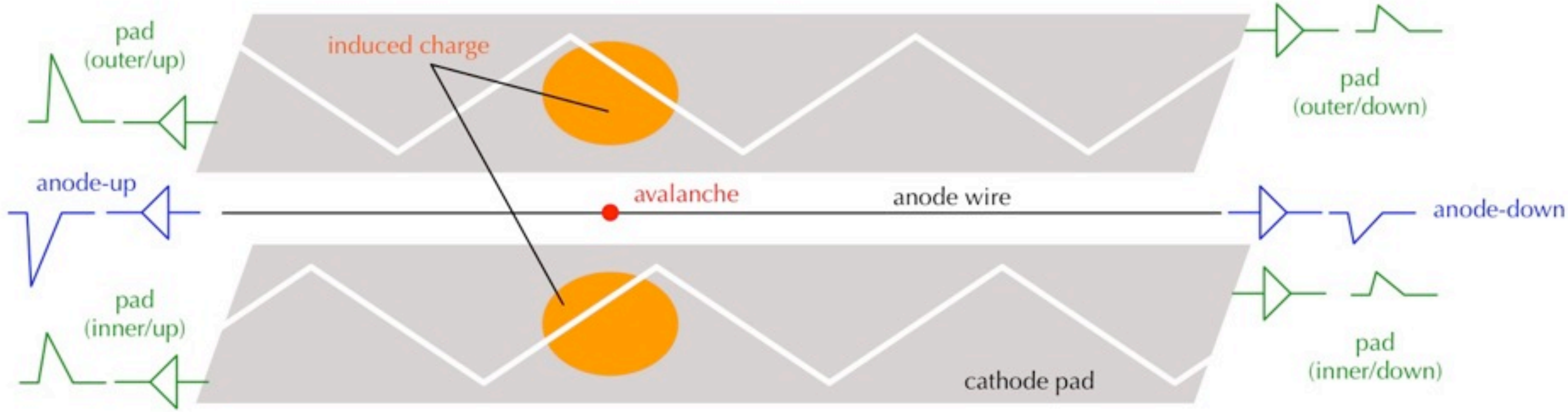
$$\varepsilon_2 = \frac{Q_{ou} - Q_{od}}{Q_{ou} + Q_{od}}$$

Vernier Pad



$$\left.\begin{array}{l} \varepsilon_1 = \dfrac{Q_{iu} - Q_{id}}{Q_{iu} + Q_{id}} \\[2em] \varepsilon_2 = \dfrac{Q_{ou} - Q_{od}}{Q_{ou} + Q_{od}} \end{array}\right\} \rightarrow \alpha = \tan^{-1} \varepsilon_2 / \varepsilon_1$$

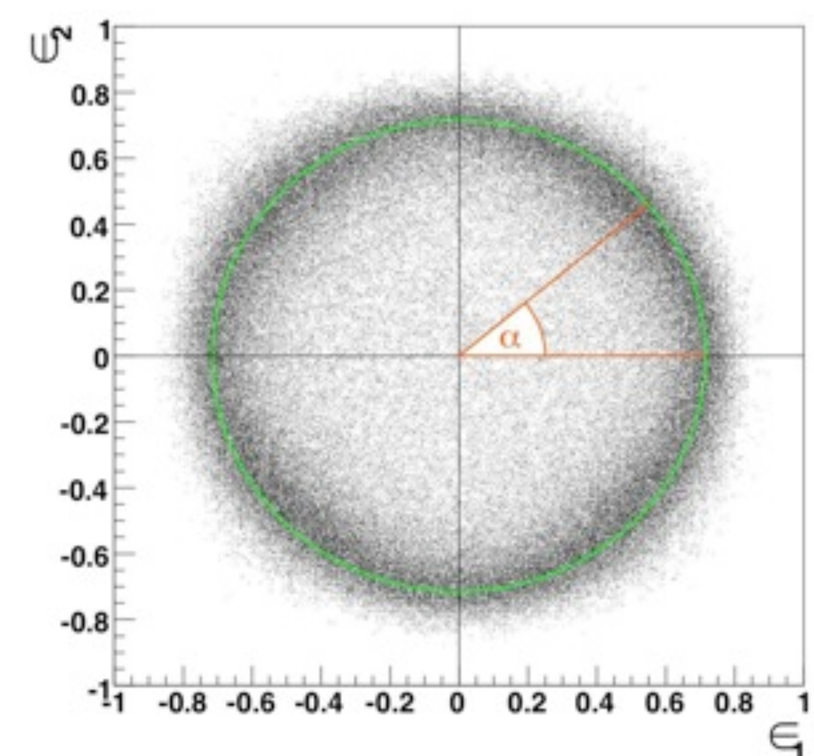
Vernier Pad



$$\varepsilon_1 = \frac{Q_{iu} - Q_{id}}{Q_{iu} + Q_{id}}$$

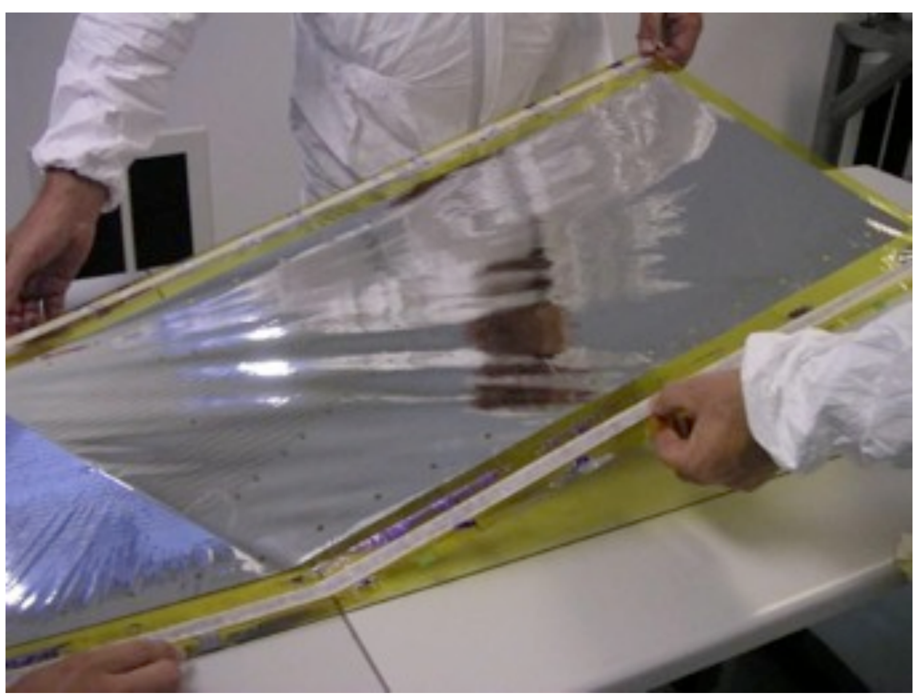
$$\varepsilon_2 = \frac{Q_{ou} - Q_{od}}{Q_{ou} + Q_{od}}$$

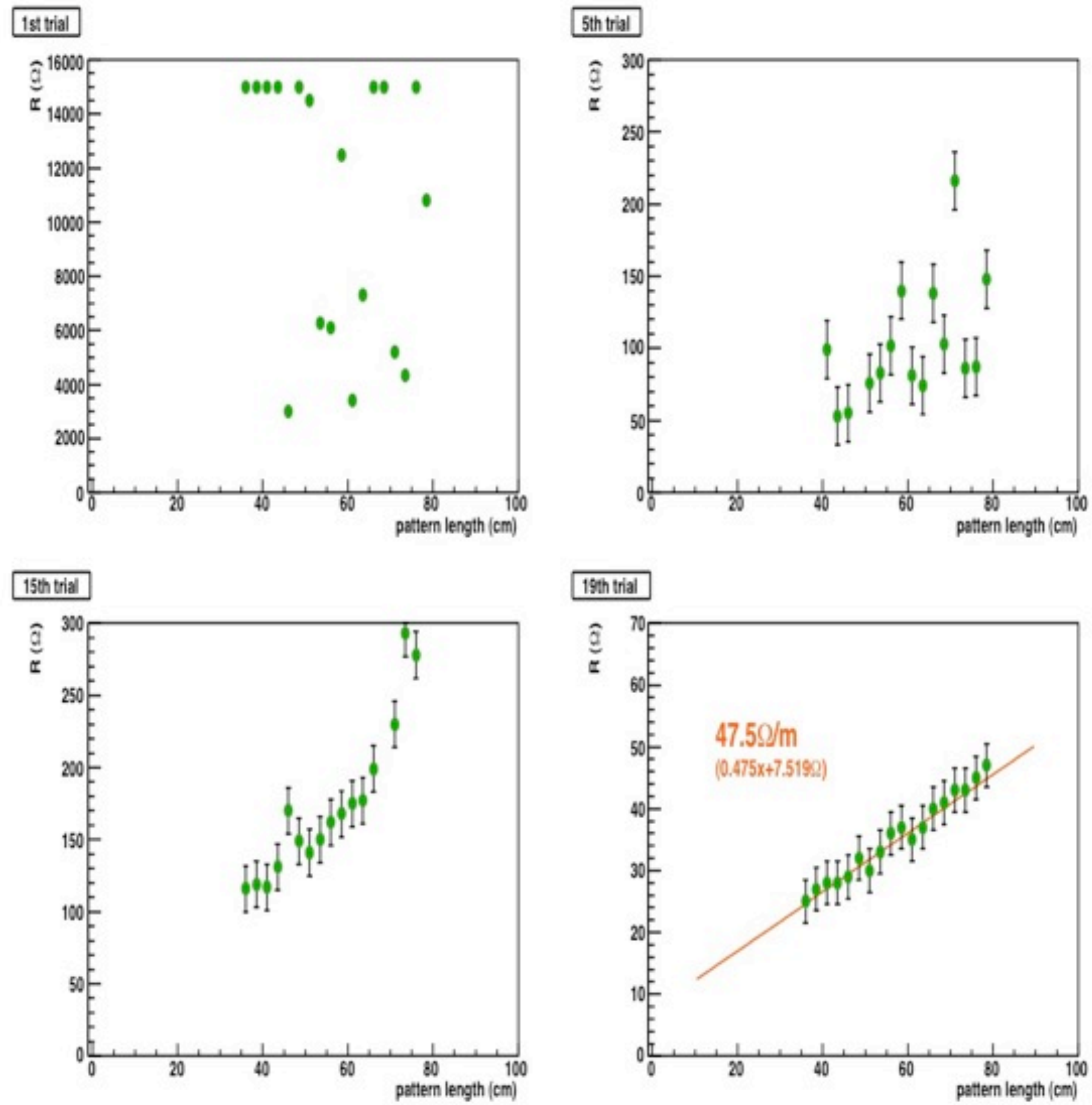
$$\alpha = \tan^{-1} \varepsilon_2 / \varepsilon_1$$



Cathode Foil

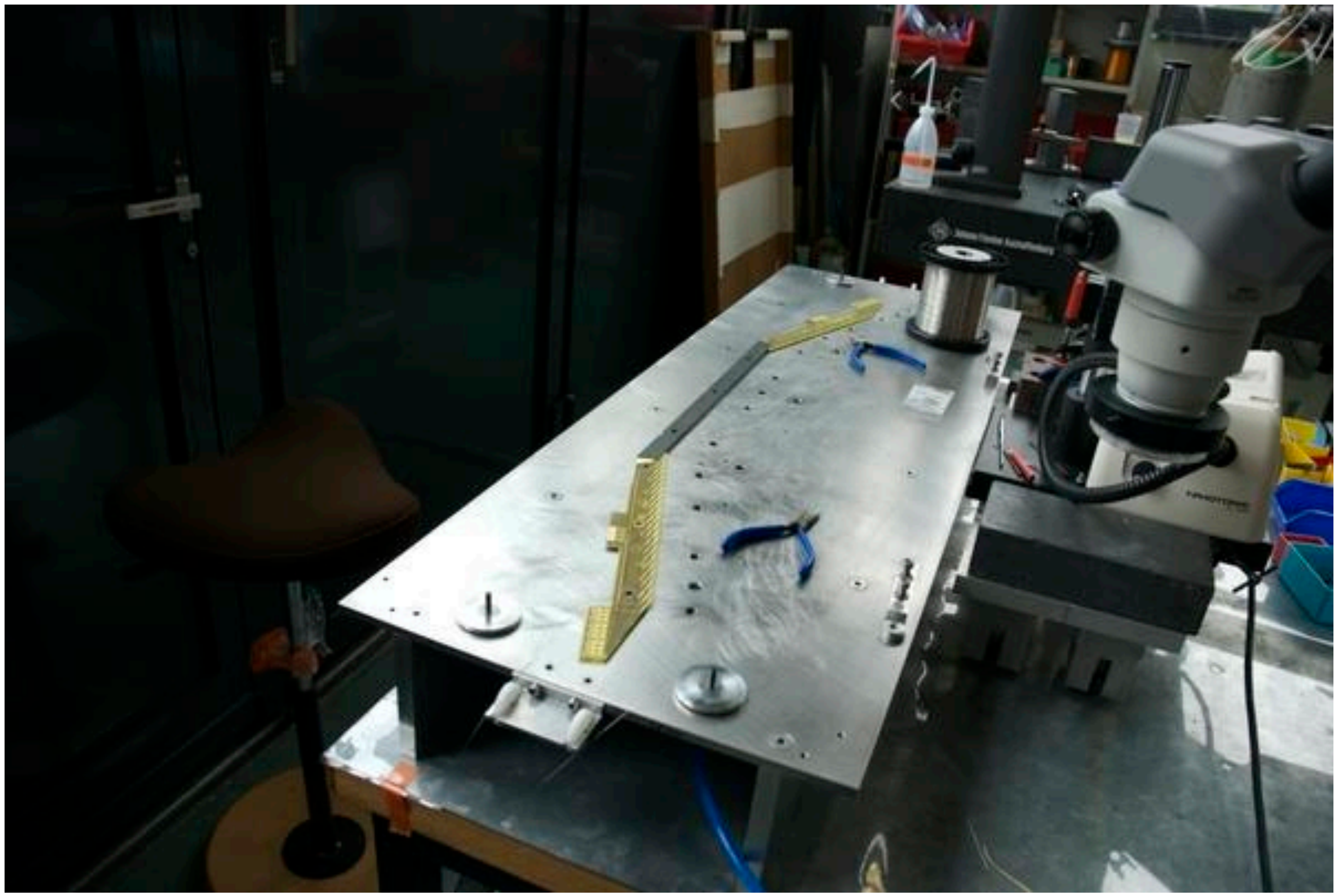
- 12.5 µm UPILEX with 400 nm Aluminum Deposition
- Uniform Resistivity and Ultra-thin foil are incompatible
- Excellent Print Accuracy is also incompatible
- 250 nm of effective thickness



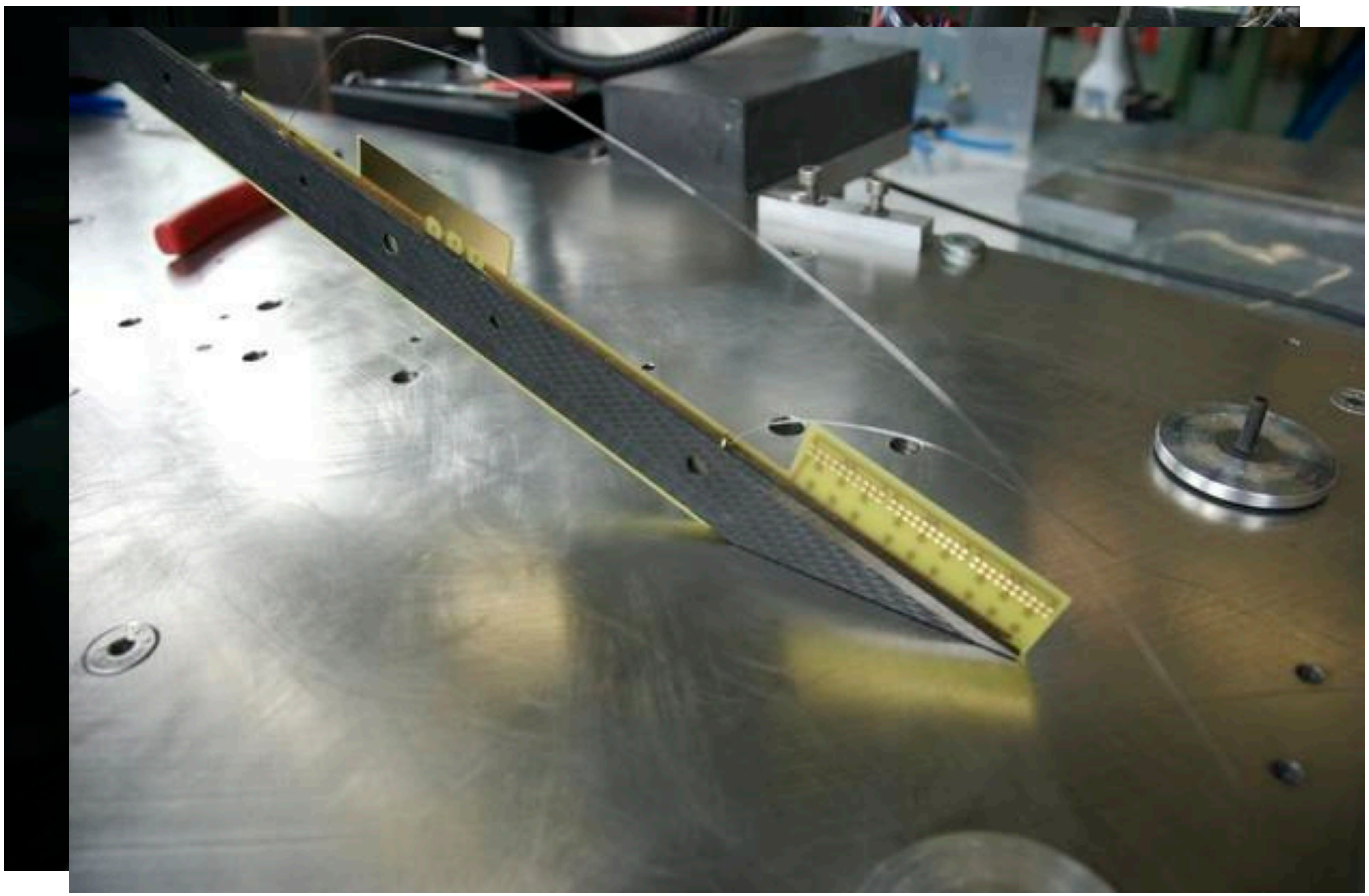


Assembly (1) - anode -

Assembly (1) - anode -

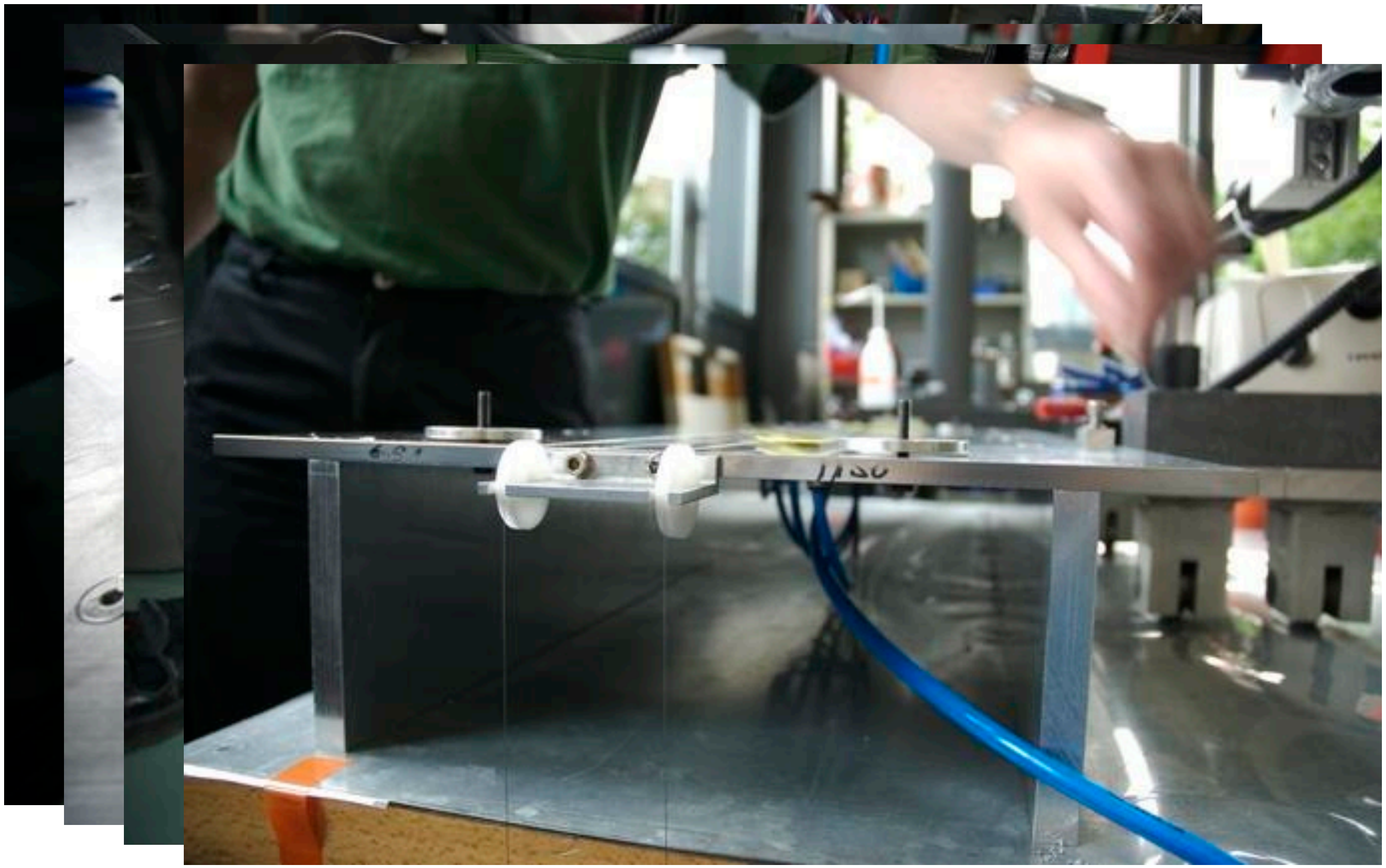


Assembly (1) - anode -

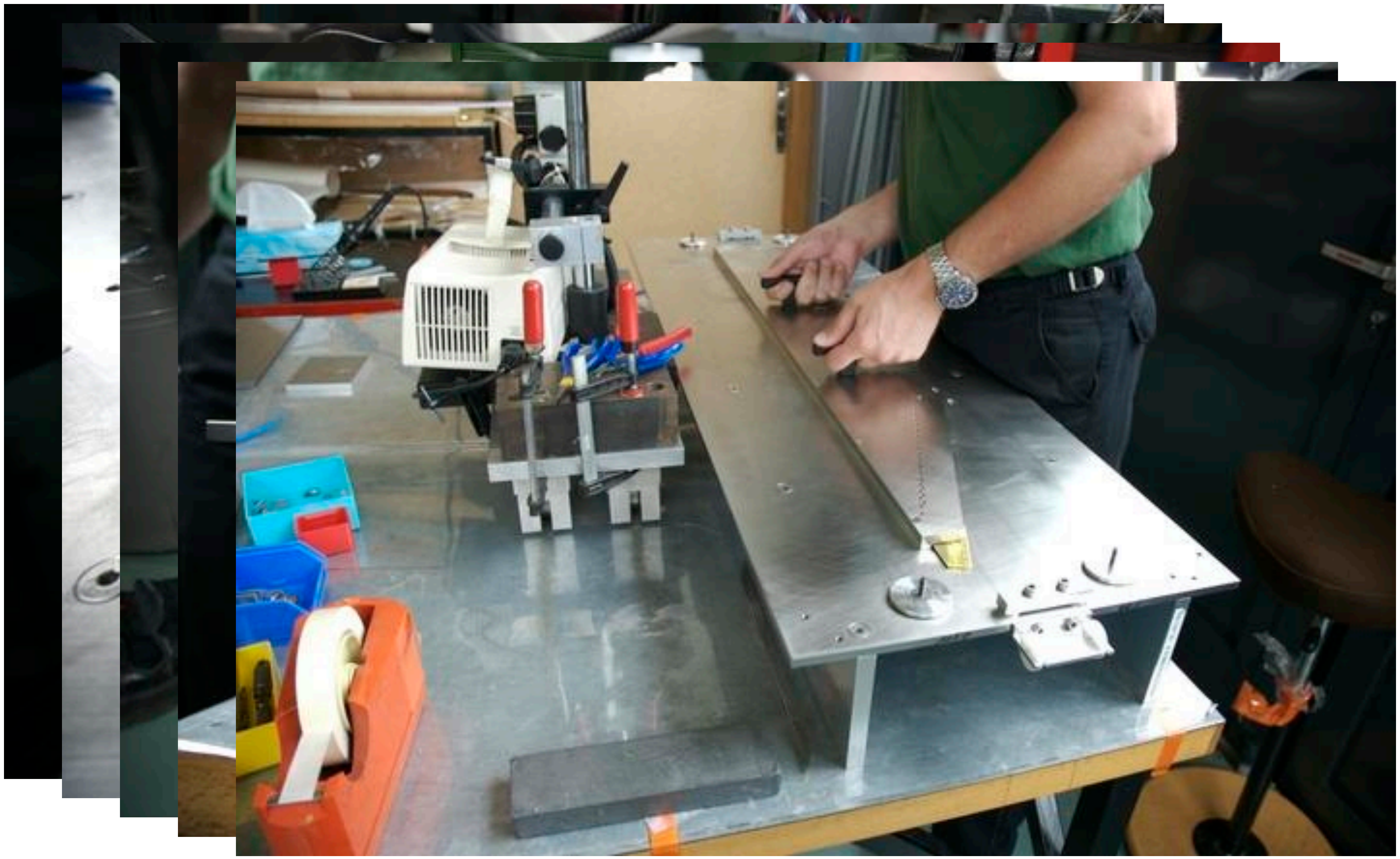


Assembly (1) - anode -

Assembly (1) - anode -

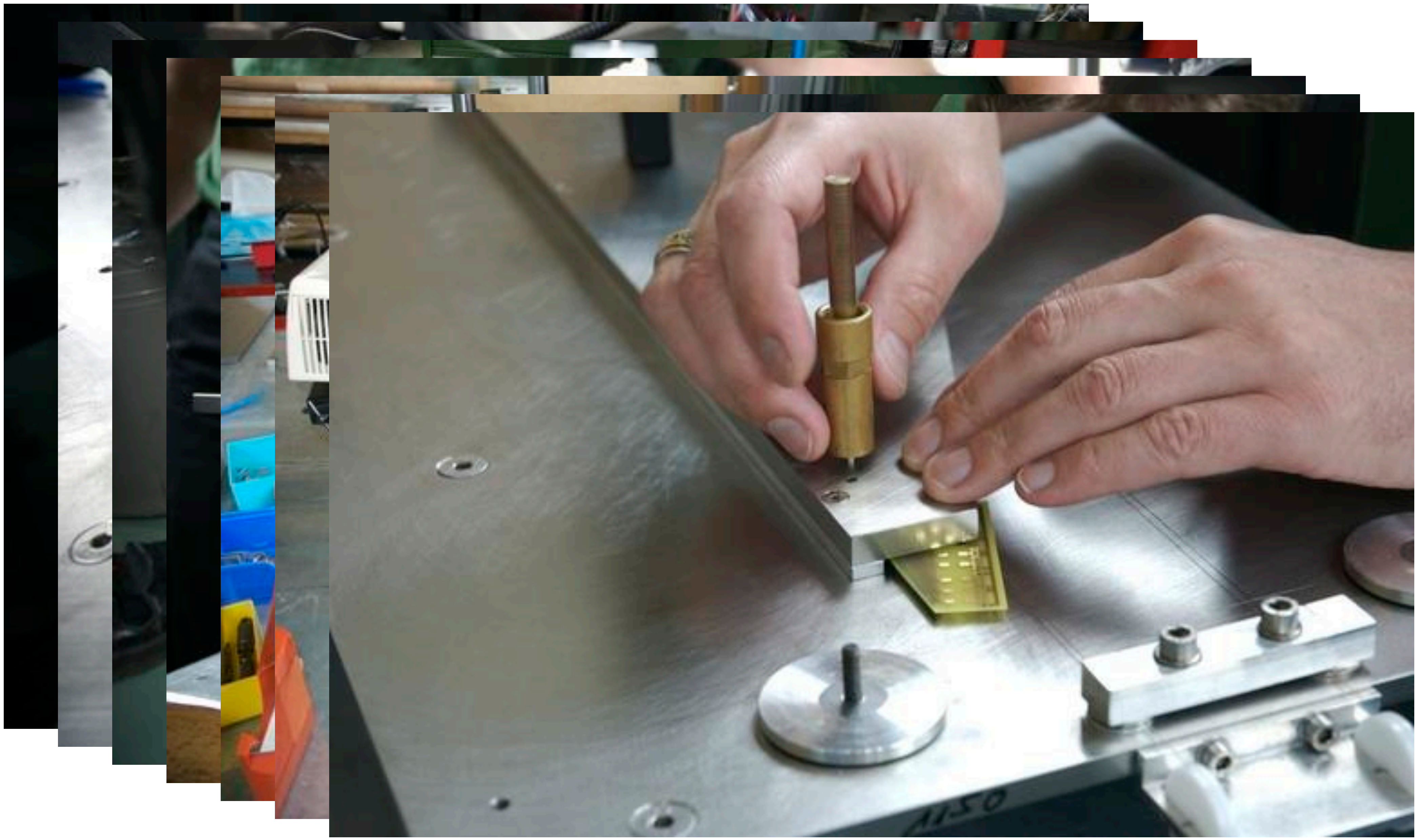


Assembly (1) - anode -

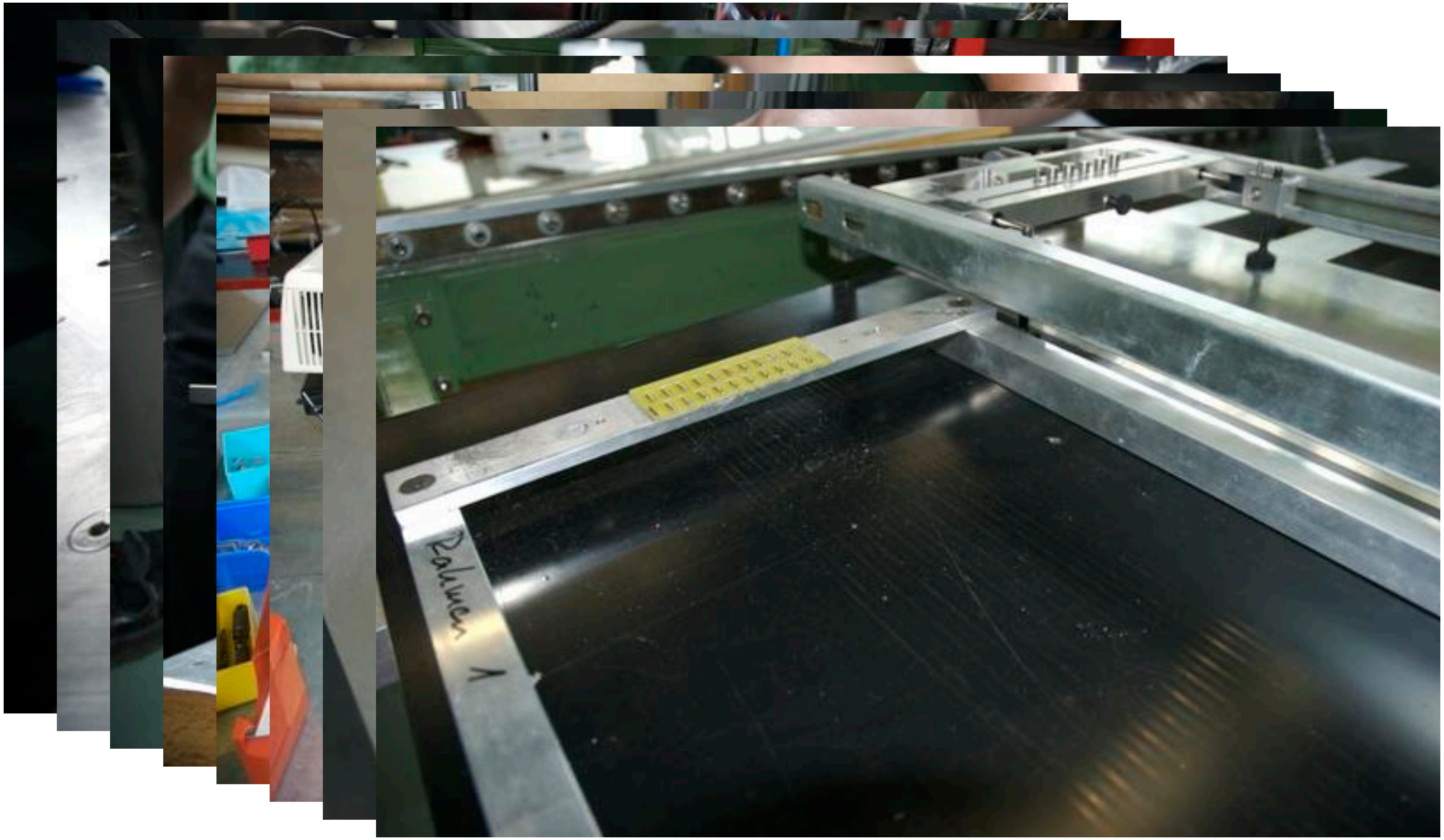


Assembly (1) - anode -

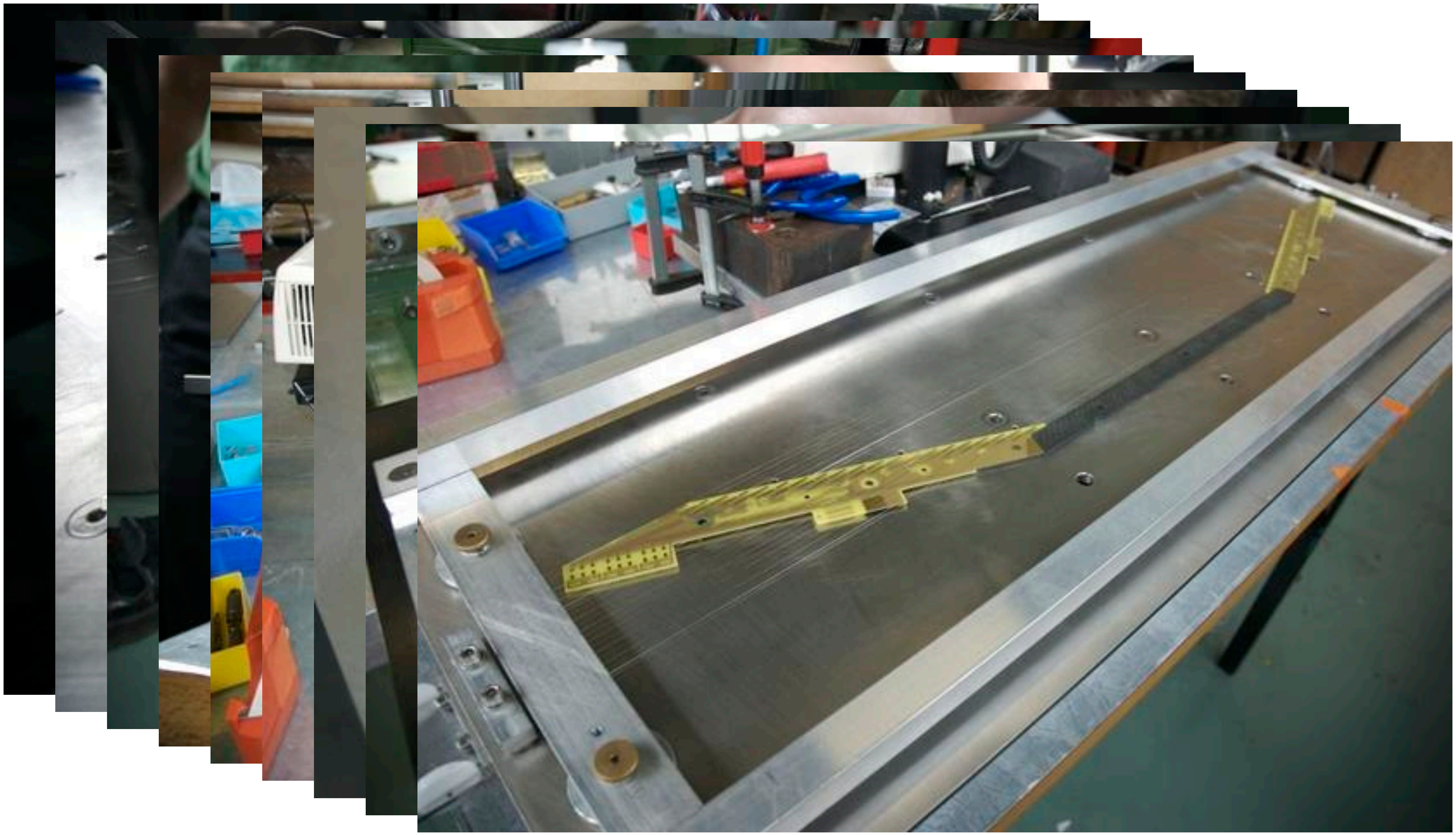
Assembly (1) - anode -



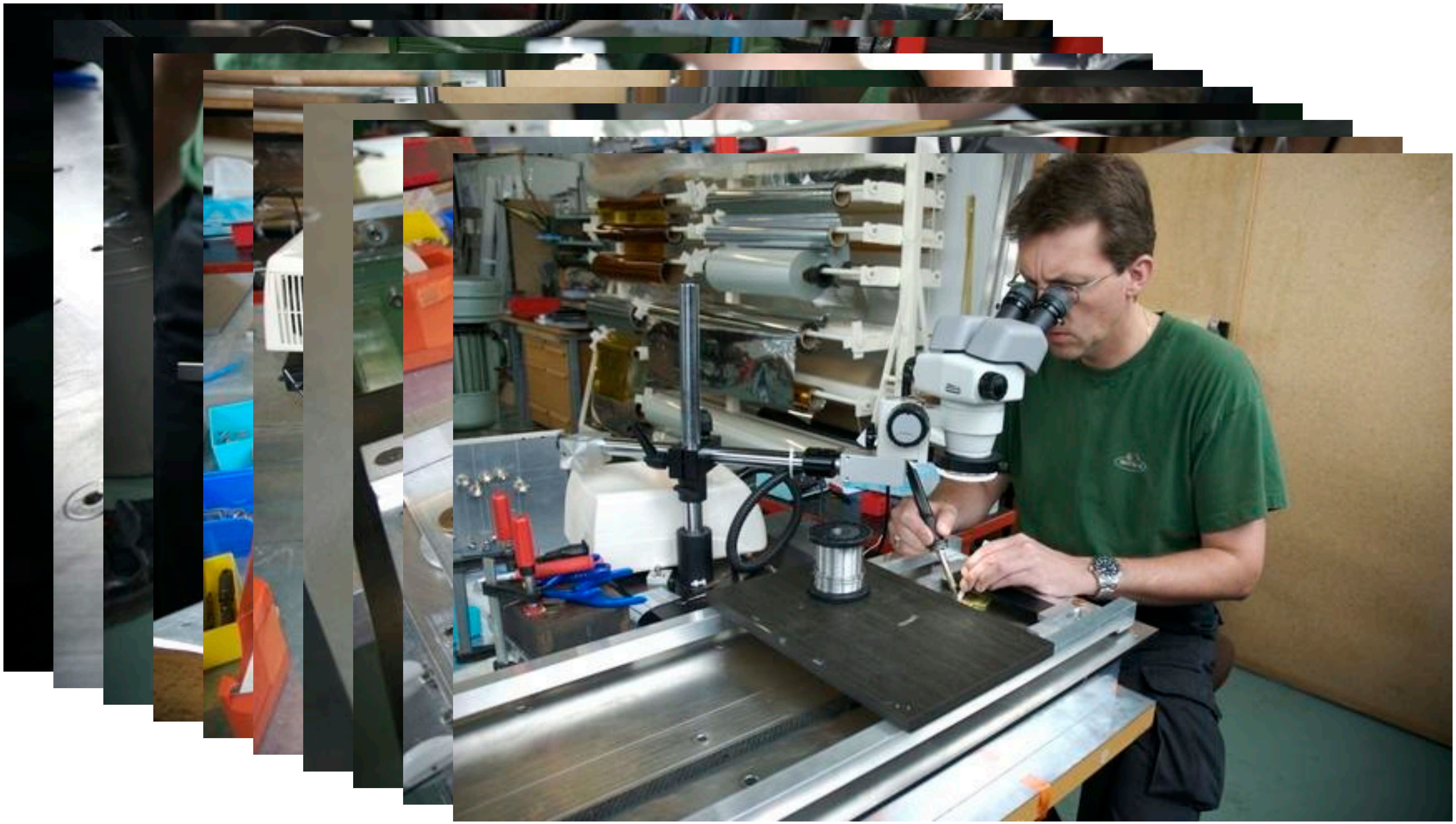
Assembly (1) - anode -



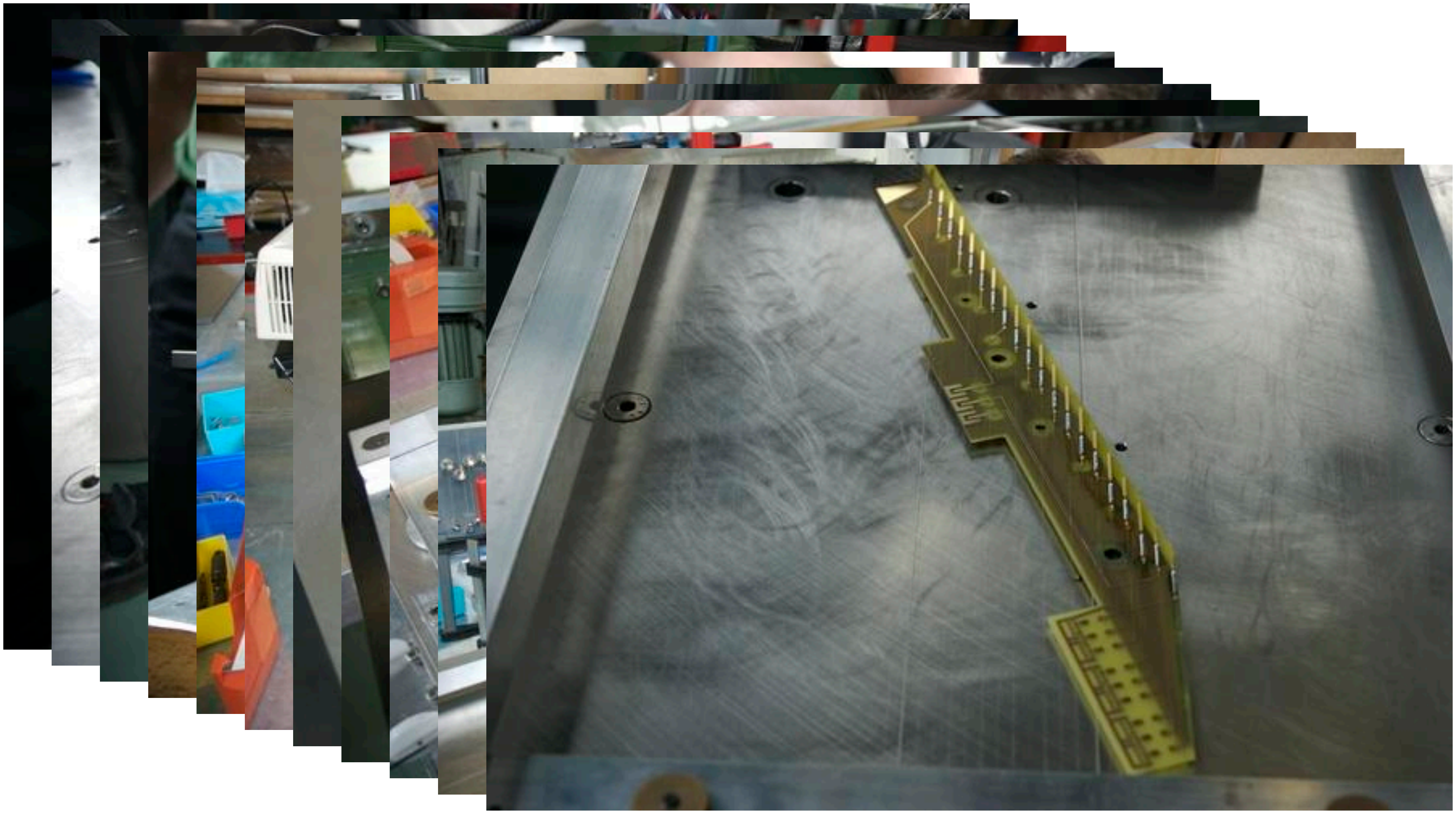
Assembly (1) - anode -



Assembly (1) - anode -



Assembly (1) - anode -



Assembly (1) - anode -

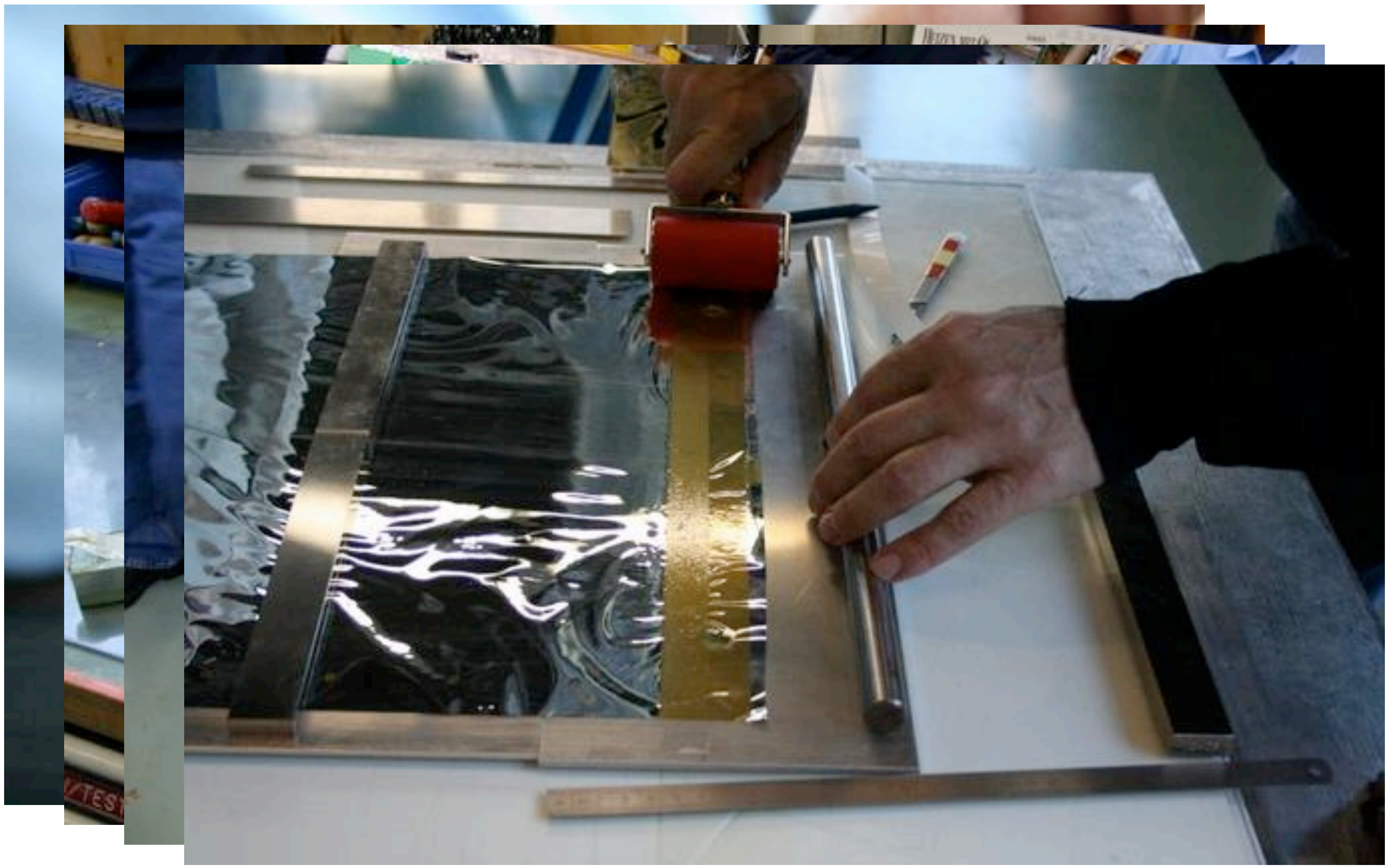
Assembly (2) - cathode -

Assembly (2) - cathode -

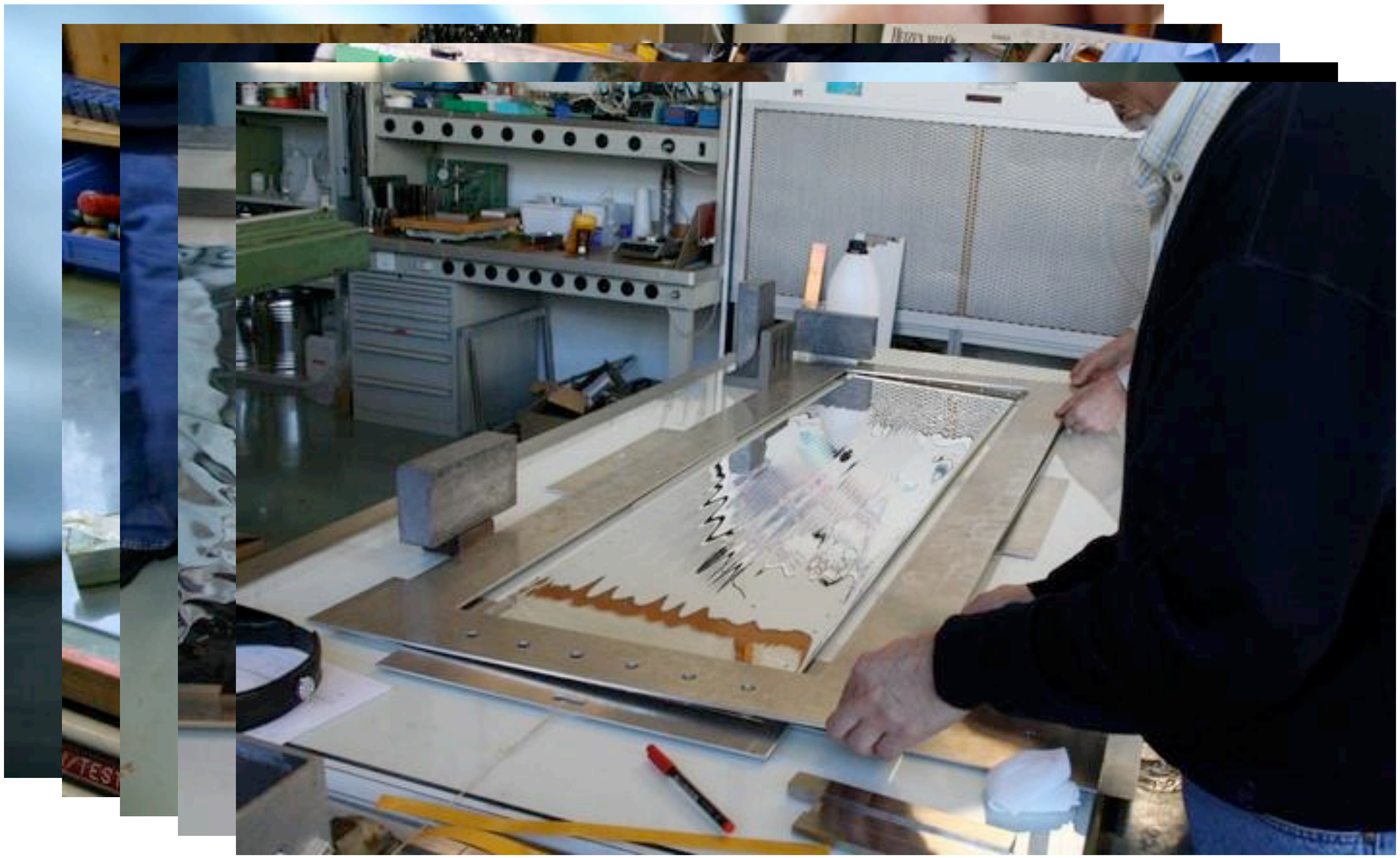
Assembly (2) - cathode -

Assembly (2) - cathode -

Assembly (2) - cathode -

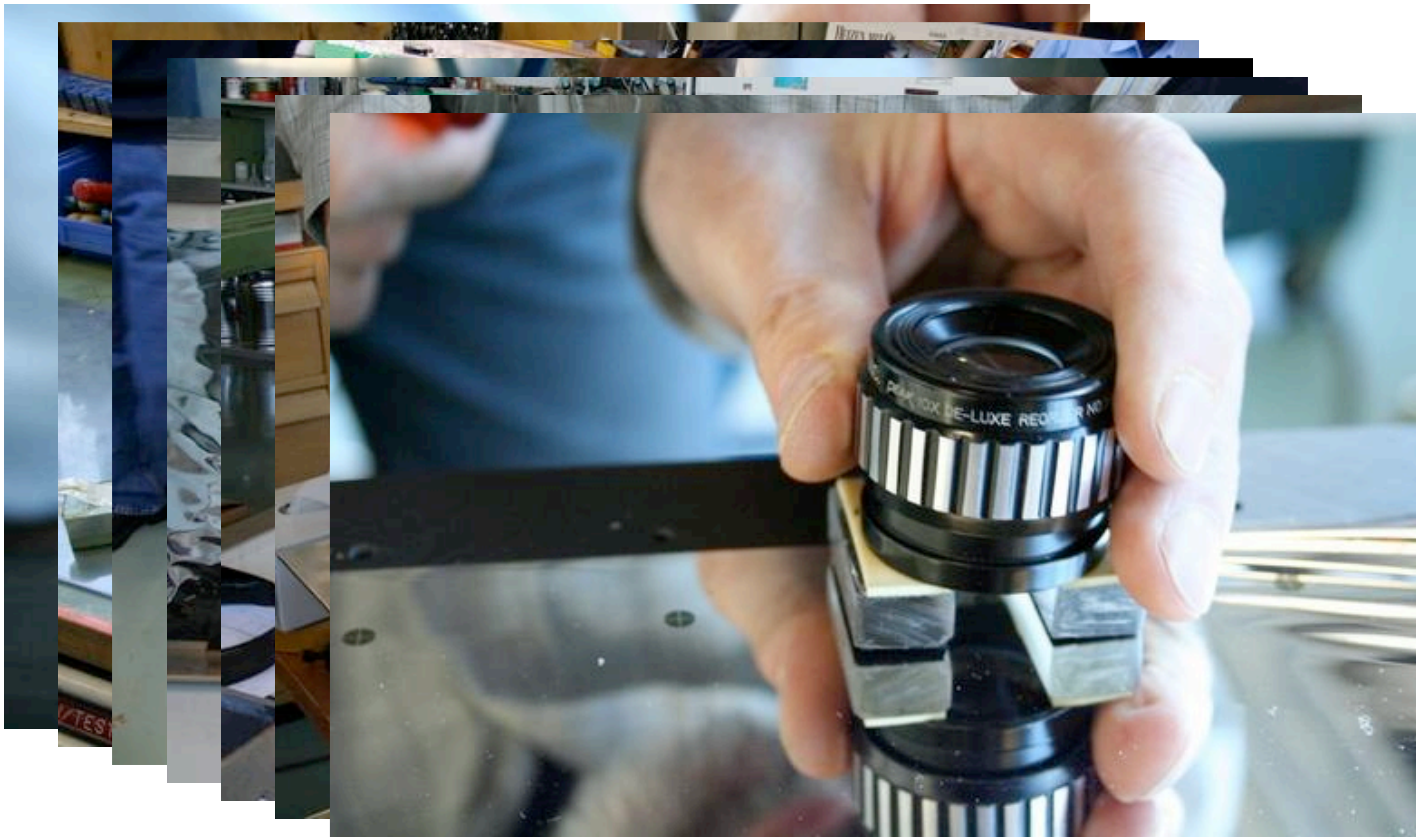


Assembly (2) - cathode -

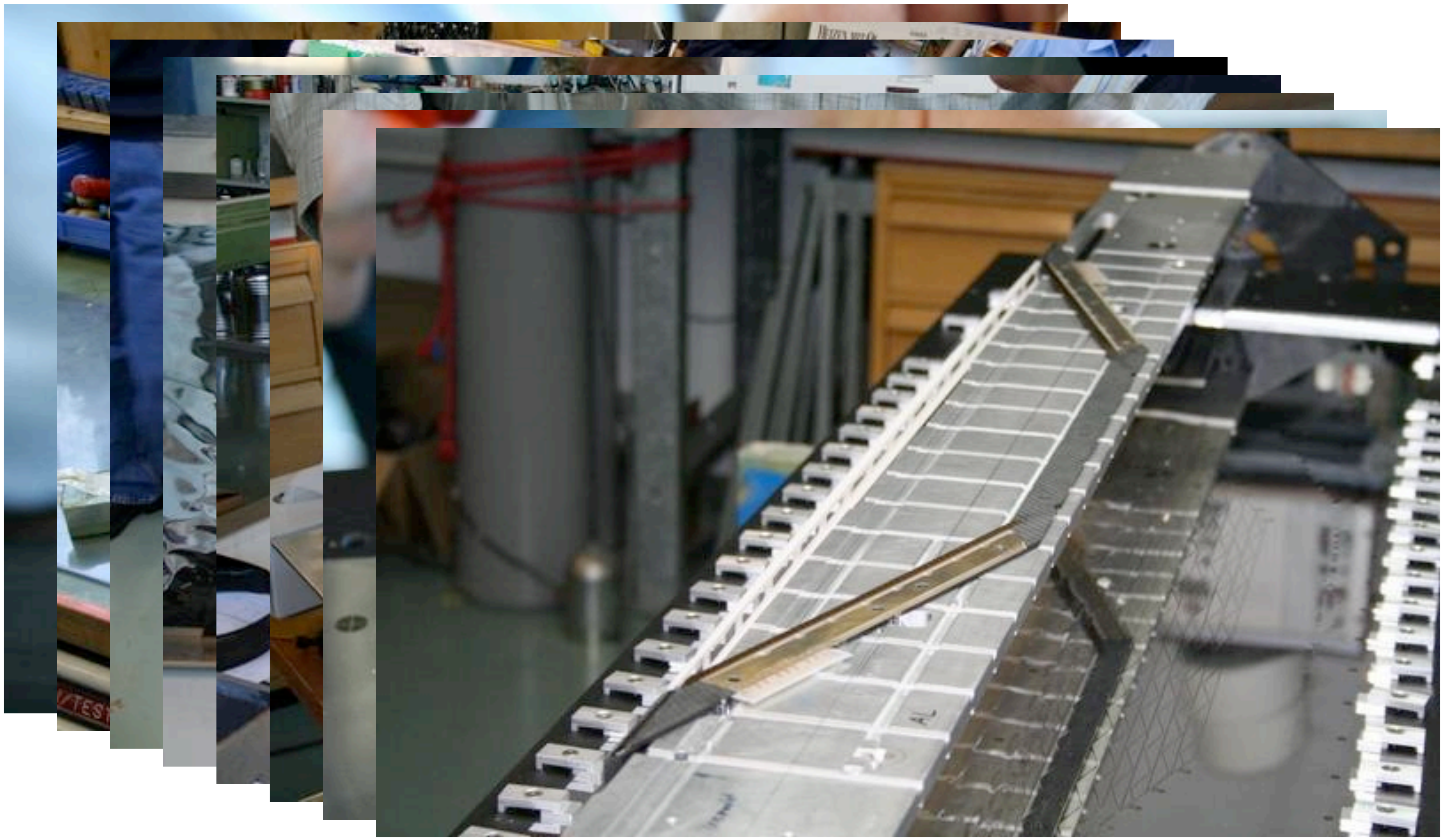


Assembly (2) - cathode -

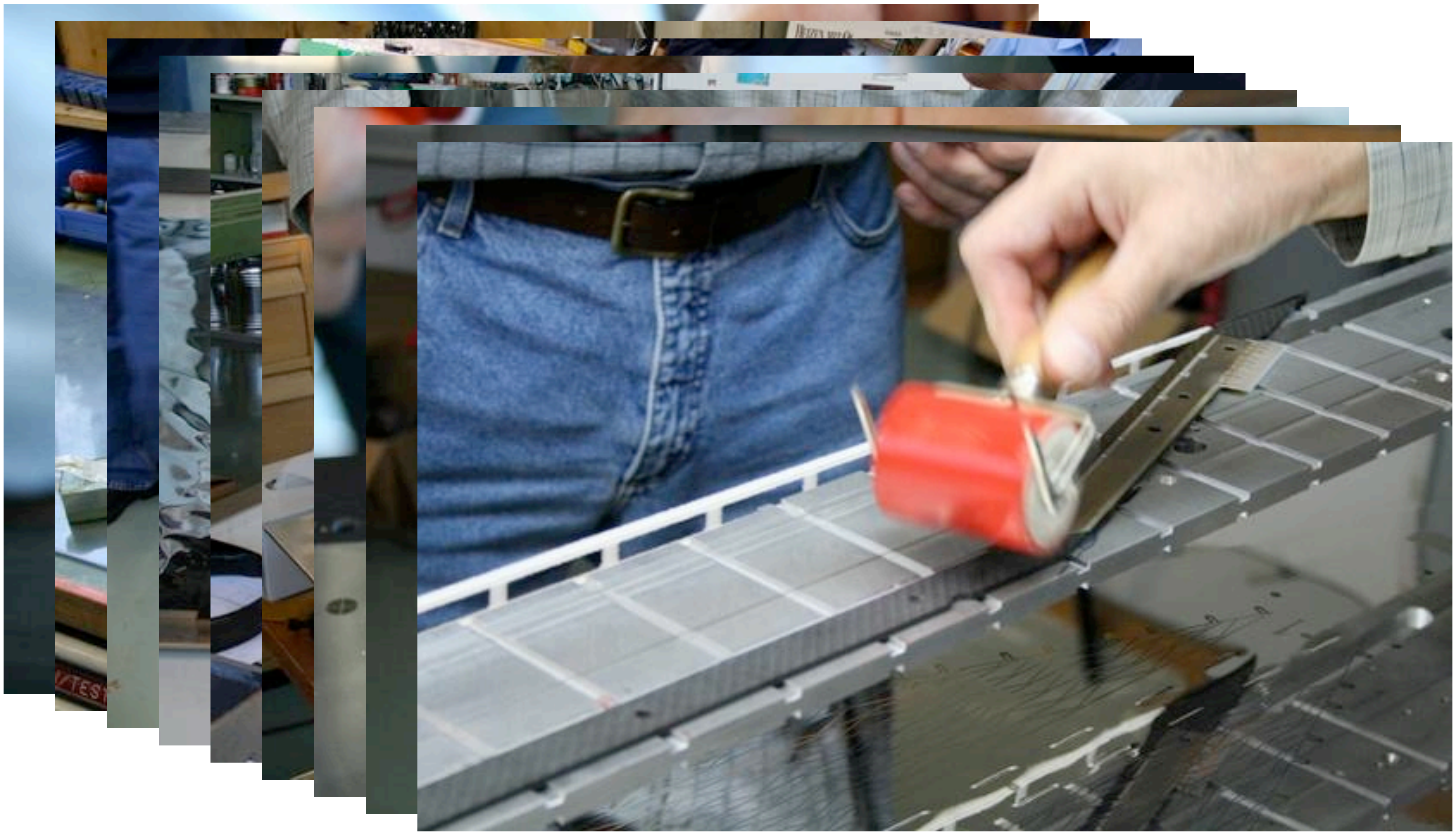
Assembly (2) - cathode -



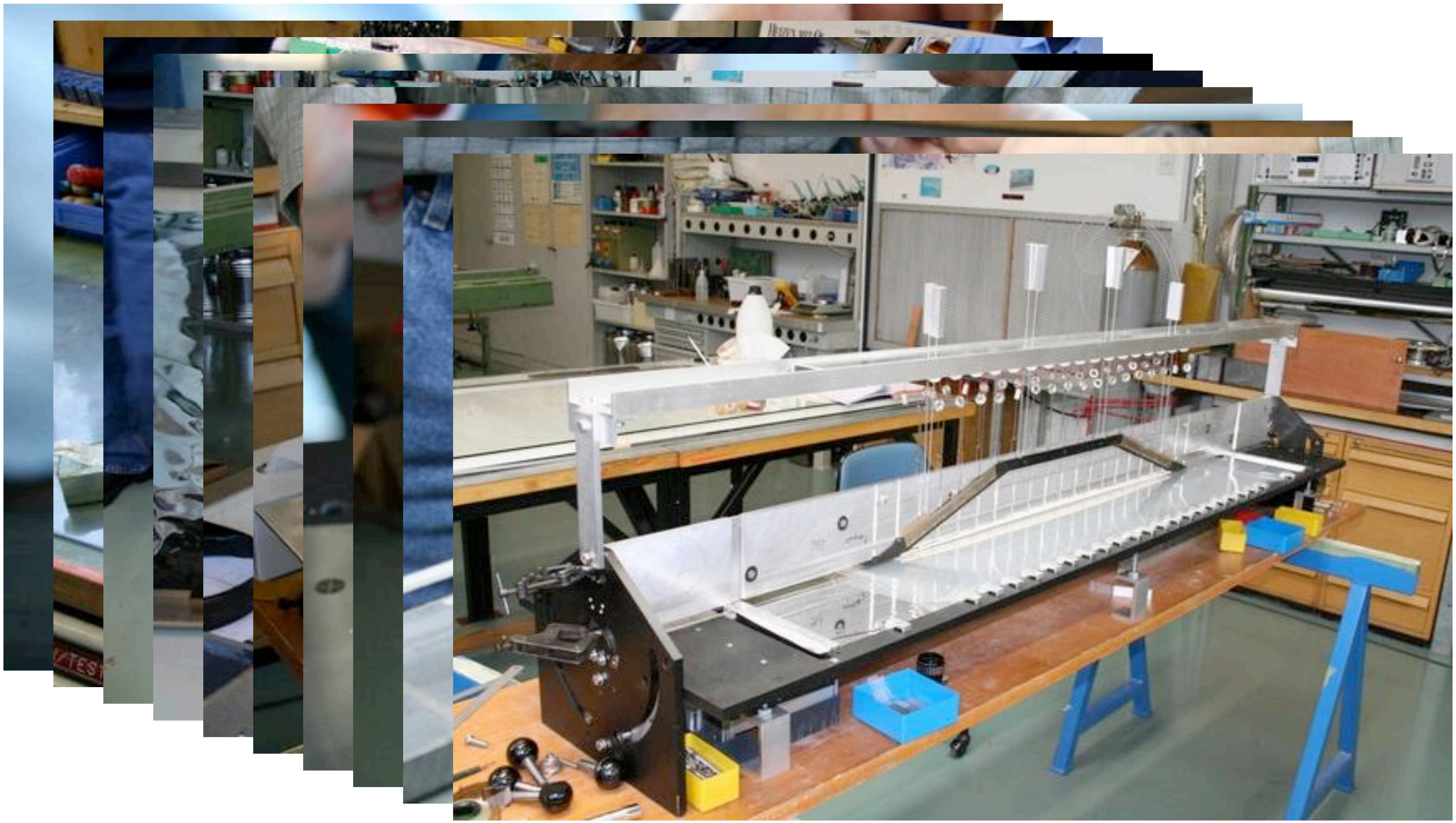
Assembly (2) - cathode -



Assembly (2) - cathode -

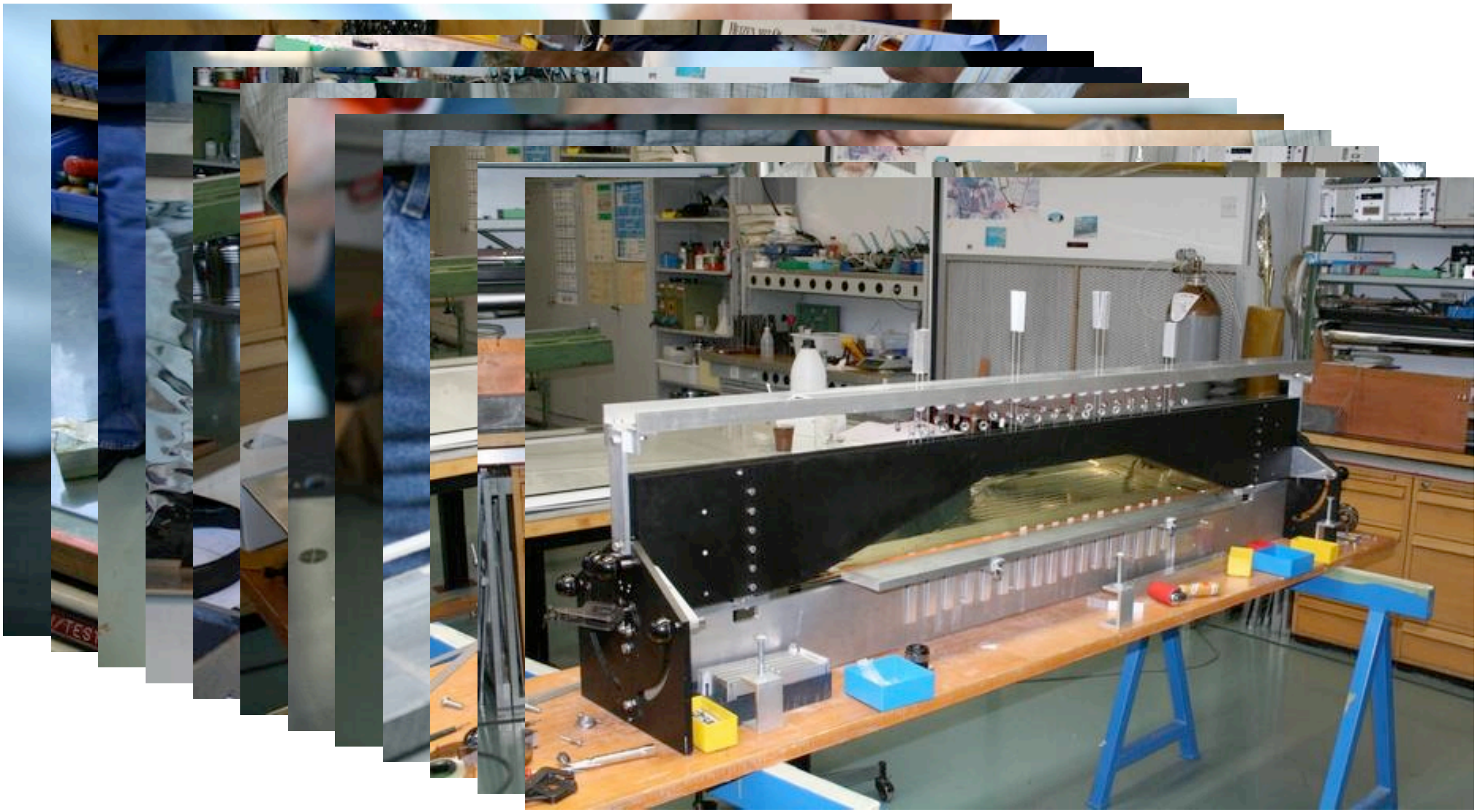


Assembly (2) - cathode -



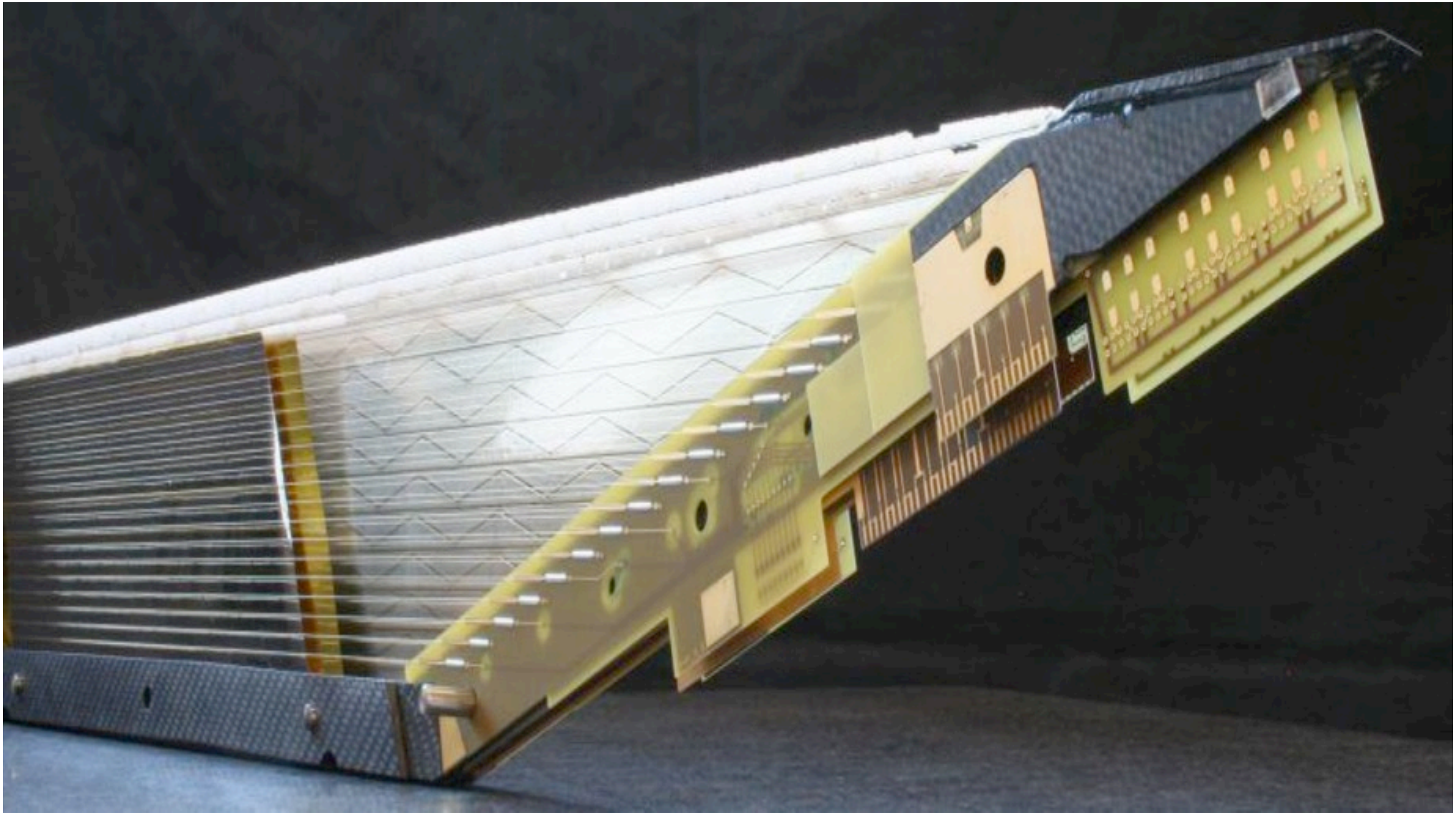
Assembly (2) - cathode -

Assembly (2) - cathode -

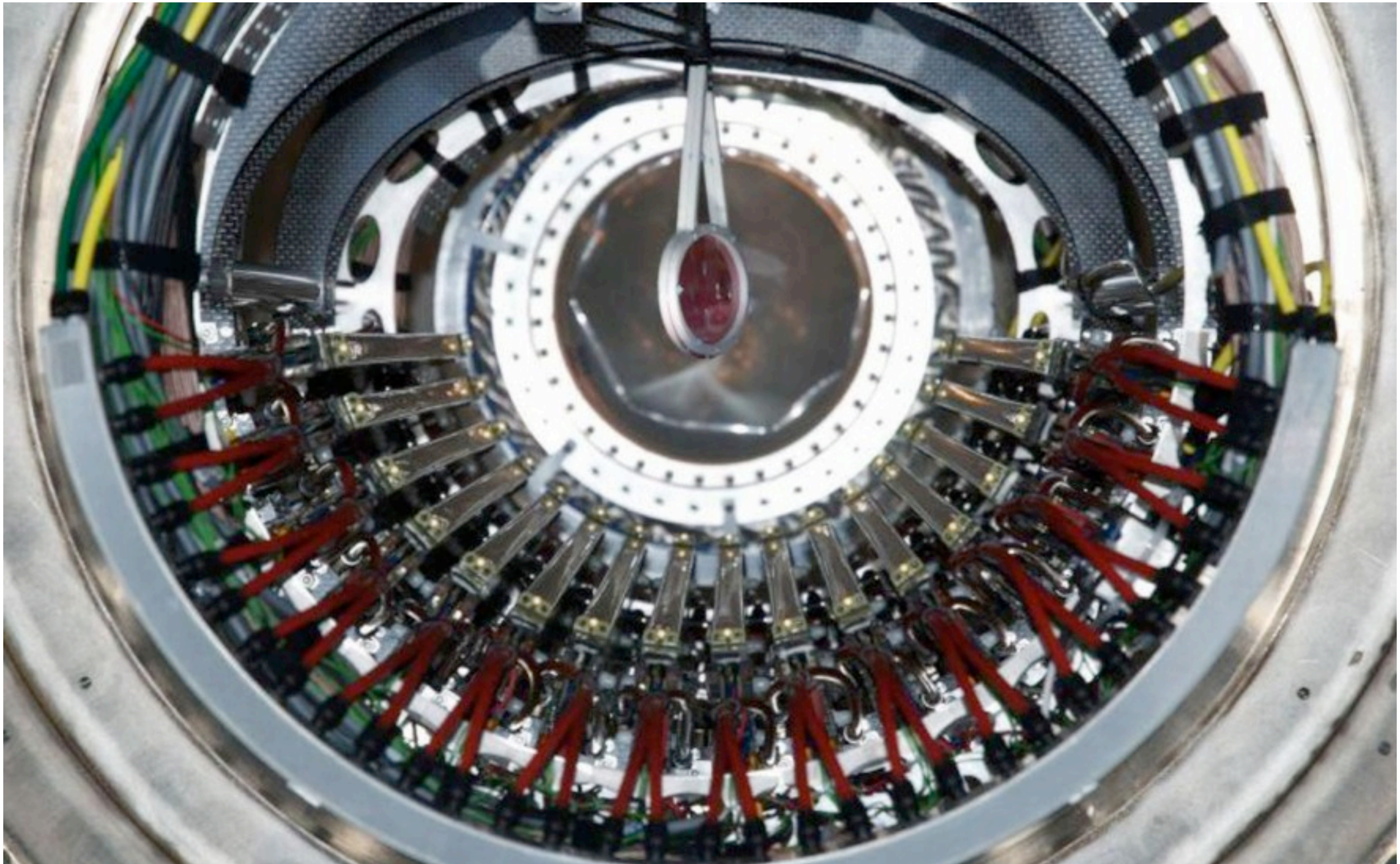


Assembly (3)

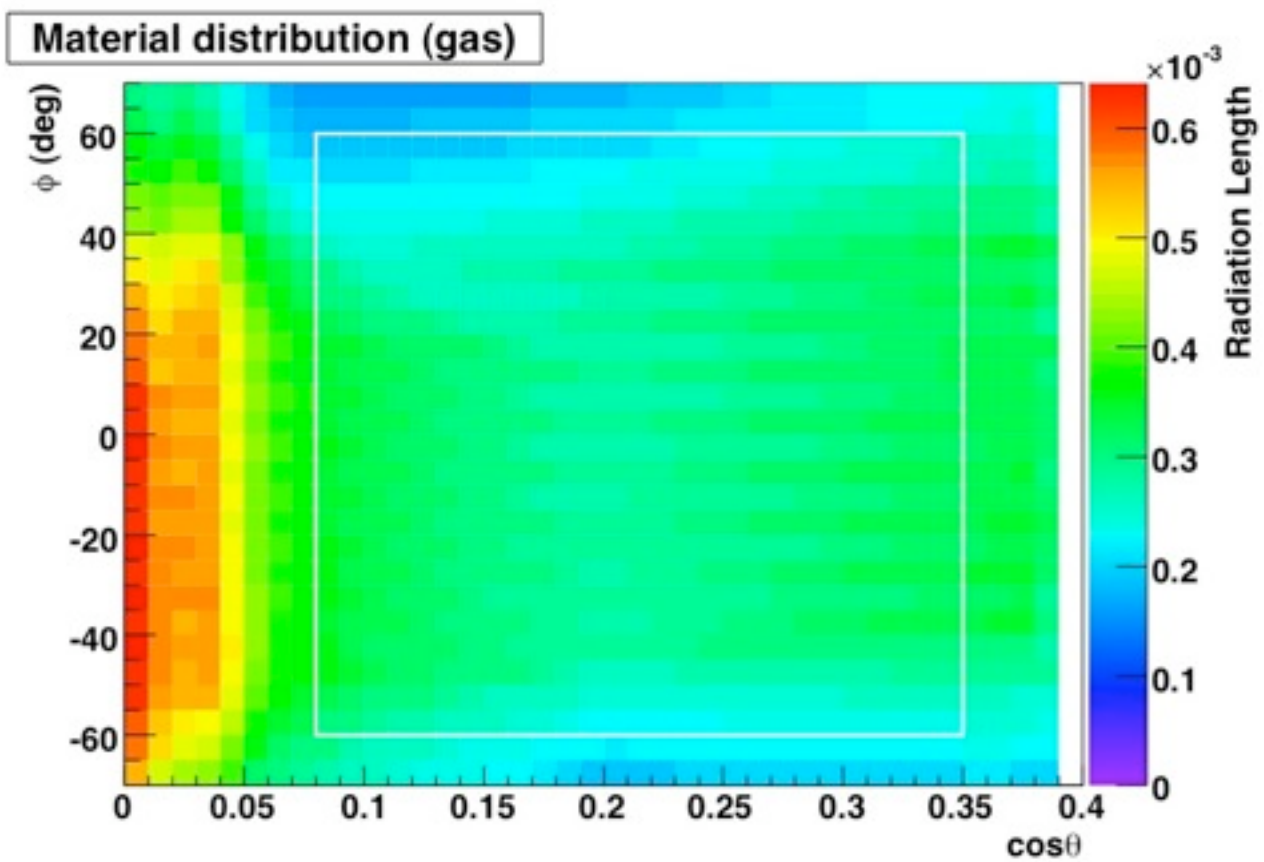
Assembly (4)

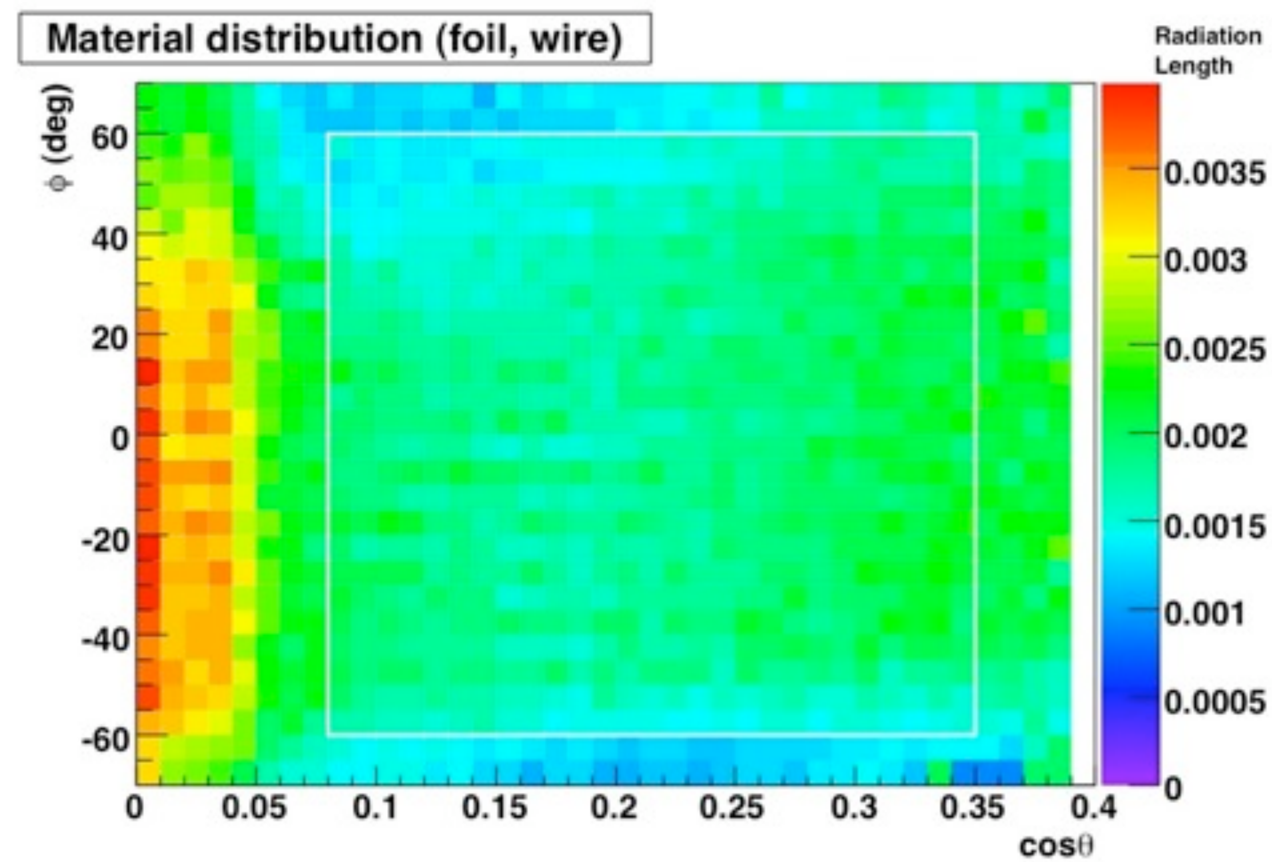


Mounting / Installation



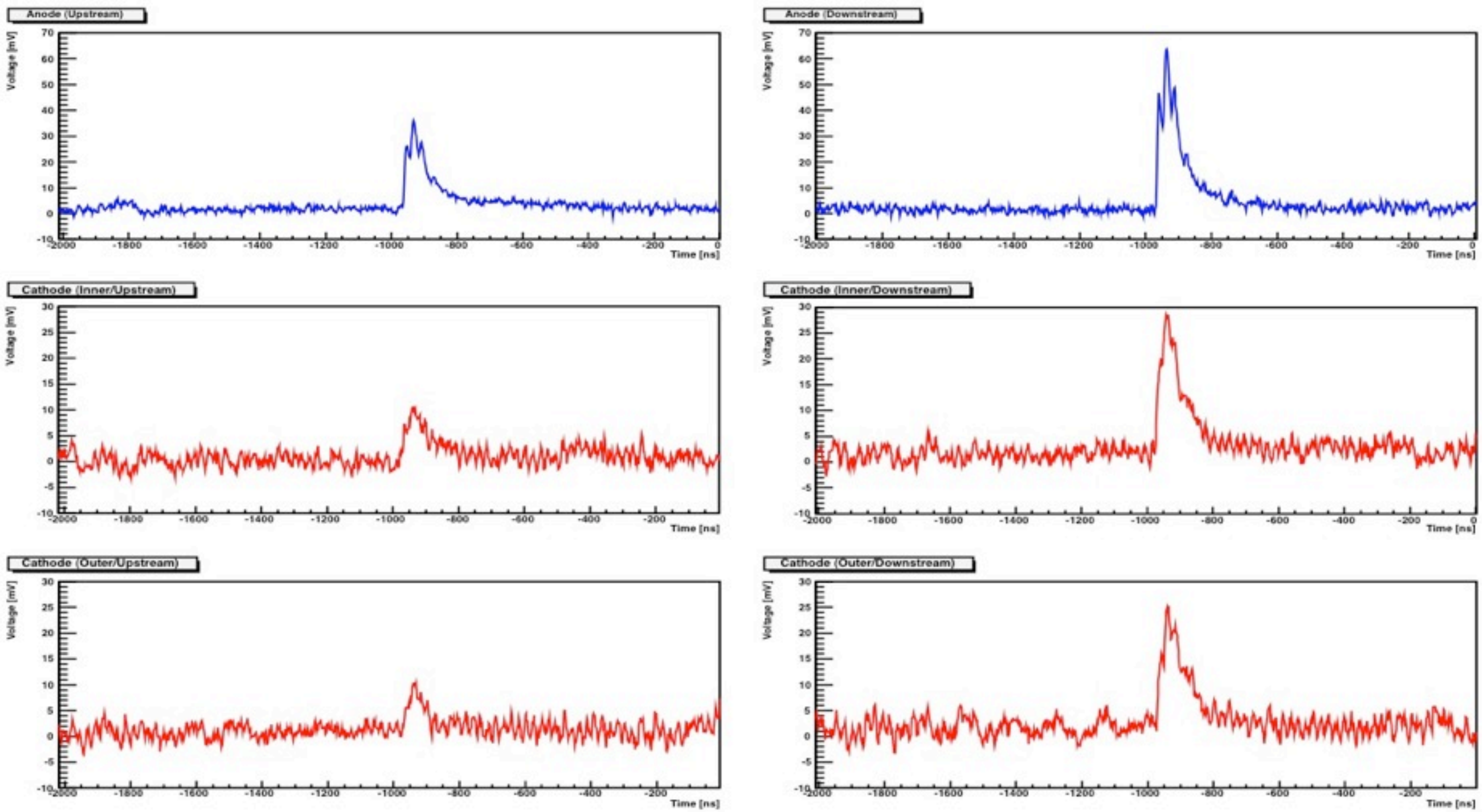
Material Amount





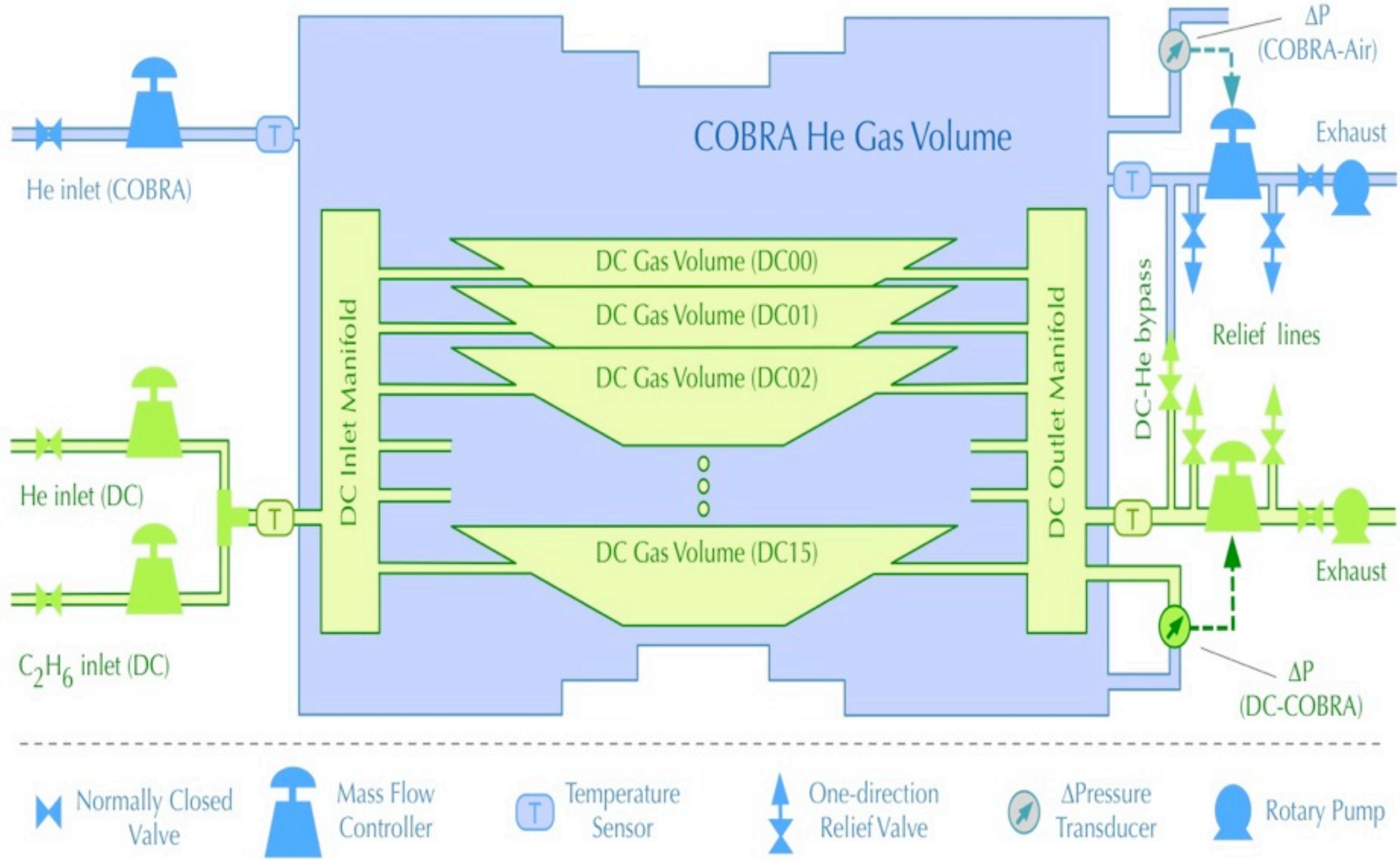
- Total Radiation Length in Tracker Fiducial Volume : $0.002\ X_0$

Readout Electronics

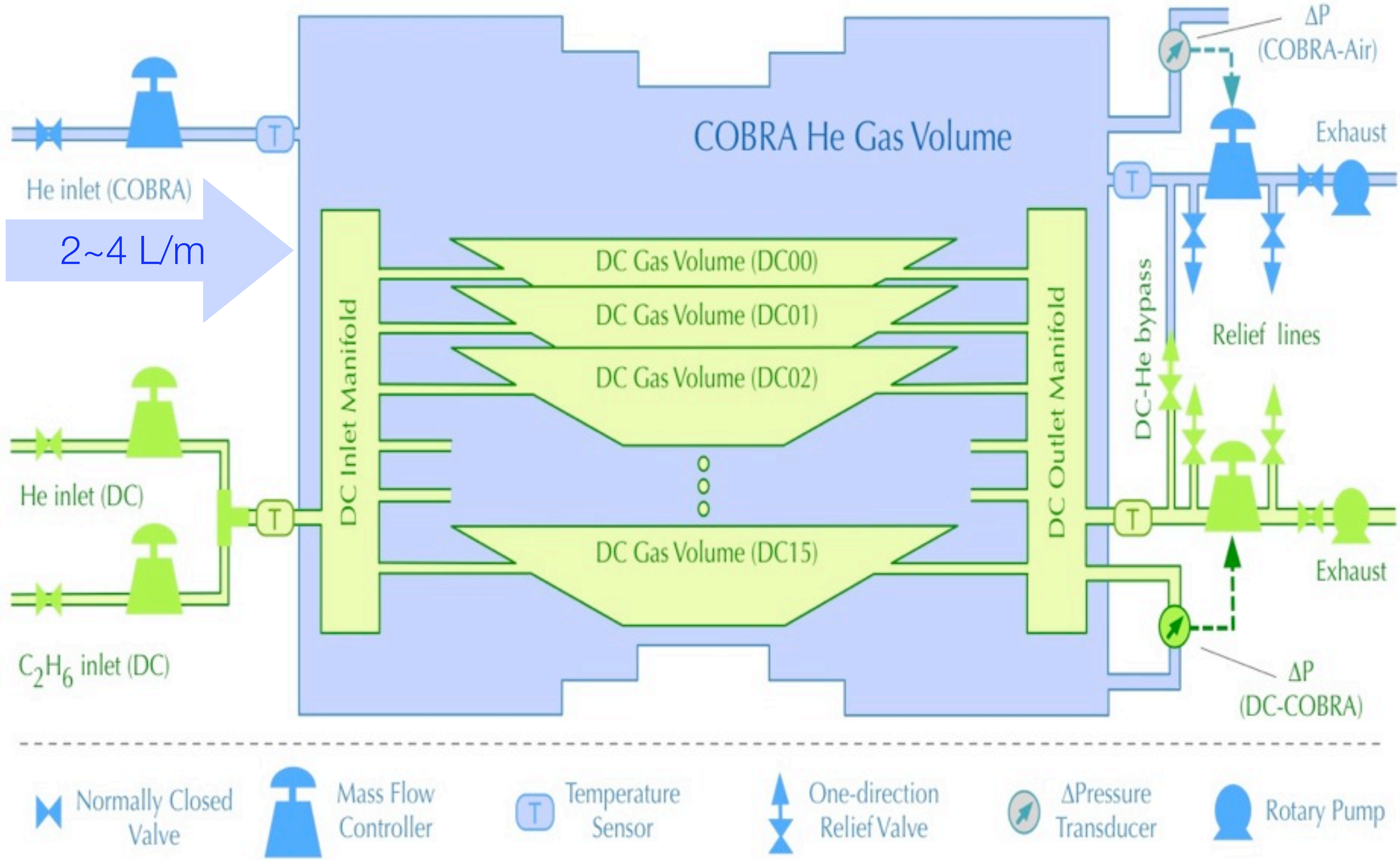


- “6 channel / cell” x 288 wires = 1728 channels

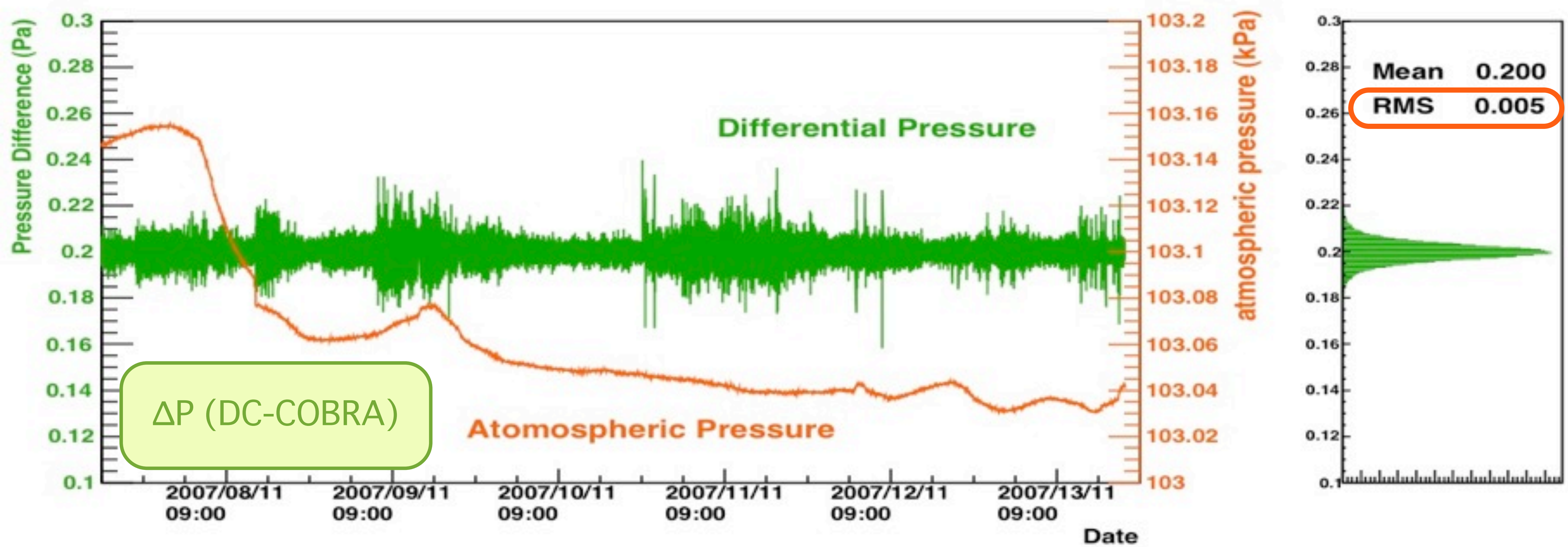
Pressure Equalization System

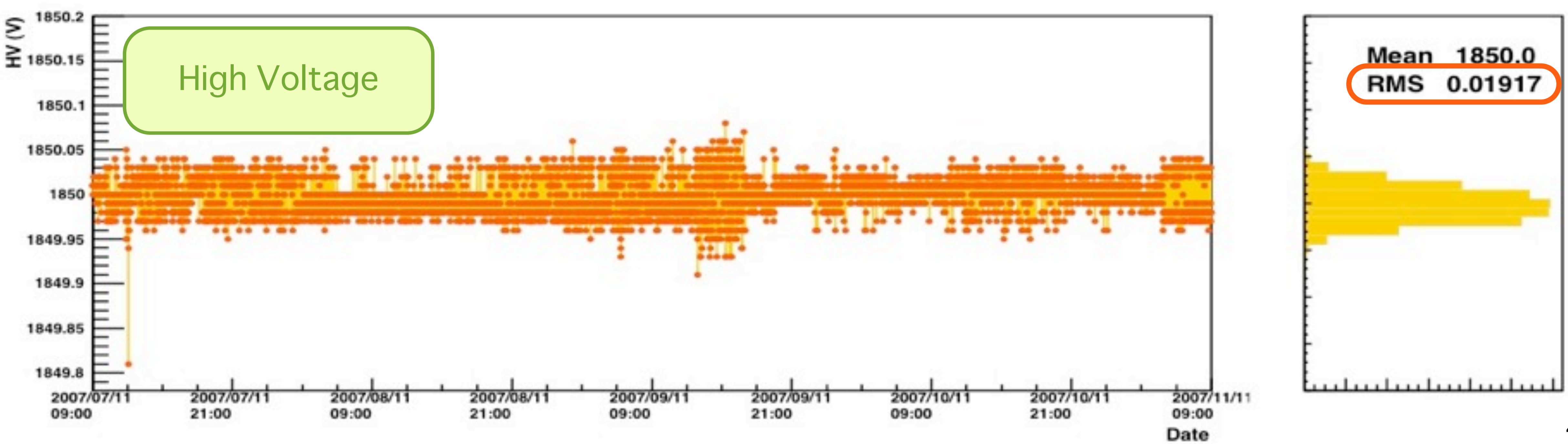


Pressure Equalization System



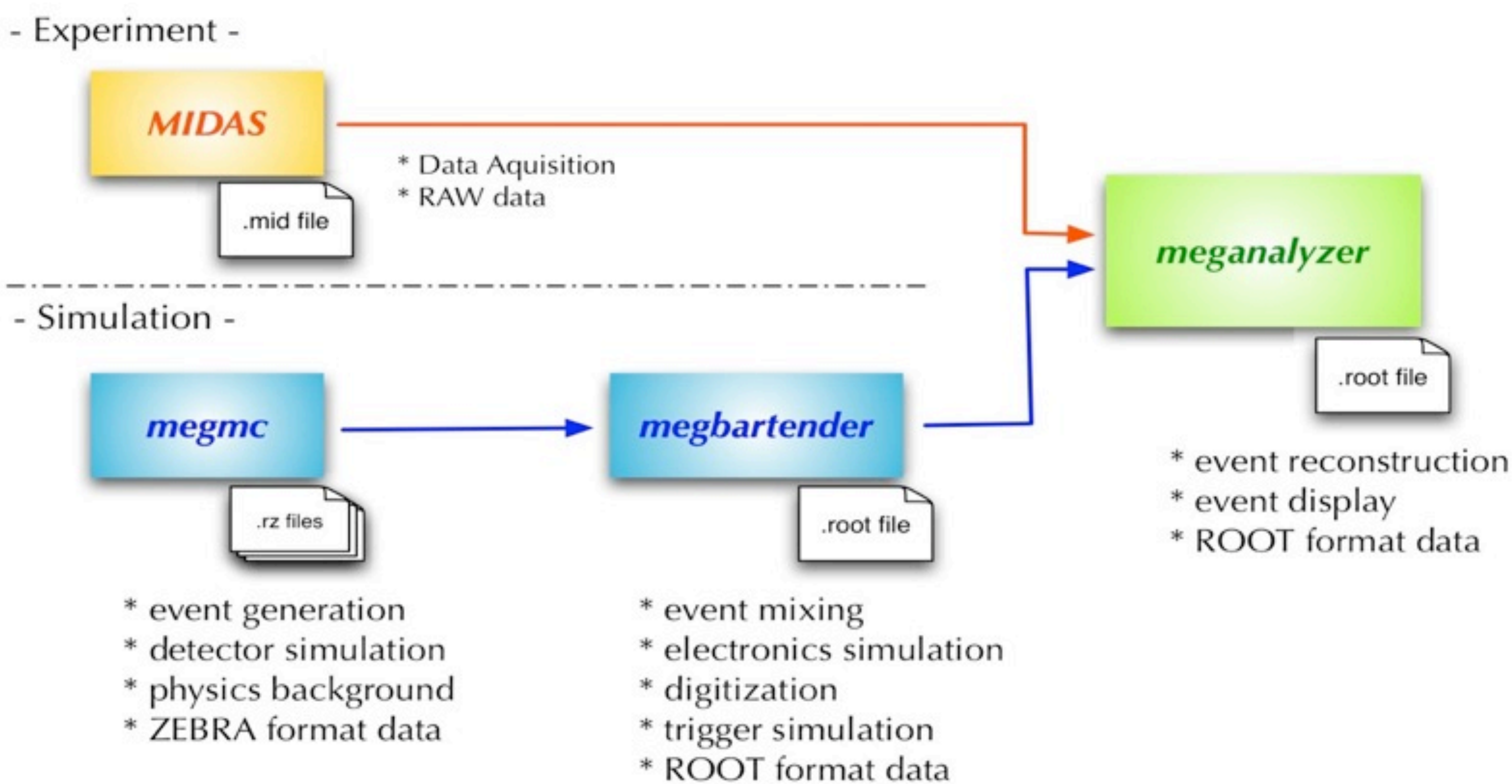
Slow-Control Stability



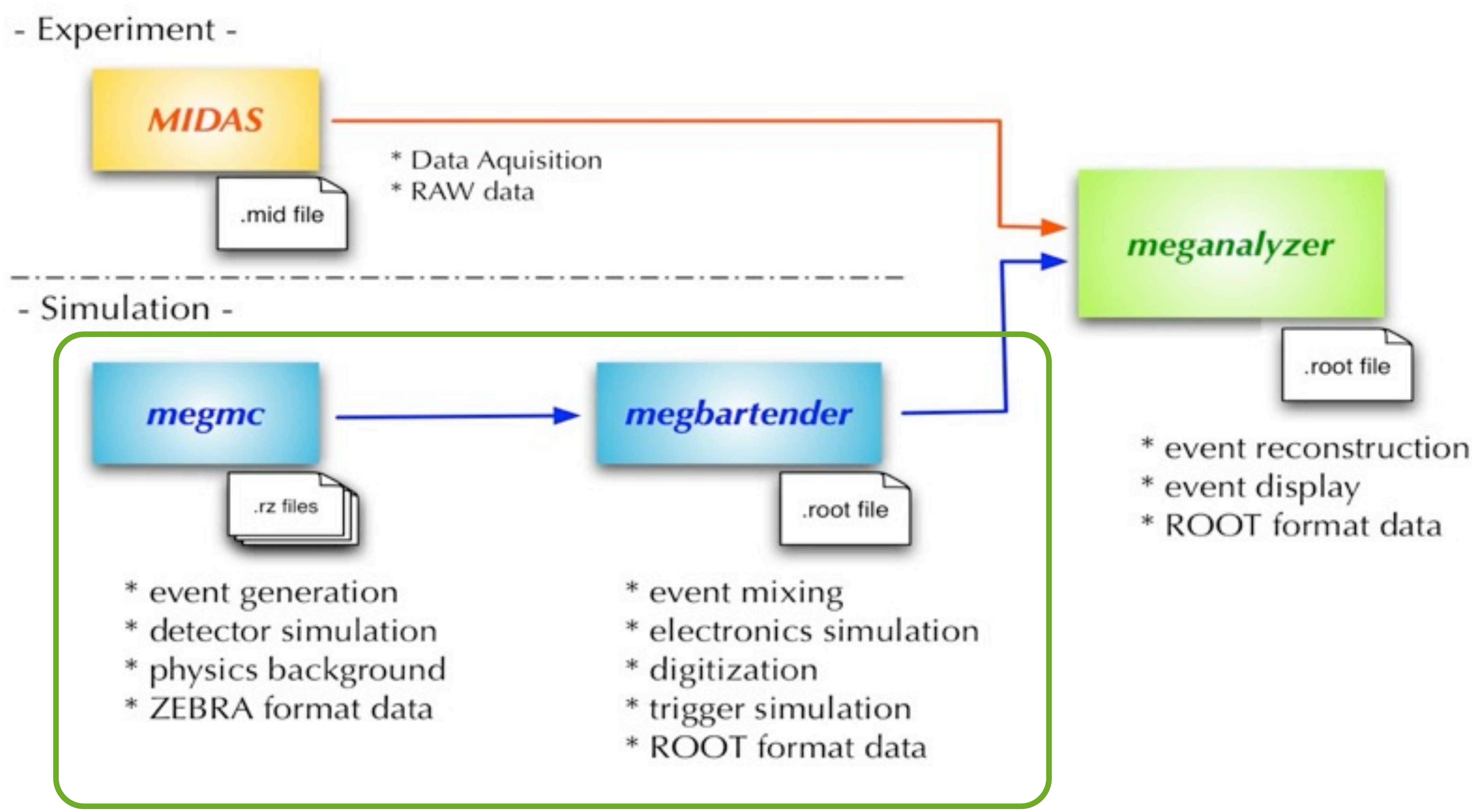


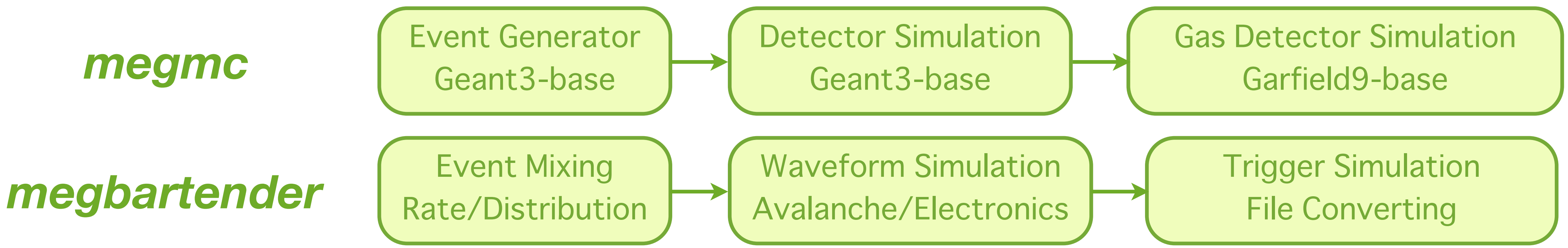
Simulation

Simulation and Analysis Flow

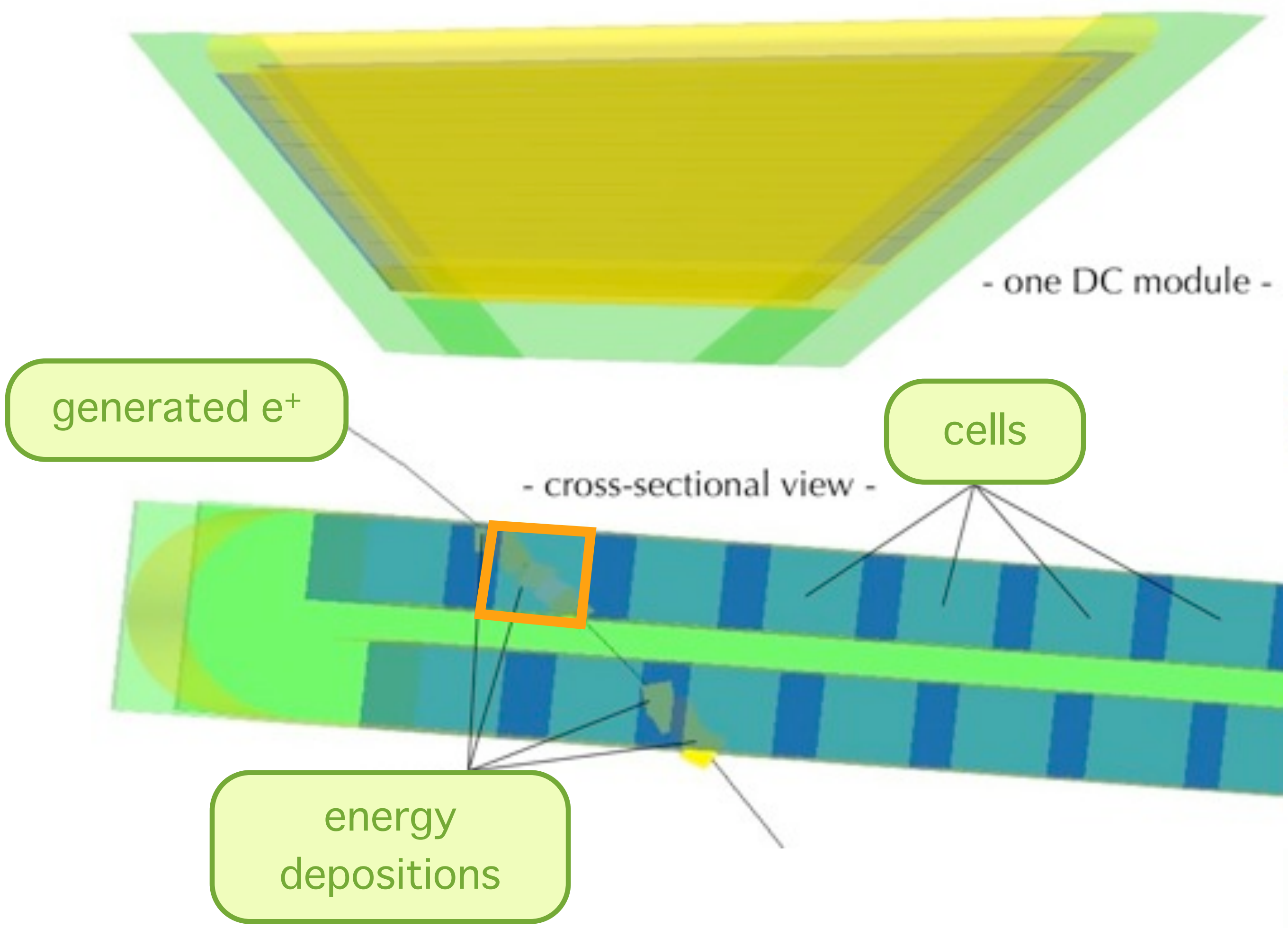


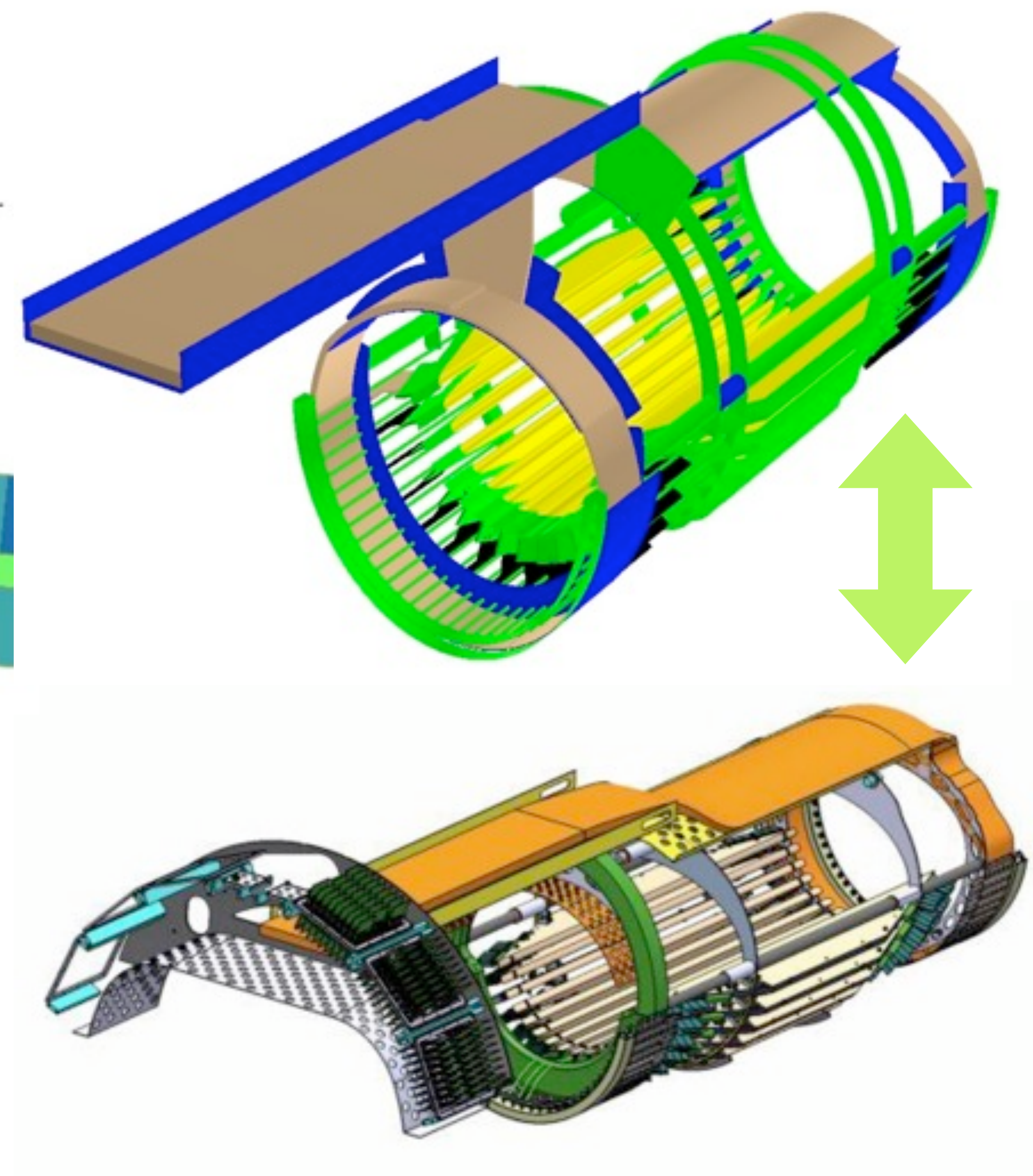
Simulation and Analysis Flow



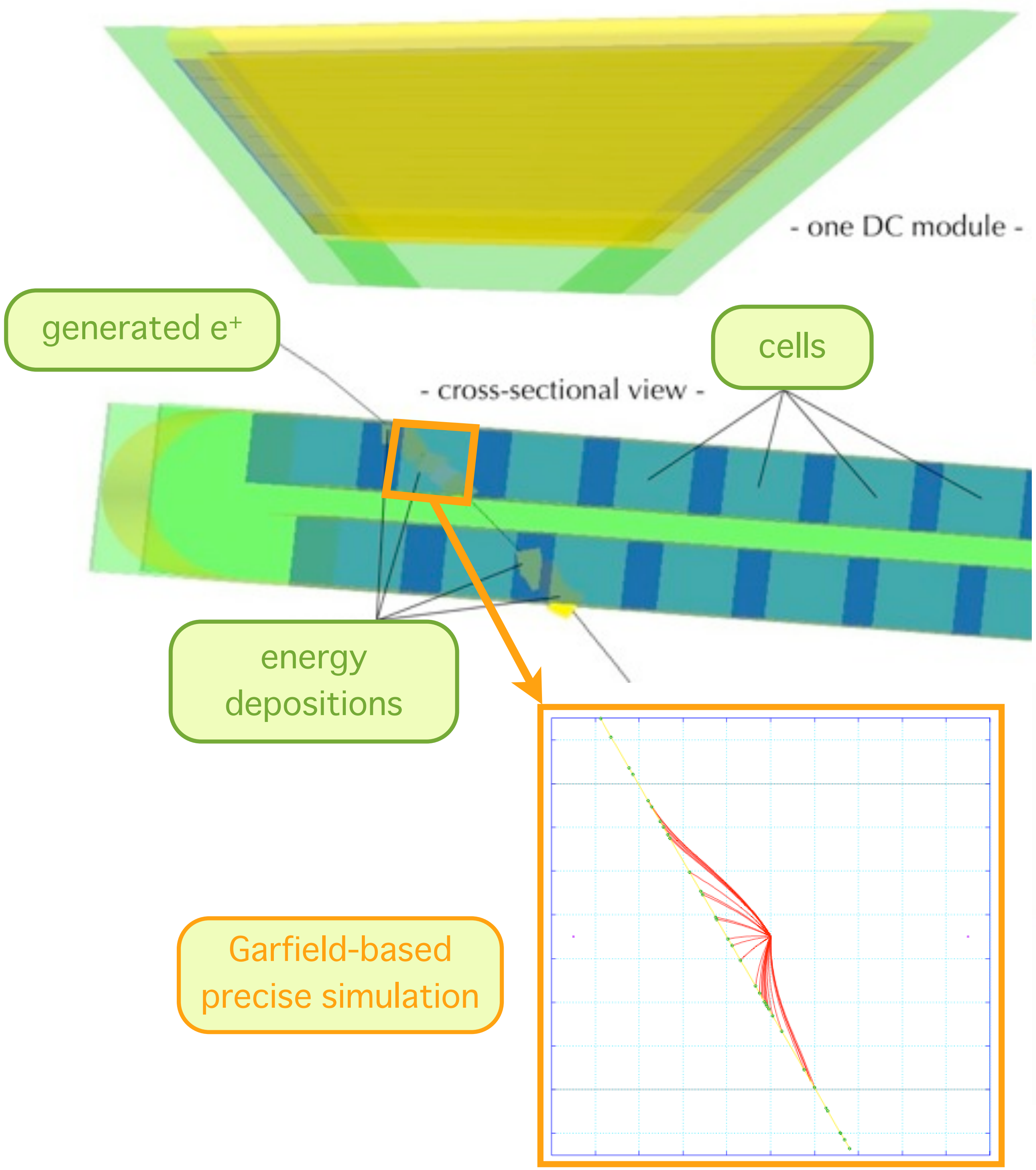


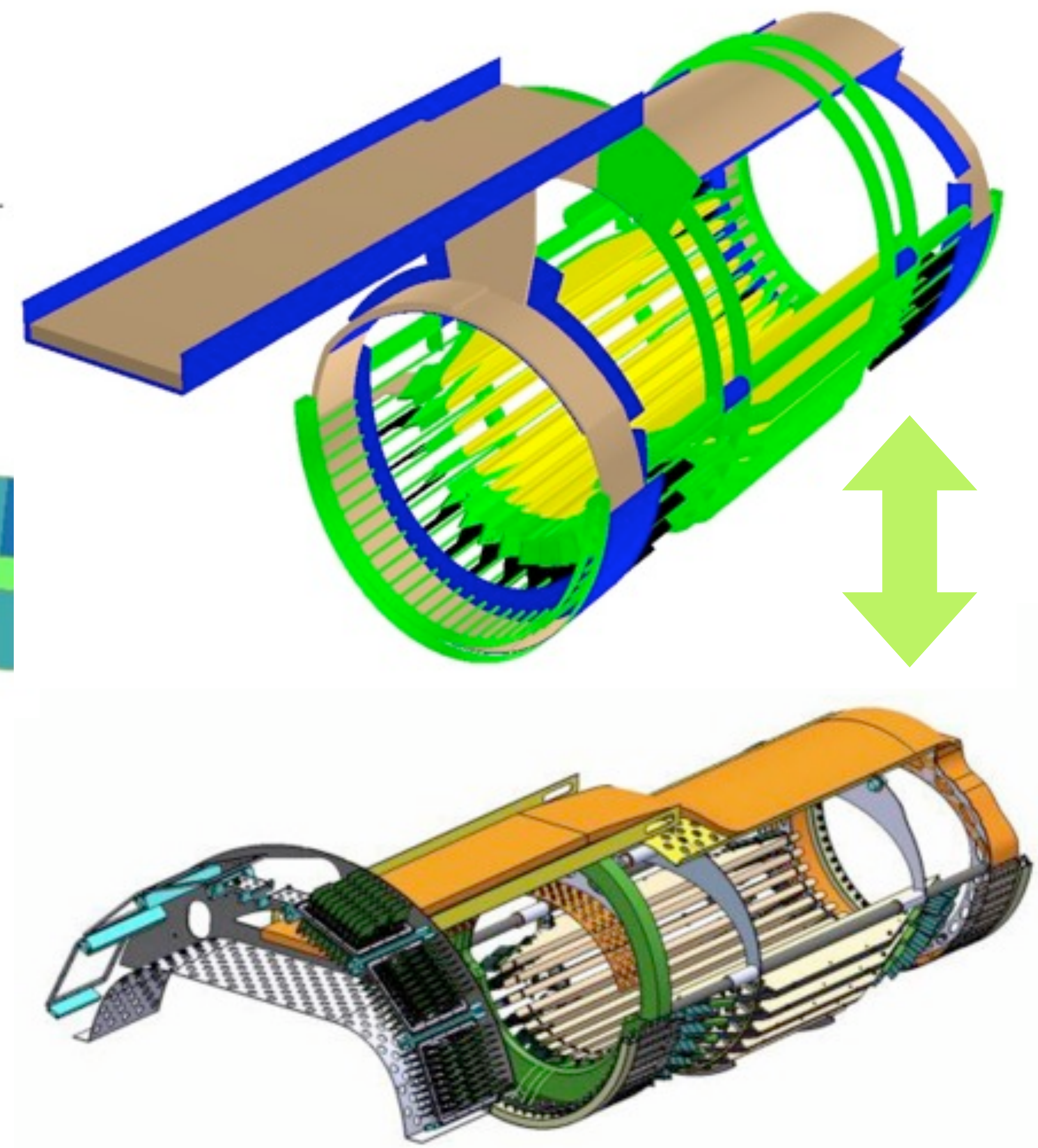
Event Generation and Detector Simulation



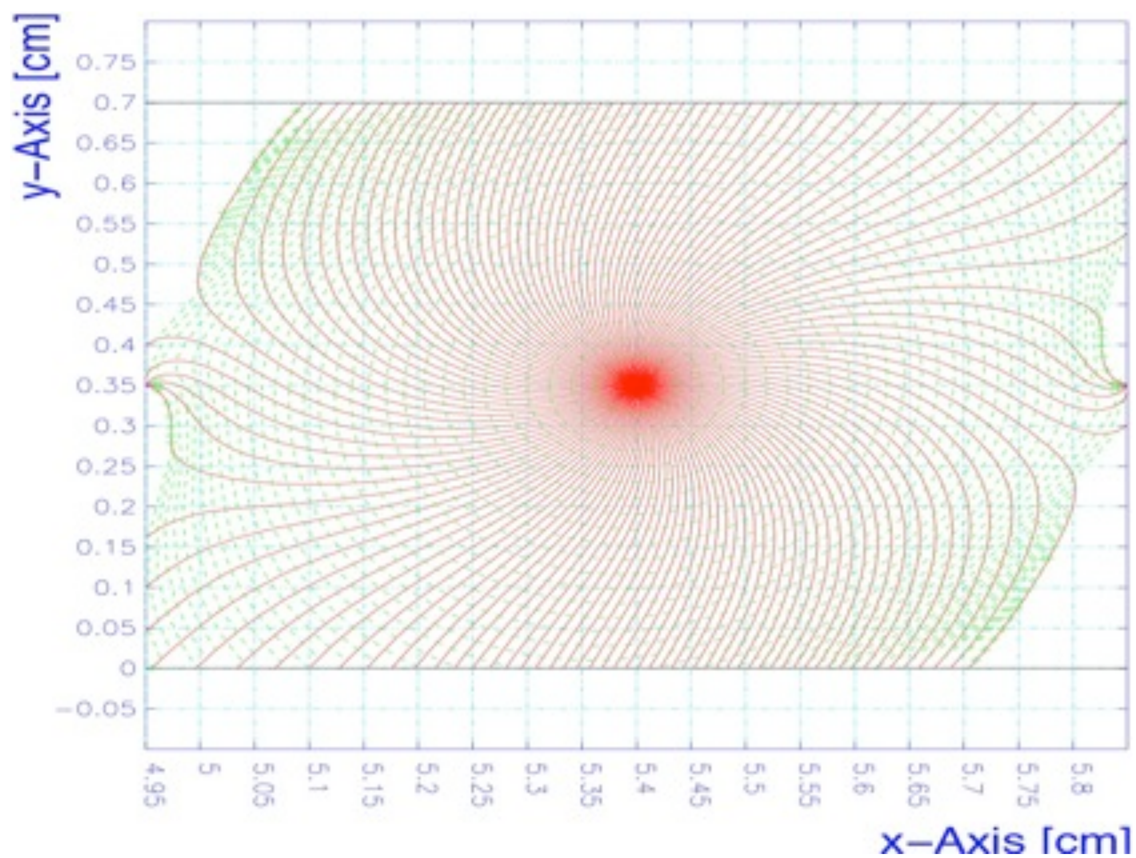


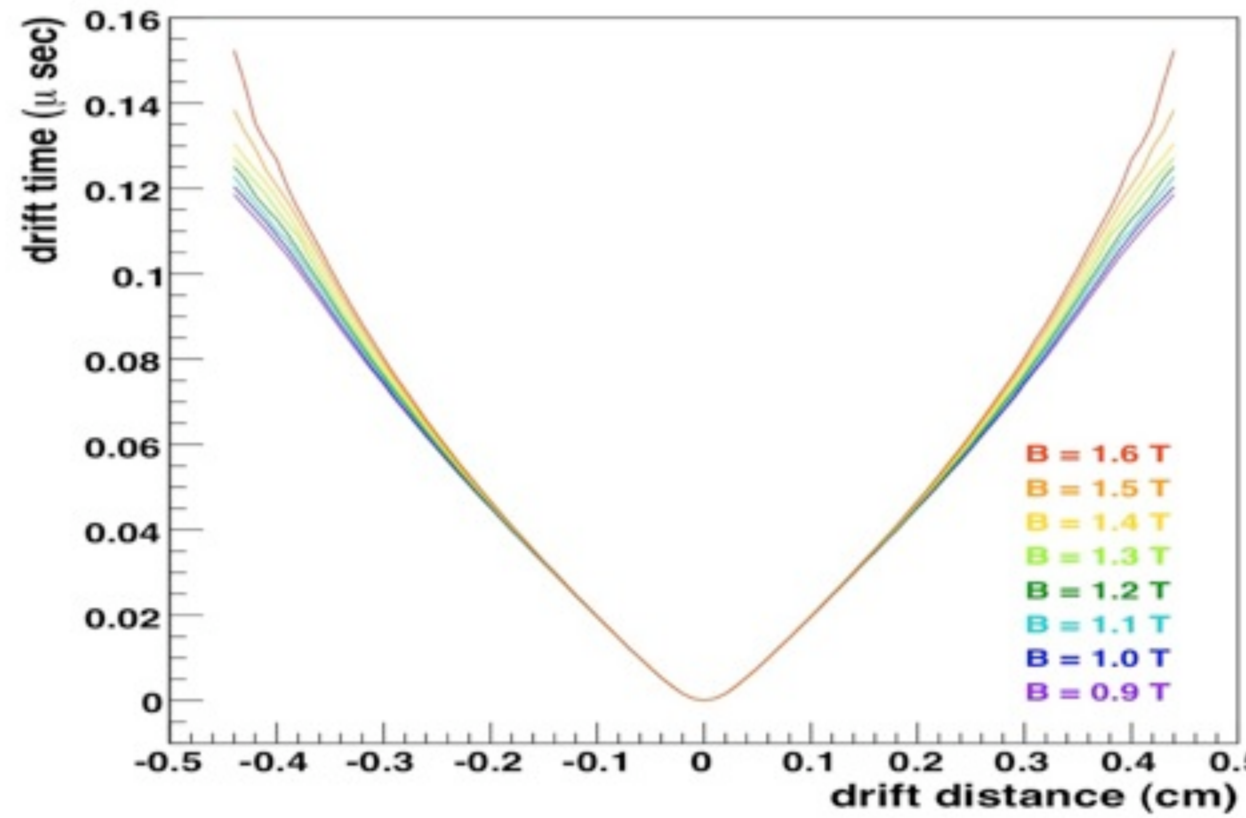
Event Generation and Detector Simulation

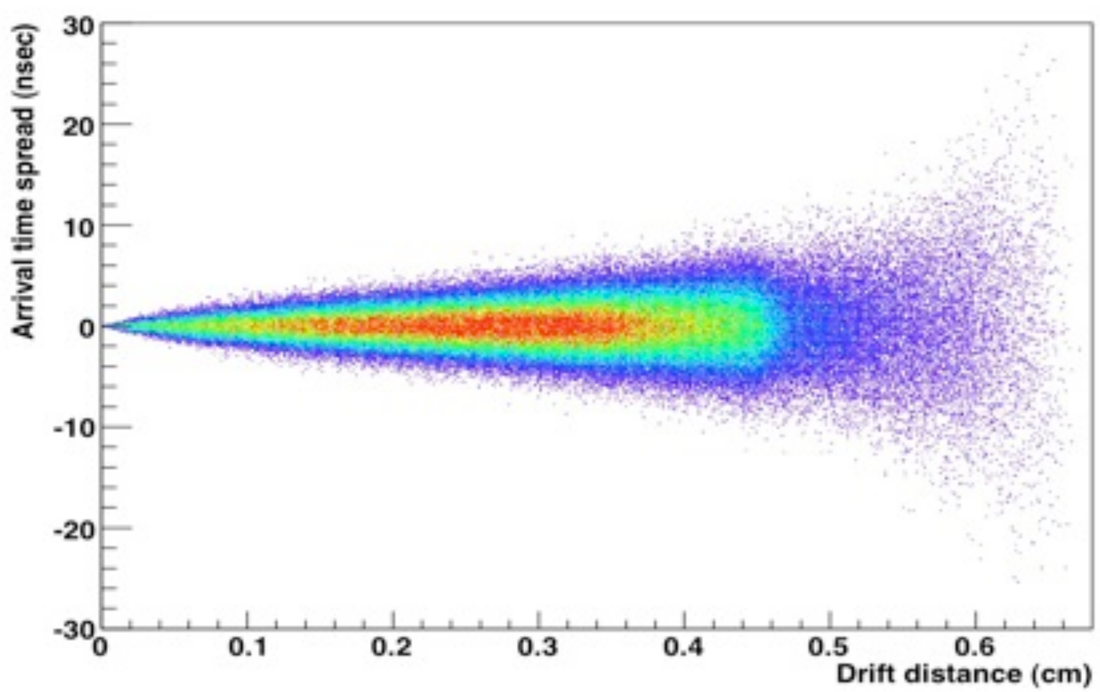


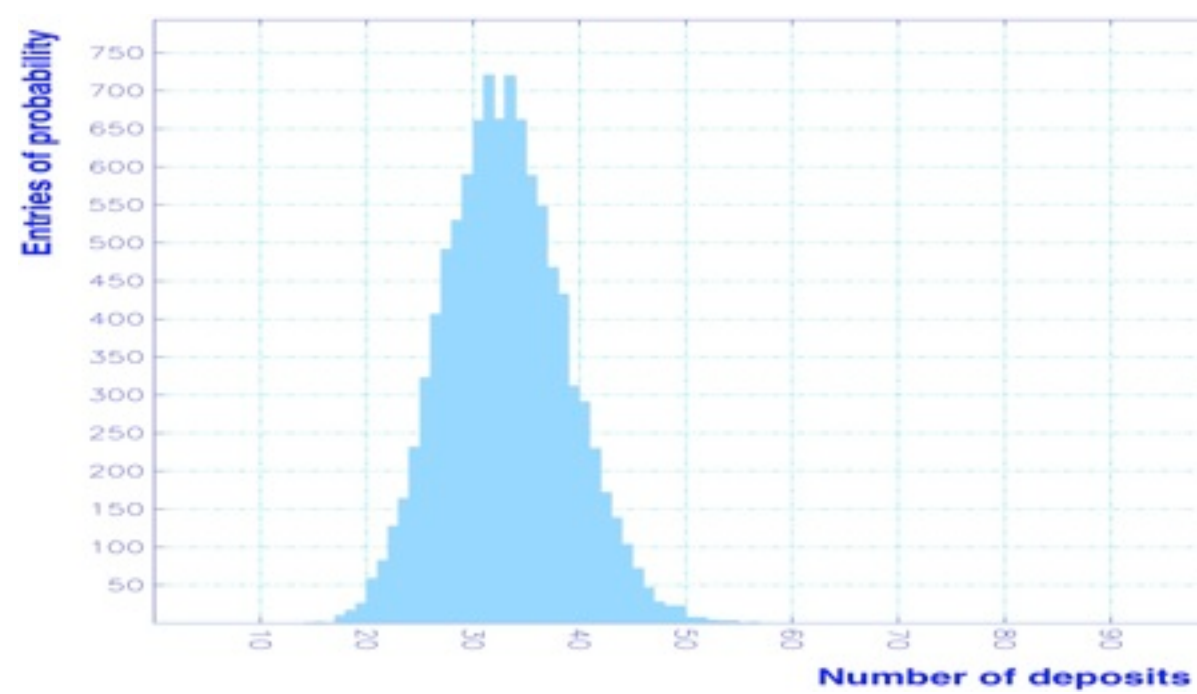


Gaseous Detector Simulation



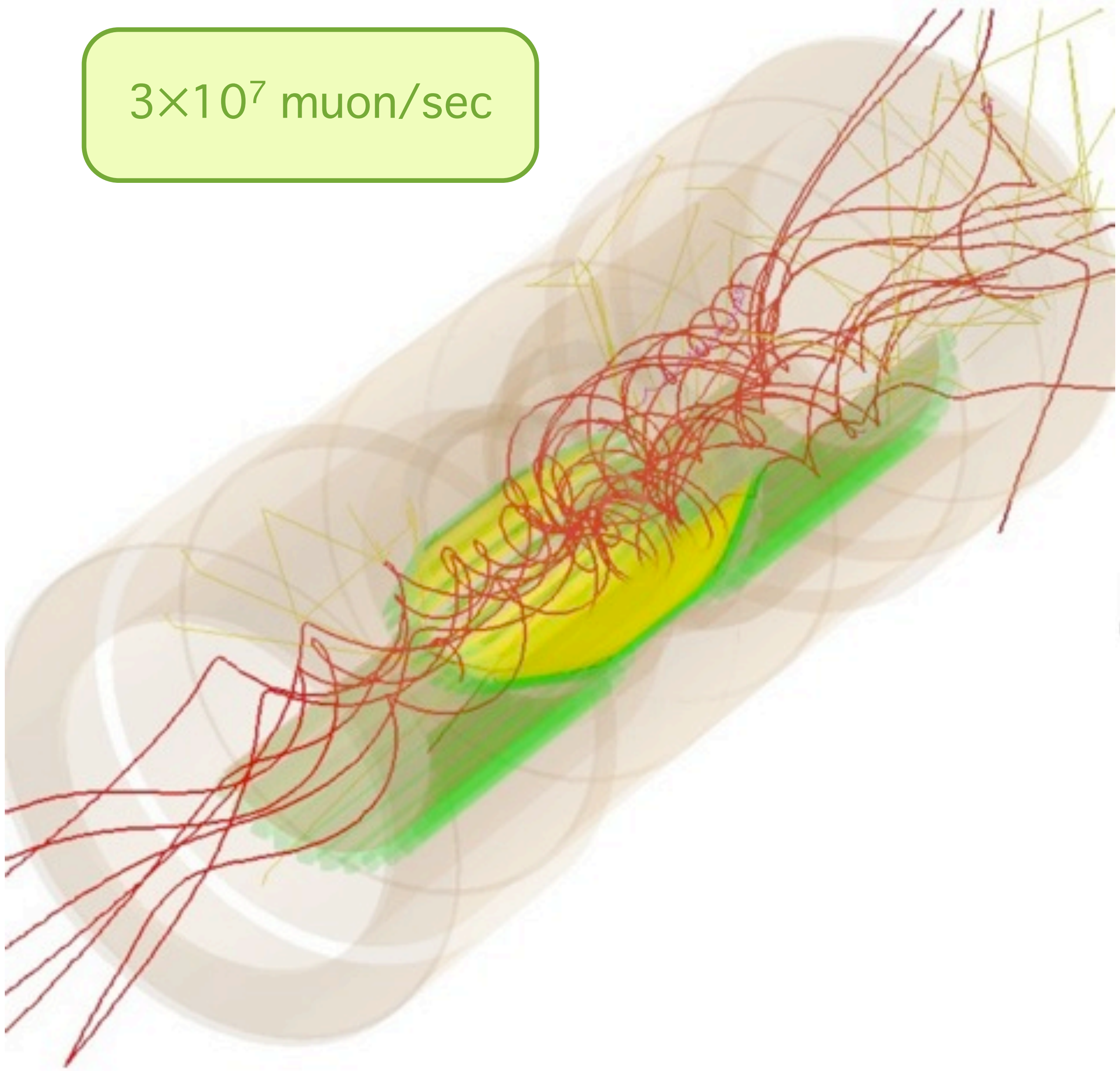


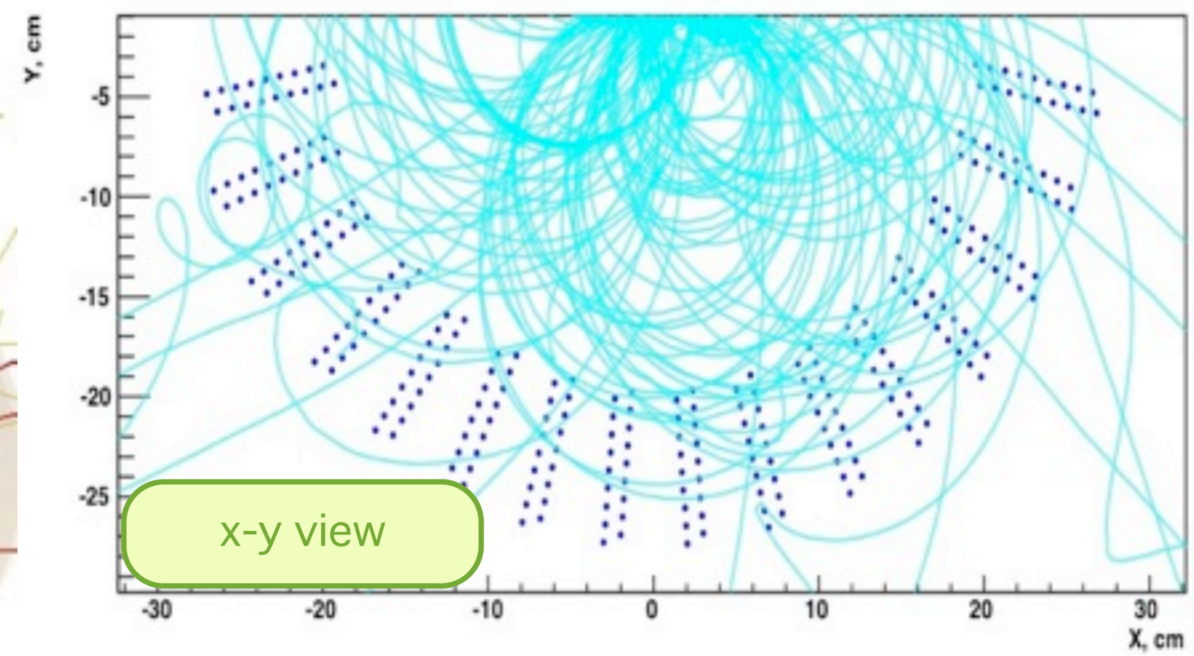


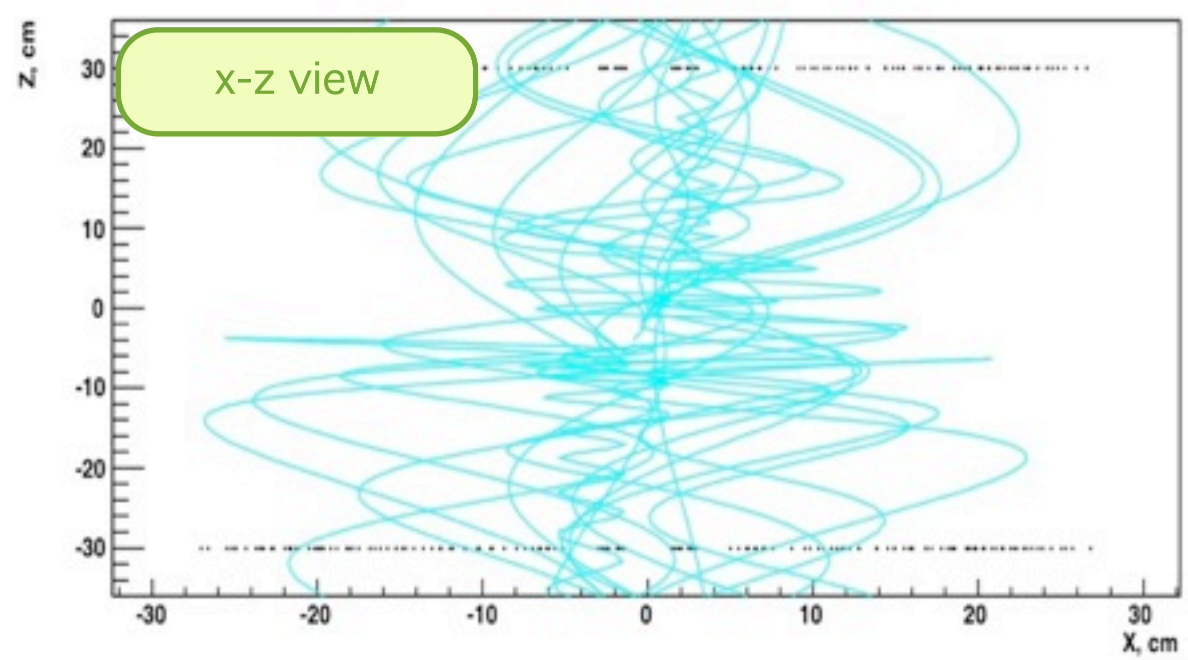


Simulation

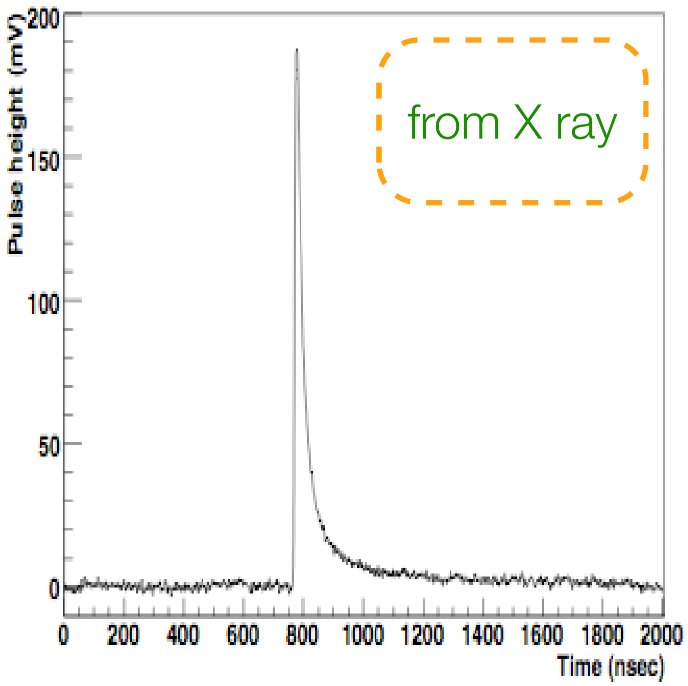
Event Mixing

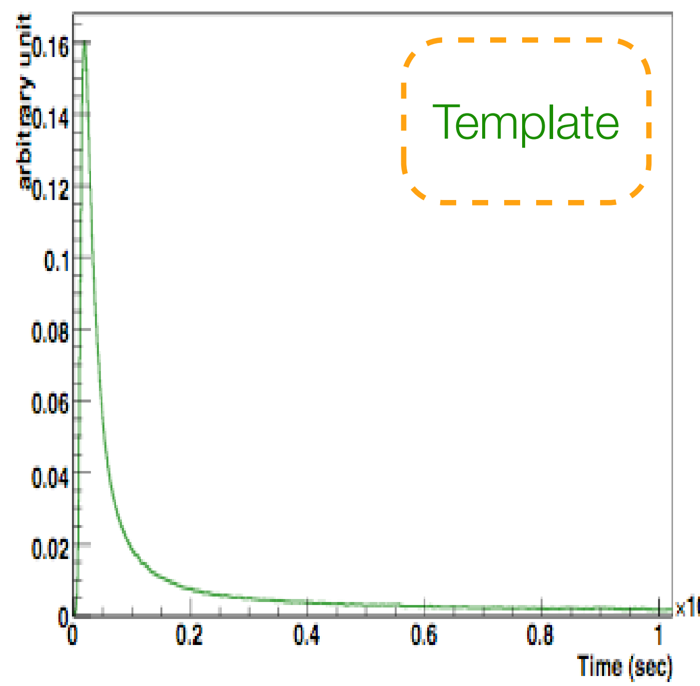


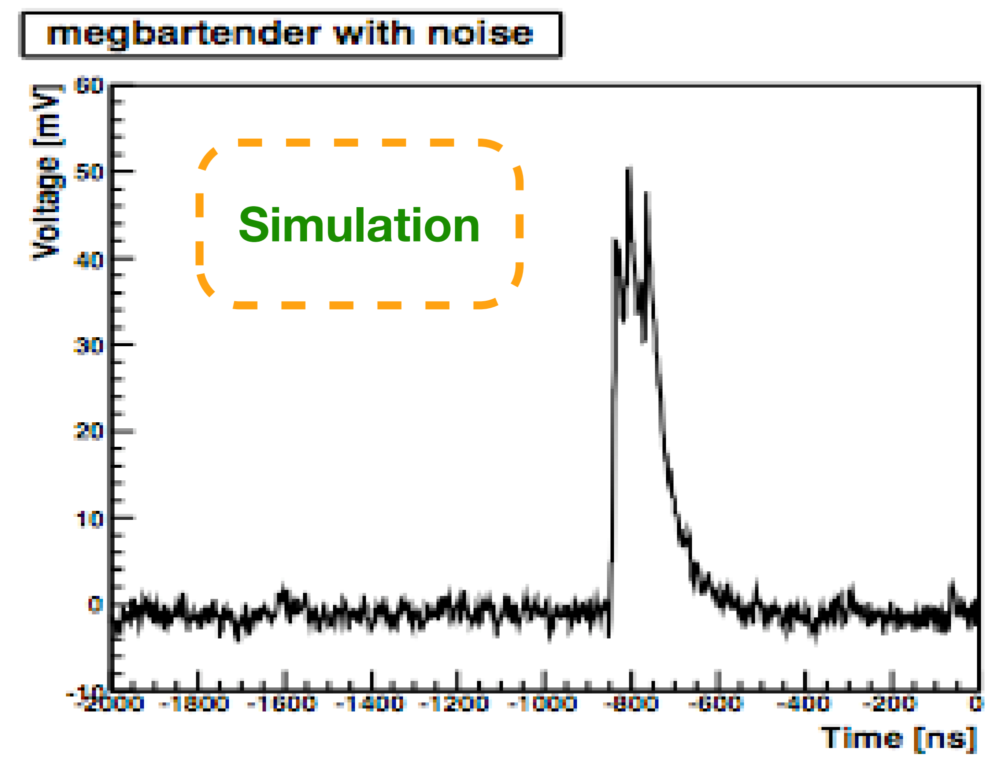


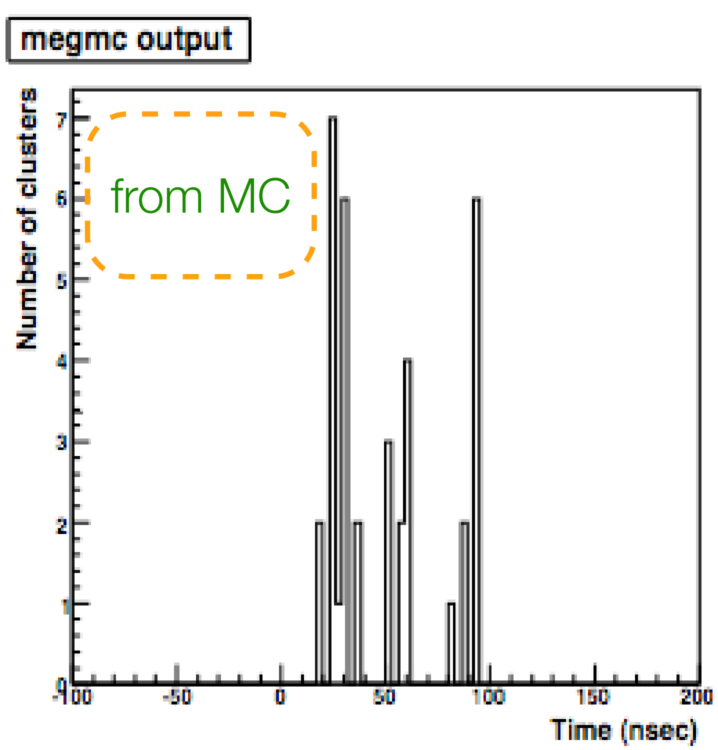


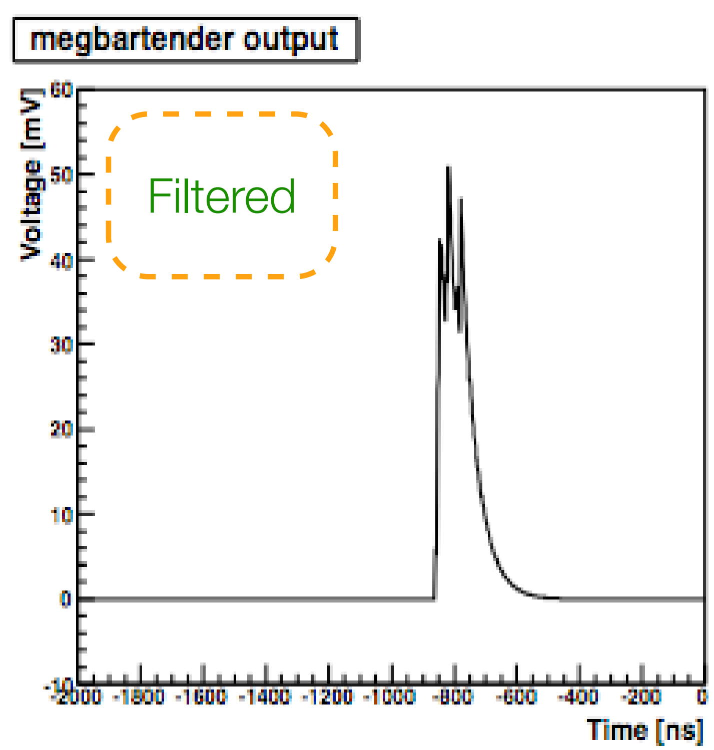
Waveform Simulation (1)

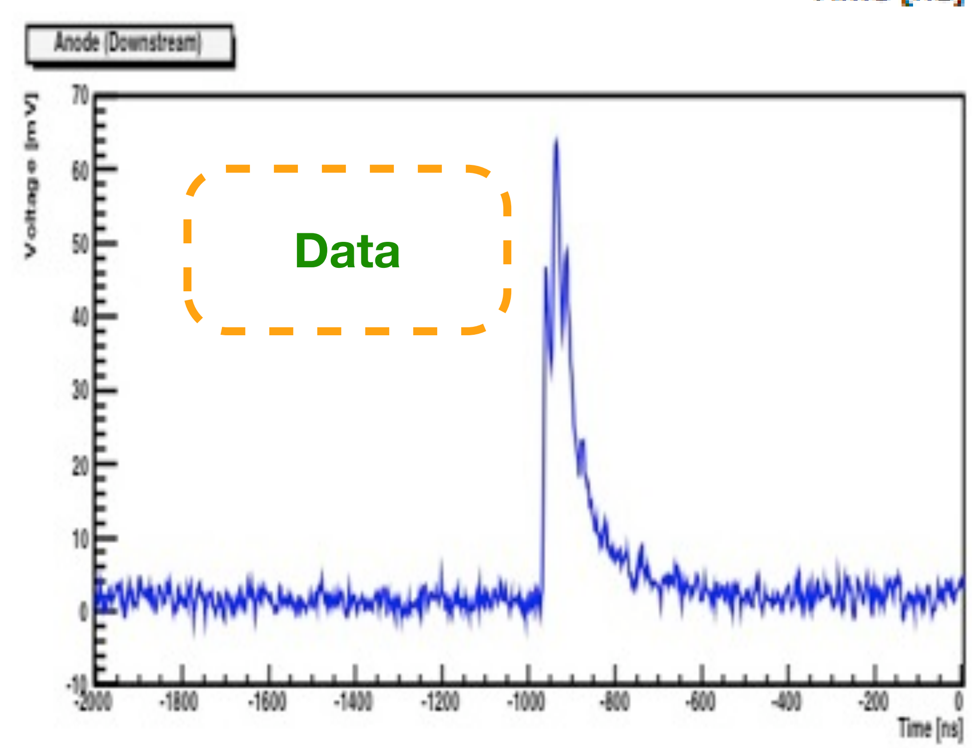




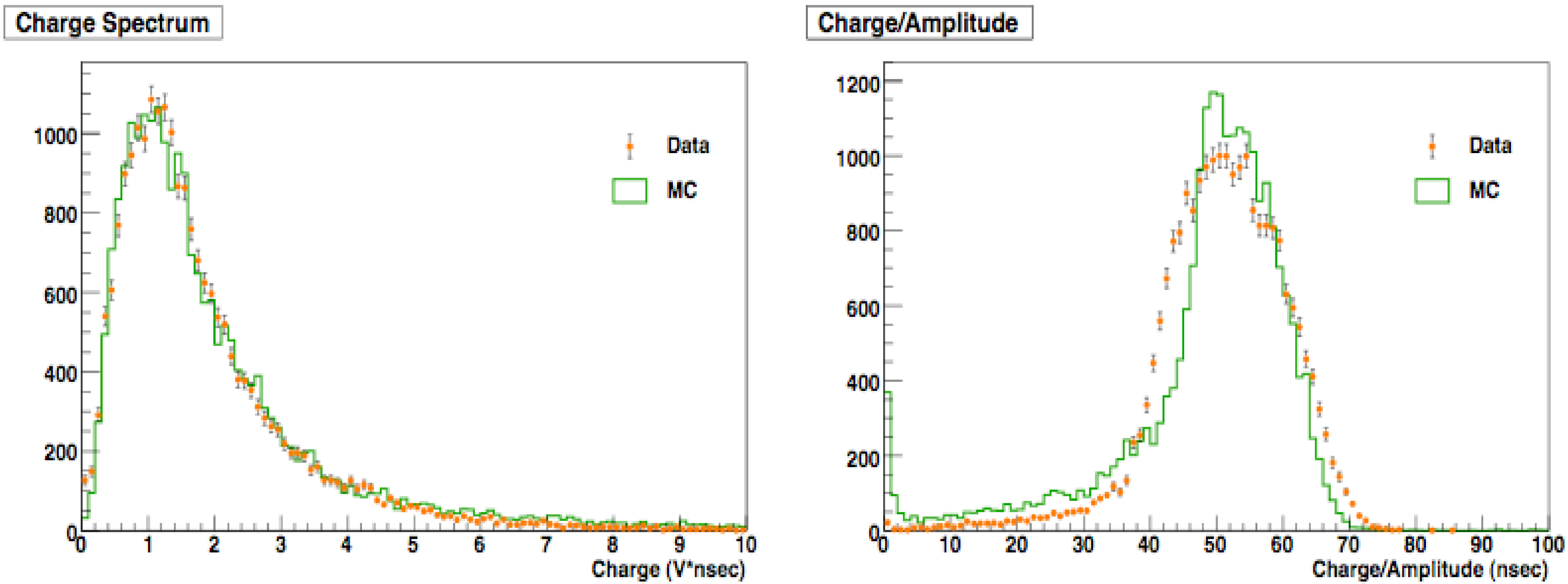








Waveform Simulation (2)

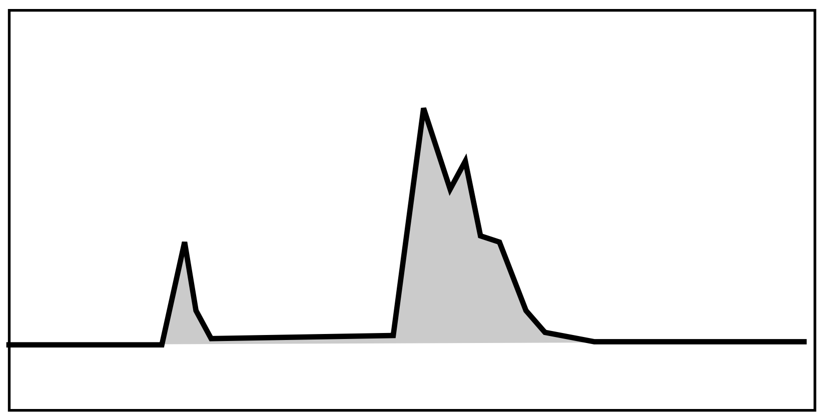


(a) Charge (b) Charge/Amplitude

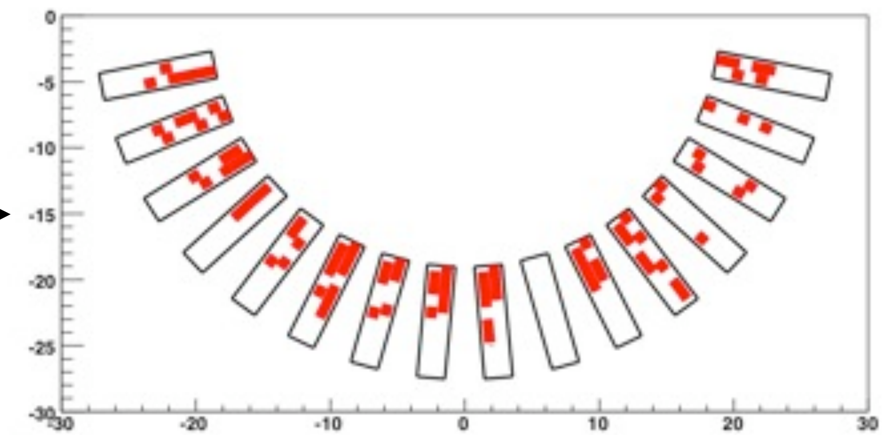
- Waveform Reproducibility
- “Charge” ~ “Height”, “Charge/Amplitude” ~ “Width” or “Shape”

Event Reconstruction

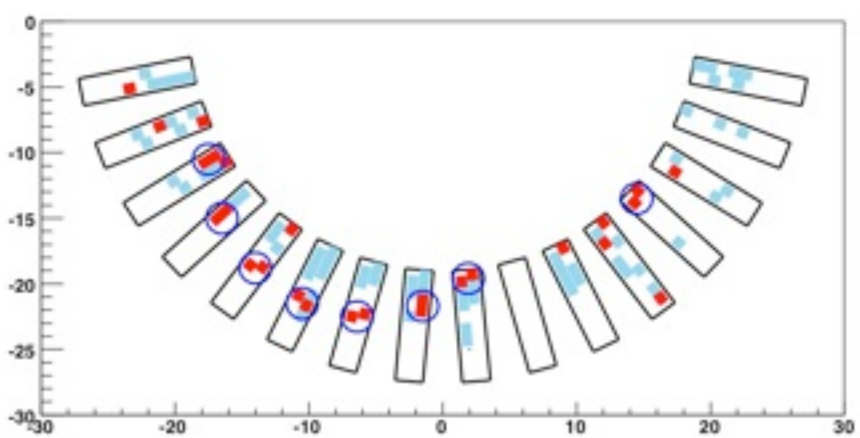
Event Reconstruction Flow



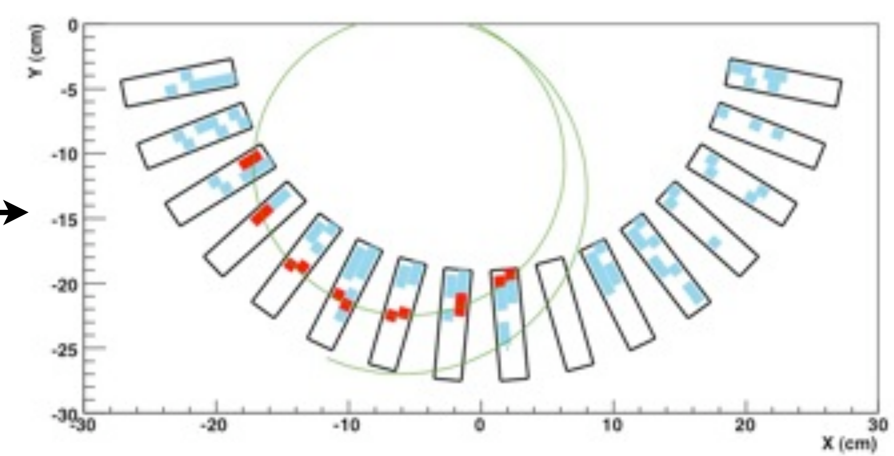
(1) Start from Waveform



(2) Hit Reconstruction



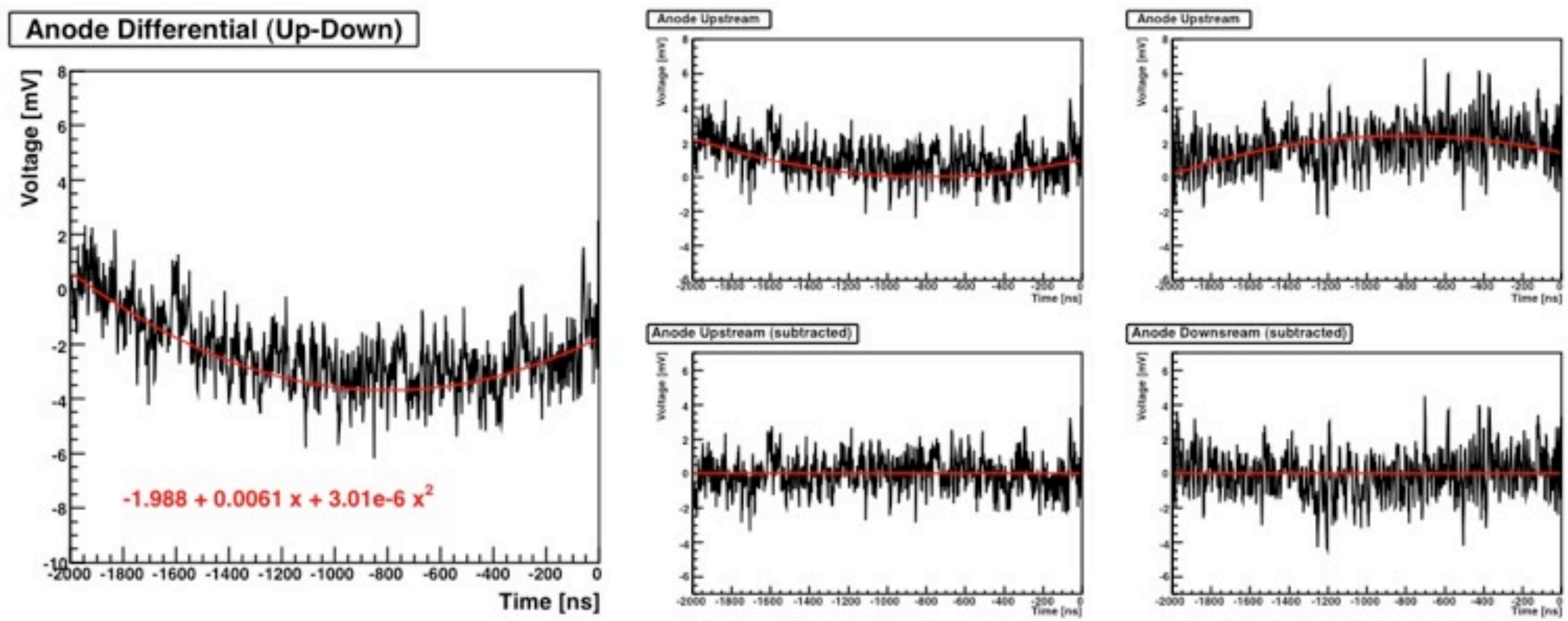
(3) Pattern Recognition



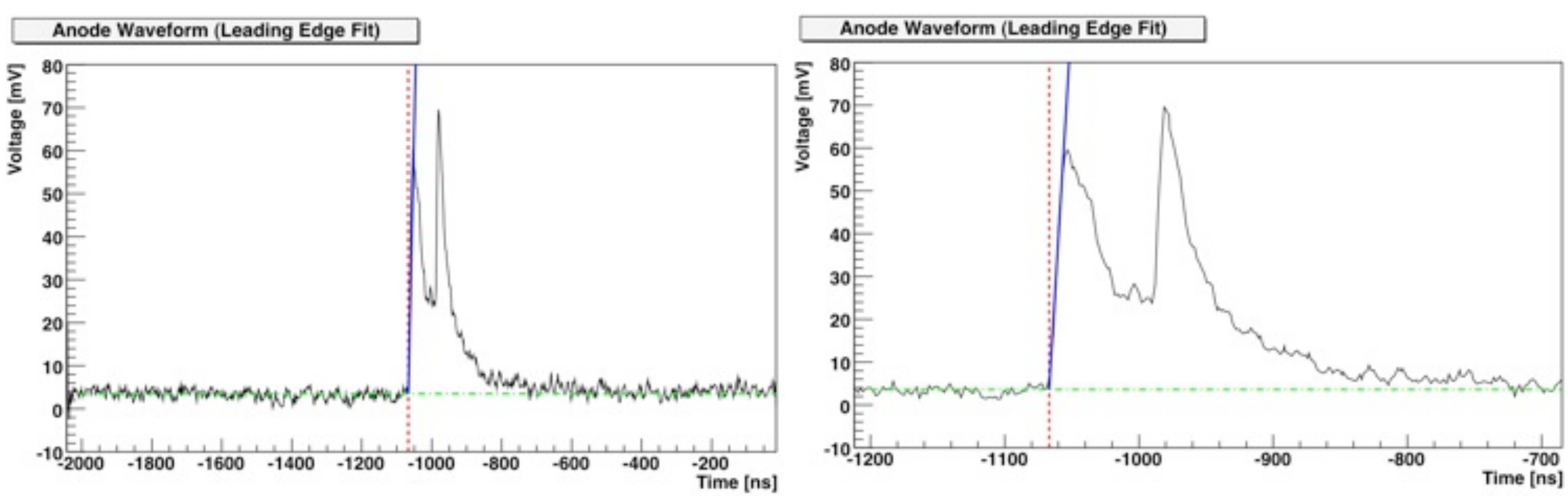
(4) Track Fitting

Hit Reconstruction

baseline fitting

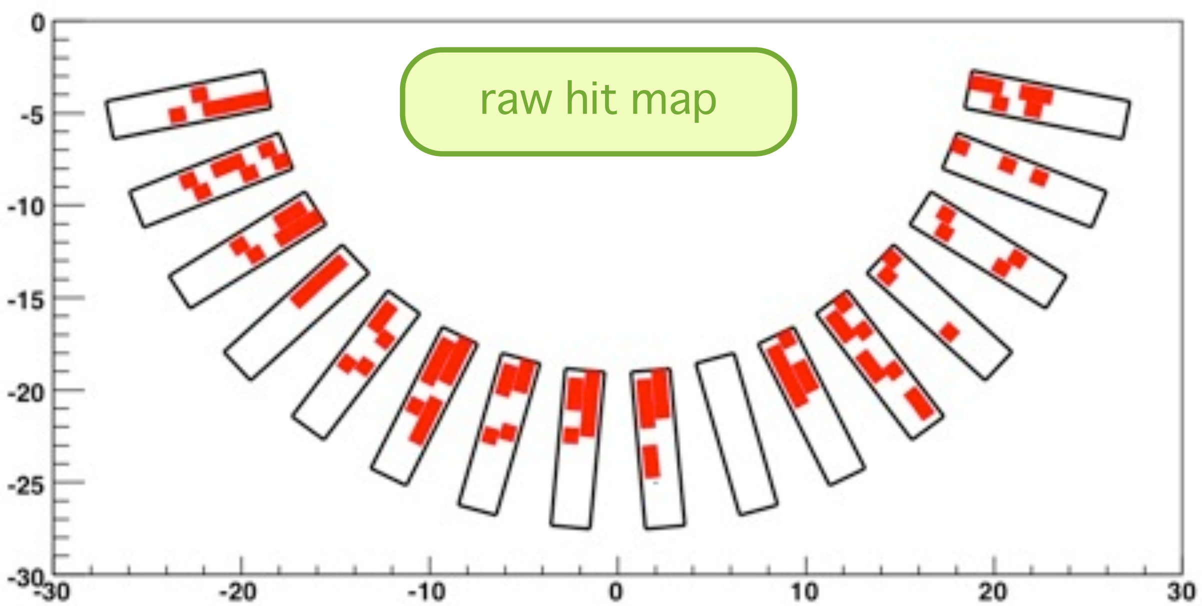


leading-edge fit

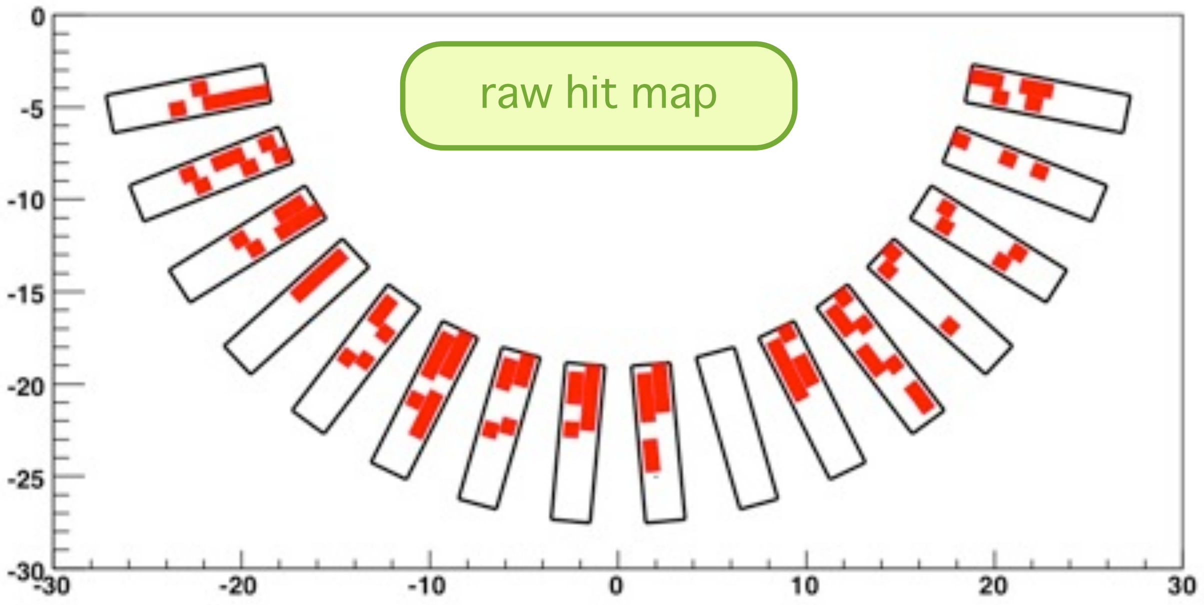


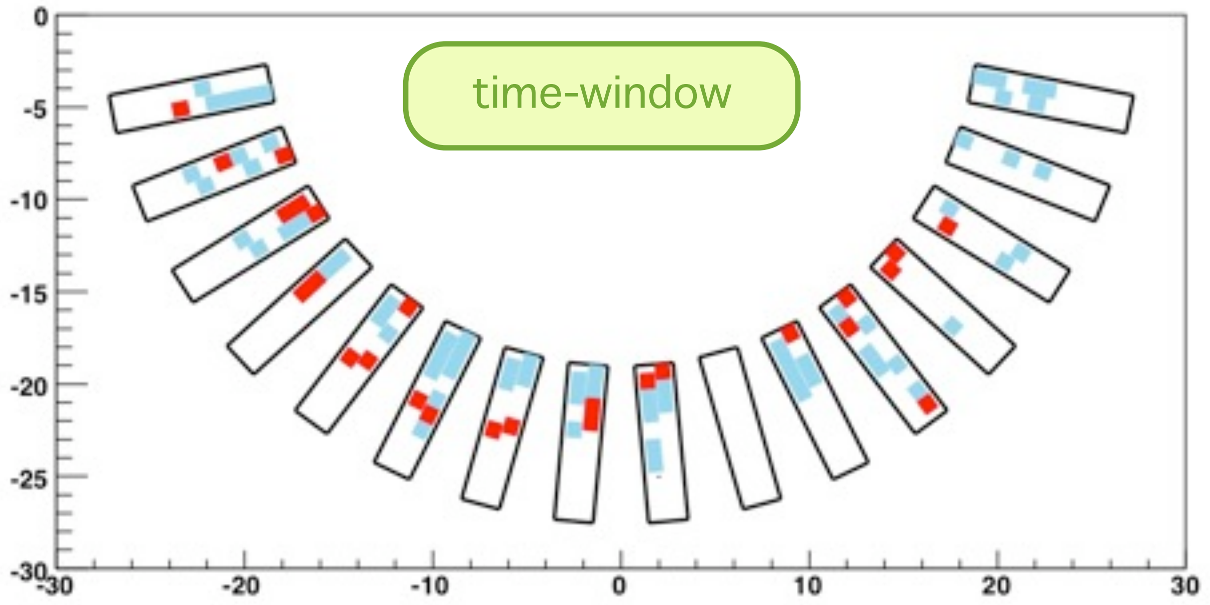
Track Finding (*x*-*y* view)

Track Finding (*x*-*y* view)

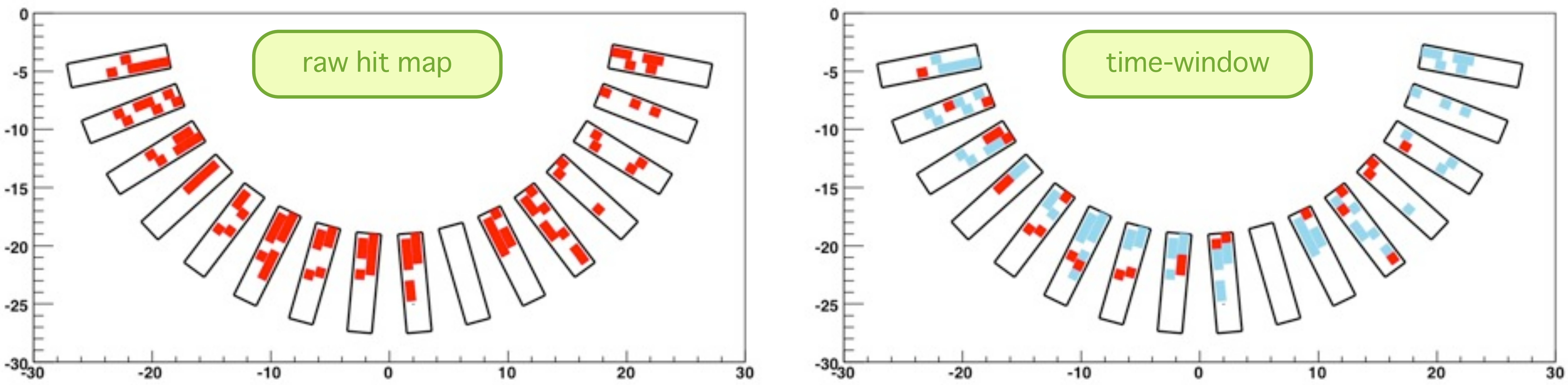


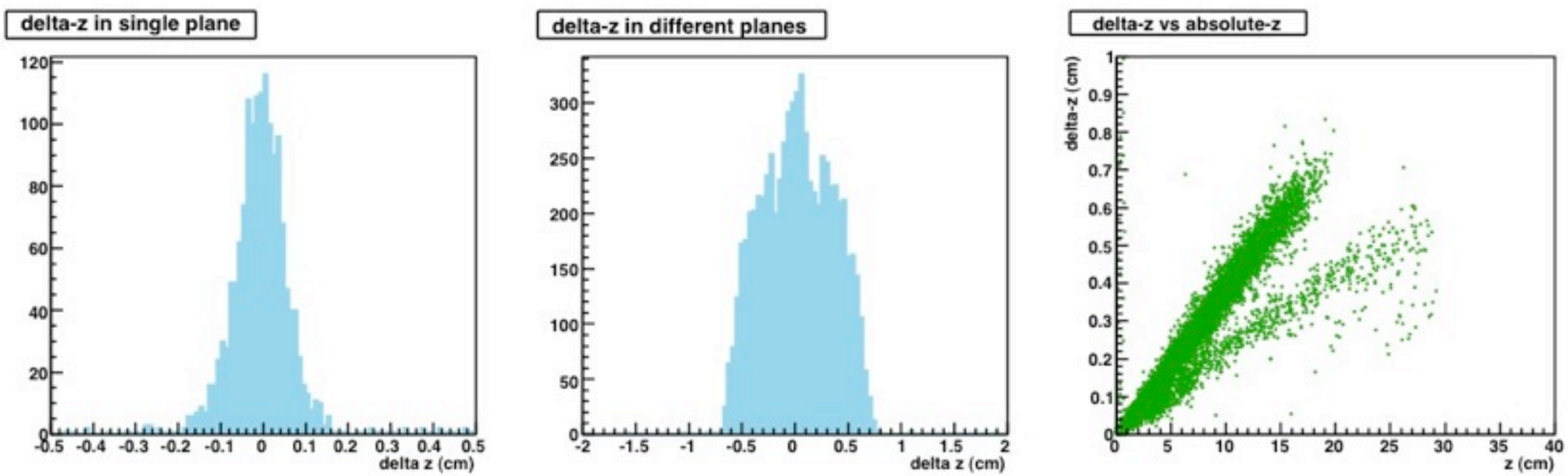
Track Finding (*x*-*y* view)



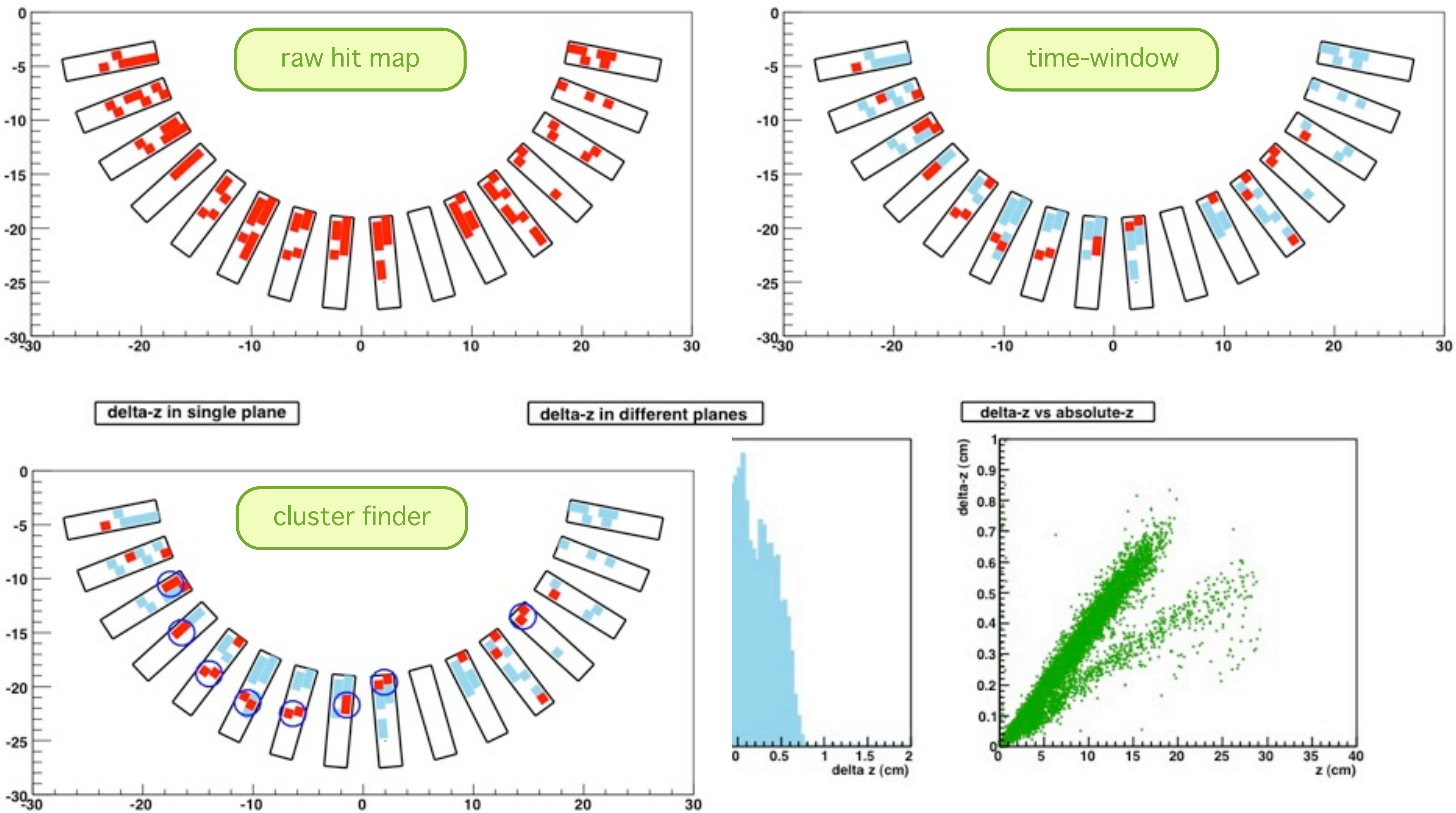


Track Finding (*x*-*y* view)

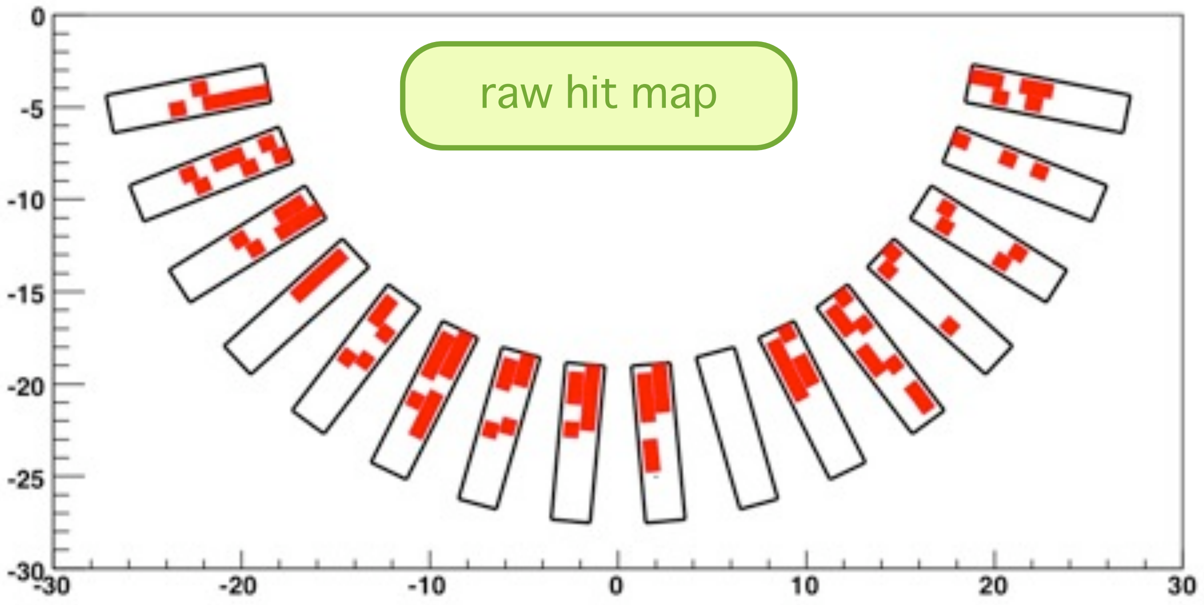


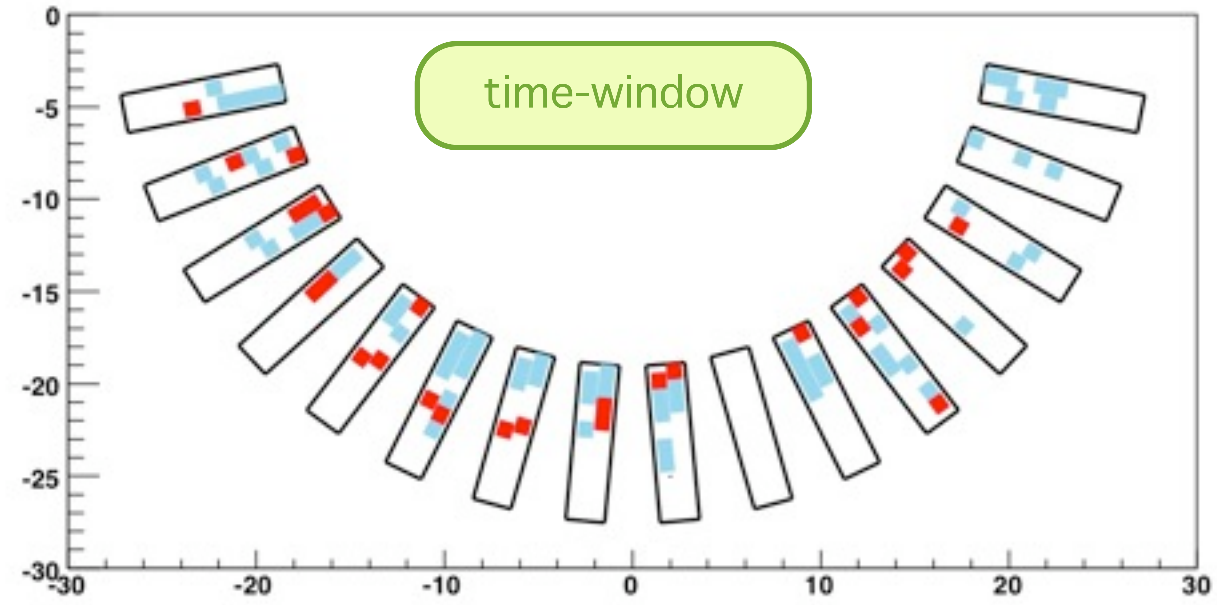


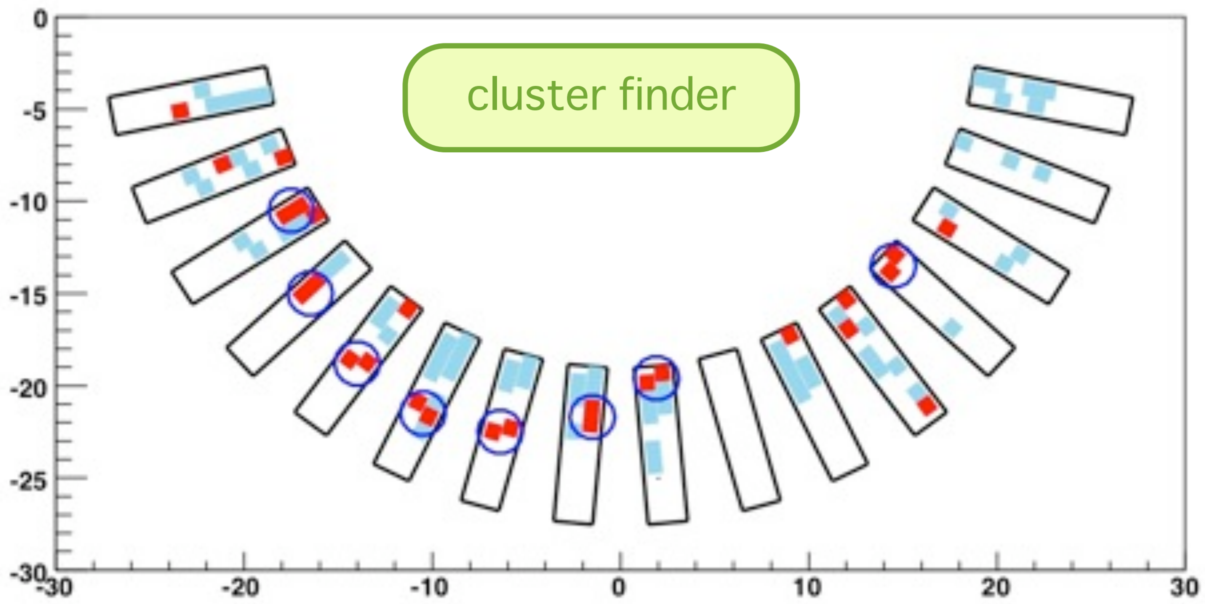
Track Finding (*x*-*y* view)



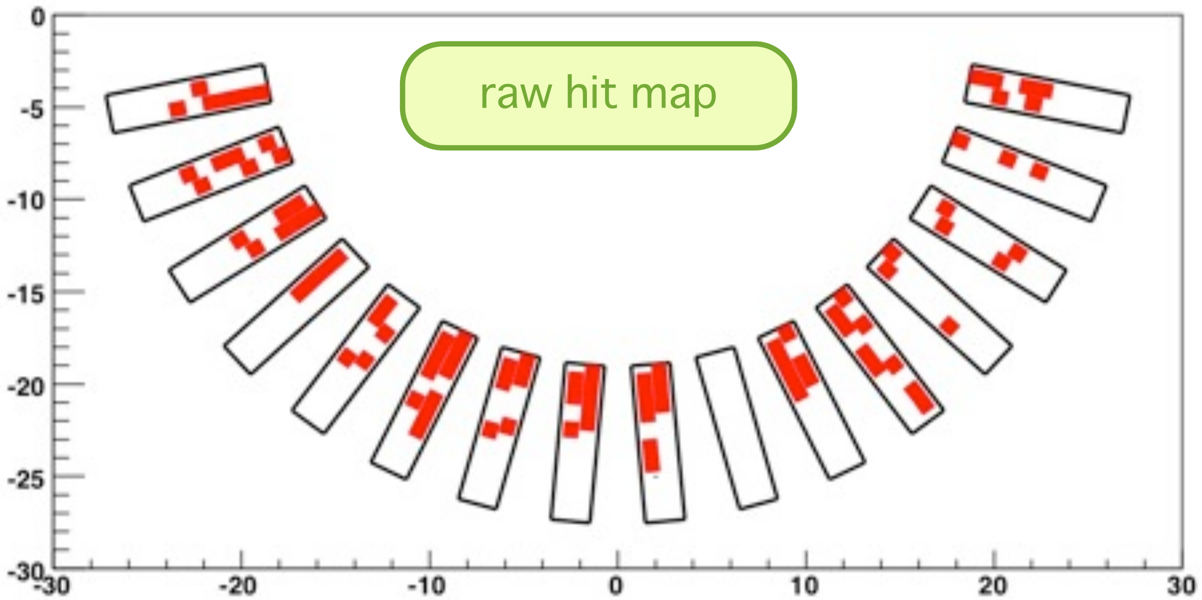
Track Finding (*x*-*y* view)

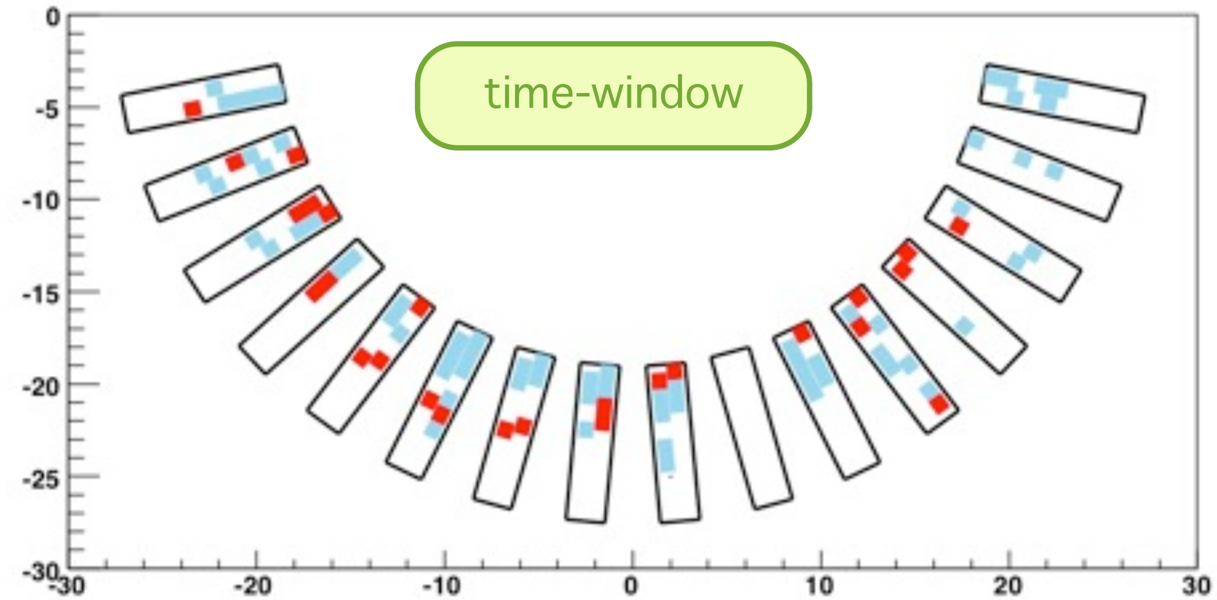


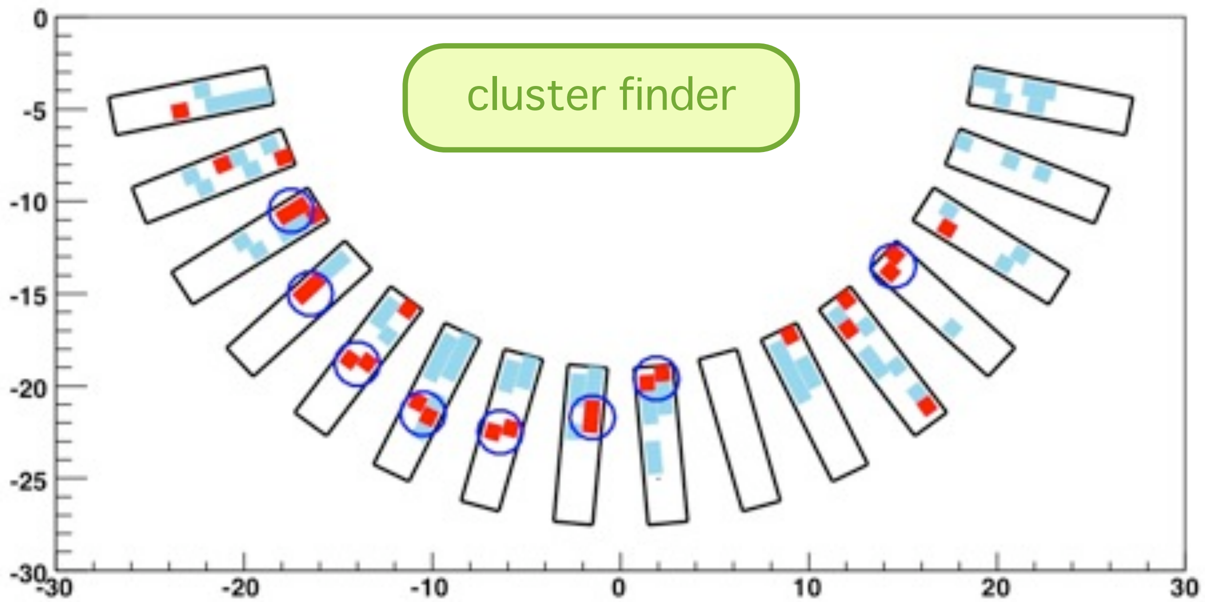


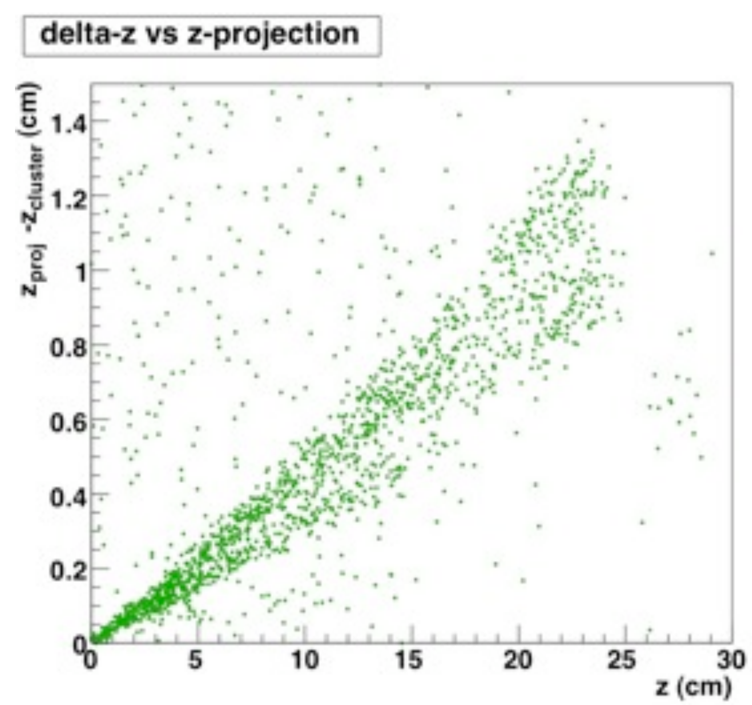


Track Finding (*x*-*y* view)

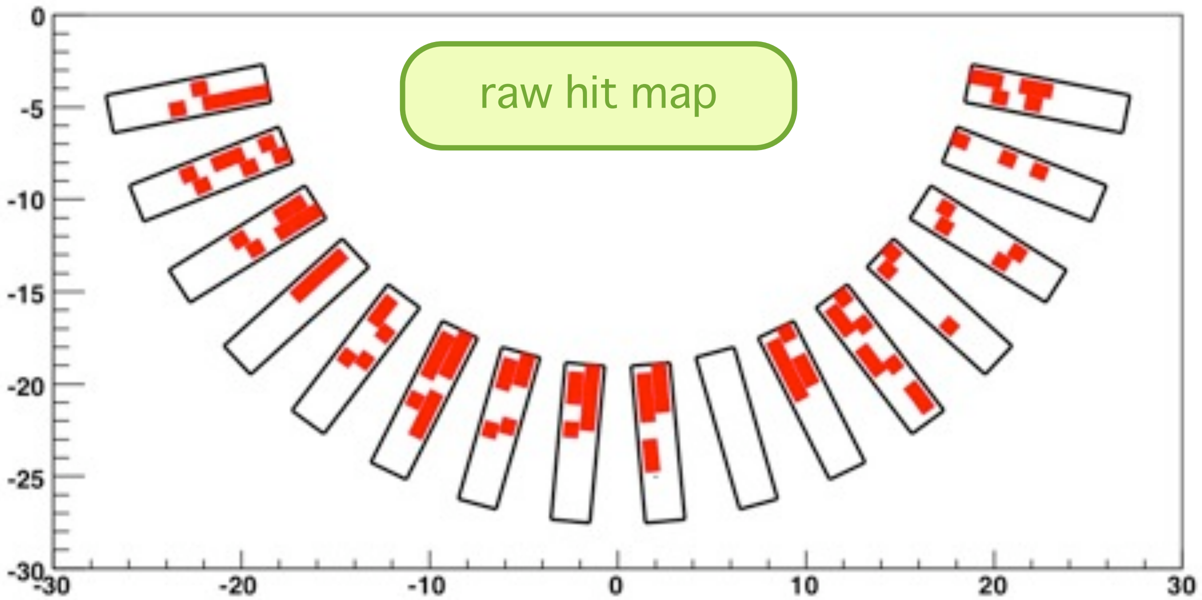


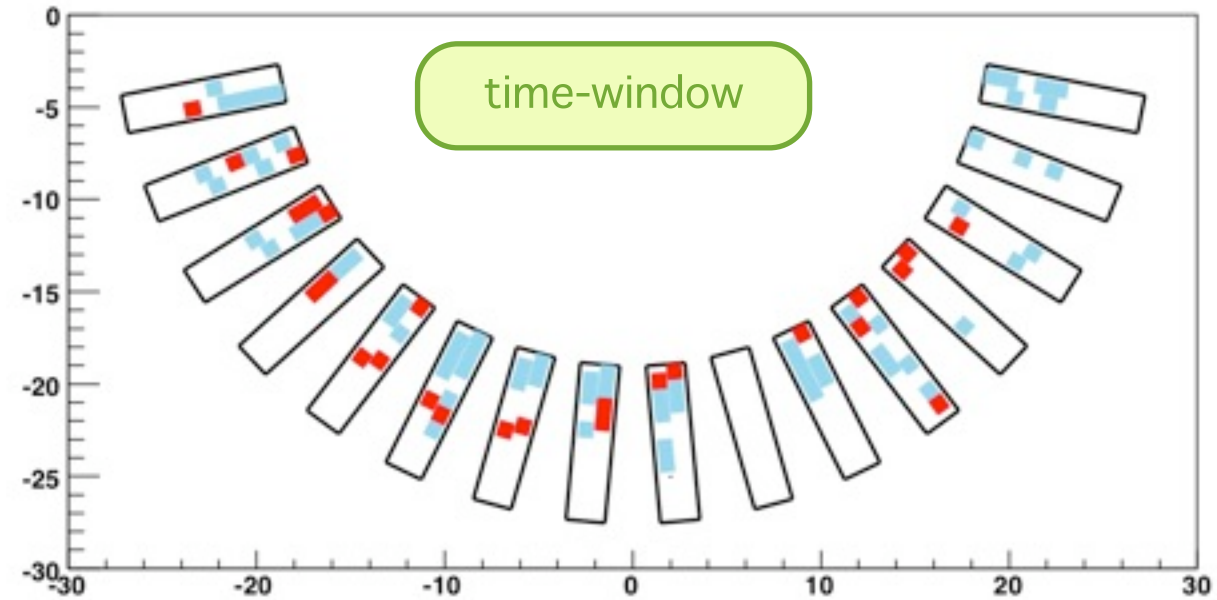


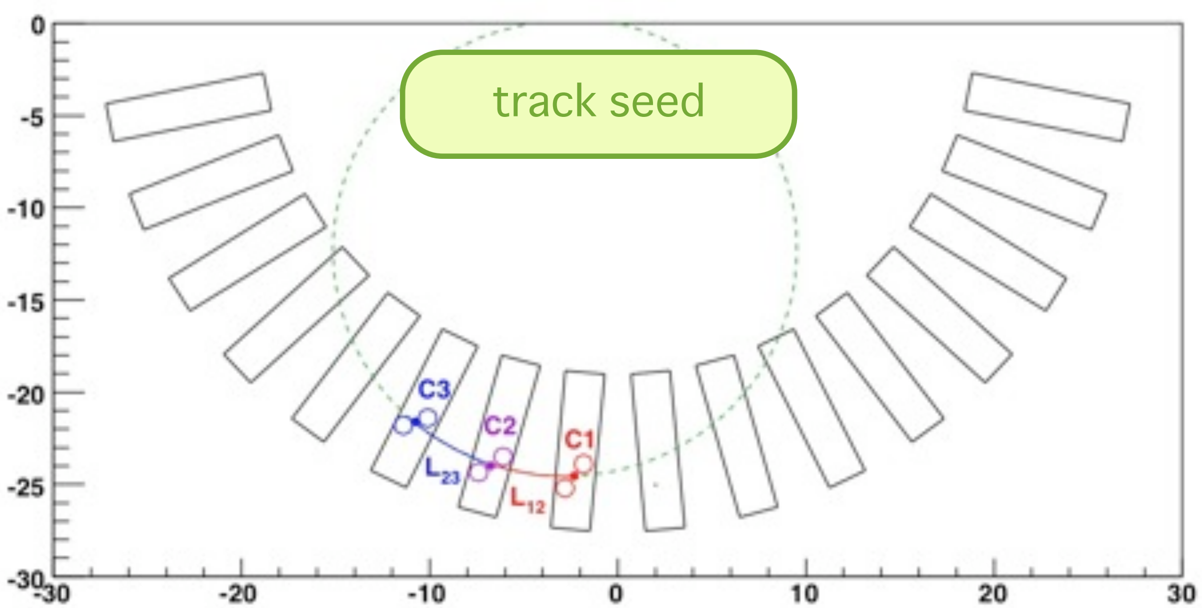


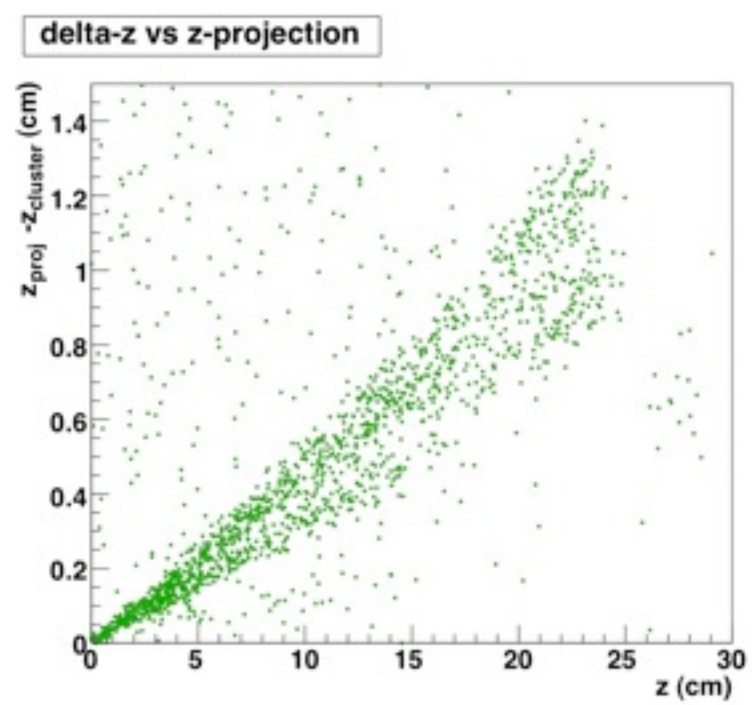


Track Finding (*x*-*y* view)

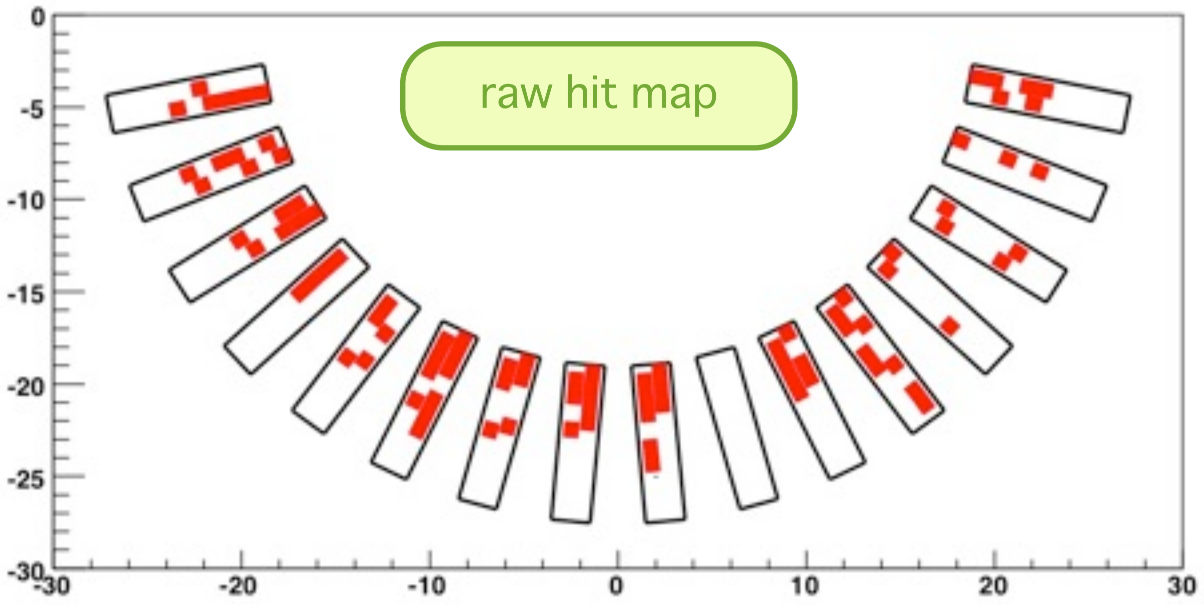


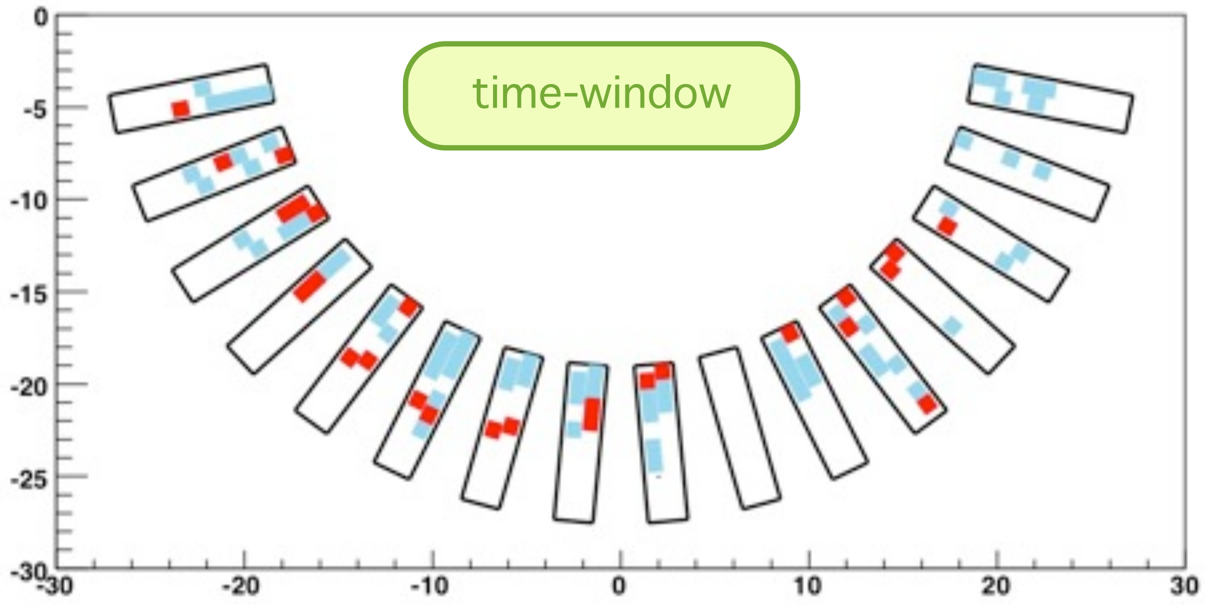


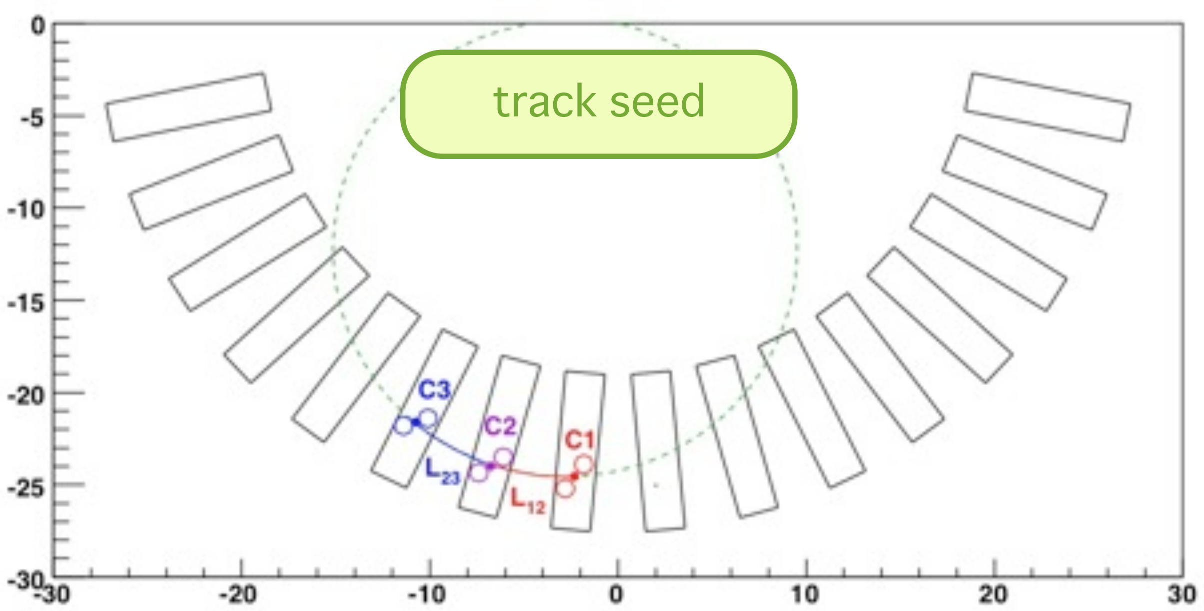




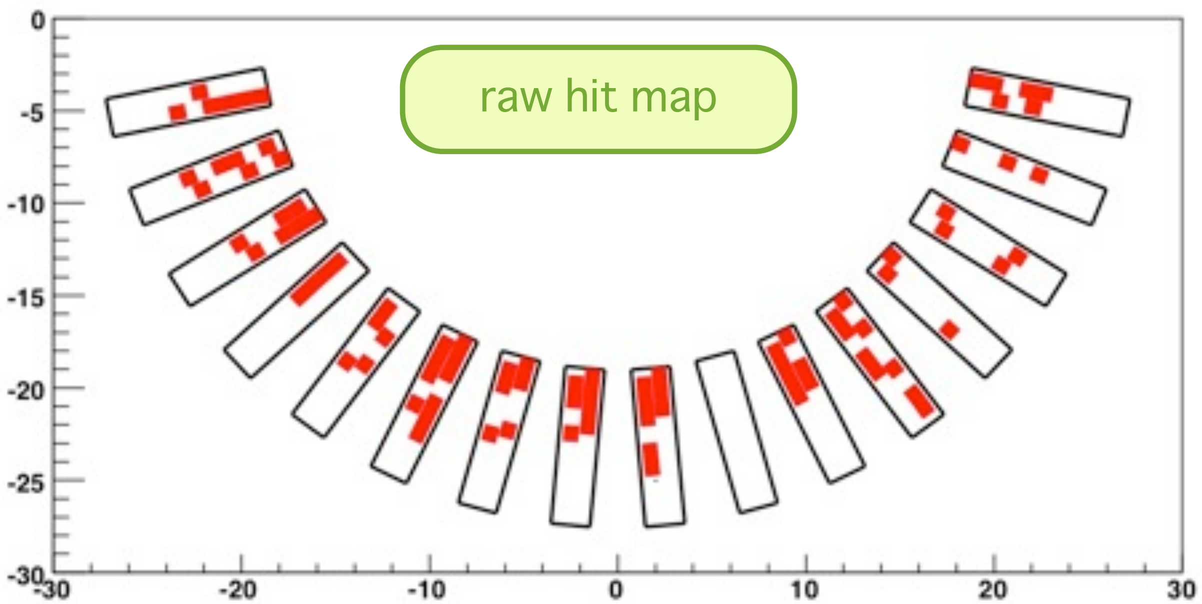
Track Finding (*x*-*y* view)

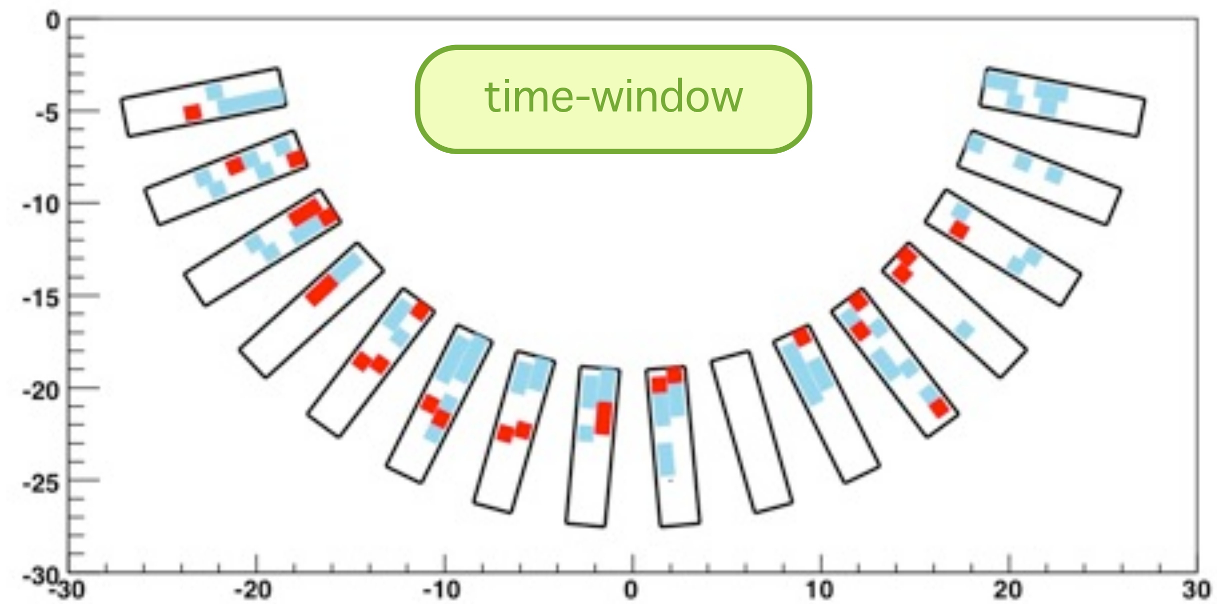


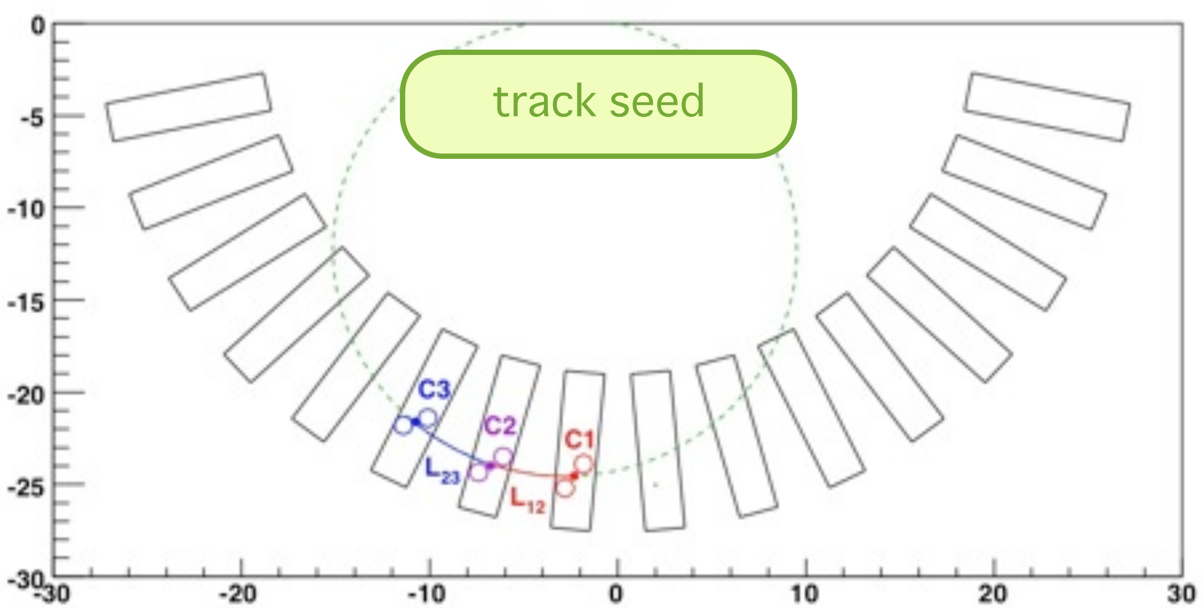


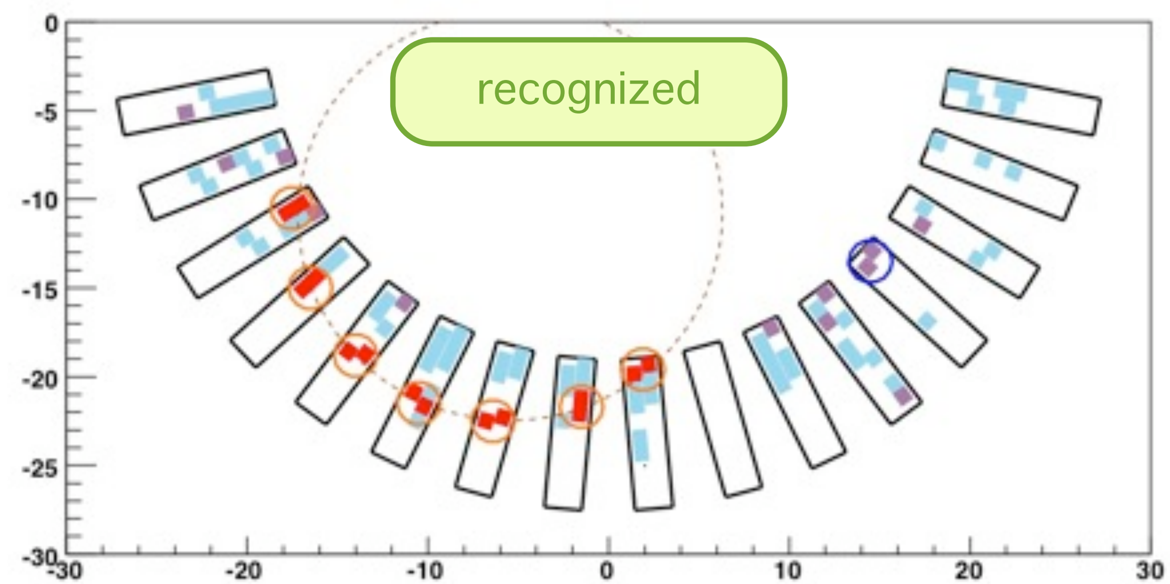


Track Finding (*x*-*y* view)

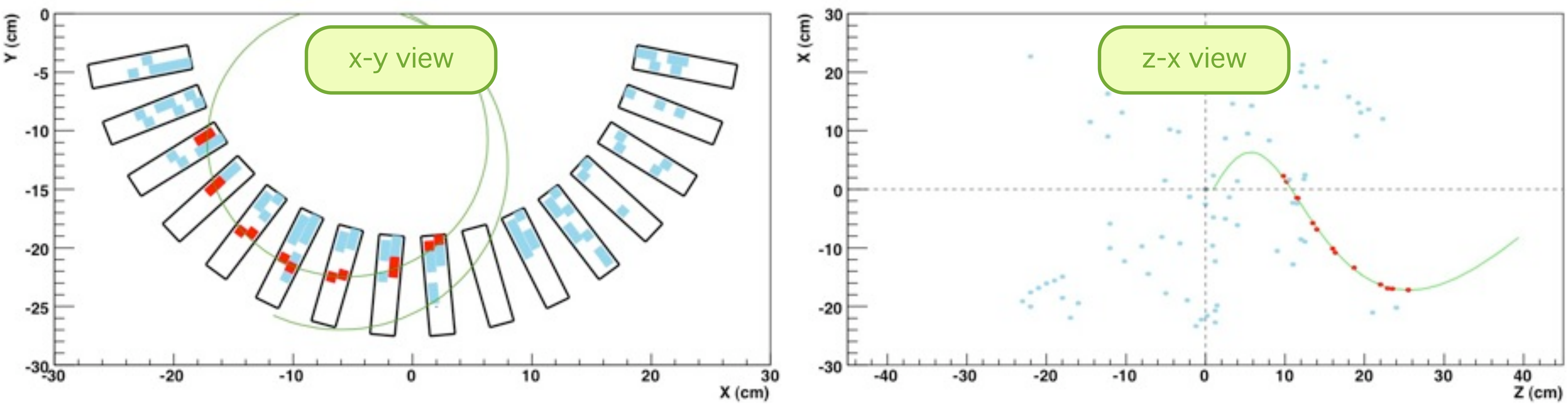






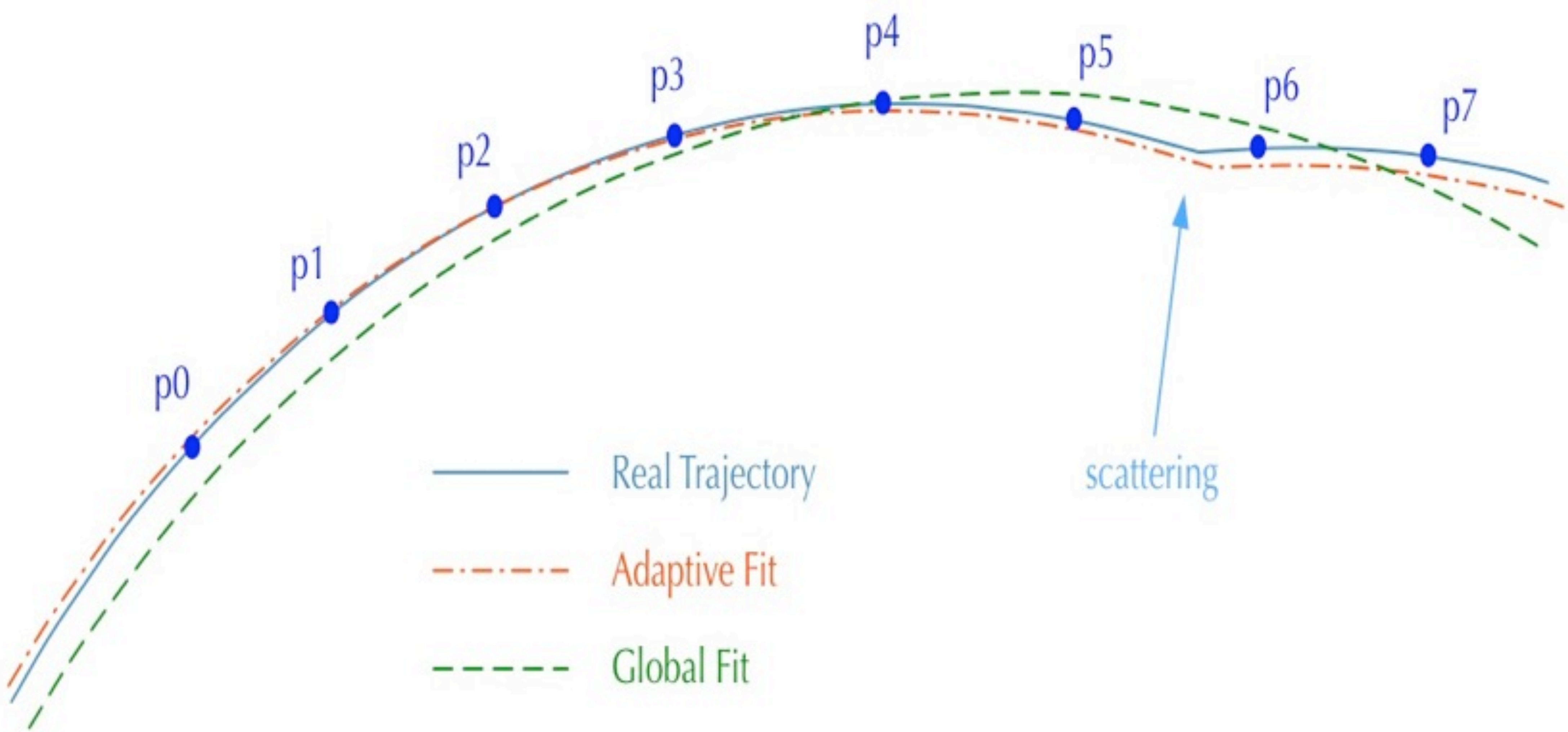


Track Finding (z-x view)



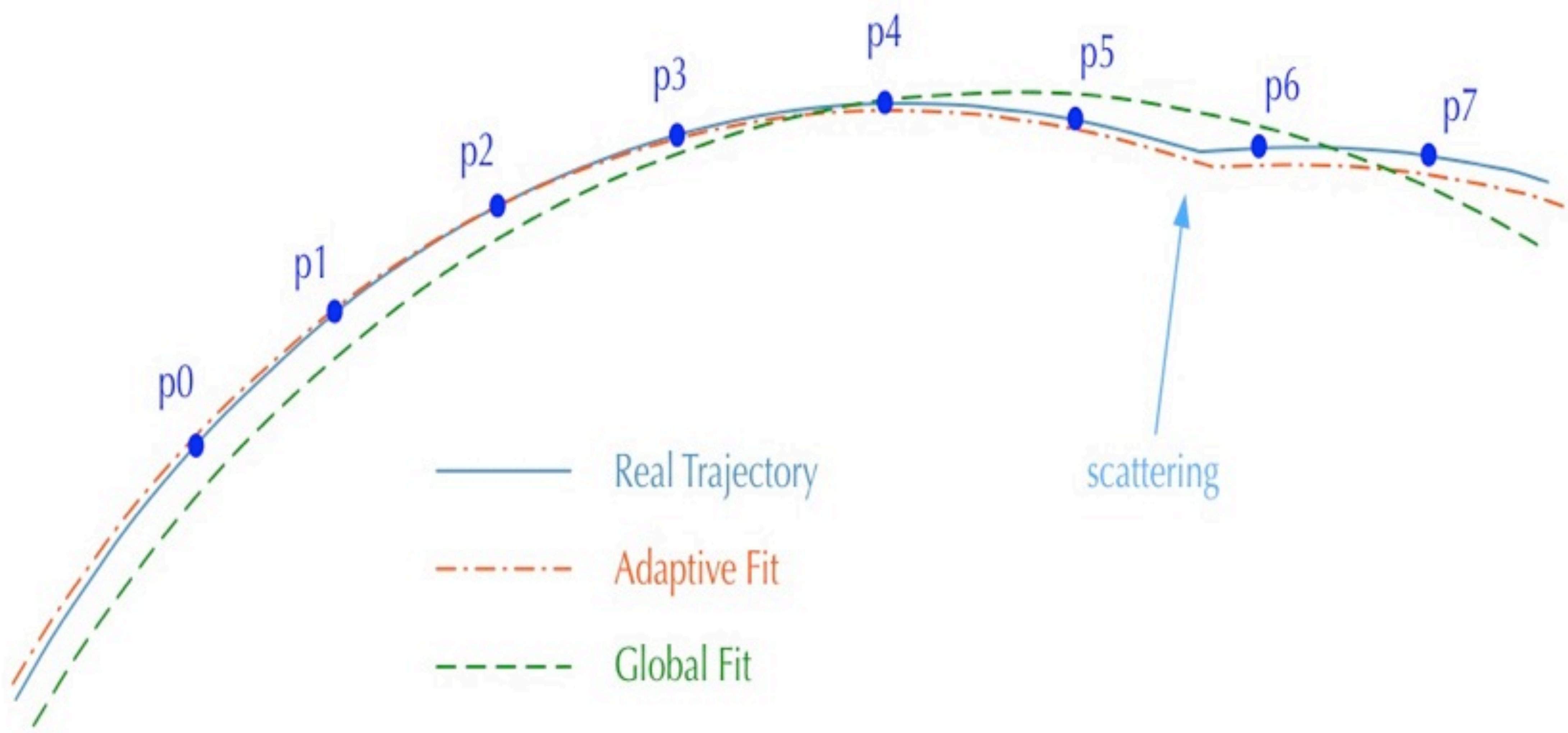
- Waveform Information Available
- 3-dimensional hit coordinates help a lot
- without adaptive filtering, very effective, very fast

Track Fitting Requirement



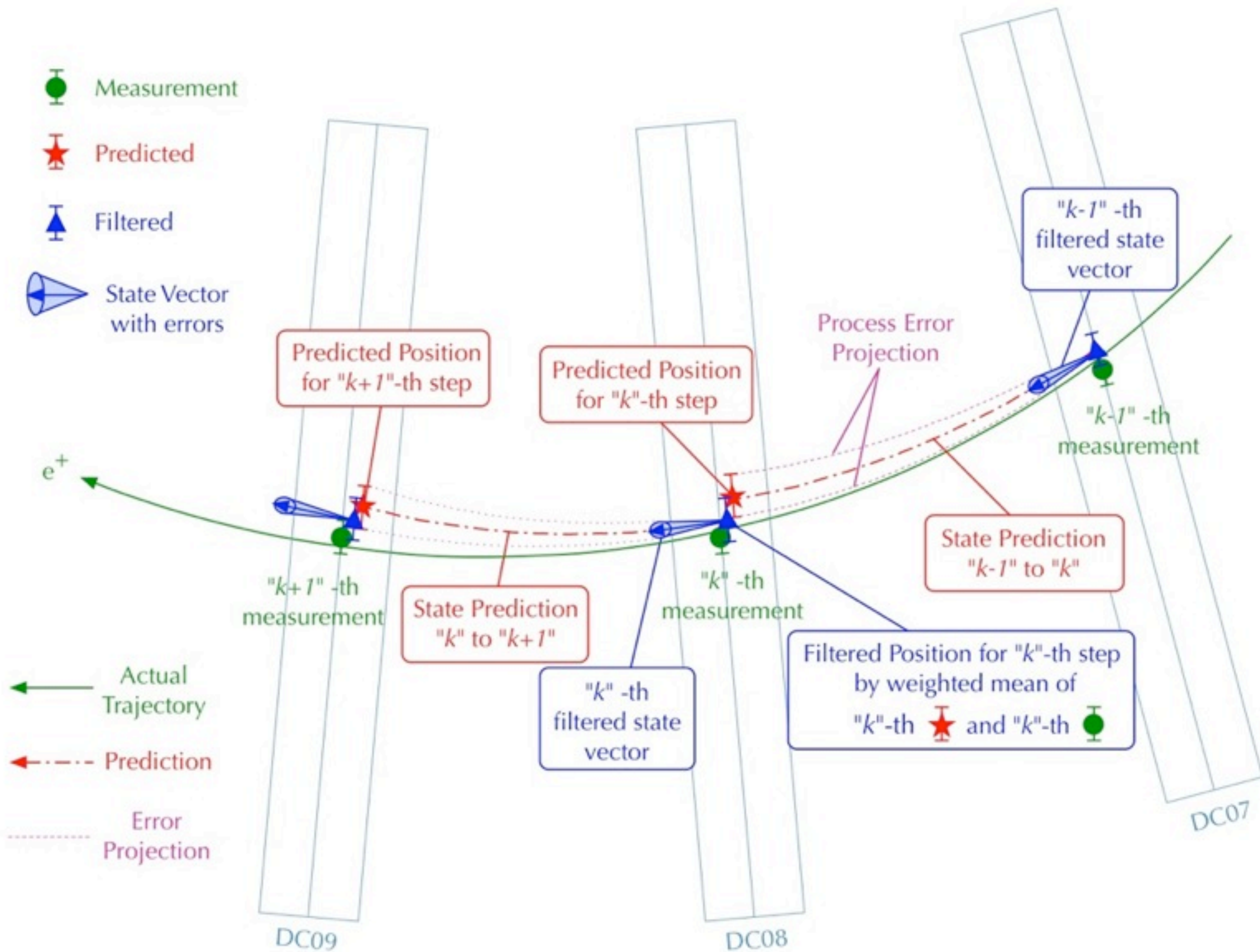
- Global Fit *vs*. Adaptive Fit
  - Speed, Accuracy, Experimental Circumstances

Track Fitting Requirement



- ~~Global Fit~~ *vs*. Adaptive Fit
  - Speed, Accuracy, Experimental Circumstances

Kalman Filter Implementation



Track Fitting

- Fitting is done by Kalman filter
- Interpolation is required, Circle Projection ???

Track Fitting

- Fitting is done by Kalman filter
- Interpolation is required, Circle Projection ??? $\longrightarrow$

- Solve Eq. of Motion

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\boldsymbol{v} \times \boldsymbol{B}$$

Track Fitting

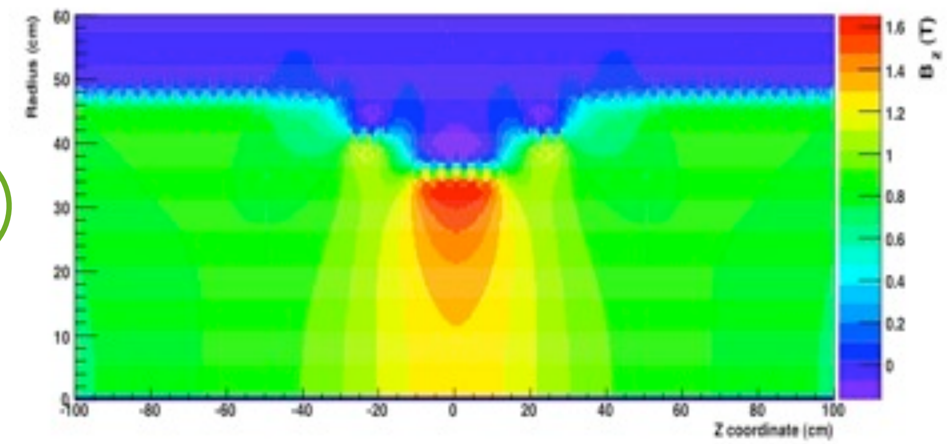
- Fitting is done by Kalman filter
- Interpolation is required, Circle Projection ??? $\longrightarrow$

- Solve Eq. of Motion

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\boldsymbol{v} \times \boldsymbol{B}$$

$$\frac{\mathrm{d}}{\mathrm{d}z}\begin{bmatrix} z \\ x \\ y \\ x' \\ y' \\ \rho \end{bmatrix} = \begin{bmatrix} 1 \\ x' \\ y' \\ \rho\sqrt{1+x'^2+y'^2}[(\boldsymbol{r}' \times \boldsymbol{B})_x - x'(\boldsymbol{r}' \times \boldsymbol{B})_z] \\ \rho\sqrt{1+x'^2+y'^2}[(\boldsymbol{r}' \times \boldsymbol{B})_y - y'(\boldsymbol{r}' \times \boldsymbol{B})_z] \\ \rho' \end{bmatrix}$$

+



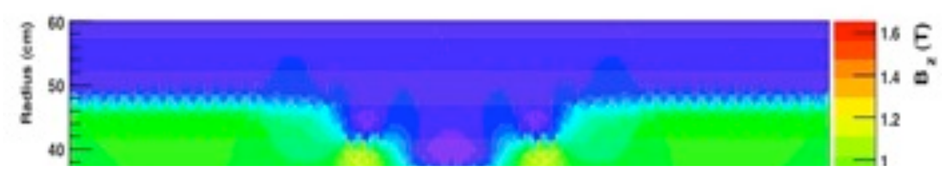
Track Fitting

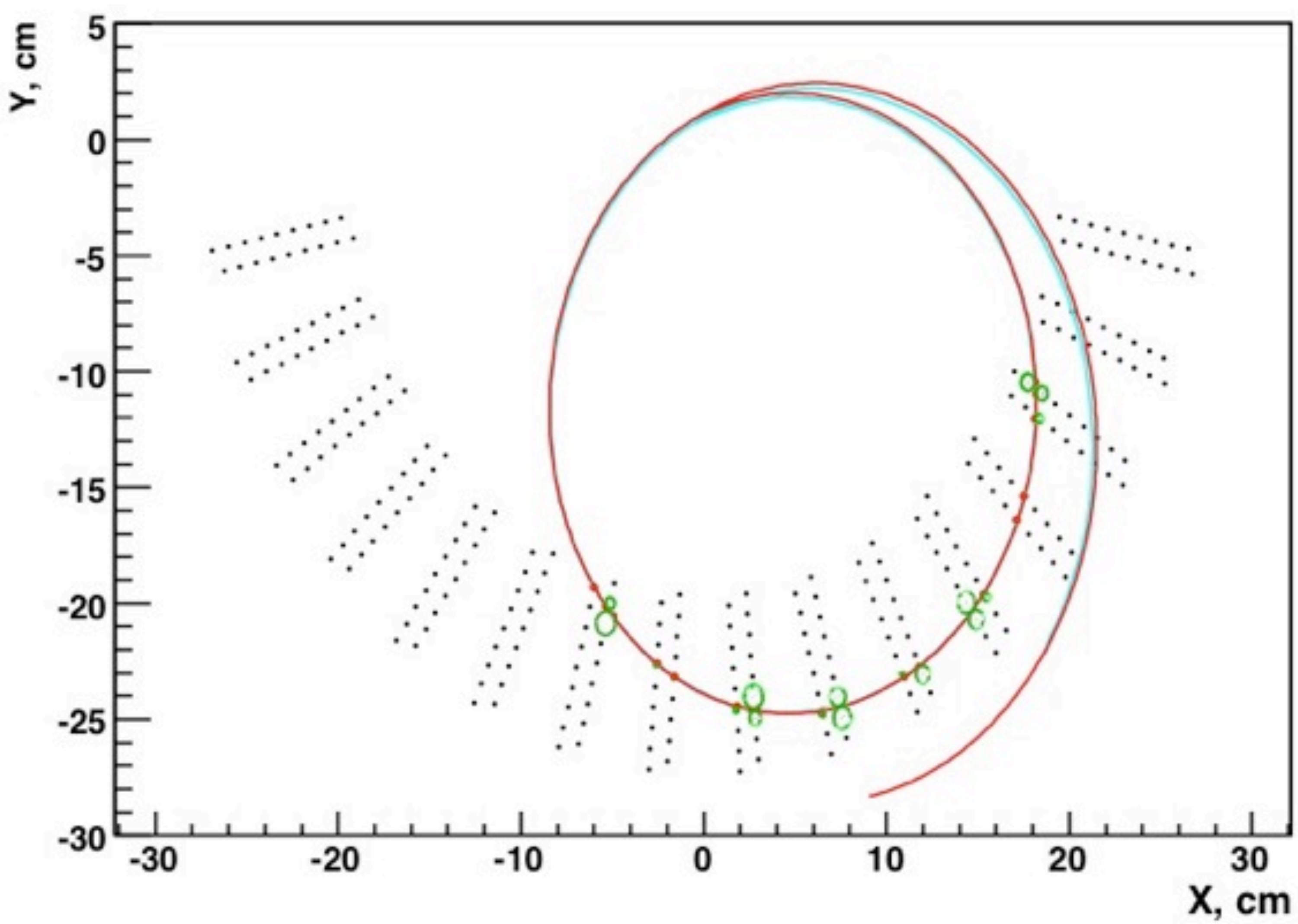
- Fitting is done by Kalman filter
- Interpolation is required, Circle Projection ???

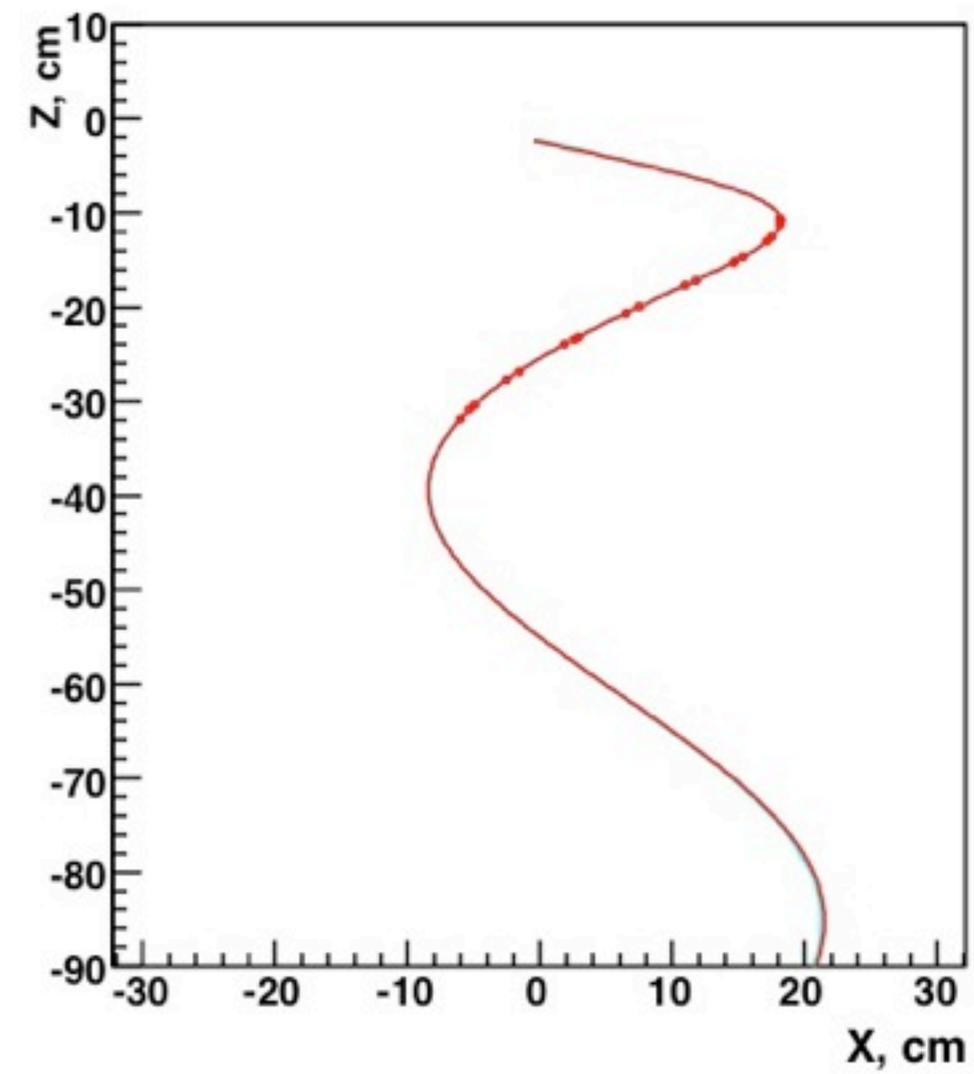
→

- Solve Eq. of Motion

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\boldsymbol{v} \times \boldsymbol{B}$$



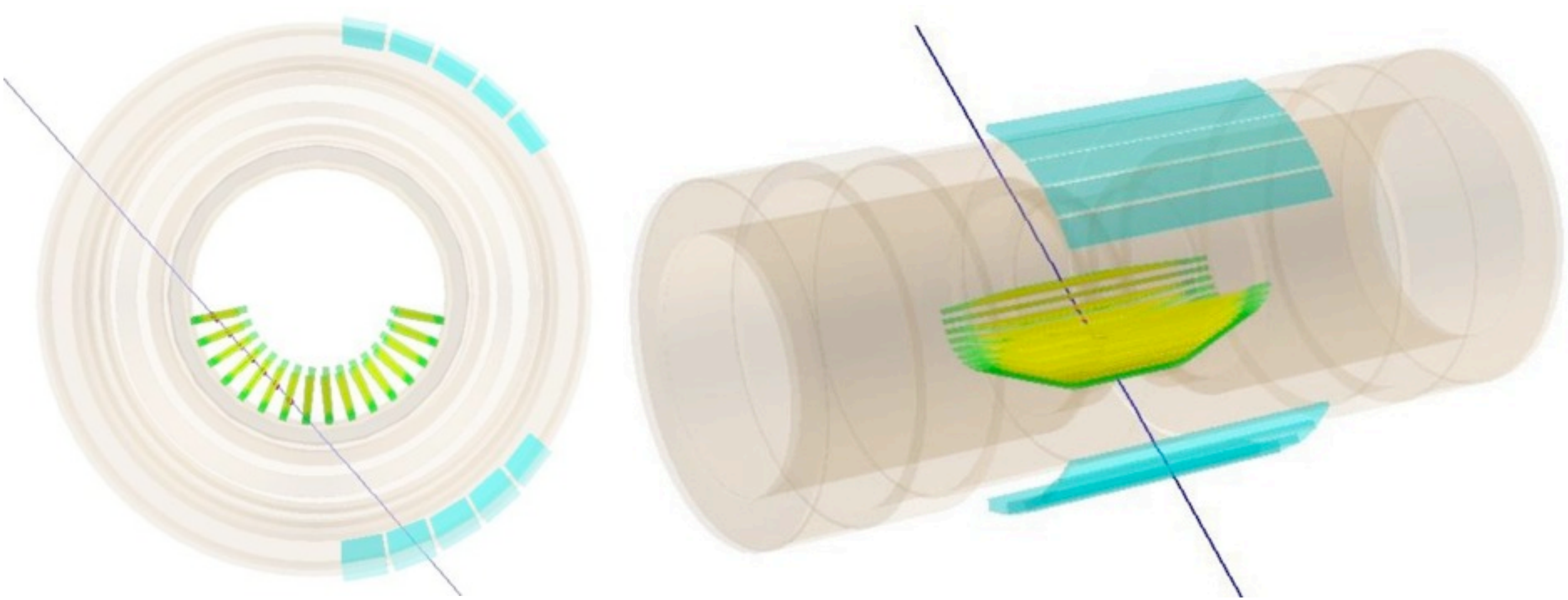




Calibration

Calibration Runs (1)

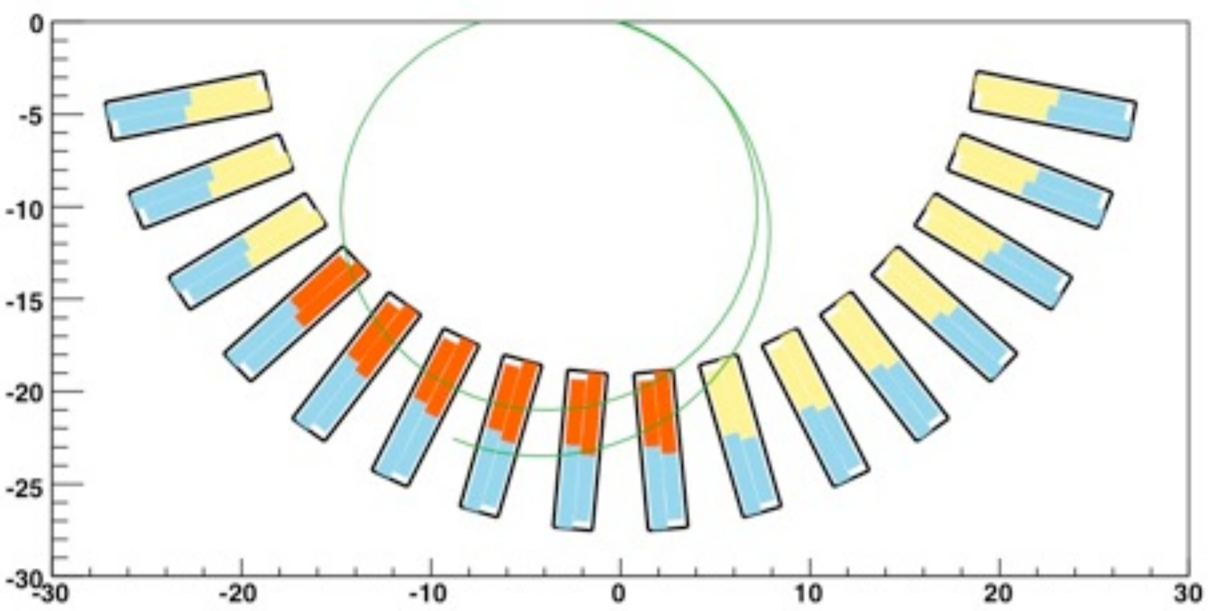
- Cosmic-Ray Trigger (w/o B-field)



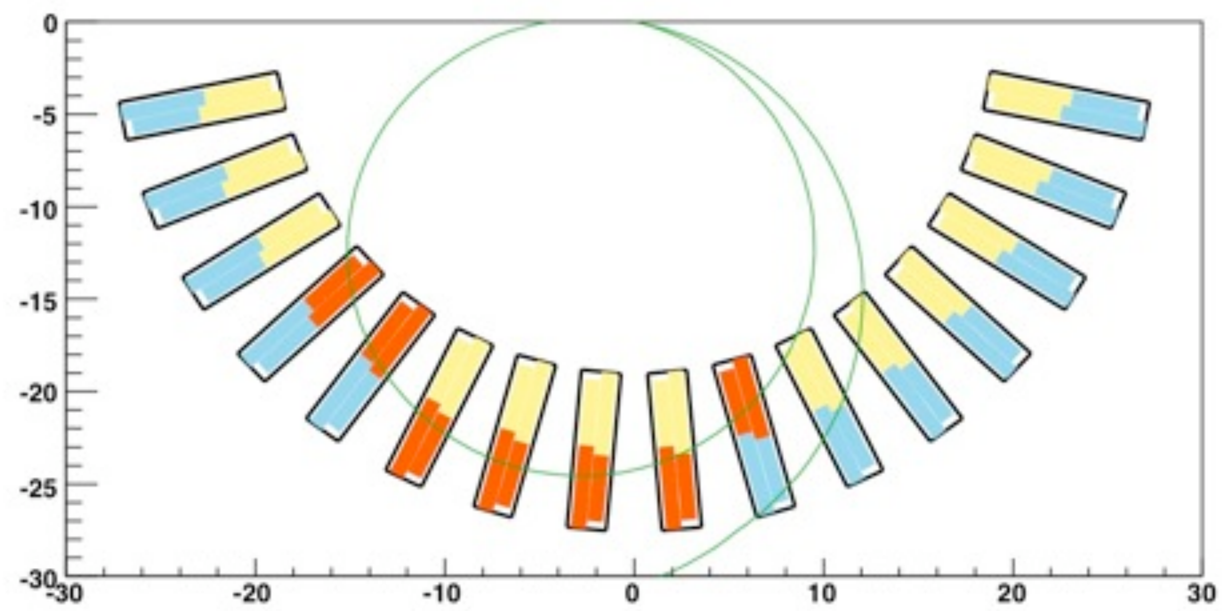
- Wire Alignment, *z*-Coordinate Calibration, (Timing Pedestal)

Calibration Runs (2)

- Michel Positron Trigger (DC self-trigger)



Normal Michel Trigger

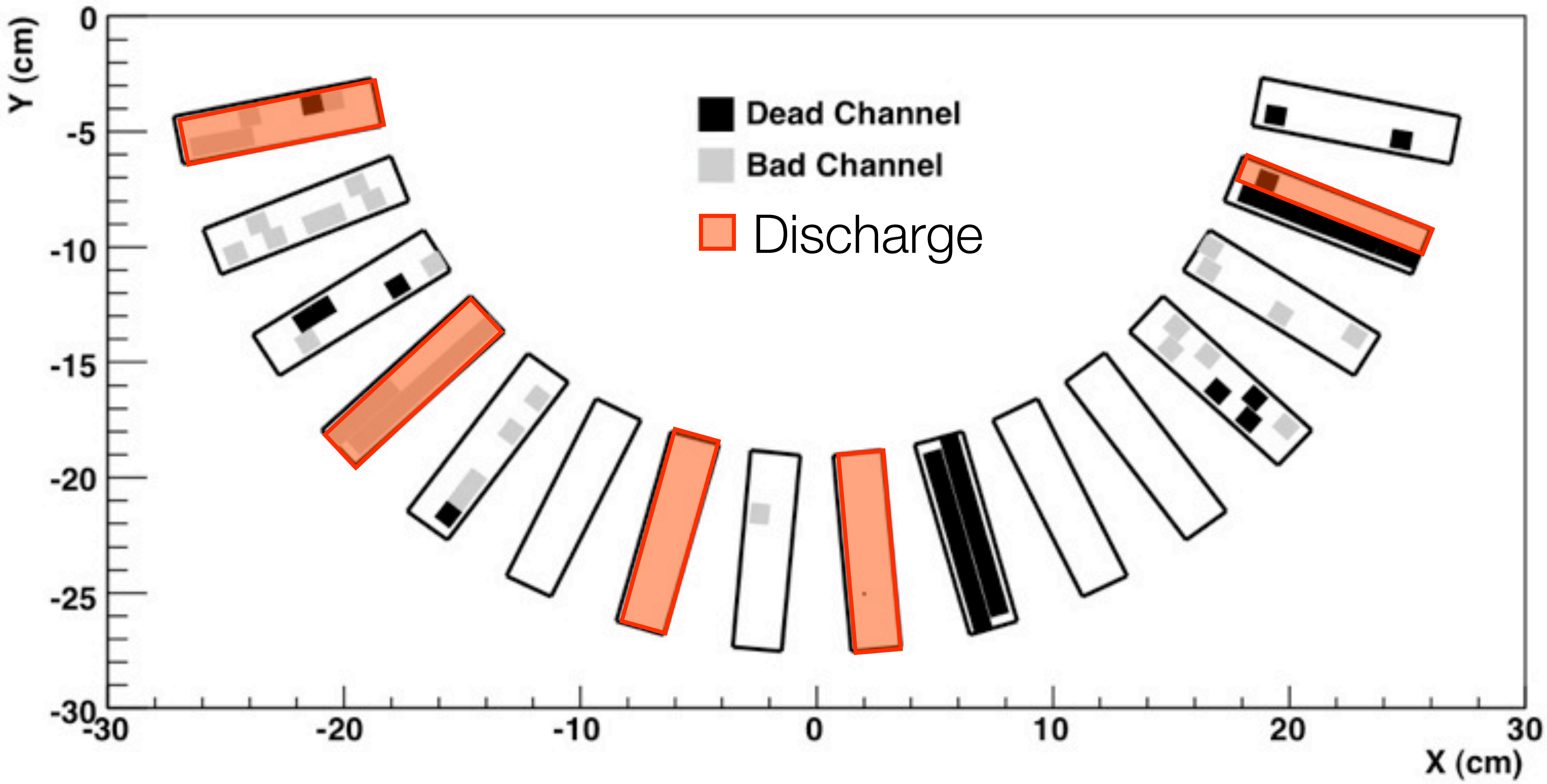


Michel Outer Trigger

- Time-to-Distance Calibration, (*z*-Coordinate Calibration)
- Detector Performance Estimation

Calibration Runs (3)

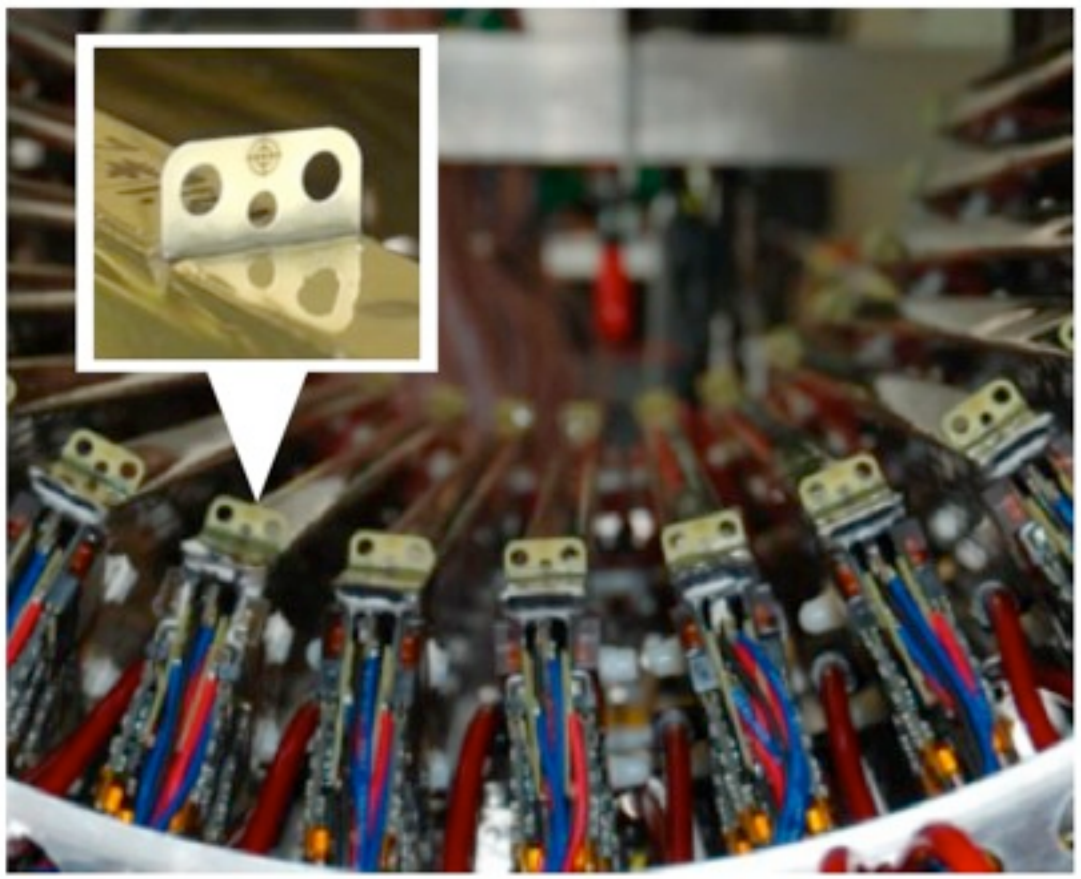
- For the Run 2007, several chamber was badly conditioned

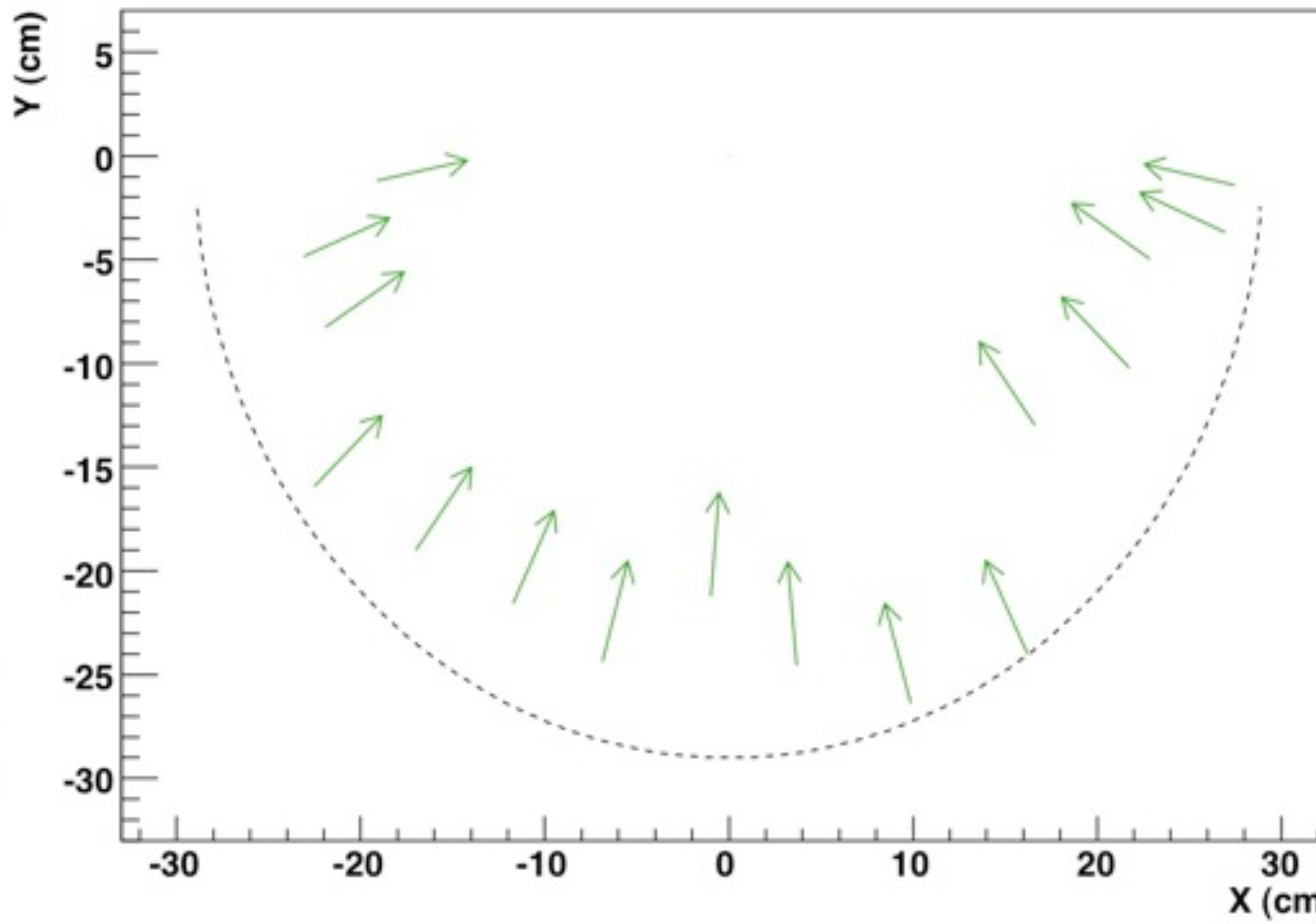


- “Feed-through Problem”
- “Discharge” Problem

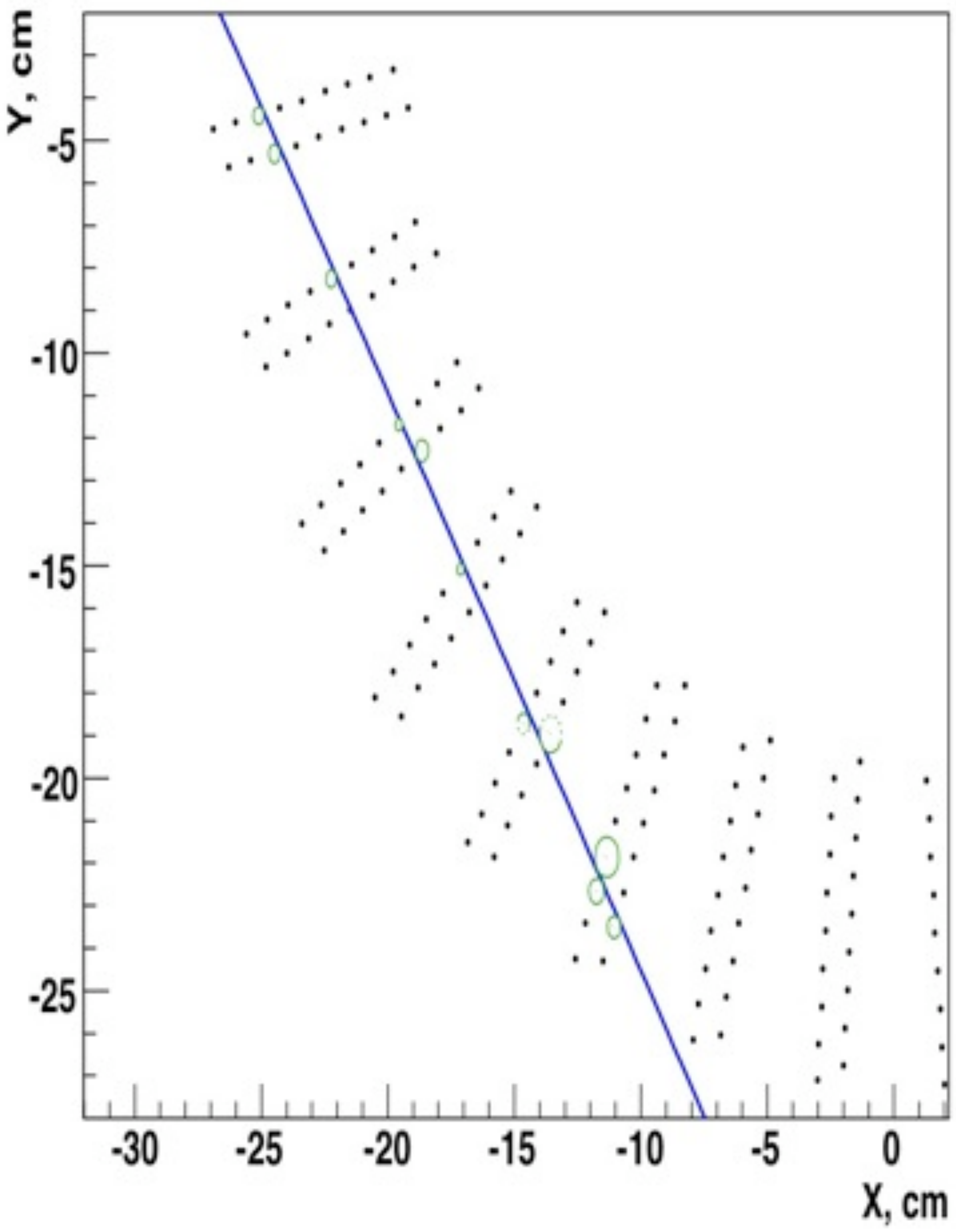
- all problems are repaired during winter shutdown 2007-2008

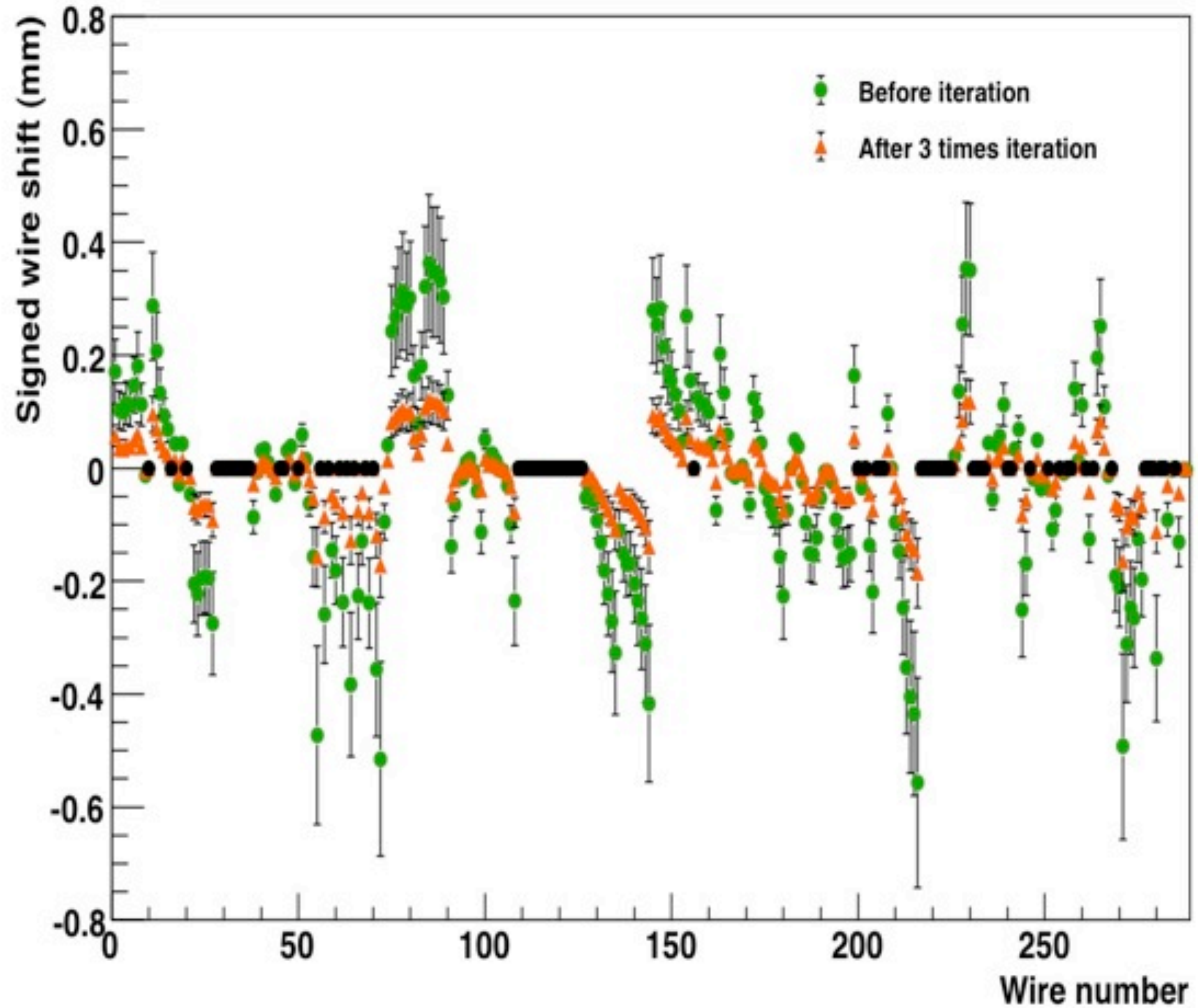
Wire Alignment





Wire Alignment





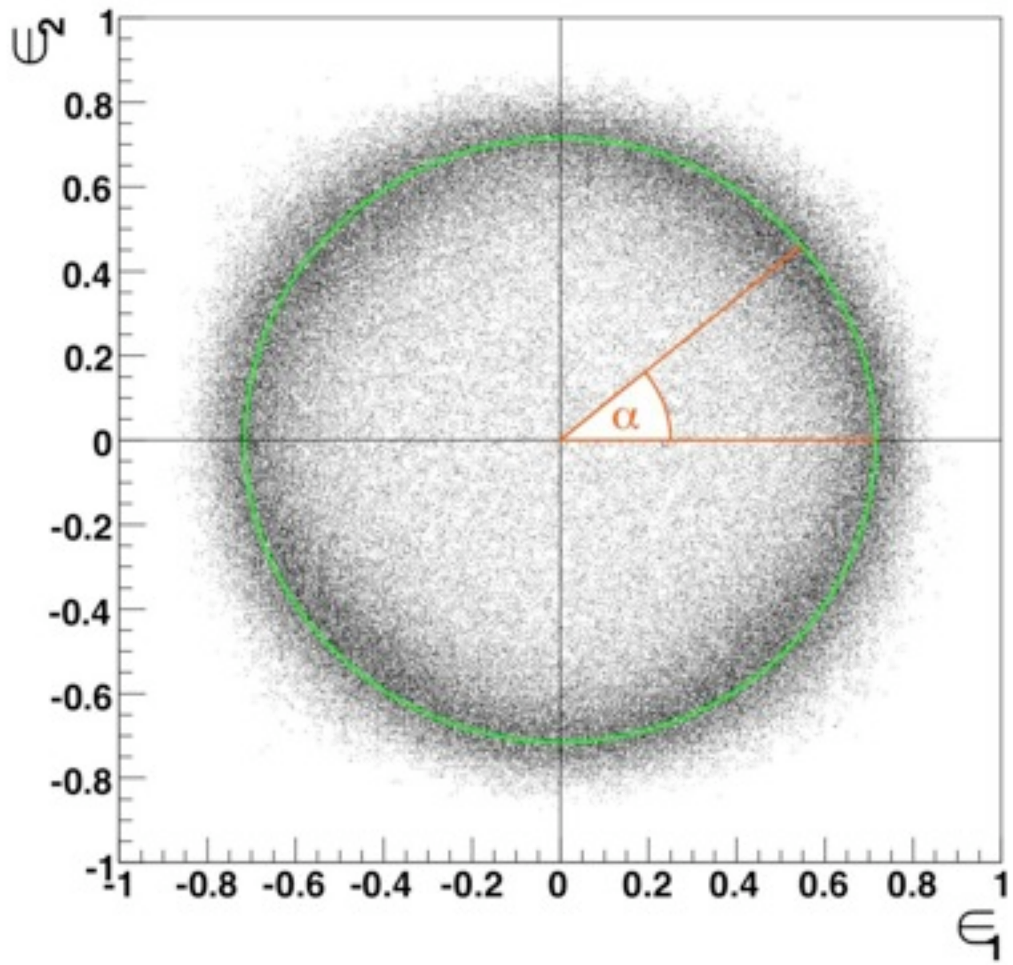
- relatively aligned with 47.3μm of accuracy

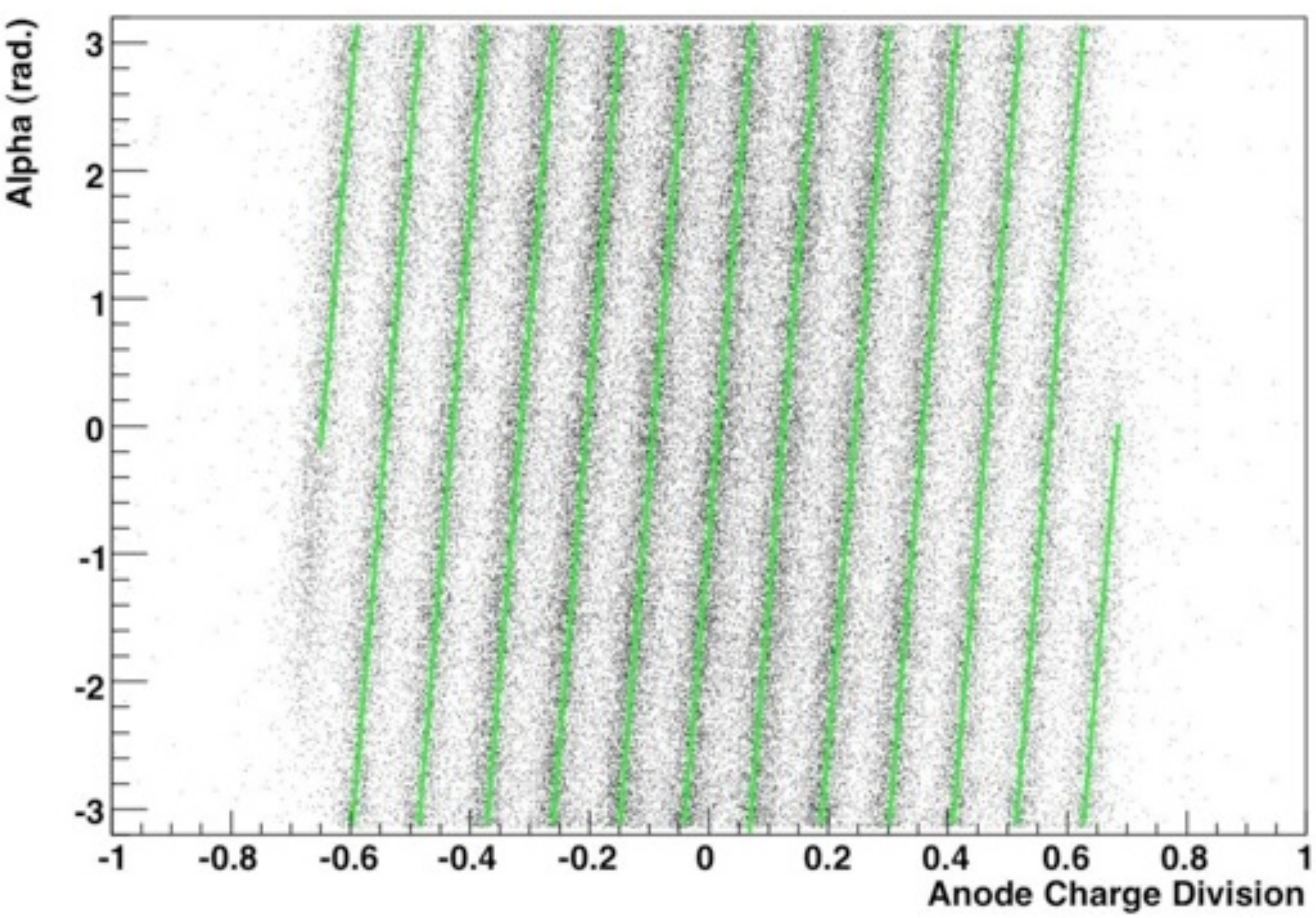
z-Coordinate Calibration (1)

- No Alternative Position Sensitive Detector (other than DC)
- z-coordinate calibration is very important to guarantee σ_p, σ_θ and σ_x on target

z-Coordinate Calibration (1)

- No Alternative Position Sensitive Detector (other than DC)
- z-coordinate calibration is very important to guarantee σ_p, σ_θ and σ_x on target

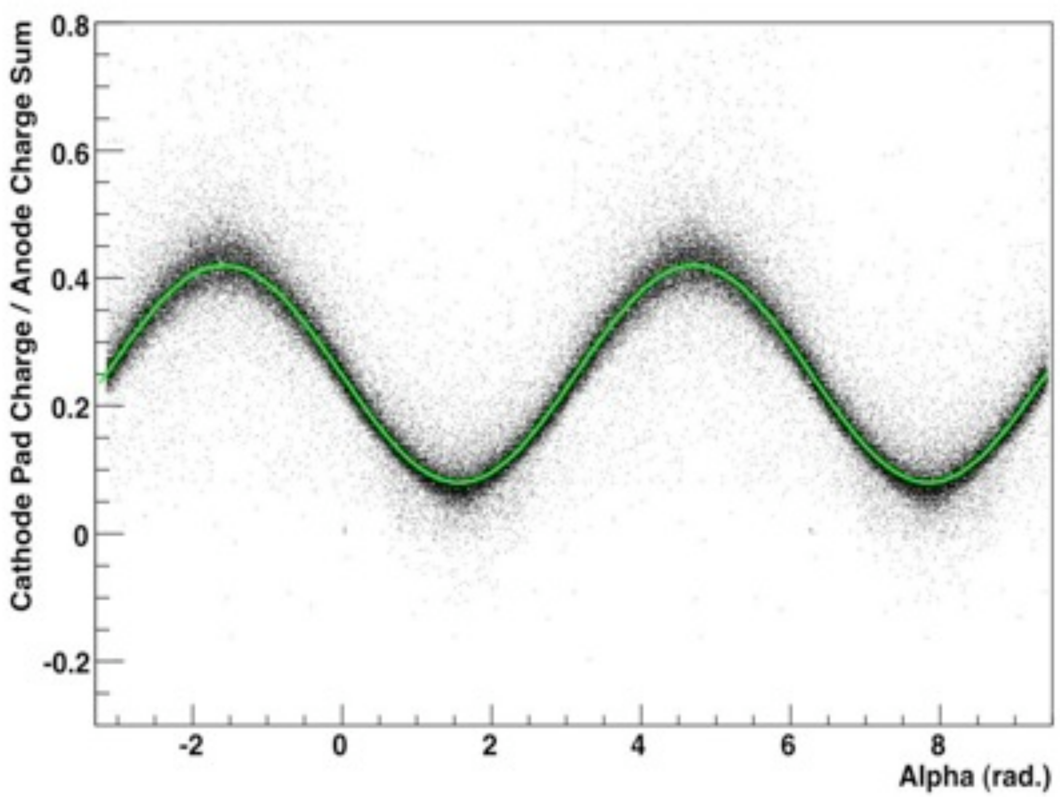


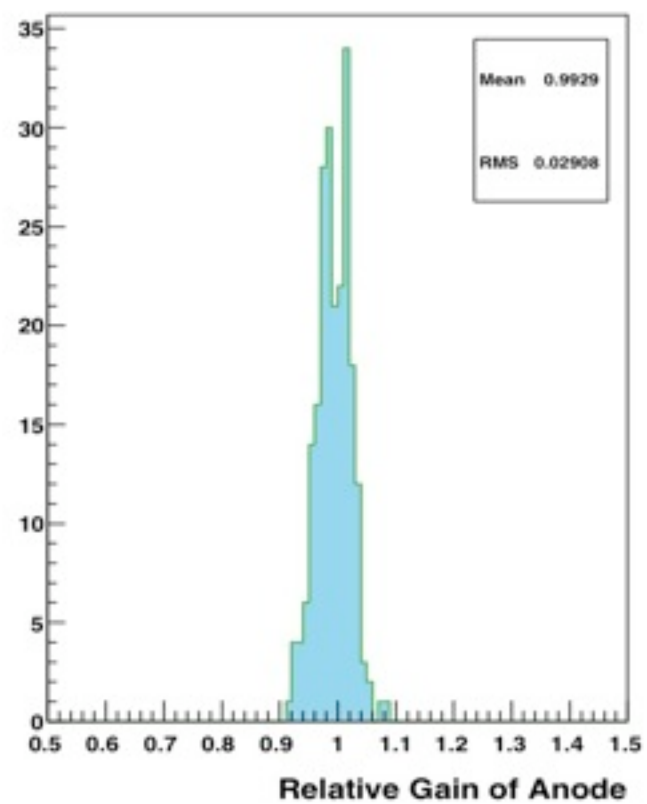


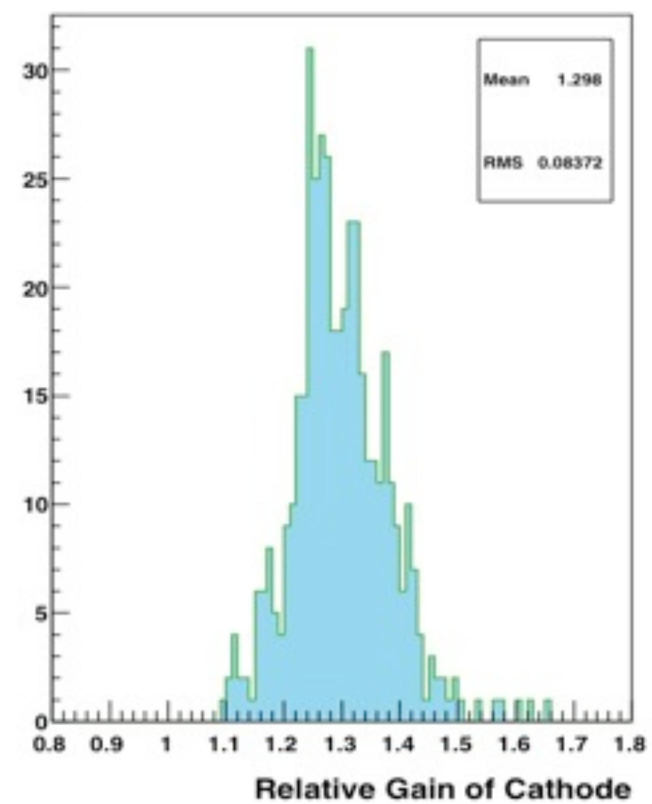
- "Vernier Period" (=5cm) can be a good position reference in z-coordinate

z-Coordinate Calibration (2)

- Iterative Method : “$z_{cathode}$” <-> “z_{anode}”
- z-Coordinate Calibration ≈ Relative Gain Calibration



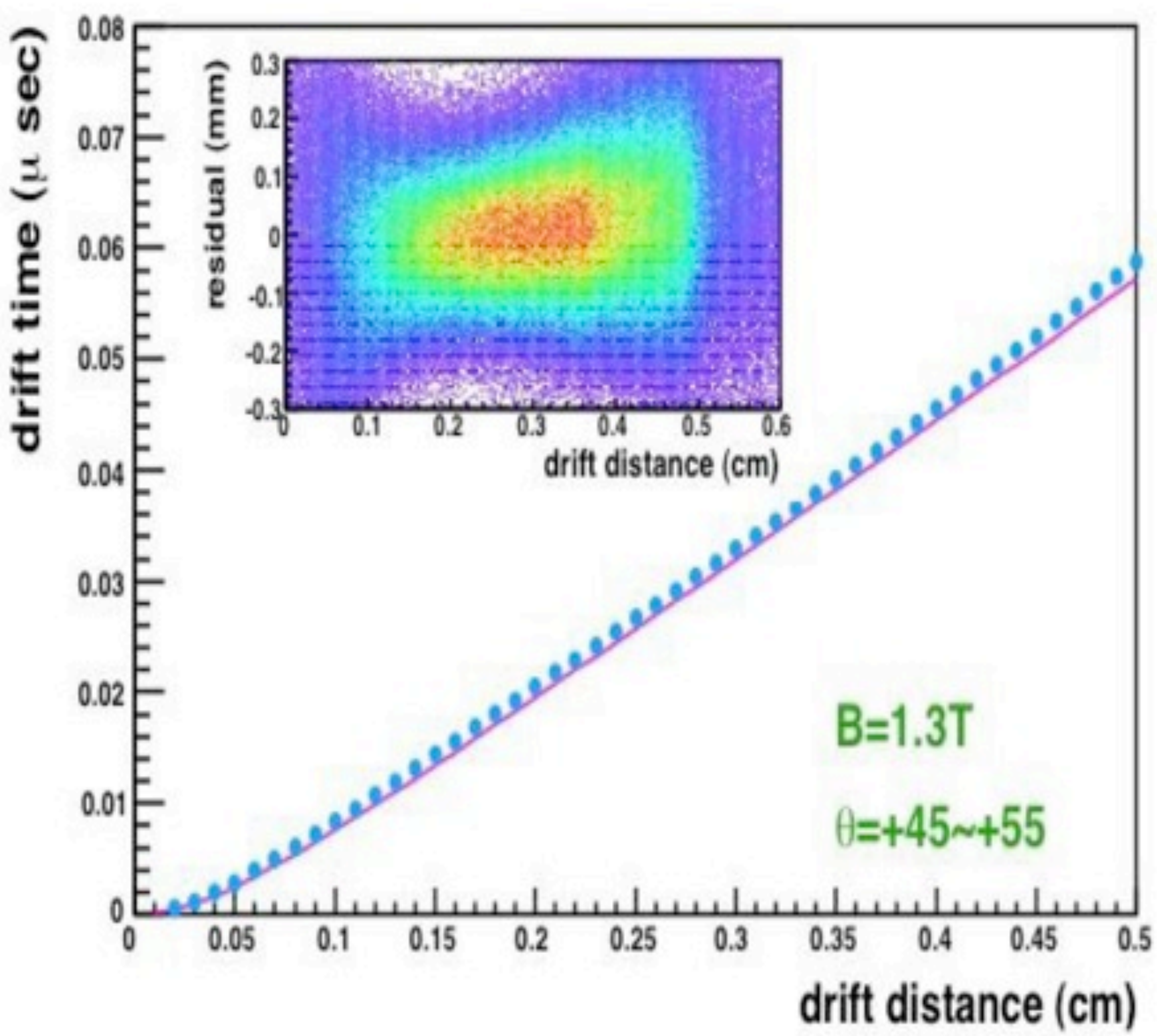


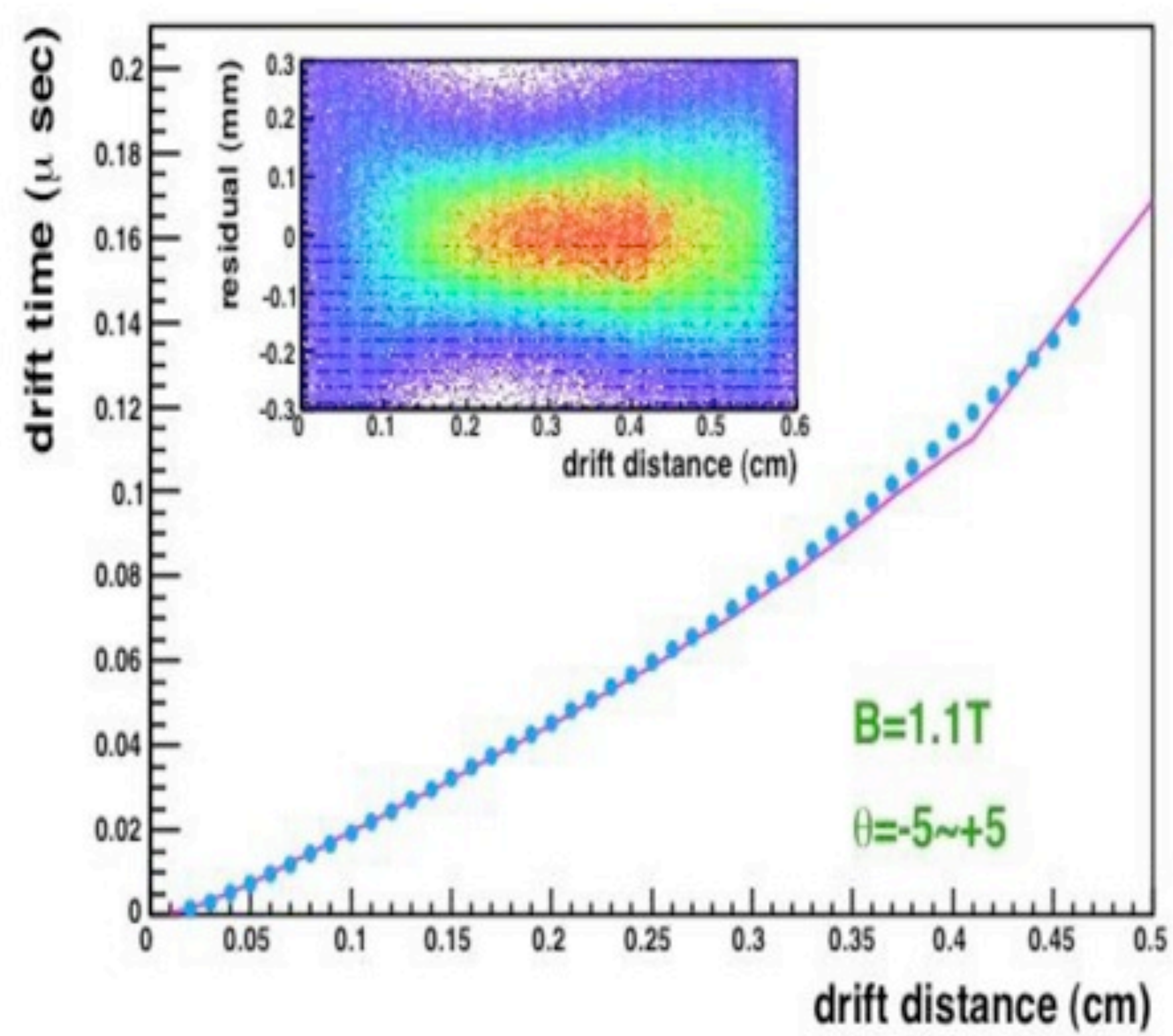


- z-alignment is also performed here, 100μm of z displacement are corrected

Time-to-Distance Calibration

- XT-map are corrected so that the *residual* is minimized
- All Cells should be calibrated individually due to B-variation





Analysis

Engineering Run 2007

- Conditioning Runs (September-October)
  - without beam, with low-intensity beam, with normal intensity beam
- Calibration Runs (October-November)
  - Cosmic-ray Runs
  - Michel Runs
    - 3M normal and 2M outer trig. with Low intensity
    - 2M outer trig. with Normal intensity
- MEG Rehearsal Run (December)
  - MEG event trigger (TC && Xenon with direction matching)

Engineering Run 2007

- Conditioning Runs (September-October)
  - without beam, with low-intensity beam, with normal intensity beam
- Calibration Runs (October-November)
  - Cosmic-ray Runs ➡ efficiency
  - Michel Runs
    - 3M normal and 2M outer trig. with Low intensity
    - 2M outer trig. with Normal intensity
- MEG Rehearsal Run (December)
  - MEG event trigger (TC && Xenon with direction matching)

Engineering Run 2007

- Conditioning Runs (September-October)
  - without beam, with low-intensity beam, with normal intensity beam
- Calibration Runs (October-November)
  - Cosmic-ray Runs → efficiency
  - Michel Runs
    - 3M normal and 2M outer trig. with Low intensity → resolutions
    - 2M outer trig. with Normal intensity
- MEG Rehearsal Run (December)
  - MEG event trigger (TC && Xenon with direction matching)

Engineering Run 2007

- Conditioning Runs (September-October)
  - without beam, with low-intensity beam, with normal intensity beam
- Calibration Runs (October-November)
  - Cosmic-ray Runs → efficiency
  - Michel Runs
    - 3M normal and 2M outer trig. with Low intensity → resolutions
    - 2M outer trig. with Normal intensity → rate dependence
- MEG Rehearsal Run (December)
  - MEG event trigger (TC && Xenon with direction matching)

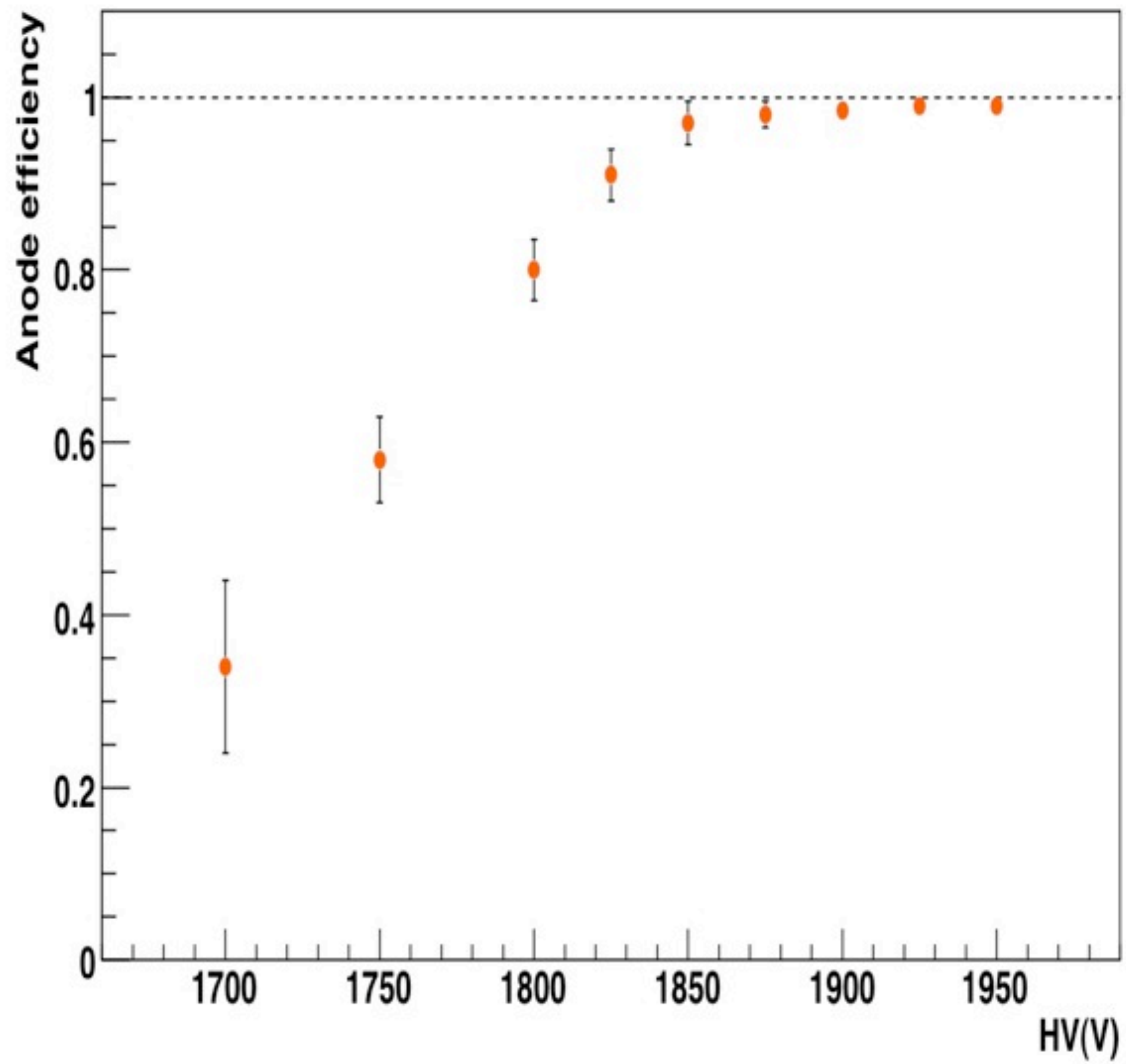
Engineering Run 2007

- Conditioning Runs (September-October)
  - without beam, with low-intensity beam, with normal intensity beam
- Calibration Runs (October-November)
  - Cosmic-ray Runs → efficiency
  - Michel Runs
    - 3M normal and 2M outer trig. with Low intensity → resolutions
    - 2M outer trig. with Normal intensity → rate dependence
- MEG Rehearsal Run (December)
  - MEG event trigger (TC && Xenon with direction matching)

→ spectrometer performance

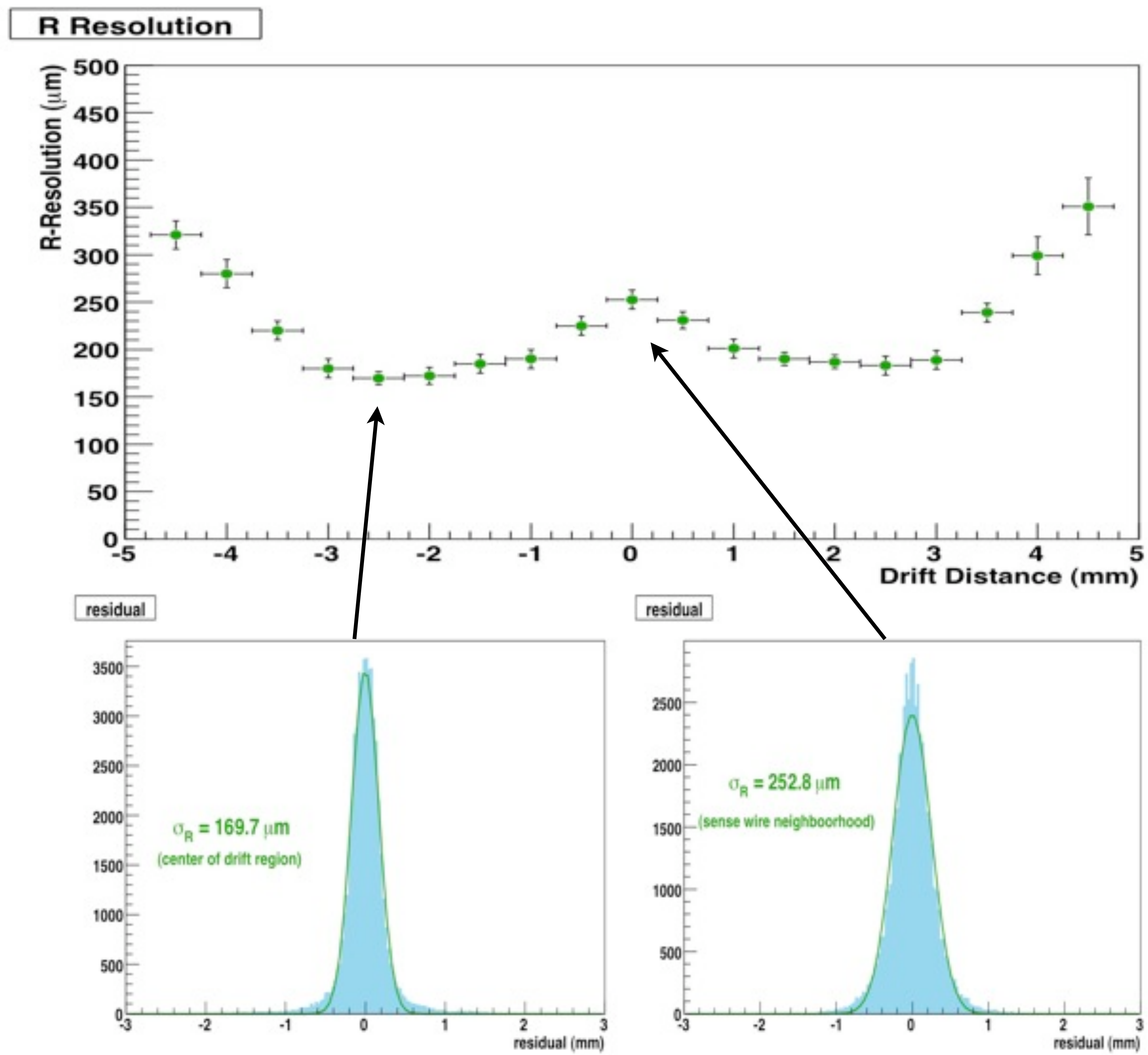
Single Hit Efficiency

- For Run 2007
  - 1850V is nominal
  - 1800V for discharge DCs

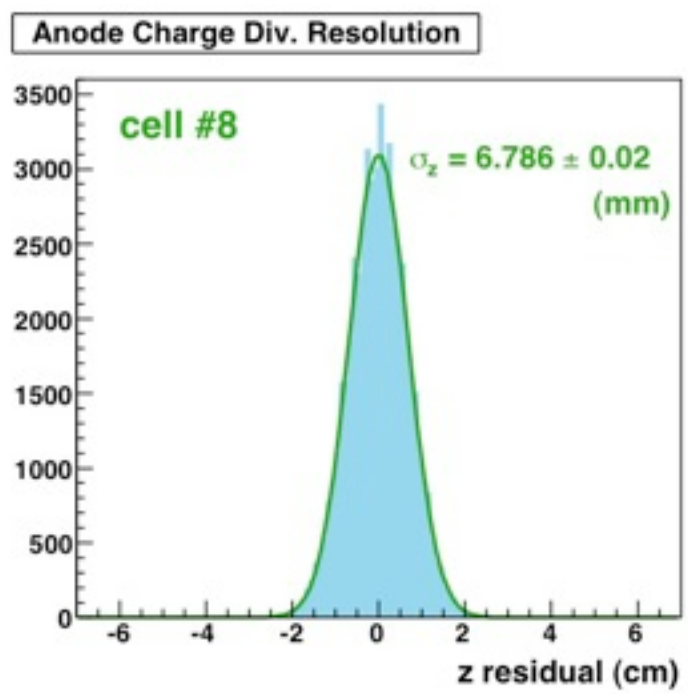


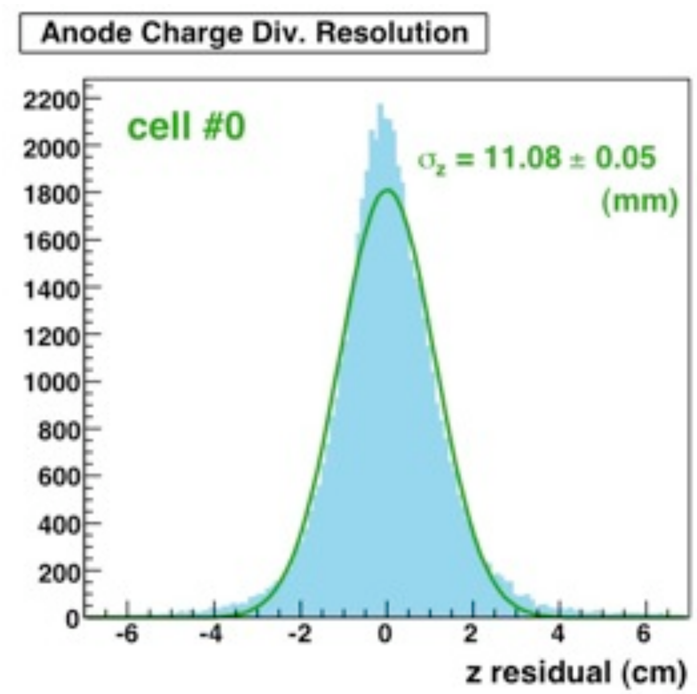
Spacial Resolution (Transverse, "*r*")

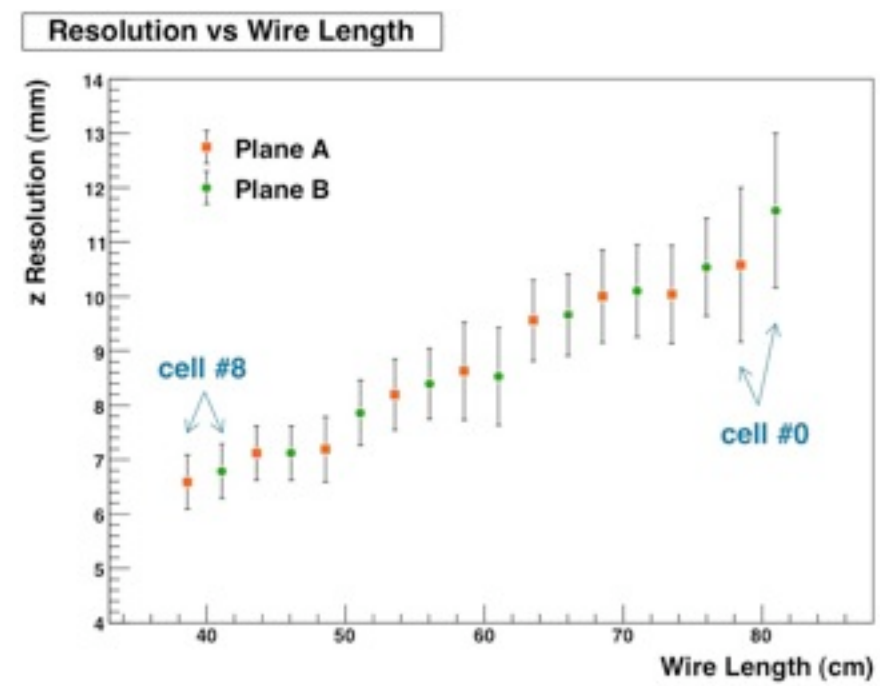
- Residual "*reconstruct - fit*"
- Slice by 0.5 mm intervals in drift distance, position dependence of R resolution is studied.
- 170~350 micron in sigma is achieved (good DC).



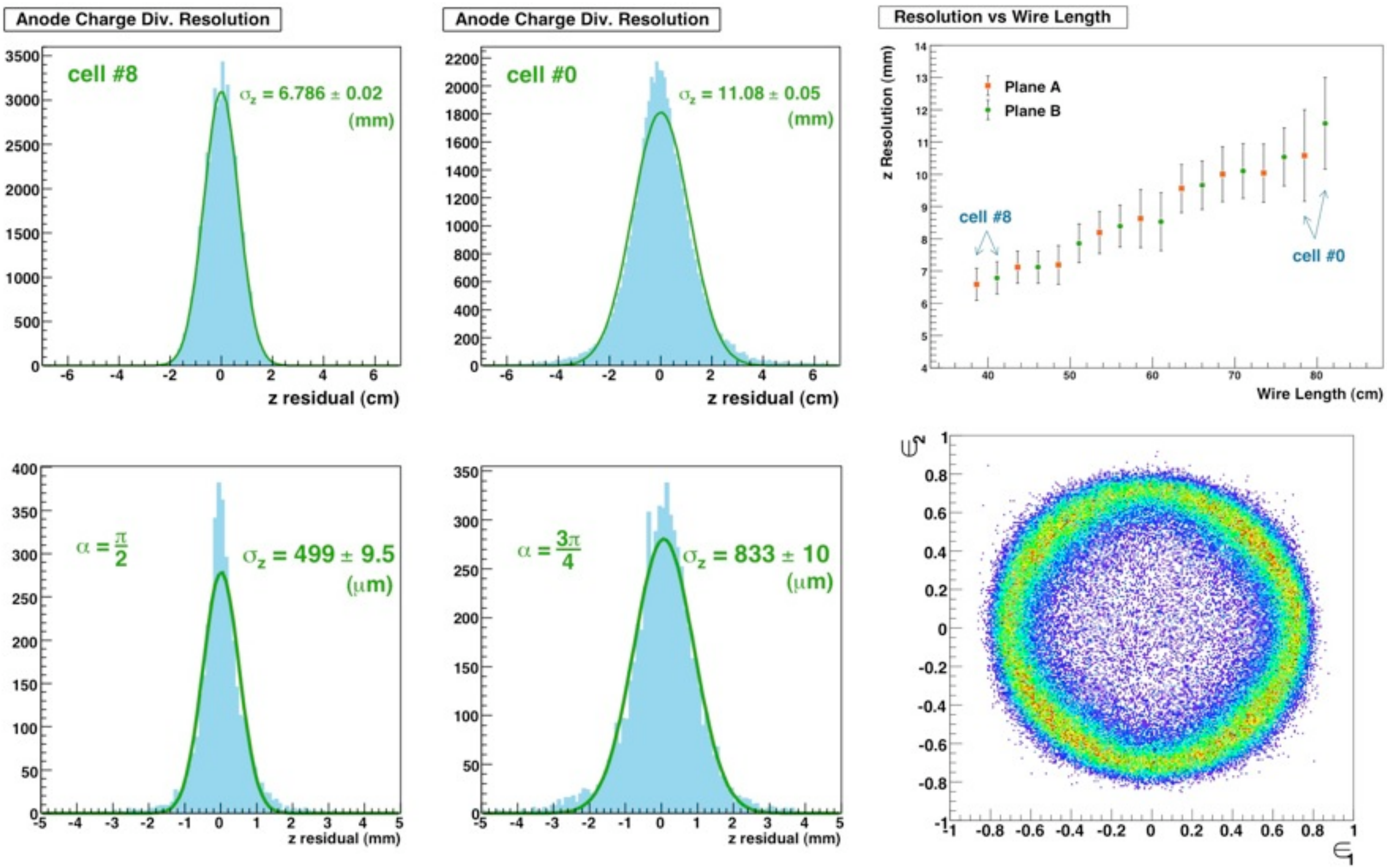
Spacial Resolution (Longitudinal, “z”)



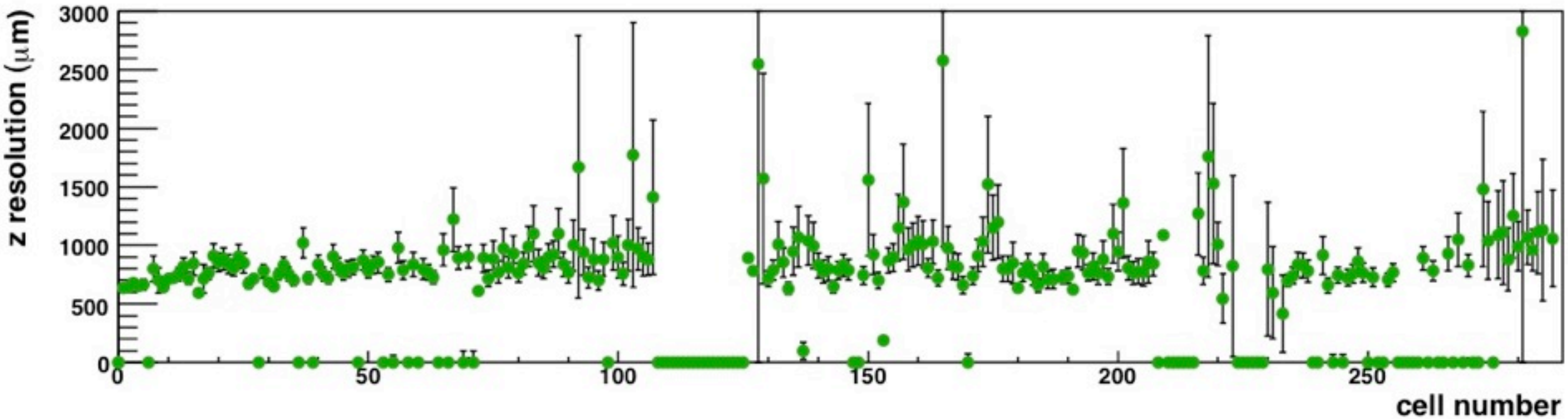


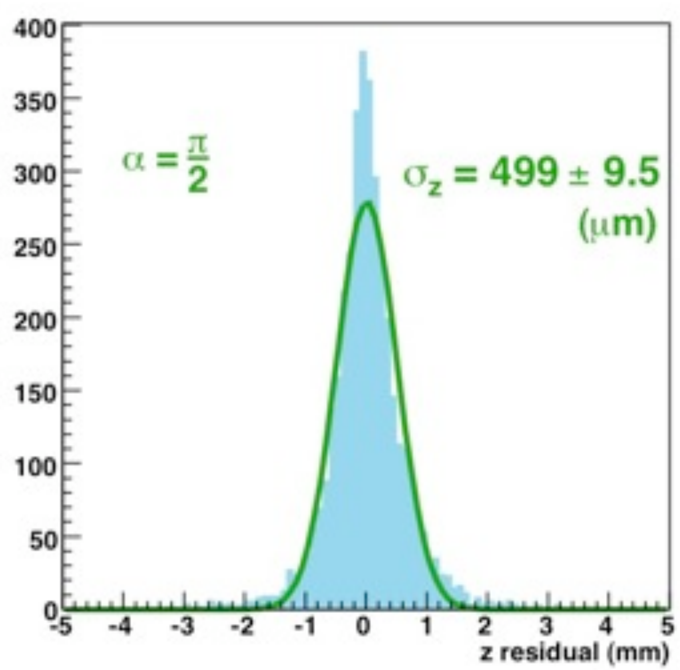


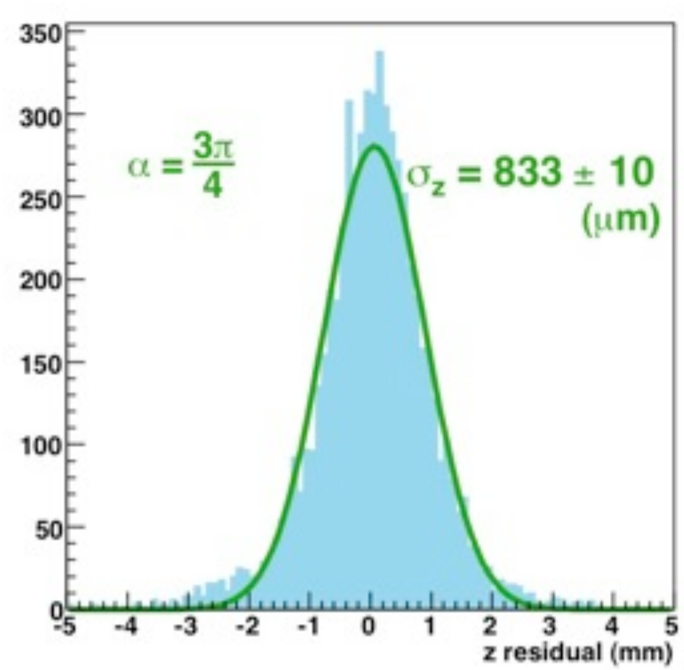
Spacial Resolution (Longitudinal, "z")

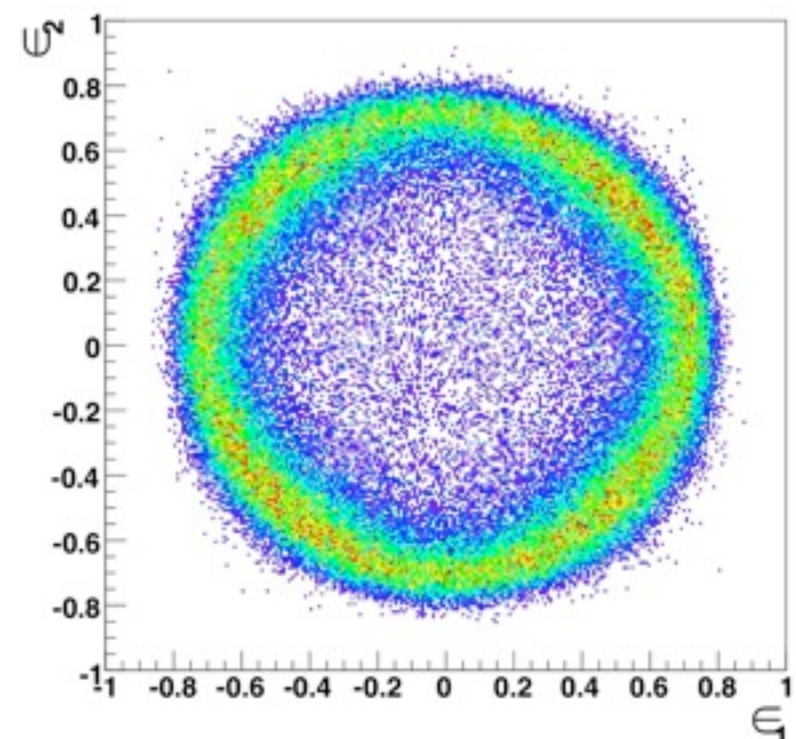


Spacial Resolution (Longitudinal, "*z*")



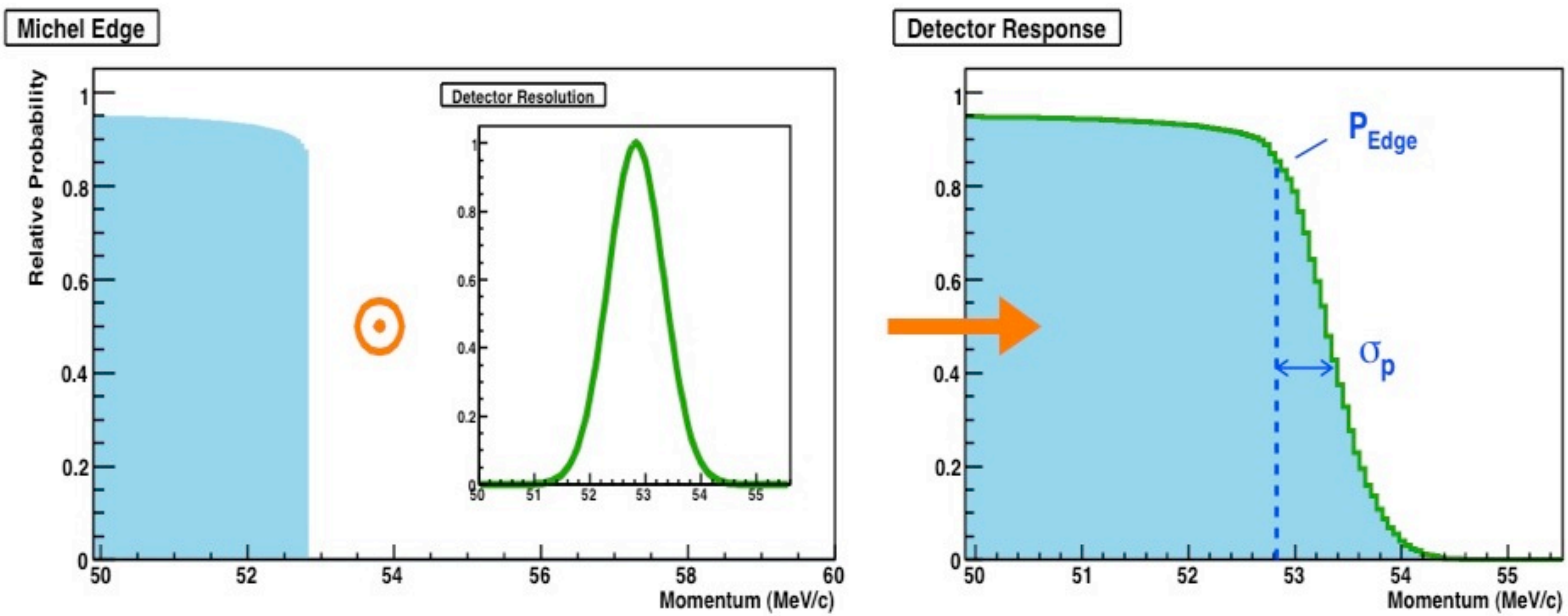






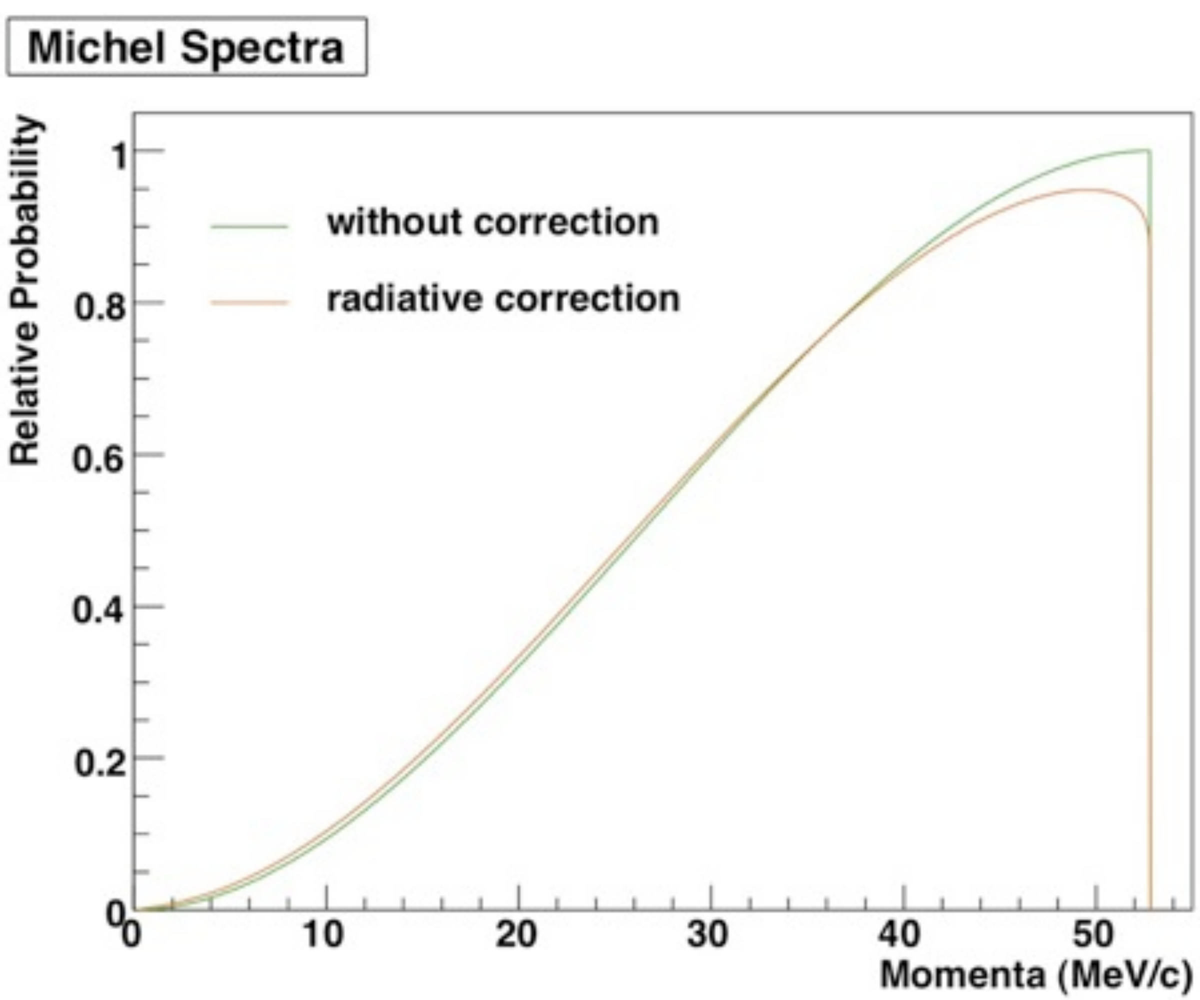
Momentum Resolution (1)

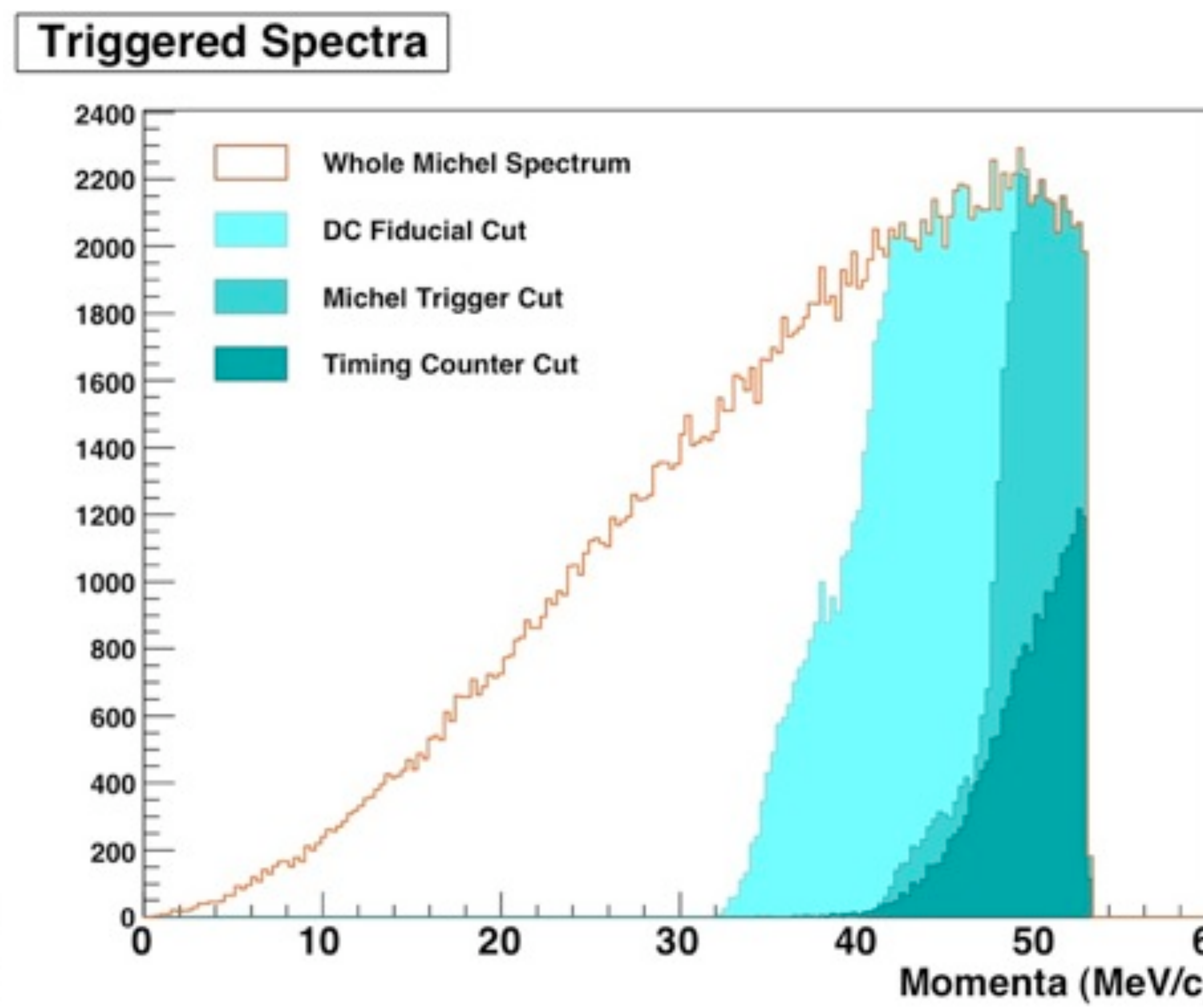
- Michel-Edge Fitting
  - Absolute Momentum Calibration
  - Momentum Resolution Estimation



Momentum Resolution (2)

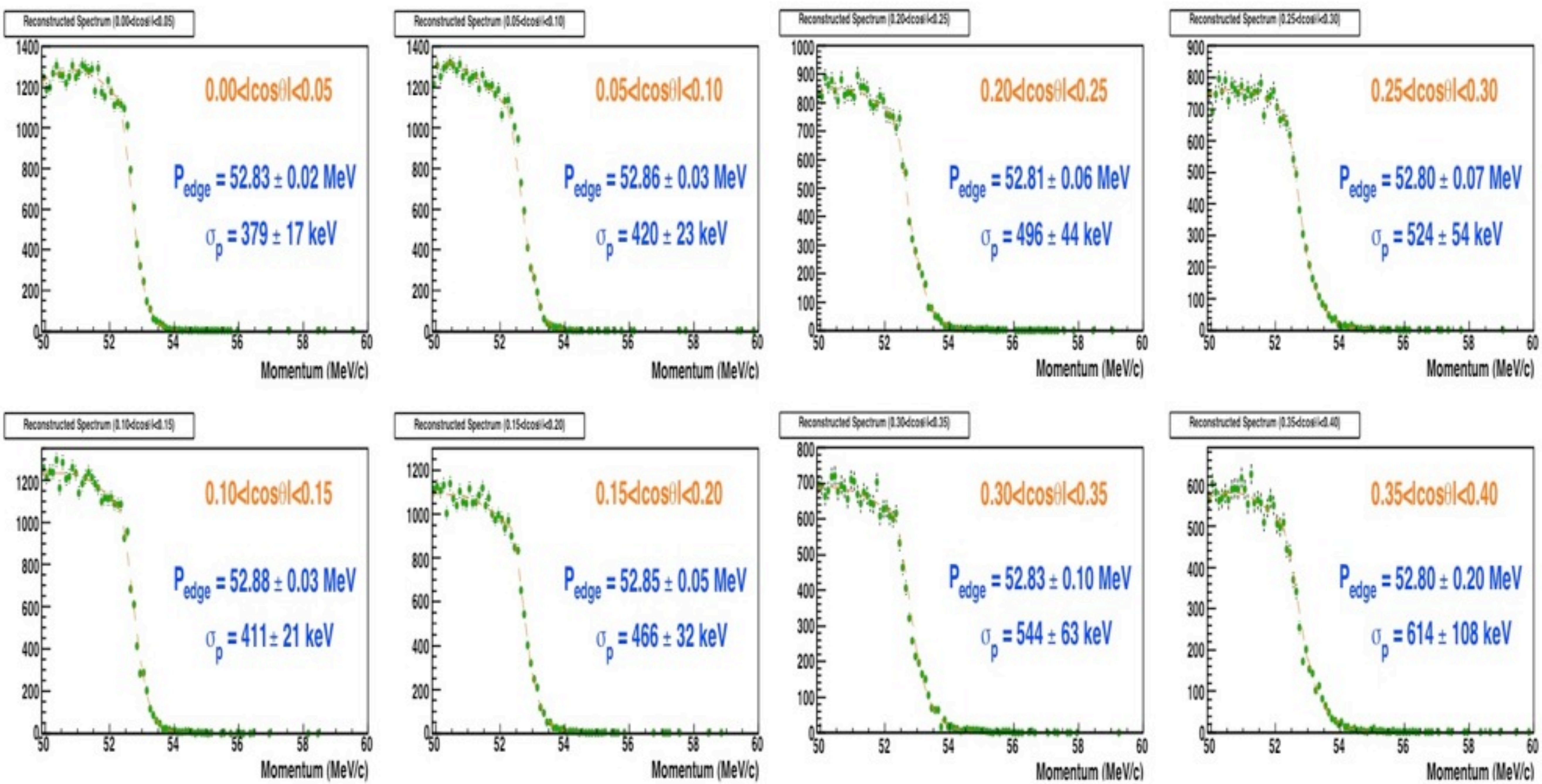
- Michel-Edge Deformation
  - Radiative Corrections to the Michel Spectrum
  - Trigger Condition Dependences





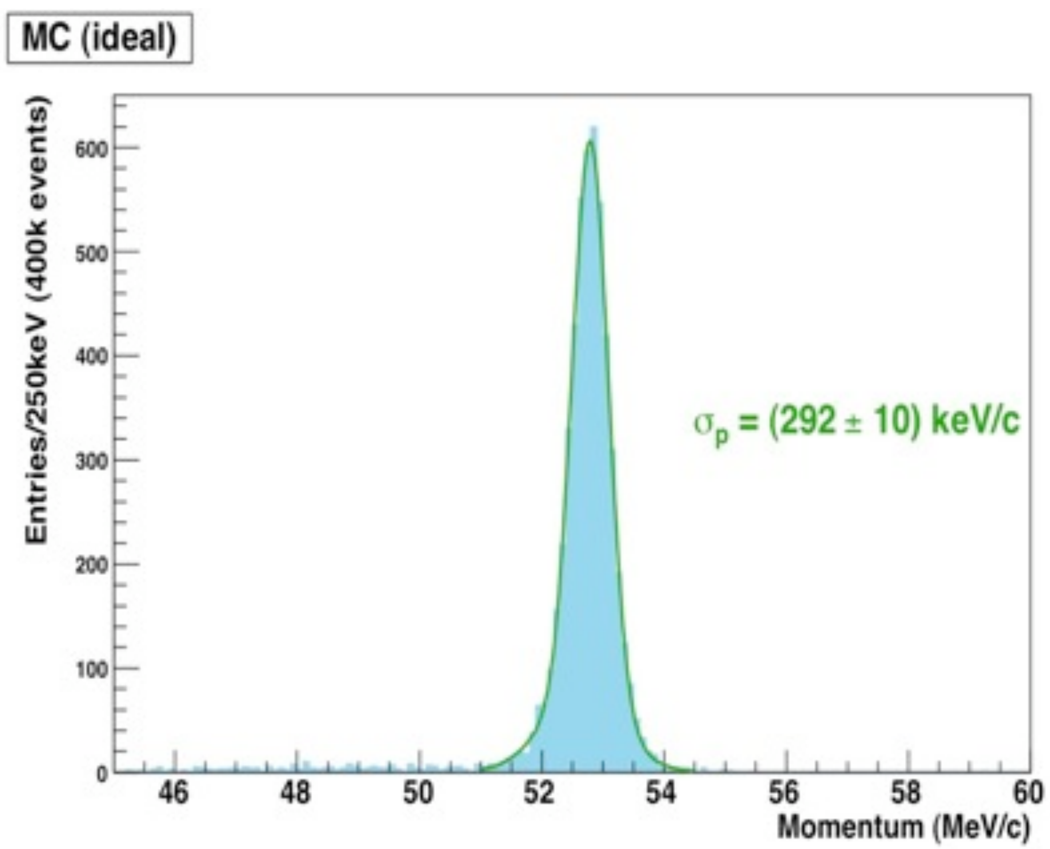
Momentum Resolution (3)

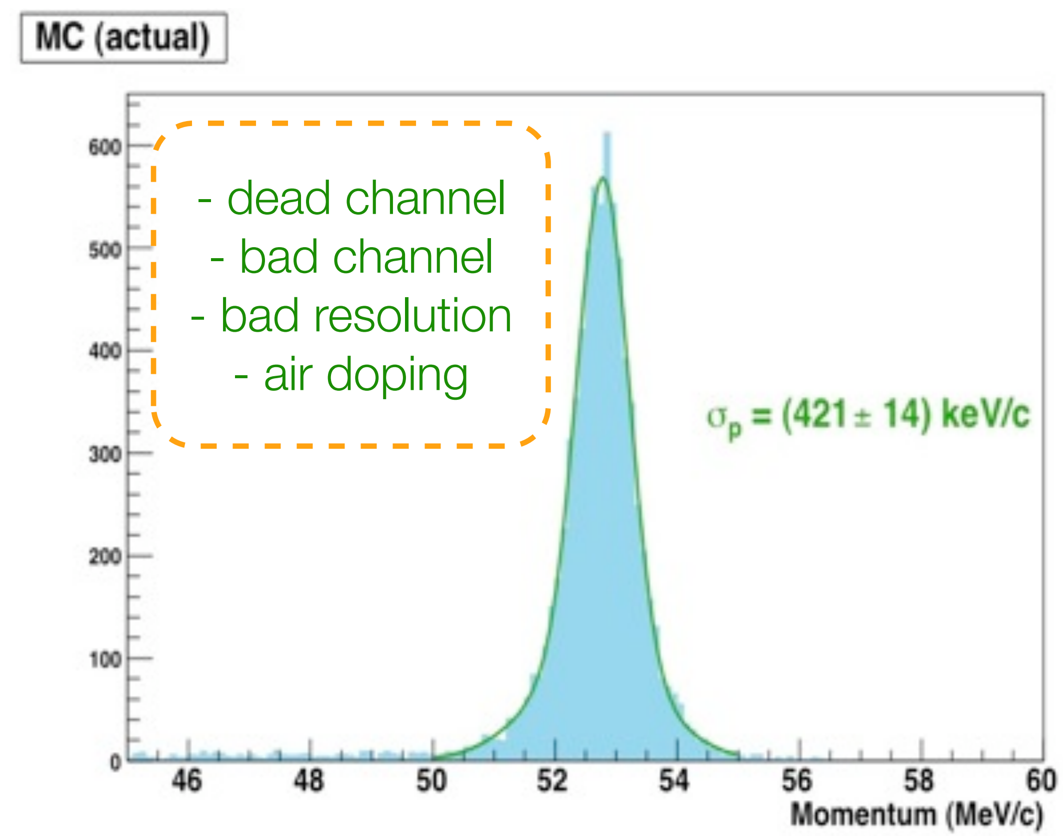
- Michel-Edge Fitting is done with several angular slices



Momentum Resolution (4)

- Resolution Estimation with monochromatic 52.8MeV e^+ by MC

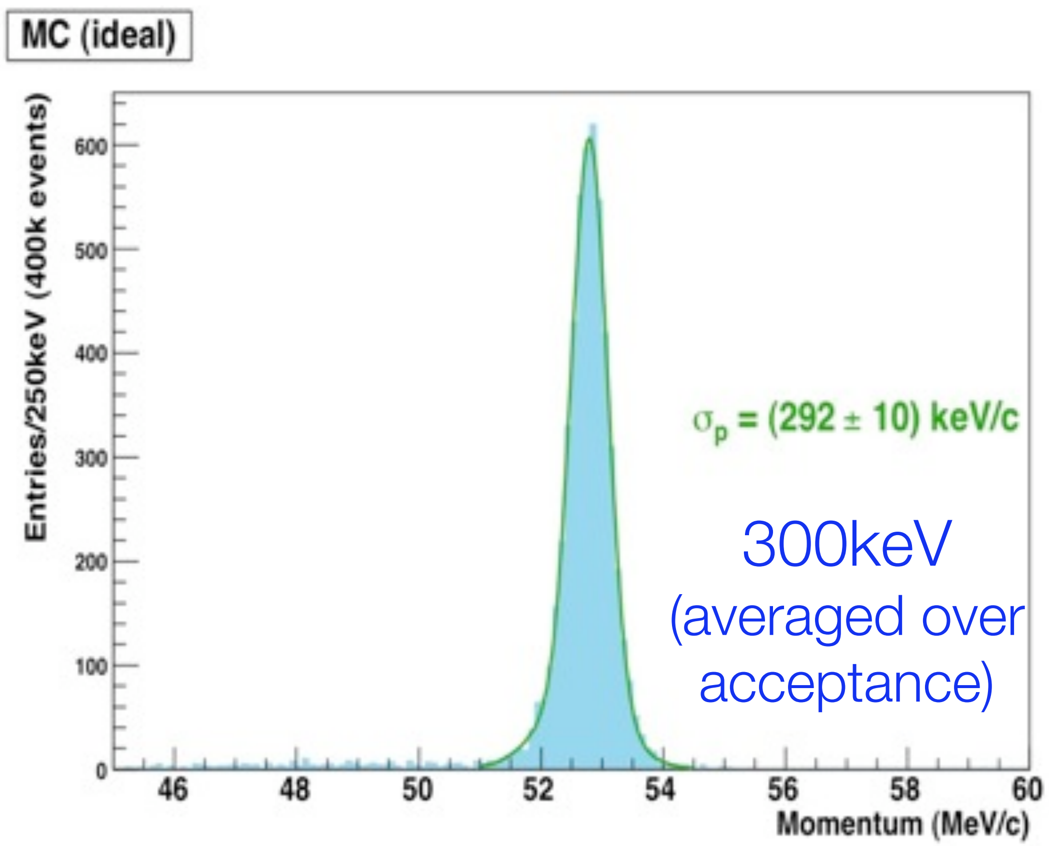


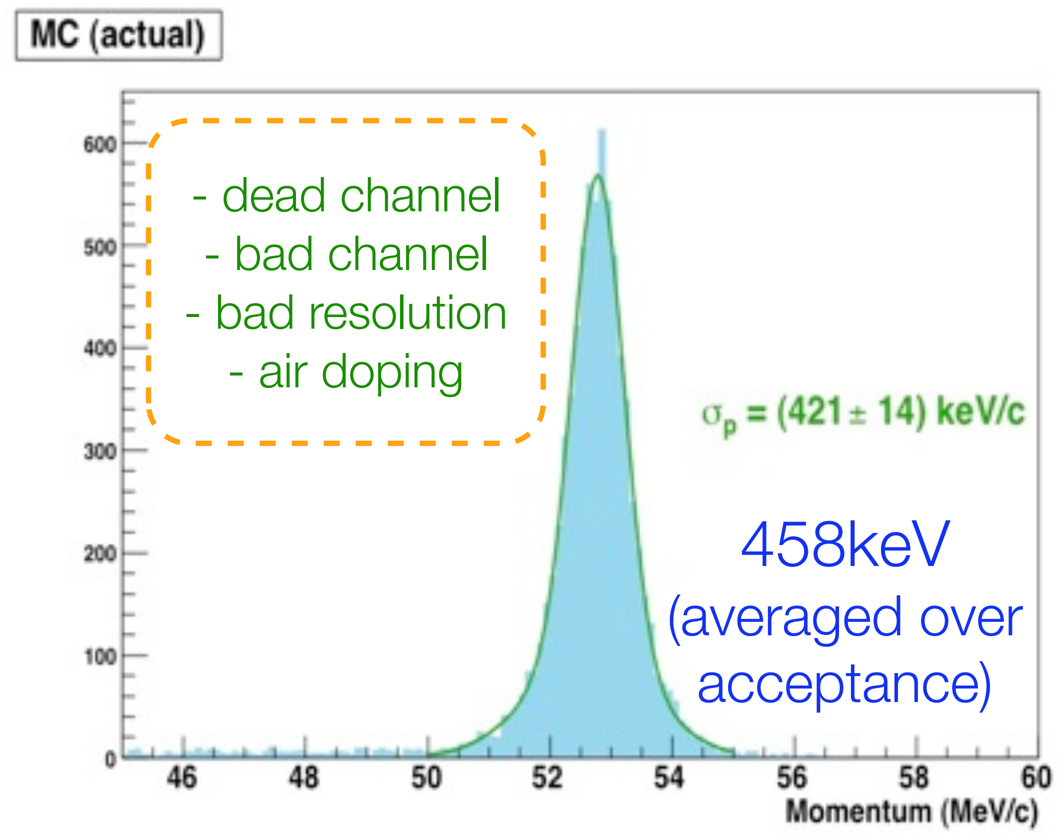


- "Actual MC"
  - Garfield part and Waveform simulation are turned off
  - Only using "Geant-Hit" degraded by each effects

Momentum Resolution (4)

- Resolution Estimation with monochromatic 52.8MeV e^+ by MC

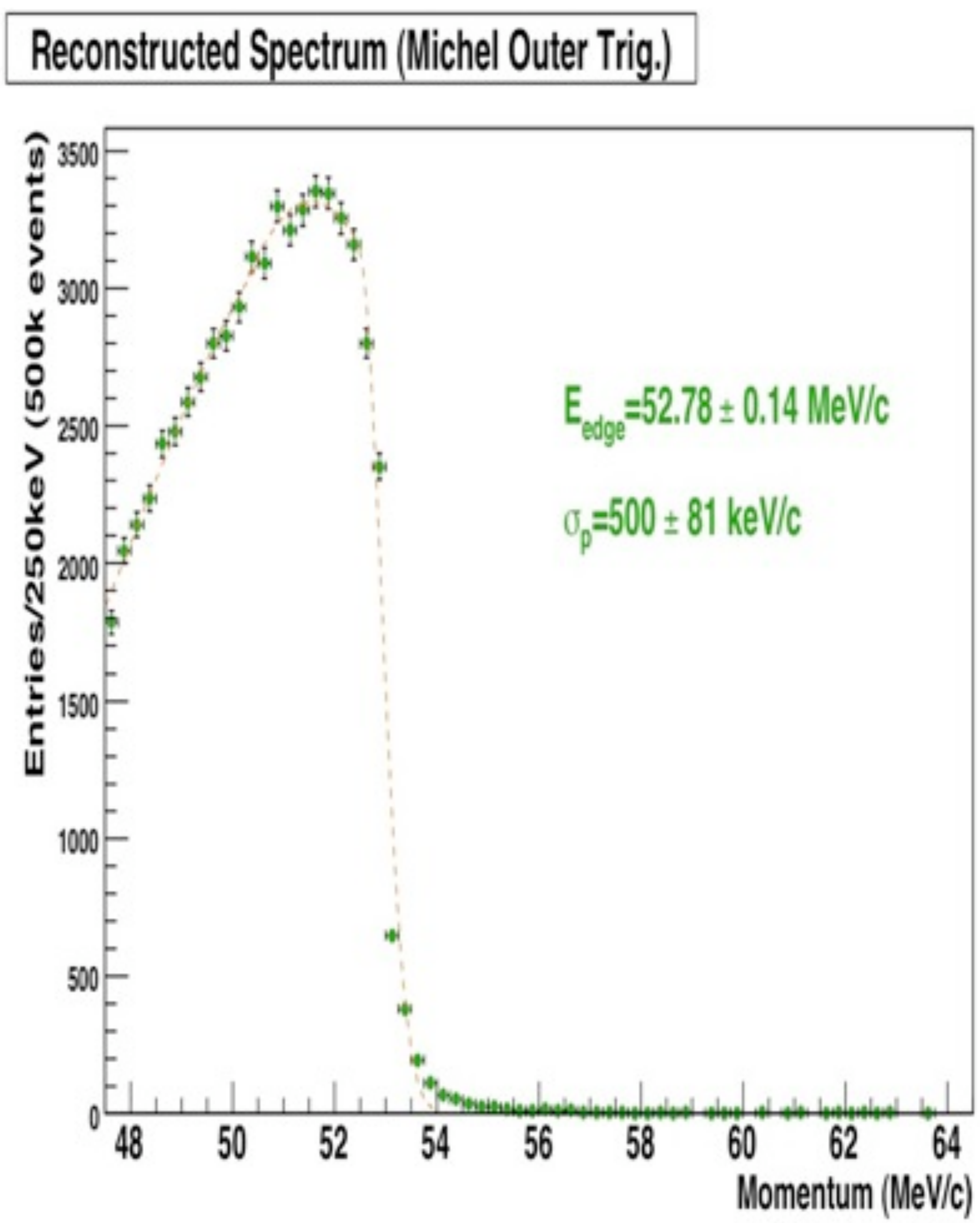


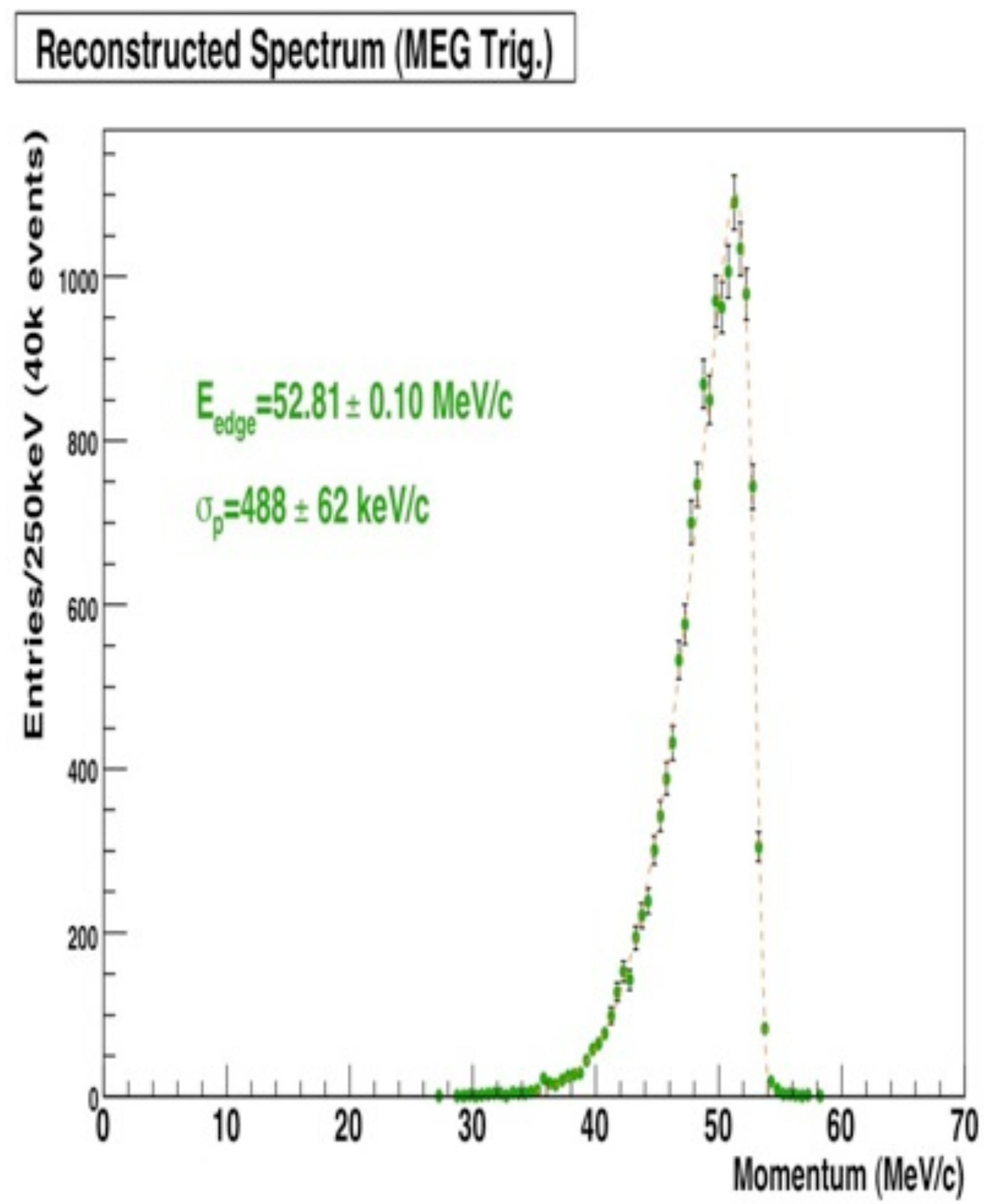


- "Actual MC"
  - Garfield part and Waveform simulation are turned off
  - Only using "Geant-Hit" degraded by each effects

Momentum Resolution (5)

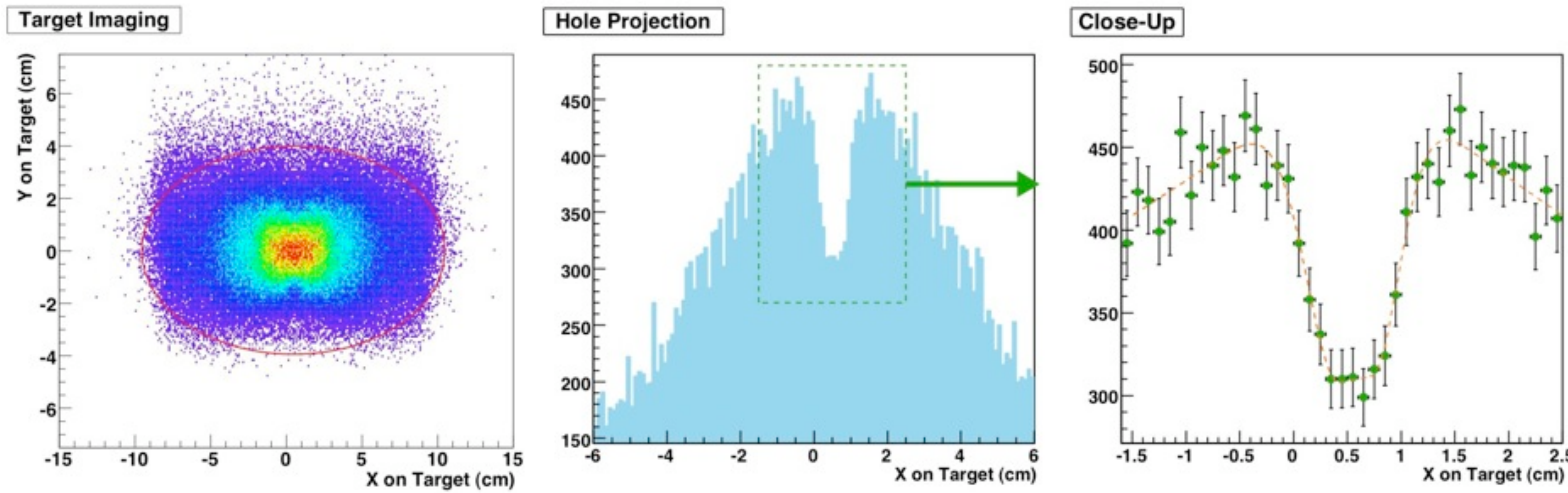
- Rate Dependence / Trigger Dependence





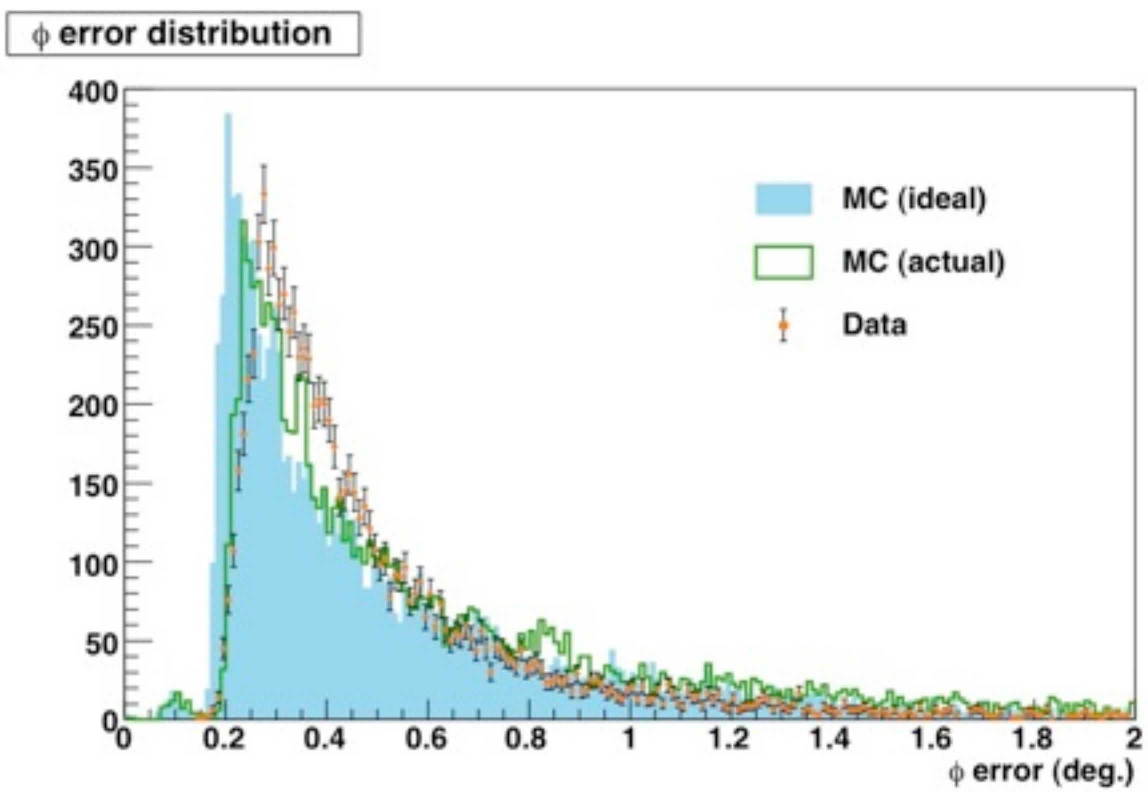
Vertex Resolution

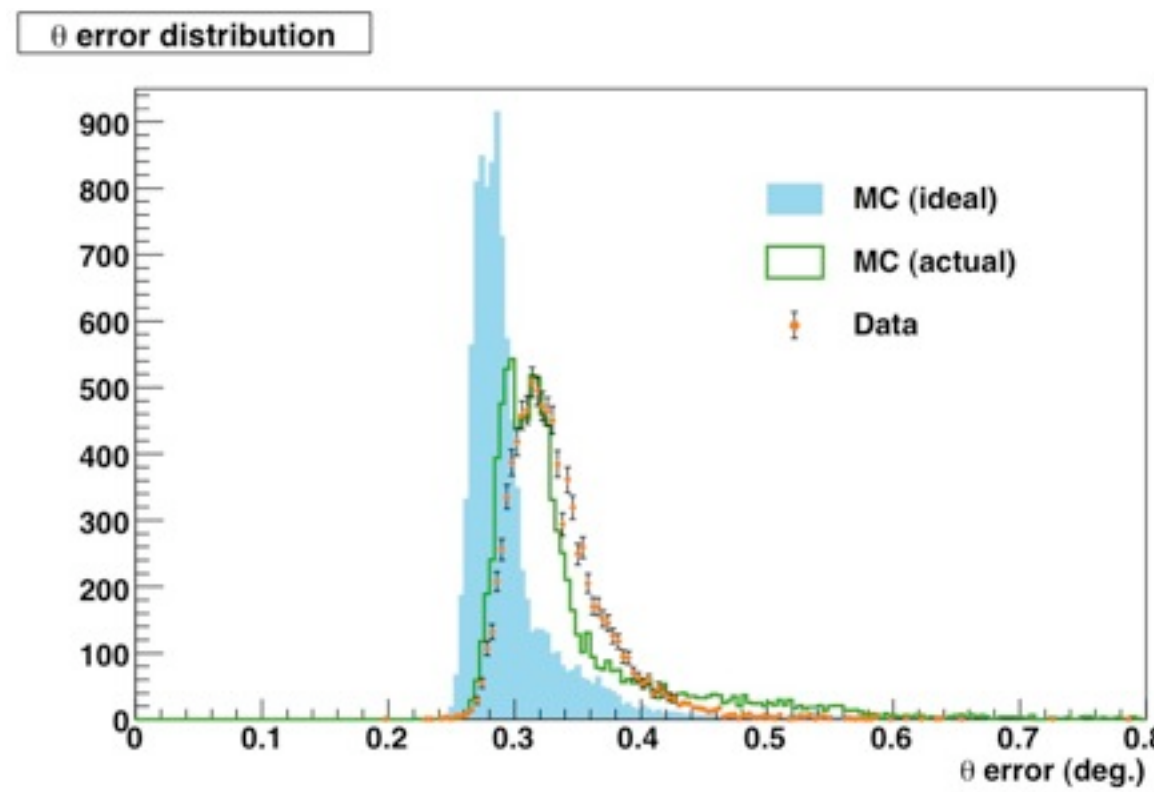
- Hole on Target can be used

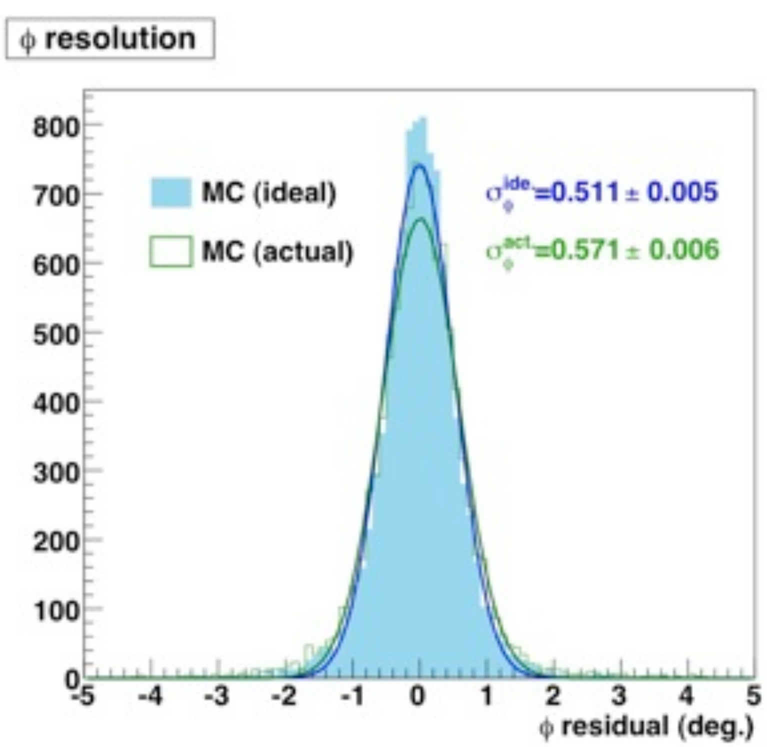


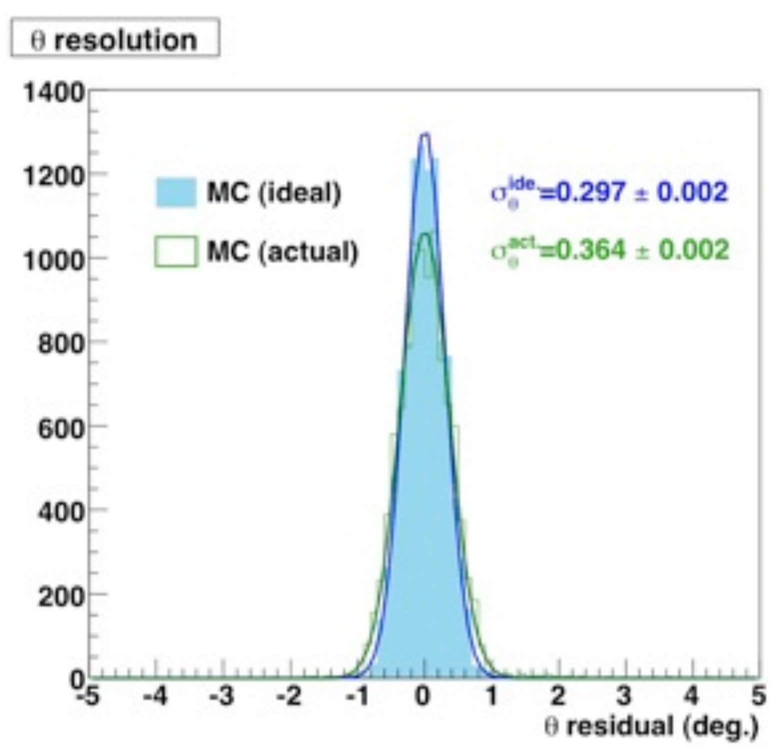
- σ_x = 1.8 mm / MC_{ideal} : σ_x = 1.1 mm
- 5.3 mm misalignment of target position can be seen

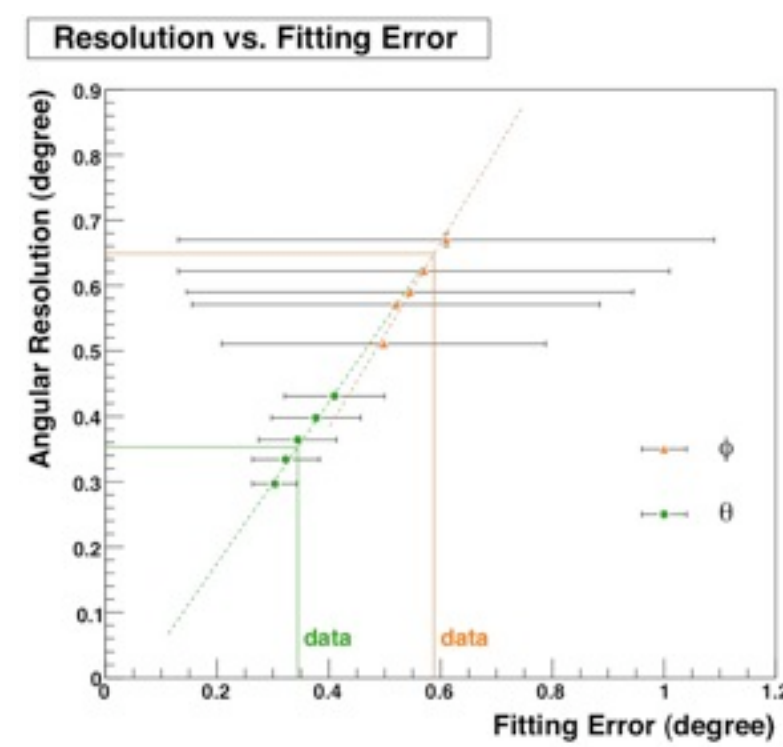
Angular Resolution





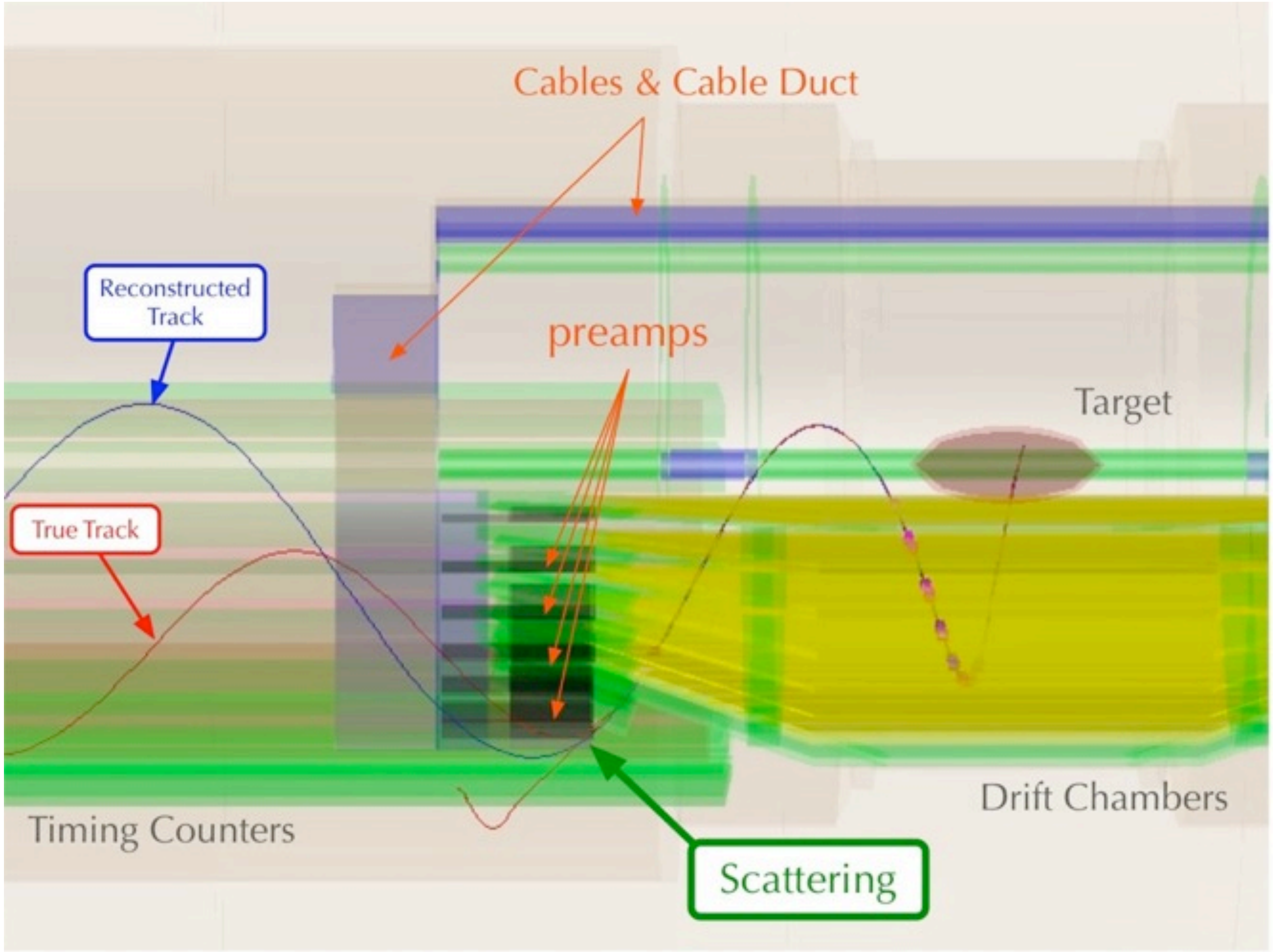






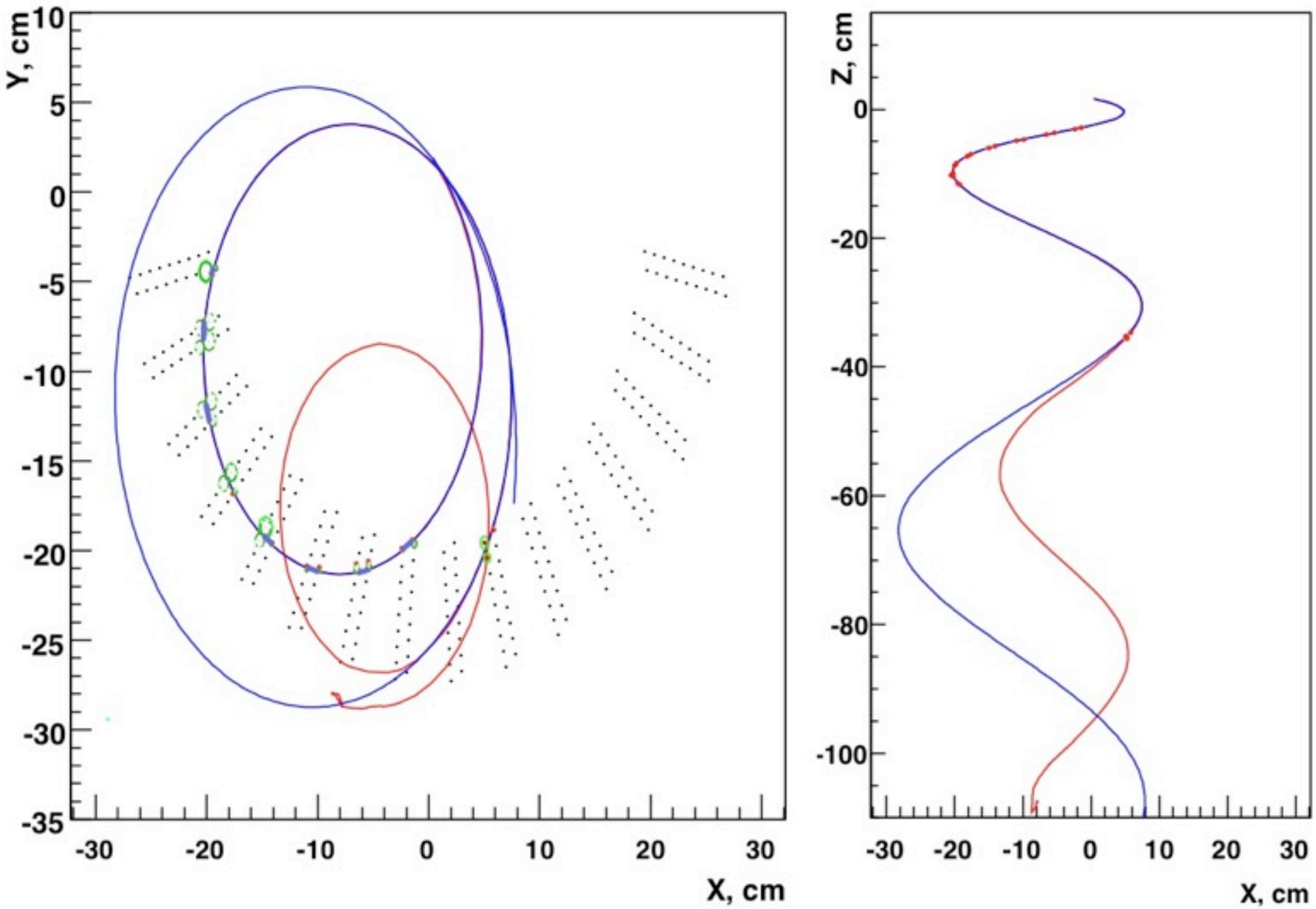
Spectrometer Efficiency (1)

- Counting Efficiency is limited by scattering between DC and TC



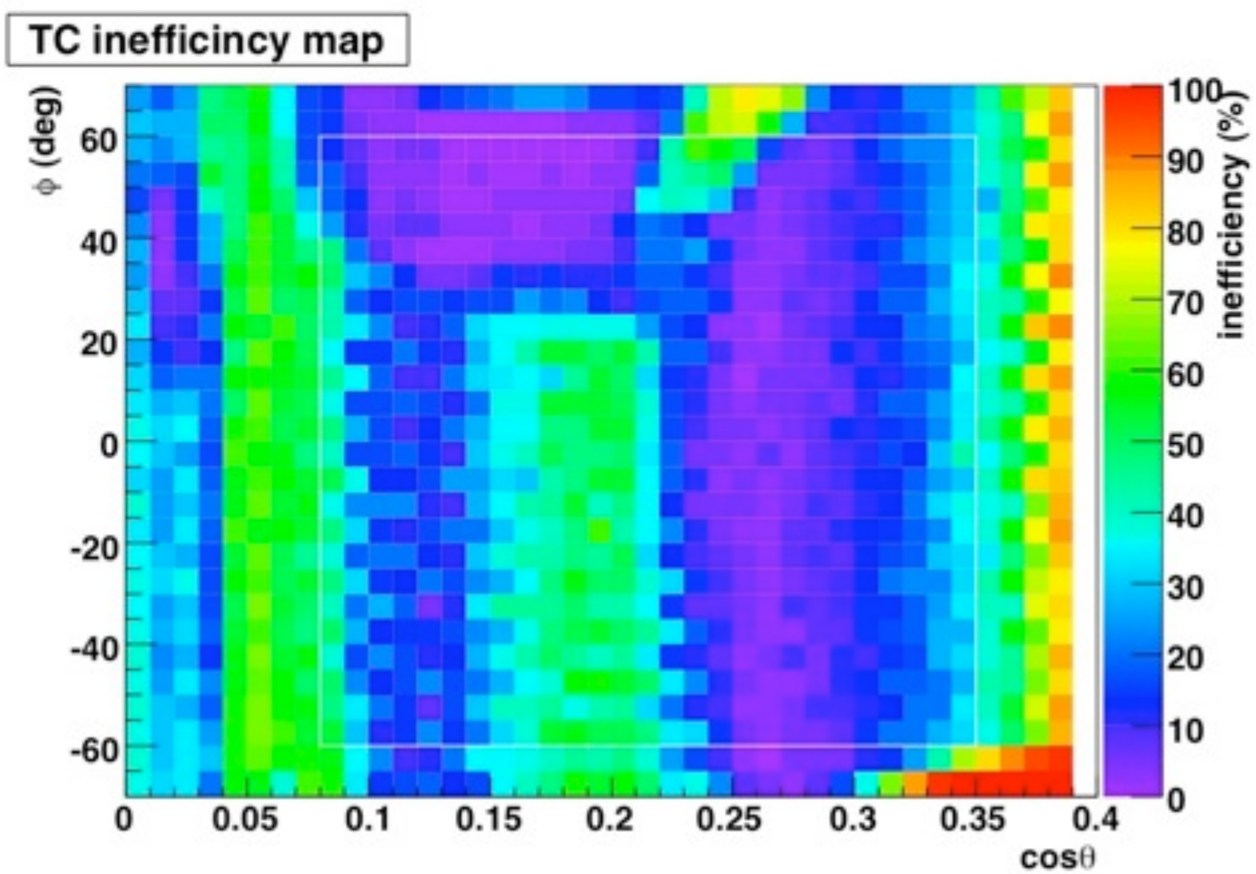
Spectrometer Efficiency (1)

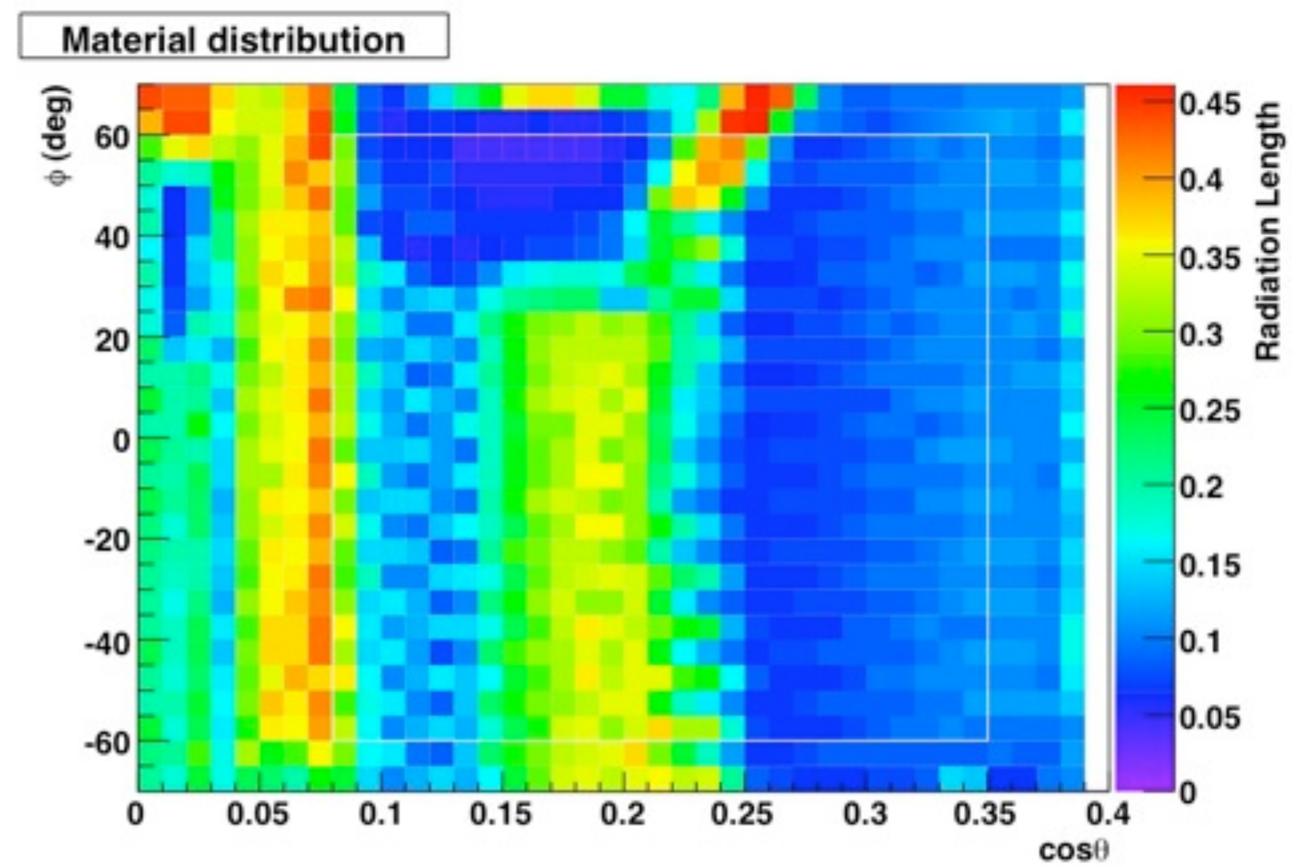
- Counting Efficiency is limited by scattering between DC and TC



Spectrometer Efficiency (2)

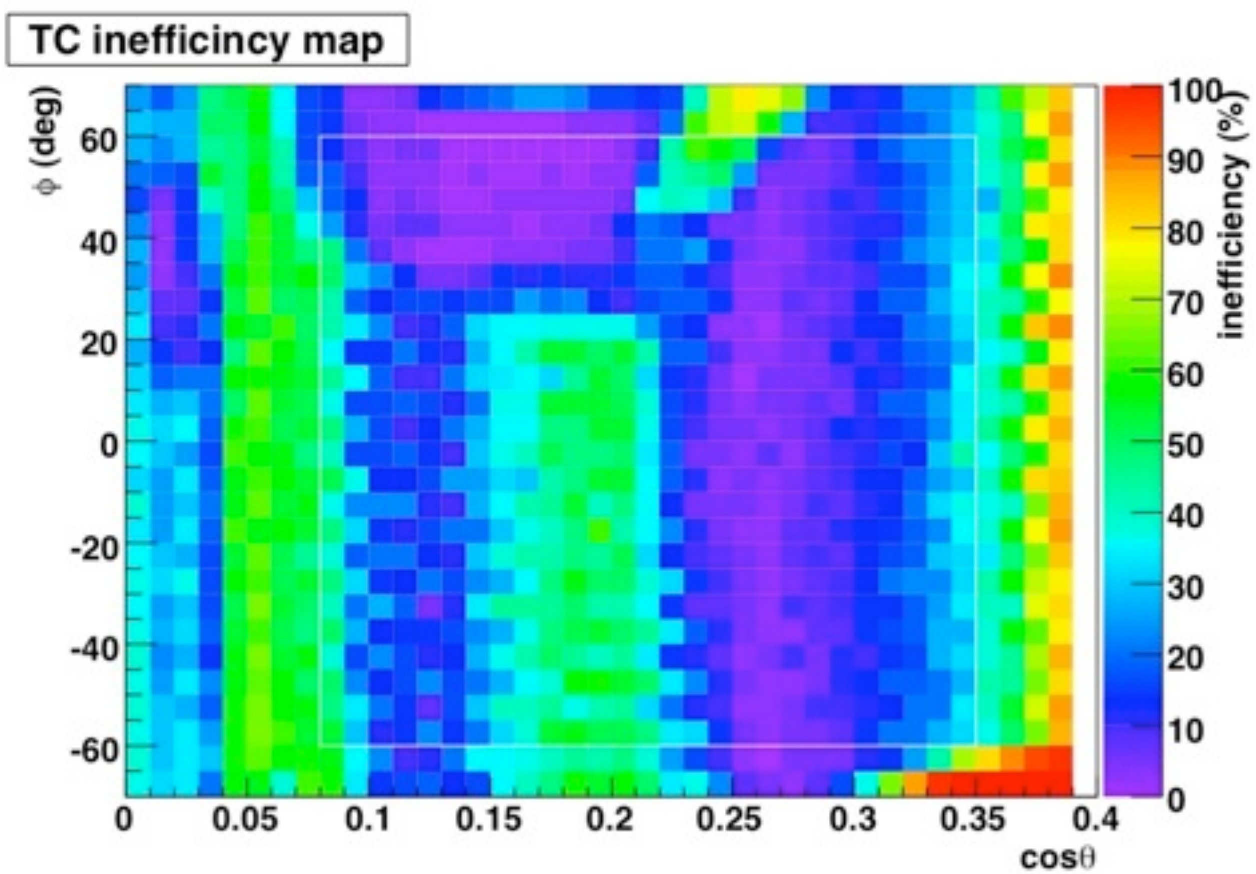
- e^+ scattering should be investigated with material distribution

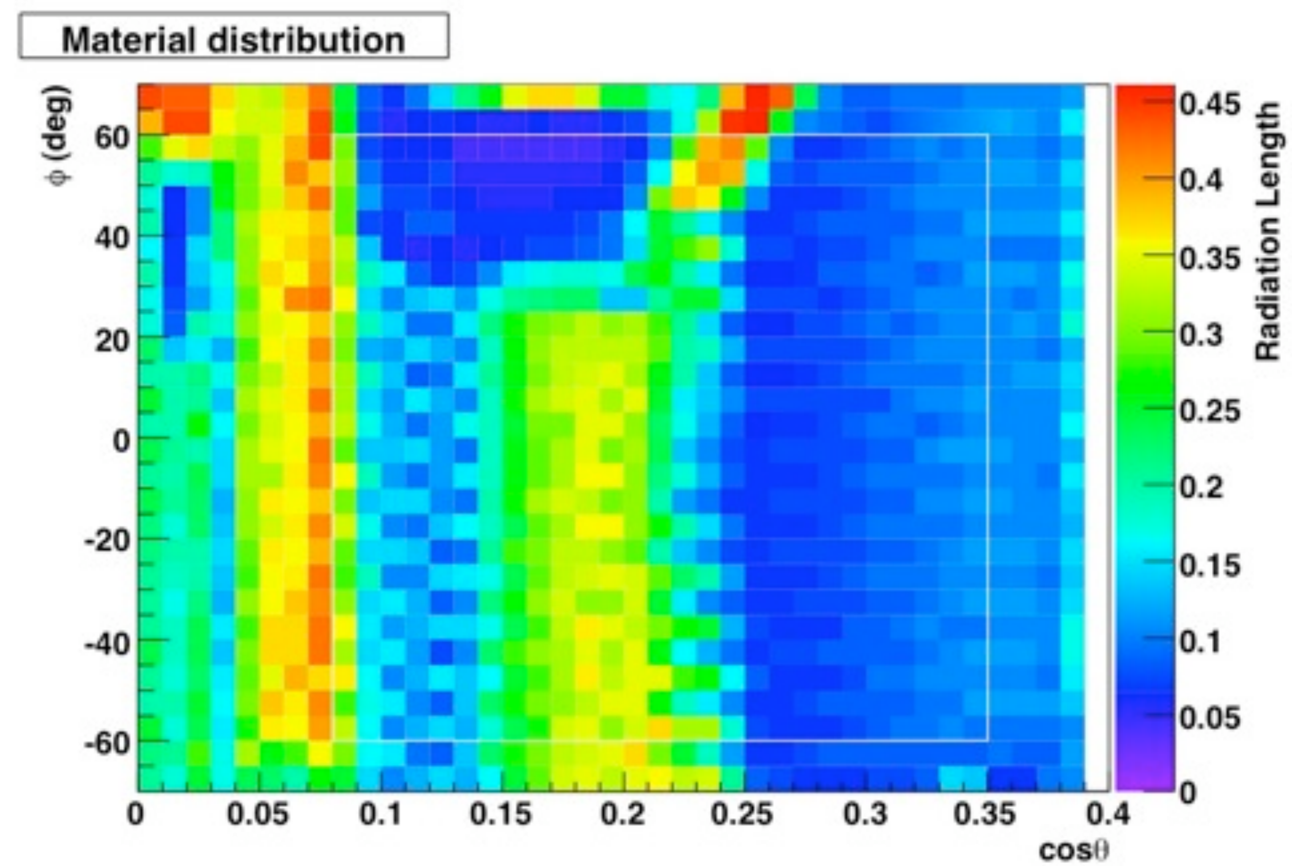




Spectrometer Efficiency (2)

- e^+ scattering should be investigated with material distribution

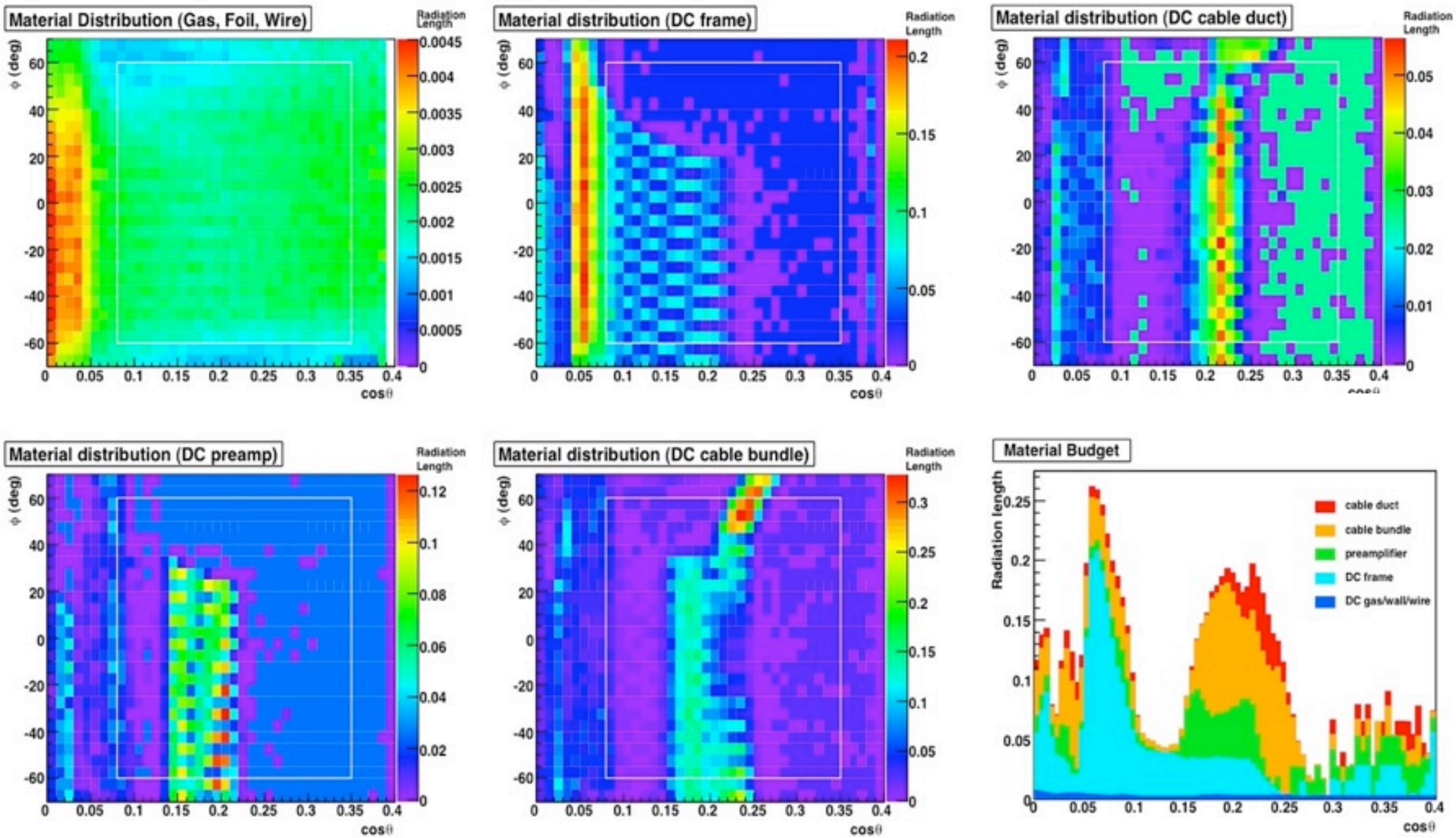




	reconstruction	spectrometer
data (2007)	65.5%	42.8%
MC (actual)	65.5%	43.8%
MC (ideal)	65.5%	63.9%

- Spectrometer Efficiency
  - $\varepsilon^{2007} = 42.8\ \%$
  - $\varepsilon^{2008} = 63.9\%$

Material Distribution



Discussion

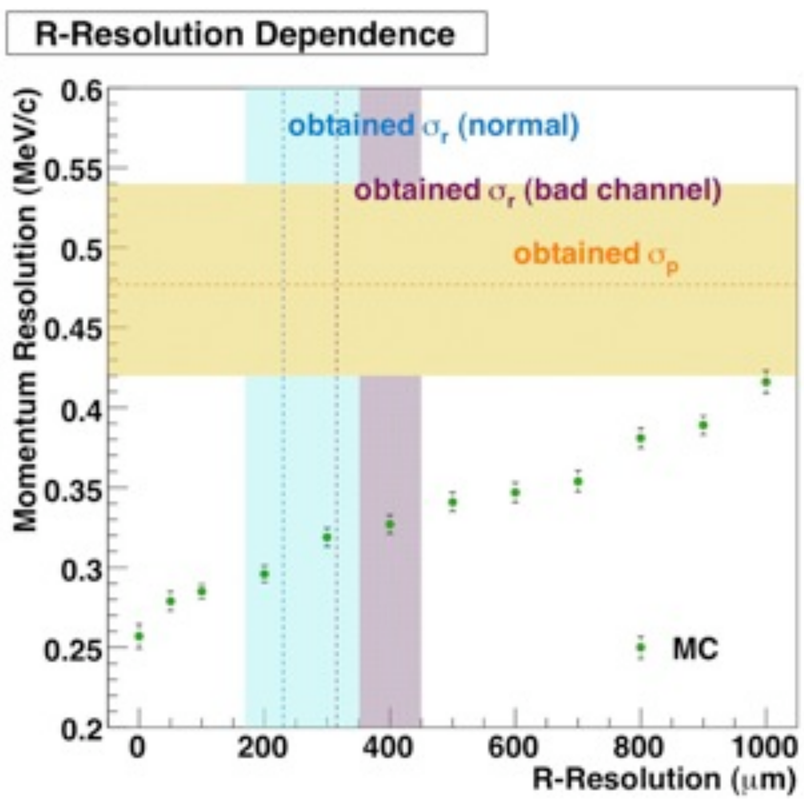
Limiting Factors (1)

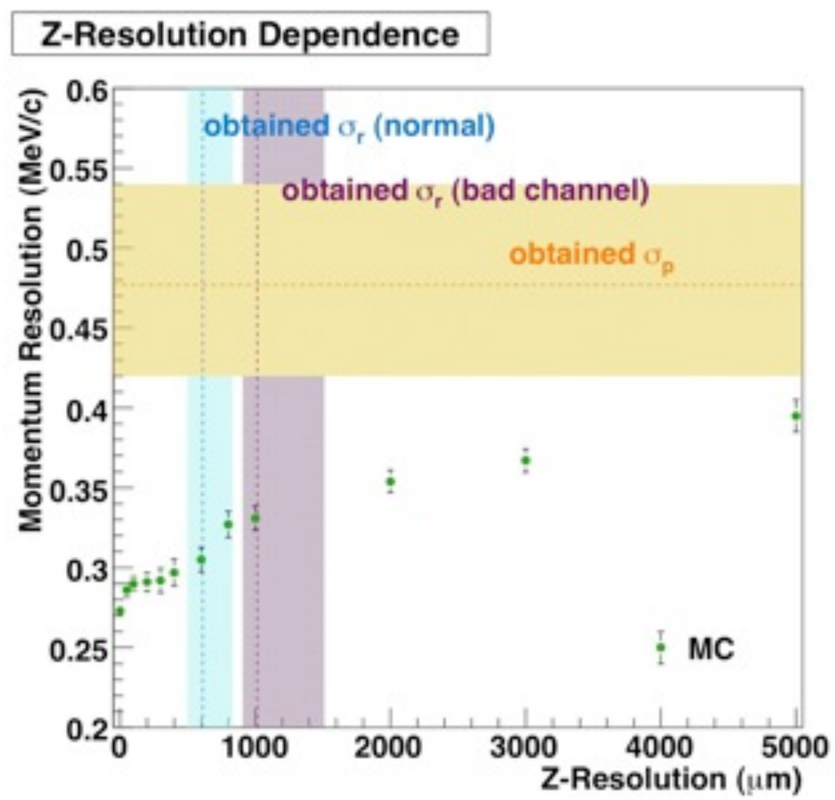
- DC Spacial Resolution

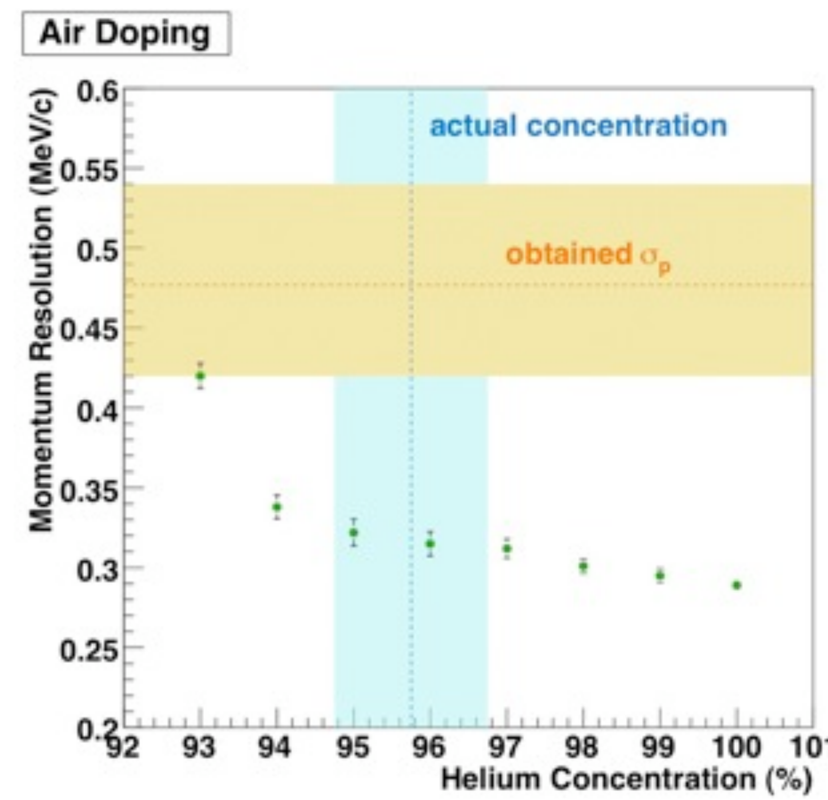
Resolutions	Effect	Uncertainty
Transverse Spacial Resolution 169 - 351 μm (data,2007)	High Voltage	± 0.40
	Gas Pressure	± 0.25
	Timing Determination	± 76.4
	Alignment (r)	± 33.5
	Electron Diffusion	± 90.1
	Multiple Scattering	± 125
	Total in quadrature	± 175
Longitudinal Spacial Resolution 499 - 833 μm (data,2007)	DRS Fake Pulse	± 138
	Alignment (z)	± 92
	Relative Gain Fluctuation	± 199
	Baseline Noise	± 109
	Multiple Scattering	± 175
	Charge Distribution	± 354
	Total in quadrature	± 484

Limiting Factors (2)

- Spectrometer Resolution
  - Missing Channels / Spacial Resolutions / Air Doping

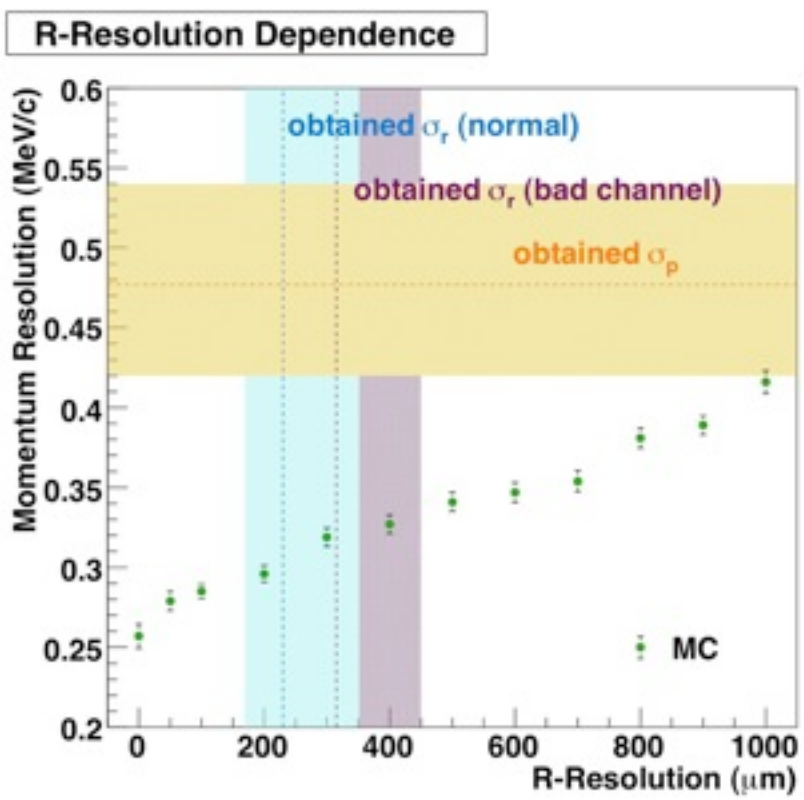


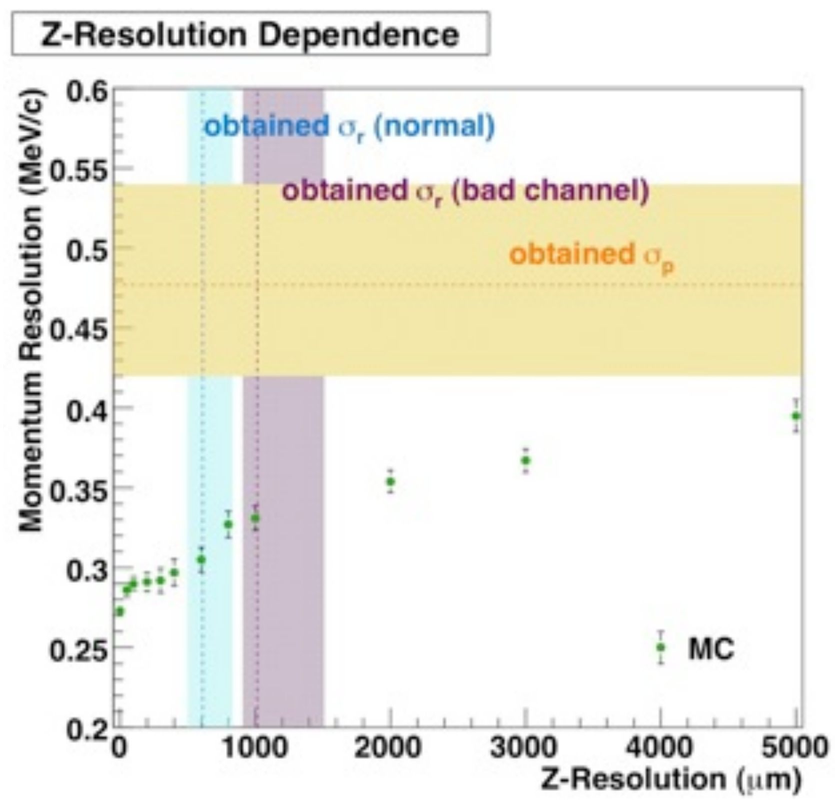


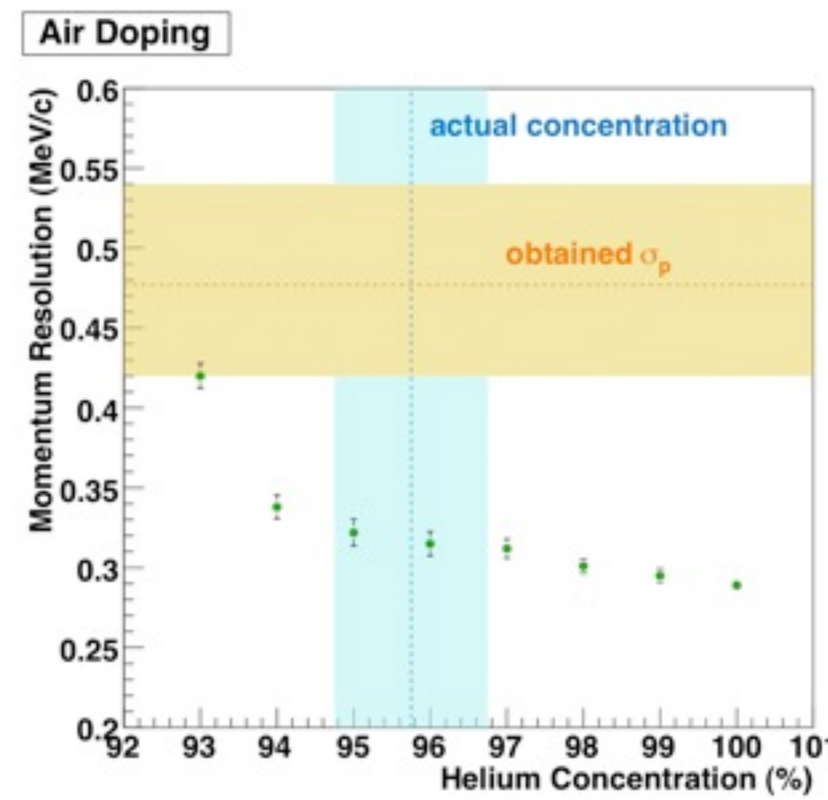


Limiting Factors (2)

- Spectrometer Resolution
  - Missing Channels / Spacial Resolutions / Air Doping



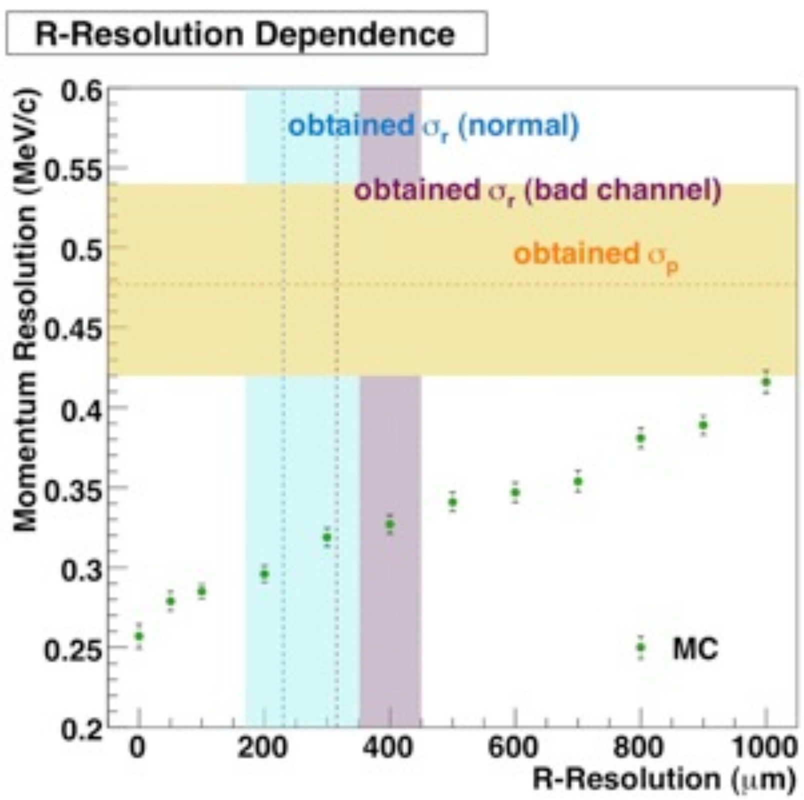


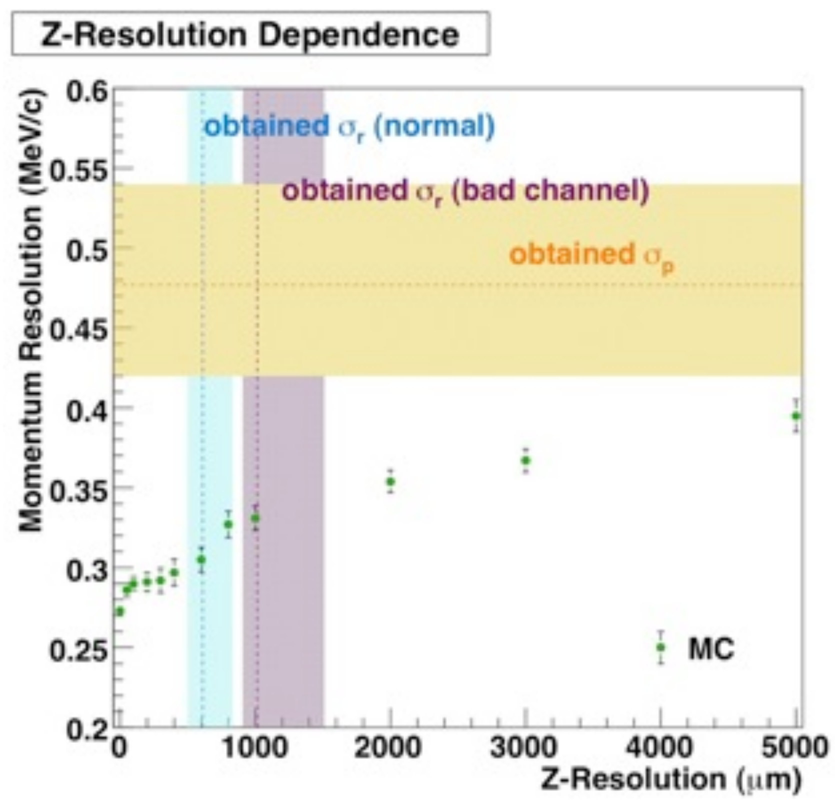


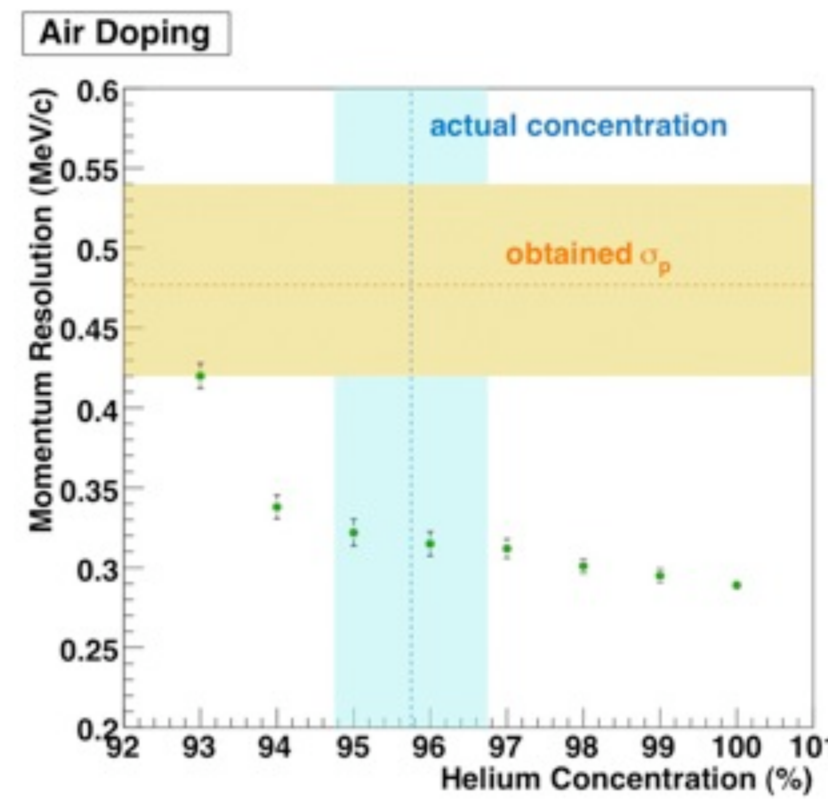
- Obtained Momentum Resolution : 477 keV (data) and 300 keV (MC^{ideal})
  - Contribution : Spacial Resolution : ± 135 keV(r), ± 164 keV (z)
  - Contribution from Air Contamination : ± 125 keV
  - Contribution from Missing Channels : ± 285 keV

Limiting Factors (2)

- Spectrometer Resolution
  - Missing Channels / Spacial Resolutions / Air Doping







- Obtained Momentum Resolution : 477 keV (data) and 300 keV (MC[ideal])
  - Contribution : Spacial Resolution : ± 135 keV(r), ± 164 keV (z)
  - Contribution from Air Contamination : ± 125 keV
  - Contribution from Missing Channels : ± 285 keV

} 461keV (sum)
458keV (MC[actual])

Limiting Factors (3)

- Is it Reasonable ??

$$(\delta k)^2 = (\delta k_{res})^2 + (\delta k_{ms})^2$$

(in uniform B field)

$$\delta k_{res} = \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+4}}$$

$$\delta k_{ms} = \frac{(0.016)(\mathrm{Gev}/c)z}{Lp\beta\cos^2\theta}\sqrt{\frac{L}{X_0}}$$

Limiting Factors (3)

- Is it Reasonable ??

$$(\delta k)^2 = (\delta k_{res})^2 + (\delta k_{ms})^2$$

(in uniform B field)

$$\left\{ \begin{aligned} \delta k_{res} &= \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+4}} \\ \delta k_{ms} &= \frac{(0.016)(\mathrm{Gev}/c)z}{Lp\beta\cos^2\theta}\sqrt{\frac{L}{X_0}} \end{aligned} \right.$$

- Obtained Momentum Resolution : 477 keV (data) and 300 keV (MC^{ideal})
    - Contribution : Spacial Resolution (factor 1.21) : ± 127 keV (r) (135 keV, MC^{actual})
    - Contribution from Air Contamination (factor 1.48) : ± 121 keV (125 keV, MC^{actual})
    - Contribution from Missing Channels (factor 1.88) : ± 224 keV (249 keV, MC^{actual})

MEG Sensitivity (1)

- Detector Performances

Quantity	Engineering Run 2007	Physics Run 2008
e^+ Momentum Resolution (%)	2.2	1.5
e^+ Angular Resolution (mrad)	14.5	11.5
e^+ Timing Resolution (ps)	127	103
γ Energy Resolution (%)	-	5.0
γ Spacial Resolution (mm)	-	9.0
γ Timing Resolution (ps)	-	150
Acceptance (%)	9	9
e^+ Detection Efficiency (%)	43.8	63.9
γ Detection Efficiency (%)	-	40
Muon Rate (/sec)	3.00E+07	3.00E+07

MEG Sensitivity (1)

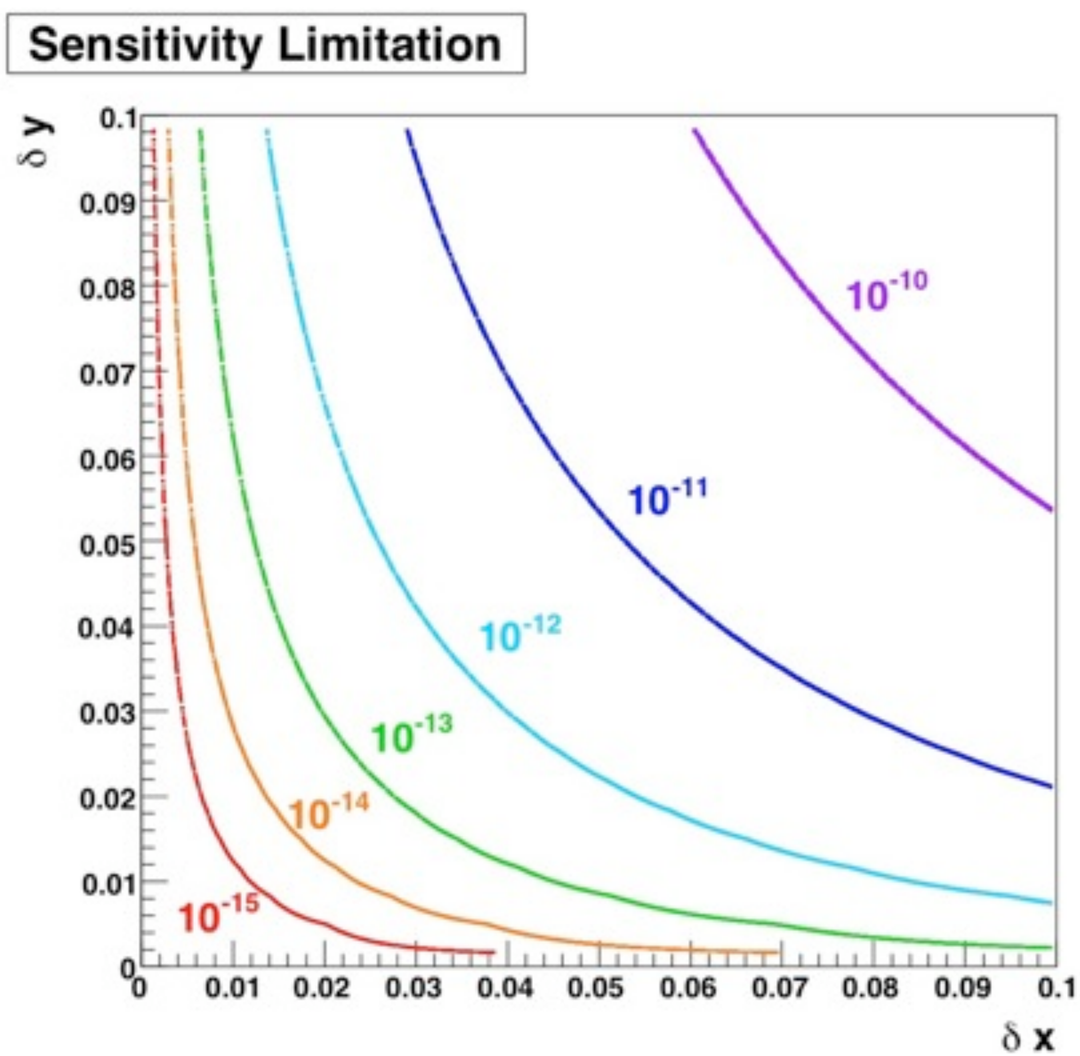
- Detector Performances

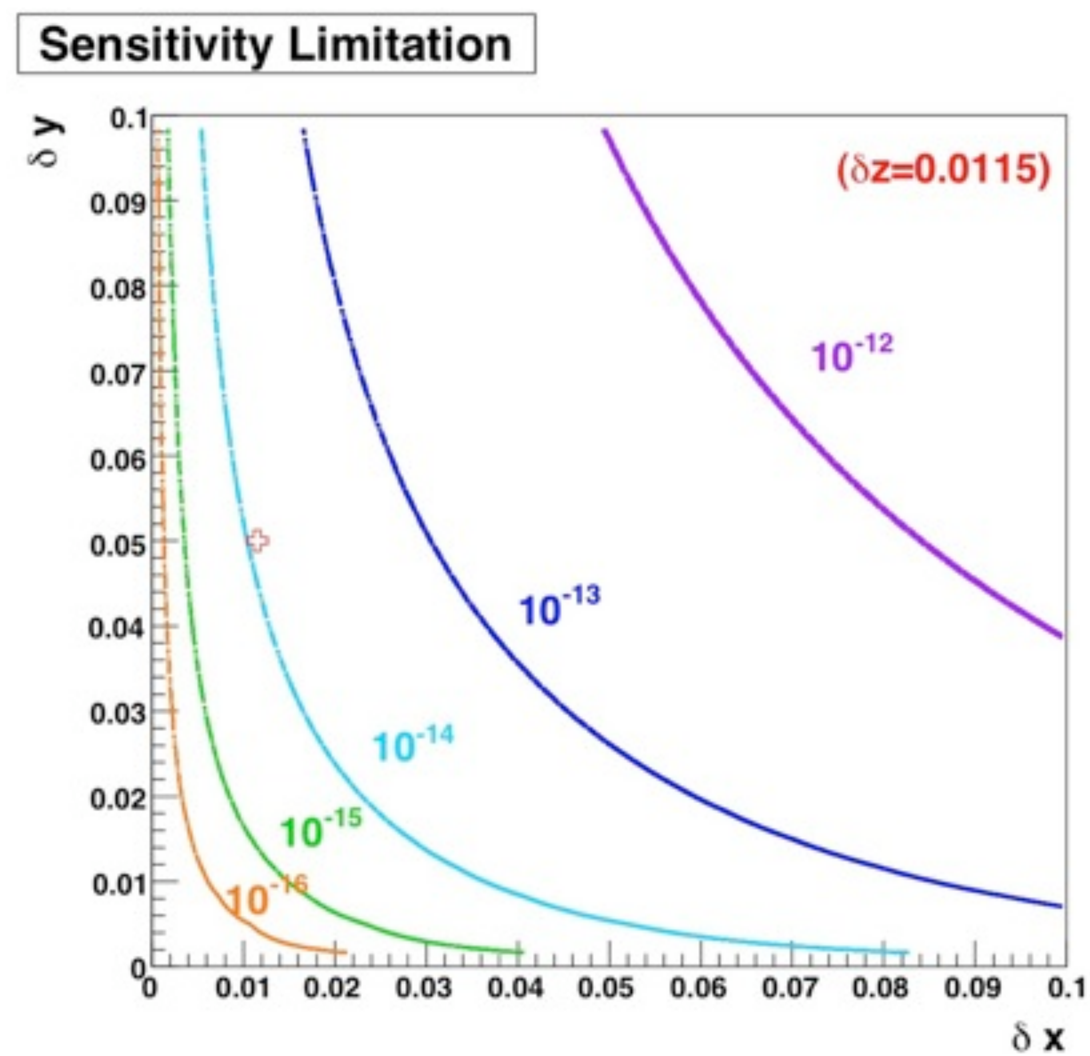
Quantity	Engineering Run 2007	Physics Run 2008 EXPECTED
e^+ Momentum Resolution (%)	2.2	1.5
e^+ Angular Resolution (mrad)	14.5	11.5
e^+ Timing Resolution (ps)	127	103
γ Energy Resolution (%)	-	5.0
γ Spacial Resolution (mm)	-	9.0
γ Timing Resolution (ps)	-	150
Acceptance (%)	9	9
e^+ Detection Efficiency (%)	43.8	63.9
γ Detection Efficiency (%)	-	40
Muon Rate (/sec)	3.00E+07	3.00E+07

MEG Sensitivity (2)

- Physics Background (Radiative Muon Decay)

$$d\mathcal{B}(\mu \to e\nu\bar{\nu}\gamma) = \frac{1}{\Gamma(\mu \to e\nu\bar{\nu})} \int_{1-\delta x}^{1} dx \int_{1-\delta y}^{1} dy \int_{0}^{\min\left[\delta z, 2\sqrt{(1-x)(1-y)}\right]} dz \frac{d\Gamma(\mu \to e\nu\bar{\nu}\gamma)}{dx dy dz}$$

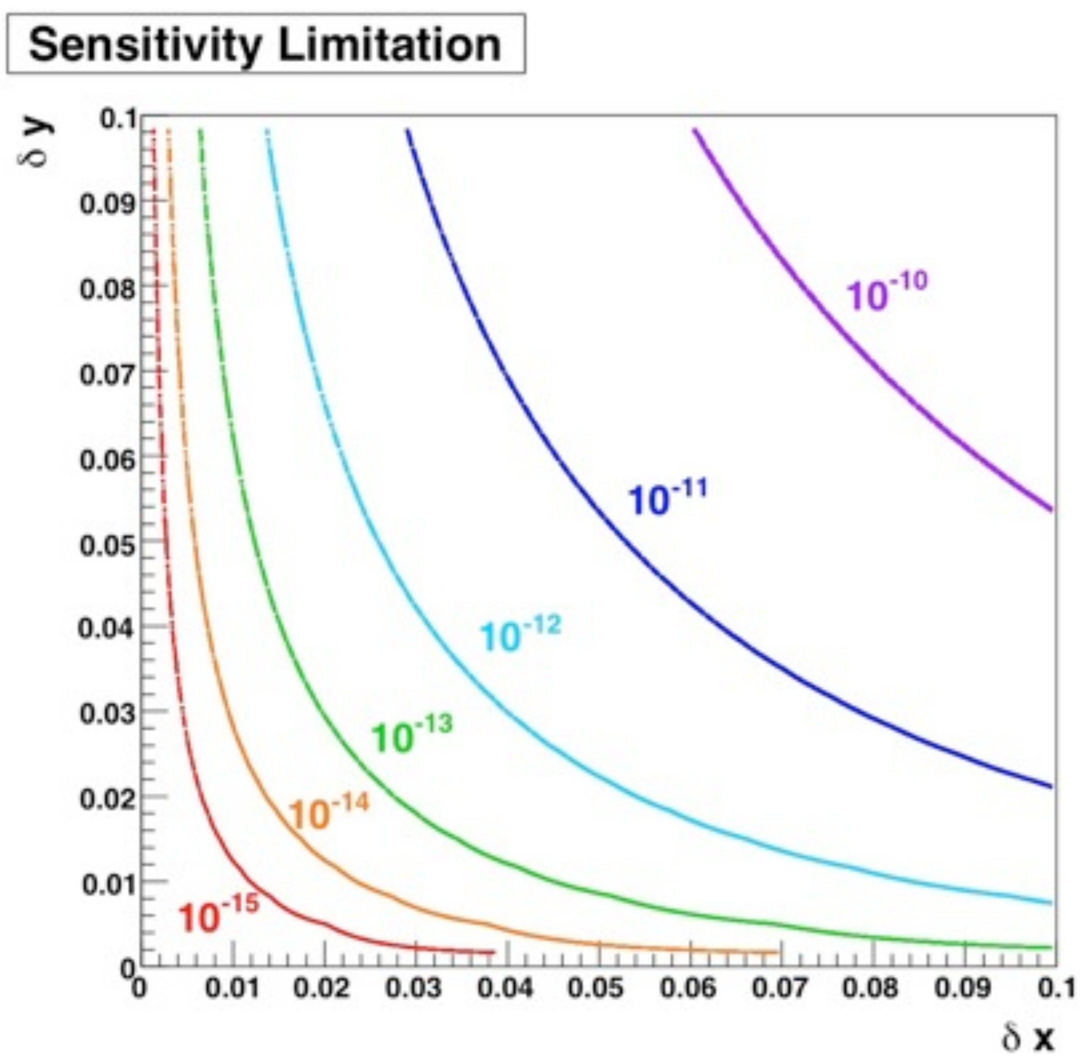


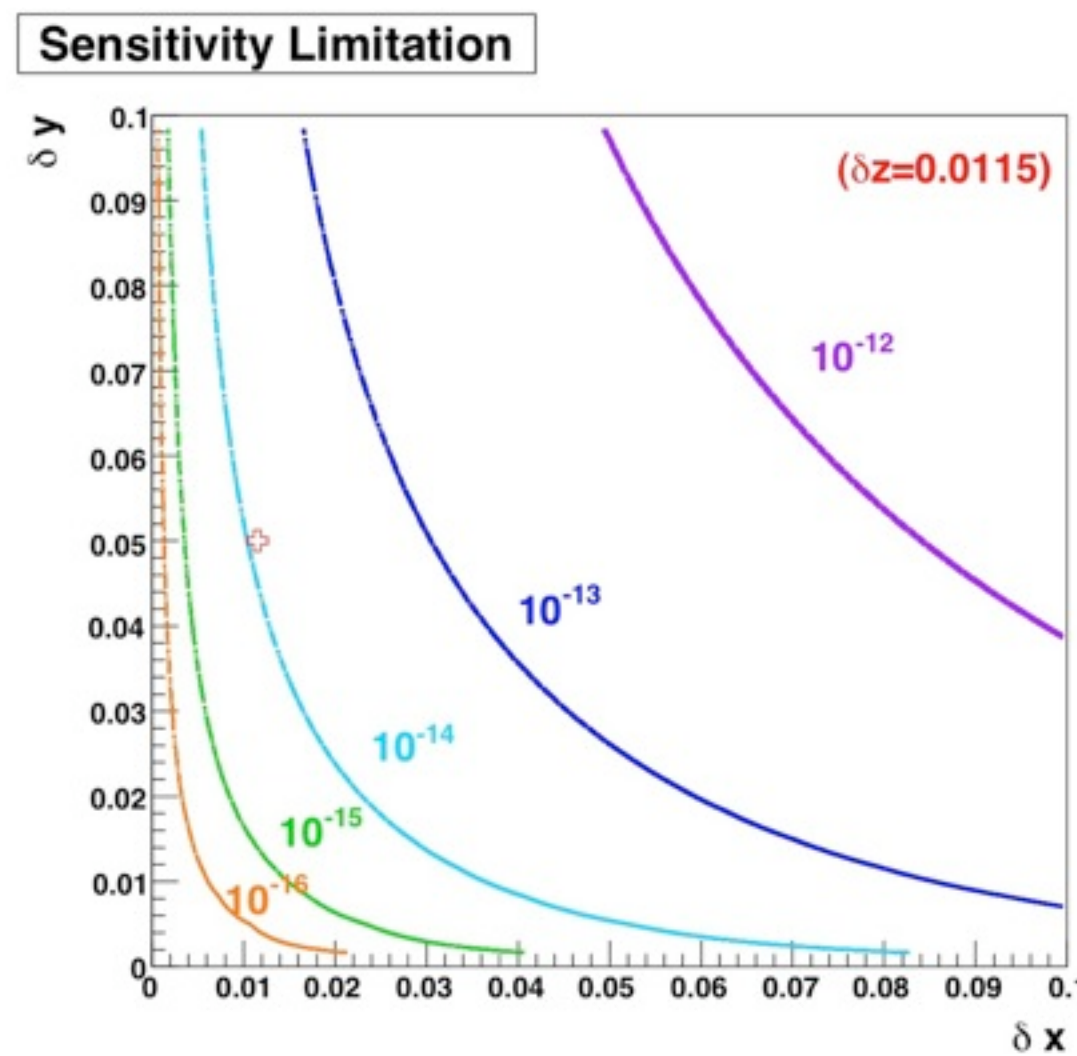


MEG Sensitivity (2)

- Physics Background (Radiative Muon Decay)

$$d\mathcal{B}(\mu \to e\nu\bar{\nu}\gamma) = \frac{1}{\Gamma(\mu \to e\nu\bar{\nu})} \int_{1-\delta x}^{1} dx \int_{1-\delta y}^{1} dy \int_{0}^{\min\left[\delta z, 2\sqrt{(1-x)(1-y)}\right]} dz \frac{d\Gamma(\mu \to e\nu\bar{\nu}\gamma)}{dx dy dz}$$



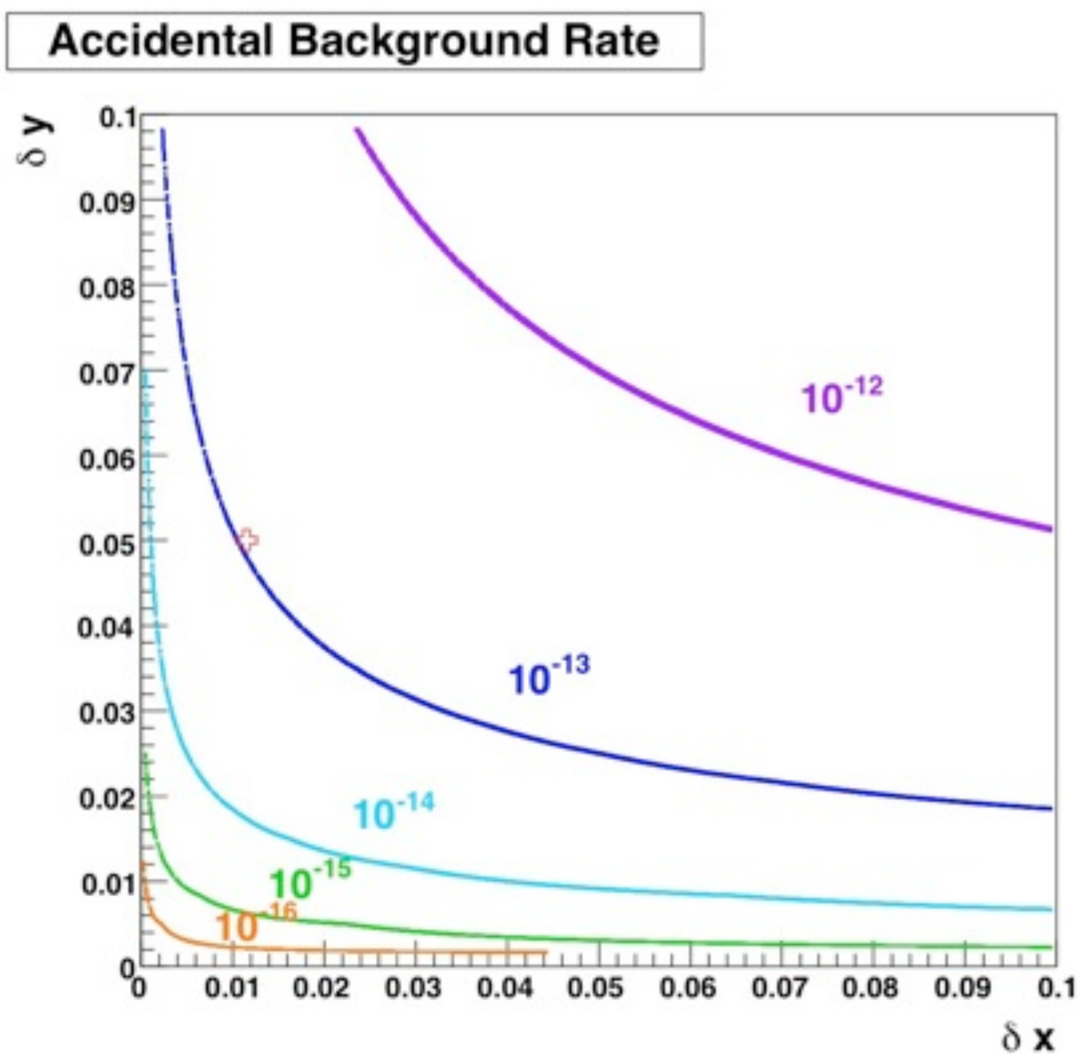


- For MEG 2008, Physics Background < 1.1×10^{-14}

MEG Sensitivity (3)

- Accidental Background

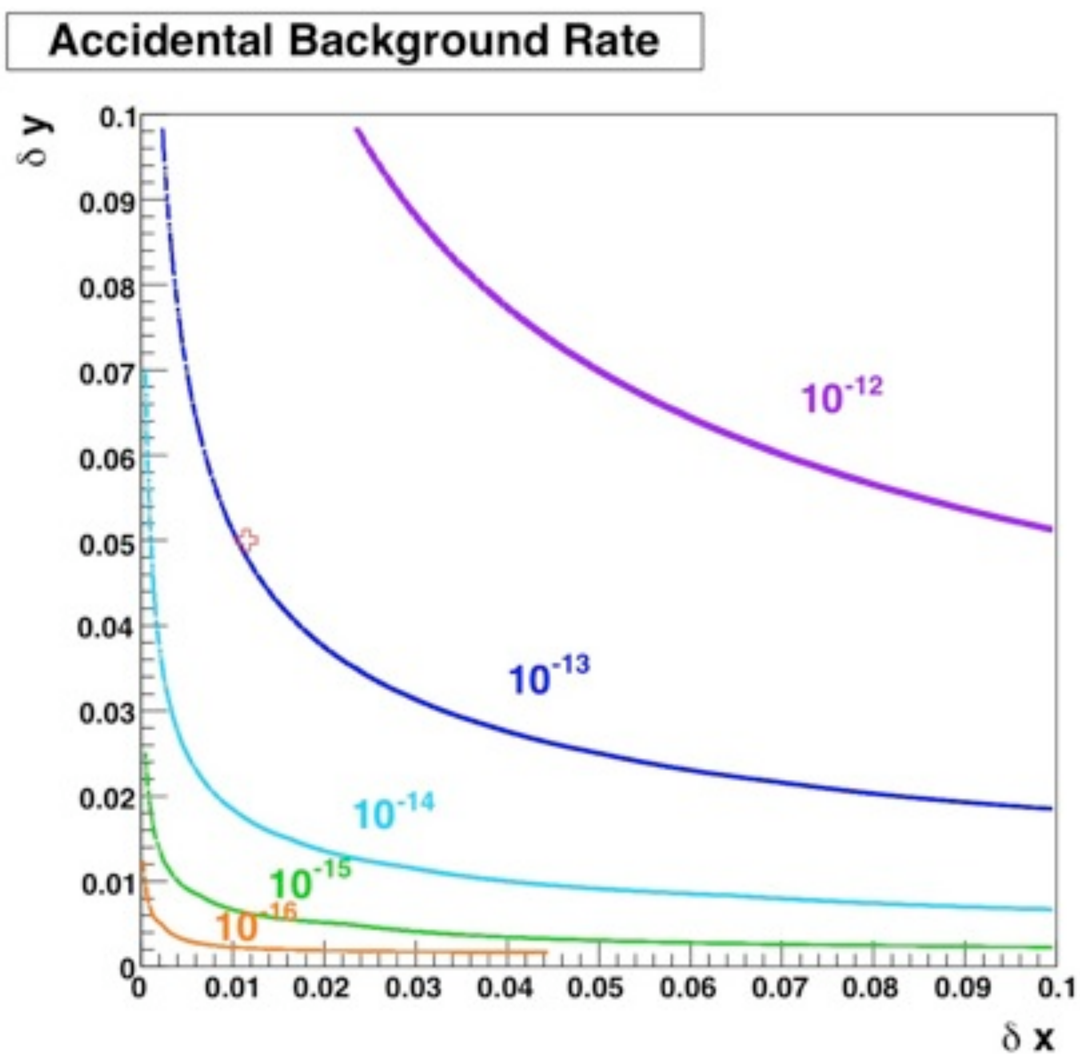
$$\mathcal{B}_{acc} = \mathcal{R}_\mu \cdot (2\delta x) \cdot \left[\frac{\alpha}{2\pi}(\delta y)^2(\ln(\delta y) + 7.33)\right] \times \left(\frac{\delta\theta^2}{4}\right) \cdot (2\delta t).$$



MEG Sensitivity (3)

- Accidental Background

$$\mathcal{B}_{acc} = \mathcal{R}_\mu \cdot (2\delta x) \cdot \left[\frac{\alpha}{2\pi}(\delta y)^2(\ln(\delta y) + 7.33)\right] \times \left(\frac{\delta\theta^2}{4}\right) \cdot (2\delta t).$$

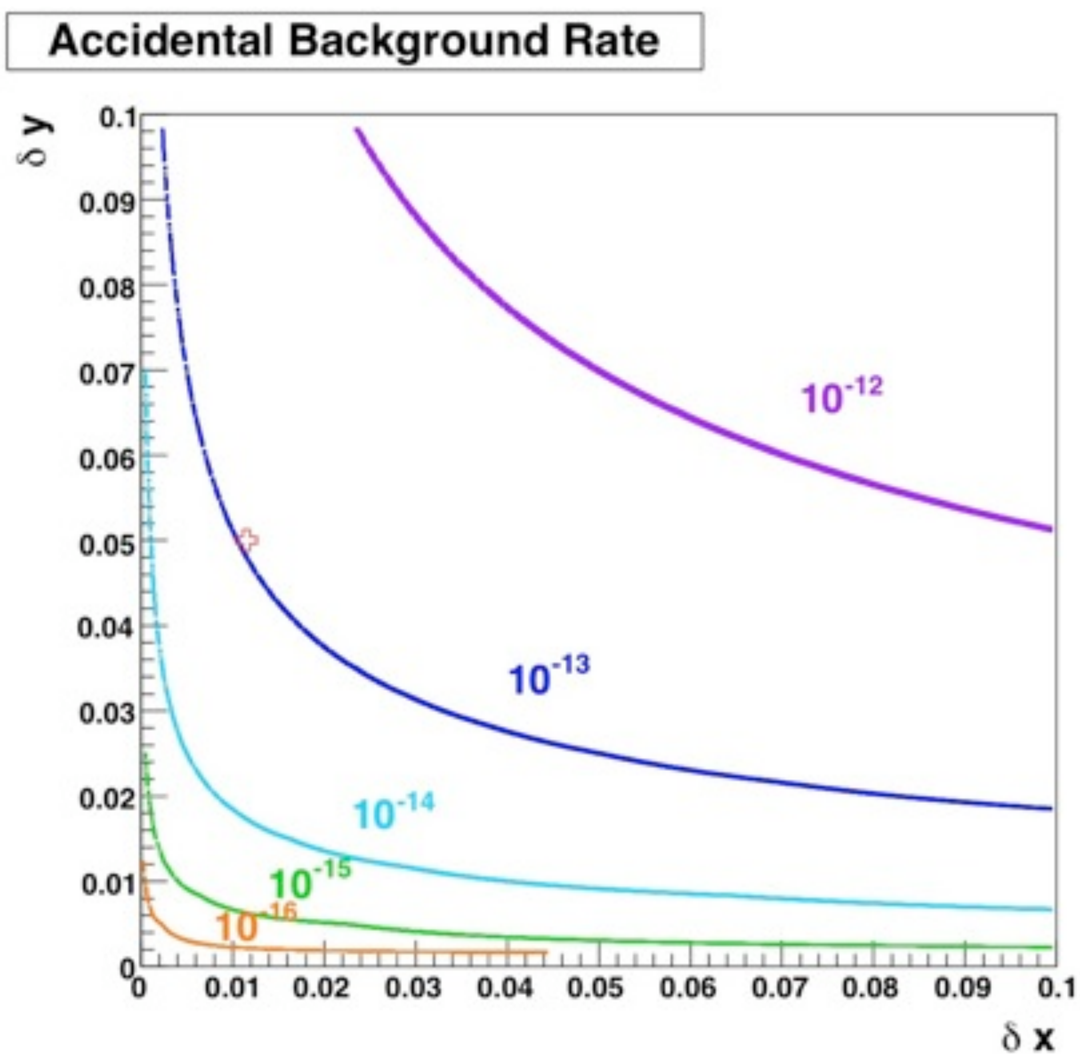


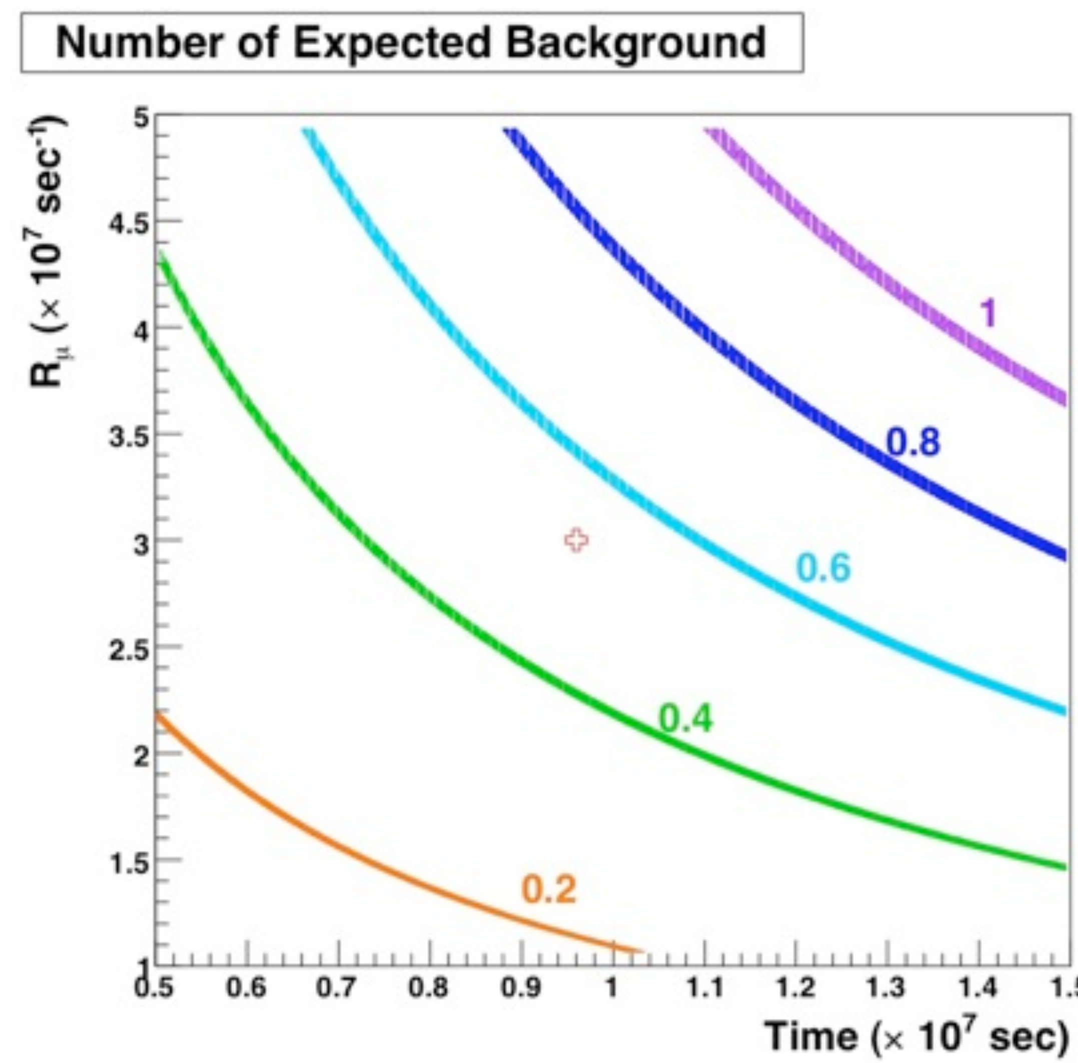
- For MEG 2008, Accidental Background < 1.2×10^{-13}

MEG Sensitivity (3)

- Accidental Background

$$\mathcal{B}_{acc} = \mathcal{R}_{\mu} \cdot (2\delta x) \cdot \left[\frac{\alpha}{2\pi}(\delta y)^2 (\ln(\delta y) + 7.33)\right] \times \left(\frac{\delta\theta^2}{4}\right) \cdot (2\delta t).$$



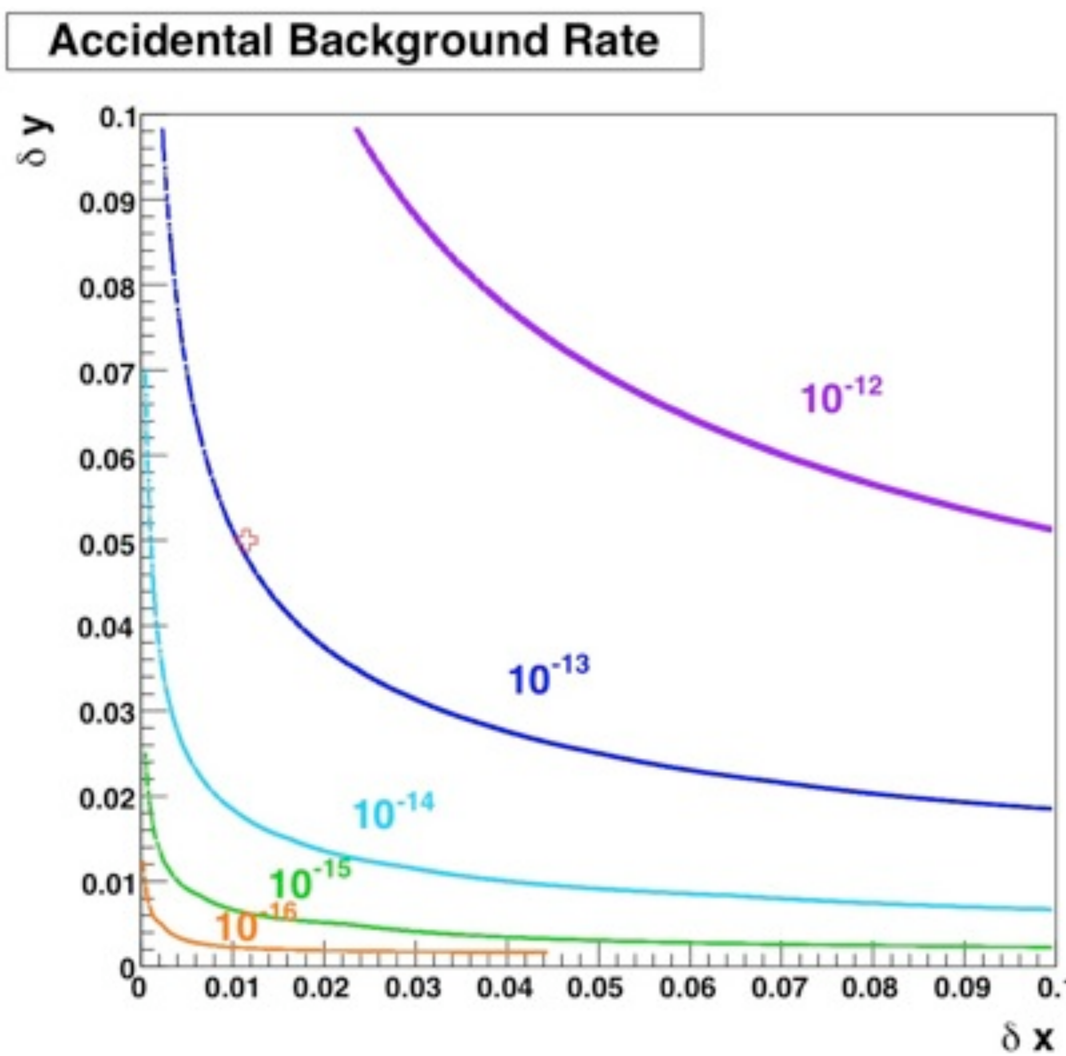


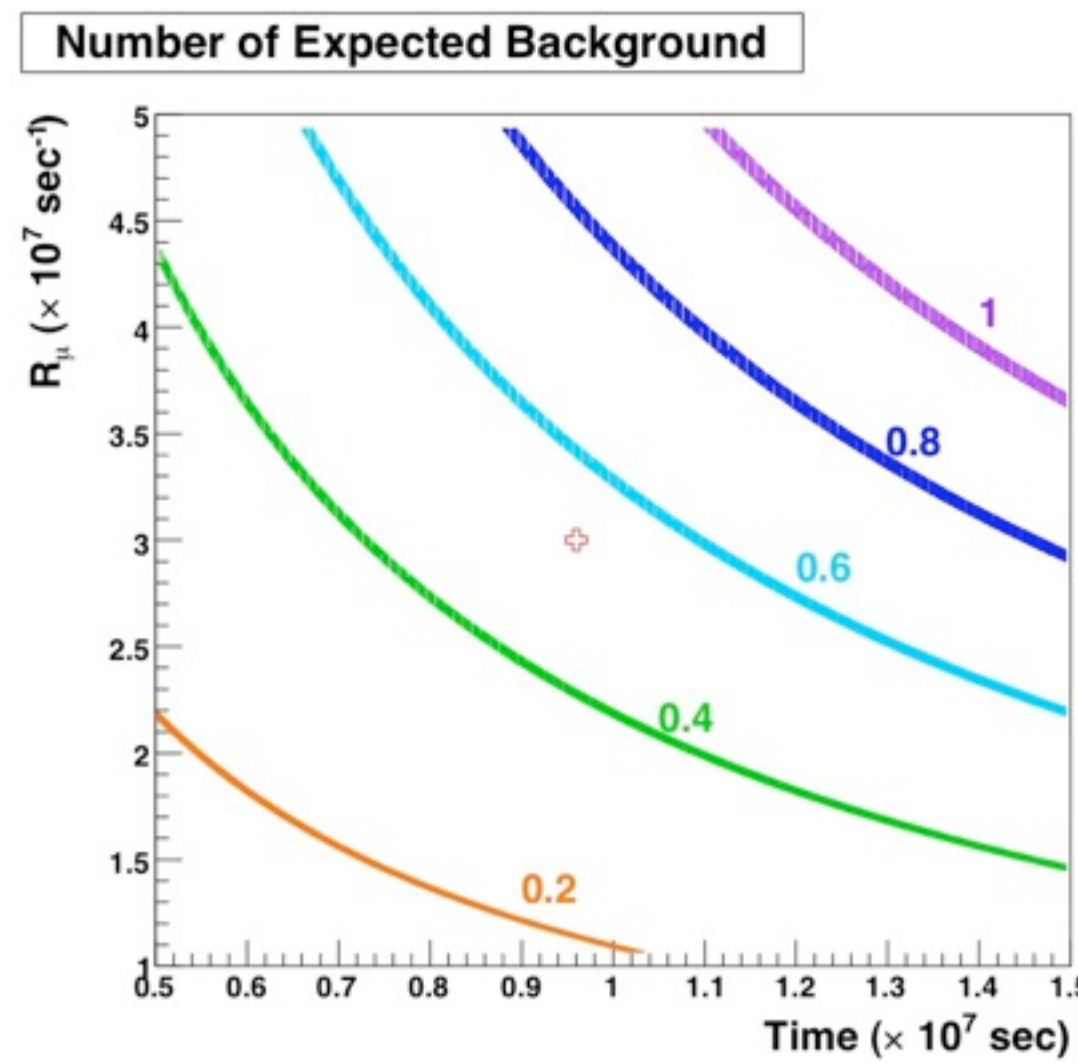
- For MEG 2008, Accidental Background < 1.2×10^{-13}

MEG Sensitivity (3)

- Accidental Background

$$\mathcal{B}_{acc} = \mathcal{R}_\mu \cdot (2\delta x) \cdot \left[\frac{\alpha}{2\pi}(\delta y)^2(\ln(\delta y) + 7.33)\right] \times \left(\frac{\delta\theta^2}{4}\right) \cdot (2\delta t).$$





- For MEG 2008, Accidental Background < 1.2×10^{-13}
- For MEG 2008, Number of Expected Background Event = 0.60

MEG Sensitivity (4)

- Single Event Sensitivity

$$\mathcal{B}(\mu^+ \to \mathrm{e}^+\gamma) = \frac{1}{\mathcal{R}_\mu \cdot T \cdot (\Omega/4\pi)} \times \frac{1}{\epsilon_\mathrm{e} \cdot \epsilon_\gamma \cdot \epsilon_\mathrm{sel}},$$

MEG Sensitivity (4)

- Single Event Sensitivity

$$\mathcal{B}(\mu^+ \to \mathrm{e}^+\gamma) = \frac{1}{\mathcal{R}_\mu \cdot T \cdot (\Omega/4\pi)} \times \frac{1}{\epsilon_\mathrm{e} \cdot \epsilon_\gamma \cdot \epsilon_\mathrm{sel}},$$

- For MEG 2008, Single Event Sensitivity :

$$B^{2008}(\mu \to e\gamma) = 2.2 \times 10^{-13}$$

MEG Sensitivity (4)

- Single Event Sensitivity

$$\mathcal{B}(\mu^+ \to \mathrm{e}^+\gamma) = \frac{1}{\mathcal{R}_\mu \cdot T \cdot (\Omega/4\pi)} \times \frac{1}{\epsilon_\mathrm{e} \cdot \epsilon_\gamma \cdot \epsilon_\mathrm{sel}},$$

- For MEG 2008, Single Event Sensitivity :

$$B^{2008}(\mu \to e\gamma) = 2.2 \times 10^{-13}$$

- For MEG 2008, Feasible Upper-limit

$$B^{2008}(\mu \to e\gamma) < 7.4 \times 10^{-13} \text{ (90\% C.L.)}$$

Conclusion

- An Innovative Positron Spectrometer has been Developed for MEG experiment
  - Highly Graded Magnetic Field
  - Very Light & Sensitive Drift Chamber System
  - Very Fast Timing Counter System
- Challenging Development on Hardware and Software both has been done
- Detector Construction was completed in summer 2007
- Engineering run (detector conditioning, beam commissioning, detector calibration) have been carried out in September - December 2007
- All the Calibration Procedures are established for Positron Spectrometer
- Positron Spectrometer worked well in high intensity muon beam with COBRA
- However, several components were not conditioned well; it made a serious deterioration.
- In consequence, we obtained 0.9% of σ_p and 6 mrad of σ_θ for 52.8 MeV/c positron
- These performances can be improved up to 0.5% of σ_p and 4 mrad of σ_θ
- MEG Physics Run 2008 can achieve $B(\mu\rightarrow e\gamma) < 7.4\times10^{-13}$ (90% C.L.)

Acknowledgements

- 東京大学
  - 森俊則氏、大谷航氏、岩本敏幸氏 、澤田龍氏
- KEK
  - 三原智氏、山田秀衛氏、小曽根健嗣氏、春山富義氏、笠見勝祐氏
- MEG Students
  - 久松康子氏、内山雄祐氏、名取寛顕氏、西村康宏氏、白雪氏、金子大輔氏

- PSI Drift Chamber Group
  - J. Egger, M. Hildebrandt, M. Schneeberi, A. Hofer, D. Fahrni, F. Barachetti, L. Meyer
- Special Thanks to:

  近野和夫氏 (林栄精器)、 (株)プリント電子研究所

後日談。。。

- In winter-spring shutdown 2008, we made the tight helium protection on DC-HV tracer line.
- Successfully all DC modules were operational !!!

後日談。。。

- In winter-spring shutdown 2008, we made the tight helium protection on DC-HV tracer line.
- Successfully all DC modules were operational !!!
- but...

後日談。。。

- In winter-spring shutdown 2008, we made the tight helium protection on DC-HV tracer line.
- Successfully all DC modules were operational !!!

- but...

- After 2 months operation, discharge happened again...
- At the beginning of physics run, 27 planes (/32) were operational, finally only 18 planes were operational at the end of physics run.

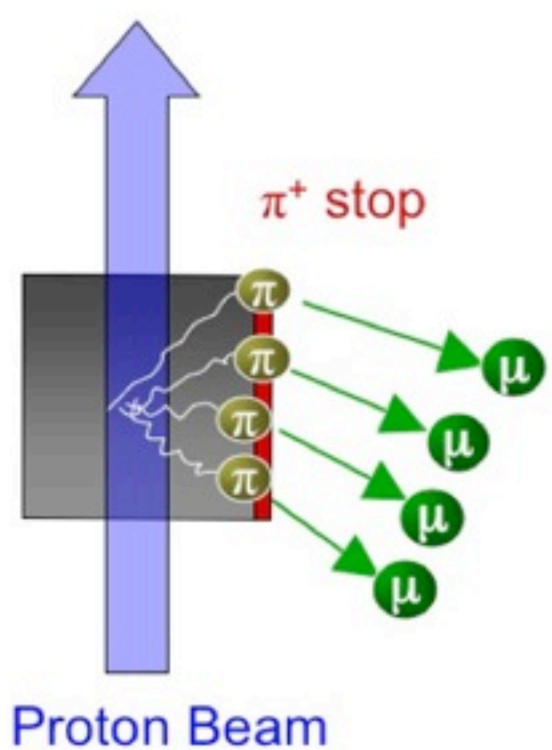
宣伝

- 29pSE01: MEG実験2008 液体キセノン検出器 I, 名取寛顕 (東大)
- 29pSE02: MEG実験2008 液体キセノン検出器 II, 西村康宏 (東大)
- 29pSE03: MEG実験2008 光電子増倍管量子効率測定の改良, 白雪 (東大)
- 29pSE04: MEG実験2008 陽電子スペクトロメータ, 西口創（KEK）
- 29pSE05: MEG実験2008 $\mu^+ \to e^+\gamma$崩壊事象探索解析 内山雄祐 (東大)

backup slides

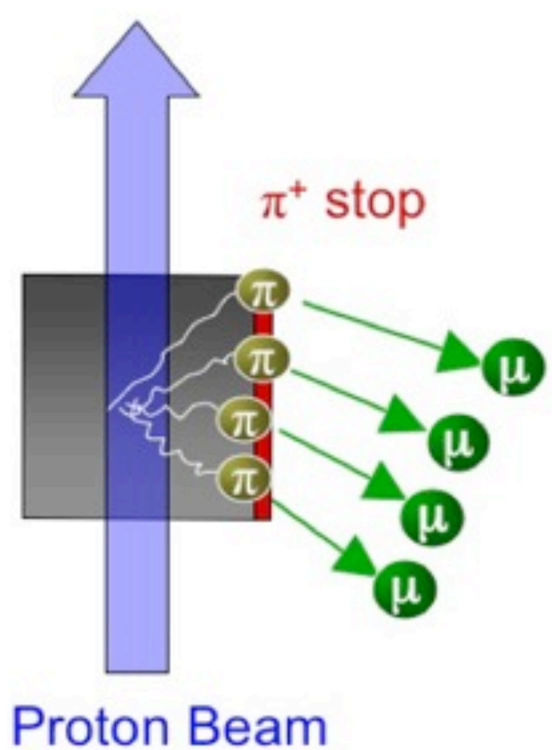
Muon Beam

- Requirements
  - Powerful Proton Driver
  - Pulsed Beam *vs*.DC Beam
  - Surface Muon *vs*. Cloud Muon



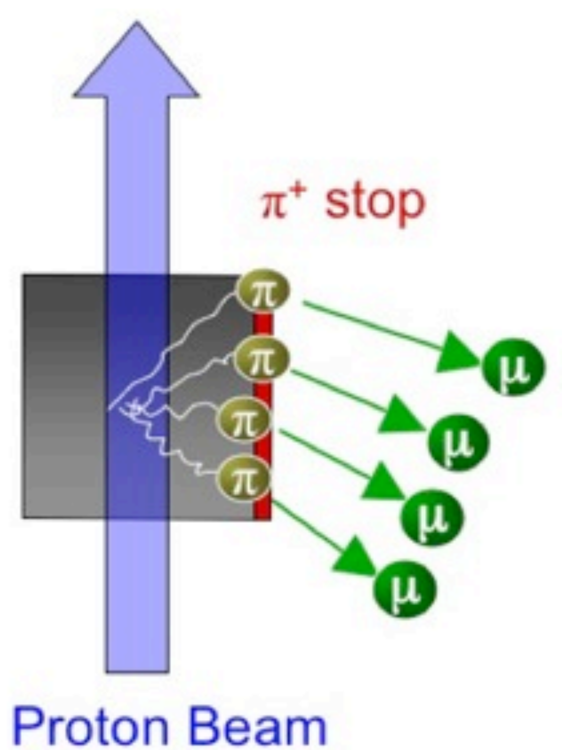
Muon Beam

- Requirements
  - Powerful Proton Driver
  - ~~Pulsed Beam~~ *vs*.DC Beam
  - Surface Muon *vs*. ~~Cloud Muon~~



Muon Beam

- Requirements
  - Powerful Proton Driver
  - ~~Pulsed Beam~~ *vs*.DC Beam
  - Surface Muon *vs*. ~~Cloud Muon~~



Paul Scherrer Institut (PSI) is the BEST Experiment Site

(1) 1.2 MW proton cyclotron

(2) Up to 2mA proton beam

(3) World Most Intense Surface Muon Beam

πE5 Beam Channel

10^8 /sec surface muon is available

Muon Stopping Target

- Requirements

  Light Material

  Thin

  (Plastic)

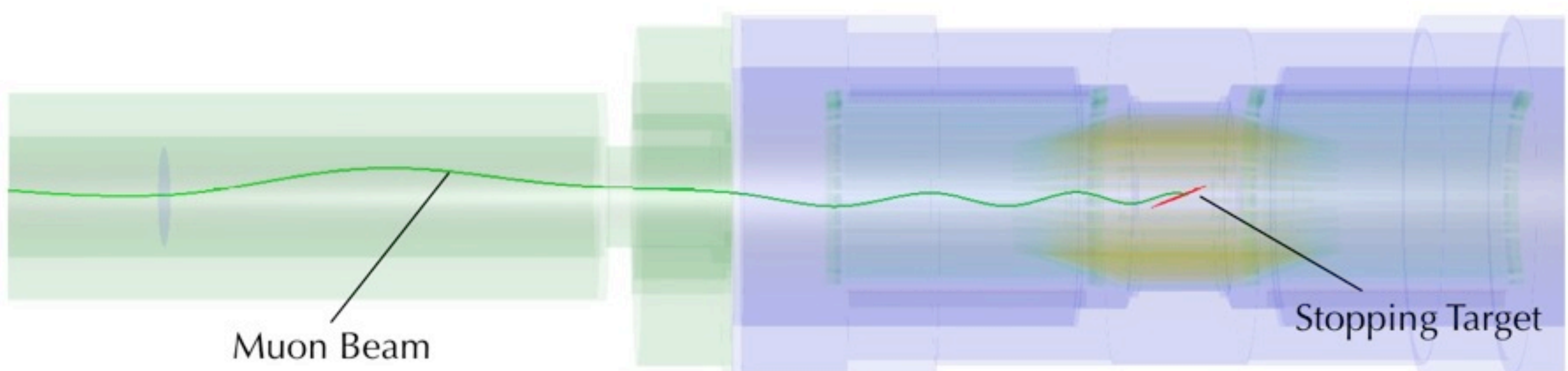
Muon Stopping Target

- Requirements

  Light Material

  Thin

  (Plastic)



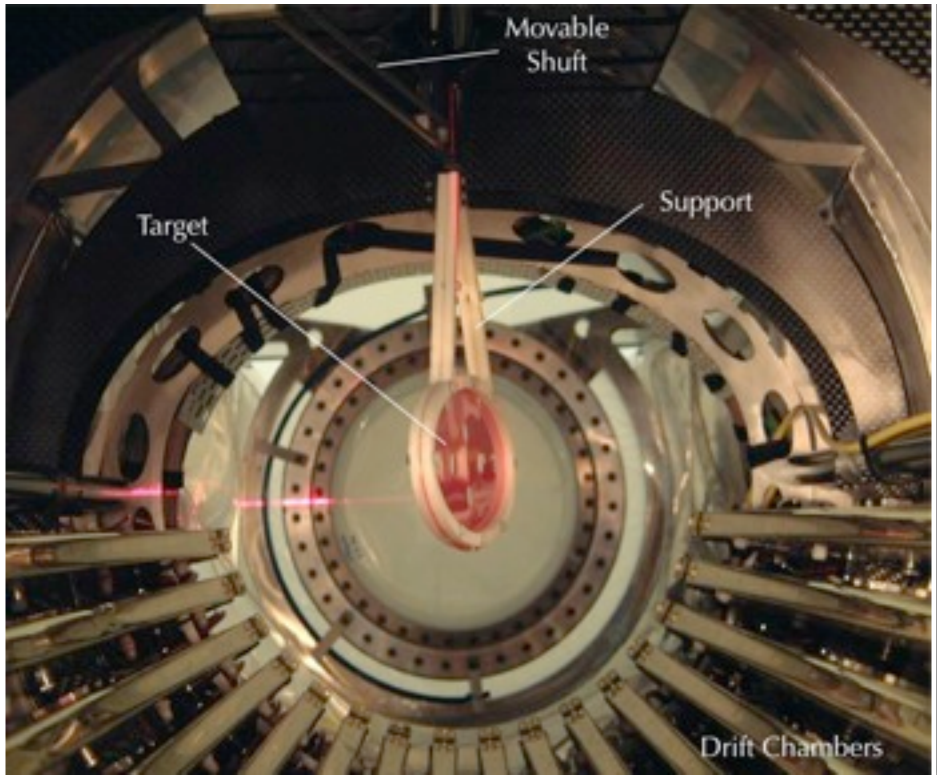
Muon Stopping Target

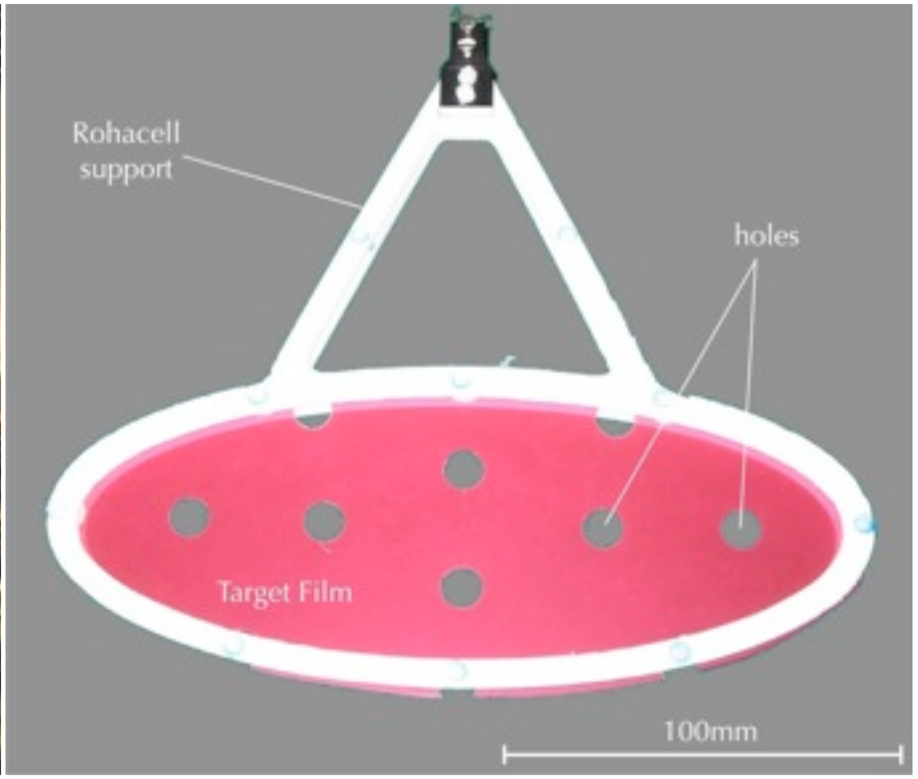
- Requirements

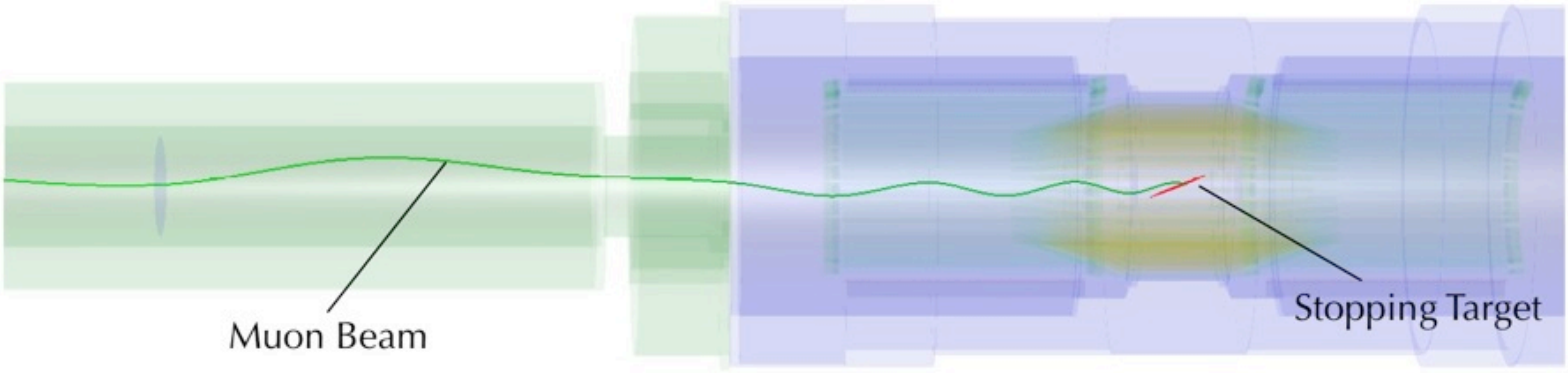
  Light Material

  Thin

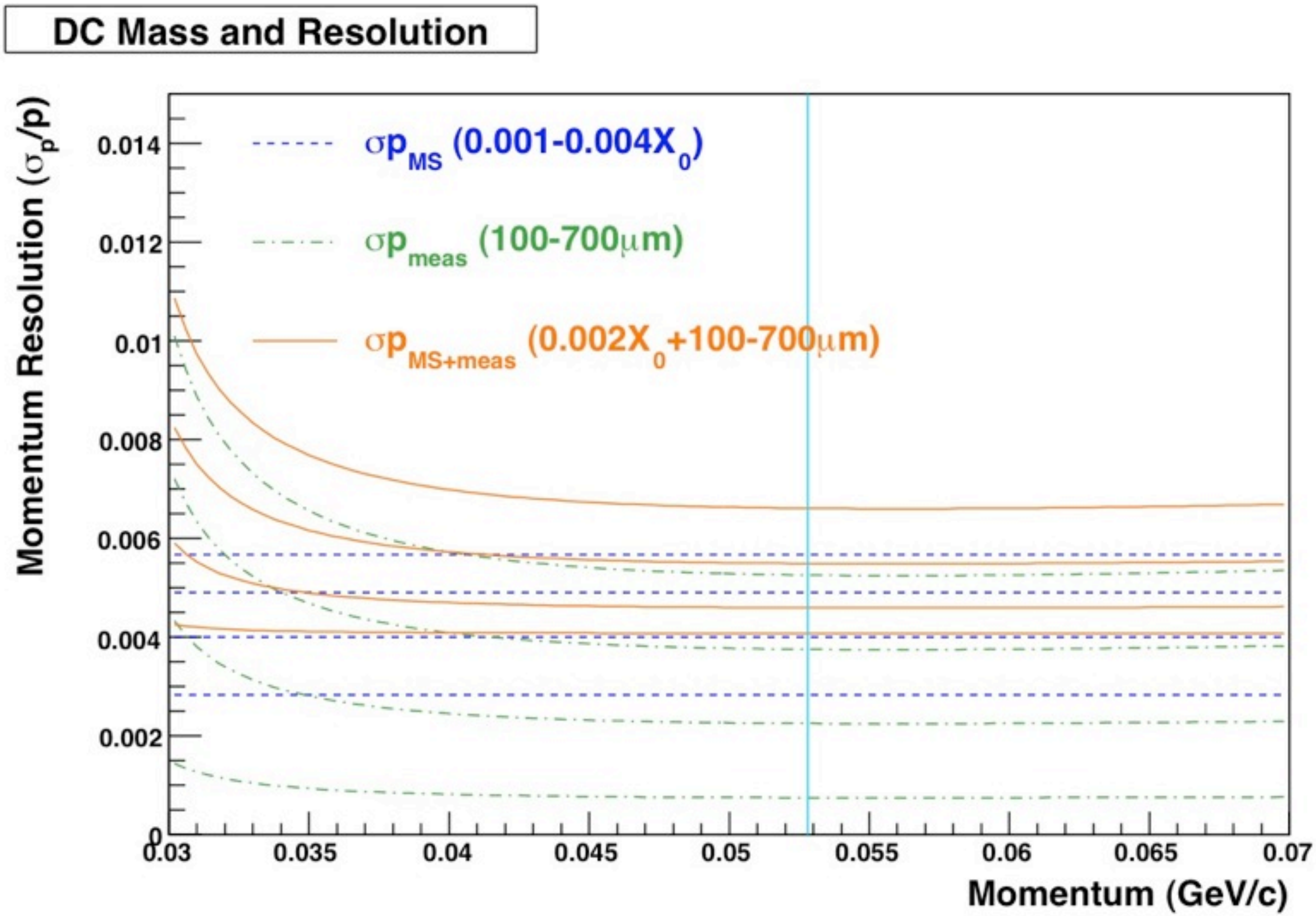
  (Plastic)



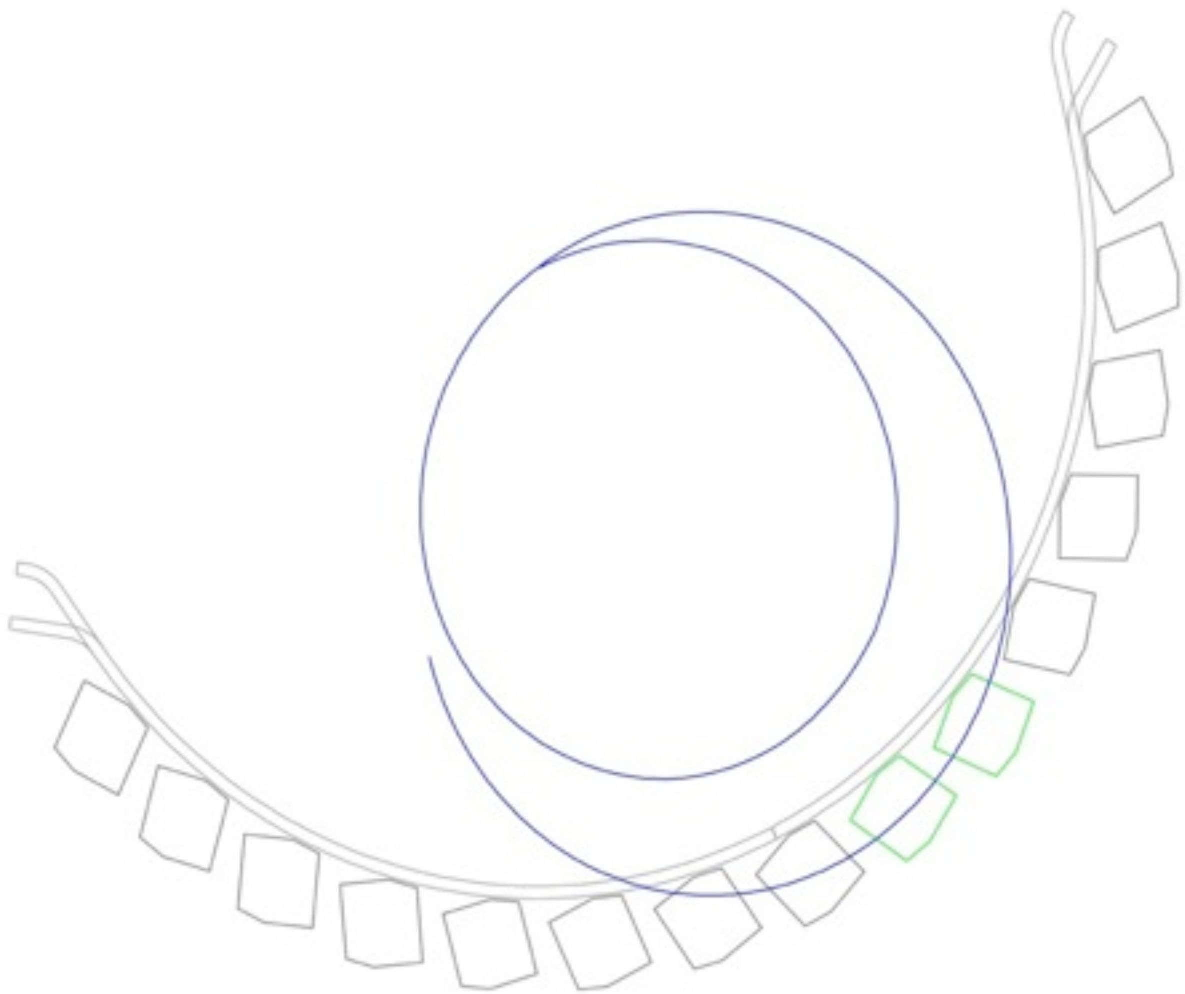


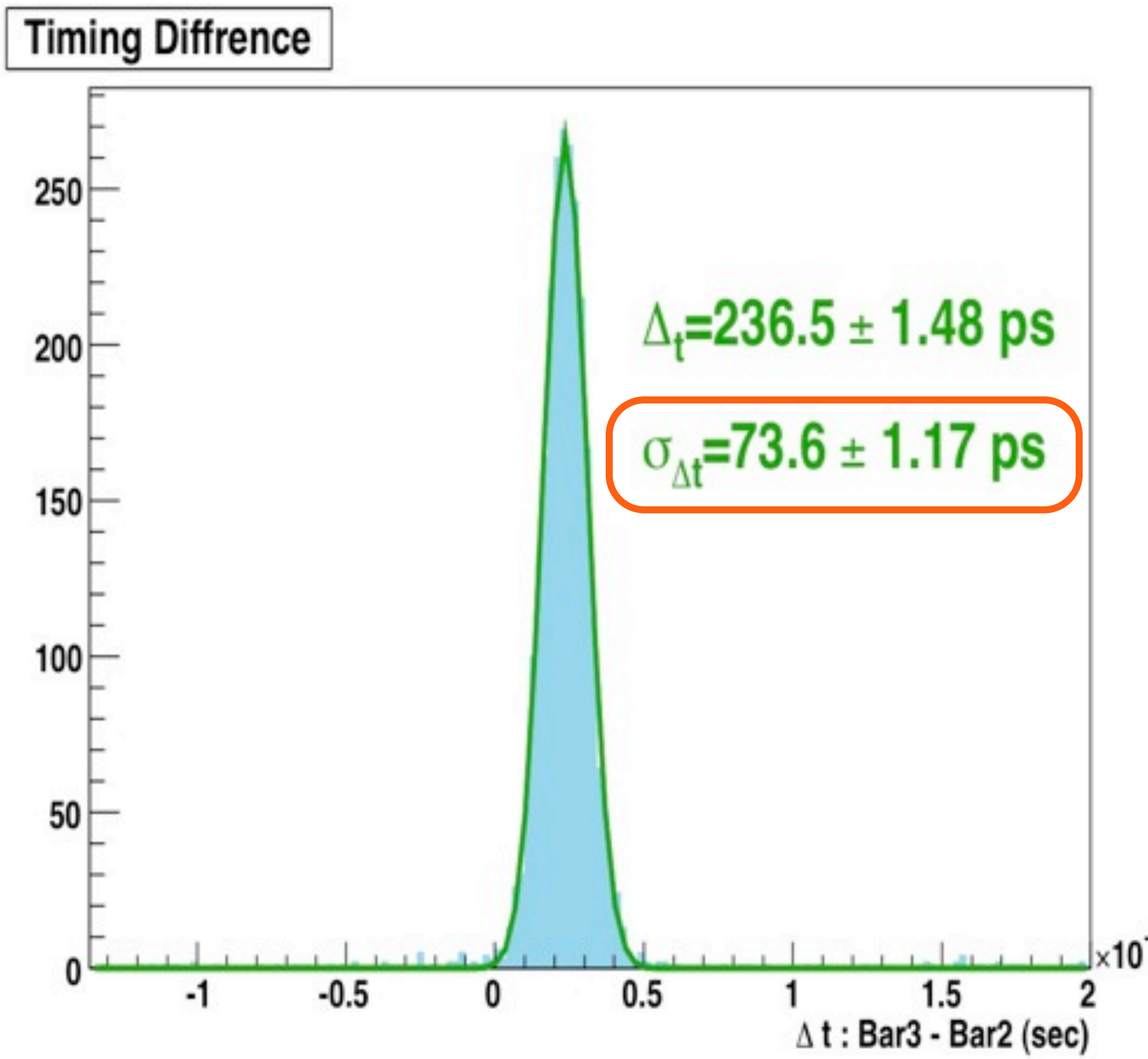


DC Requirements



"*Intrinsic*" Timing Resolution

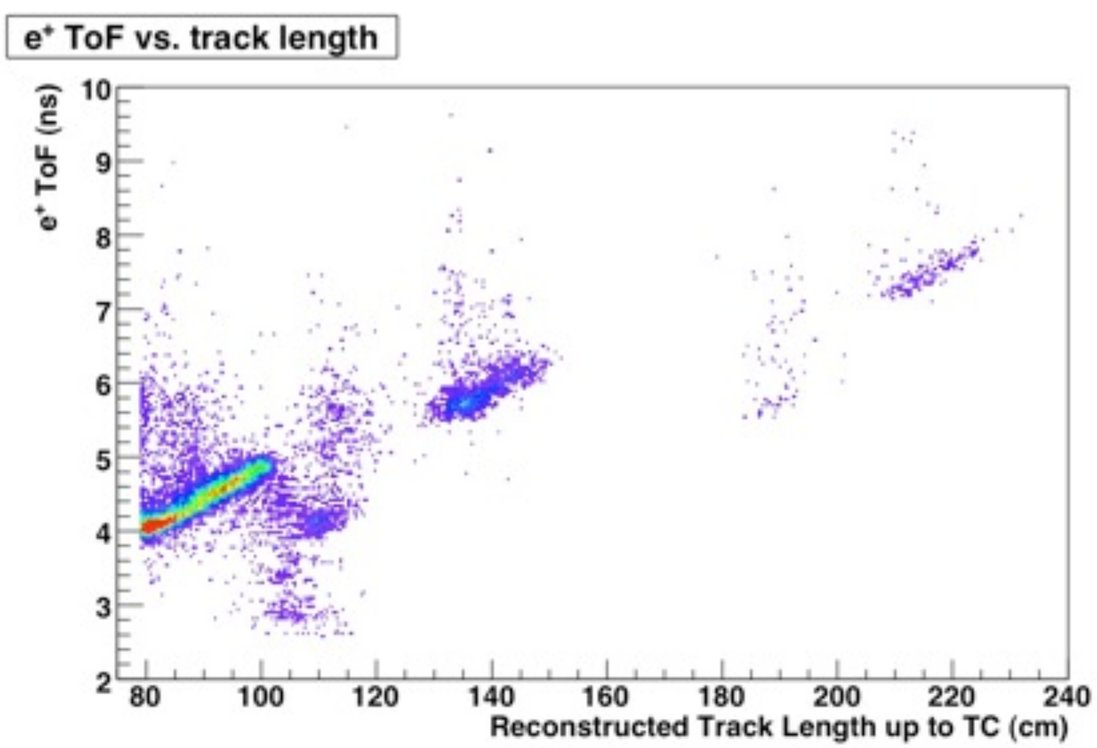


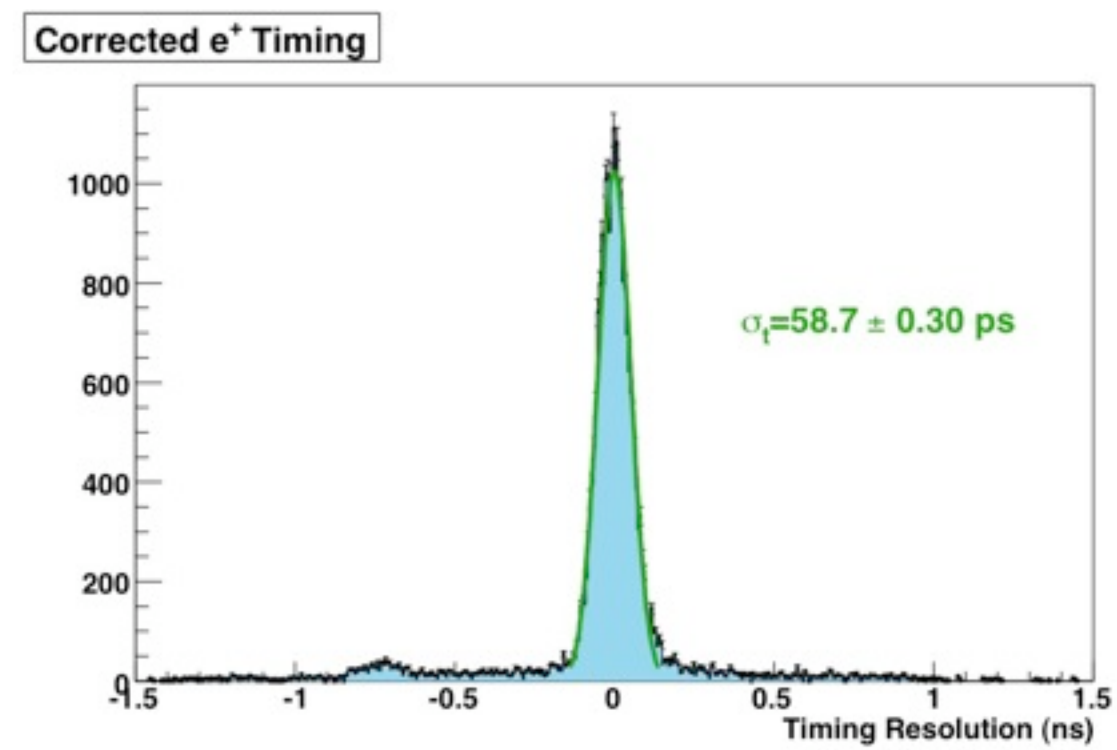


- Time Difference b/w two φ-counter
- 52 ps of timing resolution

Timing Resolution

- TC impact timing should be converted to e^+ time of flight (decay timing)
- Can be evaluated indirectly by the combination of MC and Data





- Spectrometer Timing Resolution = 58.7 ps
- Timing Uncertainty caused by Track Length Error ≈ 27 ps

Spectrometer Efficiency (1)

- Spectrometer Efficiency = Tracking Efficiency ⊗ Counting Efficiency

Track Finding Eff.

Low Rate (5×10^6 /sec)			Normal Rate (3×10^7 /sec)		
	cluster finder	track finder		cluster finder	track finder
data (2007)	99.9%	97.9%	data (2007)	99.9%	97.1%
MC (actual)	99.9%	98.1%	MC (actual)	99.9%	98.0%
MC (ideal)	100%	99.9%	MC (ideal)	100%	99.7%

Track Reconstruction Eff.

Low Rate (5×10^6 /sec)			Normal Rate (3×10^7 /sec)		
	fitting	χ^2 cut		fitting	χ^2 cut
data (2007)	77.8%	66.1%	data (2007)	75.1%	65.3%
MC (actual)	80.4%	67.2%	MC (actual)	80.2%	66.9%
MC (ideal)	99.5%	97.9%	MC (ideal)	99.2%	97.5%