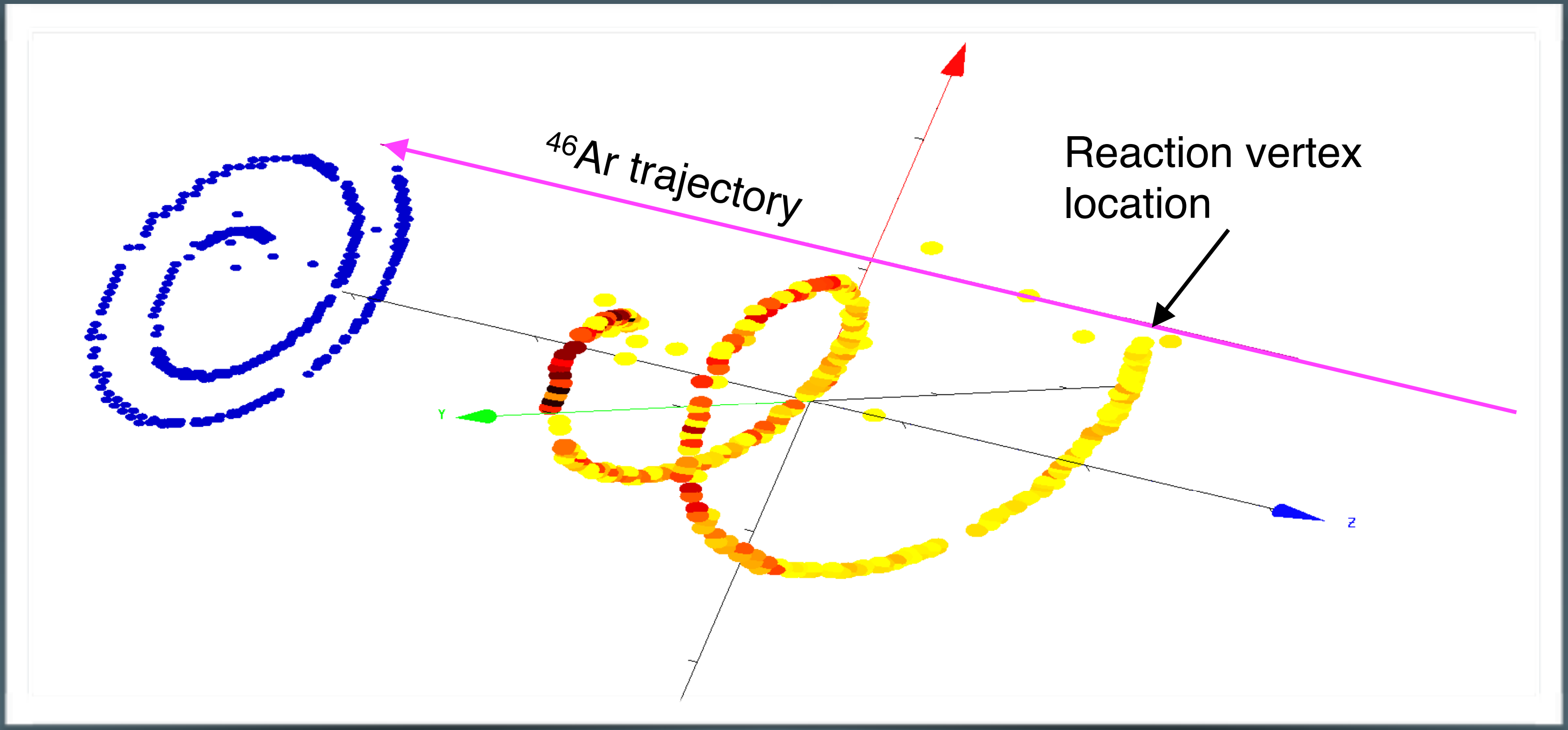


THE
ACTIVE TARGET
TIME PROJECTION CHAMBER

D. Bazin
National Superconducting Cyclotron Laboratory
Michigan State University

High luminosity with slow beams

- The “too thick target” problem
  - Reactions in solid targets at low energy in inverse kinematics leave little energy to the emitted probe particles
  - Compromise between resolution and number of nuclei in target (directly factors luminosity)
- The “active target + time projection chamber” solution
  - Target no longer inert material, but used also to detect particles
  - Gas target essential for low energies, can also be used for high energy reactions
  - Time Projection Chamber tracks particles from the vertex of the reaction (no lost energy in inert target)

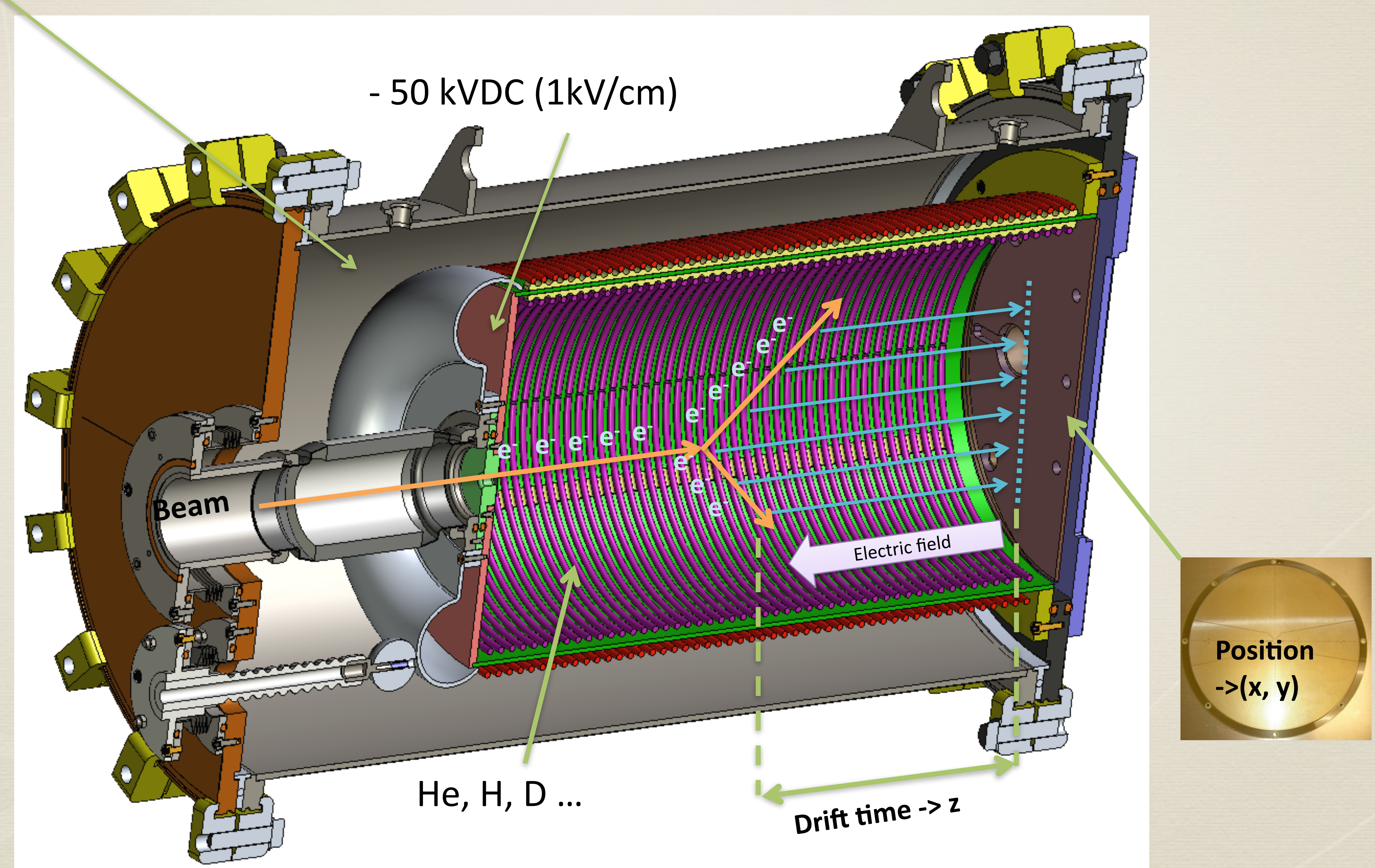
Active Target Time Projection Chamber

- A detector tailored to low energy reactions
  - Active gas target and full 4π angular coverage
  - High luminosity without loss of resolution
  - Beam slowing in gas gives excitation function
- Limitations and restrictions
  - Target gas has to provide good electron amplification (mixtures)
  - Every beam particle ionize the gas, even without reaction (trigger generation)
  - Time projection chamber is slow (rate limitation)
- Very well adapted to rare isotope beams!

Principle of operation

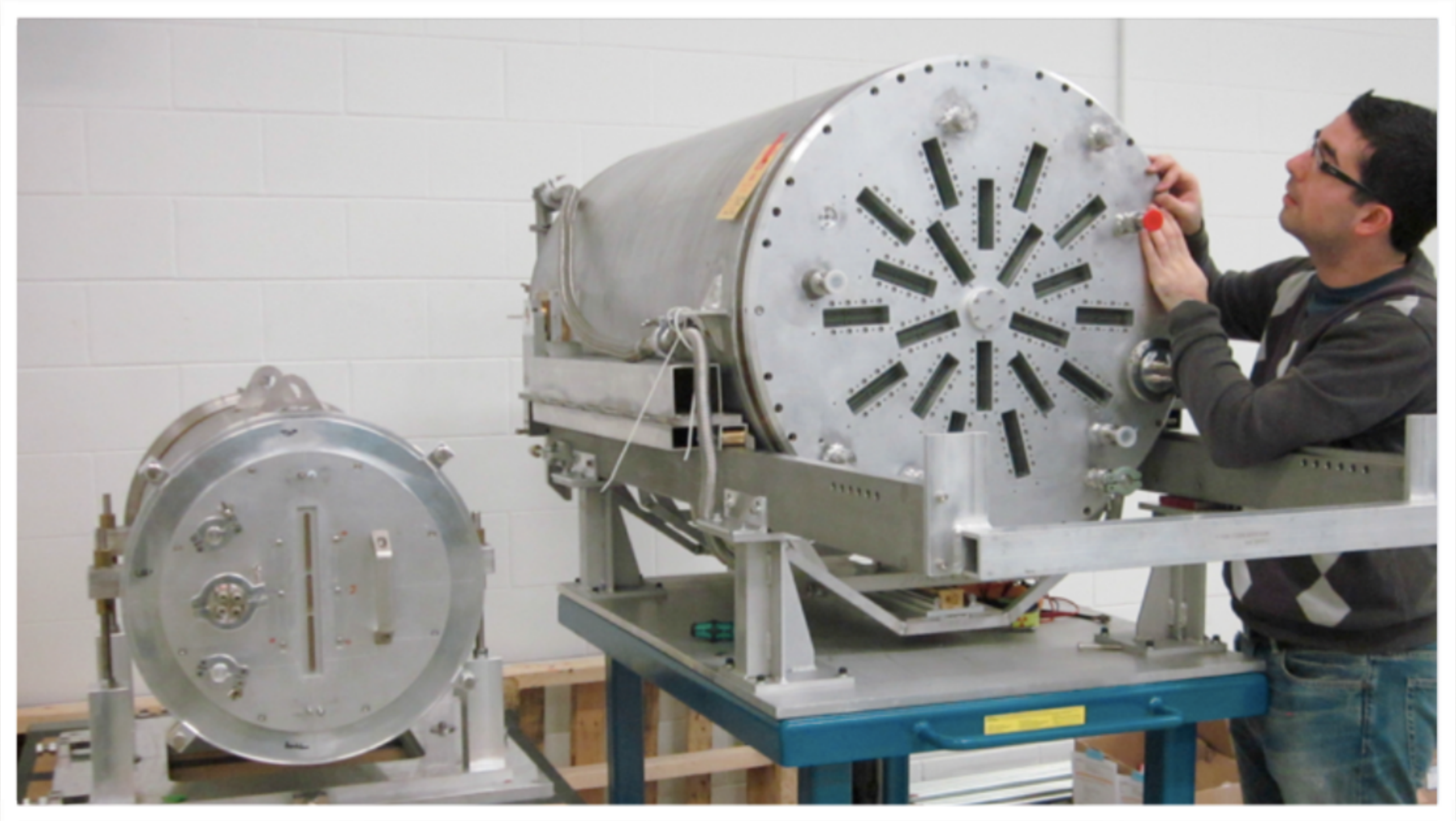
Insulator gas volume

- N_2 gas 30 kV/cm x 6 cm = 180 kV



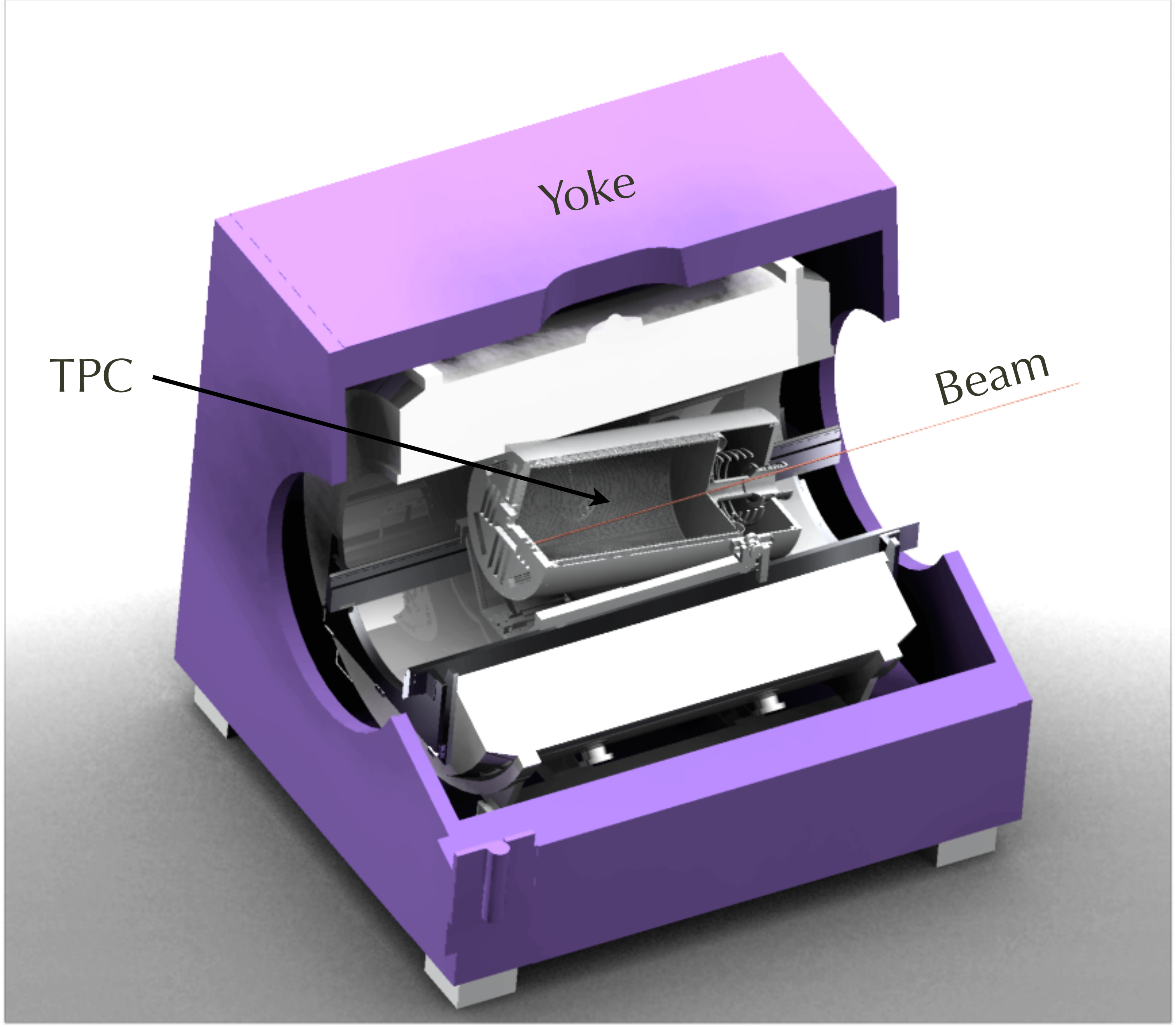
pAT-TPC and AT-TPC

- Half scale prototype: 32 liters, 256 channels
- Full scale: 250 liters, 10,240 channels

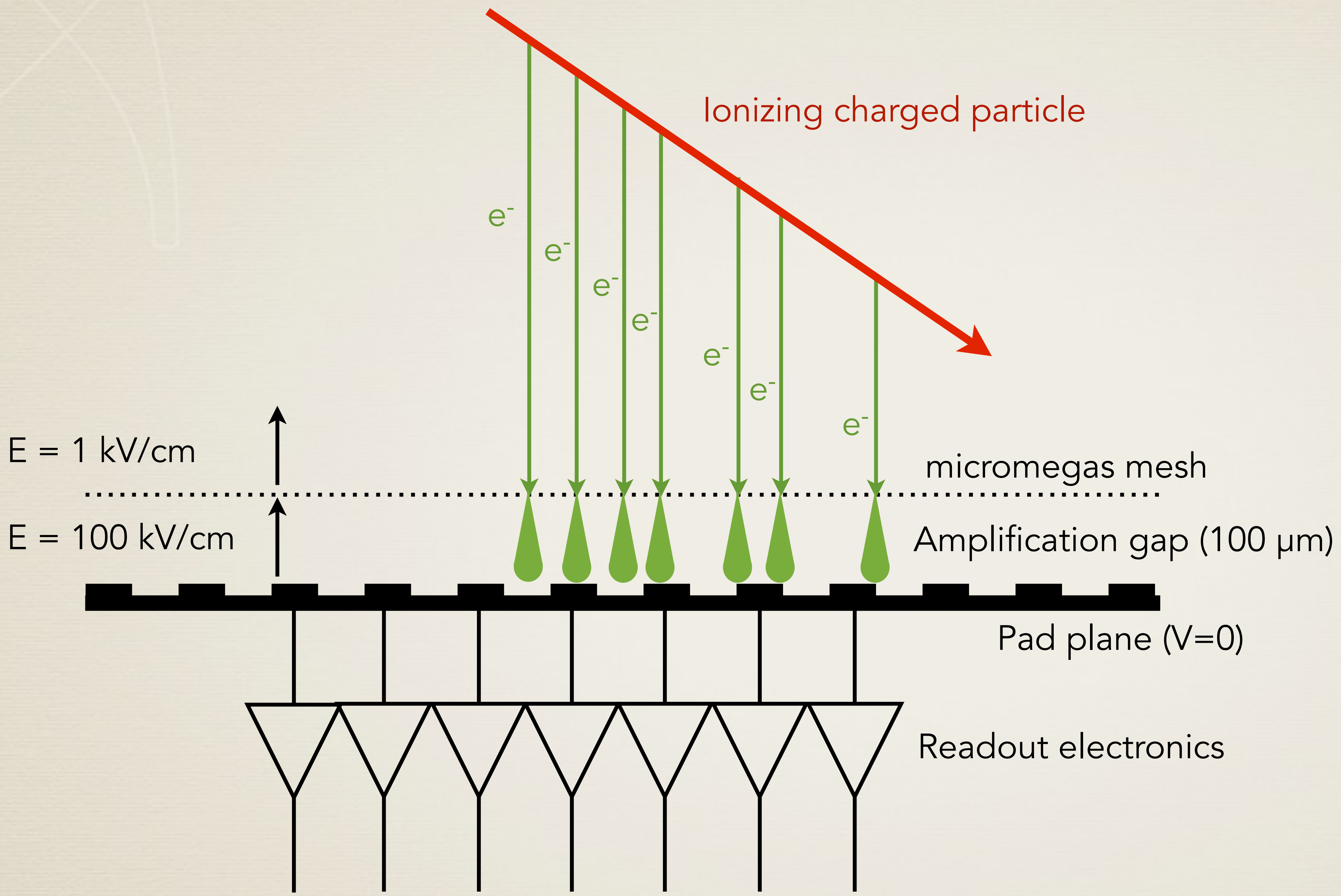


AT-TPC setup

- Straight and tilted (7°) configurations
- Tilt relative to beam axis to increase accuracy for small angles
- Placed inside 2 Tesla solenoid (increase range and measure Brho)
- 250 liters (1 m by 55 cm) active volume

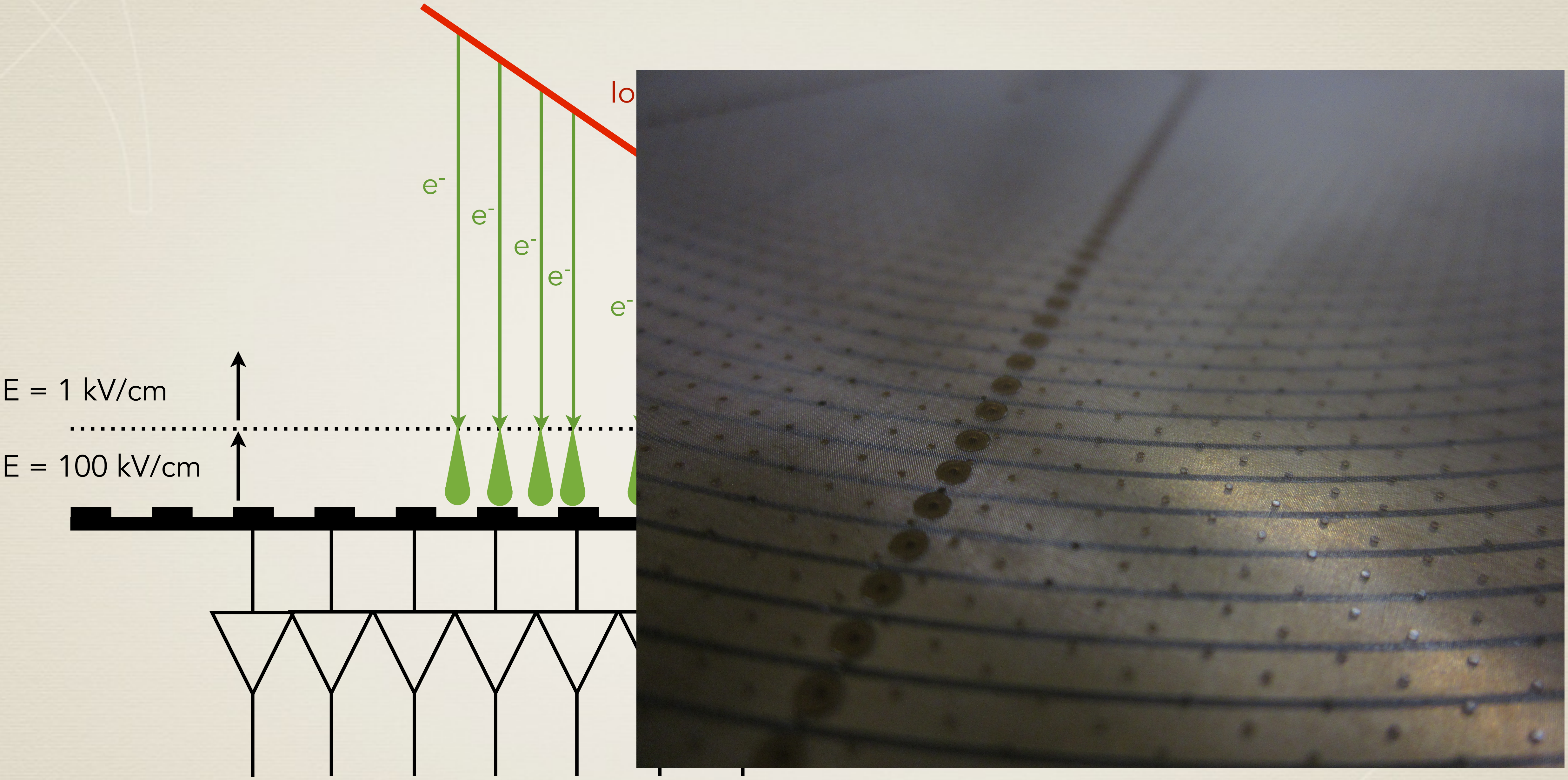


Electron amplifier: Micromegas



- Negligible charge spread, sharp images
- Very robust against sparking
- Can operate in different conditions (gases, pressures)

Electron amplifier: Micromegas



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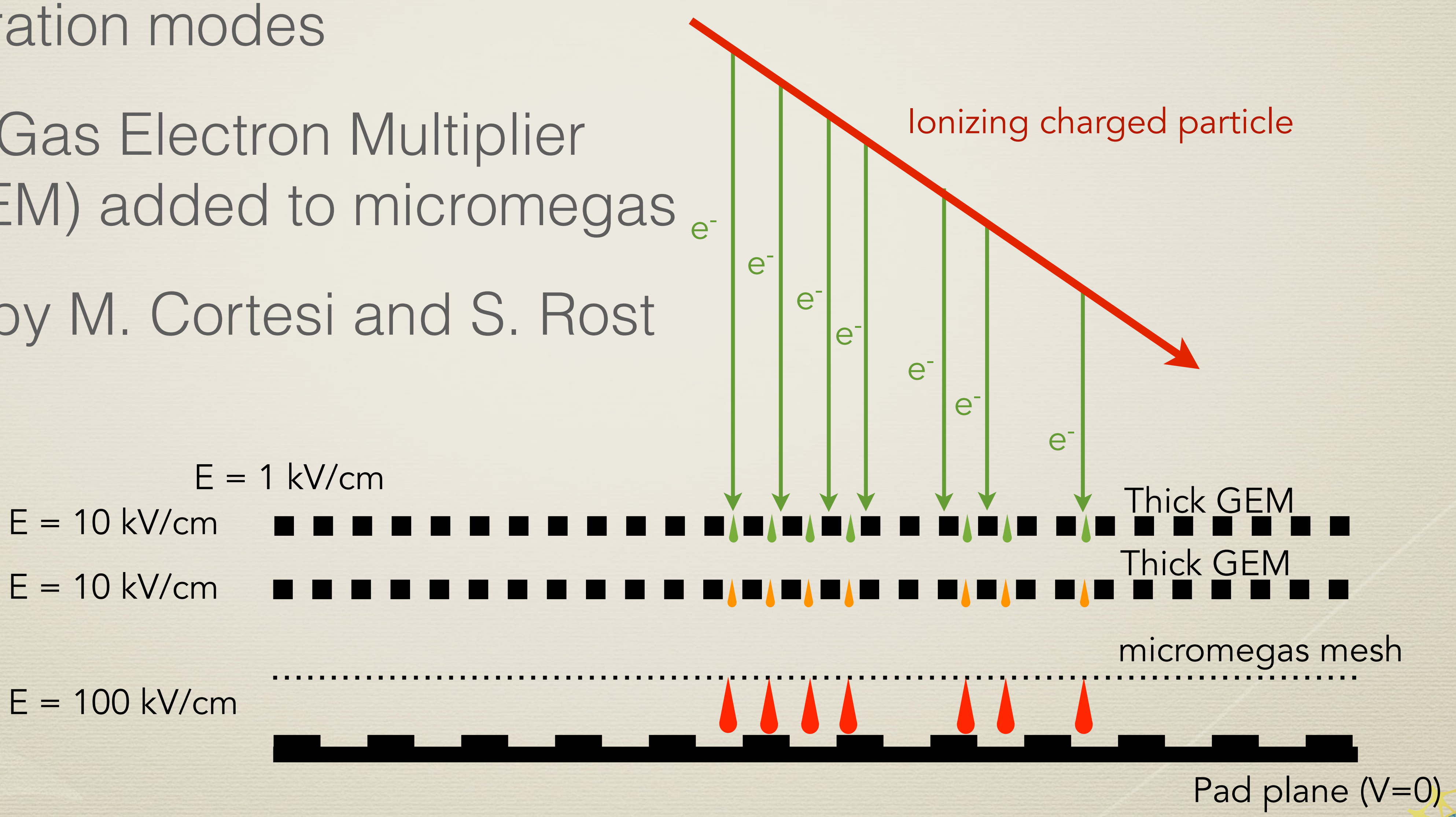
- Very robust against sparking
- Can operate in different conditions (gases, pressures)

Electron pre-amplifier: THGEM

- Electron amplification in pure He and H_2 gases
  - Difficult due to high ionization energy or vibration modes
  - Thick Gas Electron Multiplier (THGEM) added to micromegas
  - Work by M. Cortesi and S. Rost



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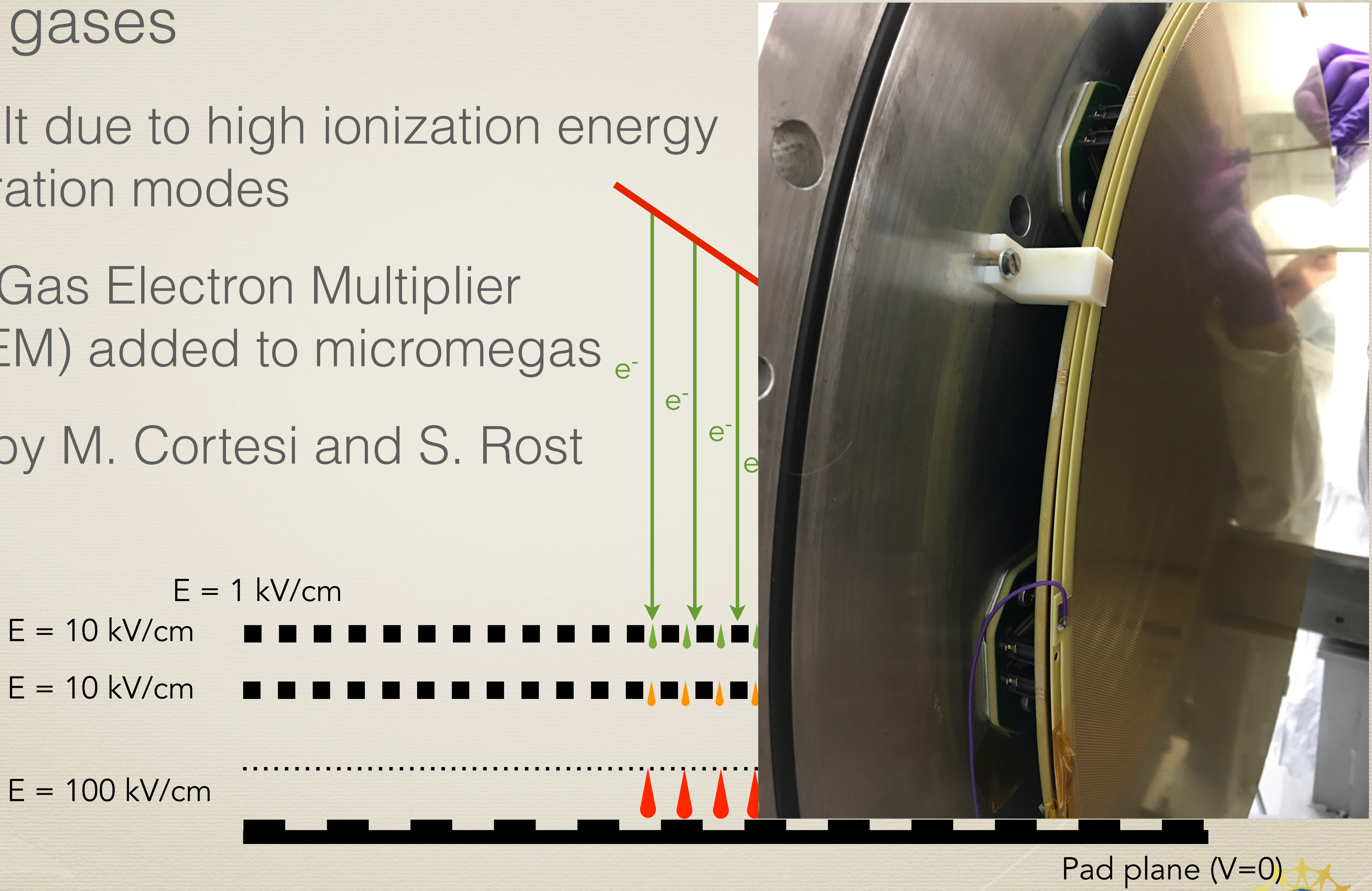
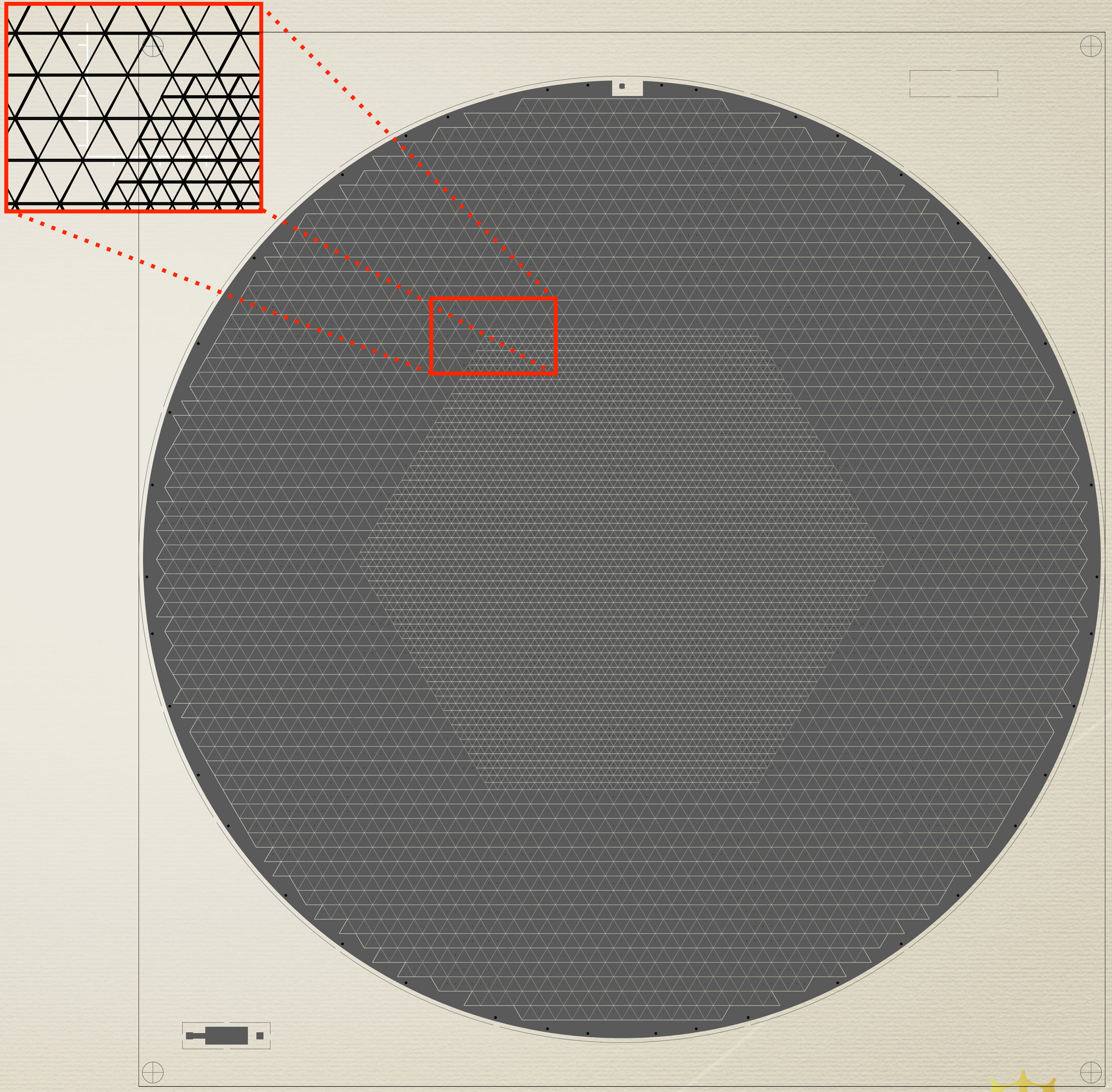


10,240 pad plane geometry

- Optimized for detector inclinations from 0° to 7° relative to beam axis
- 4 small triangles in a large one
- Small triangle side = 4.67 mm
- 55 cm diameter disk



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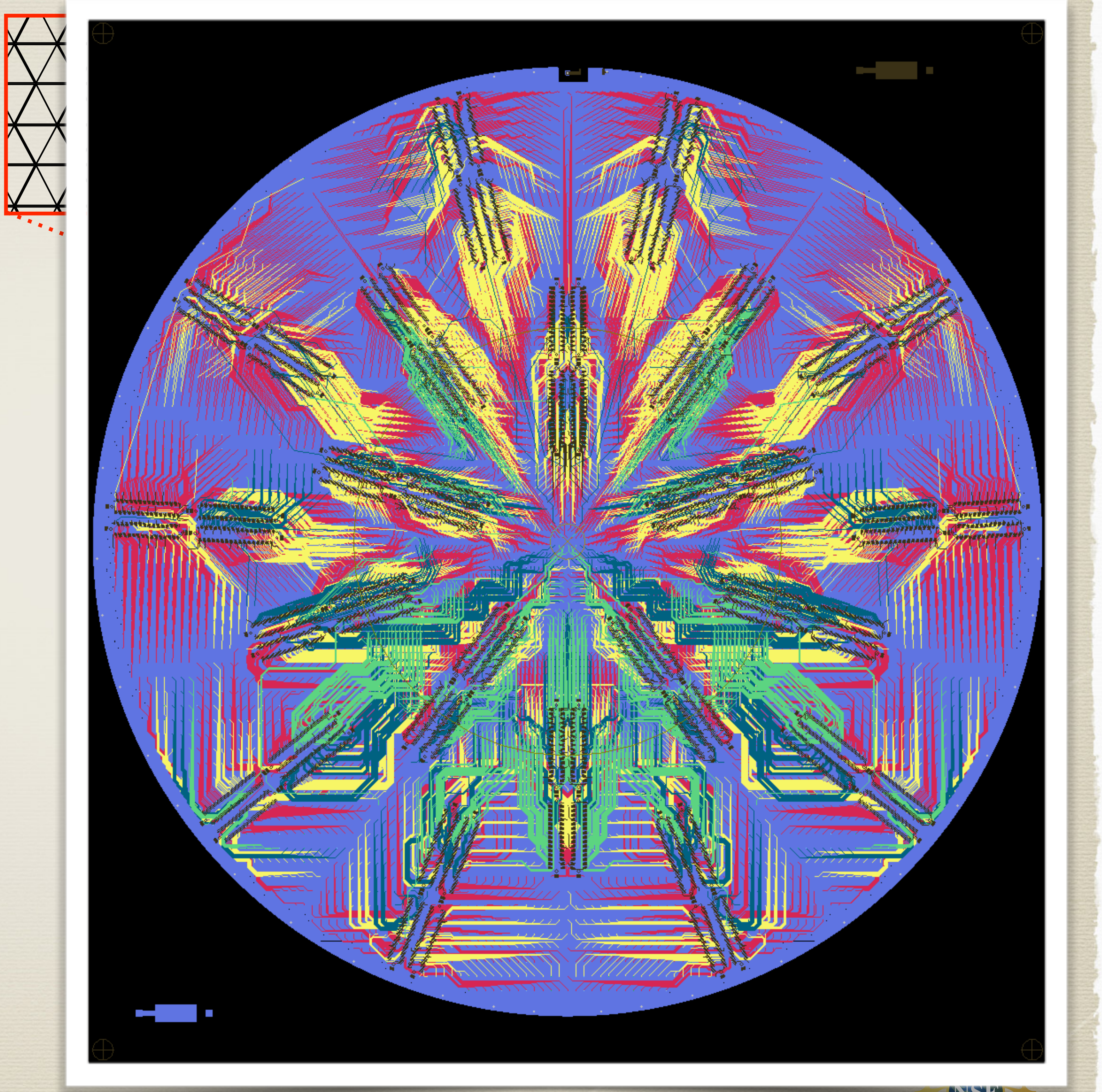
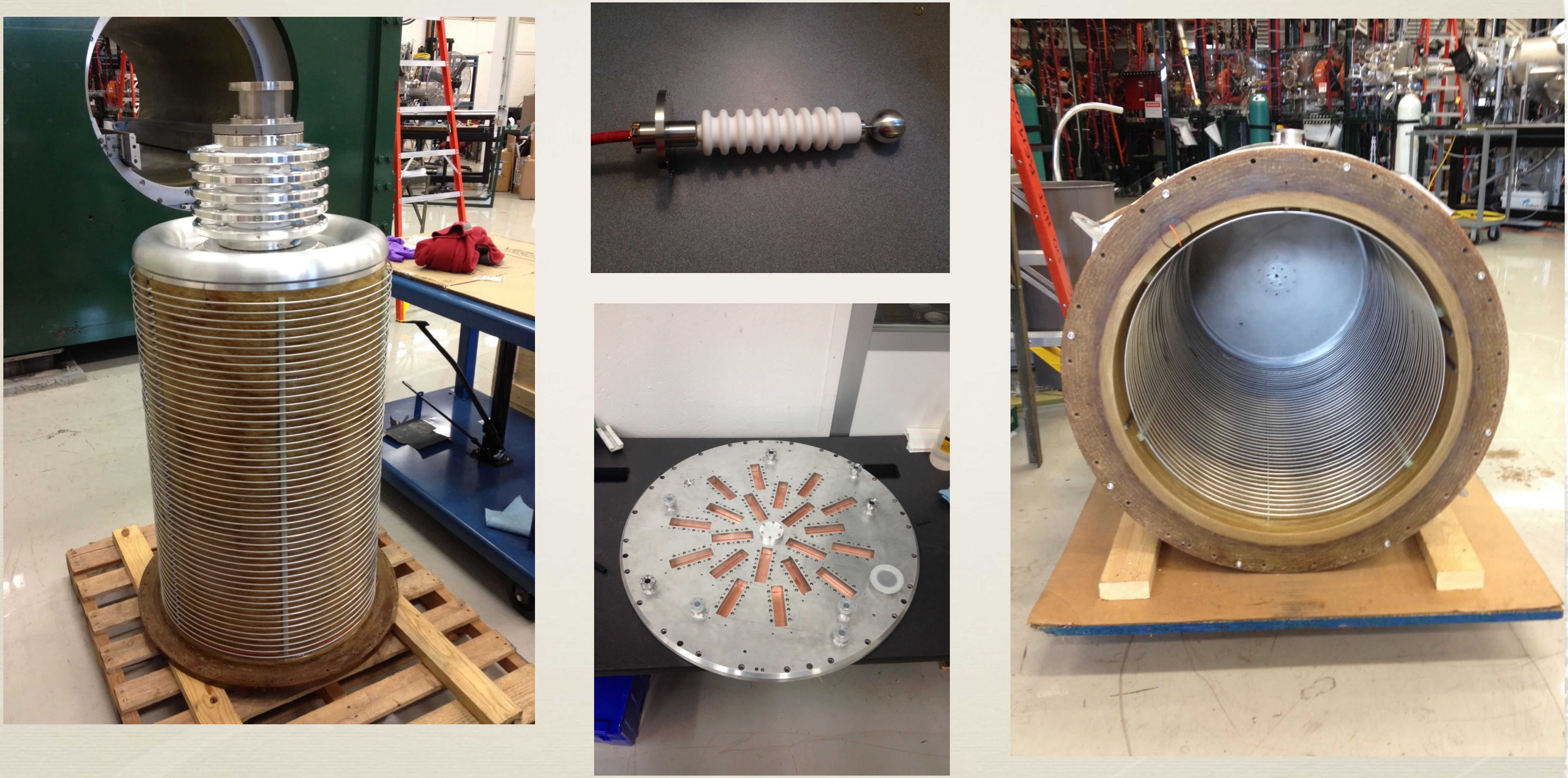


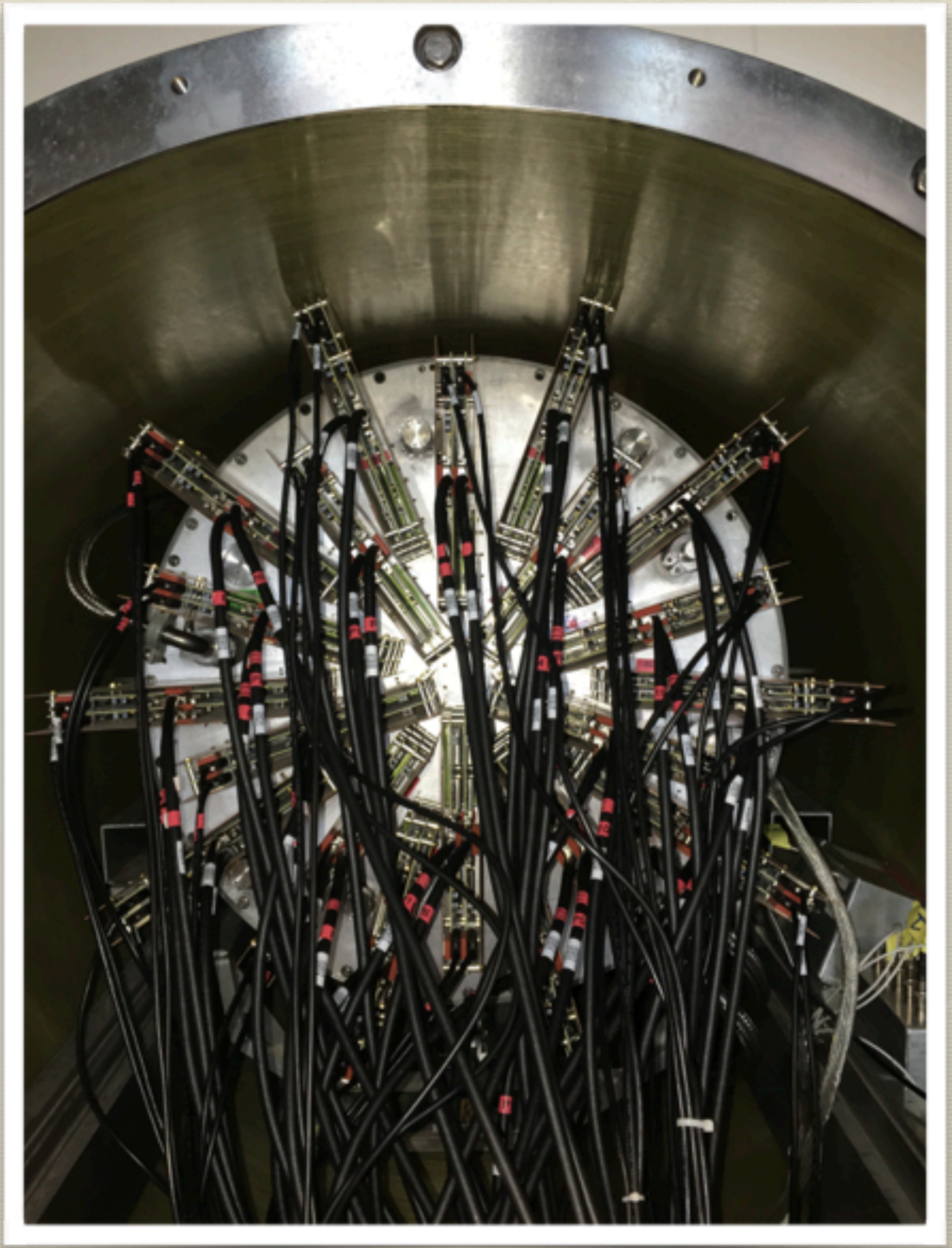
Field cage of active volume

- Based on prototype design with few improvements



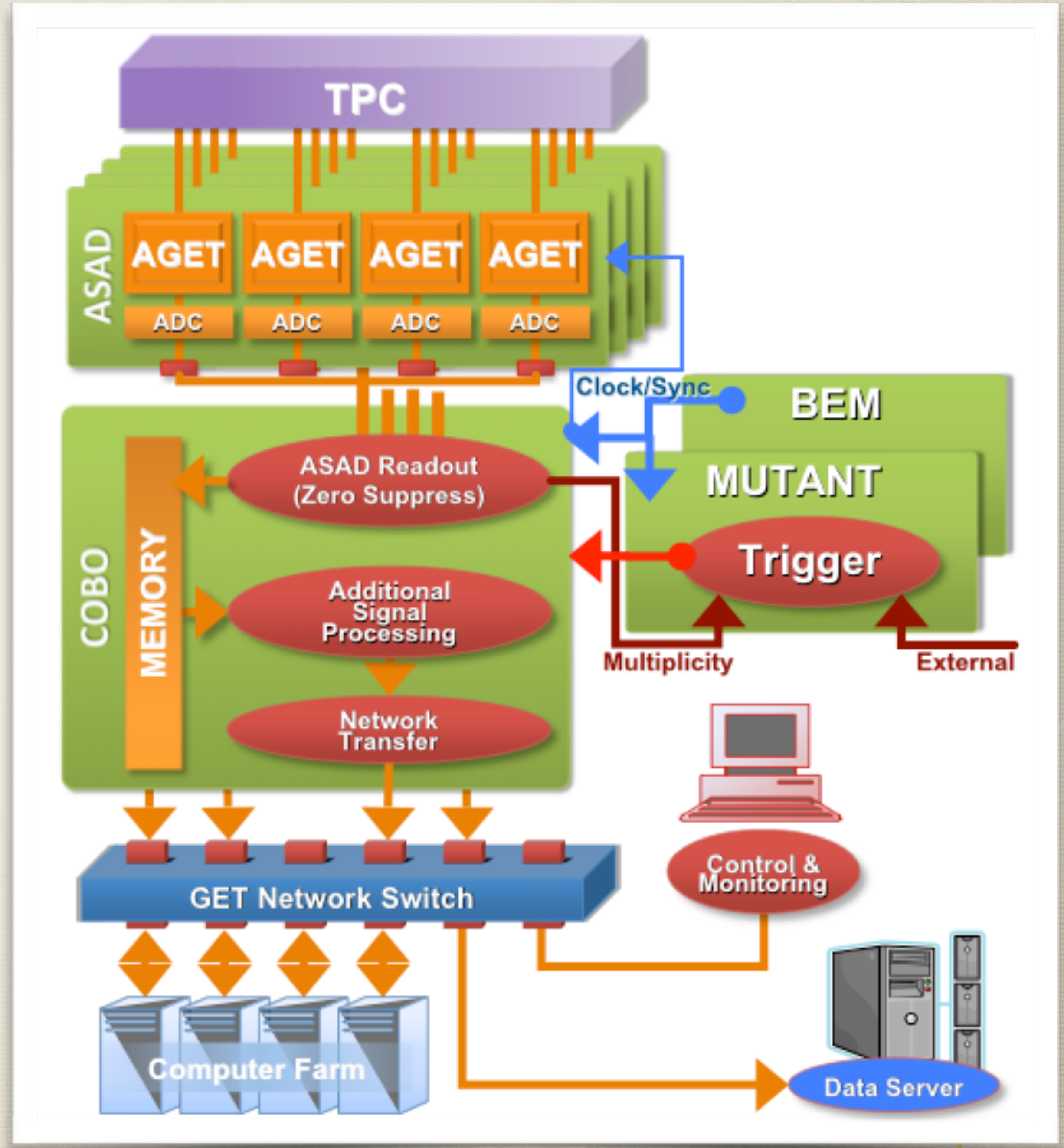
Digital Readout Electronics

- Accommodate electronics for the 10,240 pads without cable connections
- 40 front-end cards fit in pentagonal pattern
- Shielding covers electronics cards by pairs



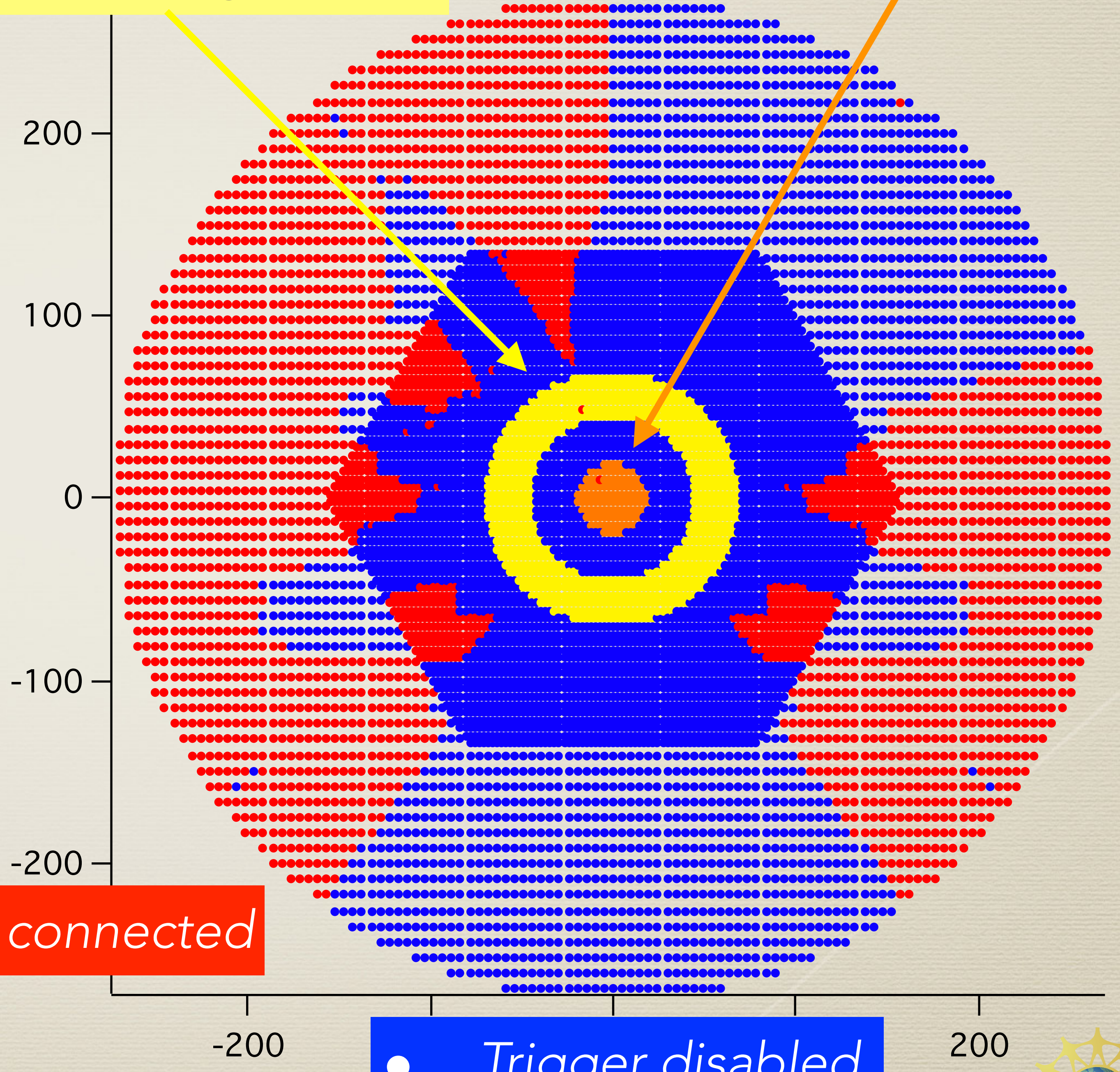
GET (General Electronics for TPCs)

- Trigger needs to filter out unreacted beam events
  - GET electronics provides discriminators on each pad
  - Running multiplicities of each AsAd routed to MuTanT through CoBos
  - Trigger configuration can be programmed
- AGET front-end chips provide various gains and shaping times



Trigger generation

- Define pad regions with different trigger attributes
- Example shows configuration for elastic scattering
- More complex pattern triggering configuration can be programmed



🟨
- *Trigger enabled*
- *Reading if hit*

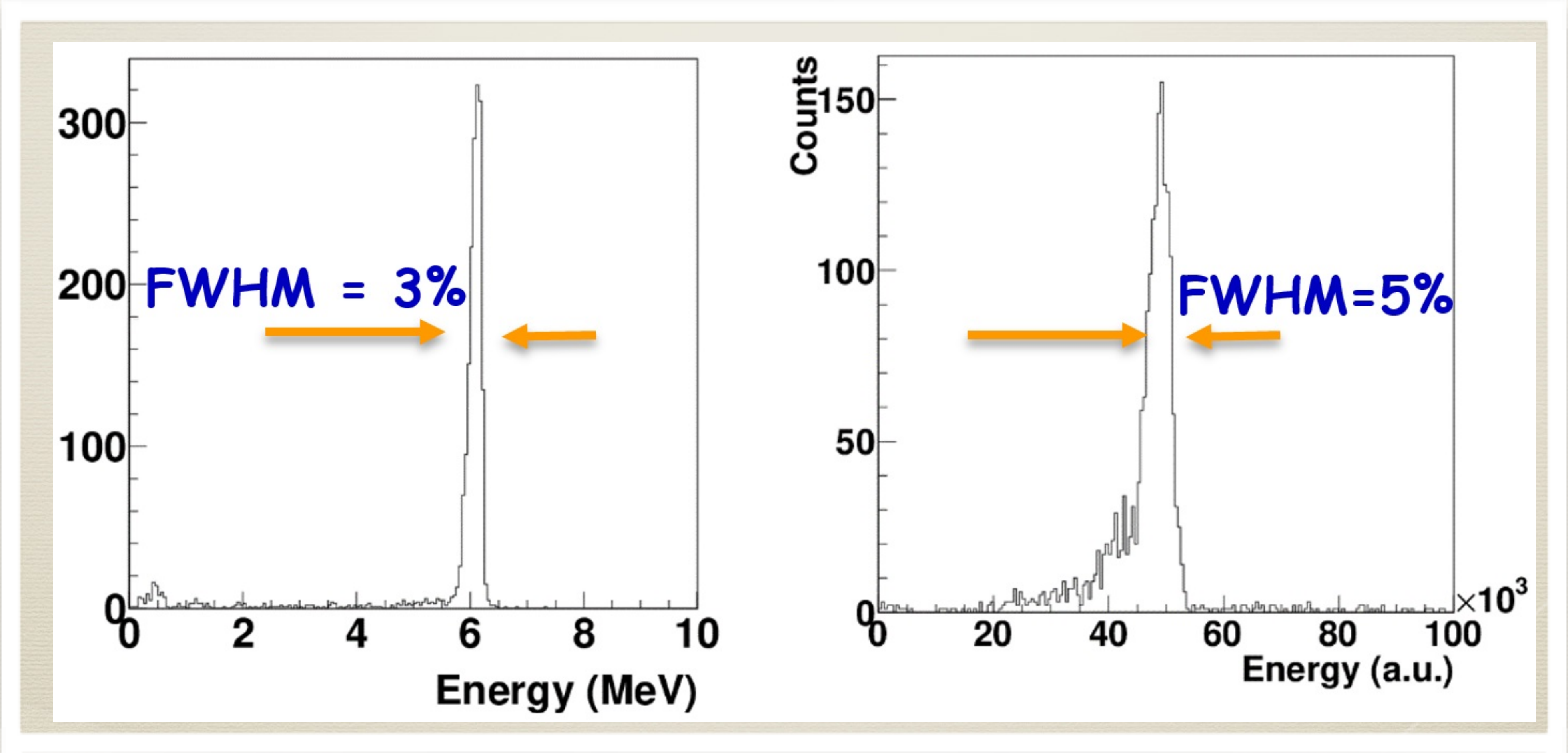
🟧
- *Trigger disabled*
- *Reading always*

🟥
- *Pad not connected*

🟦
- *Trigger disabled*
- *Reading if hit*

Energy resolution

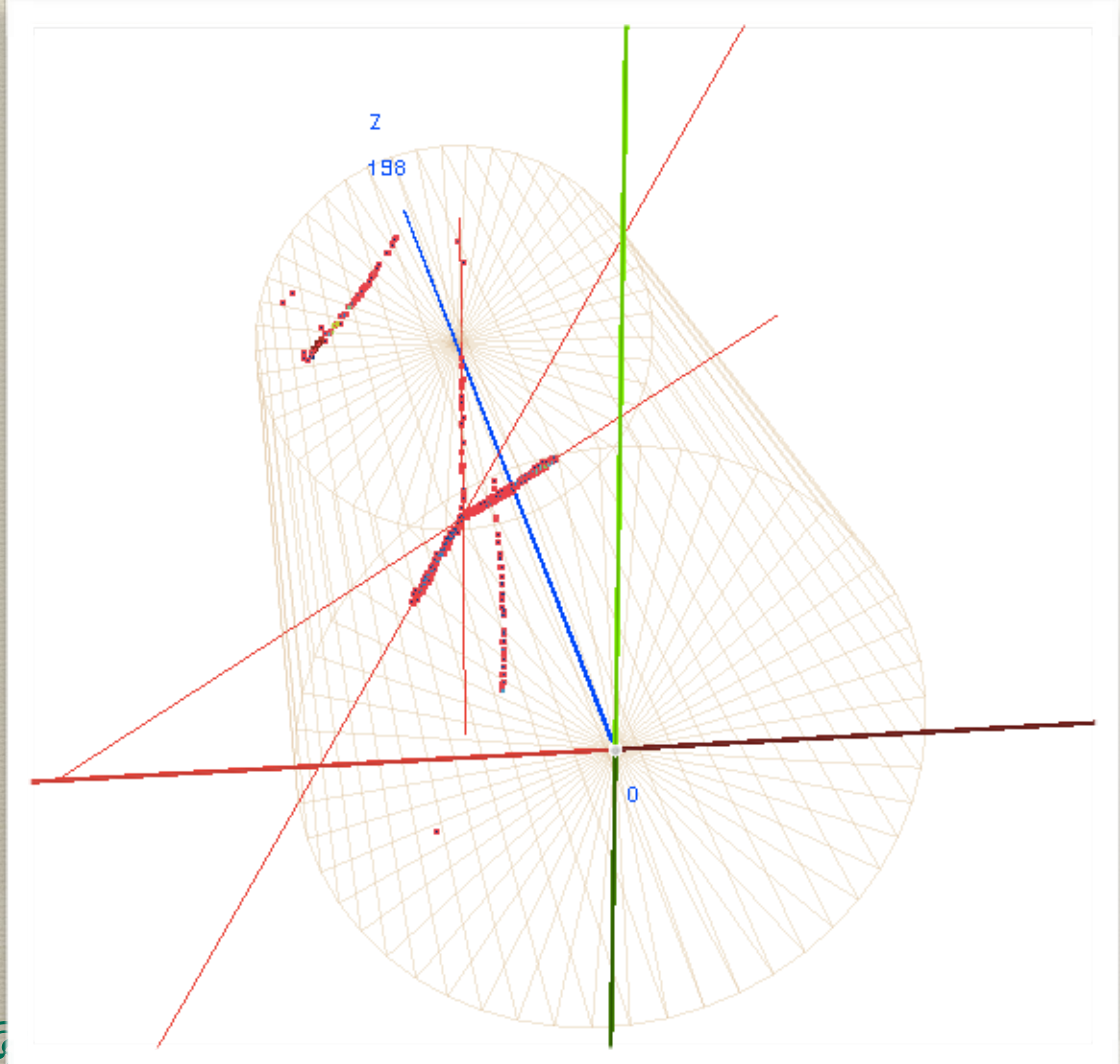
- 6.1 MeV ^{4}He from ^{252}Cf source in 50 Torr CO_2 gas
- Use M-THGEM (THGEM stack) for ē pre-amplification
- Energy resolutions: 3% from range, 5% from charge

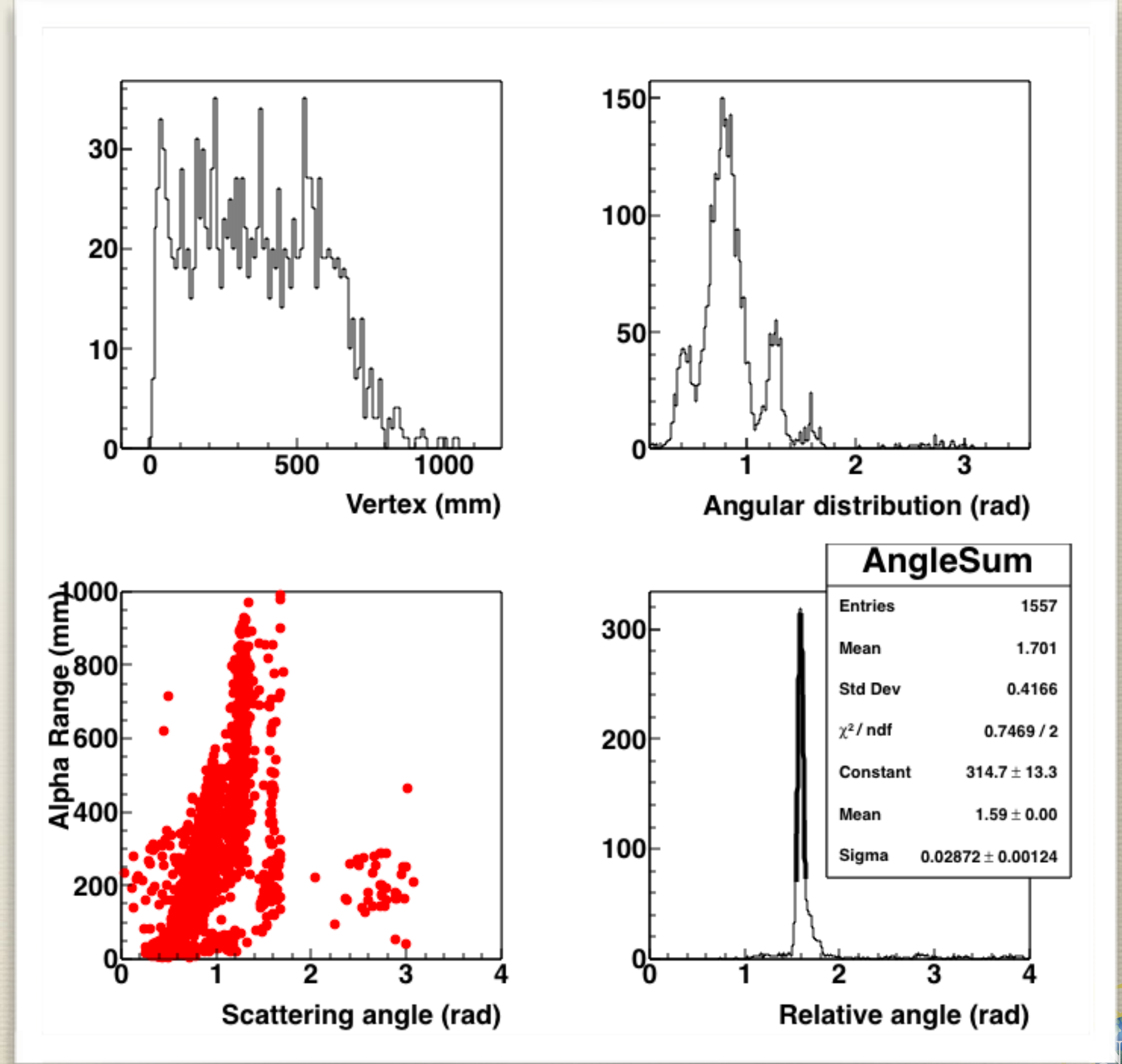


Analysis by Y. Ayyad-Limonge

$^4He+^4He$ scattering

- Gas target used: (90%)He+(10%)CO_2 at 300 Torr
- Separation of beam tracks in pile-up events when using 7° tilt configuration
- Angular resolution close to 1° (relative angle between two ^4He)
- Vertex position resolution 12.5 mm FWHM corresponds to ~30 keV/u

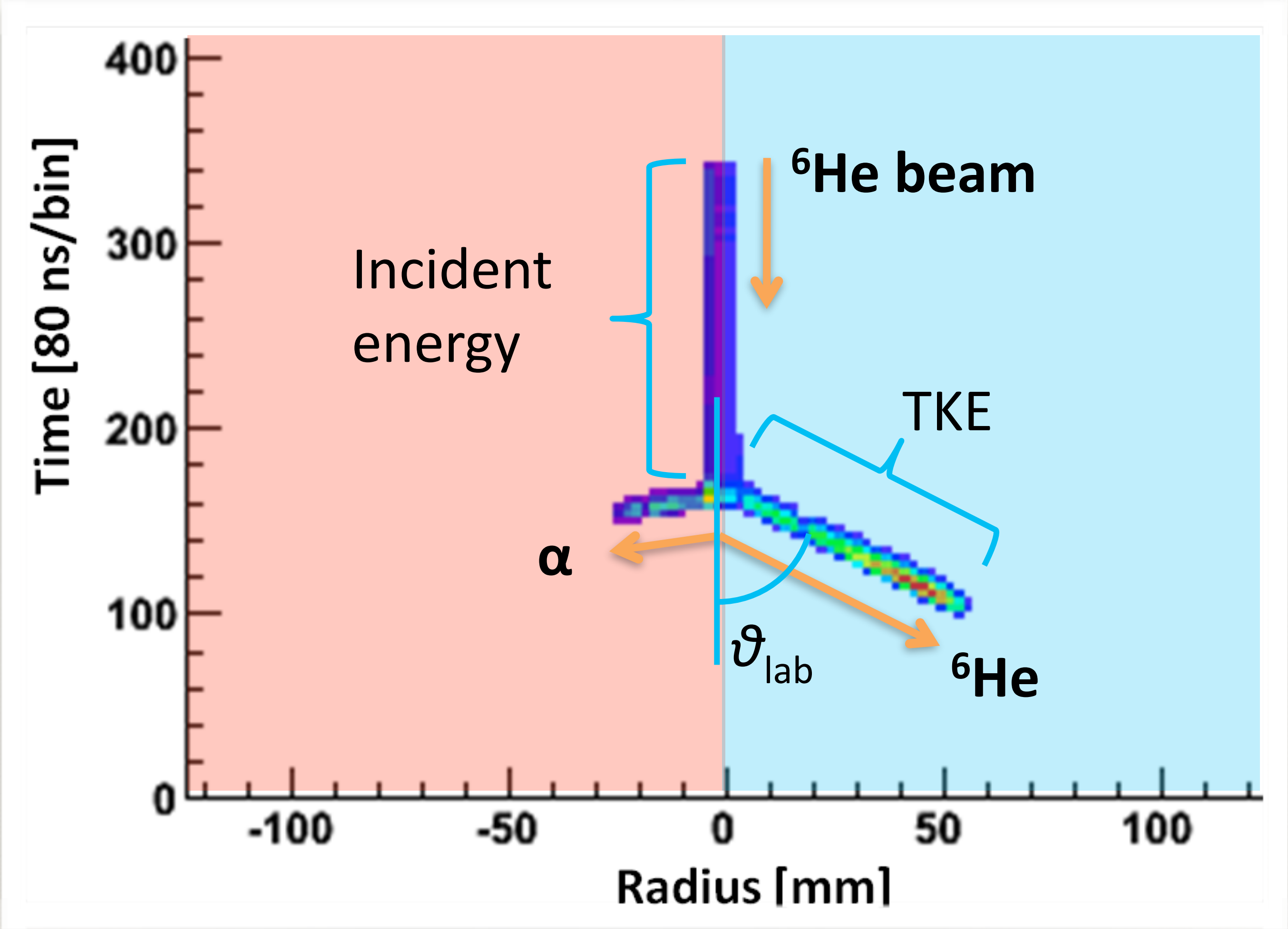




Analysis by Y. Ayyad-Limonge

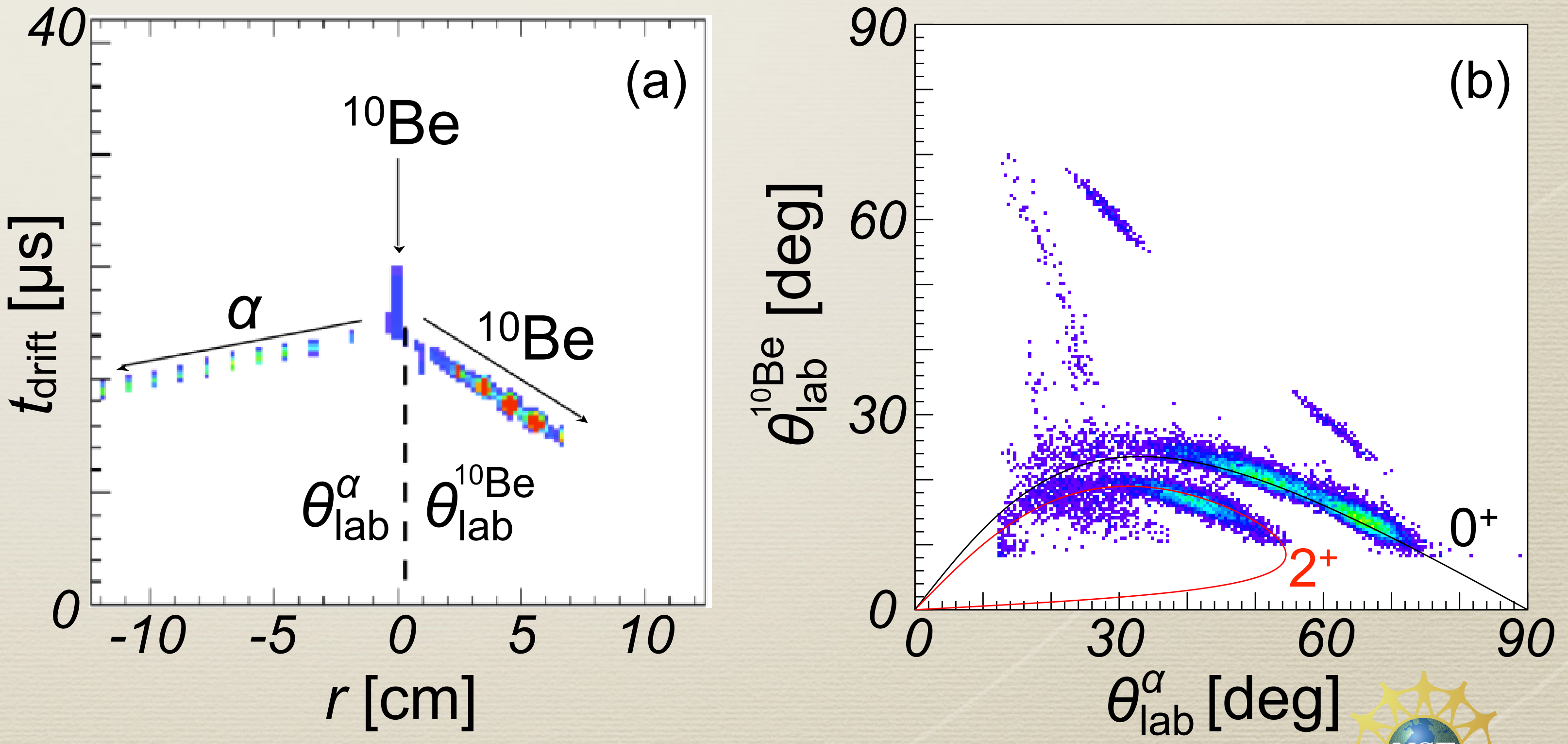
Resonant alpha scattering

- 3 experiments performed with the PAT-TPC
  - ^{6}He+^{4}He (^{10}Be), ^{10}Be+^{4}He (^{14}C) on TWINSOL @ U. of Notre-Dame
  - ^{8}He+^{4}He (^{12}Be) on ISAC2 @ TRIUMF (Dec 2015)
- Typical scattering event
  - Reaction energy determined by position of vertex
  - Both TKE and θ_{lab} can be used to calculate E_x
  - Trigger set on outer rings being hit



^{10}Be+^{4}He scattering

- Study of alpha clustering in ^{14}C excited states
  - 4 MeV/u ^{10}Be beam from ^{11}B(^{13}C,^{14}N)^{10}Be reaction
  - Dual gain on micromegas by polarization of every 5 ring +100V
  - Separation between elastic and inelastic scattering
  - Two additional loci from ^{4}He contamination in beam



A. Fritsch *et al.*, Phys. Rev. C **93**, 014321 (2016)

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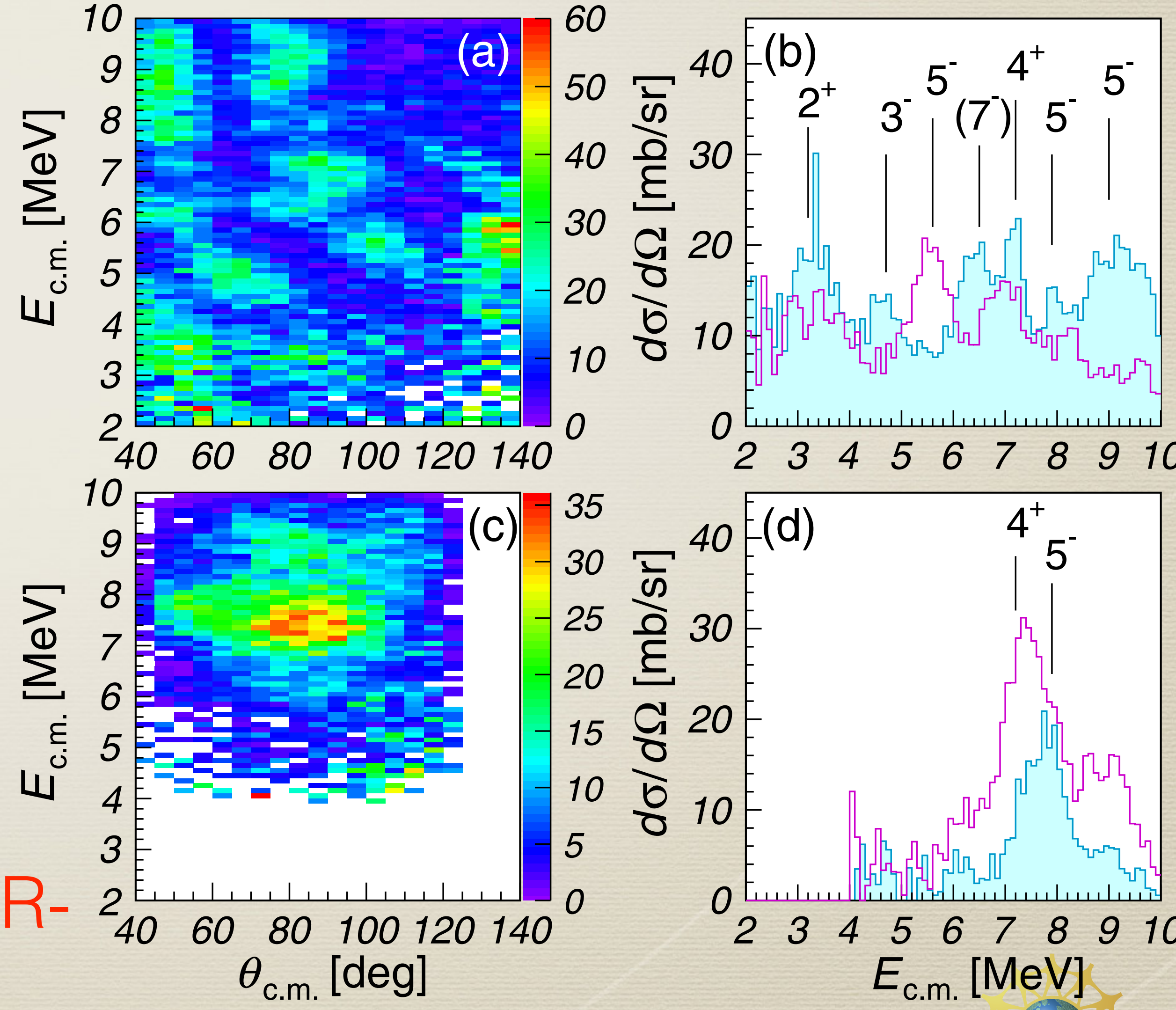
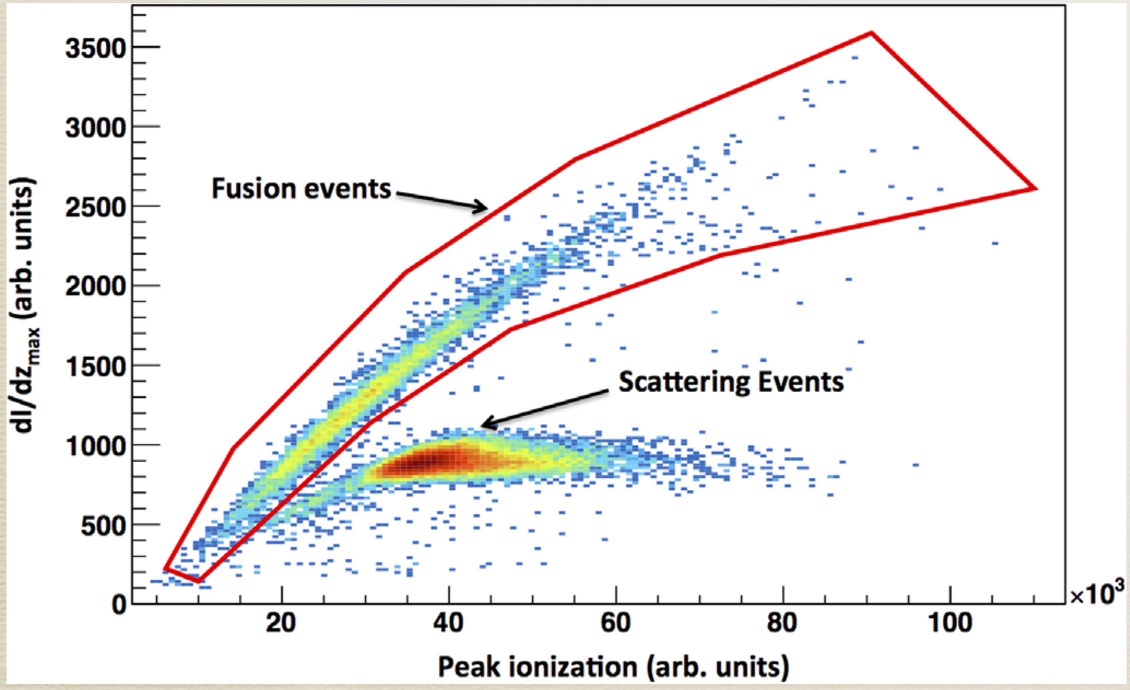
  - Dual gain on micromegas by polarization of every 5 ring +100V
  - Separation between elastic and inelastic scattering
  - Two additional loci from ^{4}He contamination in beam
- Excitation functions
  - Resonances observed and identified from comparison with R-matrix calculations

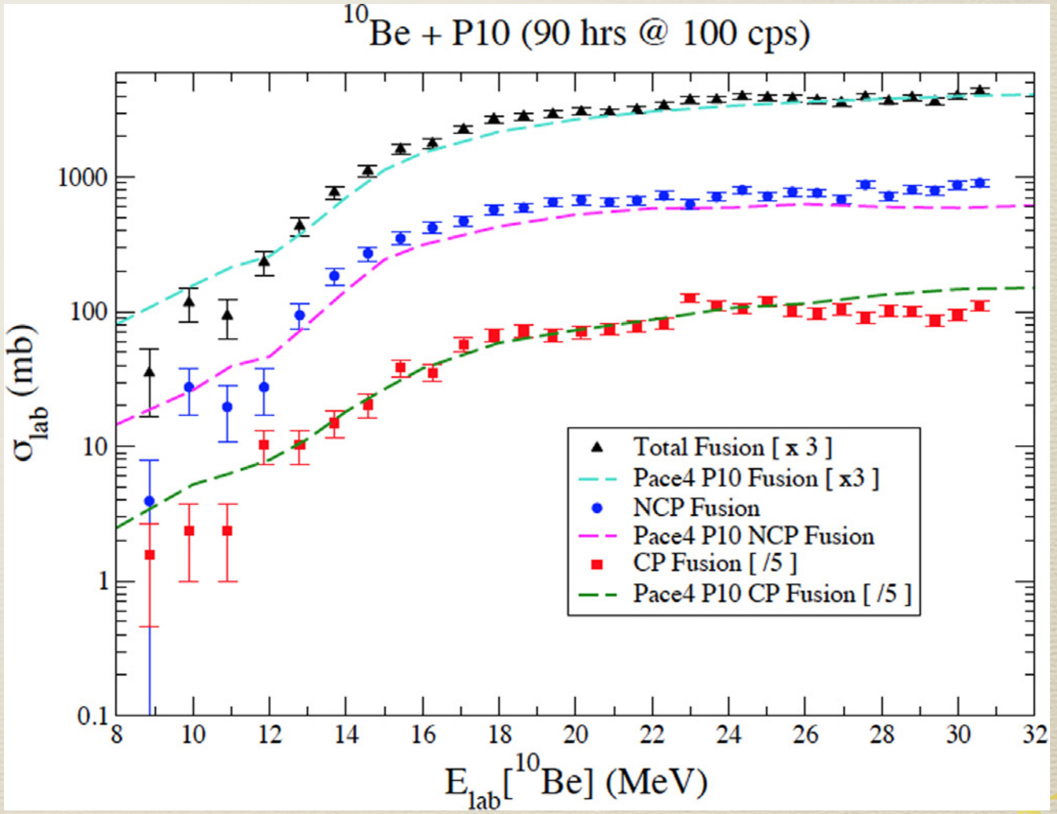


A. Fritsch *et al.*, Phys. Rev. C **93**, 014321 (2016)

Fusion of ^{10}Be + ^{40}Ar

- Experiment performed at the TWINSOL facility of Notre-Dame University using the pAT-TPC
- Trigger set on events with shorter range than ^{10}Be
- Whole excitation function using only one beam energy
- Identify different reaction mechanisms from multi-track analysis



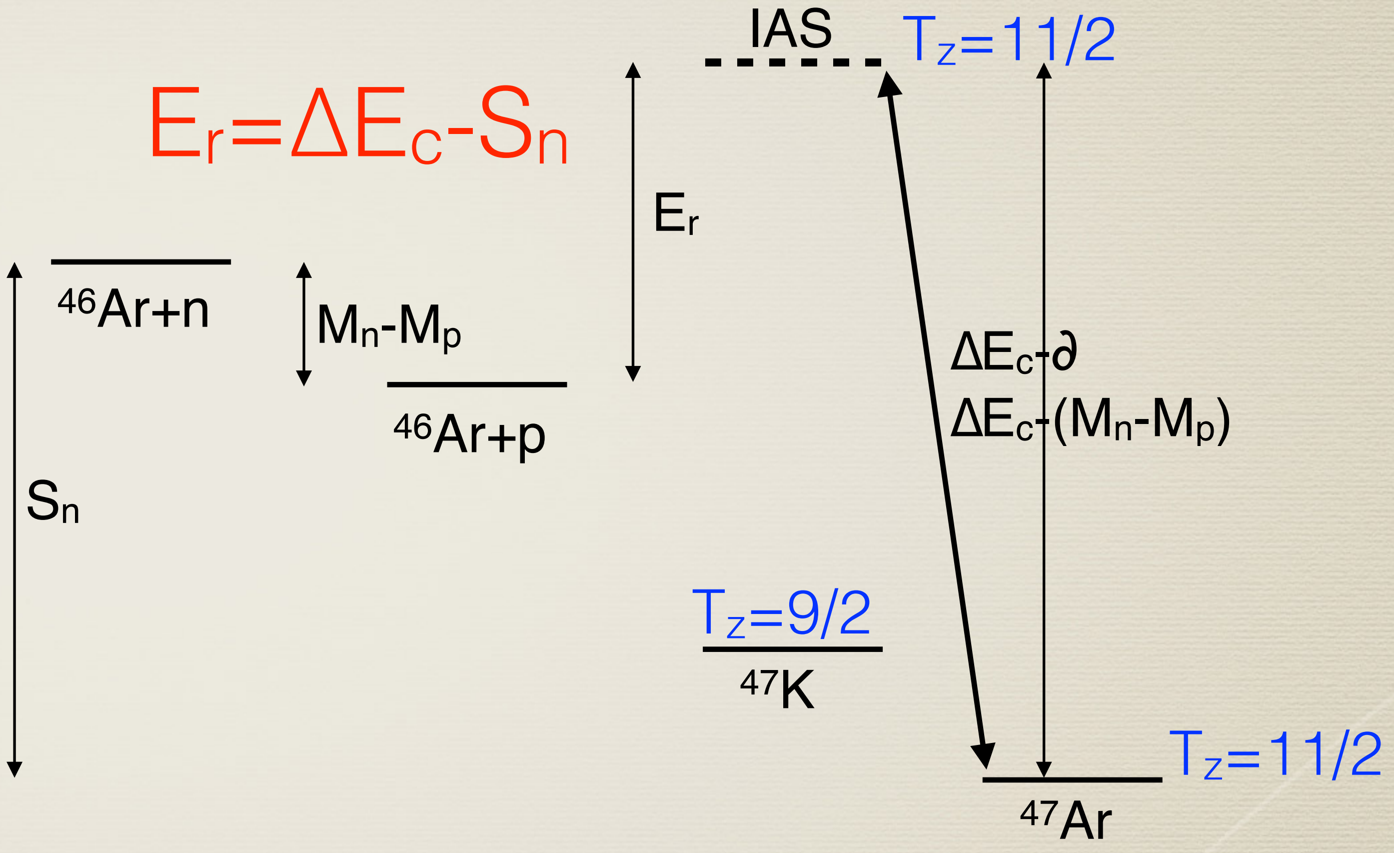


J. Kolata *et al.*, NIM A **830**, 82 (2016)

Proton resonant scattering

- Study ${}^{A+1}Z$ g.s. via Analog States of ${}^{A+1}(Z+1)$ populated via (p,p')
- Same information as (d,p)
  - Spectroscopic factors
  - Spin, parity
- Spectroscopic factors from excited states
- Coulomb displacement energies

$E_r = \Delta E_C - S_n$



IAS

$T_Z=11/2$

E_r

^{46}Ar+n

M_n-M_p

^{46}Ar+p

S_n

ΔE_C-∂

ΔE_C-(M_n-M_p)

$T_Z=9/2$

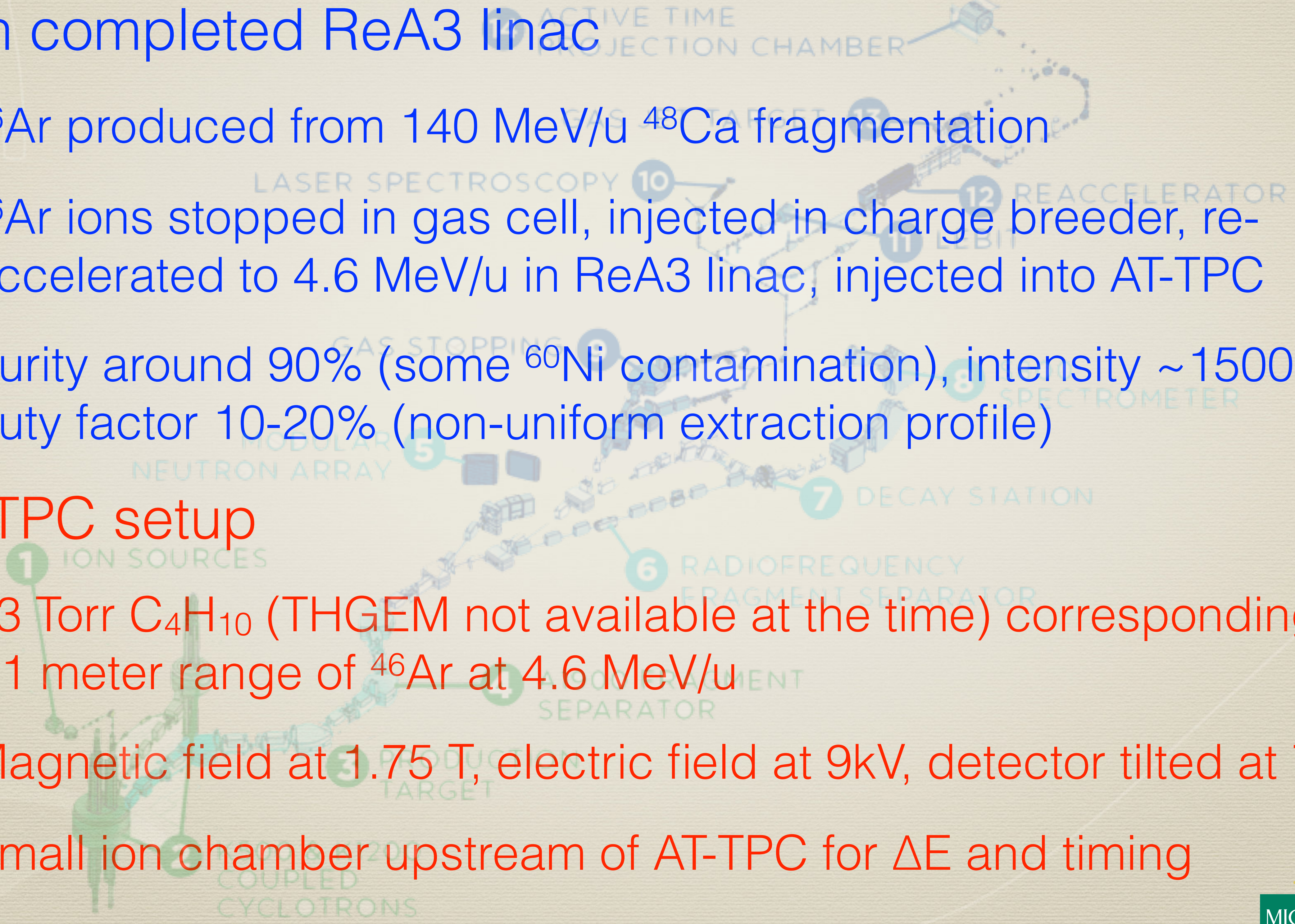
^{47}K

$T_Z=11/2$

^{47}Ar

Example: ^{46}Ar(p,p') E_r(IAS)=2.68 MeV

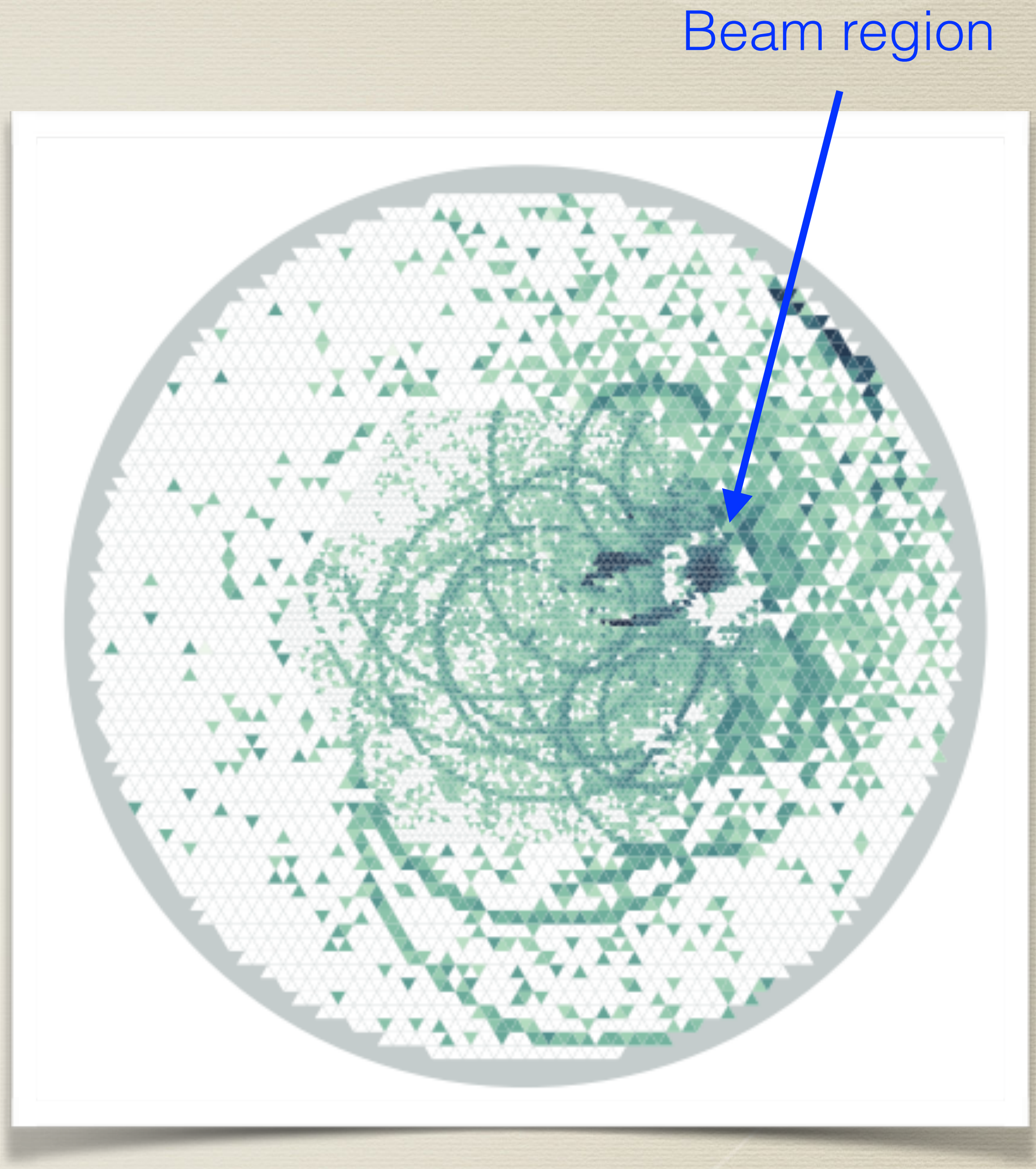
^{46}Ar + p resonant scattering



- First experiment using re-accelerated radioactive beam with completed ReA3 linac
  - ^{46}Ar produced from 140 MeV/u ^{48}Ca fragmentation
  - ^{46}Ar ions stopped in gas cell, injected in charge breeder, re-accelerated to 4.6 MeV/u in ReA3 linac, injected into AT-TPC
  - Purity around 90% (some ^{60}Ni contamination), intensity ~1500 pps, duty factor 10-20% (non-uniform extraction profile)
- AT-TPC setup
  - 23 Torr C_4H_{10} (THGEM not available at the time) corresponding to ~1 meter range of ^{46}Ar at 4.6 MeV/u
  - Magnetic field at 1.75 T, electric field at 9kV, detector tilted at 7°
  - Small ion chamber upstream of AT-TPC for ΔE and timing

Trigger conditions

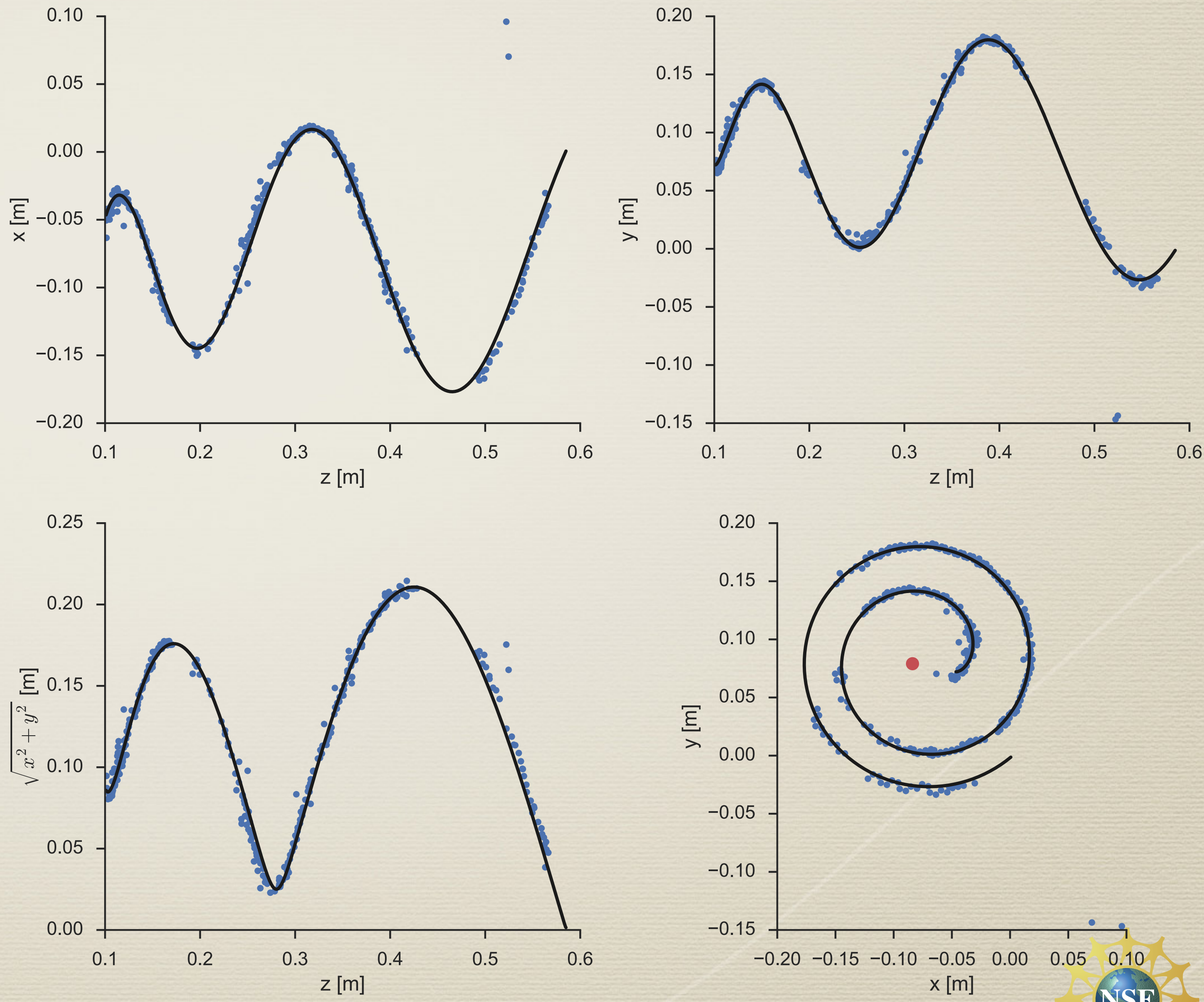
- ^{46}Ar beam tracks
  - Projected into small region away from center due to 7° tilt vs Lorentz force on electrons
  - “Beam region” set to lower gain (factor 100) and excluded from trigger generation
- Proton tracks
  - Clear spiral patterns
  - Some pads not firing due to capacitive coupling
  - Induced noise due to cross talk



Cumulated 50 events

Analysis of proton tracks

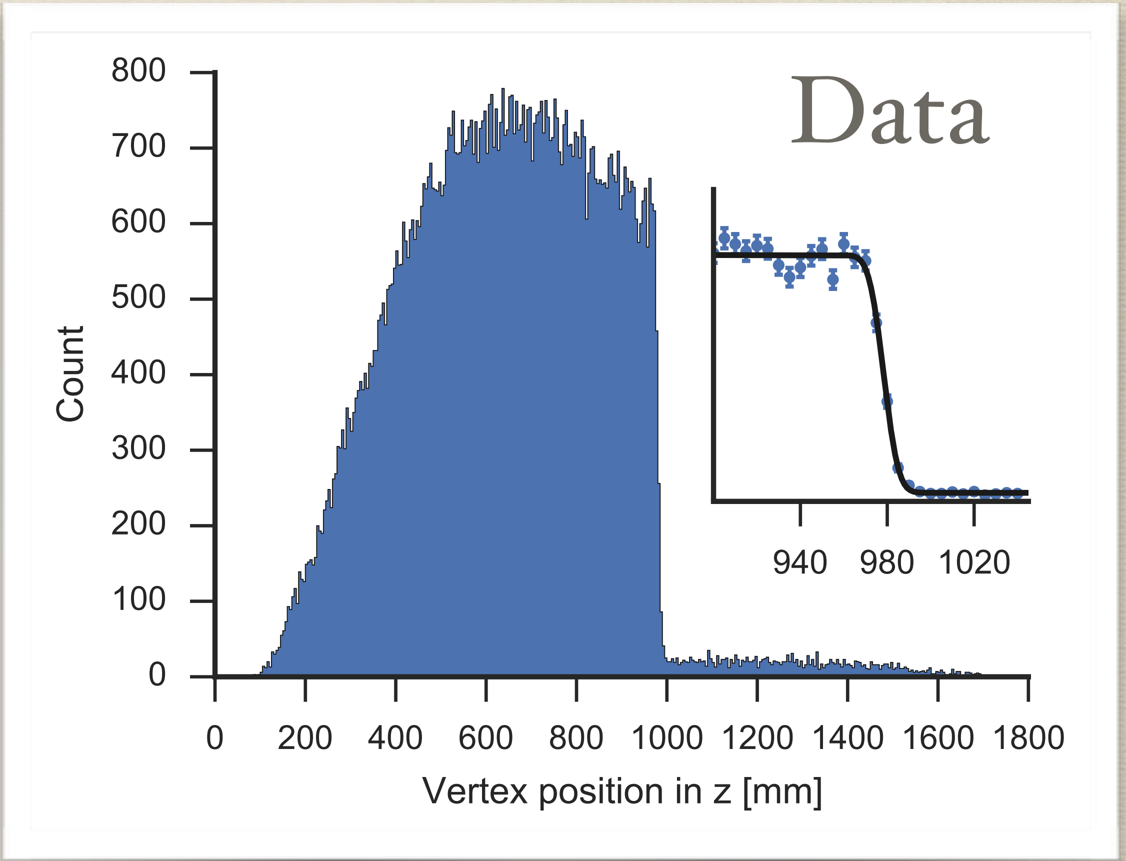
- Data cleanup, pattern recognition: Hough transforms
- Non-linear fitting algorithm: Monte-Carlo fitting
- See talk by W. Mittig

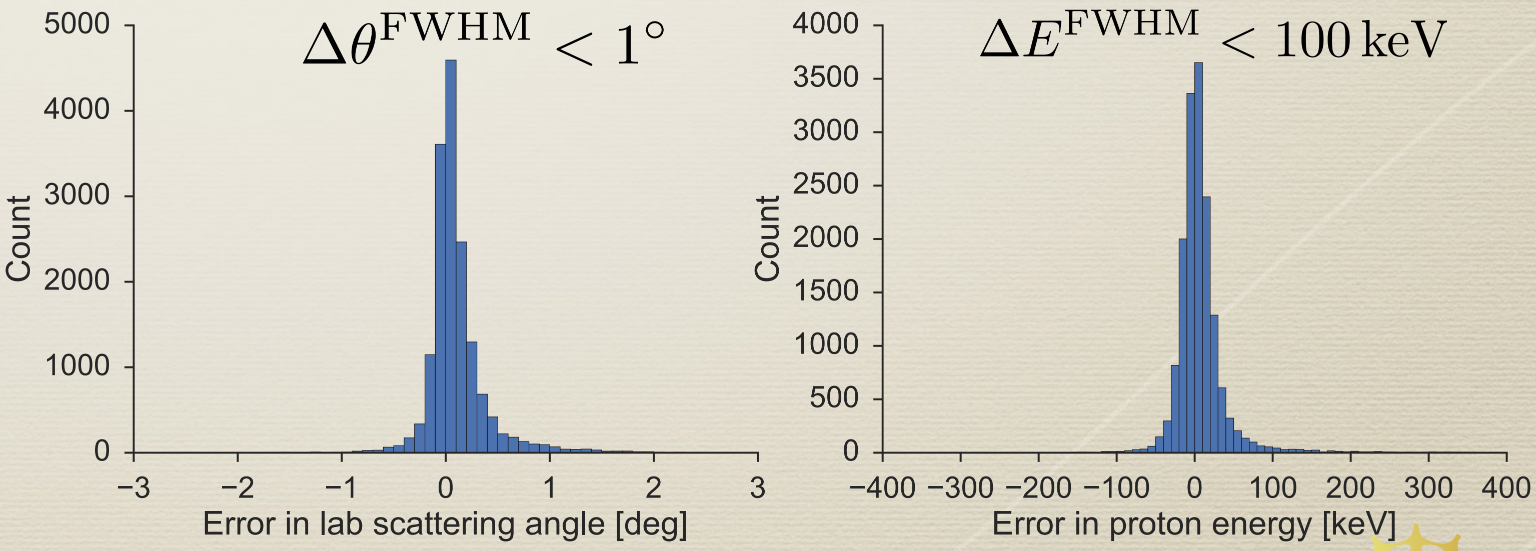


Analysis by J. Bradt

Resolutions

- Reaction vertex position resolution: 12.5 mm FWHM
- Corresponds to energy resolution of 38 keV/u
- Poor quality of ^{46}Ar beam tracks prevents determination of beam track angles
- Kinematics resolutions shown from Monte-Carlo simulations



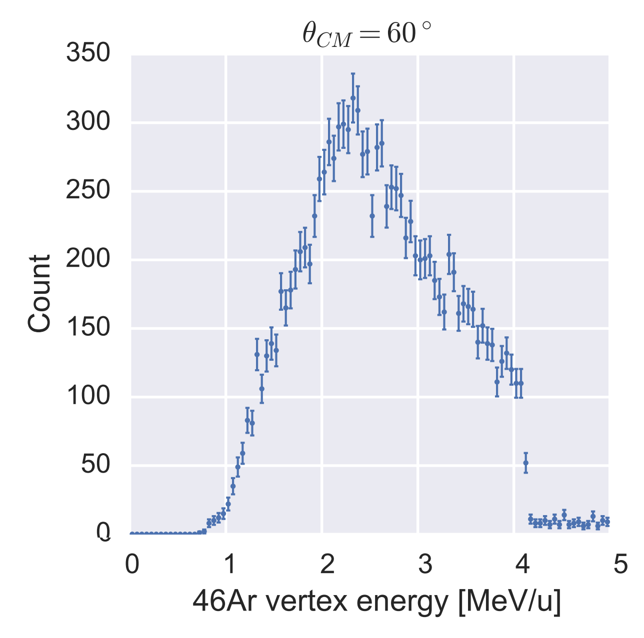


Simulation

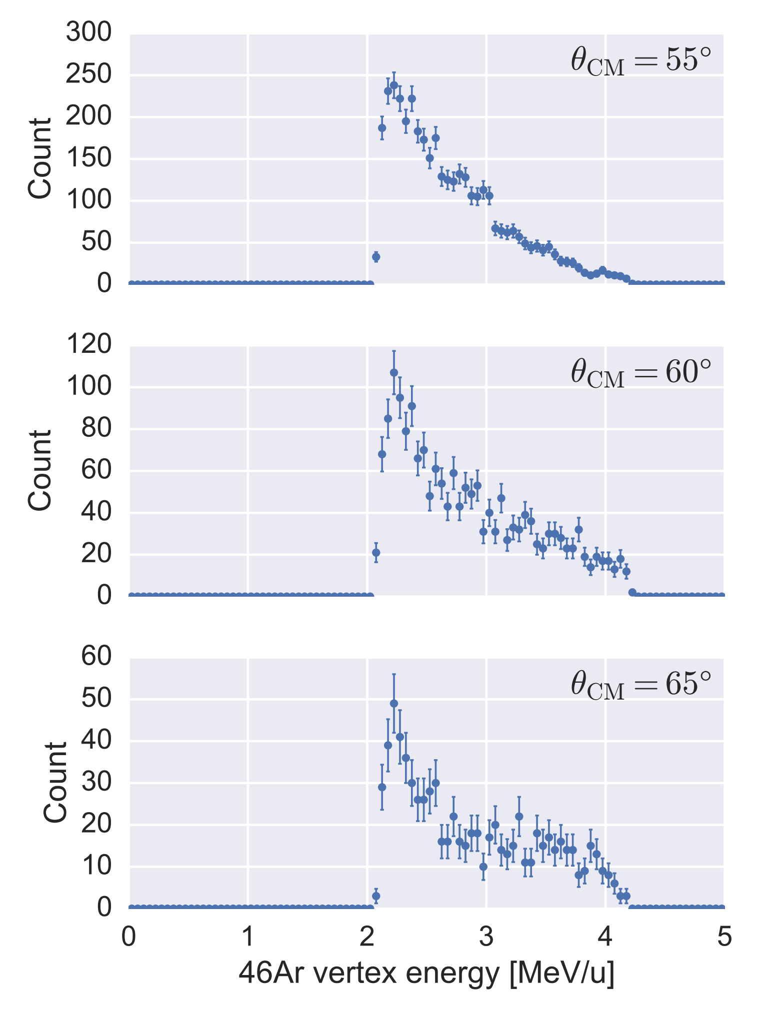
Preliminary result

- Excitation functions of ^{46}Ar + p scattering
- Compared to expected distribution using R-matrix calculation
- Statistics is borderline to clearly identify p-state resonance

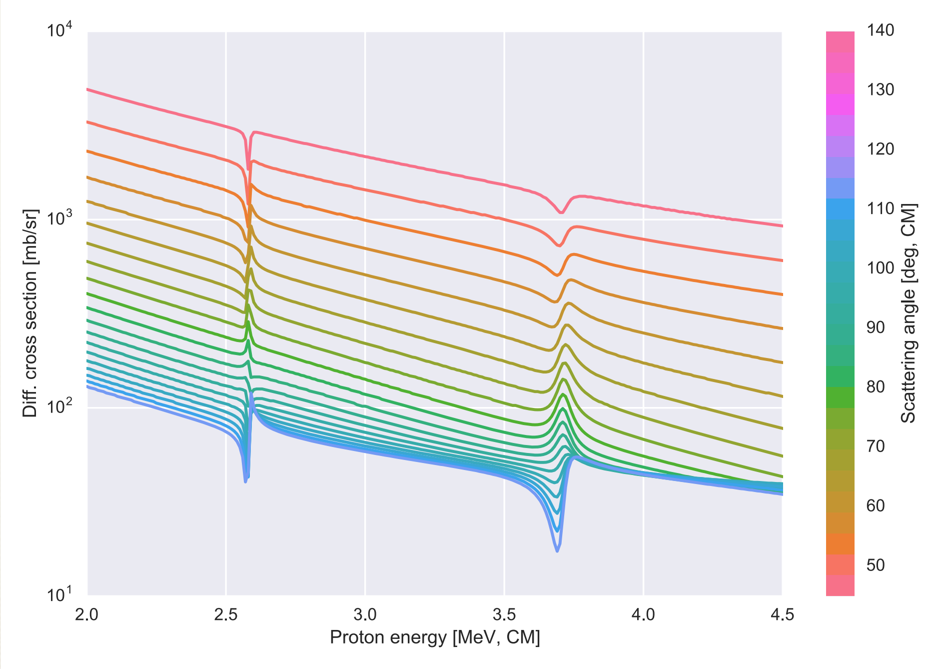
Experiment



Simulation

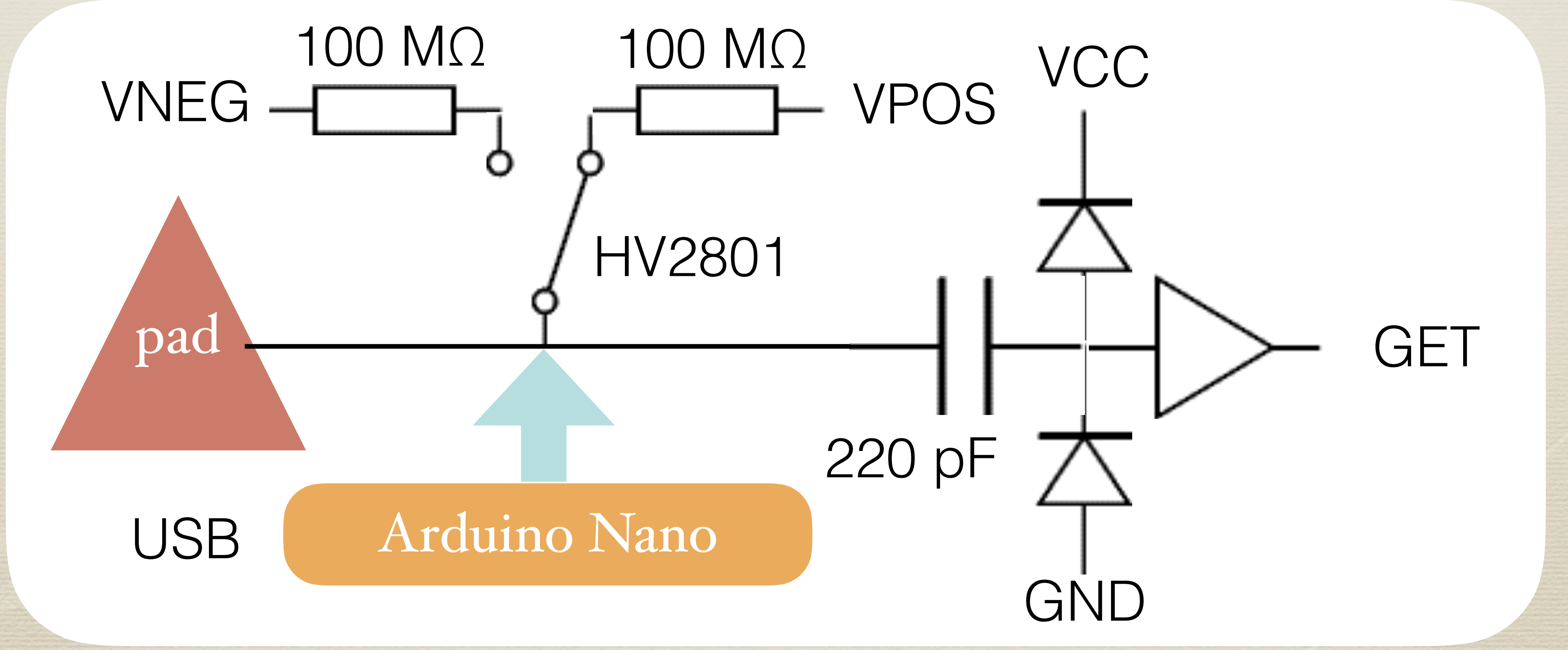


Calculation



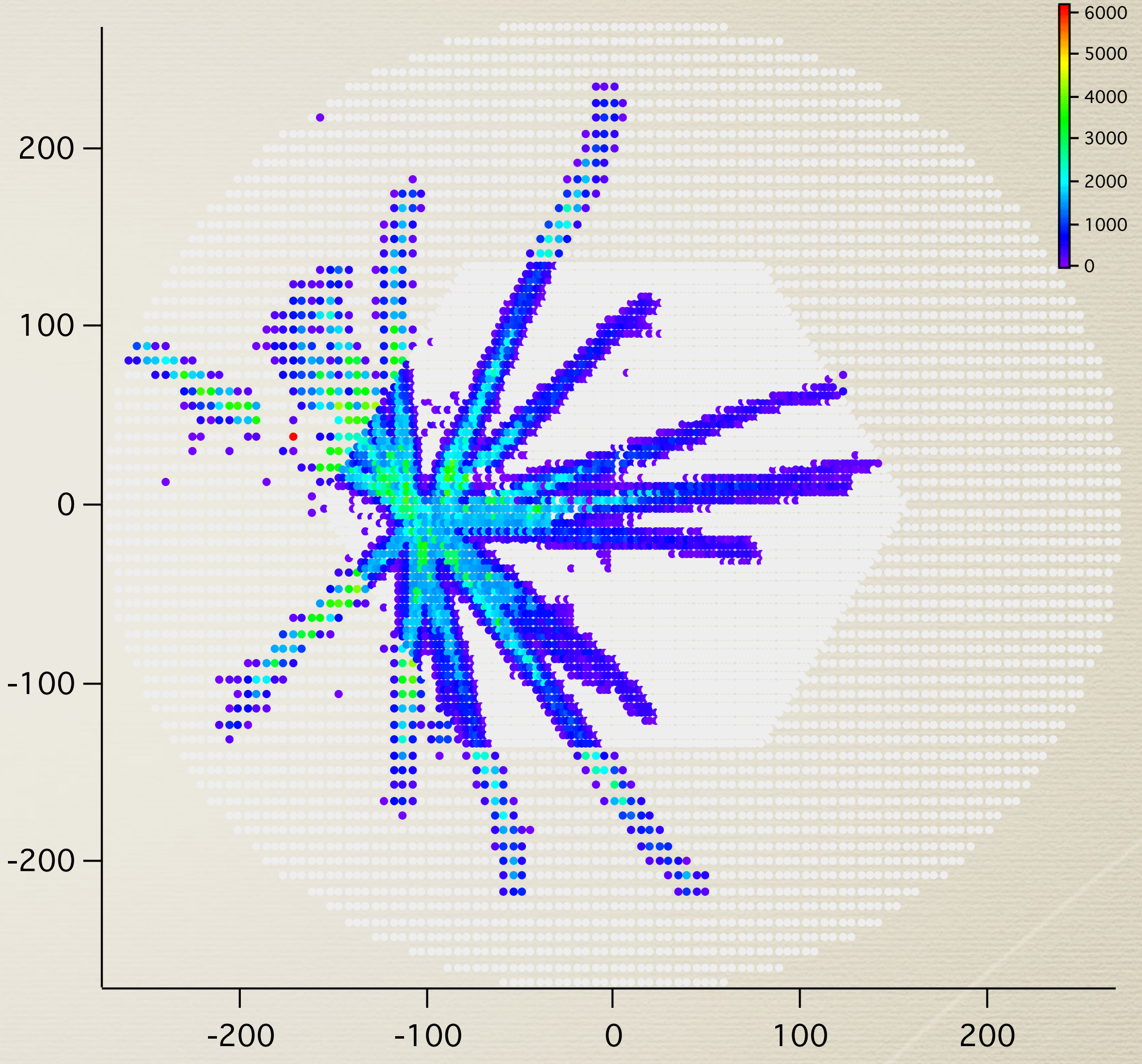
Individual pad polarization

- Necessary to compensate for largely different energy losses from particles with widely different Z
- Major issue during the ^{46}Ar+p experiment
- Use programmable HV switch on protection (ZAP) board prior to input stage of AGET chip

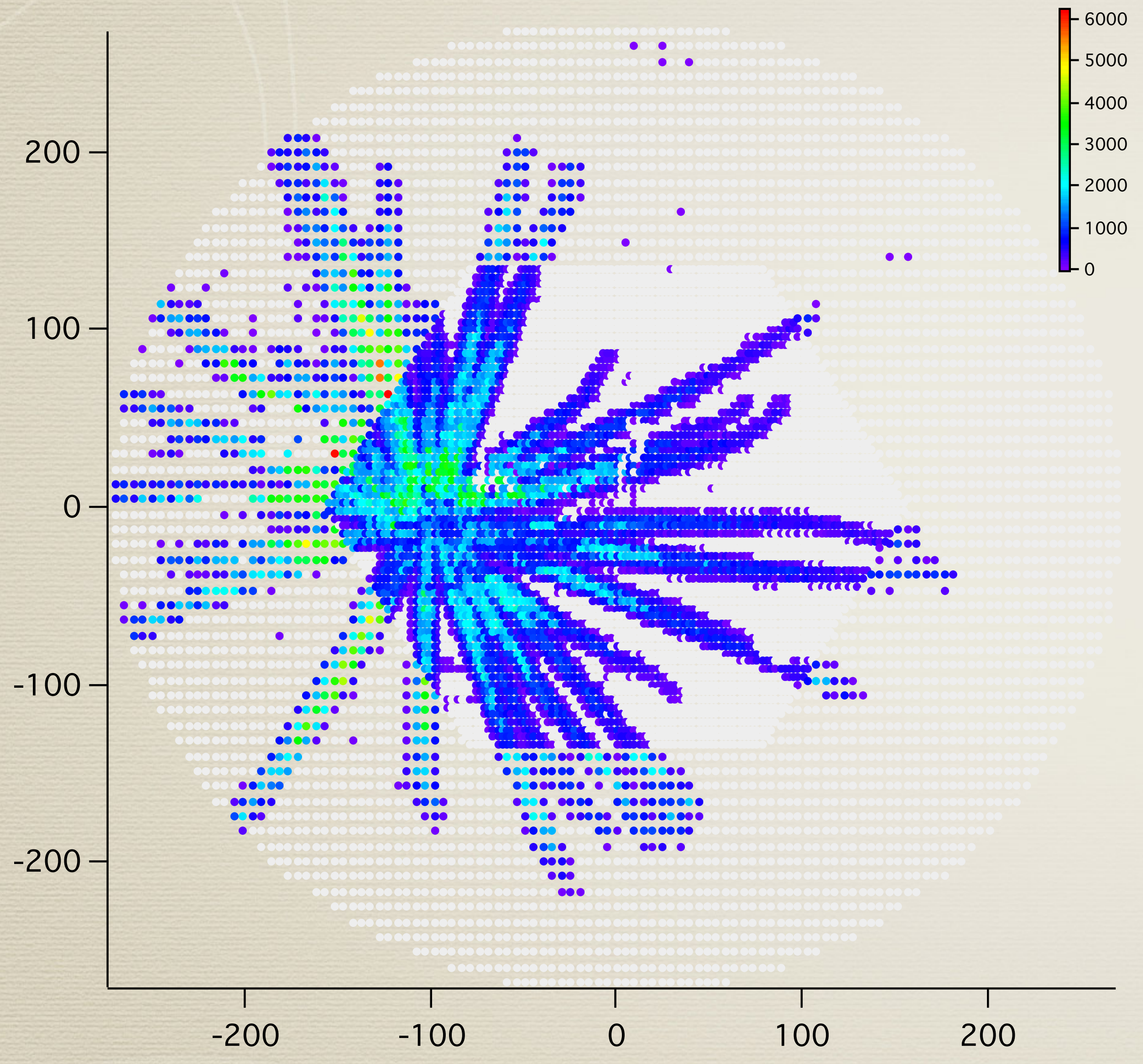


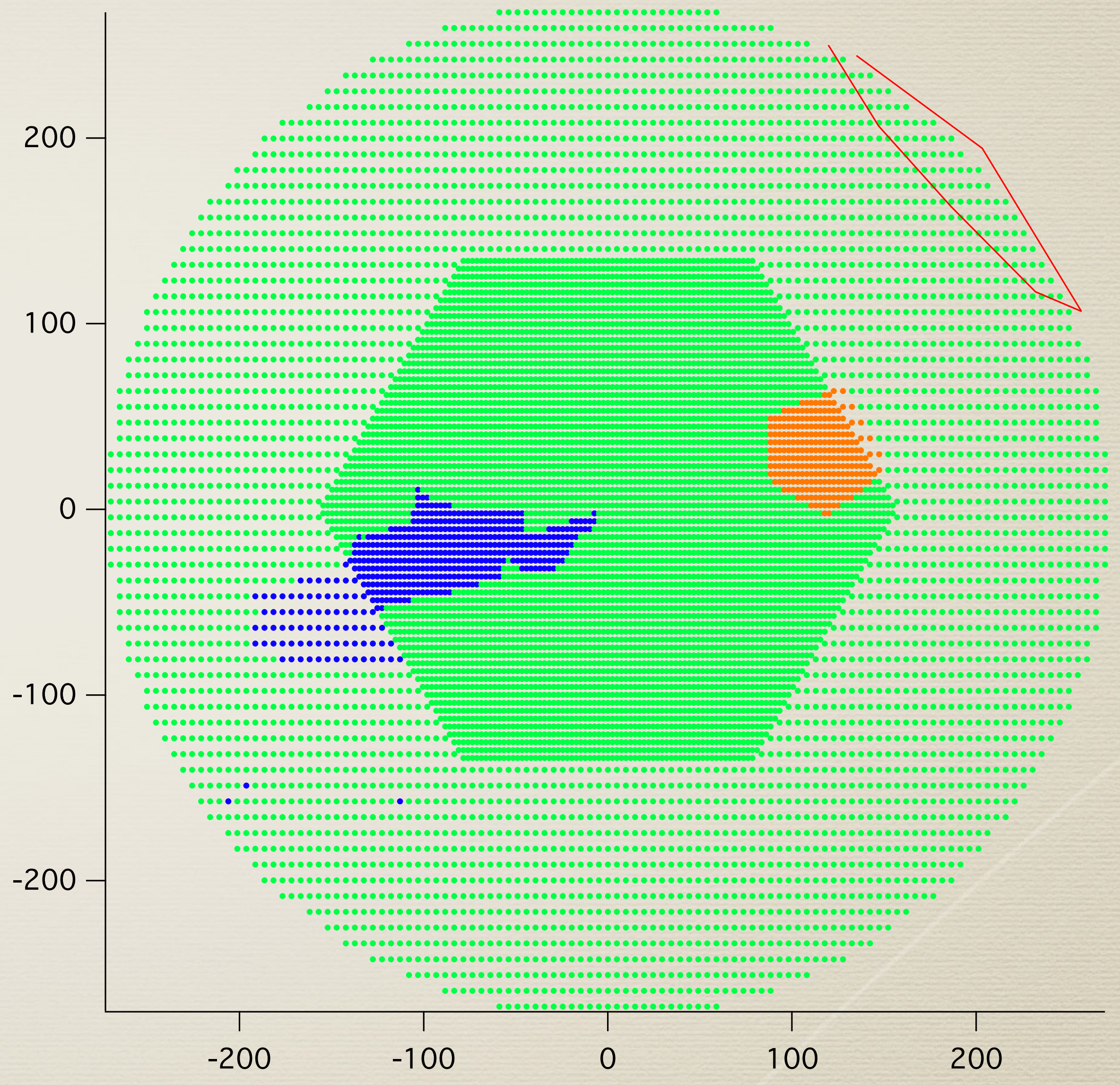
Test with fission fragments

- AT-TPC filled with 200 Torr of He (90%) + CO2 (10%)
- Cathode voltage: 20 kV
- Mesh voltage: -300 V
- Pad voltage: 0 V
- Cumulated tracks clearly shows location of source on cathode



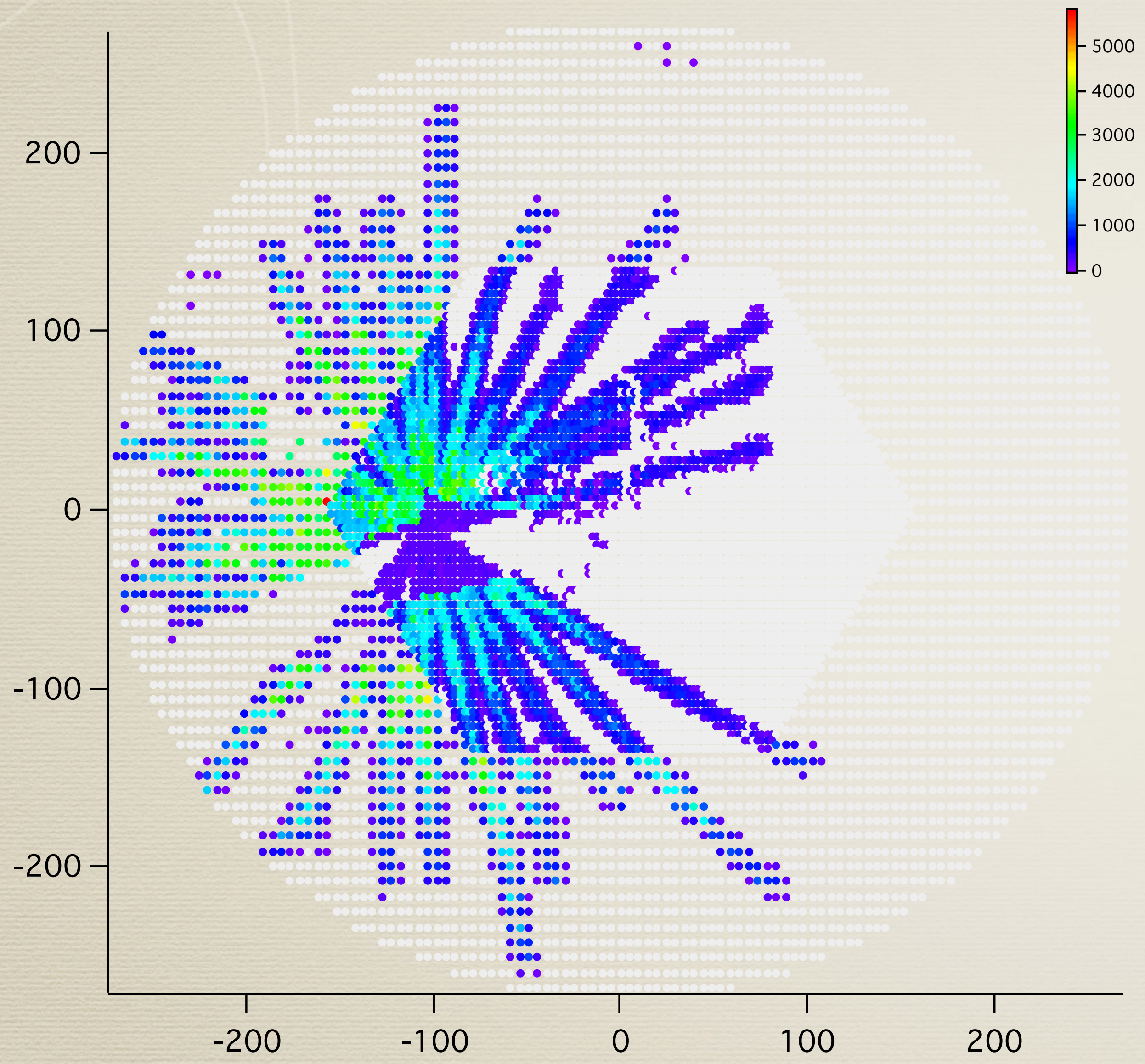
Polarization at -50 Volts

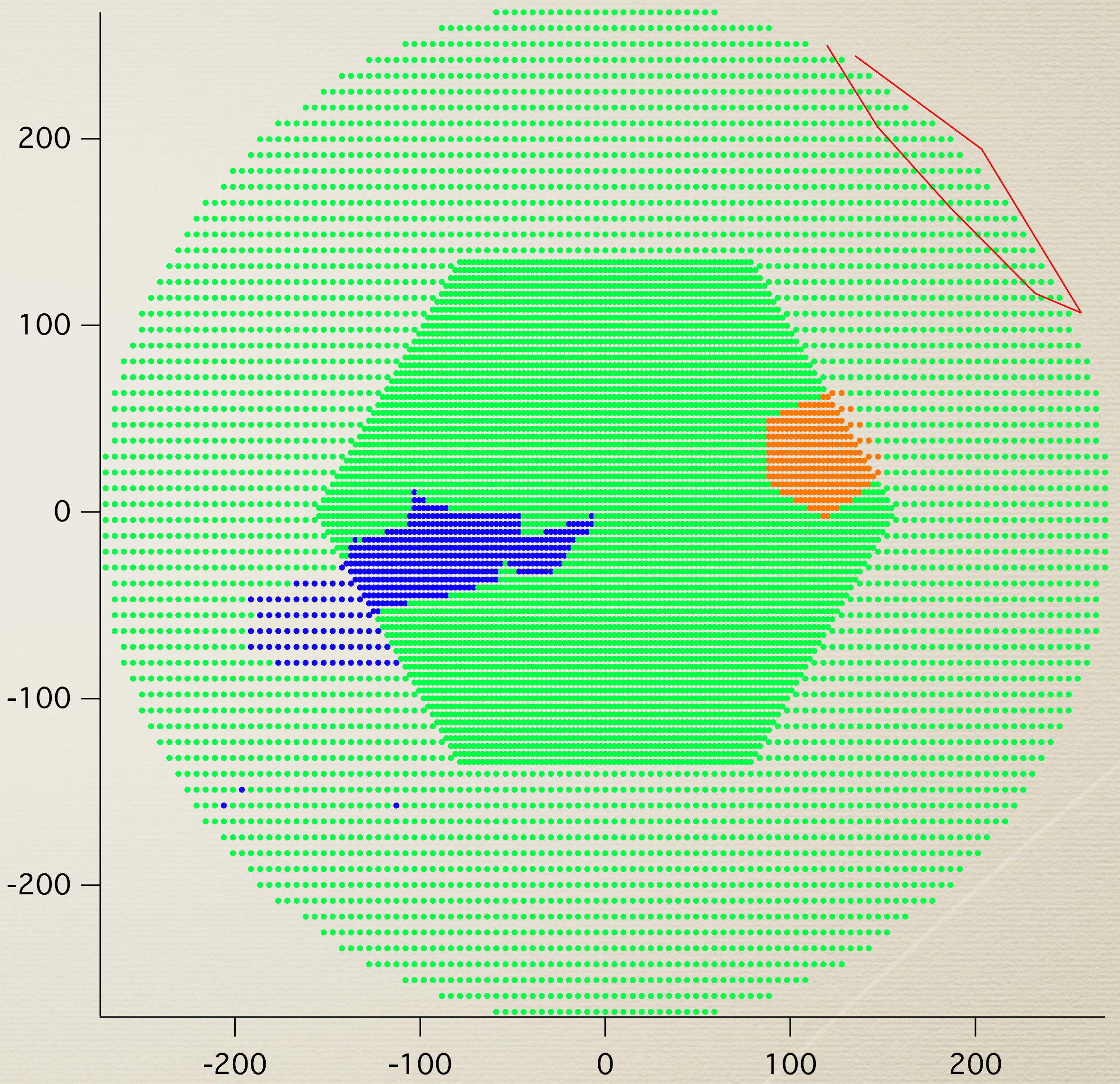




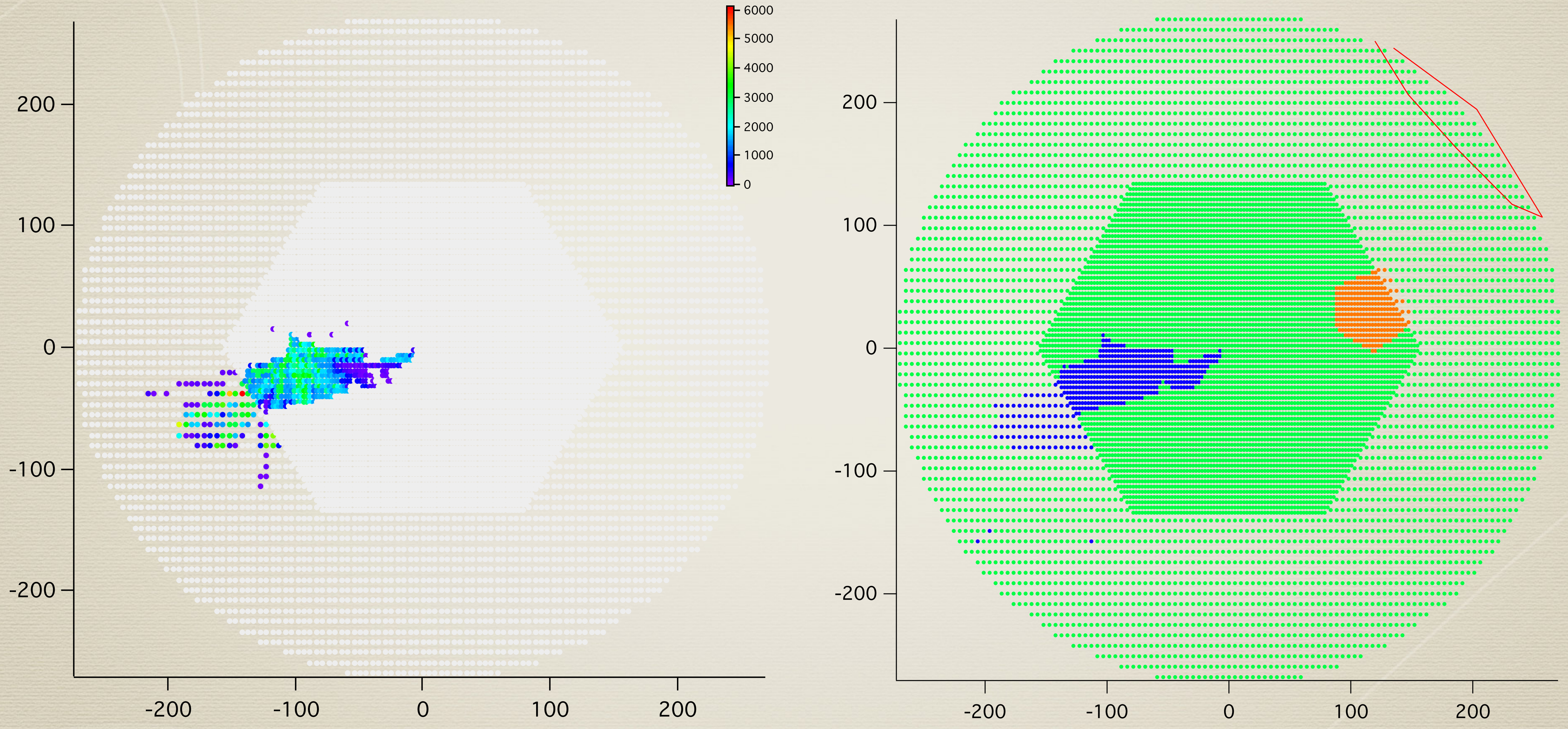
D. Bazin, Solenoidal Spectrometer Workshop, Argonne, March 24, 2017

Polarization at -150 Volts





Inverse polarization



Upcoming experiments

- e12014: measurement of the fission barriers for heavy exotic nuclei
- e15037: fusion with neutron-rich rare isotope beams (^{38}S + ^{208}Pb using solid target)
- e15238: Measurement of ANC of 12N(p,γ)13O relevant for the rap process
- e15250: direct measurement of a key reaction for the rp-process with the AT-TPC
- e16022: spectroscopy of the chlorine isotopes at the proton drip-line

Take aways

- Active Target detectors can boost luminosity of reaction experiments by orders of magnitude
- Essential for experiments using radioactive beams
- Excitation functions can be measured efficiently using only one beam energy
- Resolutions comparable to conventional detection techniques (solid state detectors)
- Effective use of entire arsenal of proven reaction tools for low-energy Nuclear Science for radioactive nuclei

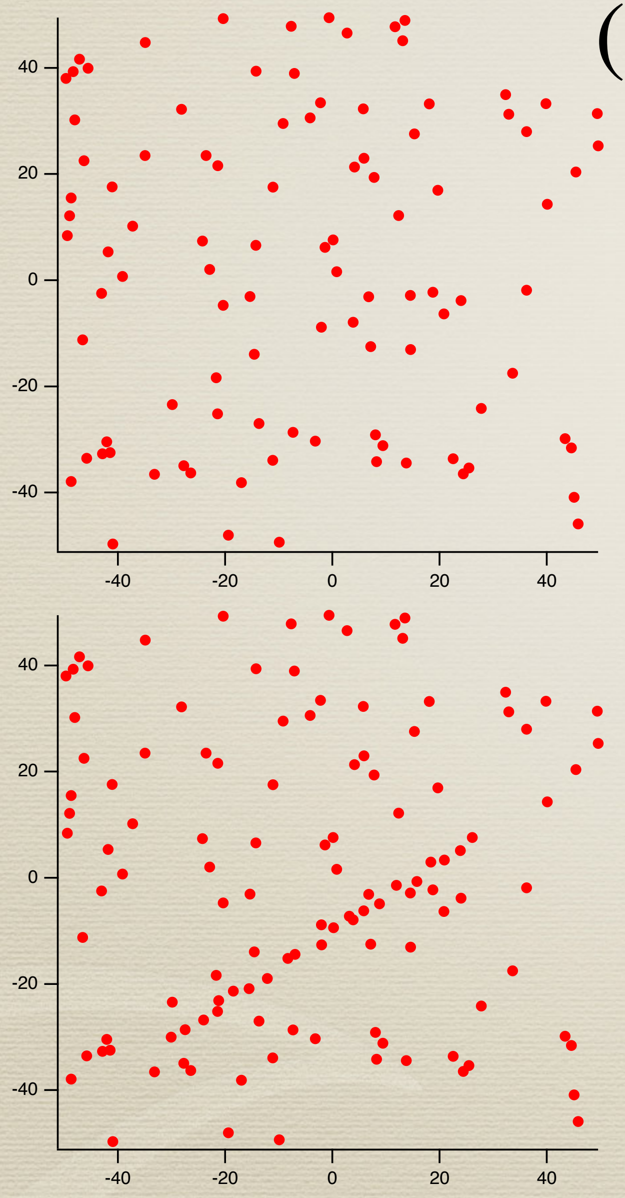
AT-TPC collaboration

- NSCL team
  - D. Bazin, W. Mittig, B. Lynch, S. Beceiro-Novo
  - J. Bradt, L. Carpenter, N. Watwood, J. Manfredi, J. Zuzelski
  - J. Yurkon, M. Cortesi
- Outside collaborators
  - T. Ahn, J. Kolata, U. Garg (U. of Notre-Dame, South Bend, IN)
  - Z. Chajecki (WMU, Kalamazoo, MI)
  - R. Kanungo (Saint Mary U., Halifax, Canada)
  - D. Suzuki (RIBF, Tokyo, Japan)
  - Y. Ayyad-Limonge (LBNL)
  - A. Fritsch (Gonzaga U., Spokane, WA)
  - F. Bechetti (UM, Ann Arbor, MI)
  - A. Gillibert, E. Pollacco (IRFU, Saclay, France)

Hough transforms

- Algorithms used in digital image processing to find patterns in noisy data
- Different parametrization can be used to find different patterns
- The example below shows linear Hough transform to identify lines

(x,y)



$$r = x\cos(\theta) + y\sin(\theta)$$

$$0 \leq \theta \leq \pi$$

(r,θ)