A COMPACT TPC FOR THE sPHENIX EXPERIMENT AT RHIC

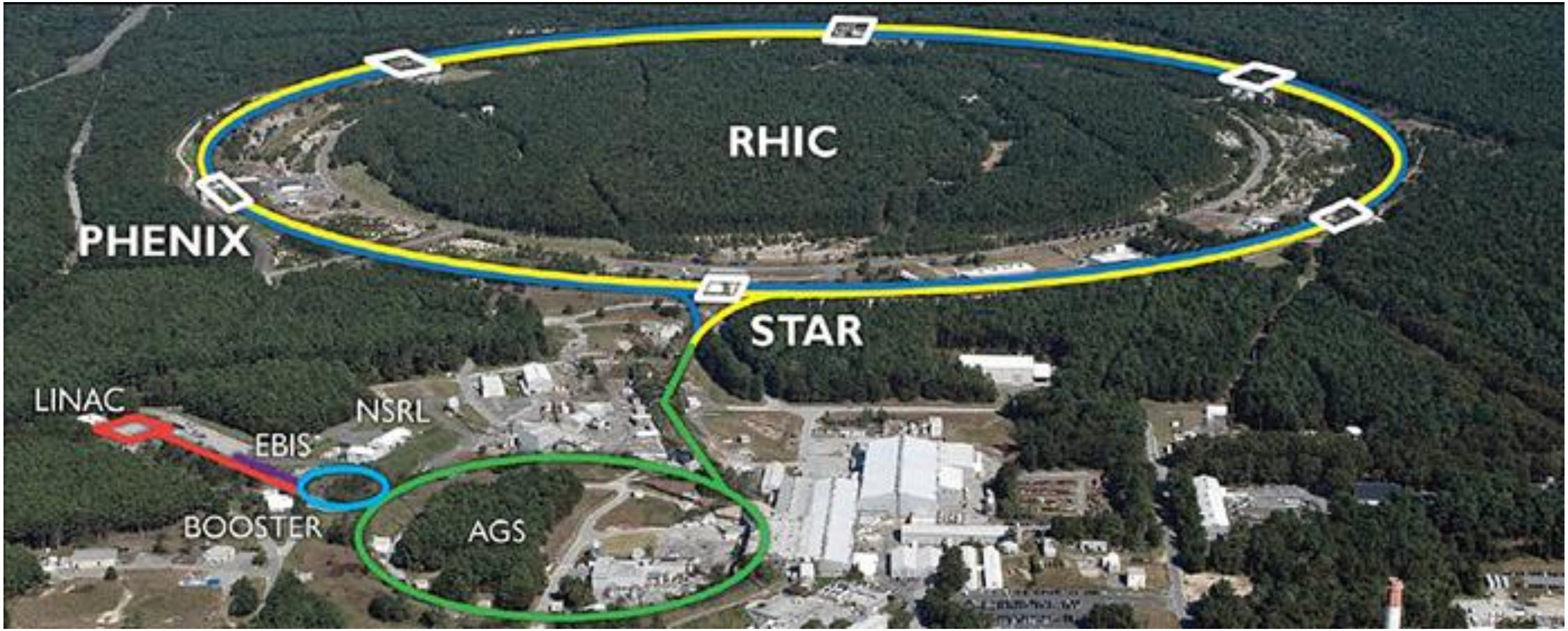
- Klaus Dehmelt

- New Horizons in Time Projection Chambers
- October 09, 2020

Stony Brook University | The State University of New York

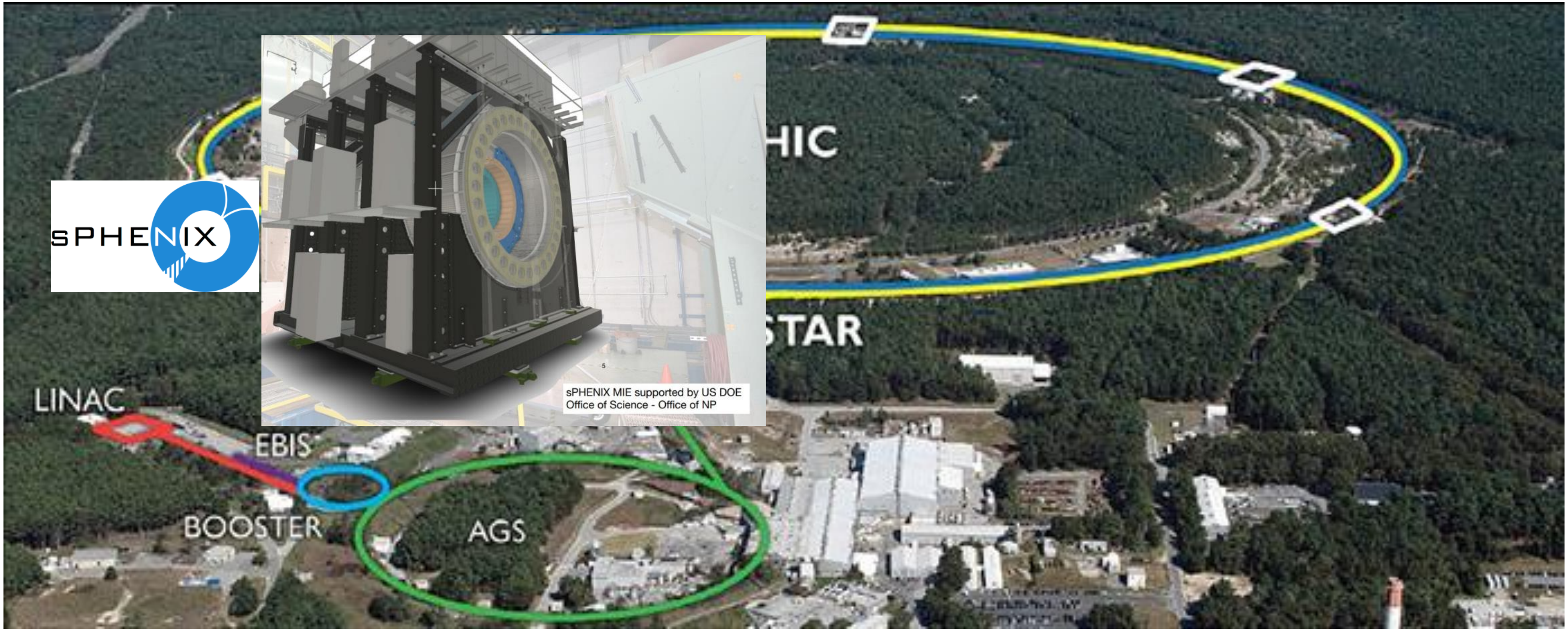
sPHENIX

sPHENIX AND THE TIME PROJECTION CHAMBER



sPHENIX AND THE TIME PROJECTION CHAMBER

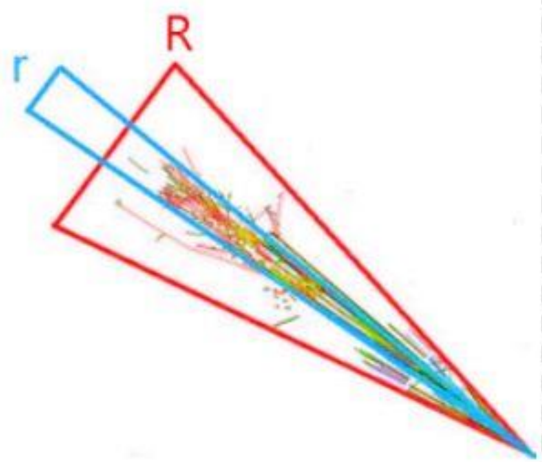
- sPHENIX @ the Relativistic Heavy Ion Collider RHIC in 2023



sPHENIX @ RHIC

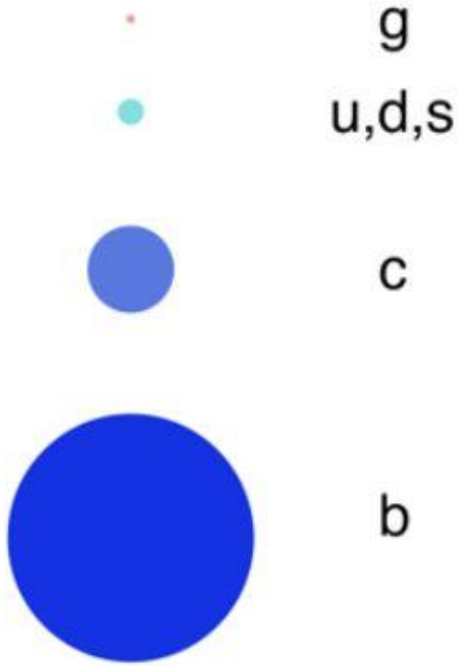
Jet cor. & substructure

Vary momentum/angular size of probe



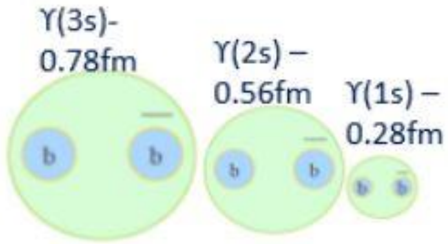
Parton energy loss

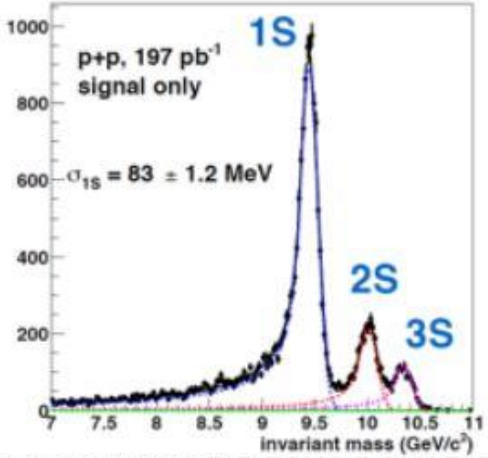
Vary mass/momentum of probe



Upsilon spectroscopy

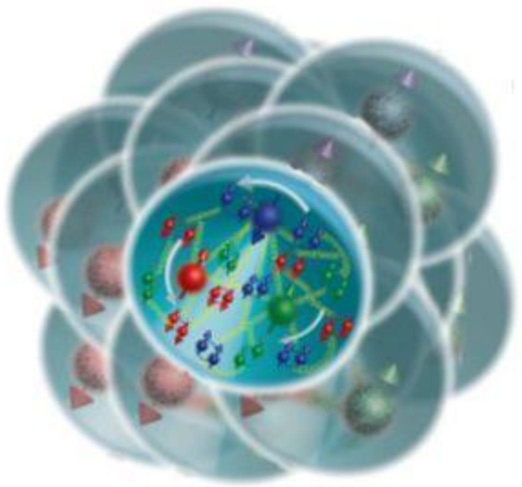
Vary size of the probe





Cold QCD

Vary temperature of QCD matter

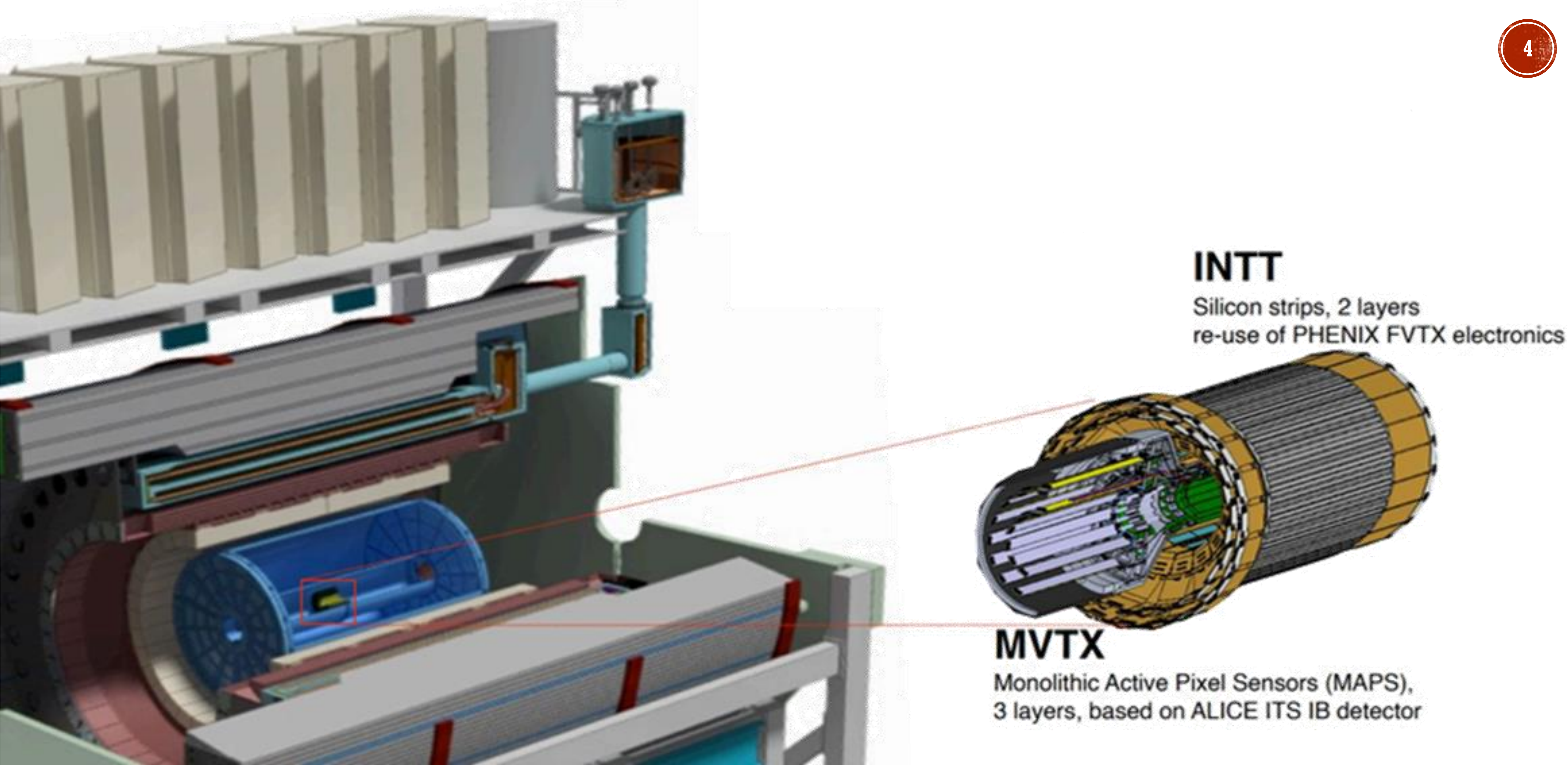


sPHENIX @ RHIC

Physics Goal	Detector Requirement
Fragmentation Functions	Excellent Momentum Resolution: dp/p ~ 0.2% for p to > 40 GeV/c
Jet Substructure	Excellent track pattern recognition
Distinguish Upsilon States	Mass resolution: $\sigma_M < 100$ MeV/c²
Heavy Flavor jet tagging	Precise DCA resolution $\sigma_{DCA} < 100$ µm
High Statistics Au+Au 200 GeV	Handle multiplicity and full RHIC luminosity

- Accomplished by
  - 3-layer Si-pixel detector (MAPS)
  - 4-layer Si-strip detector (Intermediate tracker)
  - Compact Time-Projection Chamber (TPC)
- TPC → continuous readout, small space charge distortion
- Barrel solenoid magnet (Babar) dictates dimension of TPC
  - 20 cm < radius < 78 cm, 2π azimuthal coverage
  - Total length = 211 cm → $|\eta| < 1.1$ polar coverage

sPHENIX AND THE TIME PROJECTION CHAMBER



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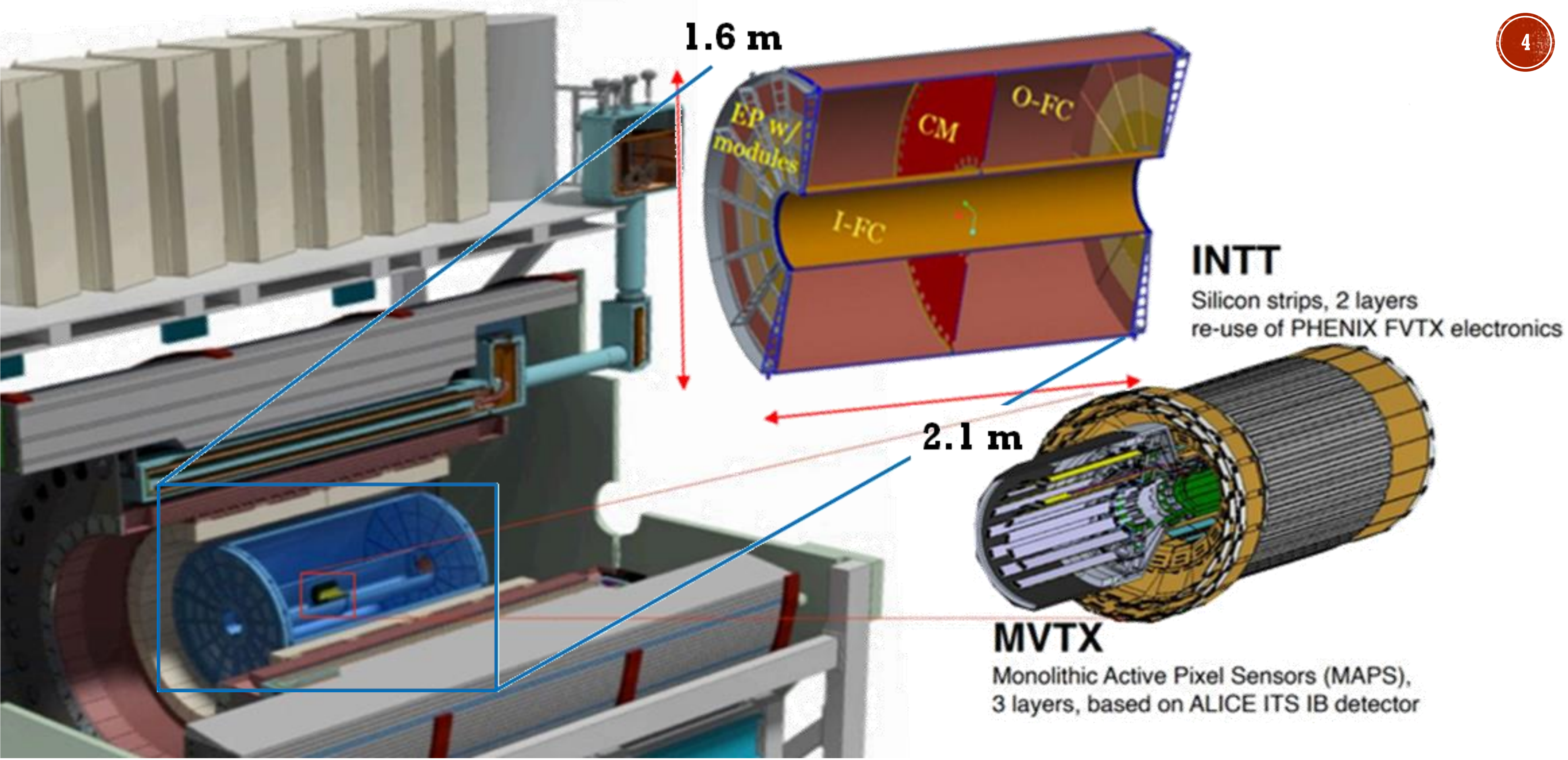
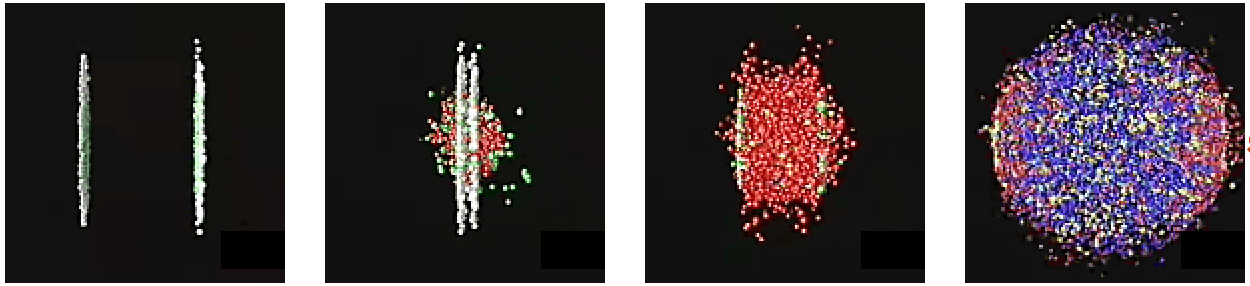
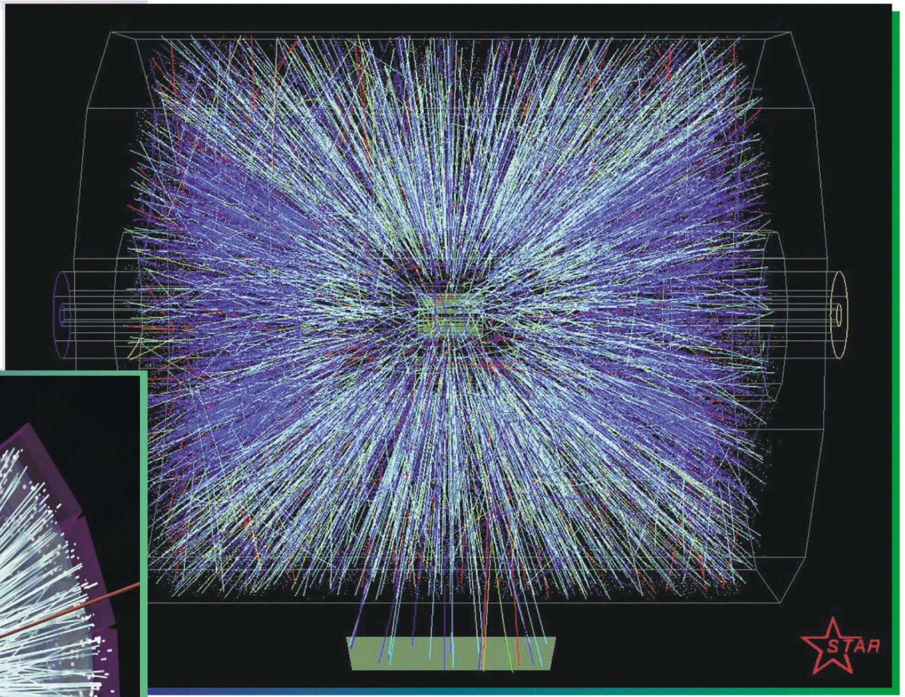
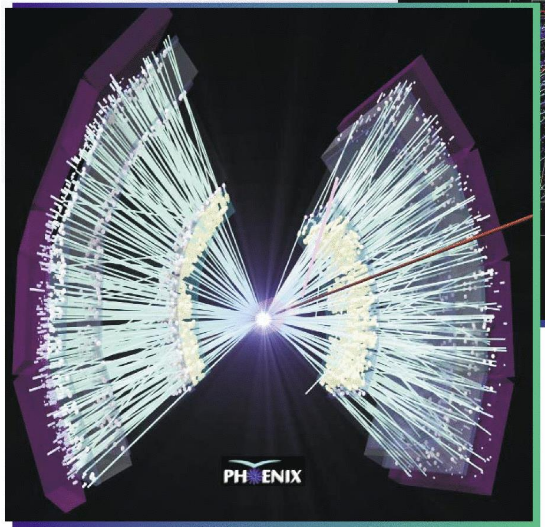


CHALLENGE: SPACE CHARGE IN sPHENIX TPC @ RHIC

- Head-on collisions Au-Au @ 200 GeV/nucleon at RHIC produce thousands of particles







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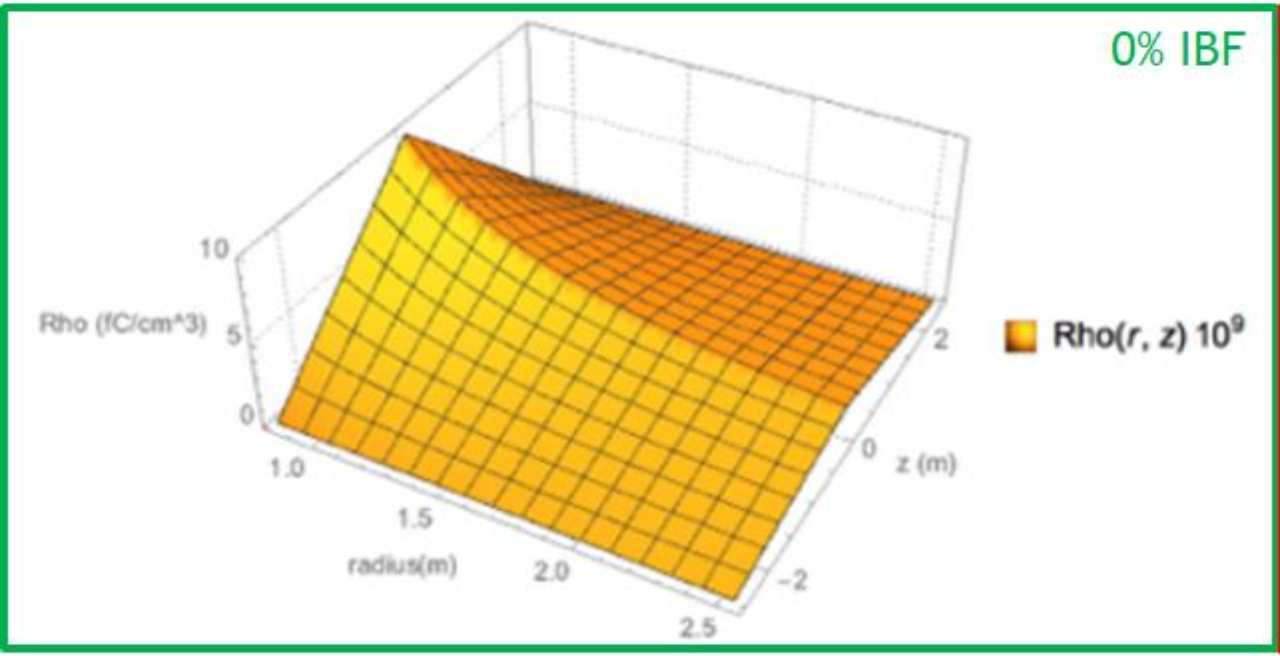
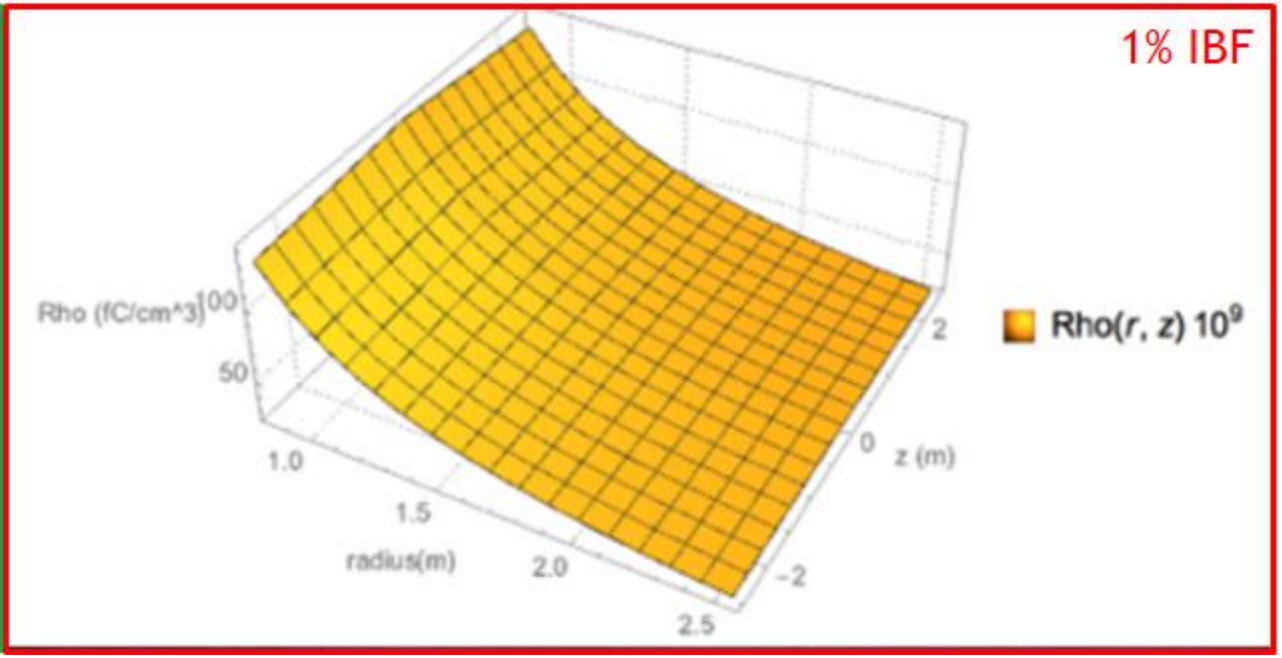




CHALLENGE: SPACE CHARGE IN sPHENIX TPC @ RHIC

- Head-on collisions Au-Au @ 200 GeV/nucleon at RHIC produce thousands of particles
- Focus on combatting Ion Back Flow IBF

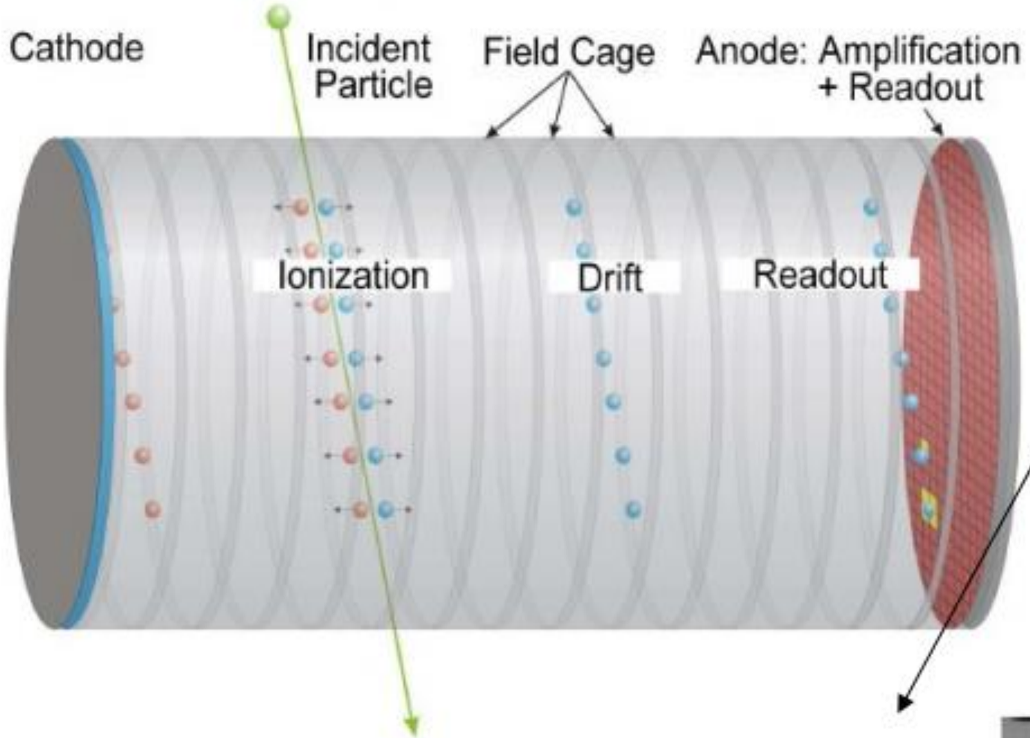
TIME PROJECTION CHAMBERS IN COLLIDER ENVIRONMENT SO FAR

- PEP4 @ SLAC
- ALEPH/DELPHI @ LEP
- STAR @ RHIC
- ALICE @ LHC
  - All had in common: MWPC amplification readout
  - Today's drawback
    - Spatial arrangement of wires -> spatial resolution
    - Slow ion signal
    - Ion backflow reduction only possible with active gating
  - Spatial resolution: **E x B** effect
  - Gate option limits high rate readout
- Solution: MPGD readout → overcome E x B, fast e^- signal, **combat Ion Back Flow w/o gating**, ALICE TPC already upgraded!

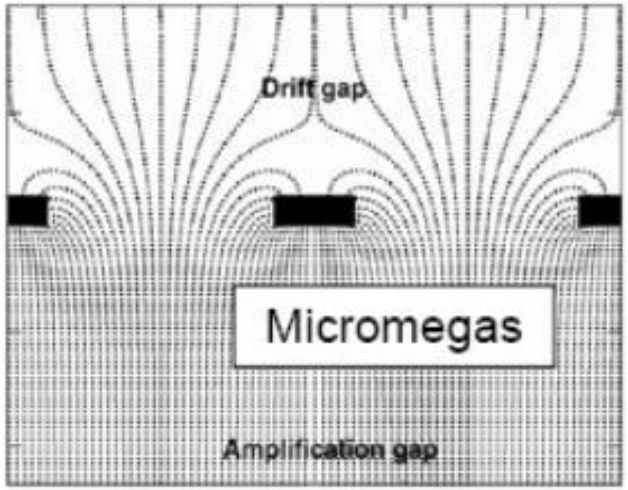
MPGD BASED TIME PROJECTION CHAMBER

- Time Projection Chamber (TPC) for
  - Momentum measurement
  - Tracking
  - Probably particle identification (PID), e.g., dE/dx

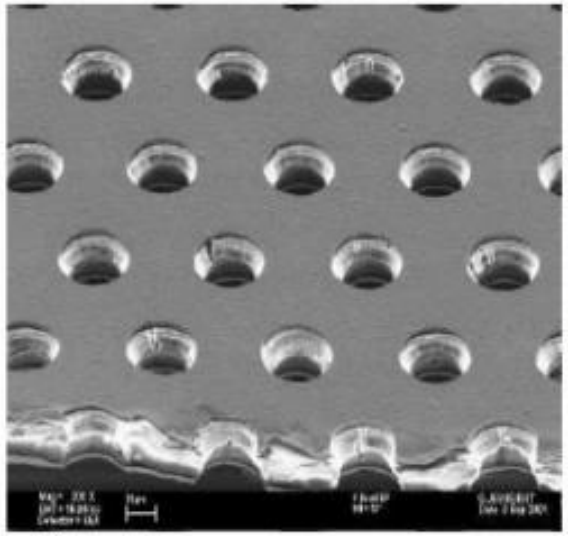
MPGD BASED TIME PROJECTION CHAMBER

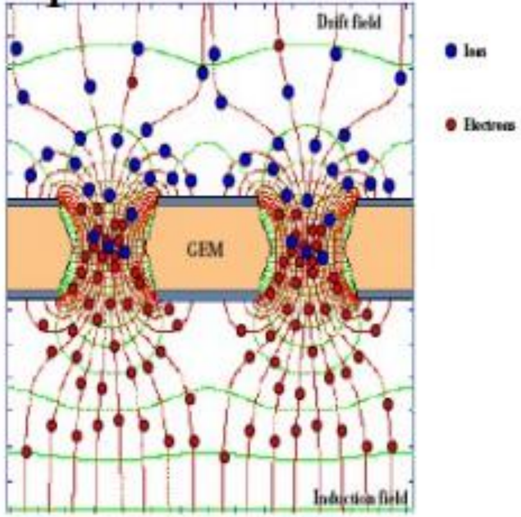


MicroPatternGasDetector
MPGD
not limited by **E** x **B** effects



Gas Electron Multiplier GEM





sPHENIX and IBF

- Several ways to combat Space Charge
  1. Make the ions fast through mass
  2. Choose the largest drift field possible
  3. Optimize amplification device's operating point
  4. Update design of field cage informed by current experience
  5. Improve amplification device
     i. Remove "gain fluctuation" before amplification
     ii. Increase number of amplification stages
  6. Multi-layer gating grid
  7. Accelerator parameters
  8. Don't let ions be created

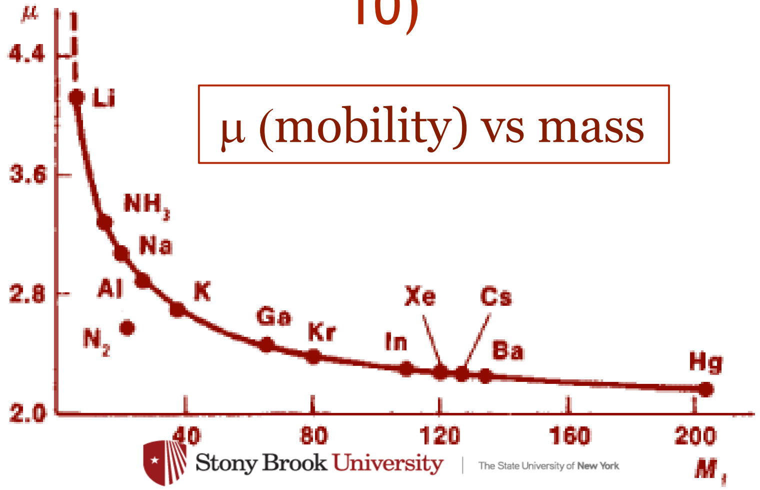
- Several ways to combat Space Charge
  1. Make the ions fast through mass

$$v_{ion} = K \cdot E$$

with K: ion mobility
E: Electric field

$$\frac{1}{K_{tot}} = \frac{f_1}{K_1} + \frac{f_2}{K_2} + \frac{f_3}{K_3} + \cdots$$

→ Choose primary gas component with low mass: Ne-based (e.g., Ne-CF_4 90-10)



sPHENIX AND IBF

- Several ways to combat Space Charge
  2. Choose the largest drift field possible

Gas	K ($\frac{cm^2}{Volt \cdot sec}$)	v_D ($E = 130\frac{V}{cm}$)	v_D ($E = 400\frac{V}{cm}$)
Ar	1.51	196	604
Ar-CH_4 90:10	1.56	203(STAR)	624
Ar-CO_2 90:10	1.45	189	582
Ne	4.2	546	1680
Ne-CH_4 90:10	3.87	503	1547
Ne-CO_2 90:10	3.27	425	1307(ALICE)
He	10.2	1326	4080
He-CH_4 90:10	7.55	981	3019
He-CO_2 90:10	5.56	722	2222
T2K	1.46	190(ILC)	584

sPHENIX AND IBF

- Several ways to combat Space Charge
  3. Optimize amplification device's operating point

  Gain on first GEM determines desired properties → compromise between energy resolution and IBF

Quad-GEM Solution for ALICE

R. Majka

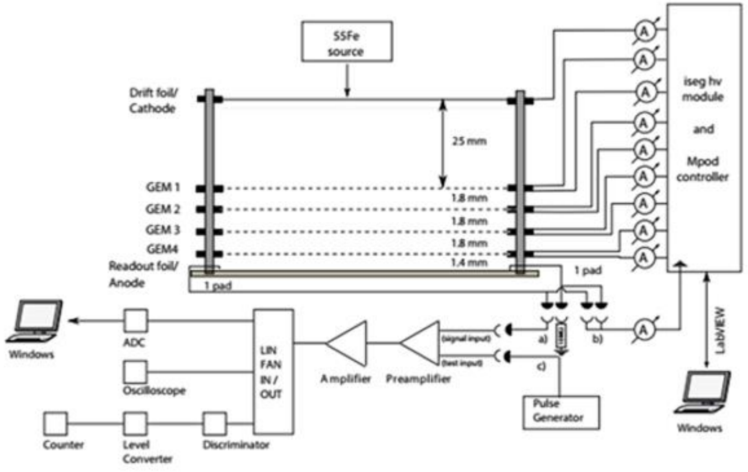
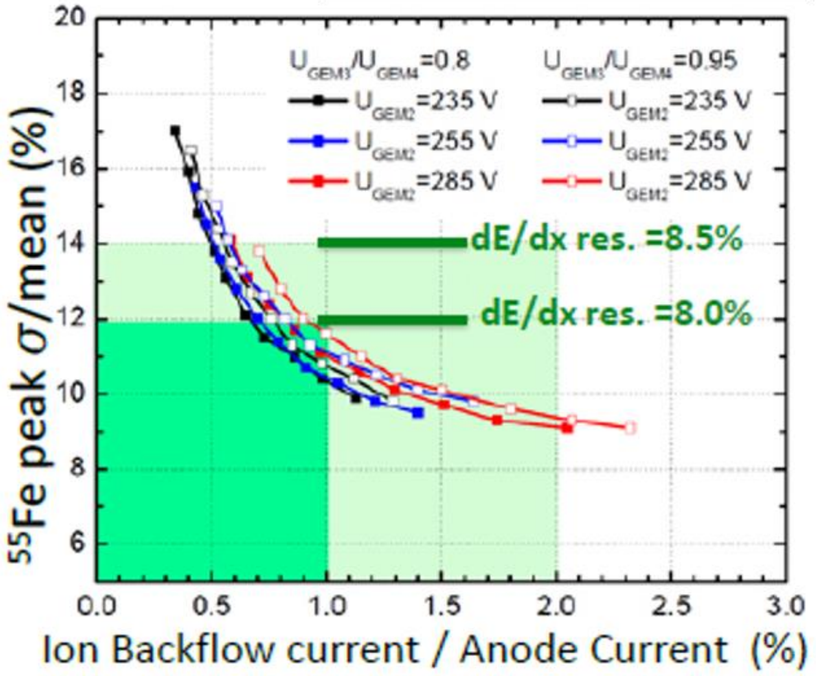


Figure 5.1: Sketch of the Munich quadruple GEM setup.



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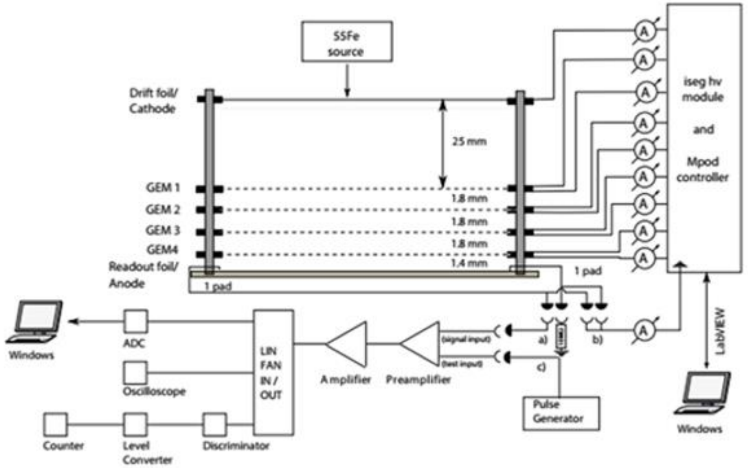

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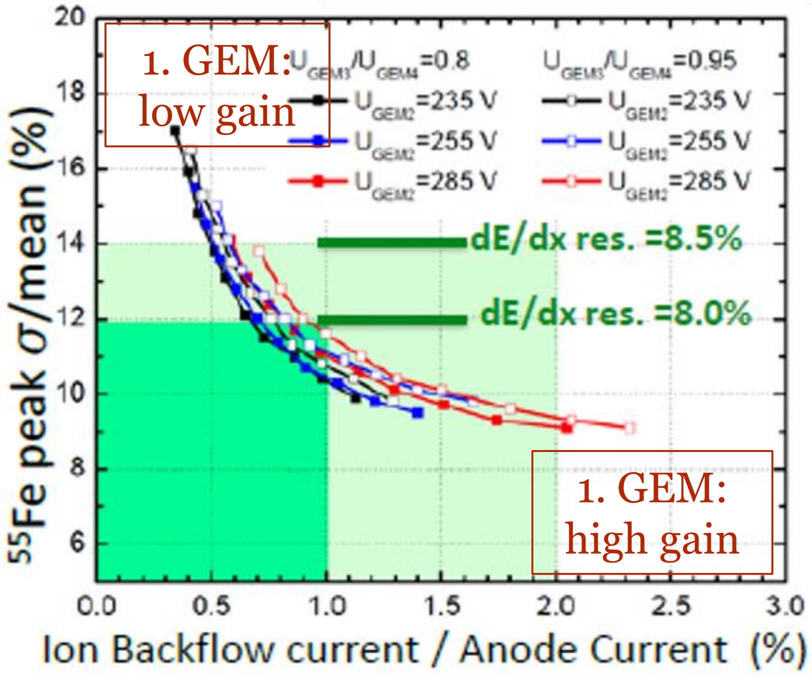

sPHENIX and IBF

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Quad-GEM Solution for sPHENIX

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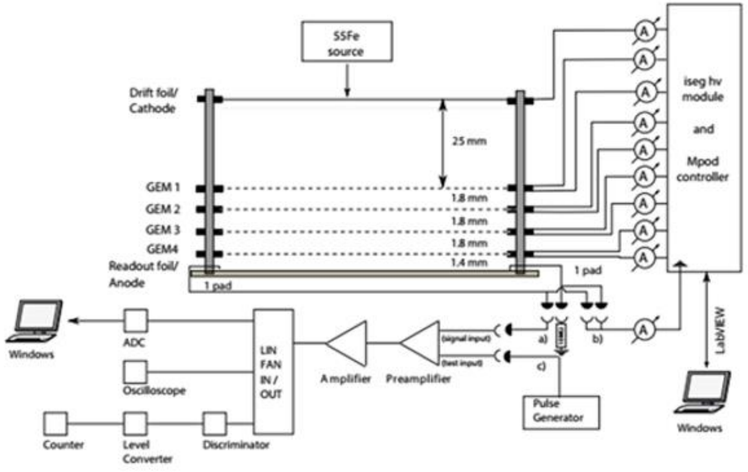

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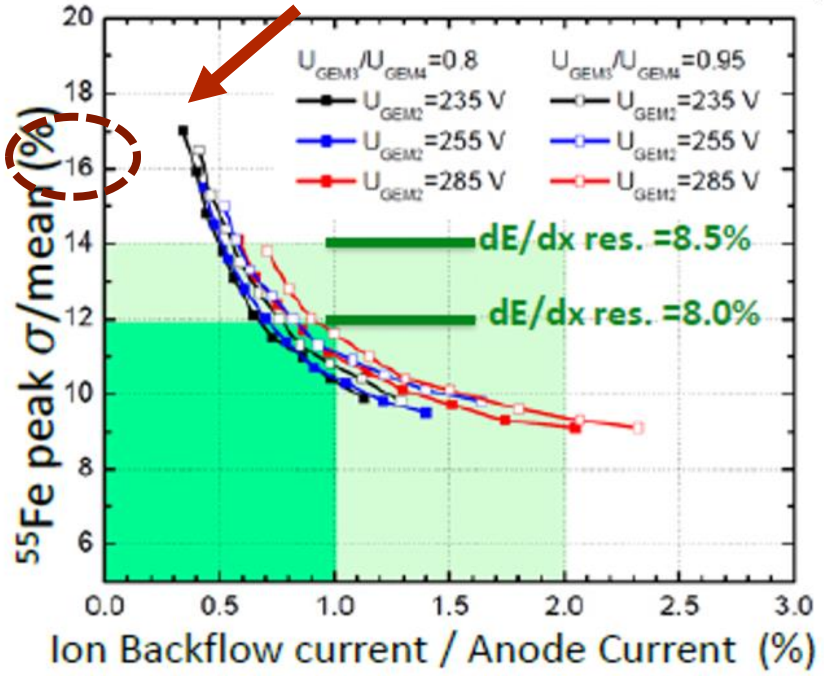

sPHENIX AND IBF

- Several ways to combat Space Charge
  3. Optimize amplification device's operating point

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Quad-GEM Solution for ePHENIX

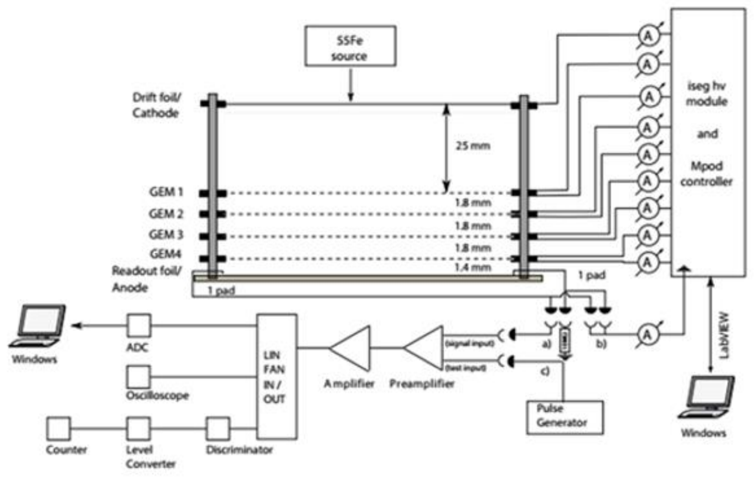


Figure 5.1: Sketch of the Munich quadruple GEM setup.

Recover dE/dx when environment allows

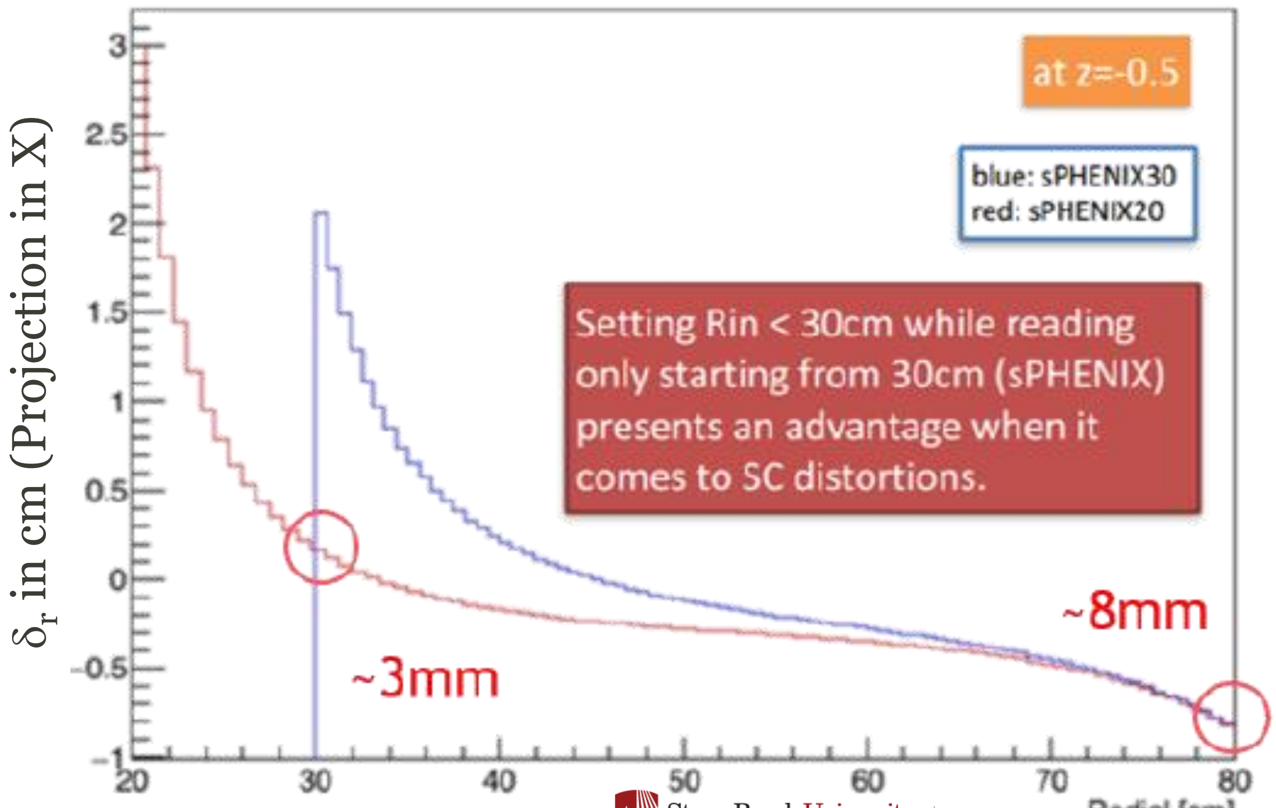
sPHENIX AND IBF

- Several ways to combat Space Charge

4. Update design of field cage informed by current experience

Space charge distortions at maximum where space charge density has discontinuity → FC entrance windows

Analytical 3-D model based on work for ALICE TPC revealed large distortions close to inner FC



Set r = 20 cm
but make volume at
r> 30 cm active

sPHENIX and IBF

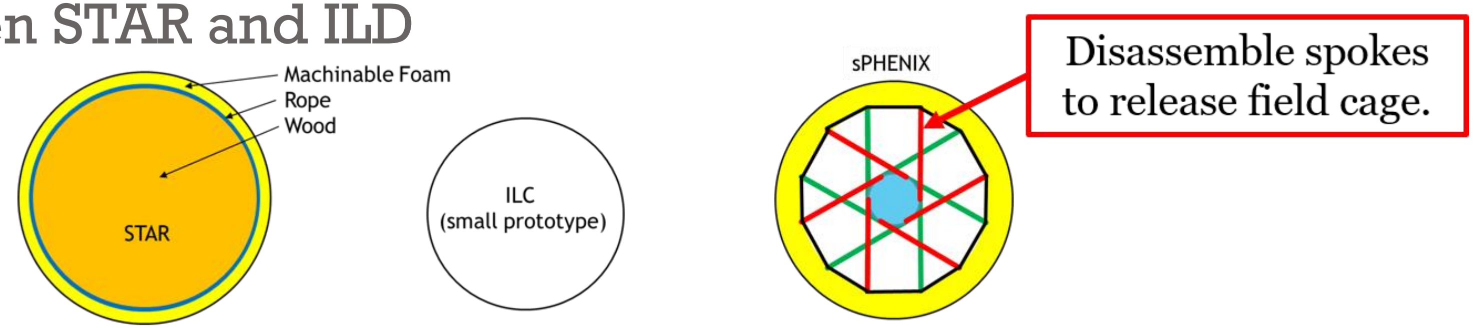
- Several ways to combat Space Charge

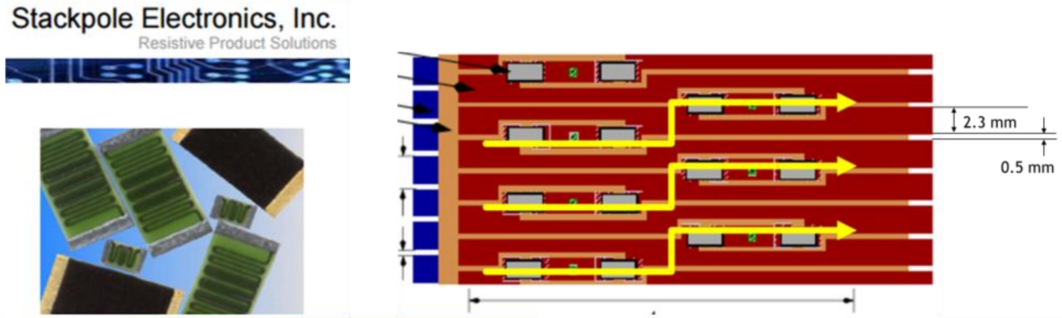
5. Improve amplification device
   i. Remove "gain fluctuation" before amplification
   ii. Increase number of amplification stages → Quintuple GEM?
6. Multi-layer gating grid
7. Accelerator parameters → Crossing angle?
8. Don't let ions be created → Electroluminescence

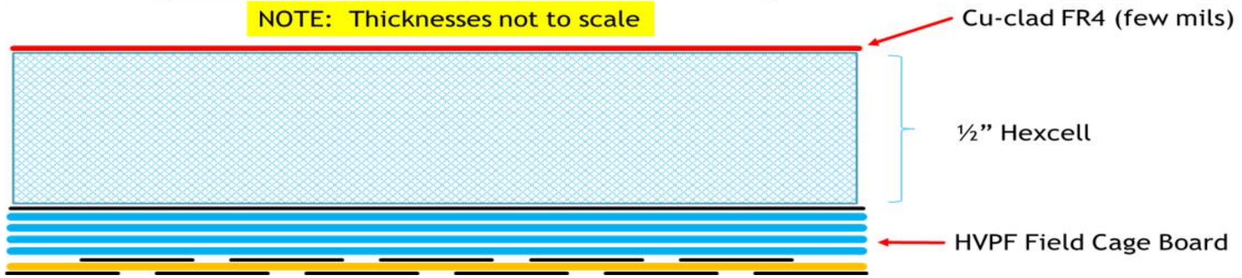
5. – 8. require (significant) R&D

sPHENIX TIME PROJECTION CHAMBER

- Field Cage → Inner/Outer for sPHENIX
  - Hybrid between STAR and ILD







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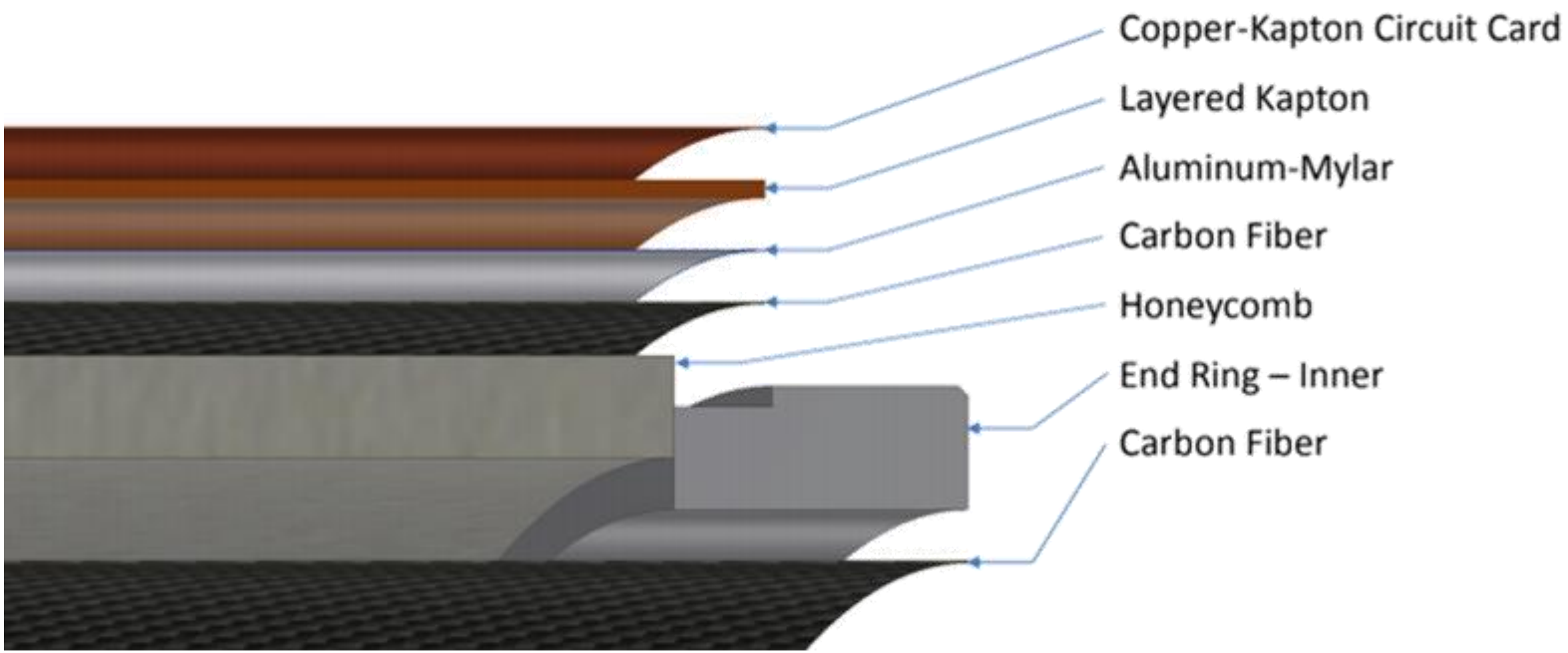

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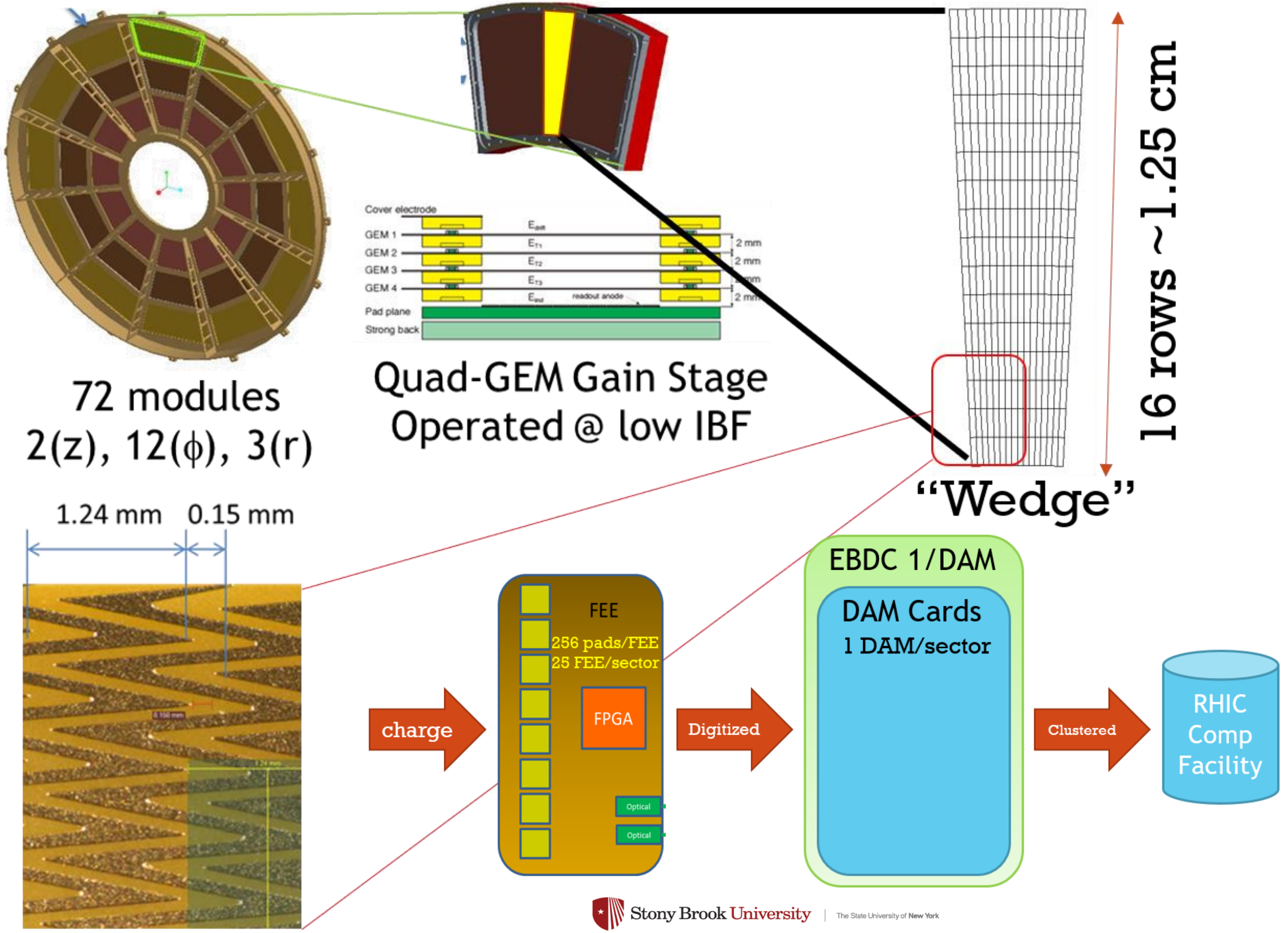
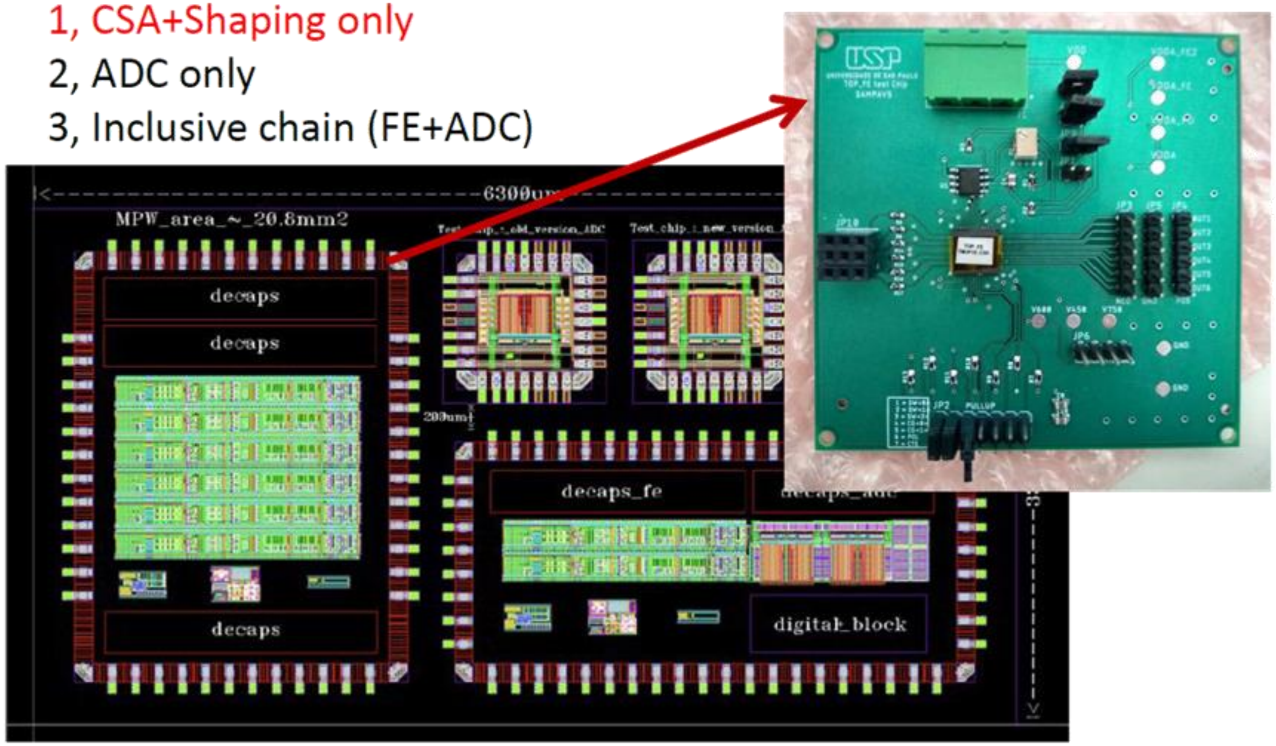


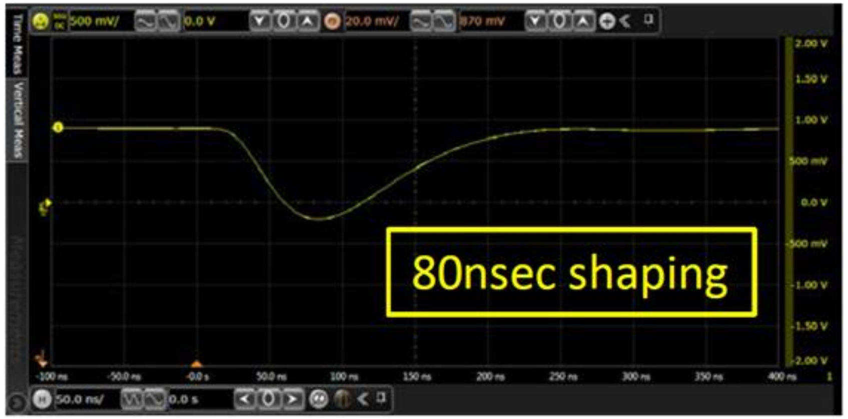
Item	Count
Field Cage	1
Modules	72+extra
FEE	624+extra
DAM	24+extra
EDBC	24+extra

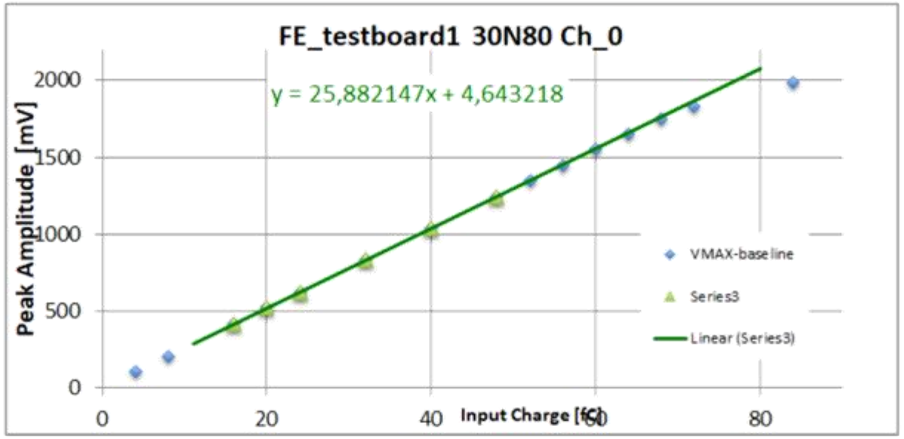
SAMPA progress (FE)

- SAMPA v5 components were produced in a multi-project wafer (MPW) run
- Initial test shows a good linearity for 80nsec shaping and 30mV/fC gain.
  - **Power consumption: 6mW/ch**
  - **Noise: ~500e @ C_{in}=0, ~600e @ C_{in}=20pF**

1, CSA+Shaping only
2, ADC only
3, Inclusive chain (FE+ADC)







sPHENIX TIME PROJECTION CHAMBER

ALICE Quadruple GEM schematics
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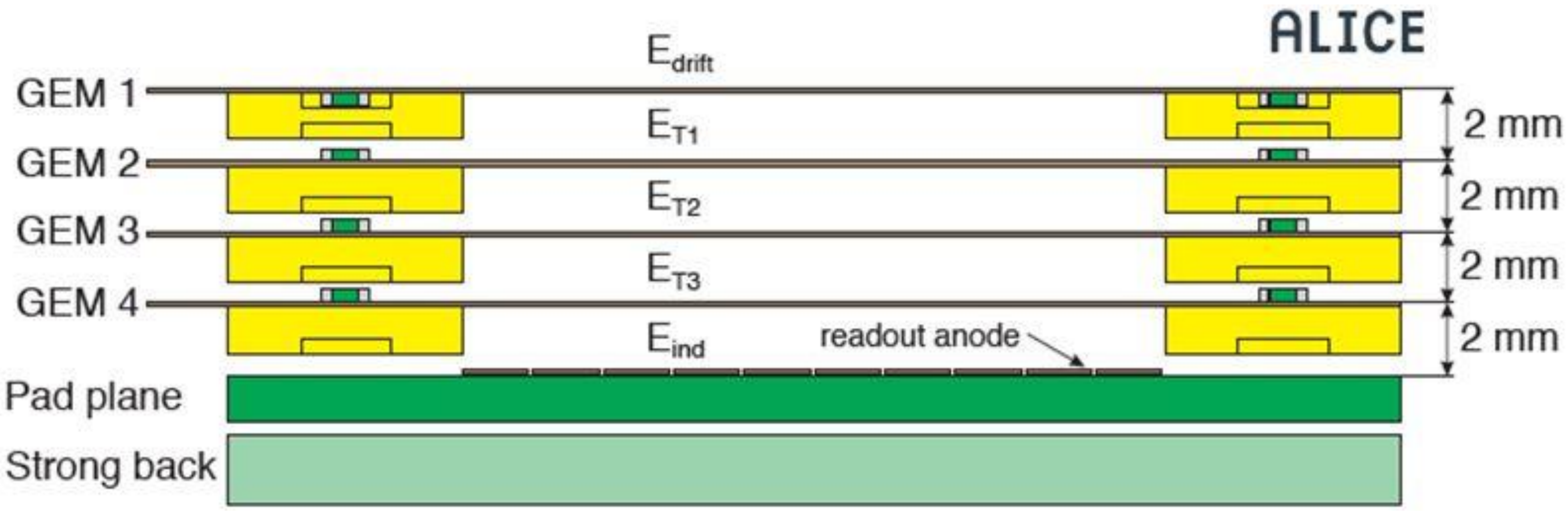

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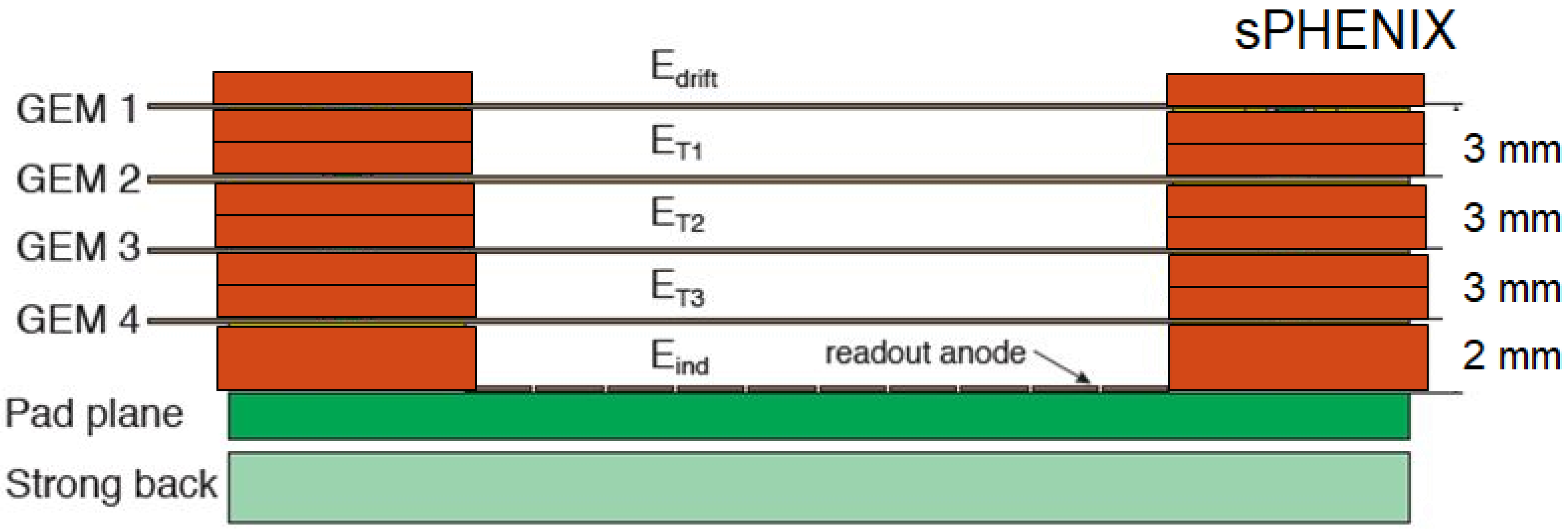
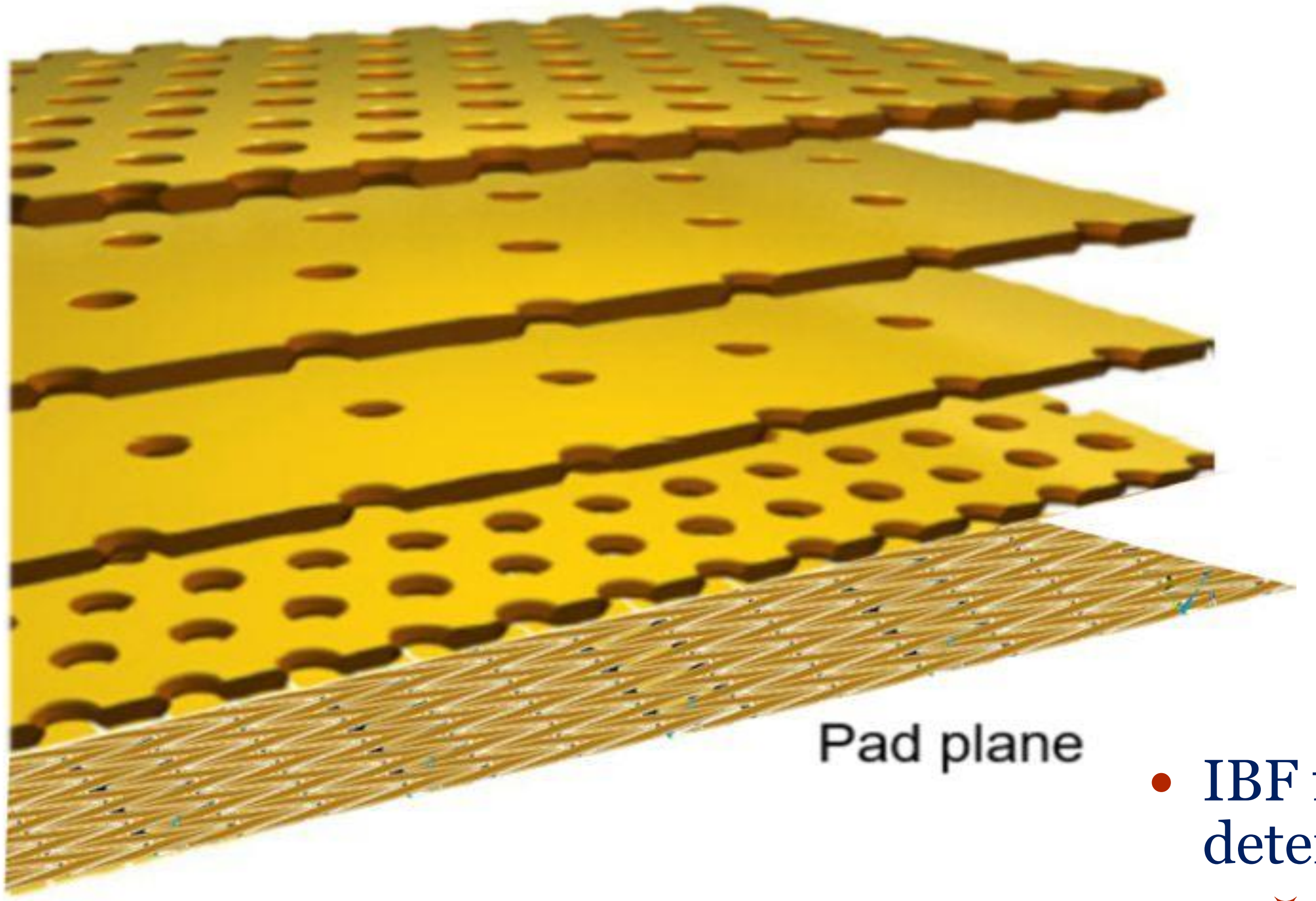


sPHENIX Time Projection Chamber

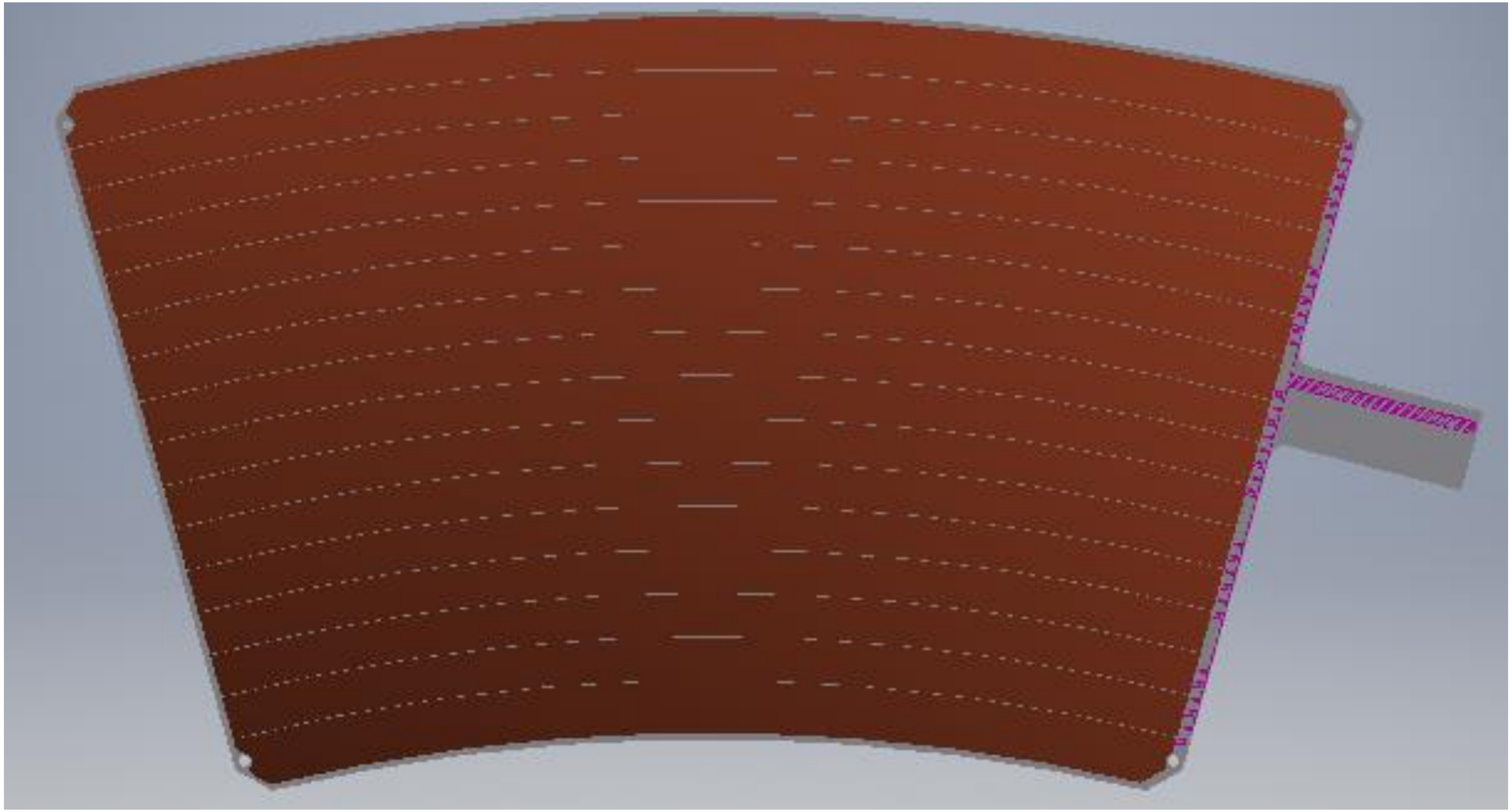


V	sPHENIX			
Setting	1	2	3	4
G1 Top	4208	4658	5124	5118
G1 Bot	3951	4401	4851	4861
G2 Top	3051	3351	3651	3661
G2 Bot	2721	3021	3321	3342
G3 Top	1821	1971	2121	2142
G3 Bot	1409	1559	1709	1709
G4 Top	1379	1529	1679	1679
G4 Bot	900	1050	1200	1200

- IBF for these configurations determined with X-ray
  - **0.44%, 0.39%, 0.33%, 0.31%**
- All configurations tested in test-beam

sPHENIX TPC: READOUT MODULES

- R2 GEM structure



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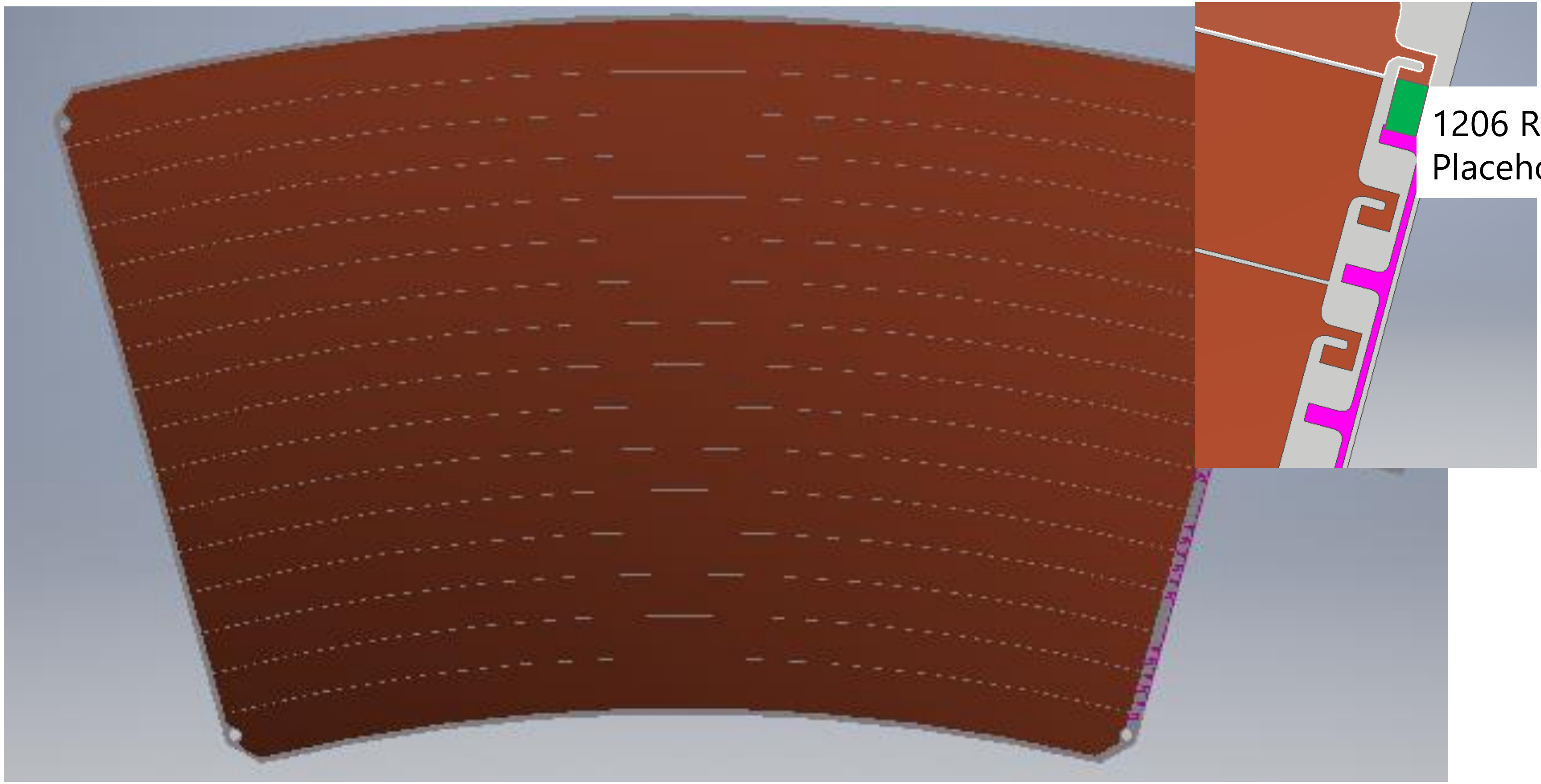

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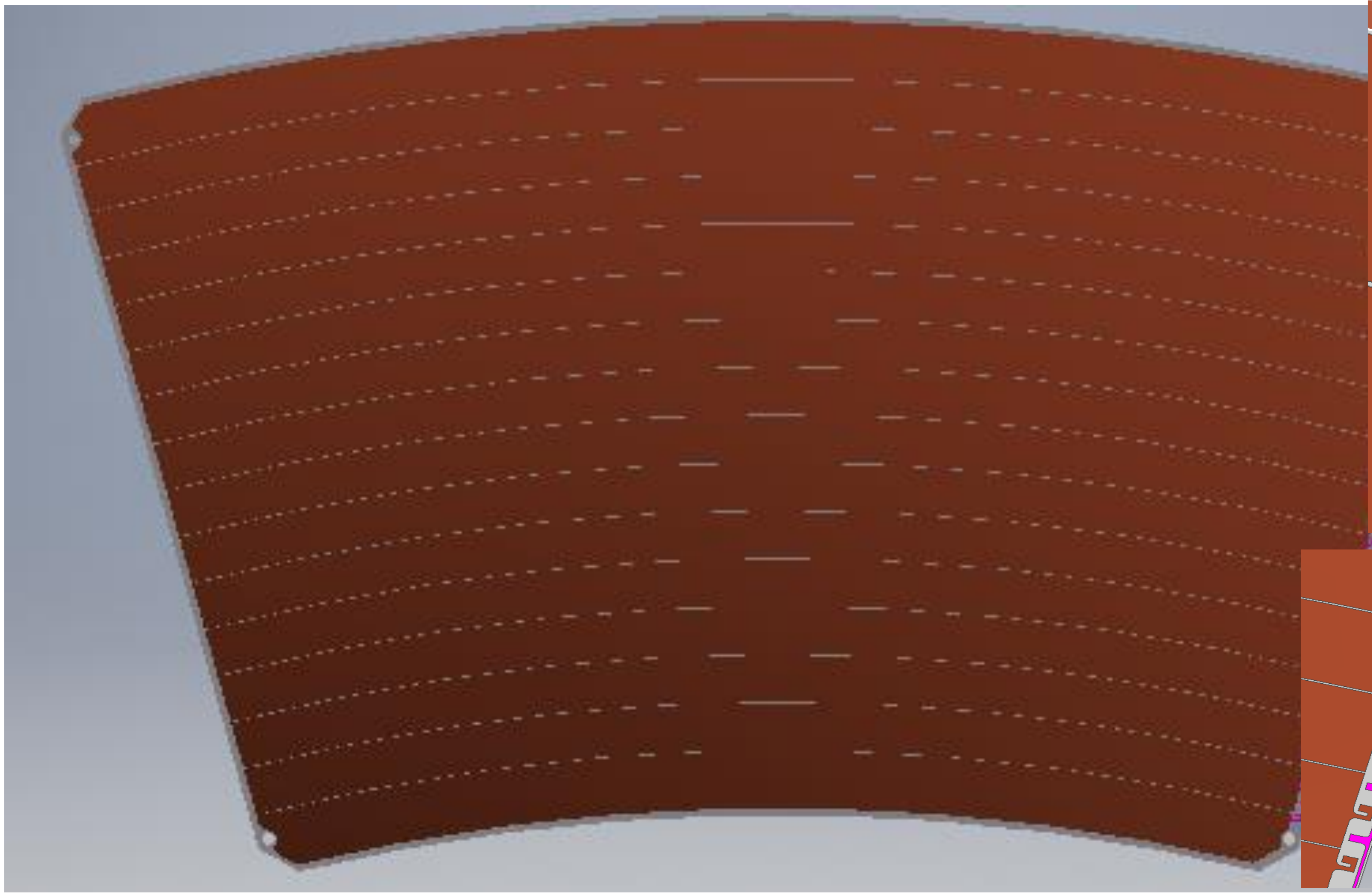

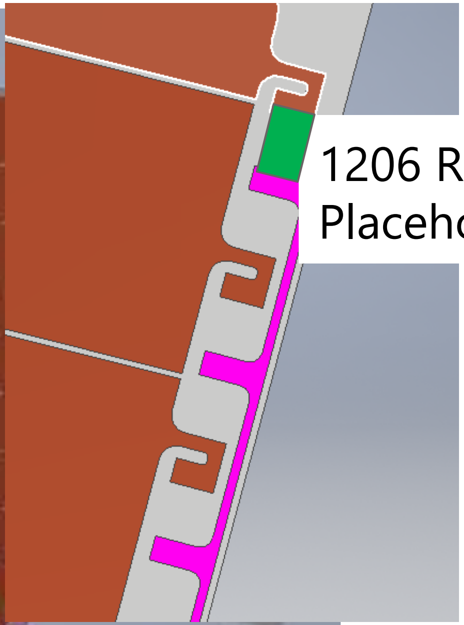

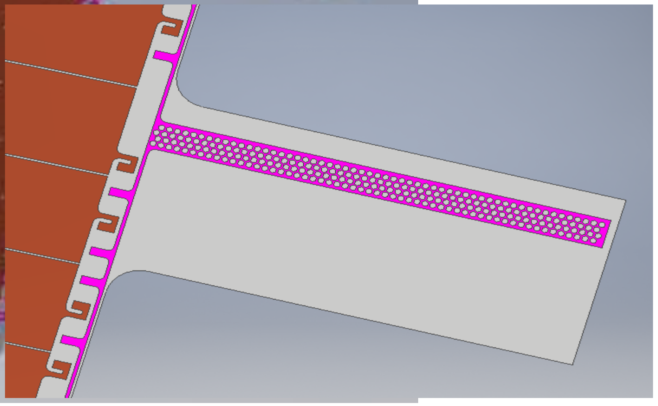

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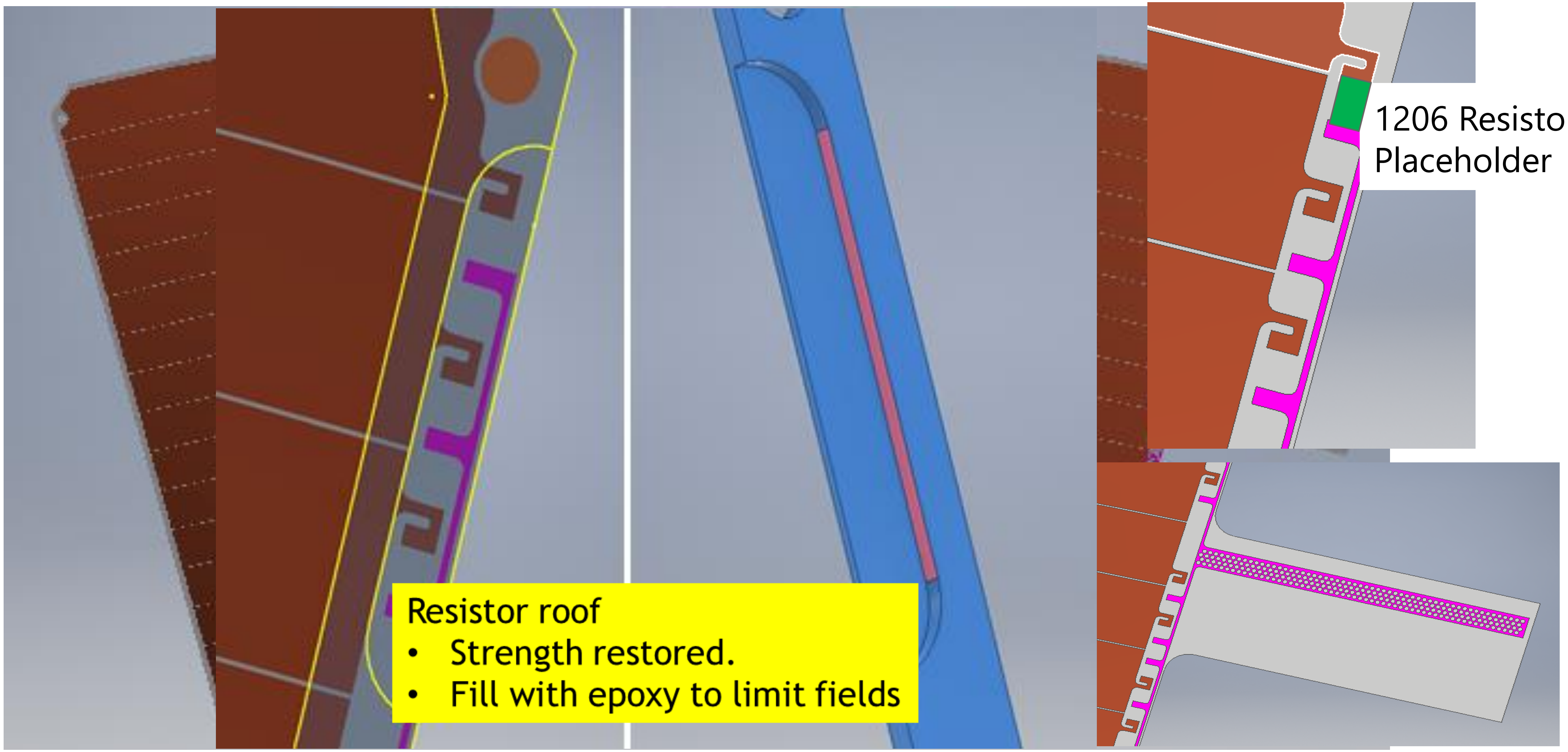

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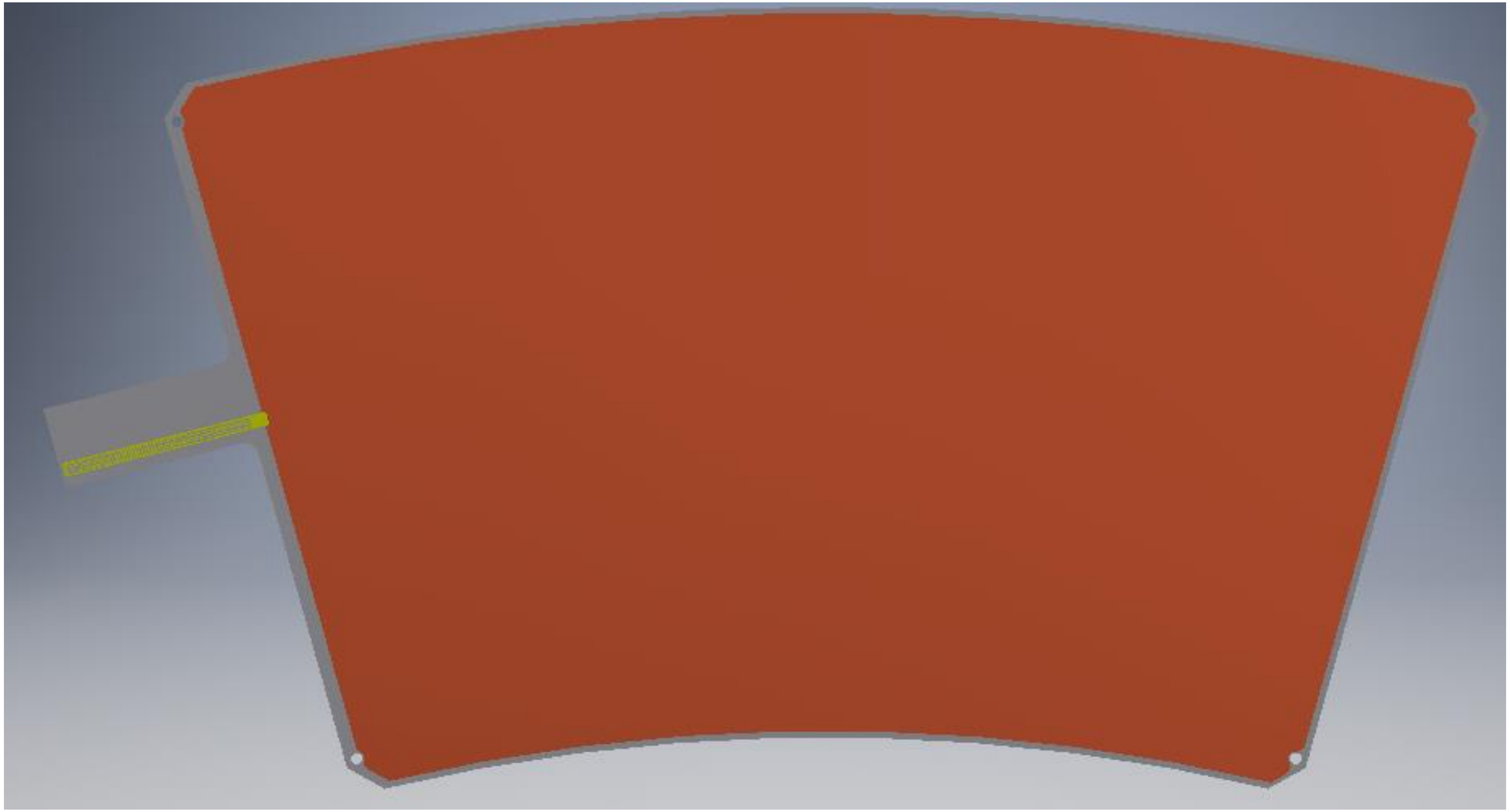

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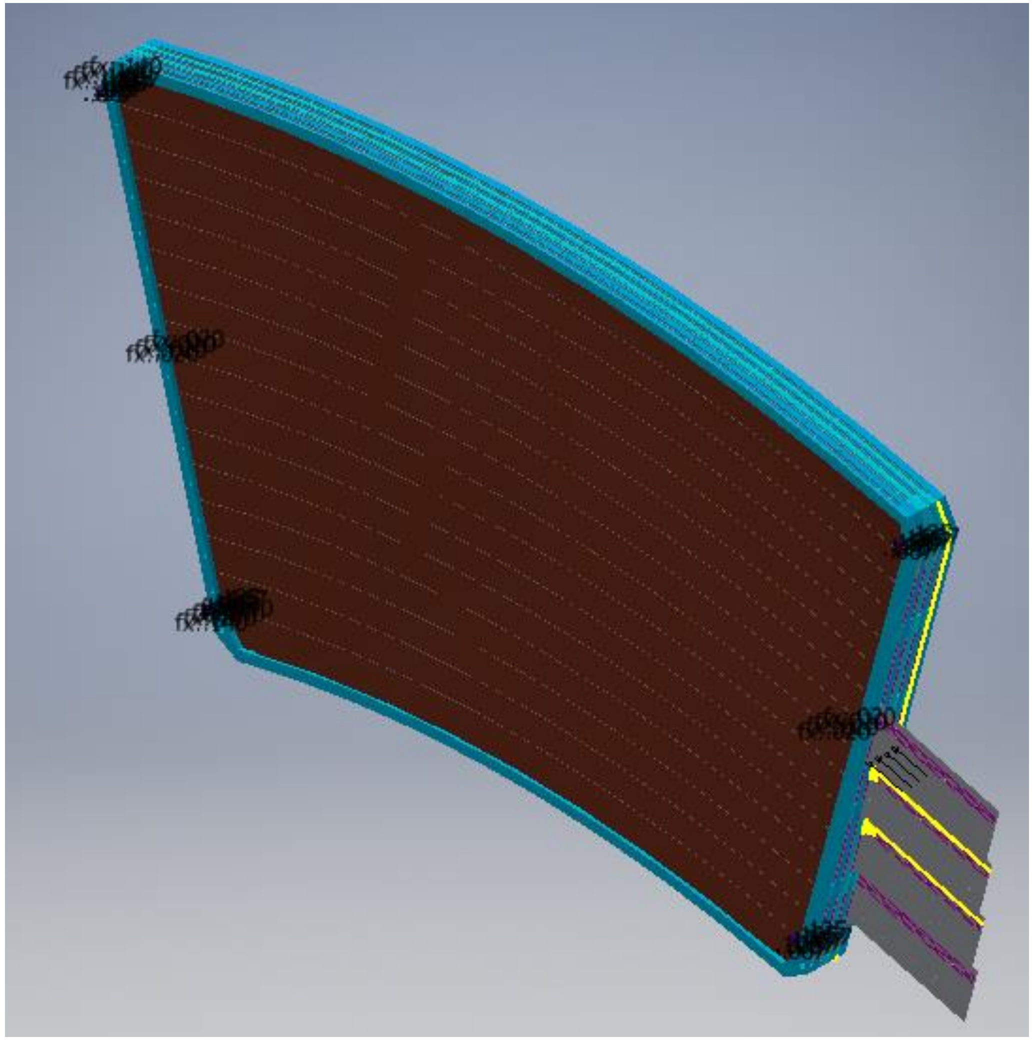

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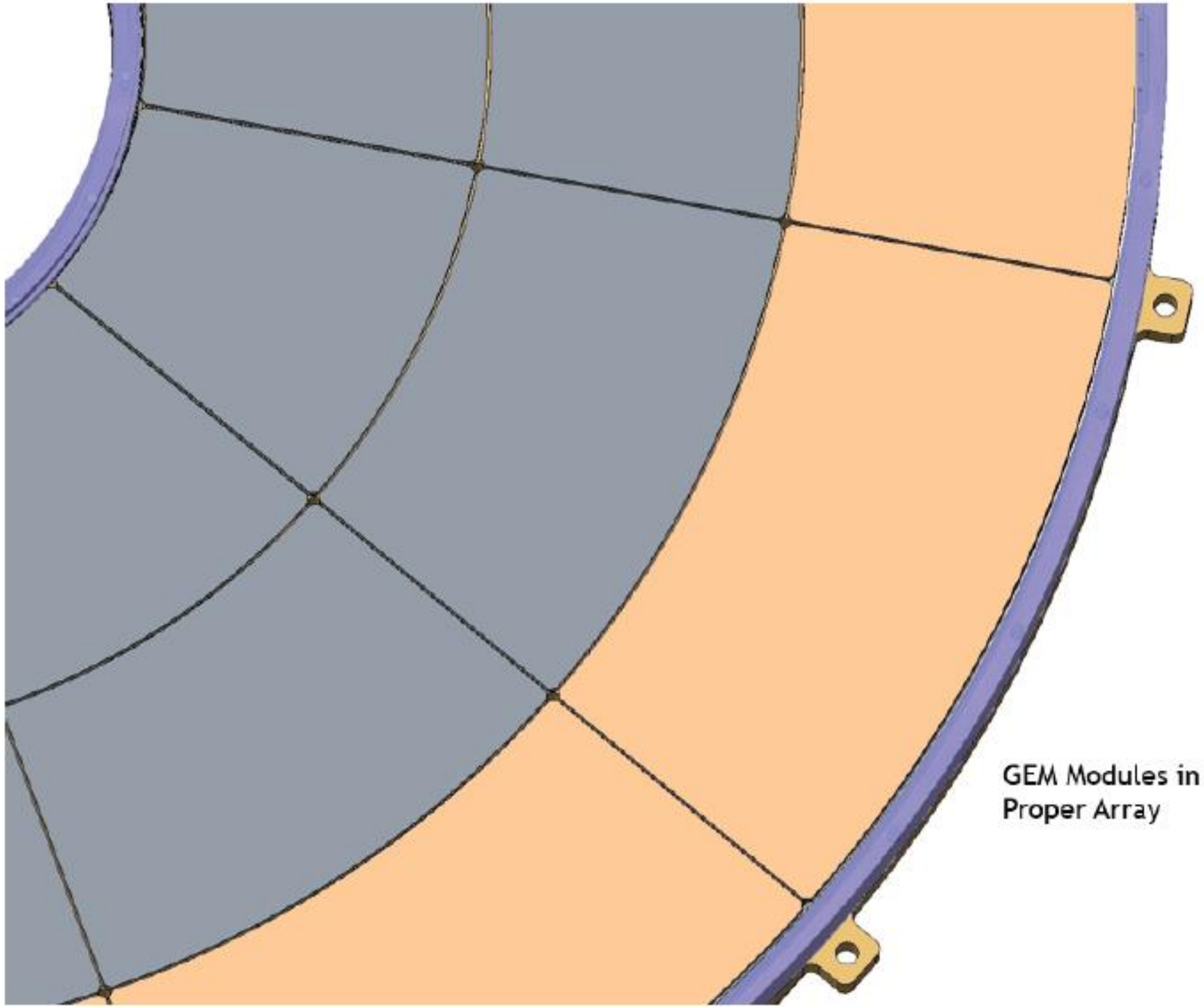

GEM Modules in their
Proper Array

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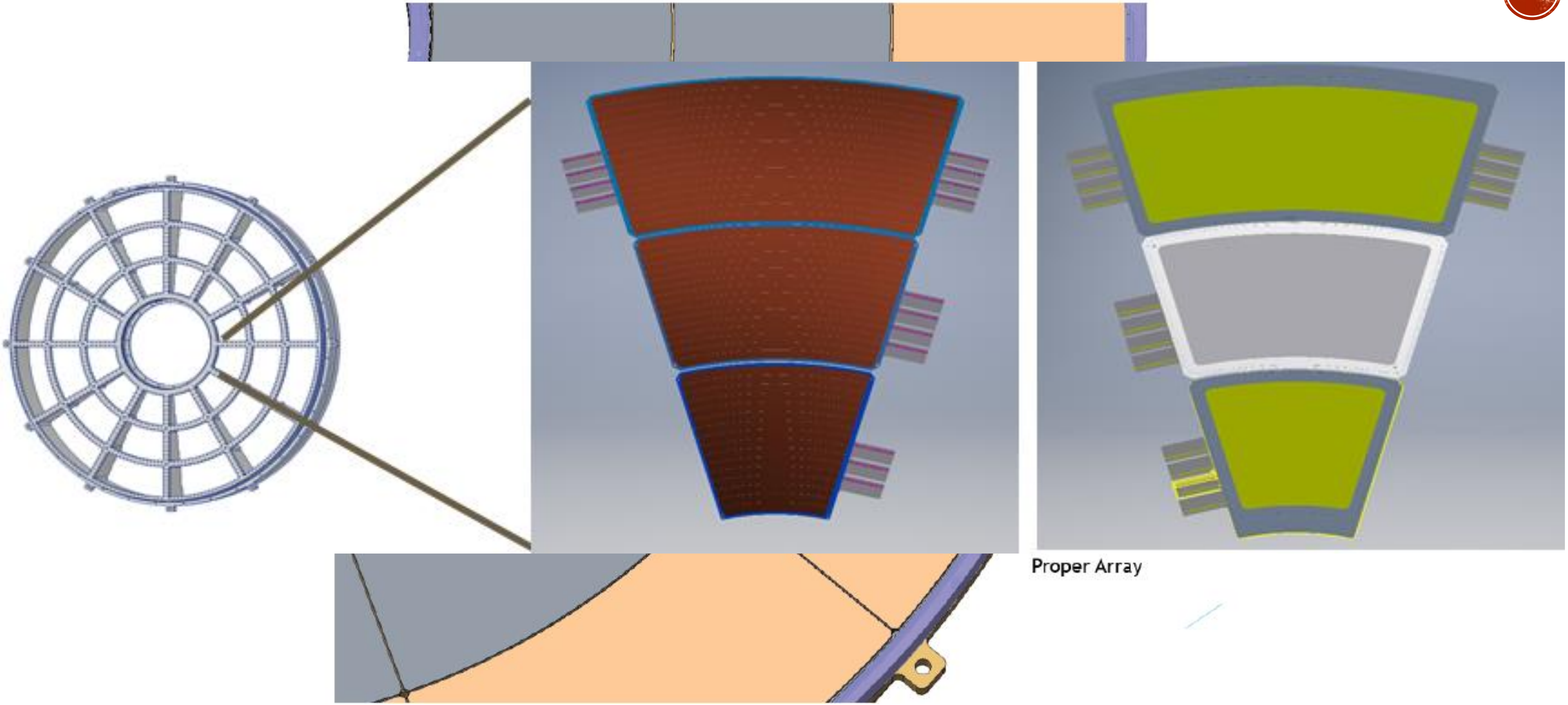

Proper Array

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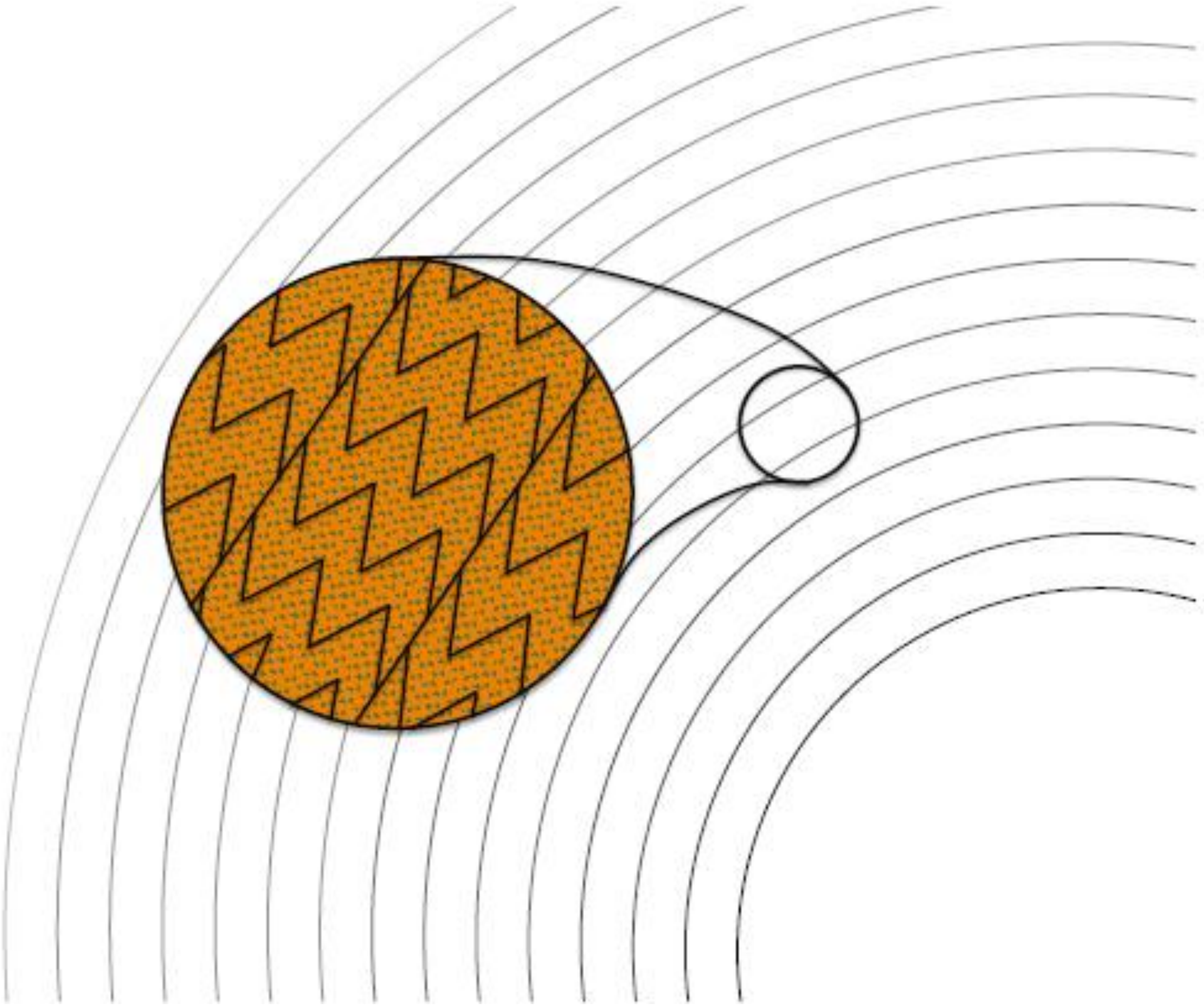

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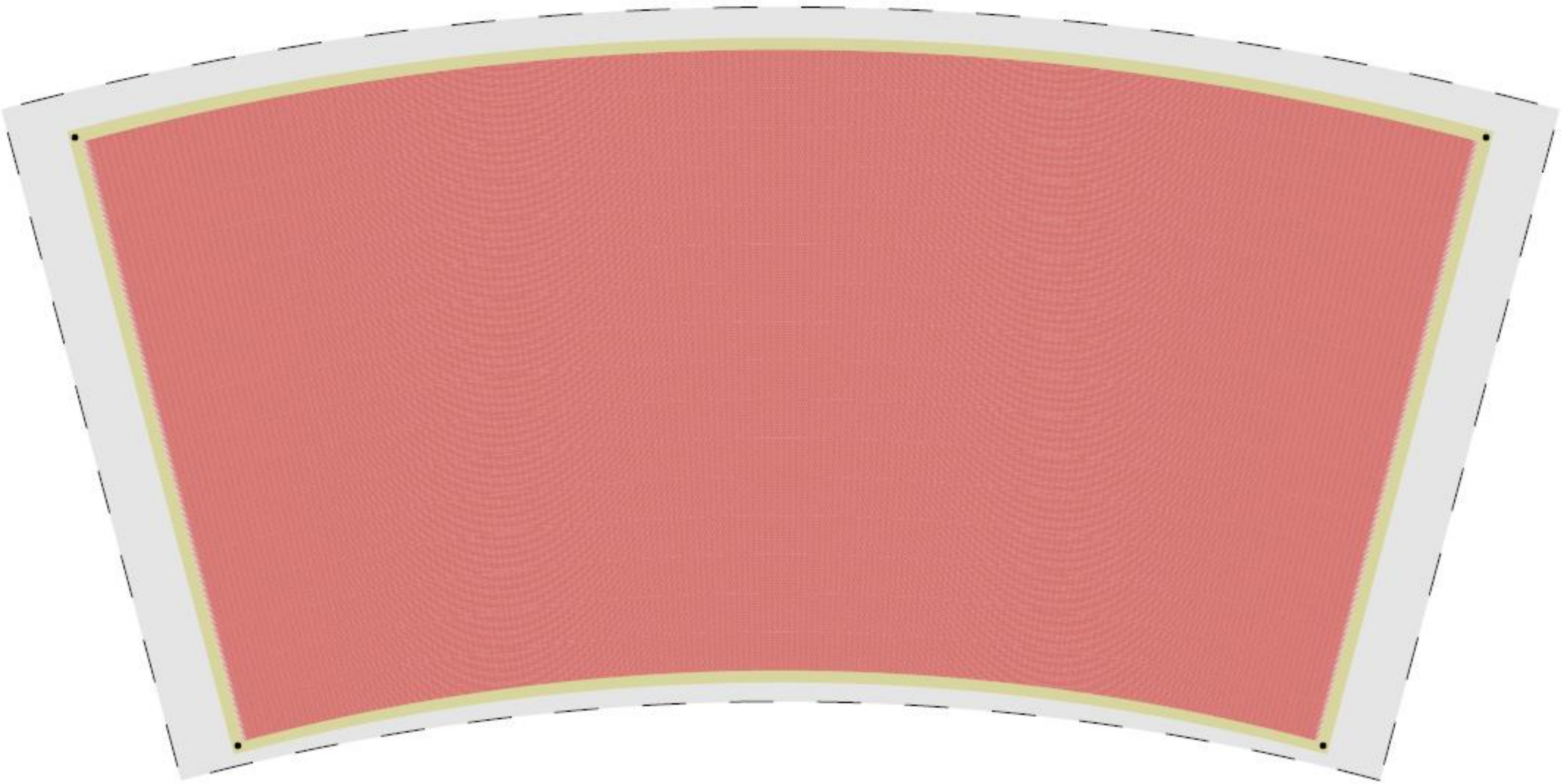

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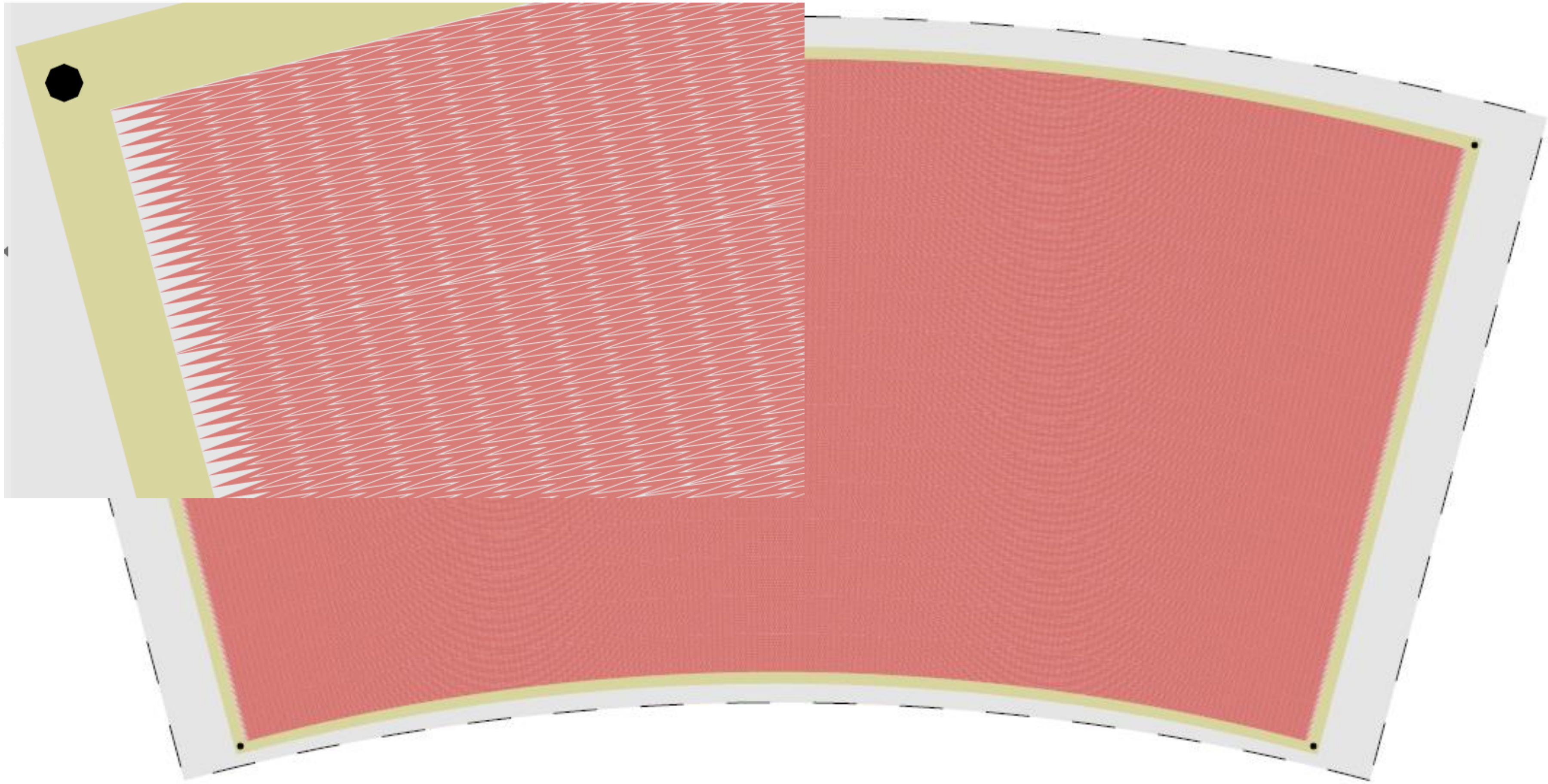


sPHENIX TPC: READOUT MODULES

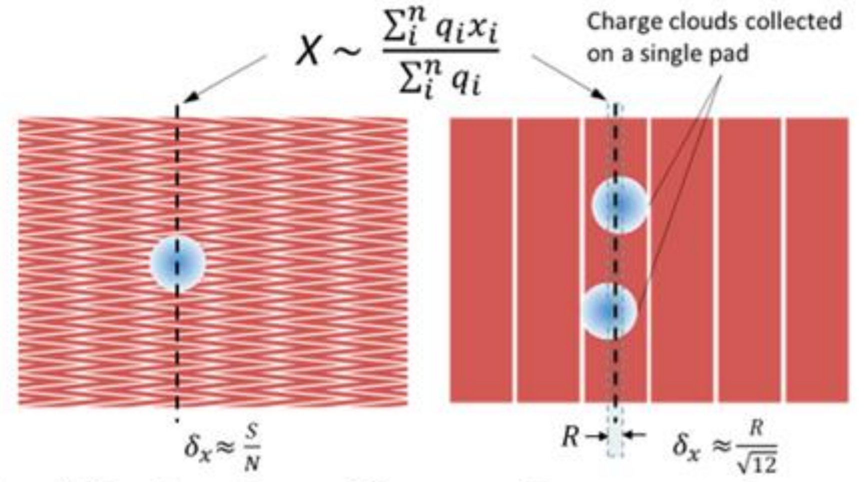
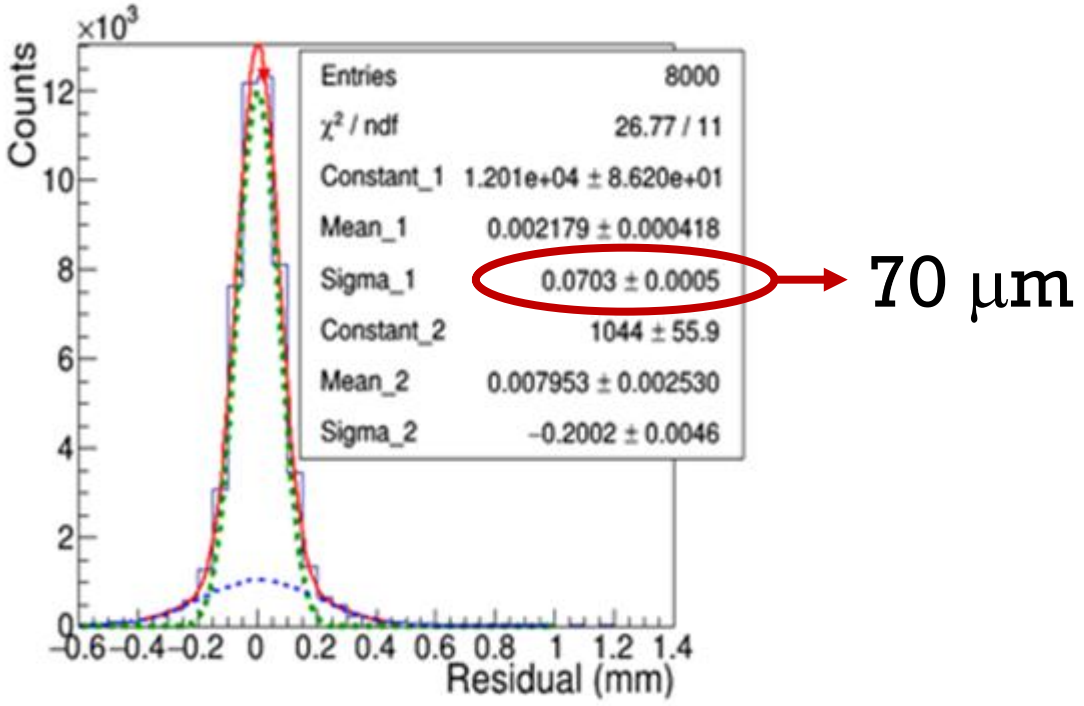


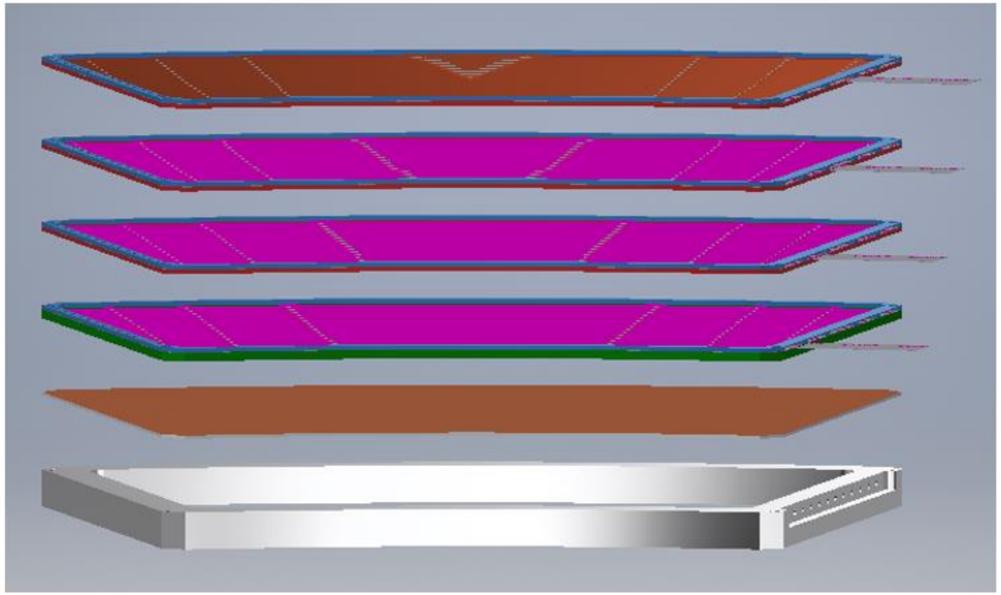
Fig. 1 Sketches of two different readout patterns demonstrate charge sharing and its impact on the centroid calculation and the related position error for a zigzag and rectangular pad geometry. 6 channels are shown for each pattern with the same pitch. (The drawings are to scale.)



- Low diffusion can cause single pad hits → poor resolution
- Zig-Zags not only minimize single hits, they achieve resolutions to a smaller fraction of pitch than rectangles
- EXTENSIVE studies at BNL lead to several principle conclusions
  - Incursions of nearly 100% are required for good linearity.
  - Tip-to-tip pitch must be controlled relative to avalanche spread.
  - Best linearity when gaps are VERY small (<100 μm).

- Incursion: percentage of pad spacing by which one ZZ penetrates its neighbor
- 100% incursion means neighbors tip penetrates to nominal pad center

sPHENIX TPC: READOUT MODULES



GEM 1

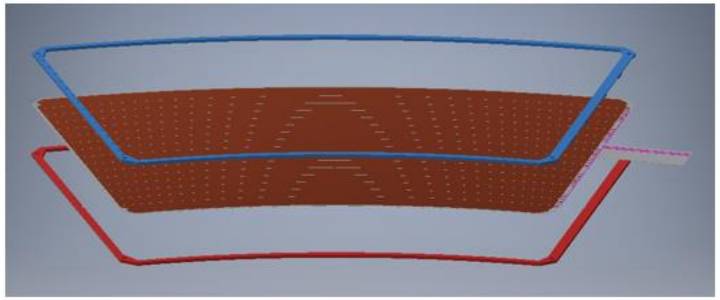
GEM 2

GEM 3

GEM 4

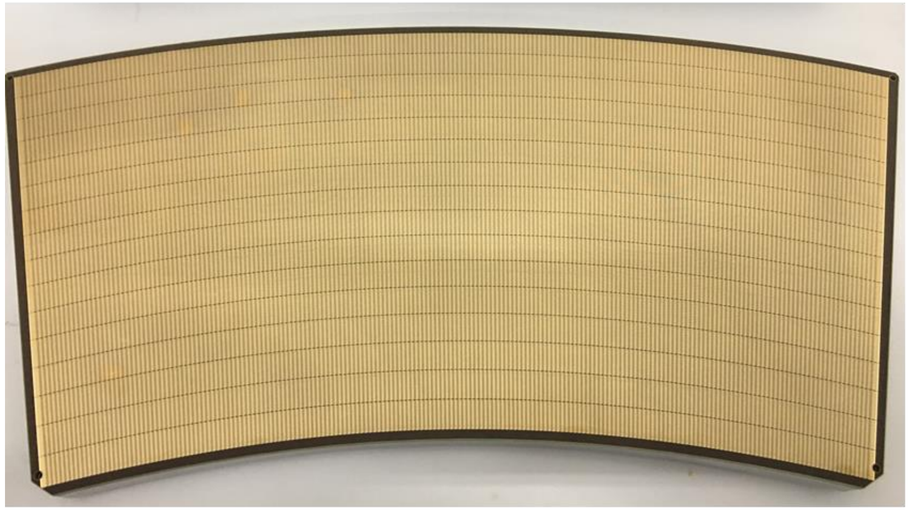
Pad Plane

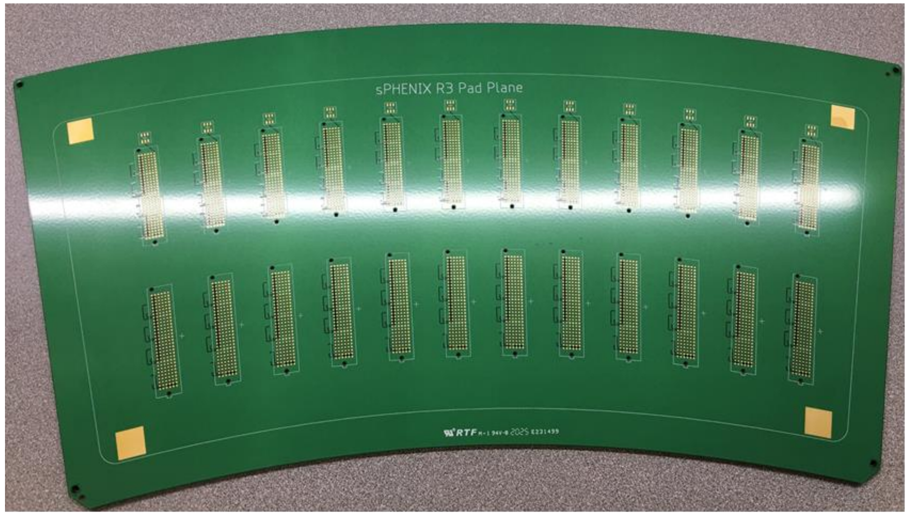
Strongback

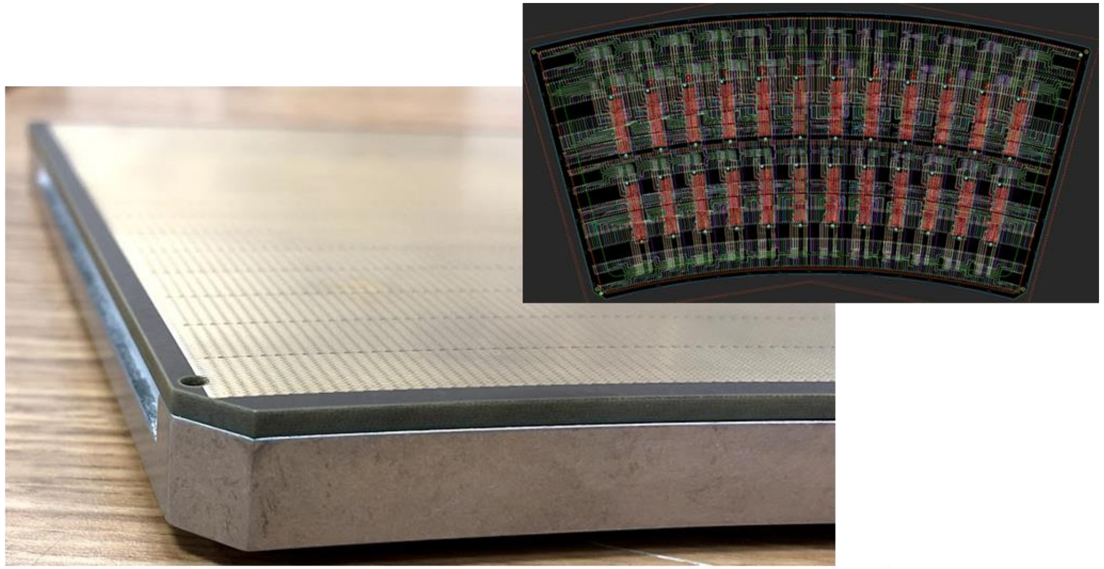


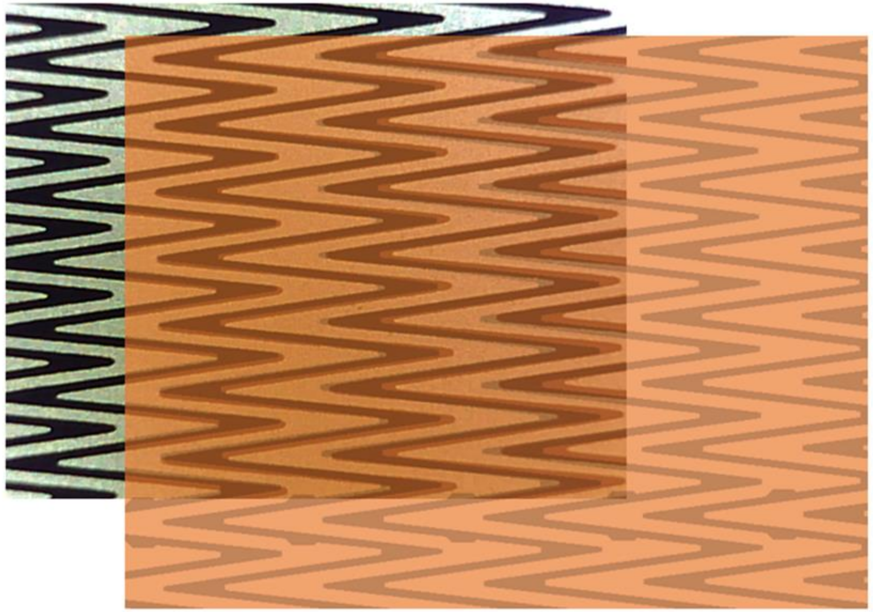
- Each GEM is made up of a Frame Front, Frame Back, and Foil.

sPHENIX TPC: READOUT MODULES

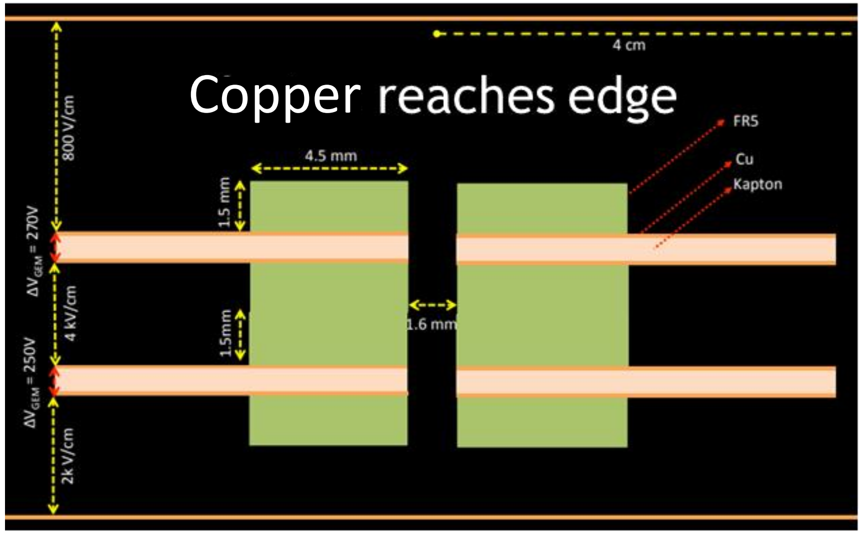


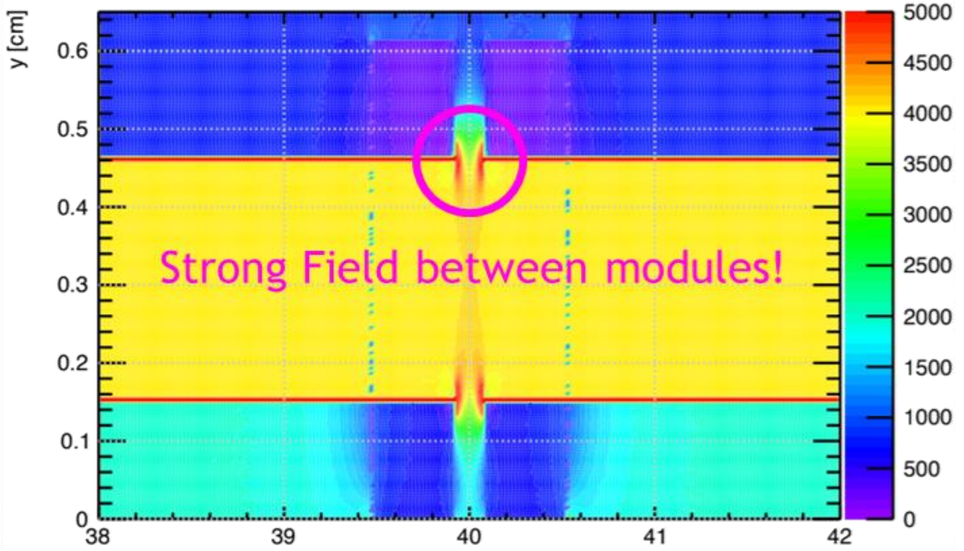


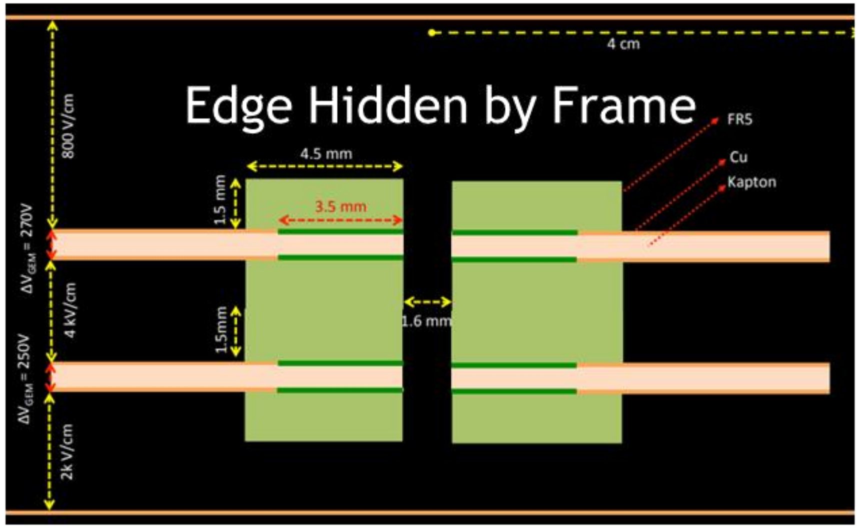


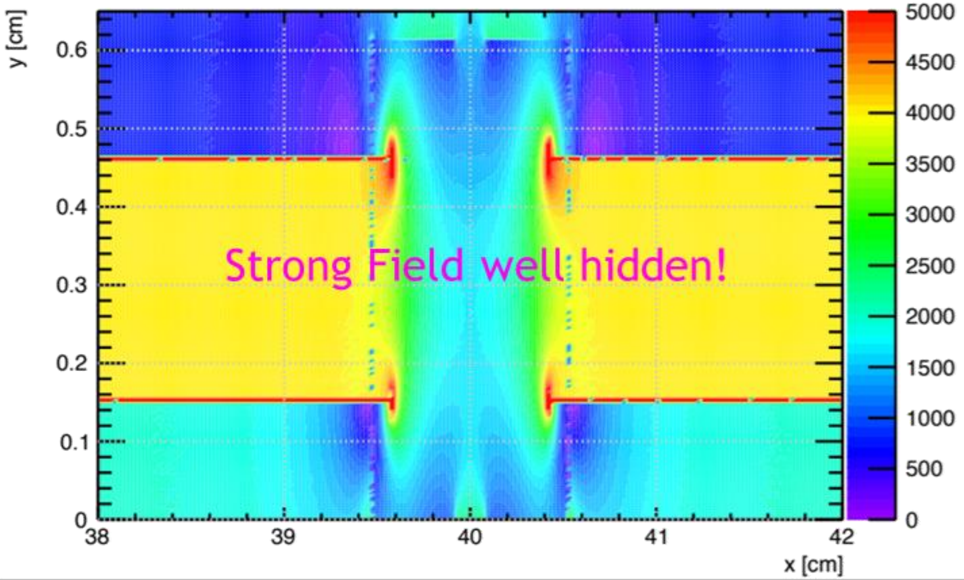


sPHENIX TPC: READOUT MODULES





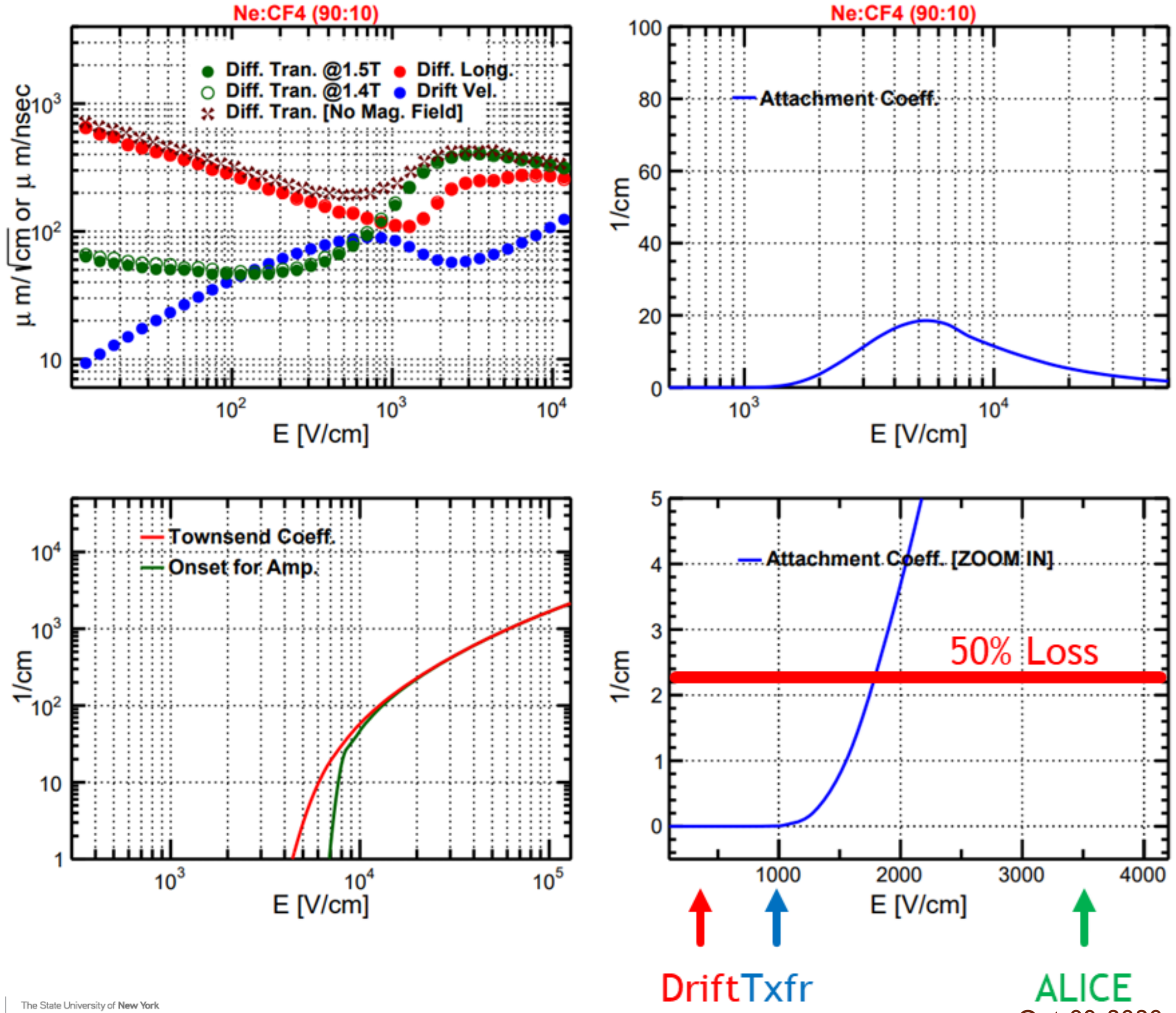




sPHENIX TPC: READOUT MODULES GAS CHOICE

- Neon: high v_{drift} for ions
- Tetrafluoromethane CF_4: cold gas, high v_{drift} for e^-
- IBF configuration

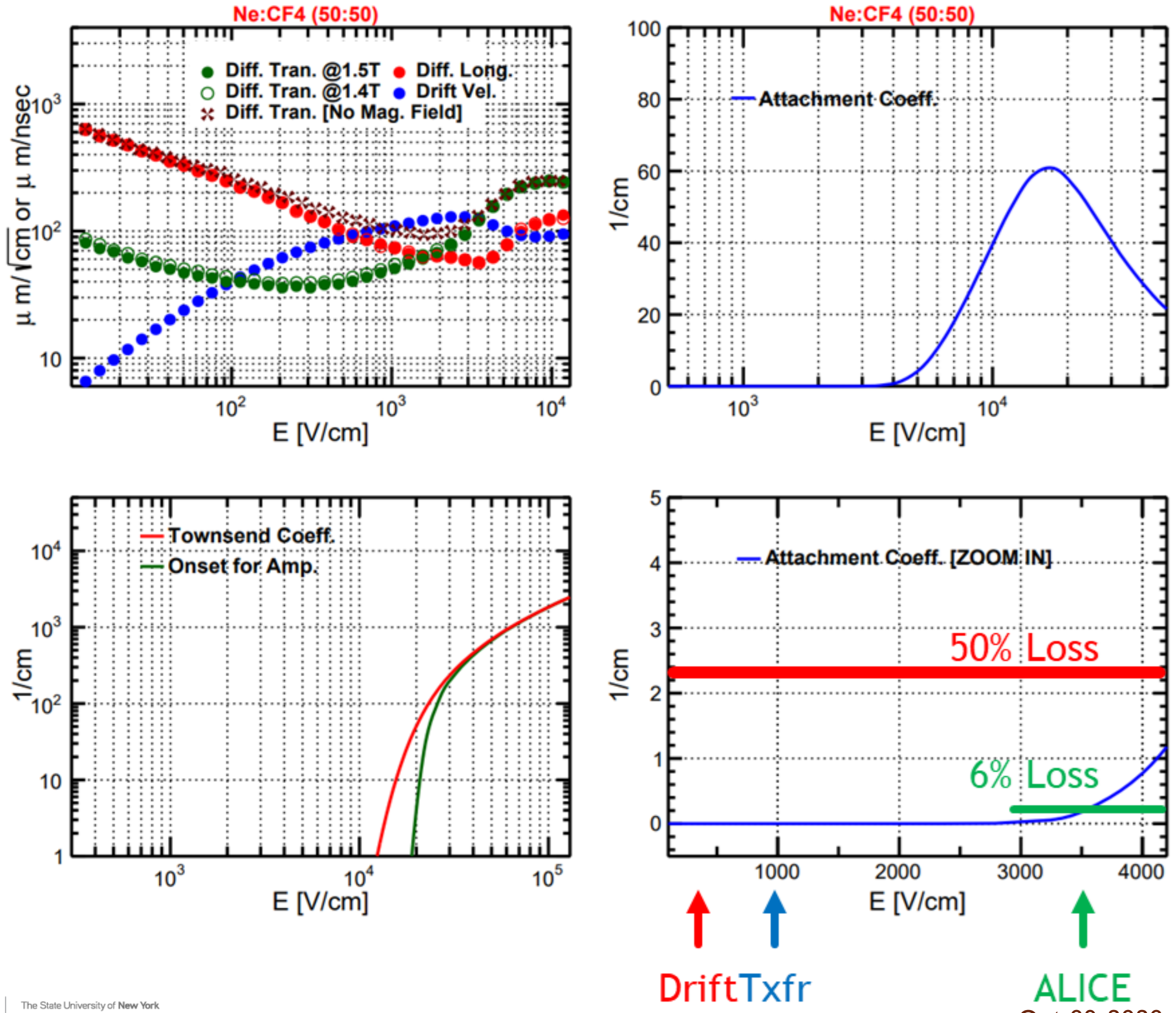
Ne:CF_4 90:10



sPHENIX TPC: READOUT MODULES GAS CHOICE

- Neon: high v_{drift} for ions
- Tetrafluoromethane CF_4: cold gas, high v_{drift} for e^-
- IBF configuration

Ne:CF_4 50:50

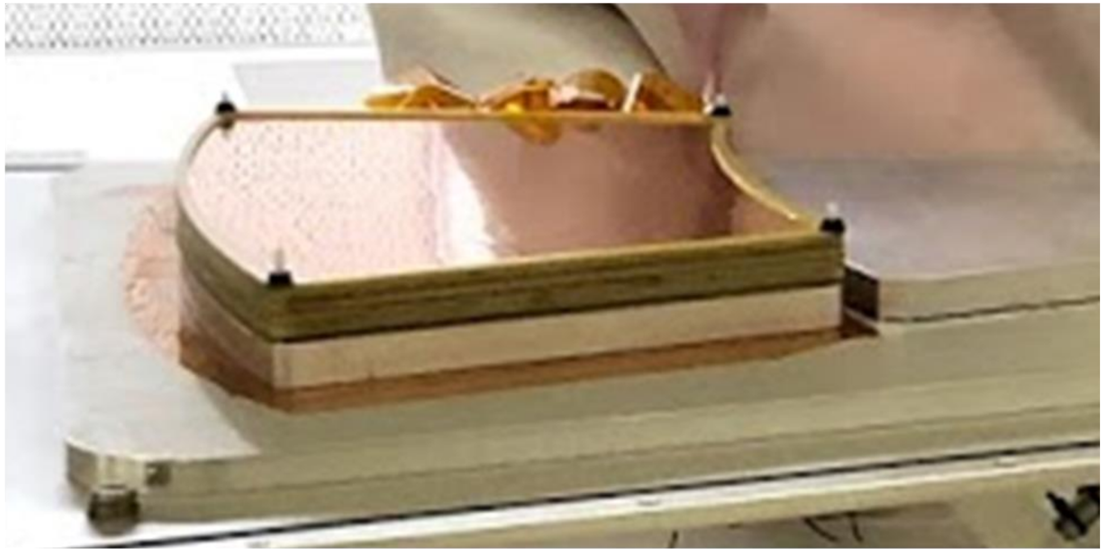


sPHENIX TPC: READOUT MODULES GAS CHOICE

	90:10	50:50	Comment
$v_{drift}\left(\frac{\mu m}{ns}\right)$	78	80	Improvement
$D_{Transverse}\left(\frac{\mu m}{\sqrt{cm}}\right)$	65	40	Improvement
$D_{Longitudinal}\left(\frac{\mu m}{\sqrt{cm}}\right)$	160	110	Improvement
$T-A\Big\|_{1000}$	62000	63000	-
$Mobility\left(\frac{cm/s}{V/cm}\right)$	3.6**	1.77	Worse
$N_{primary}\left(\frac{e}{cm}\right)$	16	31.5	Improvement
$N_{total}\left(\frac{e}{cm}\right)$	48.7	71.5	Improvement
Space Charge (arb)	1.00	1.42	Max 3mm → 4.25mm Likely Tolerable

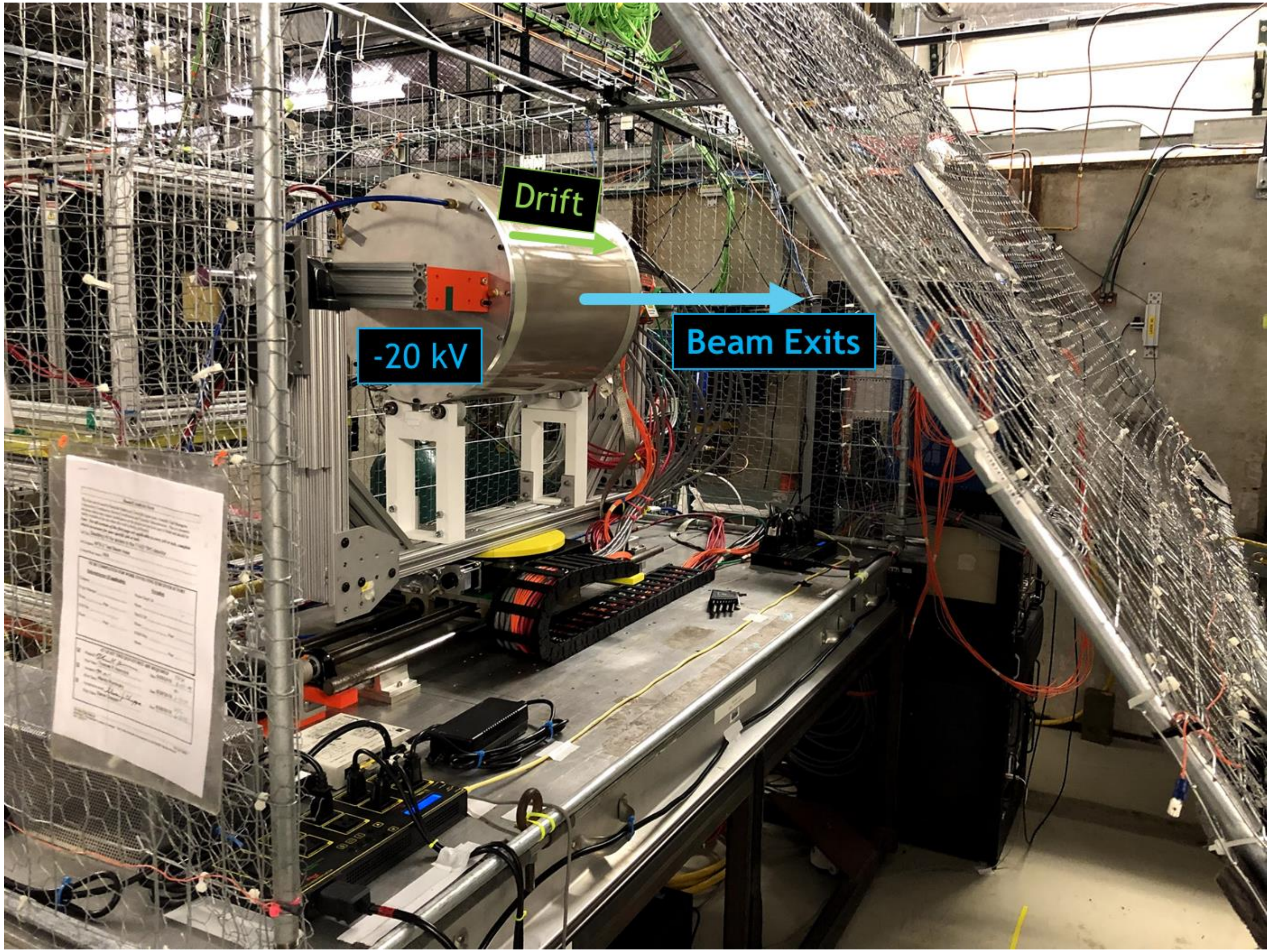
- Primaries (14%): Up by 71.5/31.5
- IBF (86%): Down by 31.5/71.5 (produce constant signal height)
- Residency up by 3.6**/1.77

sPHENIX TPC QUAD-GEM MODULE



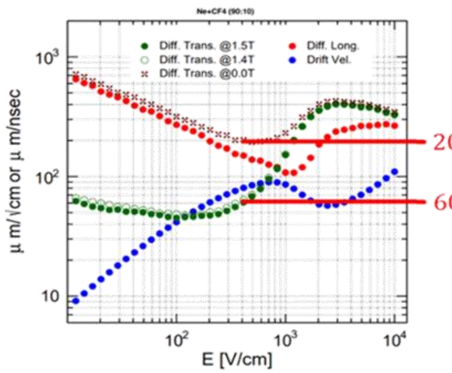
sPHENIX TPC QUAD-GEM MODULE

- Test beam @ Fermilab

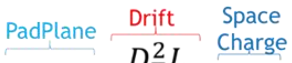


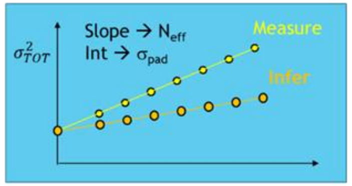
sPHENIX TPC QUAD-GEM MODULE

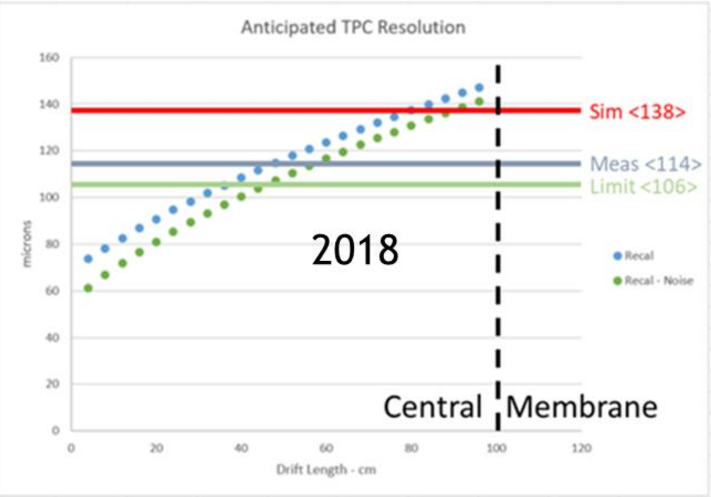
- Test beam @ Fermilab 2018

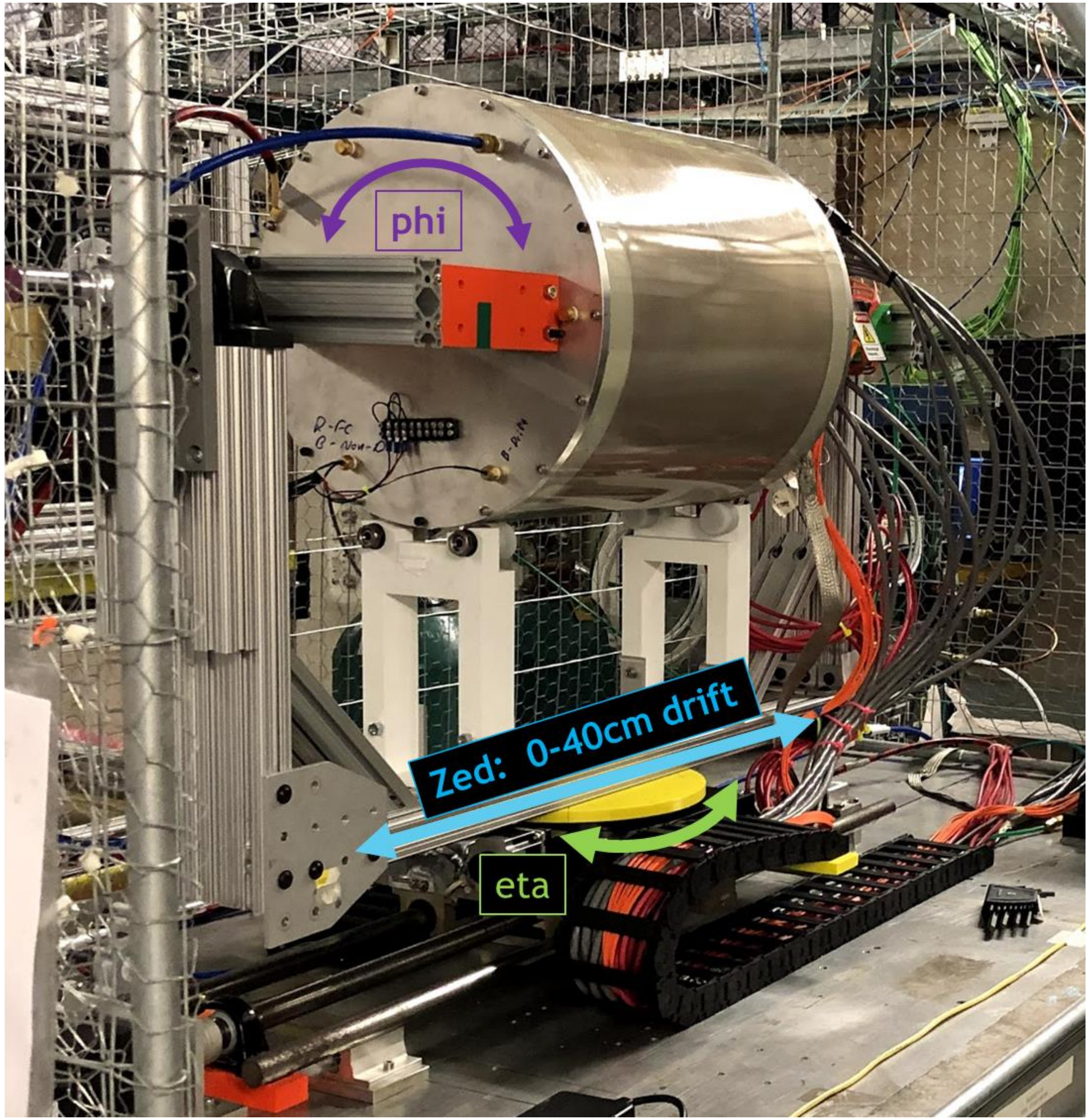


$$\sigma_{TOT}^2 = \sigma_{pad}^2 + \frac{D_T^2 L}{N_{eff}} + \sigma_{SC}^2$$



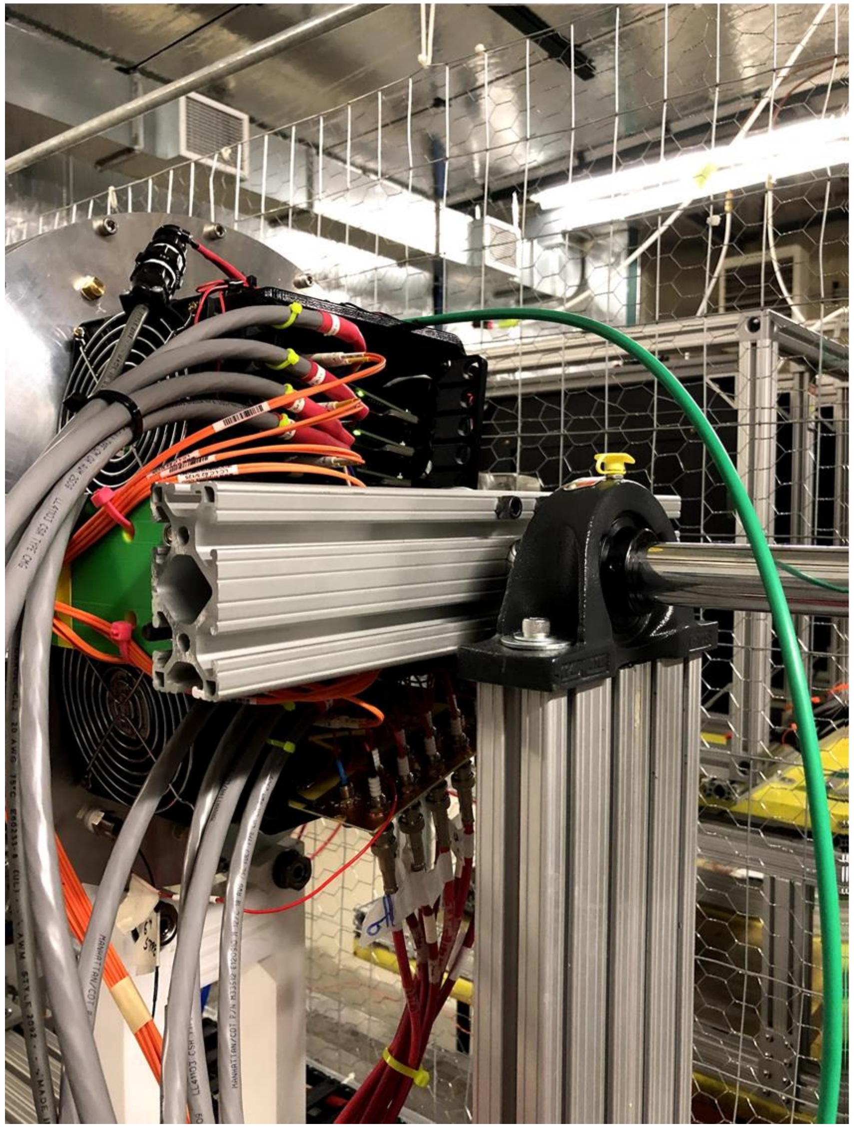


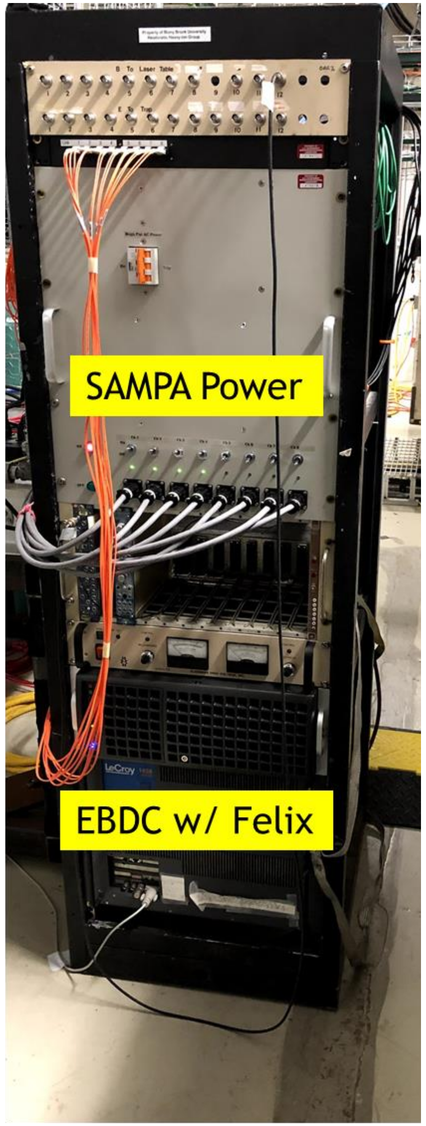




sPHENIX TPC Quad-GEM Module

- Test beam @ Fermilab 2019
  - Real sPHENIX RO
  - Independent HV
  - Low IBF configuration





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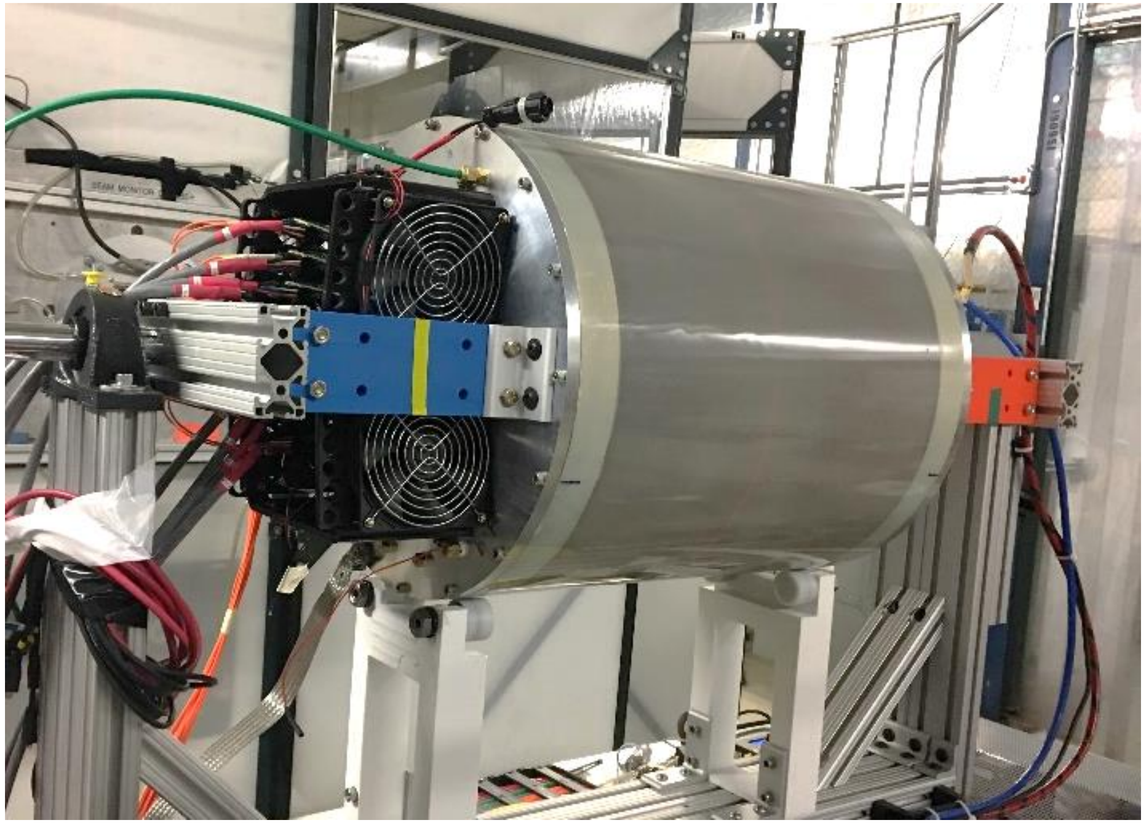

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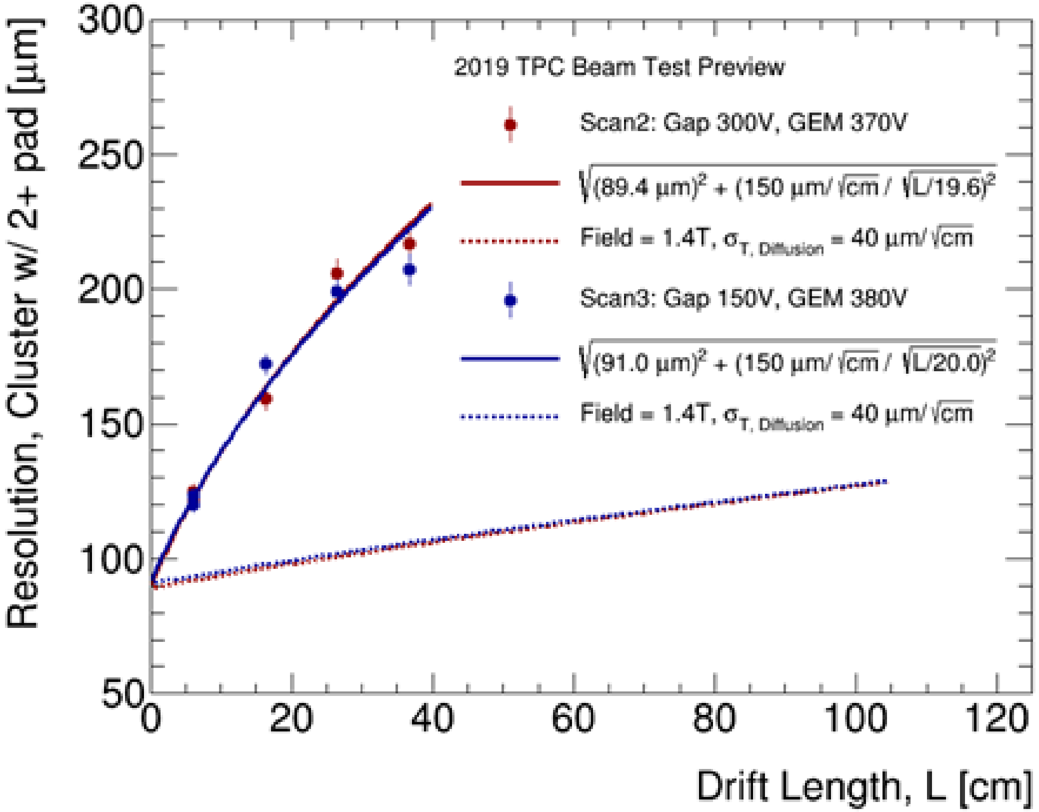

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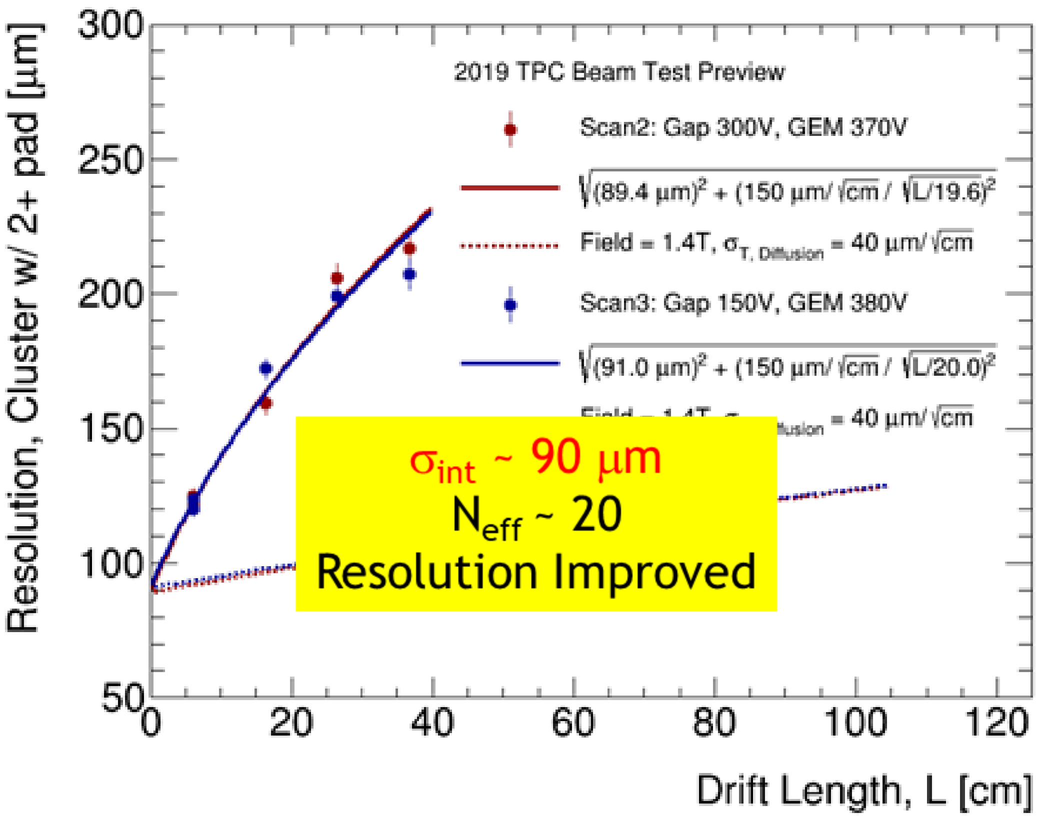
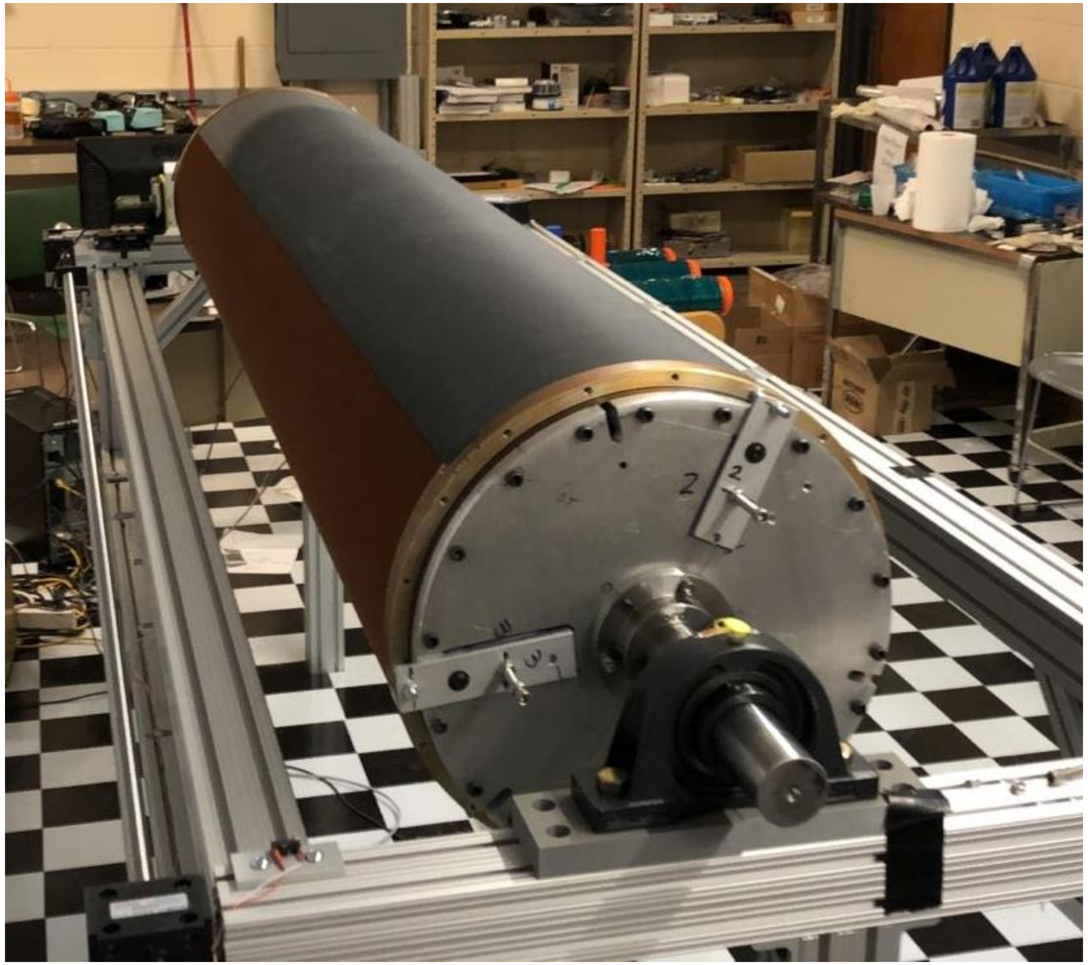


sPHENIX TPC CONSTRUCTION

- We are also building the TPC
  - Mandrel
    - Inner FC
    - Outer FC

sPHENIX TPC CONSTRUCTION



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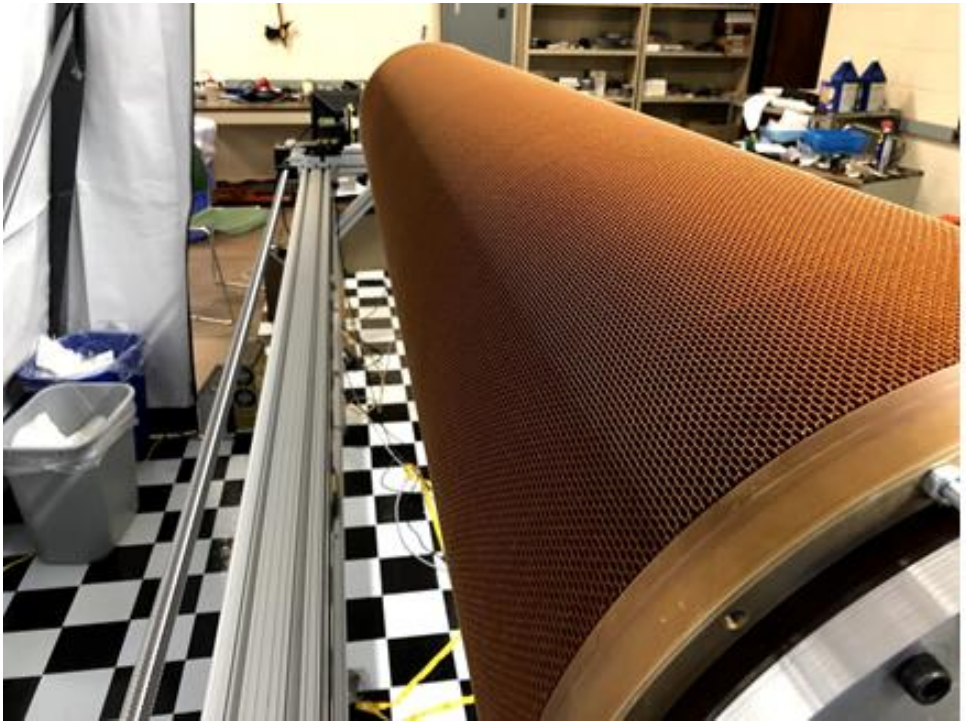
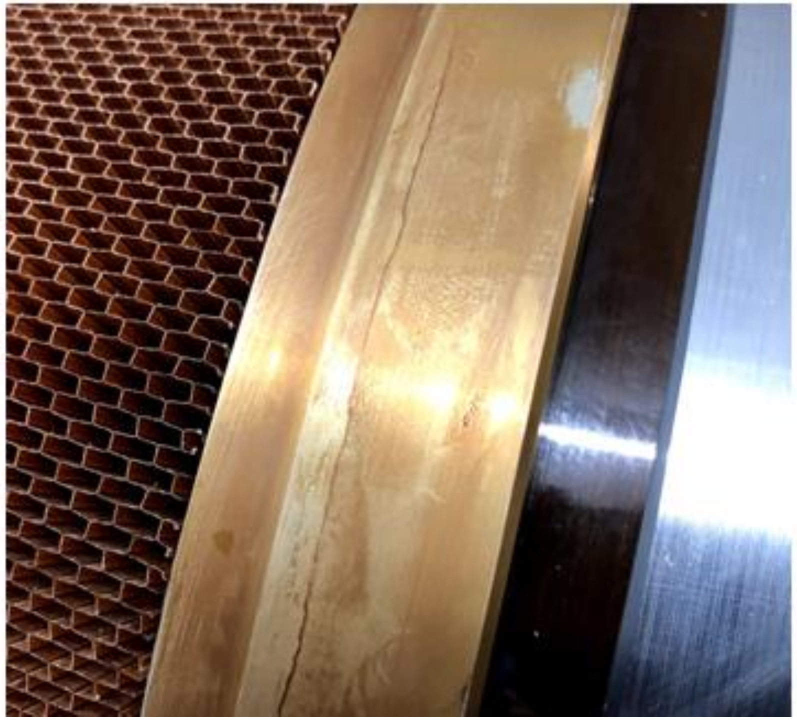
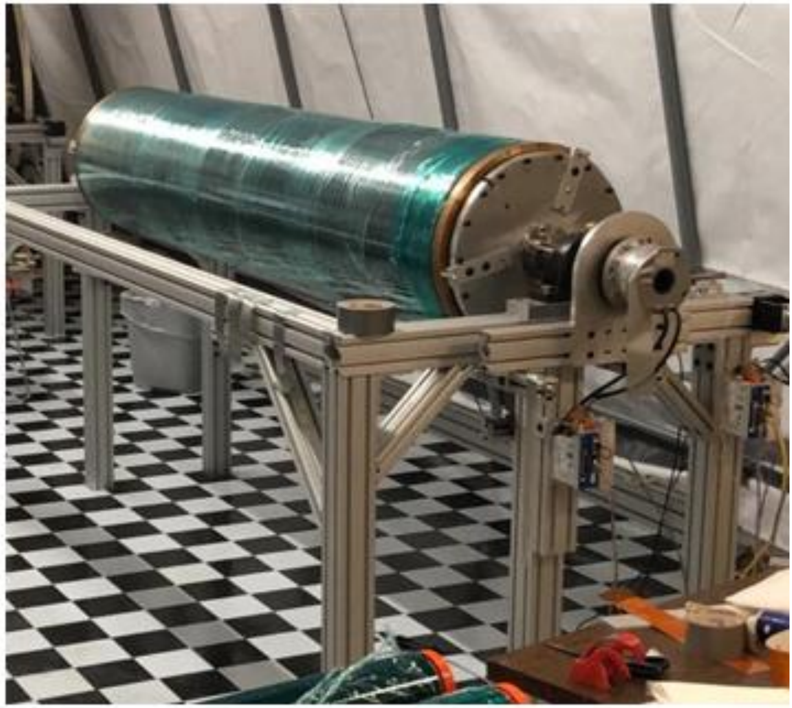

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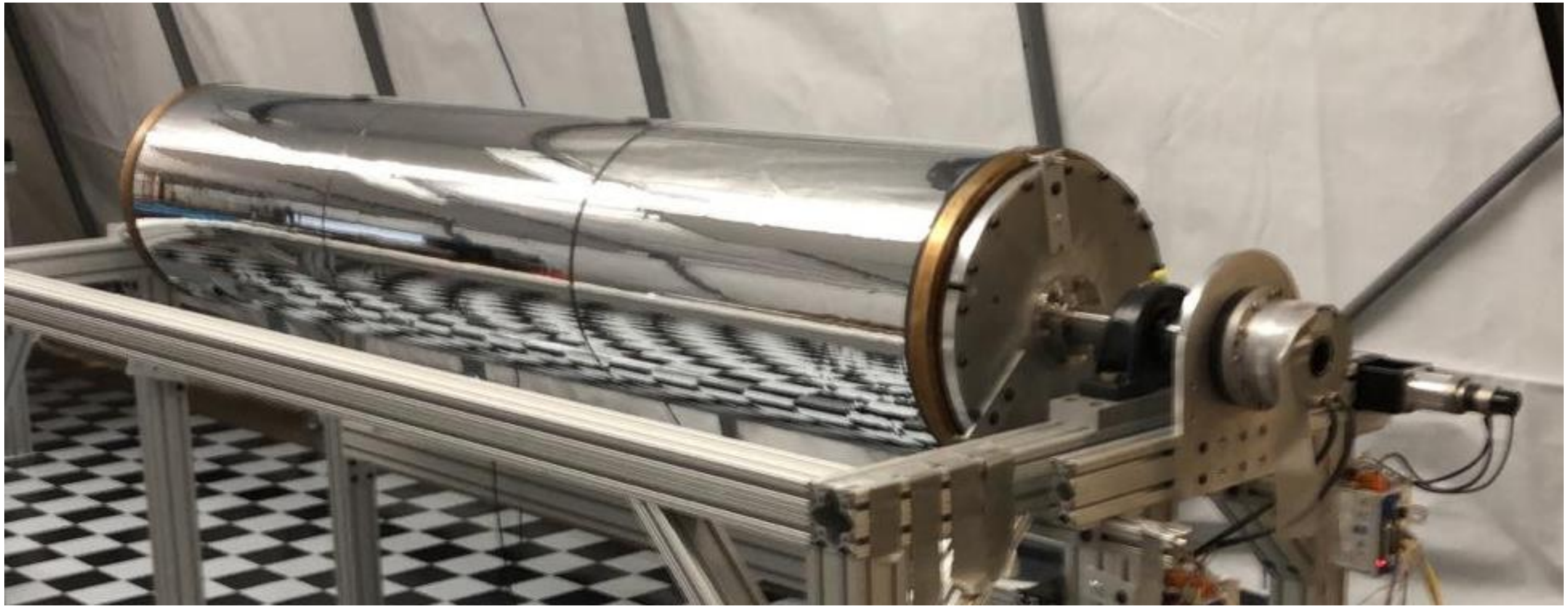

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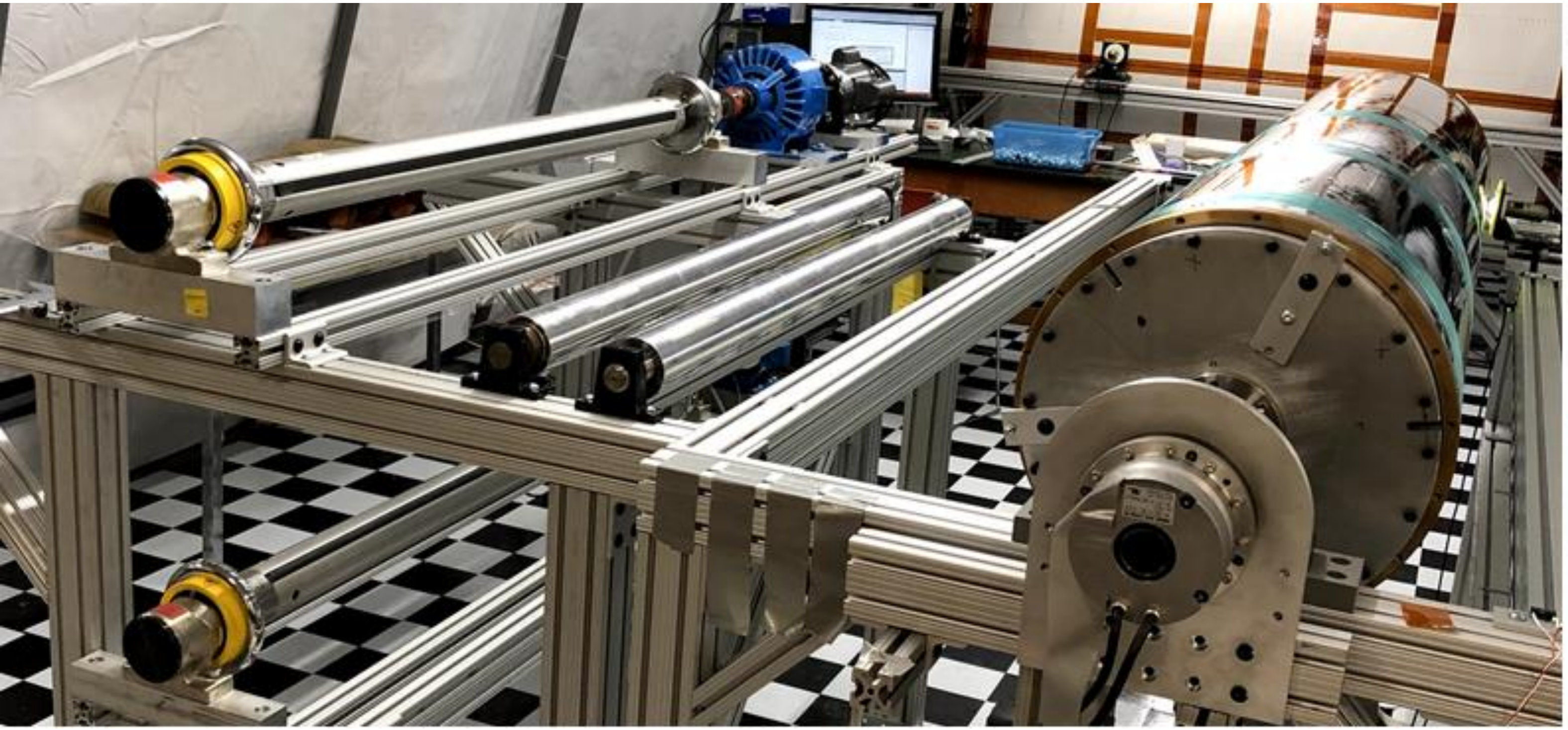

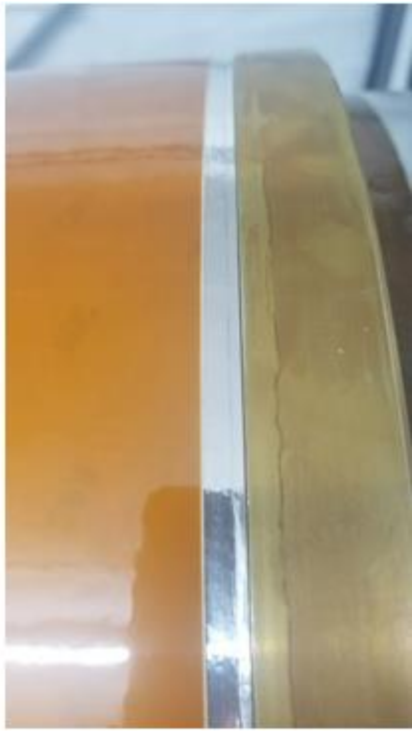

sPHENIX TPC CONSTRUCTION

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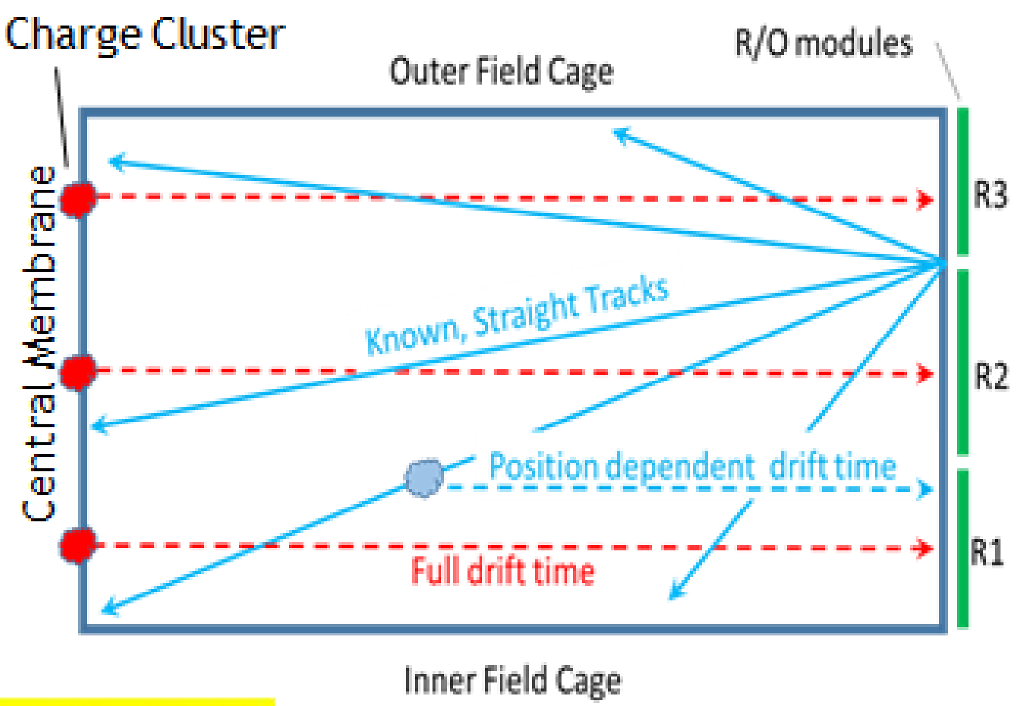
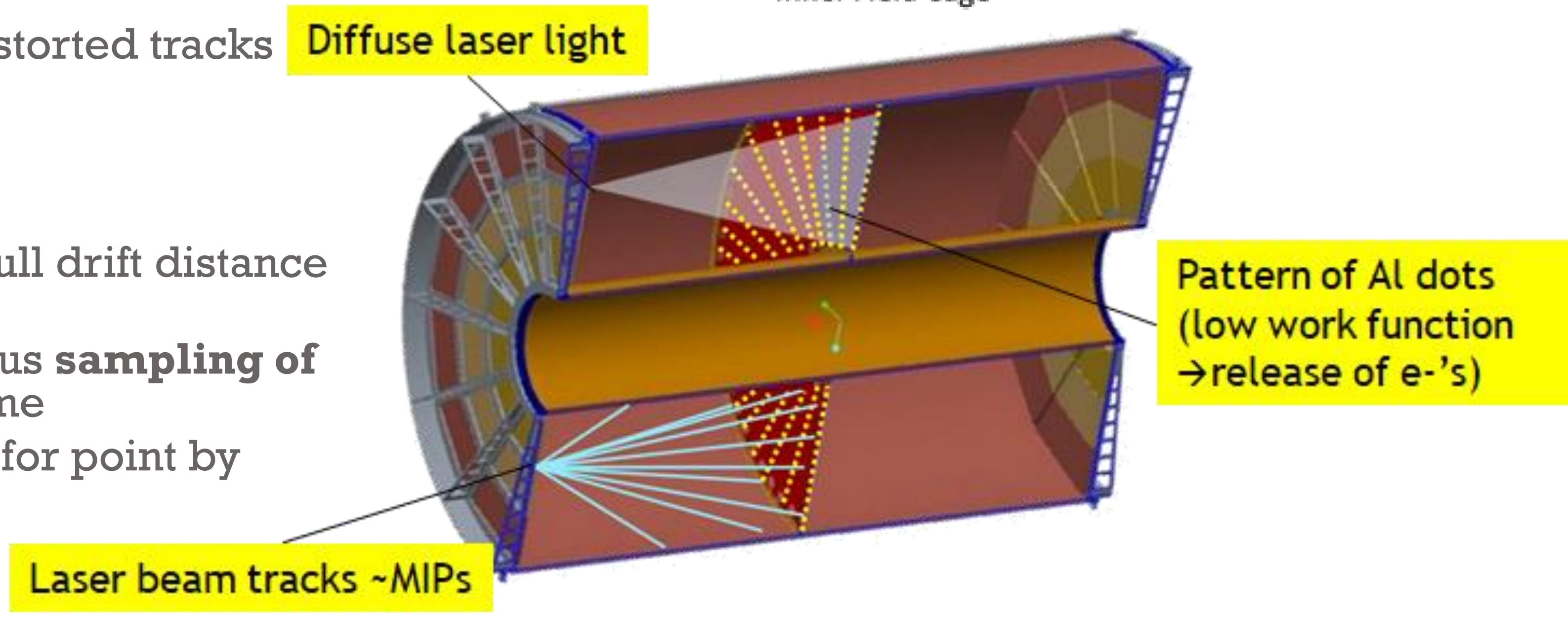
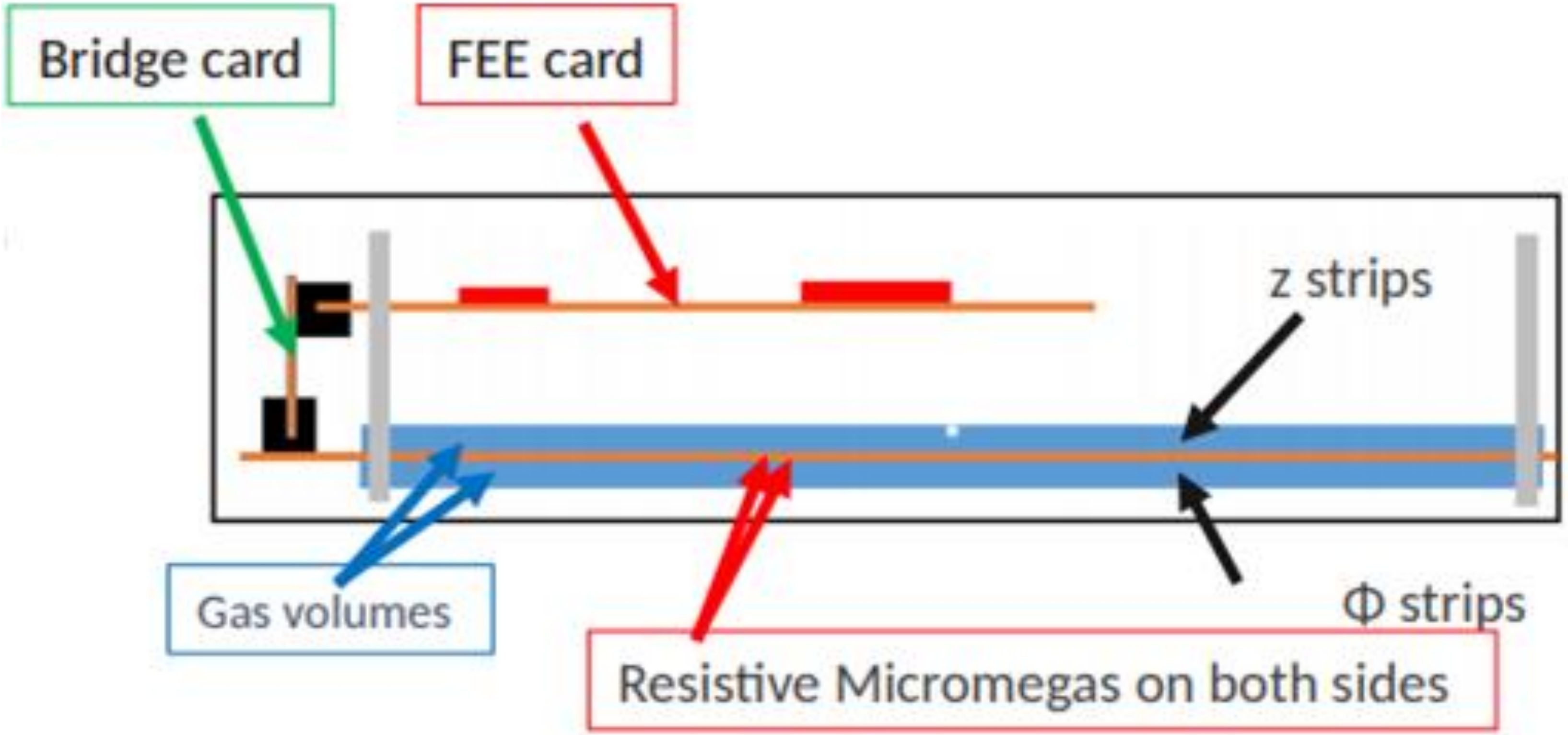
sPHENIX LASER SYSTEM

- Laser calibration
  - Determine drift velocity throughout TPC volume
  - Determine electric field distortions
  - Determine precise alignment of field cage w.r.t. endcap and magnetic field
- Strategy
  - Shine diffuse laser light onto central membrane and liberate clusters of charge
  - Shoot laser beams into TPC volume to mimic straight particle tracks
  - Compare straight tracks to displaced/distorted tracks
    - Beam ON vs OFF (space charge effect)
    - B-field ON vs OFF (**E x B** effect)
- Drift velocity
  - Charge from central membrane travels full drift distance → **absolute integrated drift velocity**
  - Single sweeping laser beam → continuous **sampling of drift velocity/**quadrant of the TPC volume
  - Integrated drift time → **hard constraint** for point by point determination of drift velocity

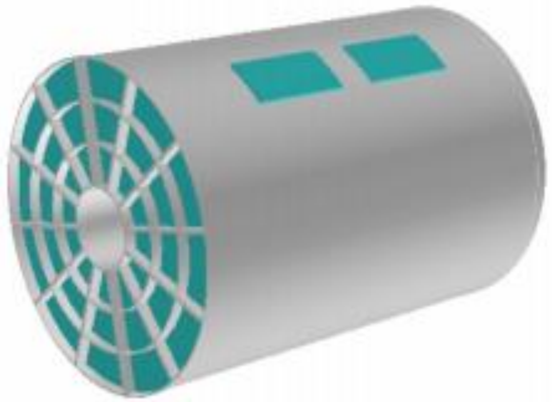




sPHENIX TPC FAST OUTER LAYER: CALIBRATION



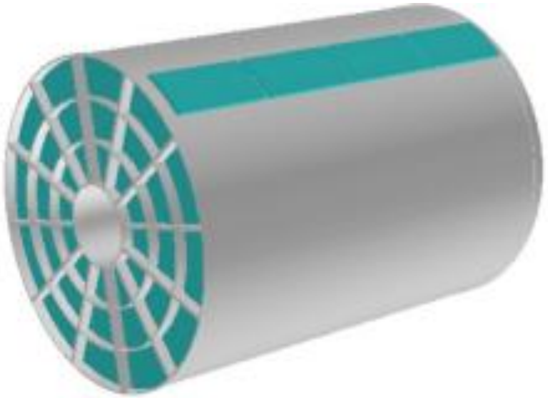
sPHENIX TPC Fast Outer Layer: Calibration



Two tiles

One on each side of the central membrane

In front of one GEM sector

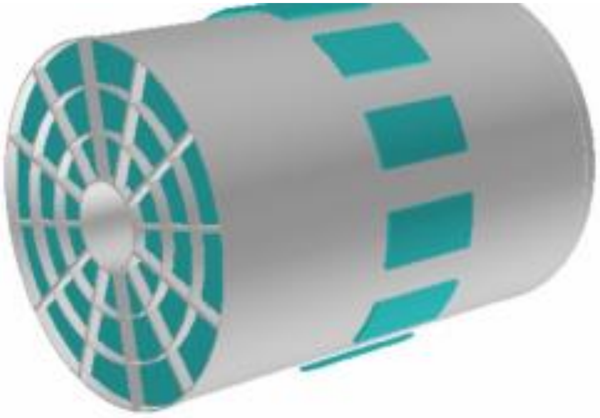


Four tiles

Covering full z acceptance

In front of one GEM sector

Allows to monitor the full z extend of the distortions



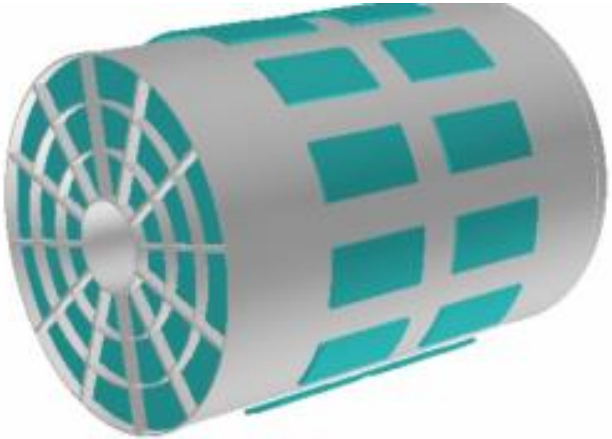
12 tiles at mid-rapidity

In front of each GEM sector

Monitor Gain/IBF fluctuations

Enables some physics at mid rapidity

Suffers from dead area due to central membrane



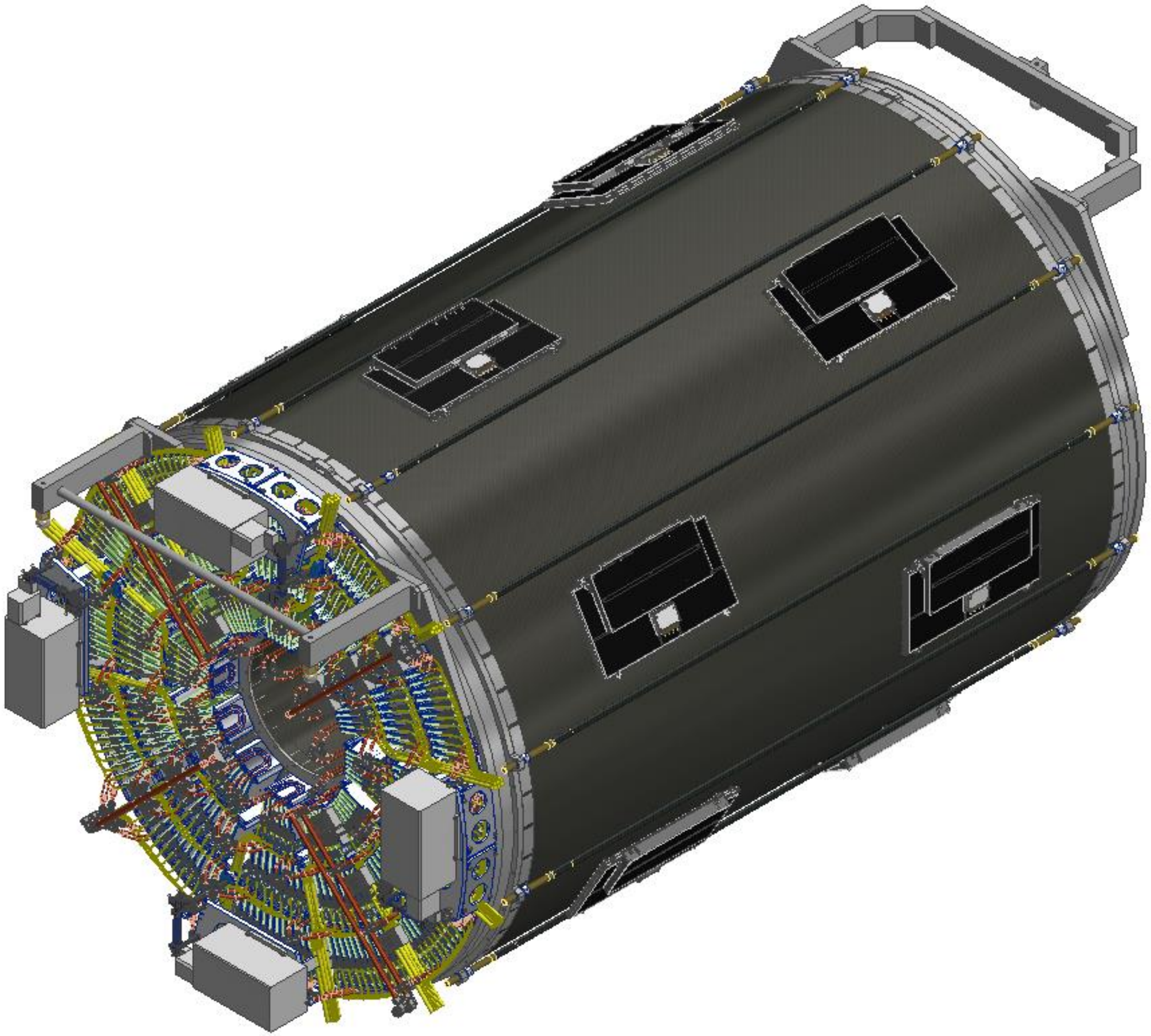
24 tiles

12 on each side of the central membrane

One tile in front of each GEM sector

Same as 12 Tiles but no dead area from CM

sPHENIX TPC FAST OUTER LAYER: CALIBRATION



CONCLUSION (SO FAR)

- TPC for Heavy Ion experiments well in business
- Heavily relied on ALICE TPC R&D and advice
- Primary goal sPHENIX TPC
  - provide momentum measurement
  - no dE/dx program
  - combat ion backflow
- MPGDs are solution
- Room for further improvement
- TPC for sPHENIX → compatible with TPC-requirements @ EIC
  - @ EIC: most likely less IBF problem
  - sPHENIX TPC designed with eye on EIC
  - Equip idle readout region
  - Change gas choice
  - Alternative MPGD solution
- Please visit: http://skipper.physics.sunysb.edu/~prakhar/tpc/ → Extensive set of simulations

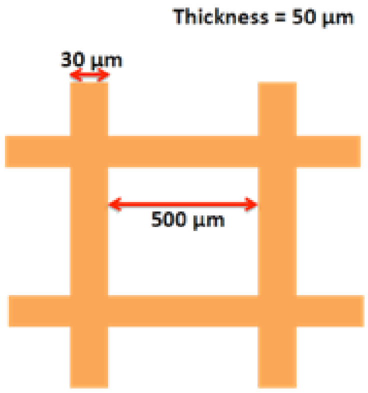
MORE

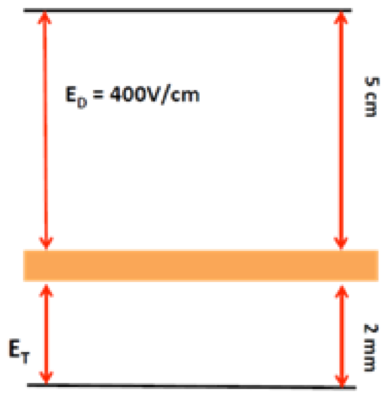
sPHENIX AND IBF

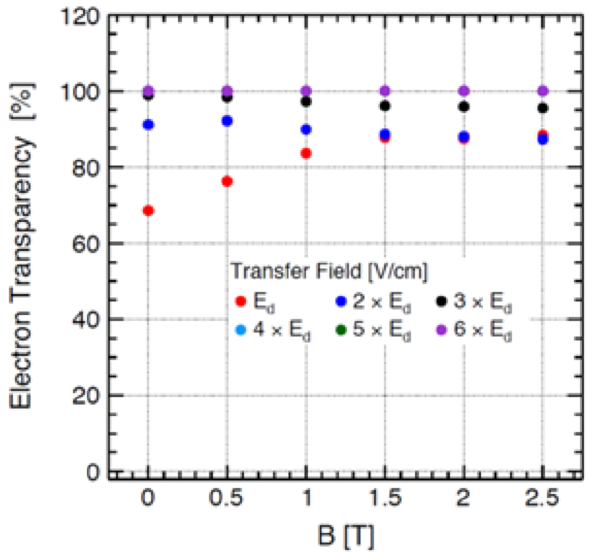
- Several ways to combat Space Charge
  5. Improve amplification device
     i. Remove "gain fluctuation" before amplification

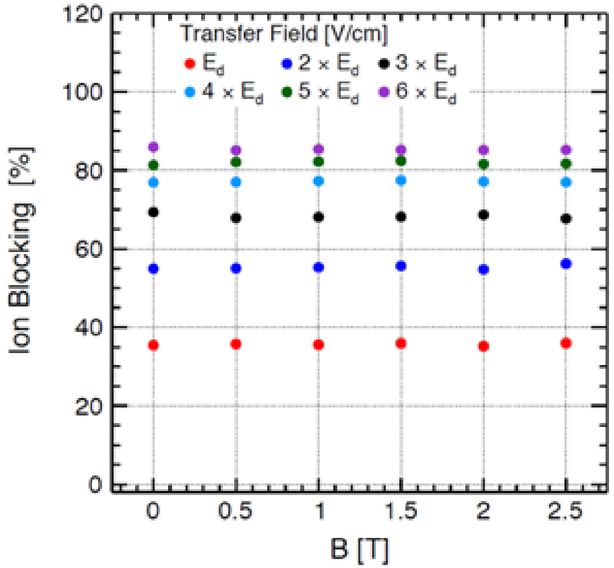
sPHENIX AND IBF

- FC design includes a "termination grid" to ensure uniformity of the field in the drift volume
- Multiple simulations:
  - Wire mesh,
  - Photo-etched
  - Square/Round Hole
- Single conclusion:
  - Tune the field ratio surrounding the mesh to block many positive ions



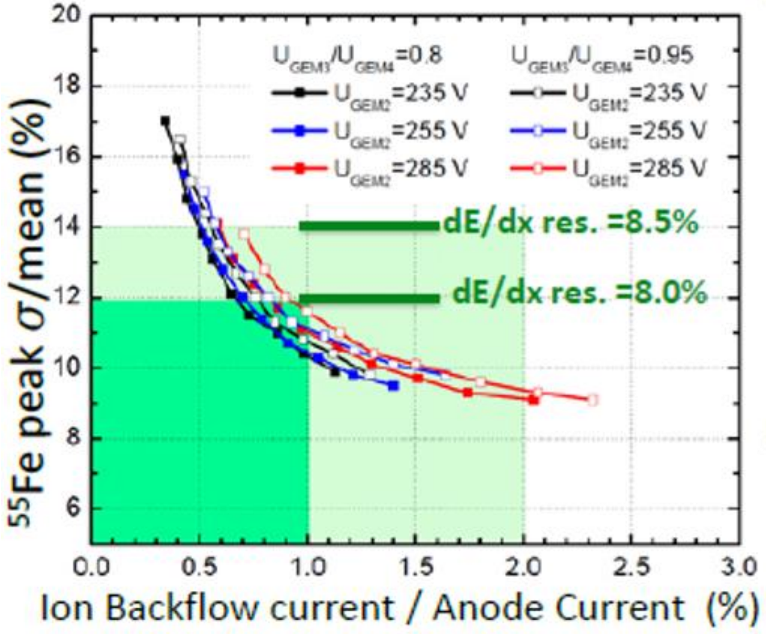


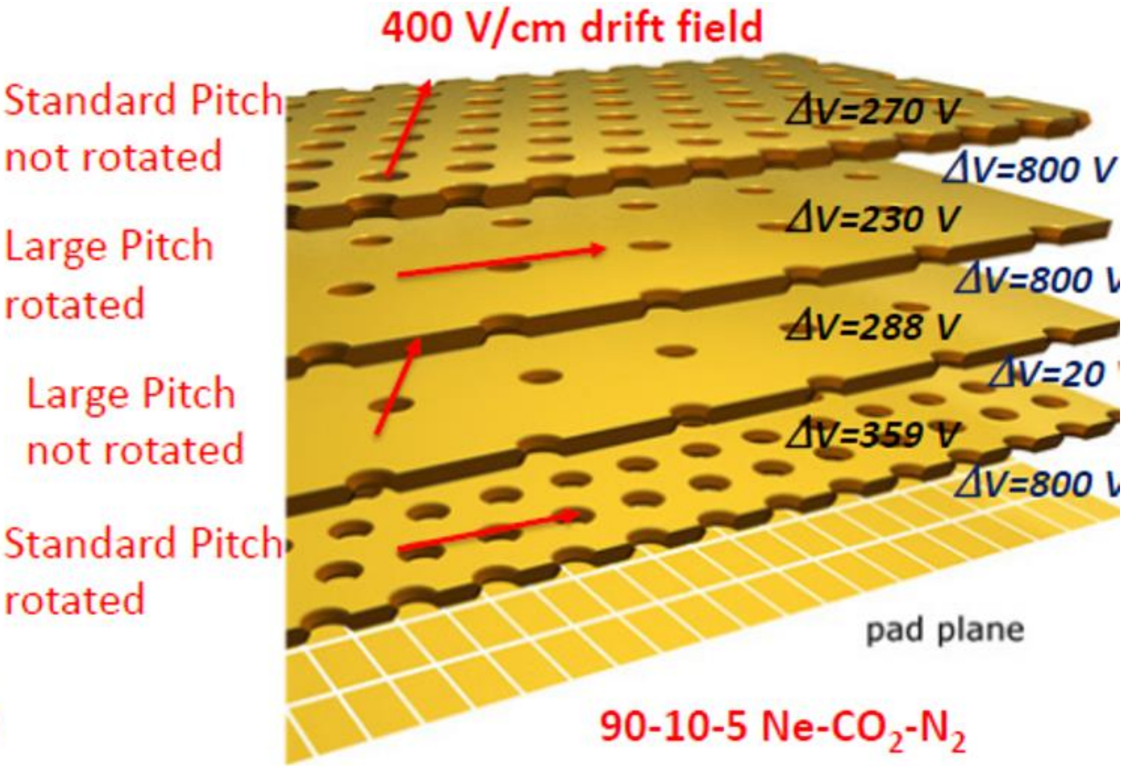




sPHENIX TIME PROJECTION CHAMBER

R. Majka

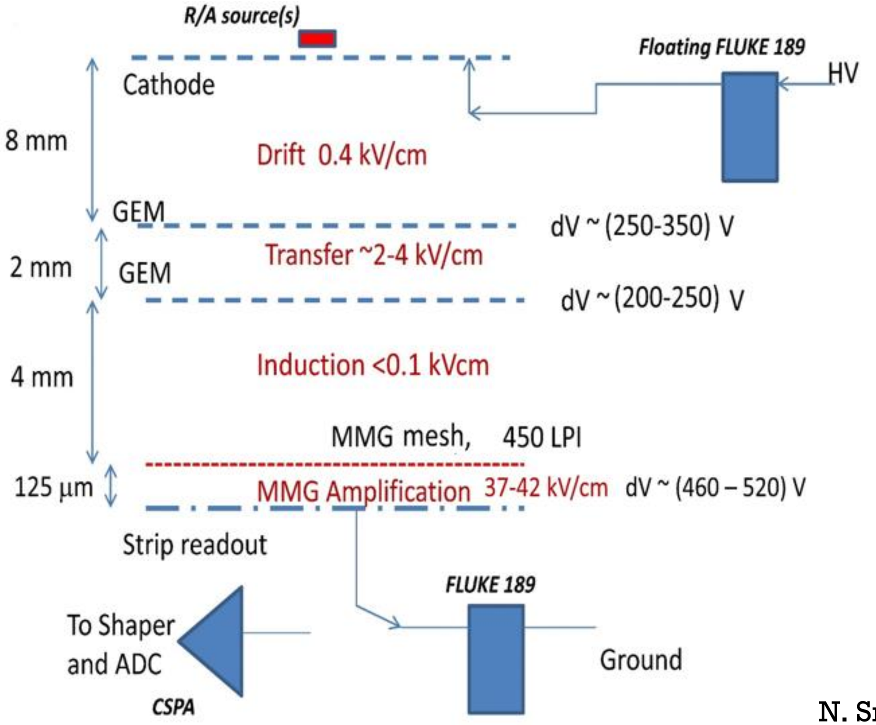


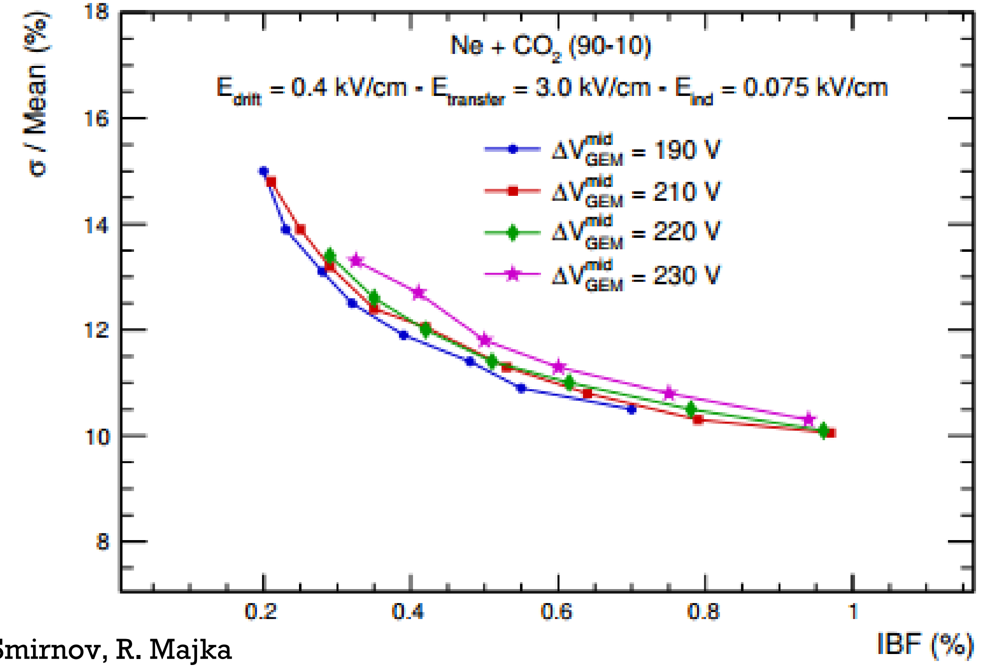


N. Smirnov, R. Majka

sPHENIX TIME PROJECTION CHAMBER

- Dual-GEM + MicroMeGas Solution from Yale

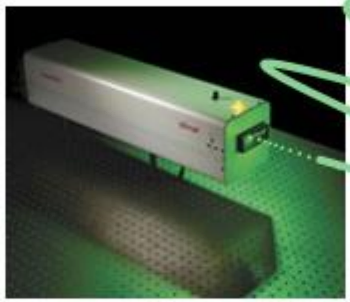


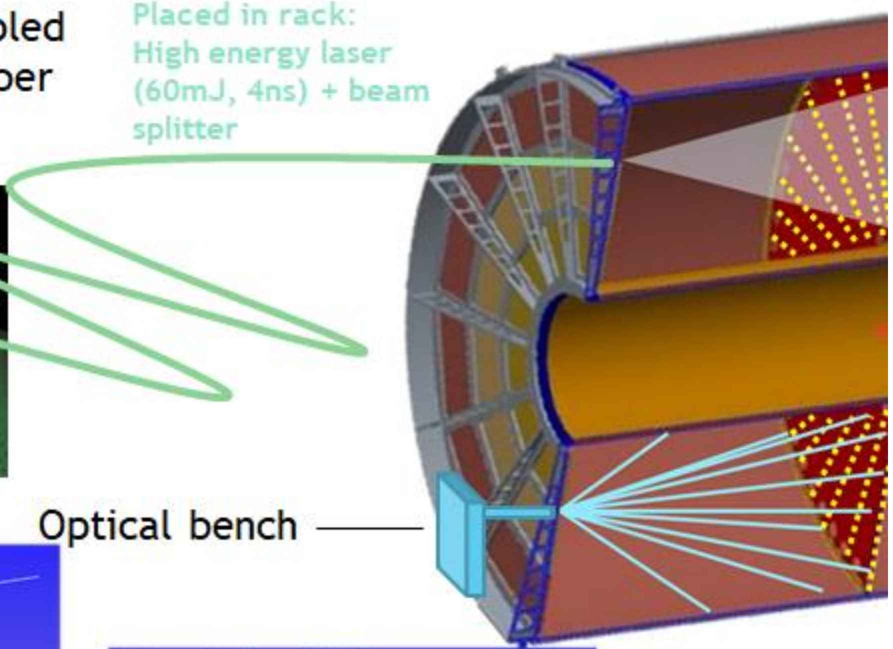


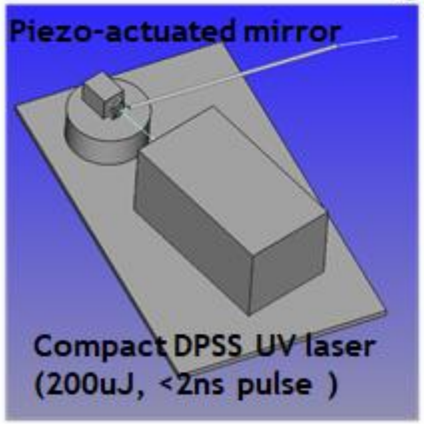
N. Smirnov, R. Majka

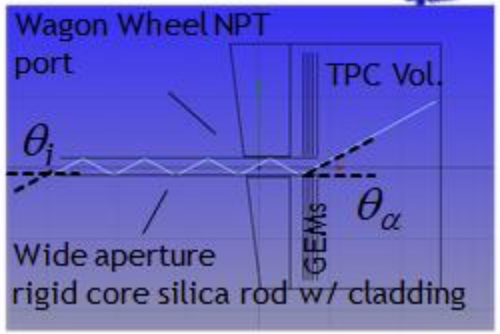
sPHENIX LASER SYSTEM: TECHNICAL OVERVIEW

- 266nm light coupled to fused silica fiber with large N.A.





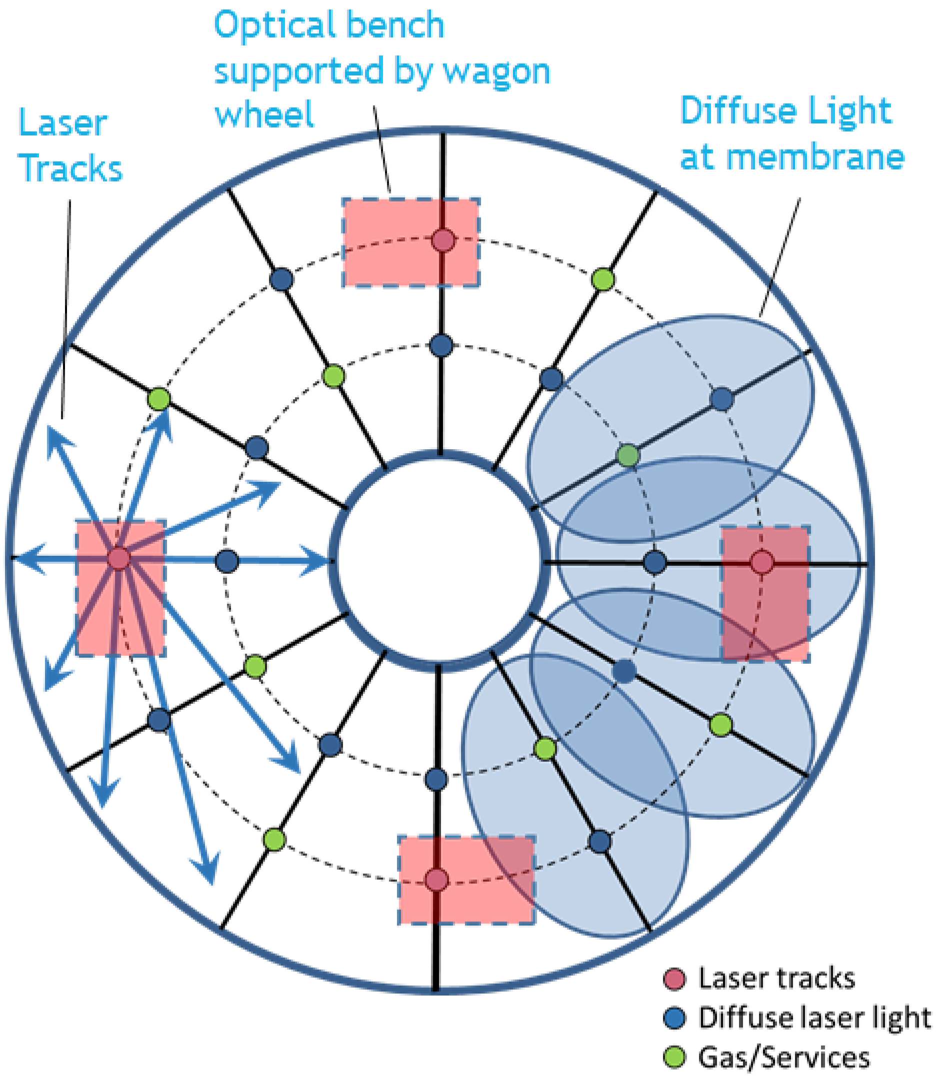




- Rigid "light pipe" delivers laser beam at controlled angles (w/ large N.A.) into TPC volume
- Micro-actuated mirror allows a single laser beam to sweep an entire quadrant of the TPC volume

Layout of TPC End Plates entrance ports

➢ Two rings of 12 ¼" NPT Feedthrough's



SAMPA progress (ADC, FE+ADC)

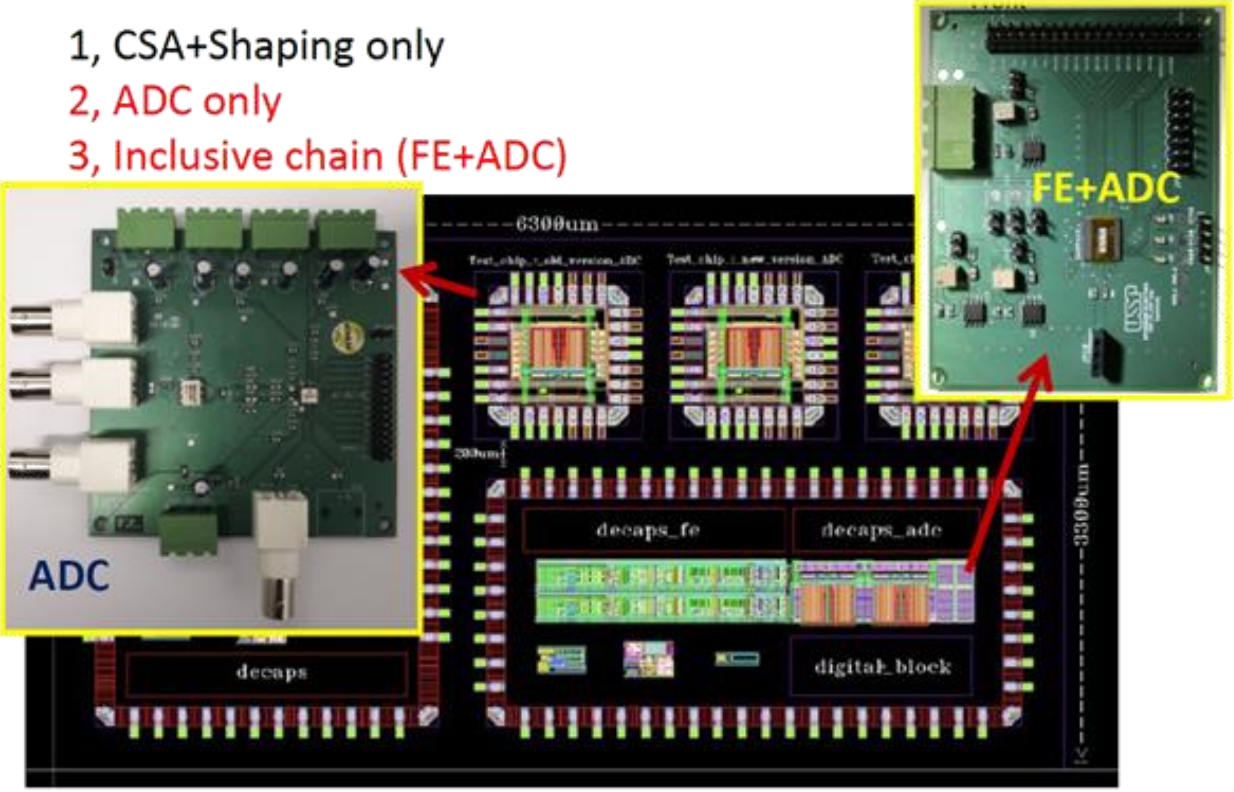
- ADC and FE+ADC components
- ENOB of ADC is found to be better than that of SAMPA v4
  - **Improvement at 18MHz is seen and is close to expected**
- Pulse shape is successfully measured by FE+ADC

	18.5 MSPs	
Amplitude (% of maximum)	ADC V4 ENOB (bits)	ADC V5 ENOB avg. (bits)
40	9.2	9.2
50	8.6	9.1
70	8.6	8.9
90	8.2	8.7

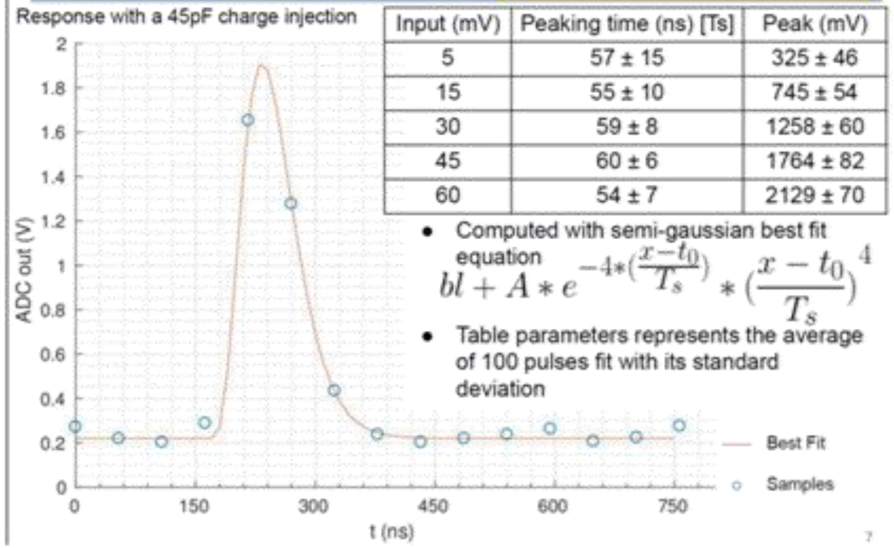
1, CSA+Shaping only

2, ADC only

3, Inclusive chain (FE+ADC)



80nsec, 30mV/fC



Input (mV)	Peaking time (ns) [Ts]	Peak (mV)
5	57 ± 15	325 ± 46
15	55 ± 10	745 ± 54
30	59 ± 8	1258 ± 60
45	60 ± 6	1764 ± 82
60	54 ± 7	2129 ± 70

- Computed with semi-gaussian best fit equation $bl + A * e^{-4*(\frac{x-t_0}{T_s})} * (\frac{x-t_0}{T_s})^4$
- Table parameters represents the average of 100 pulses fit with its standard deviation