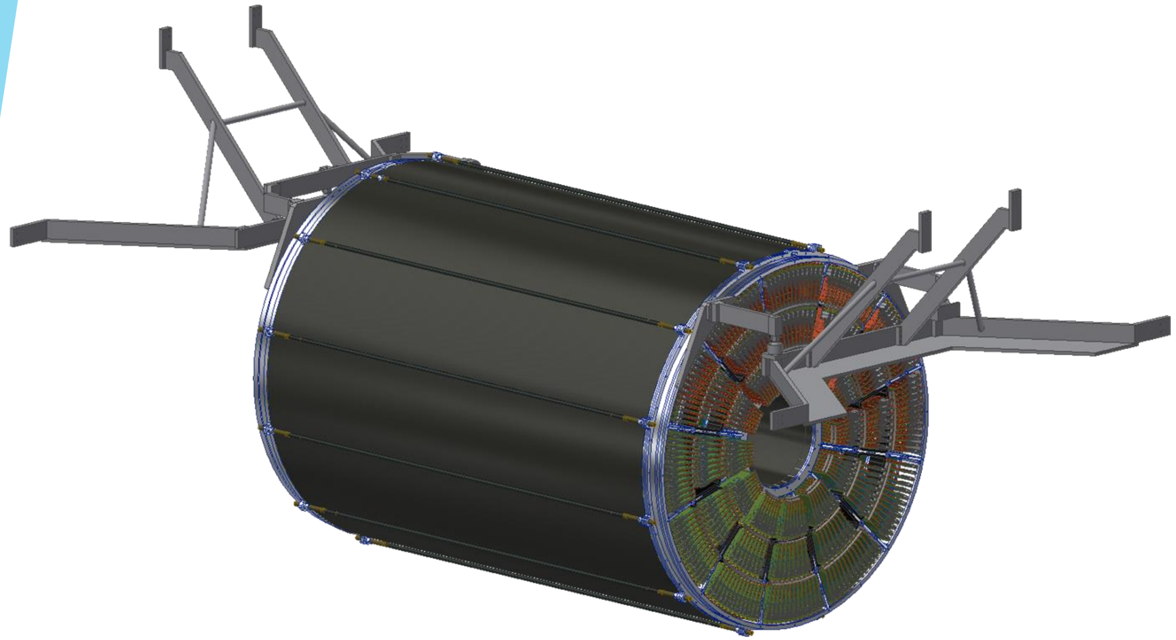
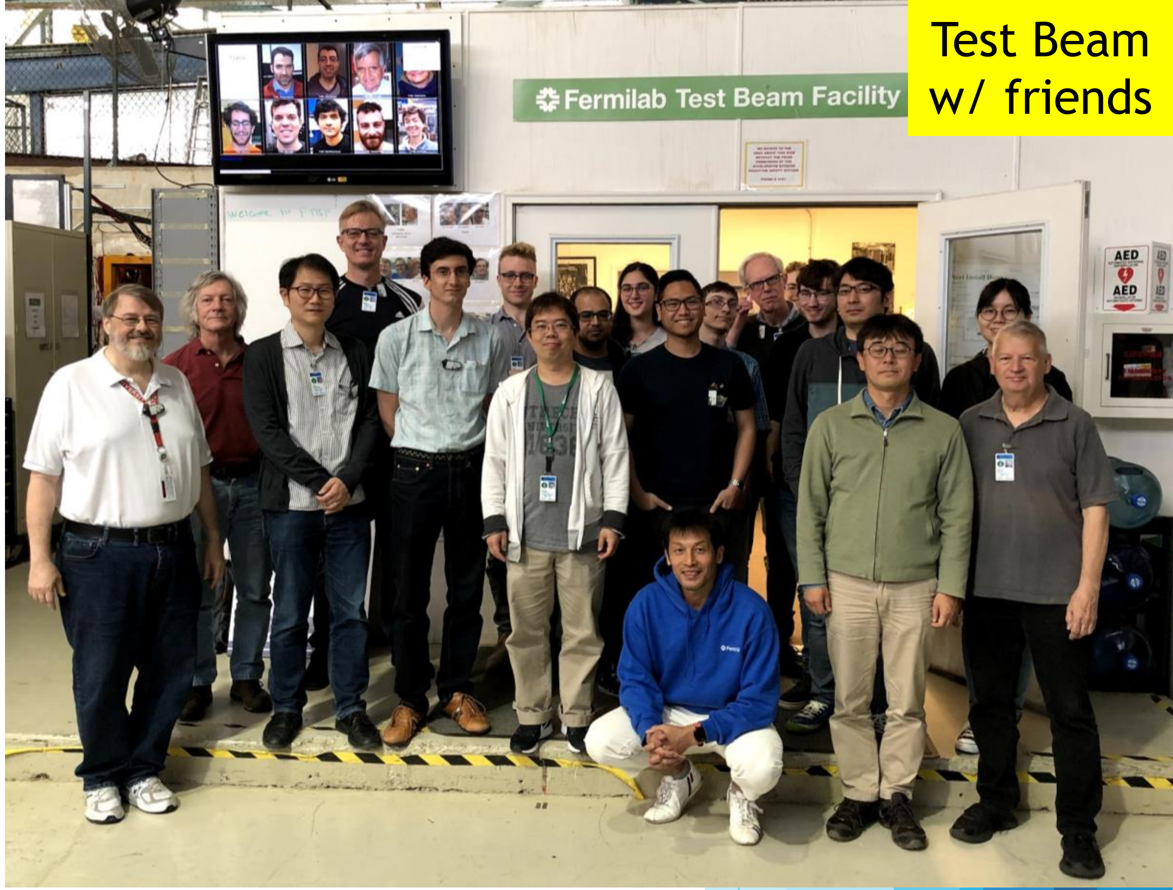




Test Beam w/ friends

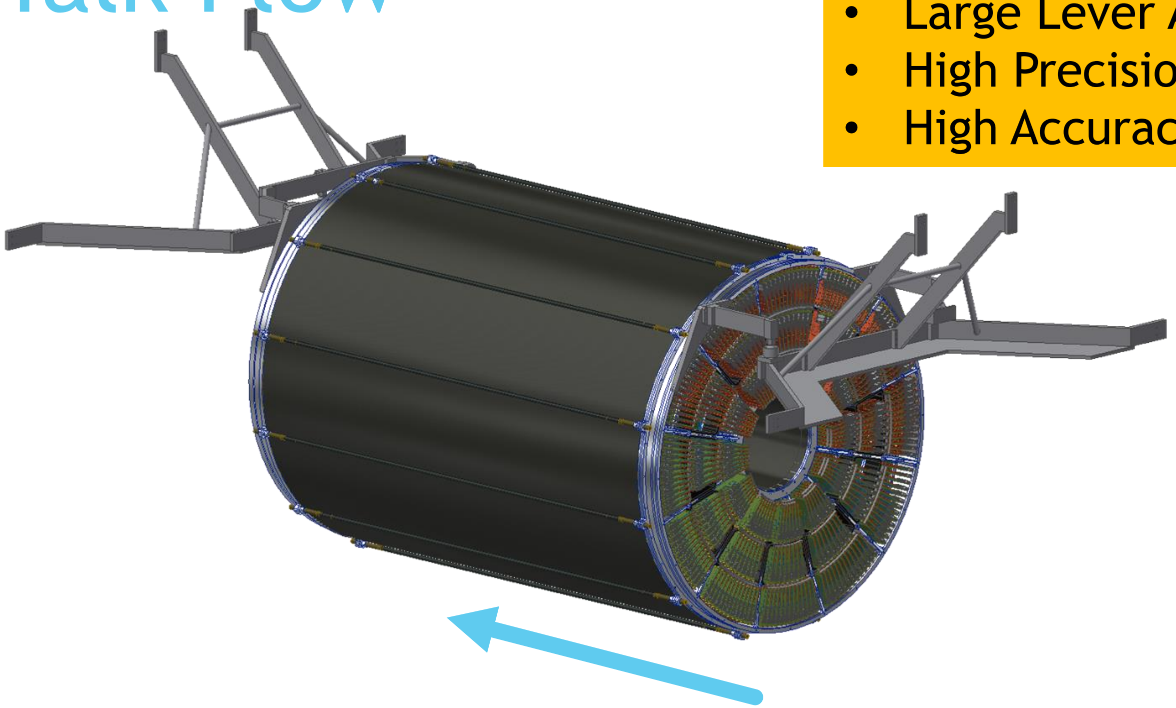
TPC Test Beam Crew:
C Beattie, K Dehmelt, J Haggerty, J Huang, L Legnosky, H Klest, J Kuczewski, N Kumar, S Kurdi, R Majka, L Martin-Depres, T Martinez, E Ramilo, T Sakaguchi, N Smirnov, F Toldo

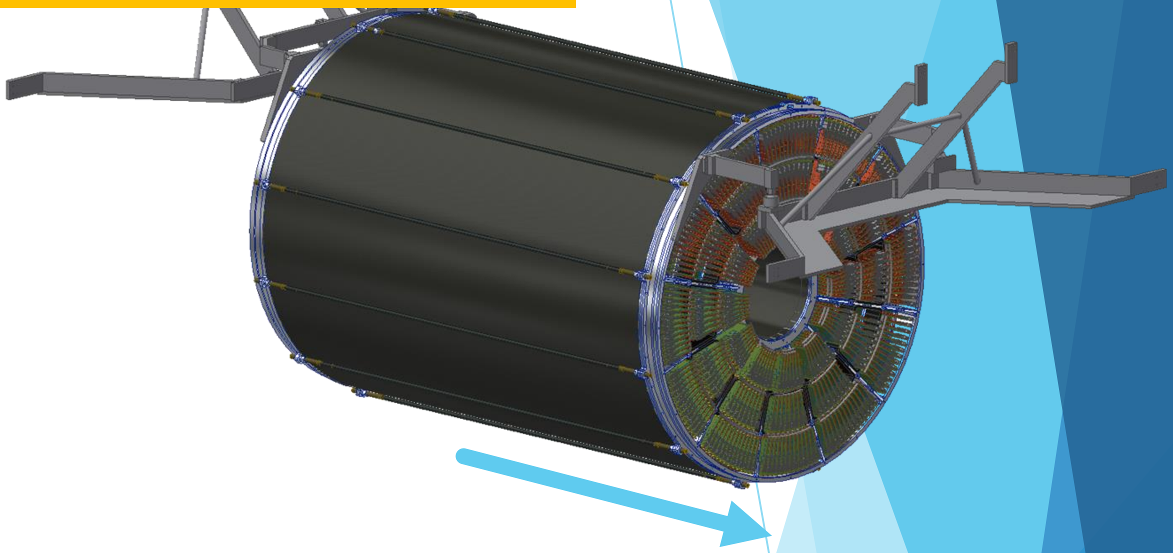
TPC Update

TK Hemmick

Talk Flow

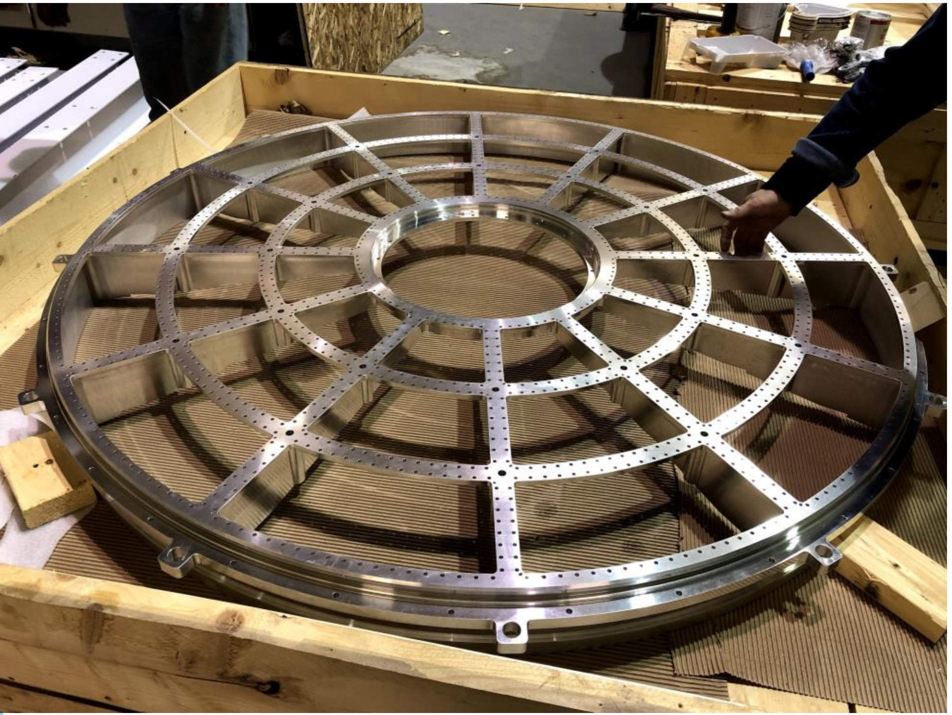
High Momentum Resolution:
- Large Lever Arm (Maximize Active Area)
- High Precision (Good Single Point Resolution)
- High Accuracy (Low Distortion)

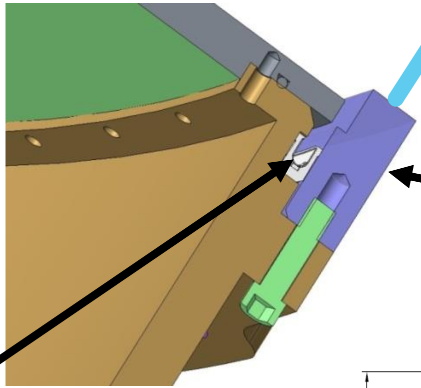




1. Mechanical Discussion from End Toward Center
   - Wagon Wheels
   - Strongbacks
   - Field Cage Mechanics
   - Potential Stripes
   - Central “Membrane”
2. Physical Discussion from Center Toward End
   - Gas Considerations
   - Space Charge
   - IBF
   - GEMs & Frames
   - ZigZag Pads
   - SAMPA & Cooling
3. Laser Calibration
4. Test Beam Results

Wagon Wheel Design

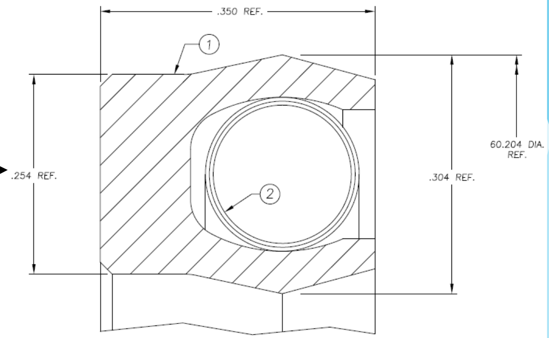


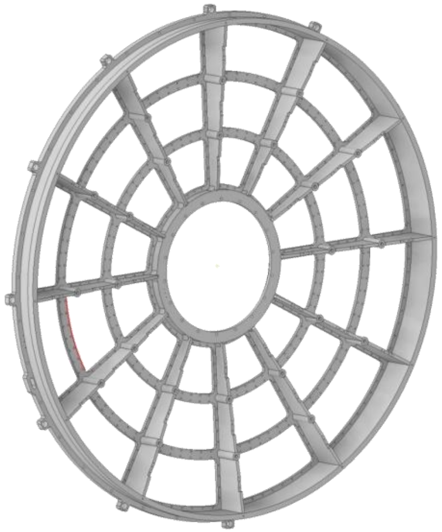


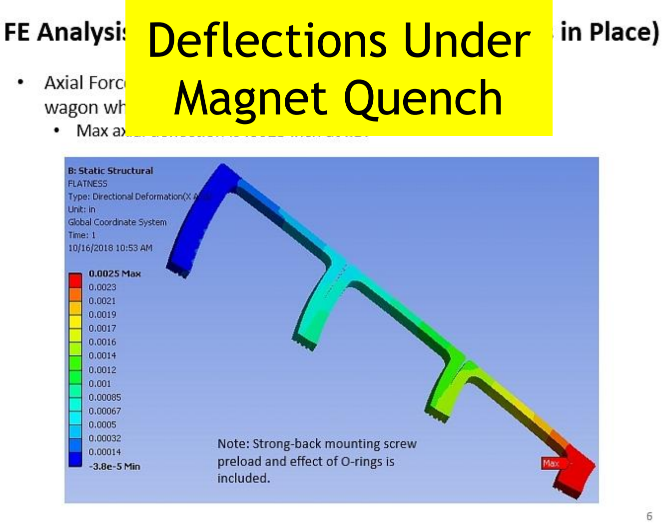
Toward Central Membrane

Aluminum End Ring

Spring-Energized Static Gland Seal for Outer Field Cage





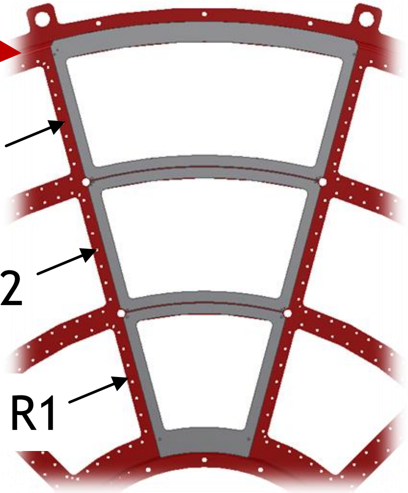


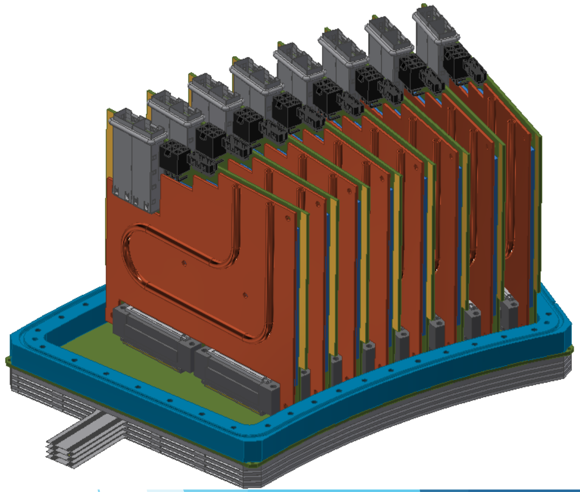
Deflections Under Magnet Quench

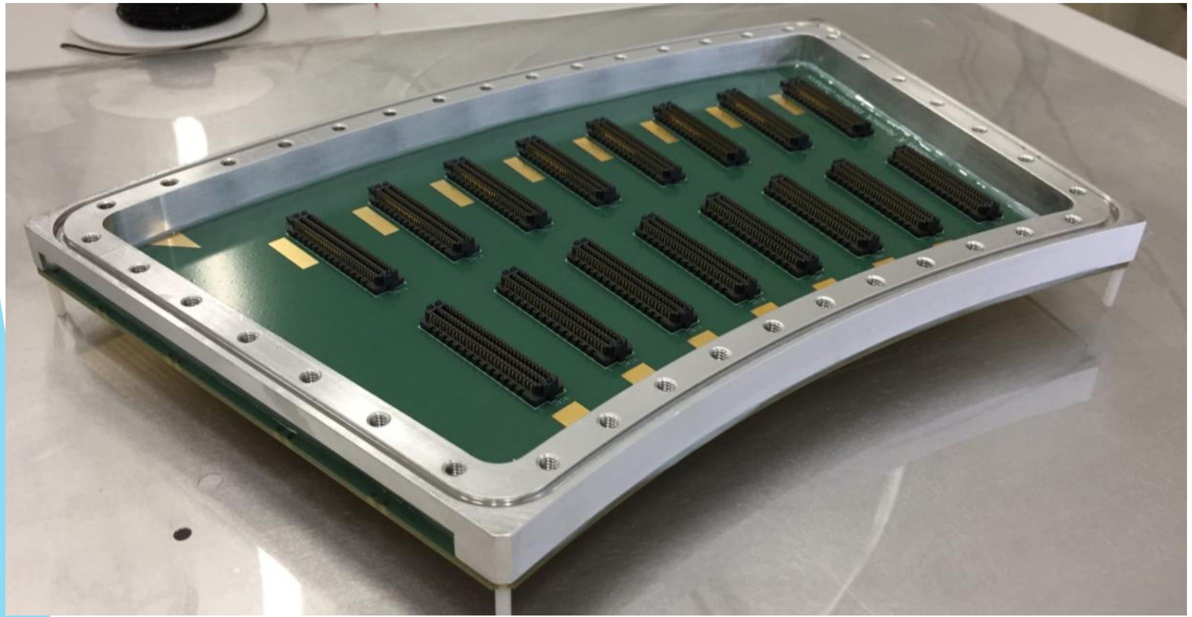
- Single piece aluminum
- “Nose” style seal to avoid distortion.
- 100% O-ring seals.
  - Viton for sealing modules.
  - Spring-energized for sealing to F.C. cylinders
  - Elgiloy (non-magnetic) spring material.
- Deflection ~50μm under magnet quench.

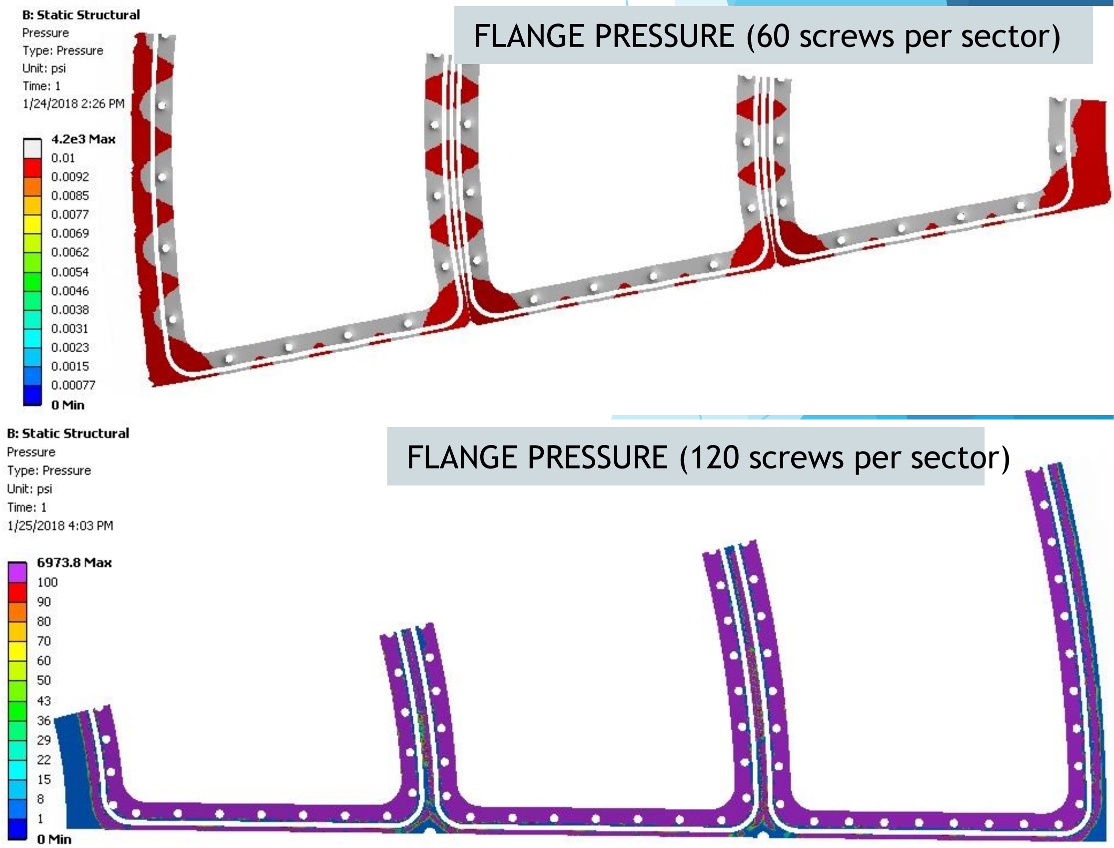
Strongbacks

- Captured O-ring (won't fall out)
- SAMTEC BGA connectors
  - 180 contacts each.
  - VERY low insertion force.
  - Flexible but requires external card support.
- FEA analysis to adjust bolt pattern for good seal and also minimal position distortion.

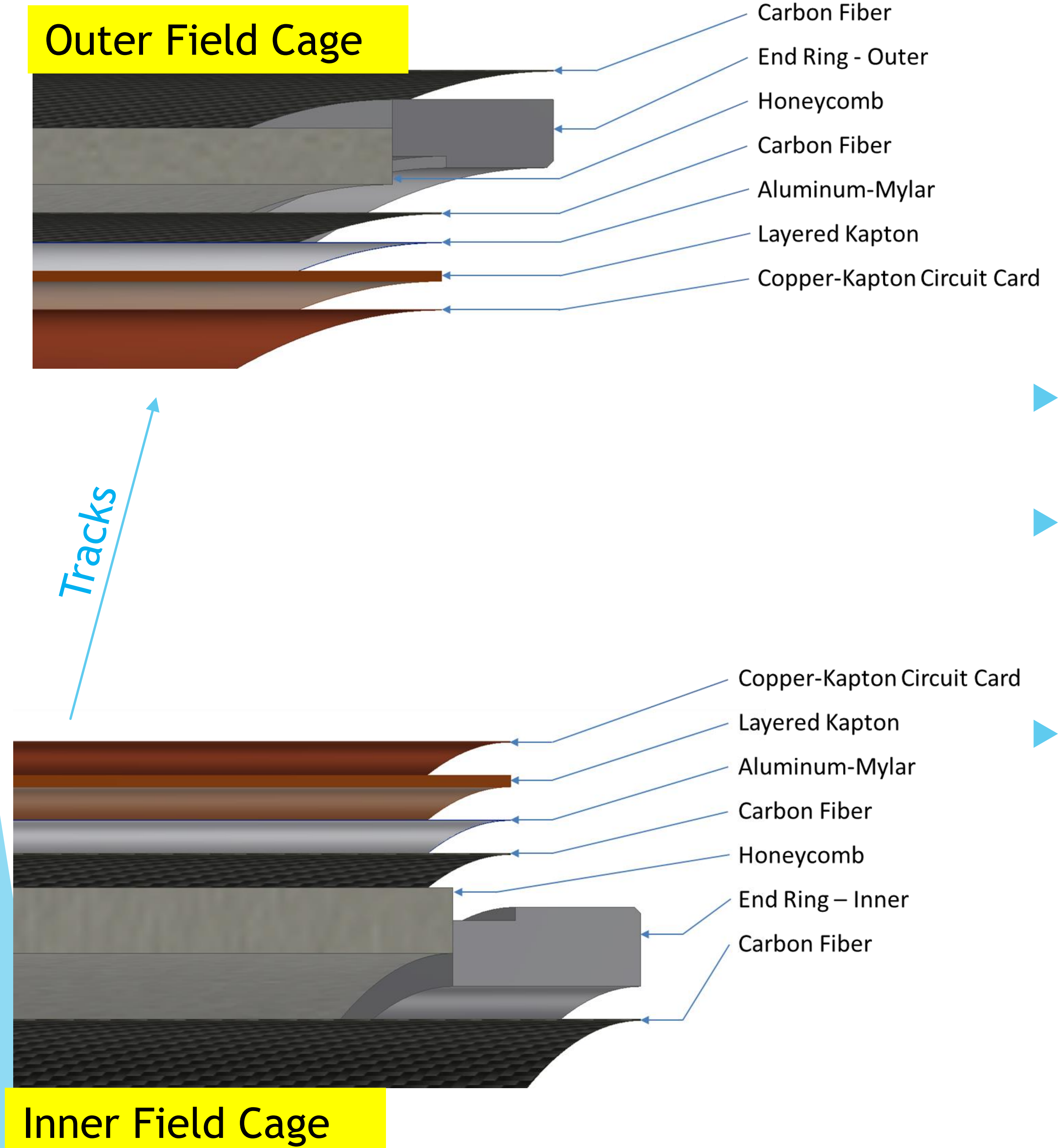




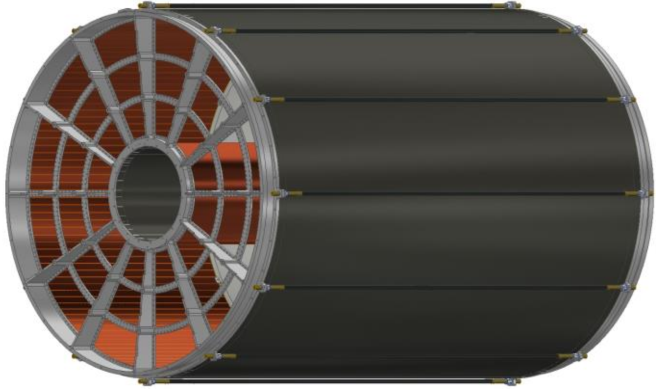


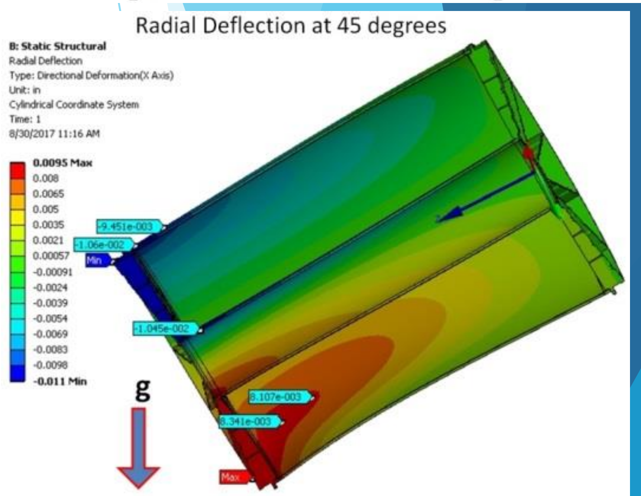


Field Cage Mechanical

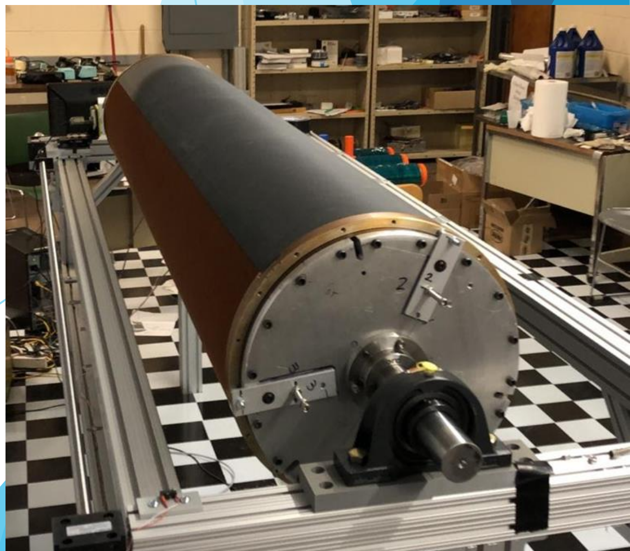


- ***Total TPC weight in this model = 652 lb***
  - Outer Field Cage = 82 lb
  - Inner Field Cage = 23 lb
  - Outer End Ring = 16 lb
  - Inner End Ring = 4.3 lb
  - Outer Honeycomb = 14 lb
  - Inner Honeycomb = 3.6 lb
  - Outer FR4 = 21 lb
  - Inner FR4 = 5.7 lb
  - End Cap = 105 lb
  - Gem Mounting Plates (1/2" thick blanks on one side) = 128 lb

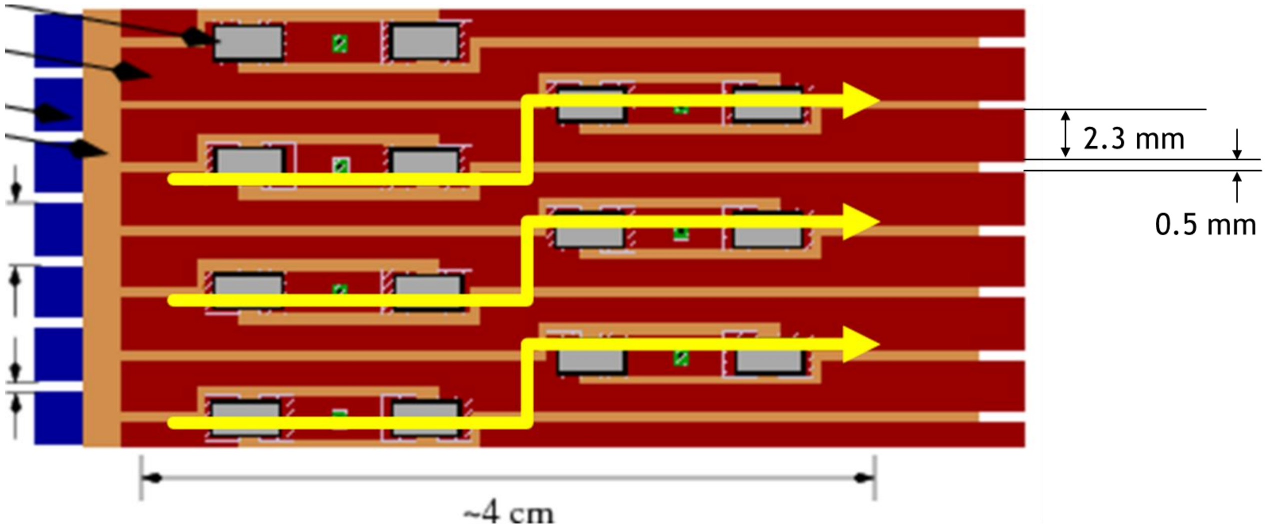


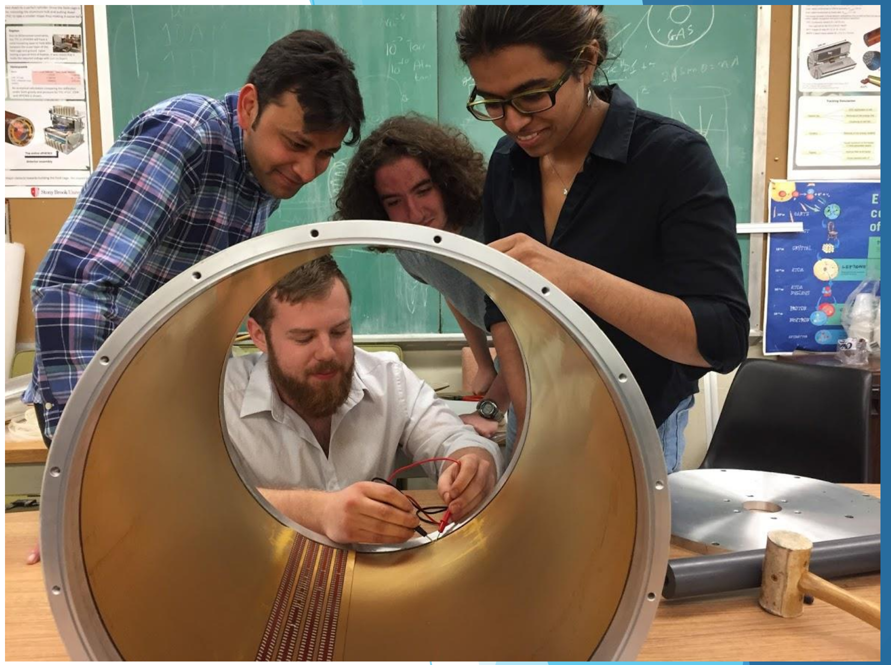


- Minimal thickness (lever arm).
- VERY strong
  - Honeycomb on bench
  - Finite Element
- Holds voltage w/ kapton
  - Sierra Circuits:
    - HV circuit card design
    - Use 1mm
  - sPHENIX
    - Use 2mm

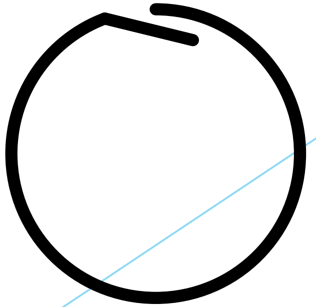


Field Shaping Stripes



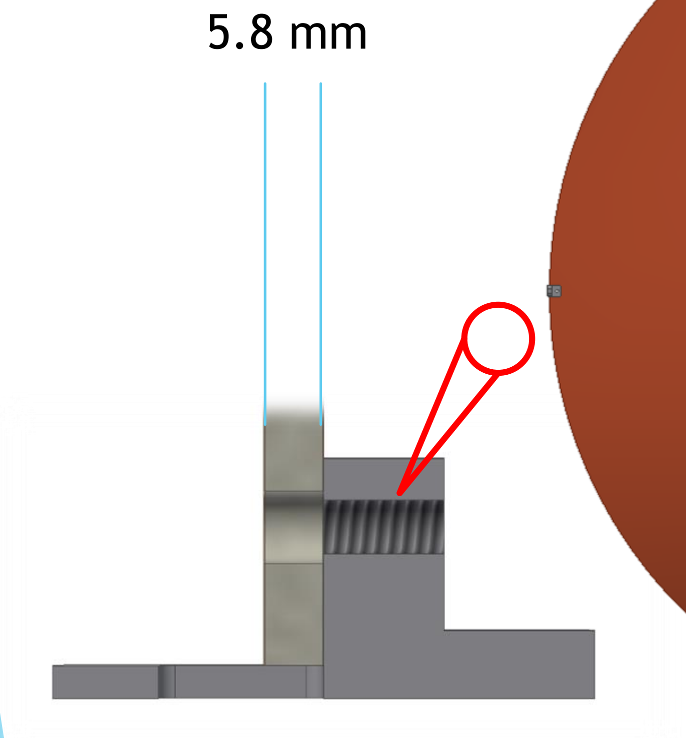


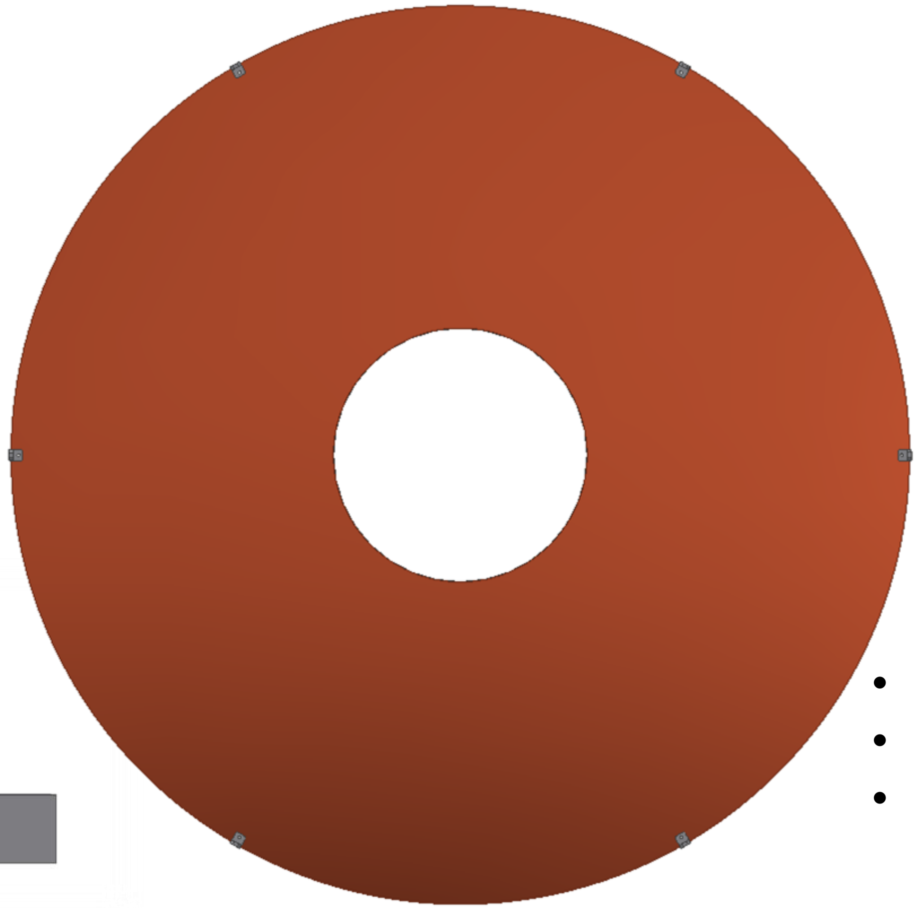
- Small pitch makes useful drift space closer to cage.
- ½ voltage on the back-side protection stripe
- Stripe-to-stripe ~1250 V in air (100 V required in service)
- High Voltage Pulse Withstanding (HVPW) resistors.
  - Survives surges of 15 kV
  - Nominal running at 50 V
- Redundant chains @ 1.06 Watts/chain (0.6 mW per resistor).
- Circuit card covers full circumference (over 5 meters long)
- Incomplete ring (magnet quench consideration)

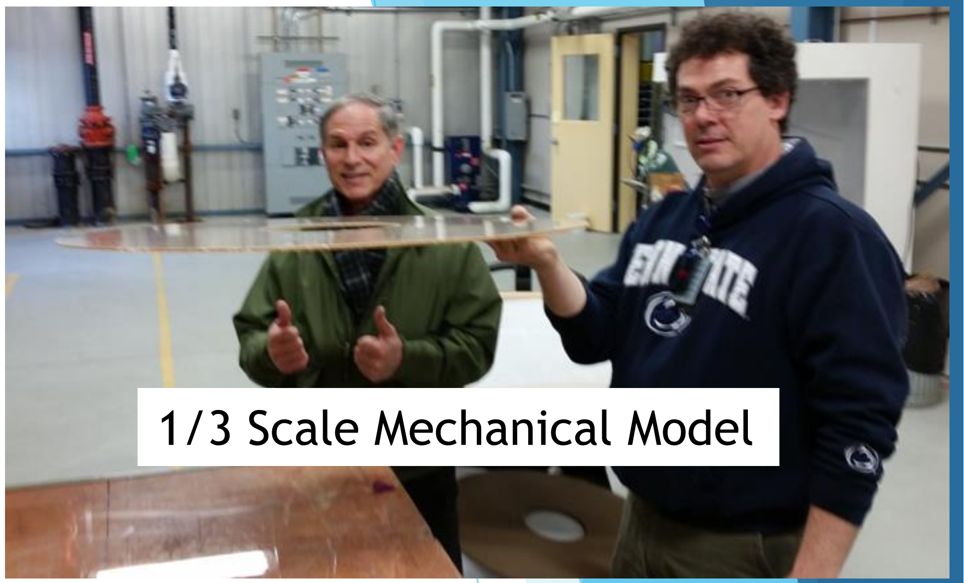


ALL Flex Company
65 flaws from 7200 resistors

Central "Membrane"

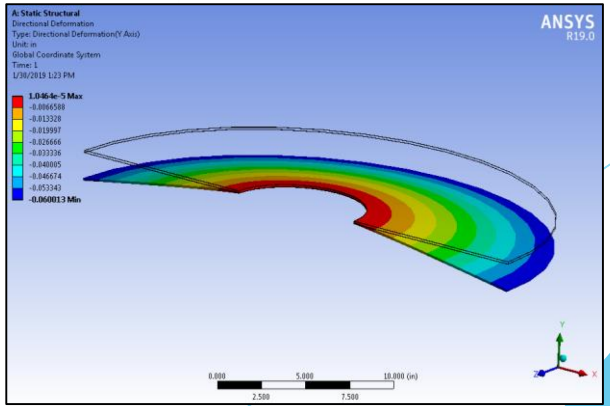






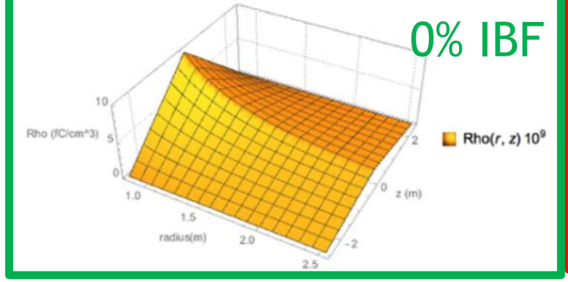
- 1/4oz copper
- 5 mil FR4
- 4 mil (100 μm) gaps

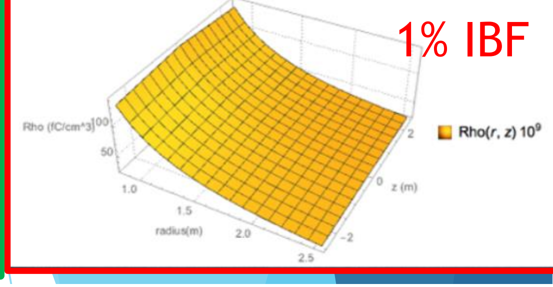
Mechanical Properties Tests



- Honeycomb sandwich
  - Immune to vibrations; sturdy under magnet quench.
- Flower Petals connected by resistors (limit Eddy)
- "Butterboard" mounting tabs.

Battling Space Charge

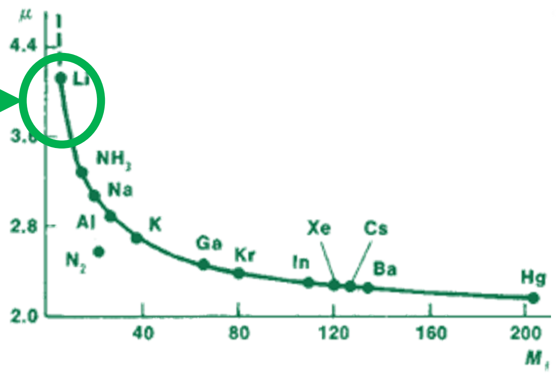




Primary IBF

$$\rho(r,z)\ \alpha\ \frac{Ionization * Multiplicity * Rate}{v_{ION}}\left[\frac{1-\frac{z}{Length}+C}{r^2}\right]$$

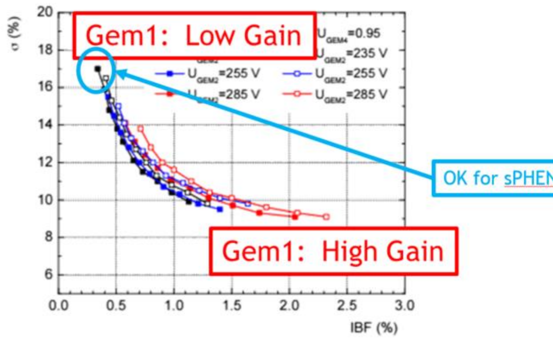
- Low Ionization: Use Low-Z Primary Gas (Ne)
- Large v_{ION}:
  - Large K: Low-Z Primary Gas (Ne)
  - Large E: (400 V/cm) field.
- Small C:
  - Bias Operating Point of MPGD for low IBF (ALICE)
  - Passive IBF shielding.
- Move the inner field cage to minimize Distortion:
  - Rates= 50-200 kHz, 100 kHz shown in figure.

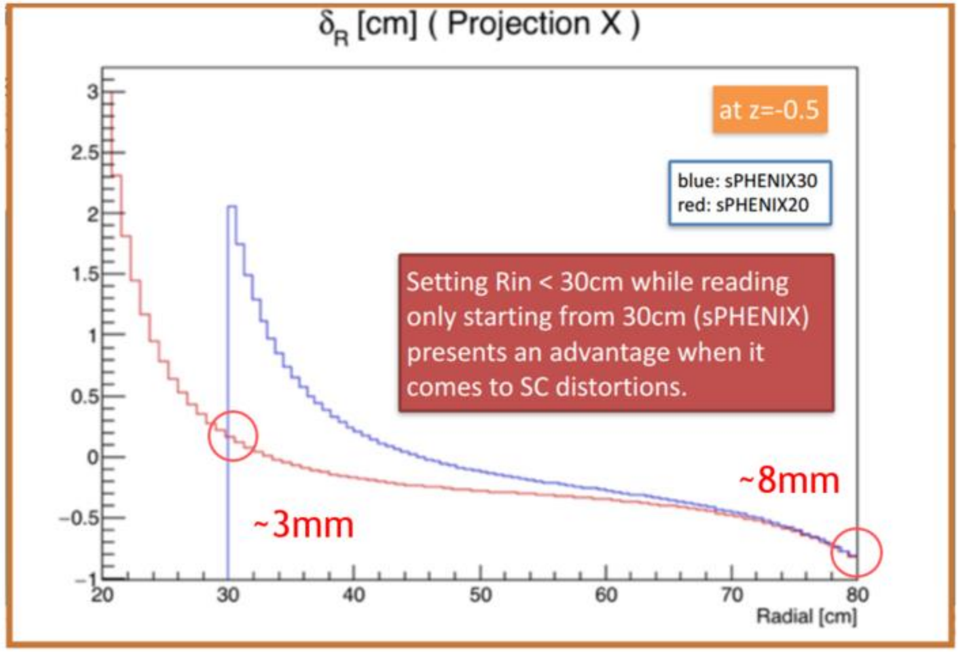


$$v_{ion\ drift} = KE$$

Drift Field

Mobility





Rossegger's Thesis (ALICE)

- Once the solutions to the homogeneous equation are known, we express the Dirac delta function in this basis:

$$\begin{aligned}
\delta(\phi-\phi') &= \frac{1}{2\pi}\sum_{m=-\infty}^{\infty} e^{im(\phi-\phi')} = \frac{1}{2\pi}\sum_{m=0}^{\infty}(2-\delta_{m0})\cos[m(\phi-\phi')], \\
\frac{\delta(r-r')}{r} &= \sum_{n=1}^{\infty}\frac{R_{mn}(r)R_{mn}(r')}{\bar{N}_{mn}^2} \quad \text{with} \quad \bar{N}_{nm}^2 = \int_a^b R_{mn}^2(r)\, r\,dr, \\
m &= 0, 1, 2, \ldots\,.
\end{aligned}$$

- After which the solution is readily obtained:

$$G(r,\phi,z;r',\phi',z') = \frac{1}{2\pi}\sum_{m=0}^{\infty}\sum_{n=1}^{\infty}(2-\delta_{m0})\cos[m(\phi-\phi')]\frac{R_{mn}(r)R_{mn}(r')}{\bar{N}_{mn}^2}\frac{\sinh(\beta_{mn}z_<)\sinh(\beta_{mn}(L-z_>))}{\beta_{mn}\sinh(\beta_{mn}L)}.$$

- Although the solution is correct, it is not assured to be readily convergent.
- Rossegger used three independent basis sets to obtain stable, differentiable, convergent solutions for the r, ϕ, and z components of the field:

$$\frac{\partial}{\partial z}G(r,\phi,z,r',\phi',z') = \frac{1}{2\pi}\sum_{m=0}^{\infty}\sum_{n=1}^{\infty}(2-\delta_{m0})\cos[m(\phi-\phi')]\frac{R_{mn}(r)R_{mn}(r')}{N_{mn}^2}\frac{\partial}{\partial z}\left(\frac{\sinh(\beta_{mn}z_<)\sinh(\beta_{mn}(L-z_>))}{\beta_{mn}\sinh(\beta_{mn}L)}\right), \tag{5.64}$$

with
$$\frac{\partial}{\partial z}(\sinh(\beta_{mn}z_<)\sinh(\beta_{mn}(L-z_>))) = \begin{cases} \beta_{mn}\cosh(\beta_{mn}z)\sinh(\beta_{mn}(L-z')), & \text{for } 0\le z<z'\le L, \\ -\beta_{mn}\cosh(\beta_{mn}(L-z))\sinh(\beta_{mn}z'), & \text{for } 0\le z'<z\le L. \end{cases}$$

$$\frac{\partial}{\partial r}G(r,\phi,z,r',\phi',z') = \frac{1}{\pi L}\sum_{m=0}^{\infty}\sum_{n=1}^{\infty}(2-\delta_{m0})\cos[m(\phi-\phi')]\sin(\beta_n z)\sin(\beta_n z')\frac{\partial}{\partial r}\left(\frac{R_{mn\,1}(r_<)R_{mn\,2}(r_>)}{I_m(\beta_n a)K_m(\beta_n b)-I_m(\beta_n b)K_m(\beta_n a)}\right), \tag{5.65}$$

with
$$\frac{\partial}{\partial r}(R_{mn\,1}(r_<)R_{mn\,2}(r_>)) = \begin{cases} R'_{mn}(a,r)R_{mn\,2}(r'), & \text{for } a\le r<r'\le b, \\ R_{mn\,1}(r')R'_{mn}(b,r), & \text{for } a\le r'<r\le b, \end{cases}$$

wherein $R'_{mn}(s,t)$ is

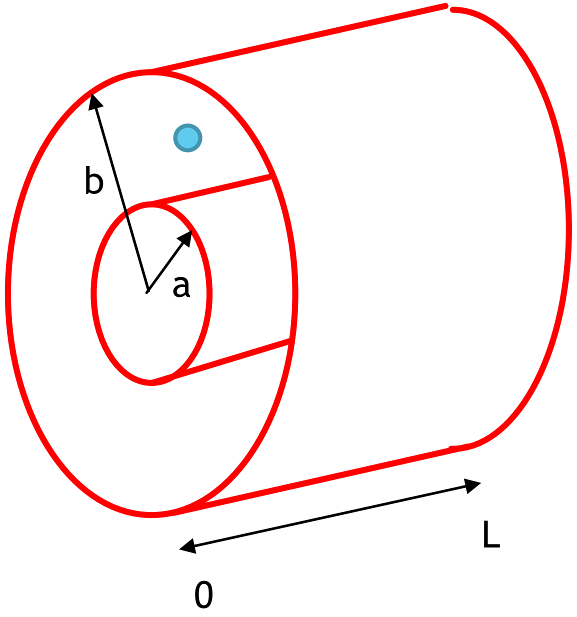
$$R'_{mn}(s,t) = \frac{\beta_n}{2}\left(K_m(\beta_n s)(I_{m-1}(\beta_n t)+I_{m+1}(\beta_n t)) + I_m(\beta_n s)(K_{m-1}(\beta_n t)+K_{m+1}(\beta_n t)\right).$$

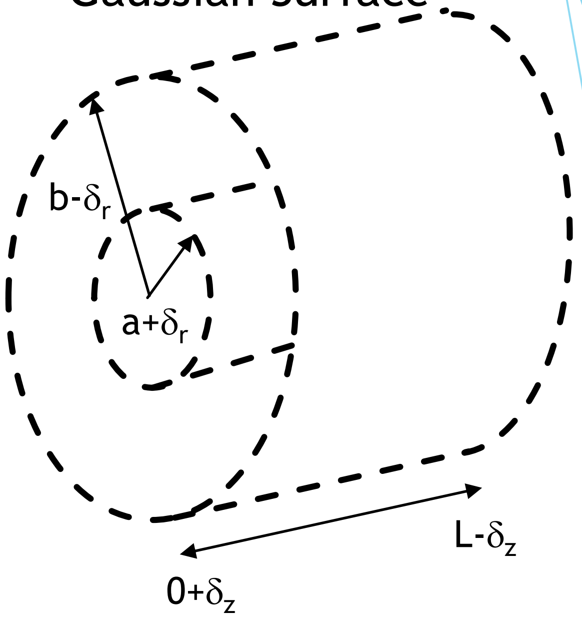
$$\frac{\partial}{\partial \phi}G(r,\phi,z,r',\phi',z') = \frac{1}{L}\sum_{k=1}^{\infty}\sum_{n=1}^{\infty}\sin(\beta_n z)\sin(\beta_n z')\frac{R_{nk}(r)R_{nk}(r')}{N_{nk}^2}\frac{\partial}{\partial\phi}\left(\frac{\cosh[\mu_{nk}(\pi-|\phi-\phi'|)]}{\mu_{nk}\sinh(\pi\mu_{nk})}\right) \tag{5.66}$$

with
$$\frac{\partial}{\partial\phi}(\cosh[\mu_{nk}(\pi-|\phi-\phi'|)]) = \begin{cases} -\mu_{nk}\sinh[\mu_{nk}(\pi-(\phi-\phi')), & \text{for } 0\le\phi'<\phi\le 2\pi \\ \mu_{nk}\sinh[\mu_{nk}(\pi-(\phi'-\phi)), & \text{for } 0\le\phi<\phi'\le 2\pi \end{cases}$$

Gauss' Law Test

$$\oint \vec{E} \cdot \vec{dA} = \frac{Q_{in}}{\epsilon_0}$$

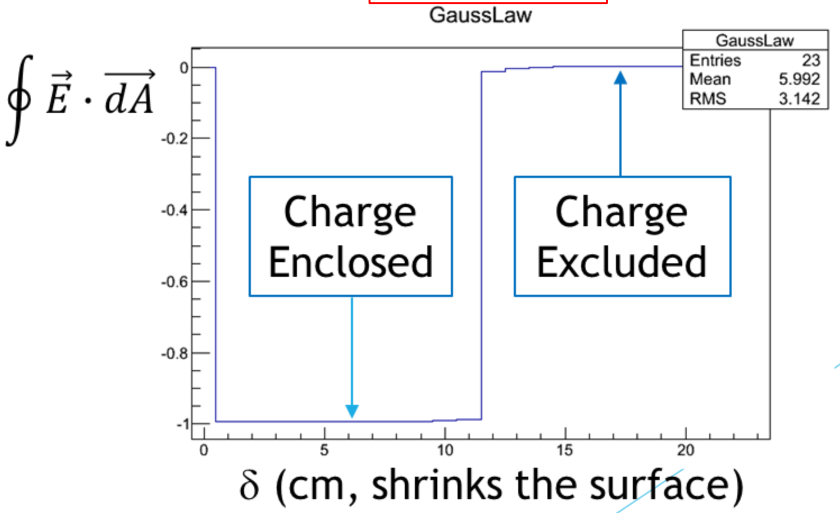




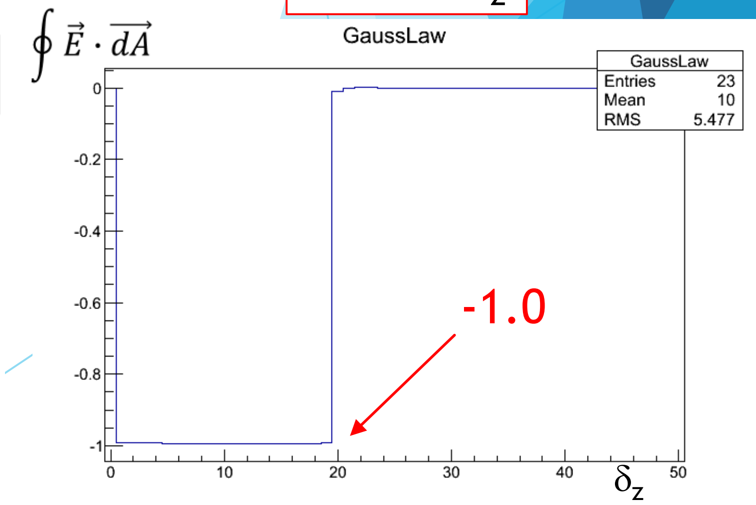
- Place single point charge.
- Gaussian surface "interior" by δ_r and by δ_z.
- Integrate Gauss' Law vs δ_r and by δ_z.
- Expectation:
  - Constant while charge enclosed.
  - Zero when charge excluded.
- Integral negative due to dropping minus:

$$\vec{E} = -\vec{\nabla} V$$

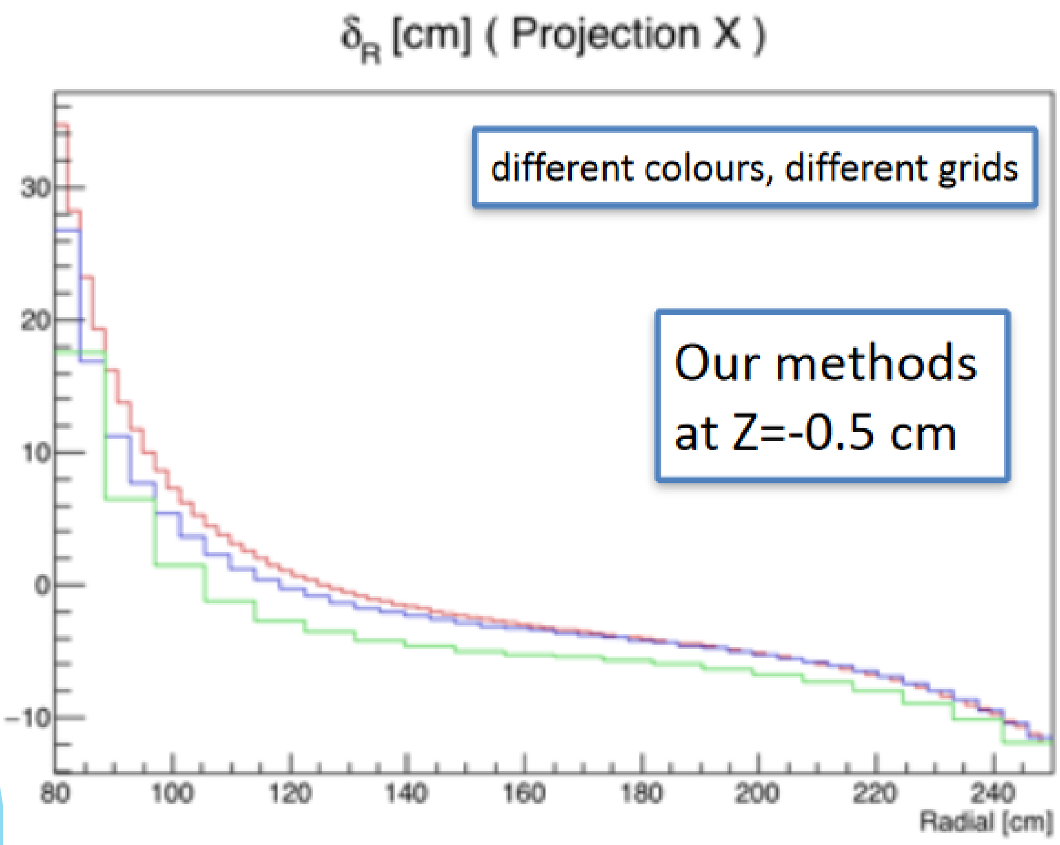
Test of E_r



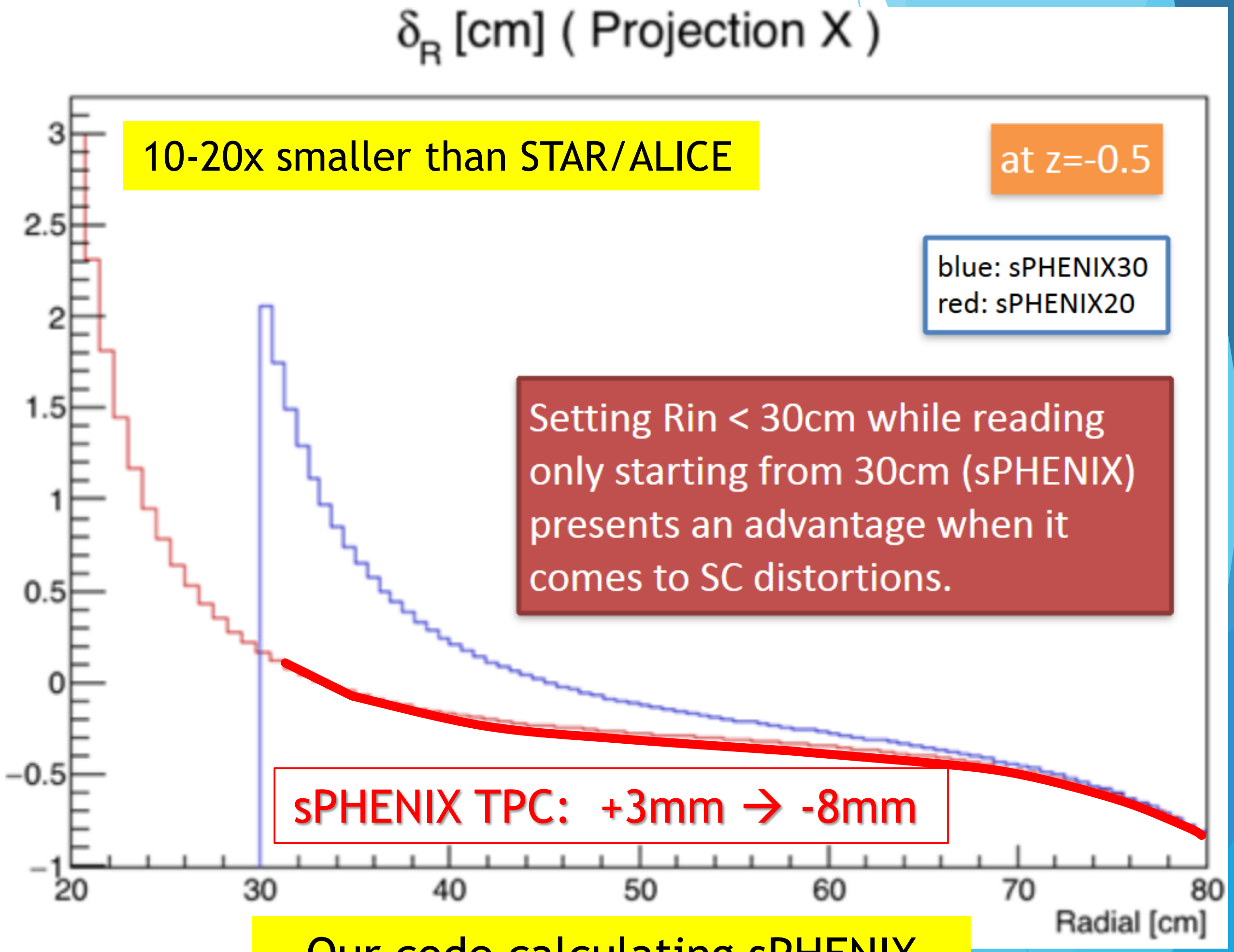
Test of E_z



IBF & SC simulations for TPC

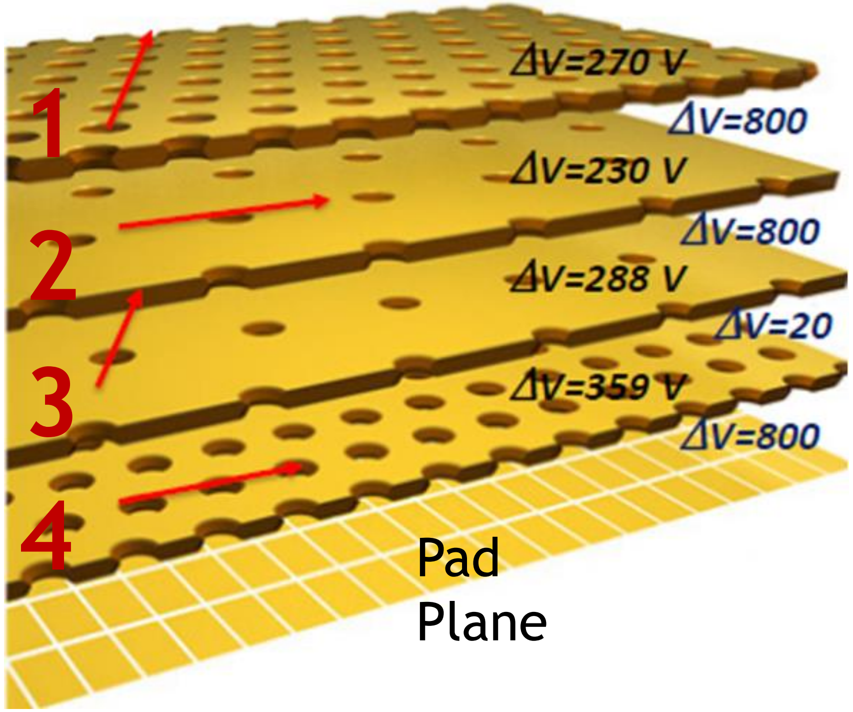


Our code calculating ALICE TDR Condition agrees with ALICE

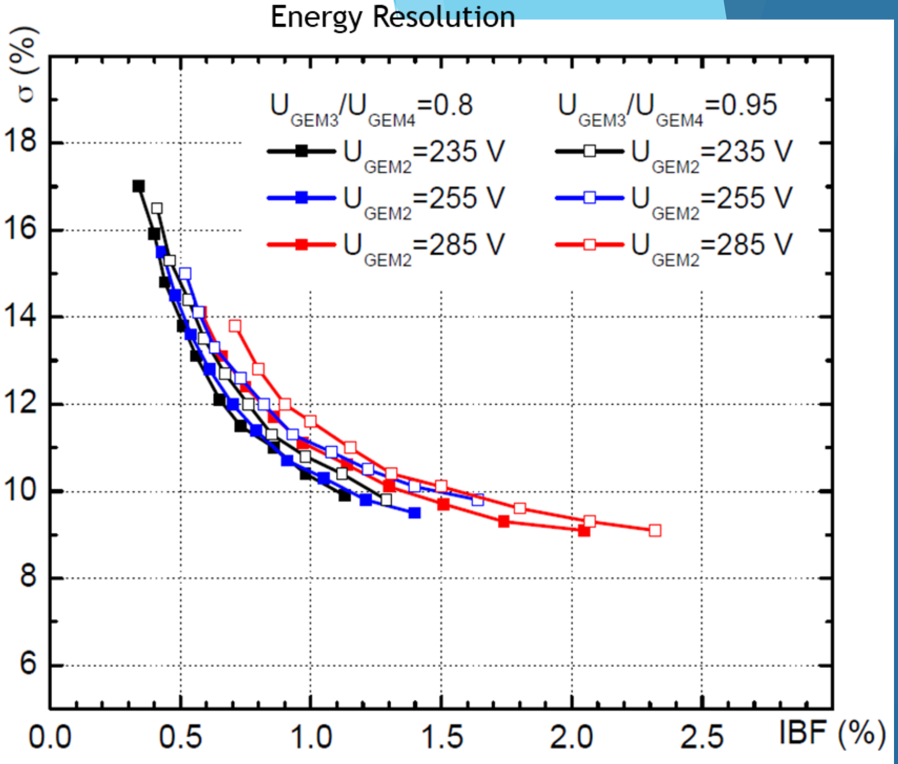


Our code calculating sPHENIX condition using "Radius Trick"

IBF from Gain Stage (conceptual)



ALICE

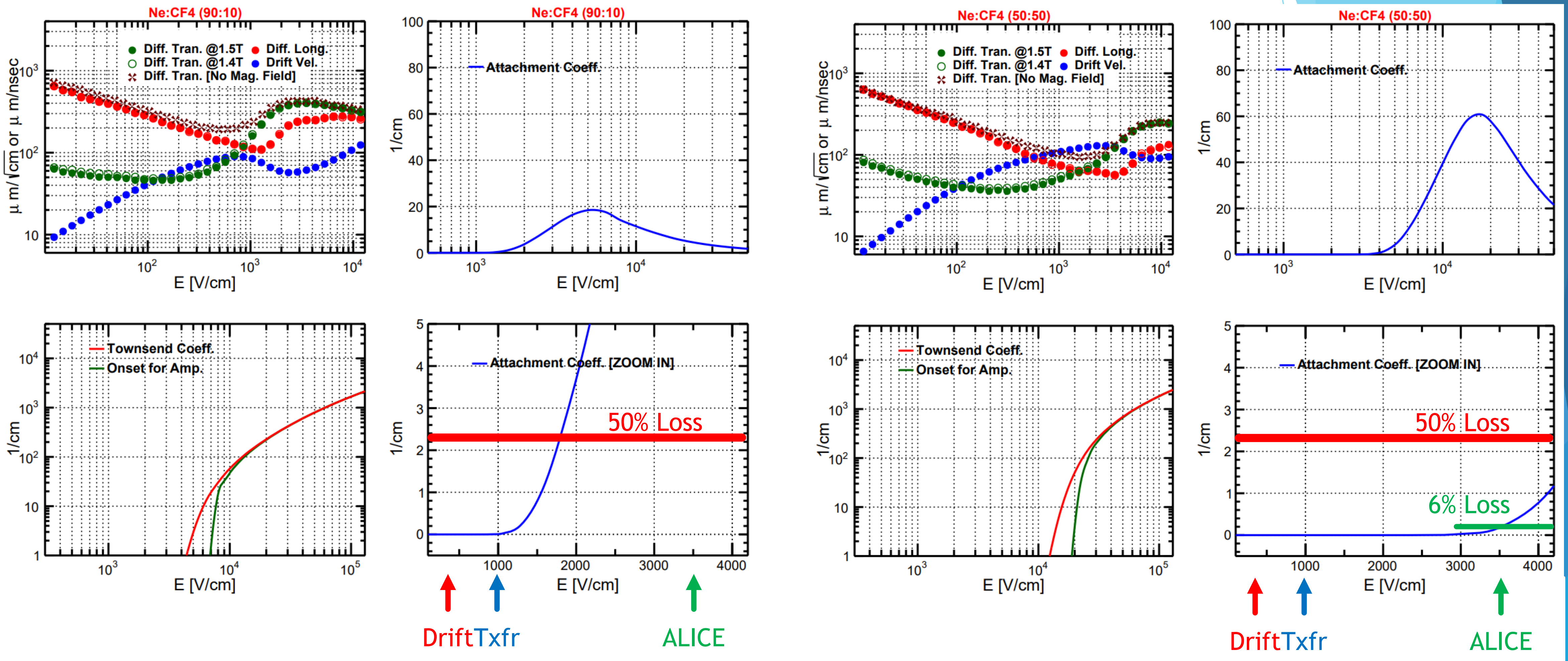


2014-03-03 TDR for the Upgrade of the ALICE TPC

- Two basic principles of achieving low IBF:
  - $E_{out} \gg E_{in}$
  - GEM1 & GEM4
  - Low collection efficiency at wide hole spacing:
    - Electron loss compensated by gain.
    - Ion loss permanent
    - GEM3 & GEM2

- Comments
  - IBF from GEM1 competes with resolution
  - Large Txfr fields are required to "ruin" electron/ion collection efficiency at widely spaced holes.
- Questions to Experts
  - What about narrowing holes in LP layers?
  - Why not larger than 280 μm pitch…300, 320?

Gas Considerations Diffusion vs Attachment



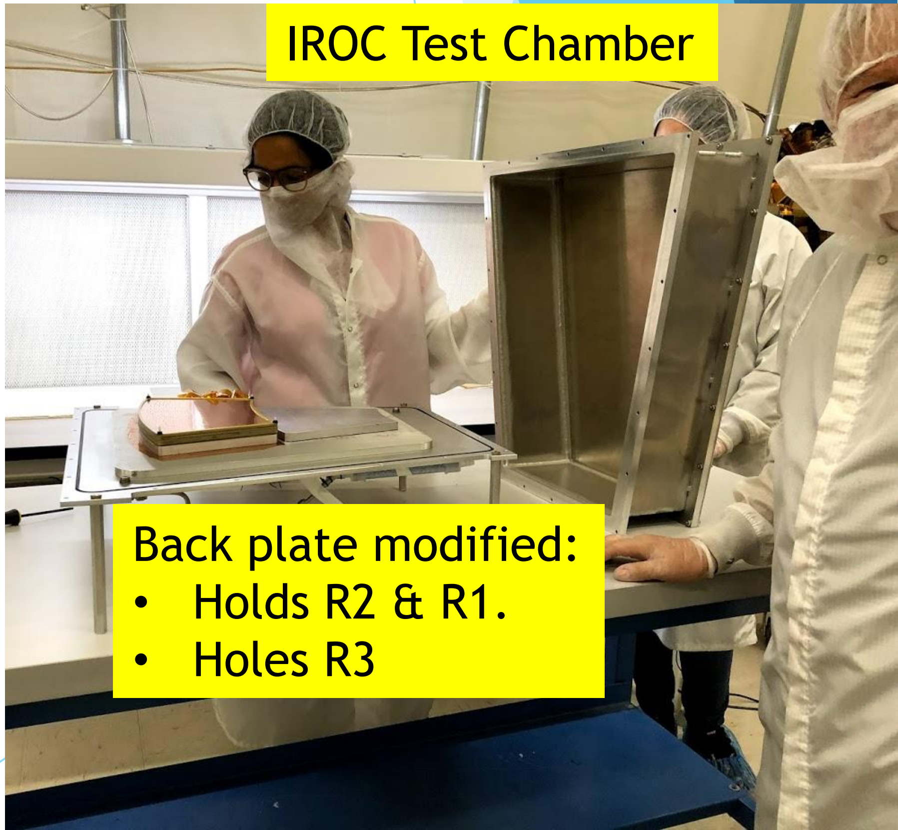
- Last year we ran “Standard” Transfer Gap fields w/ Ne:CF_4 90:10
- ALICE solution would attach electrons in transfer gap.
- Attachment point moves to safe place w/ 50:50 mixture.

Tested Low IBF Settings

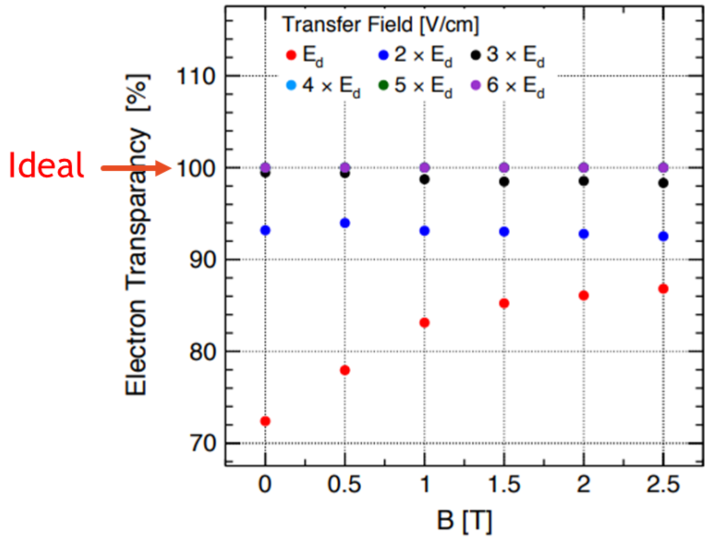
V	sphenix	0	0	0
0	1	2	3	4
G1 Top	4208	4658	5124	5118
G1 Bot	3951	4401	4851	4861
G2 Top	3051	3351	3651	3661
G2 Bot	2721	3021	3321	3342
G3 Top	1821	1971	2121	2142
G3 Bot	1409	1559	1709	1709
G4 Top	1379	1529	1679	1679
G4 Bot	900	1050	1200	1200

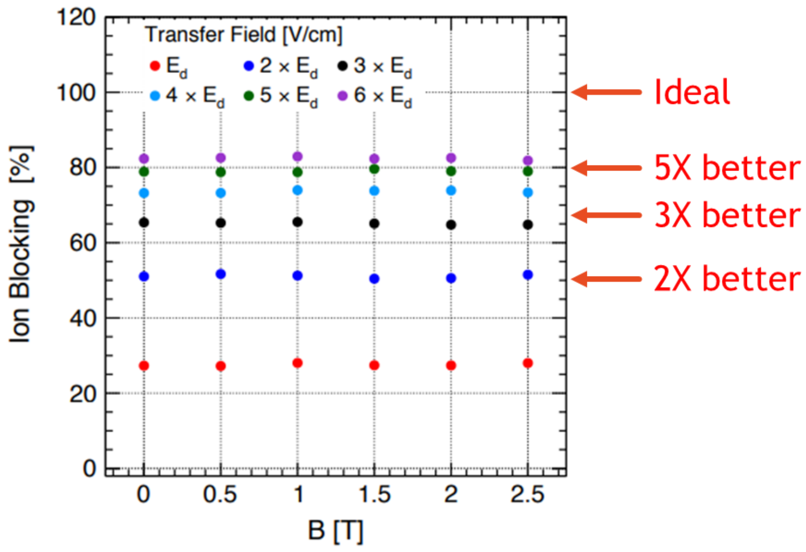
NO spark activity.
- Nikolai 4.03 run for log term in beam
- Nikolai 4.03 "blasted" with X-rays at Yale.

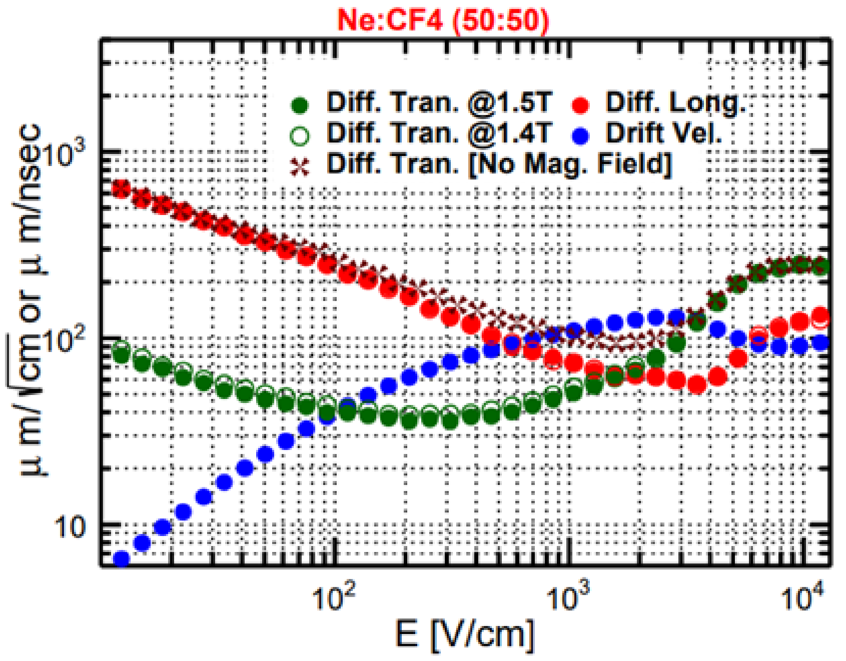
- IBF for these configurations without grid:
  - 0.44%, 0.39%, 0.33%, 0.31%
- IBF anticipated with passive grid (2X reduction):
  - 0.22%, 0.20%, 0.17%, 0.16%
- All these tested in test beam.



Static Mesh

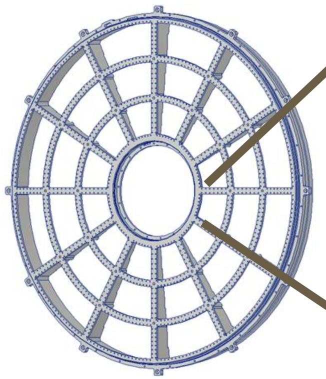




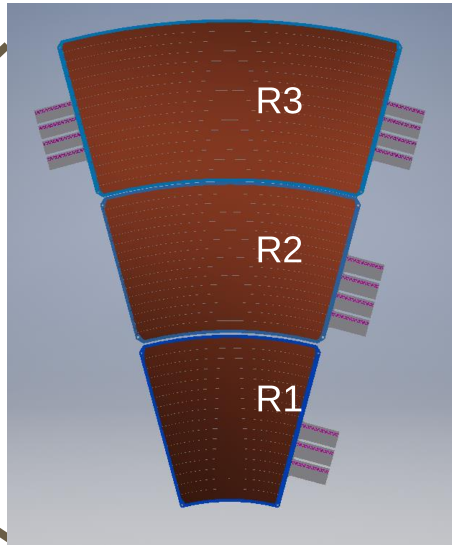


- The electrons will not couple directly from the gas to the first GEM, but pass through a fine (~90% optical transparency) mesh.
- This mesh's initial purpose was to "terminate" the drift field on a surface whose HV requirement is decoupled from the gain stage.
- The gap (~2cm) from mesh-to-GEM is sufficient that the mesh is connected to the field cage itself and the GEMstacks can turn on/off at will.
- The mesh might be run in a passive IBF blocking mode as well.
  - VERY preliminary thought: Drop main drift field to 200 V/cm and have 400 V/cm between mesh/GEM.
  - IBF is a wash (down 2X but so is mobility); HV in cage down; other stuff about the same…

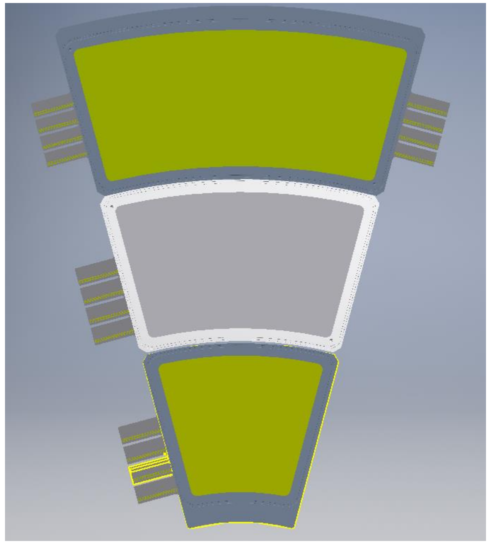
GEM Design



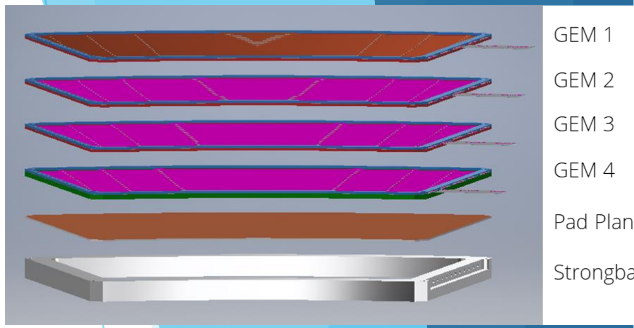
Wagon Wheel



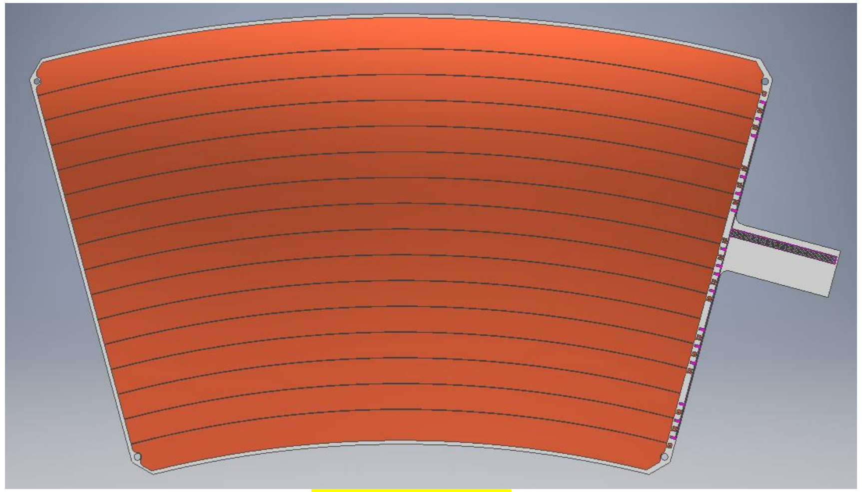
Front



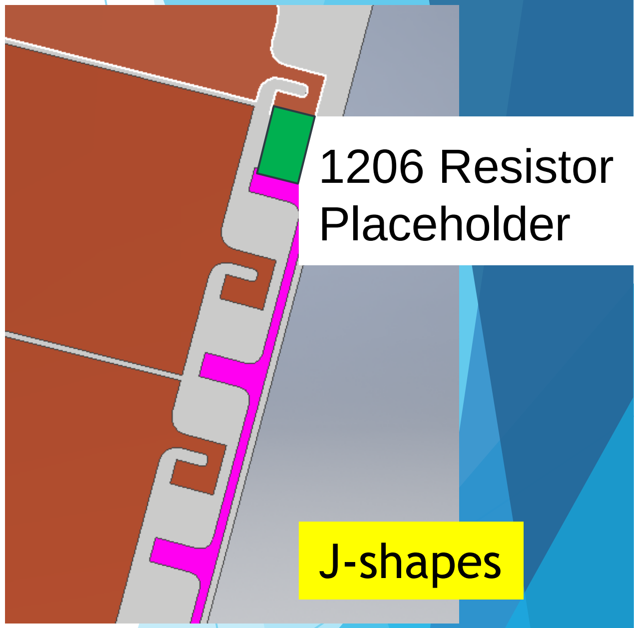
Back



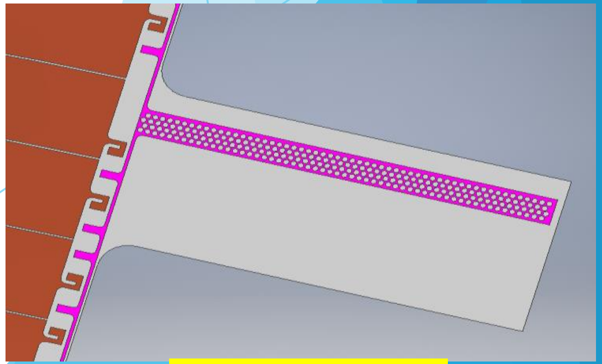
- GEMs highly segmented:
  - R1 & R2 in 16 arced rows.
  - R2 16x2 (rows by columns)
- Framed on BOTH sides
  - Personal preference Hemmick/Dehmelt
- Narrowest frames allowed by E-field
- J-shaped solder pads limit solder flow
- Hex-ribbon for longevity of flexible tab:
  - Standard industry trick.
  - Cracks prevented from **propagating.**



R2 GEM



J-shapes

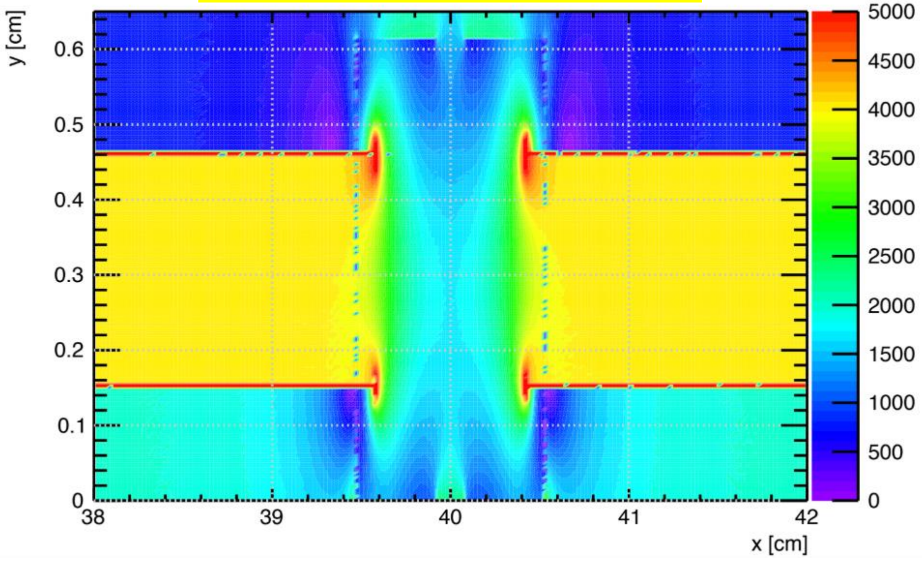


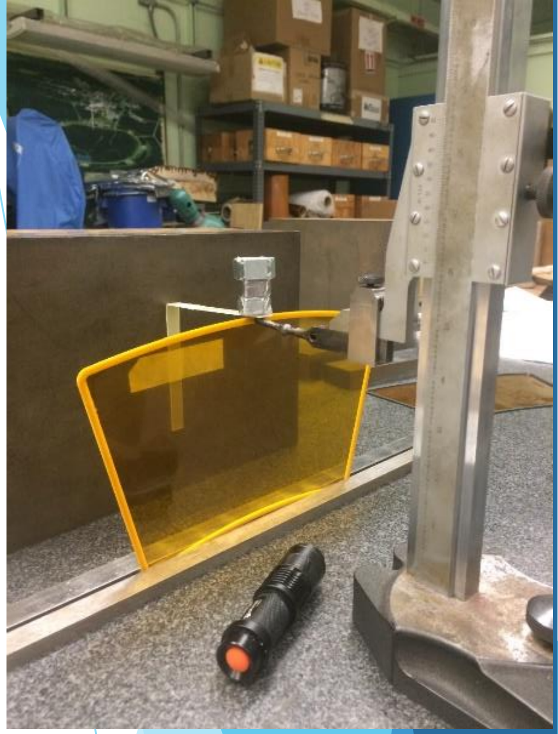
Hex-ribbon

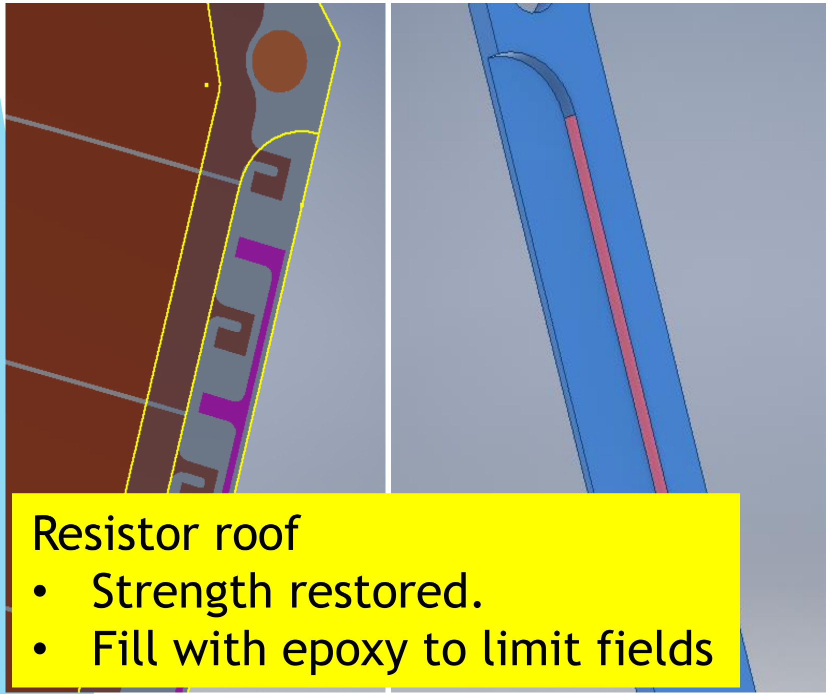
GEM Frame Design

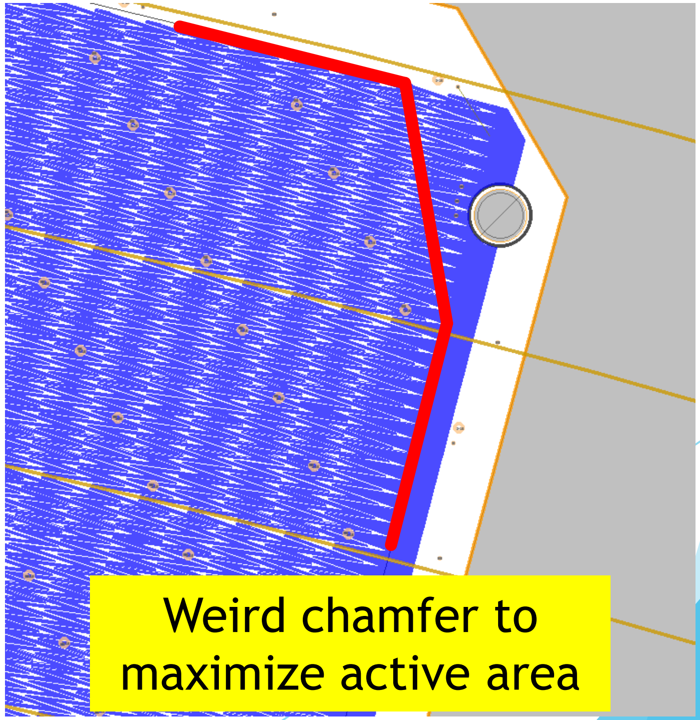
- How narrow can you frame?
  - Strong E-field contained under frame.
  - Restore strength with “resistor roof”
- Arcs are unstable under tension
  - They “pop” out of plane.
  - Wants thicker frame (3mm Gem-to-GEM)
- Strange chamfer

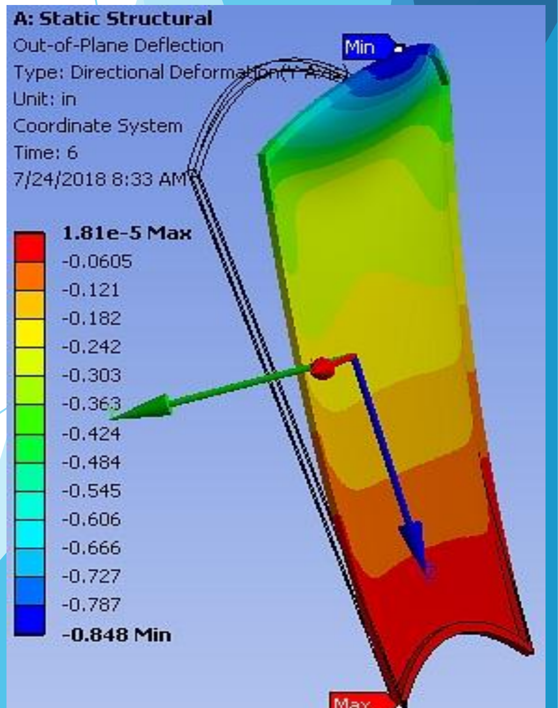
HV Leak containment











Zig-Zag Pads

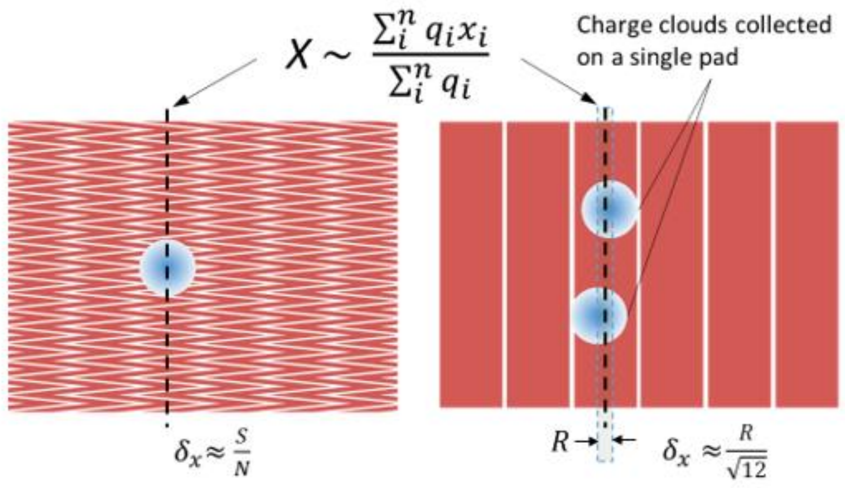
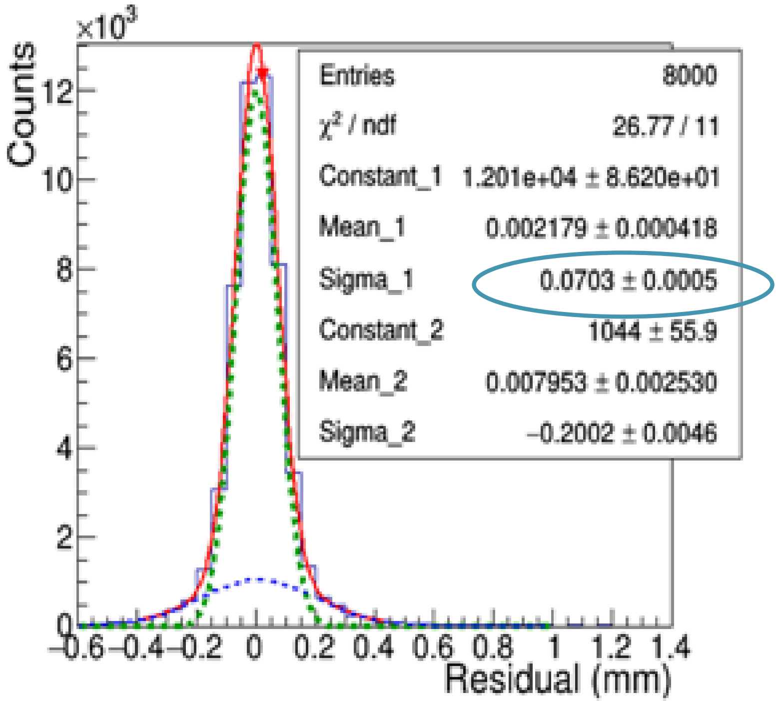


Fig. 1 Sketches of two different readout patterns demonstrate charge sharing and its impact on the centroid calculation and the related position error for a zigzag and rectangular pad geometry. 6 channels are shown for each pattern with the same pitch. (The drawings are to scale.)



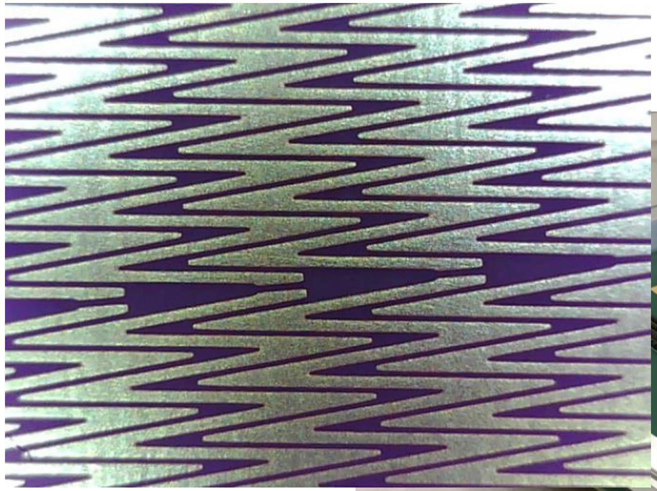
70 microns

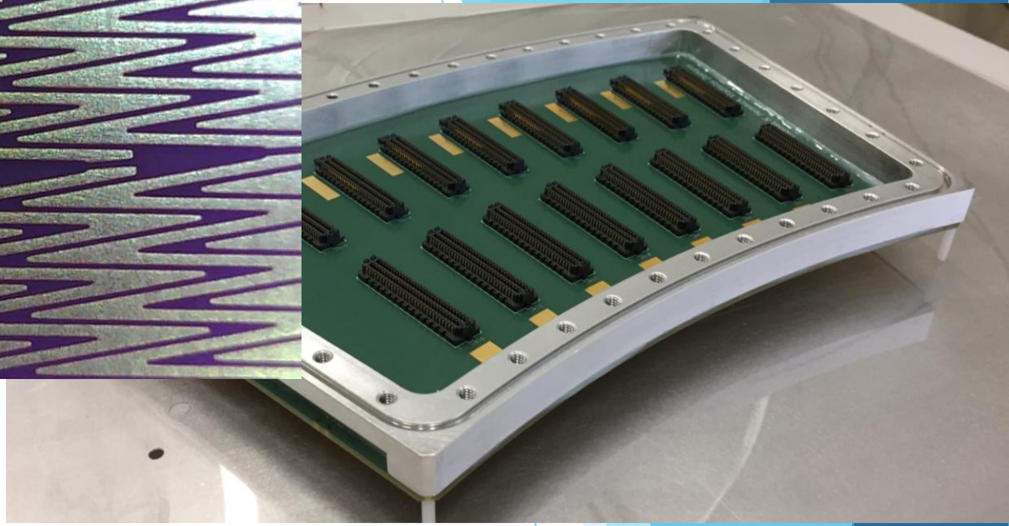
- Low diffusion can cause single pad hits (poor resolution).
- Zig-Zags not only minimize single hits, they achieve resolutions to a smaller fraction of the pitch than rectangles.
- EXTENSIVE studies at BNL lead to several principle conclusions
  - Incursions of nearly 100% are required for good linearity.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

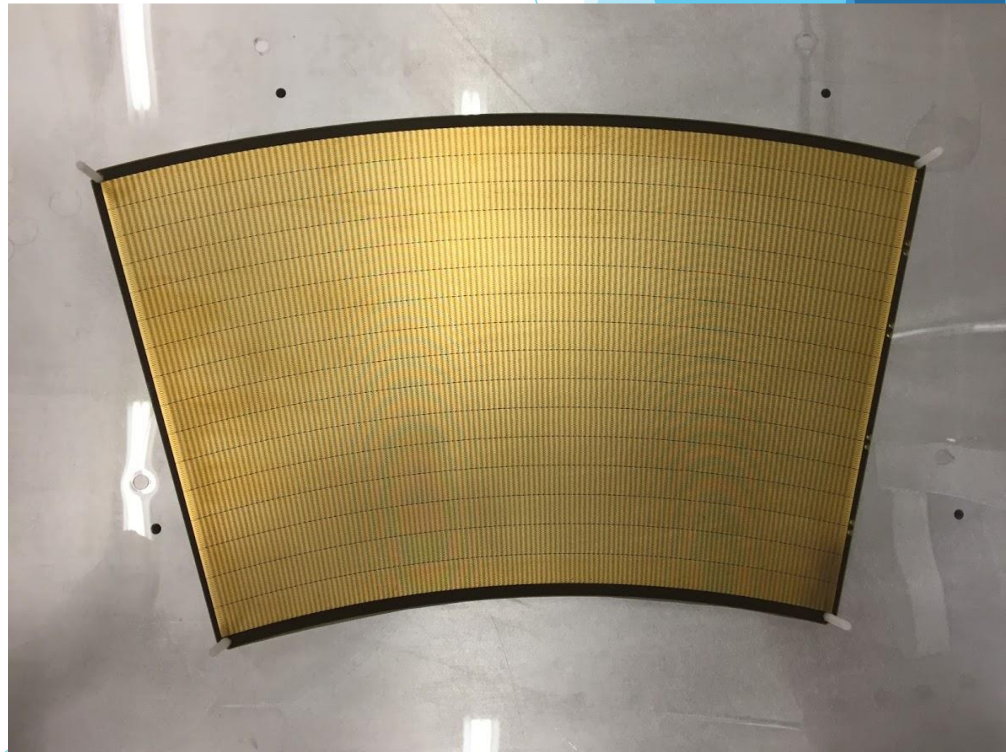
- Insursion is percentage of pad spacing by which one ZZ penetrates its neighbor.
- 100% incursion means neighbors tip penetrates to nominal pad center.

Pad Board Design

- Thick board is made very flat and “structural”.
- SAMTEC BGA-style connectors:
  - LOTS of signals in small area.
  - VERY low insertion force.
  - VERY forgiving of misalignment.
  - Card must be supported separately.
  - Because signals are “collected” trace lengths vary
  - 11-20 pF depending upon pad.
- Chemically etched circuit card
  - Large area with laser etching unreliable (company refused).
  - Negotiated gap down to 2.7 mils (68 μm)
  - Company REQUIRED “blunt tips”
  - MODIFIED ENIG.
  - Company-tested: no shorts; no opens (TTM, Califonia)
- Readout cards shifted to side allowing for HV access.
- Open ground area to play with…





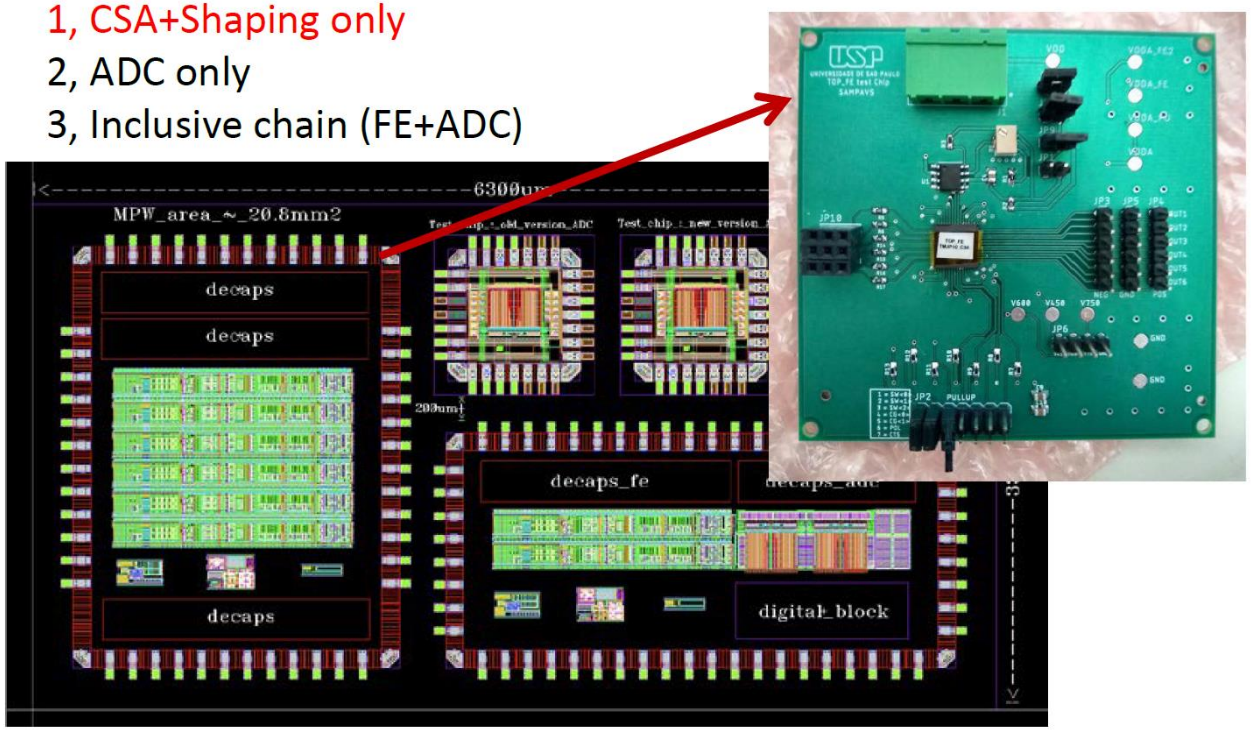


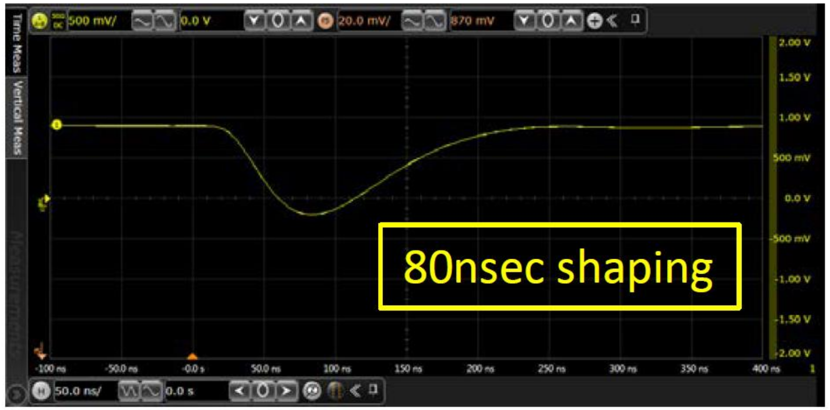
FEE: Takao S & John K.

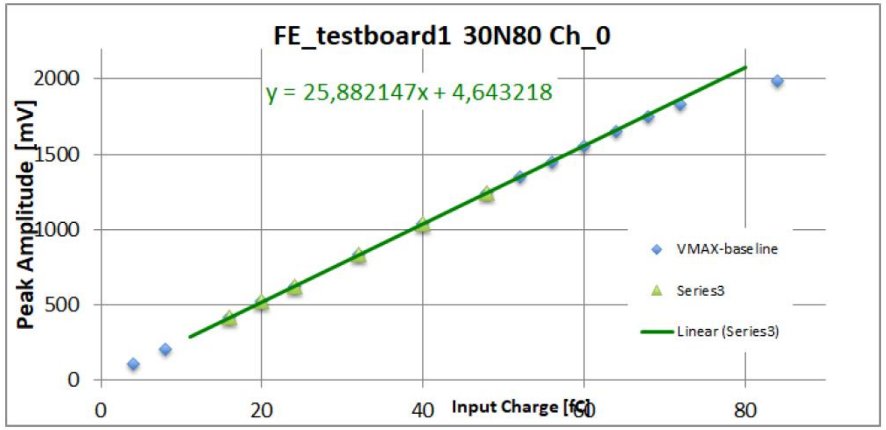
SAMPA progress (FE)

- 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)







SAMPA progress (ADC, FE+ADC)

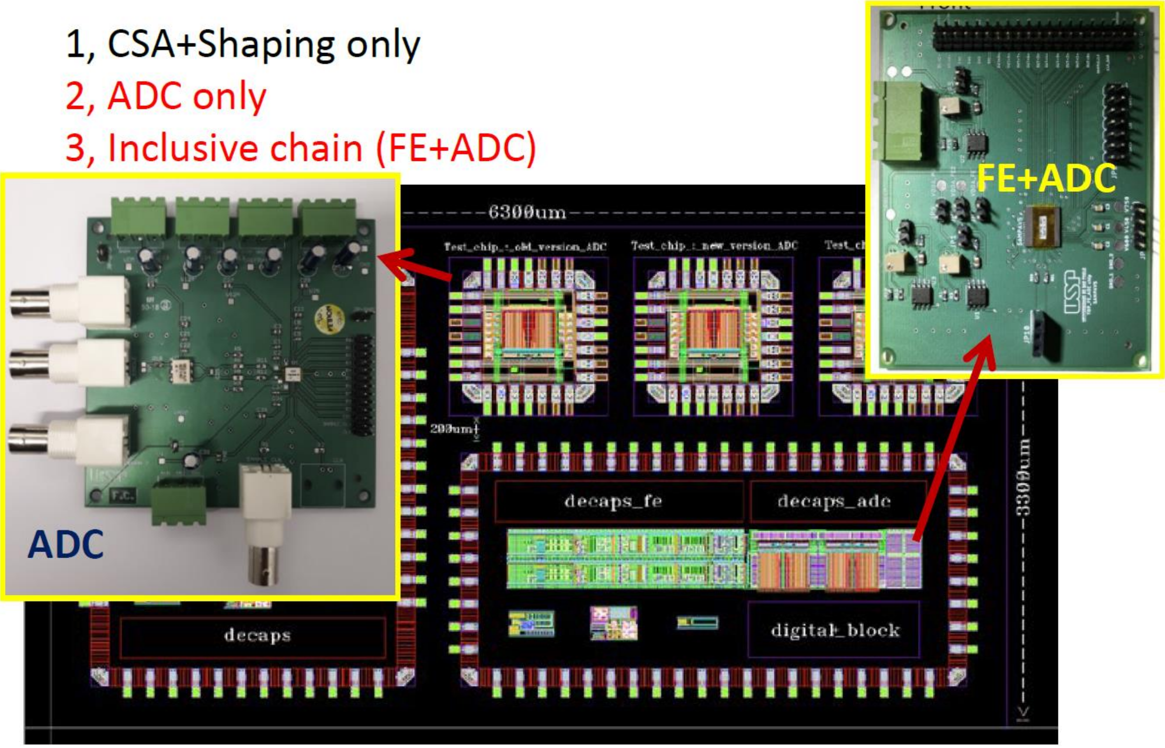
- ADC and FE+ADC components
- ENOB of ADC is found to be better than that of SAMPA v4
  - **Improvement at 18MHz is seen and is close to expected**
- Pulse shape is successfully measured by FE+ADC

	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

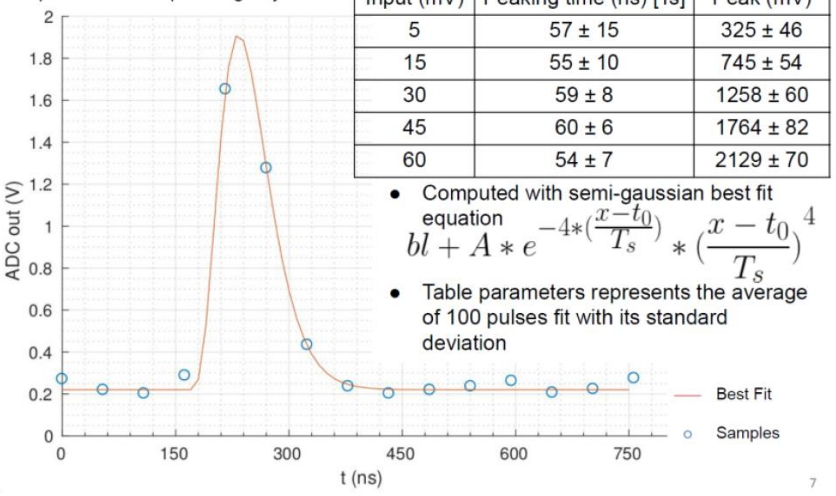
1, CSA+Shaping only

2, ADC only

3, Inclusive chain (FE+ADC)



80nsec, 30mV/fC



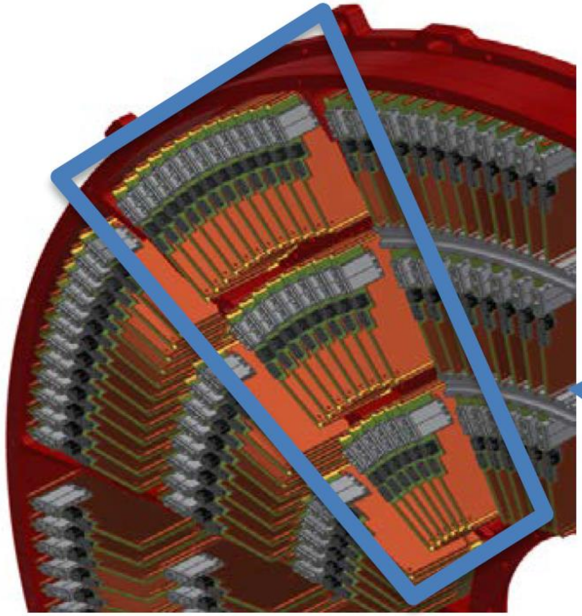
Input (mV)	Peaking time (ns) [Ts]	Peak (mV)
5	57 ± 15	325 ± 46
15	55 ± 10	745 ± 54
30	59 ± 8	1258 ± 60
45	60 ± 6	1764 ± 82
60	54 ± 7	2129 ± 70

- 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

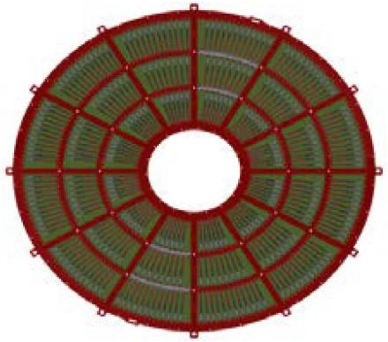
Cooling System Technical Overview

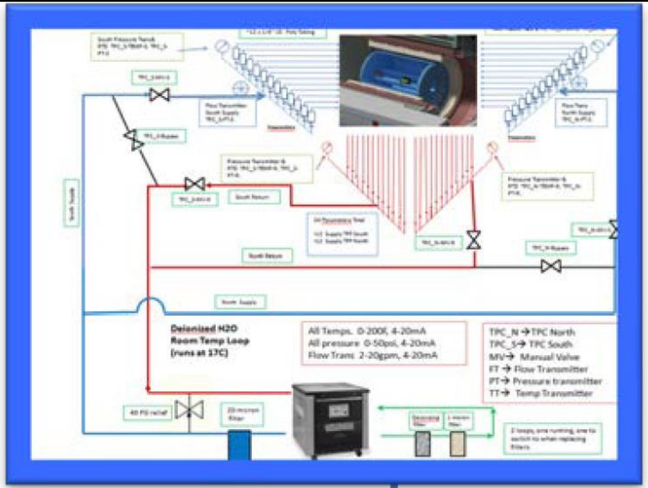
•A Cooling System(1.02.07.03)- Cooling system need to be designed to remove 12kWatts of heat from the TPC Fee's which are located on the end caps of the TPC in side the sPHENIX magnet. System to be operated below atmospheric pressure to prevent coolant leaks.

Segment system along the 12 sectors and remove 500 watts from each (26 FEE)



312 Fee Cards per End Cap:

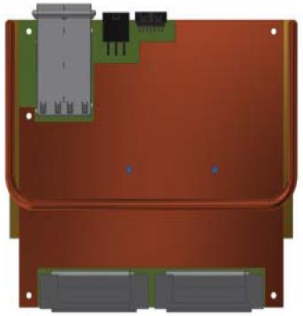




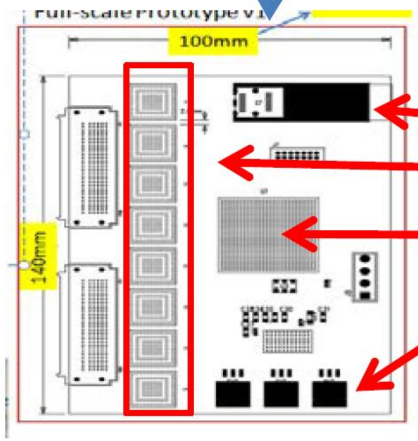
1.02.07.03 Distribution and heat removal

Chilled water sent to TPC

Covered Under WBS1.2.5



Cold Plate Thermally coupled to the Fee Board

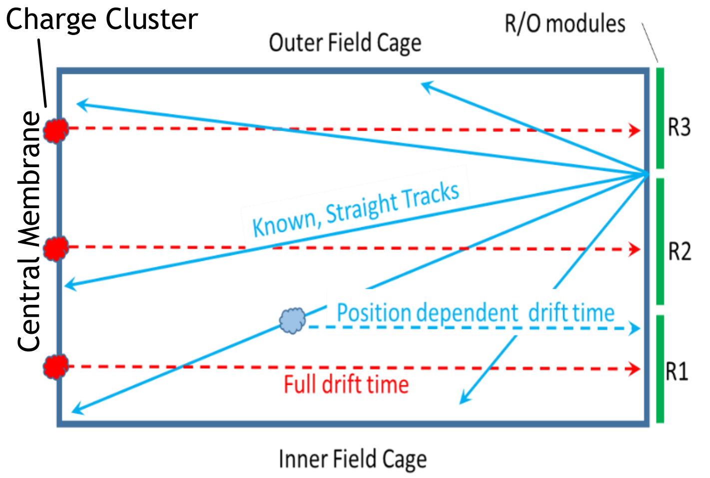


Heat Source
~1watt
~8Watts
~7watts (FPGA)
~3watts

FEE estimated max ~20 watts per board

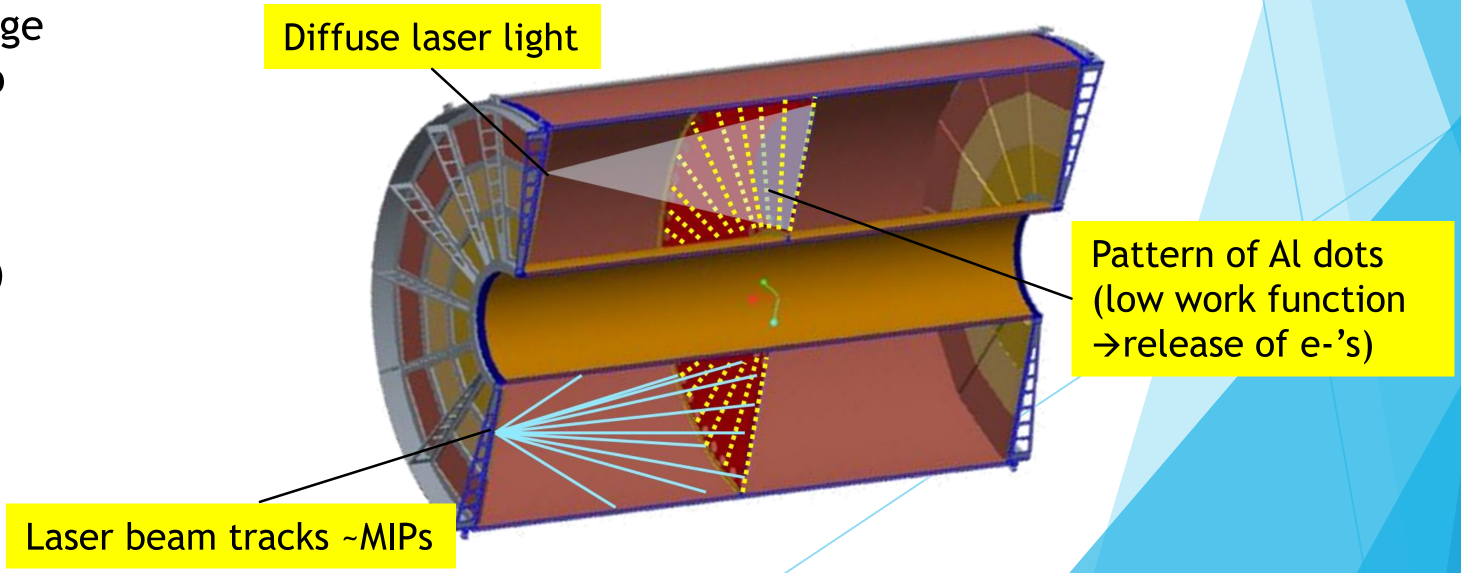
Laser Calibration Overview

PURPOSE: Calibration System
- Determine drift velocity throughout TPC vol.
- Determine electric field distortions
- Determine precise alignment of field cage w.r.t. endcap and magnetic field



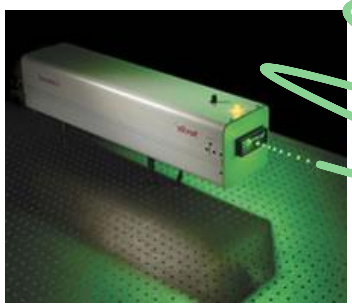
- Charge from the central membrane travels the full drift distance and reveals the **absolute integrated drift velocity**
- A single sweeping laser beam allows for a continuous **sampling of the drift velocity** over a quadrant of the TPC volume
- The integrated drift time serves as a **hard constraint** for the point by point determination of the drift velocity (using system of linear equations)

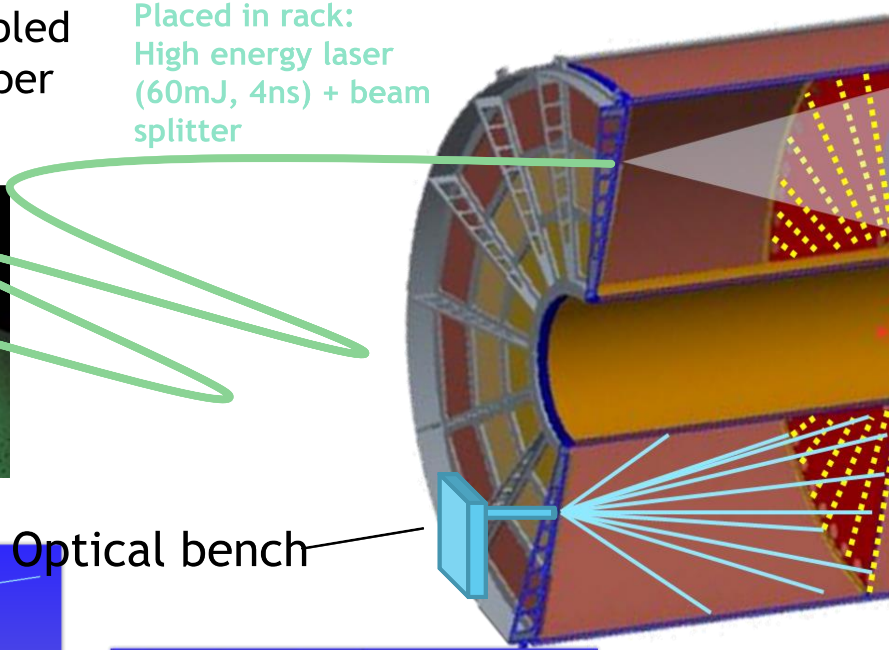
STRATEGY
- Shine **diffuse laser light** onto central membrane to liberate clusters of charge
- Shoot **laser beams** into TPC volume to mimic straight particle tracks
- Compare **straight tracks** to **displaced/distorted tracks**
  - Beam ON vs OFF (space charge effect)
  - B-Field ON vs OFF (**ExB** effect)

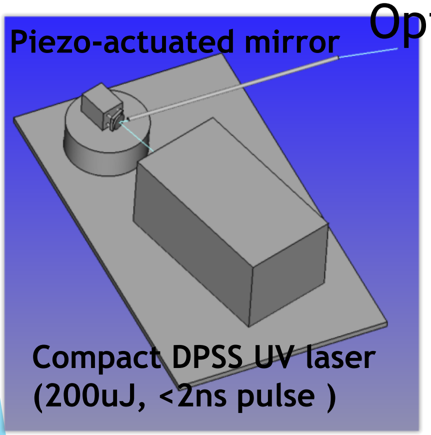


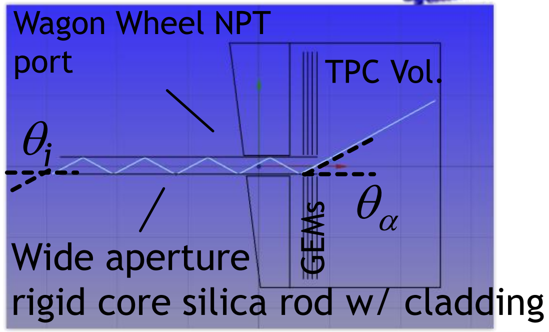
Laser Technical Overview

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



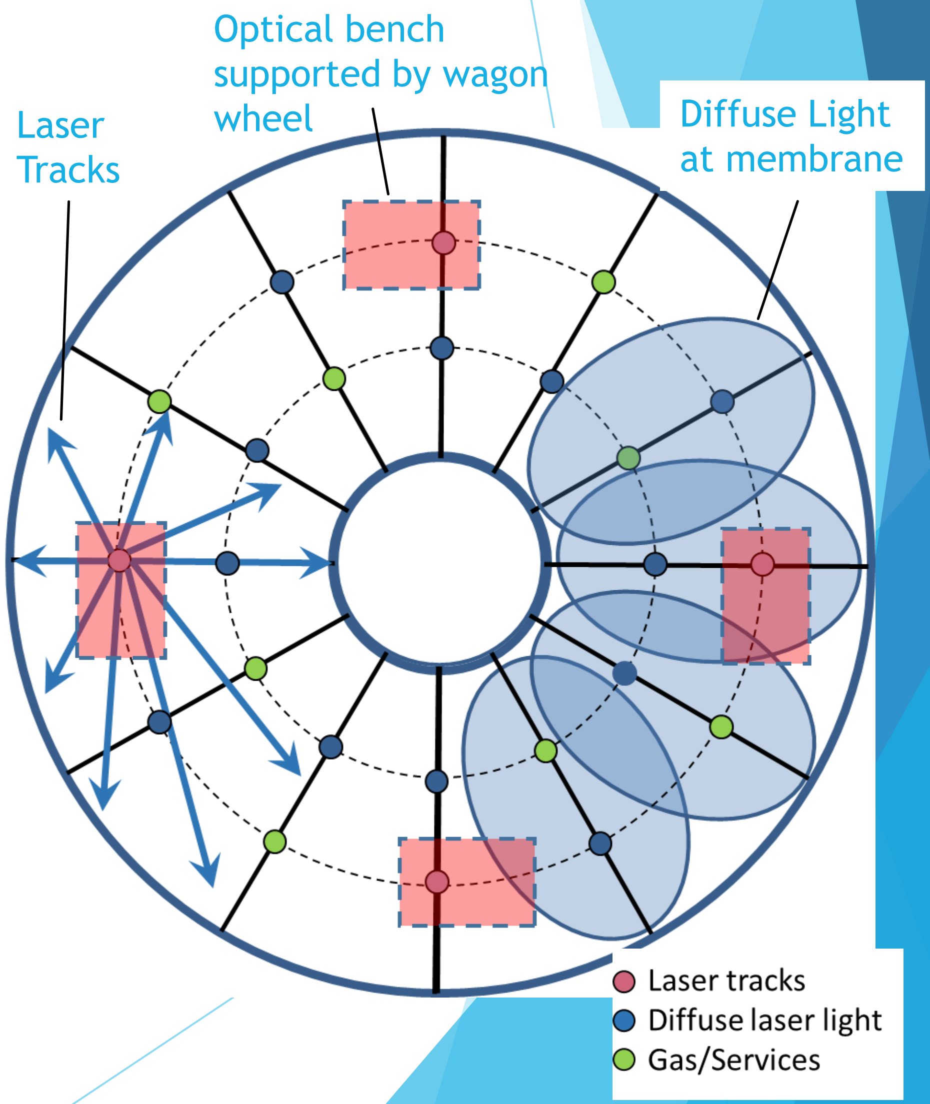






Layout of TPC Wagon Wheel entrance ports

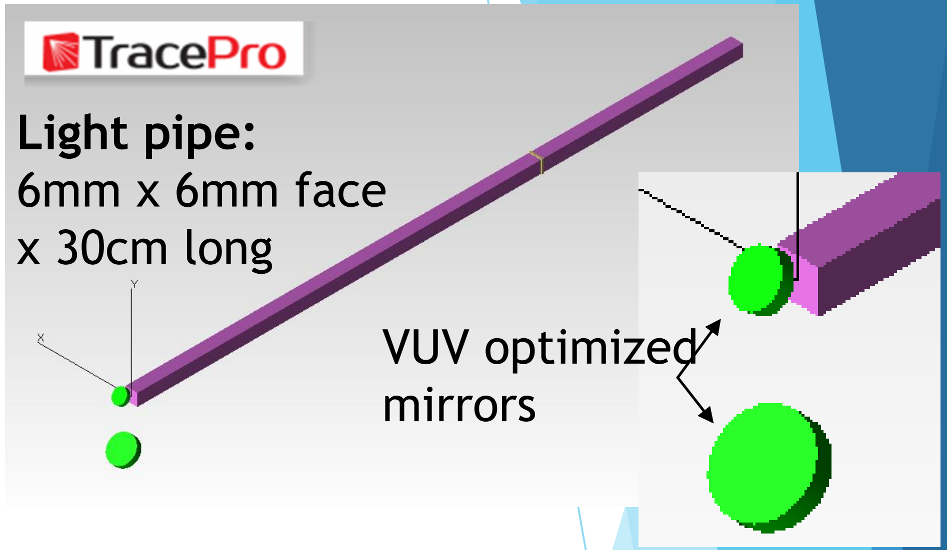
➢ Two rings of 12 ¼” NPT Feedthrough’s

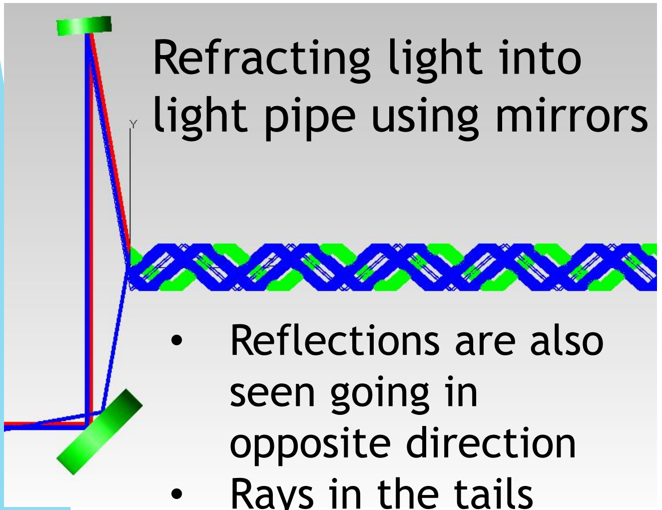


- Rigid “light pipe” delivers laser beam at controlled angles (w/ large N.A.) into TPC volume
- Micro-actuated mirror allows a single laser beam to sweep an entire quadrant of the TPC volume

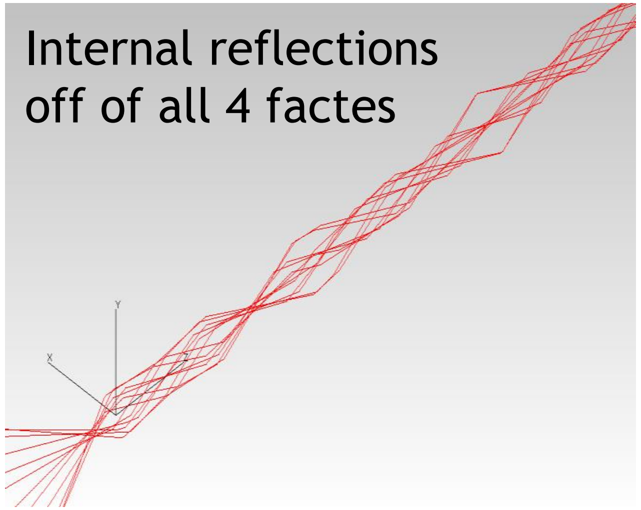
Ray Tracing Simulations

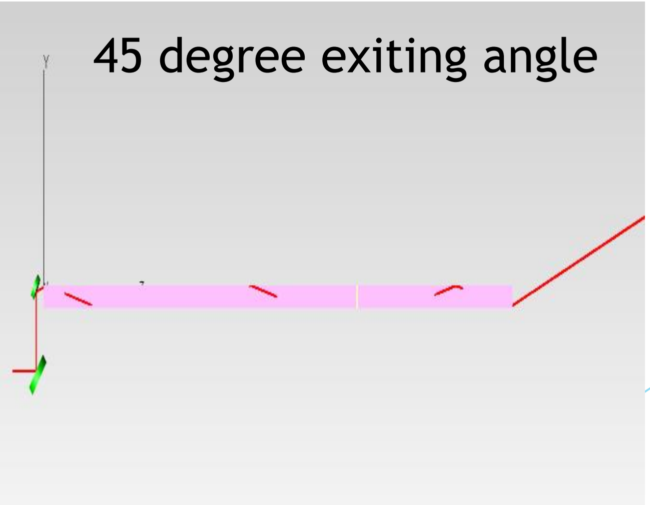
- $(x, y, z, \theta_x, \theta_y)$ degrees of freedom for beam steering allows laser beams to enter light pipe over full range of beam incident angles from 0-90degrees
- Up to ~+/-85 deg. cone angles from the exit facet of the light pipe are possible, allowing laser beams to sample almost the entire inner volume of the TPC.

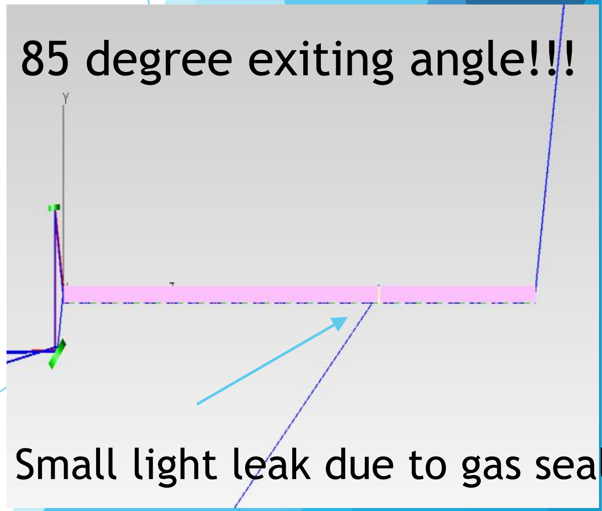




- Reflections are also seen going in opposite direction
- Rays in the tails exaggerate beam width





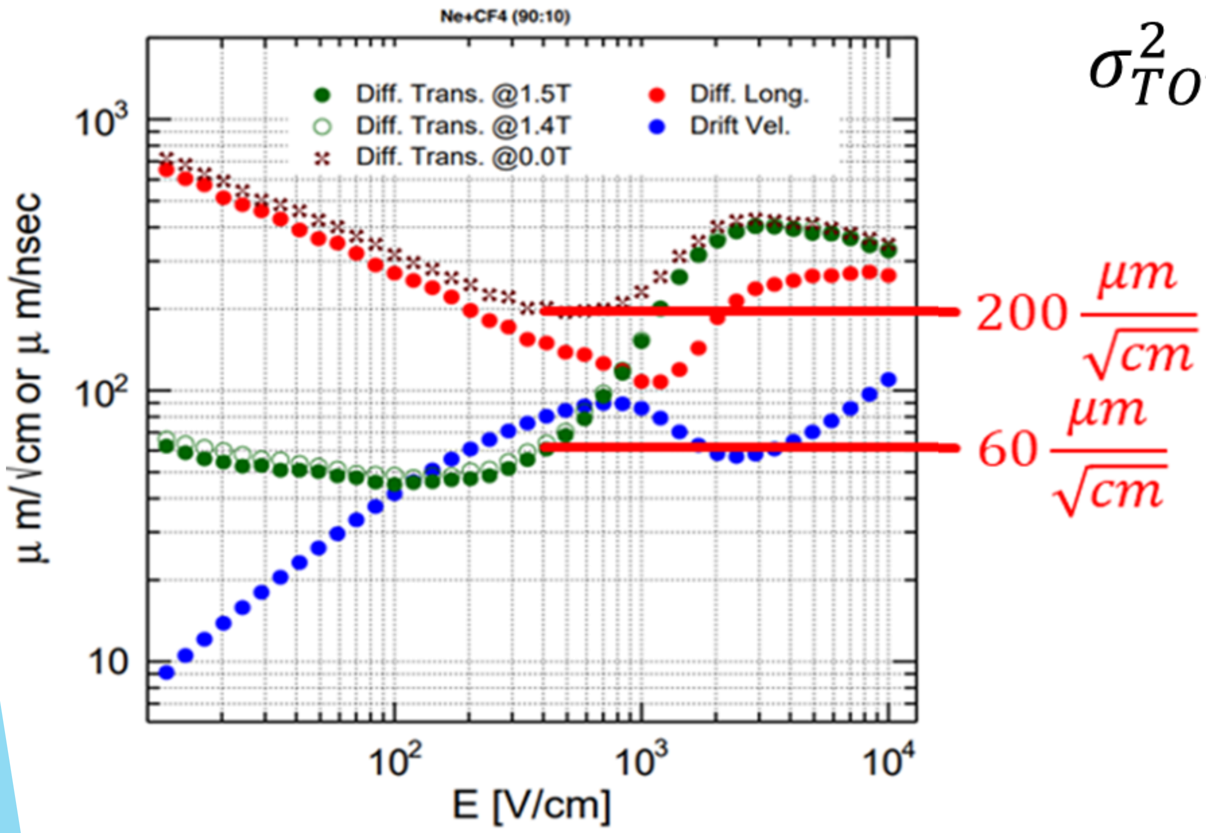


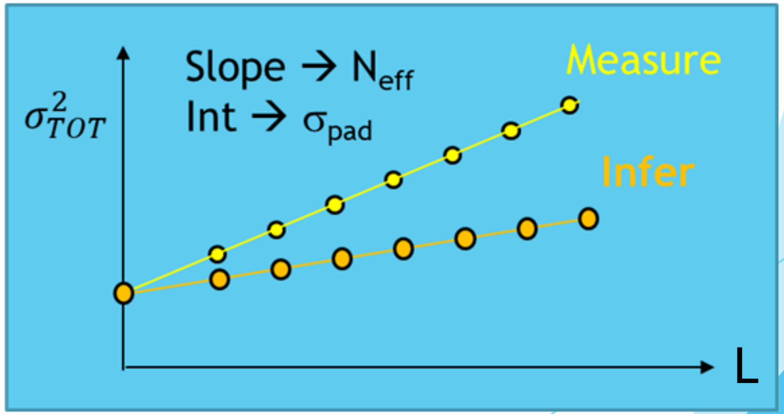
Test Beam

- Test beam campaign at Fermilab Test Beam Facility FTBF
- Main task: determine position resolution at B = 0 T and extrapolate to B = 1.4 T

PadPlane, Drift, Space Charge

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

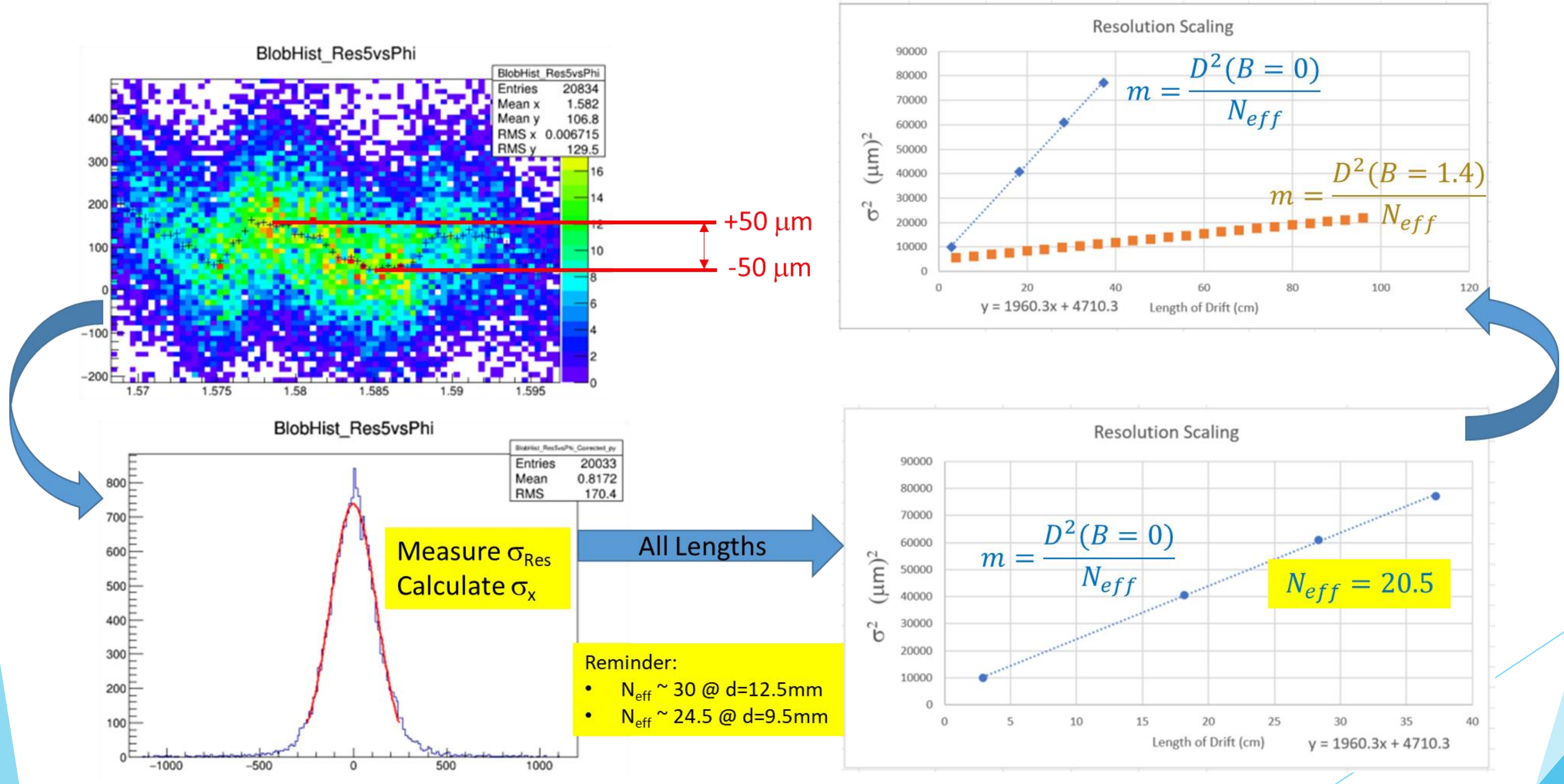




Prototype Analysis

2018 – Results final

- Main task: determine position resolution at B = 0 T and extrapolate to B = 1.4 T

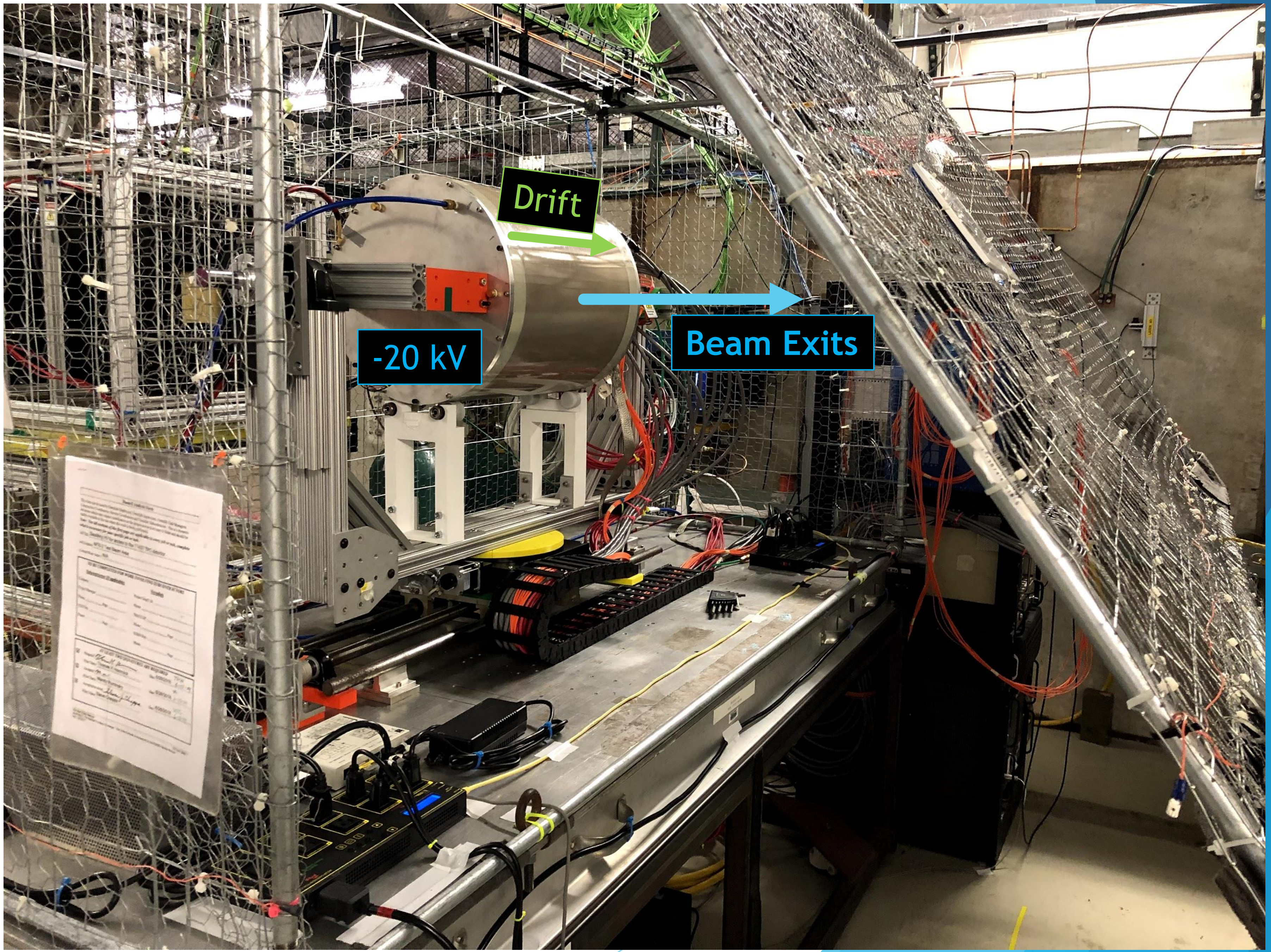


GEM Framing – BNL; Chamber Tests -- Yale

June 2019

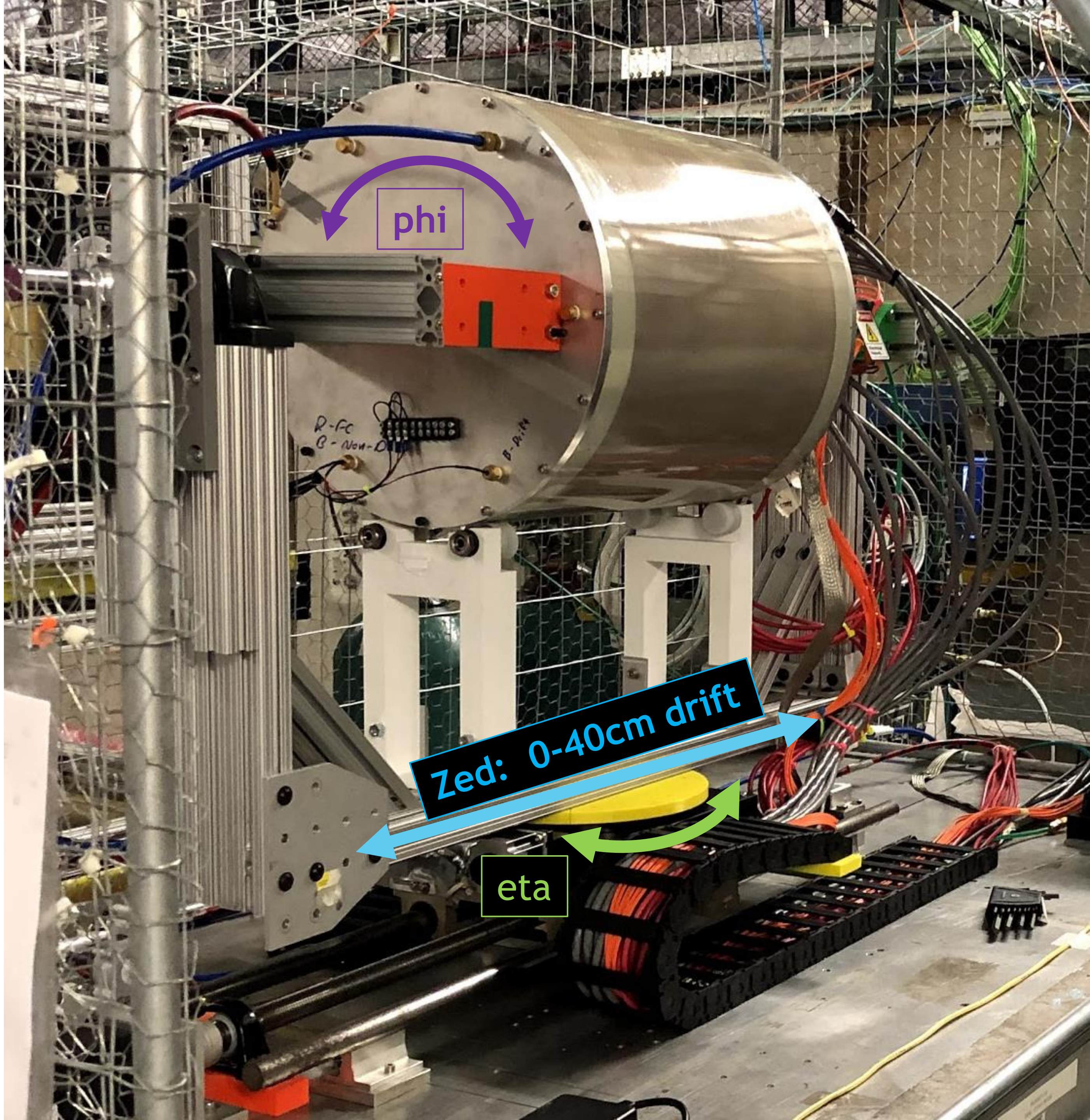
TPC Prototype

- Field cage using spare parts for Inner Field Cage.
- Face the stripes inward!
- Single ended TPC
  - Exposed HV hazard
  - 40 cm drift length.
- FNAL safety assisted in design of safety cage.
  - Chicken wire.



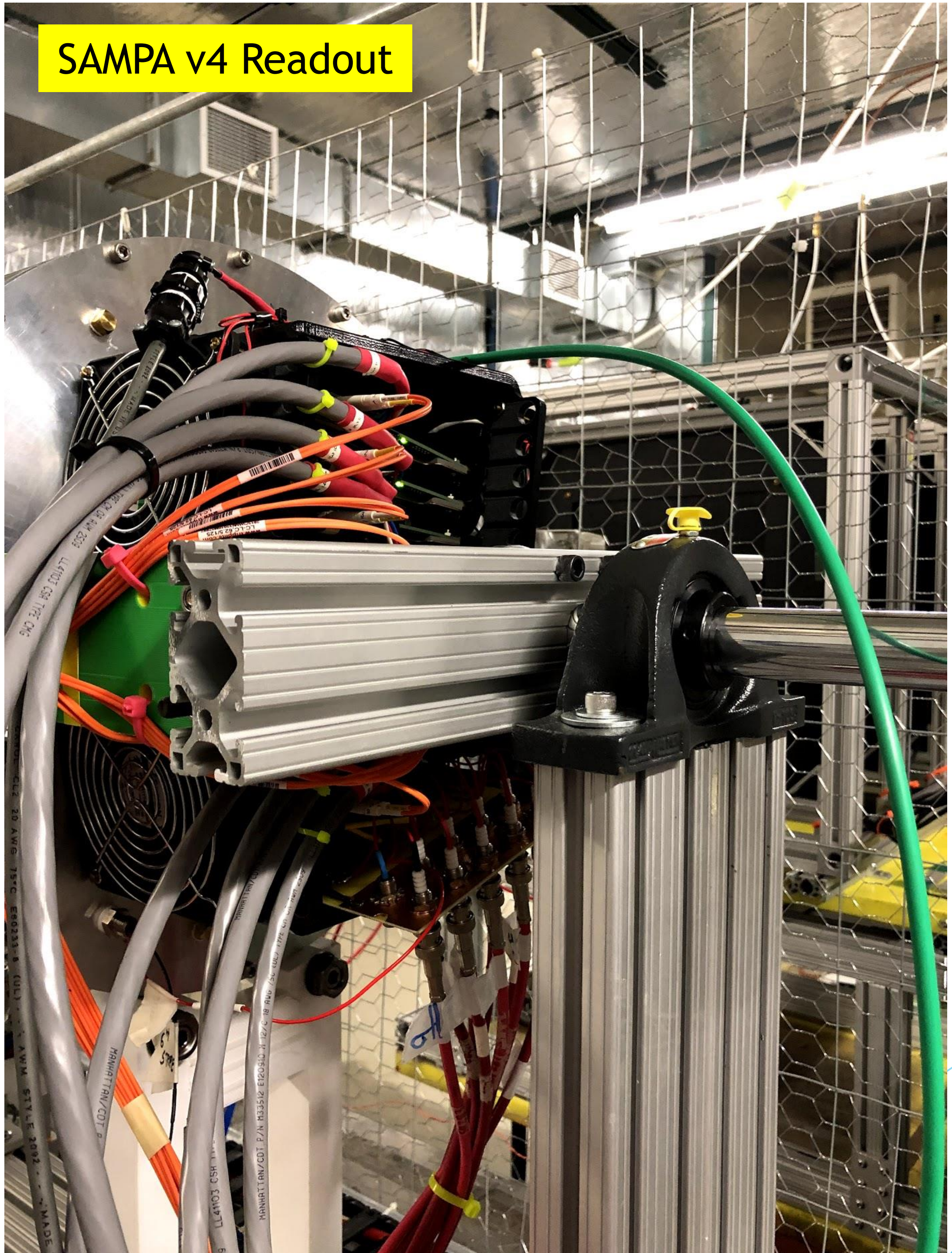
Motion via Remote

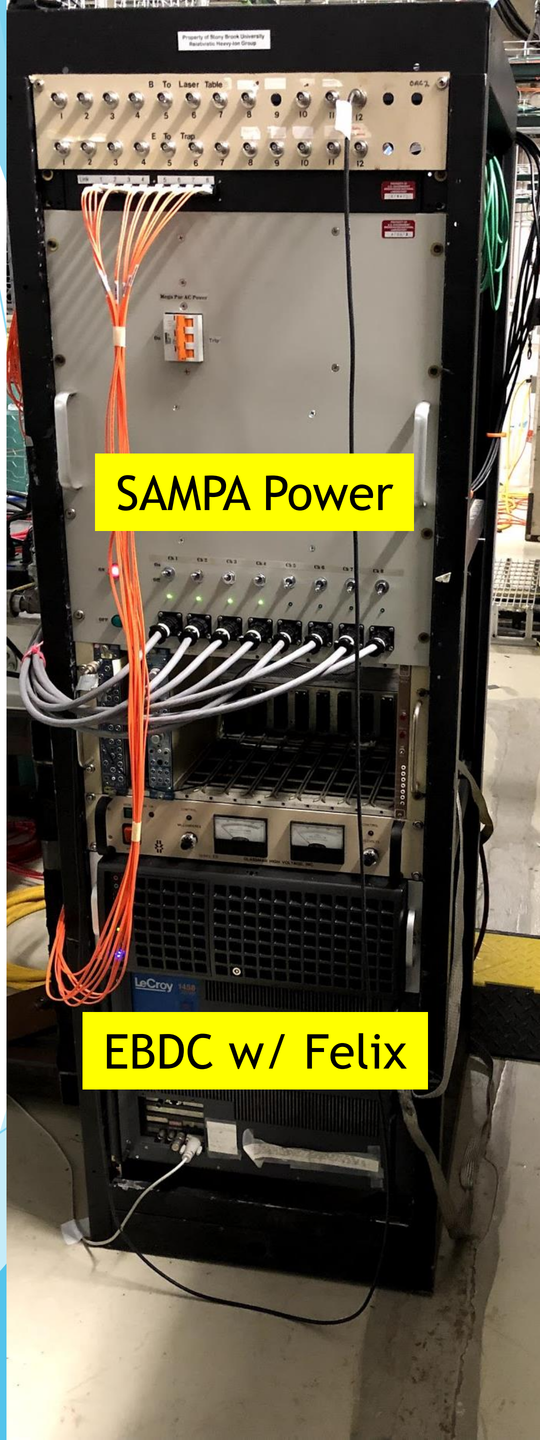
- Zed Motion:
  - Primary tool for resolution.
- **Phi Motion:**
  - Tracks at inclined phi mimic trajectories of lower momentum particles in sPHENIX.
- **Eta Motion:**
  - Mimics high eta particle trajectories by moving detector (the beam cannot move)



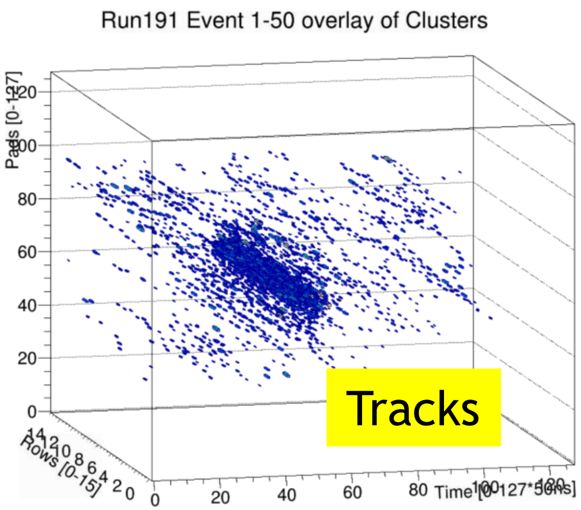
Readout

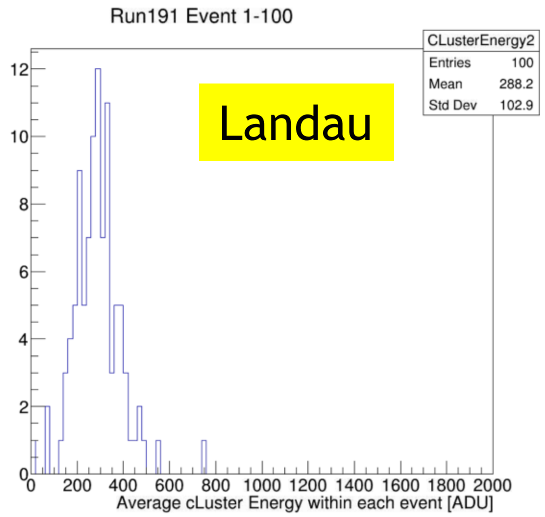
- 8 SAMPA Cards
- 8 Chips per Card
- FELIX Card in EBDC
  - Real sPHENIX Readout
- Independent HV Channels
  - Last year fixed avalanche module HV config.
  - This year on-the-fly changes ability to test many options

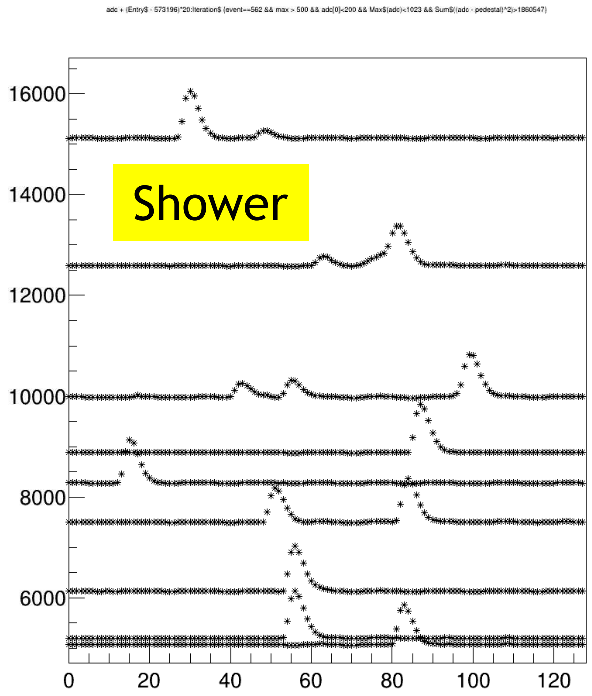


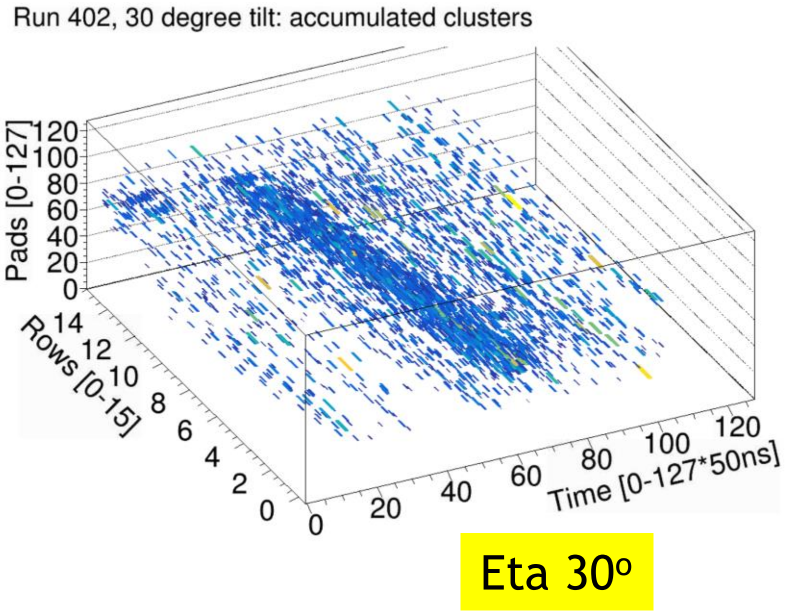


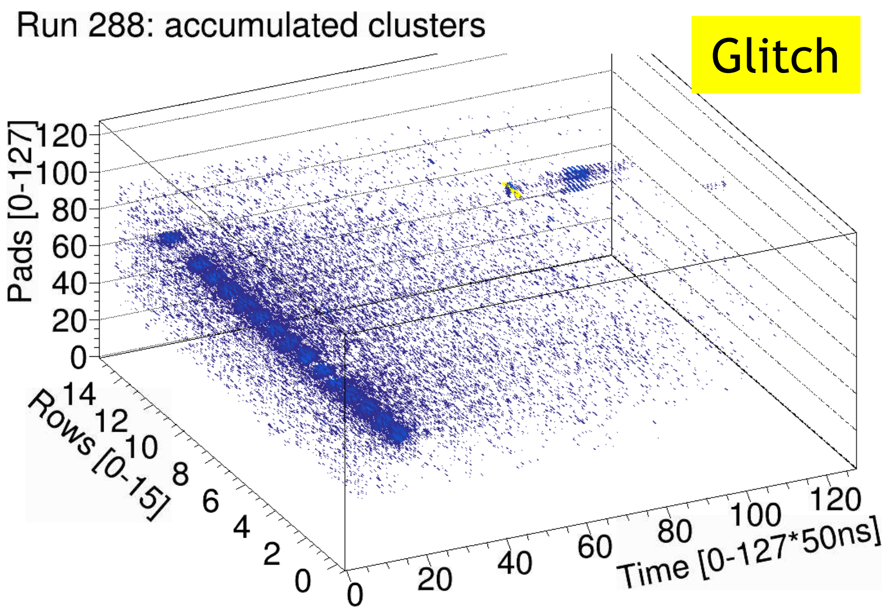
Selected Images



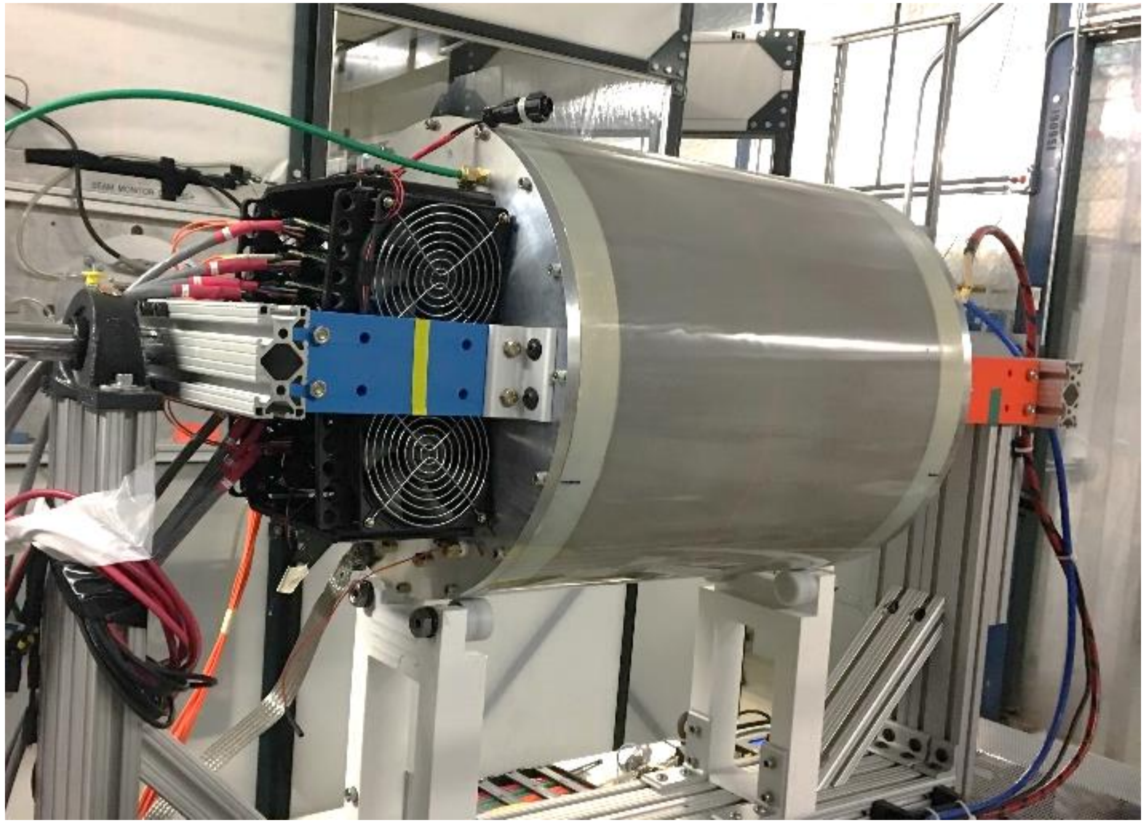


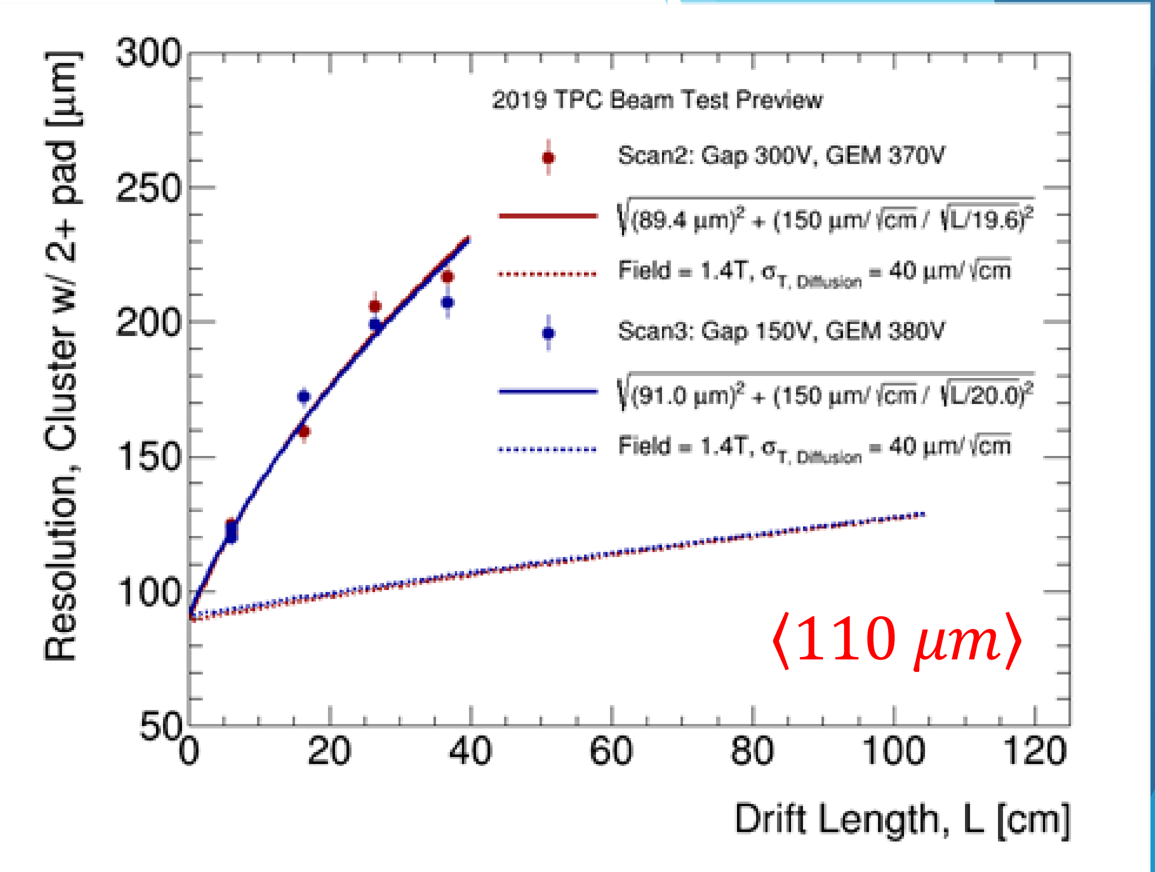






Preliminary Results





- New this year:
  - SAMPA readout.
  - 50:50 Ne CF_4 (skirts around absorption peak…improves resolution).
  - Low IBF configurations:
    - Nikolai Smirnov (Yale) provided Nikolai 1.03, 2.03, 3.03, 4.03 (all run at FNAL).

σ_{int} ~ 90 μm
N_{eff} ~ 20
Resolution Improved

*Coherent electrical noise not subtracted. Affects only constant term.

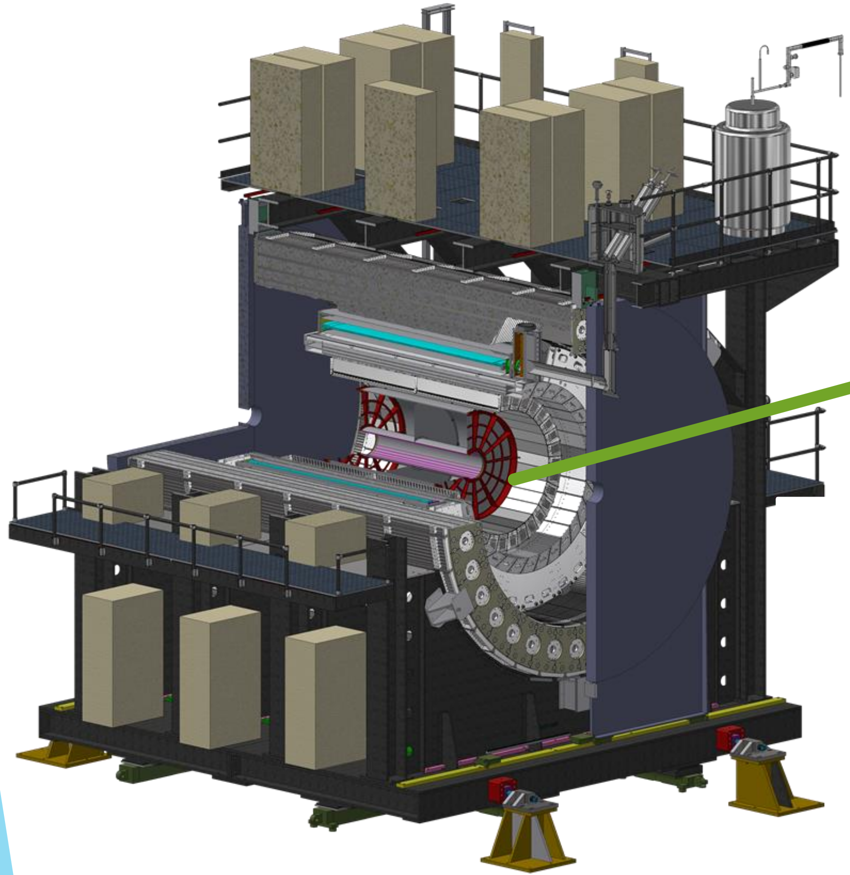
Summary

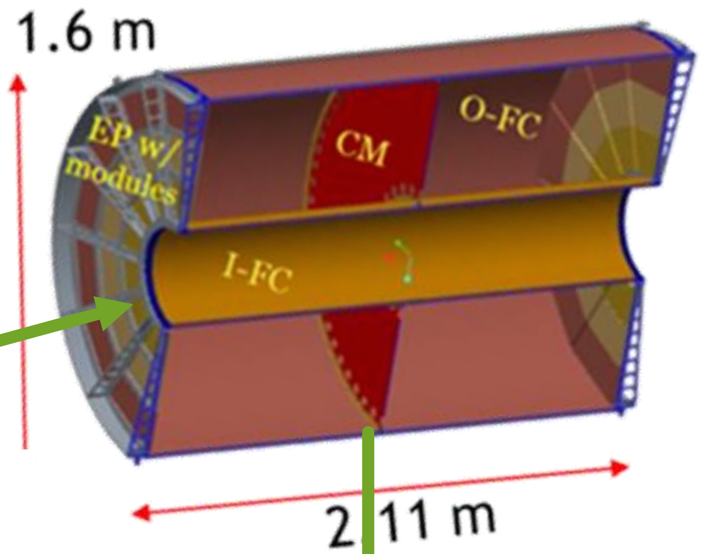
- Whirlwind our of sPHENIX TPC Design.
- Design driven by three factors:
  - Lever arm:
    Make the field cage as thin as possible (1.52 cm)
  - Precision:
    Low diffusion gas mixture read by high incursion ZigZag pads
  - Accuracy:
    Low IBF mode ala' ALICE.
    With 2019 gas mixture quite similar fields/voltages apply to sPHENIX as ALICE.
- Good results from test beam through full DAQ system.
- Much more work to do.

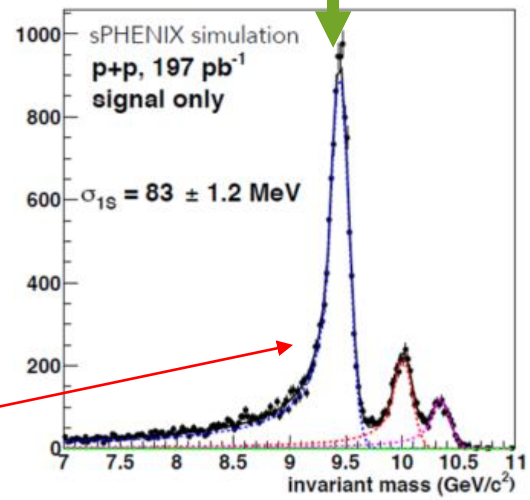
- THANK YOU to our HOSTS!
  The opportunity to learn from you is timely and HIGHLY appreciated.

Backups

The TPC







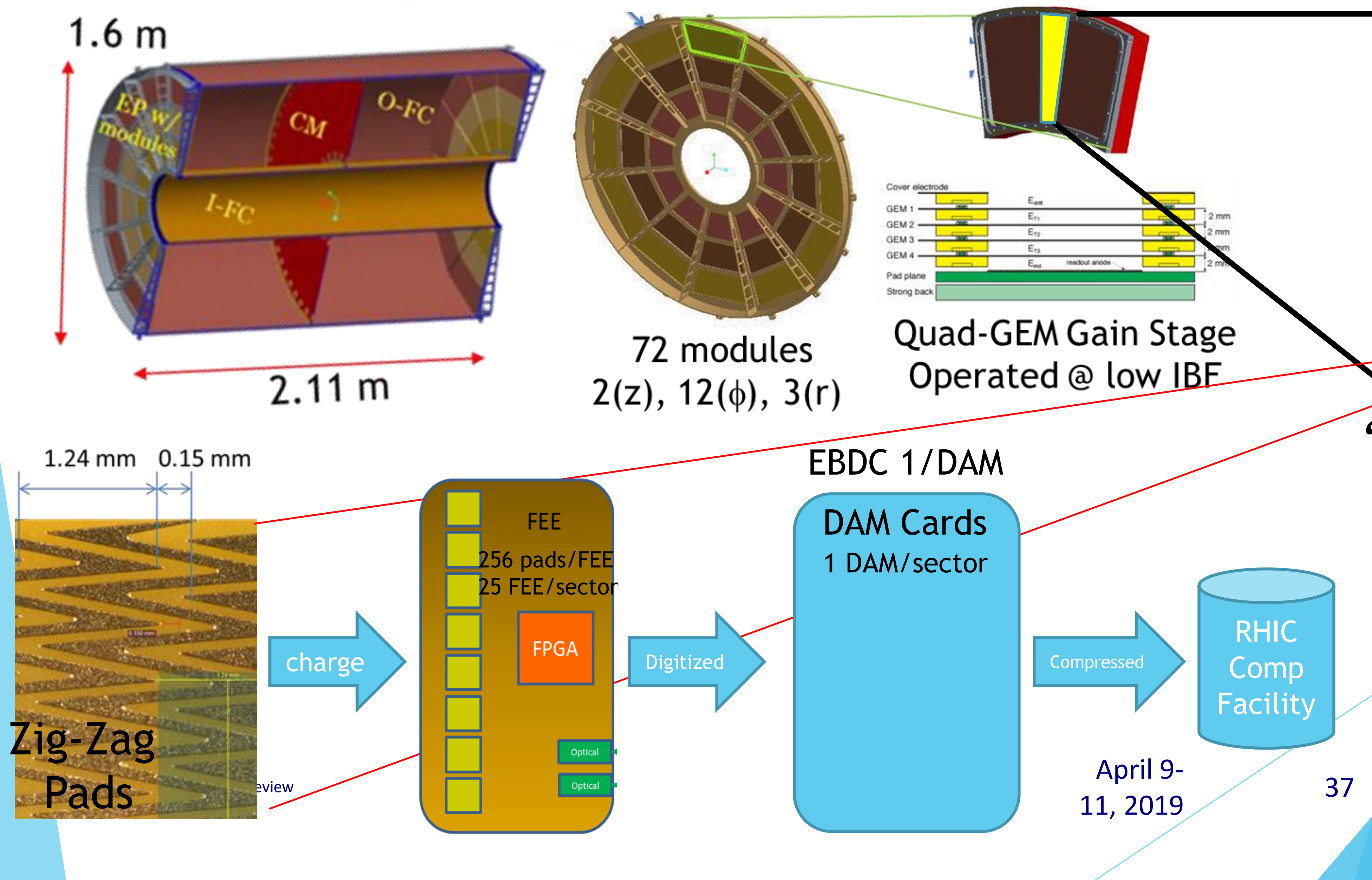
- A next-generation TPC operated in continuous readout mode using Gas-Electron Multiplier (GEM) avalanche w/ low Ion Back Flow (IBF).
- Front End Electronics (FEE) uses SAMPA chip (developed by ALICE).
- Data Aggregation Module (DAM) uses the FELIX board (ATLAS exp)

Charged Tracking in sPHENIX:
- TPC provides p-resolution

High Momentum Resolution:
- Large Lever Arm (Maximize Active Area)
- High Precision (Good Single Point Resolution)
- High Accuracy (Low Distortion)

Design choices reflect these considerations.

Technical Overview



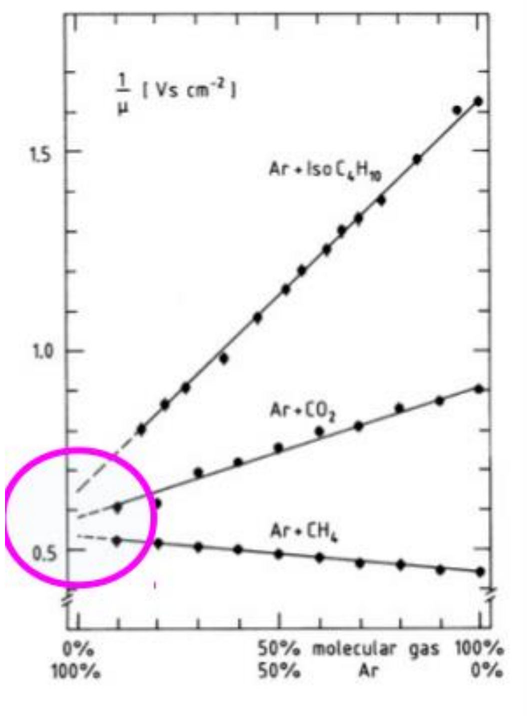
Item	Count
Field Cage	1
Modules	72
FEE	624
DAM	24
EDBC	24

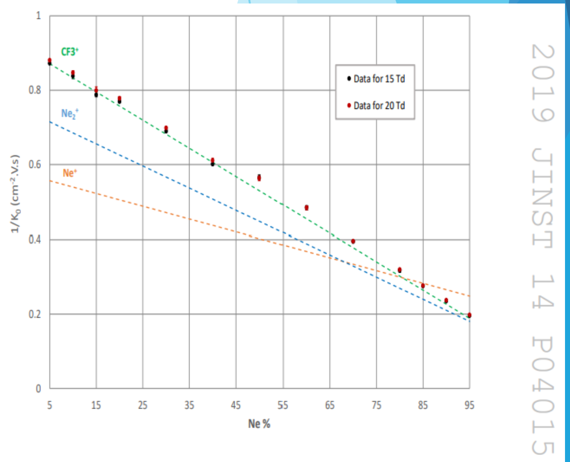
Full Gas Comparison

	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
$T-A\vert_{1000}$	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

**2019 publication has K(90:10)=4.26; sPHENIX calculation based upon 3.6

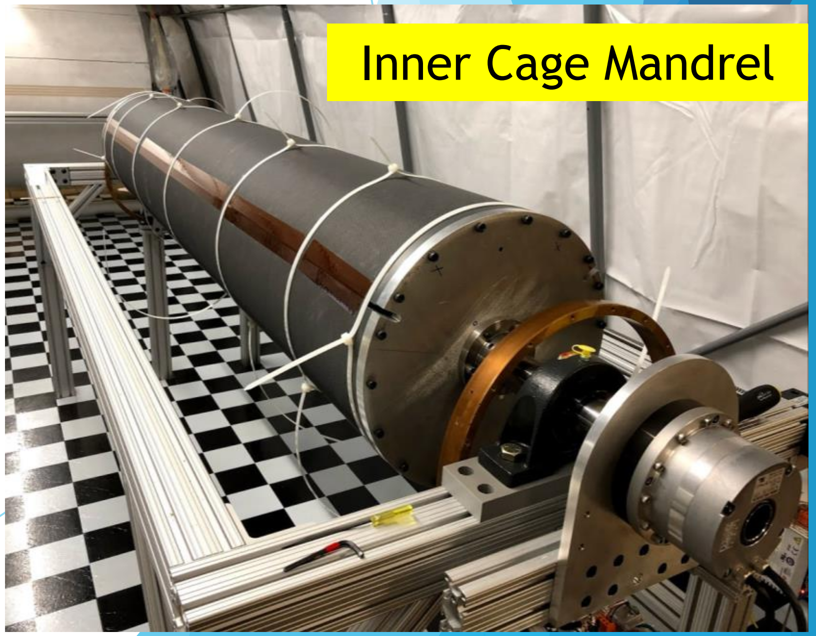




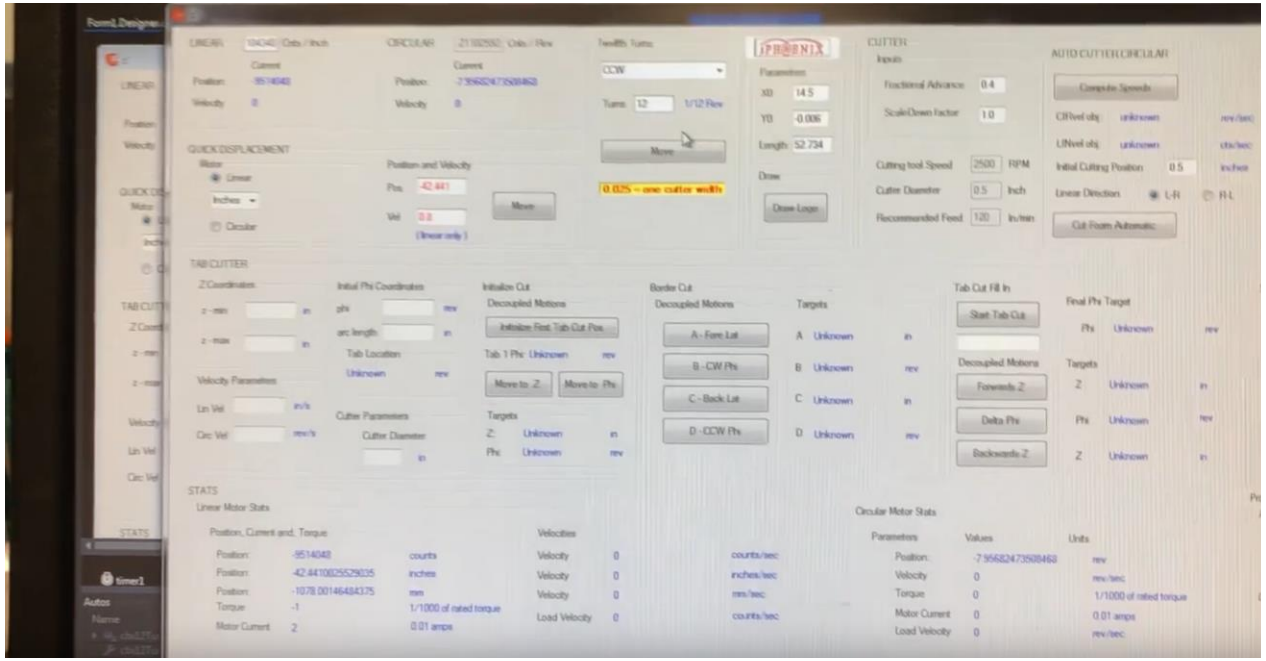
Rough numbers…requires full calculation

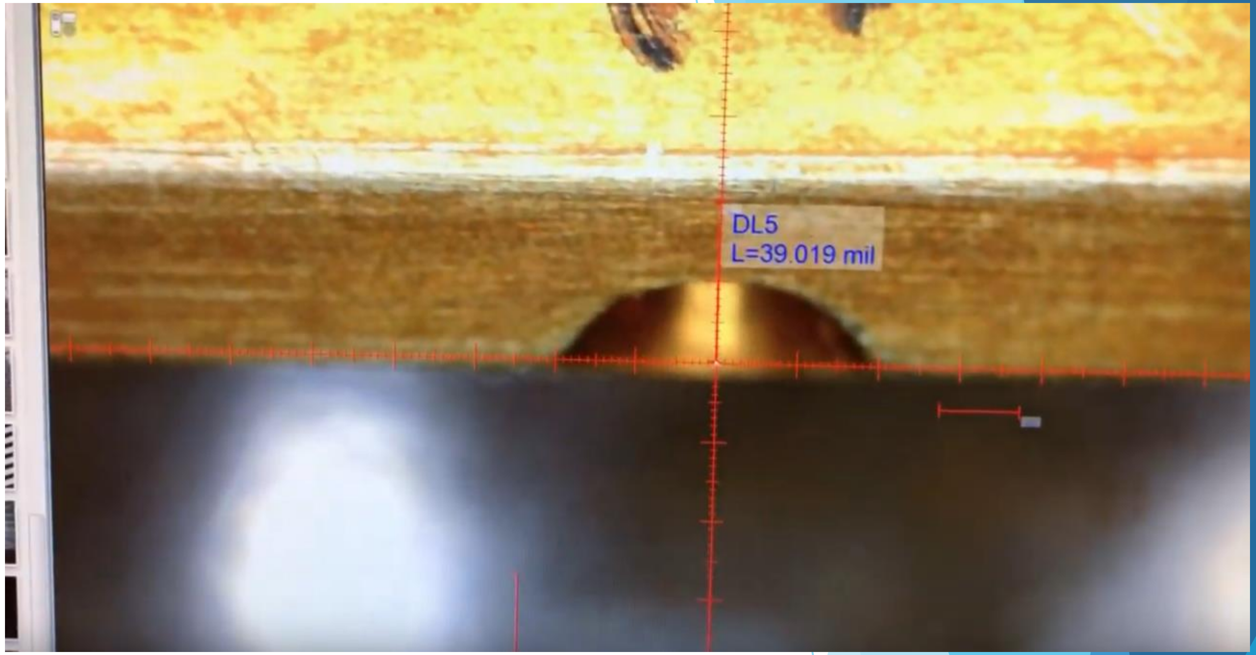
Making the Inner Field Cage

- Field cage molded to size on “mandrel”.
- Layered from inside to outside:
  - C-fiber
  - End rings
  - Honeycomb
  - C-fiber
  - Mylar
  - Kapton
  - Electrodes
- Alignment via microscope on moving stage w/ micron-level position feedback



Alignment of End Rings



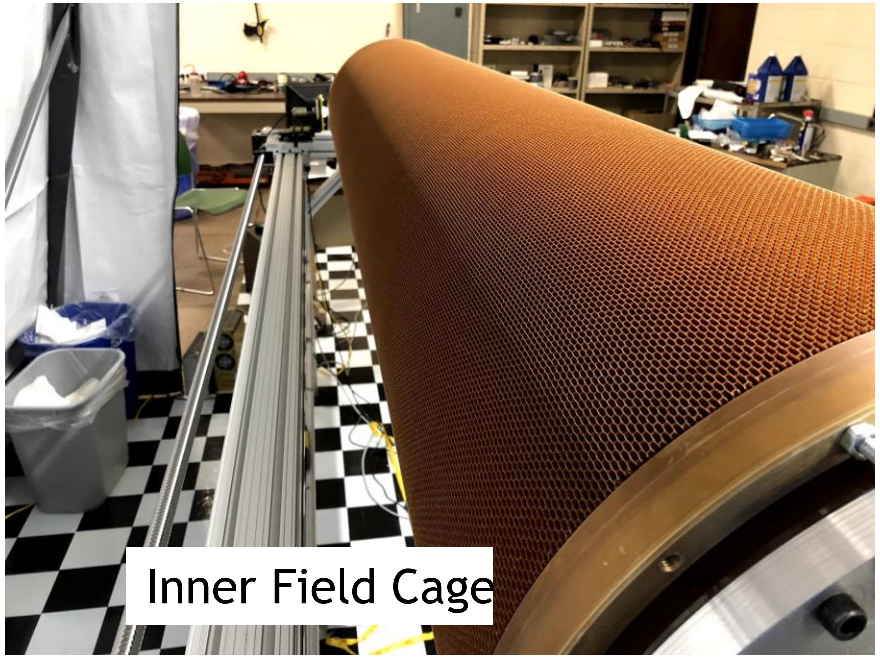


https://www.youtube.com/watch?v=i5ejhRj-pnw

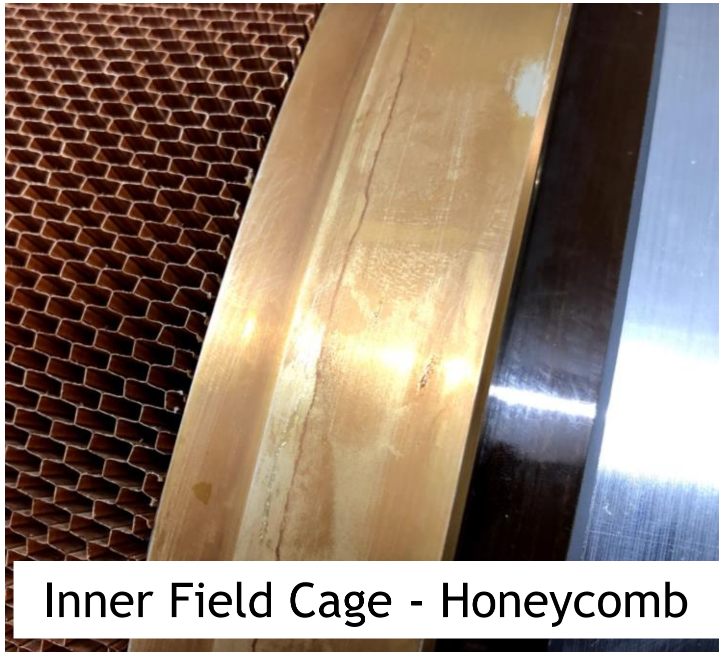
https://www.youtube.com/watch?v=3cqkh_kkEJA

- Alignment of the End Rings is the first critical step.
- Excellent results (better than 50 microns everywhere).
- Hopefully youtube embedded videos play…

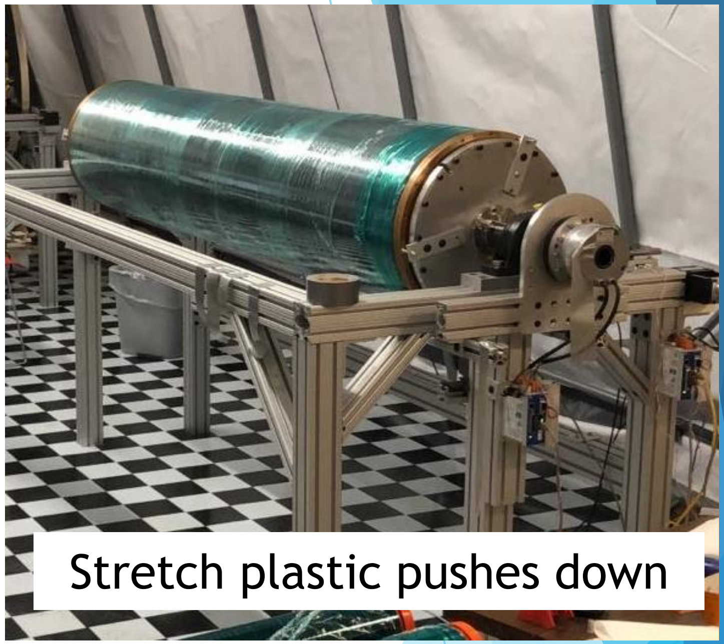
More Inner Field Cage Work



Inner Field Cage



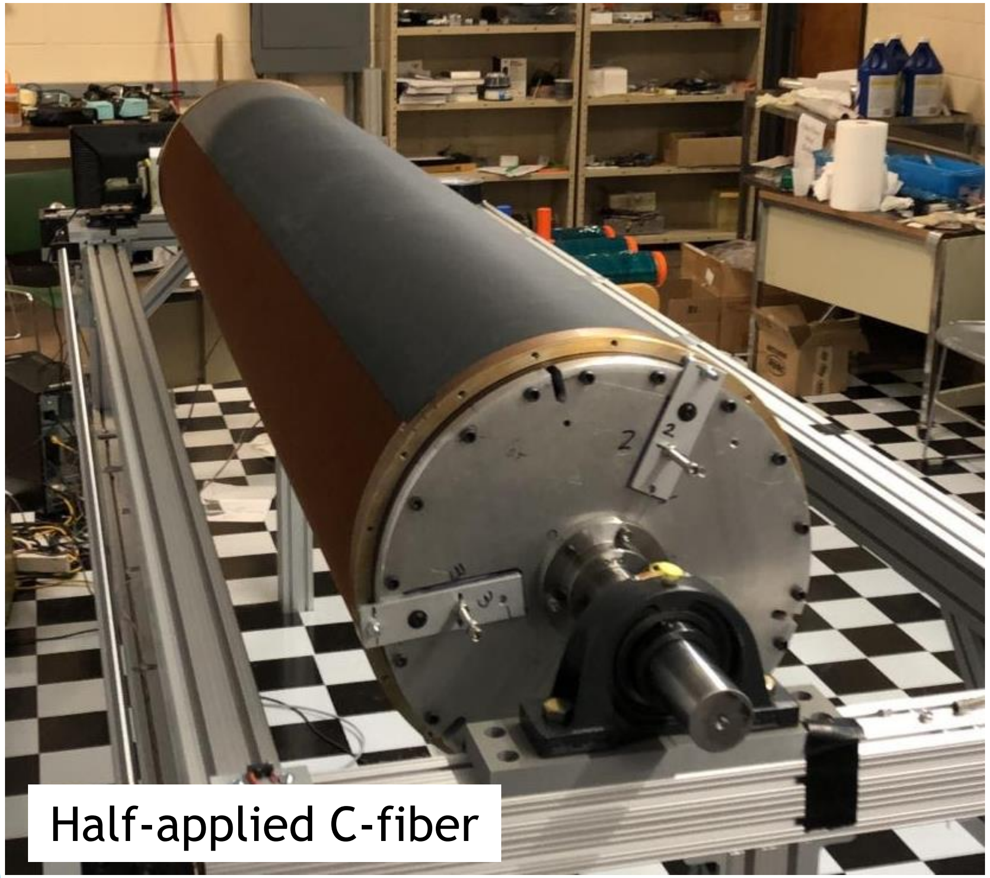
Inner Field Cage - Honeycomb



Stretch plastic pushes down

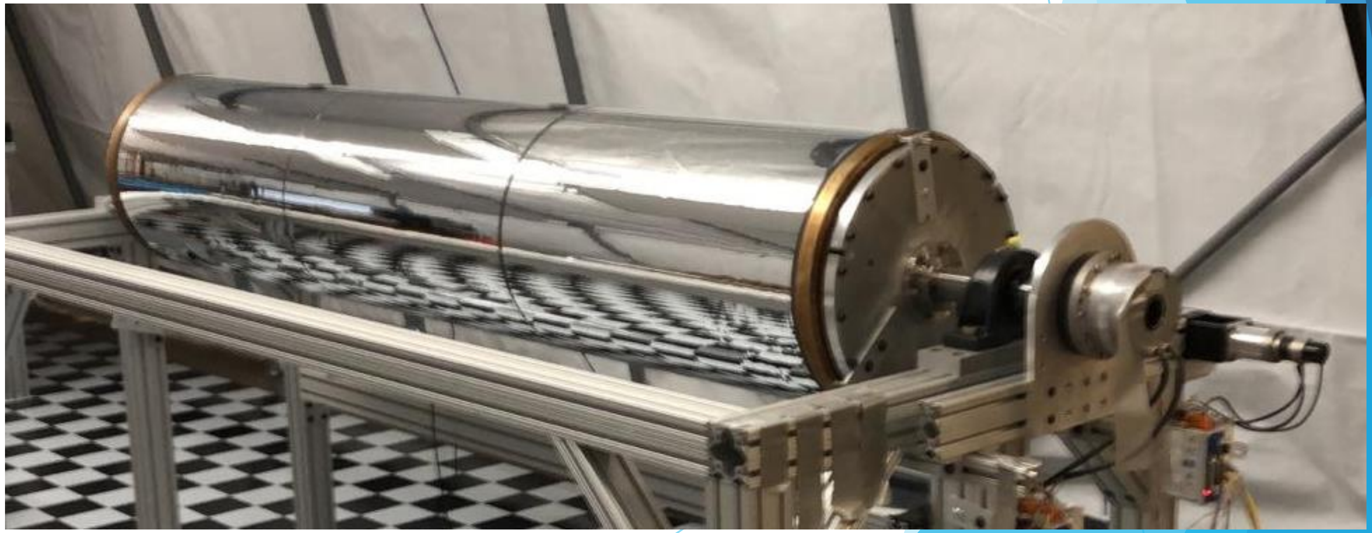
- Honeycomb provides structural support.
- “Directional” honeycomb conforms naturally to a cylinder.

Outer C-fiber & Mylar Ground



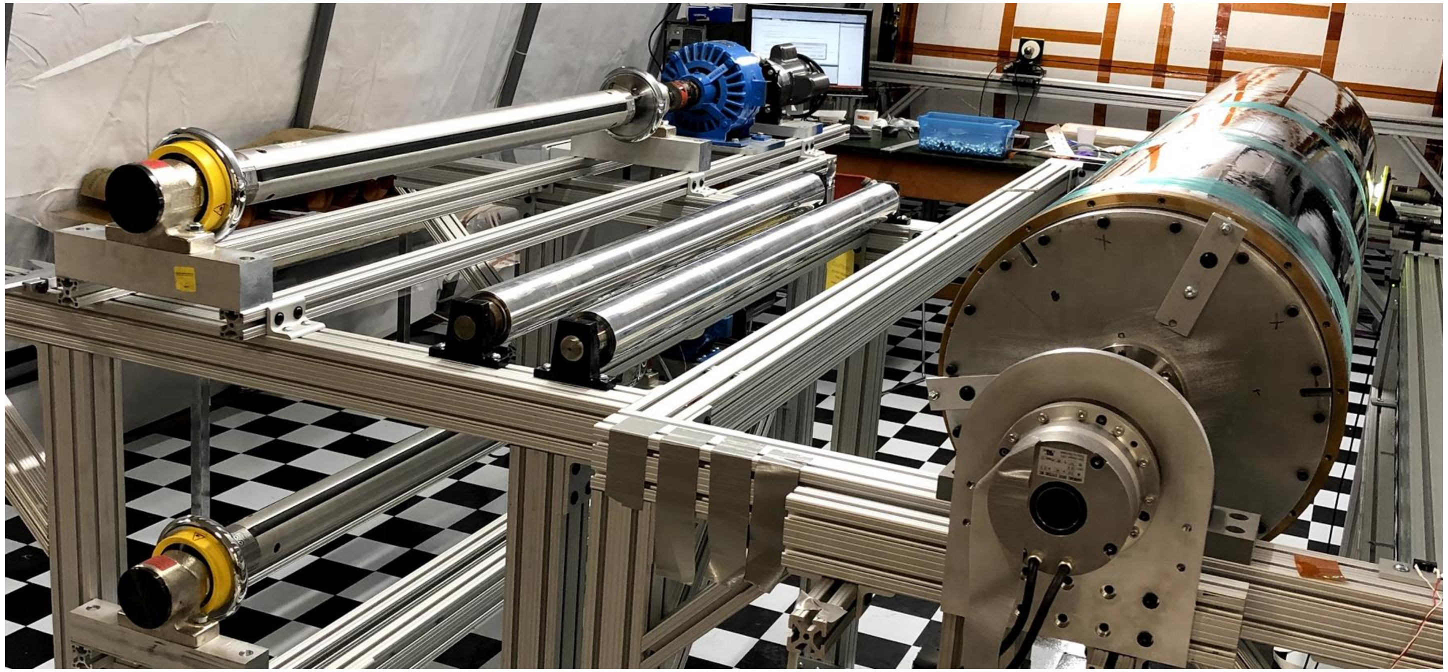
Half-applied C-fiber

Test fit—Mylar Ground



- Current Status:
  - 100% Mechanically Complete.
  - Ready for Electrical Layers.

Inner Field Cage Current Status

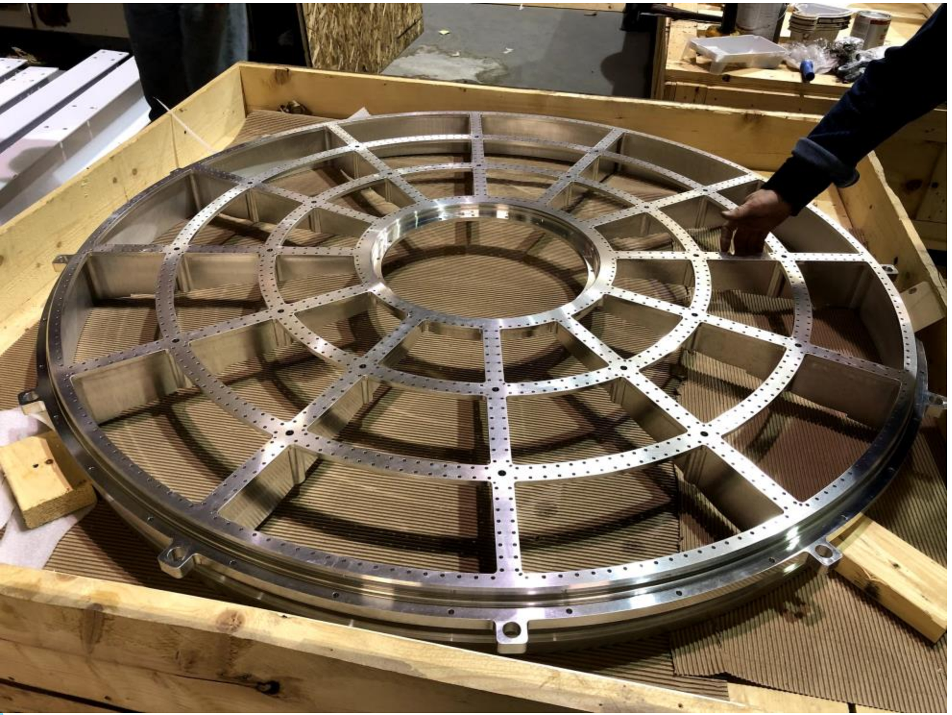


- Tensioner System used to tension the kapton foils during their application.
- Requires precise alignment so layers will produce proper edge.
- Excellent alignment achieved.
- Ready to wind since May (distracted by PD2/3 & Test Beam)

Outer Field Cage Current Status

- Ready for Striped Circuit Cards since early May.
- Distracted by PD2/3 & Test Beam

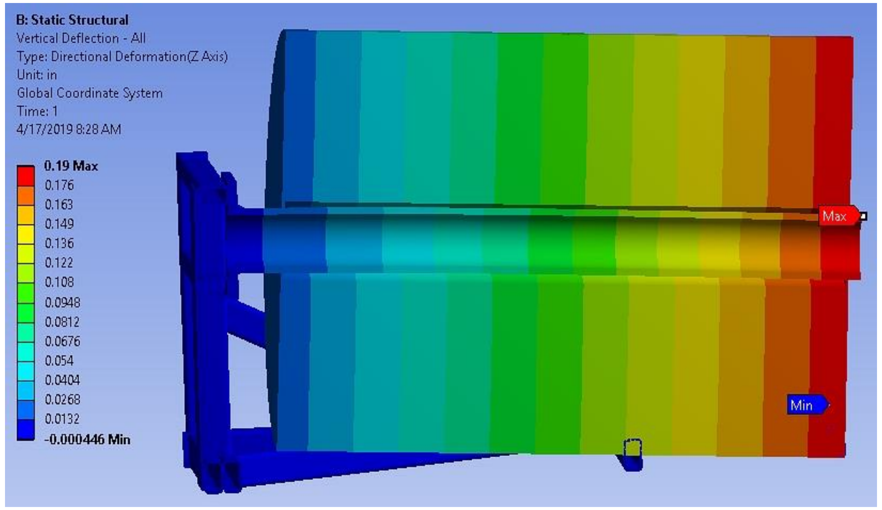
Wagon Wheel Design

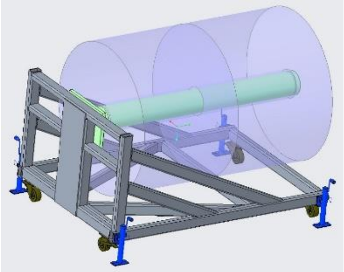


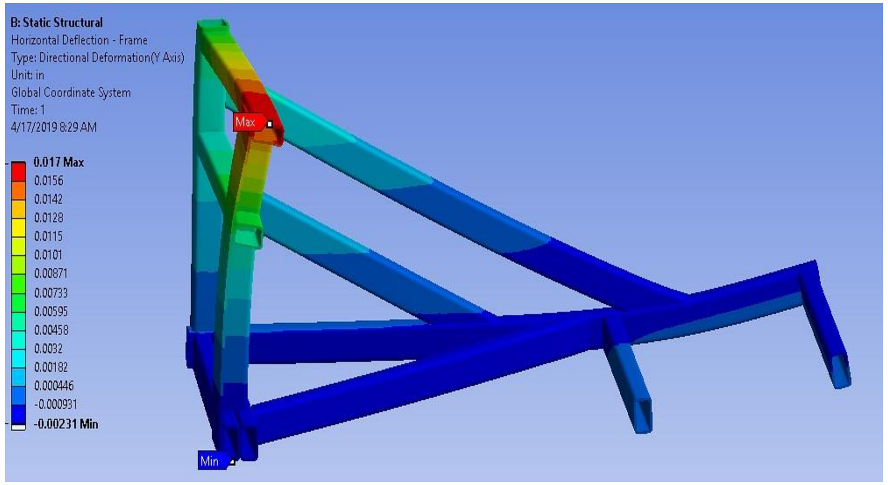
- Wagon Wheels in hand.
  - Re-inspected by BNL.
  - Passed.
- Assembly Frame built & Test Fitted w/ Wagon Wheel.
- Safe working-at-height apparatus
  - Uses cordless screwdriver for up/down.
  - Selected w/ BNL Safety Consultation.

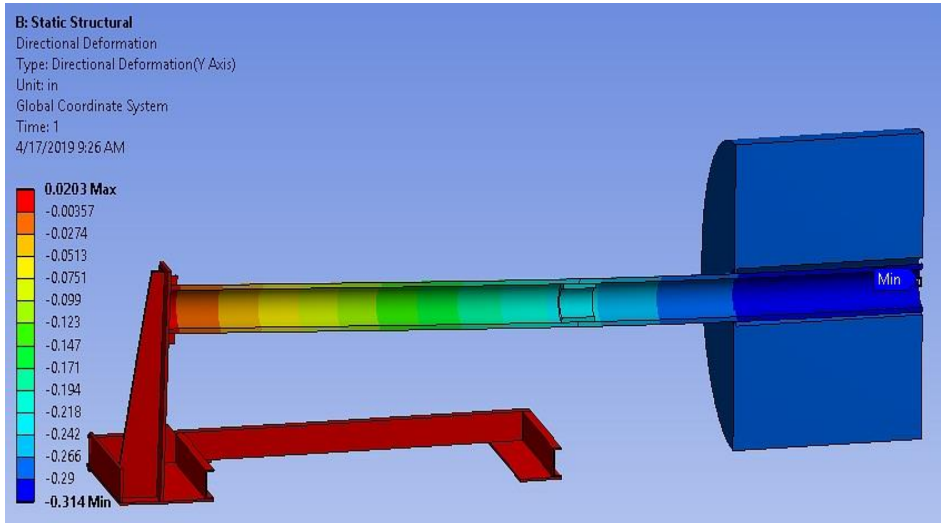
TPC Transporter Cart Simulation

- Latest design will support the TPC safely on a cantilevered aluminum tube. It can be used for TPC final assembly, transport, and installation into sPHENIX.
  - Low vertical deflection of the tube is key. FE has been used to optimize this structural feature.

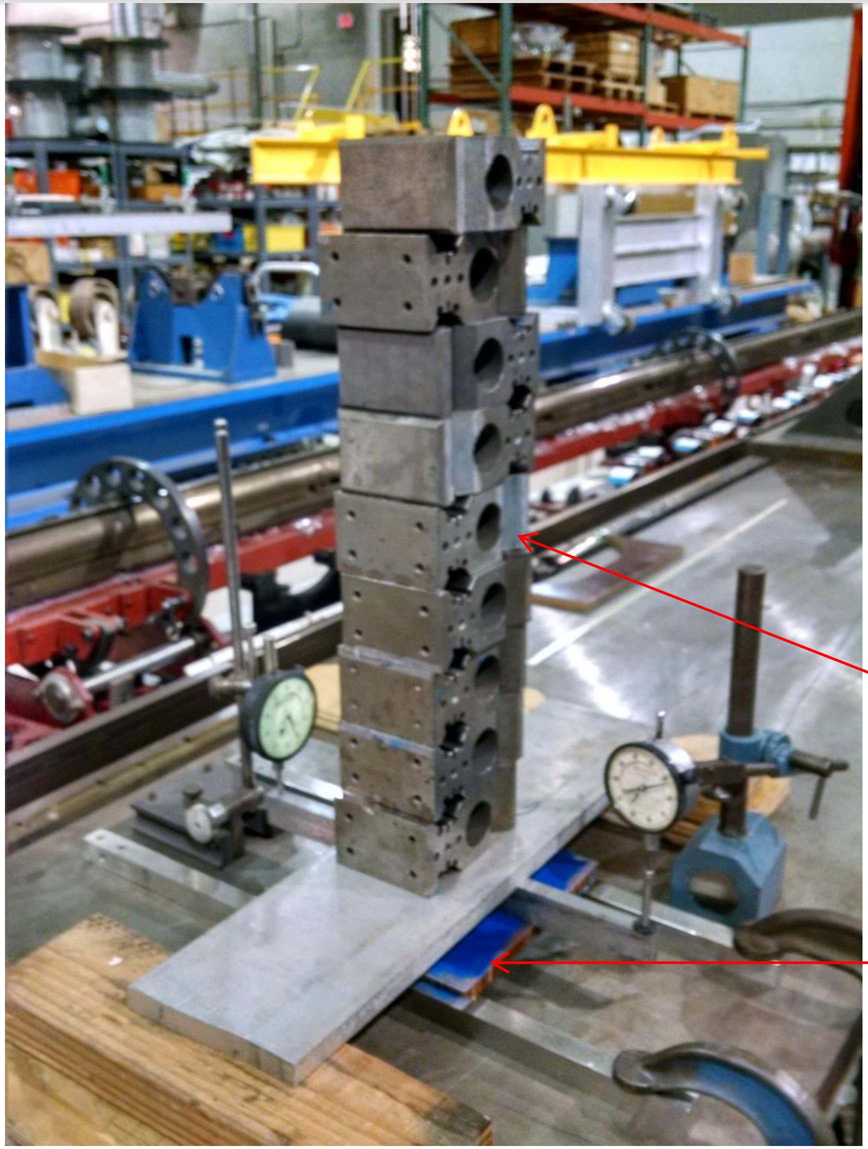


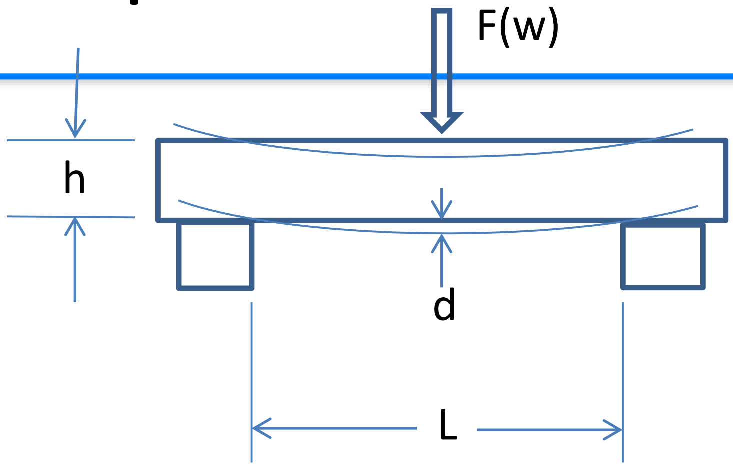






Flexural Modulus Test Set-Up



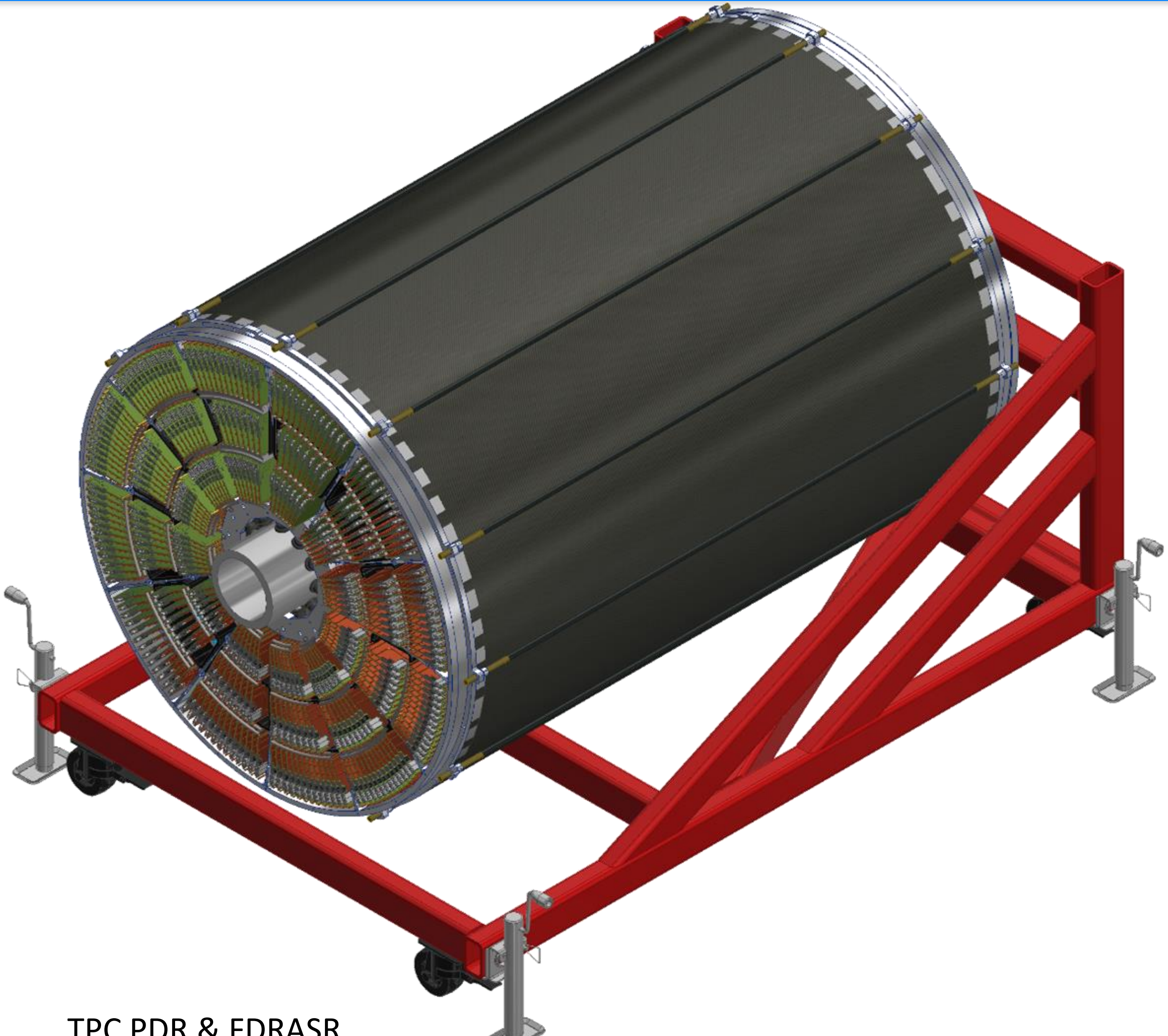


$$E_{bend} = L^3F/(4wh^3d)$$

F= 6-80 lbf
L= 5.5 inch
h=.515 inch
w=6.0 & 6.4 inch

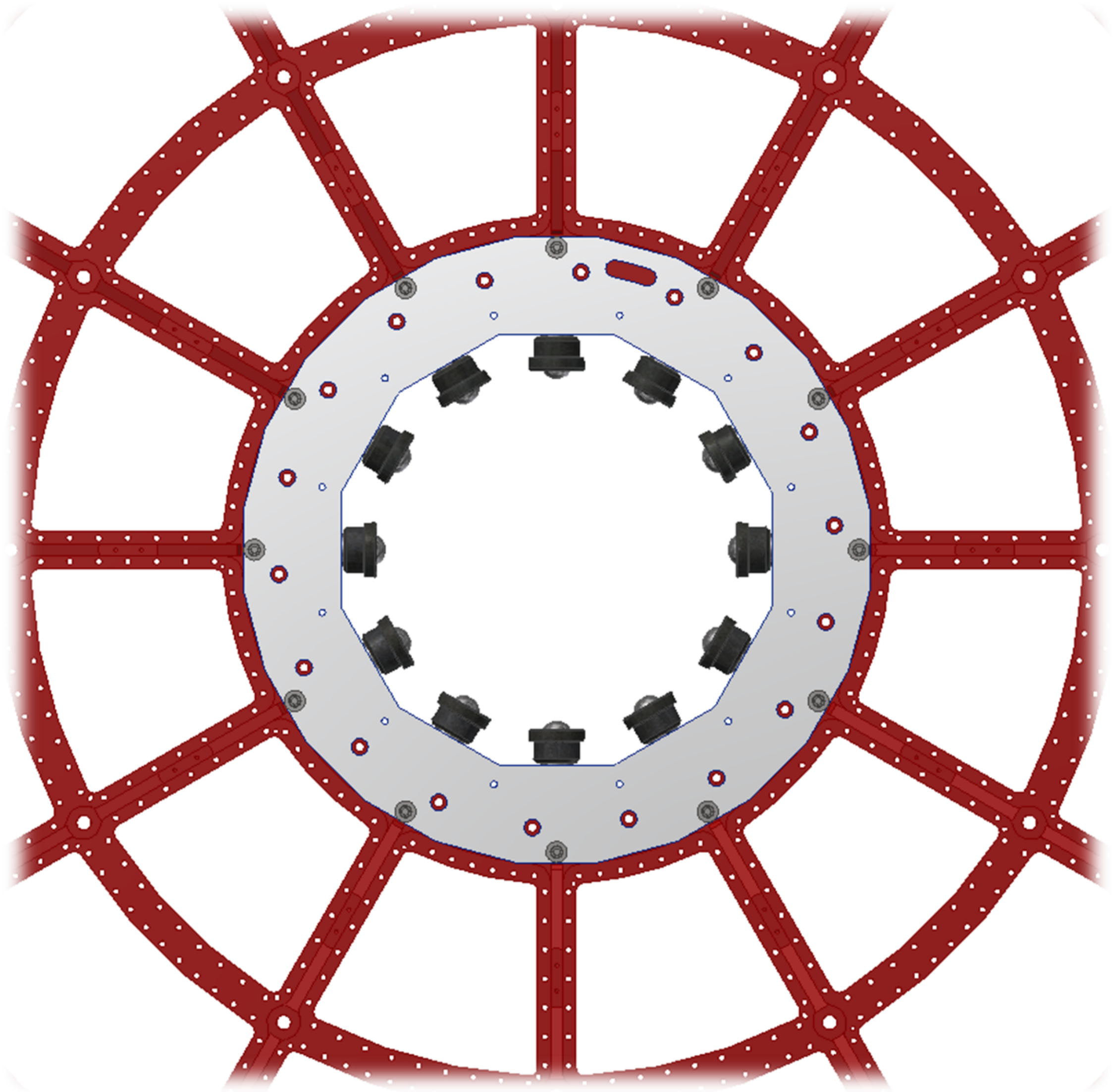
Tooling & Fixturing

- Tooling & Fixturing Components
  - **Roller Ring Assembly**
  - **Transport/Assembly Cart**



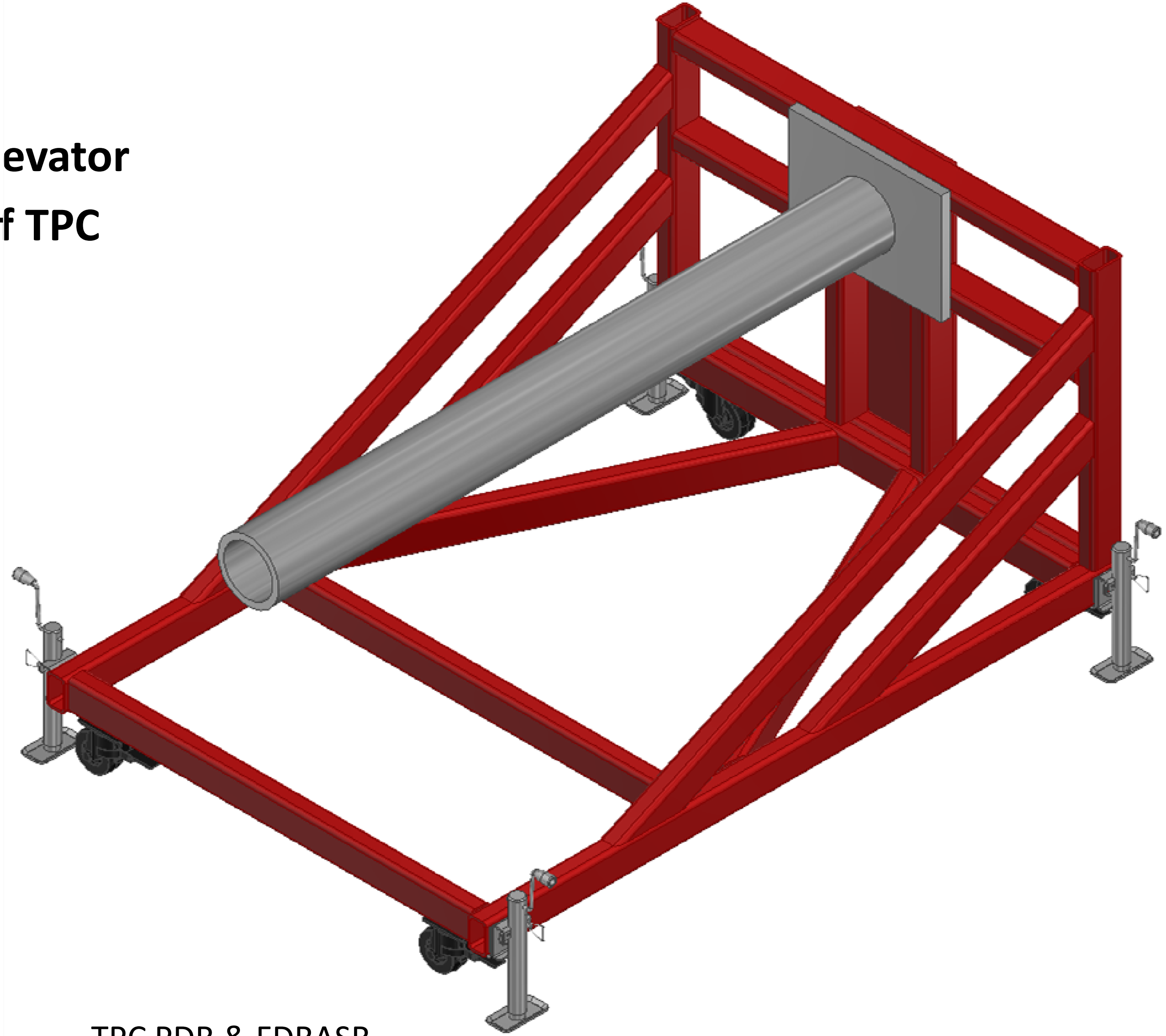
Tooling & Fixturing – Roller Ring Assembly

- Assembly Drawing Status
  - **Drawing package released (3/8/2019)**
- Assembly Components
  - **Roller Plate**
  - **Roller**
  - **Roller Washer**
  - **Mounting Washer**
  - **Mounting Screw**



Tooling & Fixturing – Transport/Assembly Cart

- Requirements
  - **Must fit in 10x10 feet freight elevator**
  - **Transportation and assembly of TPC**
- Assembly Drawing Status
  - **Model is in development**
  - **FE Analysis complete**
- Assembly Components
  - **Frame**
  - **10” Aluminum Round Tube**
  - **Caster Wheels**
  - **Leveling Jacks**



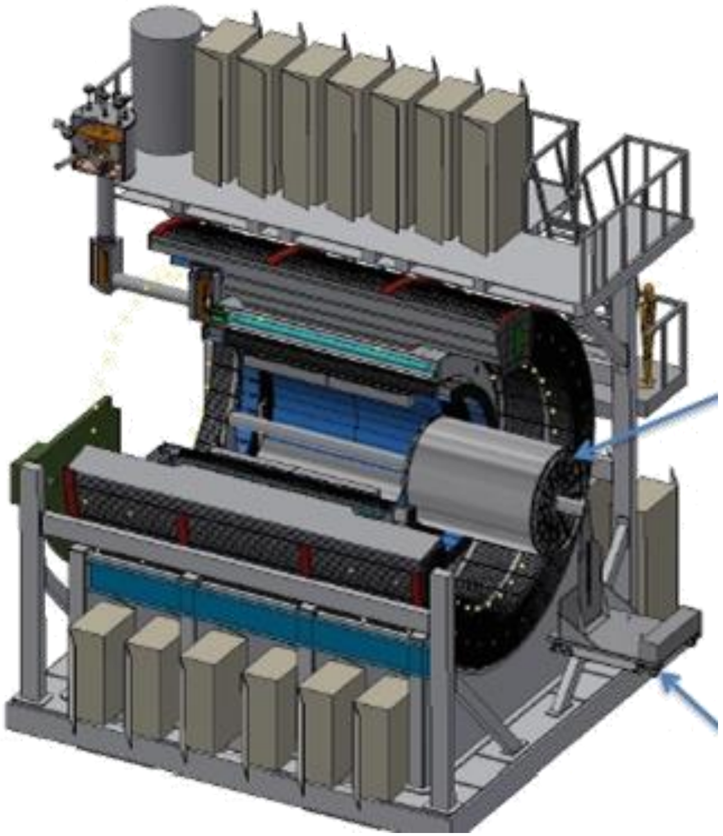
Tooling & Fixturing – Vertical Field Cage Installation

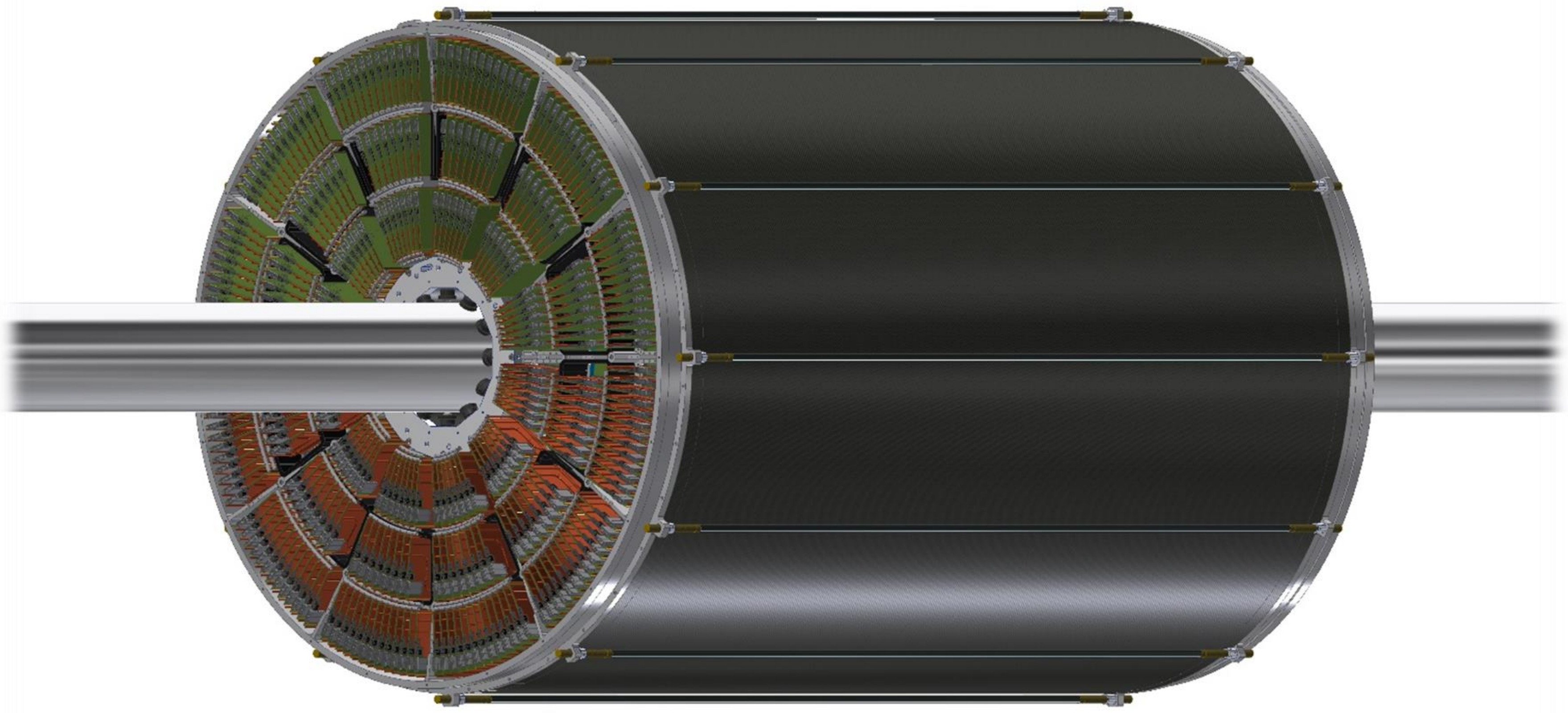
- TPC structural parts are assembled vertically at Stony Brook.
  - **Wagon Wheels**
  - **Field Cages**
  - **Central HV Plane**
  - **Tie Rods**

Tooling & Fixturing – TPC Populating on Horizontal Cart

- The TPC is then populated with the GEM assemblies while it rests on one of the Transport/Assembly Carts.

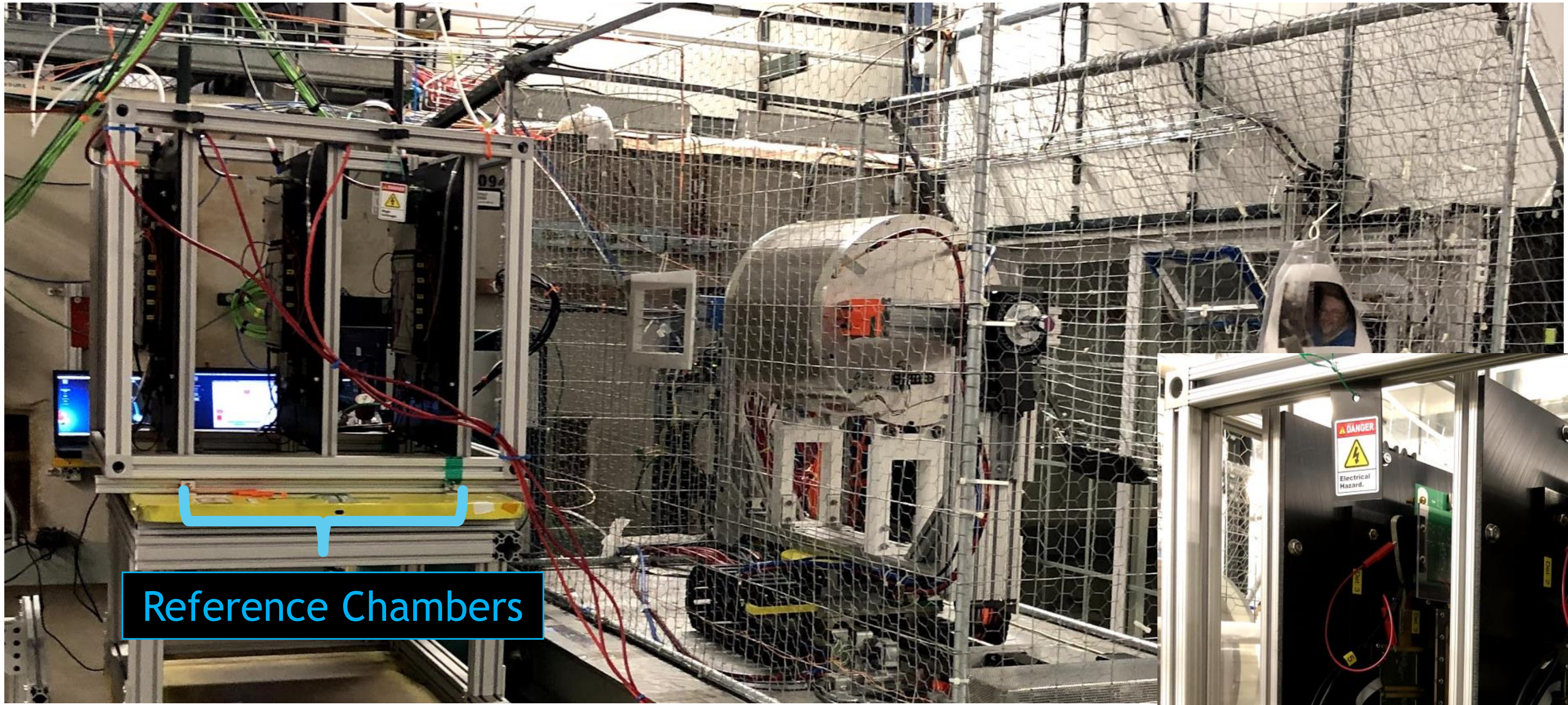
Tooling & Fixturing – TPC Installation at sPHENIX





- Utilizing the Roller Plate Assembly and a 10 inch diameter tube, the TPC will be rolled into its home within the EmCal.

New This Year:



- Last Year:
  - Internal reference: compare layers (*e.g.* 4,6 calibrates 5)
- This year:
  - External Reference Trackers (room for one 3-layer station)