Construction of time-projection chambers to probe the symmetry energy at high density

Updated on 8/28/2013

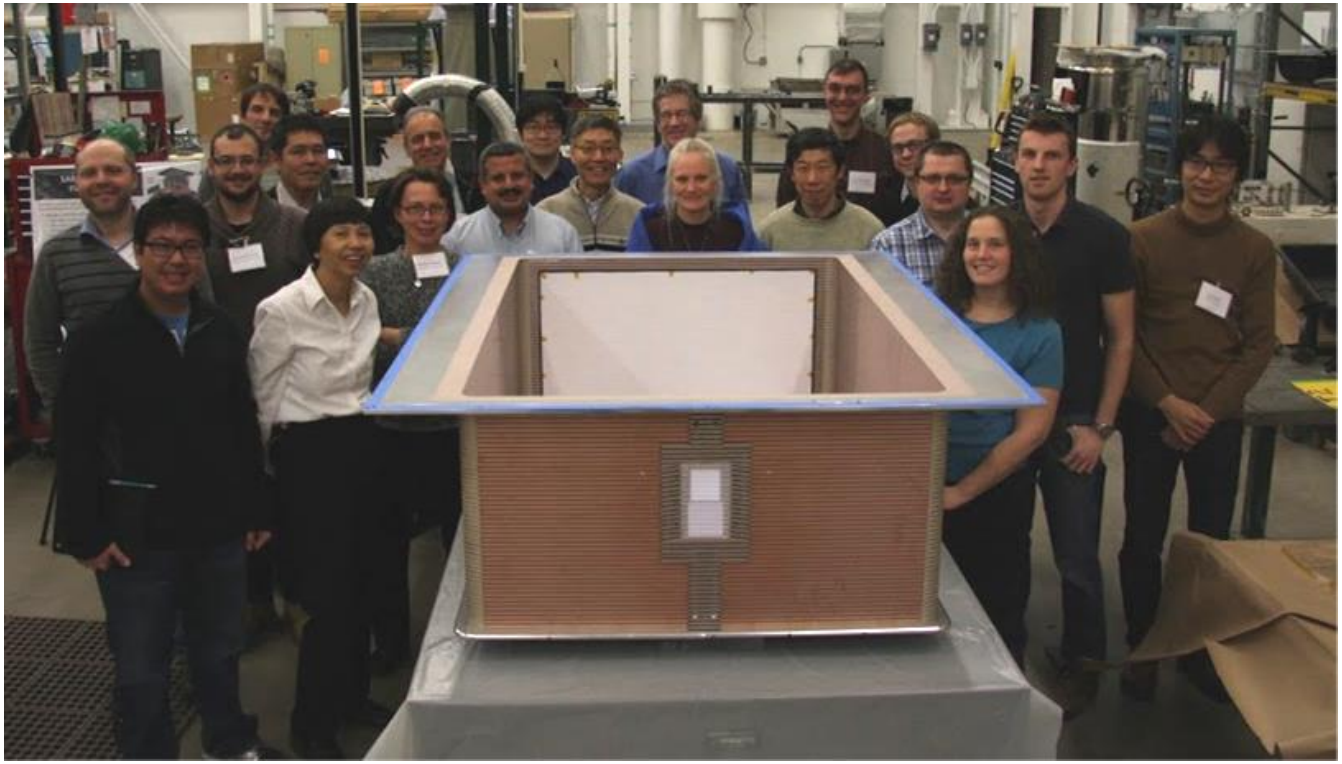
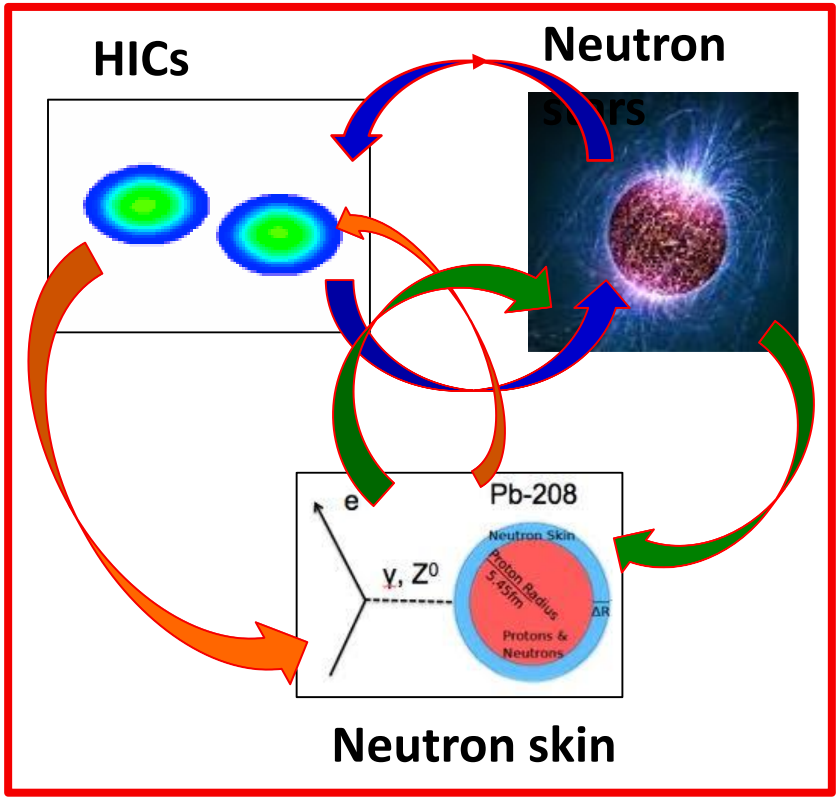


Photo from SAMURAI-TPC collaboration meeting, Jan 25, 2013, NSCL/FRIB, East Lansing

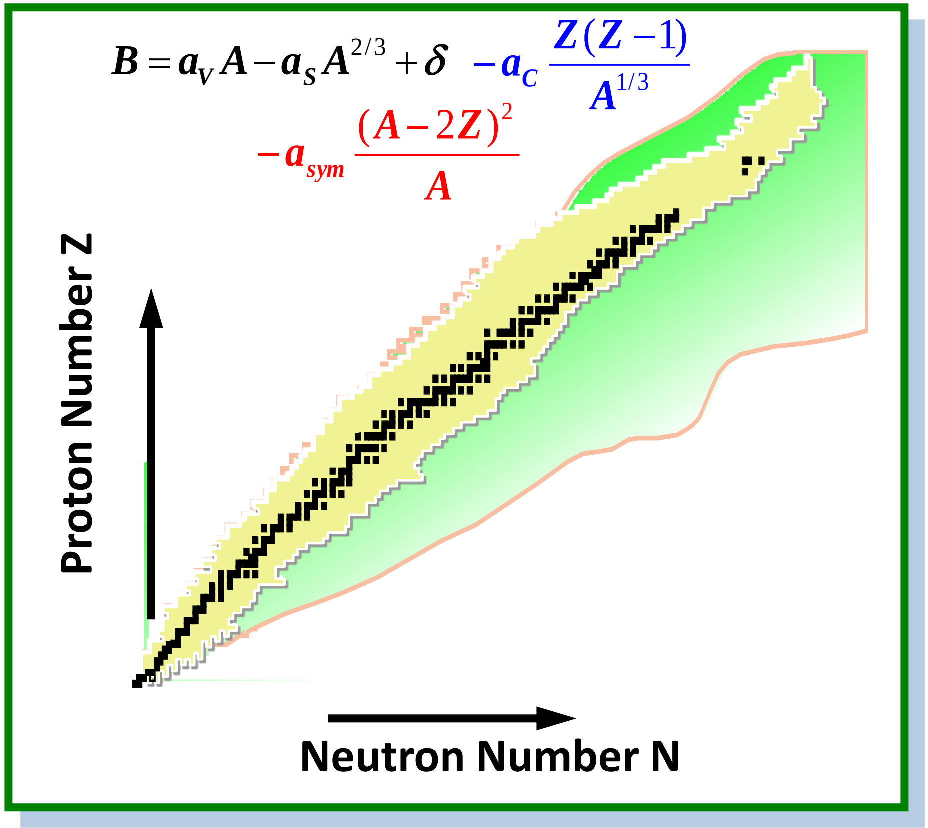
Symmetry Energy – Links between Neutron Star and Nuclear Physics

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$



$$B = a_V A - a_S A^{2/3} + \delta - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \frac{(A-2Z)^2}{A}$$



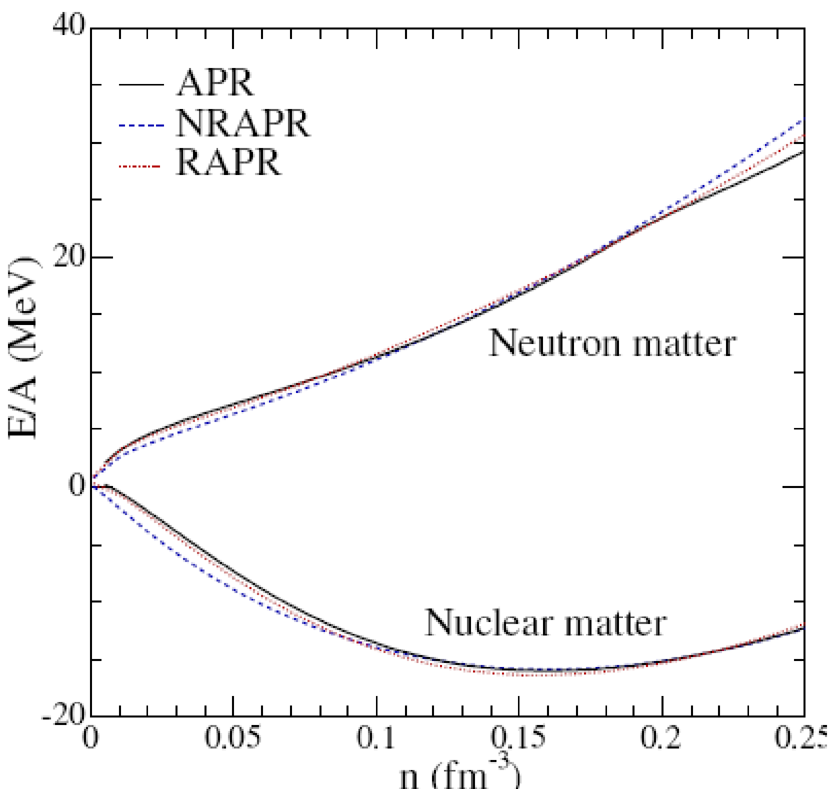
Nuclear Equation of State of asymmetric matter

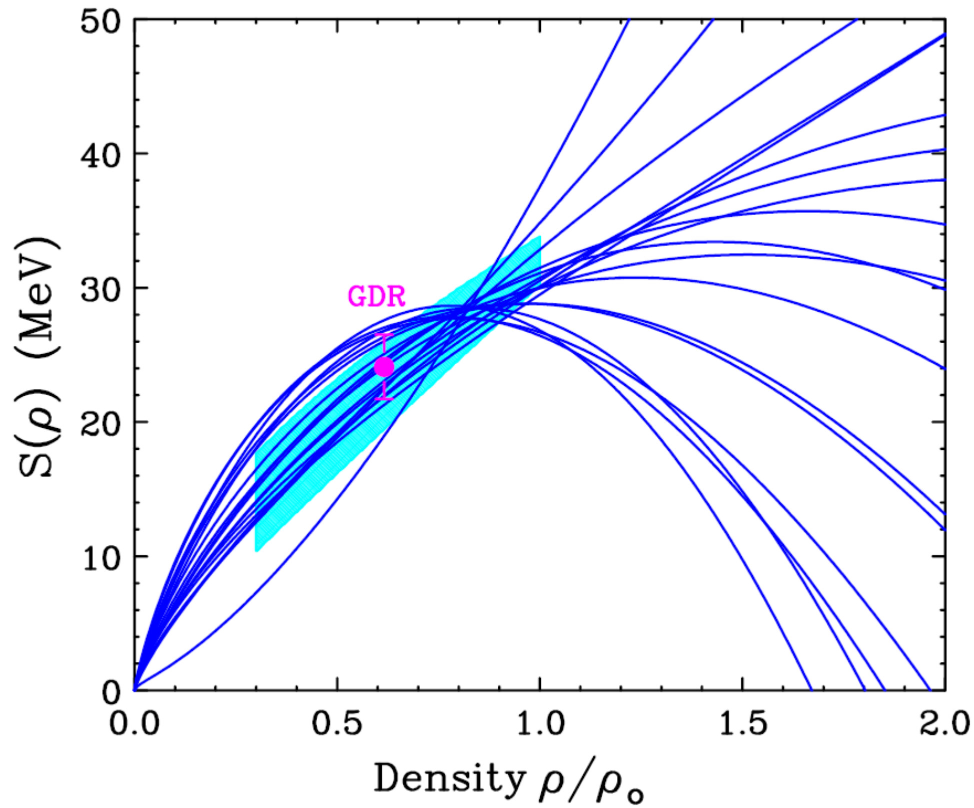
$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

$$S(\rho) = S_o + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \ldots$$

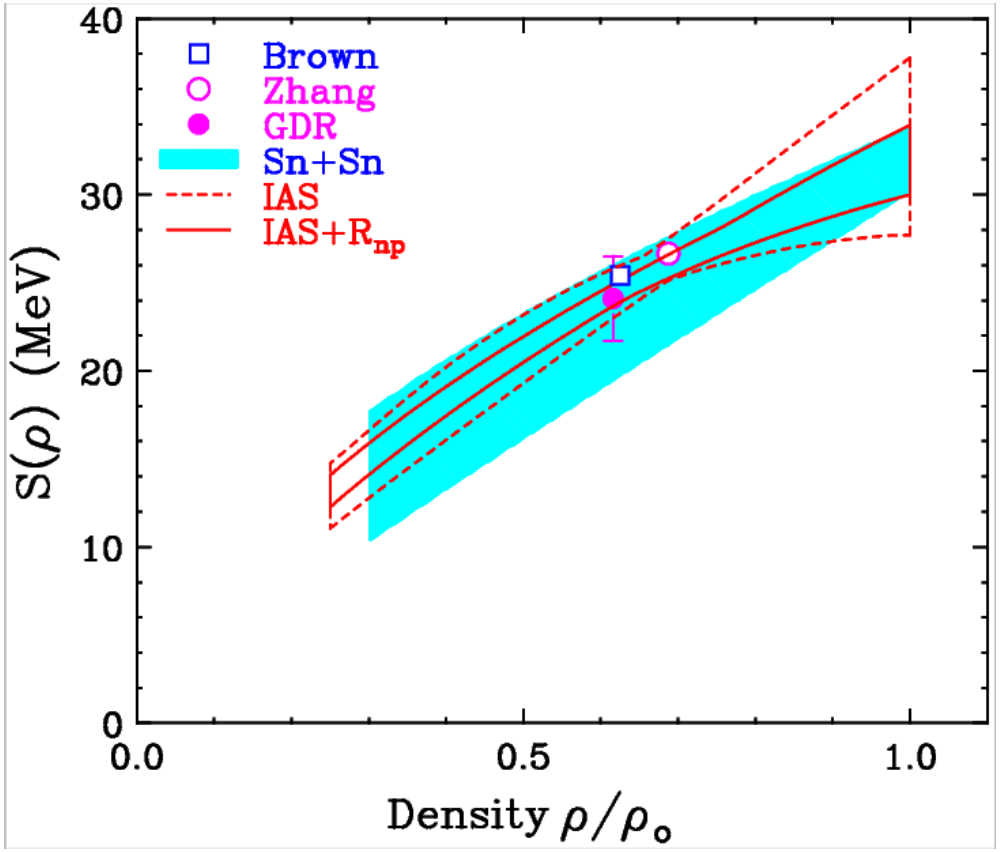
$$L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho_B}\bigg|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{sym}$$

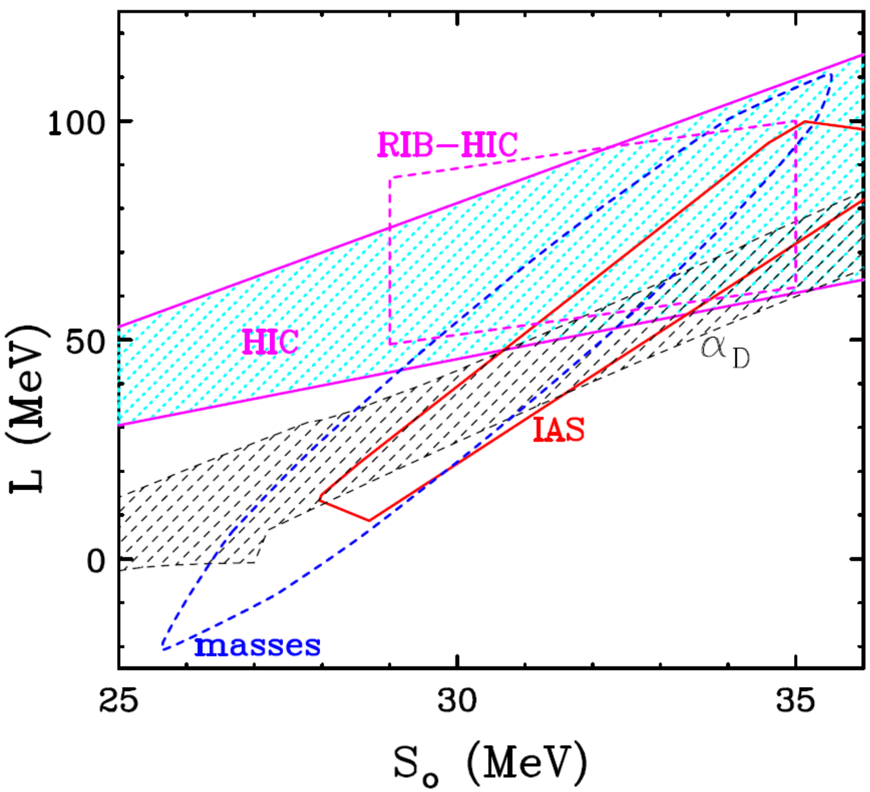




Density dependence of symmetry energy

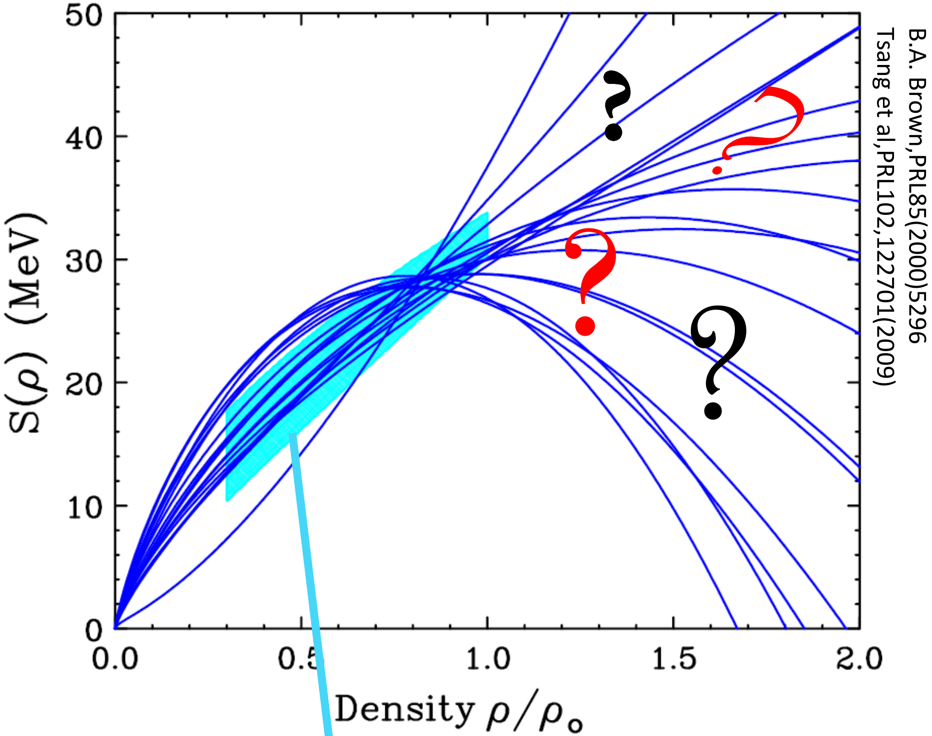
Consistent Constraints on Symmetry Energy from different experiments→ HIC is a viable probe NuSYM13 updates





The Equation of State of Asymmetric Matter

$E/A(\rho, \delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$ $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1$



The symmetry energy influences many properties of neutron stars but is highly uncertain especially at high density.

Future Directions: Constrain the symmetry energy at supra-saturation densities with comparisons of (π^-, π^+), (n, p) (t, ^{3}He) production and flows. Such observables are selectively sensitive to the symmetry energy.

At $\rho<\rho_0$, consistent constraints obtained from different observables:

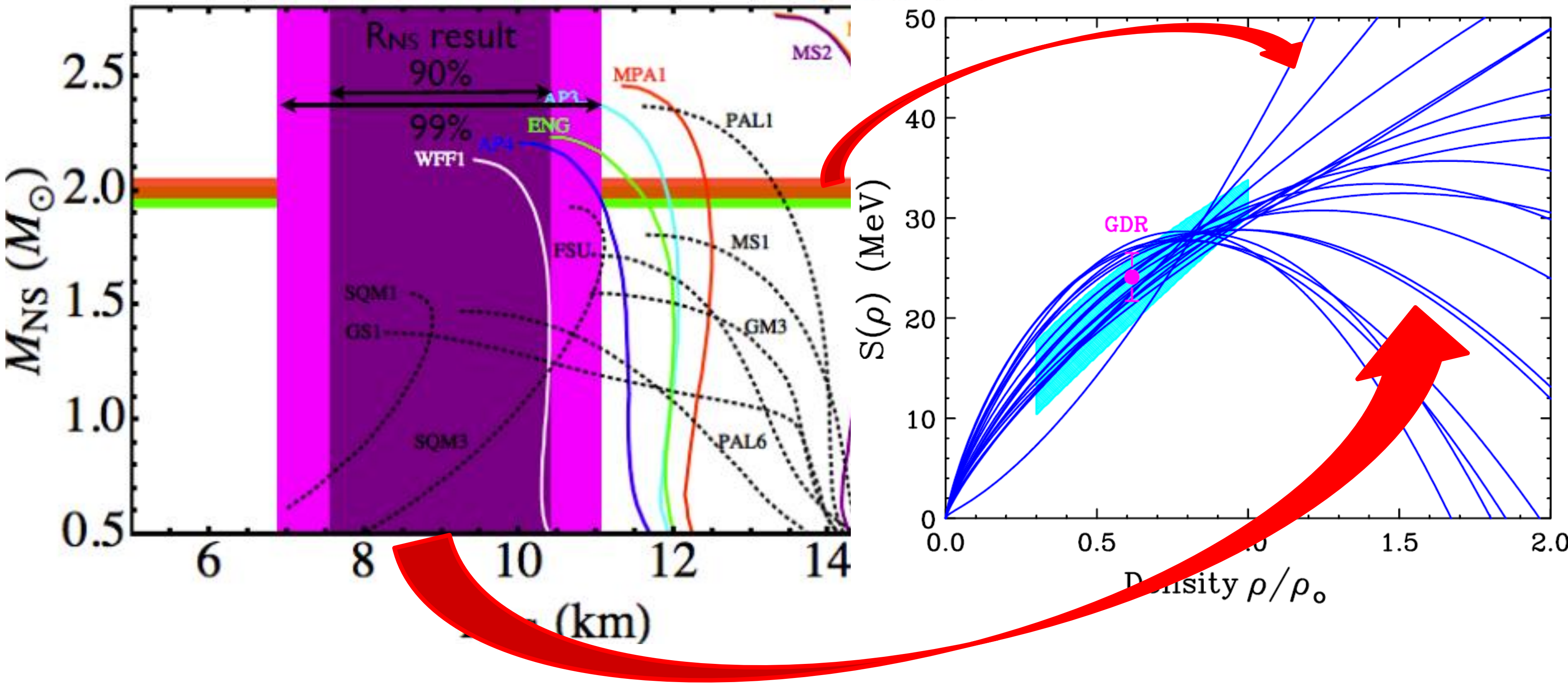
Heavy Ion Collisions , Giant Dipole Resonances, Isobaric Analog States, Nuclear masses, Pygmy Dipole Resonances, Pb skin thickness measurements, and neutron star radii.

M.B. Tsang et al., Phys. Rev. C 86, 015803 (2012) http://link.aps.org/doi/10.1103/PhysRevC.86.015803

Astrophysics and Nuclear Physics

Neutron star

Skyrme interactions



Observation:

$M_{NS} \sim 2M_{sun}$

$R_{NS} \sim 9$ km

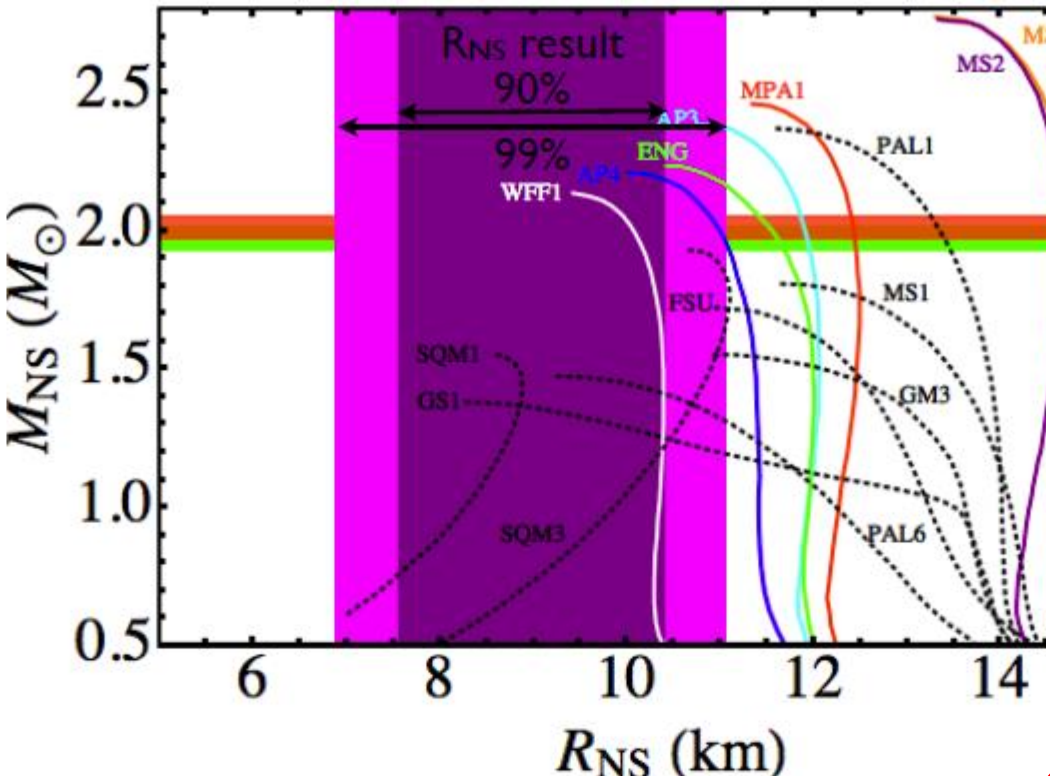
Equation of State

stiff EoS at high ρ

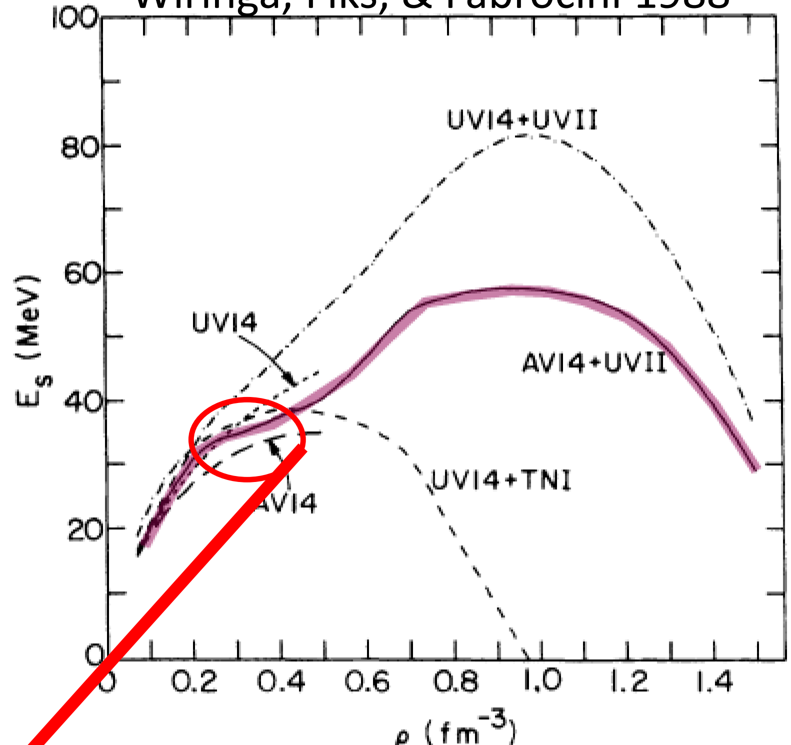
softening EoS at $\rho \sim 2\rho_0$

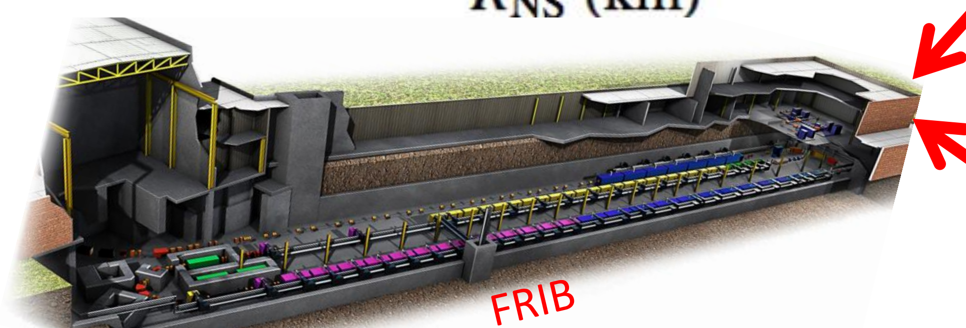
Astrophysics and Nuclear Physics

Neutron star (Rutledge, Gulliot)



AV14+UVII
Wiringa, Fiks, & Fabrocini 1988



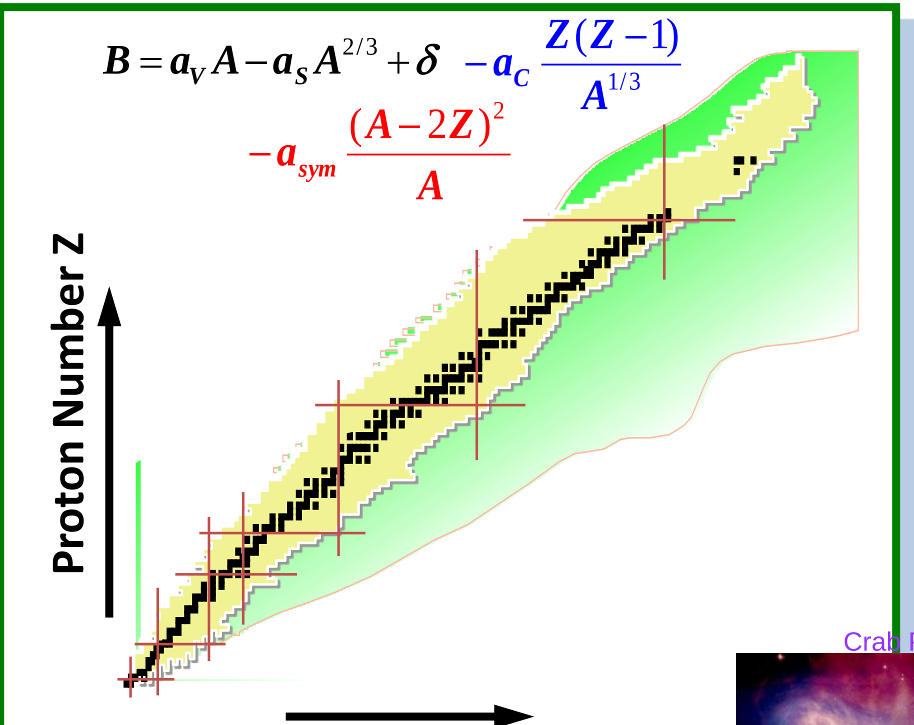


Equation of State

softening EoS at $\rho \sim 2\rho_0$

Successful Strategies used to study the symmetry energy with Heavy Ion collisions with RIB

Isospin degree of freedom



- Vary the N/Z compositions of projectile and targets e.g.
- $^{132}Sn+^{124}Sn$, $^{132}Sn+^{112}Sn$, $^{108}Sn+^{124}Sn$, $^{108}Sn+^{112}Sn$
- Measure isospin sensitive observables such as isotope distributions (isospin diffusion), n/p, t/^{3}He ratios, flow
- Simulate collisions with transport theory
- *Find the symmetry energy density dependence that describes the data.*
- *Constrain the relevant input transport variables.*

Heavy Ion Collisions at high density with RIB

Old data: Au+Au. E/A=150 to 1500 MeV

New Experiments at RIB facilities

pi-/pi+	300 MeV & 200 MeV				
Beam	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
132Sn	124Sn	1.64	1.48	1.56	0.16
132Sn	112Sn	1.64	1.24	1.44	0.40
108Sn	124Sn	1.16	1.48	1.32	-0.32
108Sn	112Sn	1.16	1.24	1.20	-0.08
124Sn	124Sn	1.48	1.48	1.48	0.00
112Sn	112Sn	1.24	1.24	1.24	0.00
112Ru	112Sn	1.55	1.24	1.38	0.31
126Sn	112Sn	1.52	1.24	1.38	0.28

6.5 days approved by June RIKEN PAC

Similar RIB reactions can be used to study isospin diffusions.

Beam	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
132Sn	64Ni	1.64	1.29	1.51	0.35
108Sn	58Ni	1.16	1.07	1.13	0.09

$$ID = \vec{j}_n - \vec{j}_p = -\rho D_\delta \vec{\nabla}\delta$$

ID Increase with $\vec{\nabla}\delta$ ← *asymmetry gradient*

Beam	tgt	N/Z(beam)	N/Z(tgt)	N/Z(CN)	N/Z diff
56Ni	58Ni	1.00	1.07	1.04	-0.07
68Ni	64Ni	1.43	1.29	1.36	0.14

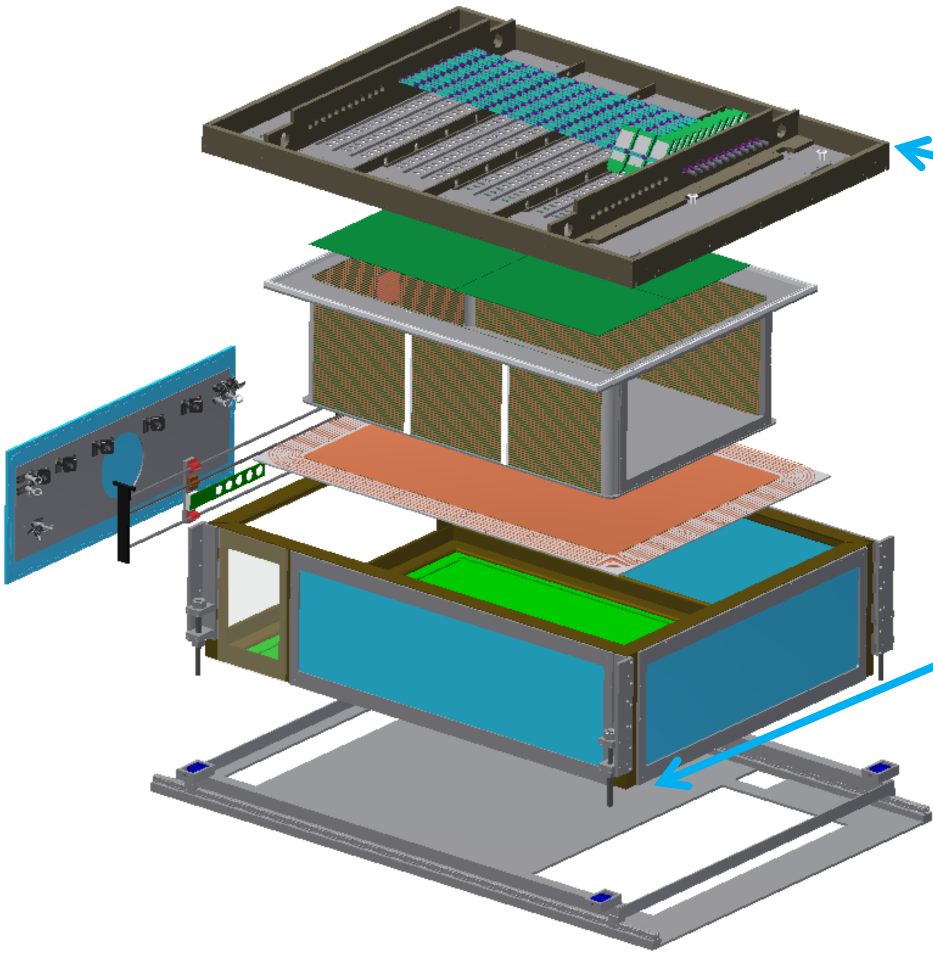
Astrophysics Nuclear Structure HI Reactions

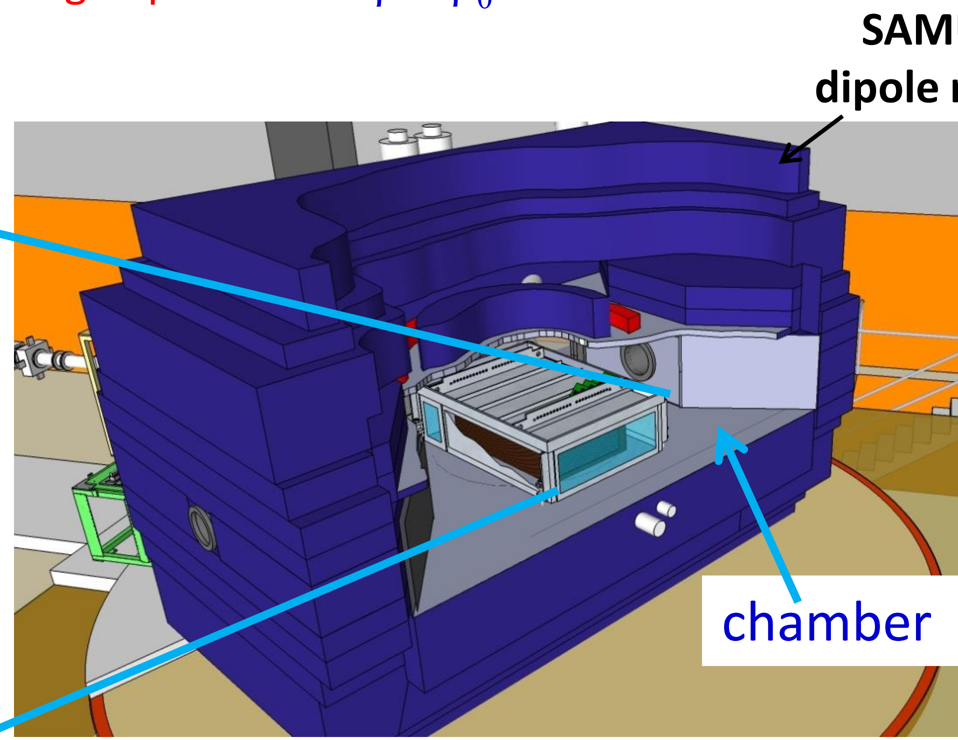
S-TPC: *Proposed research program*

Probe	Devices	E_{lab}/A (MeV)	Part./s	Main Foci	Possible Reactions	FY
$\pi^+\pi^-$,p, n,t,^{3}He	TPC Nebula	200-300 350	10^4-10^5	E_{sym} m_n^*, m_p^*	^{132}Sn+^{124}Sn, ^{108}Sn+^{112}Sn, ^{52}Ca+^{48}Ca, ^{36}Ca+^{40}Ca ^{124}Sn+^{124}Sn, ^{112}Sn+^{112}Sn	2014
$\pi^+\pi^-$ p, n,t,^{3}He	TPC Nebula	200-300	10^4-10^5	σ_{nn},σ_{pp} σ_{np}	^{100}Zr+^{40}Ca, ^{100}Ag+^{40}Ca, ^{107}Sn+^{40}Ca, ^{127}Sn+^{40}Ca	2015 - 2017

Funding:
US: DOE Grant # DE-SC0004835 (2010-2015):– "Determination of the Equation of State of Asymmetric Nuclear Matter":
To construct the Time Projection Chamber (TPC) needed for the measurements at RIKEN and to do experiments with this TPC.
Japan: Grant-in-aid for innovative area (2012-2016) :--"Nuclear Matter in neutron Stars investigated by experiments and astronomical observations":
To implement the GET electronics

MSU-TAMU-RIKEN-Kyoto initiative: Time Projection Chamber installed in the SAMURAI magnet to detect pions, charged particles at $\rho \sim 2\rho_0$



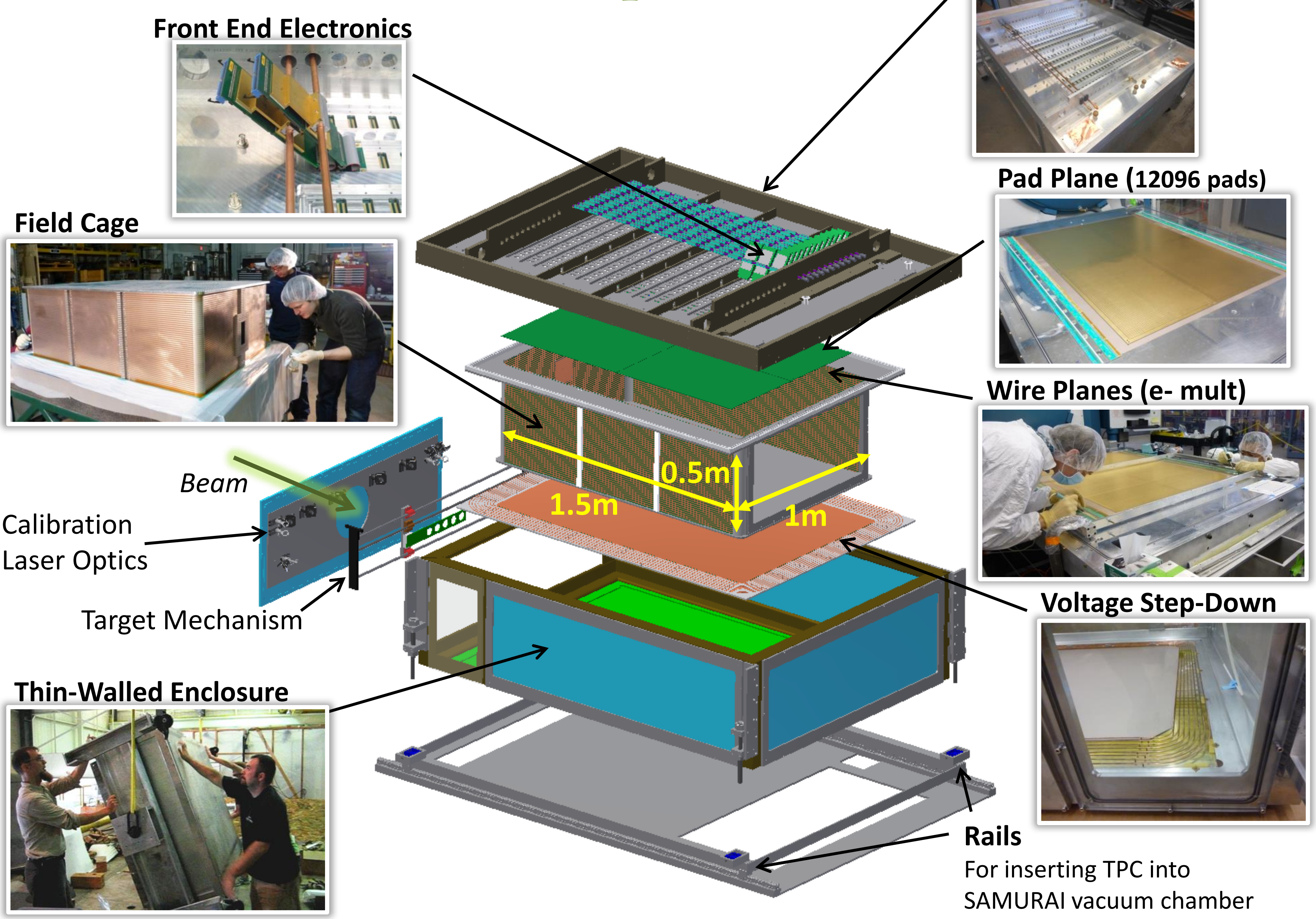


SAMURAI magnet parameters	
B_{typ}, B_{max}	0.5T, 3T
R, pole face	1 m
Gap	80 cm
Usable gap	75 cm

S-TPC: *SAMURAI Spectrometer*

- SAMURAI: high-resolution spectrometer at RIKEN, Japan
- Auxiliary detectors for heavy-ions, neutrons, and trigger

SAMURAI TPC: Exploded View



Time-projection chamber operation

TPC is a particle tracker sitting in a magnet

- Charged collision fragments ionize detector gas
- Electrons drift in E-field toward charge-sensing pads
  - **Positions** and **time** of arrival → 3D path
- Momentum from curvature of path in B-field
- Particle type from energy loss and magnetic rigidity

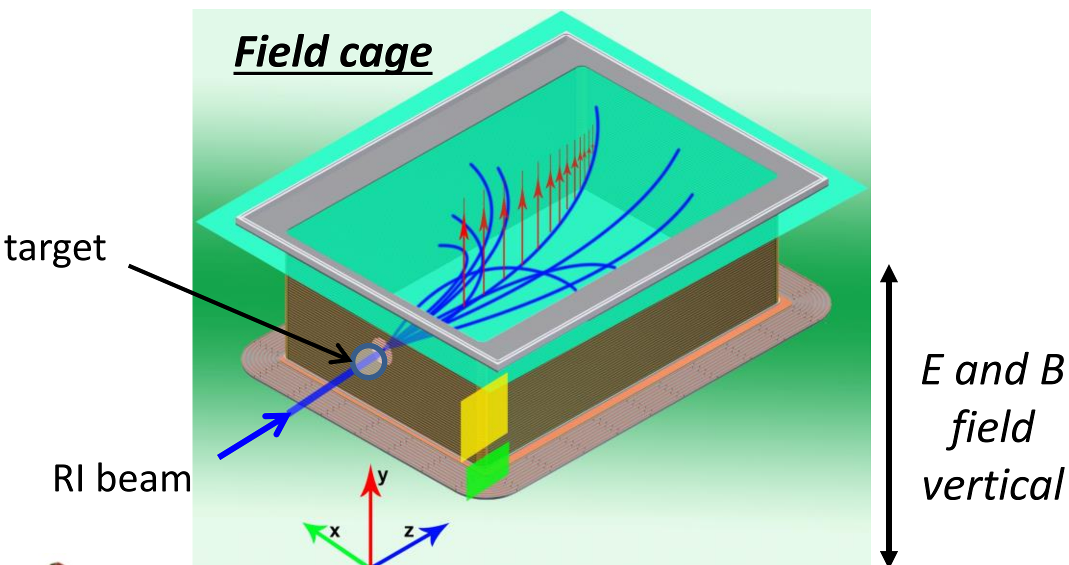


Figure courtesy of J. Estee

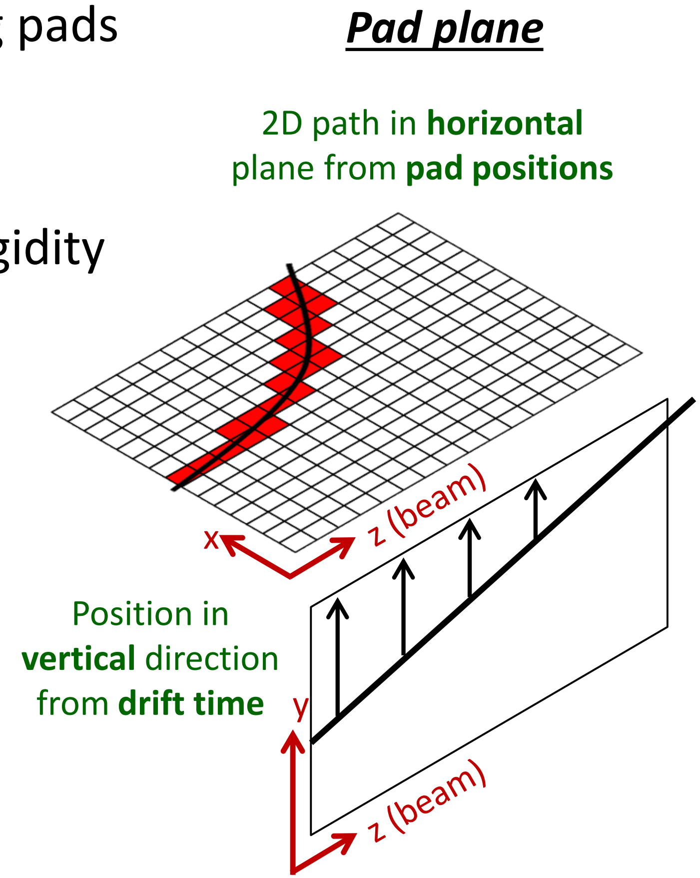
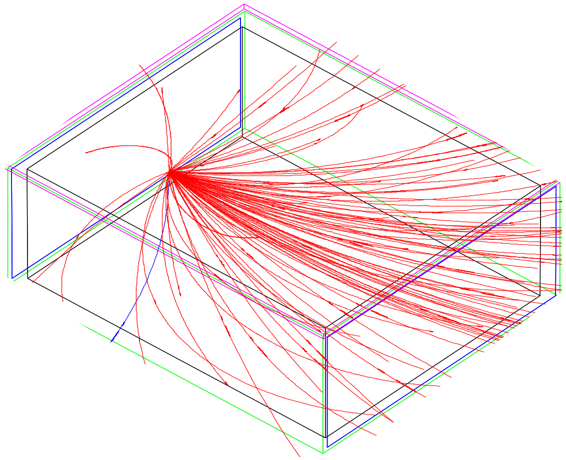


Figure courtesy of J. Barney

Desired TPC properties



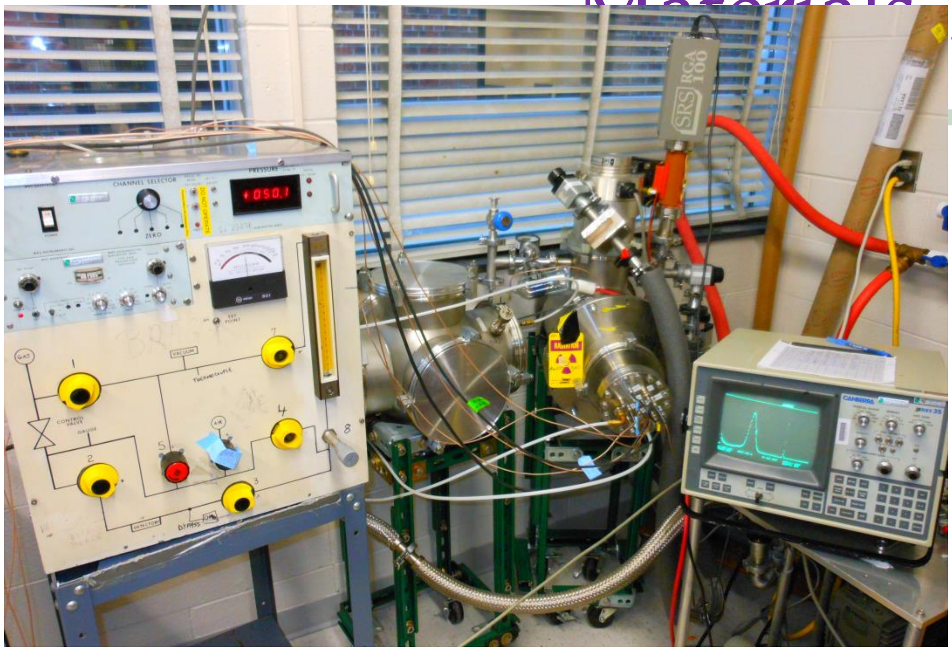
GEANT simulation
$^{132}Sn+^{124}Sn$ collisions at E/A=300 MeV

- Good efficiency for pion track reconstruction is essential.
- Initial design is based upon EOS TPC, whose properties are well documented.
- SAMURAI has same pole diameter (2 m) as HISS, but a smaller gap of 80 cm (really 75 cm) vs. the 1m gap of HISS)

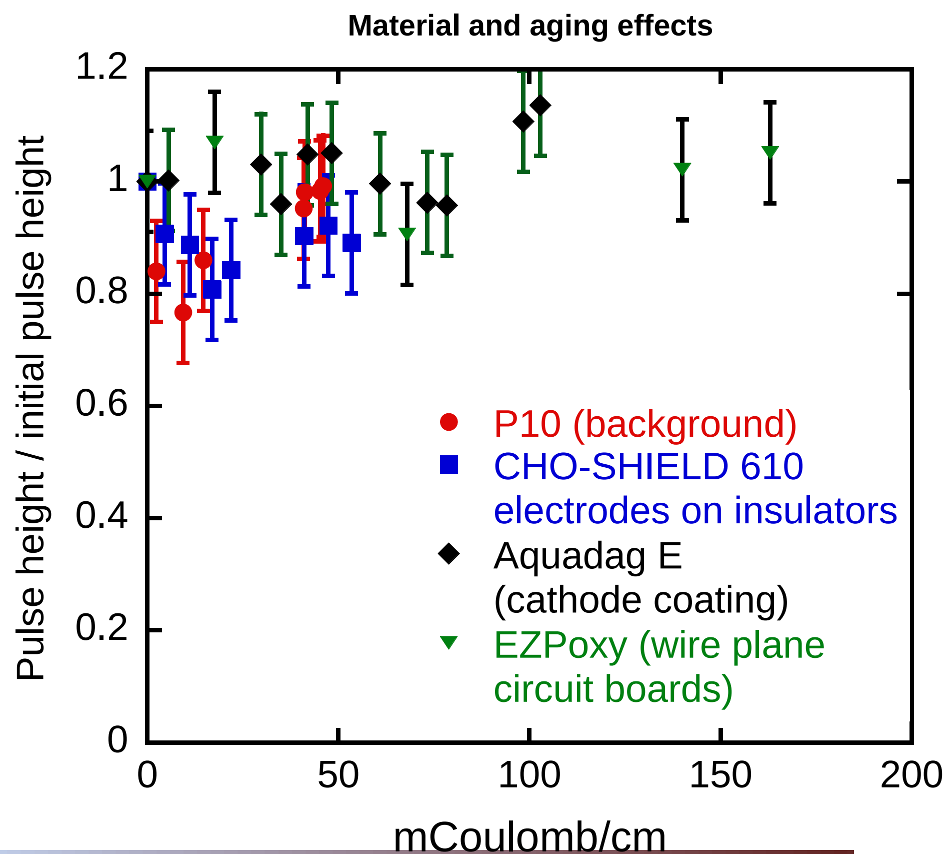
SAMURAI TPC Parameters	Values
Pad plane area	1.34m x 086 m
Number of pads	12096 (108 x 112)
Pad size	12 mm x 8 mm
Drift distance	53 cm
Pressure	1 atmosphere
dE/dx range	Z=1-3 (STAR El.), 1-8 (GET El.)
Two track resolution	2.5 cm
Multiplicity limit	200 (may impact absolute pion eff. in large systems.)

Tour stop #6a

Materials Testing



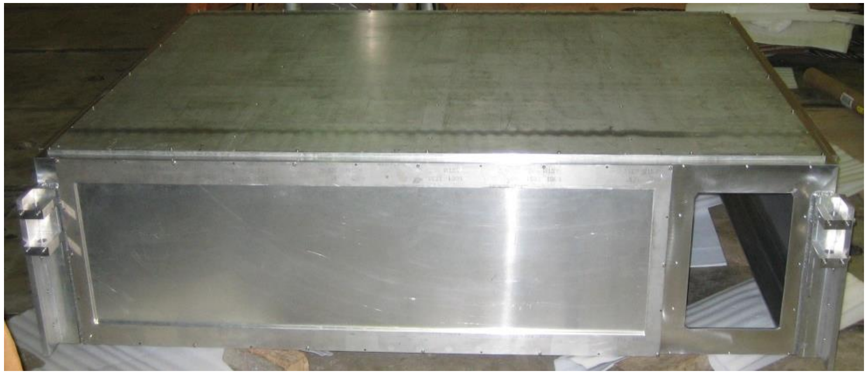
- All epoxies, conductive coatings and PCB materials were tested for aging effects in a single wire proportional counter.
- The results for the chosen materials are plotted below.



Tour stop #1b

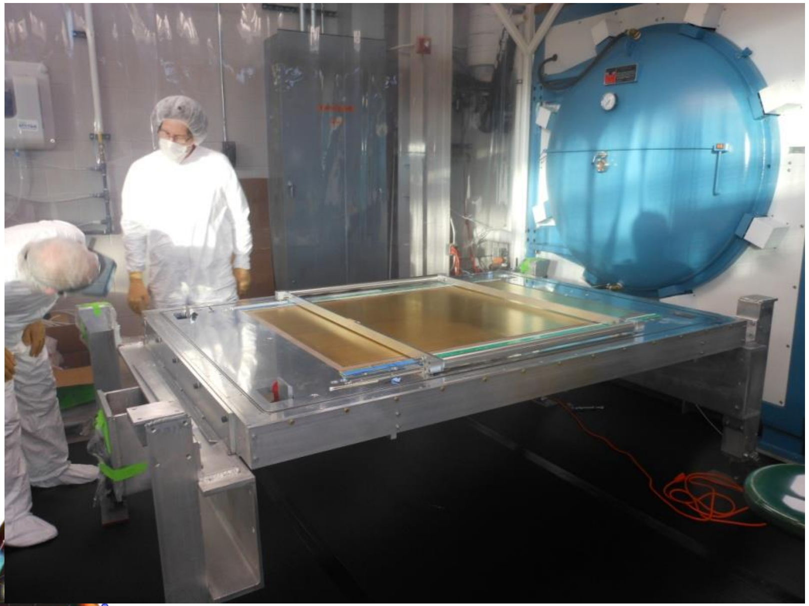
SAMURAI TPC Enclosure fabrication

A. McIntosh, Texas A&M



- Aluminum, plus Lexan windows
- **Skeleton**: Angle bar, welded and polished for sealing.
- **Sides & Downstream Walls**: framed aluminum sheet, to minimize neutron scattering
- **Bottom Plate**: Solid, to support voltage step-down
- **Upstream Plate**: Solid, ready for beamline coupling hole to be machined

Manipulation of SAMURAI TPC (~ 0.6 ton)



Motion Chassis and Hoist Beams work as designed.
The TPC Enclosure can be lifted and rotated with relative ease.
The Motion Chassis can also be mounted on the top plate and facilitates transportation of and work on the top plate.

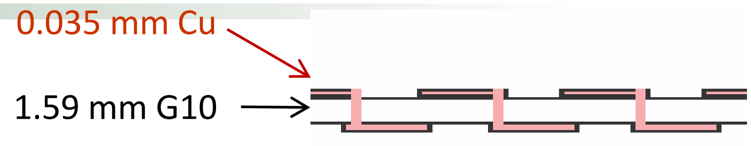
Tour stop #1a

Field cage

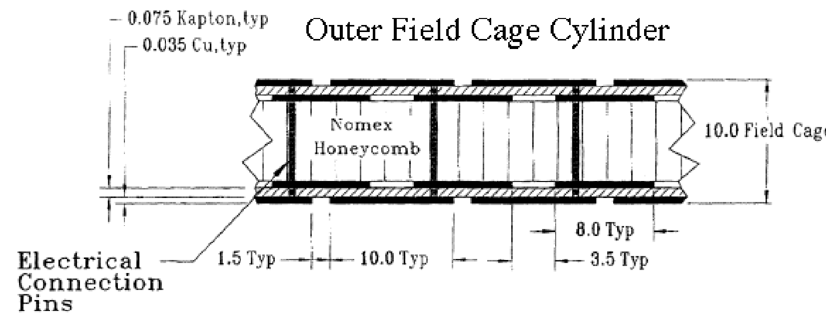
- Made of two layer PCB's
- Thin walls for particles to exit
- Gas tight (separate gas volumes)

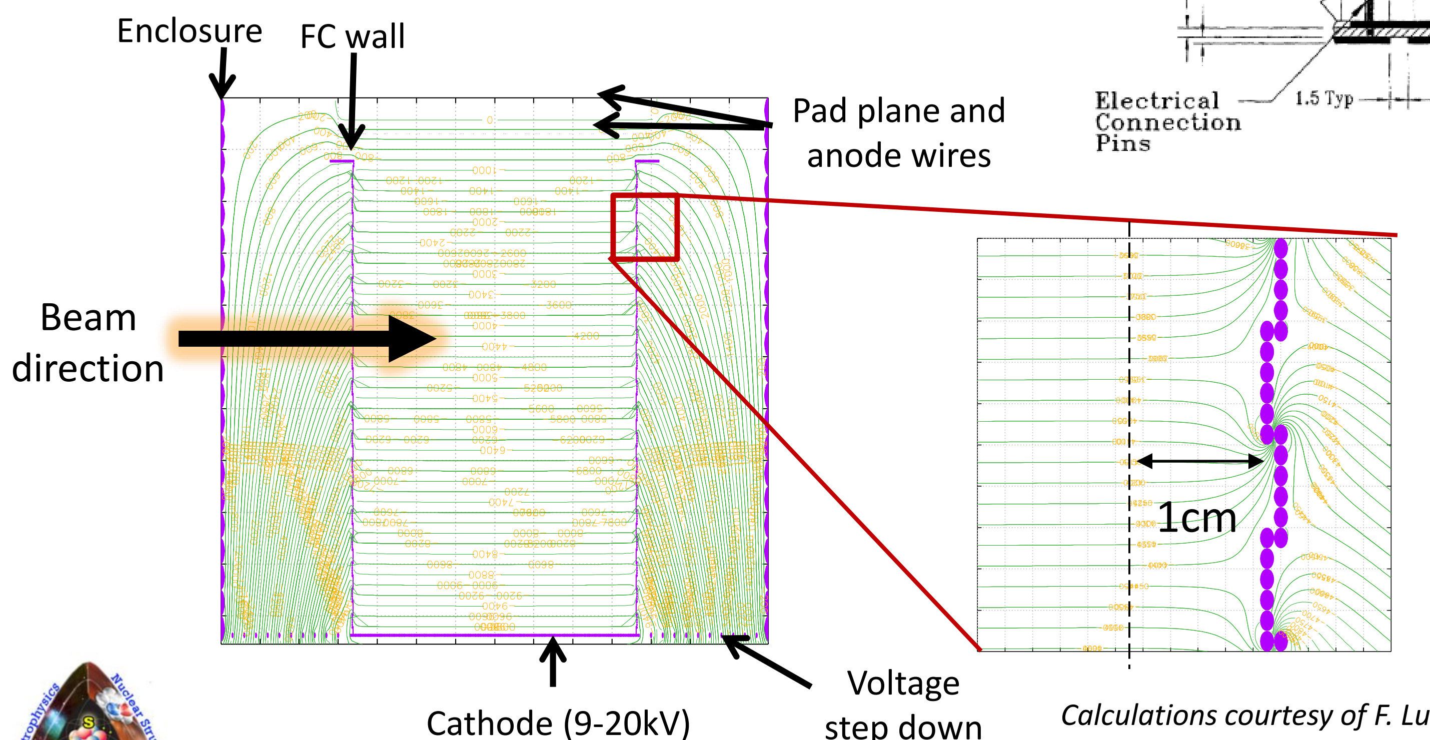
SAMURAI Design

Field Cage Side Panel



STAR Design





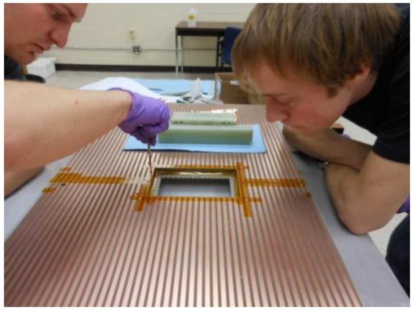
GARFIELD calculations (on scaled field cage) show uniform field lines 1cm from the walls

Calculations courtesy of F. Lu

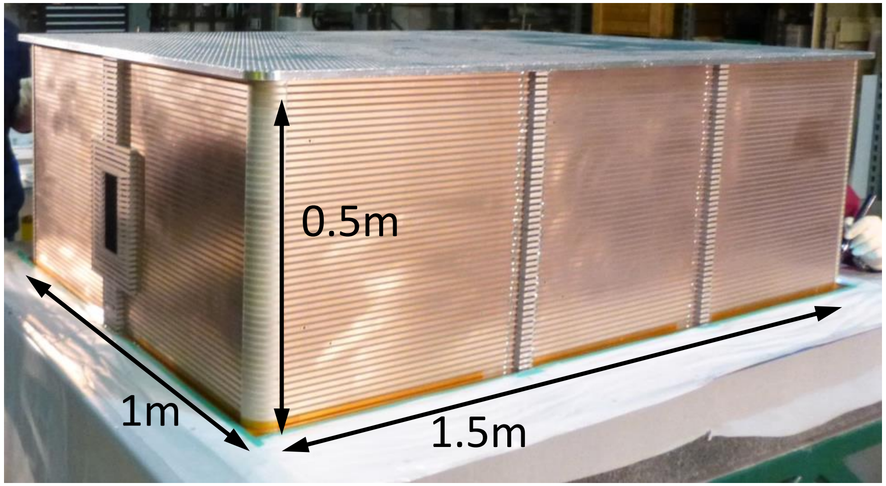
HI Reactions

S-TPC: *Field cage*

- Thin walls for particles to exit, but maintain structural stability
  - 8 circuit boards with copper strips
- Removable beam windows
  - 25um mylar entry window
  - 125um kapton exit window
- Cathode (bottom)
  - Aluminum honeycomb: light, strong
  - Graphite coating: incr. work function
- Gas tight (all seams glued)
  - Allows separate gas volumes:
    - P10 detector gas in FC
    - P10 or dry N_2 insulation gas
  - Useful in active-target mode

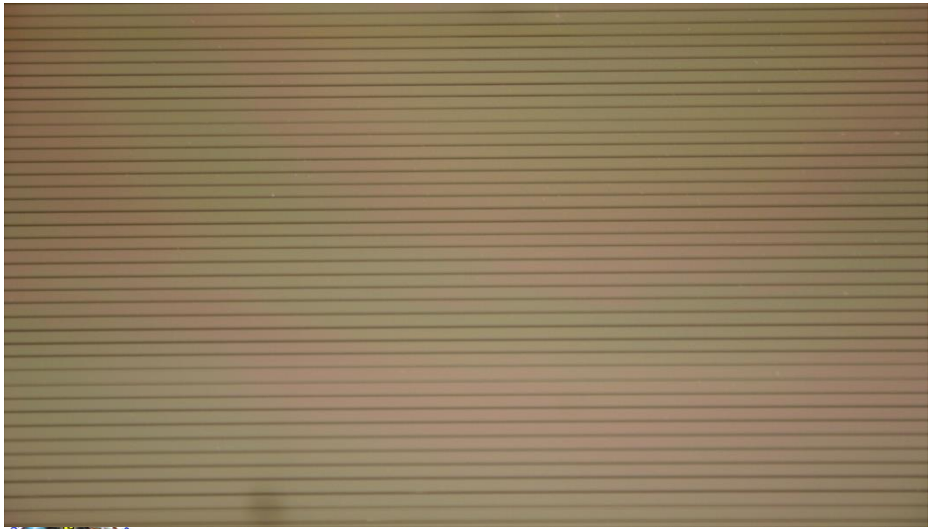


Gluing field cage together

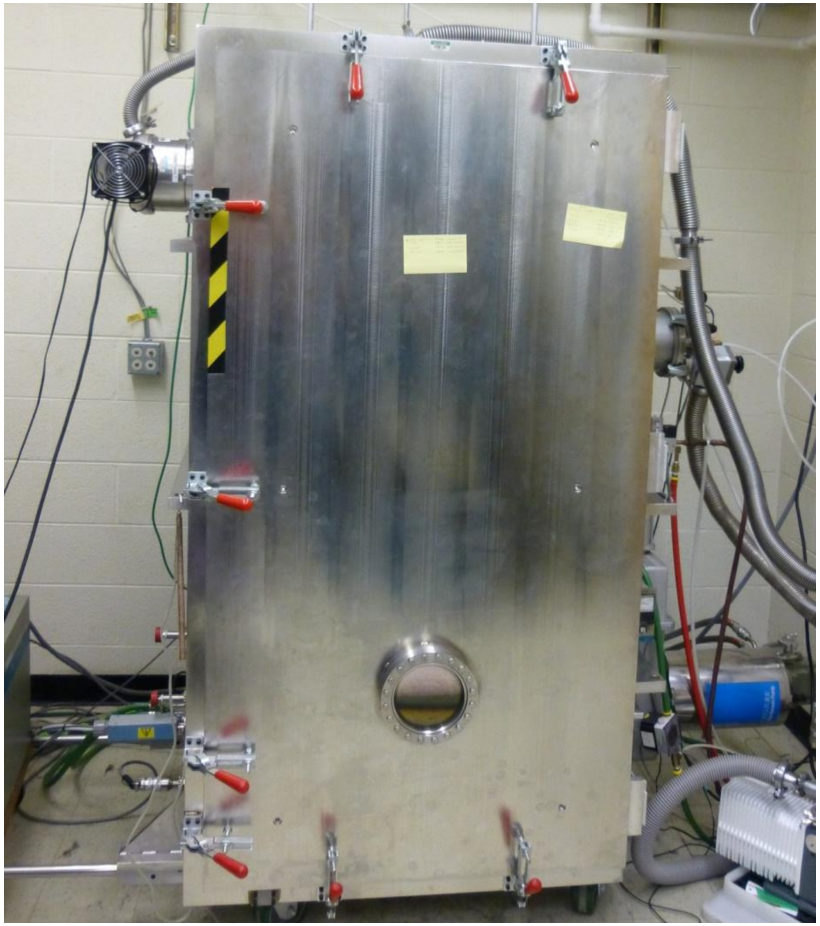


Windows on Field Cage

- Aluminum entrance and exit window electrodes will be evaporated on PPTA and Kapton foils, respectively.
- The NSCL detector lab has large evaporators and the expertise to do this.
- The picture below shows a close-up of the large field cage electrodes for a CRDC detector with 2.1 mm strips and 0.4 m gaps. The total electrode is approximately 60 cm x 30 cm.

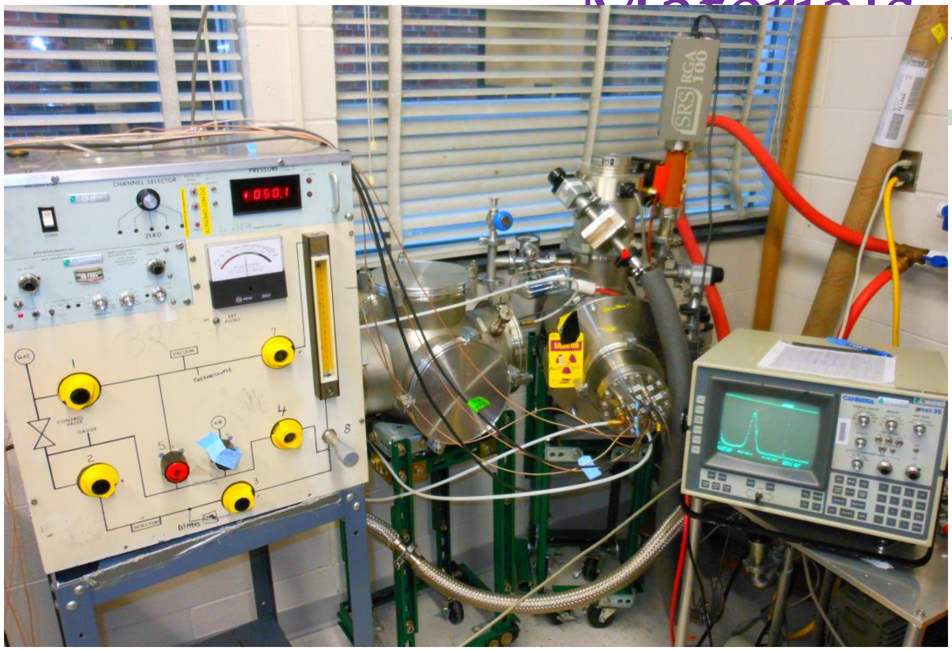


- The picture below shows the evaporator that will be used for the 85 cm x 50 cm exit window.



Tour stop #6a

Materials Testing



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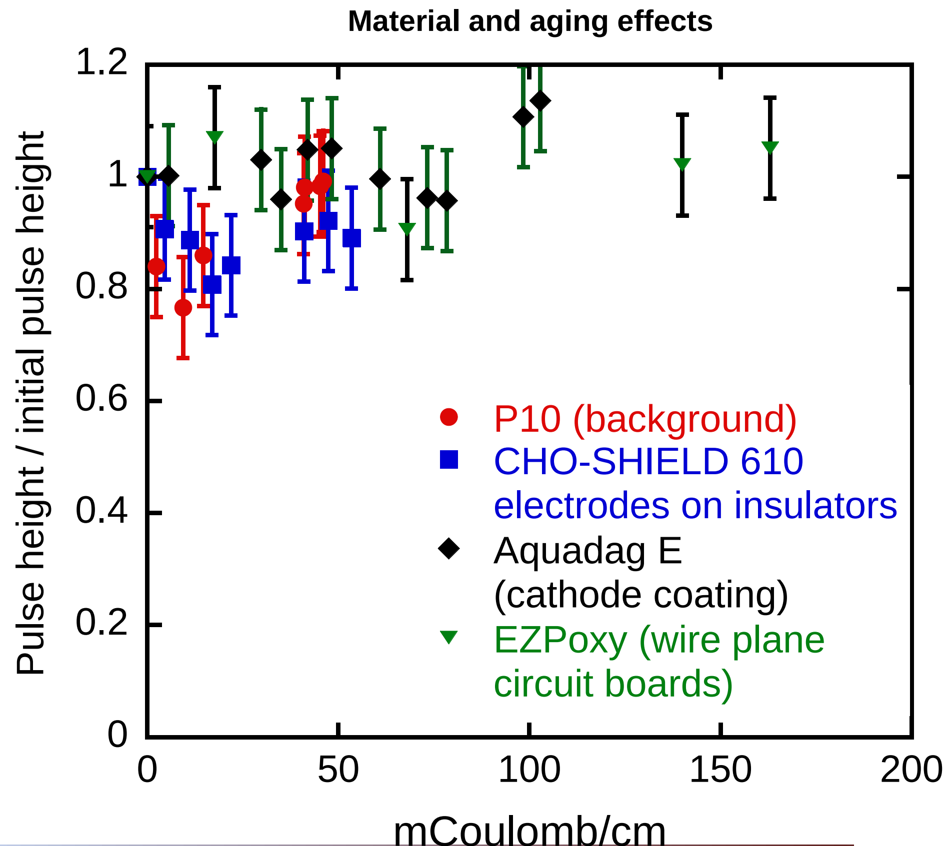
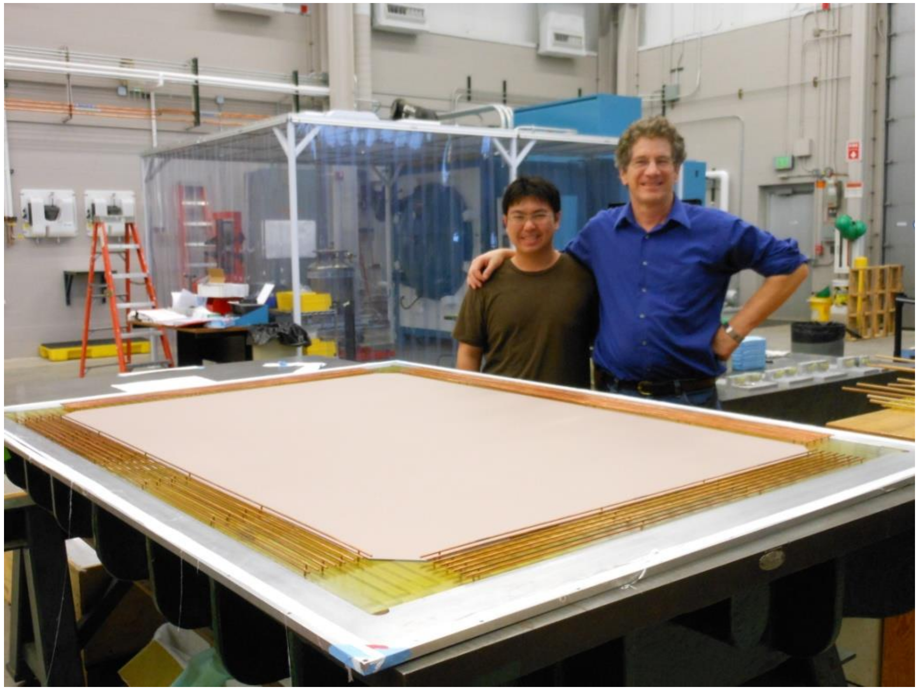
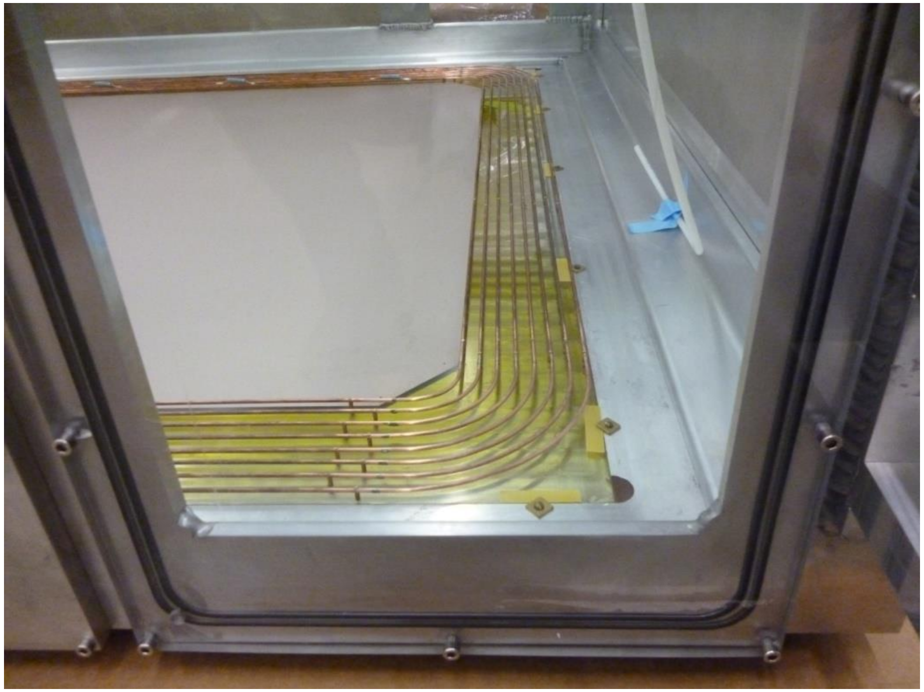


Voltage step down

Tour stop #1c





- Situated about 6 mm below the cathode
- Polycarbonate (6 mm) epoxied to bottom plate of enclosure.
- Copper-silver epoxy electrode surface below cathode is biased to the cathode voltage.
- Eight concentric copper rings step the voltage down from cathode HV to ground. This has been tested to 20 kV.

Tour stop #2a

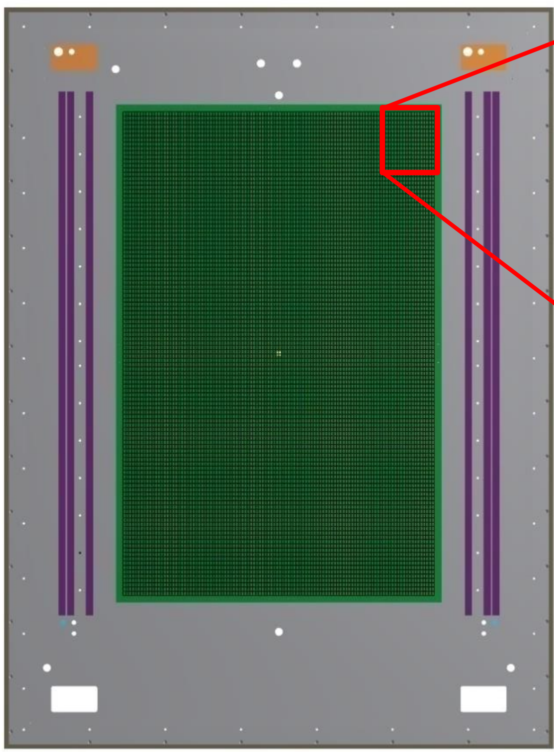
Pad plane

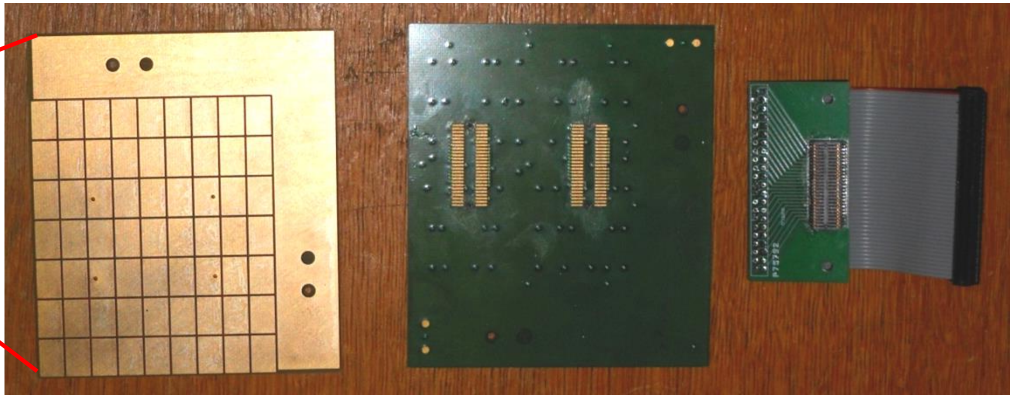
Full pad plane

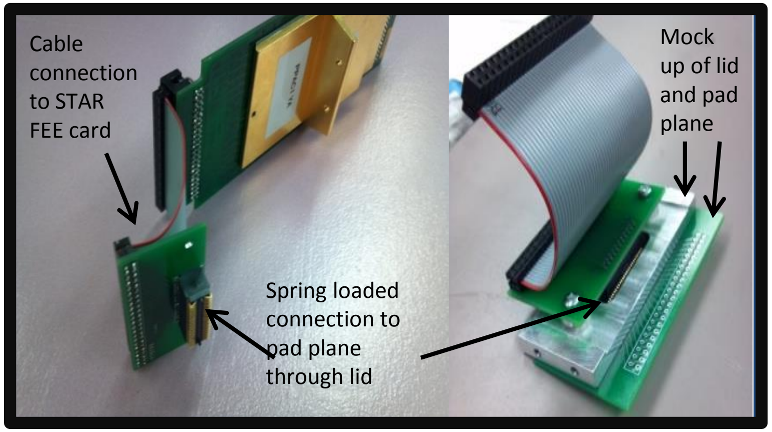
- Mounted on bottom of top plate
- 112 x 108 = 12096 pads
- Each pad: 12mm x 8mm
- *5 Month delay in fabrication*

Small scale prototype: Pad plane unit cell (192 in full plane)

- Capacitance: 10pf pad-gnd, 5pf adjacent pads
- Cross talk:
  - ~0.2% between adjacent pads
  - <0.1% between non-adjacent pads



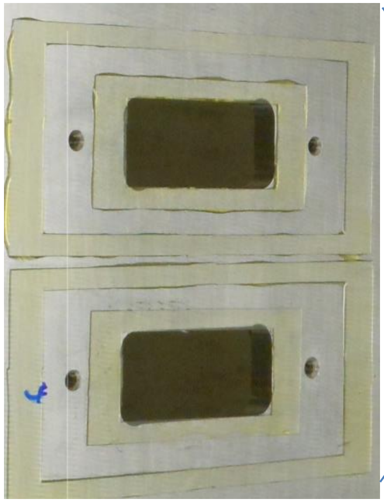




Choice of Samtec connector reduces risks of connector failure

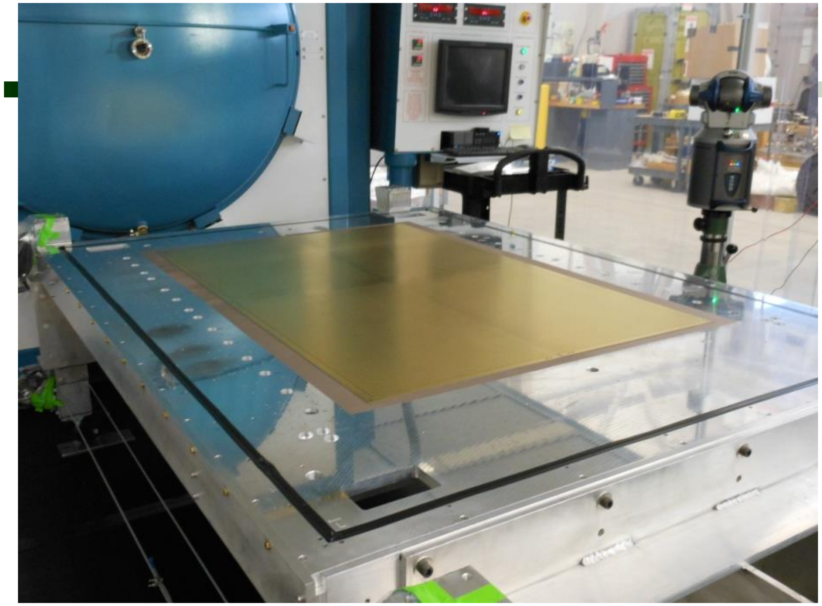
Gluing and Assembly of pad planes

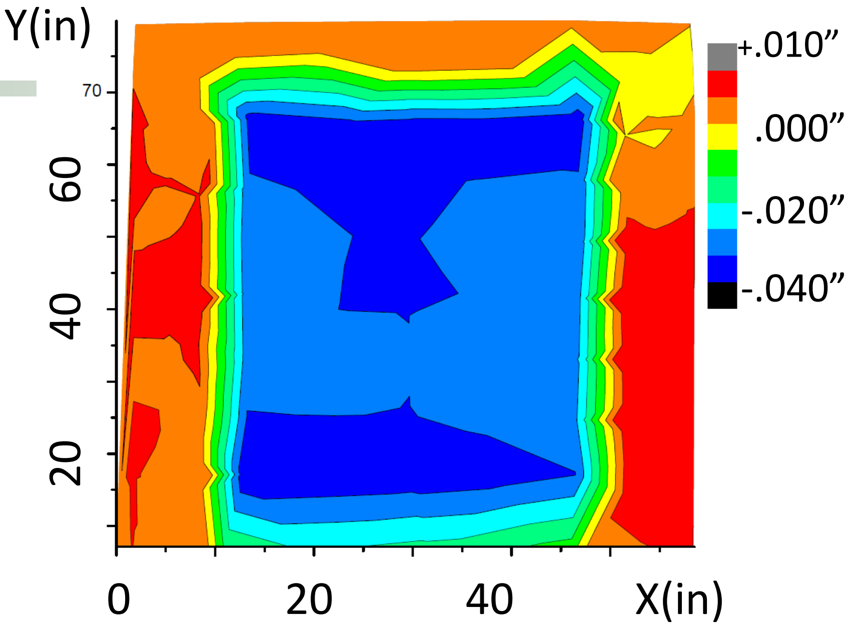
- Electrical and mechanical tests of final boards 11/21-26.
- Refining the pad plane gluing procedure 11/26-12/13.
- Gluing the pad planes 12/13-12/18.
- (Relative times for preparing vs. doing the pad plane gluing procedure reflects the adjustment from small prototype to full scale production boards.)
- Move to the clean room and prepare for wire plane production 12/18.
- Anode plane mounting 1/4 – 1/13



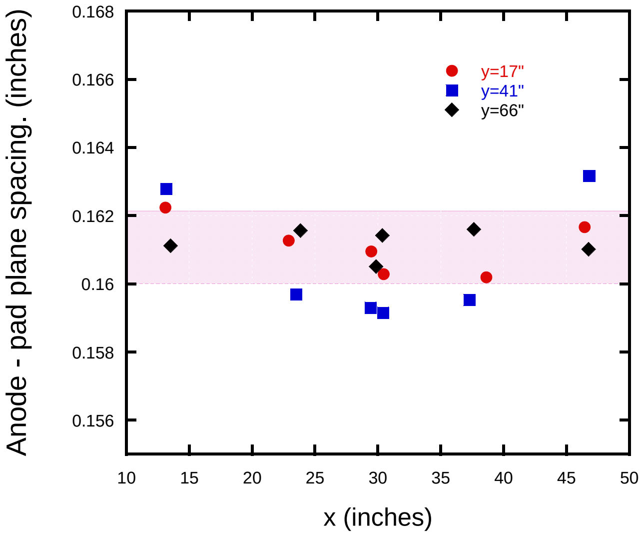
Tour step #2a

Leveling of top plate with laser

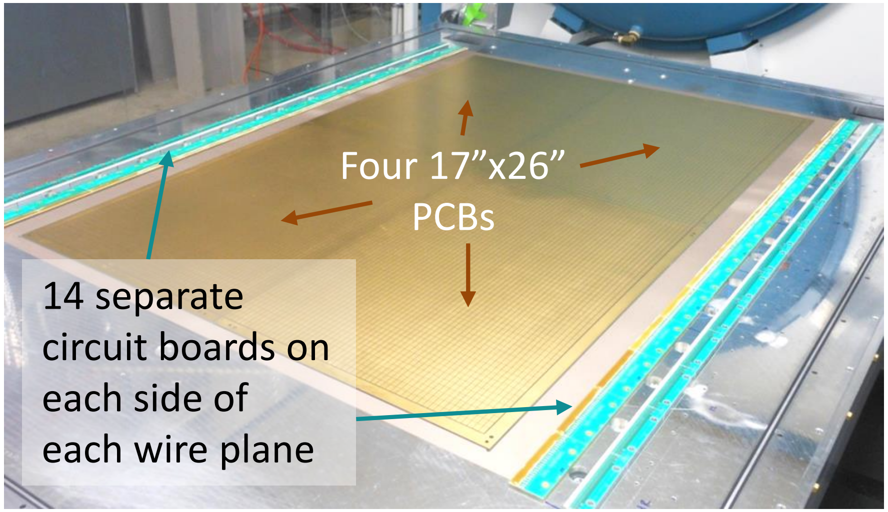


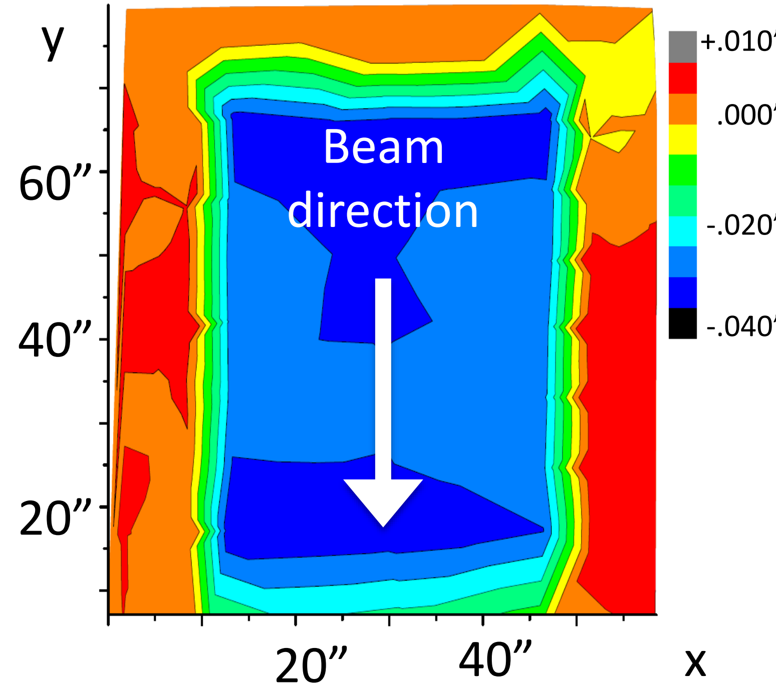


- The top plate is flat to within about 5 mils.
- The pad plane is slightly higher at the center than elsewhere. This is likely the result of the weight applied while gluing.
- Based on these measurements, we adjusted the bars for anode and ground plane to make the anode – pad plane spacing to be approximately 4.05 mm.
- As a result, pad-plane–anode wire heights should be constant to within 2 mils.



S-TPC: *Pad and wire planes*

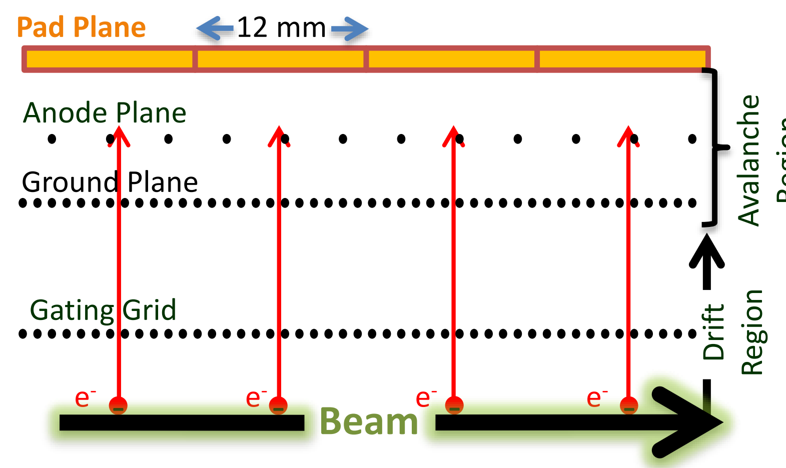




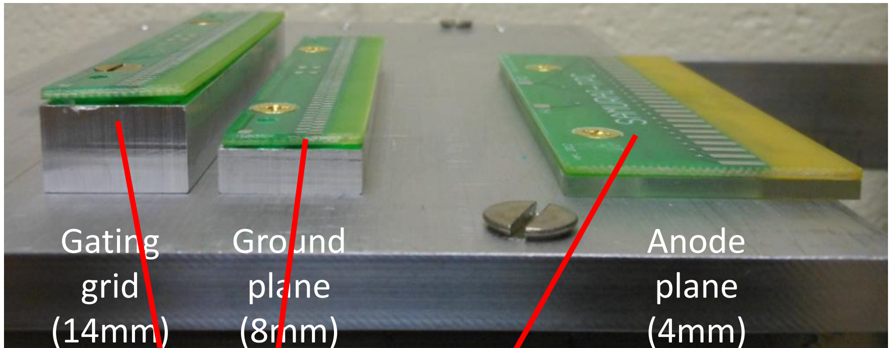
- Pad plane is ***flat to within 0.005” (125 um)***

Plane	Material	Diam (µm)	Pitch (mm)	Height (mm)	Tens. (N)	Volt. (V)	# of wires
Anode	Au-W	20	4	4	0.5	~1400	364
Ground	Cu-Be	75	1	8	1.2	0	1456
Gating	Cu-Be	75	1	14	1.2	100±30	1456

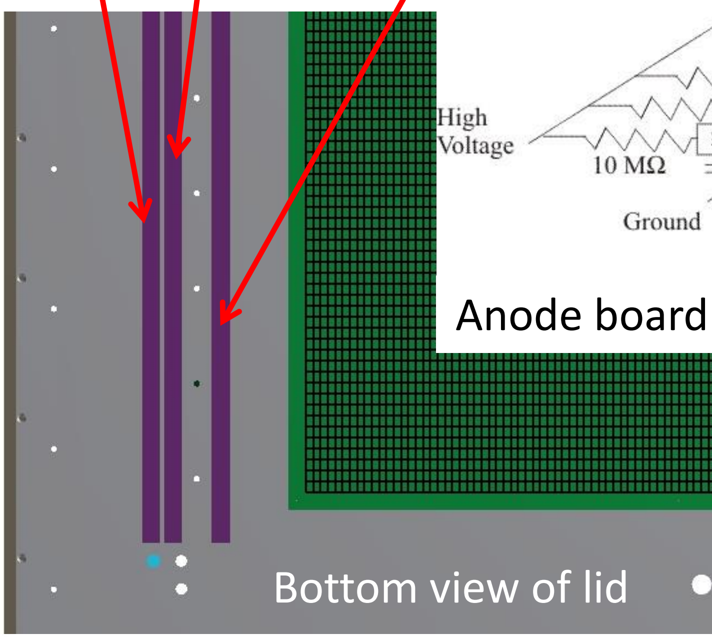
Based on STAR-TPC operating parameters



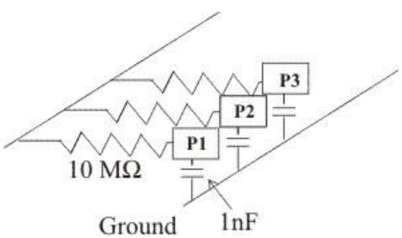
Wire planes



[Side view of test setup]



Bottom view of lid



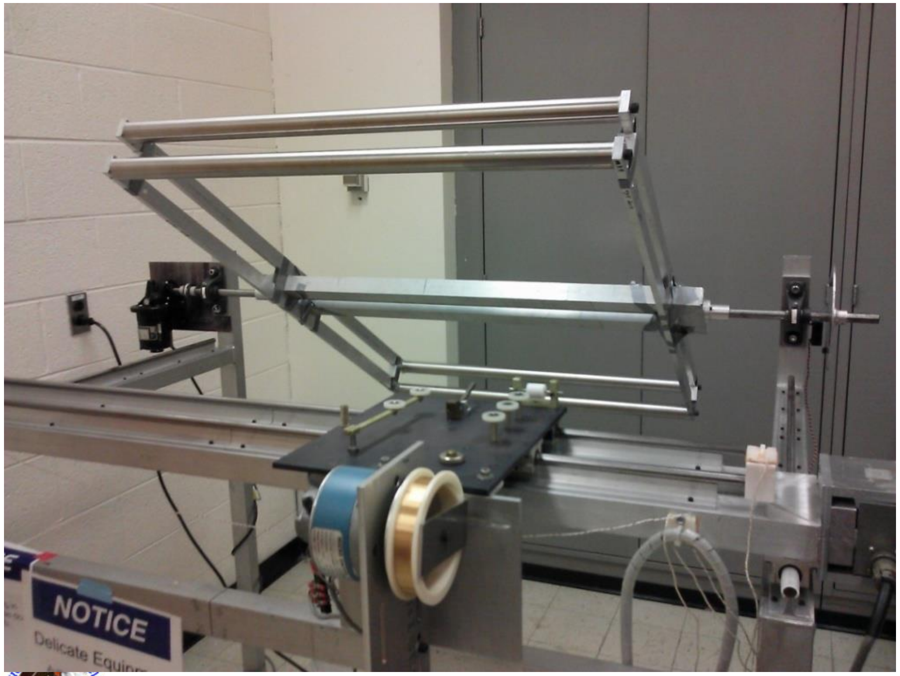
Anode board circuit

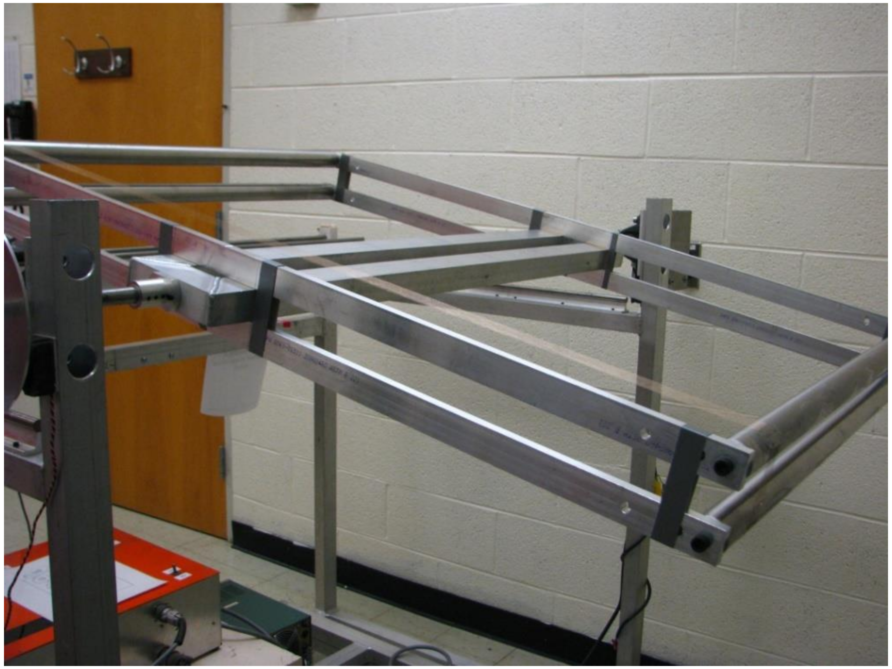
Plane	height (mm)	pitch (mm)	diameter (μm)
anode	4.05	4	20
ground	8.1	1	75
Gating grid	14	1	75

- Boards fabricated from Rogers 4003.
- Strength of glue bond to wires exceeds twice the required strength.
- Ground of Pad plane goes to BNC connector, allowing switch between self triggering, and pulsing or shorting, from the outside of TPC.

Wire planes – winding

- Wire winding and wire plane assembly are performed in separate class 10K clean areas.
- Frame size allows winding of a complete wire plane in one pass.
- Each frame holds ½ of a wire plane.



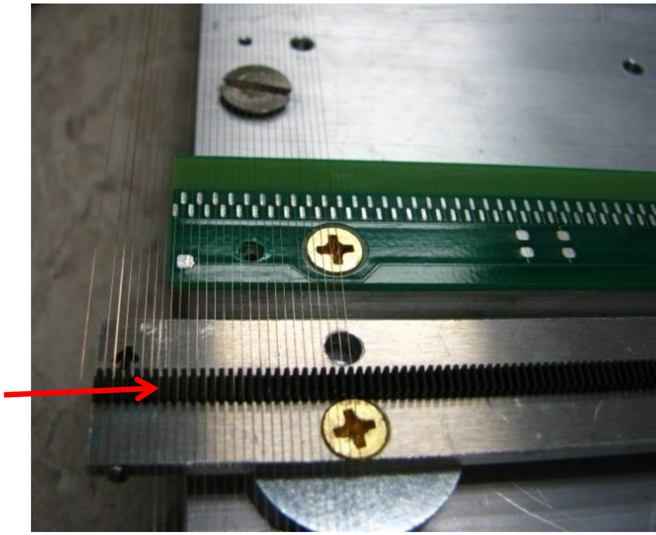


Tour stop #2b

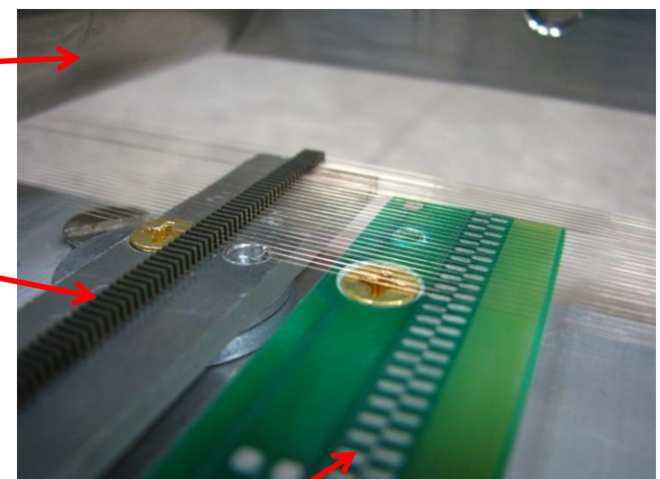
Wire planes – mounting

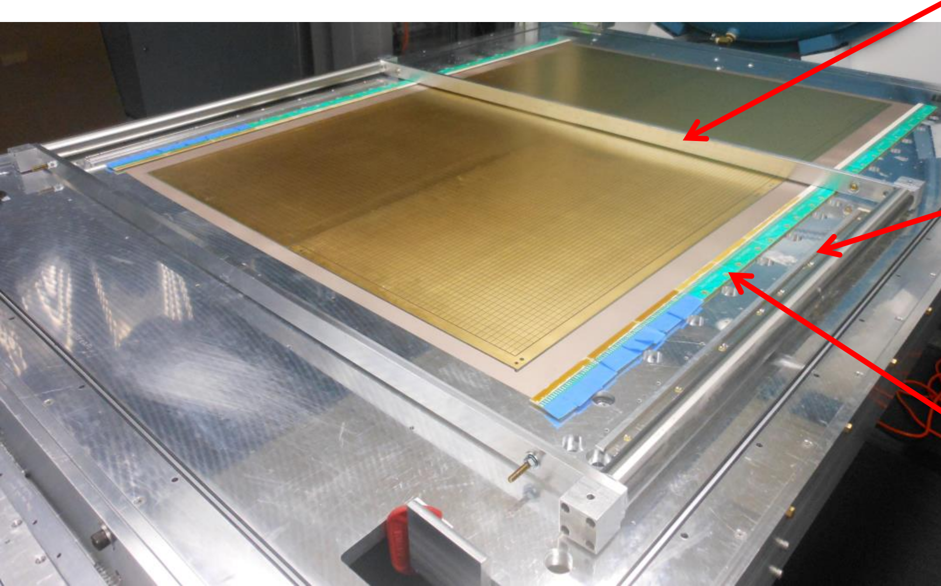
Test setup

- Wires are wound on frame in detector lab and transported in box to assembly area.
- Frame is positioned so that wires pass through teeth of comb and rest on circuit board (CB)
- Comb sets pitch, CB sets the height
- After gluing and soldering wires to CB, wires are cut and frame removed.



comb





frame

comb

circuit board with solder pads

S-TPC: *Assembly completed May 2013*

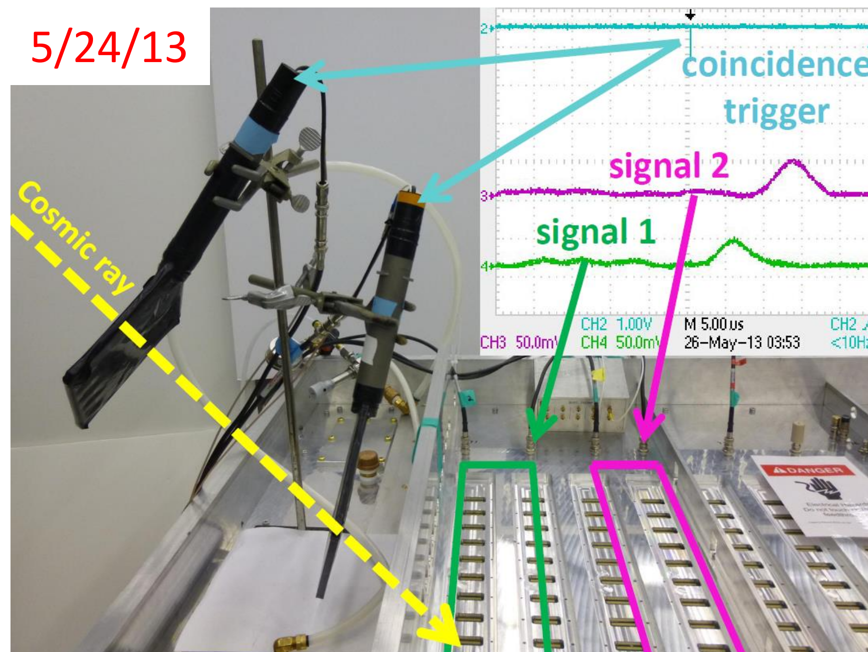
Symmetry Energy Project

- International Collaboration (US-Japan-Europe) to study Symmetry Energy over a range of densities at different facilities.
- Experiments below and around saturation density are performed at NSCL, twice saturation density at RIKEN and high densities at GSI/FAIR.
- The SAMURAI time-projection chamber detects pions (a new isospin observable) and particles produced in heavy-ion collisions.
- It extends the NSCL leadership on equation-of-state studies.

5/15/13

Installation of Field Cage

5/24/13



Detection of cosmic signals

S-TPC: *Readout electronics*

- Initial testing system using STAR FEE
  - Hardware assembled and tested
- Final: Generic Electronics system for TPCs
  - Wide dynamic range: effectively 10.5 bits
  - Self triggering
  - AsAd is 256 chan (four 64 ch. ASICs)
  - Capable of handling 1KHz – 10Gb/s
  - GET is collaborative effort of Saclay, Bordeaux, GANIL and NSCL
  - Status/completion:
    - AGET 1st batch prod.: May 2013
    - ASAD 1st batch prod.: July 2013
    - COBO 2nd prototype: April 2013,
      - 1st batch production – July 2013

STAR FEE on S-TPC

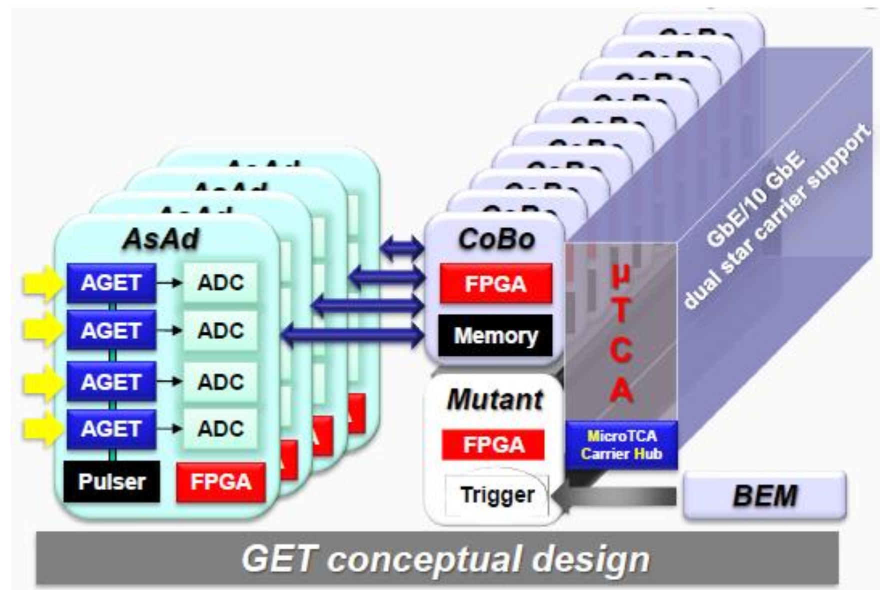
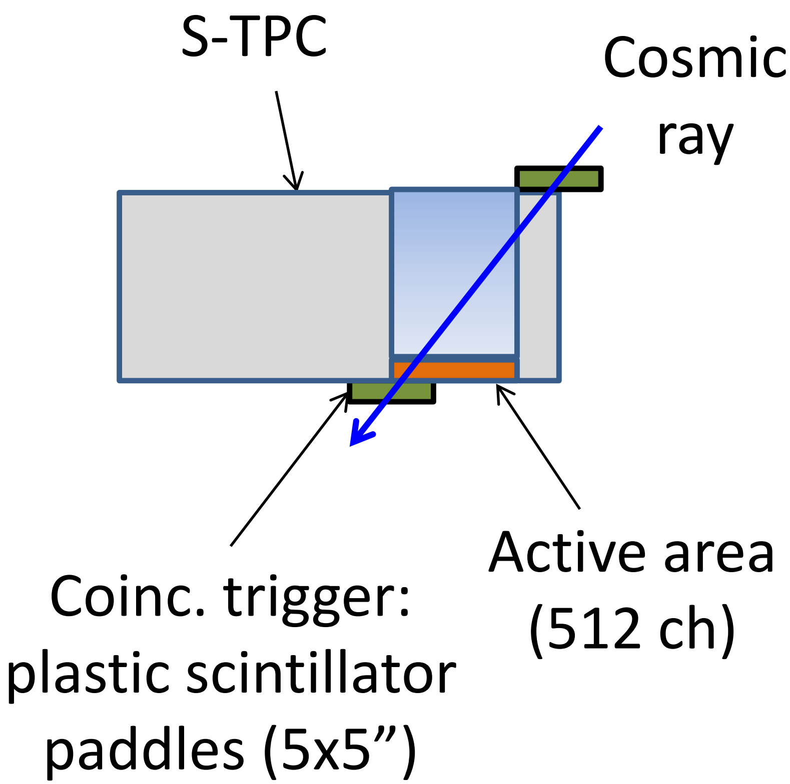


Figure courtesy of GET collaboration

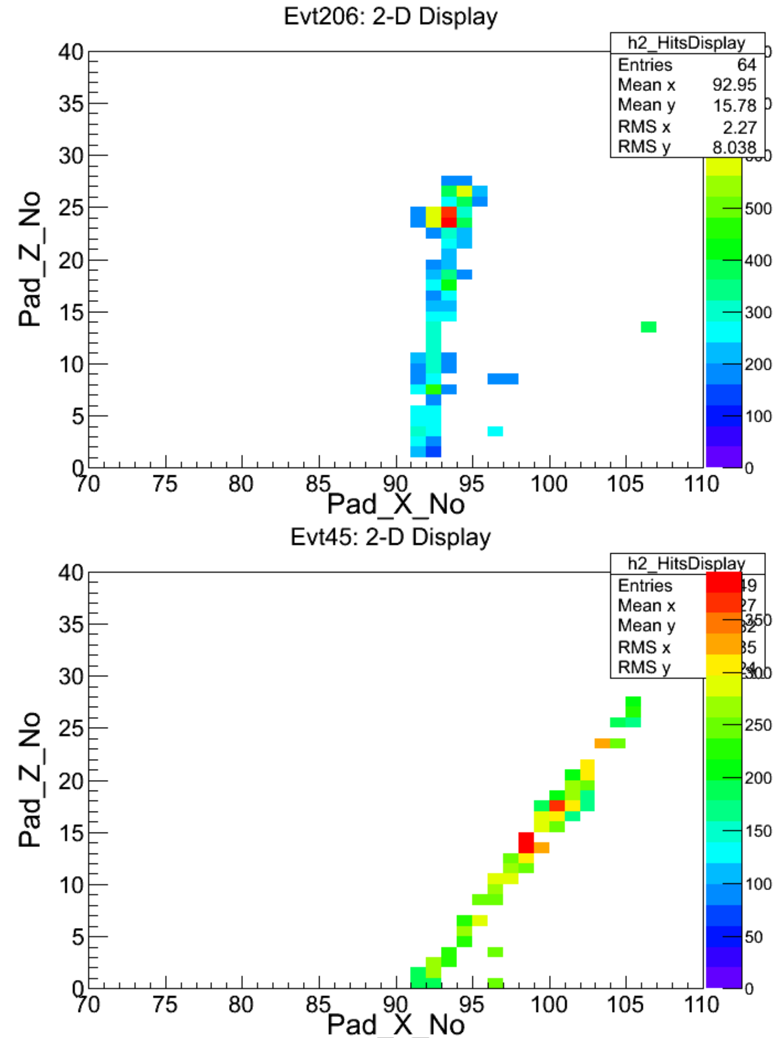
S-TPC: *Cosmic ray detection with STAR FEE cards*

July 15, 2013



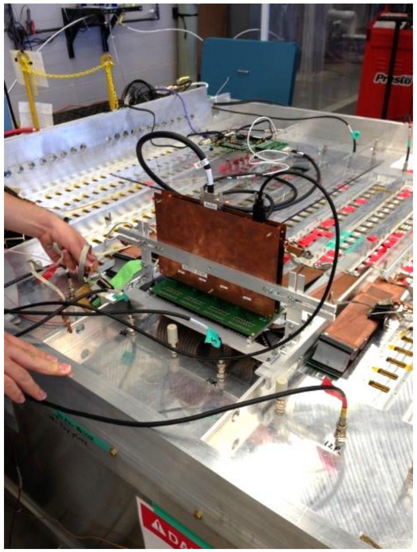
1-2 counts/min

Sample Tracks of cosmic rays



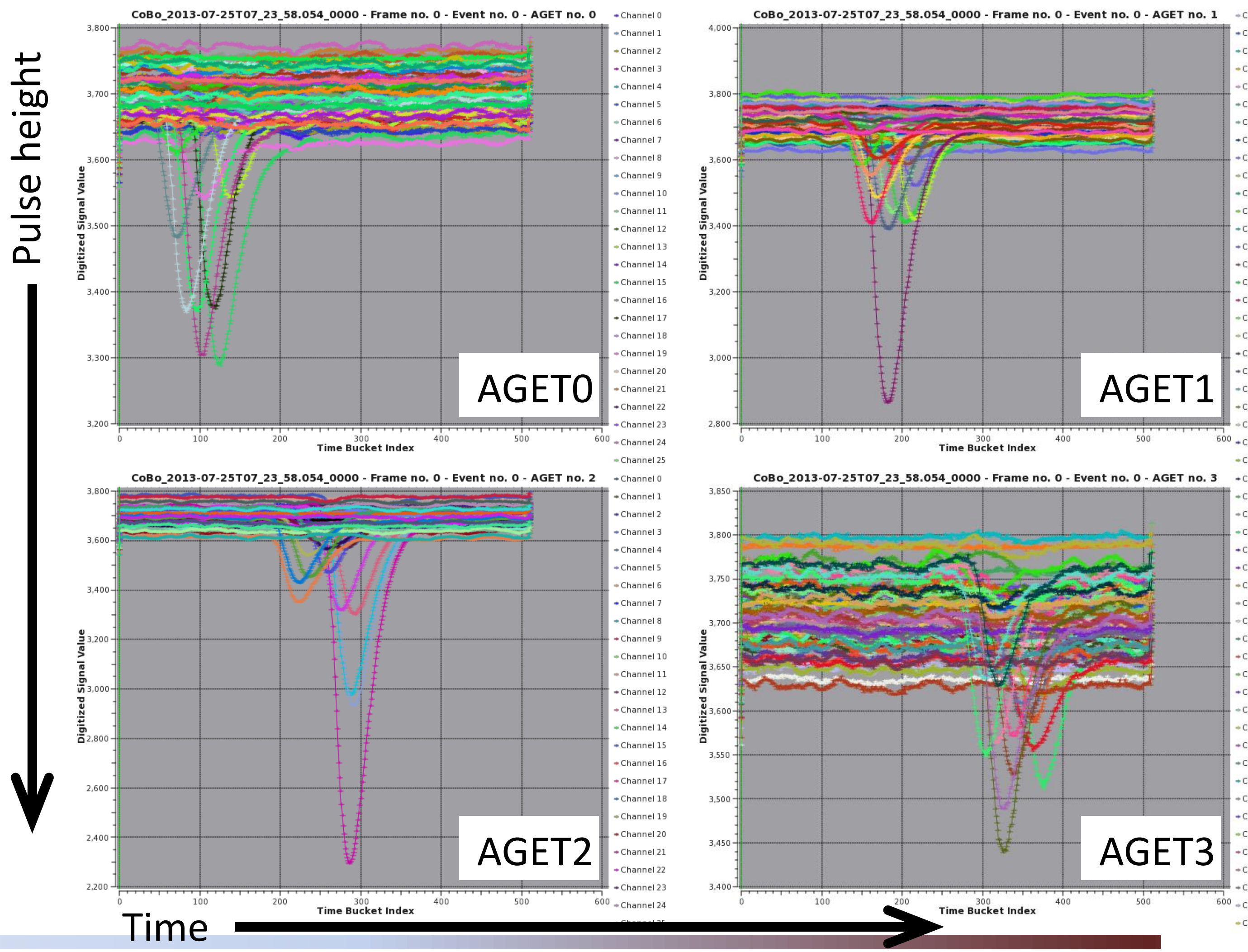
Plots courtesy of R. Wang

S-TPC: *cosmic ray detection with GET prototype*



Cosmic Event 0:
July 24th, 2013
@NSCL

Plot shows induced signal on each pad



Plots courtesy of T. Isobe

S-TPC: *cosmic ray detection with GET prototype*

10.5 bit dynamic range
1KHz – 10Gb/s

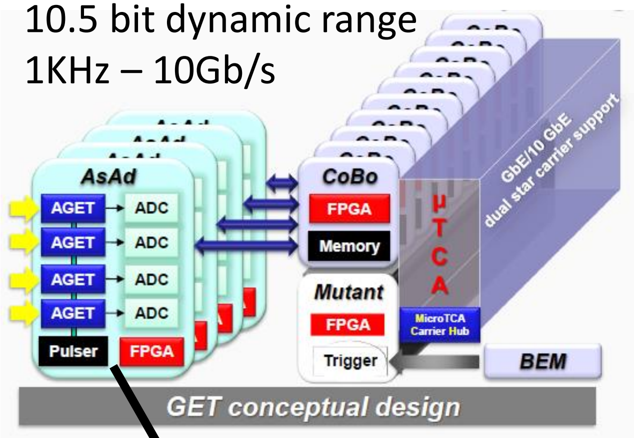
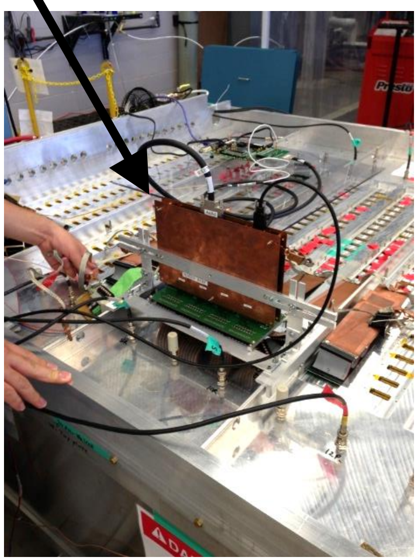
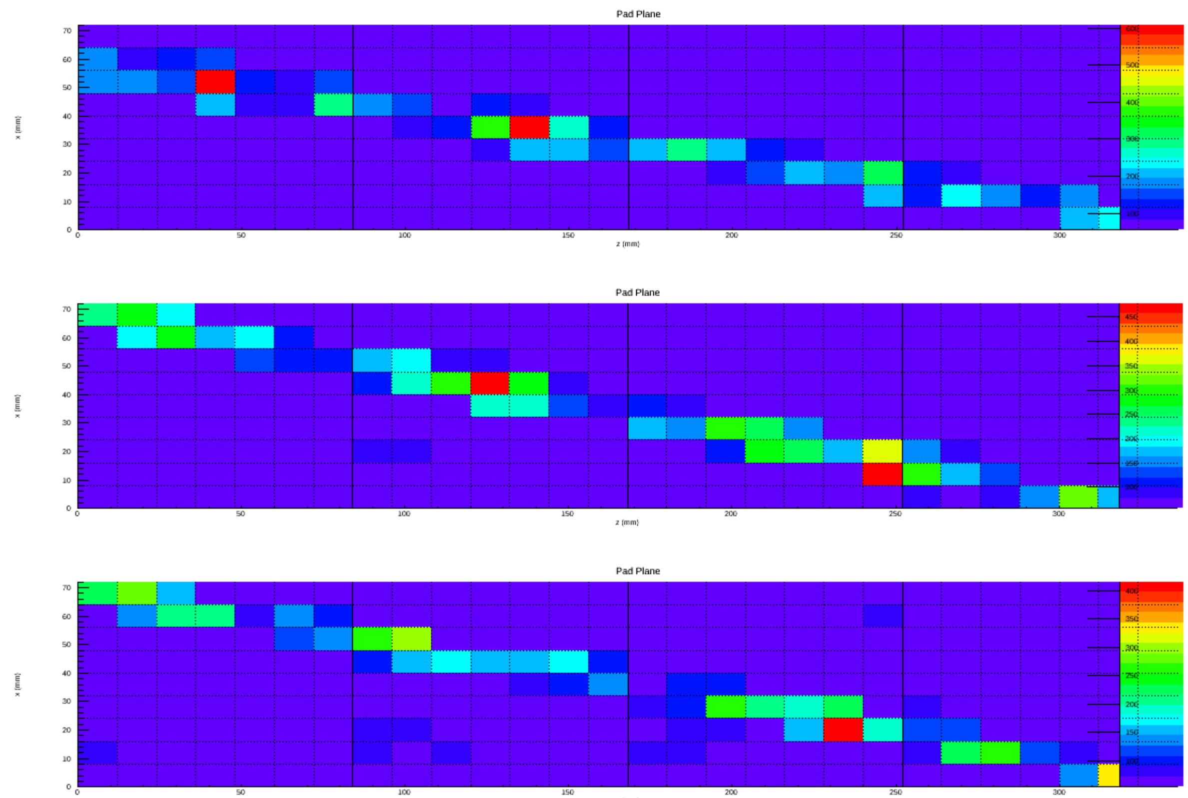


Figure courtesy of GET collab.



cosmic ray tracks detected by TPC pads

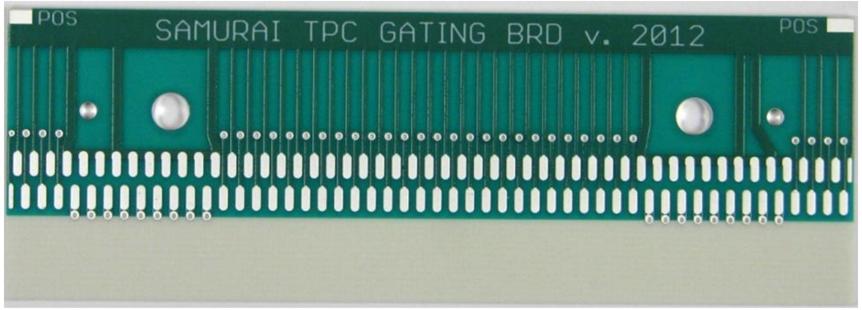


Cosmic Event on: *July 24th, 2013 @NSCL*

Plots courtesy of T. Isobe

Gating grid

- Beam height is 18.7 cm from gating grid.
- "Lost" drift length = $\Delta t_{grid} \cdot v_{drift}$ should be minimized by shortening Δt_{grid}
- Δt_{grid} is governed by three factors:
  - The capacitance of the grid (~15 nF).
  - The impedance of the driver and transmission line.
  - The matching of the currents drain the positive and negative wires on the grid as it discharges. (Charging can take longer.)



- Circuit board has an on-board 50 Ω transmission line that could be decreased to 2Ω.
- Ultimate plan is to supplement this with two commercial 4 Ω transmission lines that go along both ends of the gating grid. These will be installed after initial TPC test and after we have transmission lines that satisfy our electrical and materials testing requirements.

SAMURAI-TPC Collaboration members

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Special thanks

NSCL staff: J. Yurkon, D. Bazin, J. Pline, and many others

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University of Liverpool student: Jaime Norman

TAMU staff: R. Olsen