The iTPC Project:
Who, What, When, Where, Why and How

Jim Thomas and a cast of thousands

April 10th, 2017

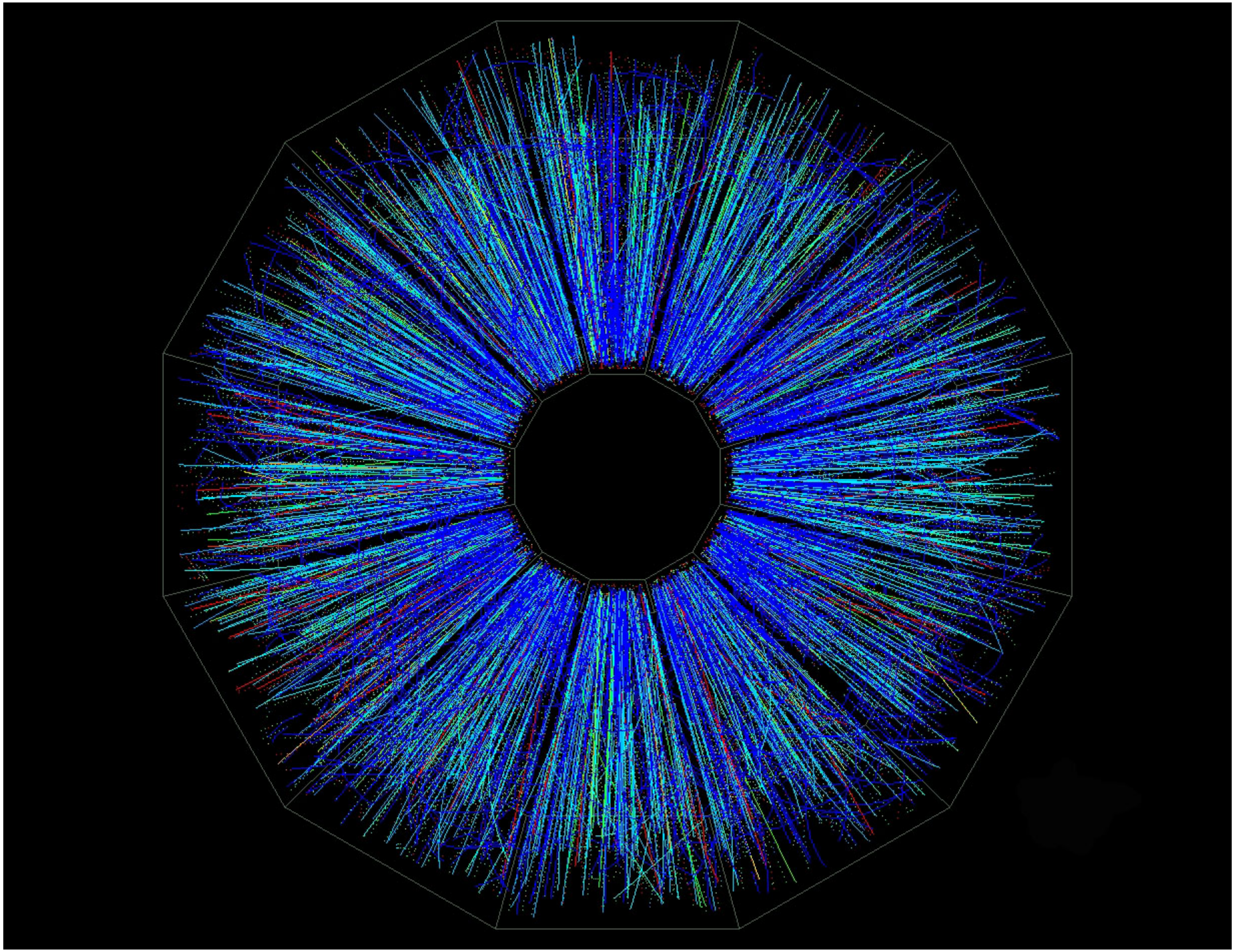
Where: Brookhaven National Laboratory

The Relativistic Heavy Ion Collider

Cost of operation: $185M / year

- **3.8 km circumference**
- **Two beams of heavy ions colliding (typically Au+Au)**
- **Classic Atom Smasher**
- **Collide Two Mercedes Benz on the hiway: depending on where hubcabs go, we are trying to reconstruct the clock on the dashboard**
- **It's a program of Microscopy**
  - **How are Atoms and Nuclei put together**

A Typical Collision



The Imaging Device – The STAR Detector at RHIC

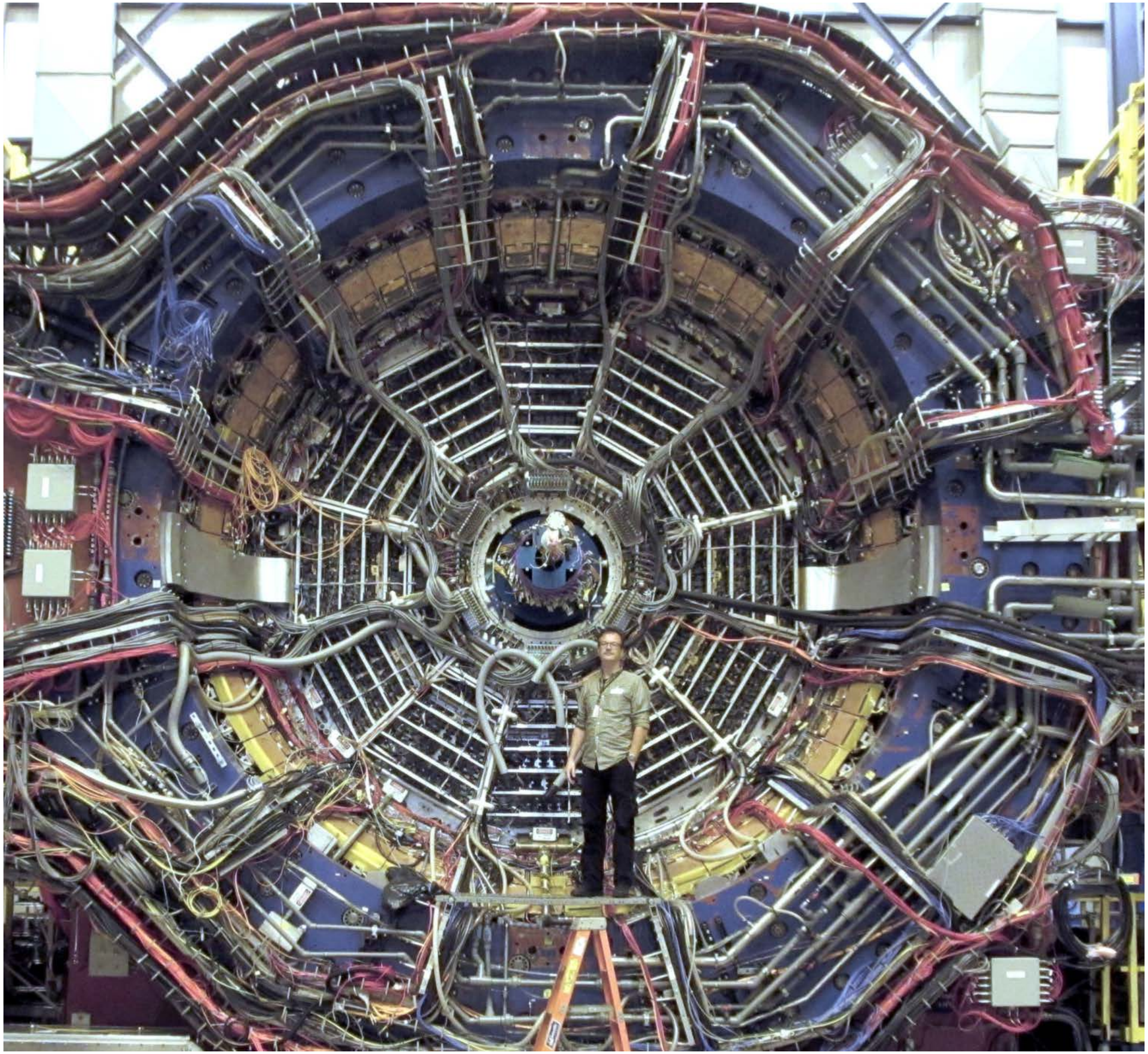
Cylindrical Symmetry

Blue Magnet

Yellow Calorimeters

Grey 12 fold Time Projection Chamber

TPC: 4m x 4m



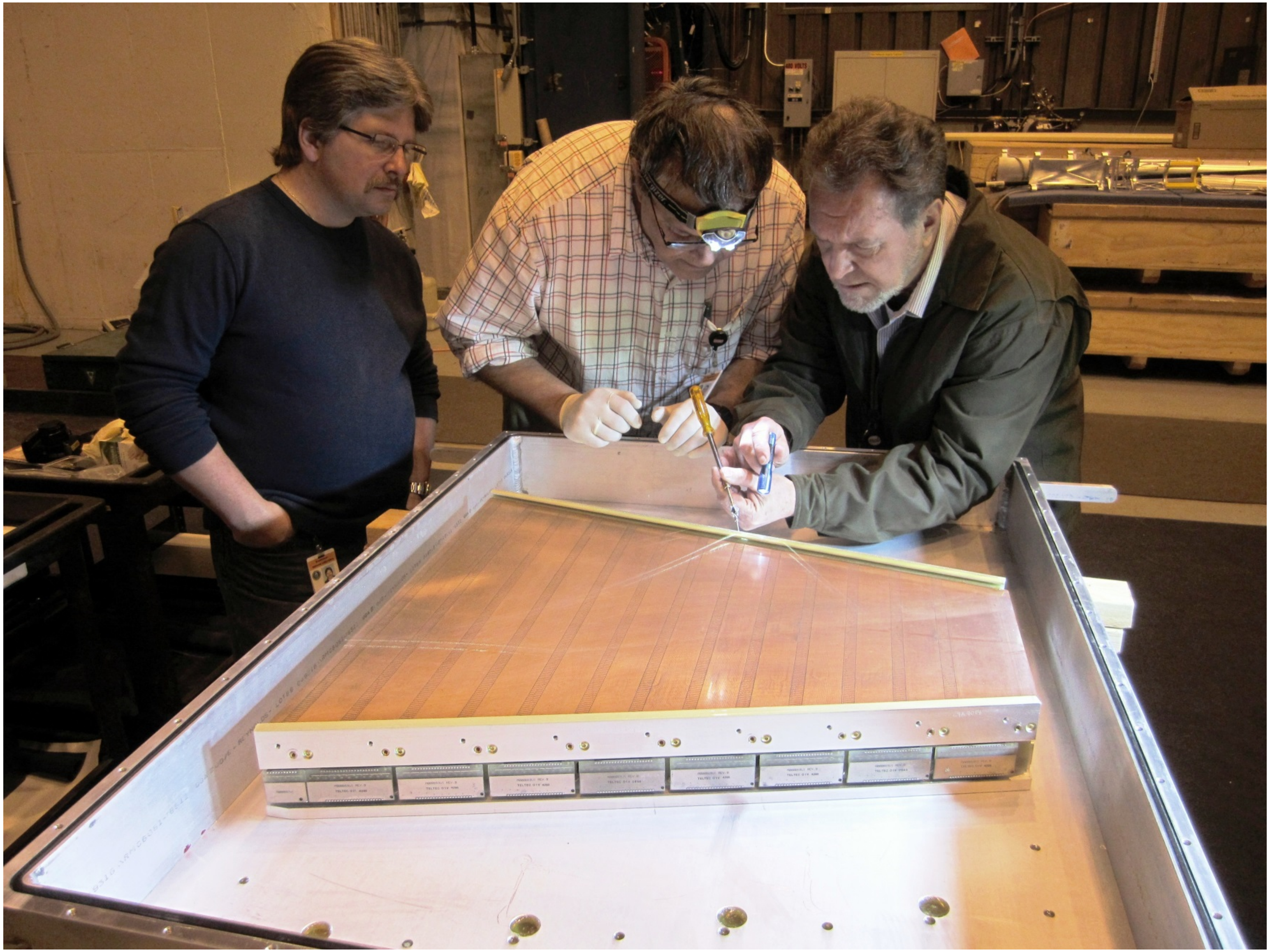
The TPC – Built in Berkeley

Flown to BNL in a C5A

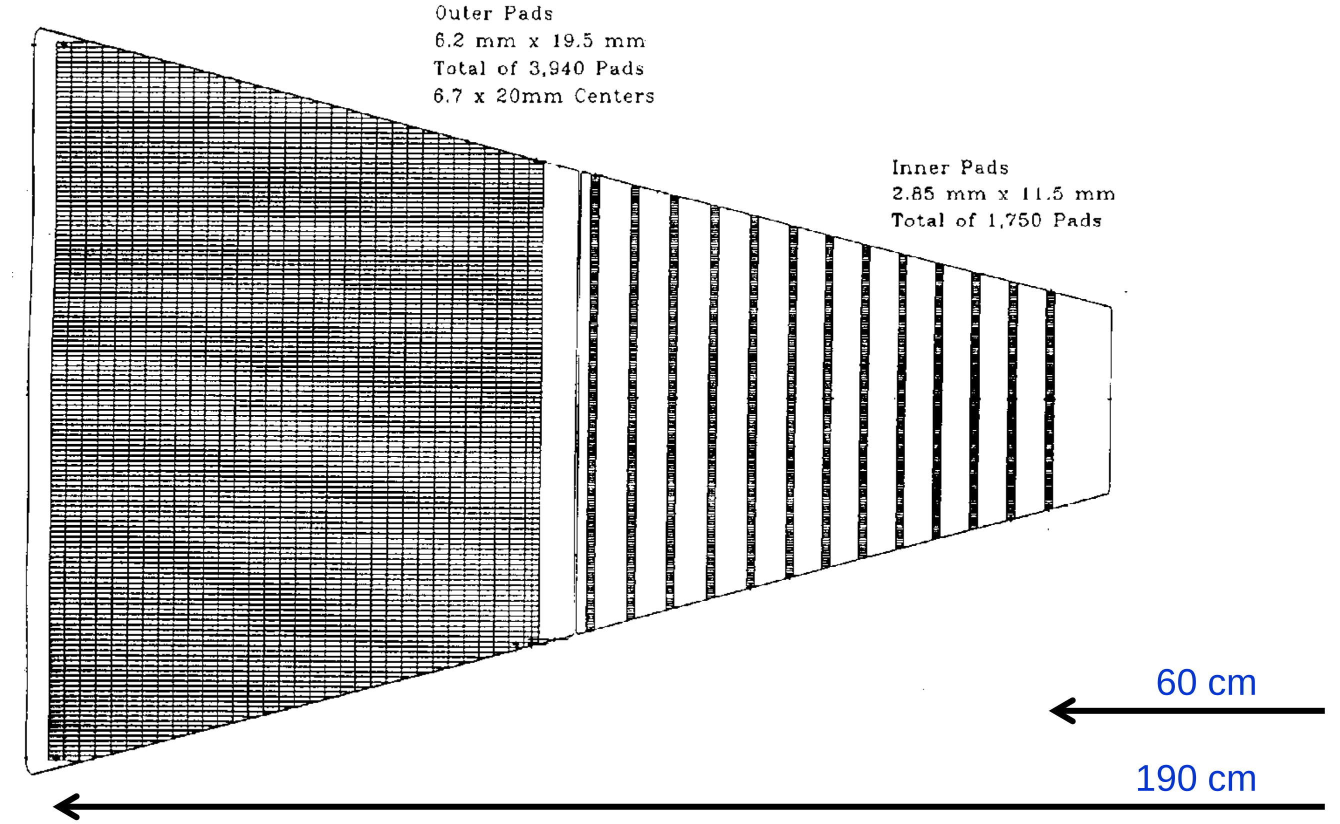
Invented in Berkeley by David Nygren (late 70's)

This one, the biggest in the world, was built by Howard Wieman and Eric Anderssen (1995)

Pixelated read-out using wire chamber & pads



Goal: Hermetic coverage and more Pixels

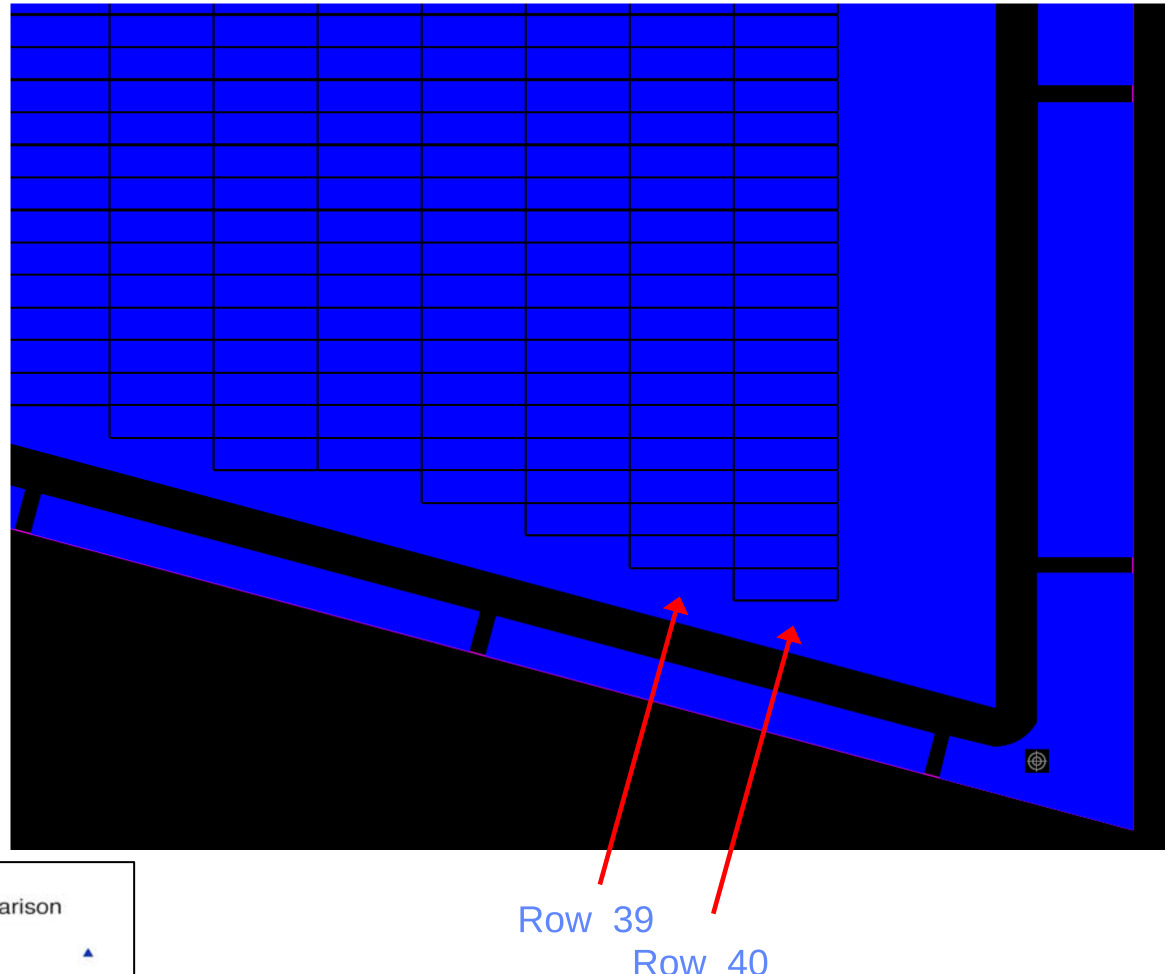


- Currently, the outer pad plane is hermetic while the inner pad plane is not
  - Goal: Add more pad rows on the inner sector, 2X total pad count

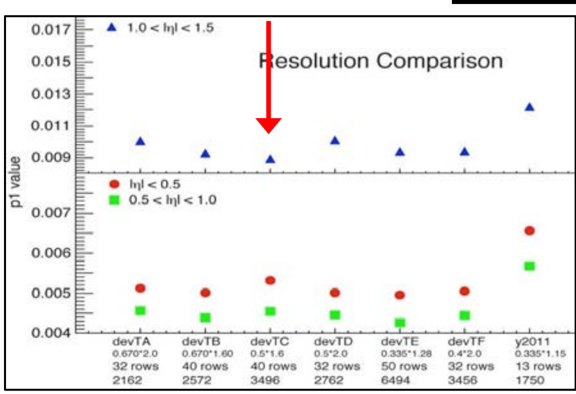
The upgrade will provide better momentum resolution, better dE/dx resolution, and improved acceptance at high η

New Pad Plane design and layout

A corner of the new inner pad plane layout design by John Hammond & Bob Scheetz



Pad Row	# of Pads
1	52
2	54
3	56
4	58
5	60
6	62
7	62
8	64
9	66
10	68
11	70
12	72
13	74
14	74
15	76
16	78
17	80
18	82
19	84
20	86
21	86
22	88
23	90
24	92
25	94
26	96
27	98
28	98
29	100
30	102
31	104
32	106
33	108
34	110
35	110
36	112
37	114
38	116
39	118
40	120
TOTAL	**3440**



Momentum (and spatial) resolution not strongly dependent on pad design within this range … it's the extra rows that are important

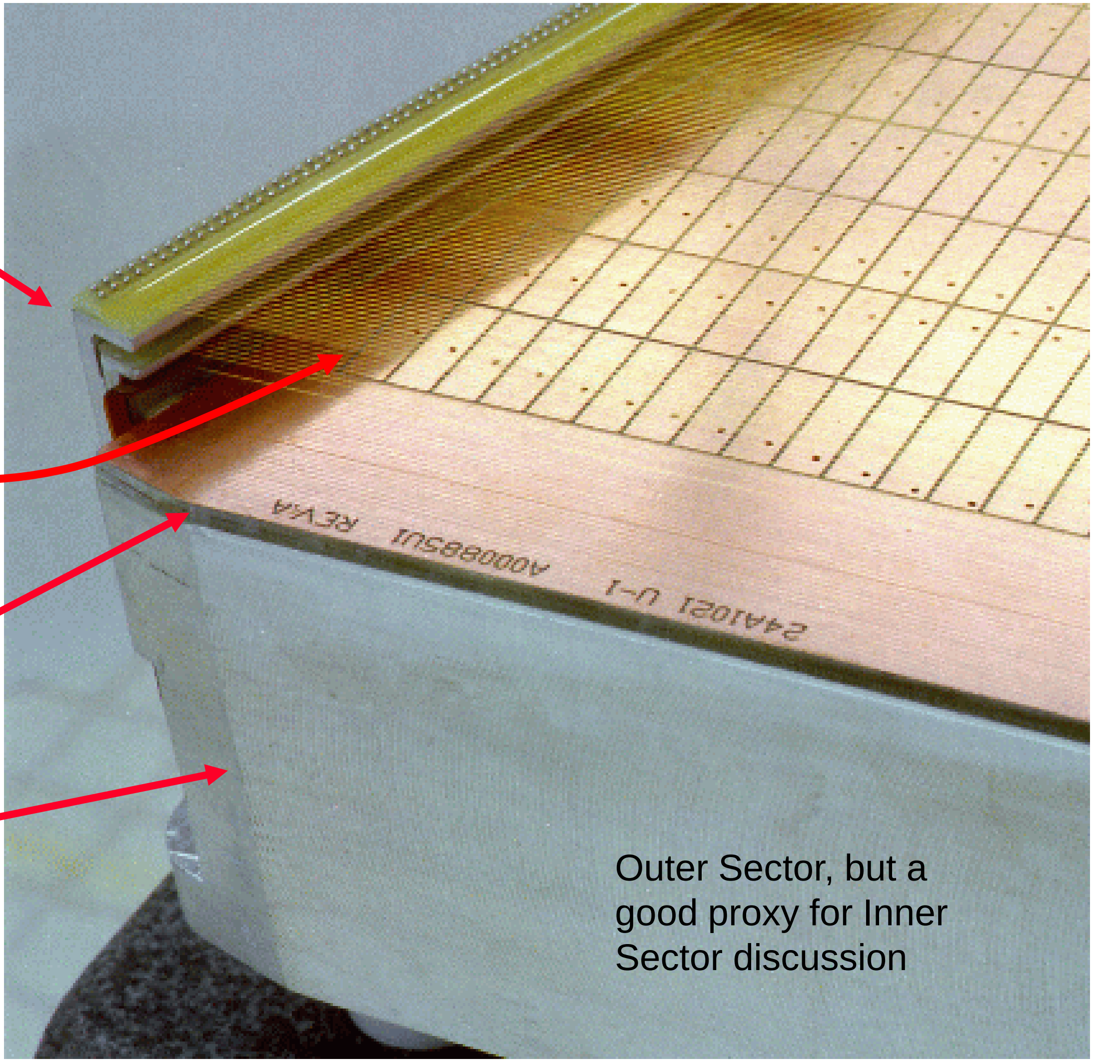
Major Items: Definition & Scope

Wire Mounts for Grids

Wire Planes:
Gated Grid, Cathode Grid,
and Anode Grid

Pad Plane with larger pads
(5x16 mm) & hermetic coverage

Strongback



Outer Sector, but a
good proxy for Inner
Sector discussion

Major Tasks

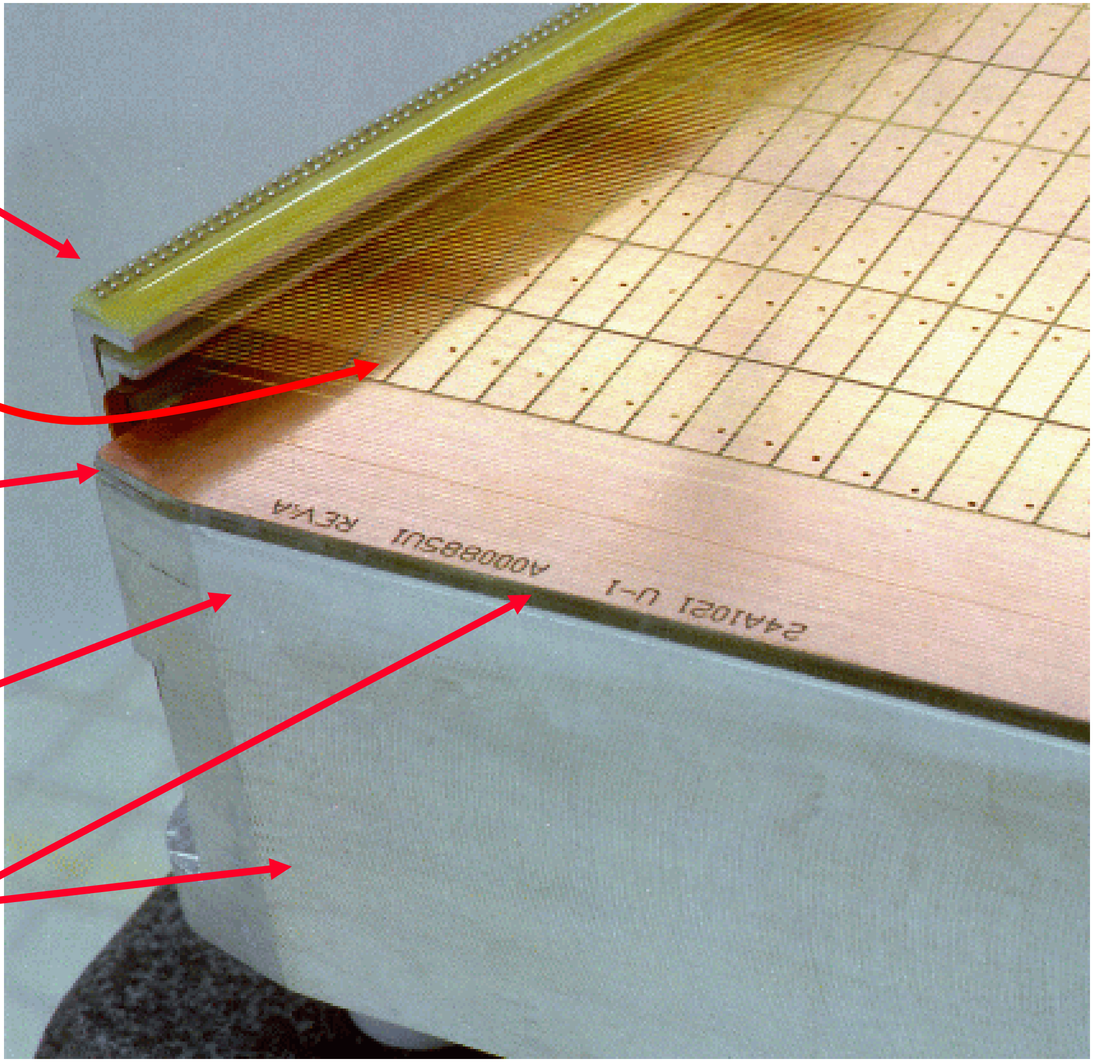
Fabricate, Align and Pin
Wire Mounts (BNL & LBL)

Wind wire grids
(Shandong University, China)

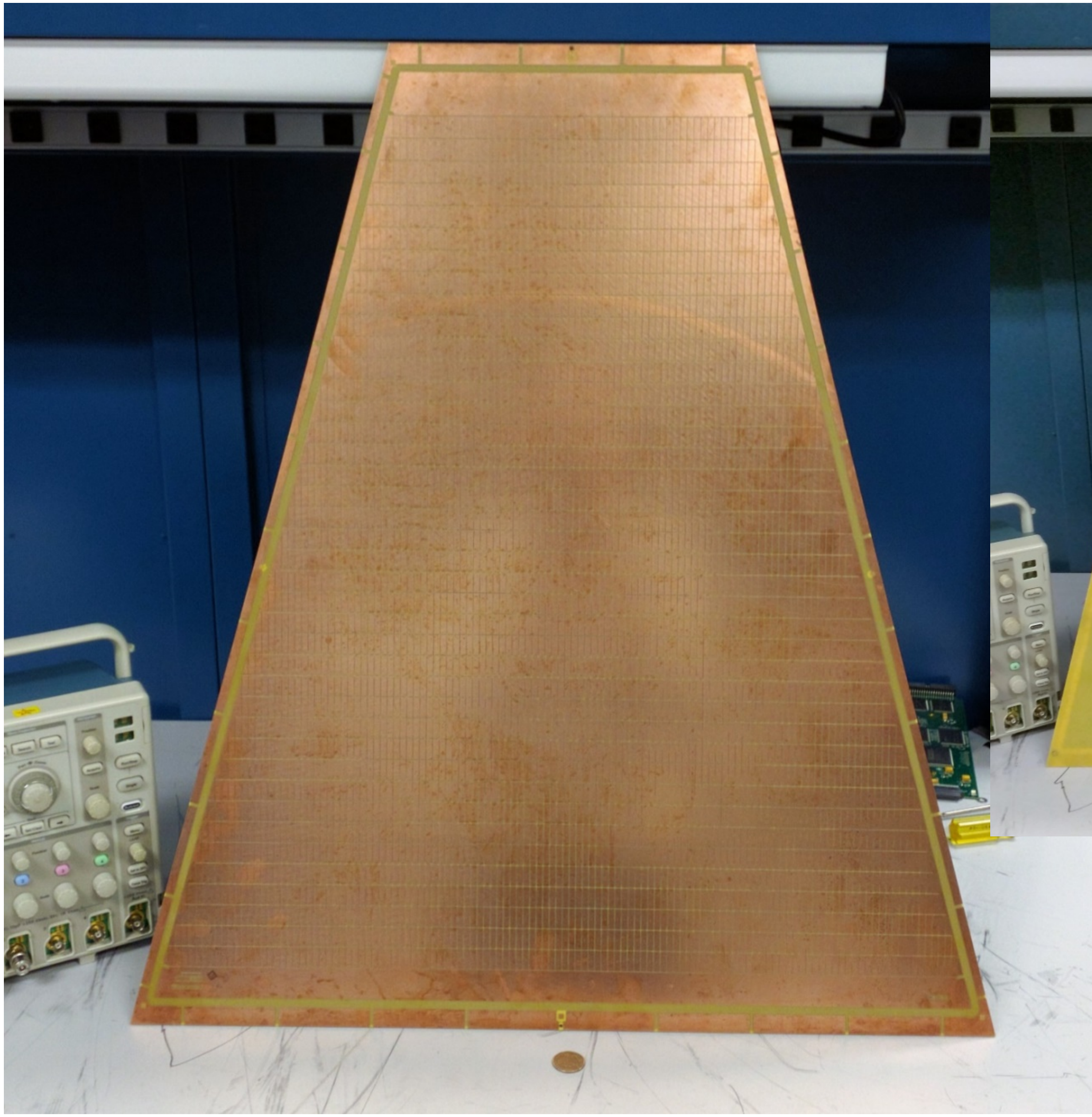
Fabricate, QA check
Align (50 μm)
Glue (< 20 μm flat)
& Trim padplane (BNL & LBL)

Fabricate strongback
& inspect (QA) (Outside vendor)

Cut to height, machine
O Ring grooves,
Survey padplane &
Document mech. specs (LBL)



Padplane Prototype undergoing tests at BNL



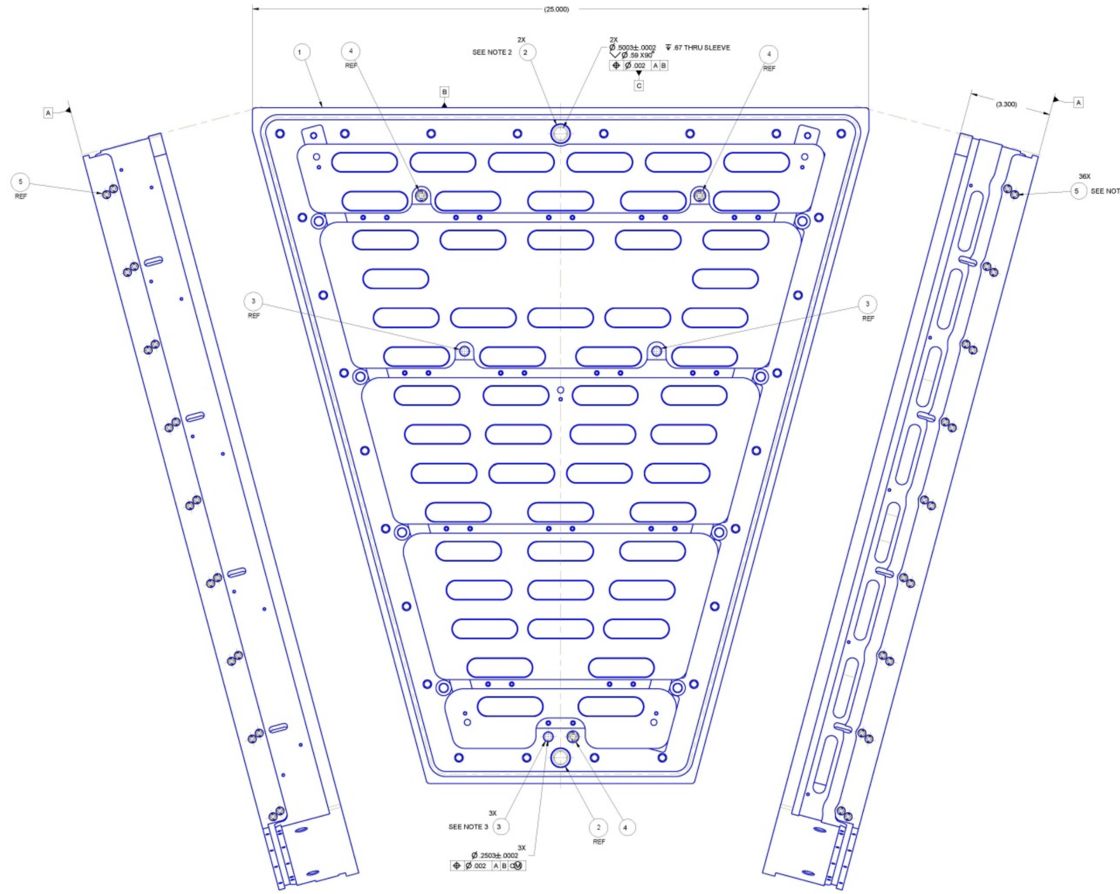
- 40 Rows
- 5x16 pads (mm)
- High density connectors (64 channels)
- Halogen free materials

Vacuum Check of Padplane

- **Vacuum integrity check with prototype padplane**
- **Granite tables typically flat to 5 μm**
- **Use vacuum to hold padplane on table**
  - **while gluing to strongback**

✓ **Good 09/01/2016**

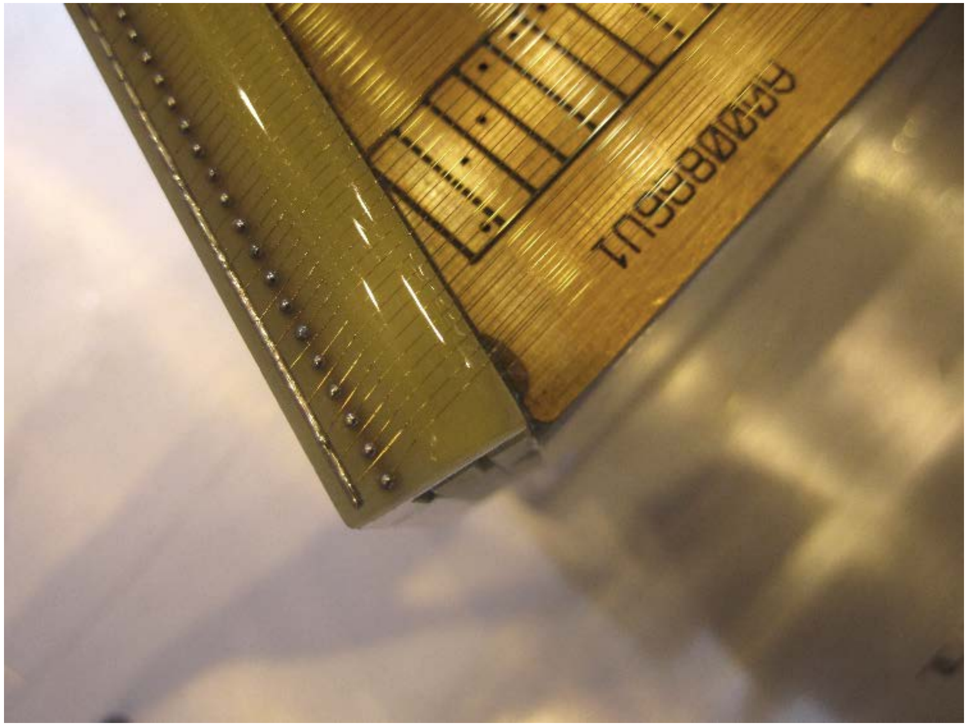
Strongback Construction is Complete 30 of 30

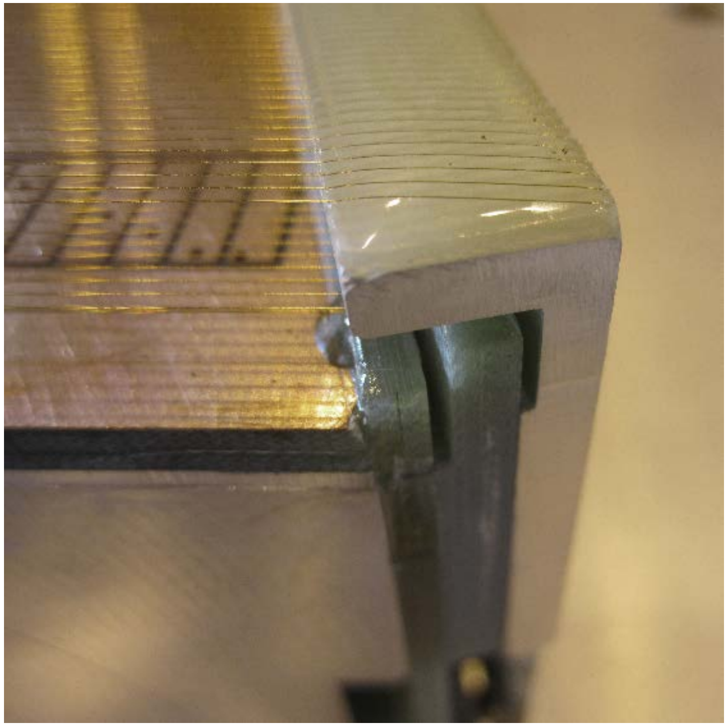


A prototype inner sector strongback is shown during fabrication at the University of Texas (circa 2013). The sector was machined out of a single piece of aluminum. Dimensions are: ~27 inches tall, ~25 inches wide and weight 55 lbs. The sector is viewed from the backside; the side upon which the electronics and cooling manifolds will eventually be mounted. More recently, 30 production strongbacks were completed at IMT Precision Machine, Hayward CA and received on 08/01/2016.

Wiremounts

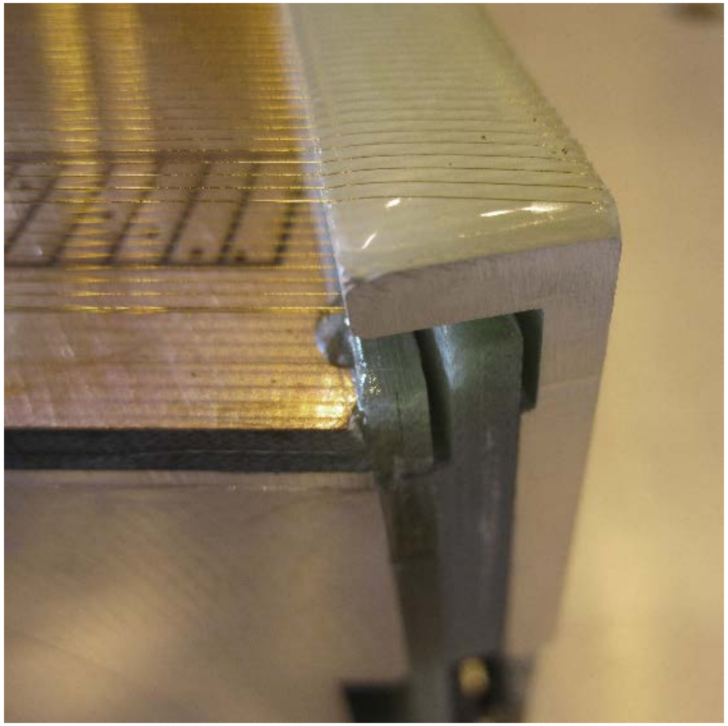
- **The Anode wires, Cathode Wires, and Gated Grid wires are mounted on structures attached to the sides of the strongback**
  - **A total of 8 wiremount parts – 4 left, 4 right**
  - **4 of the 8 contain circuit traces and electronic PCB boards (i.e. EE required)**
  - **4 of the 8 are blank G10 boards or Aluminum (with insulator boards)**
- **Construction of the Wiremount parts is complete, final QA in progress**
  - **Bonding of Wiremounts to strongback to be done @ lbl.gov**





Work Breakdown

- Strongback Fabrication (outside vendor)
- Padplane Production (outside vendor)
- Padplane QA (BNL, just in time delivery)
- Wiremount Production (outside vendor)
- Wiremount QA (BNL, just in time delivery)
- Padplane Bonding to strongback (LBL)
- Wiremount Bonding to strongback (LBL)
- Sector Metrology & QA (mechanical) (LBL)
- Wire Winding (Shandong Univ., China)
- Wire Bonding (Shandong Univ., China)
- Wire Tension & QA (tedious) (SDU, China)
- ^{55}Fe Source tests, gain check (BNL)
- Installation & Integration w/ TPC (BNL)



Parts and Pieces @ lbl.gov

Description	Number Rqrd	Number Recvd	Ready to Ship	Comments
Strongbacks	30	28 + 1p	1	One reserved for testing at BNL, will travel when needed
Padplanes	30	4 + 1p	14	Production complete. Connectors & QA on final 11 at 2 per wk
Anode Wire Mount (Left, with connectors)	30	13 + 1p	8	Production complete. Connectors & QA on final 8 at 2 per week
Anode Wire Mount (Right, without connectors)	30	32	✓	
Shield Grid Wire Mount (Left, simple)	30	32	✓	
Shield Grid Wire Mount (Right, with Cu strip & dimple)	30	32	✓	
Gated Grid Wire Mount (Left, simple)	30	32	✓	
Gated Grid Insulator Board (Left, simple - no solder dots)	30	32	✓	
Gated Grid Wire Mount (Right, with notch and trough)	30	32	✓	
Gated Grid Insulator Board (Right, with solder dots)	30	32	✓	
#5 Bronze threaded Taper pins	540	590	✓	24A0543D
#10-32 Bronze threaded inserts	1080	1100	✓	24A424A
1/4-20 Bronze threaded inserts	90	100	✓	24A425A
#10-32 x 1/2", Brass button head cap screw	540	1300	✓	Wiremount Fastenern: Choose either 1/2 or 5/8, but not both
#10-32 x 5/8", Brass button head cap screw	540	750	✓	Wiremount Fastener: Option in case 1/2" is too short
#10-32 x 3/4", Brass button head cap screw	540	1500	✓	Wiremount Fastener: 2x supplied in case 5/8" is still too short
#4-40 x 7/16, Brass button head cap screw"	180/300	500	✓	Small Electronics Boards: 10 holes per sector, 6 actually used
#4-40 x 1/4", Brass button head cap screw	150	500	✓	Fasteners for bottom of Anode Wire Mount Left
#6-32 Brass Flat head Phillips Machine Screw, 5/16" overall	720	1000	✓	Fasteners for Grid Leak walls, top and bottom
Brass Dowel Pins	120	150	✓	For aligning Grid Leak walls, top and bottom
#6-32 x 1/4", Brass Button Socket Cap screw	150	175	✓	Grounding Screw that goes inside strongback, bushing side
Aluminum spacers for #4 screws, 1/4" x 1/4"	180/300	200	✓	Small Electronics Boards: 10 holes per sector, 6 actually used

All parts in Berkeley, with exceptions noted above
Prototype sets became available at start of Fiscal Year
Production sets became available at start of Calendar Year

Schedule Drivers

- Strongbacks
  - We went to an outside vendor … they gave us very fast turn around
    - ✓ Construction & QA complete: survey & quality looks good
    - ✓ Strongbacks in storage at vendor or at LBL since August
- Padplane & Wiremounts
  - We went to an outside vendor for basic fabrication of parts. Soldering of connectors and QA are the rate limiting steps
    - ✓ Construction is complete: as-built-dimensions look good
    - ✓ 8 of 10 parts complete, 2 pieces delivered just-in-time but have surplus
- Bonding of padplane and wiremounts to strongbacks has begun
  - ✓ Tooling complete
  - ✓ First prototype & QA completed last week (4/7/2017)
- Critical Path
  - PadPlane and Wiremount bonding is sitting on the critical path
    - We are in the spotlight
  - One complete sector is needed at BNL in August for installation in Run 18
  - All sectors must be completed and installed at BNL by March 2019
    - Approximately one week per sector at LBL, 2 weeks per sector at SDU
    - These production rates do not include Transportation, QA or Installation

Risk – high level summary

- **Technical**
  - Better than 20 μm flatness requirement for PadPlane+Strongback
    - A vigorous QA plan is essential
    - We have the elements of a good QA plan in place but we need the will and discipline to stick to it
  - Shipping & damage in transit
    - We have well developed repair procedures ⇒ schedule risk
  - Bromine free materials
- **Schedule**
  - Minor schedule slips could easily affect the final installation date
    - Schedule is tight
    - Whenever schedules are tight, sharing manpower becomes a challenge
- **Management**
  - Risk of losing Engineering run in ‘18, and/or Physics run in ‘19
  - Money is in place - $605K delivered to LBL in August Fin Plan transfer
    - Funding for 27 sectors is not a problem
  - DOE NP has requested an extension of scope from 27 sectors to 30
    - Do we need more money? One of the questions for this review.

Summary

- New PadPlanes for the STAR Time Project Chamber
  - More Pixels!   40 pad rows in inner sectors, up from 13 rows, full coverage
  - Added additional fiducial marks, alignment holes and improved air paths
- Strongback is 99% the same as before
  - Re-use the existing cooling manifolds (etc.)
  - 99% perspiration, 1% inspiration.   Updated tooling required.
- Wires
  - Exactly the same as before: same wire count, same composition, same diameters, same tension, same locations, same ABDB board design, etc.
  - Same as before … but must be done again for the new strongbacks & pads
- Cost and Schedule concerns – its all about the schedule …
  - Costs are under control (?). Aided by C-NSF increasing their contributions.
  - Very tight schedule. Scheduled wisely but no scheduled float.
  - Work in B77A is currently on the project critical path, it would be nice to get out from under the spotlight

Backup Slides

Documentation from the original project

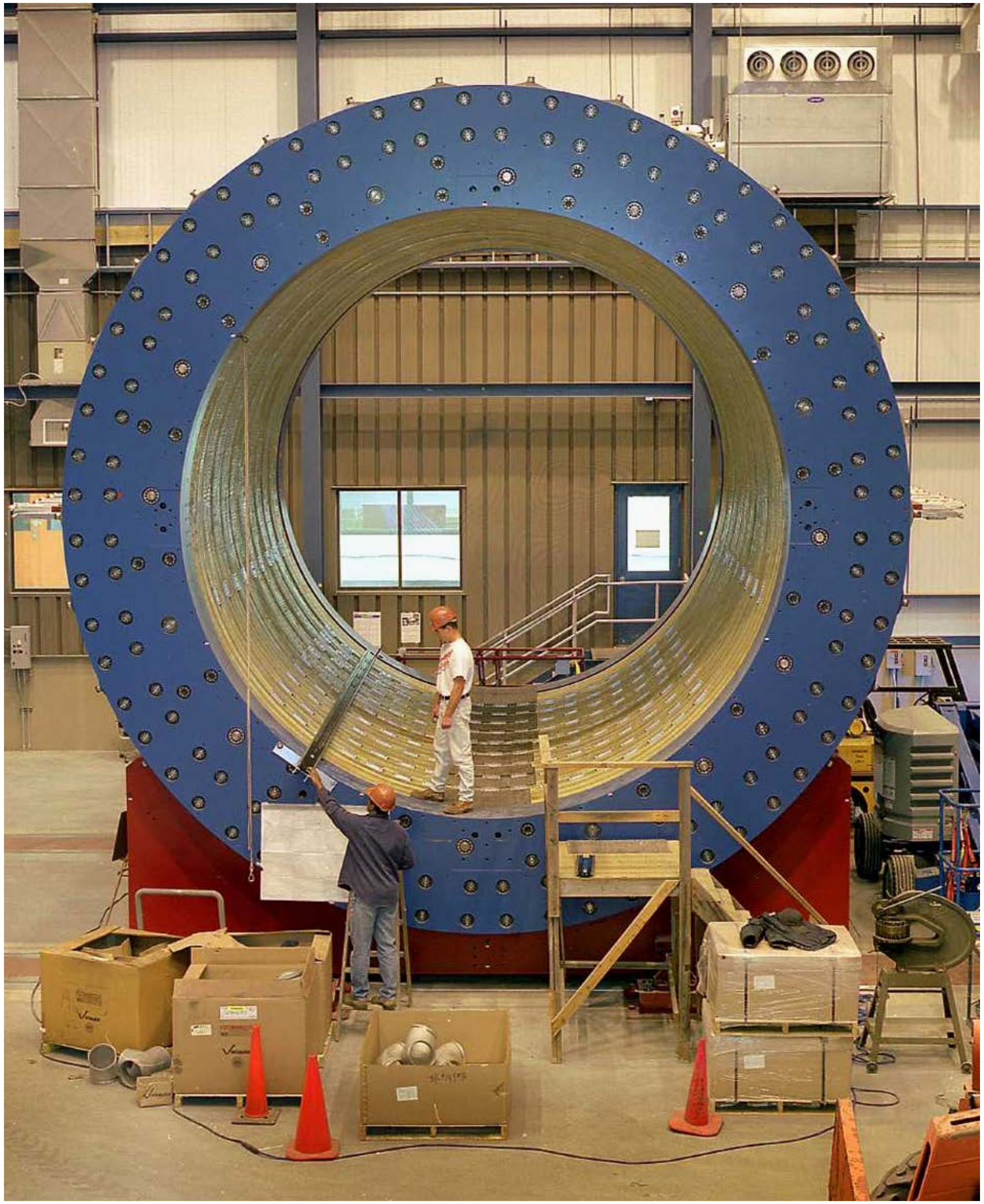
- The documentation from the original project (circa 1995) is extremely good
  - Engineering drawings for every part (dwg & pdf)
  - Electronics drawings for every board (pdf)
  - Technicians Notebooks, notes & fully documented procedures
  - Procedures well documented, QA plans and Travelers for every sector
  - And most important … Jon Wirth (retired) is enthusiastic about participating in the new project ☺

- Thus, we are standing on the shoulders of giants (I. Newton, 1676)
  - Very little "new" engineering required
    - Primarily, translation of old (2D) drawings into modern 3D CAD
  - A minimum of new features added (other than additional pad rows)
  - PadPlanes and Strongback fab is primarily a technical project
  - Archeology required to establish precise technical procedures
    - The Archeology project was time consuming but is now complete

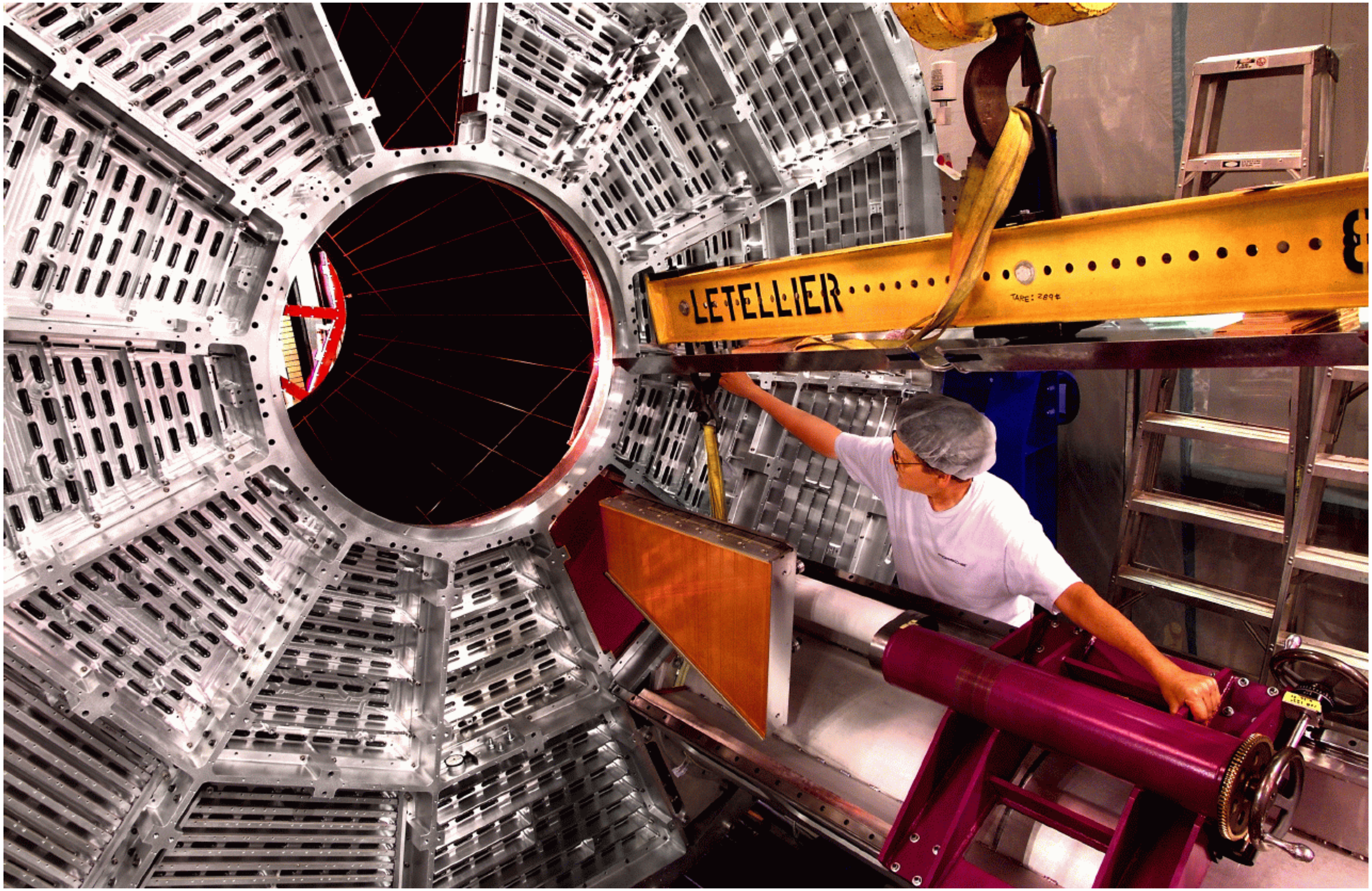
As much as possible, we are doing what was done before using the same materials & techniques

STAR without the TPC

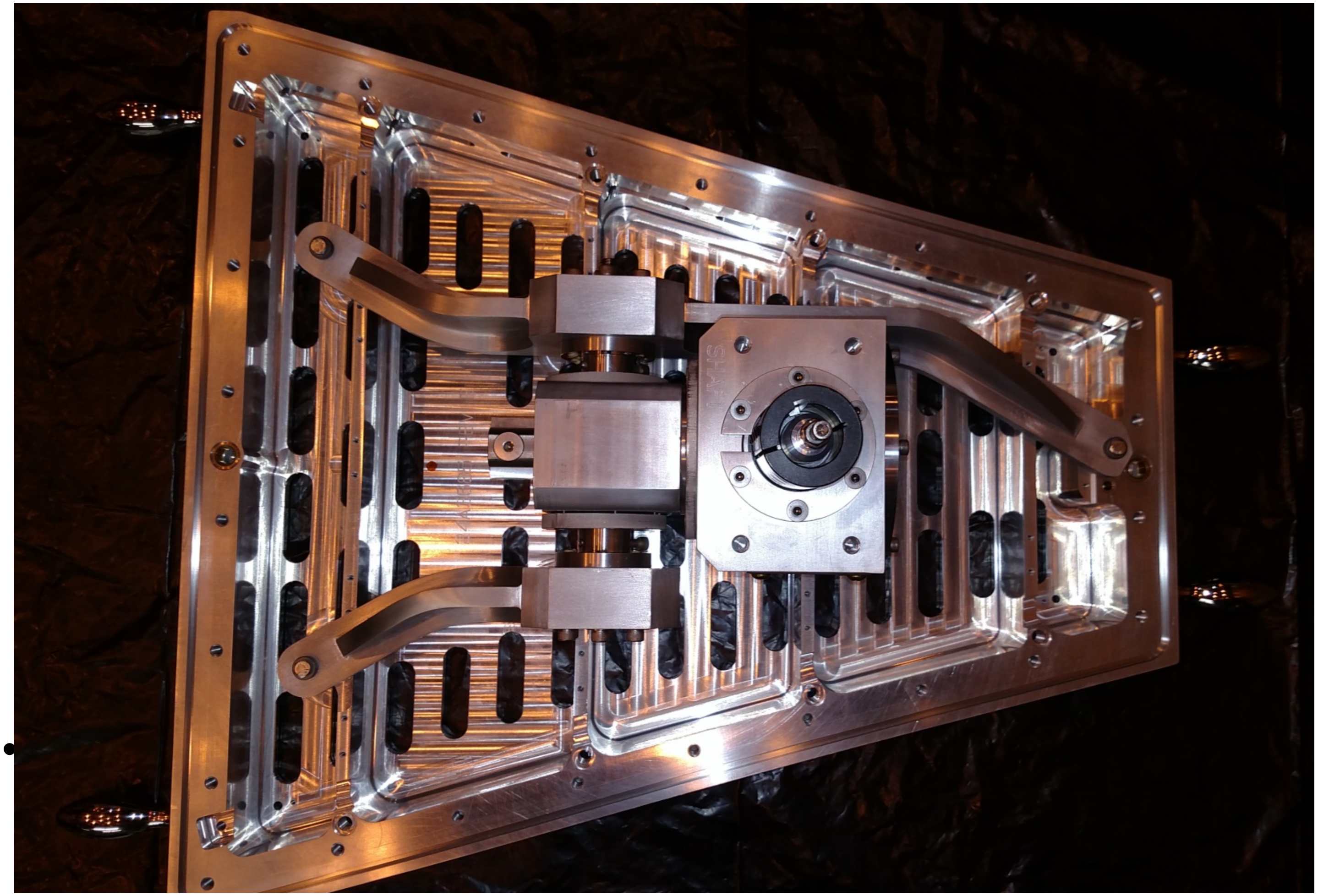
- **The TPC is the heart of STAR**



Sector Insertion – special tools required



BNL Sector Insertion Tool



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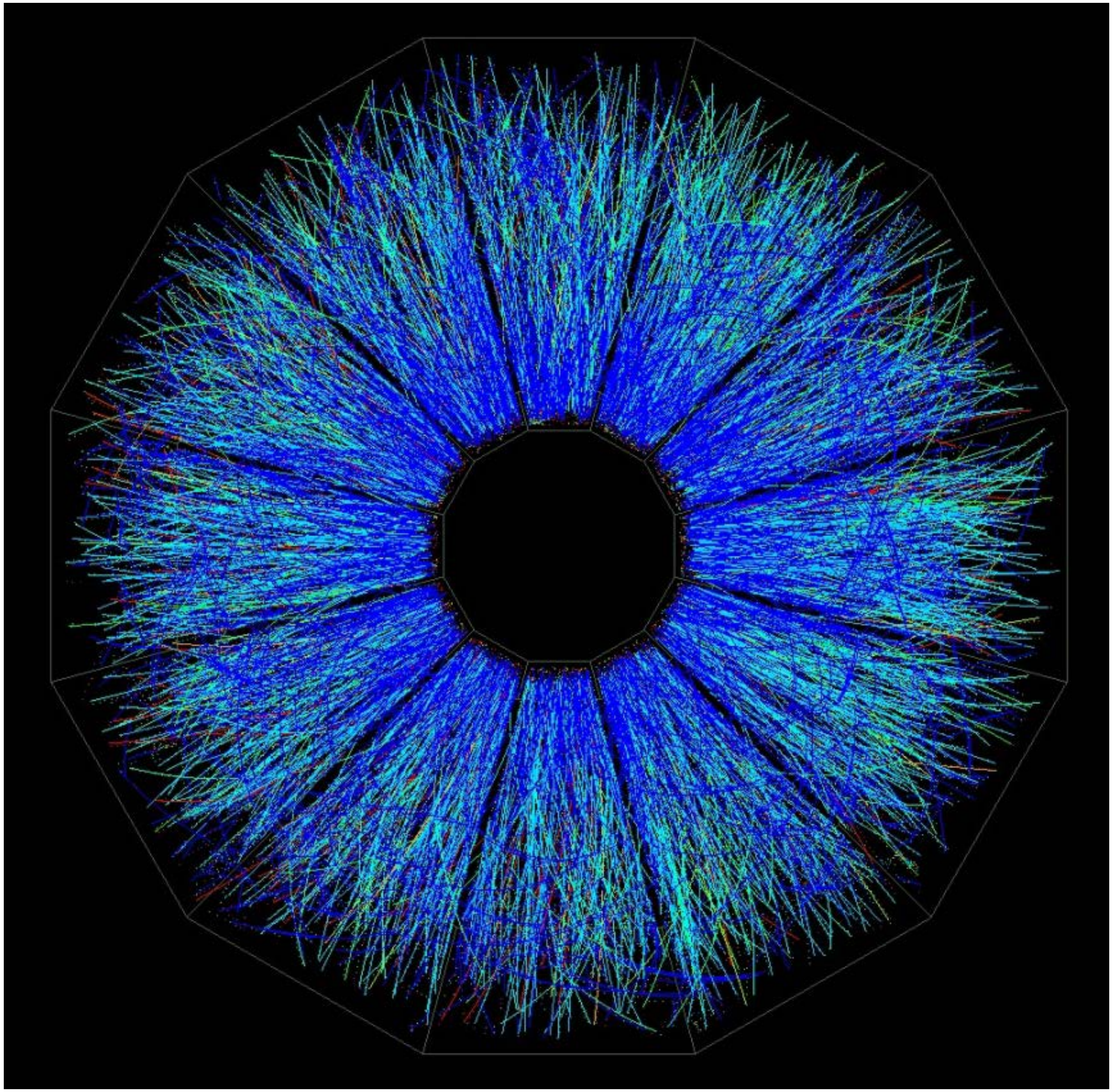
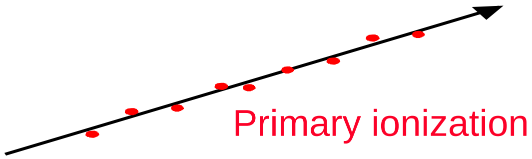
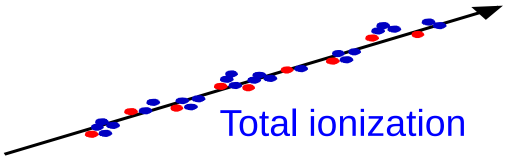
A Typical Collision



Ionization of gases

Fast charged particles ionize the atoms of a gas.





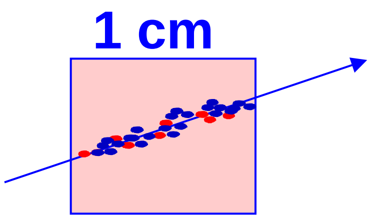
10 - 40 pairs/cm

ΔE/pair ~ 25 eV

$$n_{total} \approx 3 \ldots 4 \cdot n_{primary}$$

Often the resulting primary electron will have enough kinetic energy to ionize other atoms.

Assume detector, 1 cm thick, filled with Ar gas:



~ 100 e-ion pairs

100 electron-ion pairs are not easy to detect!

Noise of amplifier ≈ 1000 e^- (ENC) !

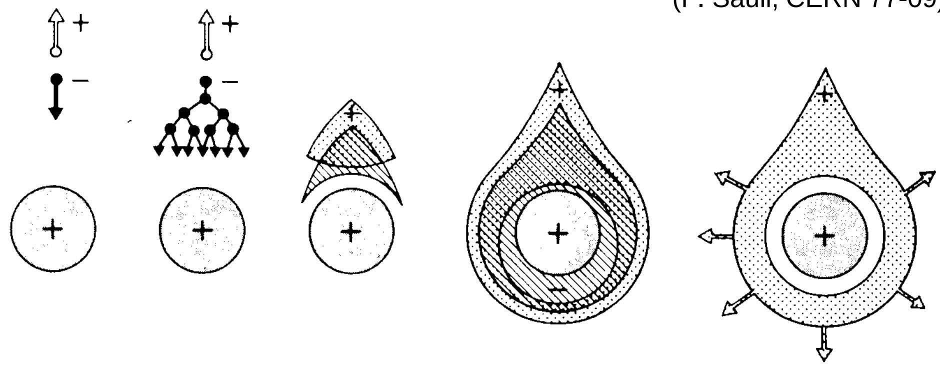
We need to increase the number of e-ion pairs.

Signal Formation - Proportional Counter

(F. Sauli, CERN 77-09)

Avalanches form within a few radii of the wire and within t < 1 ns!

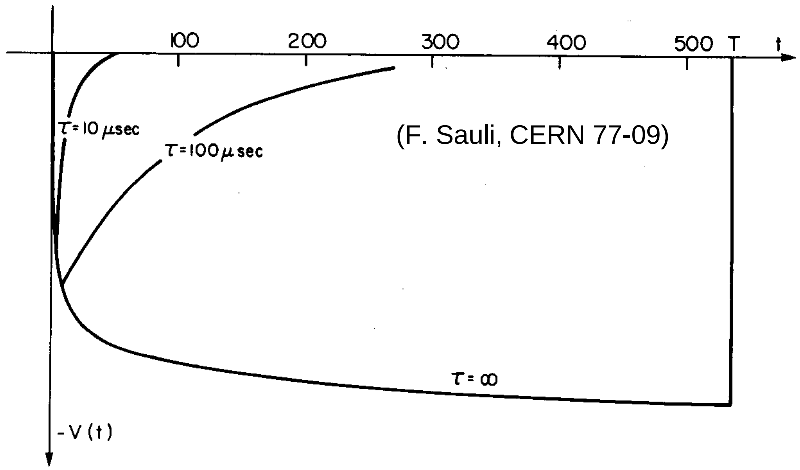
Signal induction both on anode and cathode due to moving charges (both electrons and ions).



$$dv = \frac{Q}{lCV_0}\frac{dV}{dr}dr$$

Electrons are collected on the anode wire, (i.e. *dr* is small, only a few µm).

Electrons contribute only very little to detected signal (few %).



(F. Sauli, CERN 77-09)

Ions have to drift back to cathode, i.e. *dr* is big.

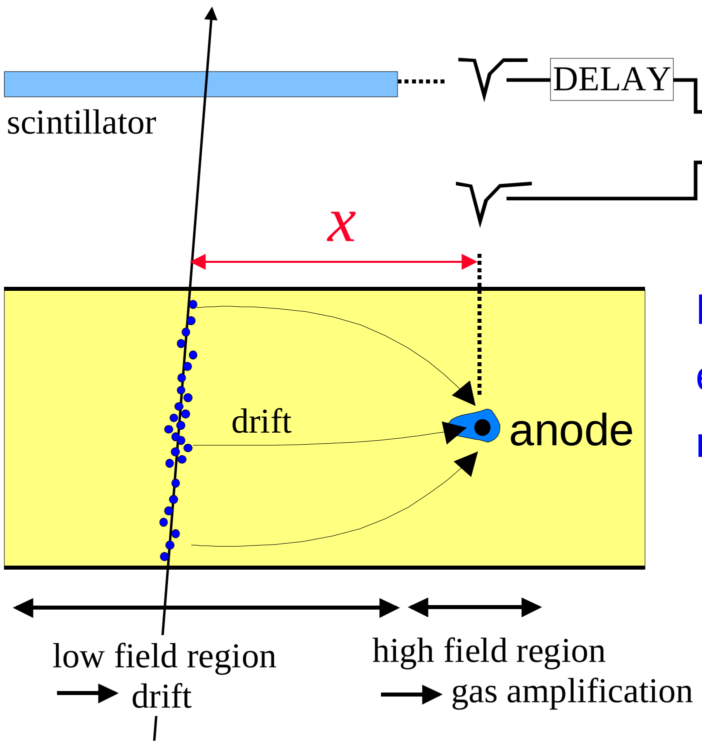
Signal duration limited by total ion drift time !

We need electronic signal differentiation to limit dead time.

The 3rd Dimension: Timing Differences with Drift Chambers

Drift Chambers :

- Reduced numbers of readout channels
- Distance between wires typically 5-10cm giving around 1-2 μs drift-time
- Resolution of 50-100μm achieved limited by field uniformity and diffusion
- Perhaps problems with occupancy of tracks in one cell.



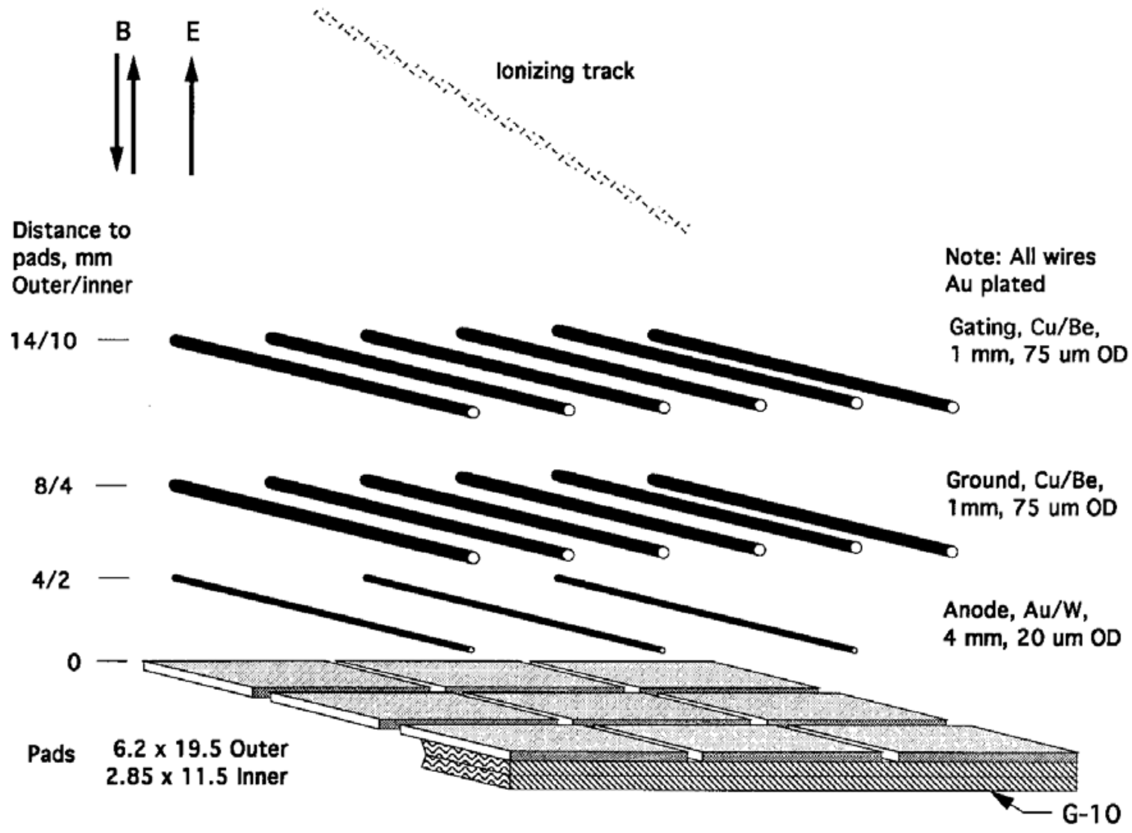
Measure arrival time of electrons at sense wire relative to a time t_0.

$$x = \int v_D(t)\,dt$$

(First studies: T. Bressani, G. Charpak, D. Rahm, C. Zupancic, 1969
First operation drift chamber: A.H. Walenta, J. Heintze, B. Schürlein, NIM 92 (1971) 373)

In P10 Gas (90% Ar, 10% CH_4), the drift velocity is about 5 cm/μsec

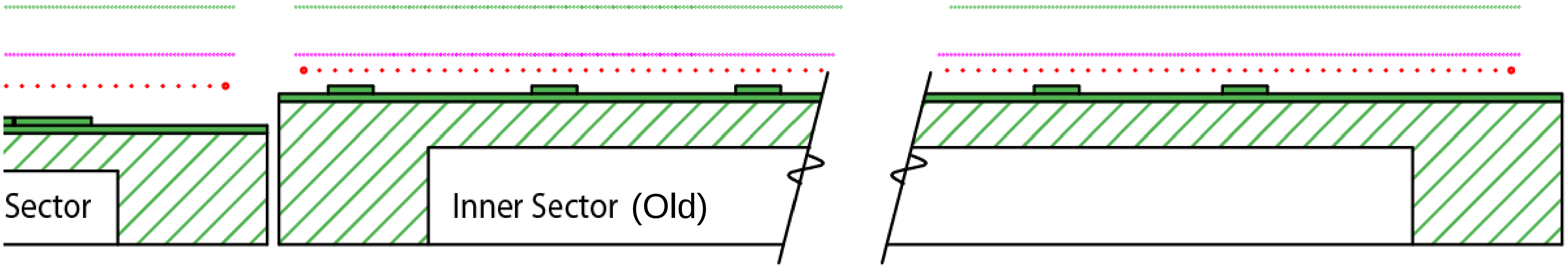
Sector Wire Geometry – special notes



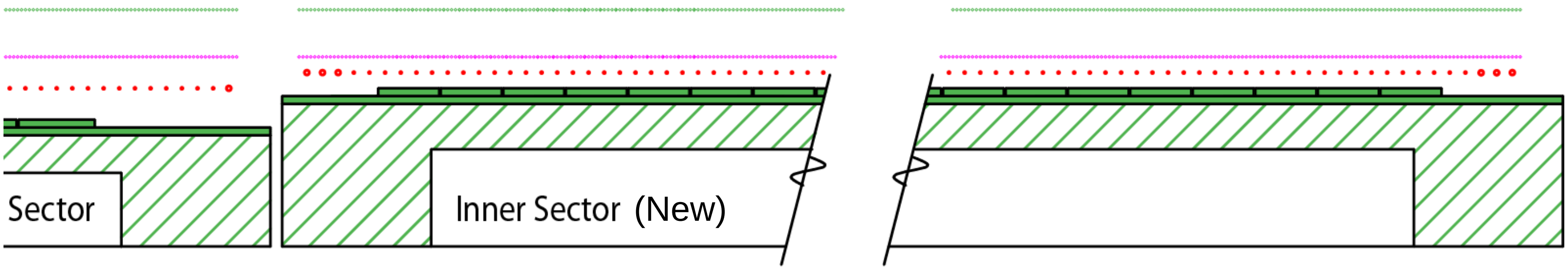
Wires are phase locked to the pad locations. 4 wires located over each pad row. We can probably tolerate a phase shift of 100 microns.

Ground wires placed directly over the Anode wires to limit sparking to pad plane.

40 Pad Rows fit perfectly with the existing grid



Anode wires spaced 4 mm apart (horizontally), Ground Shield and Gated grids spaced 1 mm apart

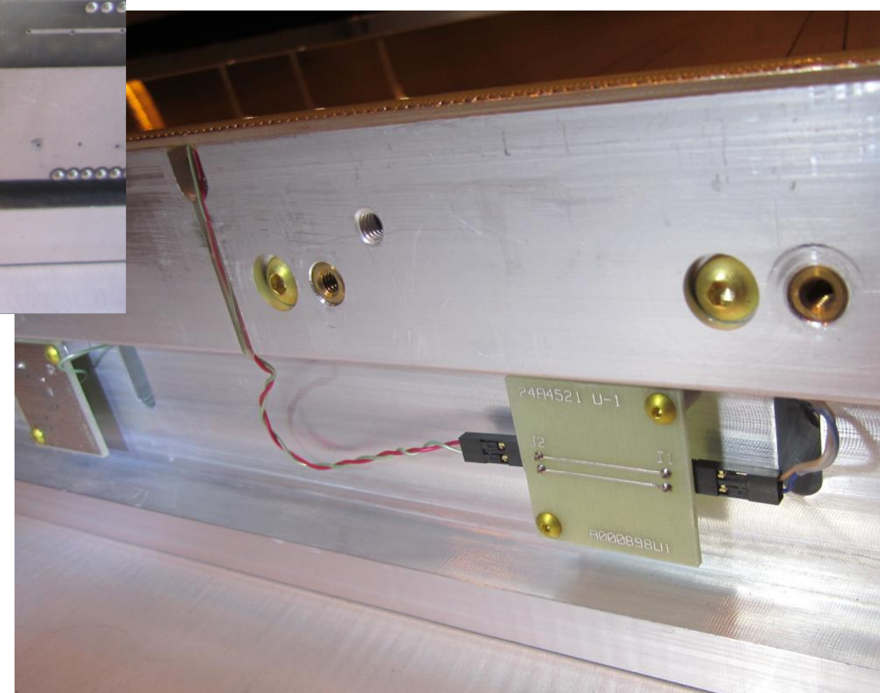


- **No need to change grid; wire locations remain the same**
- **No need to add more ABDB or wire mount channels (good)**
- **Identical pad response function on both ends of grid**

Electronics on sides – all Bromine Free boards

- Careful choice of materials required to avoid electro-negative contamination

- PadPlane
- Electronics Boards
- Epoxy
- Solder (flux)

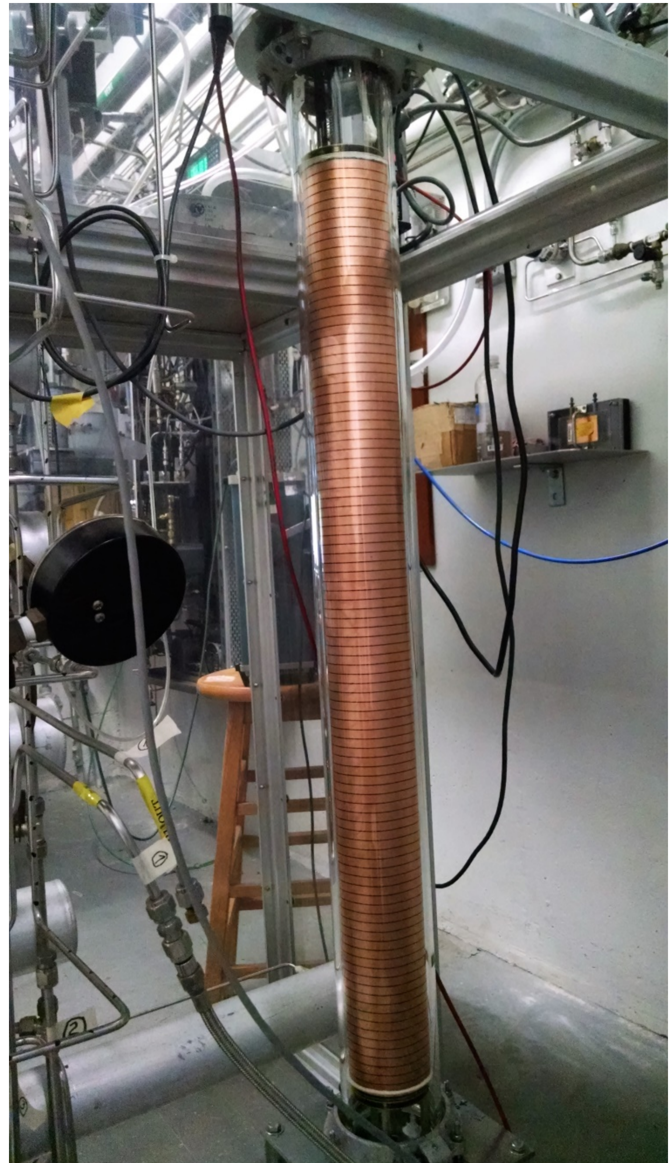


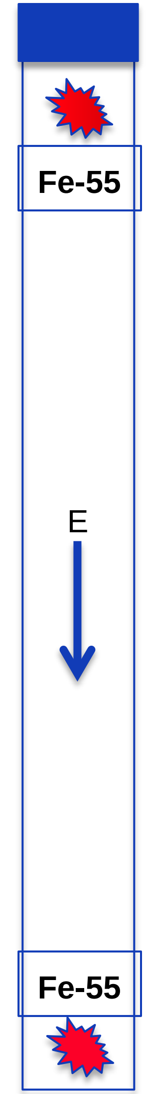
The "LBL Canary Chamber"

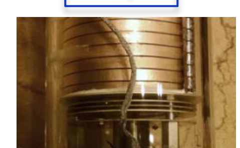
- **Previously used for PEP-4, EOS, STAR & EXO**

- **How to measure electronegative impurities in gas due to materials contamination?**
  - **Drift e⁻ through 1 m of TPC gas (P10)**
  - **Gas circulates through sample chambers & drift volume**
- **Sample chambers and control systems not shown**

- **Now installed and working at BNL 09/05/2016**
  - **Tests will start this week**
  - **e.g. Padplane, ABDB & wiremount boards**







MWPC

Parameters for the old and new sectors

Item	Inner	Outer	iTPC	Comment
Pad Pitch (center to center)	3.35 x 12	6.70 x 20	5.0 x 16	mm
Isolation gap between pads	0.5	0.5	0.5	mm
Pad Size	2.85 x 11.5	6.20 x 19.5	4.5 x 15.5	mm
Number of Pads	1750	3940	3496	
Anode to pad plane spacing	2	4	2	mm
Anode voltage	1170 V	1390 V	~ 1120 V	20:1 S/N
Anode Gas Gain	3770	1230	~ 2000	nominal
Anode Wire diameter	20 μm	20 μm	20 μm	Au plated W
Anode Wire pitch	4	4	4	mm
Anode Wires phase locked to pad location	3 wires, #2 over center	5 wires, #3 over center	4 wires, over center	grp centered over the pad

Pad Plane & wire planes must be flat to better than 20 μm to keep dE/dx resolution uniform to 1%

Wire	Diam. (μm)	Pitch (mm)	Composition	Tension (N)
Anodes	20	4	Au-plated W	0.50
Anodes—last wire	125	4	Au-plated Be–Cu	0.50
Ground plane	75	1	Au-plated Be–Cu	1.20
Gating grid	75	1	Au-plated Be–Cu	1.20

Critical Dimensions for the TPC

Item	Dimension	Comment
Length of the TPC	420 cm	Two halves, 210 cm long
Outer Diameter of the drift volume	400 cm	200 cm radius
Inner Diameter of the drift volume	100 cm	50 cm radius
Distance: cathode to ground plane	209.3 cm	Each side
Cathode	400 cm diameter	At the center of the TPC
Cathode potential	28 kV	typical
Drift gas	P10: 90% Ar, 10% CH_4	He-Ethane as an option
Drift Velocity	5.45 cm/µsec	typical
Transverse diffusion (σ)	230 µm/√cm	135 V/cm & 0.5 T
Longitudinal diffusion (σ)	360 µm/√cm	135 V/cm & 0.5 T
Magnetic Field	0, ±0.25 T, ±0.5 T	Solenoidal

Weight of TPC (lb.)

Item	Max LBNL	Max BNL Lift	Installed Wt. w/ CTB	Installed Wt. w/ TOF	Basis
IFC	107	107	107	107	close est
OFC	4991	4991	4991	4991	close est
Wheel	3100	3100	3100	3100	measured
Wheel Brkts/Adj	227	227	227	227	rough est
TOF rails	1080	1080	1080	1080	exact
Outer Sectors	2520	2520	2520	2520	measured
Inner Sectors	1752	1752	1752	1752	close est 75# ea,
Gas Manifolds at wheel	0	0	200	200	removed for lift
FEE	128	1539	1539	1539	measured
FEE Manifolds	480	480	480	480	rough
RDO	51	607	607	607	close est.
RDO manifolds	15	360	360	360	rough
RDO/FEE Cable	39	468	468	468	close est
Dist Manif/hose	240	390	390	390	rough
CTB modules (120 ea.)	0	660	3960	0	measured/ 33# ea.
TOF modules (120 ea.)	0	0	0	4800	Est, G.Mutchler 9/98
TOF cables/hose	0	0	240	240	rough
RDO elect. brkts	24	24	24	24	rough
SVT, Cone Assy &SSD	0	0	365	365	Mech Des Rev 3/98
FTPC	0	0	809	809	FDR action item 1
TOTAL	14753	18304	22409	23249	

Location of Wires and Pads

Radius (Y)	Description
0.00	Center of STAR Detector (vtx)
498.80	Bottom of Full size PC Board
512.70	Tertiary Fiducial L & R
519.05	Strongback Bottom Edge
530.00	Gated Grid Wire 1
531.00	Gated Grid Wire 2
532.00	Anode Wire 1 & GG W-3
536.00	Anode Wire 2 & GG W-7
540.00	Anode Wire 3 & GG W-11
540.25	Secondary Fiducial
544.00	Anode Wire 4 & GG W-15
548.00	Anode Wire 5 & GG W-19
558.00	Pad Row 1 - Center
574.00	Pad Row 2 - Center
1166.00	Pad Row 39 - Center
1179.45	Primary Fiducial
1182.00	Pad Row 40 - Center
1192.00	Anode Wire 166 & GG W-663
1196.00	Anode Wire 167 & GG W-667
1200.00	Anode Wire 168 & GG W-671
1204.00	Anode Wire 169 & GG W-675
1204.85	Alternate Primary Fiducial
1208.00	Anode Wire 170 & GG W-679
1209.00	Gated Grid Wire 680
1210.00	Gated Grid Wire 681
1214.32	Strongback Top Edge
1220.67	Tertiary Fiducial L & R
1235.42	Top of Full size PC Board

Repeat pad rows every 16 mm

GATED GRID WIRE
Ø.075mm BeCu , Au plated
spacing 1mm
OUTER : 689 Wires
INNER : 681 Wires
TOTAL : 1,370 Wires per Sector

SHIELD GRID WIRE
Ø.075mm BeCu , Au plated
spacing 1mm
OUTER : 689 Wires
INNER : 681 Wires
TOTAL : 1,370 Wires per Sector

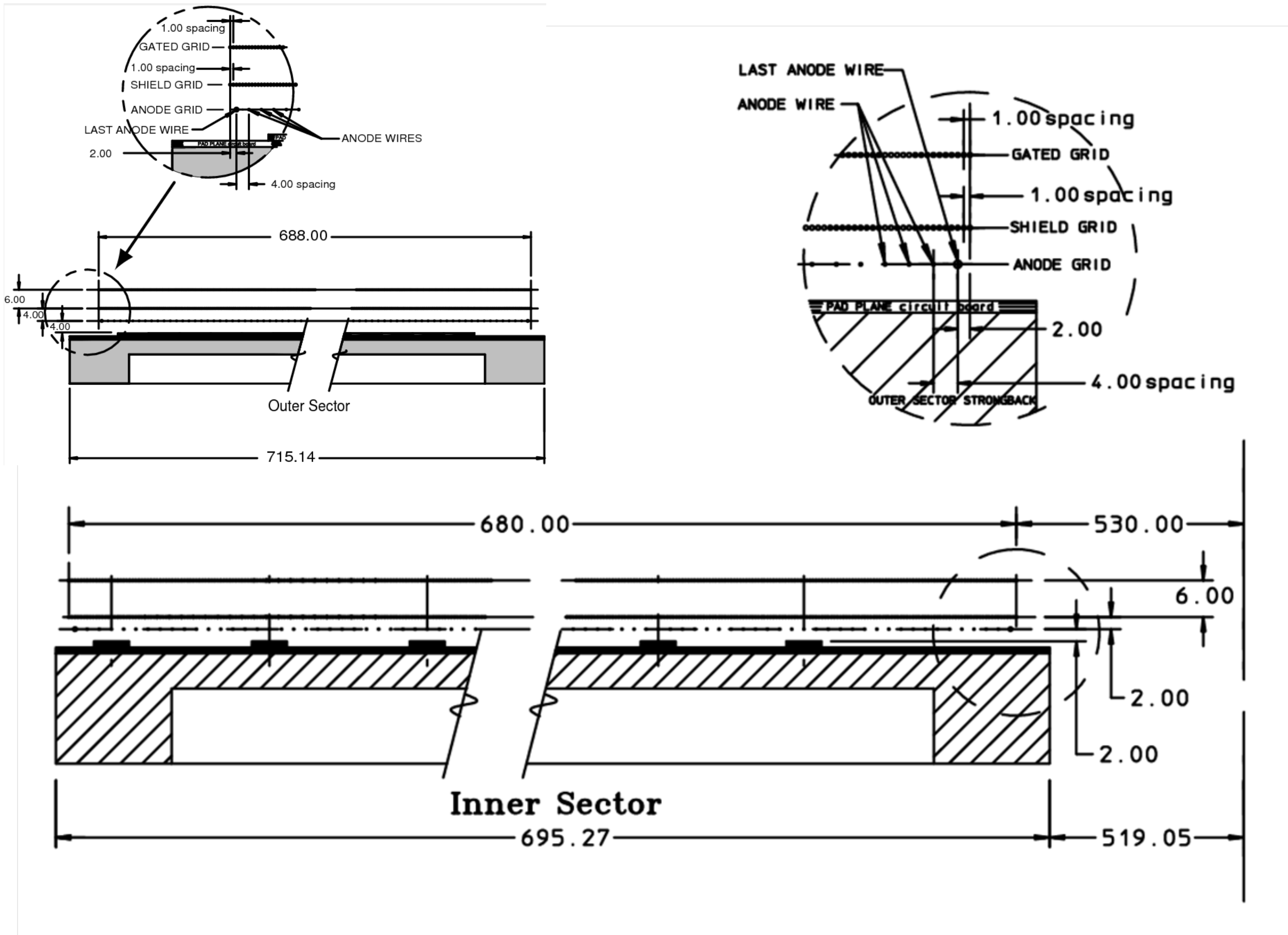
ANODE GRID WIRE
Ø.020mm W, Au plated
spacing 4mm
OUTER : 170 Wires
INNER : 164 Wires (168 in old design)
TOTAL : 334 Wires per Sector (338 in old design)

LAST ANODE WIRE
Ø.125mm BeCu , Au plated
OUTER : 2 Wires
INNER : 6 Wires (2 in old design)
TOTAL : 8 Wires per Sector (4 in old design)

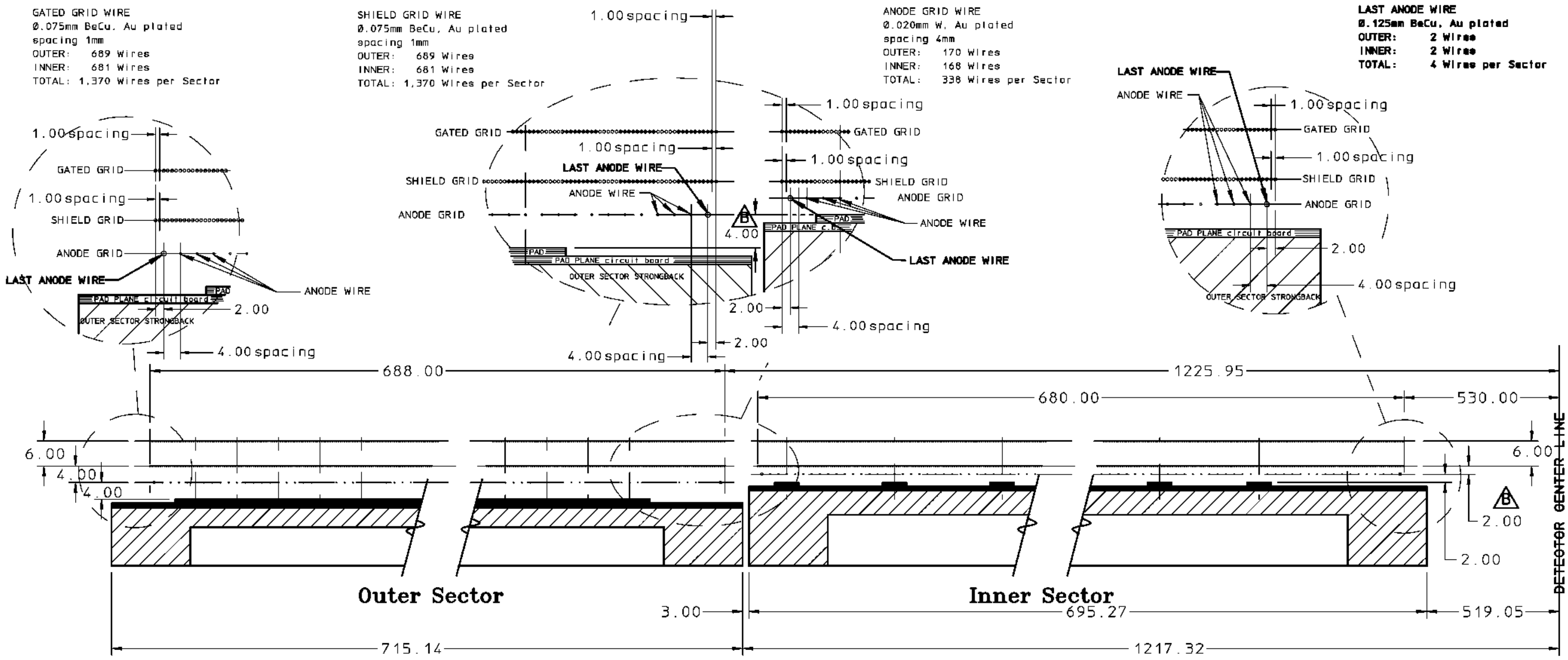
References:
LBL Drawings
24A055,
24A373,
24A374

Wire Locations are the same as before except for the replacement of 6 thin anode wires with larger diameter anode wires (0.020 mm ⇒ 0.125 mm)

Inner sector detail



Inner / Outer sector detail



- Note that inner and outer pad planes are not at the same height
- Pad plane to wire grid heights not the same (4/4/6 vs 2/2/6)
- 3 mm gap between sectors, this is an issue during installation

Average mass distributions (±10°, 1.5 < η < 2.0)

FEE	3.60 %
FEE mounting bracket	3.45 %
FEE rib	0.45 %
FEE socket	0.15 %
Cooling manifold	3.25 %
RDO card	0.90 %
Ribs	2.70 %
Sector G10	0.45 %
Sector Aluminum	3.20 %
Cables	~1% (estimate)
FEE sub Total	**7.65%**
Total	**19.15%**

Table 6: The *average* radiation length budget for the components associated with a TPC inner sector (circa 1993) averaged over the fiducial volume of the sector. The average takes out the lumps in the mass distribution (for better or worse) but also illustrates how the budget for the Al on the front face compares to the electronics and cooling budget. The sector data have been averaged over a range from 1.5 < η < 2.0 and -10 < ϕ < 10 degrees. Geant simulations courtesy of Irakli Chakaberia.