Conception, Gestation, and Birth of the Time Projection Chamber Idea

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The Scene in 1974

- Physicists had already developed:
  - Geiger-Mueller counters
  - Cloud chambers
  - Photographic emulsions
  - Bubble chambers – H_2 to heavy liquids
  - Spark chambers – optical, magnetostrictive, …
  - Streamer chambers
  - Scintillators – organic and inorganic,…
  - Multi-Wire Proportional Counter – *Charpak*
  - Drift Chambers – *Walenta, Heinze, Schurlein*

Momentum measurement in drift chambers

To measure momentum, measure the curvature of the track in a strong magnetic field.

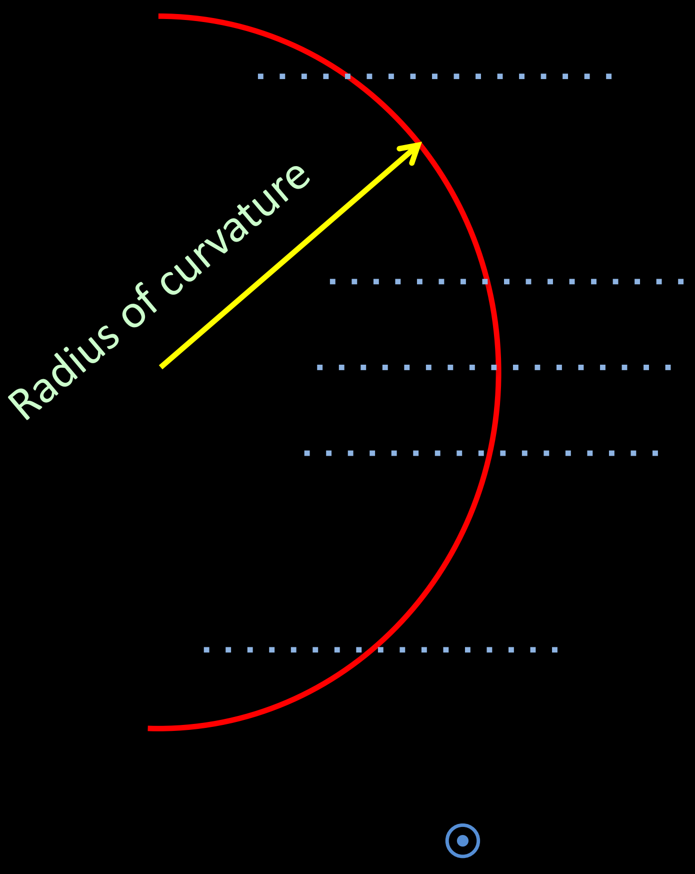
The magnetic field is perpendicular to the image plane.

The electric field is parallel to the image plane.

Ionization electrons drift to sense wires; measure time of arrival.

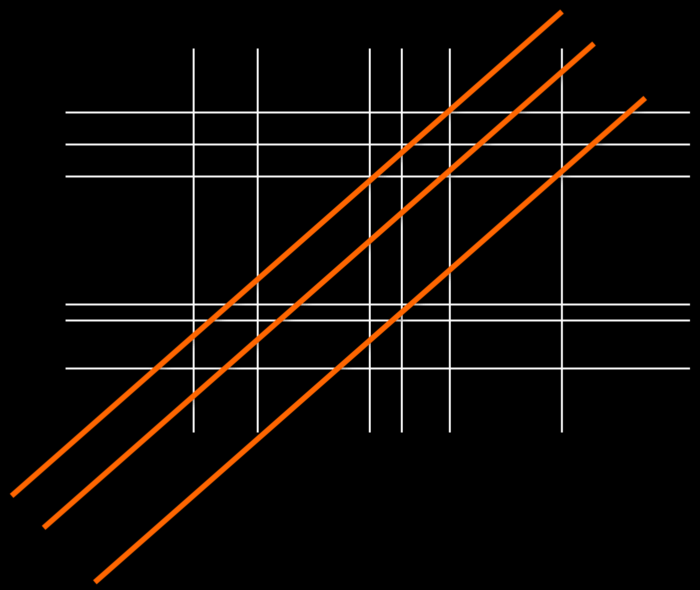
But the electrons are deflected by the magnetic field too! ***E x B ≠ 0***

E x B distortion introduces errors!



Worse: The dreaded N^2 ambiguity

- Suppose you have a detector which measures separately the x and y track coordinates.
- If N tracks appear simultaneously, then you have N x coordinates, and also N y coordinates.
- You have N^2 possible combinations of <x,y>.
- *Which are the right ones?*



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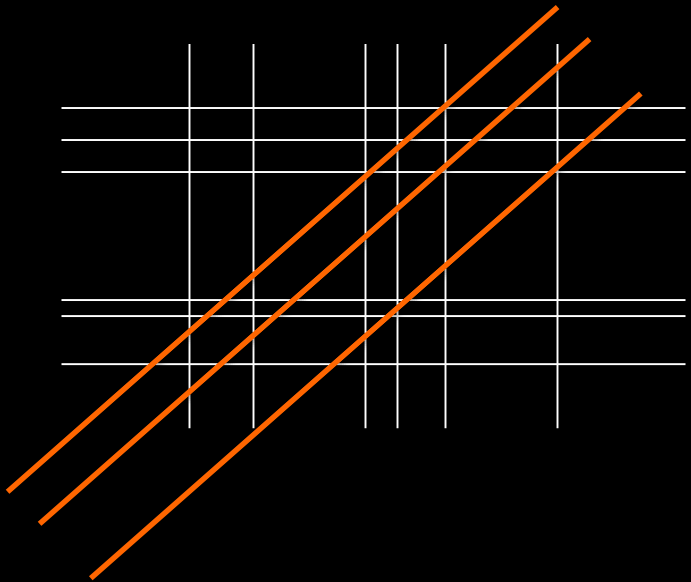
- *Which are the right ones?*
- Add more planes at different angles ?
- *Unpleasant for N > ~10*
- *Anguish rises ~ N^3*



Conception: Despair → Inspiration

February, 1974:

I was a naïve young physicist seated at a drafting table, trying to design a colliding beam experiment for SPEAR.

Issues of concern:

Complex topologies,

~4π solid angle,

momentum resolution,

particle ID,

backgrounds, rates…

Conception: Despair → Inspiration

February, 1974:

I was a naïve young physicist seated at a drafting table, trying to design a colliding beam experiment for SPEAR.

Nothing turns out to be interesting… Paper pile on the floor grows taller… Dejection turns toward defeat !

Minutes pass...

Insight #1:

I recalled an impression from graduate student days:

"Spark chamber tracks–with E-field **parallel** to B-field–
become much narrower and much brighter when B-field is on... "

Maybe a magnetic field parallel to E constricts diffusion?

Eureka:

Let’s put E-field parallel to B-field !

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After a quick trip to the Library,
I discover that

$\sigma_x = (2DT)^{1/2}$ where $D = Vl/3$

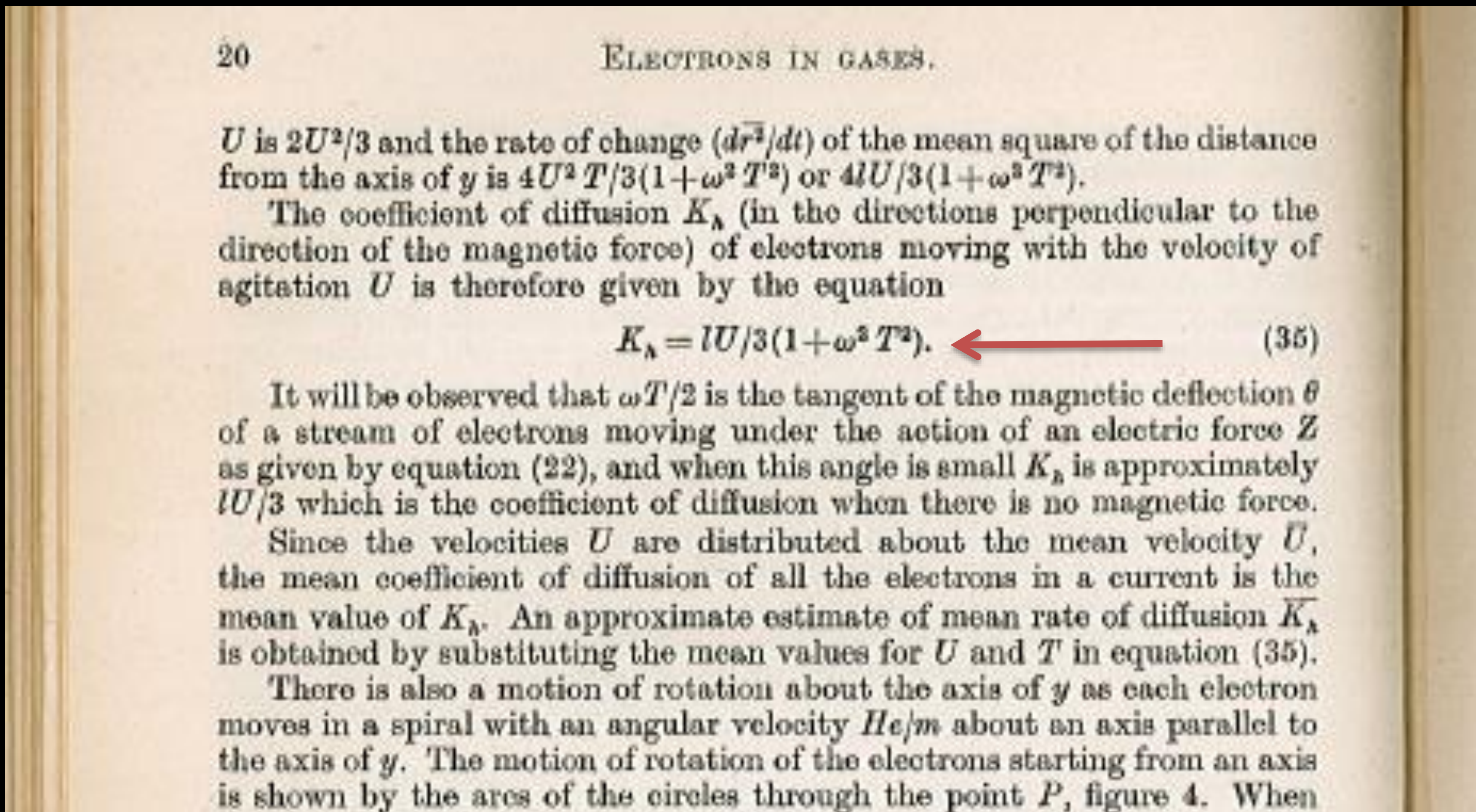
and

$D_{magnetic} = D/(1 + (\omega\tau)^2)$

ω is cyclotron frequency

τ is mean collision time = l/V

I found this equation in a book: "Electrons in Gases", by Sir J. S. E. Townsend, Hutchinson Scientific, 1948



U is $2U^2/3$ and the rate of change ($d\overline{r^2}/dt$) of the mean square of the distance from the axis of y is $4U^2T/3(1+\omega^2T^2)$ or $4lU/3(1+\omega^2T^2)$.

The coefficient of diffusion K_h (in the directions perpendicular to the direction of the magnetic force) of electrons moving with the velocity of agitation U is therefore given by the equation

$$K_h = lU/3(1+\omega^2T^2). \qquad (35)$$

It will be observed that $\omega T/2$ is the tangent of the magnetic deflection θ of a stream of electrons moving under the action of an electric force Z as given by equation (22), and when this angle is small K_h is approximately $lU/3$ which is the coefficient of diffusion when there is no magnetic force.

Since the velocities U are distributed about the mean velocity $\bar{U}$, the mean coefficient of diffusion of all the electrons in a current is the mean value of K_h. An approximate estimate of mean rate of diffusion $\overline{K_h}$ is obtained by substituting the mean values for U and T in equation (35).

There is also a motion of rotation about the axis of y as each electron moves in a spiral with an angular velocity He/m about an axis parallel to the axis of y. The motion of rotation of the electrons starting from an axis is shown by the arcs of the circles through the point P, figure 4. When

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1948 !

But - it is even worse than that!

Townsend refers to his paper in Proc. R. Soc. Lond. A **86,** p571-577 published in **1912!**

1948 !

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The velocities A_s are independent of the times t_s, so that the mean value of A^2 may be substituted for A_s^2 in this expression. Also, since A_s is the velocity in the plane xy, the mean value of A_s^2 is $\frac{2}{3}V^2$, V being the mean velocity of agitation of the ions; and, since the series of cosines $\Sigma \cos \omega t_s$, is equal to $N/(1+\omega^2T^2)$, the above expression reduces to

$$\frac{d\rho^2}{dt} = \frac{2N}{NT\omega^2} \times \frac{2V^2}{3} \times \frac{\omega^2T^2}{1+\omega^2T^2} = \frac{4V^2T}{3(1+\omega^2T^2)}.$$

The rate of diffusion K along the direction of the magnetic force is $\frac{1}{3}\lambda V$ or $\frac{1}{3}V^2T$. Hence

$$\frac{d\rho^2}{dt} = \frac{4K}{1+\omega^2T^2},$$

!

1912 !

It could be noted that:

Rarely has something so simple and so useful been ignored by so many people for so long!

Insight # 2

Argon-methane has a large Ramsauer-Townsend minimum in cross-section below 1 eV – that creates very large τ , so with that gas mixture…

$\omega\tau$ >>1, and diffusion will be strongly suppressed!

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$\omega\tau >> 1$, and diffusion will be strongly suppressed!

Very long drift distances can now be achieved!

Insight # 3

If I arrange a 2-D readout plane (x,y) then the third dimension **z** is found by drift time if event time is known.

Therefore, ionization points are placed unambiguously in 3-D

What to call this idea?

The "Time Projection Chamber" !

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What name could be sexier than that?

Proof: the "phone call"

Anyhow, I stayed up all night, and wrote… …a Proposal

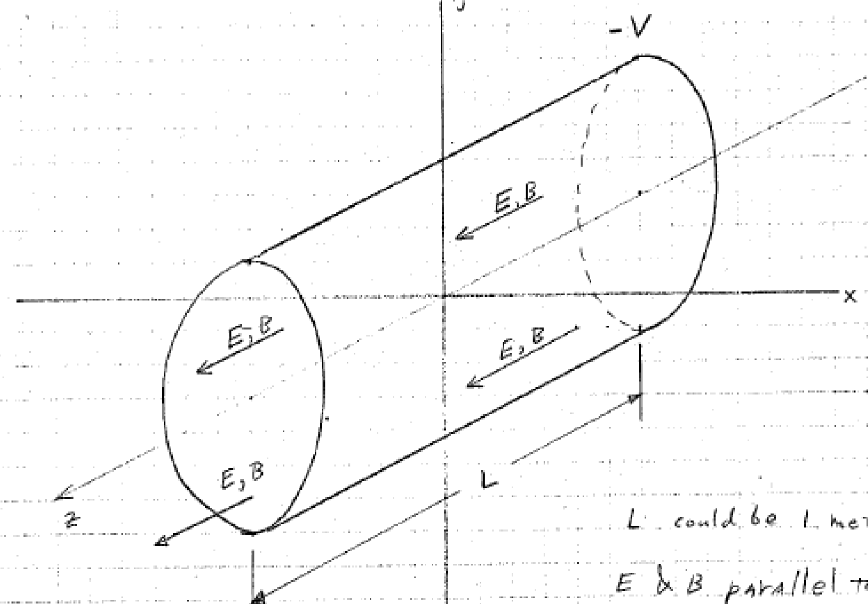
2 - 22 -74

PROPOSAL TO INVESTIGATE THE FEASIBILITY OF A NOVEL CONCEPT IN PARTICLE DETECTION

David R. Nygren

Abstract

A new approach to the problem of high energy particle detection is described, in which parallel electric and magnetic fields are employed. It appears that a particular regime of operating conditions will allow a very substantial suppression of diffusion transverse to the fields in a suitably prepared drift chamber. If the more optimistic estimates are in fact achievable, single track-segment measurement errors of only a few tens of microns in a volume $\sim 1\ m^3$ should be feasible. Additional benefits are the possibilities of unambiguous spatial reconstruction, as well as high data rate capability, high multitrack efficiency, and easy applicability to 4π geometry. A program is outlined which is designed to gain further experience with the concept, provide needed data about electronic diffusion within various gas/field environments, and hopefully lead to practical detectors.



L could be 1 meter

E & B parallel to z axis, uniform, sign of E·B is irrelevant.

Fig 1a

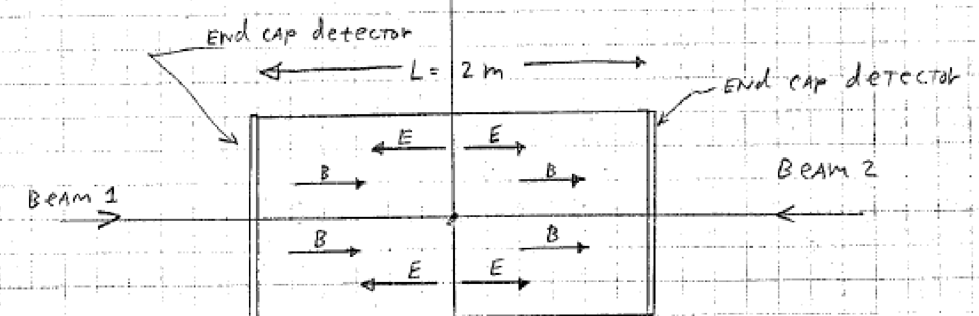


Fig 1.b. colliding beam geometry, using thin foil in plane z = 0 to establish a symmetric electric field.

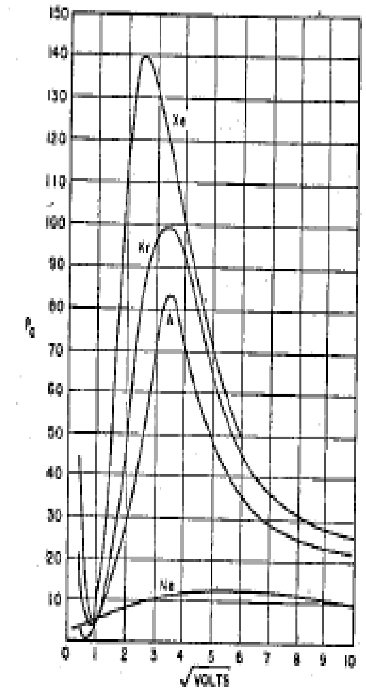
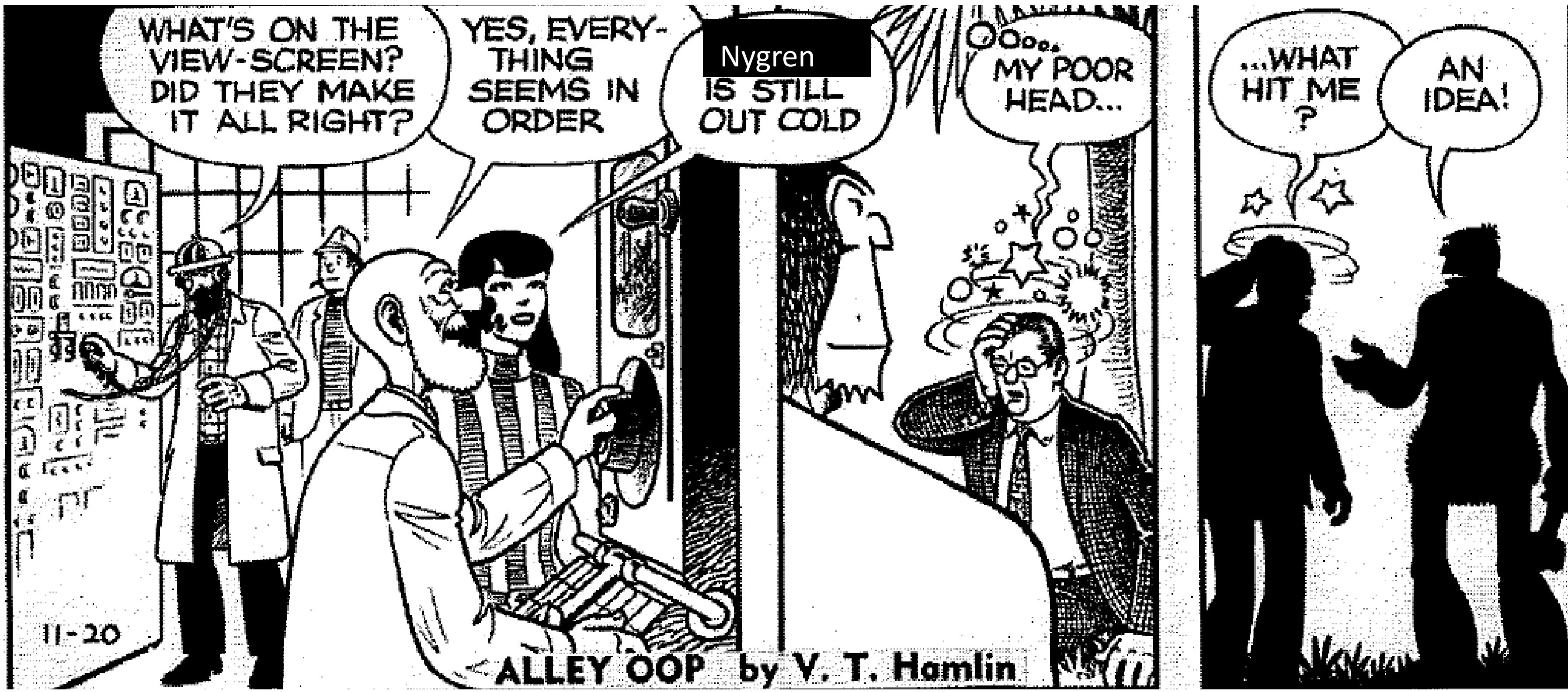


Fig. 2.14 Probability of collision for electrons in Ne, A, Kr, and Xe.*
R. B. Brode (1933)
REVS MOD PHYS J30 V5 P257

Fig. 3. Depicting the window for electrons of ~ 1 eV energy. This energy, corresponding to 40 times room temperature, implies a velocity of $6. \times 10^7$ cm/sec, or .6 mm/nsec.

The Exotic TPC: Time Machine



But… Maybe I was scooped! I subsequently found out about ISIS, at CERN!

Wade Allison 1972 - Identification of Secondaries by Ionization Sampling -

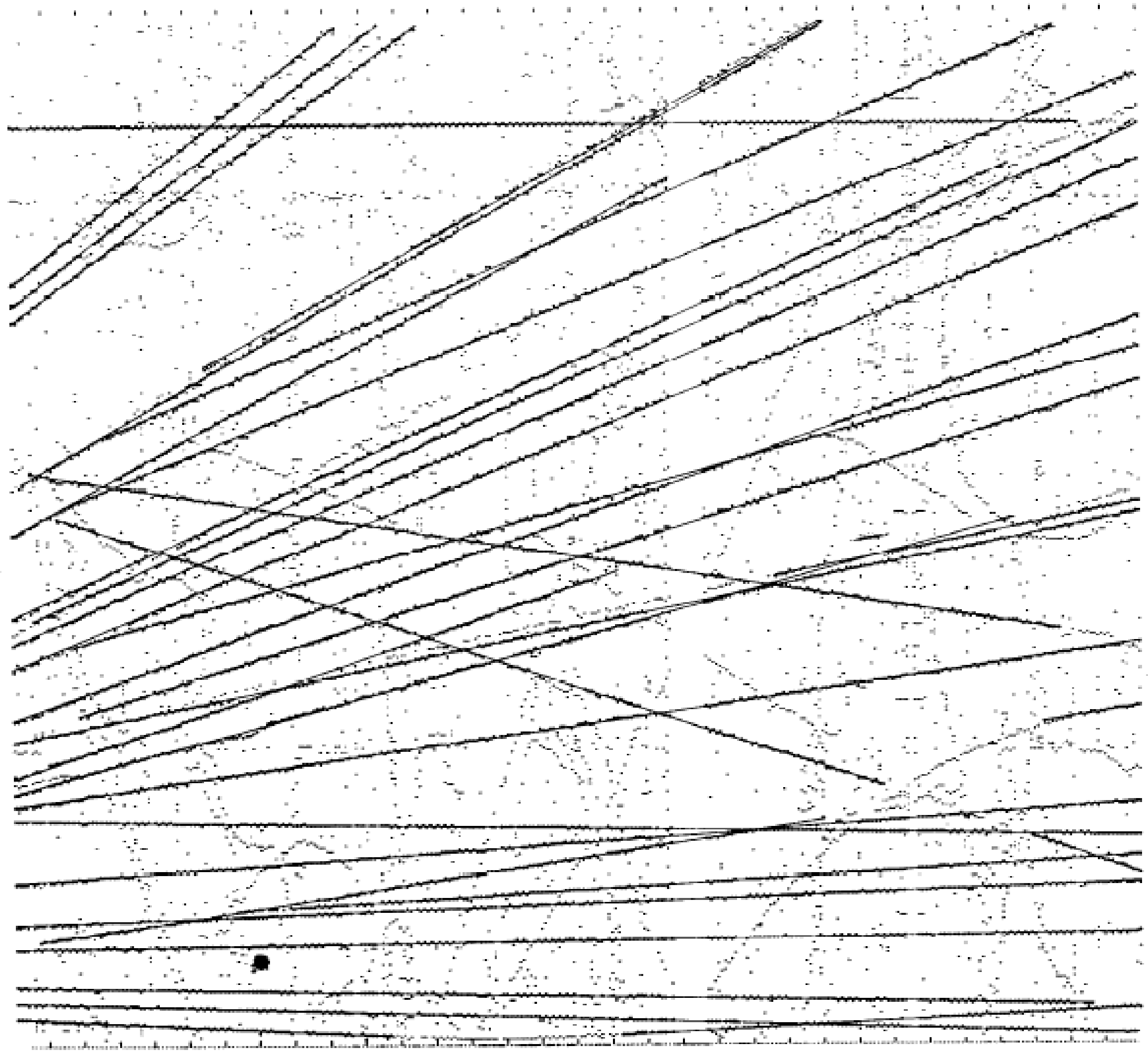


Fig. 17 Spatial data for a single event in ISIS2. Each point is a track hit and is associated with a measured pulse height (not shown). The horizontal axis (512cm) is the wire number. The vertical axis (2x200cm) is the drift direction. Tracks, low energy electrons and noise hits may be seen. Track vectors reconstructed in ISIS space are superposed on the raw data.

A rectangular box 5m long, 2m wide and 4m high, filled with argon-CO_2 at one bar pressure.

320 samples of ionization yielded 7.4% FWHM dE/dx resolution

DAQ:

Store pulse height and time whenever threshold is crossed

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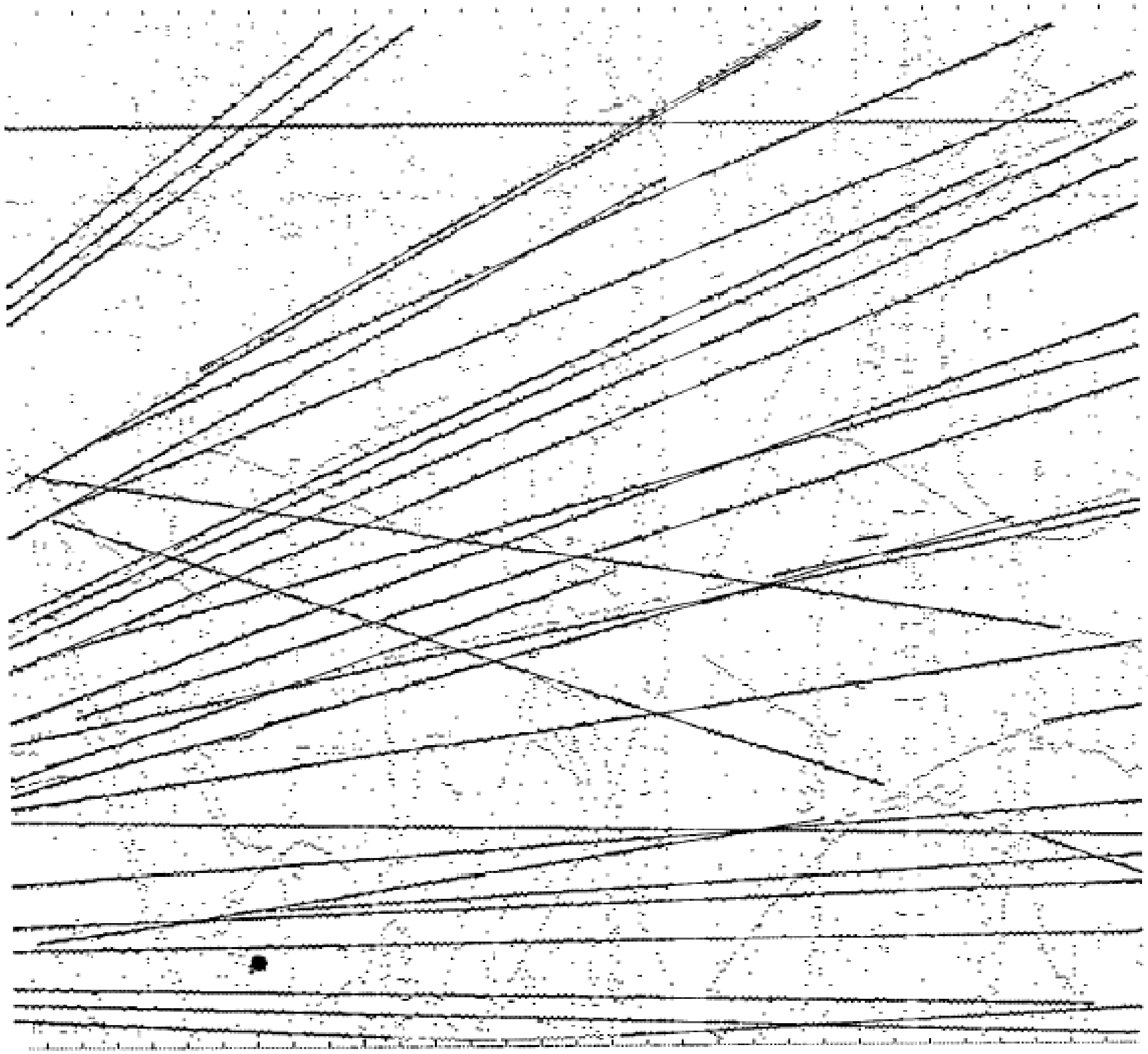

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I acknowledge Wade Allison's important contribution

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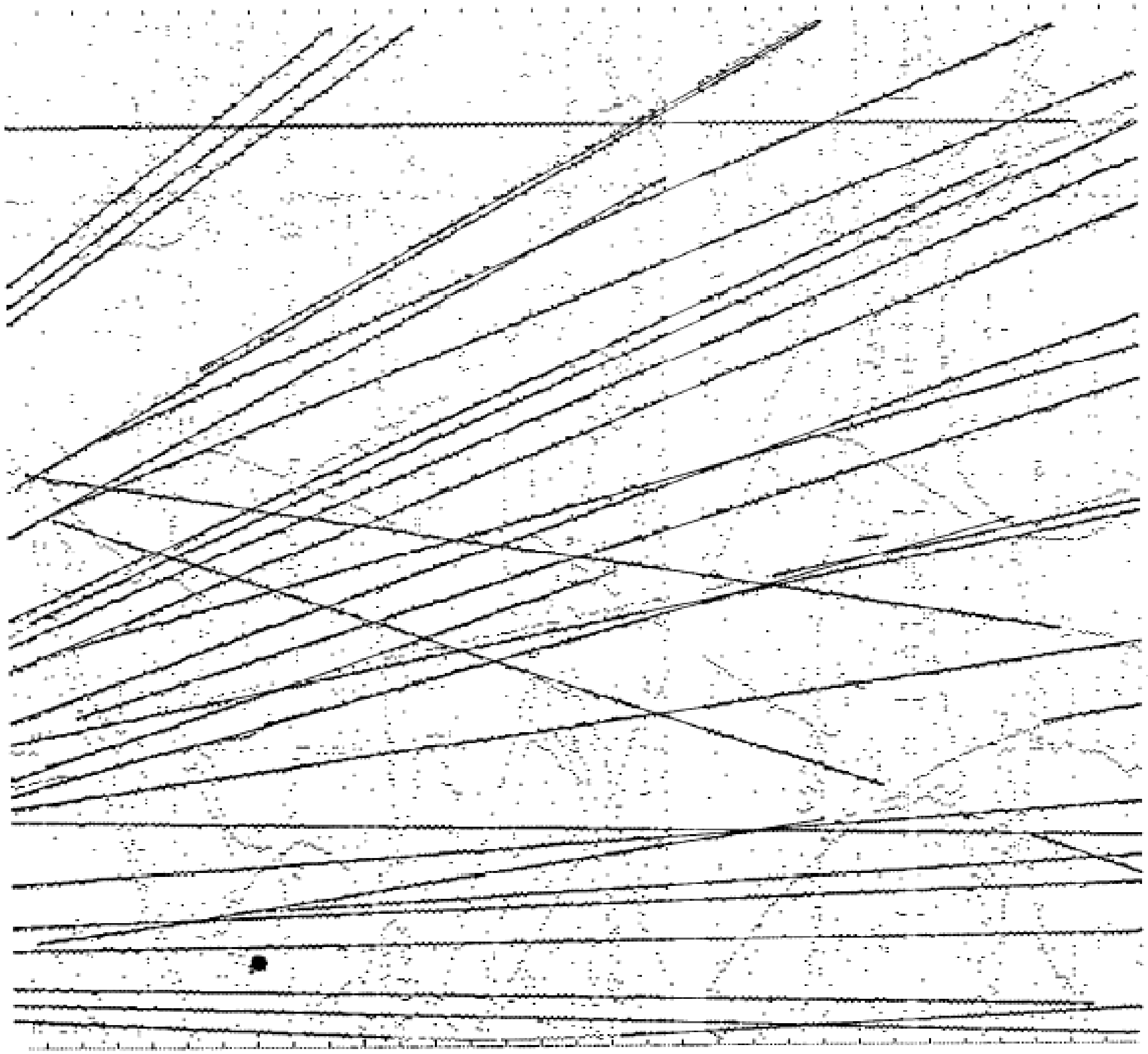

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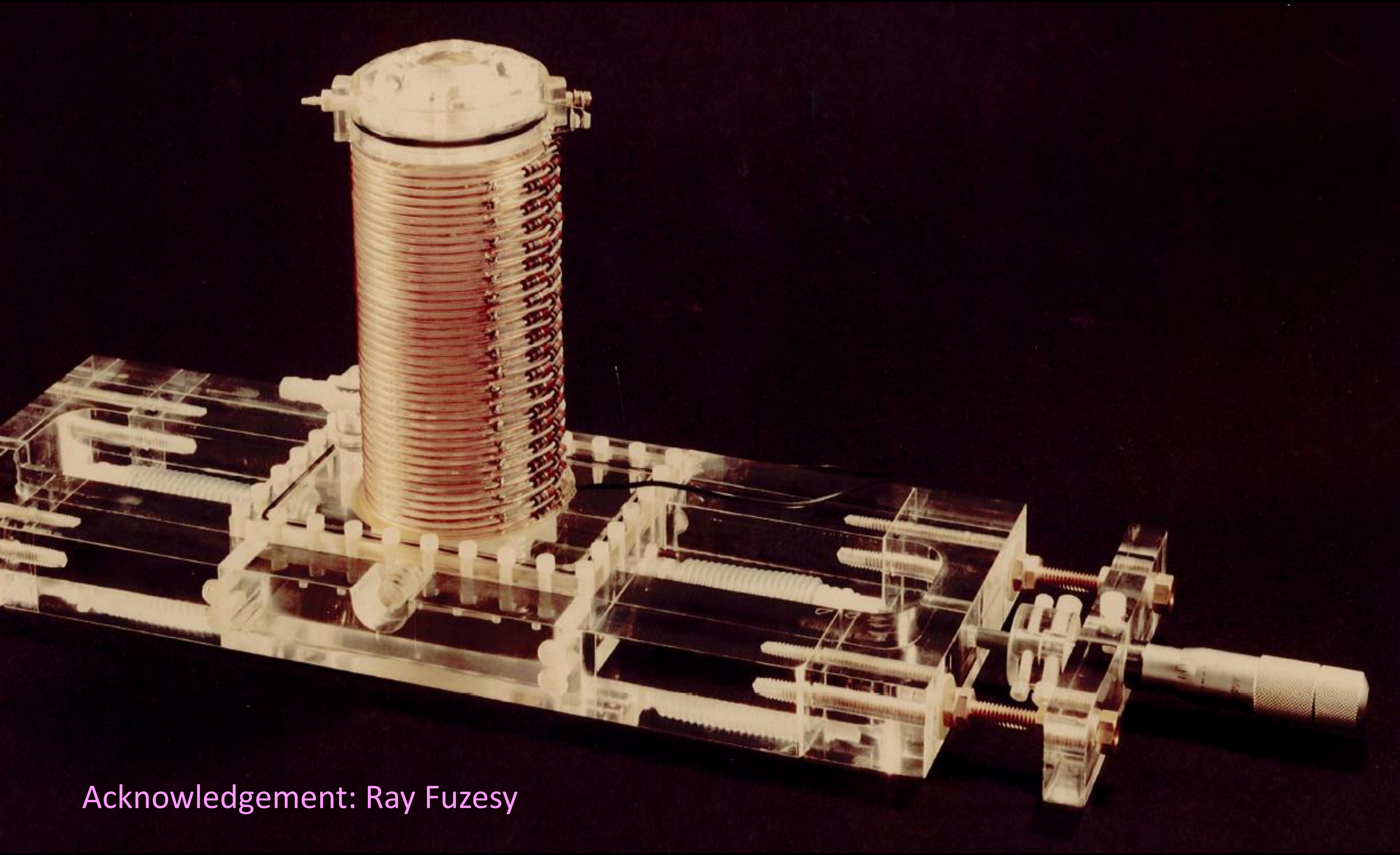
As ISIS produced only 2-D images – the last step remained

LBL - 1974: A device was built to understand diffusion in a magnetic field



Acknowledgement: Ray Fuzesy

This device measured diffusion by counting single electrons passing through a slit

-127-

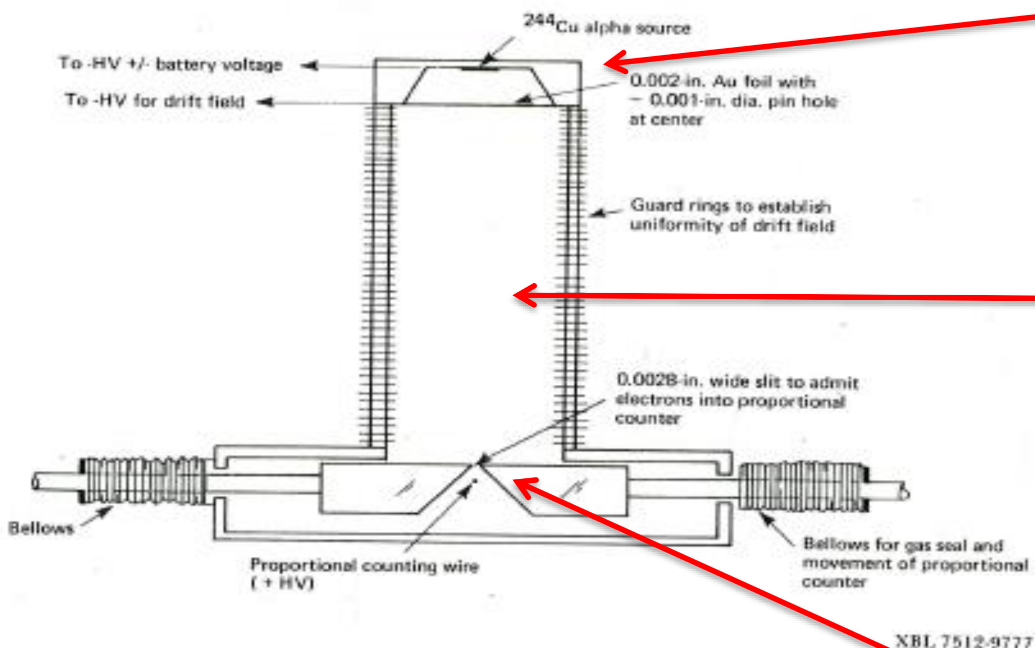


Fig. 1. Cross-section view of chamber for measurements of transverse diffusion of electrons in various proportional gas mixtures. Free electrons are continuously generated in the space above the gold foil by alpha particles born in the curium source. A weak electric field of either polarity can be created in this space by a battery which rides with the potential of the gold foil. Thus electrons can be driven either towards the pin hole or away from it to study signal/background ratios, typically 100 to 1000 to 1. Not shown in this figure is a micrometer which moves the proportional counter assembly remotely.

α particles ionize gas in small cavity; electrons diffuse through pinhole

Drift region

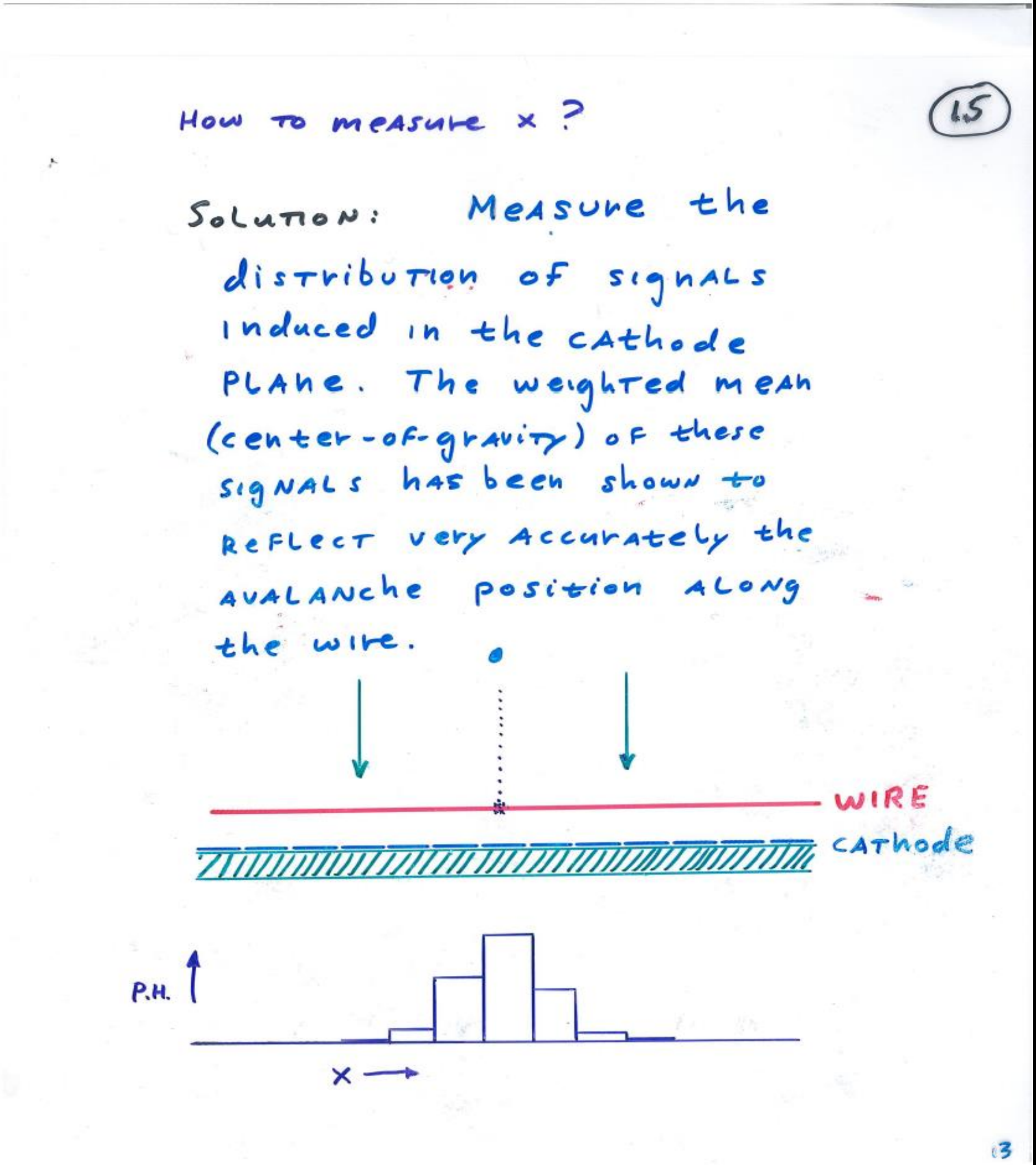
Electrons can pass through slit here and be amplified

PEP 1975 Summer Study

Insight #4

How to obtain 2-D spatial readout from a plane of wires… ?

A transparency of mine, from 1975



Charpak had recently shown that the positive ions created in an avalanche around a sense wire induce signals in nearby electrodes as they move away from the wire.

This is the scheme we chose to measure x: **pads** under the sense wire plane. This was quite new at the time.

Insight #5

- Issue: no way to read out ~14,000 channels!
- Idea: Let's try <u>continuous waveform sampling !</u>
  - **Fairchild** **CCD** linear array for delay-line applications appears in 1975
  - Let's continuously capture information at **super-high**-rate: 10 MHz !

    then, when trigger occurs,

  - Readout analog signals slowly and digitize captured analog information

Insight #5

CCD device didn't work if clock frequency changes!

- Fairchild device was segmented, with diodes at "corners"
- Fairchild graciously redesigned the internals to avoid "corners"
- An enabling technology - essential to ultimate success of PEP-4.

- First HEP realization of continuous waveform sampling !

Gestation: Elation → Experiment

- Pivot: forget about SPEAR – let's go for PEP!
- To do:
  - Demonstrations of performance…
  - Collaboration to be formed…
  - Detector to be designed…
  - Proposal to be written?

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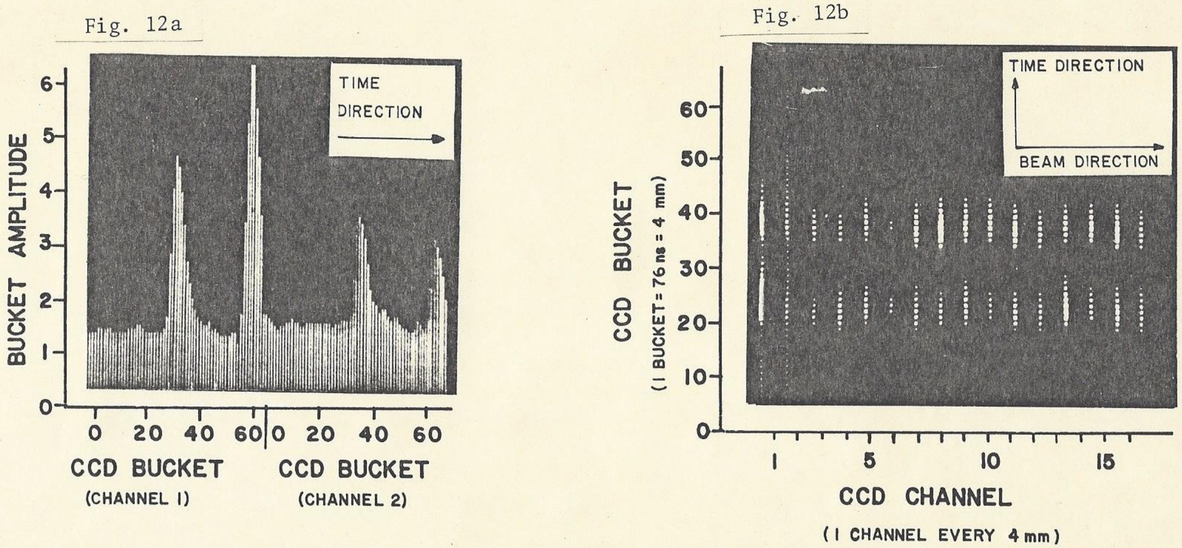
  - Proposal to be written?
- Strategies for success…?
  - Defeat powerful SLAC groups?

First test – a shoebox size µTPC



1 bar Ar-Ch_4

Figure 12 a) CCD bucket amplitude vs bucket number for a two-track event in the TPC prototype chamber.
b) Representation of the CCD bucket amplitudes for all 16 CCD channels for a two-track event in the TPC prototype

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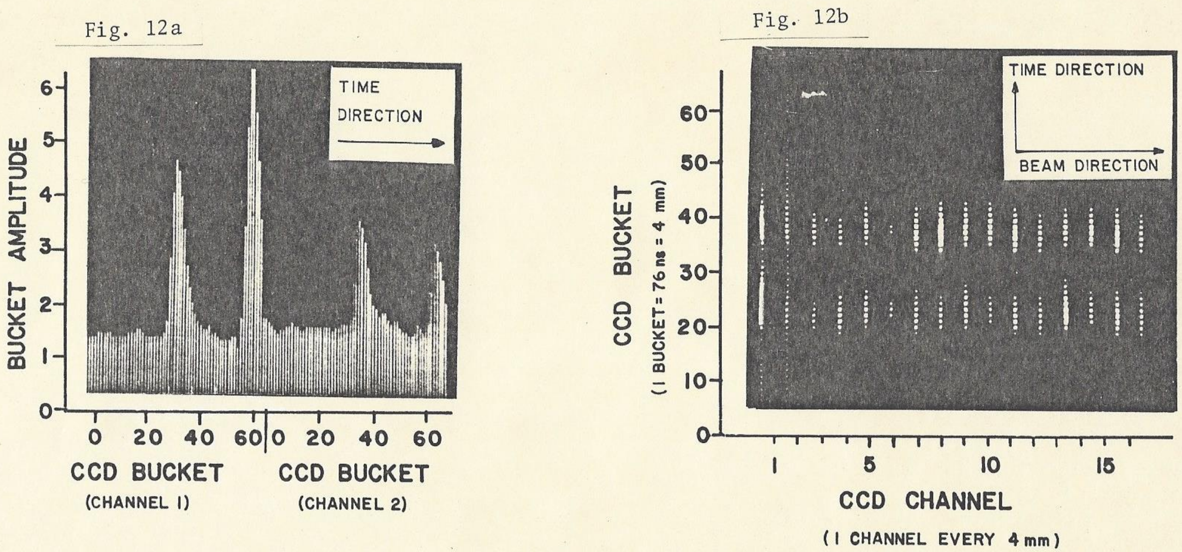

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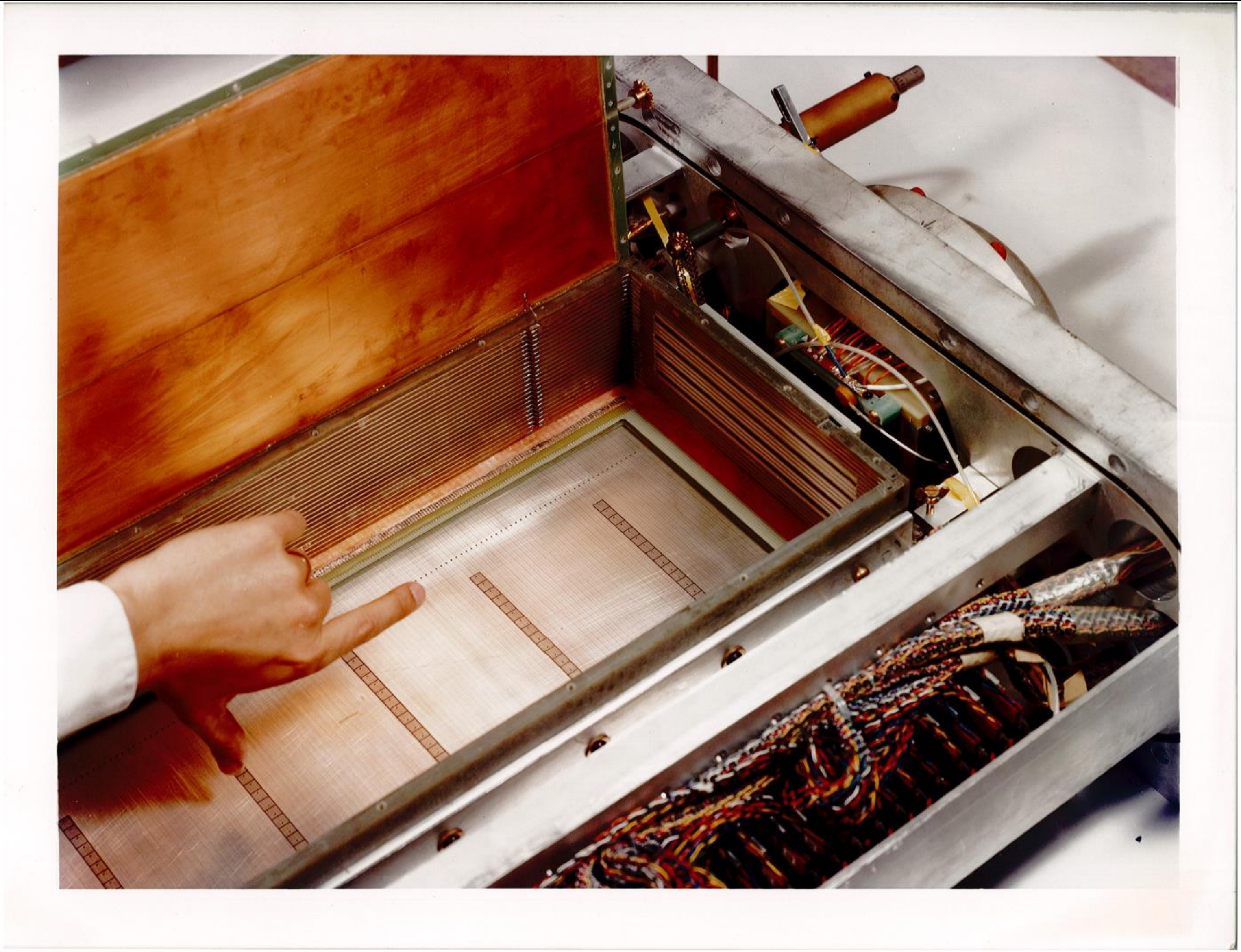
Figure 12 a) CCD bucket amplitude vs bucket number for a two-track event in the TPC prototype chamber.
b) Representation of the CCD bucket amplitudes for all 16 CCD channels for a two-track event in the TPC prototype.

It works nicely!

A serious TPC prototype – a "slice" of a sector – was built in a hurry and run at the Bevatron in a pressurized vessel inside a big magnet



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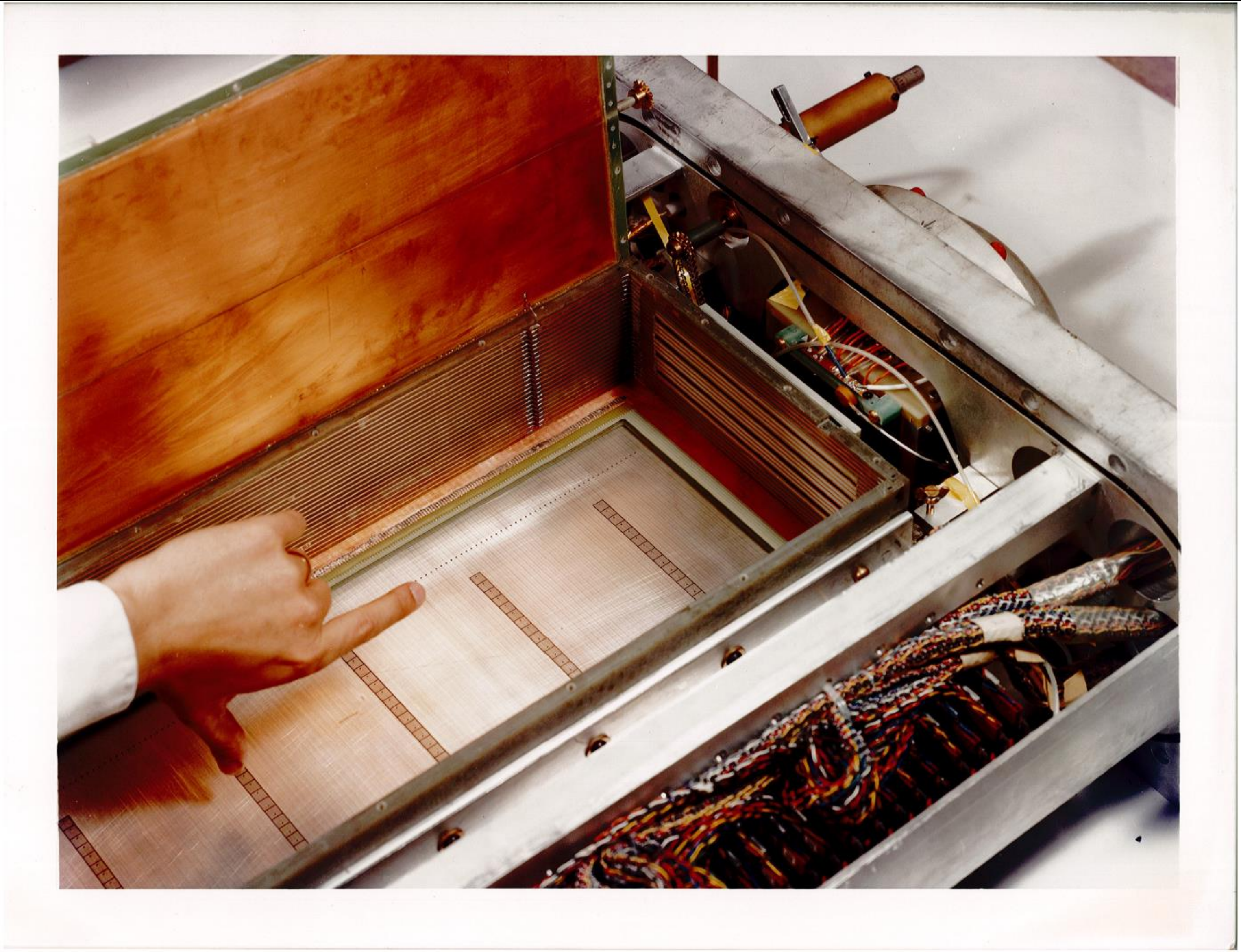

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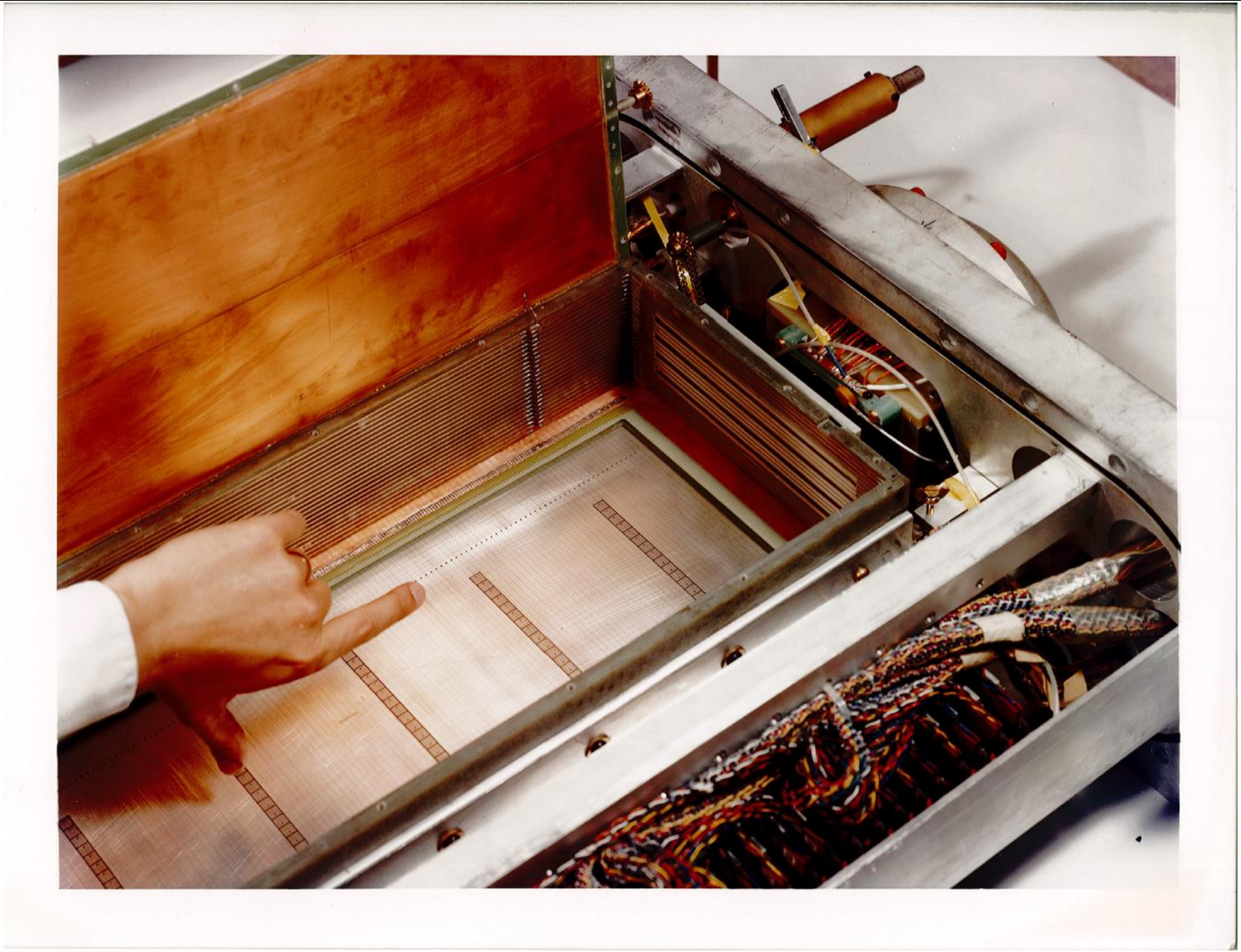
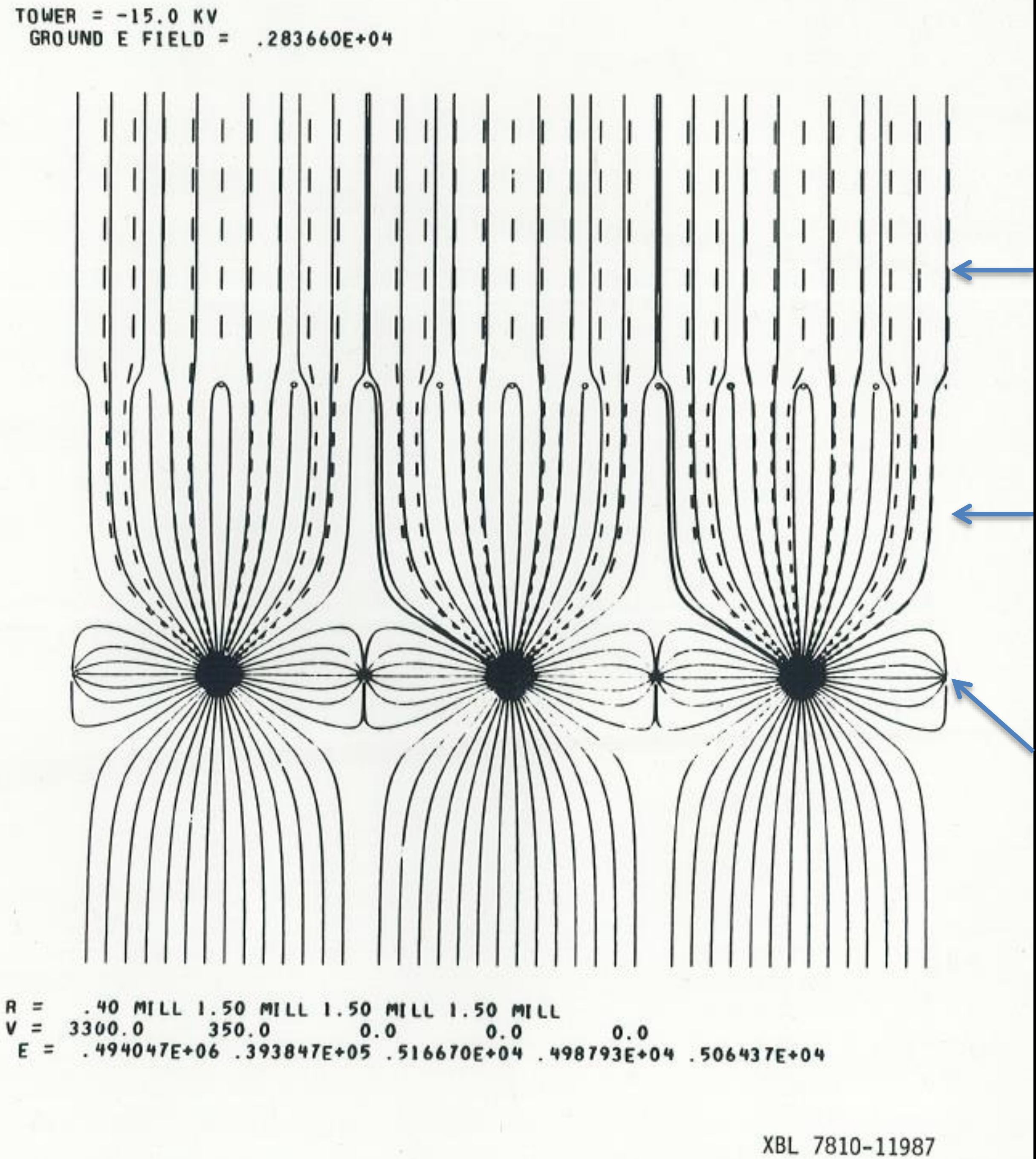


A just-in-time effort for our proposal to SLAC, submitted December, 1976

The Hydrox gas purifier spat some metallic dust into the chamber, which caused sparks, breaking wires!

An emergency fix worked, and we got excellent data just-in-time!

The wire plane

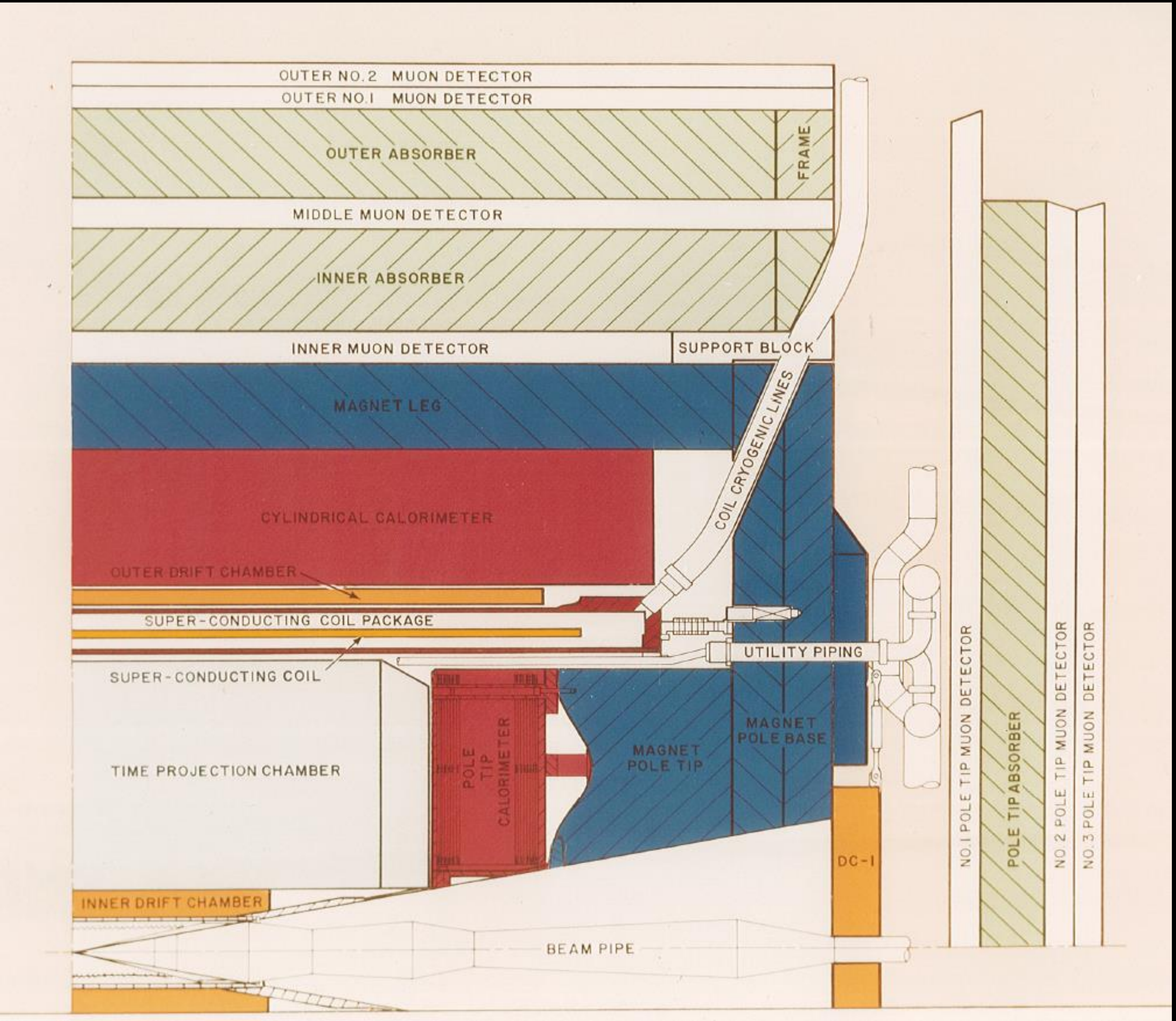


The electric field of the drift region, extending far above, is separated electrostatically from the sense plane by a plane of wires.

The higher electric field in this region draws the electrons past, to the anode wires

“Field” wires in between the anode wires stabilize the anode plan, and give flexibility in operating V

Proposal submitted – just in time!



Parameters:

Drift length: 1m
Wire pitch: 4 mm
Six sectors/endcap
192 wires/sector
~1,000 pads/sector

Argon-CH_4 at 8.5 bars, to improve dE/dx resolution for particle ID.

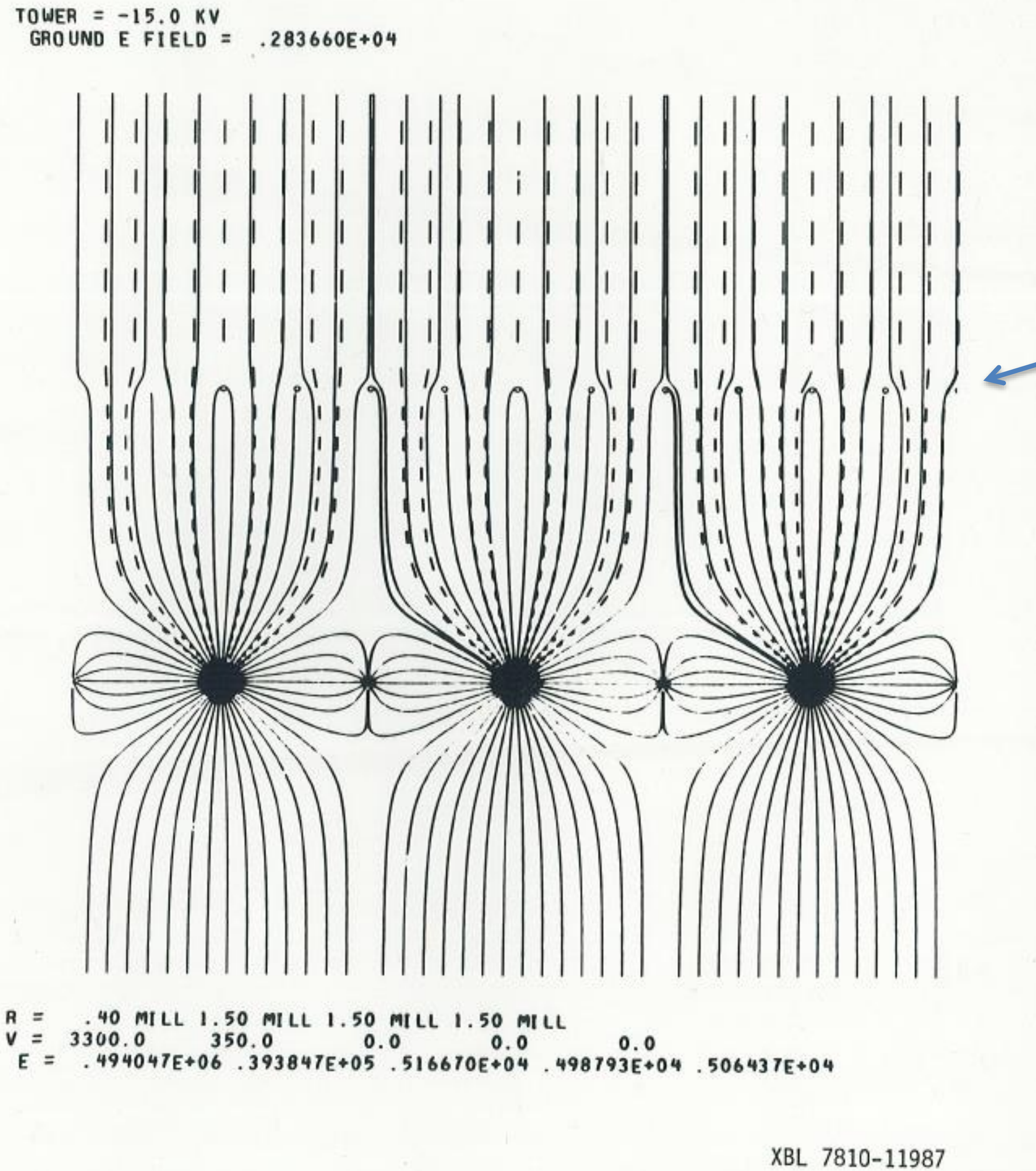
No separate pressure vessel !

Proposal submitted – just in time!

- Owen Chamberlain, UCB prof and Nobel Laureate for discovery of the antiproton, had resigned from SLAC PAC to join PEP-4 effort.

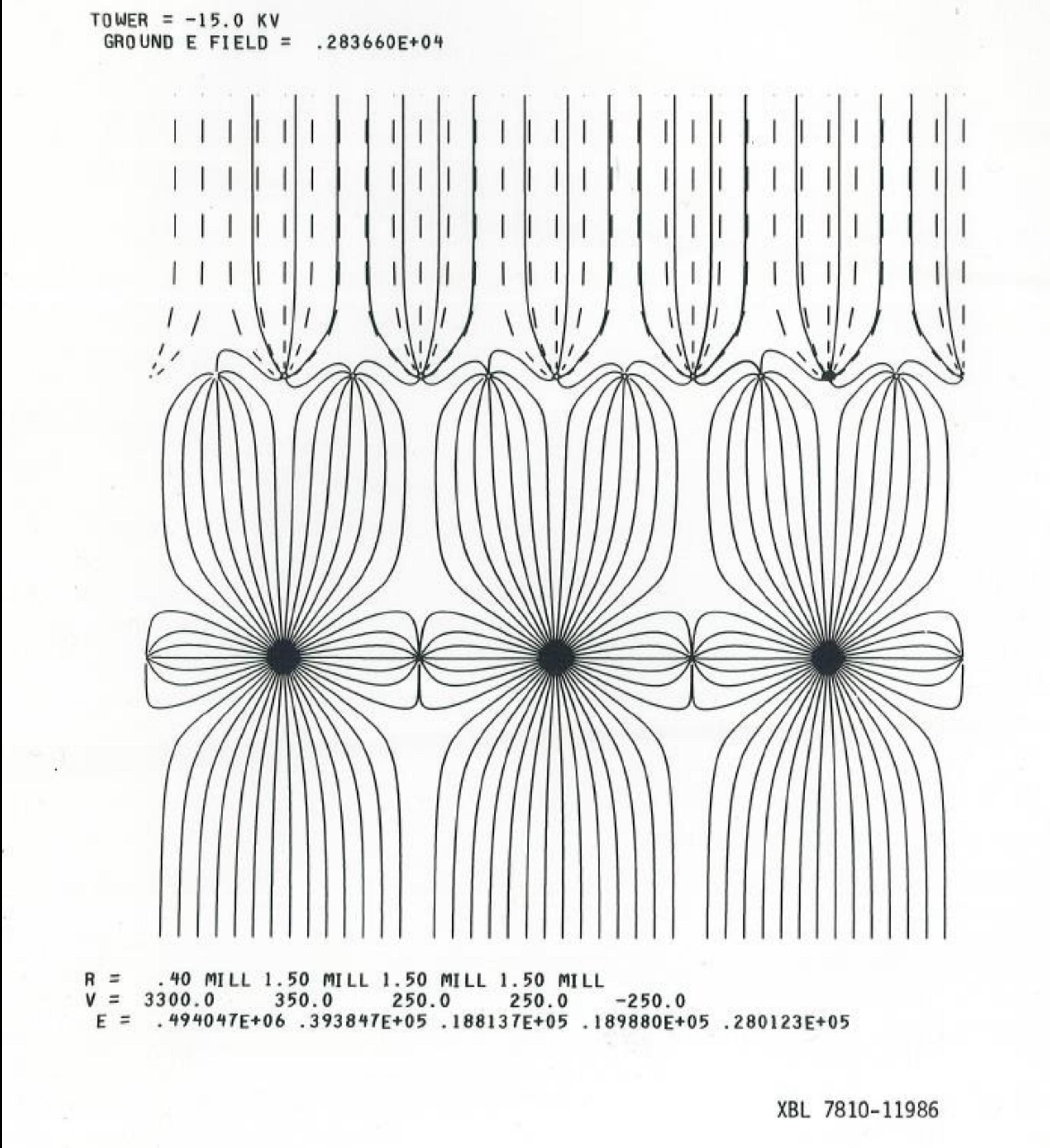
Proposal submitted – just in time!

- But a new problem appeared: positive ions!
  - Ions created in the avalanche flowed back
  - Ions move very slowly toward the cathode
  - Space charge distorts the electric field…
  - Resolutions and reconstruction degrade



Reality sets in

A **"positive ion gating grid"** was needed, not just a plane of wires.



Insight #6

The "Gating Grid"

The gating grid is pulsed, and applies ±ΔV on alternate wires, preventing positive ions from escaping back into the drift region.

Gestation: must evolve toward birth!

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- SLAC 1977: Proposal defense of PEP-4!
  - Sense of competition is extremely tense!

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We Won!!!

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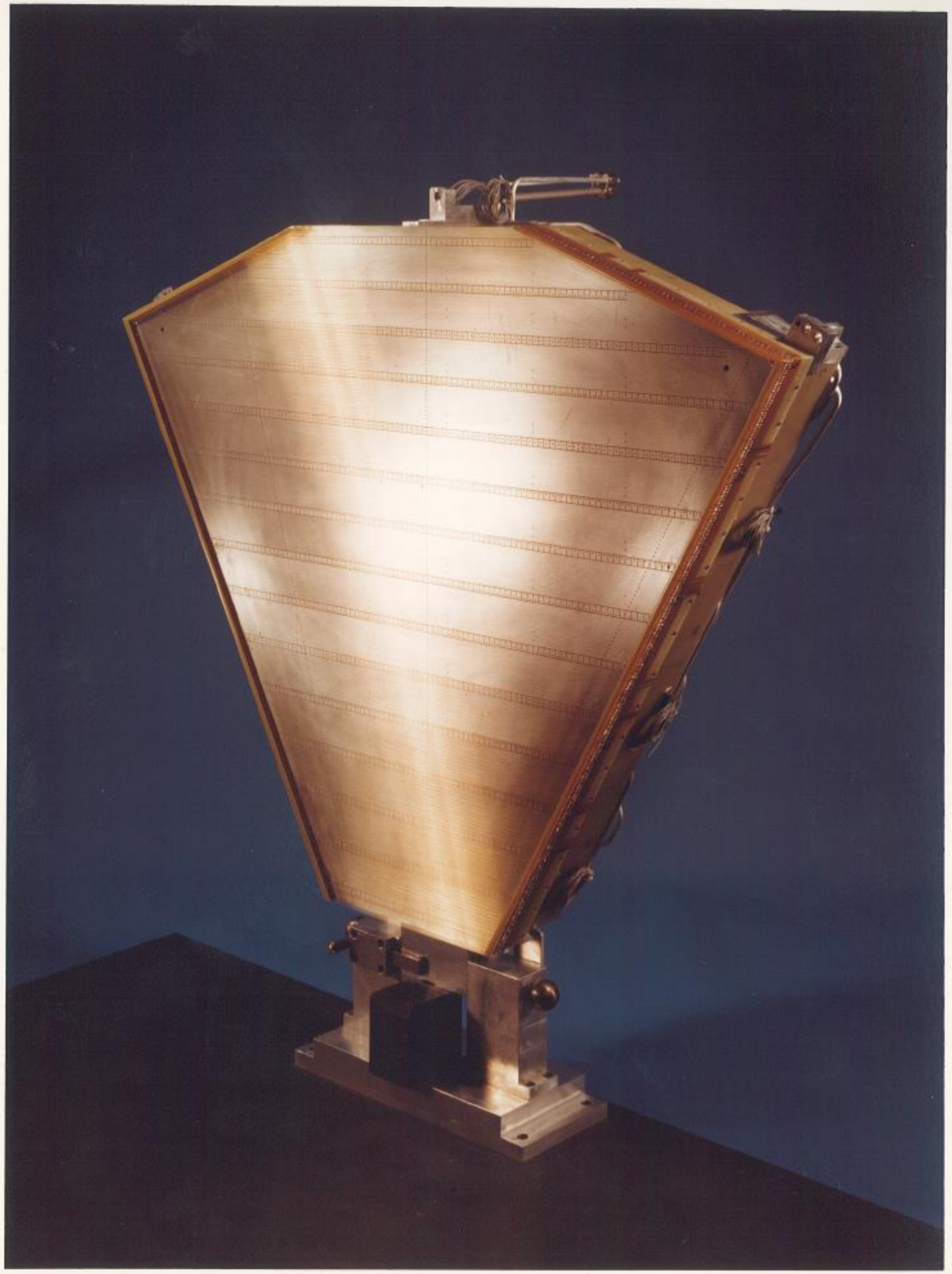
Delivery

- Usually uncomfortable, sometimes painful, but ultimately a moment of joy for the mother and a great sense of accomplishment for the father.
- In the case of PEP-4, delivery was a very wild ride, after which most participants could declare some success, and seek calmer pastures elsewhere.
- But it really was a success.



The TPC sector

192sense wires

~1000 pads

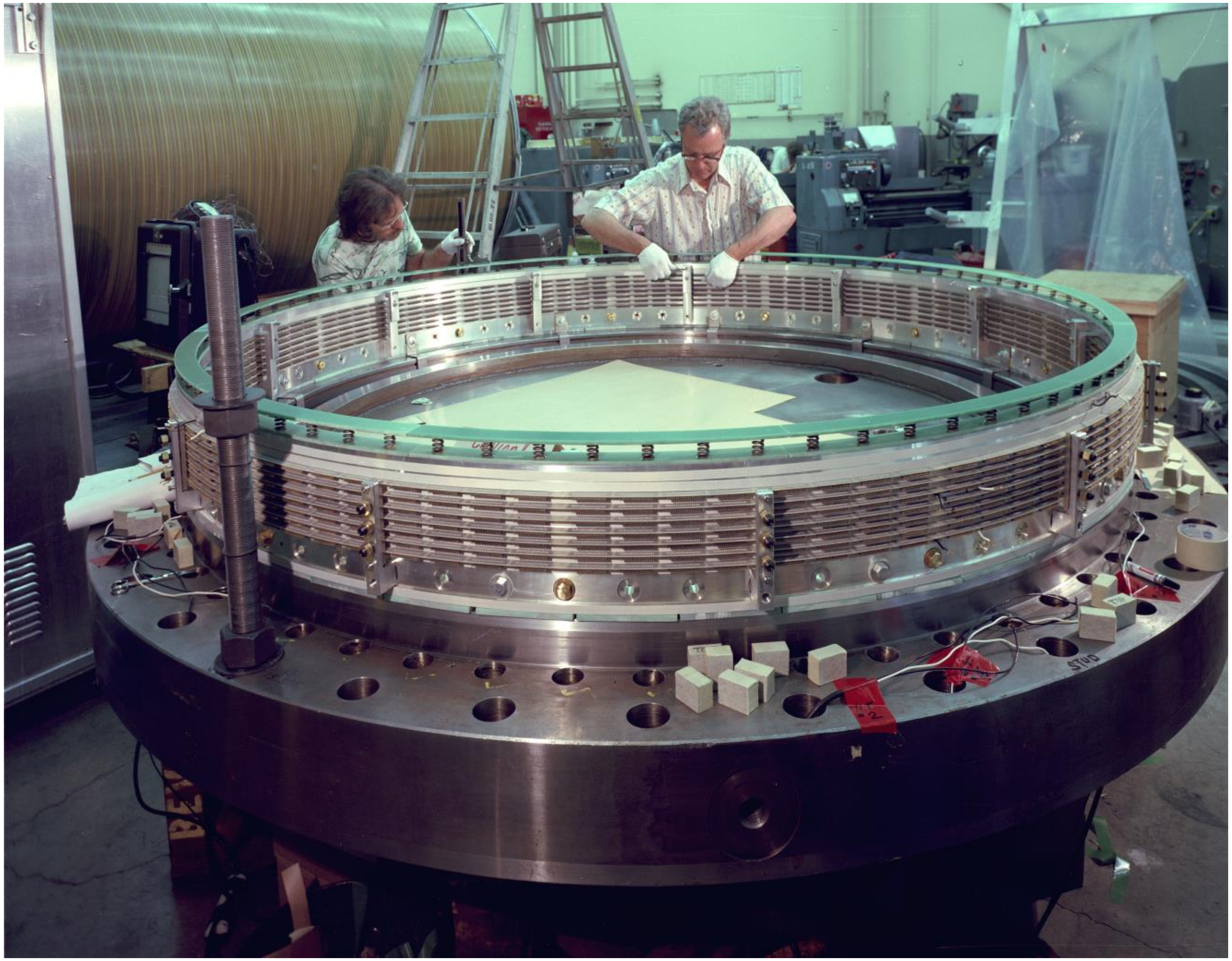
calibration source holes

cooling water circuit and

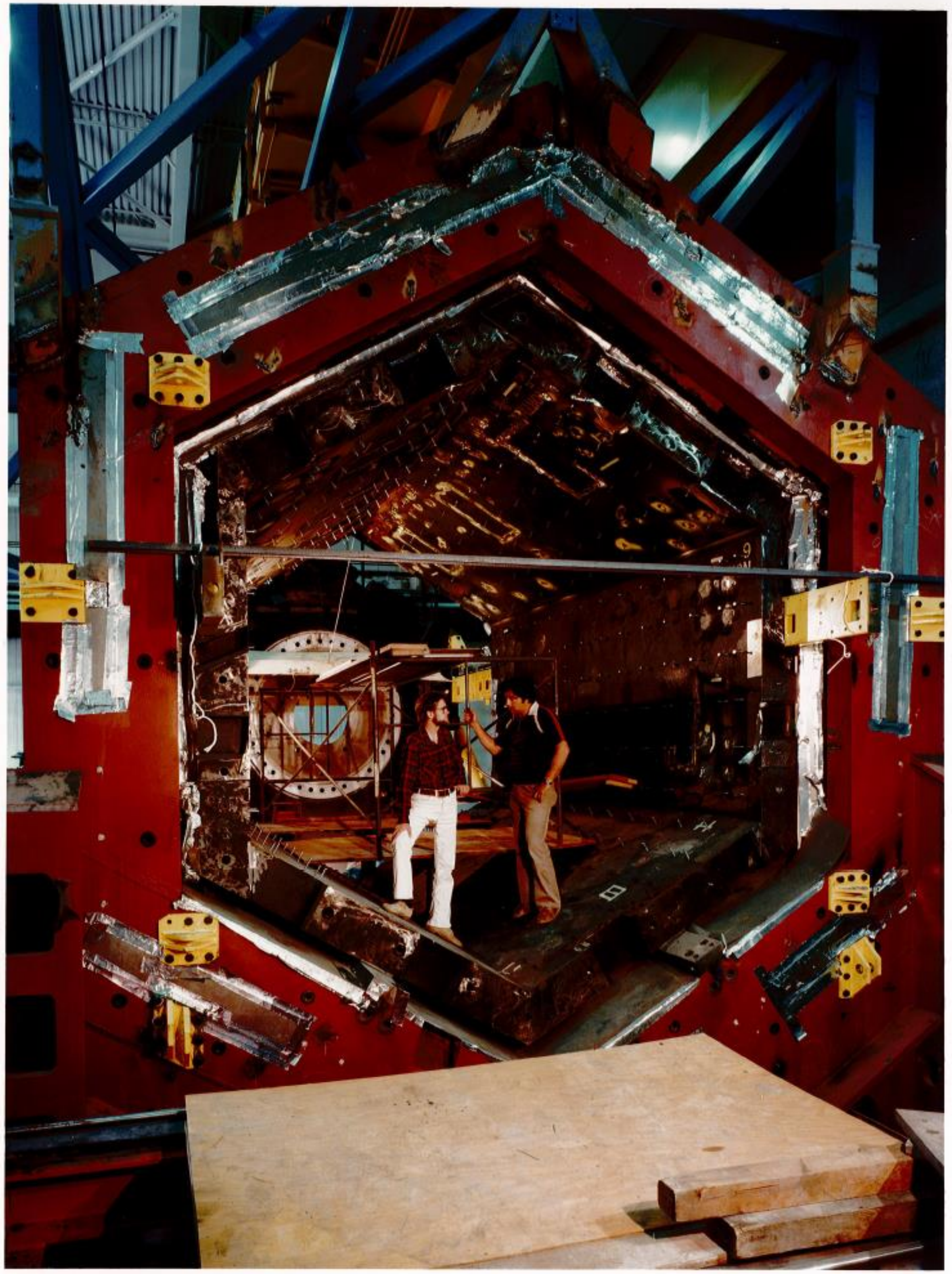
electronics on back side

Credit:
Ray Fusezy, Peter Robrish
et al.

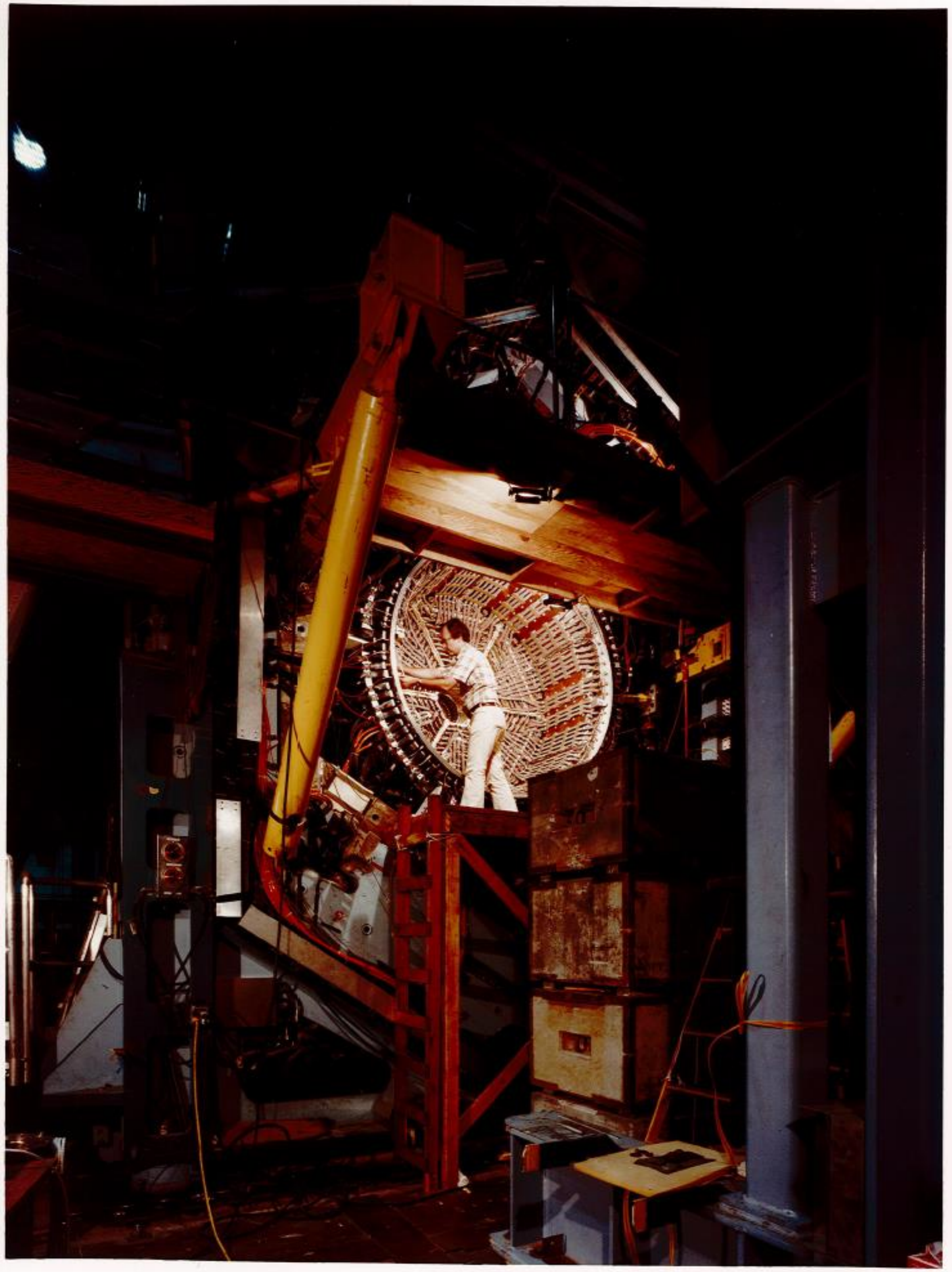
The Magnificent Feed-through Rings



The superconducting solenoid takes shape at LBNL shops



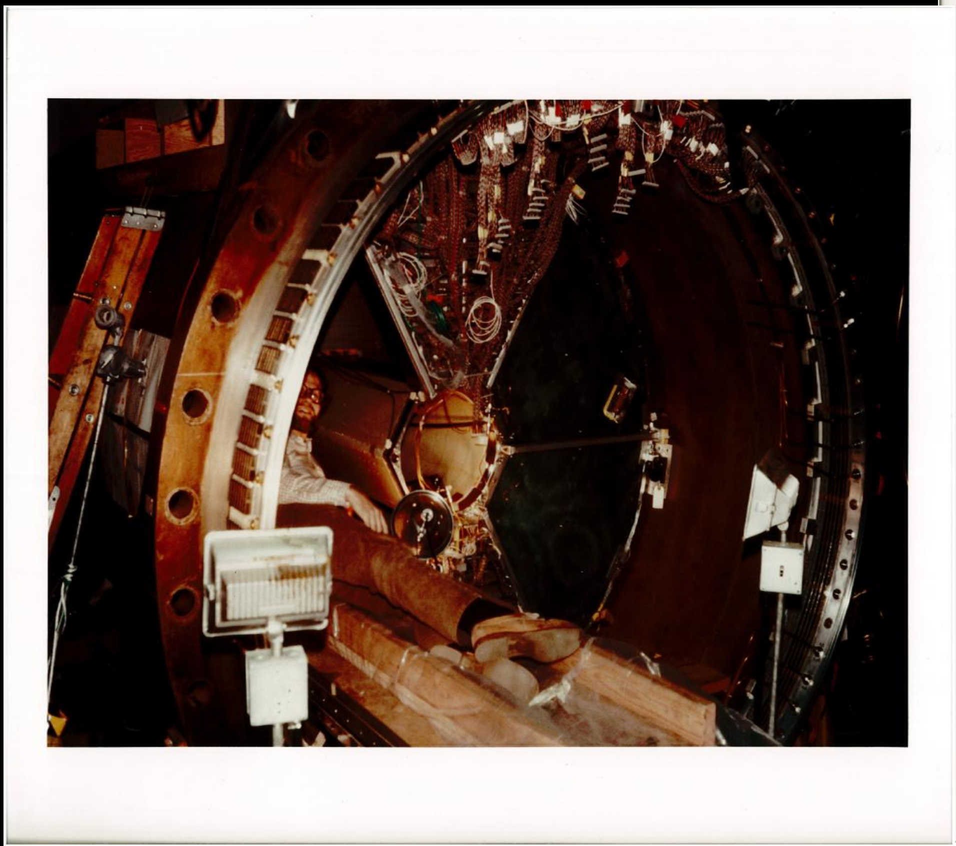
The TPC starts to take shape at SLAC

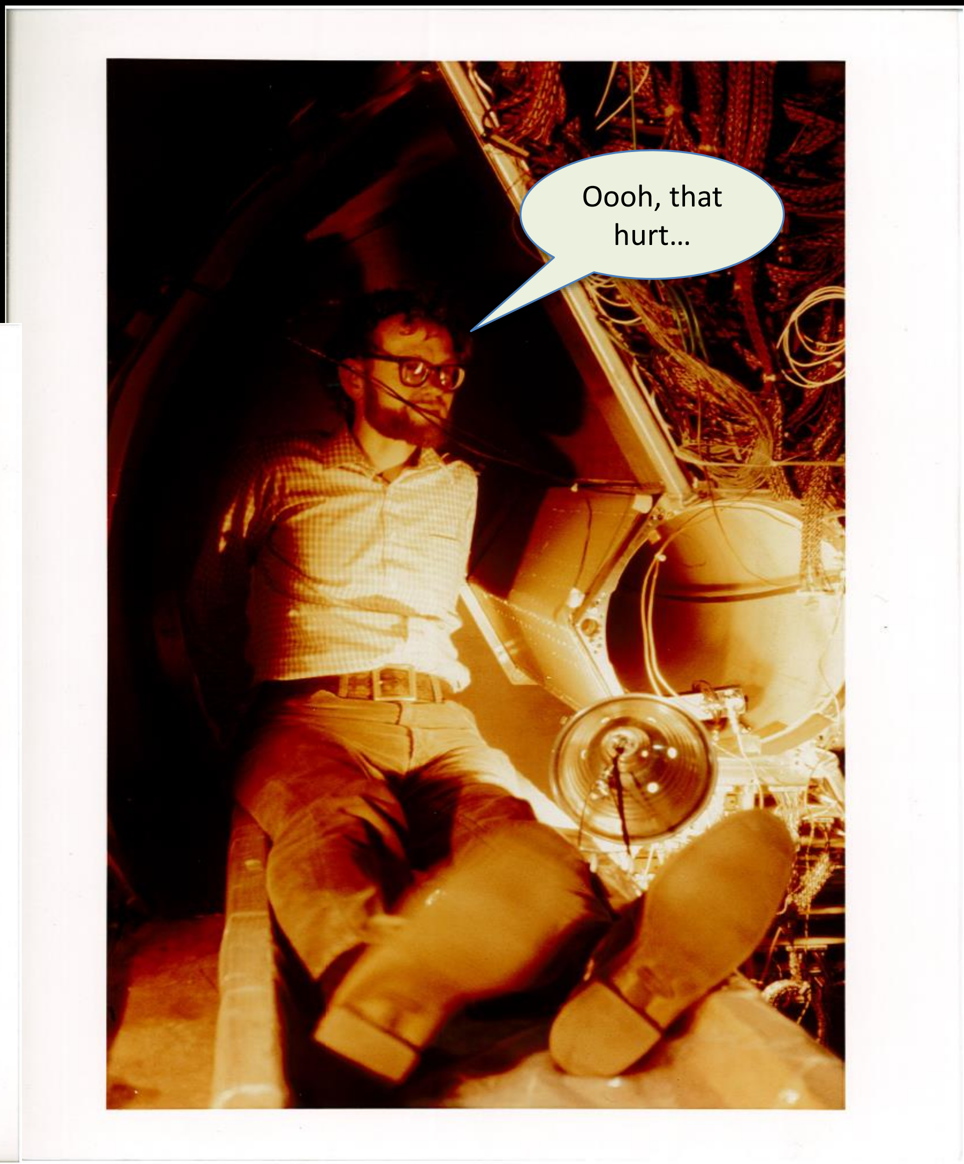


Stu Loken, late at night, wiring up one end of the TPC electronics

The TPC started to work, but tracks showed big distortions!

G-10 field cages had 1mm Cu/10 mm; this was insufficient to control E field. To fix the electric field distortions, we placed copper tape over the 1 mm traces of the field cages. It worked, but was a royal pain to install





Owen Chamberlain, inspecting repairs to the inner field cage

At yet another service interval, when the magnet was fixed, the tape was removed and replaced by a polyurethane coating with high conductivity, which established uniform equipotentials


The superconducting solenoid takes shape at LBNL shops
The magnet failed not once, but twice!

TPC: parallel E and B

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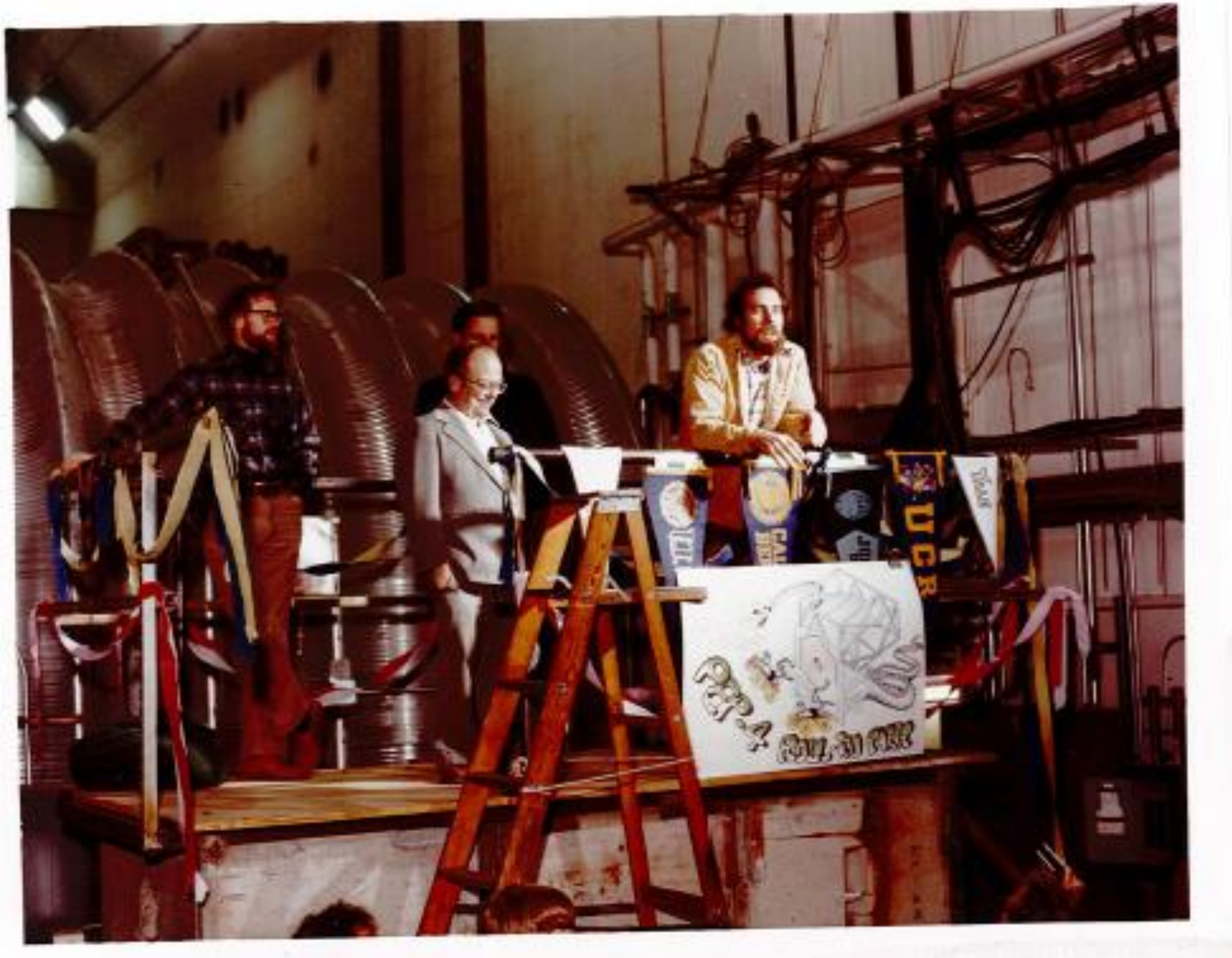
- Pief Panofsky, SLAC Director, called a special PAC meeting, to try to salvage his investment

TPC: parallel E and B

- The most important physical elements in the PEP-4 TPC are the **electric** and **magnetic** fields
- **We screwed up both of these.**
  - E-field distortions from weak boundary conditions
  - B-field distortions from failure of superconductor
- Pief Panofsky, SLAC Director, called a special PAC meeting, to try to salvage his investment
- Upshot: PEP-4 must continue!

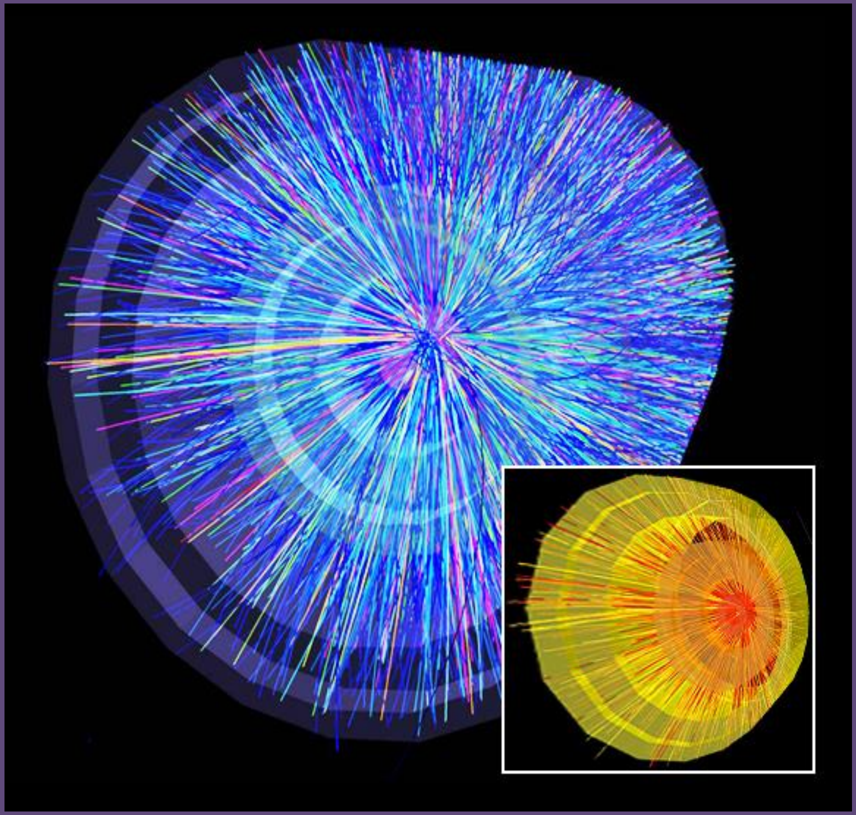

TPC
623N
Getting
ready for
roll-in….

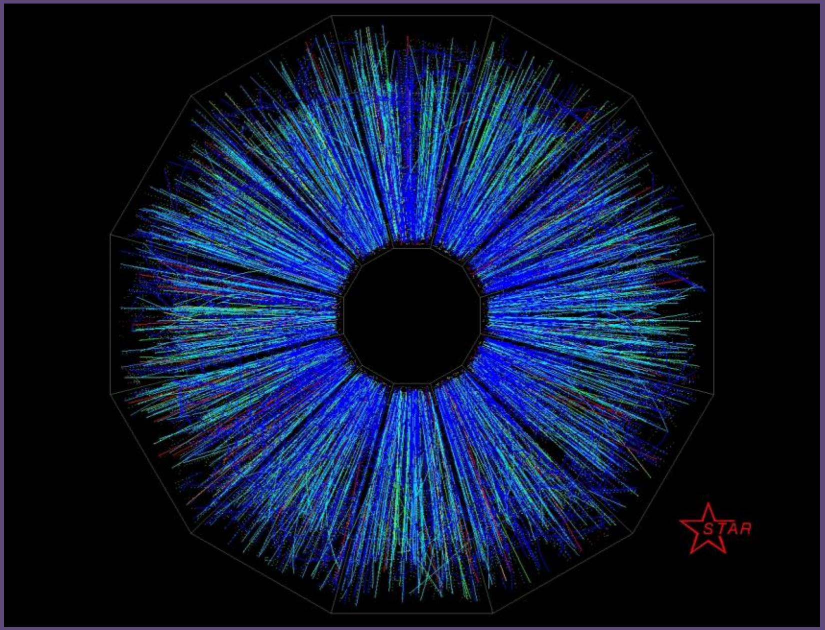


David Nygren, Pief Panofsky, David Shirley, Jay Marx

David Nygren, Pief Panofsky, David Shirley, Jay Marx

Large TPCs in action today





But eventually, delivery occured…

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  - dE/dx resolution unsurpassed to this day
  - σ_z = 1 ns rms along drift direction
- Not one graduate student abandoned ship

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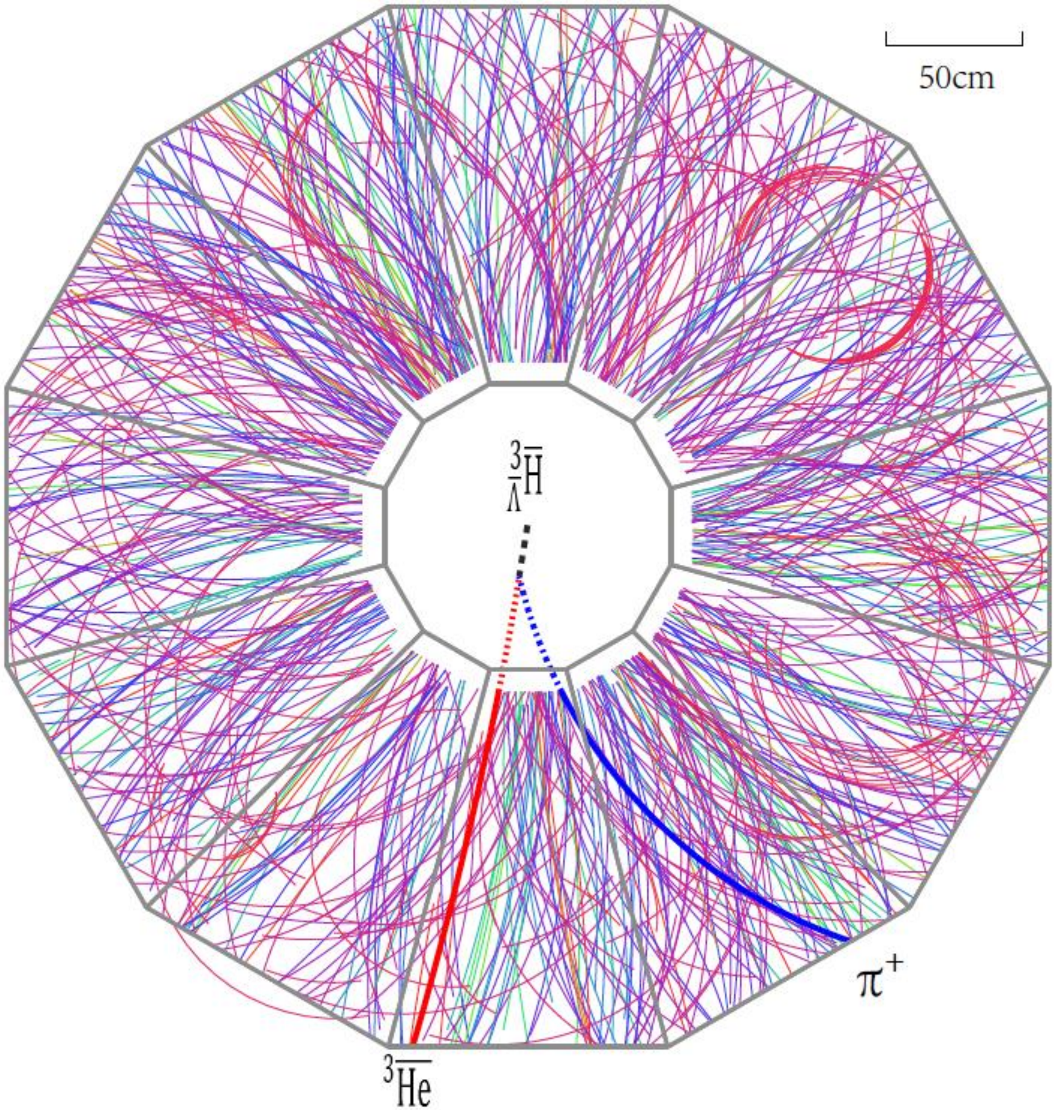
- I am grateful to all engineers, technicians, students, colleagues, SLAC and LBNL lab directors and DOE for not giving up.

Many Diverse TPC Applications

- $e^+ e^-$ collisions
  - PEP-4/9
  - TOPAZ
  - DELPHI
  - ALEPH
- P-bar-p collision (CDF, D0)
- pp collisions (FNAL)
- *ν* - *N* collisions
  - T2K
  - ICARUS
  - Spherical TPC
  - **DUNE,** gas and LAr
- n - (p or He) recoils
- accelerator commissioning

- Rare decays and events
  - $\mu \to e \gamma$ TRIUMF,…
  - $\beta \beta$ decay UCI, EXO, NEXT-
  - WIMP - *N* collisions
  - axion searches (CAST)
- Space & Astronomy
  - x-ray polarimetry, imaging
- γ-p (LEGS - BNL)
- μ-lifetime (μcap - PSI)
- *N* - *N* collisions
  - NA35, 36, 49
  - STAR
  - ALICE
  - SAMURAI
- … …

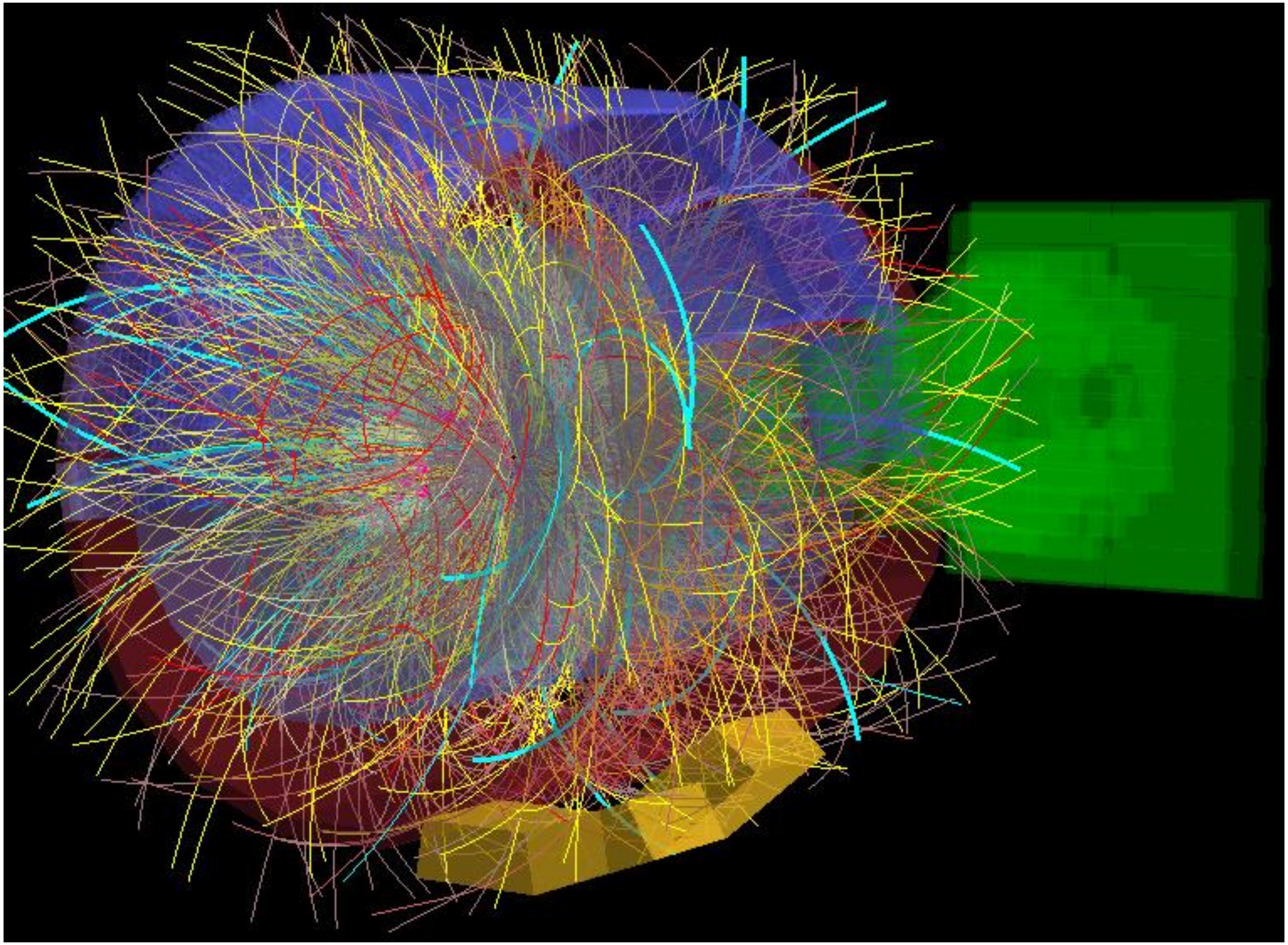


Credit: Hank Crawford

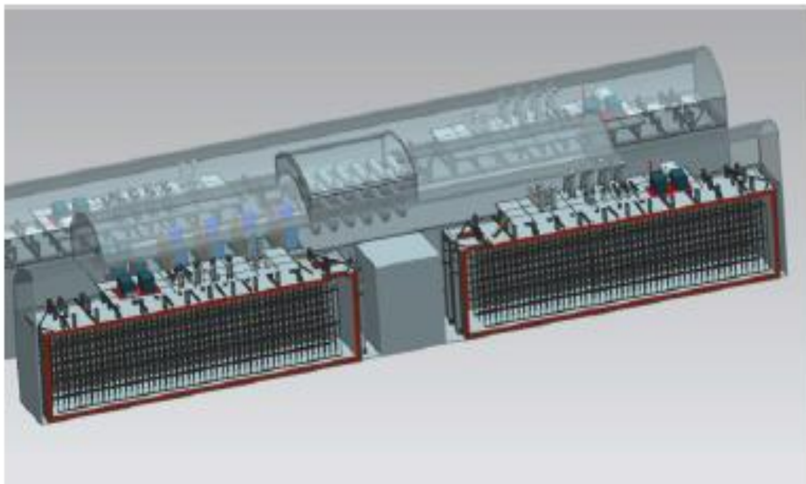
STAR TPC:

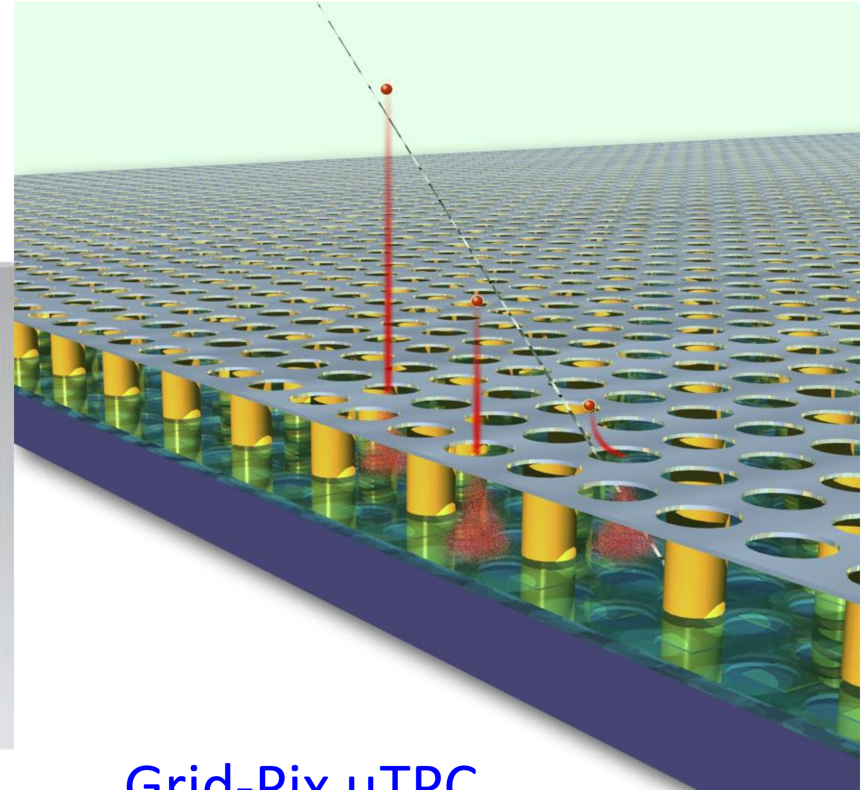
Production of anti-strange ^{3}H followed by decay to anti-^{3}He

ALICE event



Scale





DUNE Liquid Argon TPC
m_2 = 10 kton

Grid-Pix μTPC
$m_1 \sim 0.01$ g

m_2/m_1 ratio: $\sim 10^{12}$

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- Are there lessons buried here, somewhere?

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“Imagination is more important than knowledge.”

PEP-4: A lot of chutzpah is good, but tremendous and sustained support are needed too!

Thank you