R&D Opportunities in Linear Collider Tracking

Dan Peterson
Cornell University
LCCOM 19-April-2002

Baseline Detectors
Momentum resolution and implications
Jet track density and implications

Resolution and segmentation in various technology, R&D issues

- TPCs
- drift chambers / jet chambers
  - (baseline in Asia, not considered in N.A. or Europe)
- new technology gas amplification TPCs
- all silicon trackers

Simulation work

Physics Goals, Implications

clean Higgs signal from di-lepton recoil mass
end-point mass spectra in SUSY cascades

$d(1/P_t) \sim$ few 10^{-5} /GeV

jet energies in W+W- final states (energy flow analysis)

exceptional pattern recognition,
2-track separation

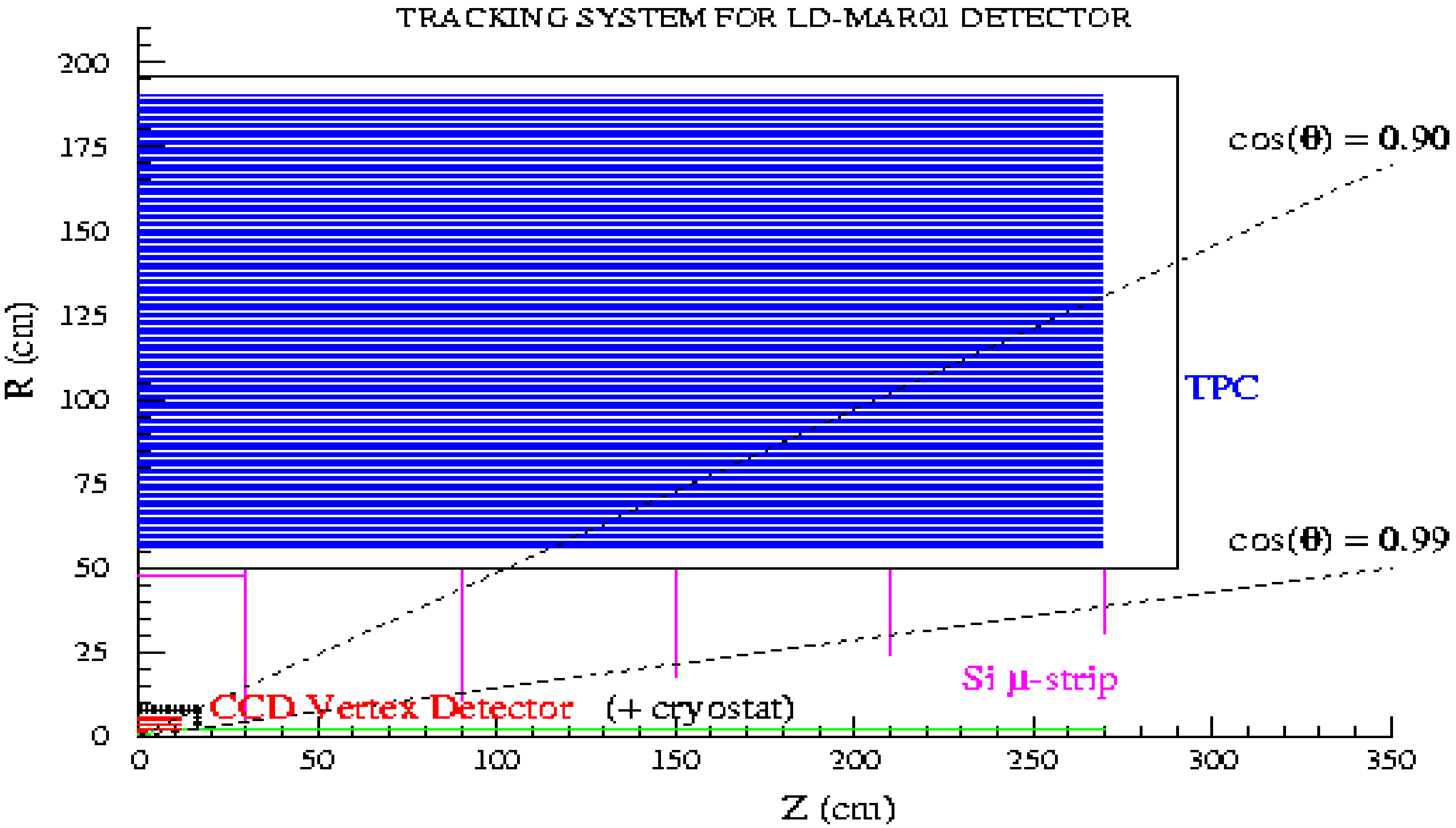
Primary and secondary vertex reconstruction

radially continuous tracking

The large detector baseline design, LD

Goal: optimized tracking precision
with large tracking volume

Magnetic field□□Tesla



North American LD baseline design
Stolen from K. Riles, Chicago Linear Collider Workshop, 7-Jan-2002

The □silicon detector□ baseline design, □ D

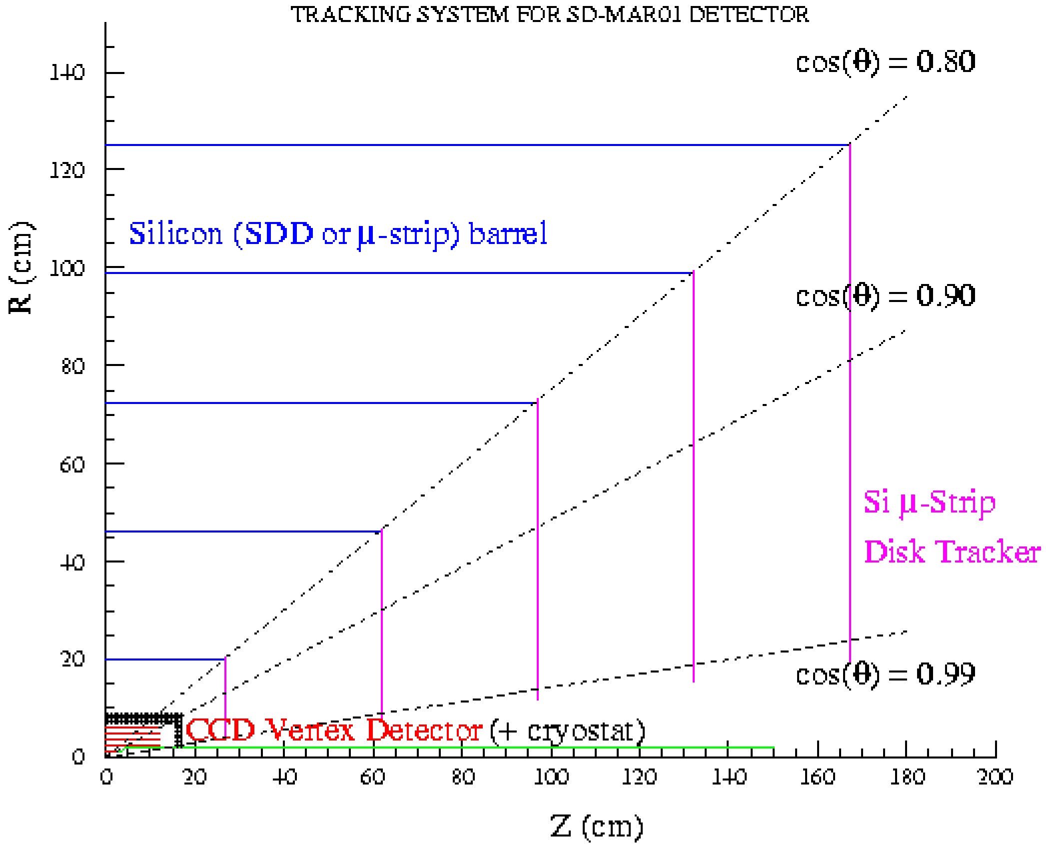
Energy flow calorimetry -□
Expensive calorimeter -□
Small calorimeter -□

Limit tracking system
Outer radius to 125 cm

Compensate for a
smaller measurement length

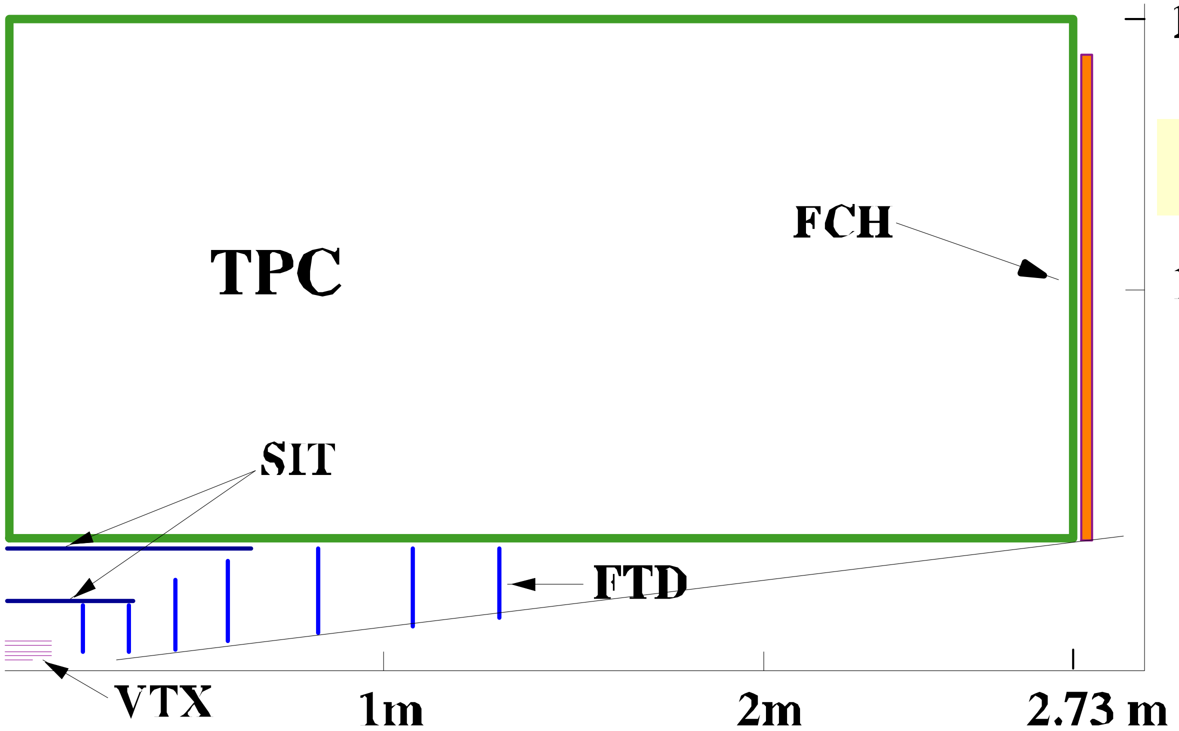
with
improved spatial resolution
(although fewer points)
and
higher magnetic field

Magnetic field □5 Tesla



North American SD baseline design
Stolen from K. Riles, Chicago Linear Collider Workshop, 7-Jan-2002

TESLA tracking system



Magnetic field□□Tesla

cos(θ)□995

Stolen from TESLA TDR

(differences, wrt North American LD)

1.□m radius (*vs* 2 m) , □Tesla field (*vs* □Tesla in N.American LD)

S□T is an intermediate tracking device, 2 layers

□CH is a straw tube device, □double layers, resolves TESLA bunch (□□0 ns)

Momentum Resolution □ Spatial Resolution

PHYSICS GOAL□

$\delta(1/p_t)$ □□x 10 $^{-5}$ / GeV

$\delta(1/R)$□$\sigma/L^2\ (□20/(N+□))^{.5}$

L is the measured track length

σ is the measurement error

Pinning the fit at the IP improves resolution by ~ 2/□

R□P_t / (.□GeV/Tesla B)

use measurement length□

L □ 2 meters (LD)

use N □100

$\delta(1/P_t)$□$\dfrac{\sigma/L^2\ (□20/(N+□))^{.5}}{(.□\text{GeV/Tesla B})}$

σ/B □20 micron/Tesla,

or

σ □100 micron resolution, with B □5 Tesla

Momentum Resolution

$\delta(1/p_t)$□goal is difficult with
tracking chamber
and vertex detector alone.

Try an intermediate silicon device,

R□.□5 meter, $\sigma_{r\phi}$ □10μm, N□2

(relaxed) PHYSICS GOAL□

$\delta(1/p_t)$□□x 10^{-5} / GeV

(relaxed) magnetic field□
□Tesla

Tracker□2m OR , 0.5m □R
Vertex detector□5 layer, 10 μm

tracker 100 μm ----à $\delta(1/p)$□5.0 x 10^{-5} /GeV
with VD only, no int. tracker (consistent with previous slide)

tracker 100 μm ----à $\delta(1/p)$□ □.5 x 10^{-5} /GeV
with VD and int. tracker

tracker 150 μm ----à $\delta(1/p)$□ □.2 x 10^{-5} /GeV
with VD and int. tracker

tracker 150 μm ----à $\delta(1/p)$□ □.0 x 10^{-5} /GeV
with VD and int. tracker (misaligned by 25 μm, 1 mil)

□Results from
Dan's fast MC

Spatial Resolution

Spatial resolution requirement is aggressive, 100 µm in 5 Tesla field.

(This result is for a **large chamber** (r□2 m) in combination with a **perfect vertex detector** which constrains the fit at the vertex.)

Momentum resolution goal can be met with 150 µm in □Tesla field.

(This result is for LD, a **large chamber** (r□2 m) with a **vertex detector** and **intermediate detector** , both σ □10 µm.)
However, the resolution is sensitive to misalignments .

Large TPCs do not meet either spatial resolution goal. For example,

Aleph□σ □1□0 µm, STAR □σ □500 µm .

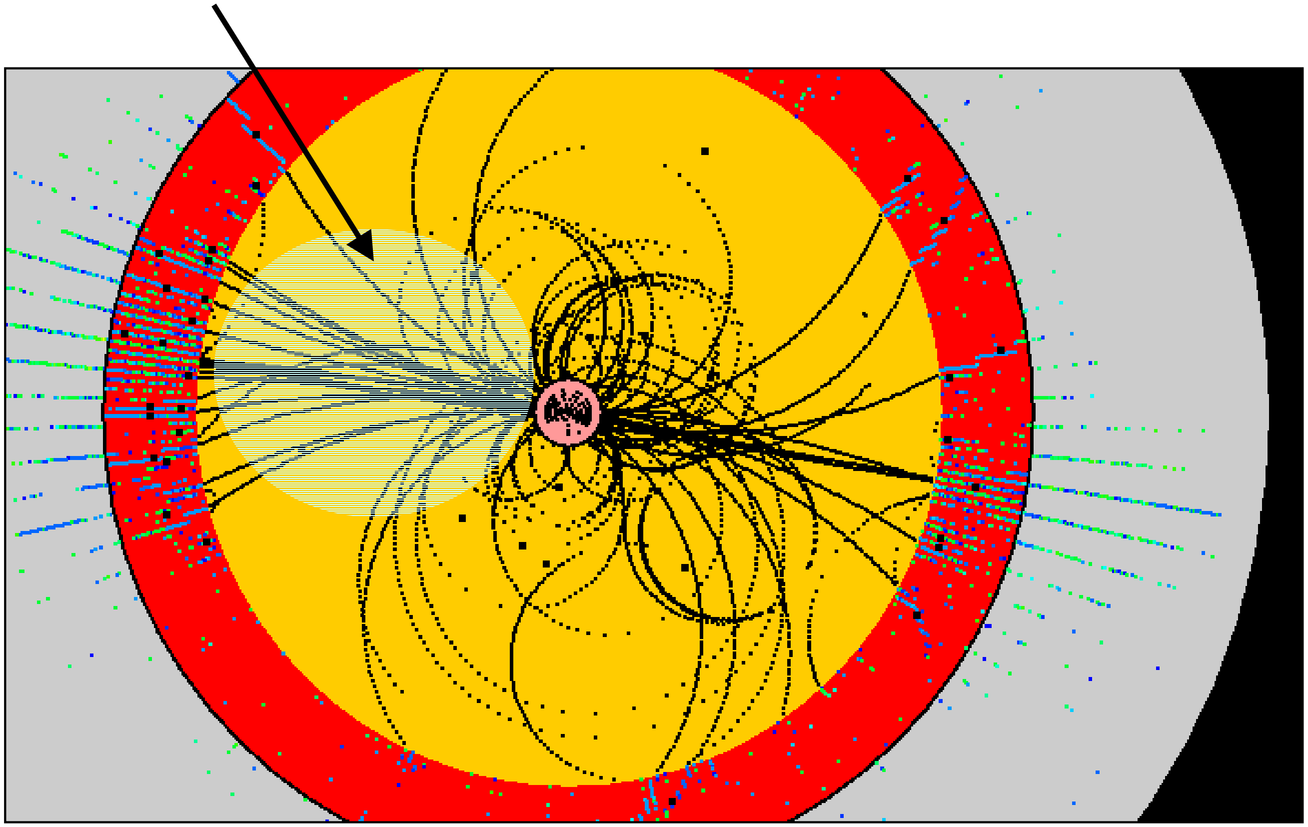
This resolution is partially related to the pad spacing, which comes with the induction readout.
Aleph resolution is □□ of the pad spacing (□.2 mm).
STAR resolution is □1□□ of the pad spacing (□.2 or 2.9 mm).

Drift chambers can provide 100 µm spatial resolution.
Let's see what else is a problem □.

Track Density

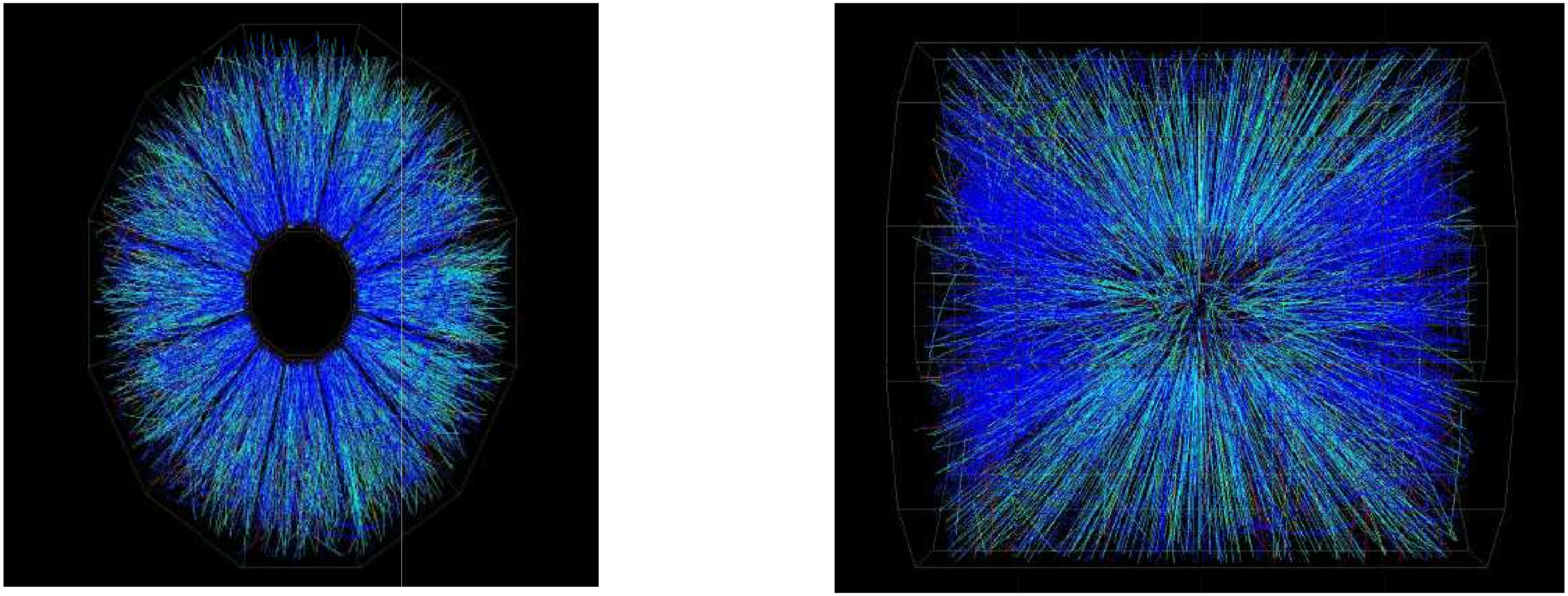
This □typical□jet has 19 tracks projected onto an azimuthal angle of □0^{o}.
This is a track density of □□tracks/ster (for conical jets) .

□will use □□□tracks/ster as pattern recognition goal.



JAS 2D LCD Event Display
Stolen from N. Graf, Chicago Linear Collider Workshop, 7- Jan-2002

Compare with the STAR TPC



Is 100 tracks/ster large□ Yes, that would be 1250 tracks in the event.
STAR observes 1000 to 2000 tracks per event.
Is this demonstration that a TPC can operate with this track density□

No, perfect efficiency is not a goal at STAR□look at those panel cracks□

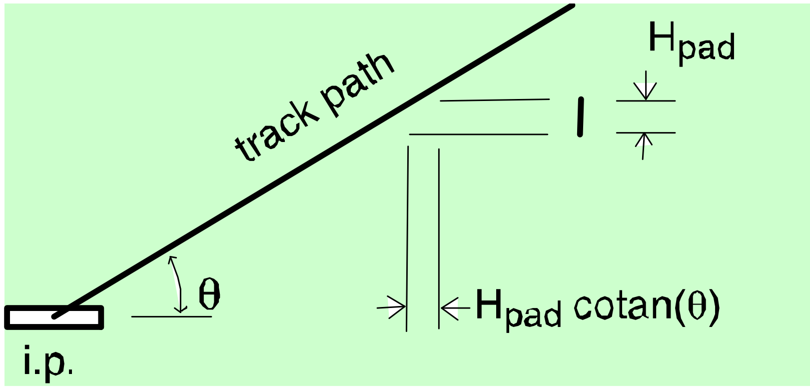
Spatial resolution requirement is relaxed□ σ □500 μm.
Must do better□

multi-track event in STAR TPC at RHIC
Stolen from J. Thomas, Vienna Conference on Instrumentation , 22-Feb-2001

TPC Segmentation and Occupancy

(induction read-out)

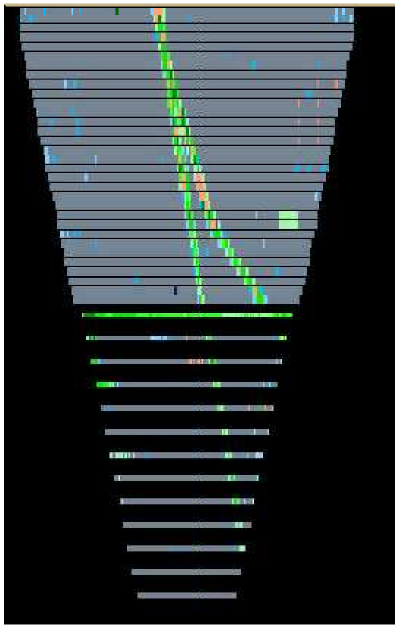
□**segmentation** is limited by the signal time width, but usually by the □travel of the track.
□segmentation is typically equal to height of the pad, 10mm □20 mm □

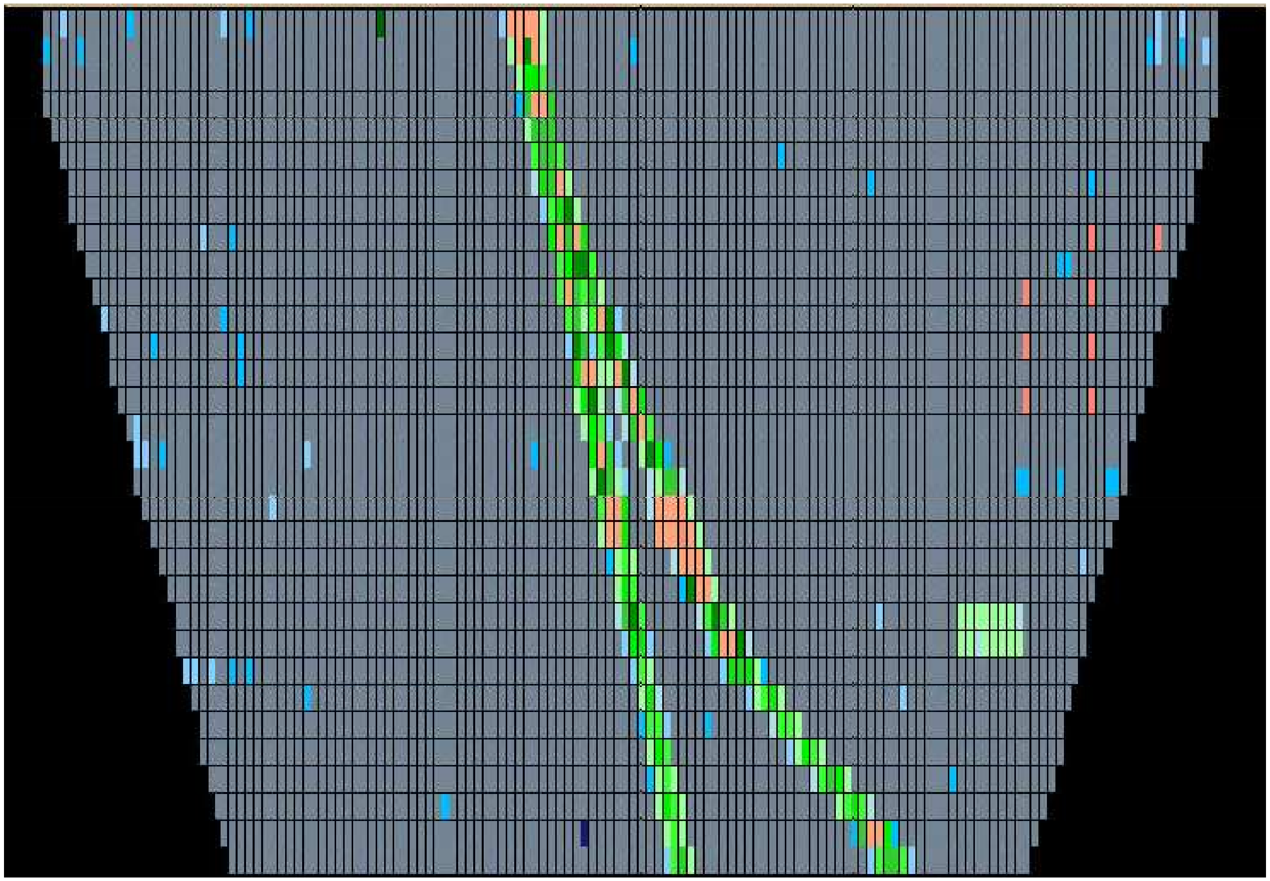


r□φ segmentation is limited by the induction read-out.
(Gas amplification is due to an avalanche on a wire.
Induction signals on pads are read out.)
STAR signal width, 2-track separation□ 25 mm.

Occupancy at r□50 cm,
with r-φ segm.□2.5 cm, □segm. □1 cm, segmentation is 1/1000 ster□
occupancy (in jet) is 10□ , there will be overlapping tracks

Track Overlap in a TPC





Overlapping tracks are complicated in a TPC.

Pulse height signals on pads can not be resolved beyond the intrinsic segmentation of the device.

Merged signals have ambiguous position measurement□□□σ.

Two tracks in STAR TPC
Stolen from J. Thomas, Vienna Conference on Instrumentation , 22-Feb-2001

LCD projects, TPC (induction) tracker

The (induction) TPC is the baseline, or backup, for advanced readout methods (described later).

Spatial resolution optimization, goal of 150 µm in a large induction TPC.

Ion feedback suppression: gating grids (long gate time at TESLA)

Gas studies: aging, velocity (clearing time), quenching, neutron absorption

Alignment:

internal alignment and drift path in an inhomogeneous B field

extrapolation to an intermediate tracker: hardware & tracking.
(with poorer resolution, system is more dependent on intermediate tracker)

(simulation)
Optimize pattern recognition in an environment of significant track overlap.

Drift Chambers

Drift chambers are largely not considered by North America and Europe groups.

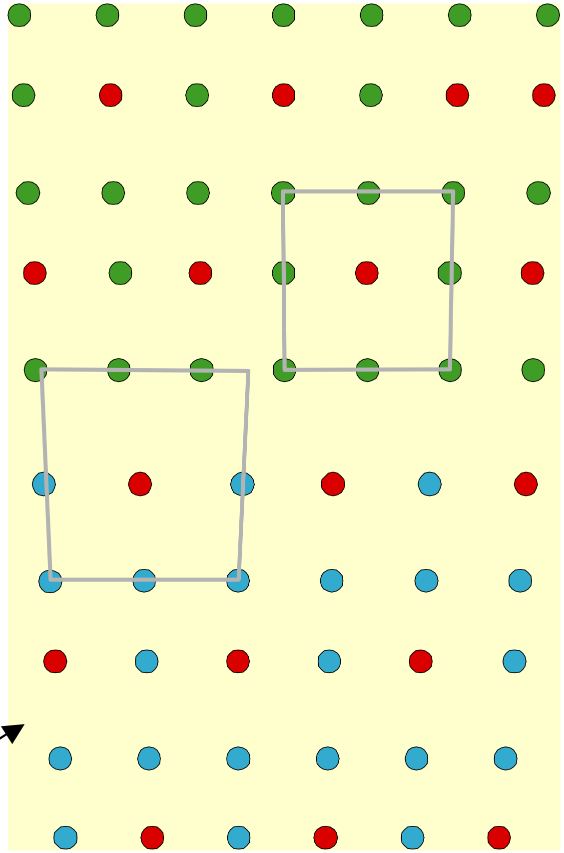
Disadvantages□

□poor segmentation□(discussion follows)
wire sag and electro-mechanical instability
wire tension load on endplate, endplate thickness
Lorentz angle in a high magnetic field
current limitation

Drift Chamber (Jet) is the baseline design in Asia.

Advantages□

spatial resolution□□□μm for □0□ of hits (CLEO)
2-track separation better than segmentation
(will discuss for 1□mm square cell design)



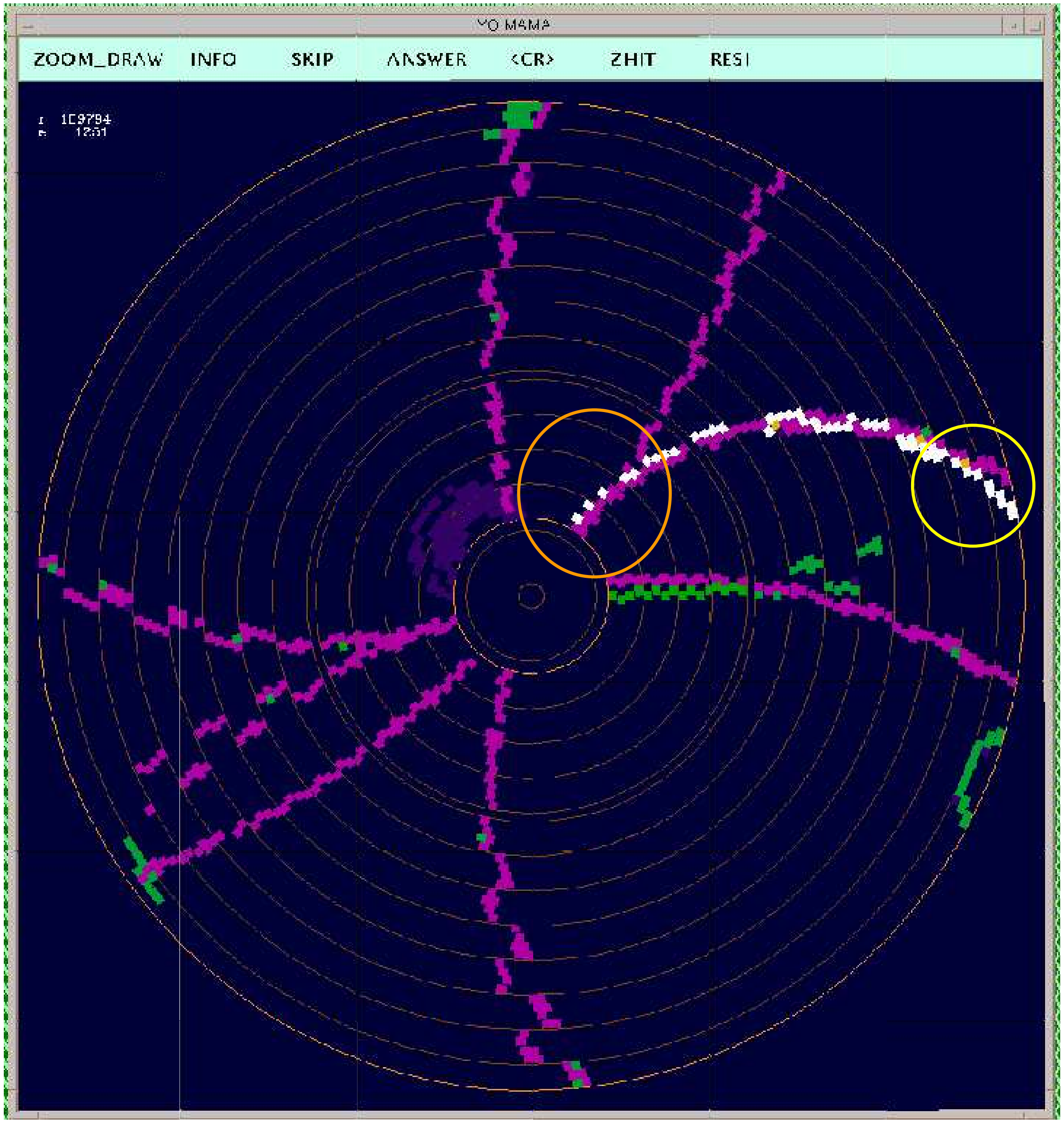
Track Overlap in a square cell drift chamber

In drift chambers,
there is no □segmentation.

jet track density□19 tracks/□0°
□□tracks/radian
0.□tracks/cm at R□50 cm

Within the orange circle□
□tracks within 2 cell widths
(note separation□yellow circle).
Observed density□
1.1 tracks/cm
55 tracks/radian at R□50 cm

Tracks are resolved up **to** this density if sufficient separation exists elsewhere on the track.



CLEO MC event

Track Overlap in a square cell drift chamber, resolved

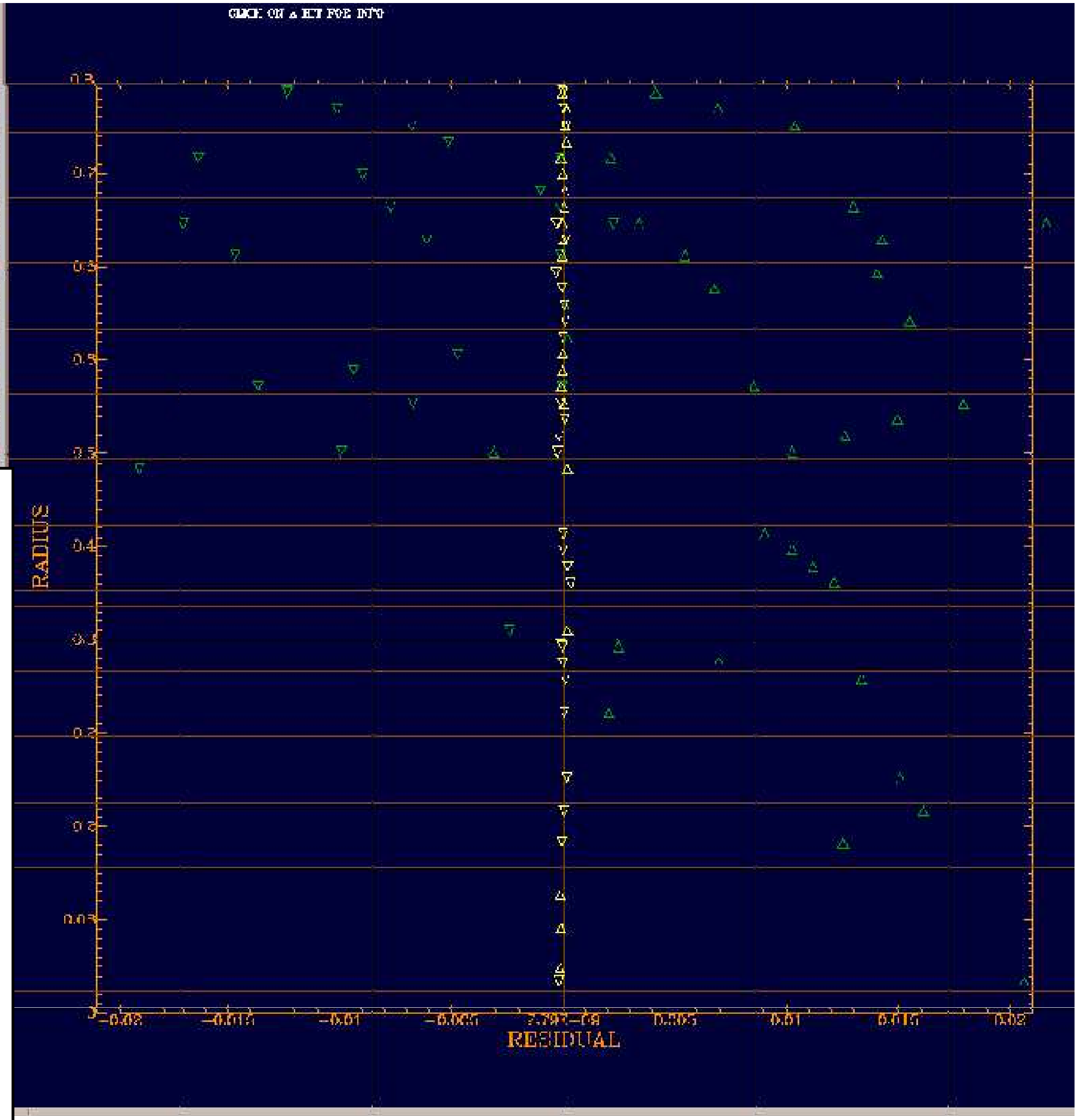
Multi-tracks can be resolved beyond the
device intrinsic segmentation
because
the time measurement is valid for one of the tracks.

(some of the hits, all the time)

Method involves extrapolating in from isolated hit region.

Track separation is better than intrinsic segmentation.

Applies to Jet Chamber.



Display of hit residuals (horizontal) of hits on a track (in white on prev. slide) .

Jet Chambers

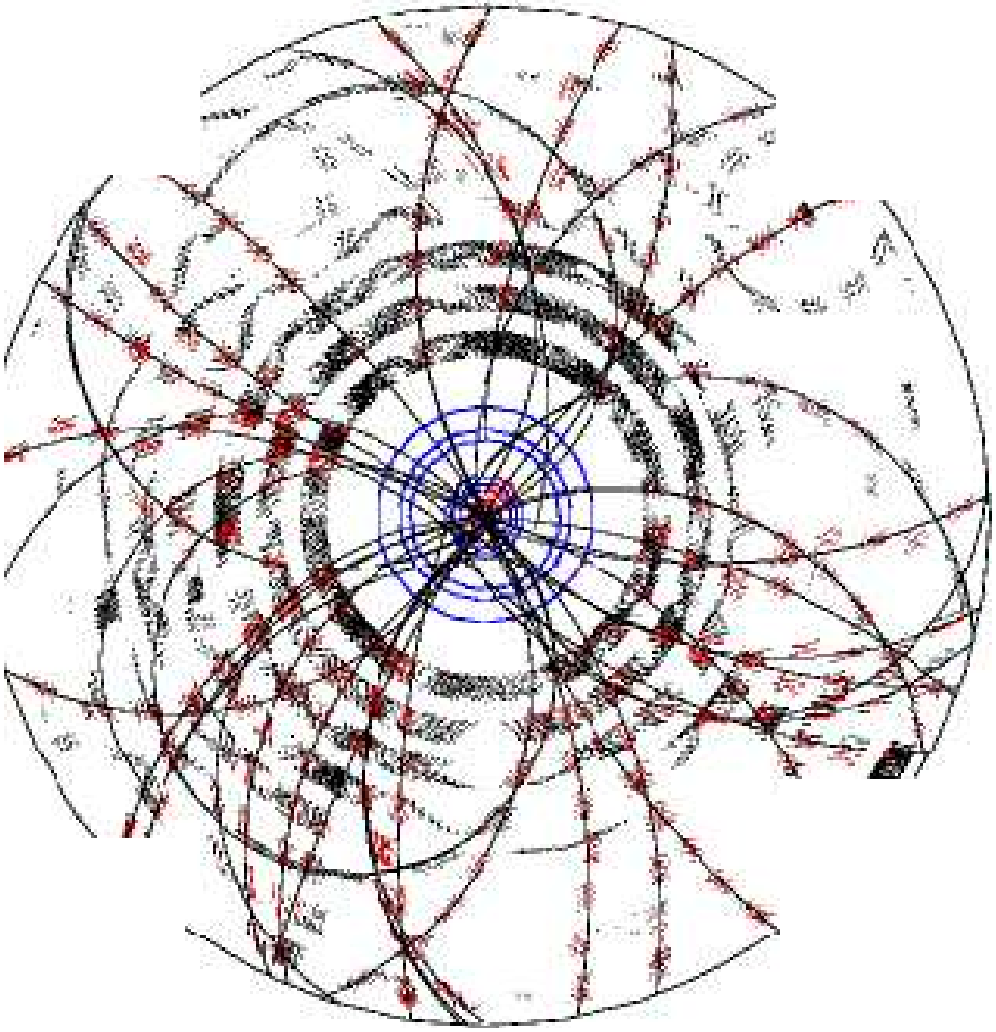
Jet chamber□□mm segmentation
(a 2 mm track separation,
measured in a single layer,
is doubled by the ambiguity)

(while the square cell example
had 1□mm segmentation)

Track separation is better
than the □mm segmentation
as shown for the
case of square cell chamber.

Disadvantage□
discontinuous tracking due to
complicated field cage shaping

Expect a track density **limit** of
1 track/□mm at R□50 cm
125 tracks/radian



CD□event

CDF Jet Chamber event
Stolen from Y-K Kim, 2001 Lepton Photon Symposium , 23-July-2001

□□D, Jet Chamber, ongoing/planned (□E□)

I will discuss these □□D results

- Wire sag and electro-mechanical instability
- 2-track separation
- Lorentz angle (and drift velocity)
- Spatial resolution

Understood at □L□□□

- Stable operation of stereo cells
- Aluminum wire creep

I will not discuss results/plans in

- Gas gain saturation (affects dE/dx, 2-track separation)
- Neutron backgrounds
- Optimization of gas mixture

What should be studied

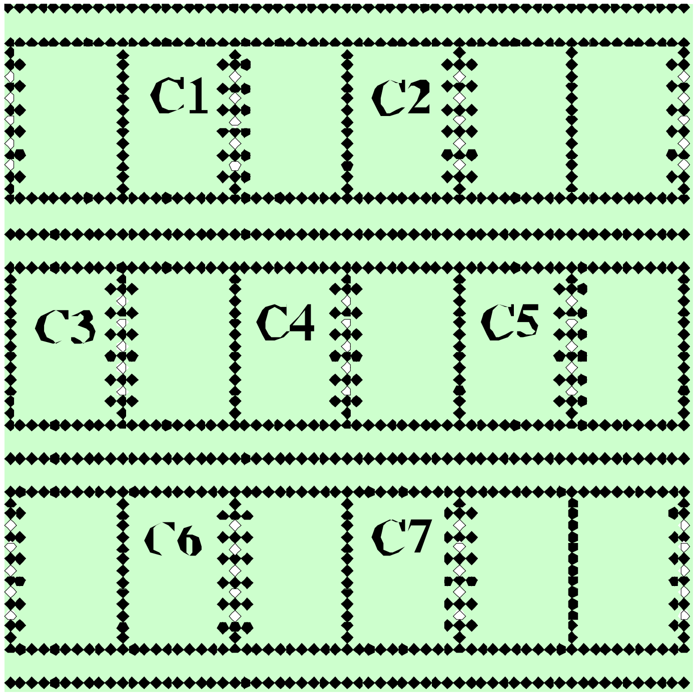
- Careful study to reconstruction vs track density with full MC.

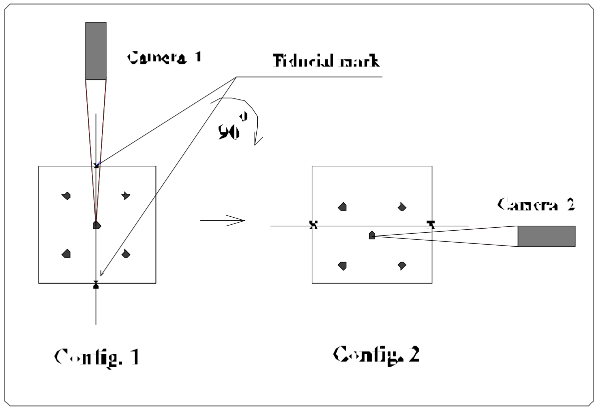
Jet Chamber:
Wire sag,
electro-mechanical instability

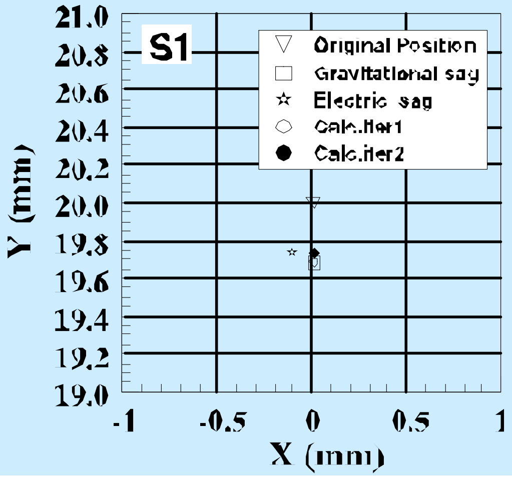
5 sense wires/cell, □cm height
5 cm drift
Note: triple field wire will reduce instability

Wire positions measured with CCD cameras.

Sense wire sag: ~ □00 µm , field □00 µm
Motion with voltage on minimal,
no instability observed

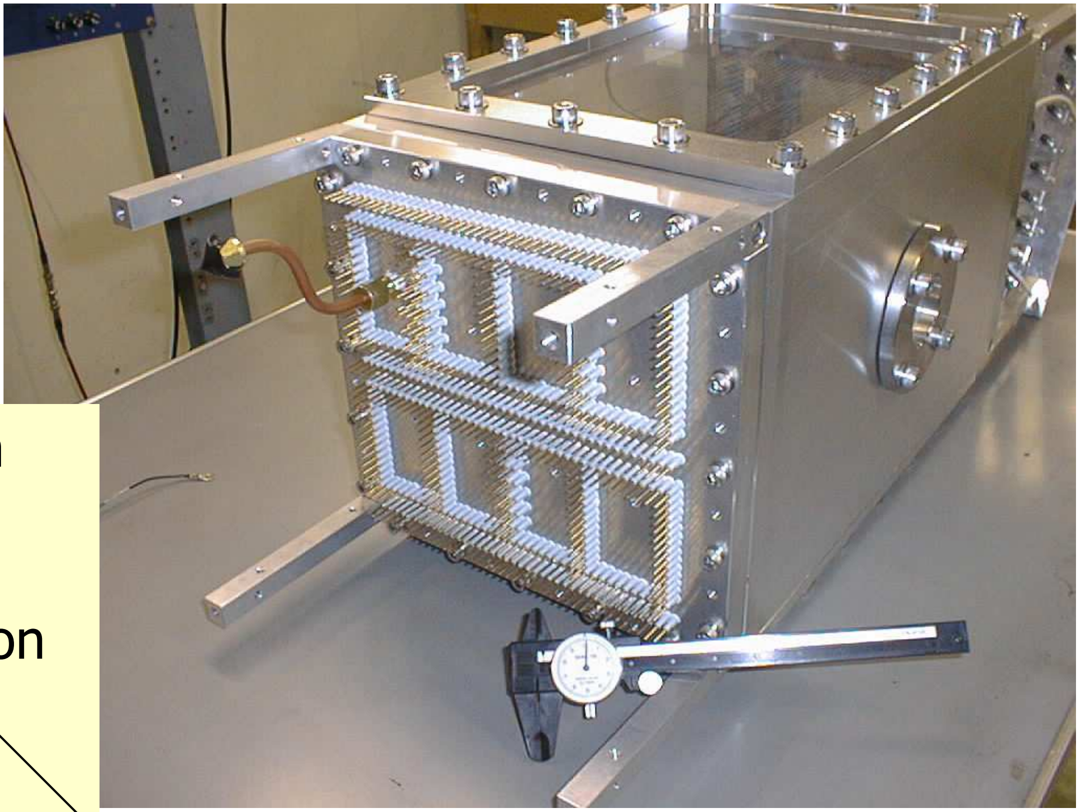






Stolen from JLC website, N. Khalatyan, Tsingua

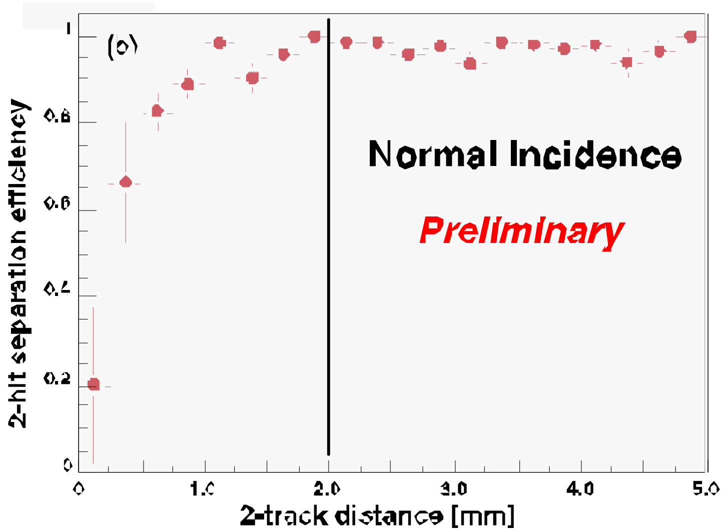
Jet Chamber
2-track separation

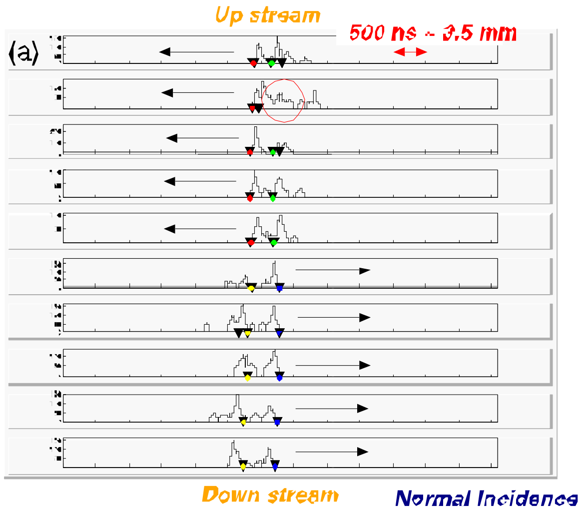


Small jet cell chamber in test beam
e^+e^- pairs from conversions

FADC signals analyzed for separation

Observe 2 mm separation





Stolen from JLC website, K. Fujii, FermiLab 2000

Jet Chamber: Lorentz Angle, Spatial Resolution

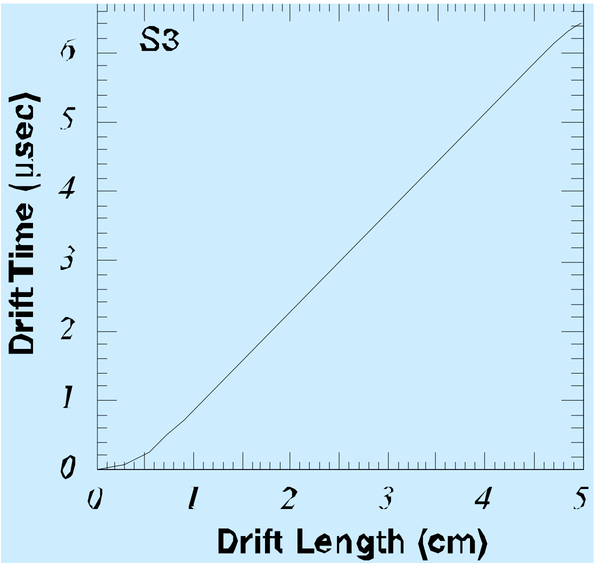
CO_2 – Isobutane (90:[illegible]0)

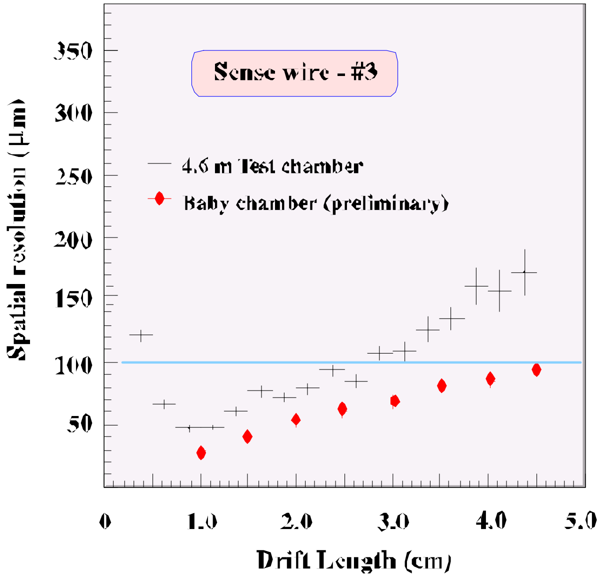
velocity [illegible].[illegible]µm/ns, (faster near wire)

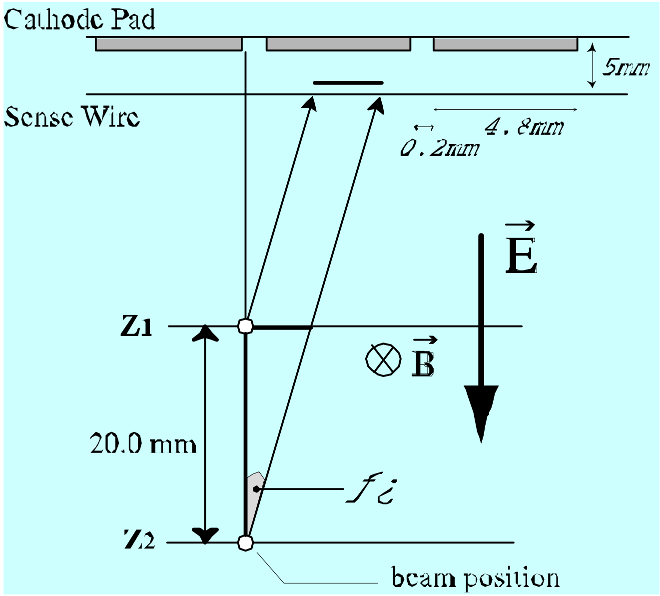
live time [illegible]µs

Lorentz angle [illegible]10° at 2 Tesla, 19° at [illegible] Tesla

Resolution 100 – 150 µm

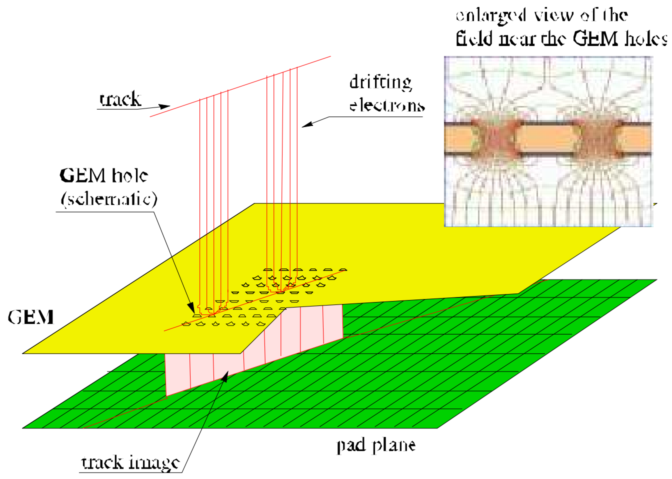


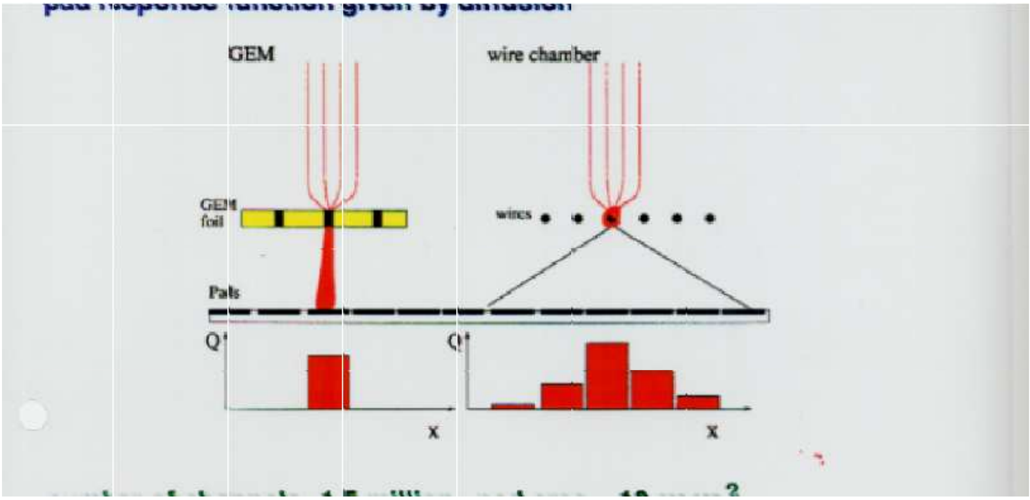




Stolen from JLC website, N. Khalatyan, Tsingua

TP□ □ith G□□ or □icro□ □G□□ read□o□t





Advantages□electron collection, 100 µm spacing

Signal width is significantly reduced, improved segmentation

E x B effect (in radial part of electric field)
which limits resolution in an induction readout
is reduced with signal width

Problems□

New technology

Signal width may be <u>too</u> small.

Must extract optimum resolution with finite □of channels.

Gem TPC read-out
Stolen from TESLA TDR

Signal size in GEM and induction read-out
Stolen from M. Ronan, Vienna Conf. on Instrumentation , 22-Feb-2001

LCD, TPC, GEM/MicroMEGAS read-out

Pad size: narrow electron cloud ~ 1mm

requires 1mm pads to provide charge sharing, O(10^6) pads

wider pads (5mm) will have poor resolution: w/$(12)^{1/2}$

Pad shape: methods of spreading signal to limit channel count and improve resolution

chevrons, ganging, induction.

Beware, efforts to spread signal may compromise 2-track separation.

Aging: GEMs can fail at high gain, relatively new technology, dependence on gas choice

Gas: diffusion, velocity

Active R&D

Achen, Carleton/Montreal, DESY/Hamburg, Karlsruhe, Krakow,
LBNL, MPI-Munich, MPI, NIKHEF,
Novosibirsk, Orsay/Saclay, Purdue

GEM point resolution, Carleton

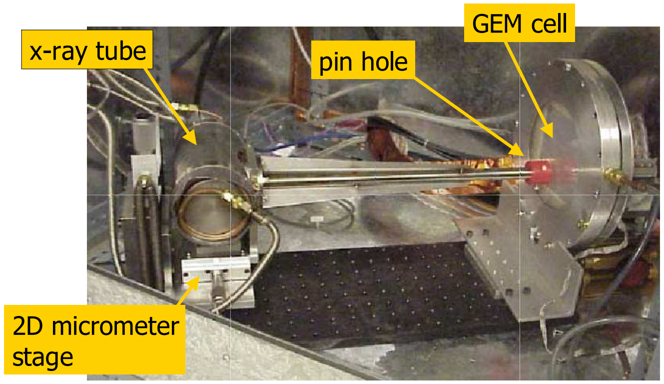
X-ray incident on indicated point. (not a TPC)

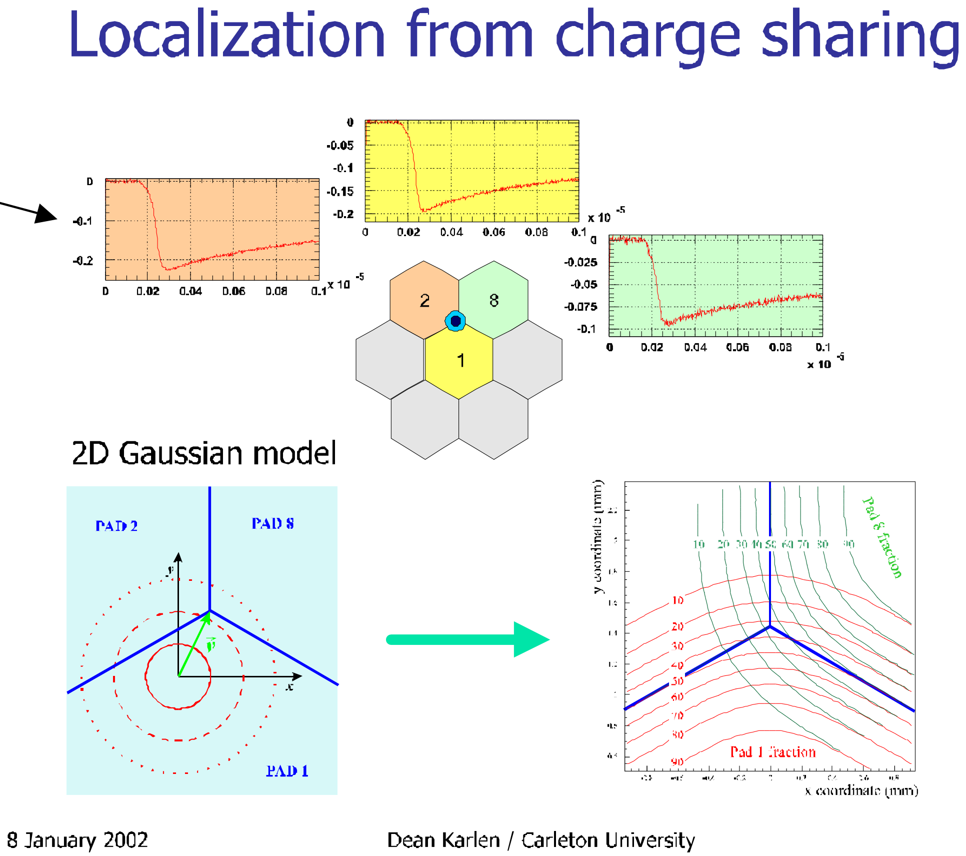
Charge shared signal is observed on □pads (2.5 mm hex).

Direct charge collection signal has about 1 µs width, 10 MHz

Charge sharing contours (lower right) indicate that signal width is 1 mm.

Spatial resolution is □100 µm, but only 1mm from boundaries.




Localization from charge sharing

8 January 2002

Dean Karlen / Carleton University

X-ray signal spatial resolution
Stolen from D. Karlen , Chicago Linear Collider Workshop, 7-Jan-2002

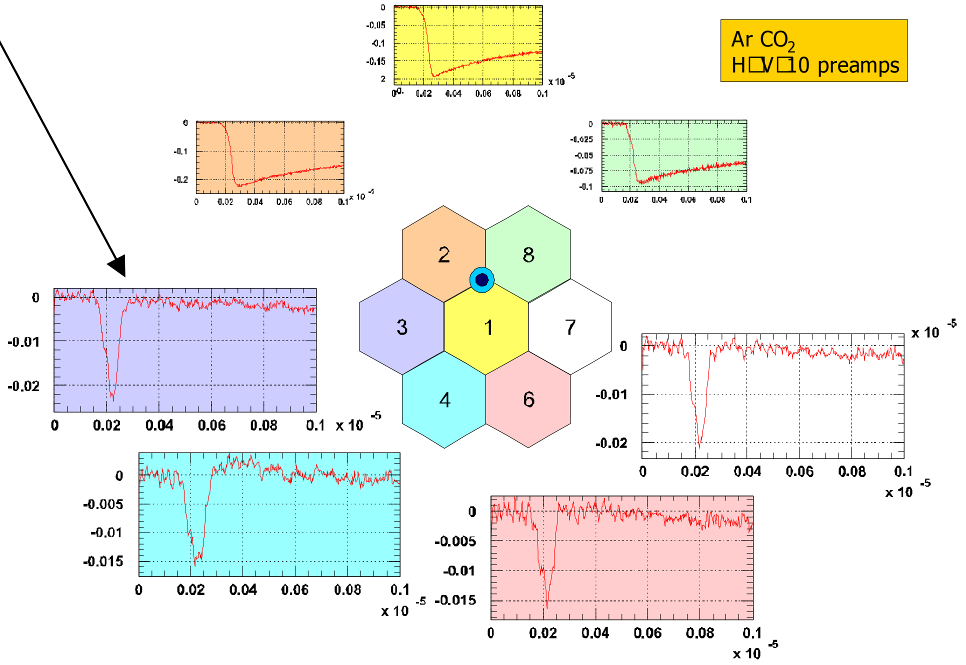
GEM point resolution (induction), Carleton

Also measured induction signals on □neighboring pads.
(same event)

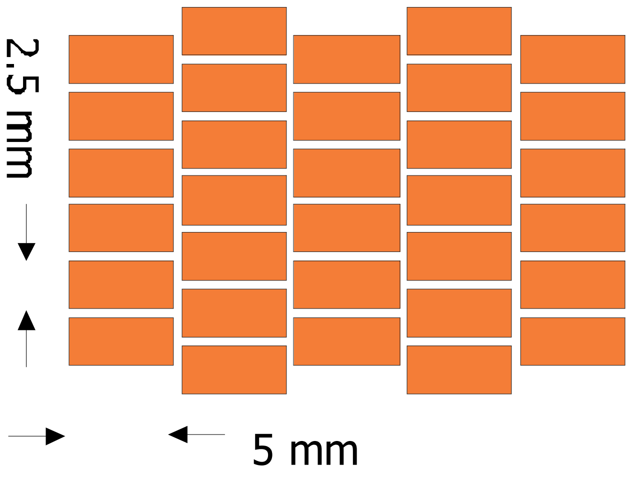
Spatial resolution is □100 µm and
not dependent on 1 mm pad size.

Signal width (threshold-threshold)
0.1 µs, requires 50-100 MHz

However, induction is
inconsistent with 2-track separation□
could be used in isolated sections to improve resolution.



TPC with GEM Readout, Carleton



Resolution with P10 gas

220 µm , □□10 mm

5□0 µm , □0□□□150 mm

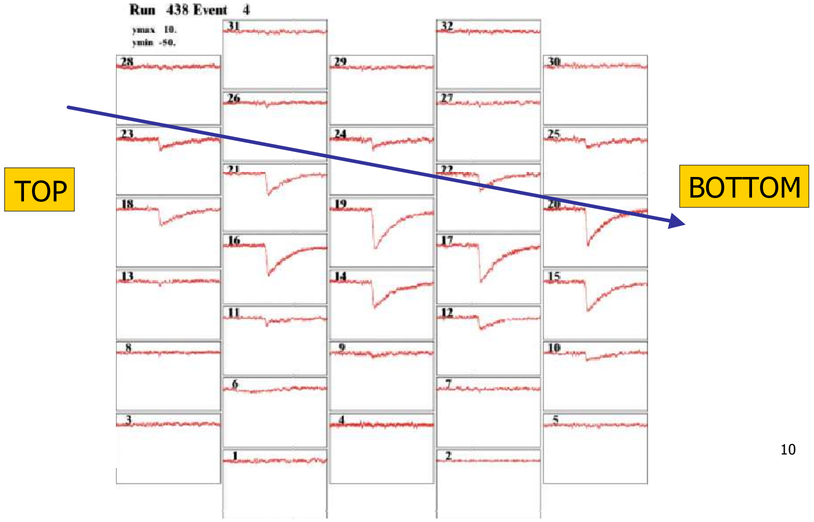
Explanation: large diffusion contribution (no magnetic field)

Extrapolates to 200 µm at □□0

Questions:

ion statistics □ (5 mm pad height)

anomalous electron cloud size □



Cosmic signal spatial resolution
Stolen from D. Karlen , Chicago Linear Collider Workshop, 7-Jan-2002

Micro Pattern Detector Aging (Radiation Hardness), Purdue

Example triple GEM with PCB readout

Gas Ar/CO$_2$ □0/□0 (99.99□)

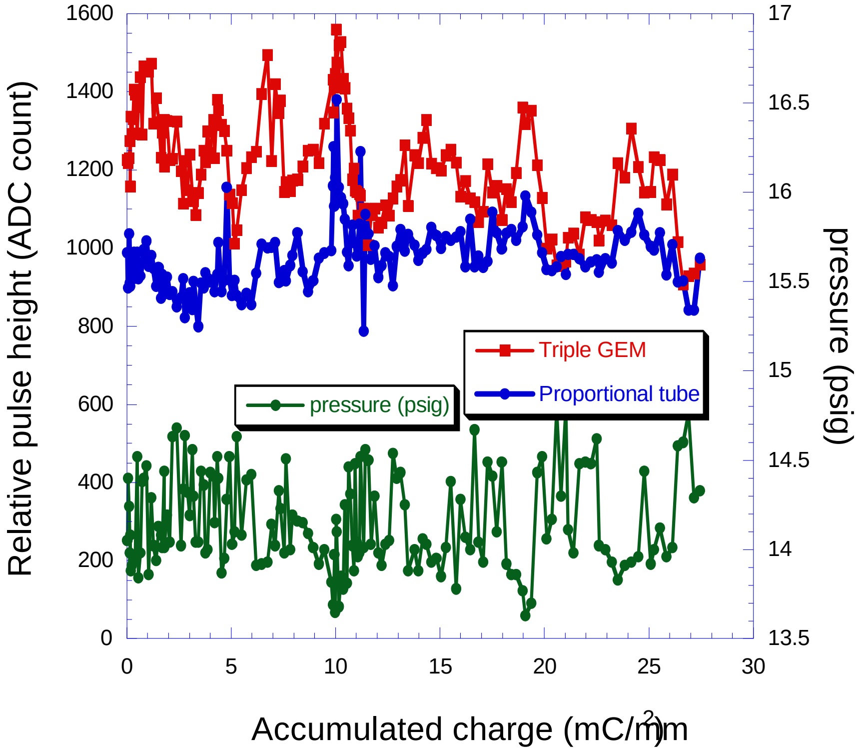
GEM1 □ □00 V
GEM2 □ □90 V
GEM□□□□0 V
PCB as e$^-$ collector

Cr □-rays (5.□□eV)
□ □x 10$^{□}$H□/mm^2 for □50hrs

Gas gain □,000

Detector performance small (~15□ gain loss) after ~ □years □LHC 10 cm from □P. No visual sign of aging.

Best result obtained with a GEM.



Similar result obtained with
A MicroMEGAS + GEM

Stolen from I. Shipsey, NIM A 478 (2002) 263

LCD, TPC, GEM or MicroMEGAS readout, cont.

Tests in high magnetic field: reduce transverse diffusion, surprises

Electronics: sampling rate, Aleph: 11 MHz,
100 Mhz required for faster gas or induction from neighboring pads
Typical live time may be 50 μs, store 1 ms exposure at TESLA .

Amplification: signal size, break-down limit, pad height, gas

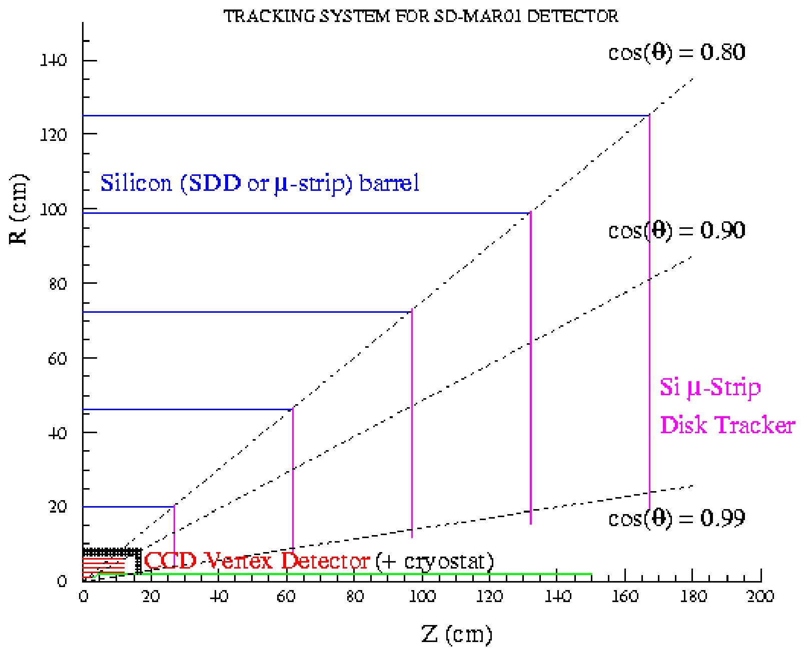
Mechanical: mounting gas amplifiers, minimizing inactive regions
high speed sampling may require cooling

(and, as in induction read-out TPC)
Ion feed-back: multi-GEMs or MicroMEGAS (appears better)
and/or gating grid

Gas: quenching with hydrocarbons *vs* neutron cross section

Alignment methods: internal, external, consistant with improved resolution
(and, in an inhomogeneous magnetic field)

All Silicon Tracking



$$\delta(1/P_t) \square \frac{\sigma/L^2 \left(\square 20/(N+\square)\right)^{.5}}{(.\square \text{GeV/Tesla } B)}$$

With L□1.25 m, B□5 Tesla,

σ □10 μm, N□□

$\delta(1/p)$□ □.□x 10^{-5} /GeV

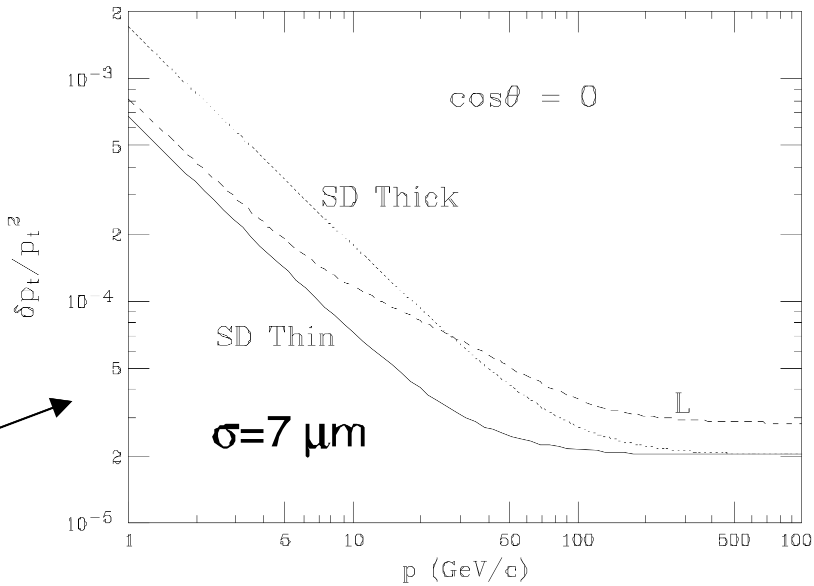
Provides□improved segmentation
$\delta(1/P_t)$ in a small package

Diasadvatages□
- pattern recognition issues
- material issues (low momentum)
- limited dE/dx

2 technologies being pursued by North American groups

Silicon μ-strip

Silicon Drift



Stolen from B Schumm, SILC phone/web meeting, 4-Apr-2002

□ □ D , all silicon tracking

Organizational meeting□April □, Bruce Schumm, UCSC

Silicon µ-strip□R&D, UC Santa Cruz□

reduce material, detectors must be very thin, 200 µm + no support
(CLEO □00 µm plus support)
to compete with budget of TPC (1.□□ $\square_0$ in inner support)

long shaping time, allows ultra low noise for thin detectors, 10 µs
(CLEO □□µs)

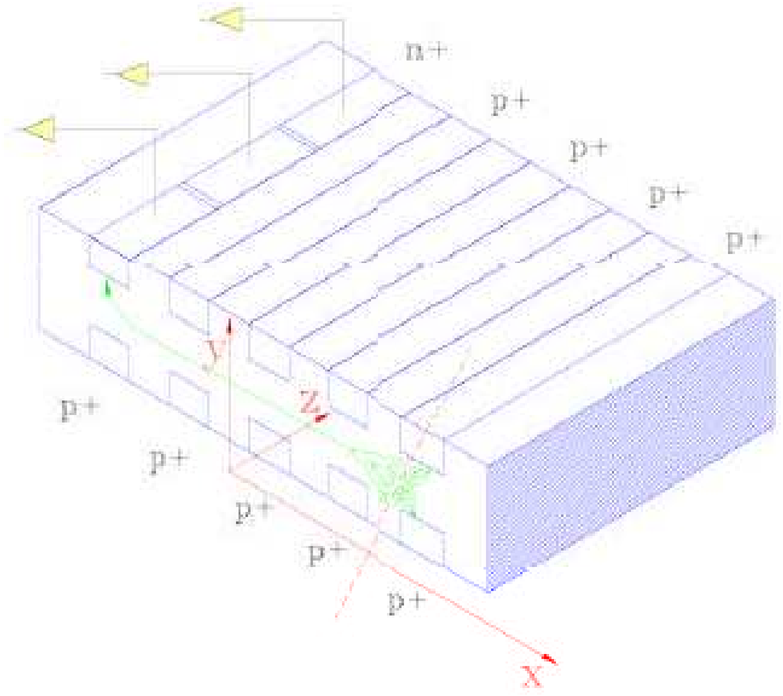
minimal support material, possibly tensioned

power cycling, reduce heat load, can this be done without adding noise□

resolution, 50 µm pitch with centroid finding for required □µm

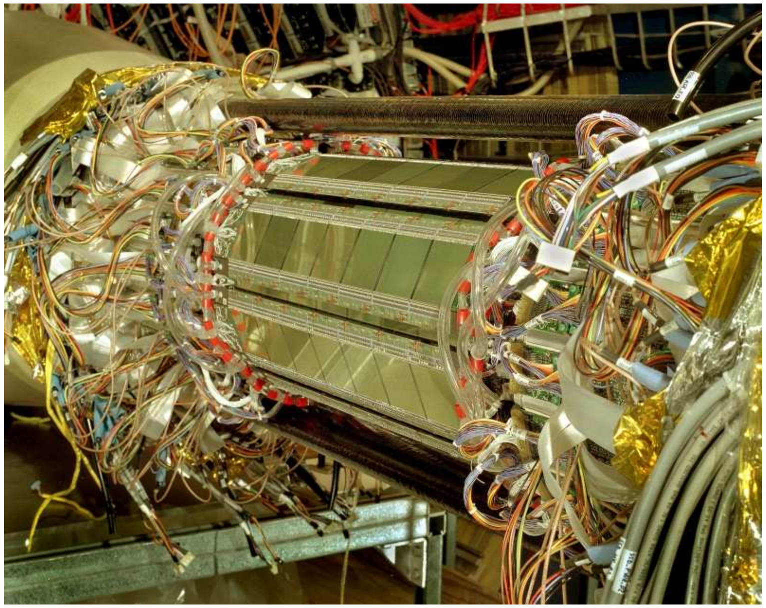
Silicon Drift □R&D, Wayne State (next page)

Silicon Drift Detector



Electron drift in silicon,
r-φ from pad, z from drift time
Maximum drift□5 μs

Mature technology, STAR vertex detector



LC Central tracker
Five layers

Goals□
Radiation length / layer □0.5 □
σ (r-φ) □ □μm,   σ (□) □10 μm

Wafer size□10 by 10 cm
Wafers□□000 (incl. spares)
Channels□□,□0□,□□0 (2□0 μm pitch)

Stolen from V. L. Rykov , Chicago Linear Collider Workshop, 7-Jan-2002

SDD, silicon drift detector

Ongoing/planned at Wayne State

Improve radiation length, STAR is 1.[illegible] per layer

- Reduce wafer thickness from [illegible]00 to 150μm
- Move FEE to edges or change from hybrid to SV[illegible]
- Air cooling vs. water cooling

More extensive radiation damage studies.

- Detectors/FEE can withstand around 100 krad (γ,n)

Improve position resolution to 5μm

- Decrease anode pitch from 250 to 100μm.

- Stiffen resistor chain and drift faster.
- PASA is BIPOLAR (intrinsically rad. hard.)
- SCA can be produced in rad. hard process

Intermediate tracker, Forward Disks

Motivation: improve momentum resolution
extend efficiency to cos(θ)=.995

Technology: spatial resolution goal requires silicon technology
pixel devices
or the silicon devices proposed for all silicon tracking

Performance Issues: many tracking studies to
optimize performance and prove effectiveness (below)

Mechanical Issues: solve mounting problems.
Structures must be rigid and aligned to the central tracker,
(note: degraded resolution for 25 μm misalignment)
yet independent of central tracker (for access).

□ □ D , physics motivation

Physics motivation studies will require a FAST Monte Carlo.

Momentum resolution□realistic requirements (point of diminishing returns)
for Higgs recoil mass and slepton endpoint spectrum,
taking into account other width contributions□
particle decay widths, initial state radiation, beam energy spread.

Material budget□realistic requirements,
compelling physics example that determines the material limit,
What $\delta p/p$ is required at 1 GeV/c □
What photon conversion rate is unacceptable □

dE/dx □Compelling physics example where dE/dx make a difference.

Shamelessly stolen from K. Riles, Chicago Linear Collider Workshop, 7-Jan-2002

□ □ D , system performance □ pat□rec□

System performance studies will require a FULL Monte Carlo.
including alignment errors, efficiency, detector response function,
noise from multiple bunches, backsplash, beam

Performance enhancers□
intermediate silicon tracking layer□
how much does this help for pat. rec. , δp/p □
intermediate scintillating fiber layer (timing, bunch tagging)
outer layer (extrapolation into calorimeter)
outer end-cap tracker (δp/p at low θ)

Performance in very high noise environment□(higher than expected 1□)

Performance with large electric field distortion (TPC) due to space charge
(although GEM/MicroMEGAS proponents confident that ion feedback
will be suppressed, maybe with gating grid
and primary ionization is claimed sufficient for expected accelerator backgrounds)

Wire saturation□(in a drift chamber) from larger than expected
accelerator backgrounds, degrades time resolution, efficiency

Shamelessly stolen from K. Riles, Chicago Linear Collider Workshop, 7-Jan-2002

□ □ D , pattern recognition issues

requires FULL Monte Carlo as on previous slide.

Mature pattern recognition that performs in high density environment
(which might include)

Non-linear methods□allowing for global determination of the ambiguity
arising from different matching of high-quality track-segments

Energy Flow Performance□
realistic comparison of track separation performance
□D and 2D, silicon and gas options
TPC with induction *vs* GEM/MicroMEGAS, GEM with induction
evaluate (charge spreading) pad design for track separation

Silicon tracking□demonstrated □stand-alone□track reconstruction,
□ for □all silicon□tracking options
including reconstruction of decays in flight
(fewer, more precise, hits *vs* continuum of less precise hits)
□ for silicon forward discs
□ for vertex detector, including self contained tracking □seeds□
successfully extrapolated into the outer tracker

Mostly stolen from K. Riles, Chicago Linear Collider Workshop, 7-Jan-2002

R & D opportunities in Tracking

TPC

Spatial resolution optimization, goal of 150 μm in a large induction TPC.
Ion feedback suppression□gating grids (long gate time at TESLA)
Gas studies□aging, velocity (clearing time), quenching, neutron absorption
Alignment□internal alignment and drift path in an inhomogeneous B field
extrapolation to an intermediate tracker□hardware & tracking.
Optimize pattern recognition in an environment of significant track overlap.

Advanced readout TPC

Pad size□ narrow electron cloud ~ 1mm
requires 1mm pads to provide charge sharing, □ (10□) pads wider pads (5mm□) will have poor resolution□w/(12)$^{1/2}$
Pad shape□methods of spreading signal to limit channel count and improve resolution chevrons□ ganging□ induction□

Amplification□signal size, break-down limit, pad height, gas
Gas□further studies studies□diffusion
Tests in high magnetic field□reduce transverse diffusion, surprises
Electronics□sampling rate, Aleph□11 MHz, 100 Mh□required for faster gas or induction from neighboring pads
Typical live time may be 50 μs, store 1 ms exposure at TESLA .
Aging□GEMs can fail at high gain, relatively new technology, dependence on gas choice
Mechanical□mounting gas amplifiers, minimizing inactive regions high speed sampling may require cooling

Silicon μ-strip tracker

reduce material, detectors must be very thin, 200 μm + no support to compete with budget of TPC (1.□□ $□_0$ in inner support)
long shaping time, allows ultra low noise for thin detectors, 10 μs
minimal support material, possibly tensioned
power cycling, reduce heat load, can this be done without adding noise□
resolution, 50 μm pitch with centroid finding for required □μm

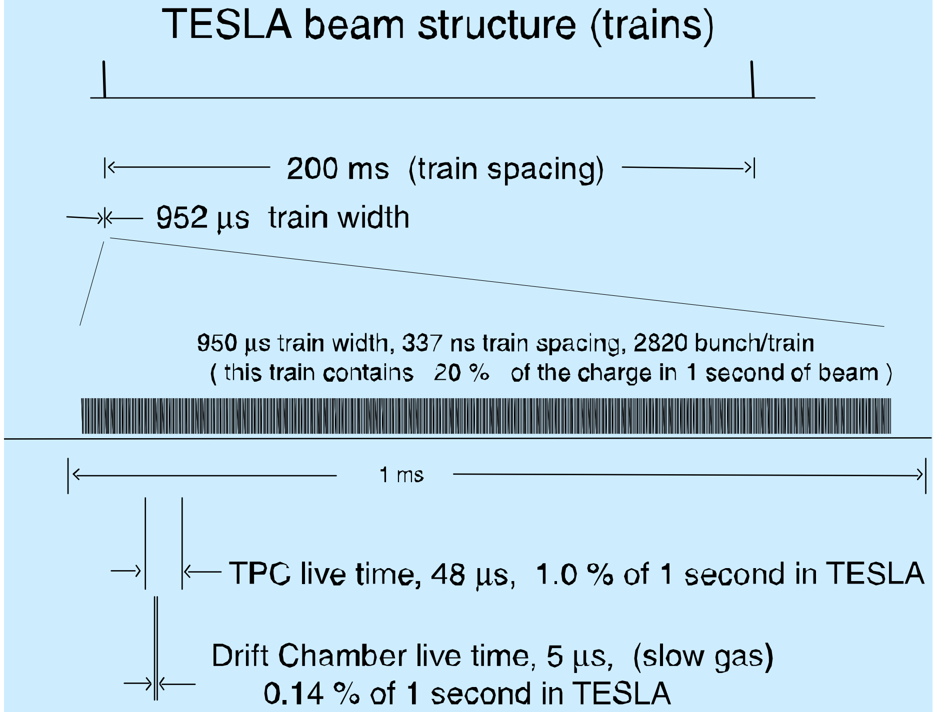
Silicon drift

Improve radiation length, STAR is 1.□□ per layer, require 0.5□
radiation damage studies.
Improve position resolution to 5μm . Decrease anode pitch from 250 to 100μm.

Simulations

Momentum resolution□realistic requirements for Higgs recoil mass and slepton endpoint spectrum,
Material budget□realistic requirements, compelling physics example that determines the material limit,
dE/dx □Compelling physics example where dE/dx make a difference.
Performance enhancers□intermediate silicon tracking layer□how much does this help for pat. rec. , δp/p □
intermediate scintillating fiber layer (timing, bunch tagging)
outer □layer (extrapolation into calorimeter)
outer end-cap tracker (δp/p at low θ)
Performance in very high noise environment□(higher than expected 1□)
Performance with large electric field distortion (TPC) due to space charge
Wire saturation□(in a drift chamber) from larger than expected accelerator backgrounds, degrades time resolution, efficiency
Mature pattern recognition that performs in high density environment
Energy Flow Performance□realistic comparison of track separation performance 3D and 2D, silicon and gas options
Silicon tracking□ □stand-alone□track reconstruction, for □all silicon□tracking options , silicon forward discs vertex detector

Beam Structure Issues



TESLA beam structure (trains)

200 ms (train spacing)

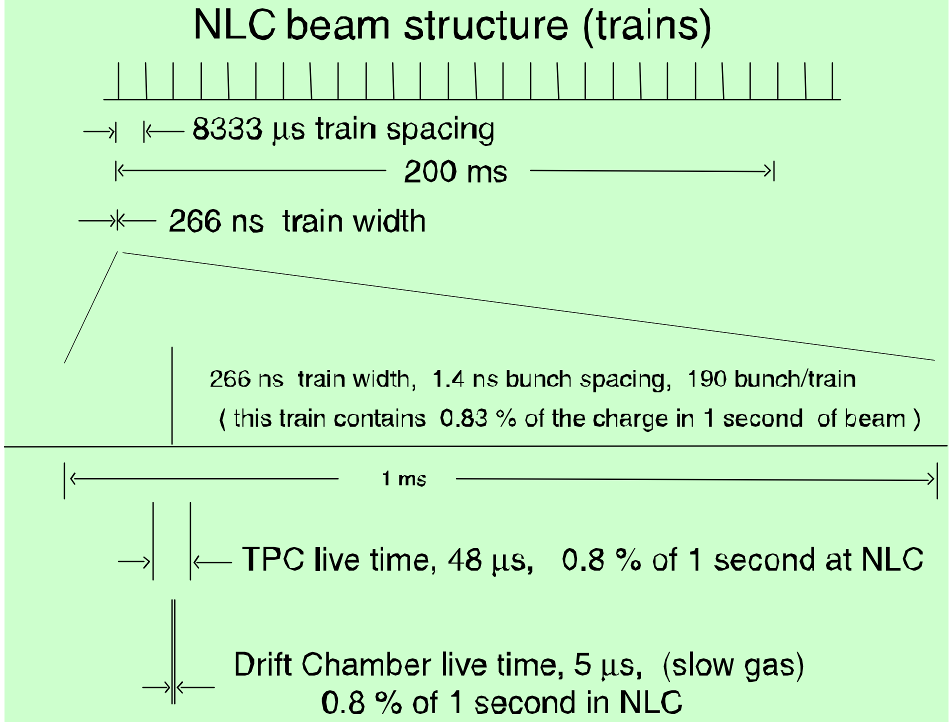
952 µs train width

950 µs train width, 337 ns train spacing, 2820 bunch/train
(this train contains 20 % of the charge in 1 second of beam)

1 ms

TPC live time, 48 µs, 1.0 % of 1 second in TESLA

Drift Chamber live time, 5 µs, (slow gas)
0.14 % of 1 second in TESLA



NLC beam structure (trains)

8333 µs train spacing

200 ms

266 ns train width

266 ns train width, 1.4 ns bunch spacing, 190 bunch/train
(this train contains 0.83 % of the charge in 1 second of beam)

1 ms

TPC live time, 48 µs, 0.8 % of 1 second at NLC

Drift Chamber live time, 5 µs, (slow gas)
0.8 % of 1 second in NLC

A TPC is not a trigger device.
Although the maximum drift is about 50 µs, data collected throughout the entire train width (950 µs at TESLA) must be stored in the electronics, 20,000 time buckets/channel at 20 MHz Compress data during train.

A Drift Chamber is sensitive to the same amount of radiation (one train) as a TPC in NLC/JLC. TPC segmentation provide noise immunity.
However, a drift chamber would have reduced beam noise at TESLA.