The Development of Large-Area Psec TOF Systems

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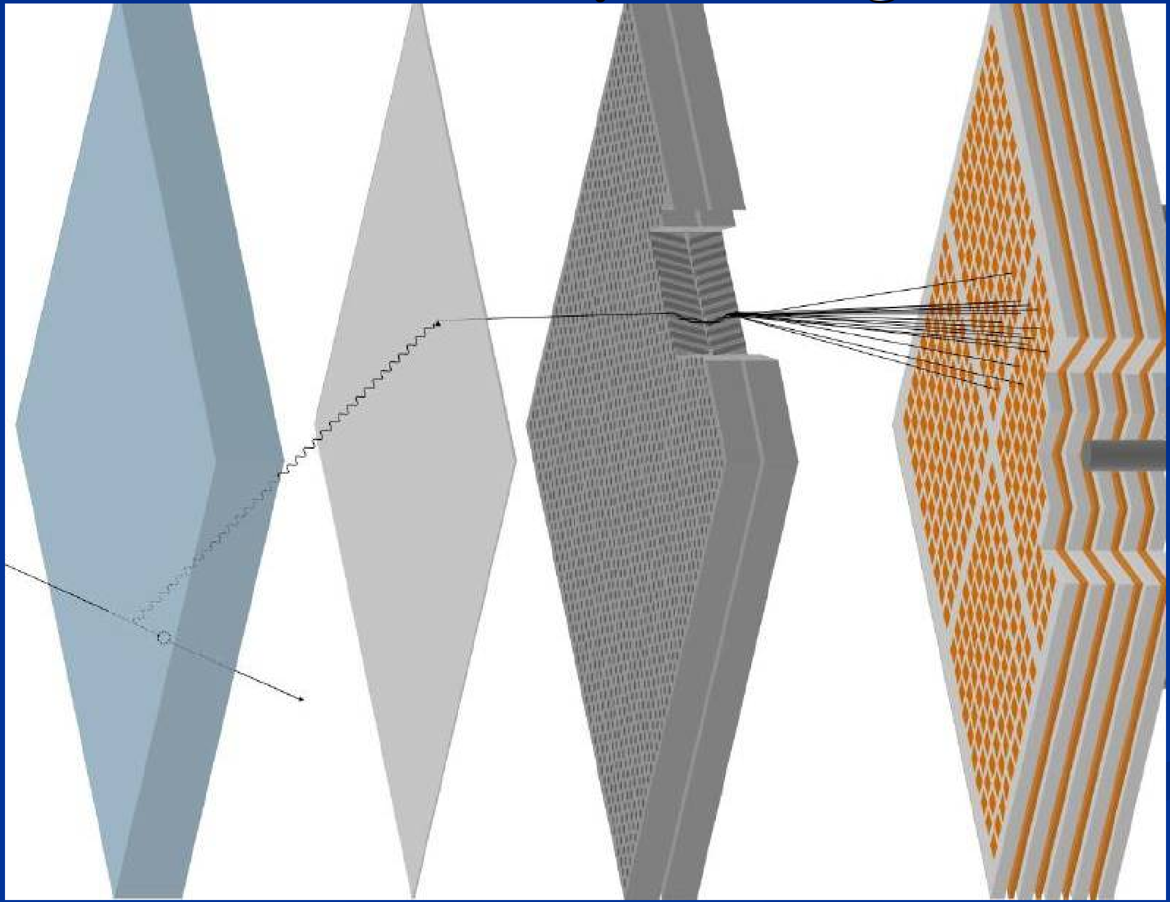


Introduction

- Resolution on time measurements translates into resolution in space, which in turn impact momentum and energy measurements.
- Silicon Strip Detectors and Pixels have reduced position resolutions to ~5-10 microns or better.
- Time resolution hasn't kept pace- not much changed since the 60's in large-scale TOF system resolutions and technologies (thick scint. or crystals, PM's, NIM/Camac/VME TDC's)
- Improving time measurements is fundamental , and can affect many fields: particle physics, medical imaging, accelerators, astro and nuclear physics, laser ranging, ….
- Need to understand what are the limiting underlying physical processes- e.g. source line widths, photon statistics, e/photon path length variations.
- **What is the ultimate limit for different applications?**

OUTLINE

1. Introduction: why picosec, and why `large-area'?
2. HEP needs: particles and quark flow, heavy particles, displaced vertices, photon origin
3. Three key developments since the 60's: MicroChannel Plates (MCPs), 200 GHZ electronics, and `end-to-end' simulation
4. The need for `end-to-end' simulation
5. Positron-Emission Tomography (PET): looks like HEP: data rate, # of channels, S/N, data-acquisition, real-time imaging (not my area..)
6. What determines the ultimate limits? Applications?

Cast of Characters

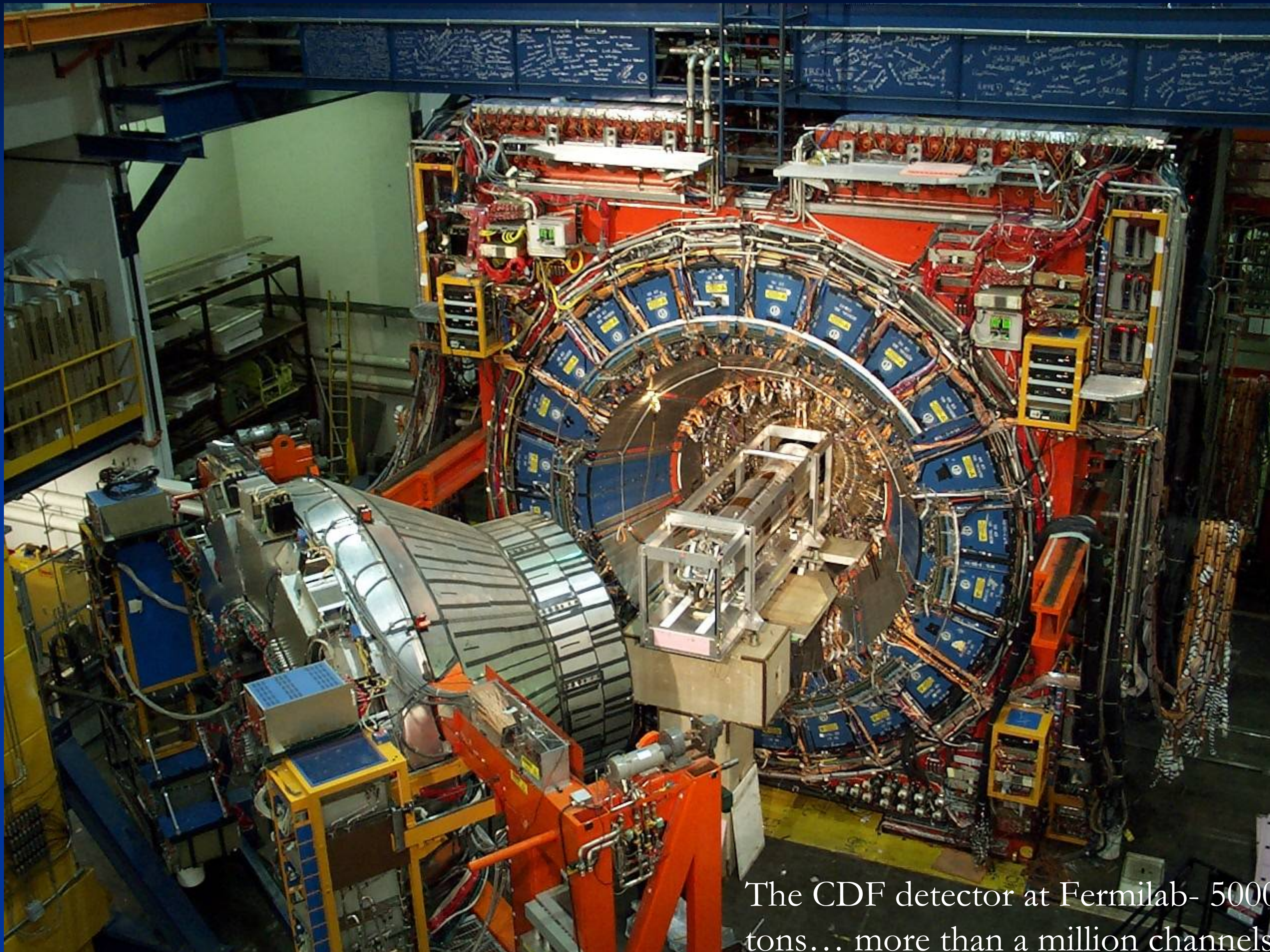
From 2005 slide

Timothy Credo	IMSA senior (Harvard next year)
Robert Schroll	Theory grad student (Physics335)
Shreyas Baht	UC undergrad- just joined
Fukun Tang	EFI Electronics Engineer
Harold Sanders	Head, EFI Elec. Devel. Gp.
HJF	

Many thanks to Katsushi Arisaka (UCLA), Alan Bross (FNAL), Paul Hink (Burle), Mario Kasahara (Hamamatsu), Bruce Laprade (Burle), John Martin (Burle), and Wilma Raso (Burle), and to Joe Lykken and Maria Spiropulu for causing this.

Now with David Yu , Jakob Van Santen (students), Karen Byrum (physicist) and Gary Drake (Elec. Engineer) of Argonne National Lab, and Prof.'s Chin-Tu Chen and Chien-Minh Kao of the Dept of Radiology, Univ. of Chicago. Also have a MOU in progress with Saclay in France, and a close working relationship to Jerry Va'vra at SLAC. Have developed a community (e.g. Saclay workshop)

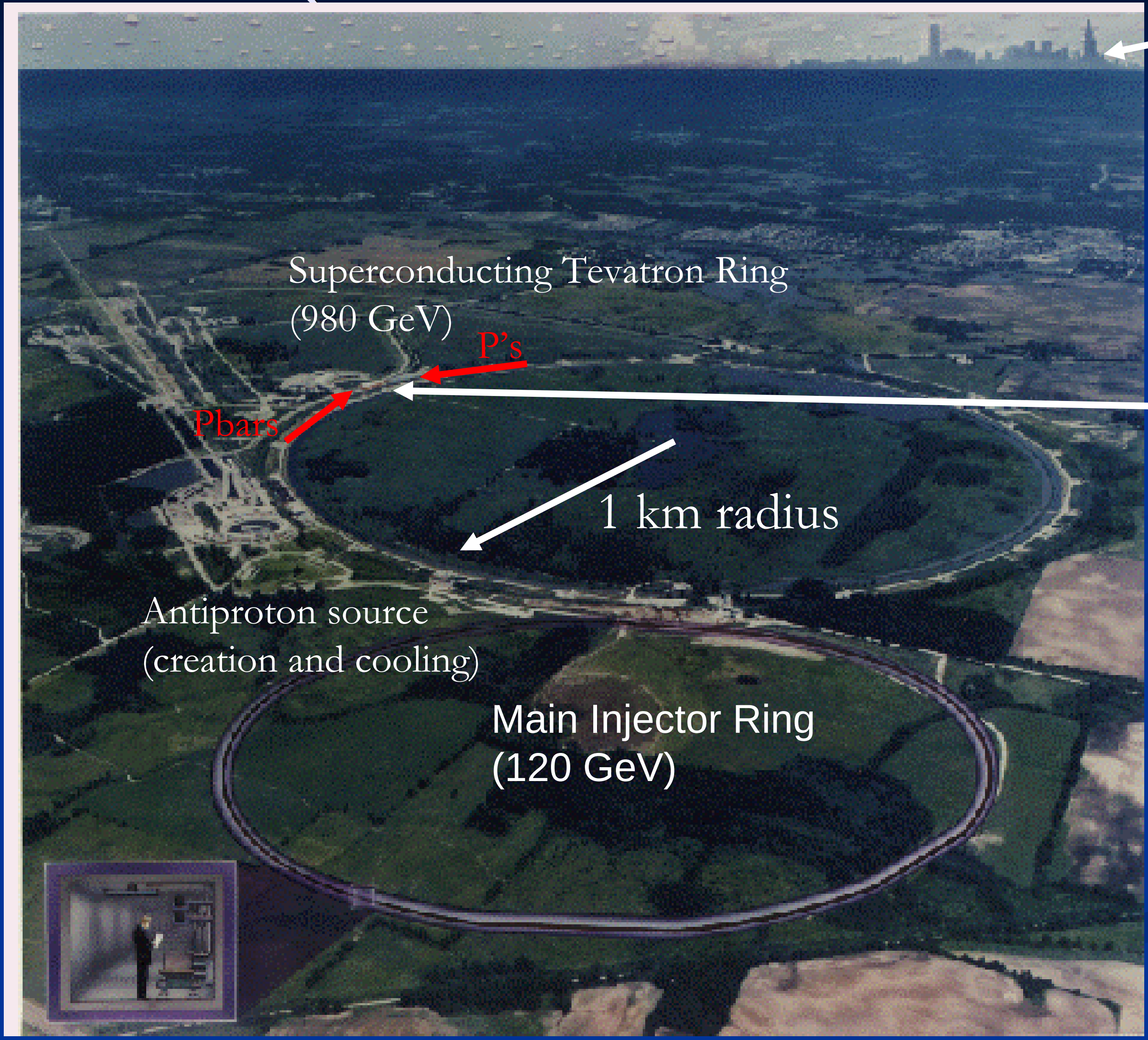
My motivation- High Energy Collisions- understnding the basic forces and particles of nature- hopefully reflecting underlying symmetries



The CDF detector at Fermilab- 5000 tons… more than a million channels

But small compared to Atlas and CMS!

Fermilab (40 miles west of Chicago)



CDF is here

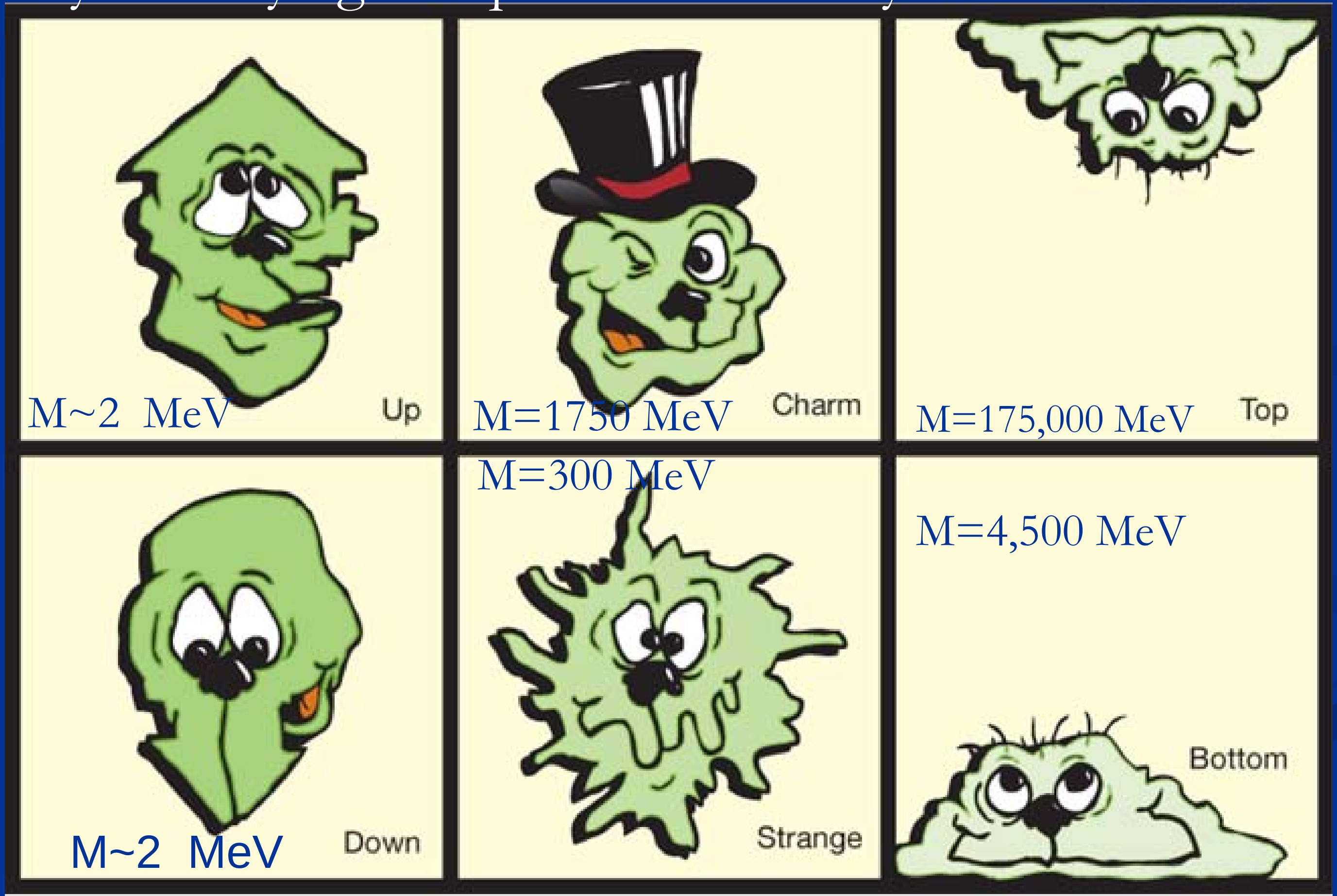
We give tours-
come visit!

The unexplained structure of basic building blocks-e.g. quarks

The up and down quarks are light (few MeV), but one can trace the others by measuring the mass of the particles containing them. Different models of the forces and symmetries predict different processes that are distinguishable by identifying the quarks. Hence my own interest.

Q=2/3

Q=-1/3



2 TeV (> 3ergs) pbar-p collisions

(apologies for bluriness-ps to pdf to ppt…)

The Basics- Page 1

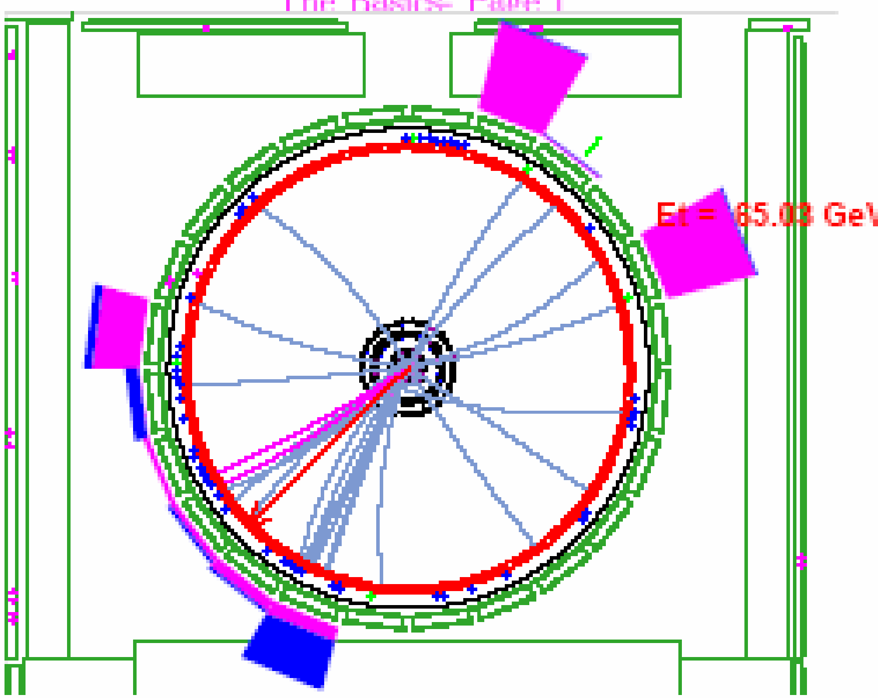


Figure 2:

For each track, $\beta = L/\Delta t$, where $L \equiv$ track length (helix) from vertex to outer radius, and:

Δt= (time at outer radius $-t_0$), where t_0 is the time of interaction.

Beam's Eye View

The Basics- Page 2

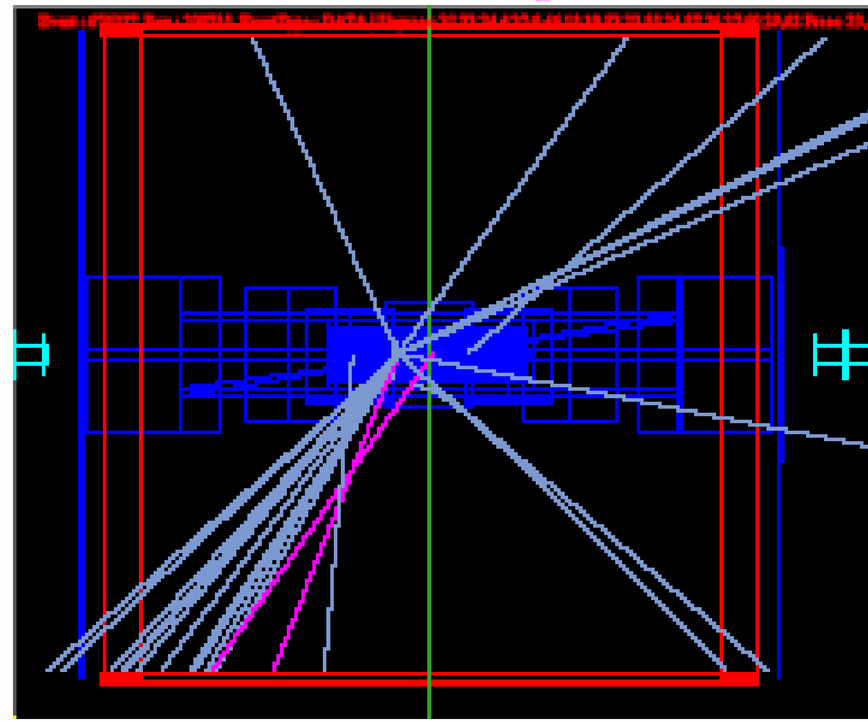


Figure 3:

R-Z (side) view of the same event. Note the mis-reconstructed tracks in this view (no slouch detector-96 layers of COT, 7 or 8 silicon).

Side View

~ 10 million collisions/sec; 1 million electronics channels

The basics of particle ID by TOF

What sets the 1 psec goal for HEP?

The Basics- Identifying particles by measuring velocity and momentum.

Identifying particles by measuring velocity and momentum.

Particle masses: e : 0.00051 MeV; μ^-:105.7 MeV;π^+: 139.6 MeV; K^+: 493.7 MeV; p: 938.3 MeV;

Basic Special Relativity in HEP units (electrical engineers in the audience)
Work in nsec and feet $\Longrightarrow$ c=1:

$$\beta \equiv v/c; \gamma \equiv \frac{1}{\sqrt{1-\beta^2}}; E^2 = p^2 + m^2; \qquad (1)$$

What we need is $p = \beta\gamma m$. Solve for m given p and β.

Measure p from the curvature in the field, and β (and hence γ) from the time-of-transit and length of the trajectory.

Separation with a 1.5-m Radius Solenoid (CDF)

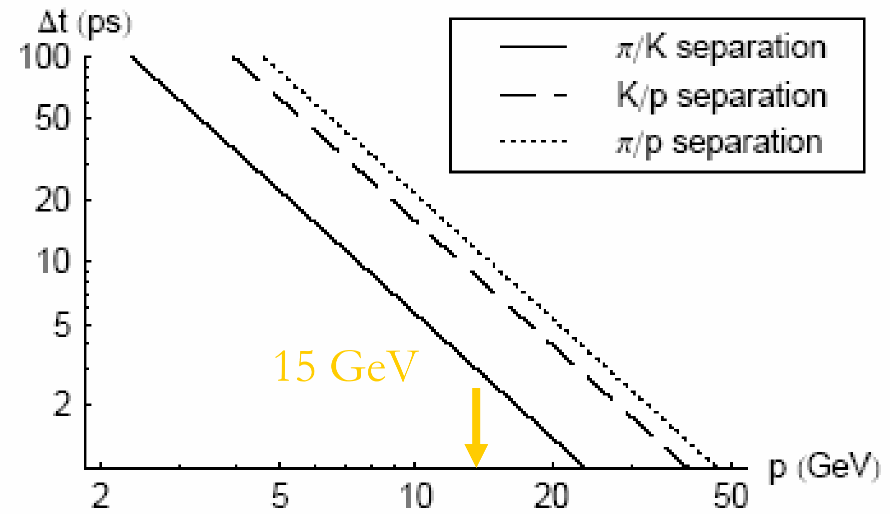
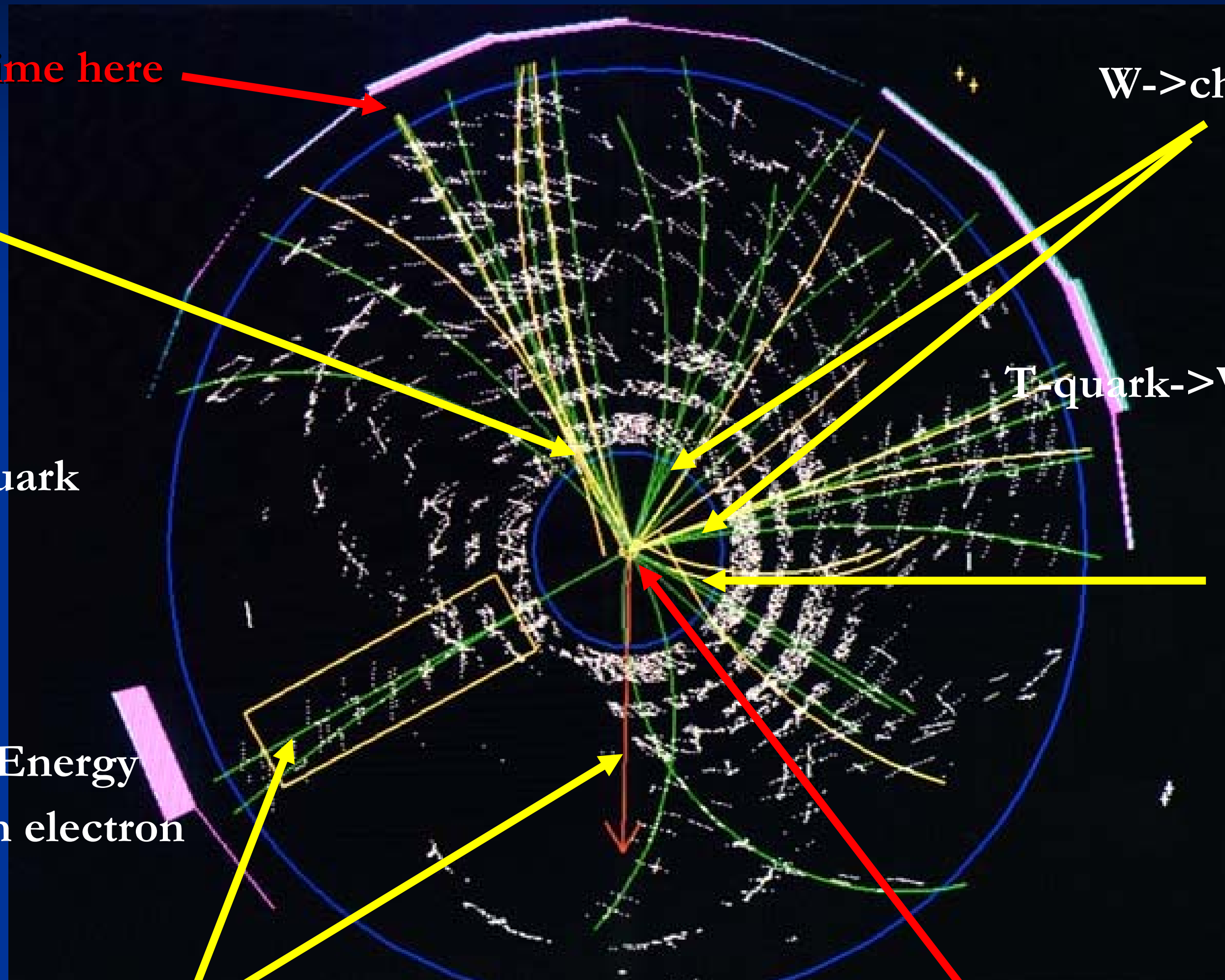


Figure 4: Contours of 1-sigma separation for pions, kaons, and protons versus the time resolution of the particle flight time over a 1.5-meter path for a detector with 1psec resolution.

A real CDF Top Quark Event

T-Tbar -> W^+bW^-bbar



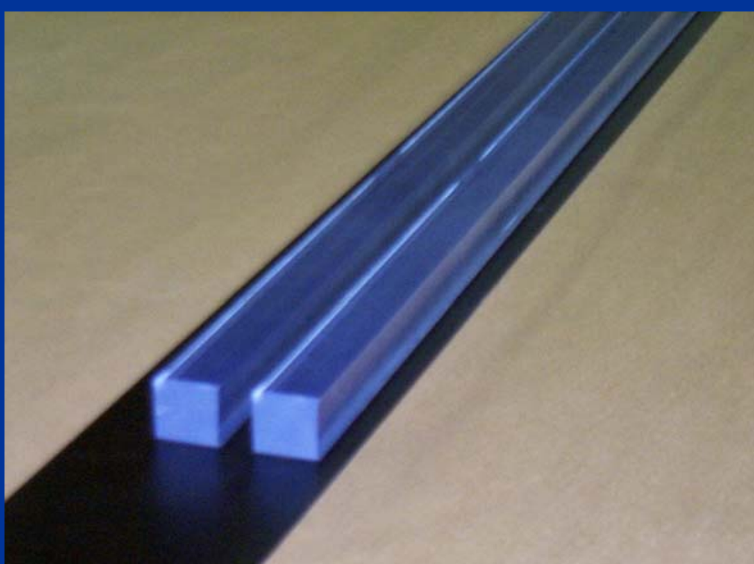
Can we follow the color flow through kaons, cham, bottom? TOF!

Why has 100 psec been the # for 60 yrs?

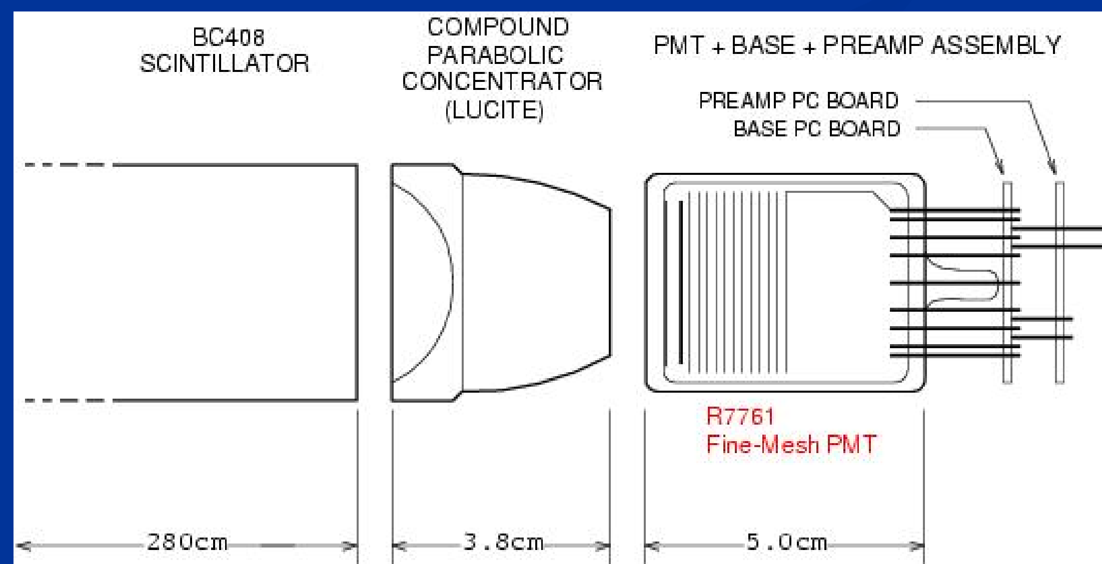
Typical path lengths for light and electrons are set by physical dimensions of the light collection and amplifying device.

These are now on the order of an inch. One inch is 100 psec

That's what we measure- no surprise! (pictures from T. Credo)

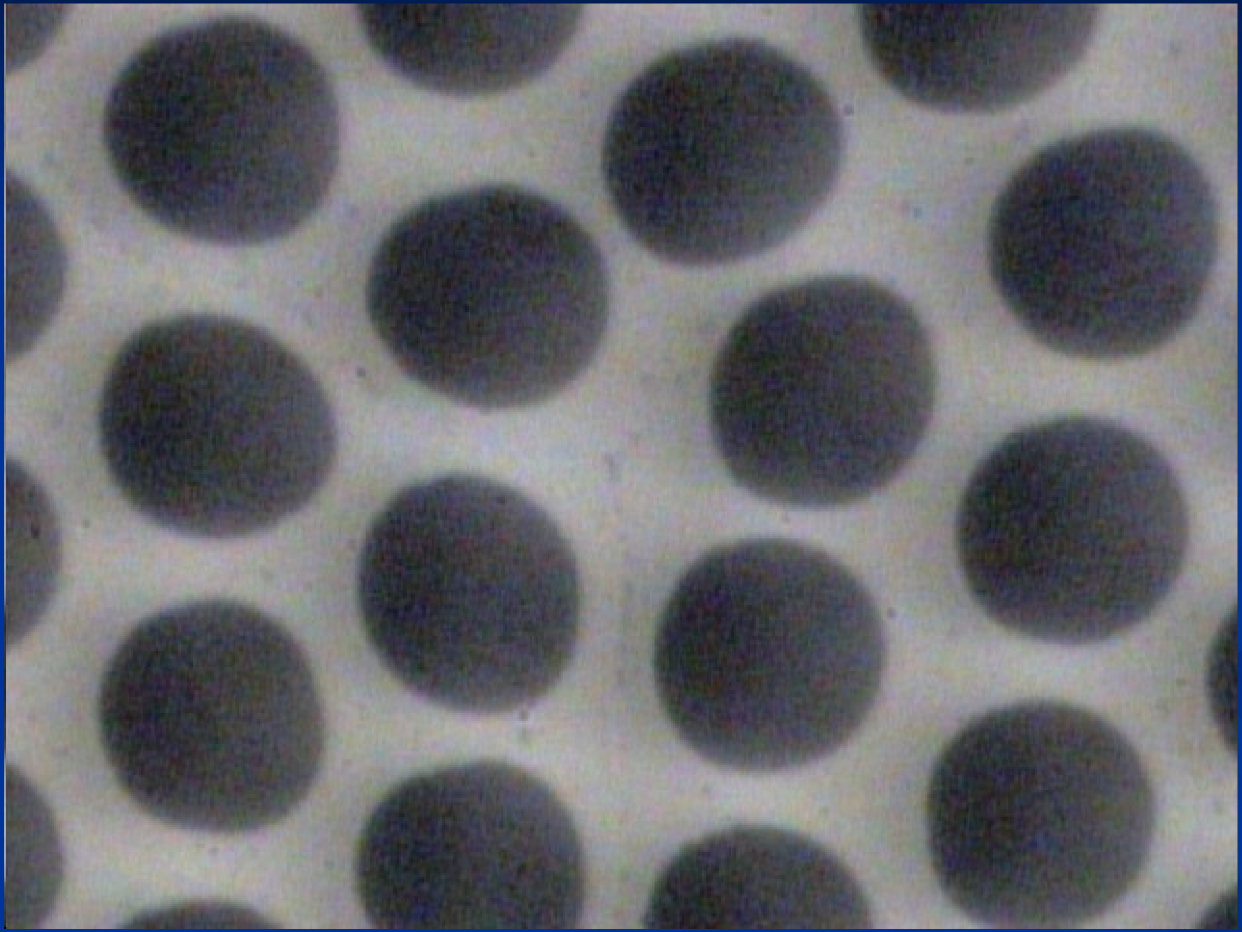


Typical Light Source (With Bounces)



Typical Detection Device (With Long Path Lengths)

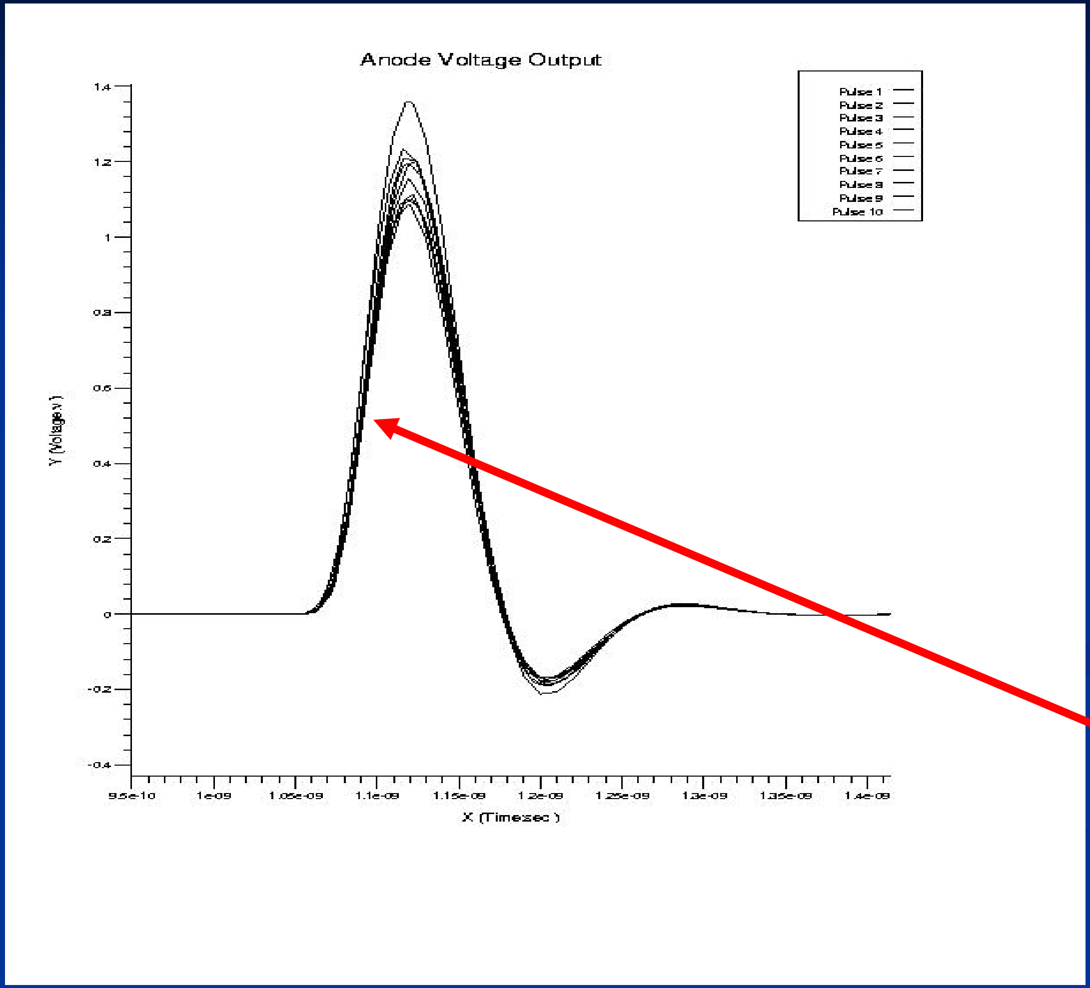
Major advances for TOF measurements:



Micro-photograph of Burle 25 micron tube- Greg Sellberg (Fermilab)

1. Development of MCP's with 6-10 micron pore diameters (300 micron = 1 psec)

Major advances for TOF measurements:

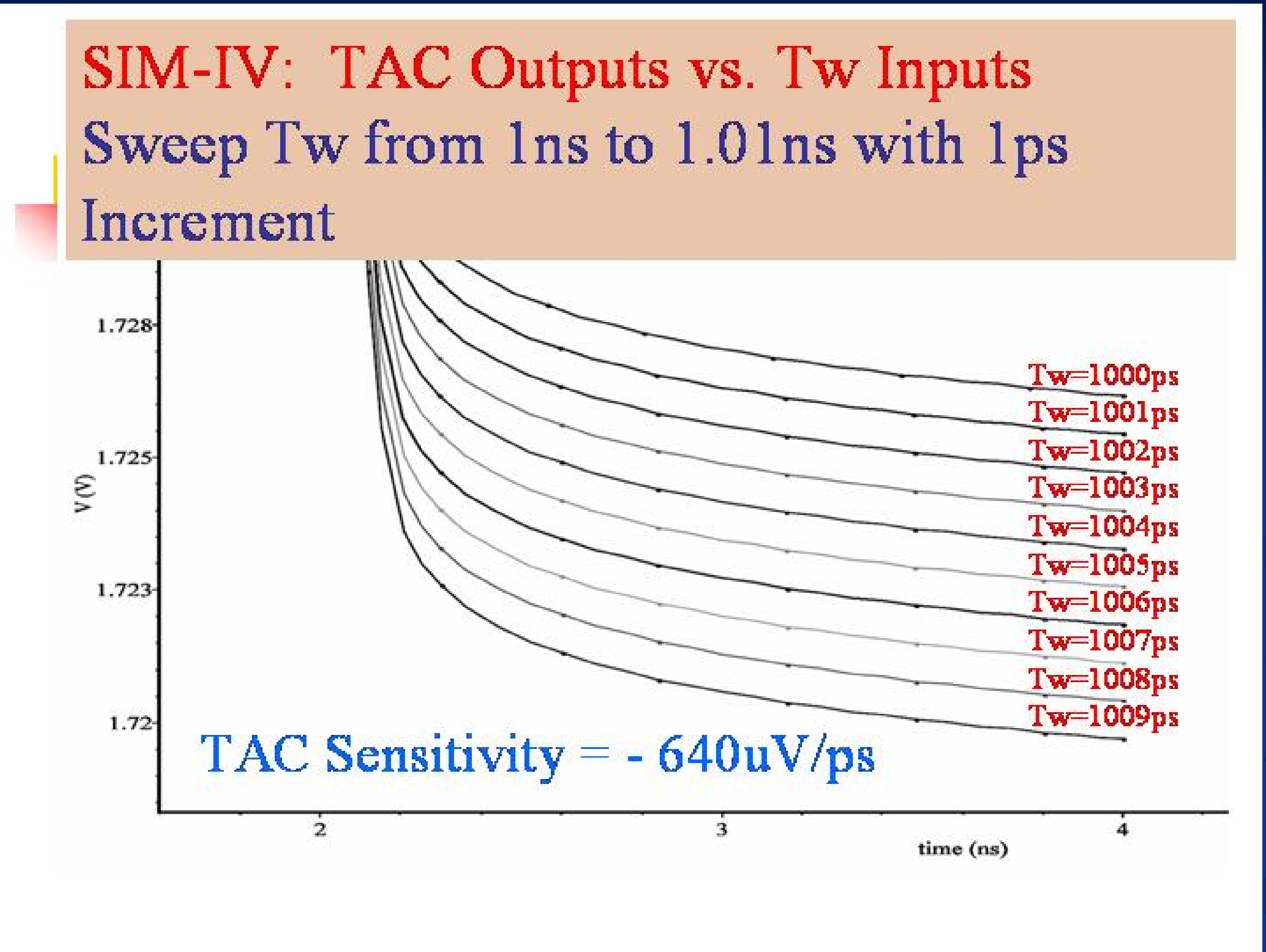


Output at anode from simulation of 10 particles going through fused quartz window- T. Credo, R. Schroll

Jitter on leading edge 0.86 psec

2. Ability to simulate electronics and systems to predict design performance

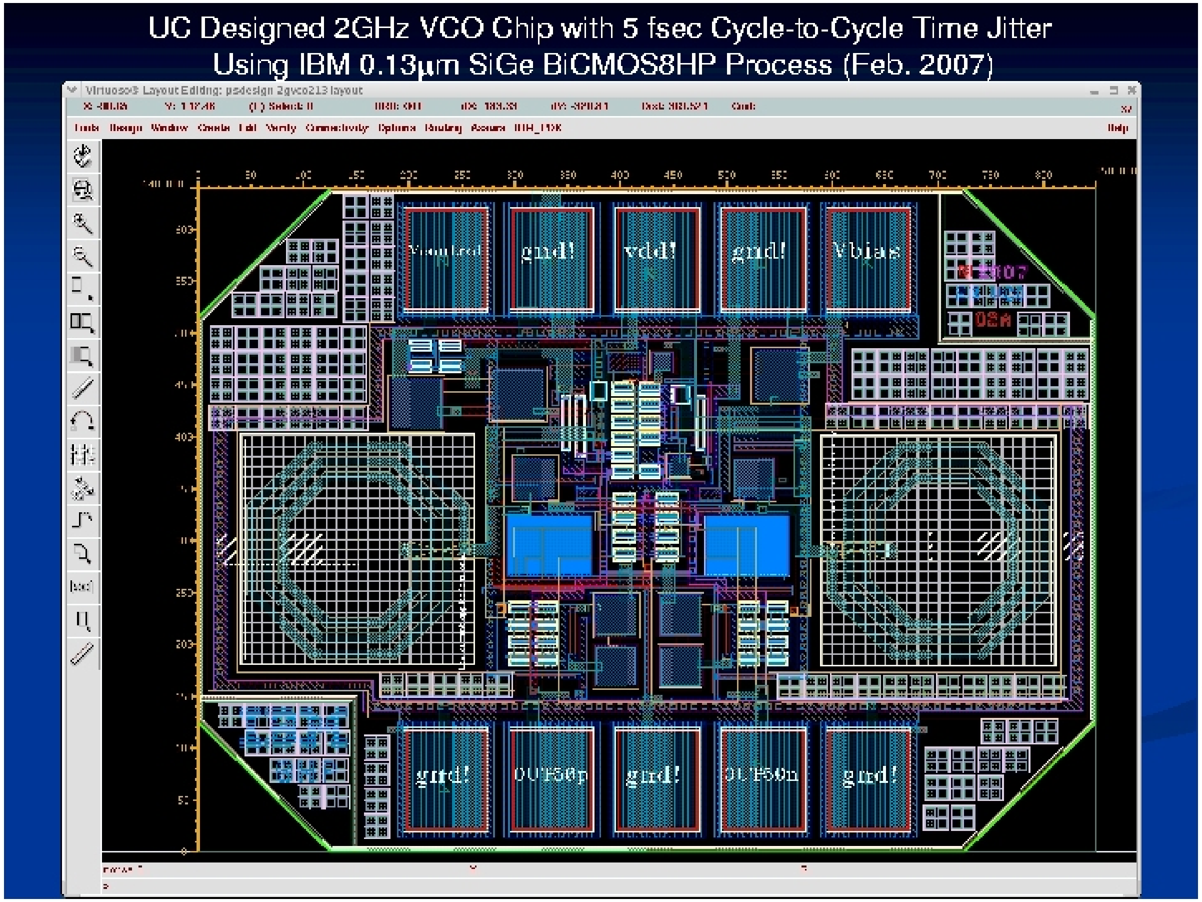
Major advances for TOF measurements:



Simulation with IHP Gen3 SiGe process- Fukun Tang (EFI-EDG)

3. Electronics with typical gate jitters << 1 psec

Major advances for TOF measurements:



Most Recent work-

IBM 8HP SiGe process
See talk by Fukun Tang (EFI-EDG) at Saclay wkshp

http://hep.uchicago.edu/psec/conf.html

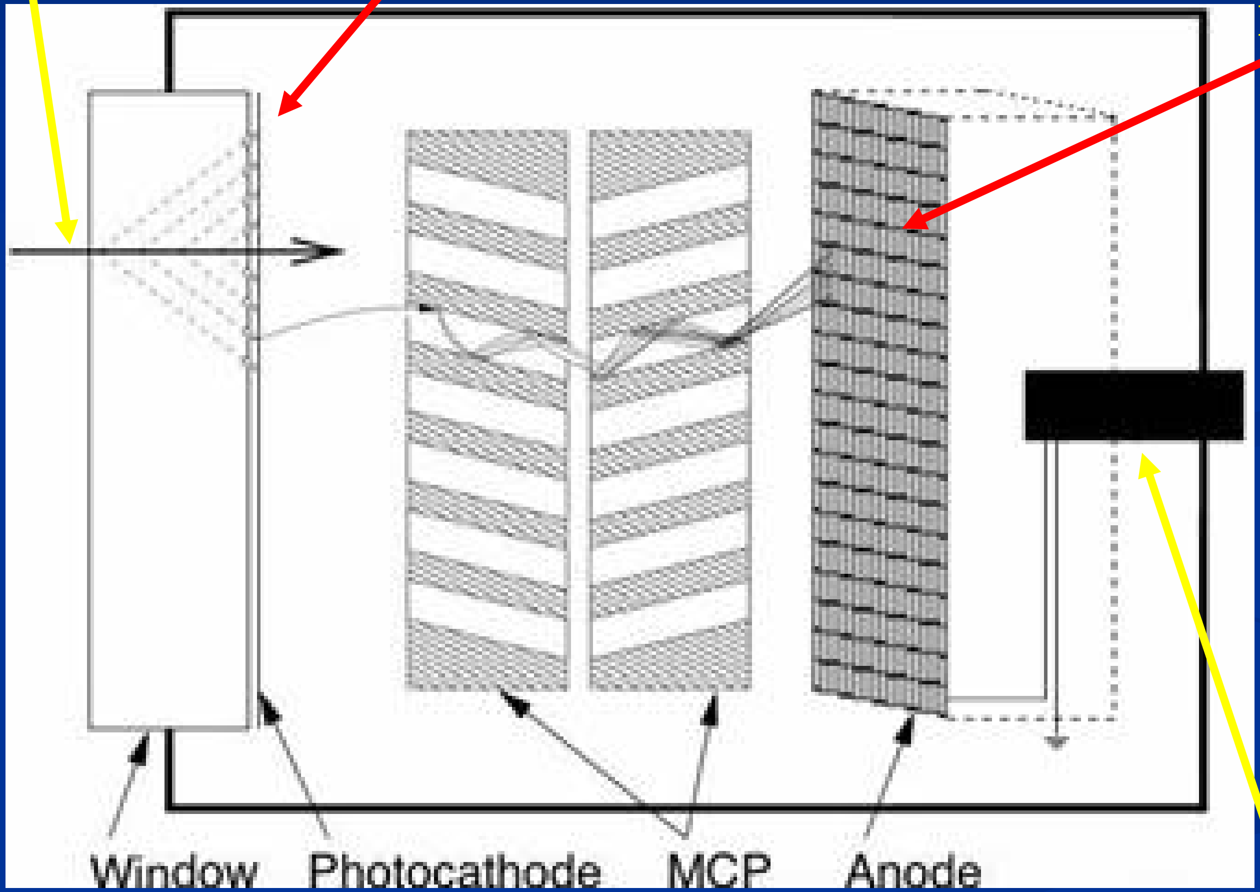
3a. Oscillator with predicted jitter ~5 femtosec (!) (basis for PLL for our 1-psec TDC) .

Solutions: Generating the signal

Use Cherenkov light - fast

Incoming rel. particle

Custom Anode with Equal-Time Transmission Lines + Capacitative. Return

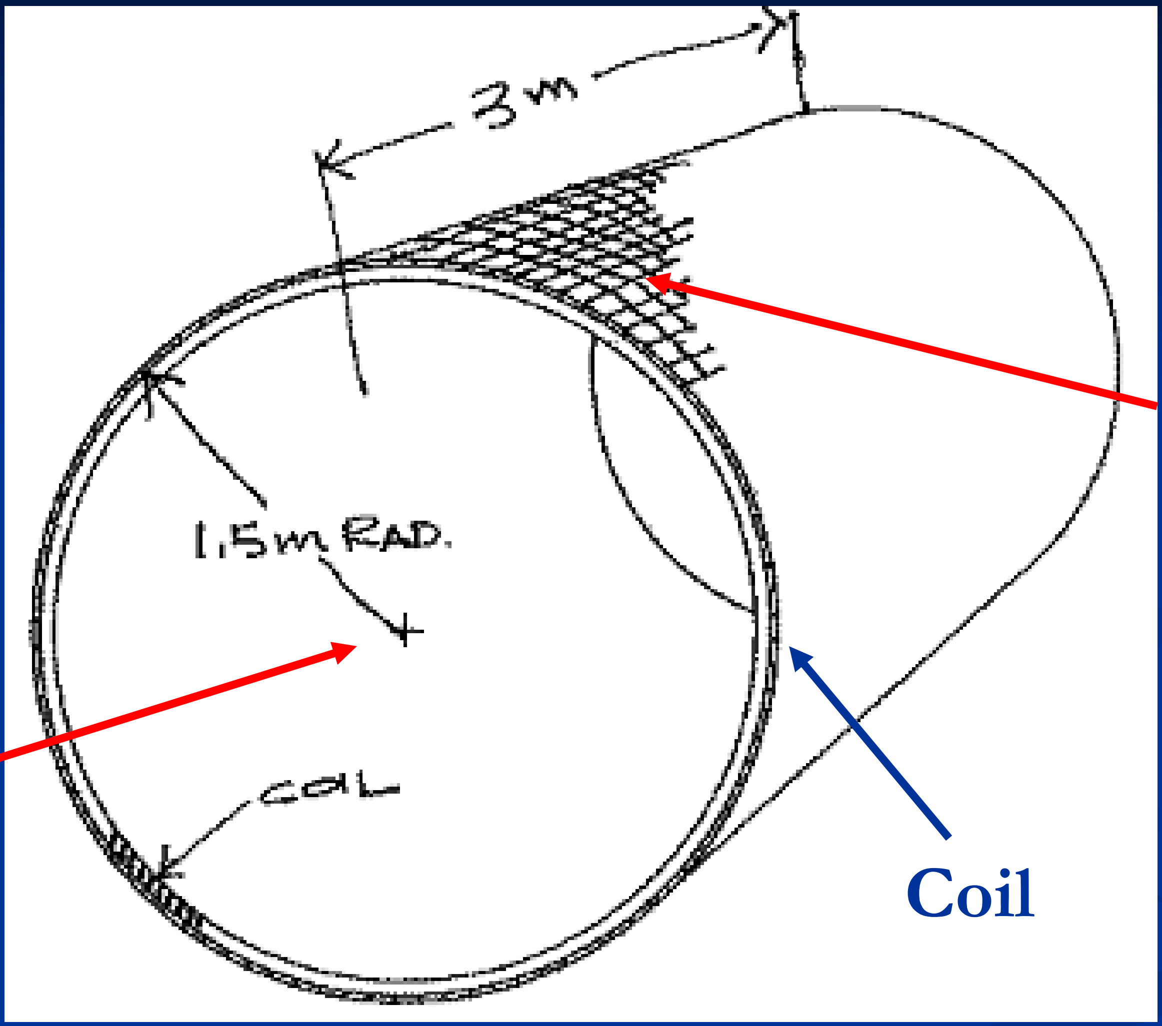


A 2" x 2" MCP- actual thickness ~3/4"

e.g. Burle (Photonis) 85022- with mods per our work

Collect charge here-differential Input to 200 GHz TDC chip

Geometry for a Collider Detector



Beam Axis

Coil

2” by 2” MCP’s

Typical Area:

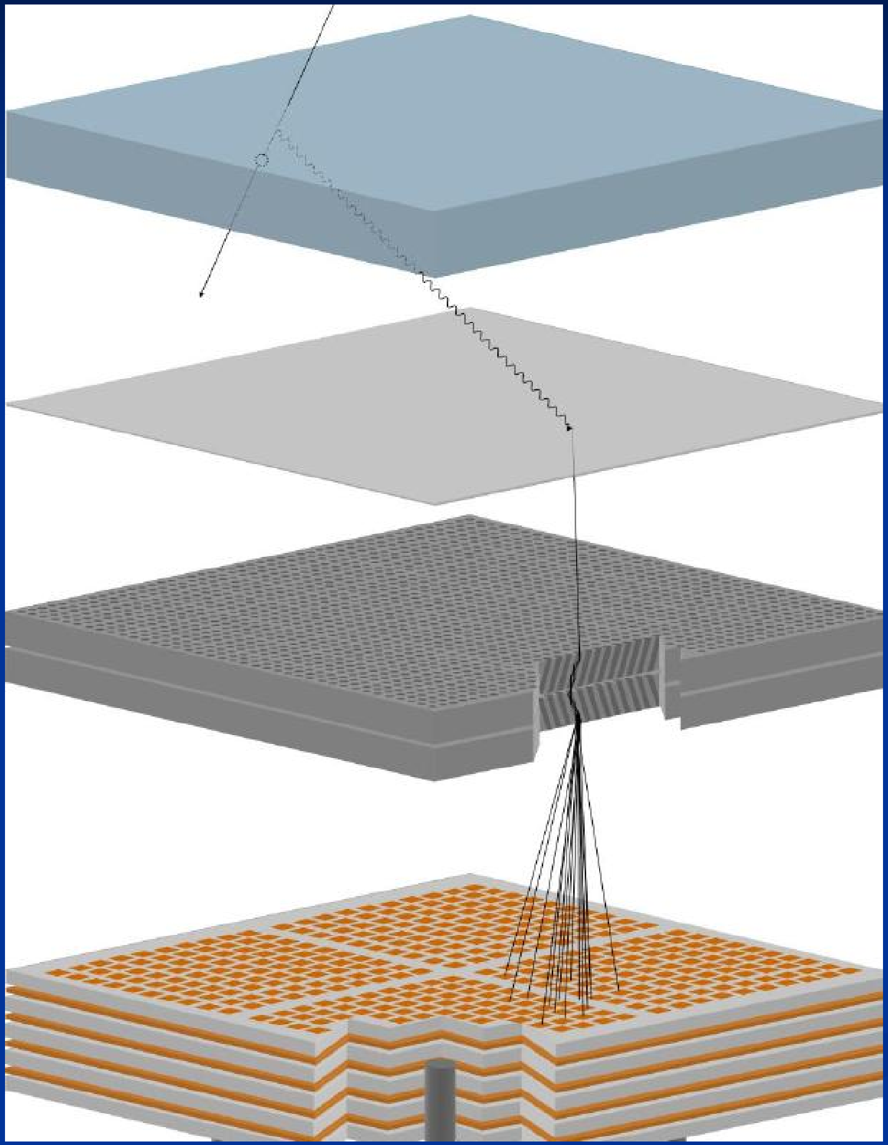
28 sq m (CDF)

25 sq m (LHC)

=>10K MCP’s

Space in the radial direction is expensive- need a thin segmented detector

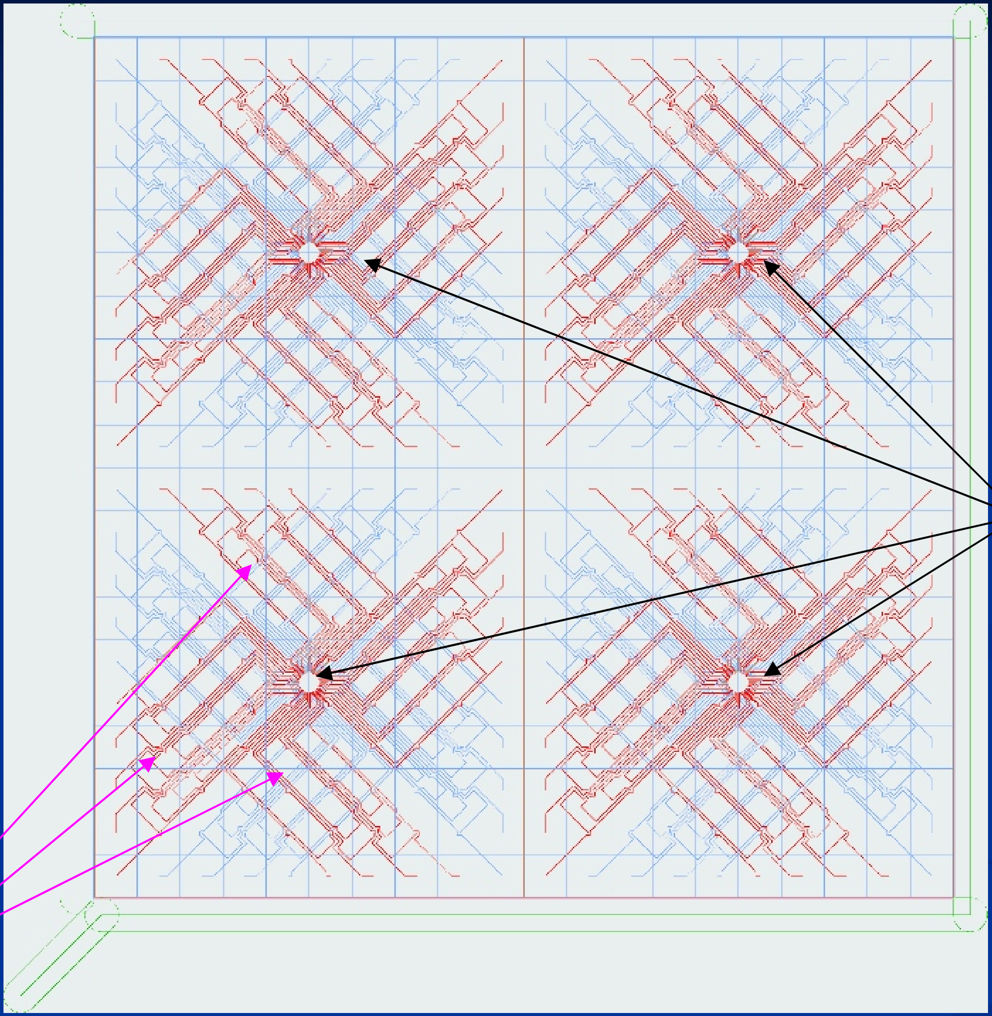
Small dim. Anode Structure?



1. RF Transmission Lines
2. Summing smaller anode pads into 1” by 1” readout pixels
3. An equal time sum- make transmission lines equal propagation times
4. Work on leading edge- ringing not a problem for this fine segmentation

Equal-Time Collector Anode

Module divided into 4 1”x1” pixels (good for CDF,e.g)

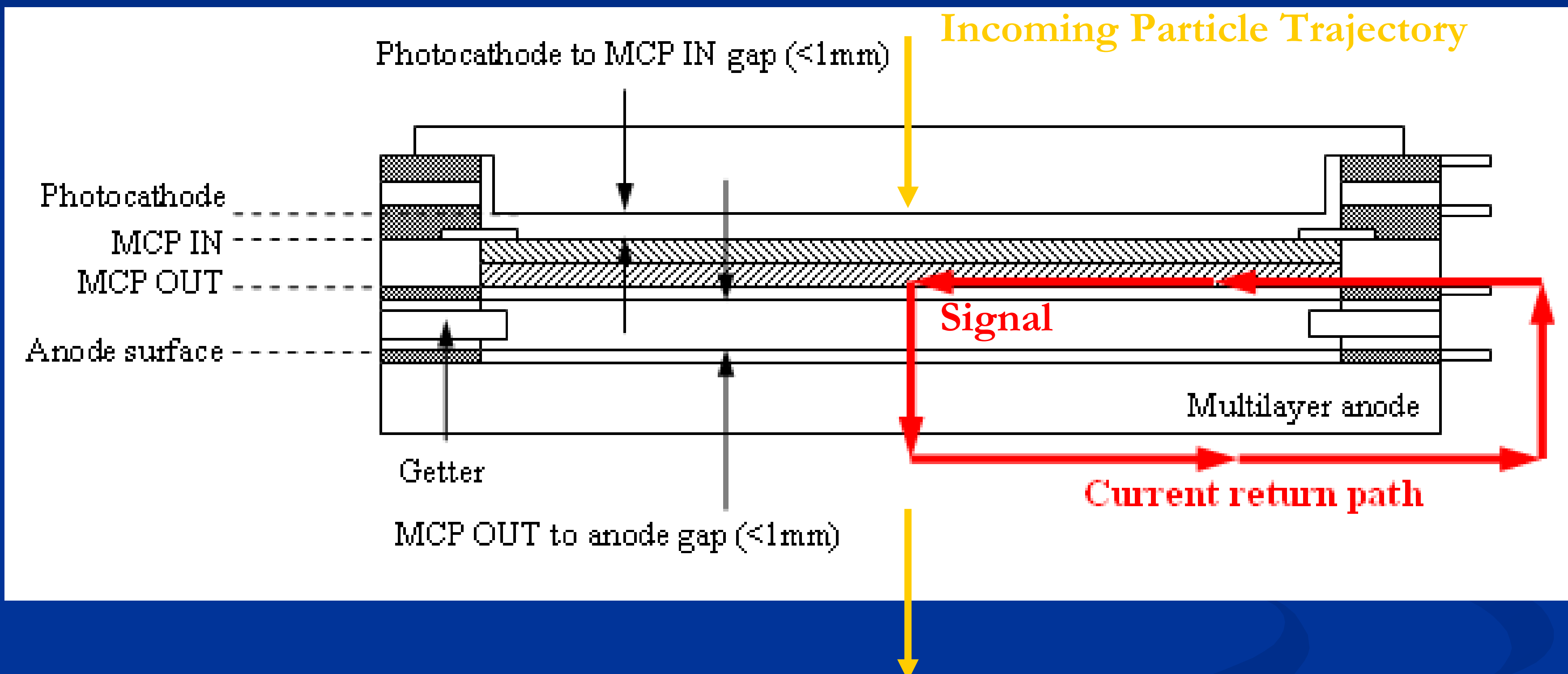


4 differential outputs- each to a 200:1 `time stretcher’ chip (ASIC) directly on back of module

Equal-time transmission-line traces to differential output pins (S and R)

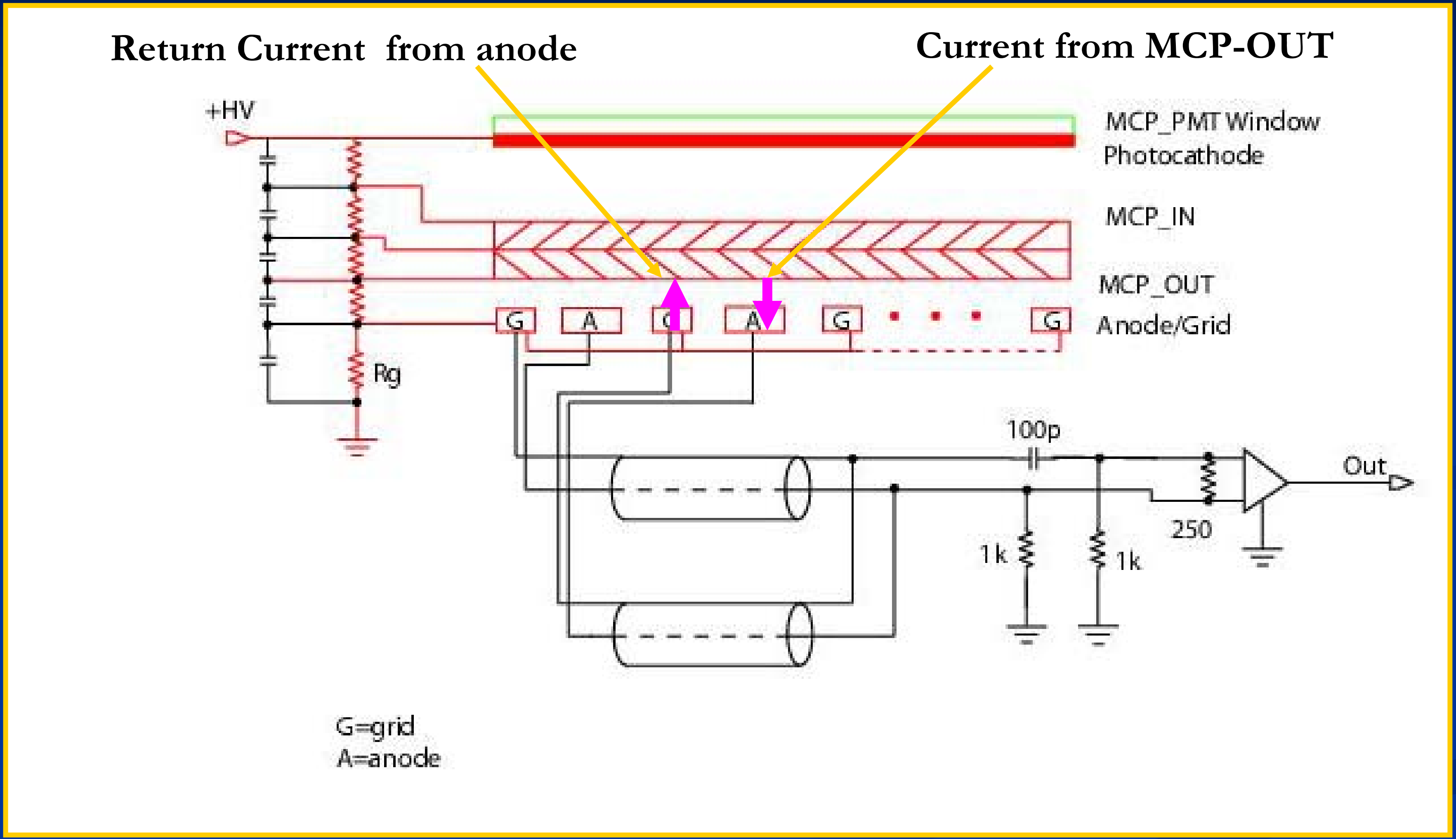
Anode Return Path Problem

Current out of MCP is inherently fast- but return path depends on where in the tube the signal is, and can be long and so rise-time is variable



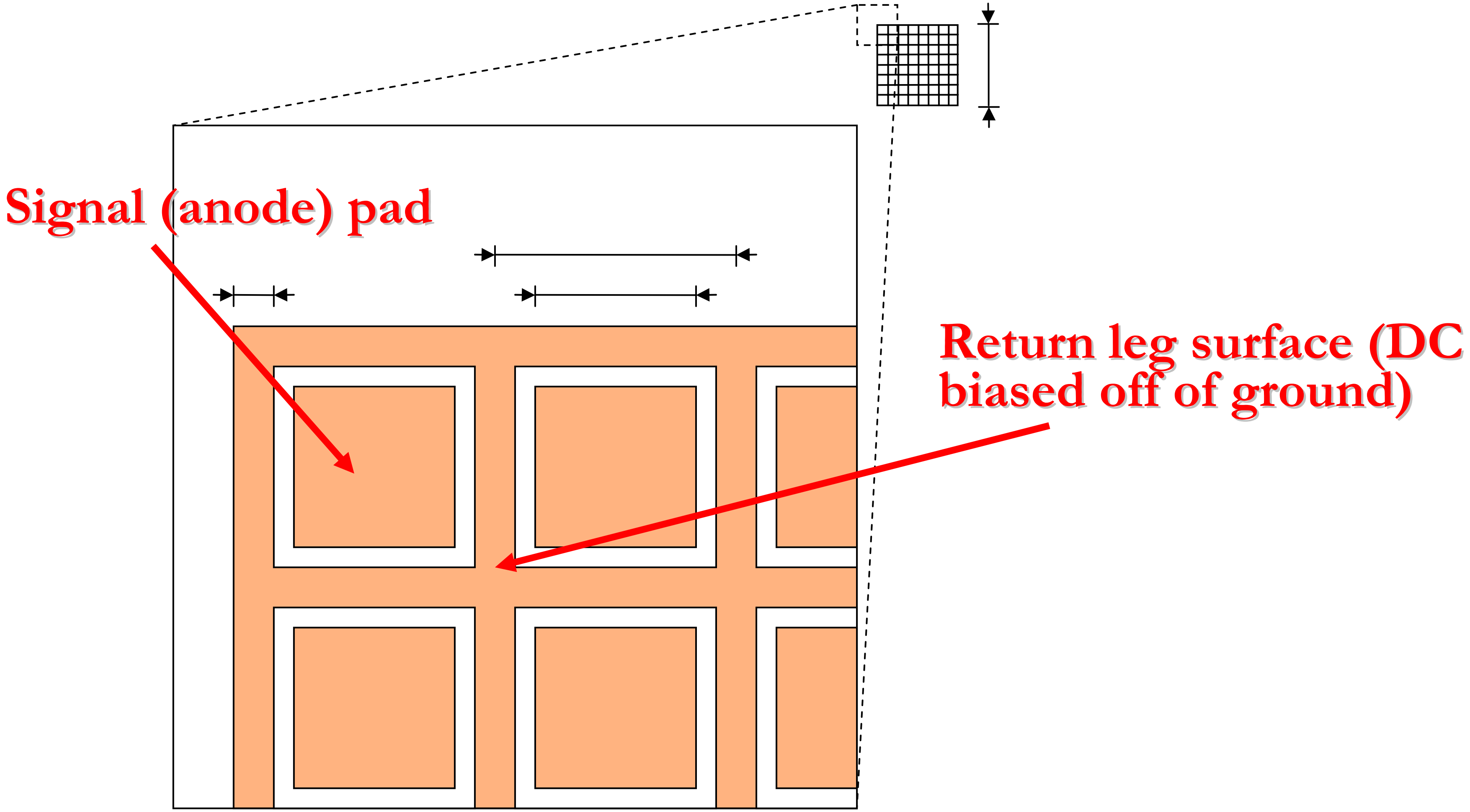
Would like to have return path be short, and located right next to signal current crossing MCP-OUT to Anode Gap

Capacitive Return Path Proposal



Proposal: Decrease MCP-OUT to Anode gap and capacitively couple the return (?)

Solving the return-path problem (?)– Add a grid to the anode layout



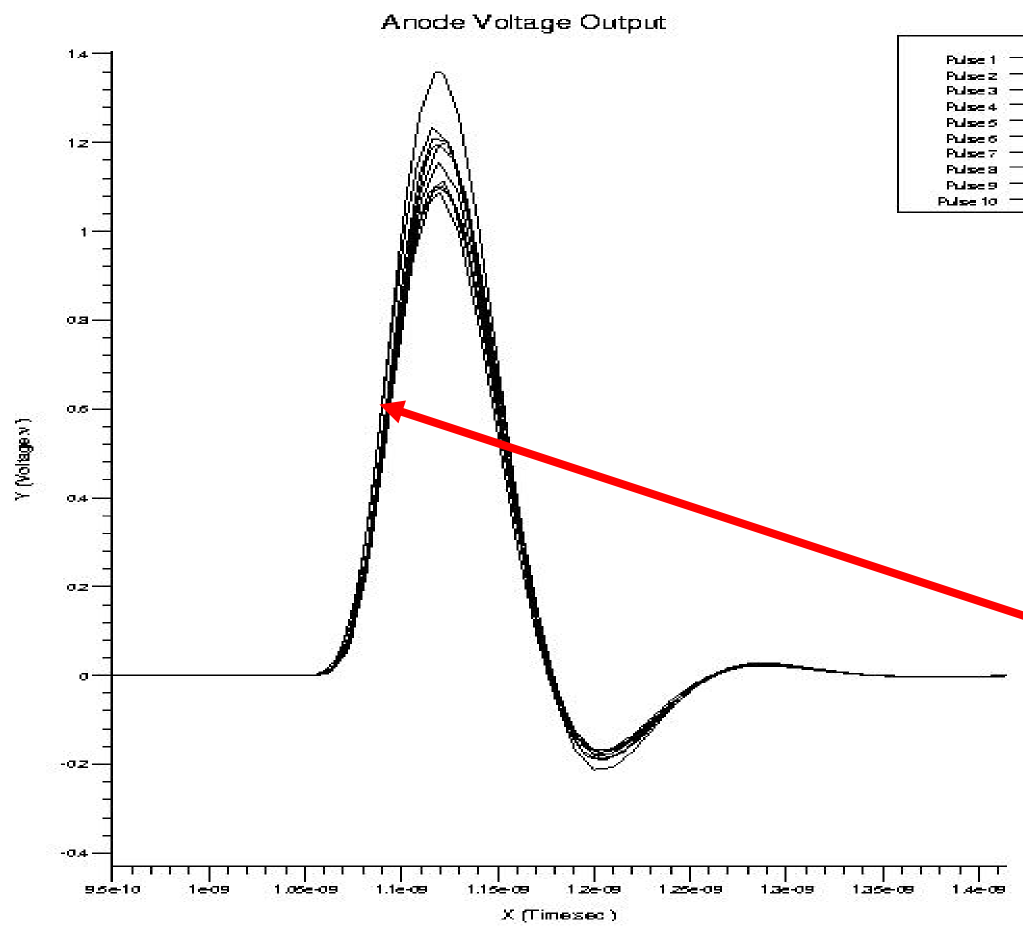
Mounting electronics on back of MCP- matching

Conducting Epoxy- machine deposited by Greg Sellberg (Fermilab)

Temporary Solution for prototyping- can have custom anodes built and installed in MCP

($, but more so time…)

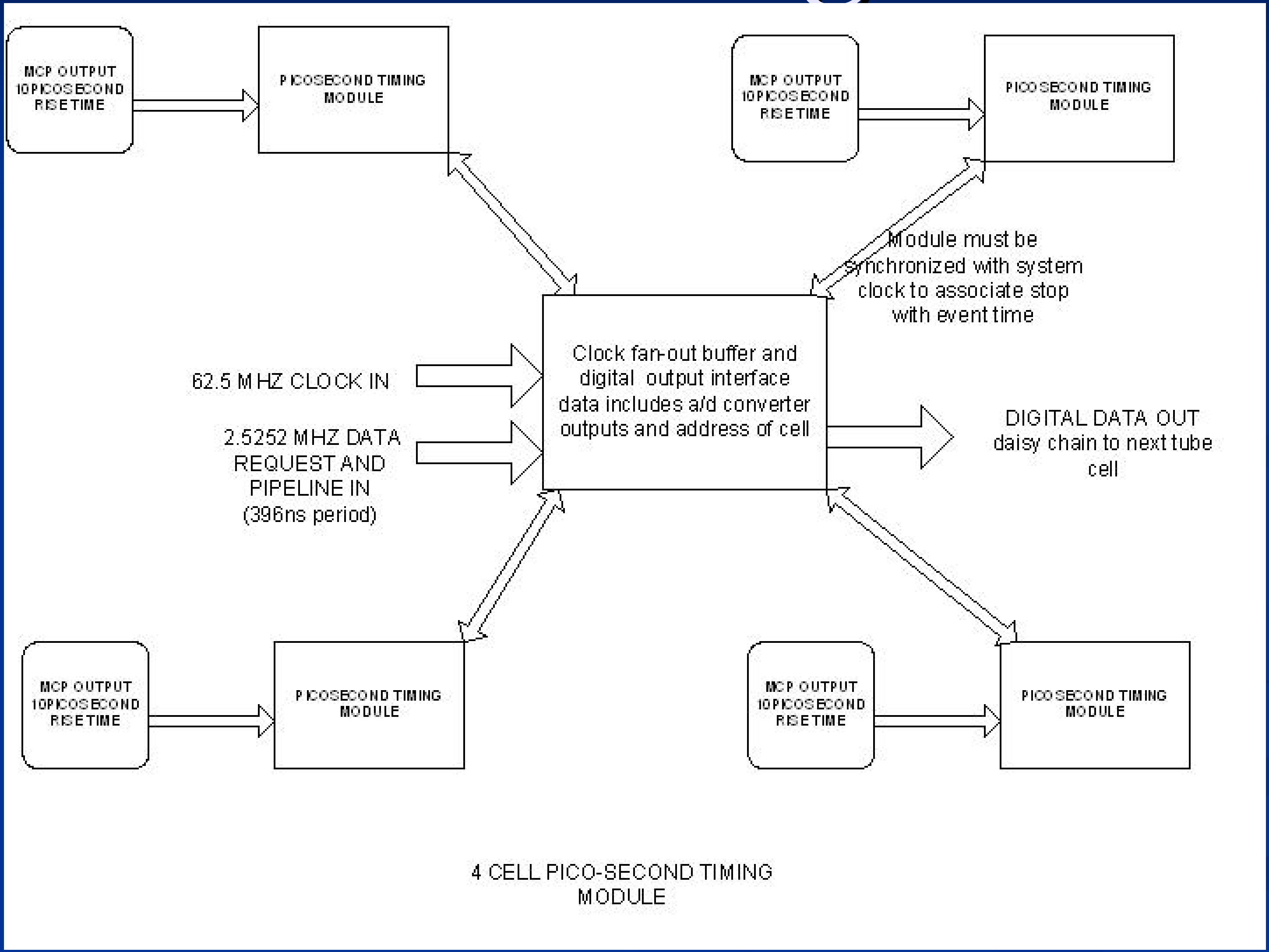
End-to-End Simulation Result



Output at anode from simulation of 10 particles going through fused quartz window- T. Credo, R. Schroll

Jitter on leading edge 0.86 psec

EDG's Unique Capabilities - Harold's Design for Readout



Each module ha
5 chips- 4 TDC
chips (one per
quadrant) and a
DAQ `mother'
chip.

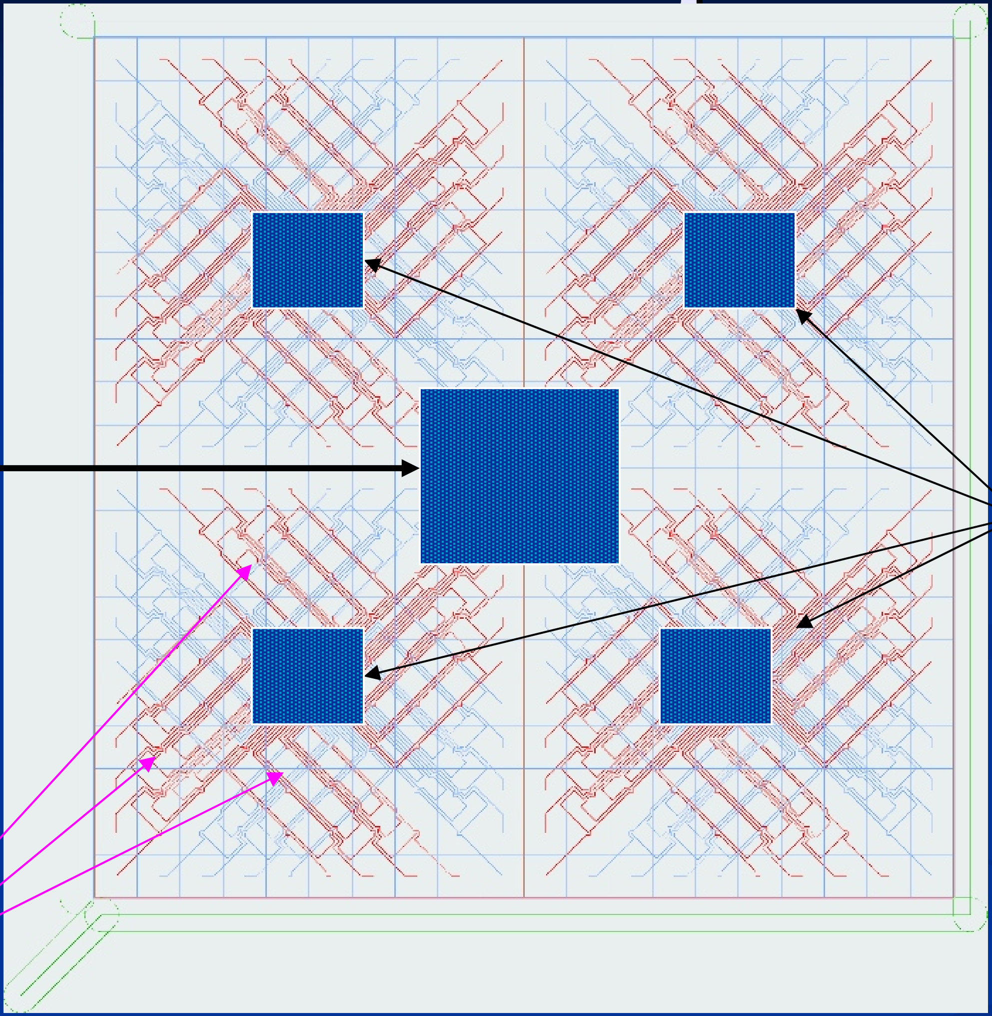
Problems are
stability,
calibration, rel.
phase, noise.

Both chips are
underway

Placement of chips on module

Module divided into 4 1”x1” pixels (good for CDF,e.g)

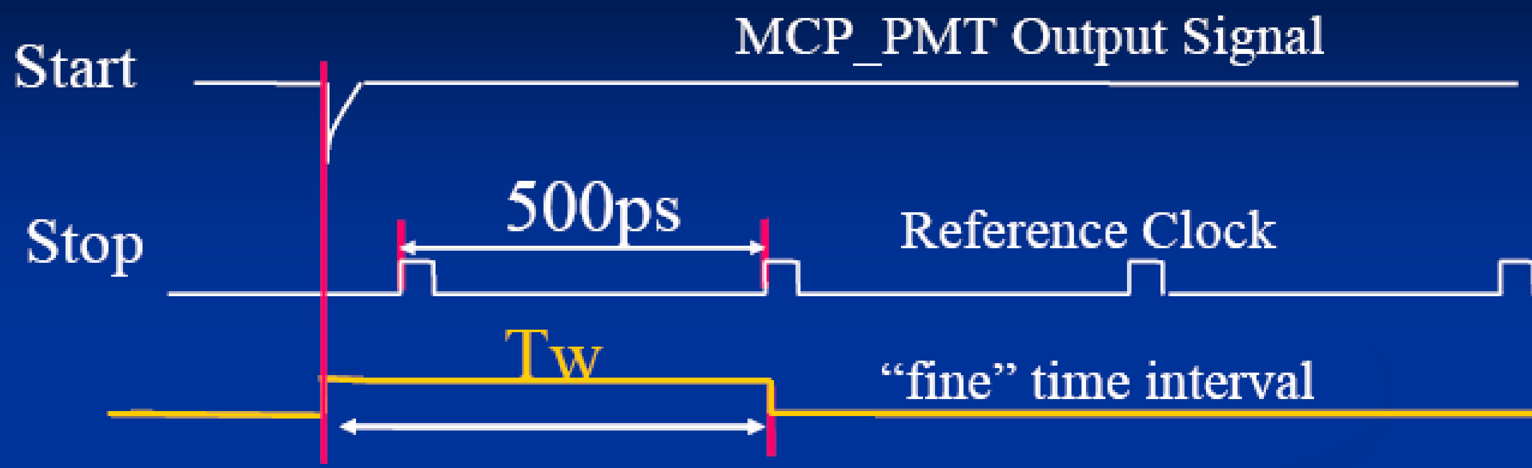
`DAQ’ Chip TDC, digital readout, clock distribution, calibration, housekeeping



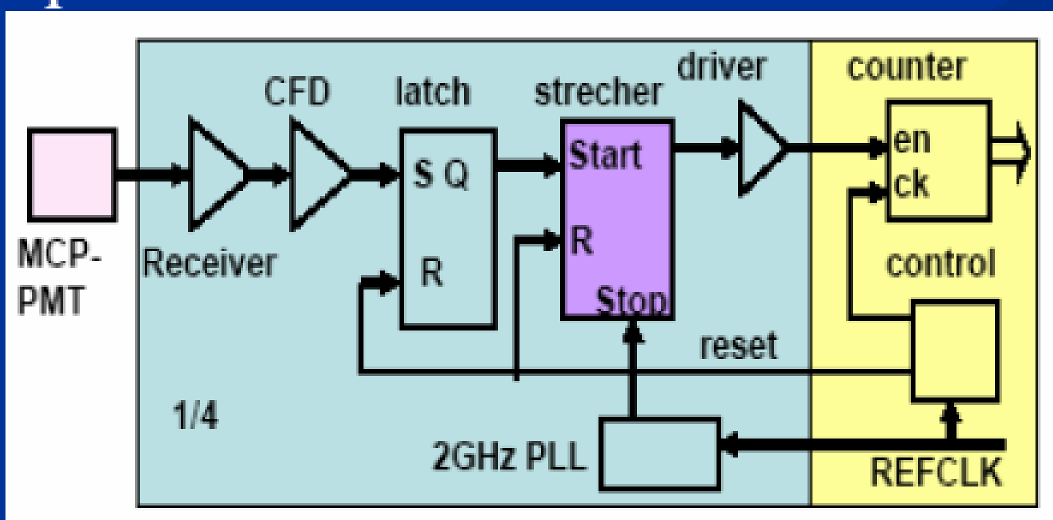
200:1 `time stretcher’ chips

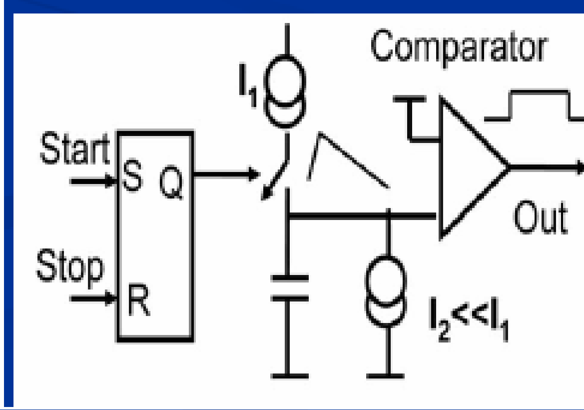
Equal-time transmission-line traces to differential output pins (S and R)

Proposed Time Stretcher TDC with 1ps Resolution



psFront-end





http://hep.uchicago.edu/psec/conf.html Tang slide- March 8, 2007 Saclay France

Tang slide- March 8, 2007 Saclay France

Electronics Requirements & Process Evaluations

Input signal bandwidth:	*~23.3GHz*
Input signal width (FWHM):	*~40ps*
TDC resolution:	*~1ps*

Minimum Requirements:

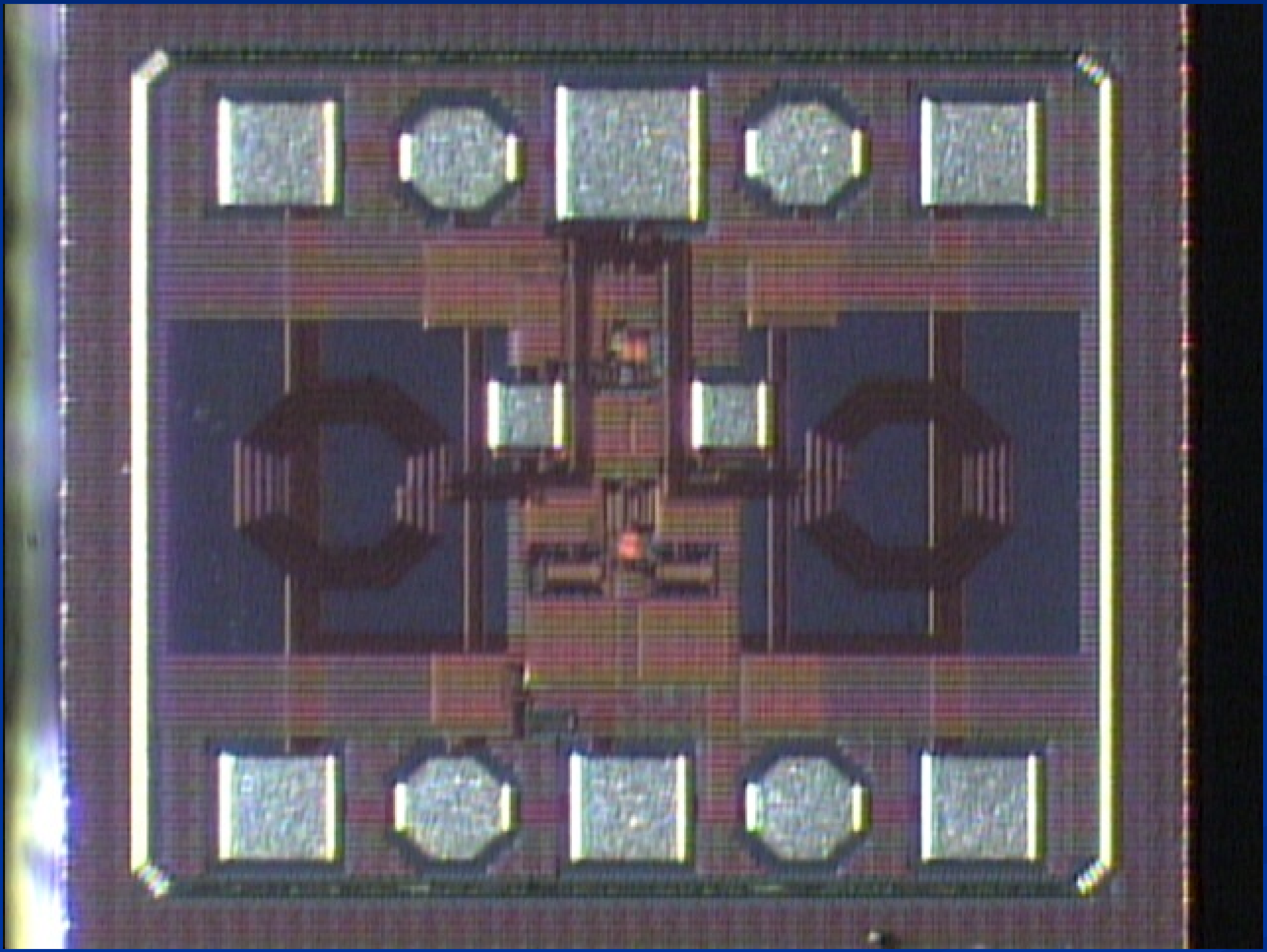
- ultra low noise, ultra high f_T transistors
  - \> 5-10x of the input signal bandwidth ~*(110-220GHz)*
- stable passive components
  - Inductors, MIM Capacitors, Resistors, Varactors …

Available Processes:

- IHP SiGe BiCMOS 0.25µm technology:
  (SG25H1, SG25H2) --- *Europractice*
- IBM SiGe BiCMOS 0.13µm Technology:
  (8HP) --- *MOSIS*

Saclay, France March 8-9 2007

Microphotograph of IHP VCO Chip (submitted through Europractice)



Taken at Fermilab by Hogan –

Design by Fukun Tang

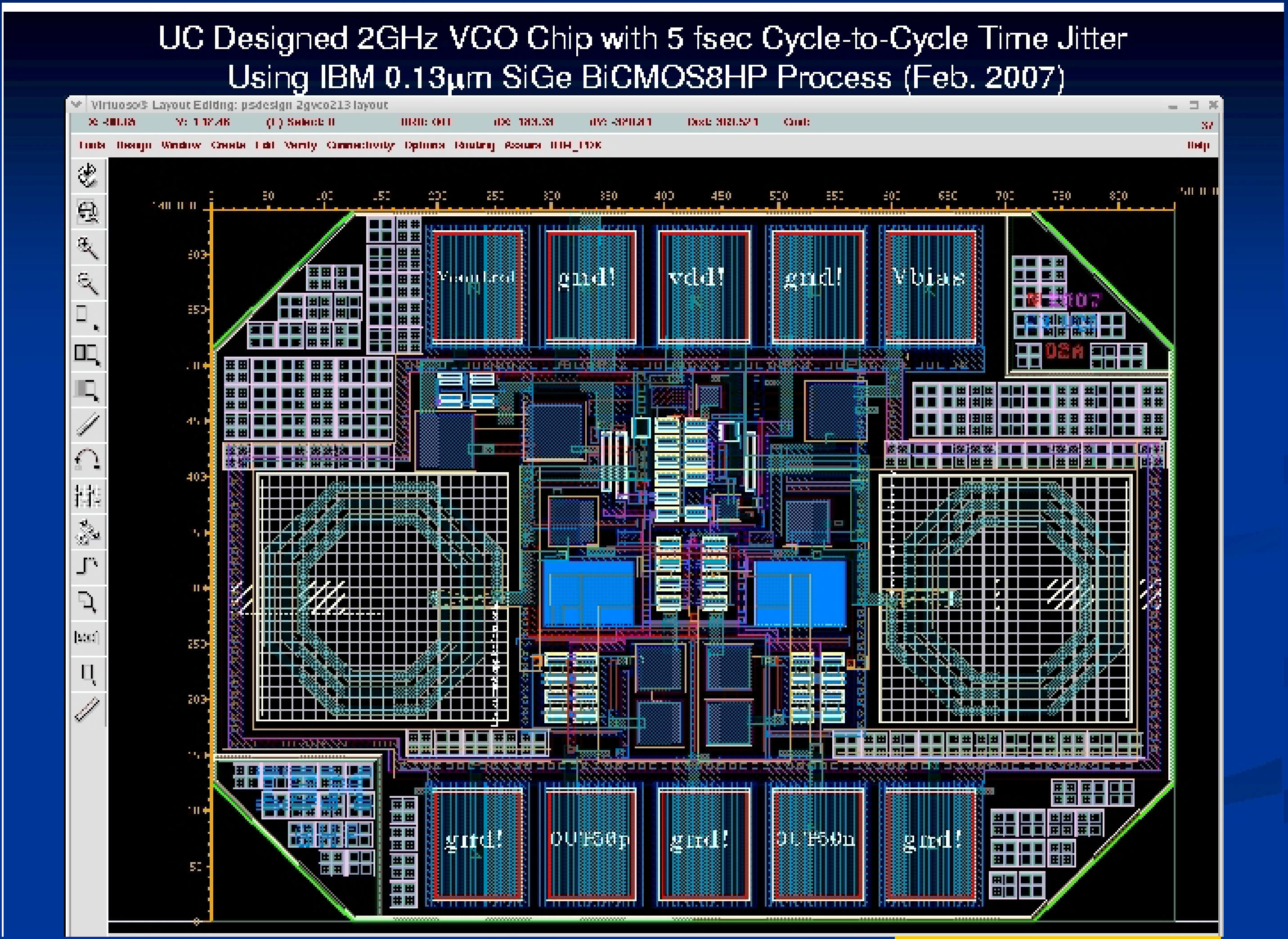
Affordable: <10K/shot

Training Classes (Europe)

But- meager technical support, libraries, … (nice folks tho- structural)

So, switched to IBM 8HP- same 2-GHz VCO in 8HP

Fukun Tang, UC



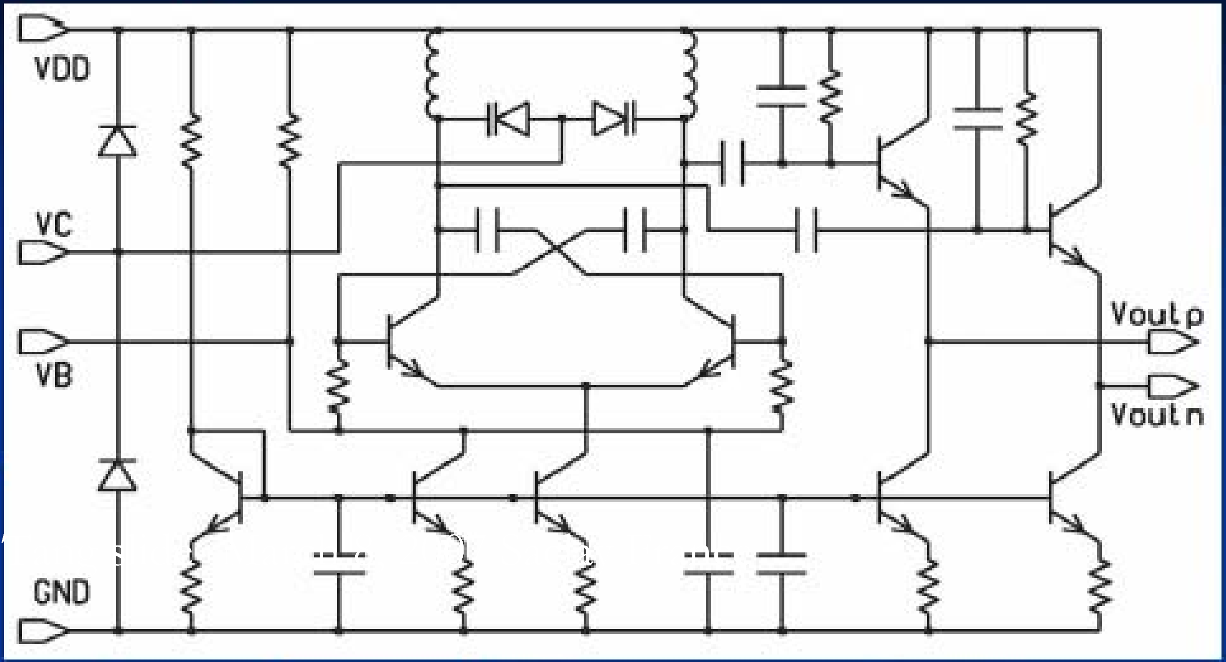
Chip Size: 850x640μ

2GHz VCO Design using IBM SiGe BiCMOS8HP Process

EDA Tools:
Cadence Virtuoso
Analog Environment

Verification Tools:

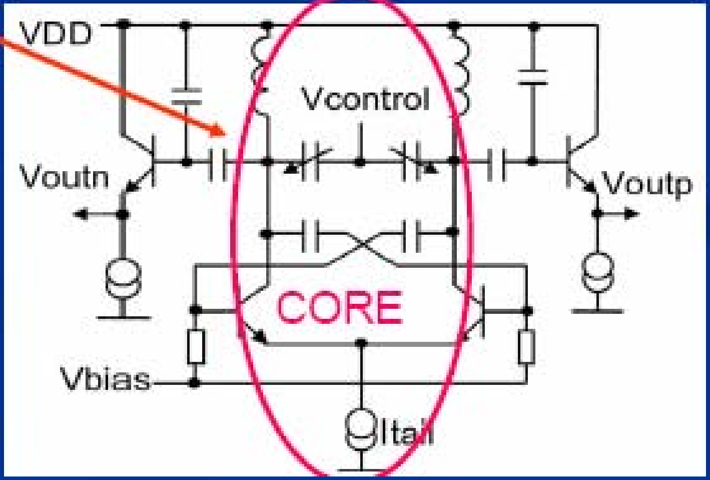
Diva/Assura



Simplified VCO Schematic

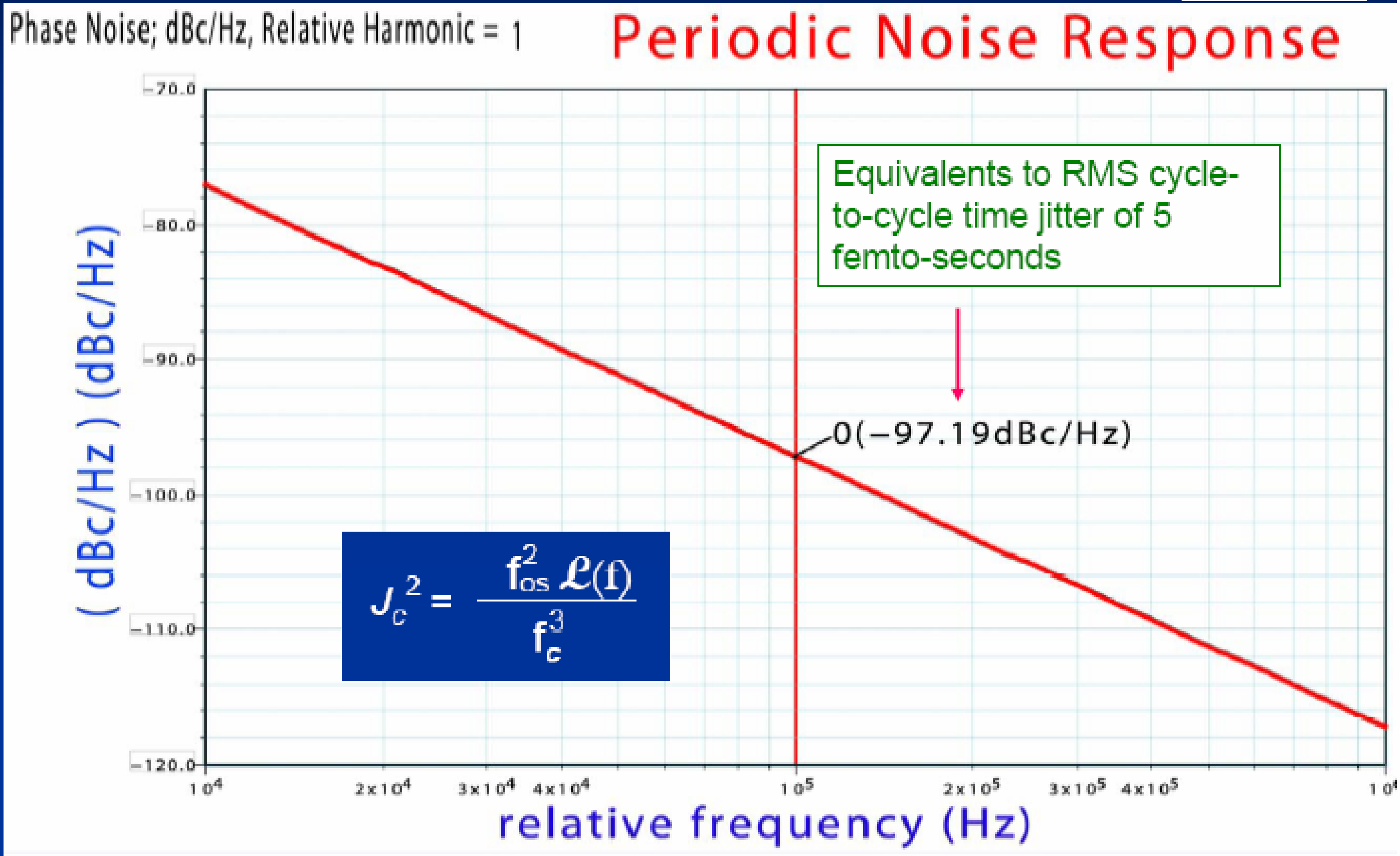
Core

- Purely hetero-junction transistors
- Negative resistance
- On-chip high-Q LC tank
- High Frequency PN diode Varactors
- Capacitor voltage dividers
- 130Mhz tuning range
- Full differential 50-ohm line drivers



VCO Post Layout Simulation Result (Final)

Output Phase Noise Spectra Plot



DAQ Chip- 1/module

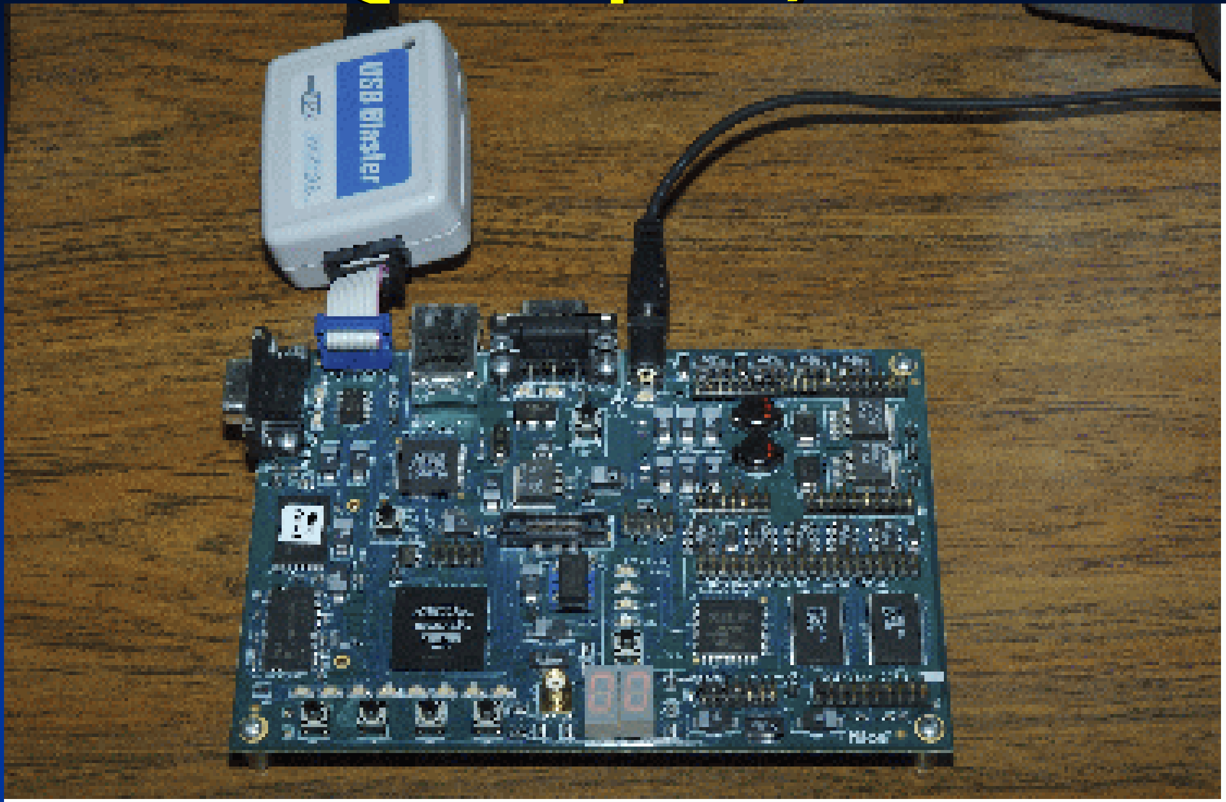


Figure 14: Altera development board with USB JTAG interface.

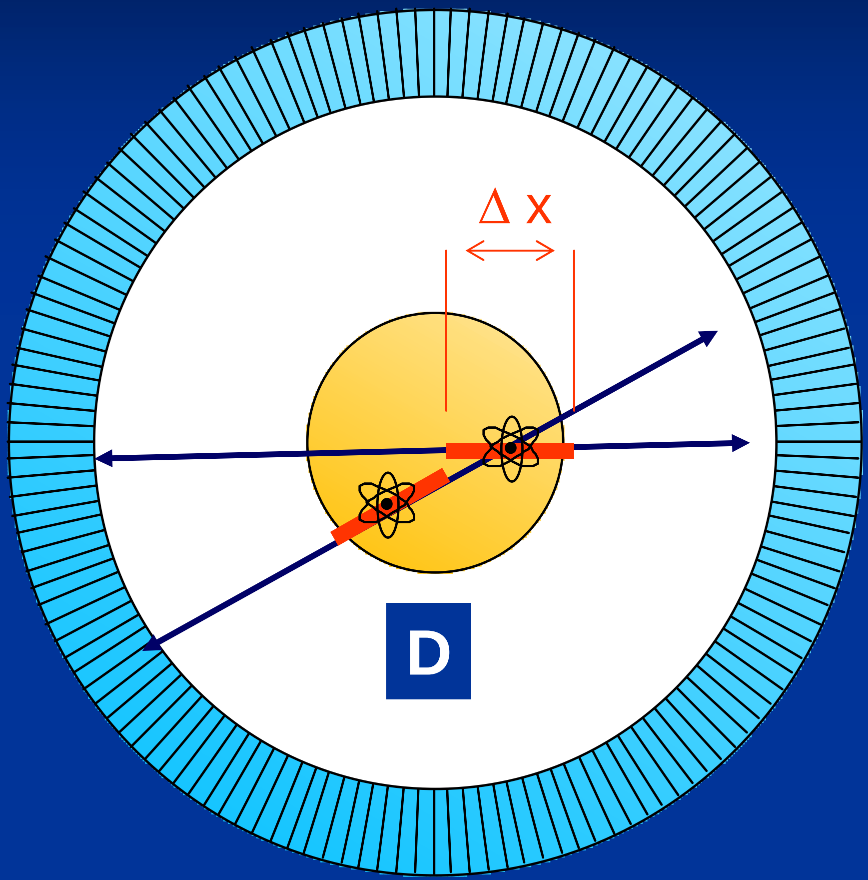
- Jakob Van Santen (4th yr undergrad) implemented the DAQ chip functionality in an Altera FPGA- tool-rich environment allowed simulation of the functionality and VHDL output
- ASIC will be designed at Argonne by John Anderson and Gary Drake.
- Again, simulation means one doesn't have to do trial-and-error.

Why is simulation essential?

- Want optimized MCP/Photodetector design- complex problem in electrostatics, fast circuits, surface physics, ….
- Want maximum performance without trial-and-error optimization (time, cost, performance)
- At these speeds (~1 psec) cannot probe electronics
- Debugging is impossible any other way.

Time-of-Flight Tomograph

Slide from Chin-Tu Chen (UC) talk at Saclay Workshop



- *depends on timing resolution of detectors*
- *weighted back-projection along line-of-response (LOR)*

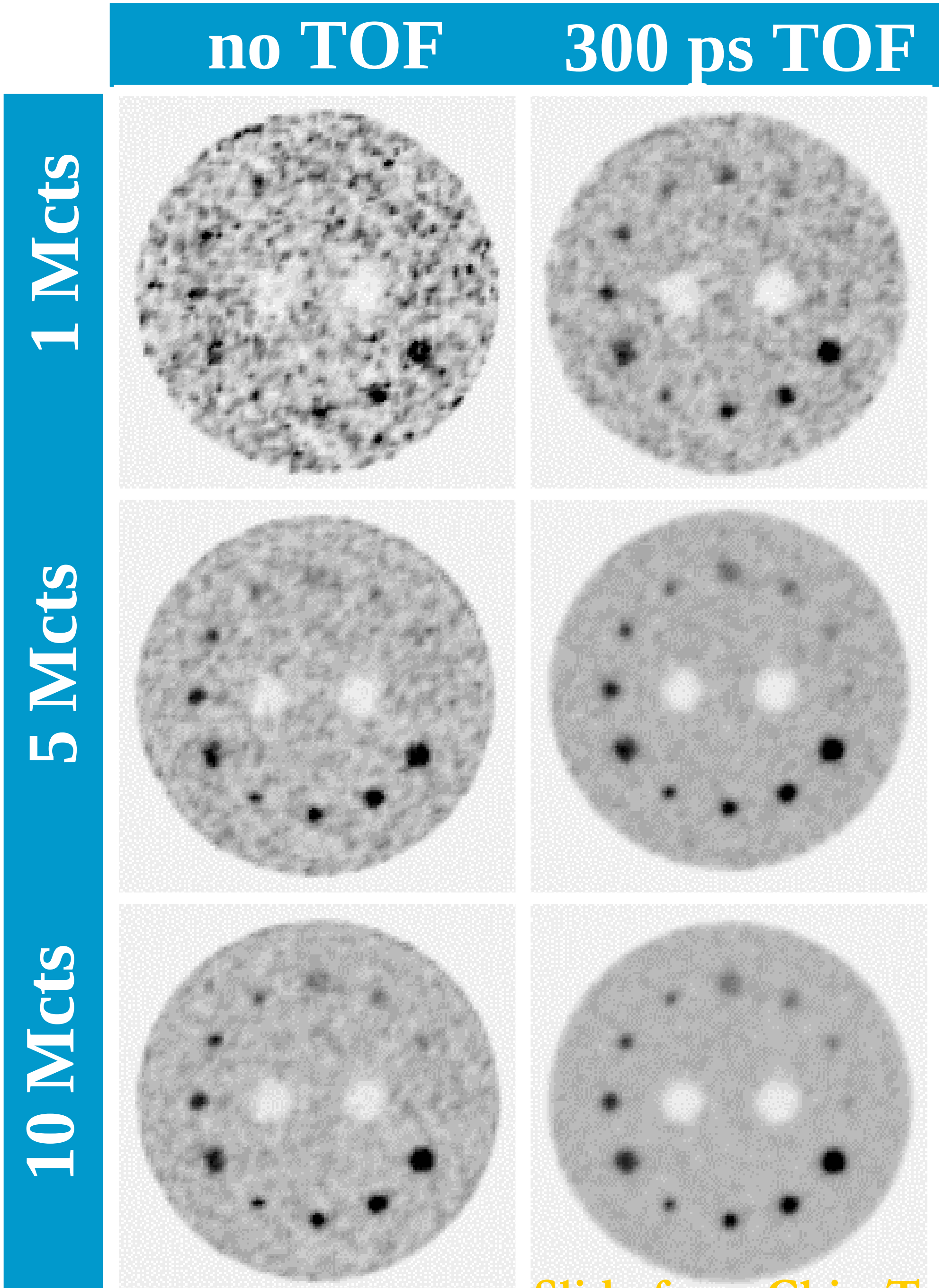
Δ x = uncertainty in position along LOR

= c · Δt/2

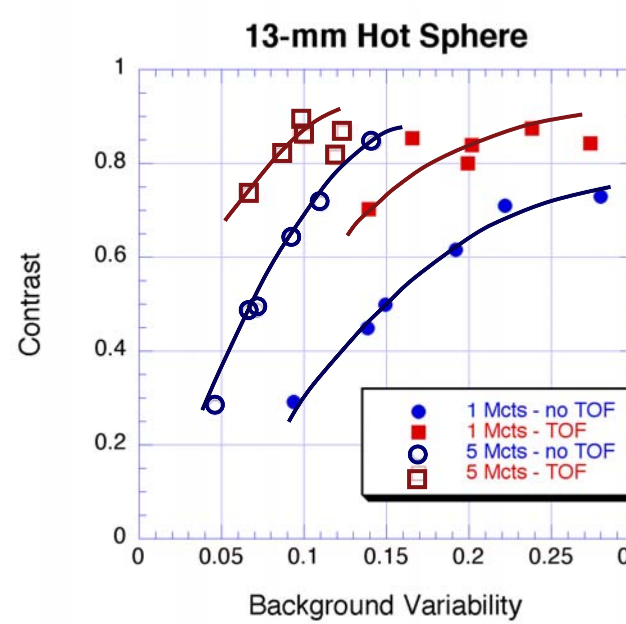
Our goal is 30 psec TOF+reconstruction

Benefit of TOF

Better image quality
Faster scan time

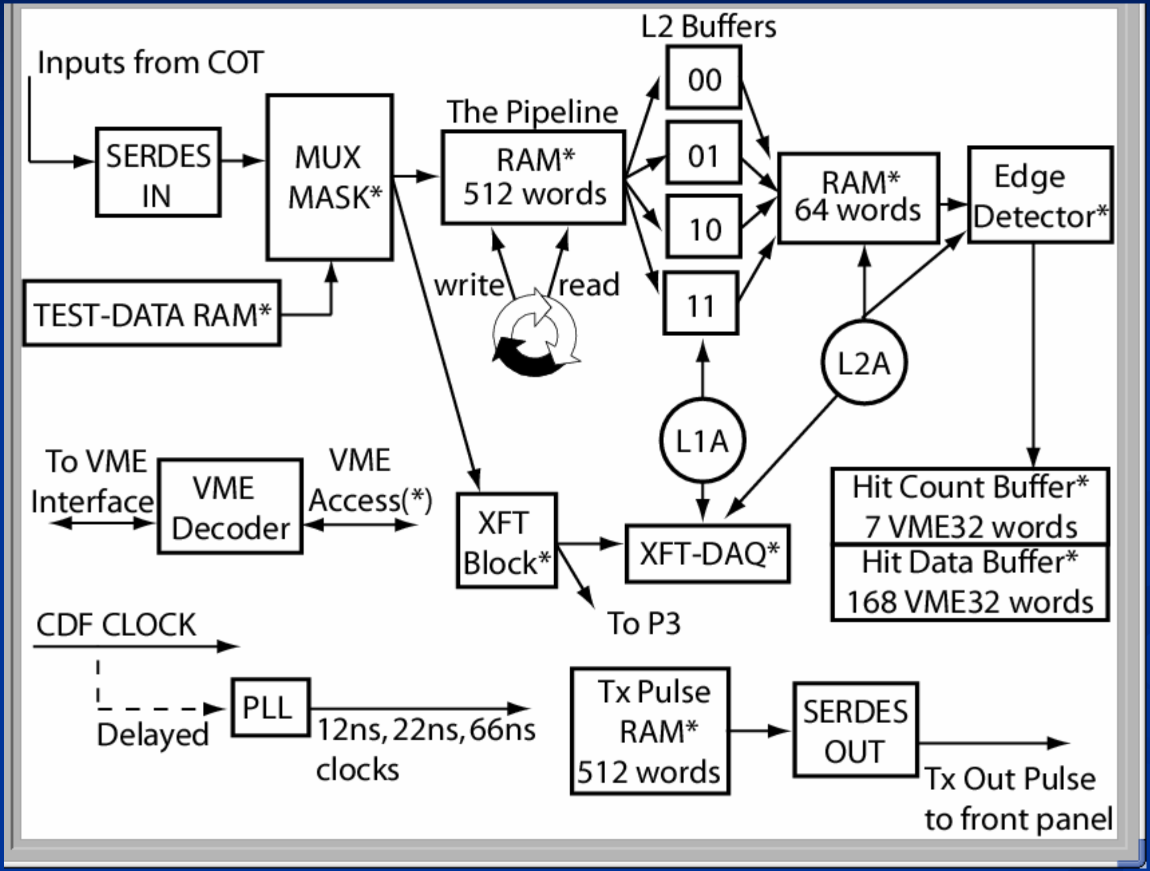


5Mcts TOF
5Mcts
1Mcts TOF
1Mcts



Slide from Chin-Tu Chen (UC) talk at Saclay Workshop

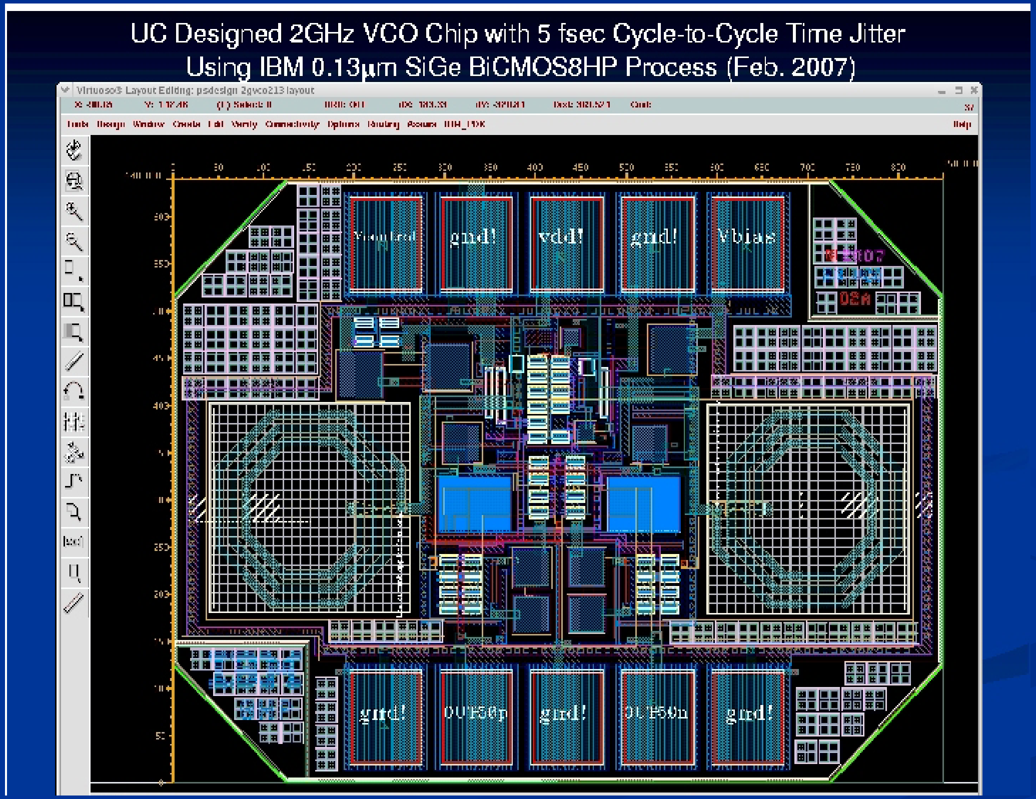
Back-end Processing for PET



Example of a TDC for CDF we designed in Altera- has trigger logic, pipeline, pattern recognition, ….- lots of local `region-of-interest' analysis. Speeds real-time imaging. 48 channels/chip

Status of First (VCO) Chip Submission

- Were on path for Feb 26 MOSIS submission of VCO with 8HP…
- Tapeout/Details available at http://edg.uchicago.edu/psec/
- Starting on Phase-Detector; then Charge-Pump; then Const. Fraction Discriminator- long ways to go! (we are beginners…)



SOME REFERENCES

Saclay Workshop (March 8,9-07; talks on PET, Detectors, Electronics, Simulation… (in particular see talks of Chen, LeDu, Genat, Jarron,…)

http://indico.cern.ch/contributionListDisplay.py?confId=13750
http://hep.uchicago.edu/psec/conf.html

ANL/UC effort, links (workshops, talks,references…)

http://hep.uchicago.edu/psec/

http://hep.uchicago.edu/~frisch/

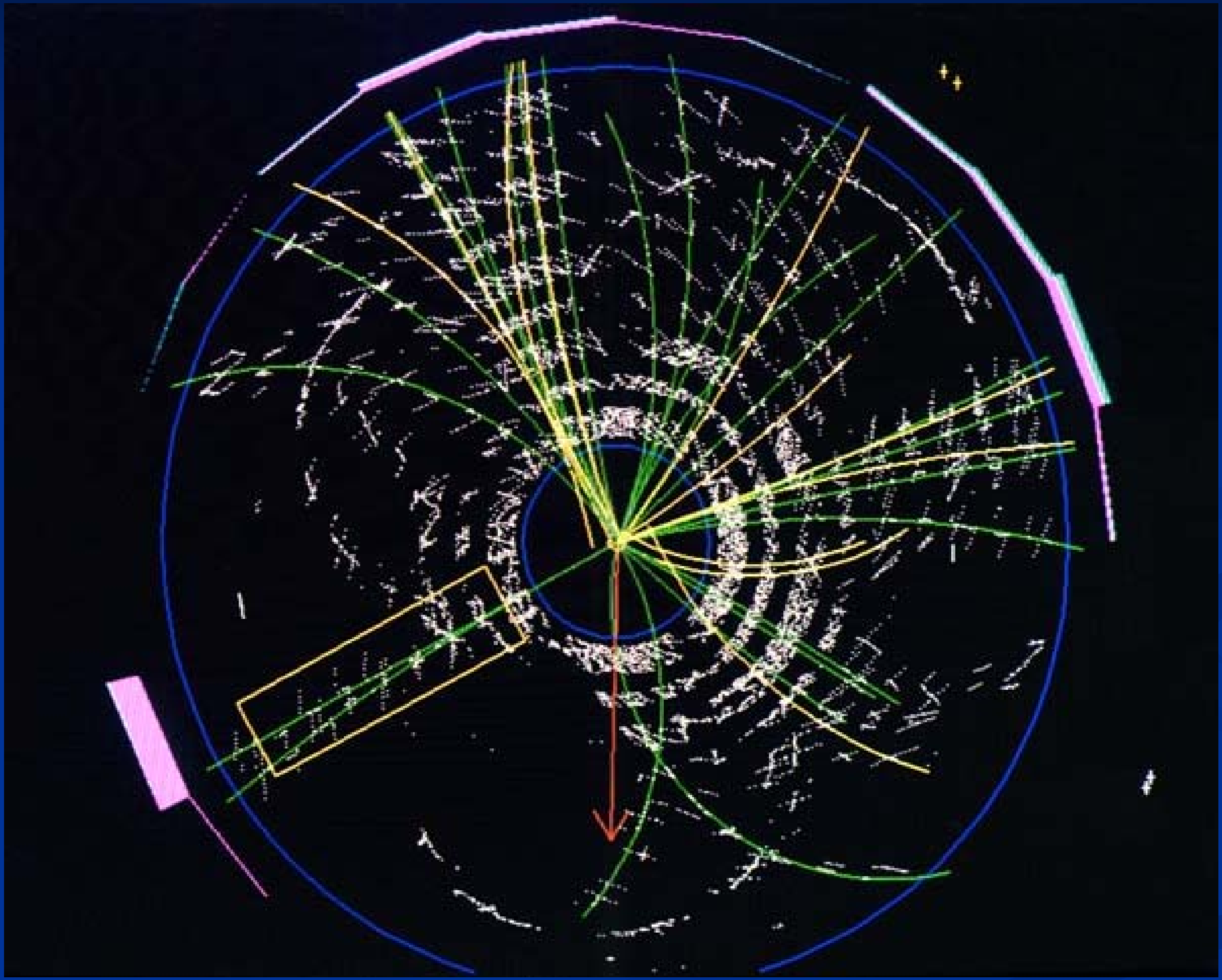
J. Va'vra et al latest paper: on MCP timing:

Nucl. Inst. Mett A572, 459 (2007)

Questions (we are just starting)

1. What determines the ultimate limits?
2. Are there other techniques? (e.g. SiPM's, …)?
3. Could one integrate the electronics into the MCP structure- 3D silicon (Paul Horn, Pierre Jarron)?
4. Will the capacitative return work?
5. How to calibrate the darn thing (a big system)?!
6. How to distribute the clock
7. What is the time structure of signals from crystals in PET? (photon arrival at psec level)
8. Can we join forces with others and go faster?

The End-



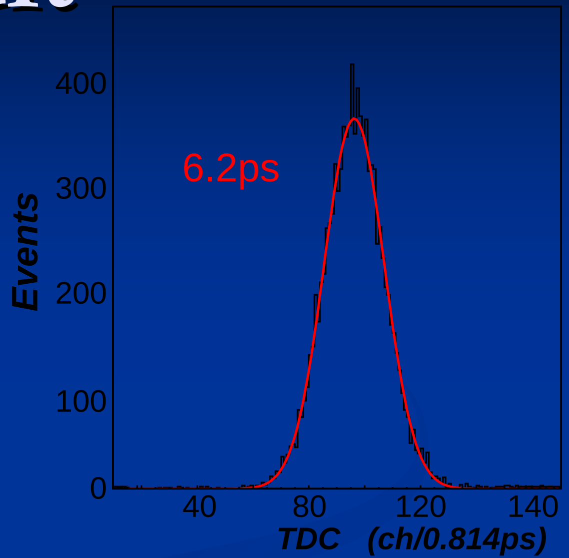
Backup Slides

Slide from K.Inami (Nagoya university, Japan)- http://indico.cern.ch/contributionListDisplay.py?confId=13750

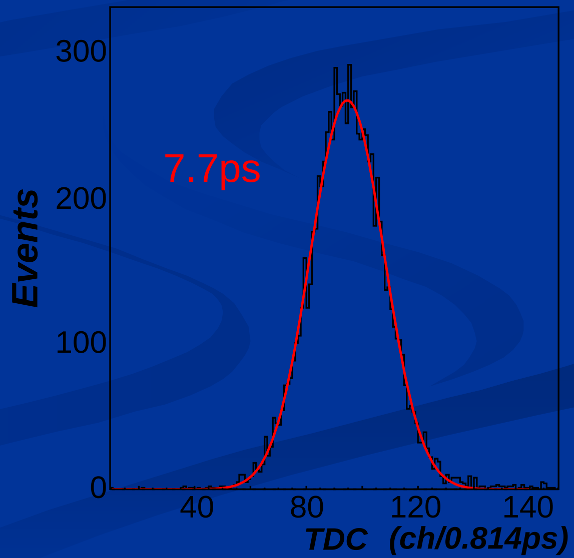
Beam test result

Jerry Va'vra has new similar results (see ref's)

- With 10mm quartz radiator
  - +3mm quartz window
  - Number of photons ~ 180
  - Time resolution = 6.2ps
  - Intrinsic resolution ~ 4.7ps



- Without quartz radiator
  - 3mm quartz window
  - Number of photons ~ 80
    - Expectation ~ 20 photo-electrons
  - Time resolution = 7.7ps



Slide from Chin-Tu Chen (UC) talk at Saclay Workshop –see url in references….

PET, TOFPET & SPECT

Disclaimer- I know almost nothing about PET- need Chin-Tu or Patrick LeDu!

Chin-Tu Chen

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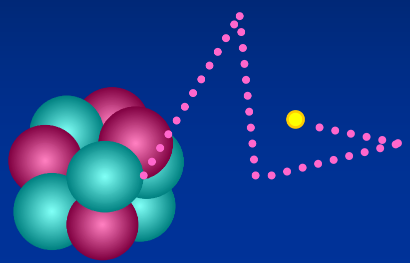
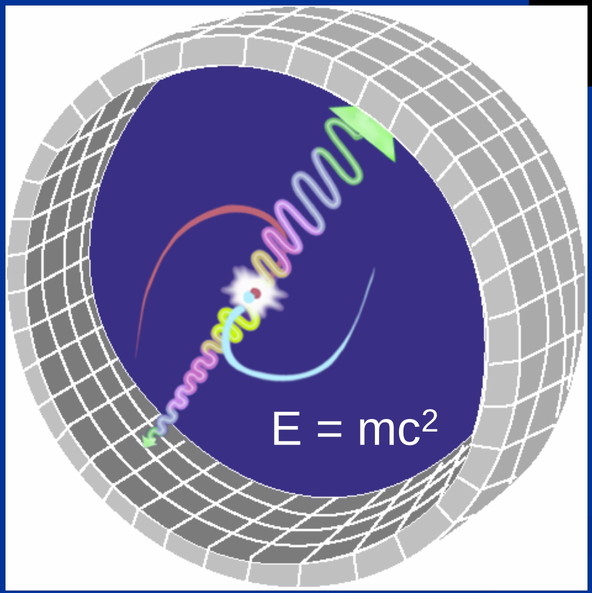
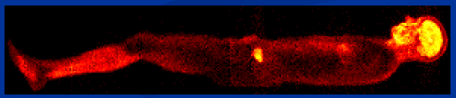
PET Principle



P ⟶ N + e^+ + n + energy





Slide from Chin-Tu Chen (UC) talk at Saclay Workshop

TOFPET DREAM

Slide from Chin-Tu Chen (UC) talk at Saclay Workshop

30 picosec TOF

4.5 mm LOR Resolution

30-50 may be possible (LeDu)

10 picosec TOF

1.5 mm LOR Resolution

3 pico-sec TOF

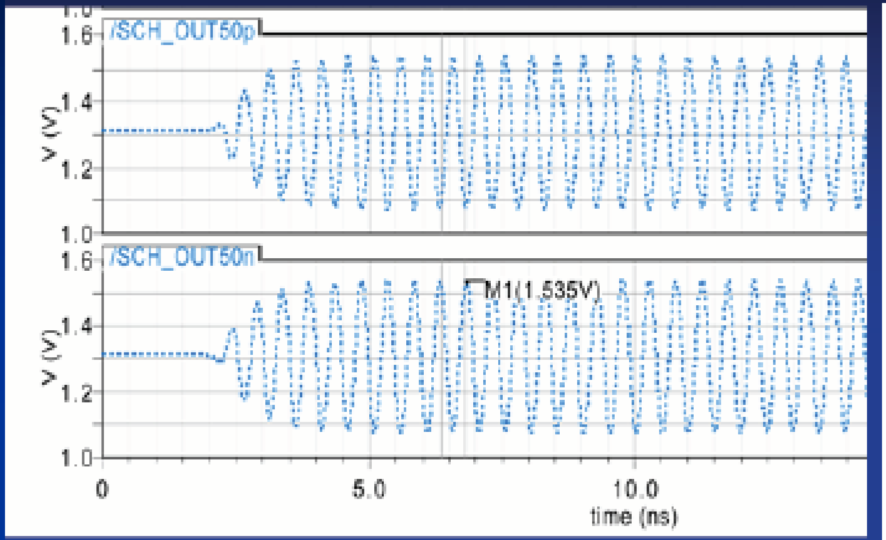
0.45 mm LOR Resolution

Histogramming

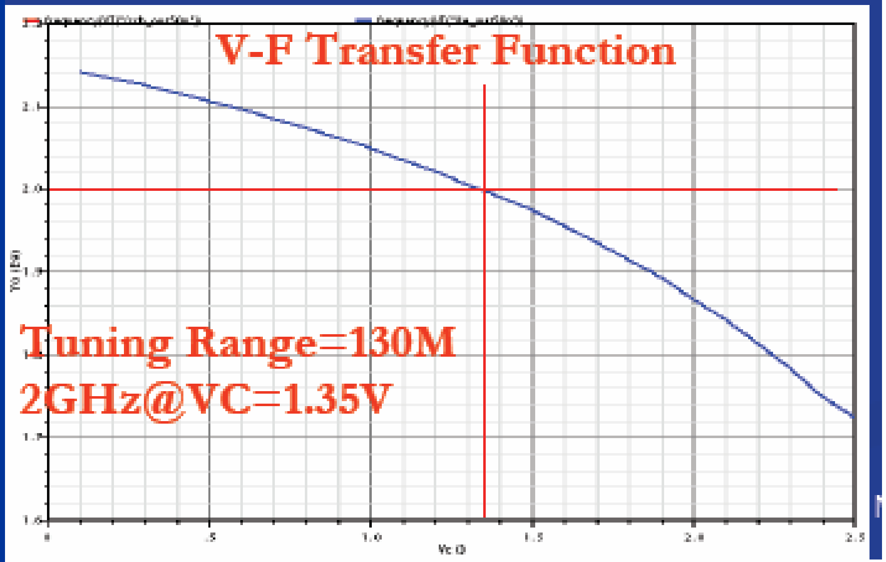
No "Reconstruction"

VCO Schematic (Pre-layout) Simulation Result

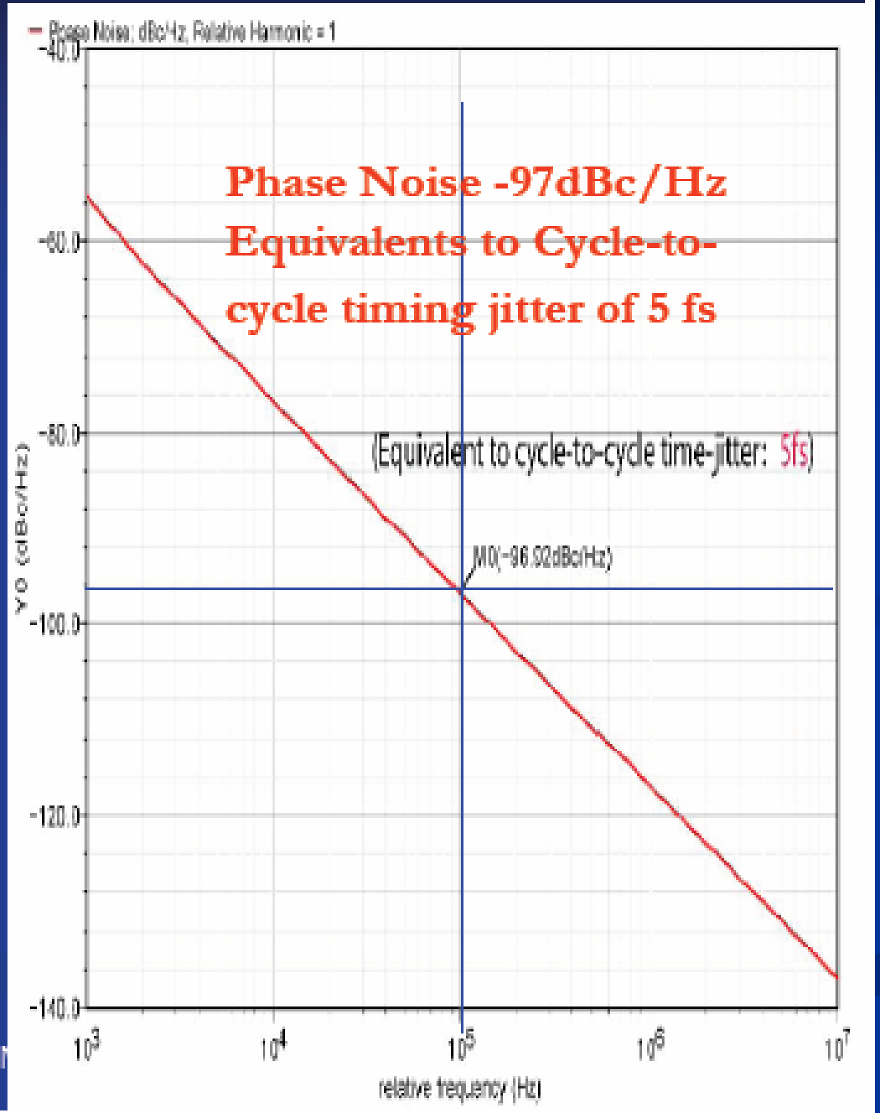
Transit Outputs



V-F Transfer Function



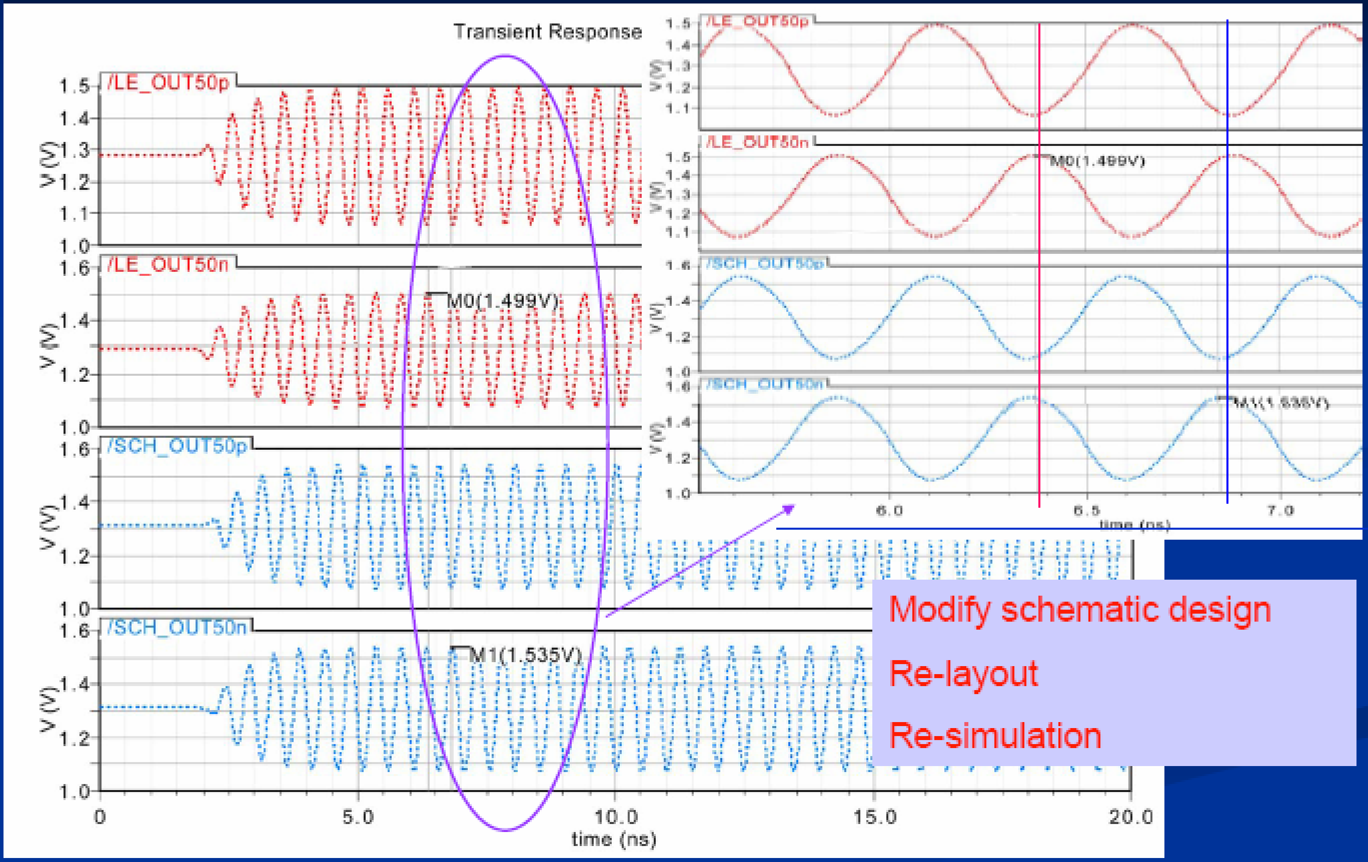
Phase Noise



Tang slide: http://hep.uchicago.edu/psec/conf.html

VCO Post Layout Transit Simulation Result (Final)

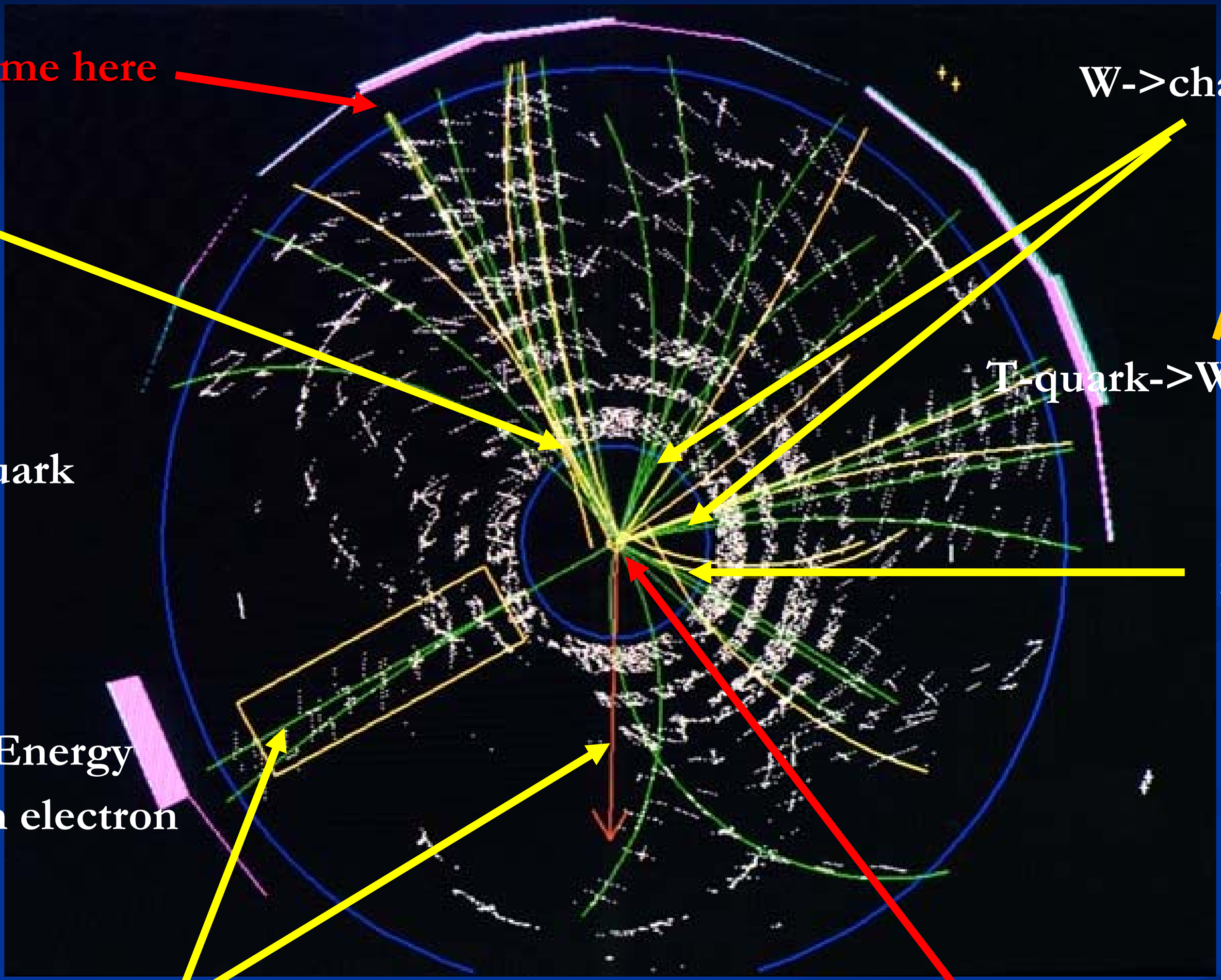
Transit Output Waveforms



Saclay, France March 8-9 2007

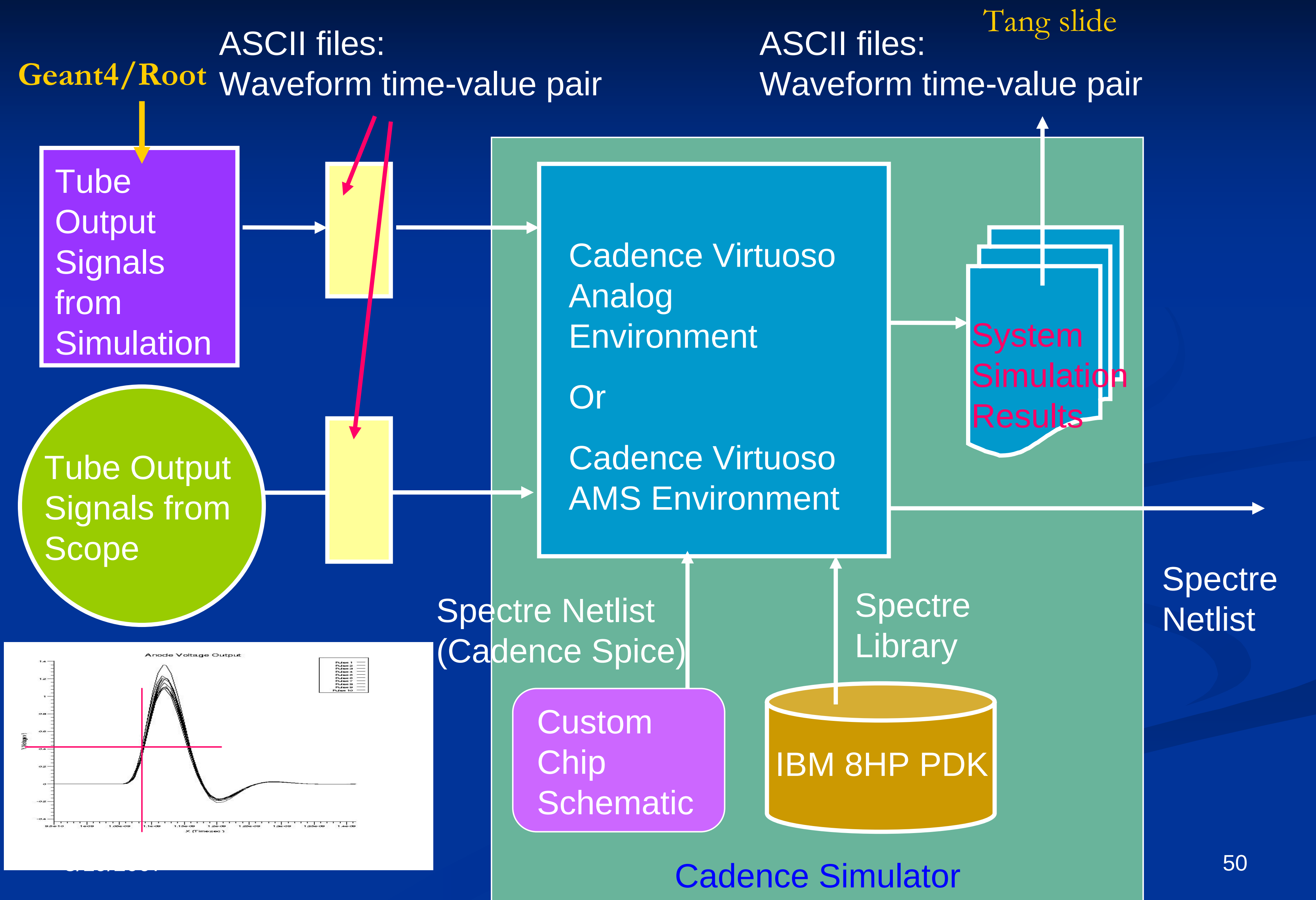
The Future- Triggering?

T-Tbar -> W^+bW^-bbar



Can we follow the color flow of the partons themselves?

Interface to Other Simulation Tools



Questions on Simulation-Tasks (for discussion at Saclay)

1. Framework- what is the modern CS approach?
2. Listing the modules- is there an architype set of modules?
3. Do we have any of these modules at present?
4. Can we specify the interfaces between modules- info and formats?
5. Do we have any of these interfaces at present?
6. Does it make sense to do Medical Imaging and HEP in one framework?
7. Are there existing simulations for MCP's?

What sets the 1 psec goal for HEP?

Separation with a 1.5-m Radius Solenoid (CDF)

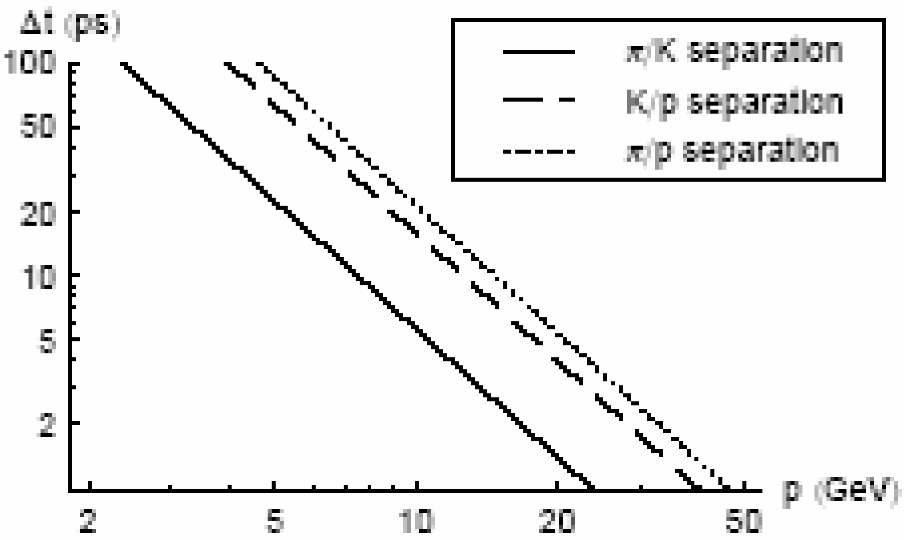


Figure 4: Contours of 1-sigma separation for pions, kaons, and protons versus the time resolution of the particle flight time over a 1.5-meter path for a detector with 1psec resolution.

Getting the Start Time: t_0.

Collisions at the Tevatron (e.g.) have a distribution in times with a sigma of ≈ 1.4 nsec (1.4 thousand psec's). Rather than measure the start time, t_0, at the origin, we fit the tracks from a single vertex for the t_0.
At present we do this with the tracking chamber (COT), with a resolution on the order of a nsec.
At CDF: t_0 is correlated with z_{vertex}! (From the new TAMU EM timing system in CDF (Goncharov, Krutelyov, Toback)).

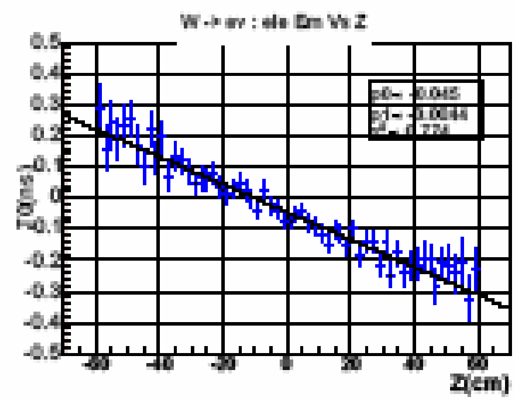


Figure 5:

Point is that each vertex has a time– fitting the tracks can tie charged particles to vertices. Fitting photons likewise is also possible if we know L, as we know beta.

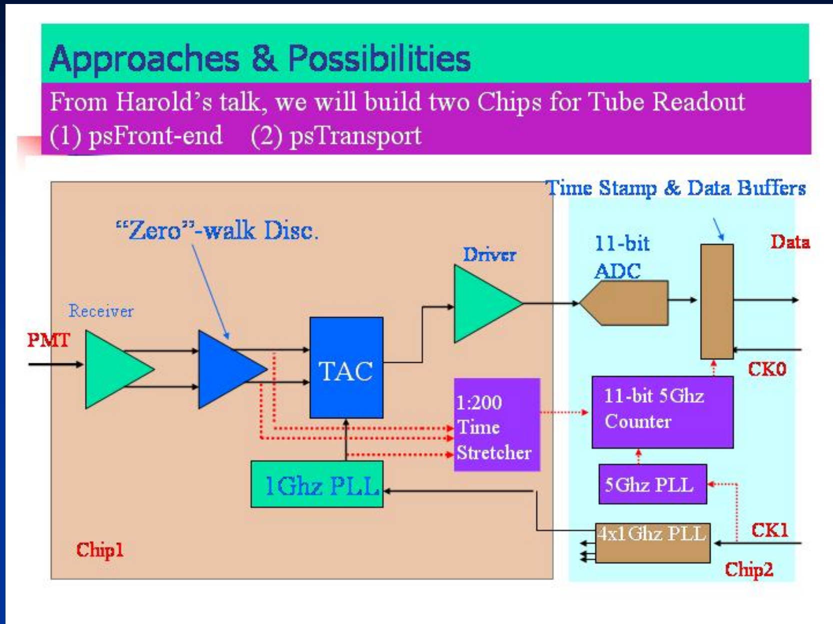
Simulation for Coil Showering and various PMTs

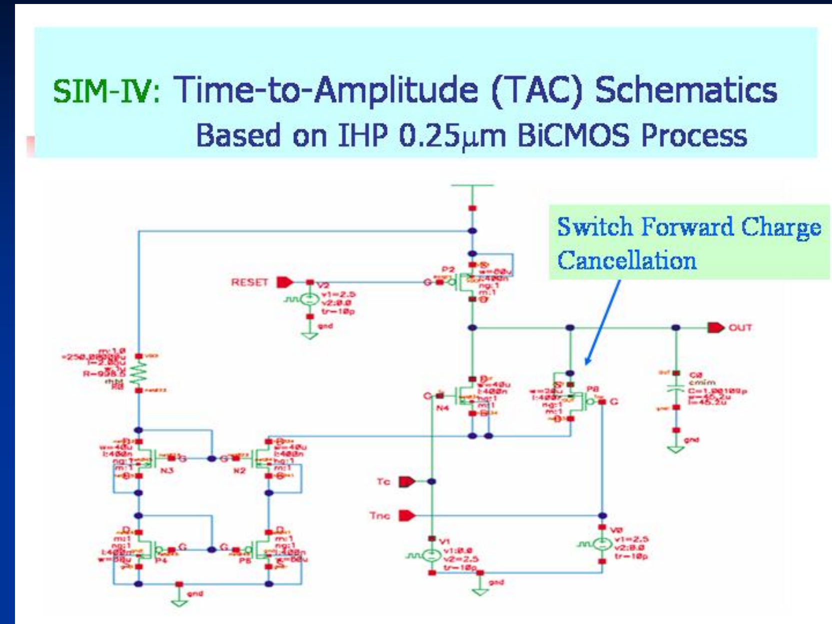
- Right now, we have a simulation using GEANT4, ROOT, connected by a python script
- GEANT4: pi^{+} enters solenoid, e- showers
- ROOT: MCP simulation - get position, time of arrival of charge at anode pads
- Both parts are approximations
- Could we make this more modular?
- Could we use GATE (Geant4 Application for Tomographic Emission) to simplify present and future modifications?
- Working with Chin-tu Chen, Chien-Minh Kao and group, - they know GATE well. And, new, at Saclay Irene Buvat attended and expressed good intentions in getting the OpenGATE Collaboration involved.

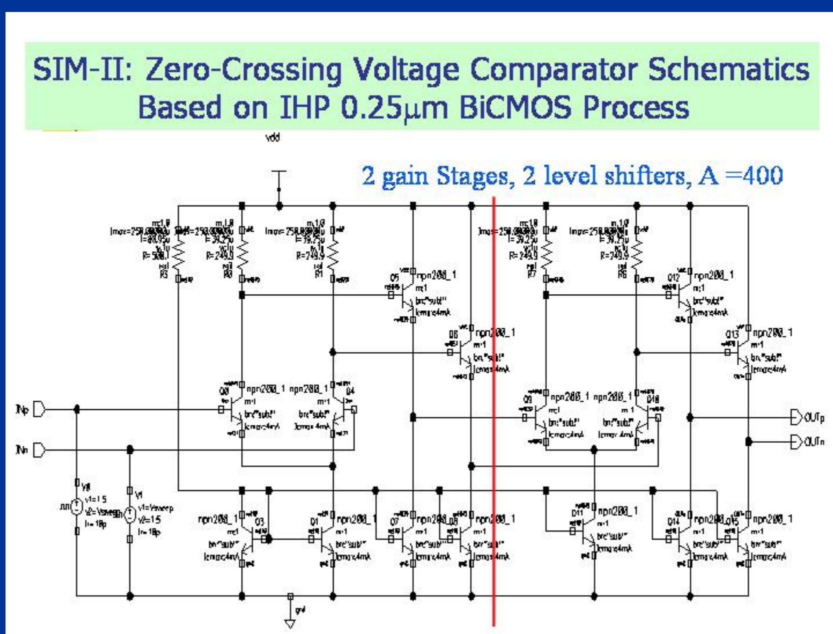
Present Status of ANL/UC

1. Have a simulation of Cherenkov radiation in MCP into electronics
2. Have placed an order with Burle/Photonis- have the 1st of 4 tubes and have a good working relationship (their good will and expertise is a major part of the effort): 10 micron tube in the works; optimized versions discussed;
3. Harold and Tang have a good grasp of the overall system problems and scope, and have a top-level design plus details
4. Have licences and tools from IHP and IBM working on our work stations. Made VCO in IHP; have design in IBM 8HP process.
5. Have modeled DAQ/System chip in Altera (Jakob Van Santen); ANL will continue in faster format.
6. ANL has built a test stand with working DAQ, very-fast laser, and has made contact with advanced accel folks:(+students)
7. Have established strong working relationship with Chin-Tu Chen's PET group at UC; Have proposed a program in the application of HEP to med imaging.
8. Have found Greg Sellberg and Hogan at Fermilab to offer expert precision assembly advice and help (wonderful tools and talent!).
9. Are working with Jerry V'avra (SLAC); draft MOU with Saclay

Simulation of Circuits (Tang)







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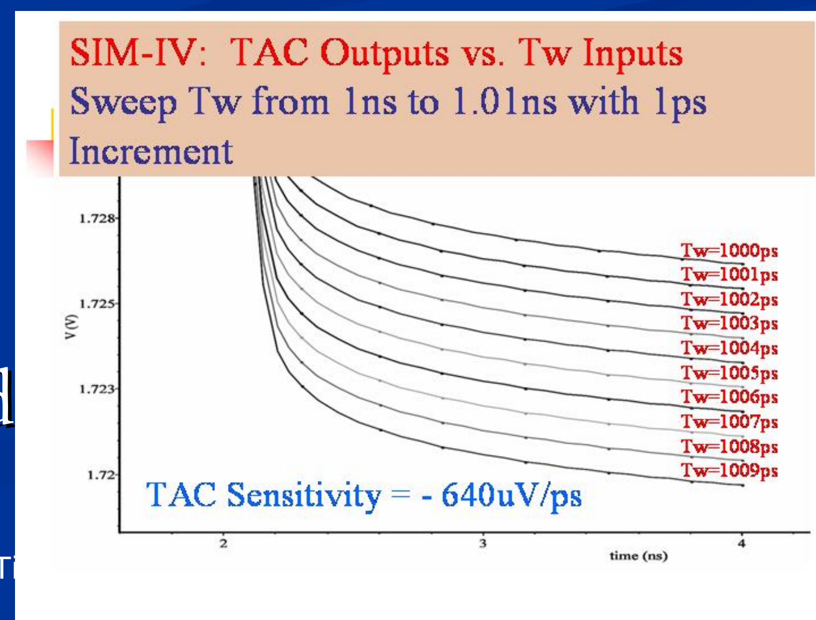


Psec Ti

Shreyas Bhat slide

Input Source code, Macros Files
- Geometry
- Materials
- Particle:
  - Type
  - Energy
  - Initial Positions, Momentum
- Physics processes
- Verbose level

π+ Generation, Coil Showering
GEANT4

Have position, time, momentum, kinetic energy of each particle for each step (including upon entrance to PMT)

- Need to redo geometry (local approx. cylinder)
- Need to redo field
- Need to connect two modules (python script in place for older simulation)

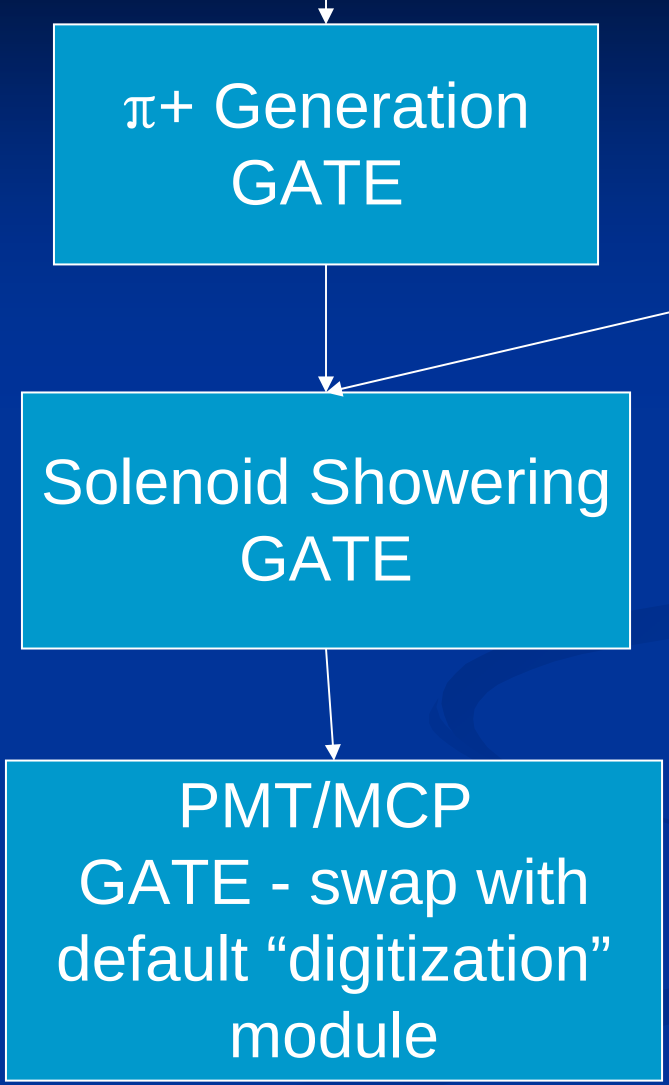
PMT/MCP
GEANT4 - swappable

Pure GEANT4

Get position, time

Shreyas Bhat slide

Input Macros Files - precompiled source
- Geometry
- Materials
- Particle:
  - Type
  - Energy
  - Initial Positions, Momentum
- Verbose level



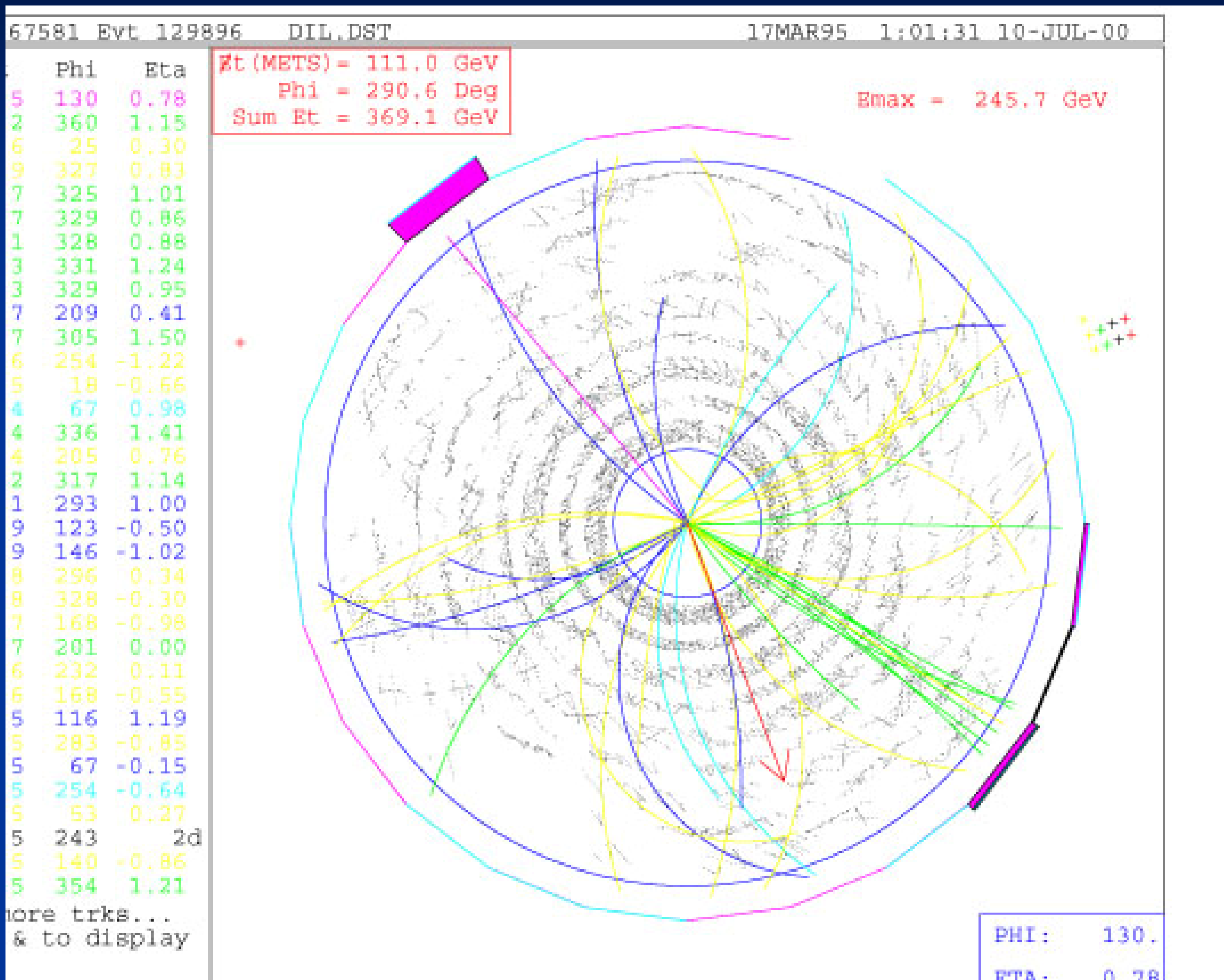
Physics processes macros file

But, we need to write Source code for Magnetic Field, recompile

GATE

Get position, time

A real CDF event- r-phi view



Key idea- fit t_0 (start) from all tracks

The Future of Psec Timing-

From the work of the Nagoya Group, Jerry Va'vra, and ourselves it looks that the psec goal is not impossible. It's a new field, and we have made first forays, and understand some fundamentals (e.g. need no bounces and short distances), but it's entirely possible, even likely, that there are still much better ideas out there.

Big Questions:

- **What determines the ultimate limits?**
- **Are there other techniques? (e.g. all Silicon)?**