The Development of Large-Area Psec-Resolution TOF Systems

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An introduction- many thanks to many folks- my collaborators, and esp. Patrick, Christophe, and Saclay for organizing and hosting this meeting.

OUTLINE

1. Introduction;
2. Three Key Developments since the 60's: a) MCP's, 200 GHZ electronics, and End-to-end Simulation;
3. HEP Needs: Particle ID and Flavor Flow, Heavy Particles, Displaced Vertices, Photon Vertex Determination;
4. The Need for End-to-End Simulation in Parallel;
5. Other Areas? Other techniques?
6. What Determines the Ultimate Limits?
7. A Wish List of Answers to Questions.

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 ~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, Lecroy 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?

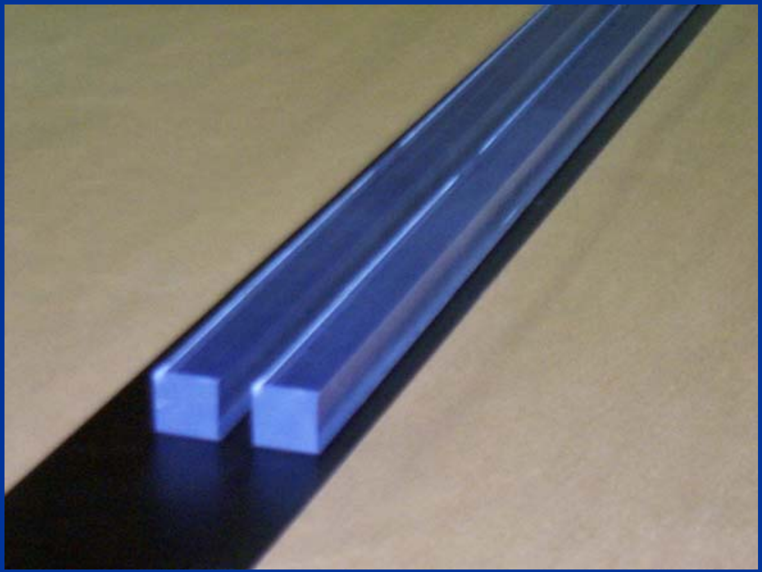
Possible Collider Applications

- Separating b from b-bar in measuring the top mass (lessens combinatorics => much better resolution)
- Identifying csbar and udbar modes of the W to jj decays in the top mass analysis
- Separating out vertices from different collisions at the LHC in the z-t plane
- Identifying photons with vertices at the LHC (requires spatial resolution and converter ahead of the TOF system
- Locating the Higgs vertex in H to gamma-gamma at the LHC (mass resolution)
- Kaon ID in same-sign tagging in B physics (X3 in CDF Bs mixing analysis)
- Fixed target geometries- LHCb, Diffractive LHC Higgs, (and rare K and charm fixed-target experiments)
- Super-B factory (Nagoya Group, V'avra at SLAC)
- Strange, Charm, Beauty and Baryon Flow in Heavy Ion Collisions.. Etc.

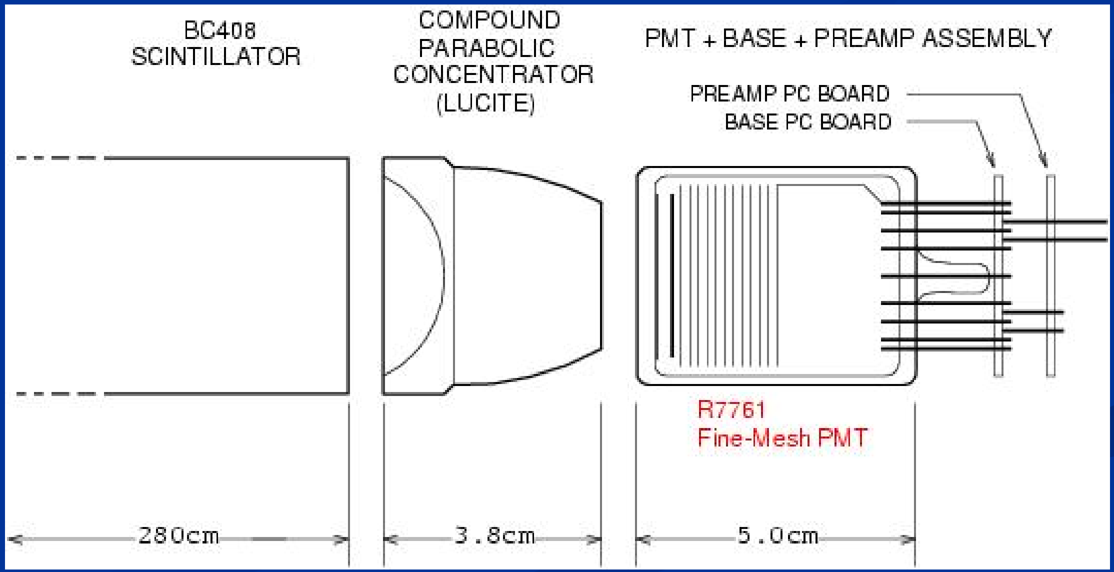
Why has 100 psec been the # for 60 yrs?

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)

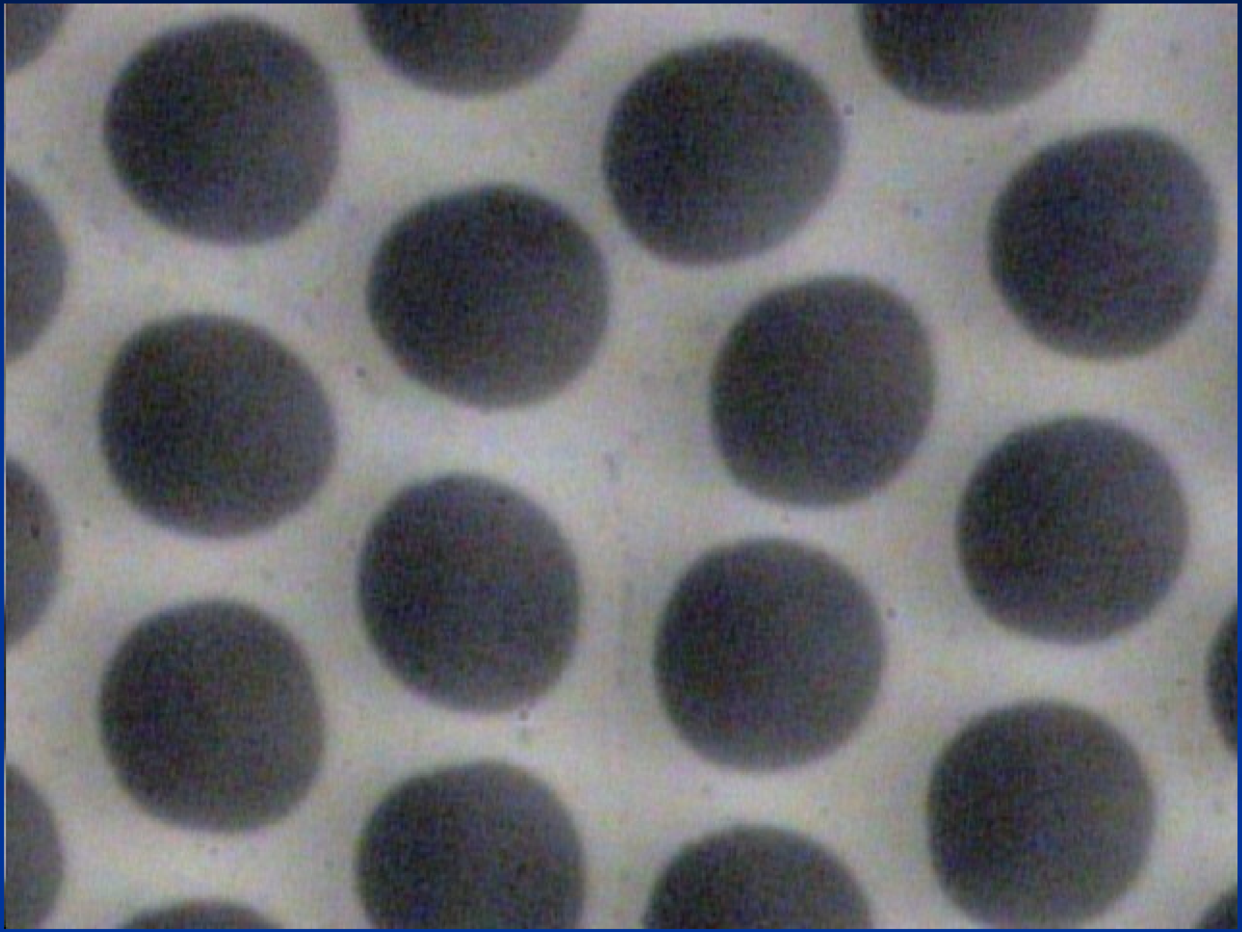


Typical Light Source (With Bounces)



Typical Detection Device (With Long Path Lengths)

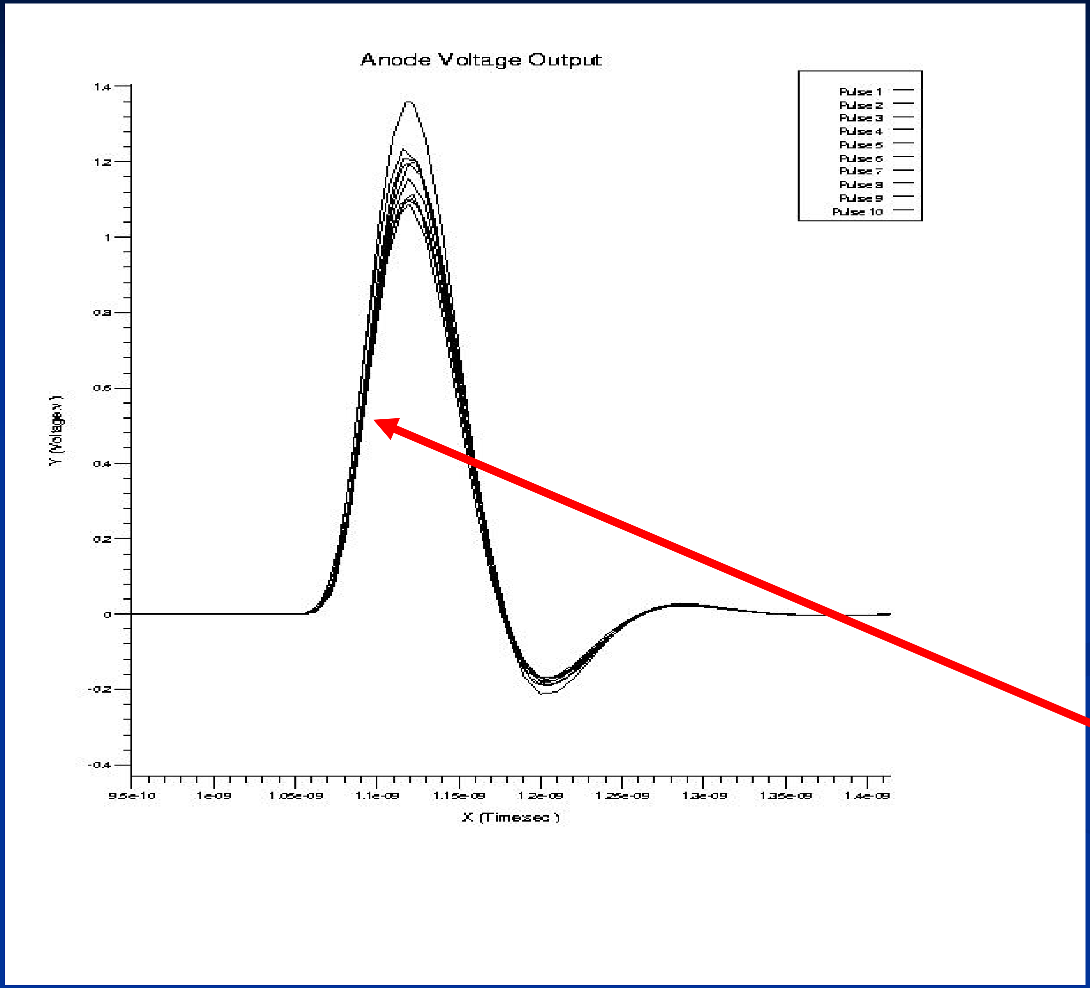
Major advances for TOF measurements:



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

1. Development of MCP's with 6-10 micron pore diameters

Major advances for TOF measurements:

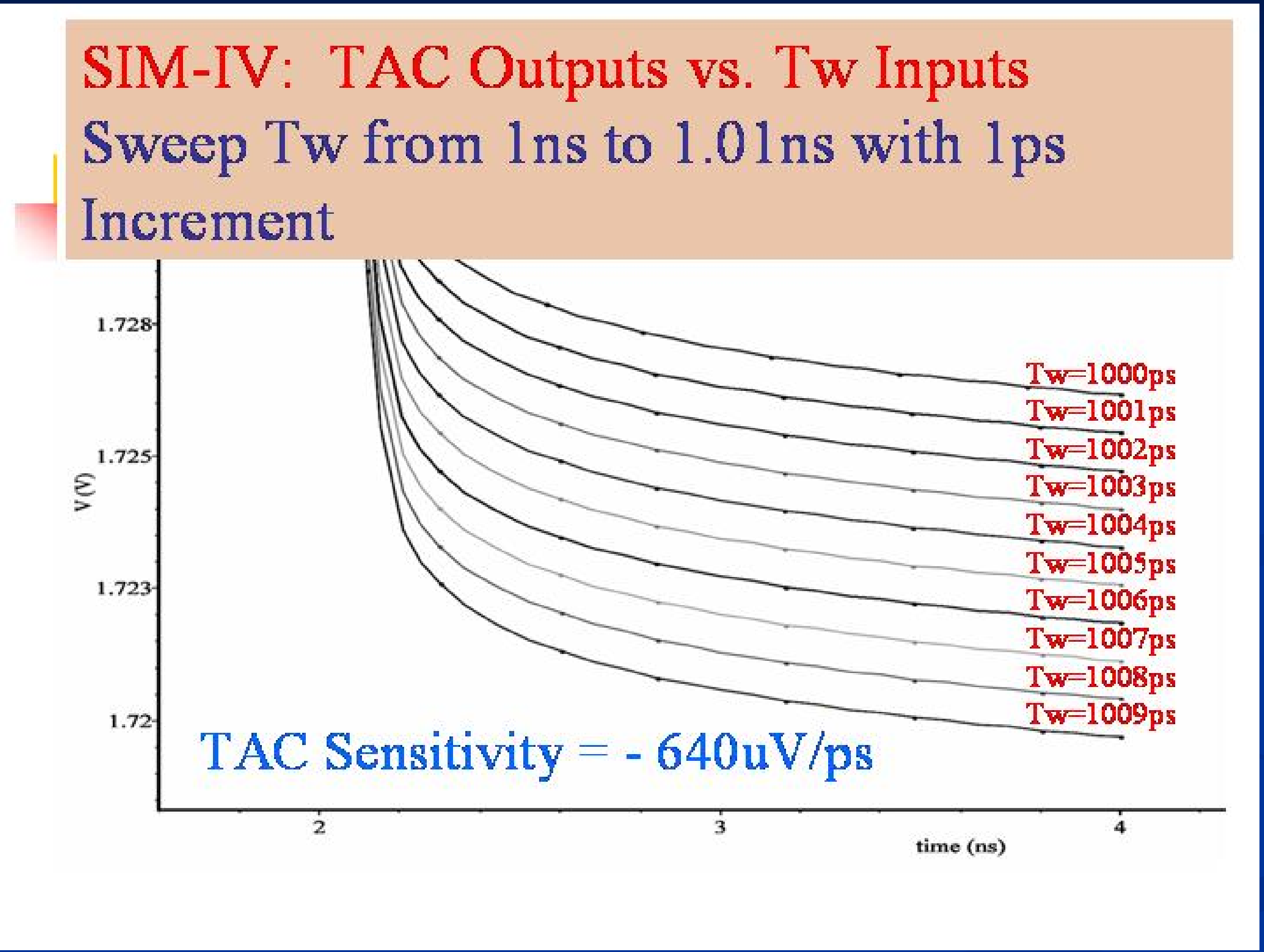


Output at anode from simulation of 10 particles going through fused quartz window- T. Credo, R. Schroll

Jitter on leading edge 0.86 psec

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

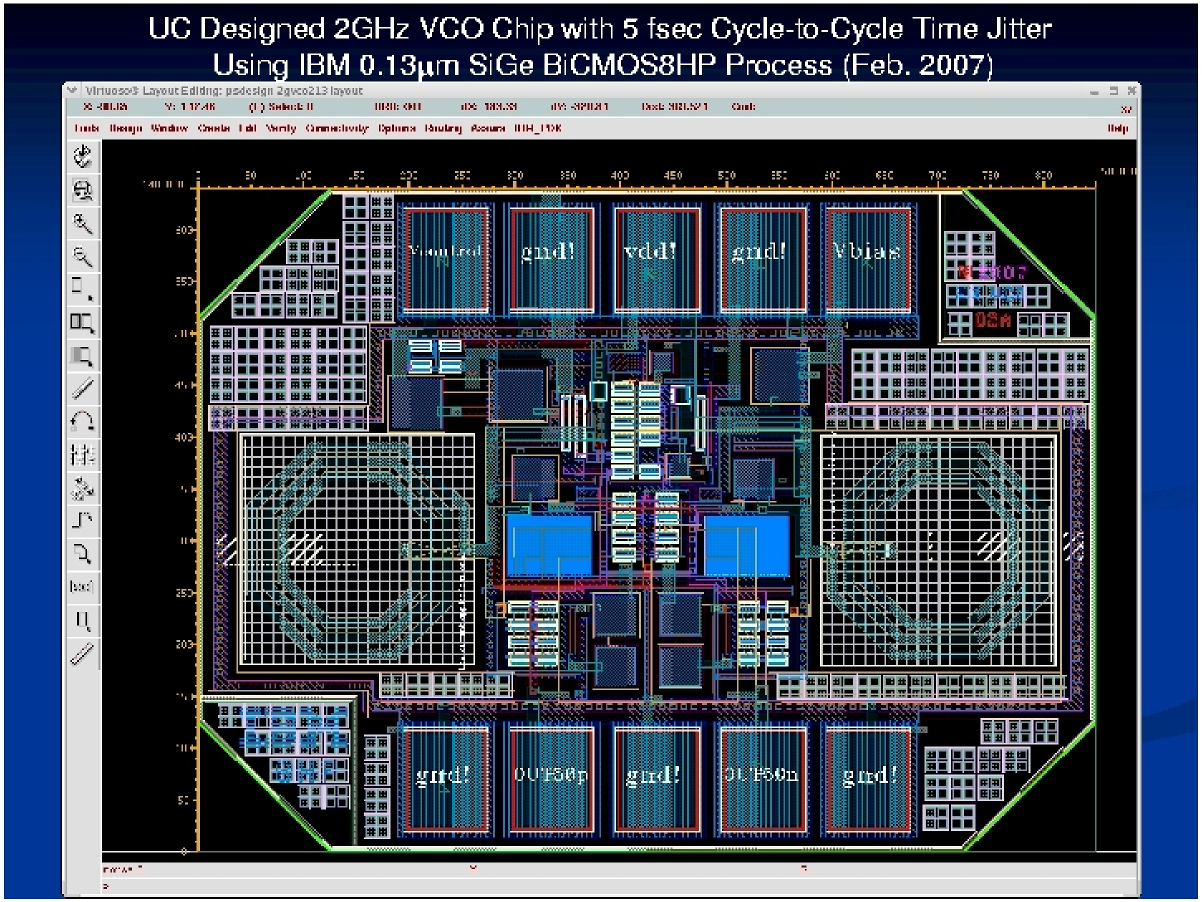
Major advances for TOF measurements:



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)

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

A real CDF Top Quark Event

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

Measure transit time here (stop)

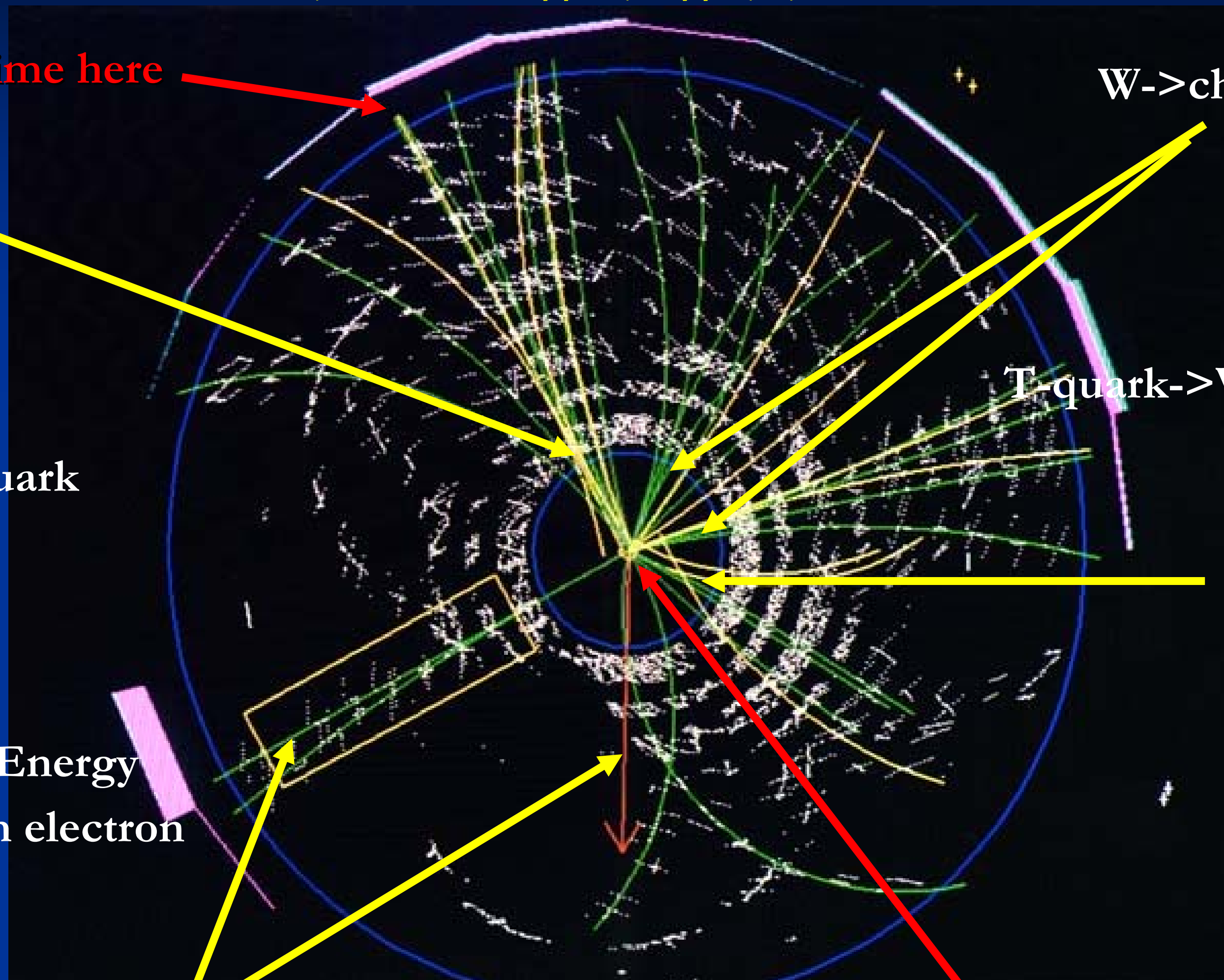
W->charm sbar

B-quark

T-quark->W+bquark

T-quark->W+bquark

B-quark



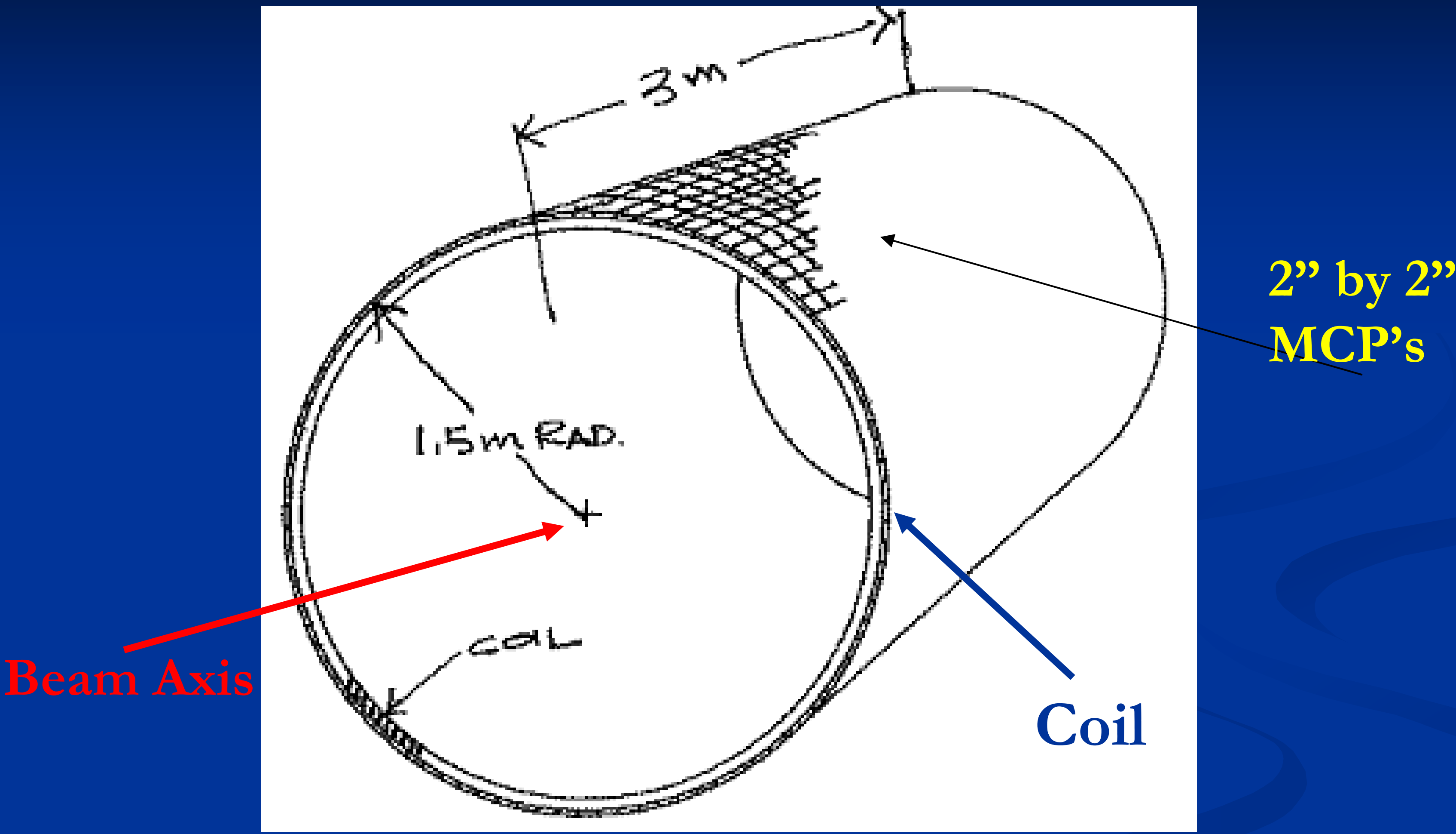
Cal. Energy From electron

W->electron+neutrino

Fit t_0 (start) from all tracks

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

Geometry for a Collider Detector

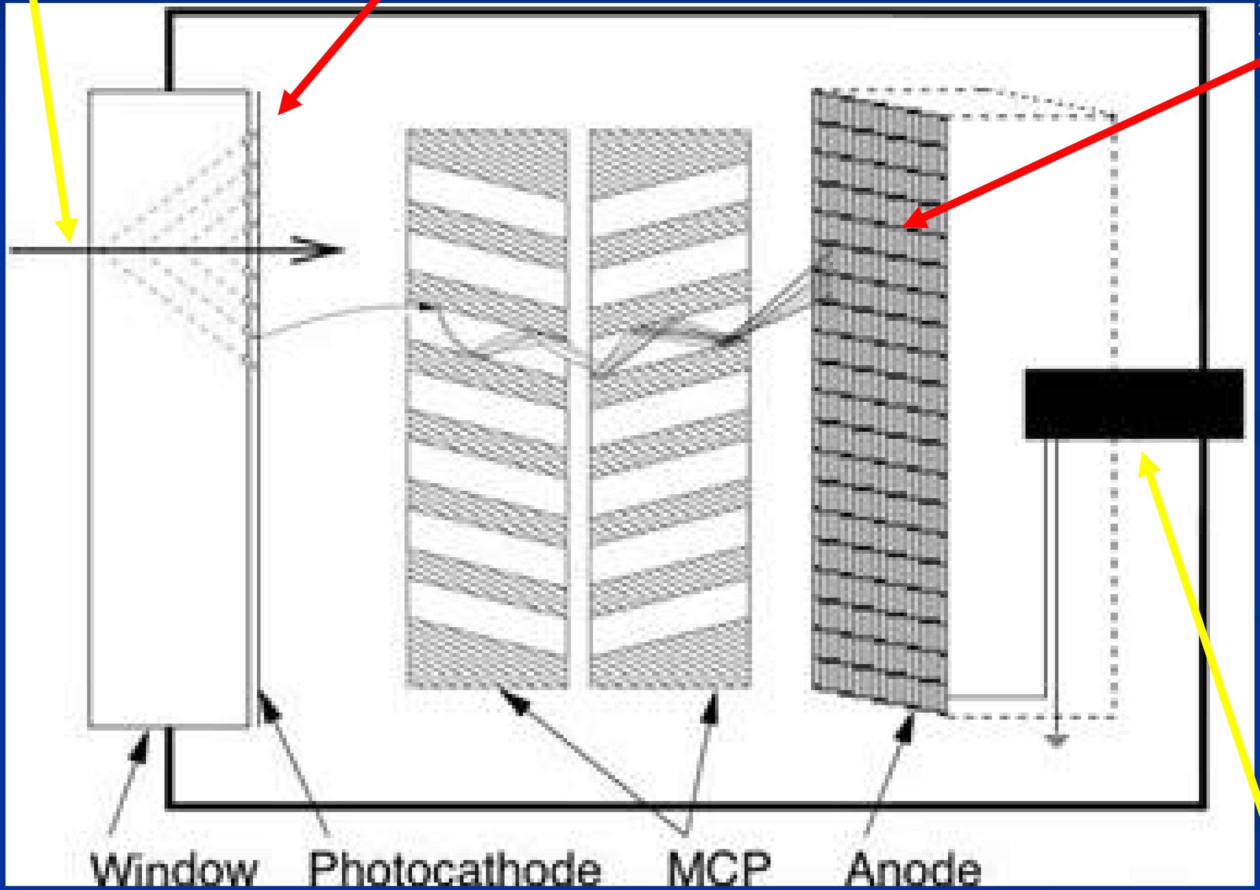


"r" is expensive- need a thin segmented detector

Generating the signal

Use Cherenkov light - fast

Incoming rel. particle



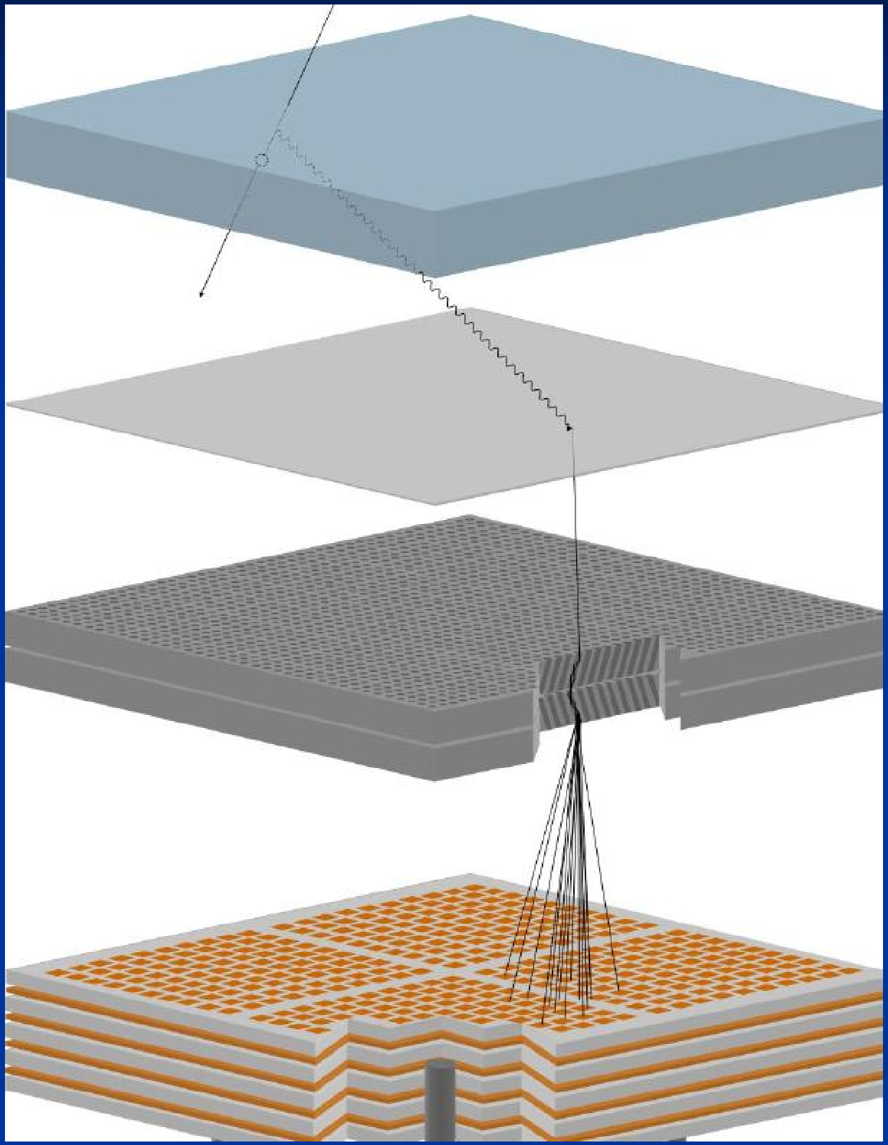
Custom Anode with Equal-Time Transmission Lines + Capacitative. Return

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

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

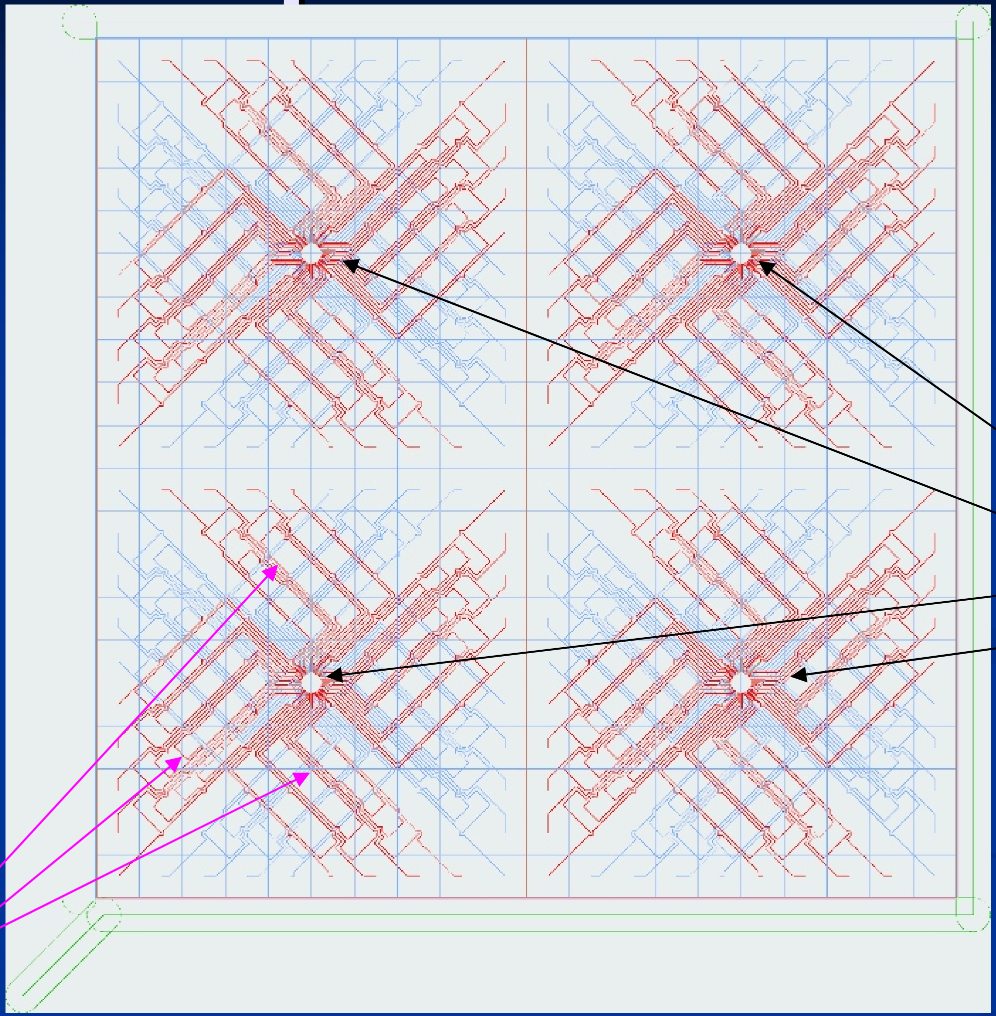
Collect charge here-differential Input to 200 GHz TDC chip

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

Tim's Equal-Time Collector



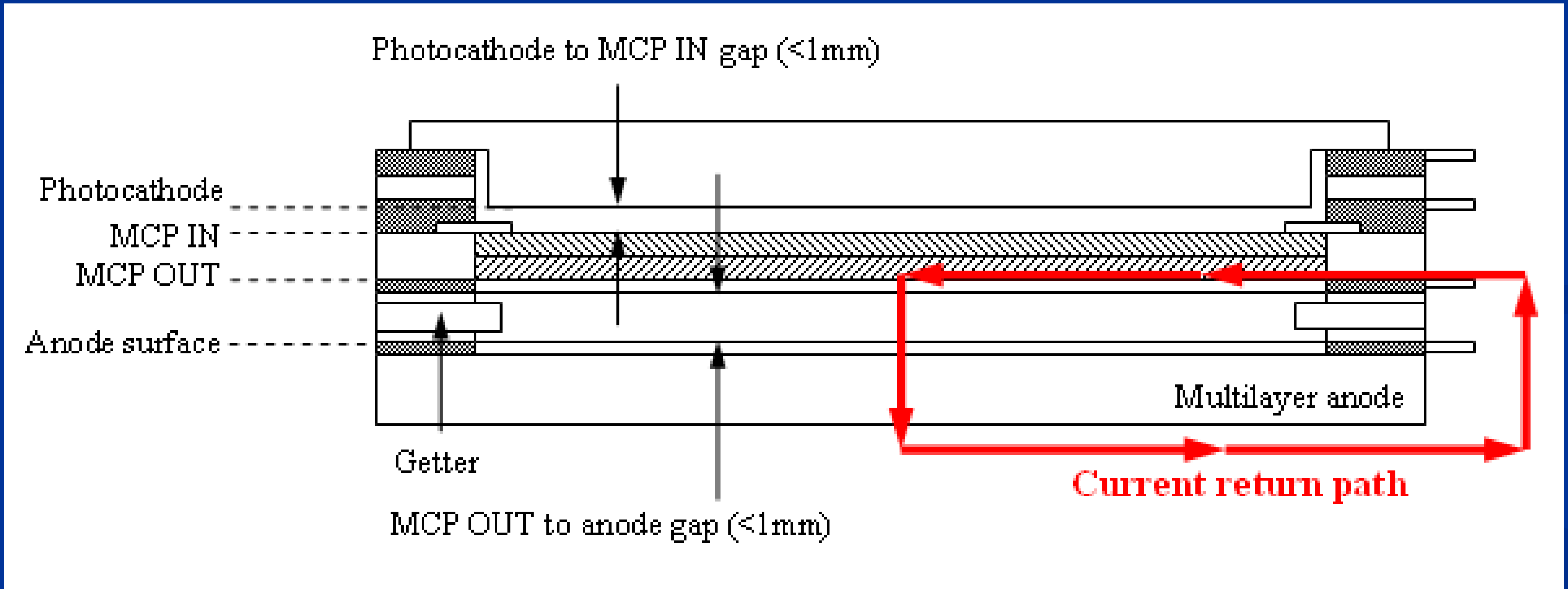
4 Outputs- each to a TDC chip (ASIC)

Chip to have < 1psec resolution(!)

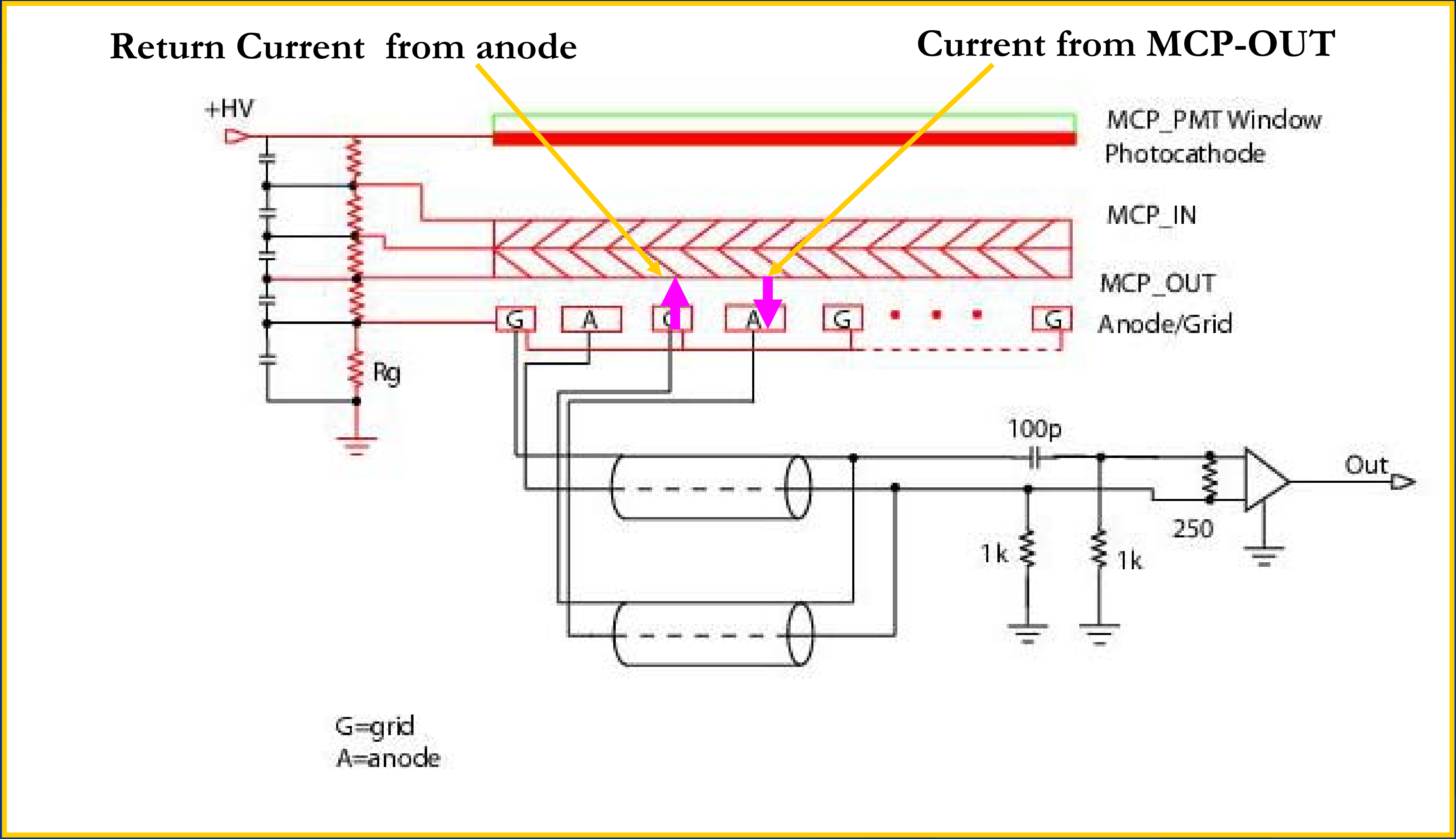
-we are doing this in the EDG (Harold, Tang).

Equal-time transmission-line traces to output pin

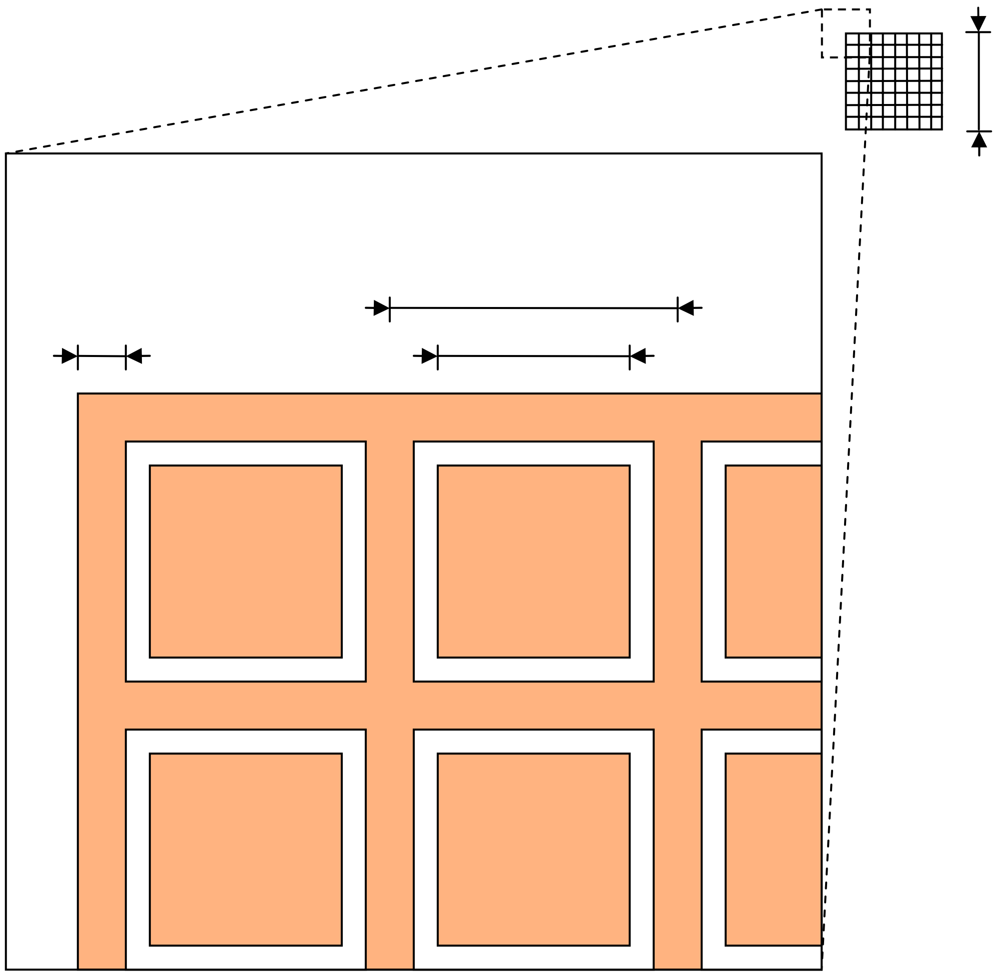
Anode Return Path Problem



Capacitive Return Path Proposal



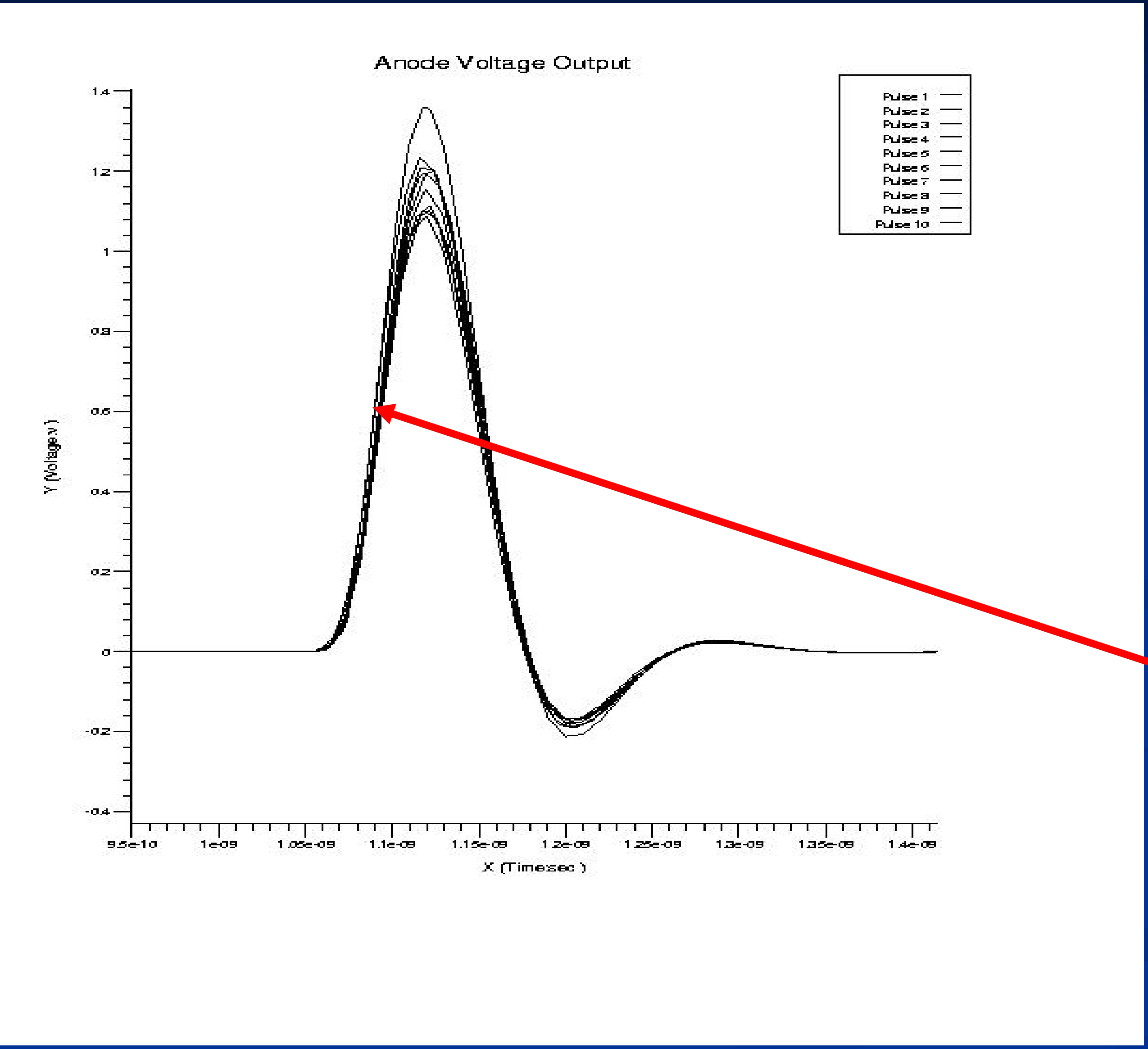
Solving the return-path problem



Mounting electronics on back of MCP- matching

Conducting Epoxy- machine deposited by Greg Sellberg (Fermilab)

End-to-End Simulation Result



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

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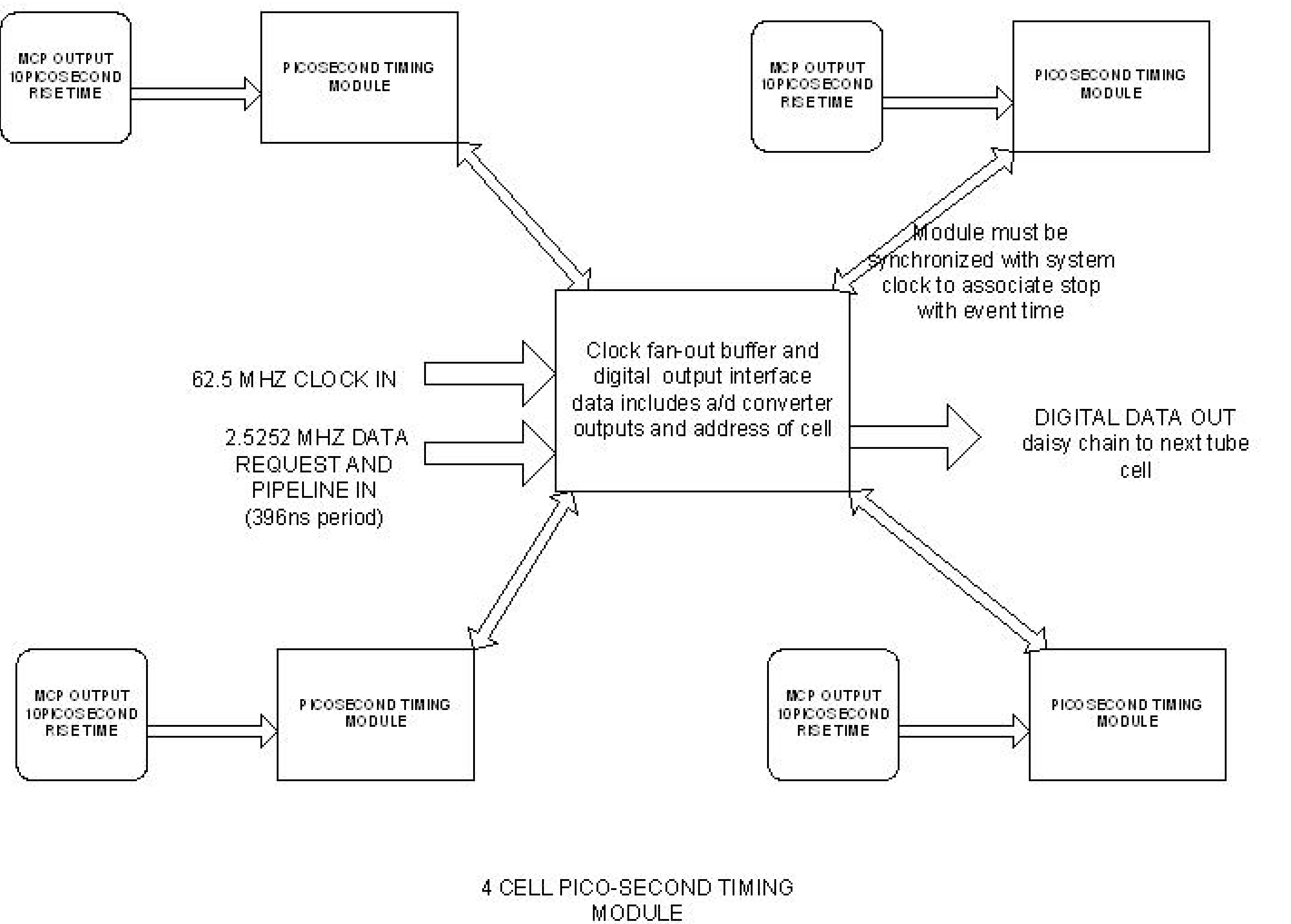
EDG's Unique Capabilities - Harold's Design for Readout

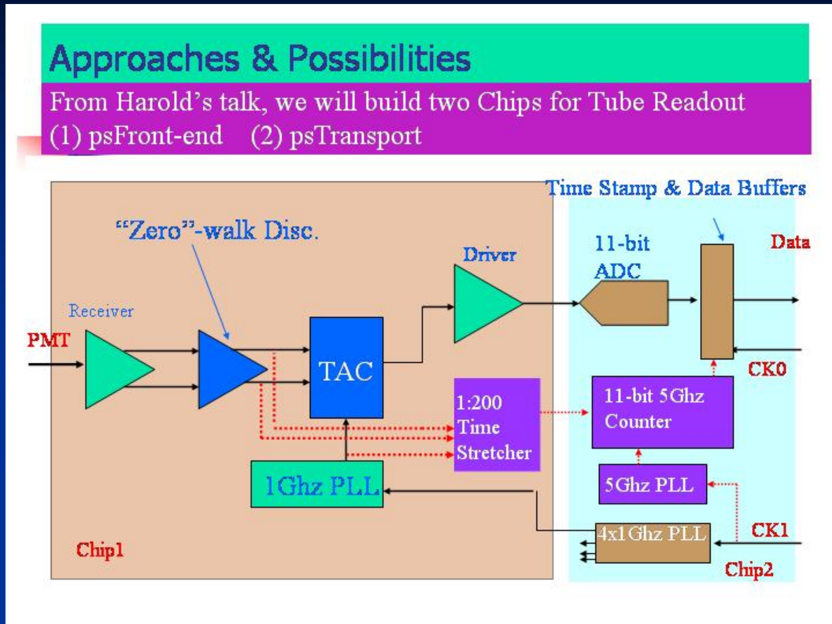


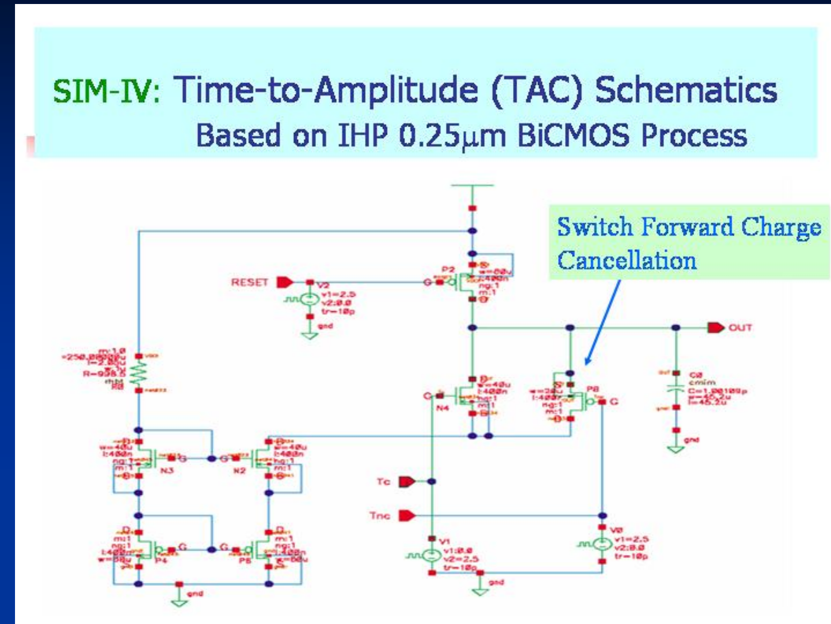
Each module ha
5 chips- 4 TDC
chips (one per
quadrant) and a
DAQ `mother'
chip.

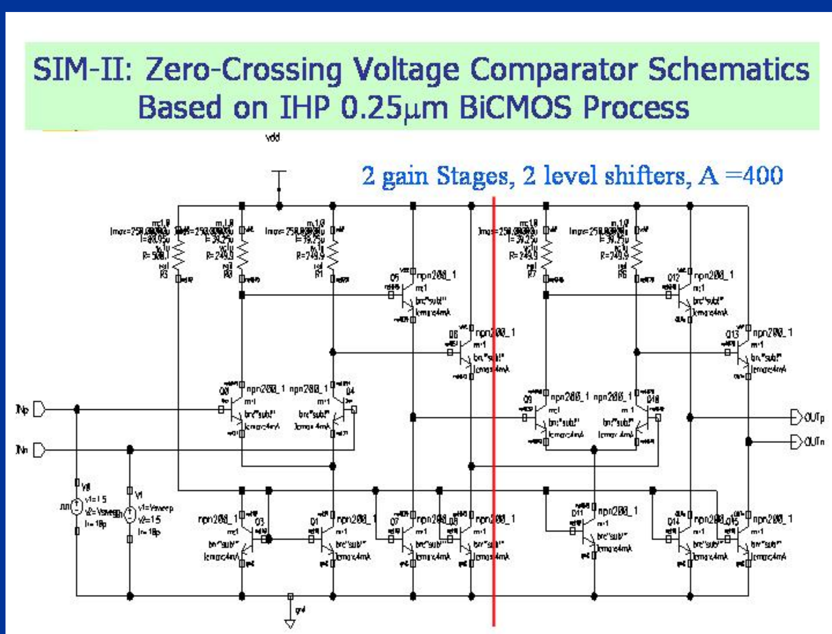
Problems are
stability,
calibration, rel.
phase, noise.

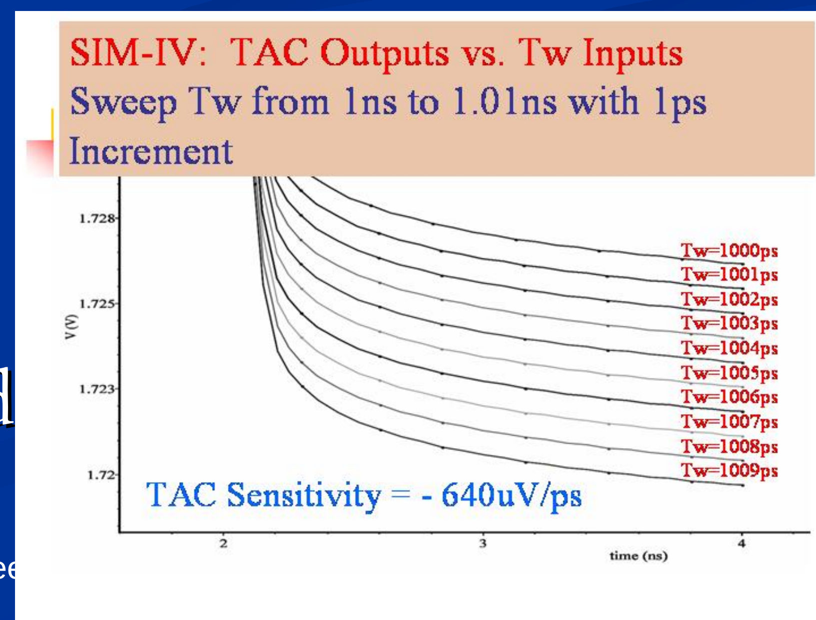
Both chips are
underway

Simulation of Circuits (Tang)









Readout with sub-psec resolution:

Tang's Time Stretcher- 4 chips/2x2in module

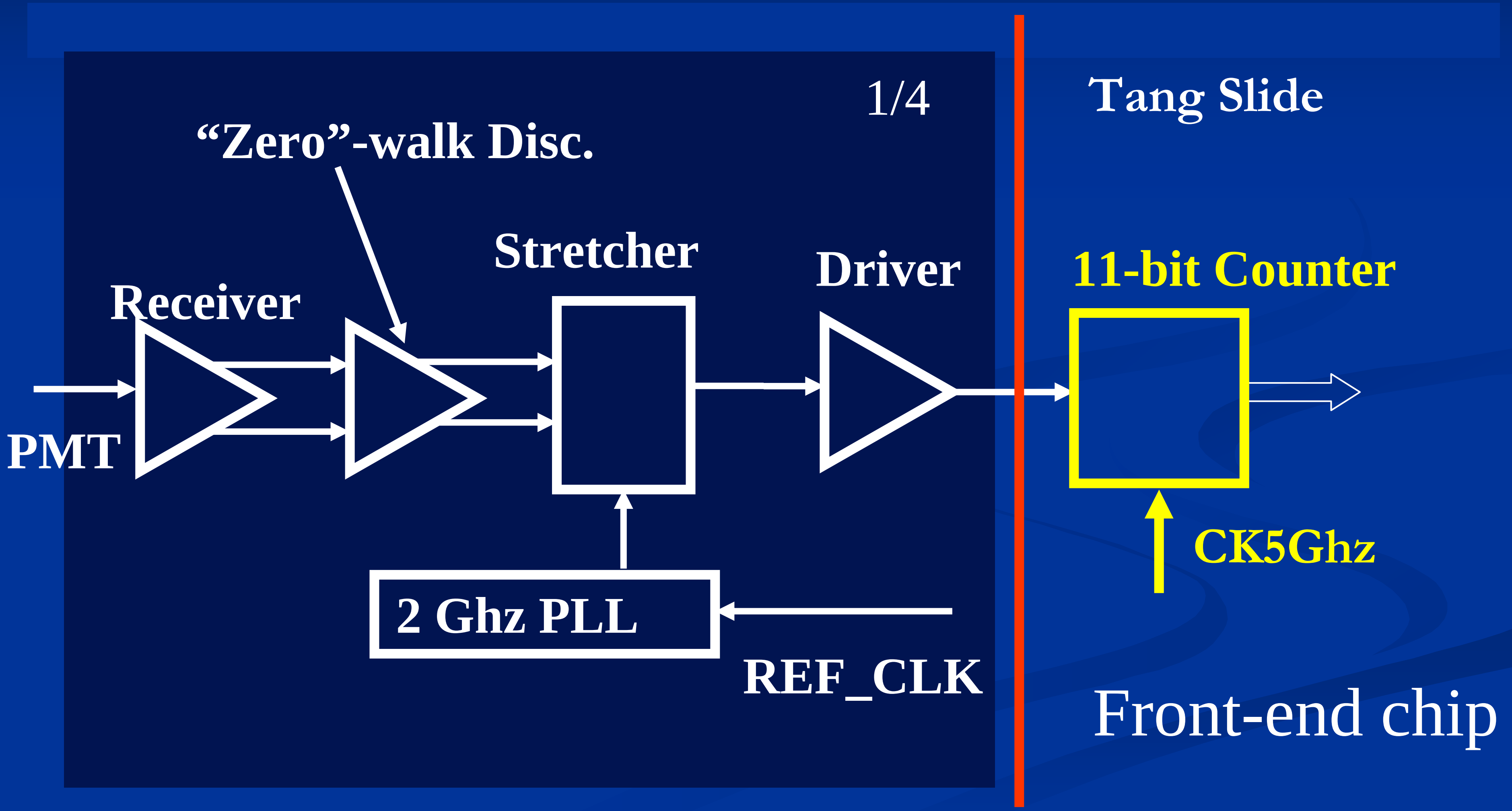
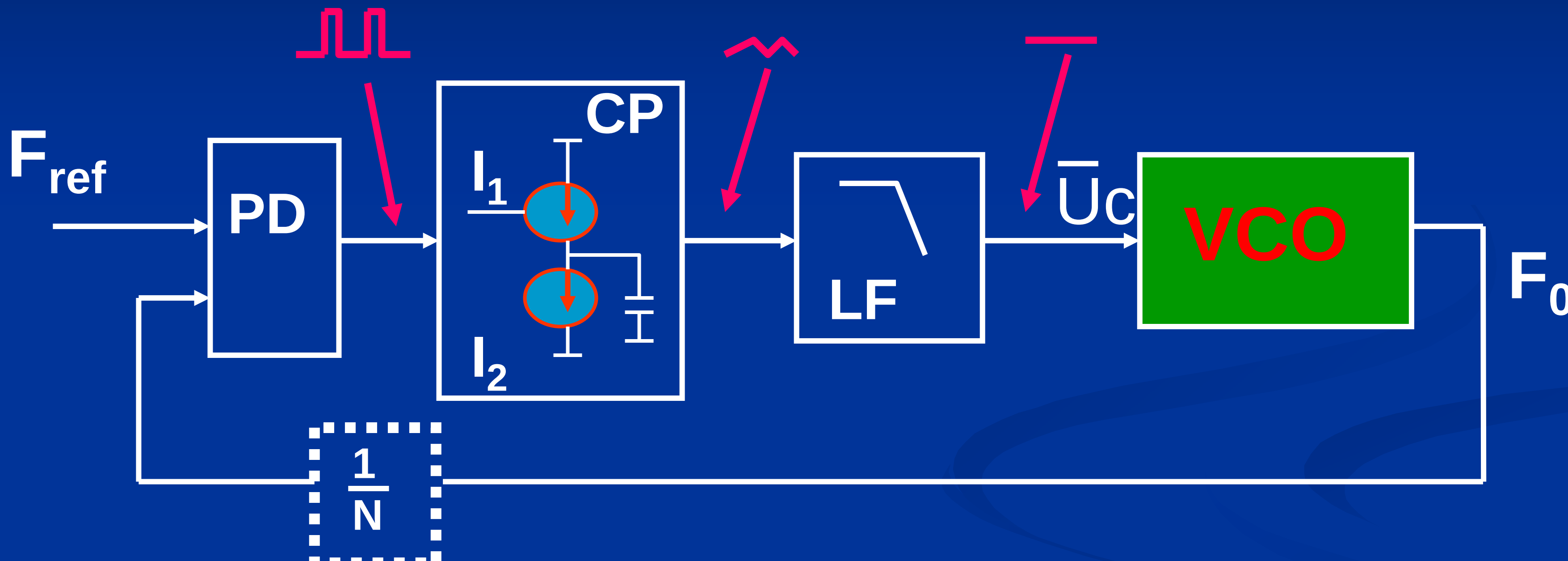


Diagram of Phase-Locked Loop

Tang Slide



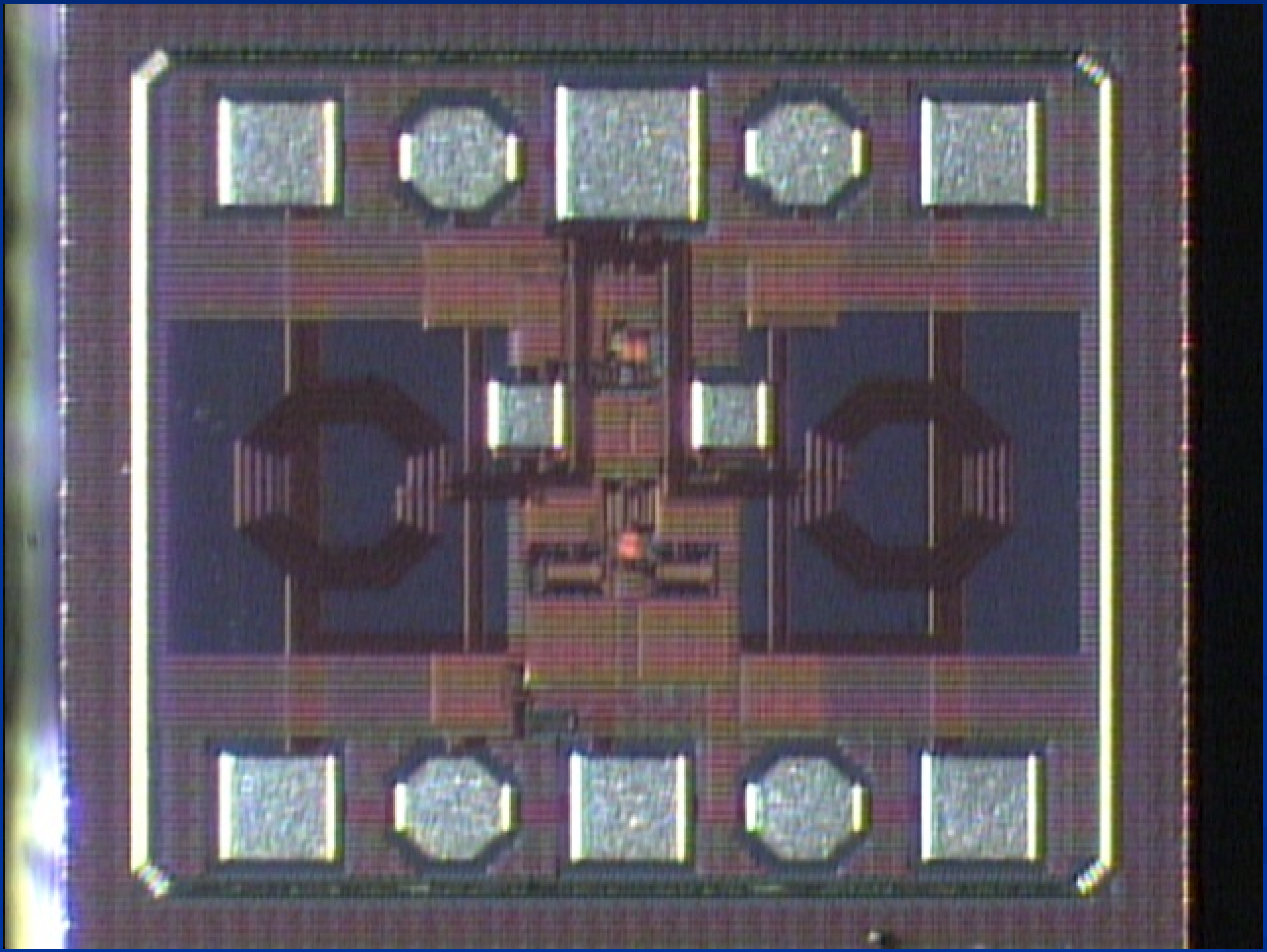
PD: Phase Detector

CP: Charge Pump

LF: Loop Filter

VCO: Voltage Controlled Oscillator

Microphotograph of IHP Chip



Taken at Fermilab by Hogan –

Design by Fukun Tang

DAQ Chip- 1/module

- Jakob Van Santen implemented the DAQ chip functionality in an Altera FPGA- tool-rich environment allowed simulation of the functionality and VHDL output before chip construction (Senior Thesis project in Physics)
- Will be designed in IBM process (we think) at Argonne by Gary Drake and co.
- Again, simulation means one doesn't have to do trial-and-error.

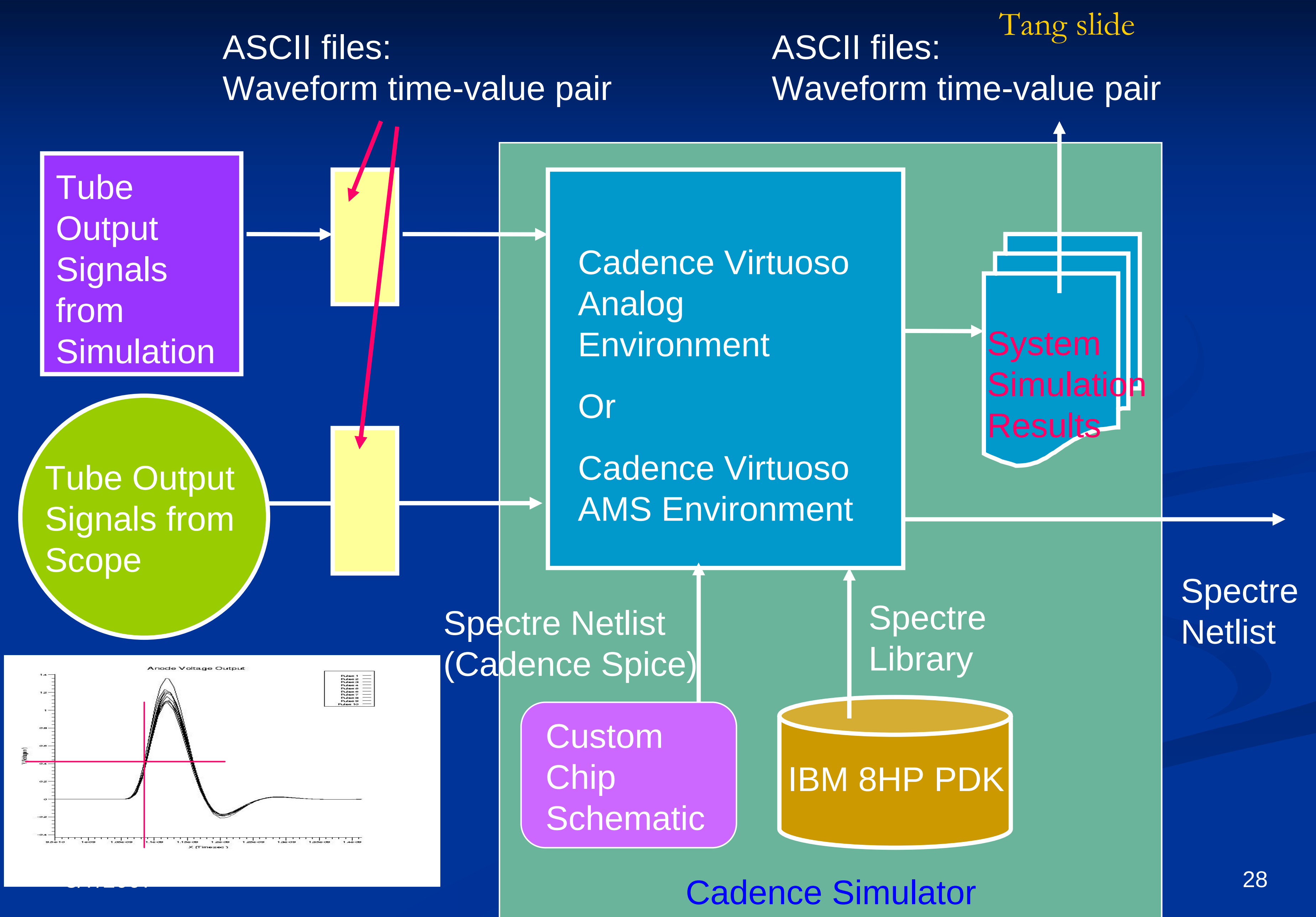
Why is simulation essential?

- 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 (for many reasons!)
- Debugging is impossible any other way.

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 less home-brew and 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 very well!

Interface to Other Simulation Tools



Questions on Simulation-Tasks (for discussion)

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?

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

The Future of Psec Timing- Big Questions:

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.

Questions:

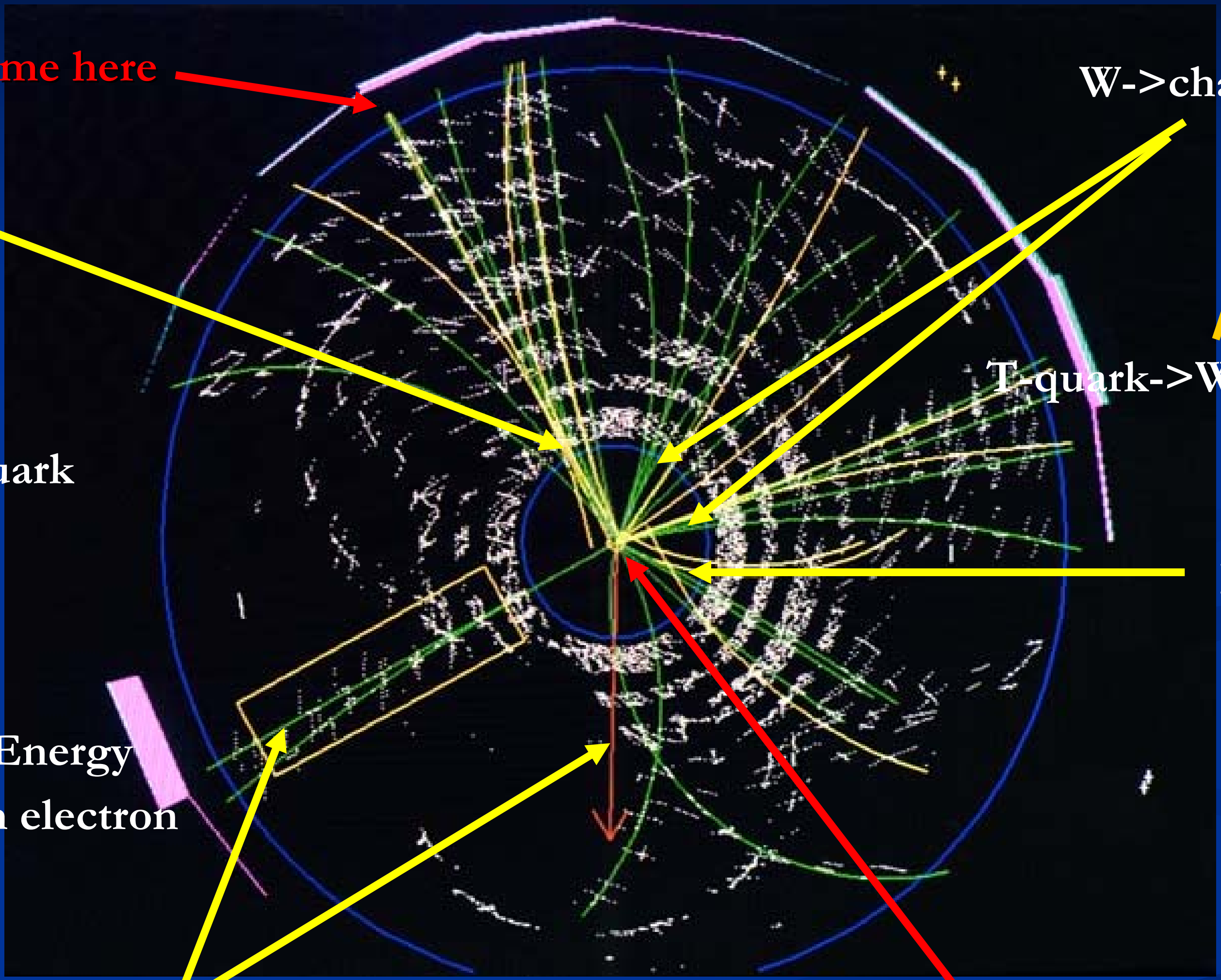
- Are there other techniques? (e.g. all Silicon)?
- What determines the ultimate limits?

Smaller Questions for Which I'd Love to Know the Answers

- What is the time structure of signals from crystals in PET? (amplitude vs time at psec level)
- Could one integrate the electronics into the MCP structure- 3D silicon (Paul Horn)?
- Will the capacitative return work?
- How to calibrate the darn thing (a big system)?
- How to distribute the clock
- Can we join forces with others and go faster?

The Future- Triggering?

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



Can we follow the color flow of the partons themselves?

That's All…

Backup Slides

Shreyas Bhat slide

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

⇨+ 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.❾ 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

⇨+ Generation
GATE

Physics processes macros file

Solenoid Showering
GATE

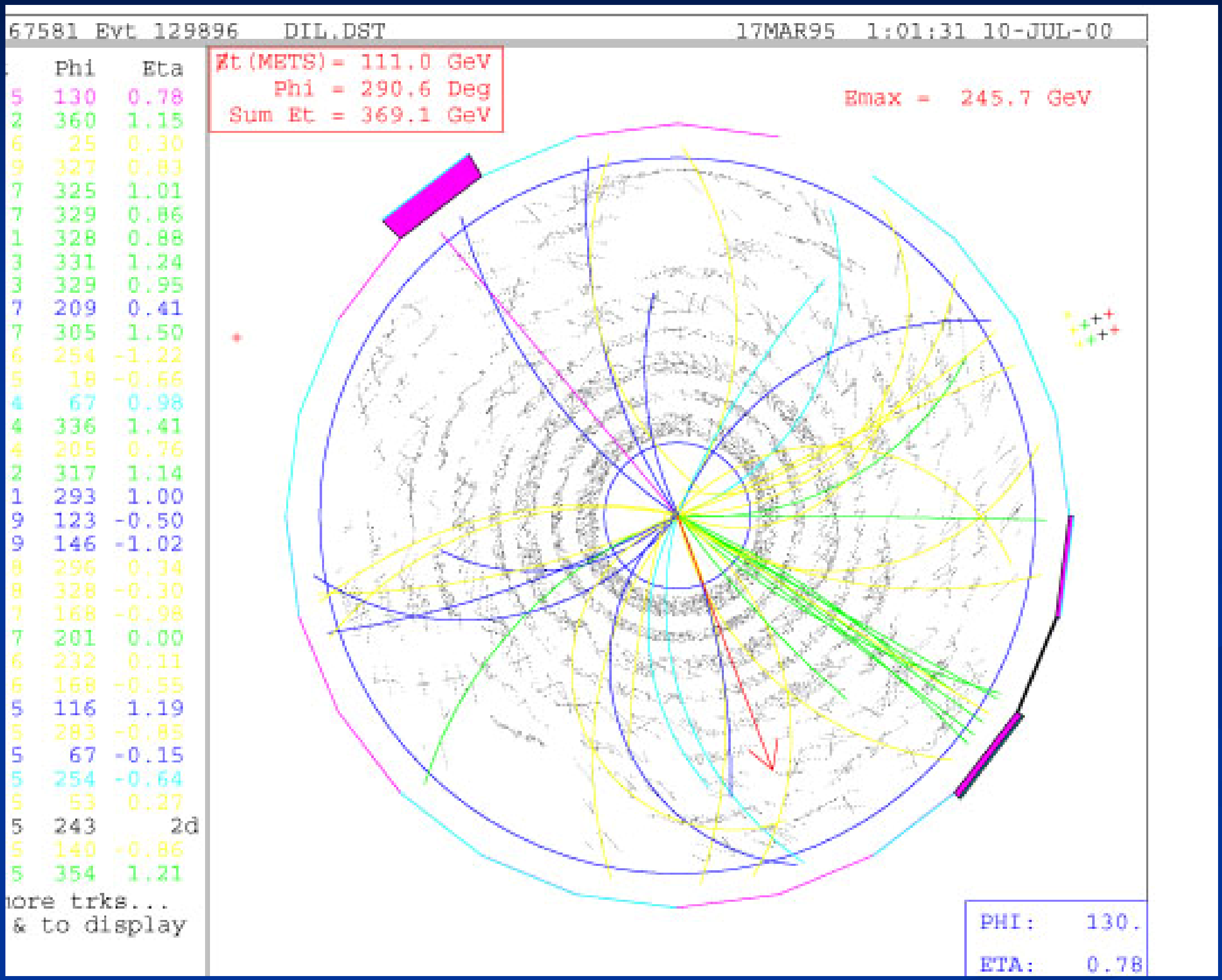
But, we need to write Source code for Magnetic Field, recompile

PMT/MCP
GATE - swap with default “digitization” module

Get position, time

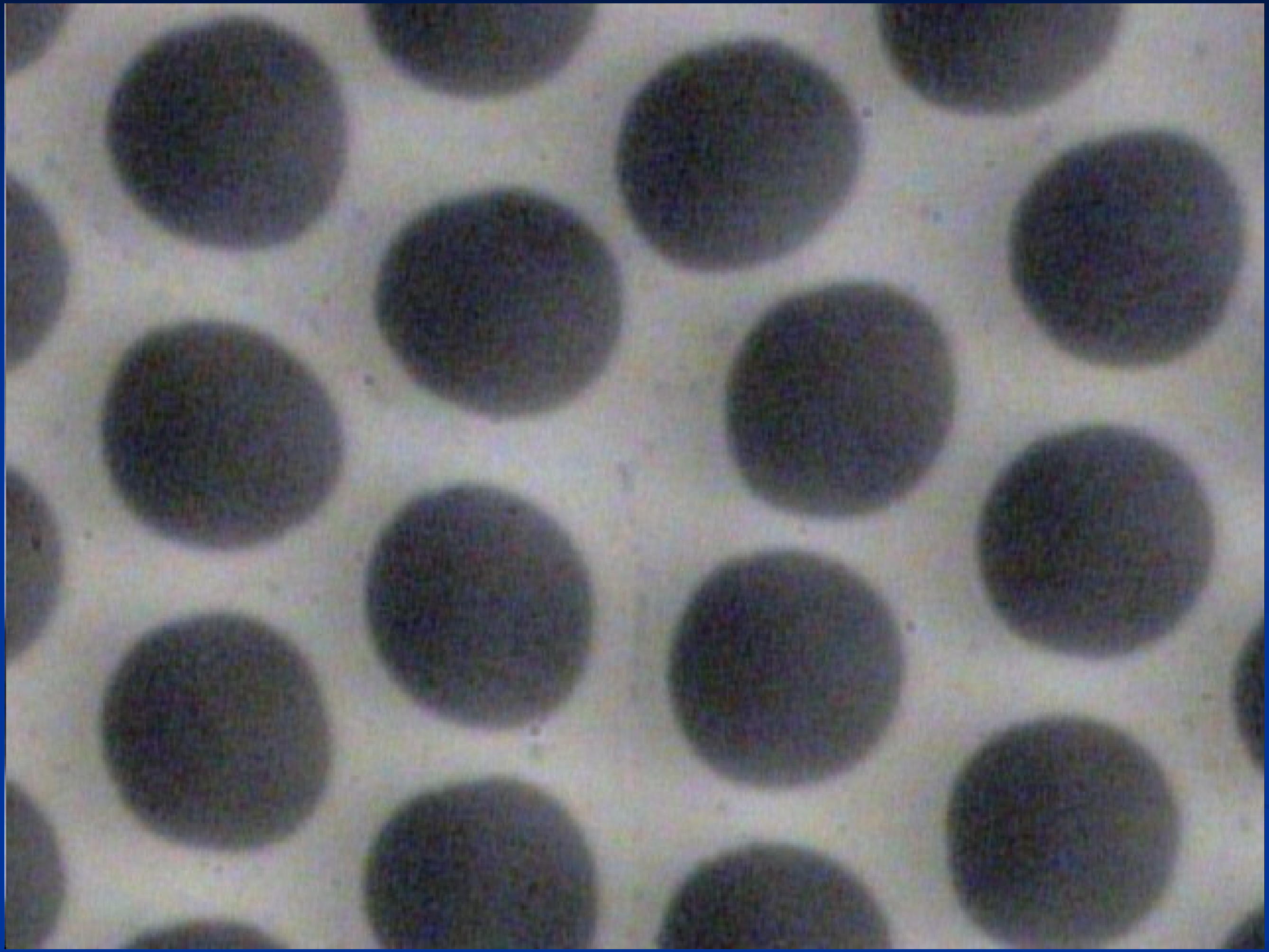
GATE

A real CDF event- r-phi view



Key idea- fit t_0 (start) from all tracks

MCP's have path lengths <<1 psec:



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

Can buy MCP's with 6-10 micron pore diameters