Diamond for Beam Profile Monitoring

A brief history and first results

May 20, 2004

Kara Hoffman

The University of Chicago

Enrico Fermi Institute

and the MuCool Collaboration

Motivation

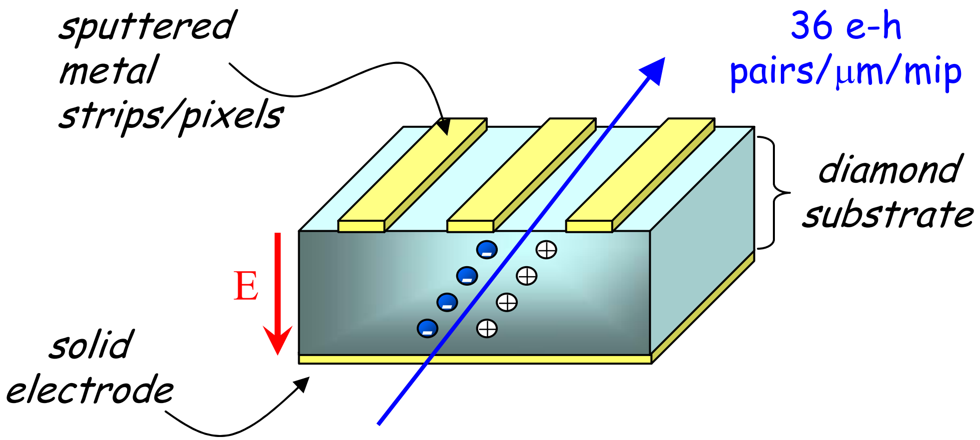
- While disturbing the beam as little as possible measure:
  - intensity
  - size/profile in 2 dimensions?
  - timing between bunches or pulses

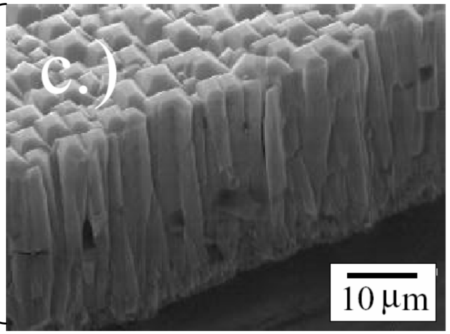
- The beam must be accurately measured in an environment with a lot of electromagnetic noise (high beam currents, solenoids, rf,…) and over a wide range of intensities.

Muon Test Facility

Parameter	**Minimum**	**Maximum**	**Unit**
Beam Size ($\pm3\sigma$) at D.U.T.*	1	30	cm
Beam Divergence† ($\pm3\sigma$) at D.U.T.*	±0.5	±14	mr
Number of Pulses per Second		15	
Number of Protons per Pulse	1.6	16	10^{12}
Pulse Duration	5.0	50	µs

Polycrystalline CVD Diamond





Physical Property at 300 K	*Diamond*
band gap [eV]	5.45
Electron mobility [cm^2/Vs]	2200
Hole mobility [cm^2/Vs]	1600
Breakdown field [V/m]	10^7
Resistivity ρ [Ω cm]	$>10^{13}$
Dielectric constant ε_r	5.7
Thermal conductivity [W/cm K]	20
Lattice constant [Å]	3.57
Energy to remove an atom from the lattice [eV]	80
Energy to create an e-h pair [eV]	13

induced charge: $dq = e\dfrac{dx}{L}$

dx= distance e-holes drift apart

$$dx = (\mu_+\tau_+ + \mu_-\tau_-)E$$

μ = *carrier mobility,*

τ = *carrier lifetime*

high binding energy - makes it rad hard

high resistivity - allows it to maintain high E field

Charge collection efficiency dependent upon:

•grain boundaries

•in-grain defects

My Gedankenexperiment

At 36 e-h pairs/um/mip the signal will be huge –too big!

Possible solutions:

- Turn down the voltage might compromise time resolution
- Get material with rotten efficiency "black diamond" with small carrier τ
- Get a killer power supply (literally) to maintain bias while drawing huge currents Agilent 6035A (1050 W)
- May be (somewhat) self modulating space charge, recombination…

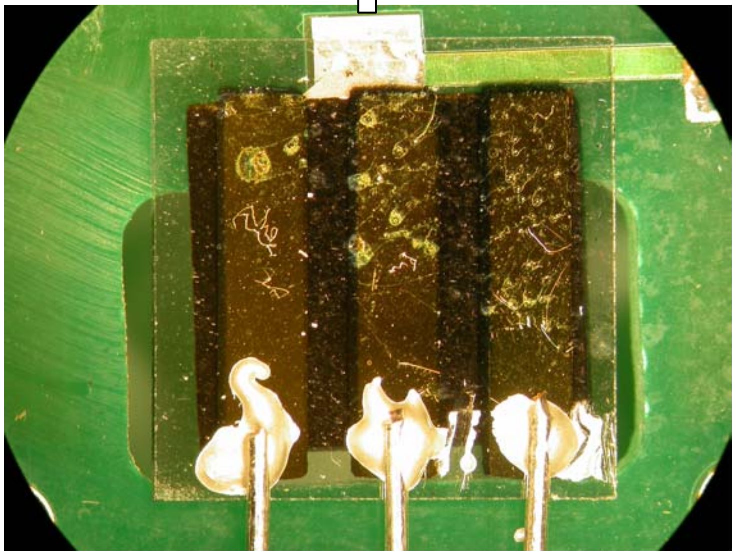
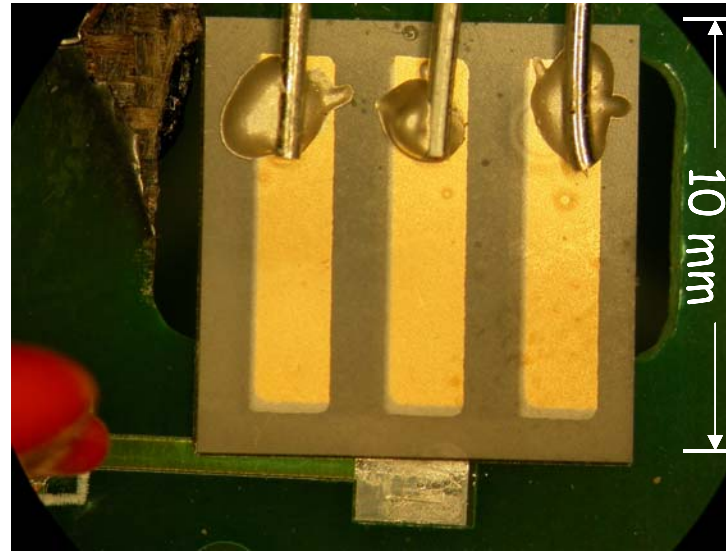
The data you are about to see tests these hypotheses…

What about radiation effects?

- Starting with material with a poor efficiency –so hope that the change in density of trapping sites is less pronounced.

Has yet to be addressed.

Two diamond profilers have been tested in a beam…

Transparent	Black
	
Collection distance =100 μm Thickness = ~600 μm Manufacturer = DeBeers	Collection distance =40μm? Thickness = ~300 μm Manufacturer = Norton diamond?
large signals due to relatively high efficiencies Expensive (~$1500/sq.cm)	larger number of charge trapping sites modulates large signals shorter carrier lifetimes give better time response much cheaper

Electronics

several time constants in the circuit:

τ=diamond (capacitor) x readout resistor

- 1 GHz bandwidth
- 400 ps rise time
- 10 GS/s sample rate

Diamond capacitor

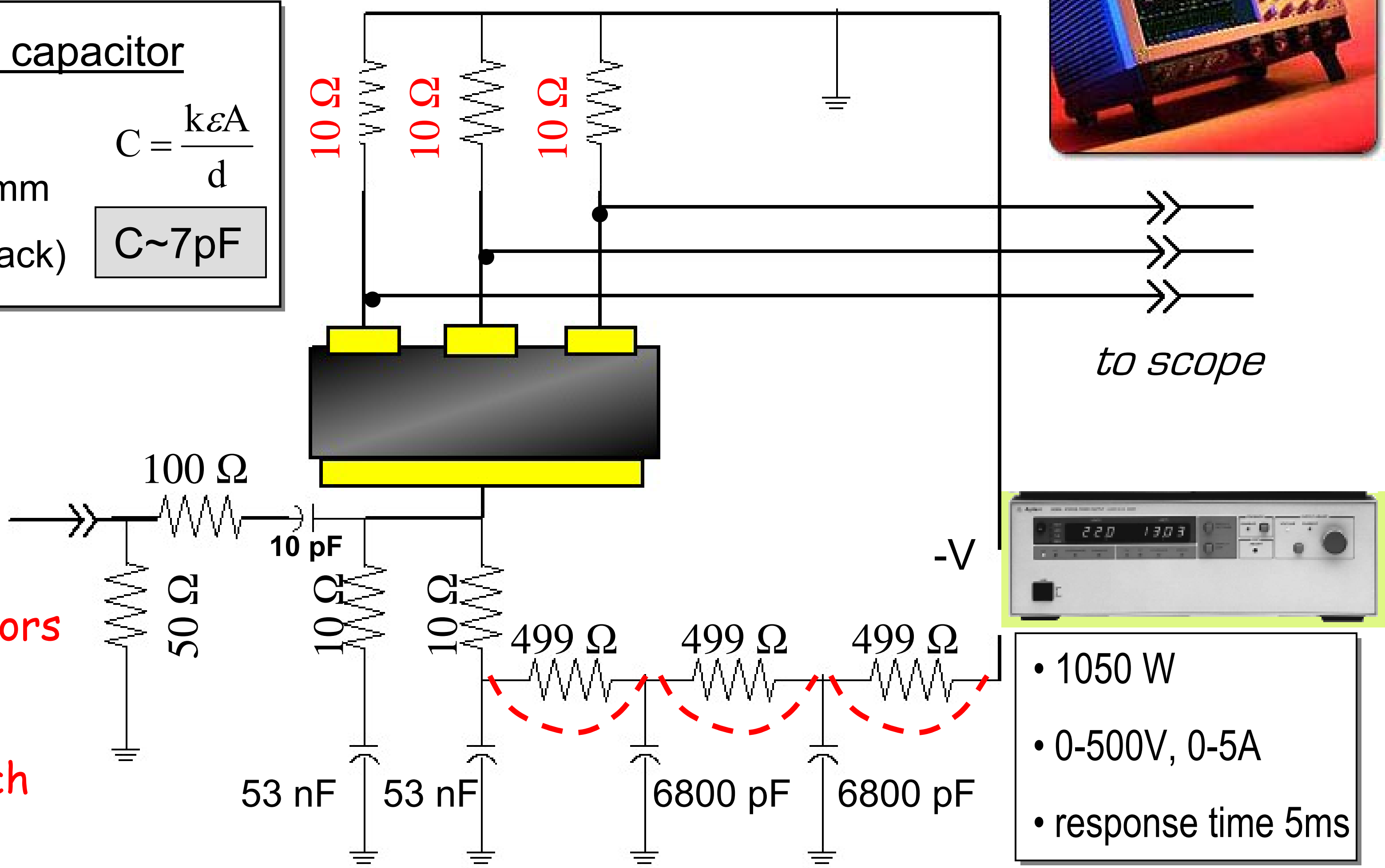
k=5.7

A=~6mm x 8mm

d=330 μm (black)

$$C = \frac{k\varepsilon A}{d}$$

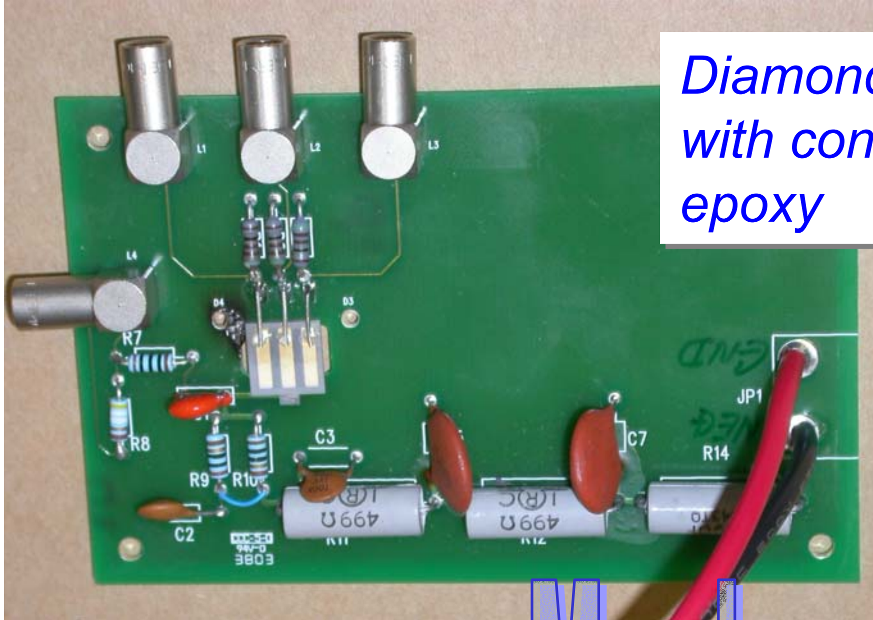
C~7pF

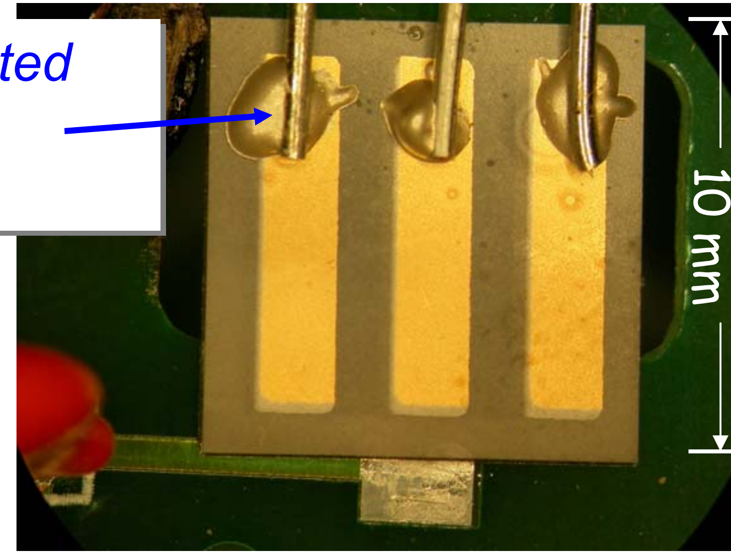


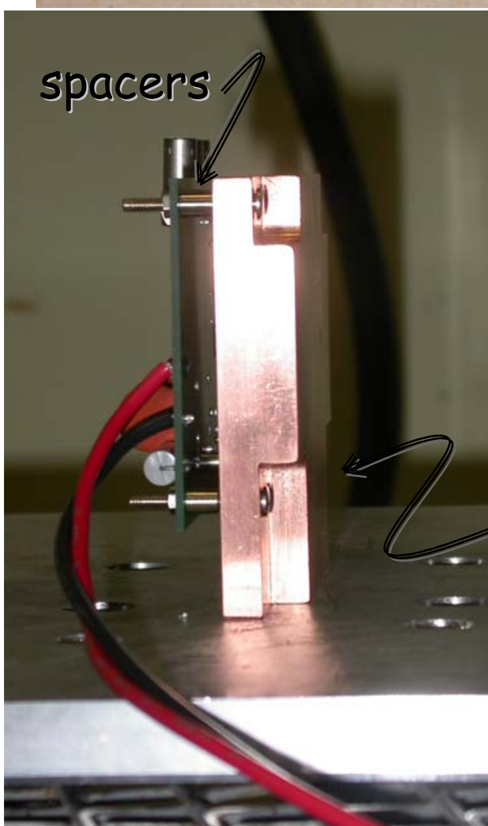
τ=(big capacitors in parallel) x other resistors=much bigger time constants

- 1050 W
- 0-500V, 0-5A
- response time 5ms

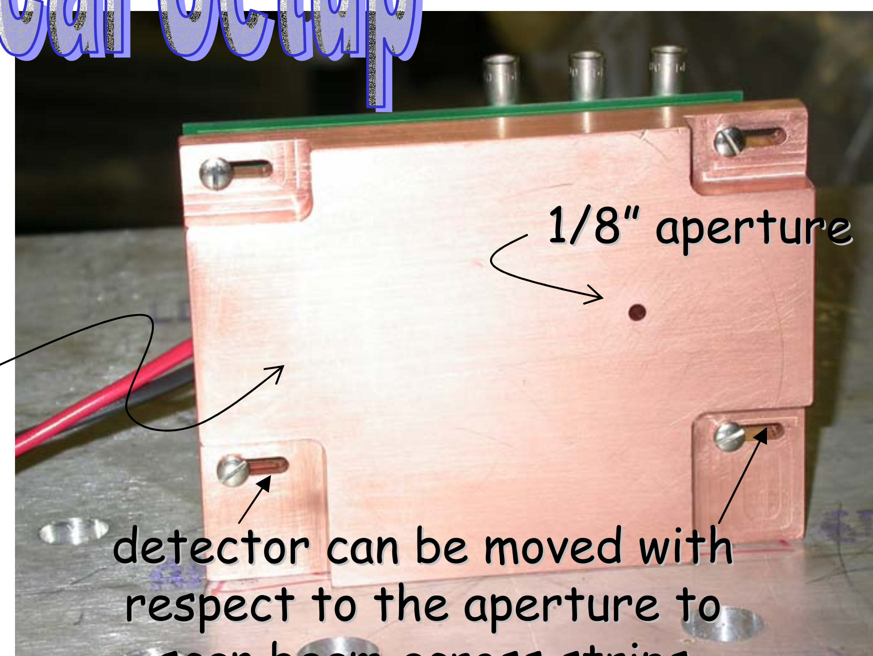
Mechanical Setup







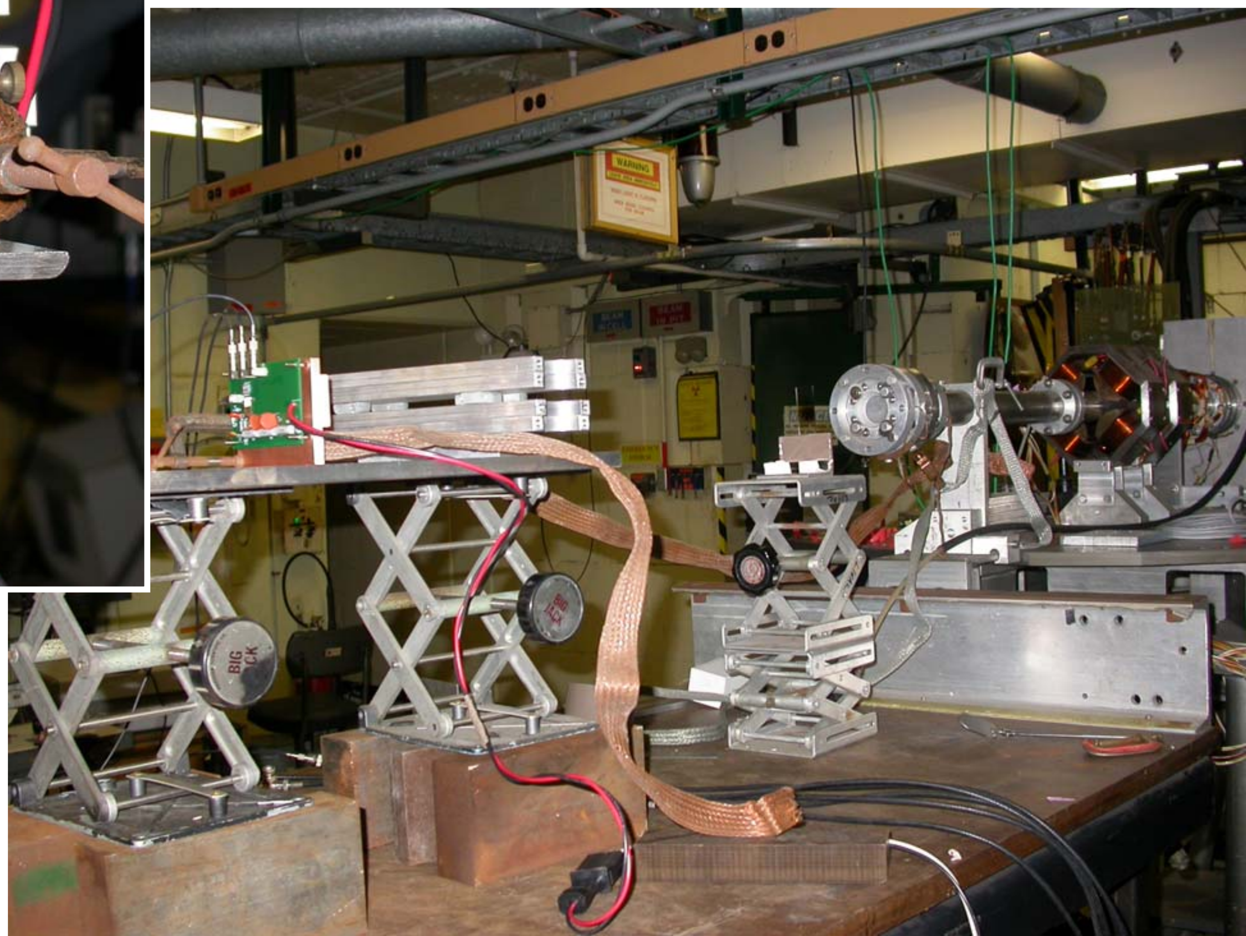
copper shielding block



Beamtests

Argonne Chemistry Linac

- 20 MeV electrons
- Max intensity: 23 nC/pulse $\approx 1.4 \times 10^{11}\, e^{-}$
- Beam size ~1 cm at end of beampipe
- Pulse width can be varied from subnansecond to ~10 ns



Four beamtests

- Jan 15, 2004
- Jan 22, 2004

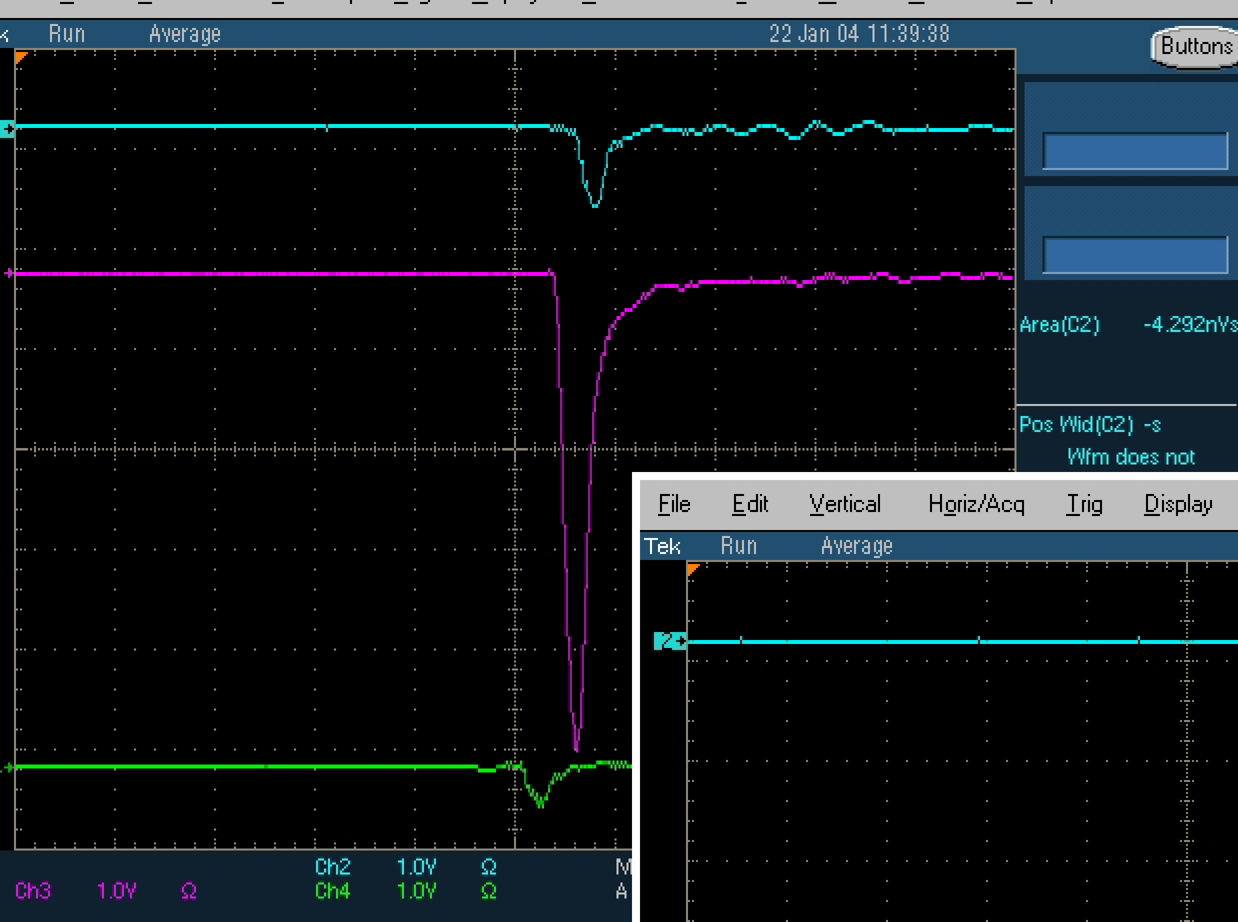
$\}$ *Proof of principle*

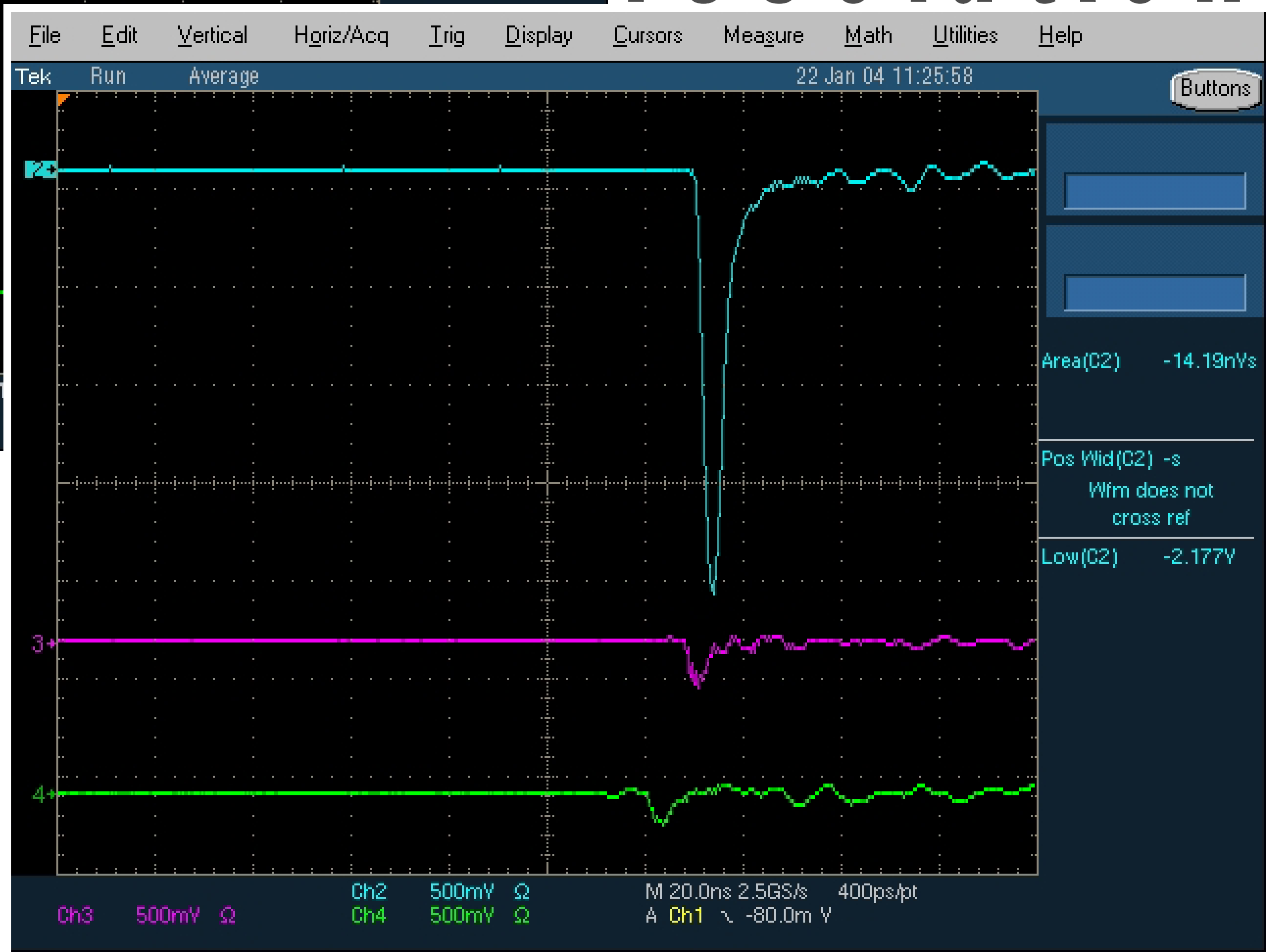
- April 7, 2004
- April 28, 2004

$\}$ *More rigorous studies*

Proof of principle: Part I

Space resolution

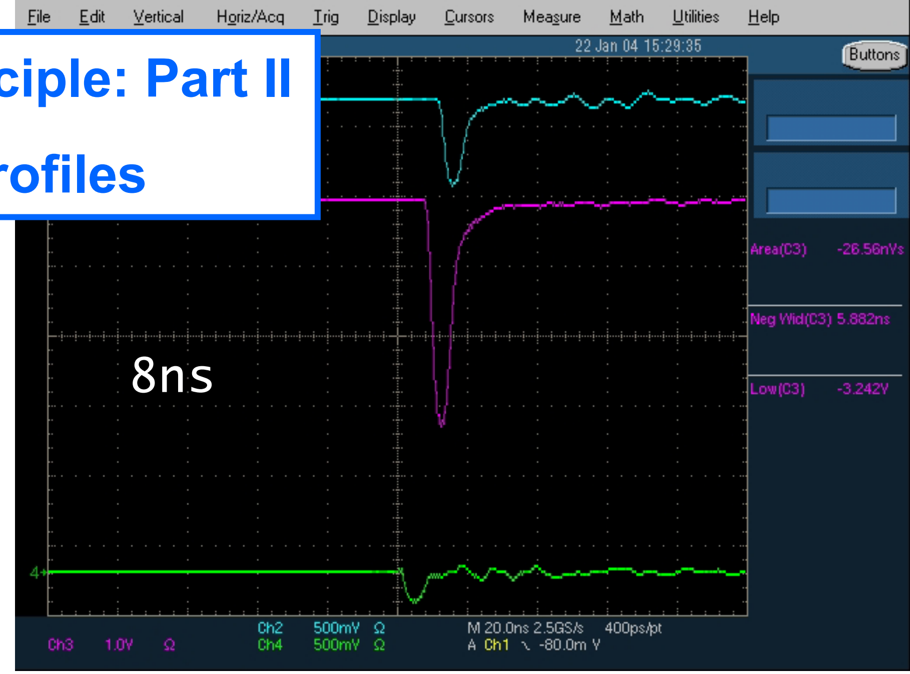




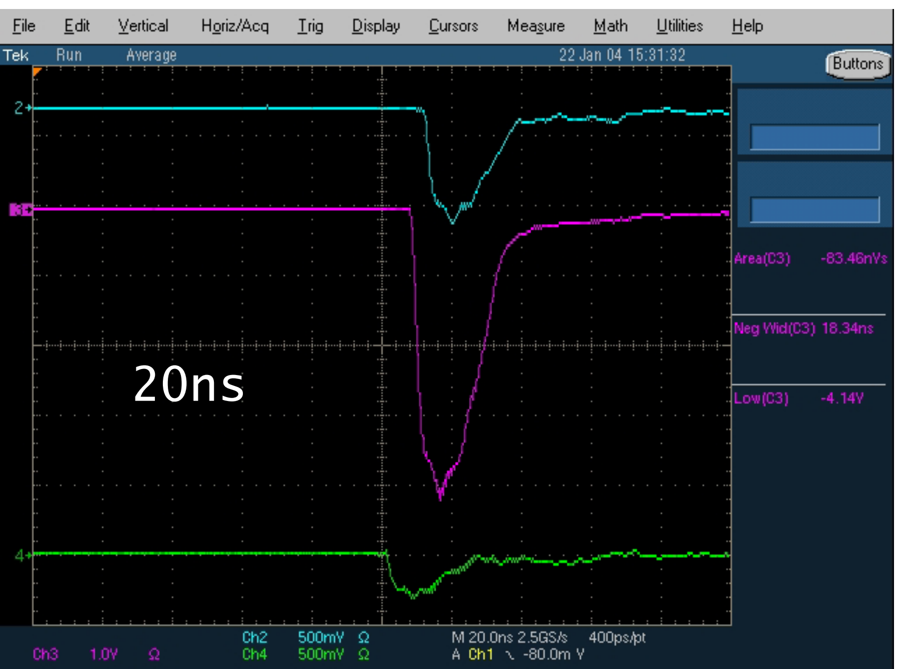
Aperture moved from in front of far strip to in front of middle strip.

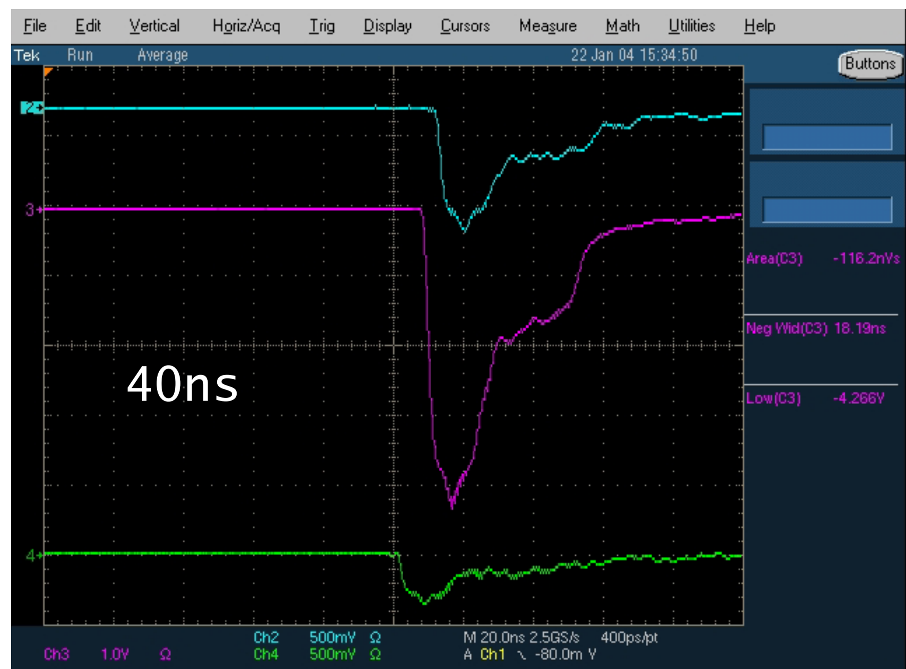
Proof of principle: Part II

Time profiles



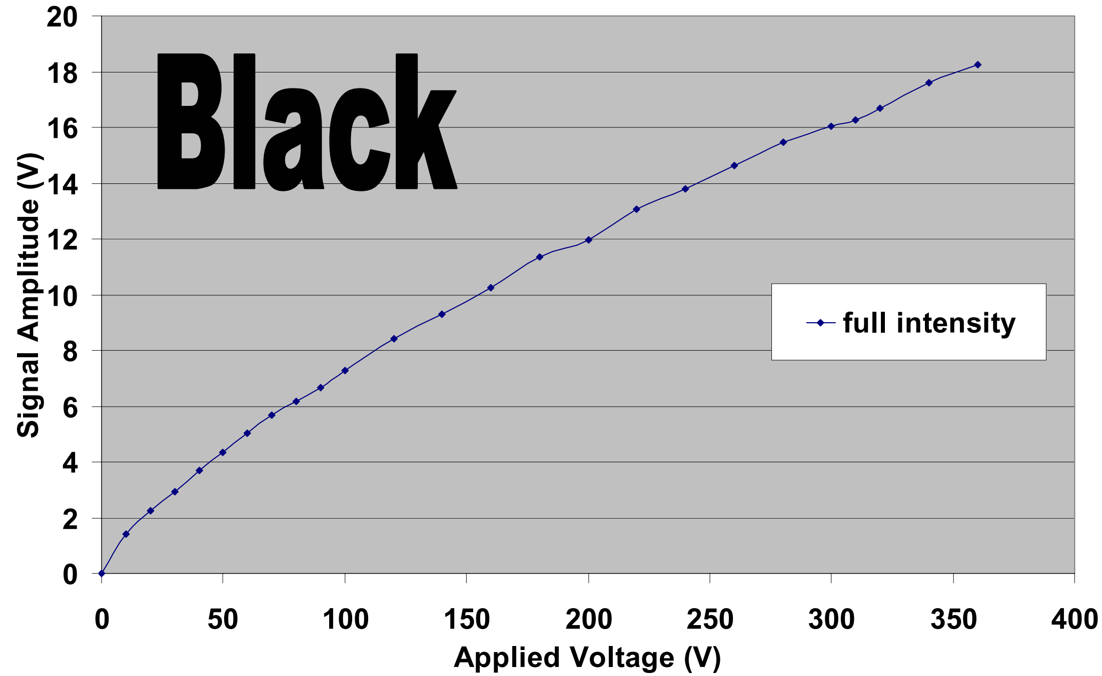
Longitudinal profile: time resolution smaller than the pulse width

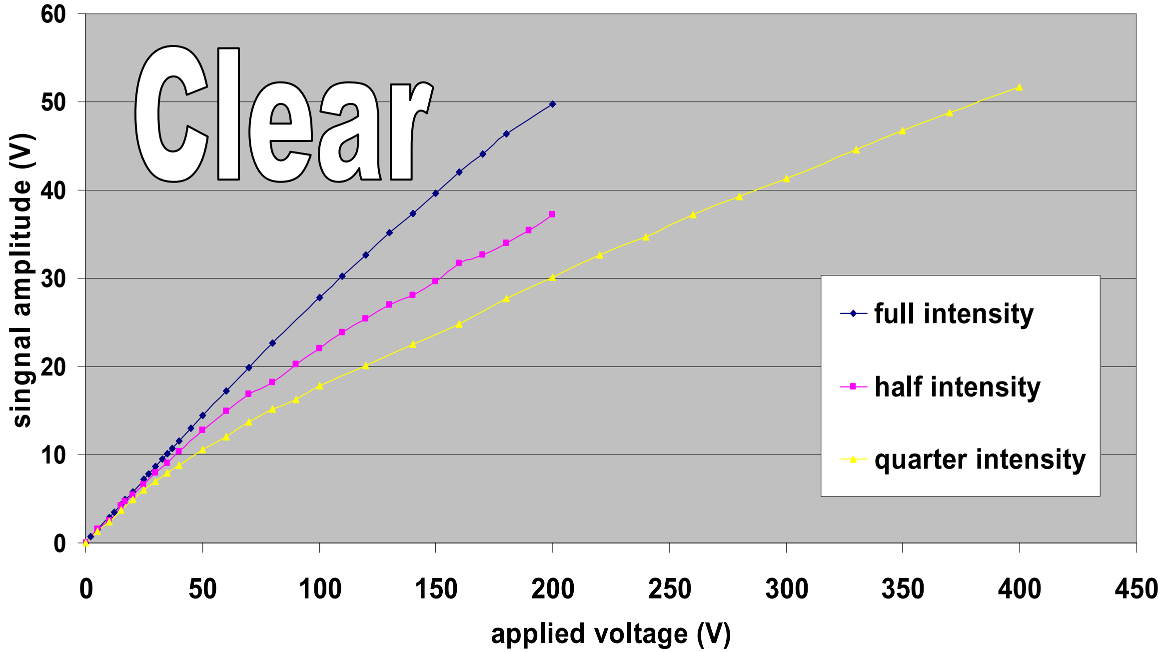




Signal Amplitude

As a function of bias voltage and intensity

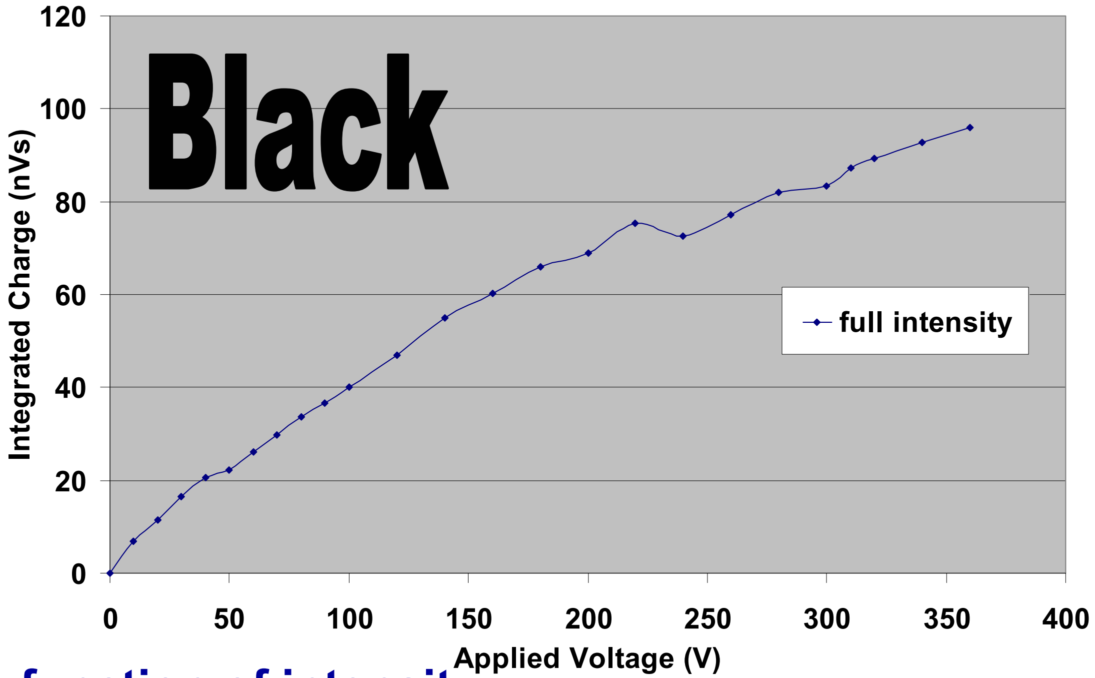




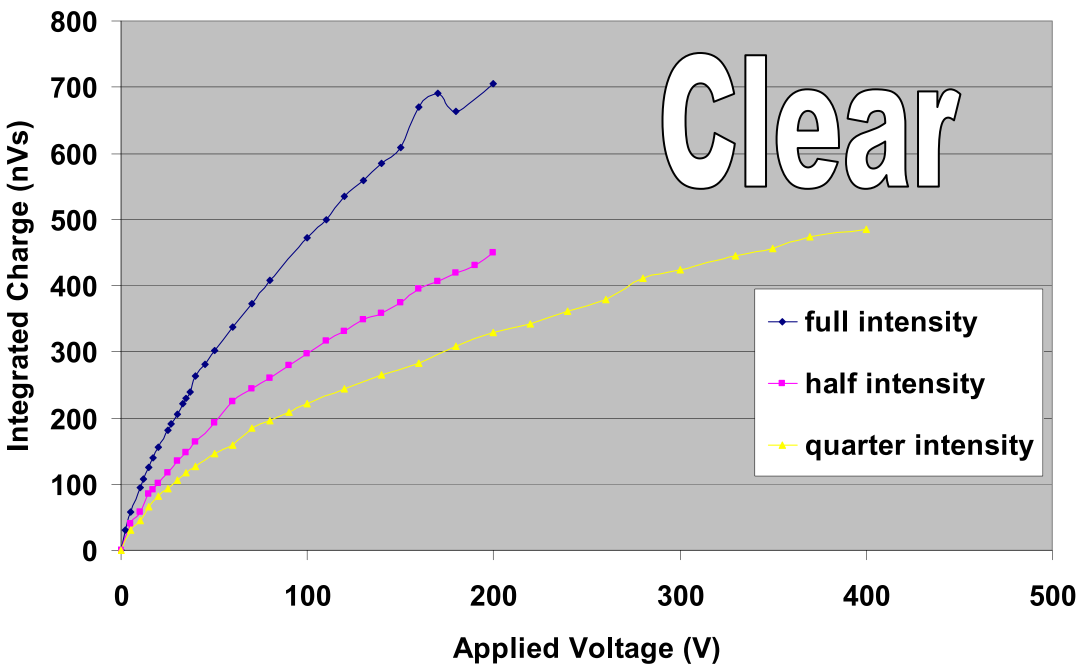
- Clear diamond has much bigger signals (no big surprise)
- Amplitude isn't linear as a function of intensity (uh-oh)
- But amplitude isn't the figure of merit, it is the amount of charge induced…

Total Charge

That is, the integrated area under the pulse…



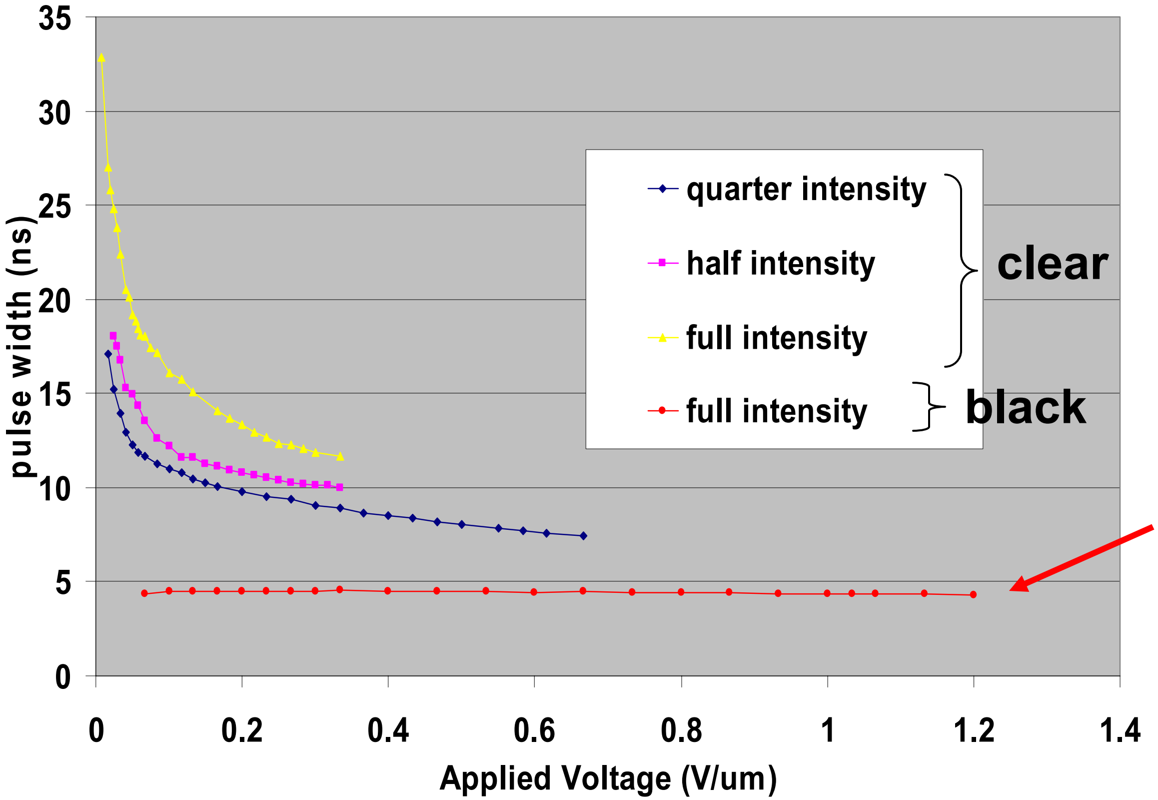
Response much more linear as a function of intensity…



…but if the total charge is linear and the amplitude is not, then the pulses must be getting wider as a function of intensity!

Signal pulse width

for electron bunches of 4 ns nominal width



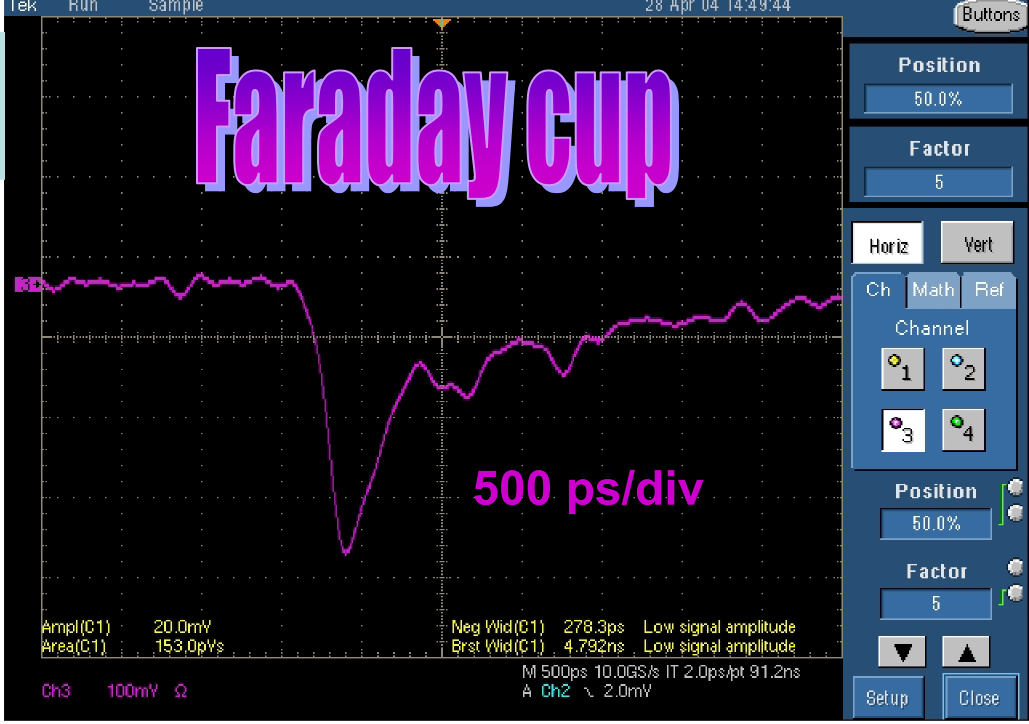
clear diamond has consistently wider pulses under same conditions- narrowest pulses achieved ~6ns

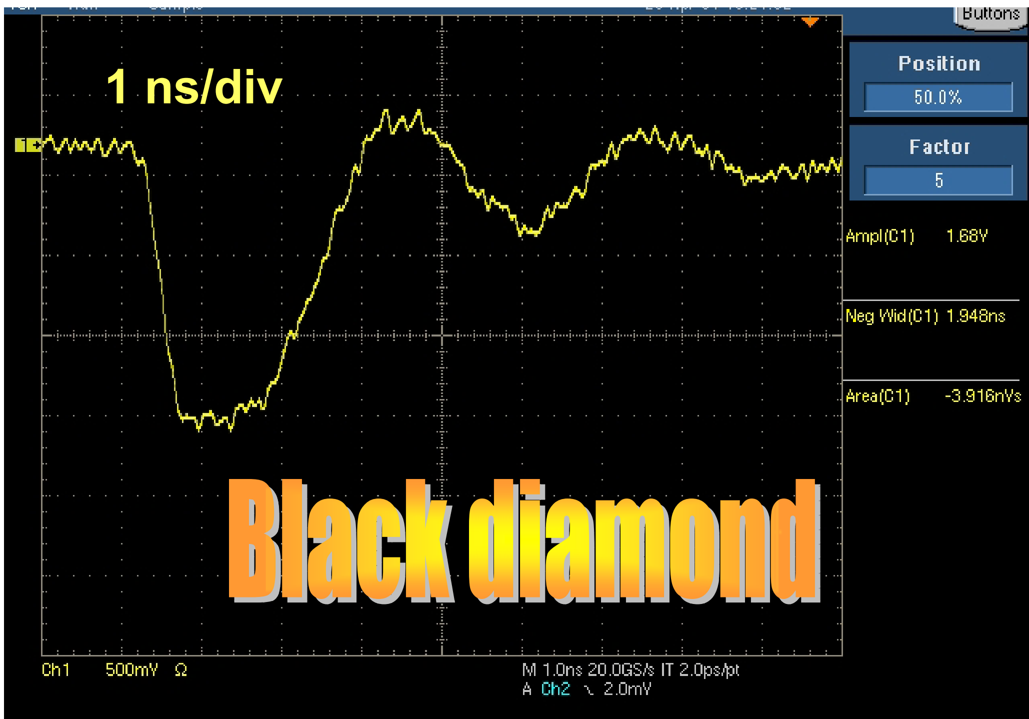
black diamond signal width is always the same as the 4ns bunch width

Conclusion: black diamond has better intrinsic resolution which is better than 4 ns

What is the intrinsic time resolution of the black diamond?

- For this you need the Rolls Royce of scopes and mine is a mere Cadillac- borrowed a Tektronix 7404 with 4GHz bandwidth and 20 Gs/s sample rate
- Tuned the beam up for subnanosecond pulses
- Got a time profile of the beam using a fast Faraday cup
- Compare to black diamond- fast rise time the narrowest measured pulse width is 2 ns
- Dialed the intensity way down- this width does not seem to be intensity dependent
- An effect of the thickness, perhaps???





A few words on intensity and saturation

It was a major goal of mine to address this, but it really needs more study (or a better setup).

Based on geometrical arguments we estimate the maximum intensity we reached as follows:

full beam: 23 nC/pulse

$$\approx 1.4 \times 10^{11}\, e^-$$

beam size at highest intensity point: 4 sq. cm

$$\approx 3 \times 10^{10}\, e^- / \mathrm{cm}^2$$

$$\approx 2 \times 10^{9}\, e^-$$

through 1/8" hole

At the highest intensity, the response changed when we tweaked the intensity…so I cautiously claim it wasn't saturated.

What now?

•Would like to try thinner "black" diamonds, we don't need the charge. (A German company, Fraunhofer Gesellschaft, claims they can provide free standing diamond in tens of microns thickness.)

•Would like to make studies more systematic (i.e. change only one variable, collection distance or thickness, at once). To this end, we tried to have a black diamond thinned. That failed.

•Need to work on understanding intensity.

•Need to study radiation effects in diamond with short carrier lifetimes.