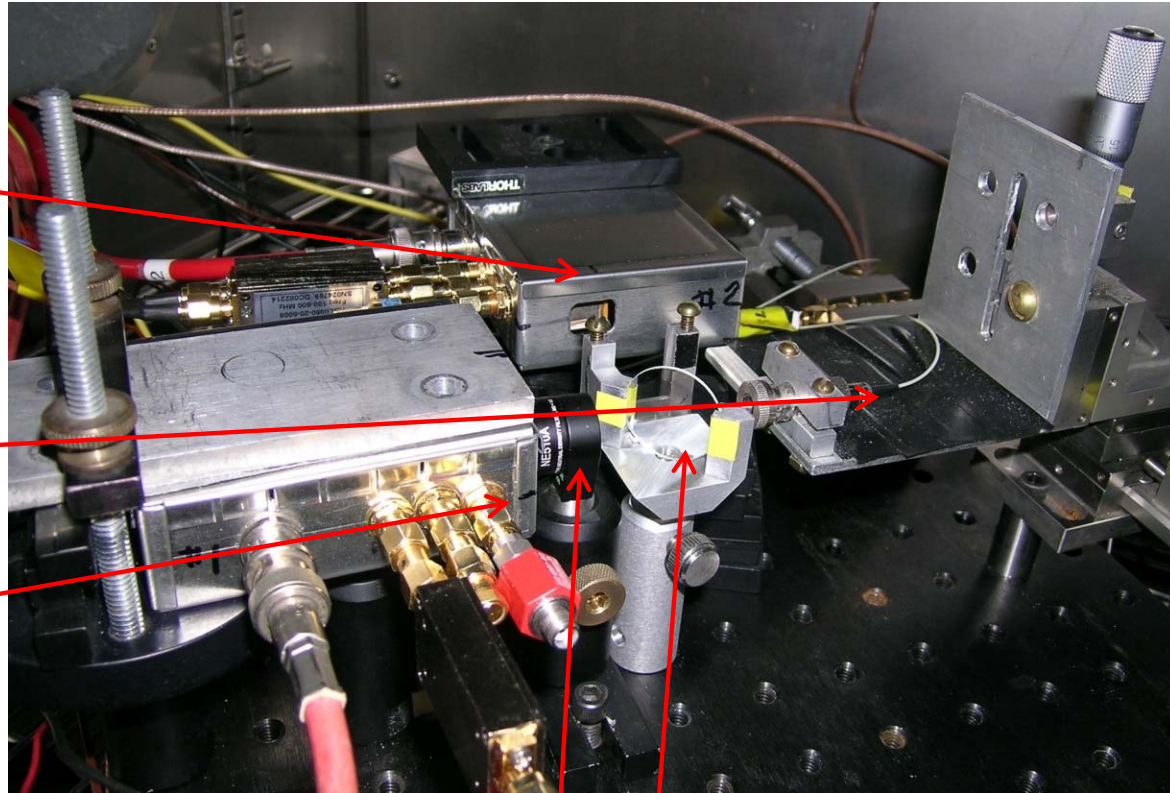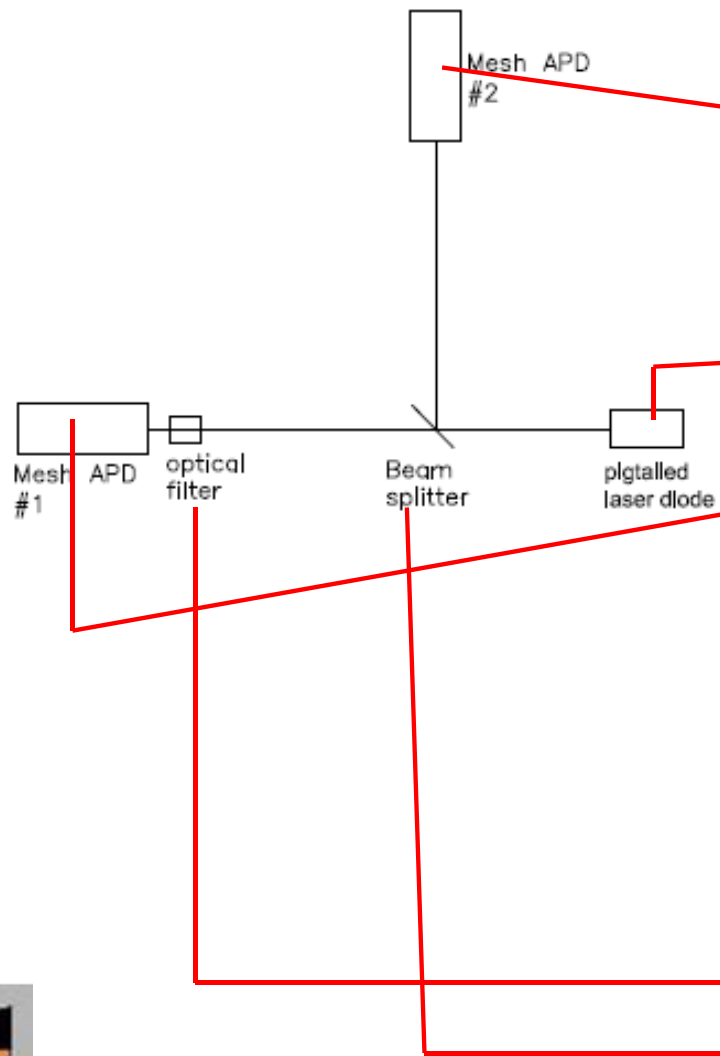# APD time resolution study with beam splitter

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(5/29/2015)
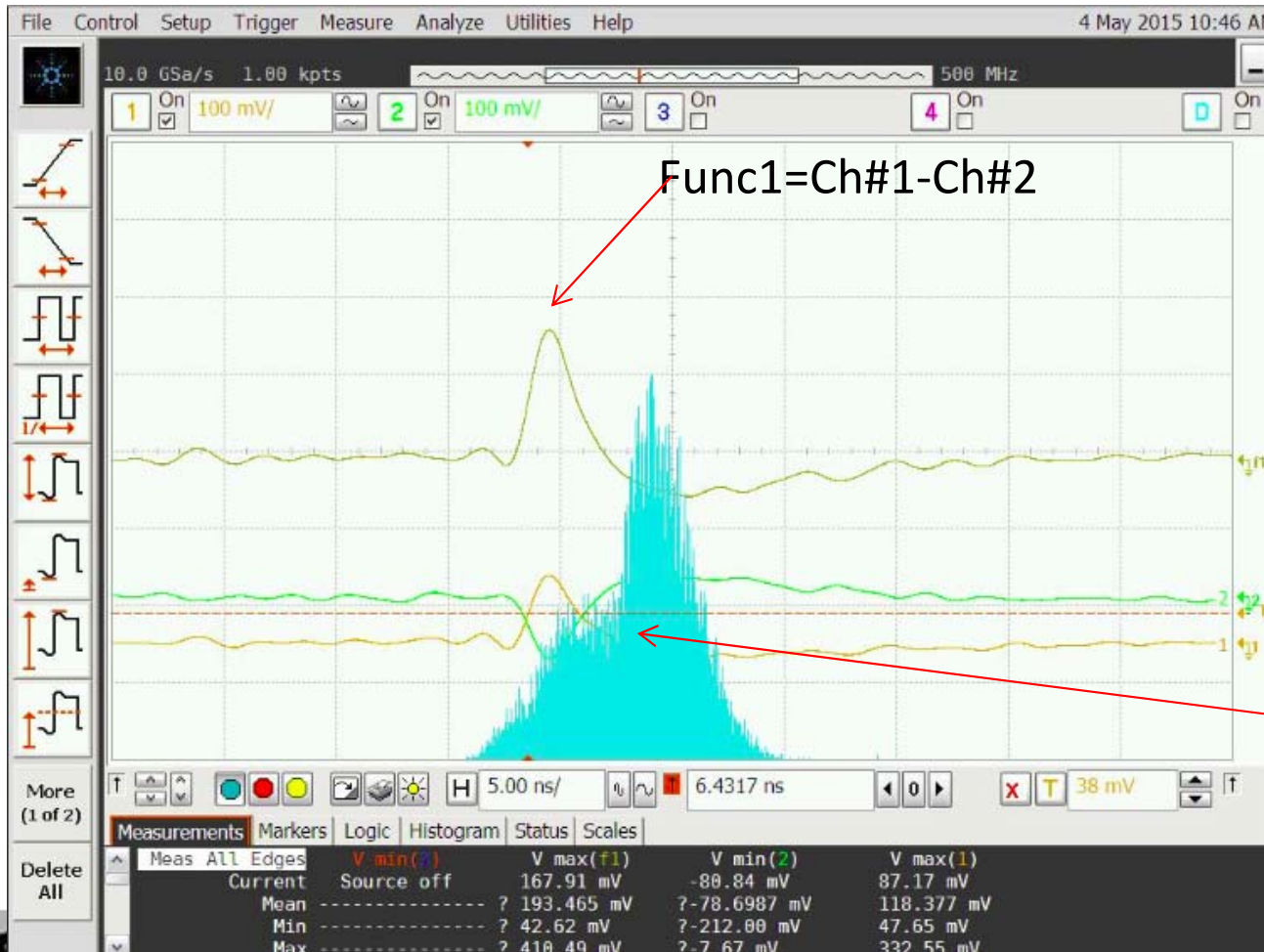
Beam splitter test setup

APD test box

Measured Fe-55 spectrum

Wenteq 5008 amplifiers used in the test. Spectrum of Fe-55 for APD #2, HV @ -1800 V:

APD #1 has thicker layer of epoxy on the mesh, which absorbs Fe55 x-ray, so the counting rate is quite low, we didn't record its Fe55 spectrum.
Ch#1 – APD#2 cathode;
Ch#2 – APD#2 mesh;
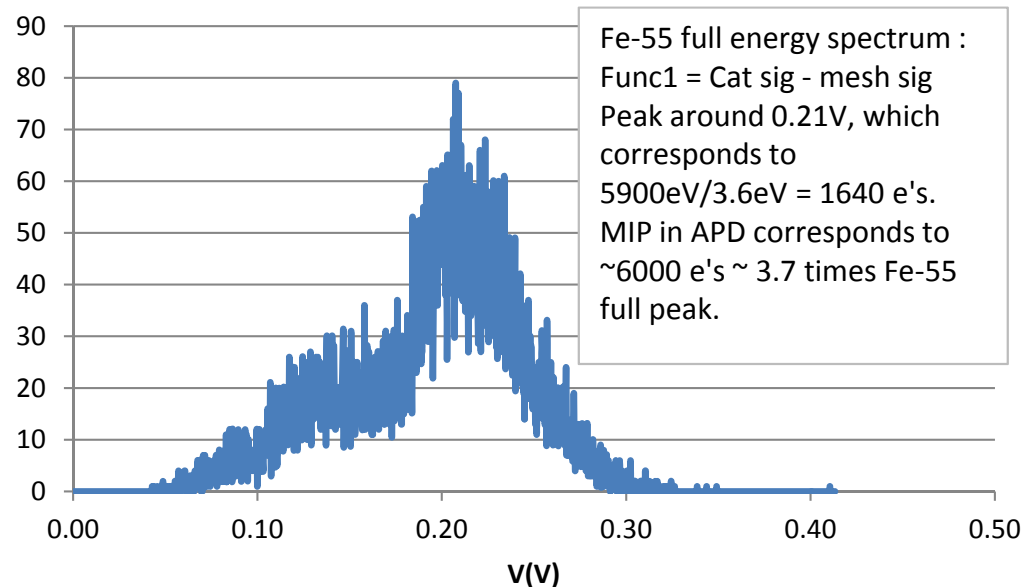Ch#3 – APD#1 mesh;
Ch#4 – trigger;
Func1 – Ch#1 – Ch#2;
Histogram of Func1 – See next slide for details.

Measured Fe-55 spectrum

Measured spectrum for Fe-55, HV @ -1800 V.

Fe-55 full energy spectrum :
Func1 = Cat sig - mesh sig
Peak around 0.21V, which corresponds to
5900eV/3.6eV = 1640 e's.
MIP in APD corresponds to ~6000 e's ~ 3.7 times Fe-55 full peak.

Fe55 peak is at ~210 mV, which corresponds to 5900/3.6 = 1639 e-h pairs. In 60-um silicon layer MIP particle can create ~6000 e-h pairs. We should adjust laser intensity to 6000/1639 = 3.7 times Fe55 peak, ~**210 mV * 3.7 = 780 mV**, to mimic MIP signal.
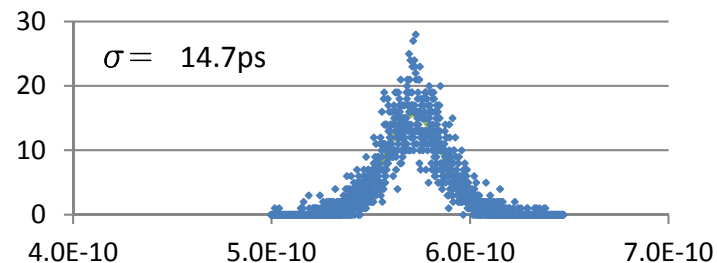
Time resolution

Adjust HP pulser's output to tune the laser beam intensity until V_{Func1} is in neighborhood of 780 mV. For APD #1 only mesh signal is available, so we adjust its mesh signal size close to APD #2 mesh signal: 365 mV. After this adjustment both channels can mimic MIP signal with laser beam. Measure time resolution between these two APDs.
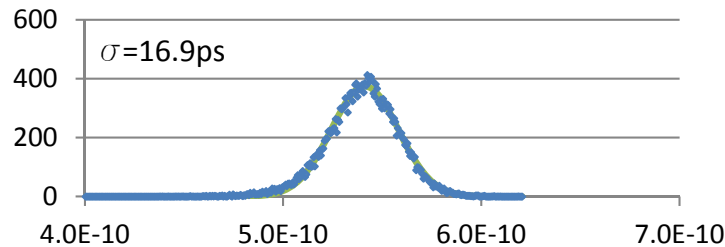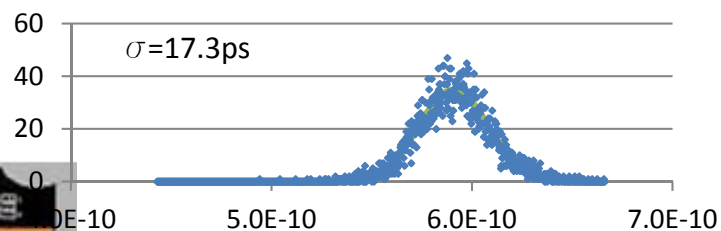

dt = APD#2 mesh to APD#1 mesh
$\sigma(dt)$ = 16.9 ps

dt = APD#2 Func1 to APD#1 mesh
$\sigma(dt)$ = 15.6 ps
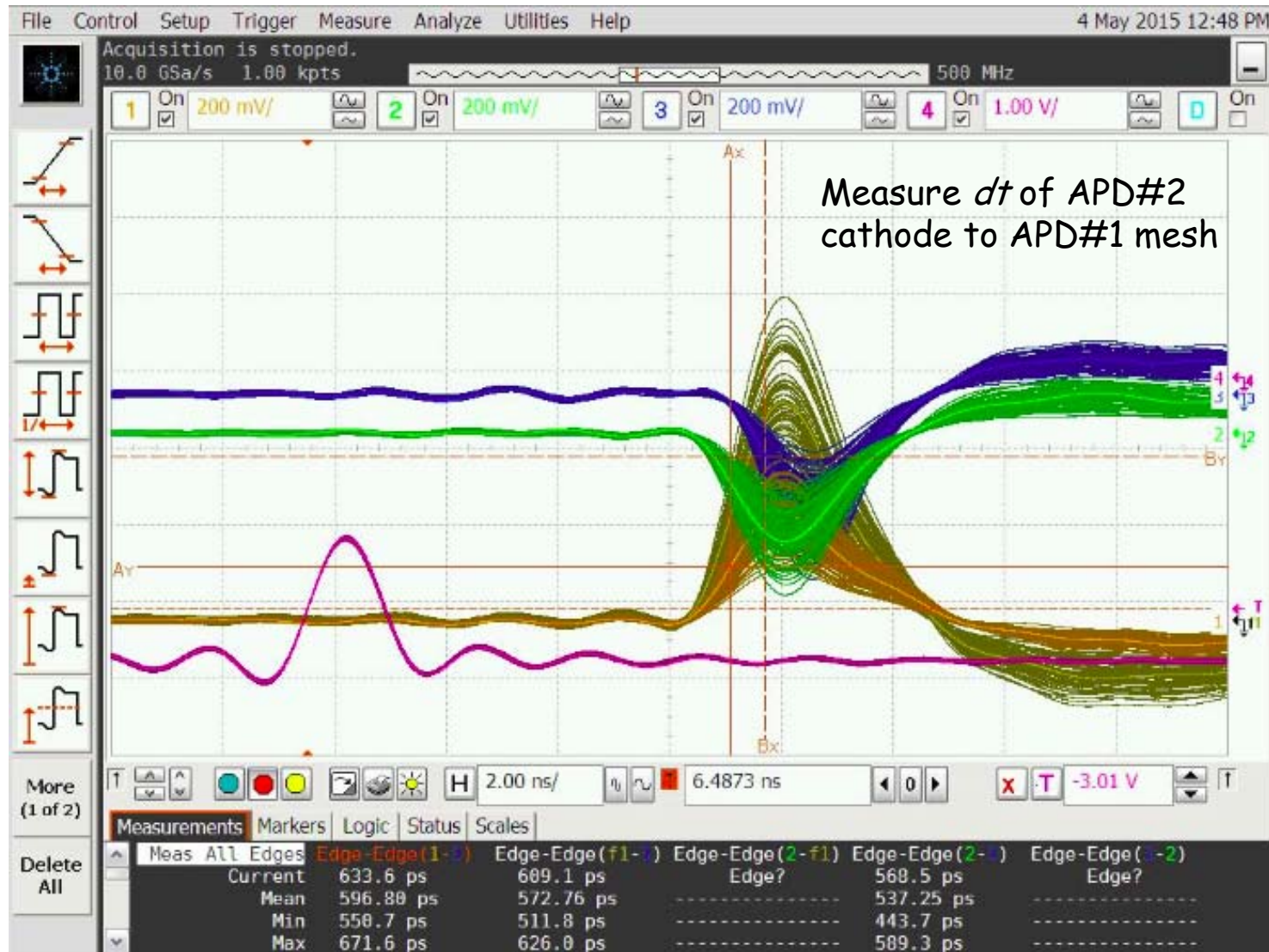Thus we can derive the single APD's time resolution = 15.6/$\sqrt{2}$ = 11 ps.

dt = APD#2 cathode to APD#1 mesh
$\sigma(dt)$ = 17.3 ps

Illustration of dt measurement

The following is a screen capture of the time measurement, several dozens of events are overlapped.

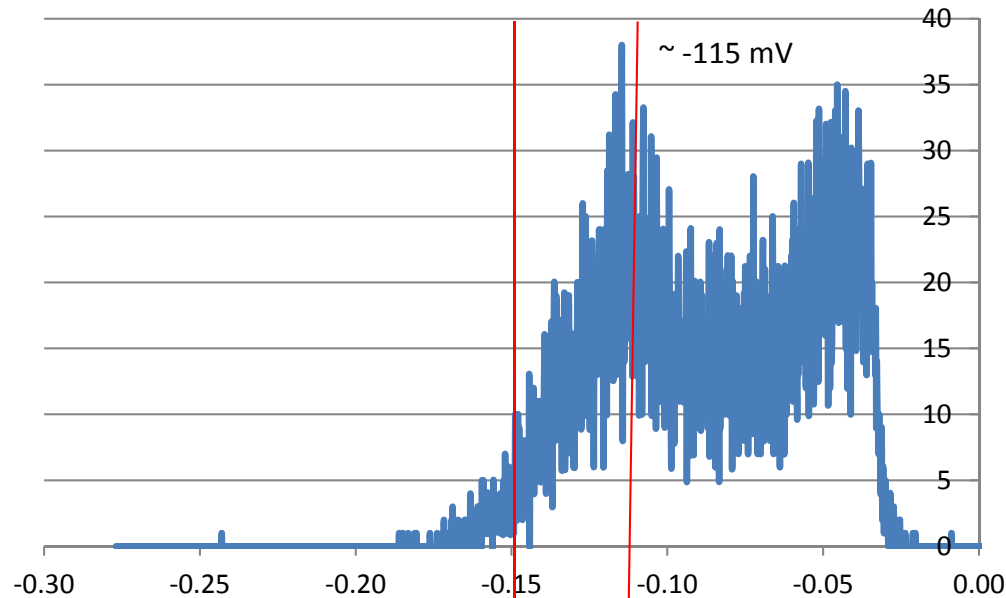Measure *dt* of APD#2 cathode to APD#1 mesh

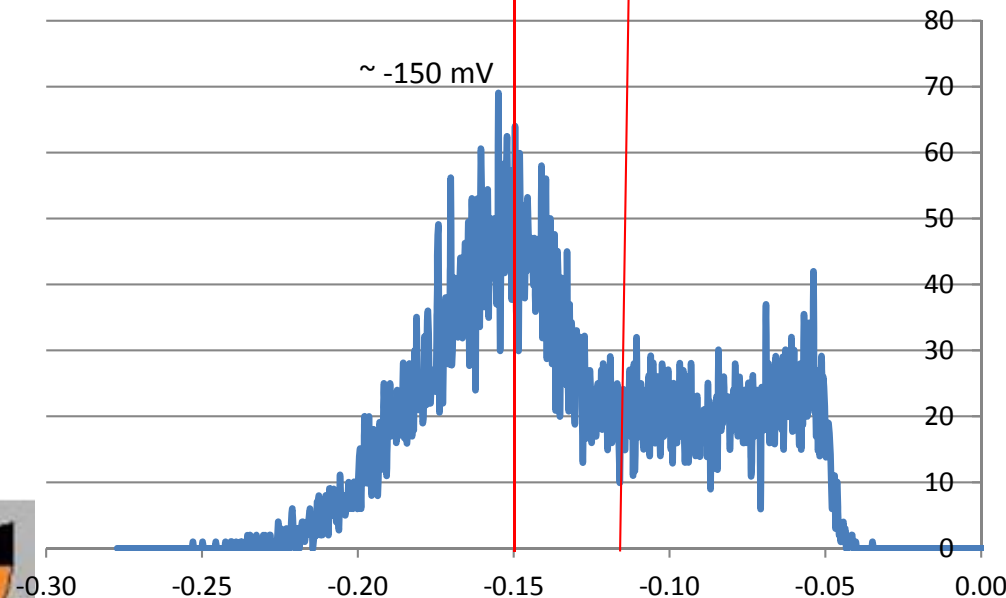Ch#3: APD#1 mesh

Ch#2: APD#2 mesh

Ch#1: APD#2 cathode

Cathode termination effect on mesh signal

Fe55 spectrum measured on mesh electrode, cathode output terminated by 50 ohm.

Fe55 spectrum measured on mesh electrode, cathode output terminated by 0 ohm. Signal is larger than 50 ohm termination scenario.

Interesting observation of the induced signal on anode

We have noticed that when we shift the laser beam along with x-direction, the induced signal on anode is also shifting along with time. This phenomenon must relate to the mechanism of signal formation in the APD.
For this test we only use APD#2, all three channels available on the Agilent scope are hooked up to this APD: mesh(ch#1), cathode(ch#2) and anode(ch#3), leave the 4-th one as the trigger channel.

APD#2

x

Laser diode

splitter

Interesting observation of the induced signal on anode

$x = 2$ mm

anode

trigger

7 mm
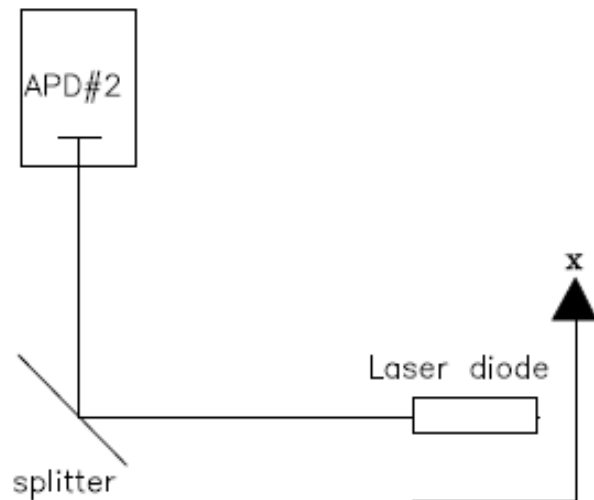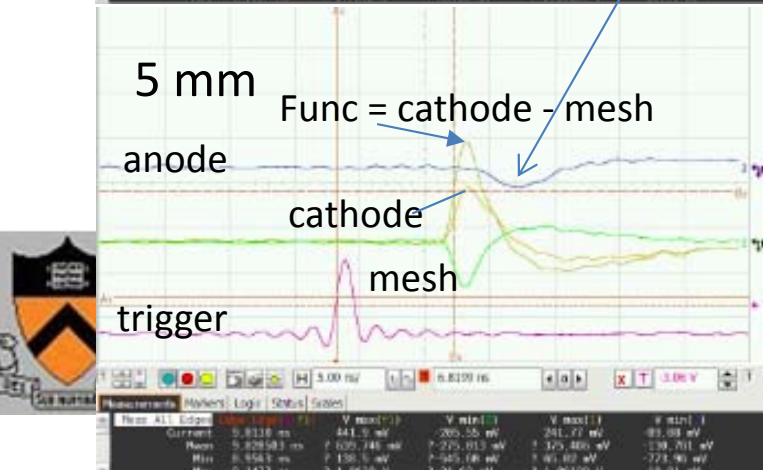
Notice how this anode signal is shifting while moving beam spot position along x direction

3 mm

9 mm

The mesh and cathode signals are not shifting except the cathode signal at 2mm shows little bit latter.

5 mm

Func = cathode - mesh

anode

cathode

mesh

trigger
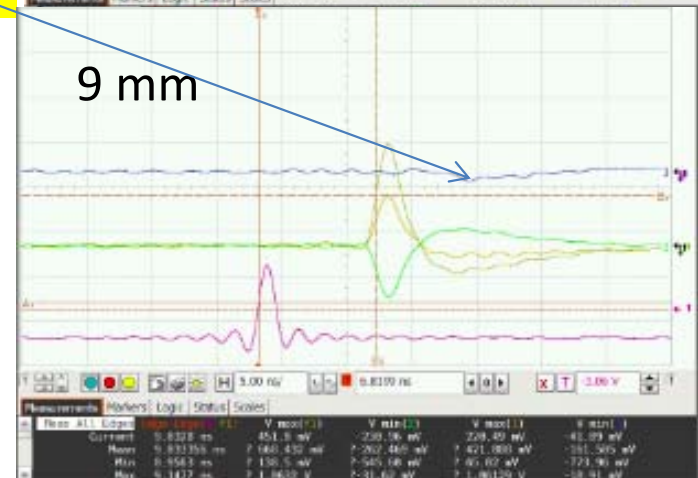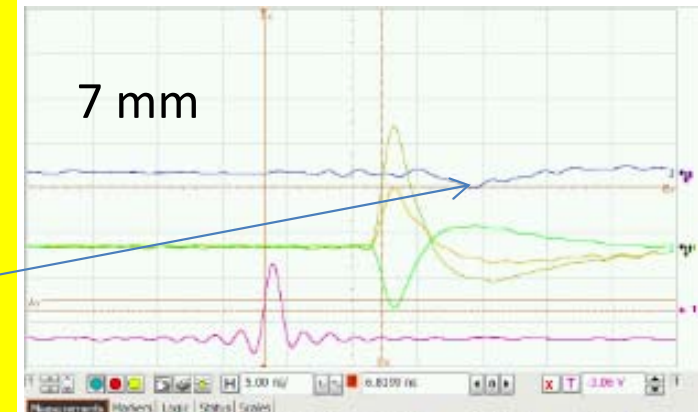
Timing of the induced signal on various electrodes
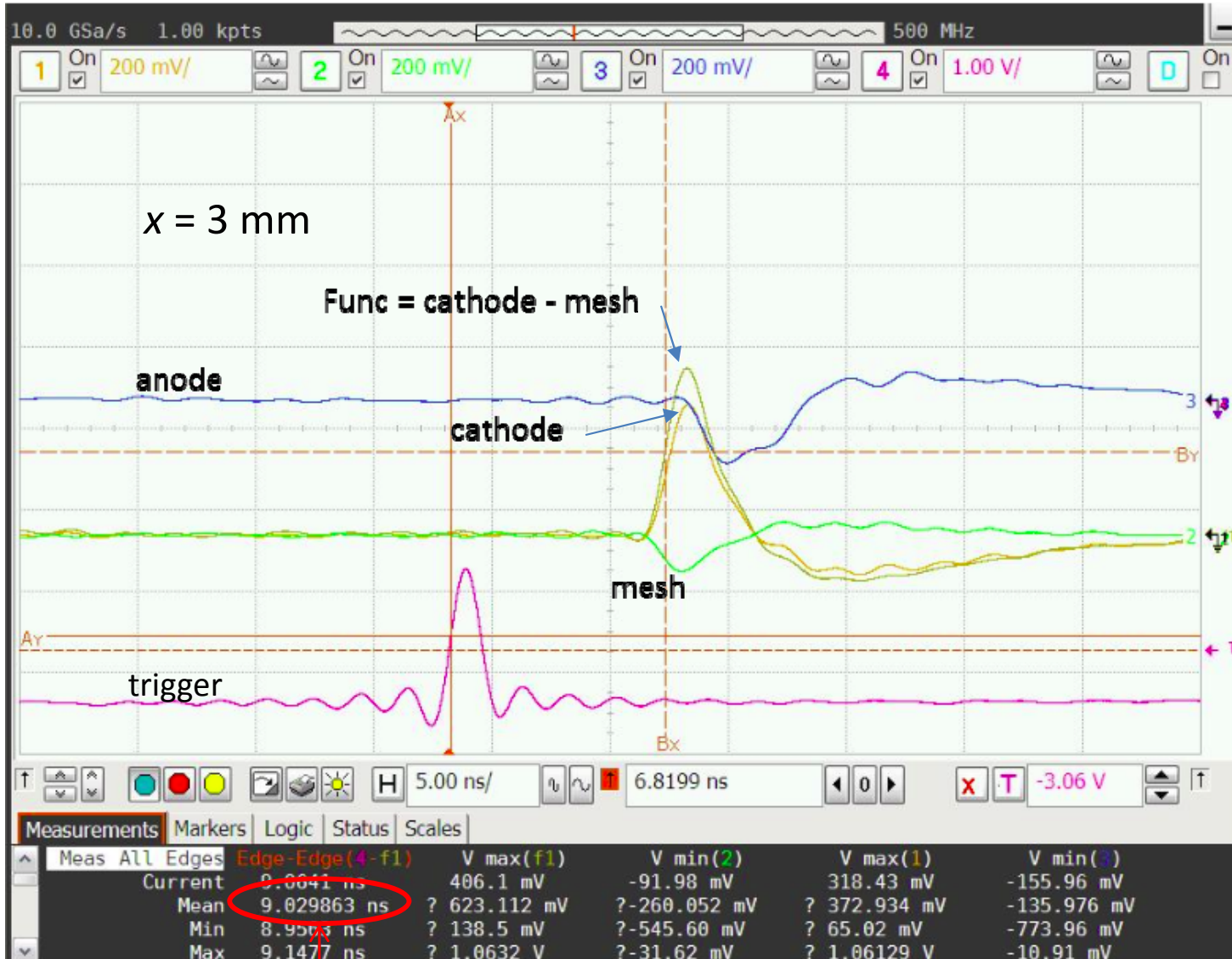
The induced signal on the electrodes are due to the movement of the source charge in the APD, so it is hard to understand why the time of the anode signal is so later than the signals on other electrodes? The screen captures on previous slide also reveal the time interval between laser diode trigger signal and Function signal (cathode – mesh): Summary see next slide.

Timing of the induced signal on mesh/cathode

Five different x locations:

x (mm)	2	3	5	7	9
Δt (ns)	9.0328	9.0299	9.0285	9.0305	9.0334

The mean value of Δt = 9.0310 ns, $\sigma(\Delta t)$ = 0.0018 ns
We can see the timing of the mesh and cathode signal is not shifting with laser spot position, only anode signal is wandering around.

Possible explanation of the anode behavior

On my report made on 2/5/2015 "Signal from anode, cathode and mesh of RMD 8x8mm mesh APD" the scanned signal amplitude distribution was presented. I attach five slides from that report in the following:
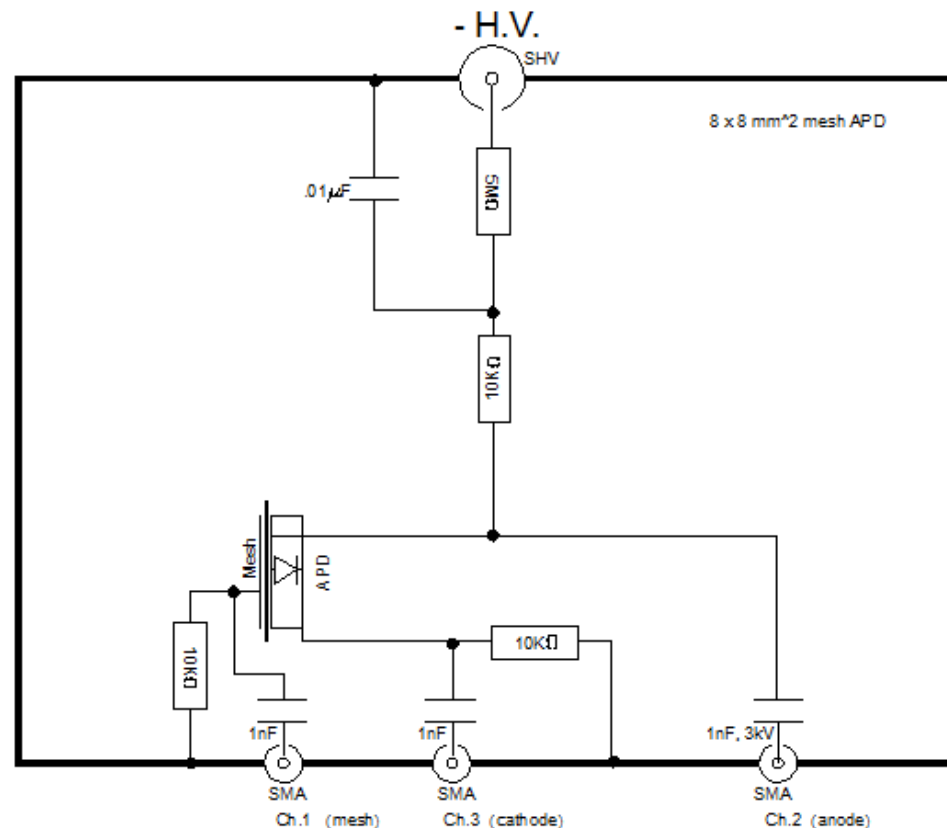
Please note the coordinate system of 2/5/2015 test is somewhat different from this recent test, therefore when you compare the signal variation with x you should only pay attention to the relative x variation, not the absolute x value.

To understand the signal formation of APD we have to gather more information, which includes the difference of the signal size and shape on various electrodes.
For a 64 mm² mesh APD we can get three signals from Anode, Cathode and Mesh, respectively. With the help of Agilent digital scope we also can get various combination of these signals in real time, such as cathode-mesh, anode-mesh, e

Test setup

Lens of laser diode

x

Test box

Box open window

Mesh APD

y

Coordinate system
used in this test

Front view of mesh APD

Back view of mesh APD

Test setup

The Laser Diode used in this test is WSLP-980-010m-4-PD fiber coupled laser diode, 9-nm, 10-mW laser diode, 6-μm thick, 80-cm long fiber.
The trigger pulse is coming from HP8131A pulse generator.
Parameters used are:
V_{high} = 0;
V_{low} = -3.6V (varies later);
Width = 0.5 ns;
Freq = 10 kHz.
All three channels use Wenteq 5008 amplifier.
-1750 V is applied to the 64 mm^2 mesh APD.
The lens of the laser diode is mounted on an *x-y* stage, thus the laser beam can move along with *x* and *y* direction.
The tested mesh APD S/N: 431-3-A.

Scan results from various channels

We scan a 64 mm^2 mesh APD along with x and y directions for various channels: Cathode, Mesh, Anode, Cathode-Mesh and Anode-Mesh as shown below: Cathode-Mesh signal has wide flat distribution both on x and y directions:
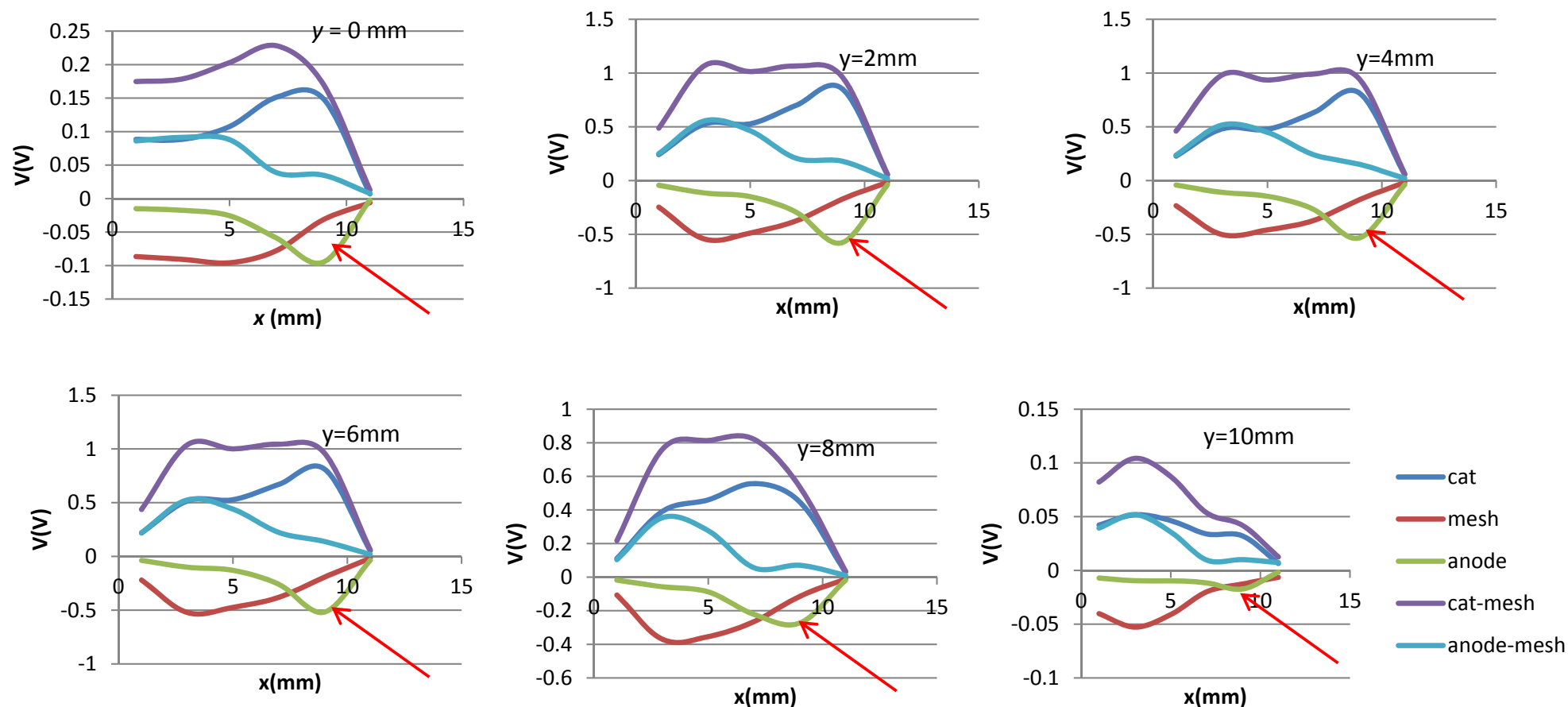
Anode readout pin is at x = 10 mm

Induced signal vs. beam position

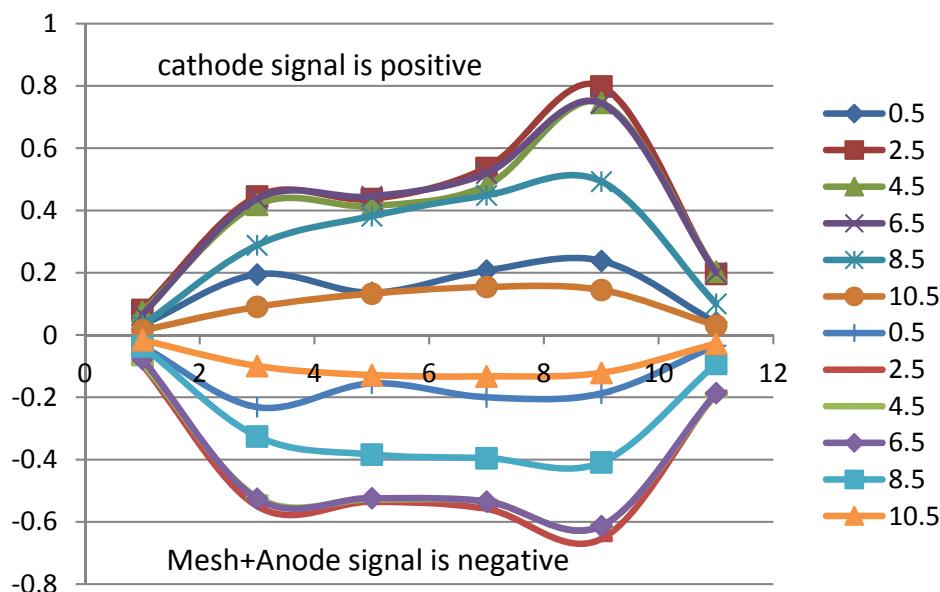This plot clearly shows induced current on cathode electrode is almost the mirror image of the induced current on anode + mesh electrodes. The induced signal from cathode is the largest one.

If we combine all three signals together and produce a signal = Cathode – (Mesh + Anode), we can double the signal size, also can reduce common mode noise, that can further improve the time resolution. In the following tests we use Cathode-Mesh signal to measure the time resolution, it does show better results.

Next slide is Dick's sketch of mesh APD, it can helps us to understand above statement.

Dick's sketch of mesh APD

screen = mesh

Kapton

APD

Cathode electrode

Si with sintered Au

Al_2O_3
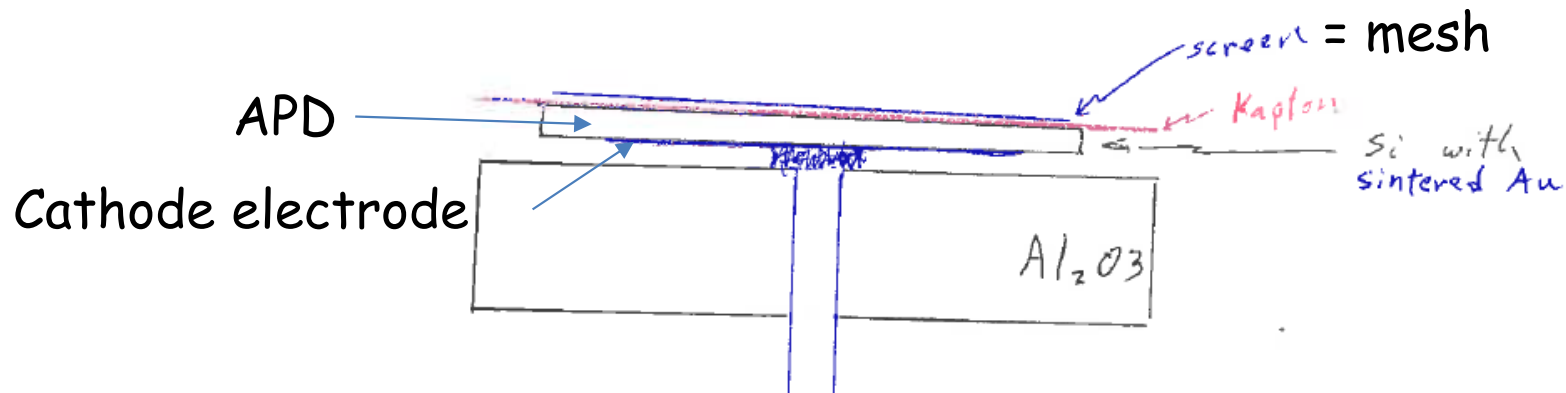
   According to Dick's sketch if we believe the induced signal model we can see that the cathode electrode should be the best place to obtain the induced signal because the bottom electrode is Au-sintered and covers entire back side (8x8 mm^2), there is no other electrode in between this electrode and the P-N junction.
   The anode side mesh electrode, although covers the entire APD active area, but there is anode electrode in between the mesh and P-N junction, therefore the induced signal on mesh electrode is partly shielded by the anode. This picture is strongly endorsed by our test result on the previous slide.

Possible explanation of the strange timing behavior of the anode

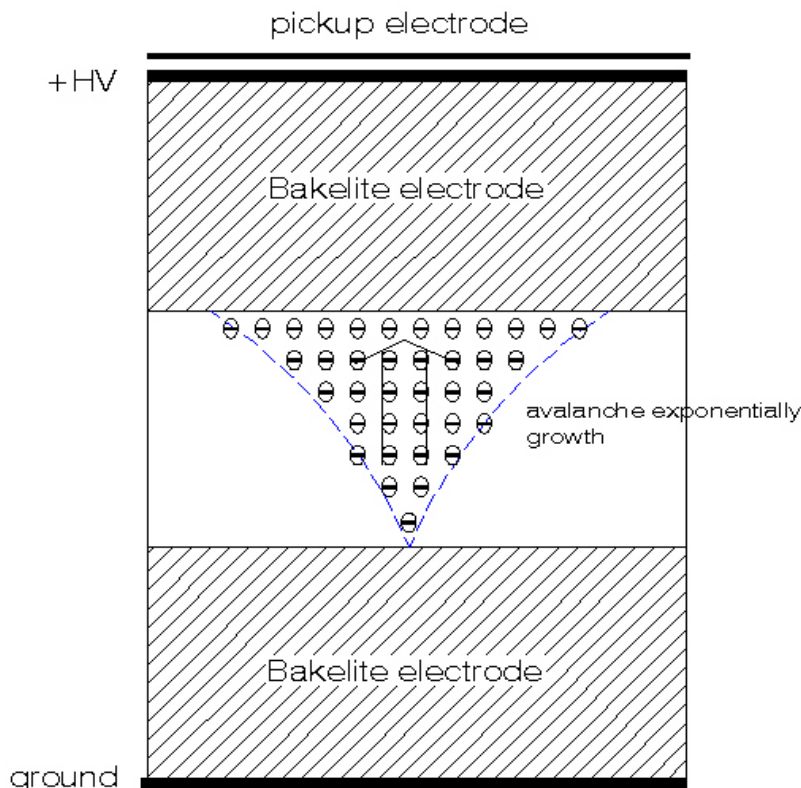## (See my old report "Simulation of RMD APD with VTCAD" 10/29/2012)

The signal obtained on APD's electrodes is not due to either electron or holes collected on the electrodes. It is the induced signal originated by the avalanche at the P-N junction. The mechanism is very similar to RPC chamber*, which is explained in the following:

The movement of the charge in the electric field induces a current signal on the pickup electrode.

Induced signal mechanism in RPC chamber

According to Ramo's theorem:

$$i(t) = \frac{E_w}{V_w} v e_0 N(t)$$

where e_0 is the electrons charge, $N(t)$ is the number of electrons presented at time t, v is the electron drift velocity, E_w (weighting field) is the electric field in the gap if we set the pickup electrode to V_w and ground all other electrodes.

* Induced signal in RPC, C. Lu, SNIC Symposium, SLAC, Stanford, California, 3-6 April, 2006.
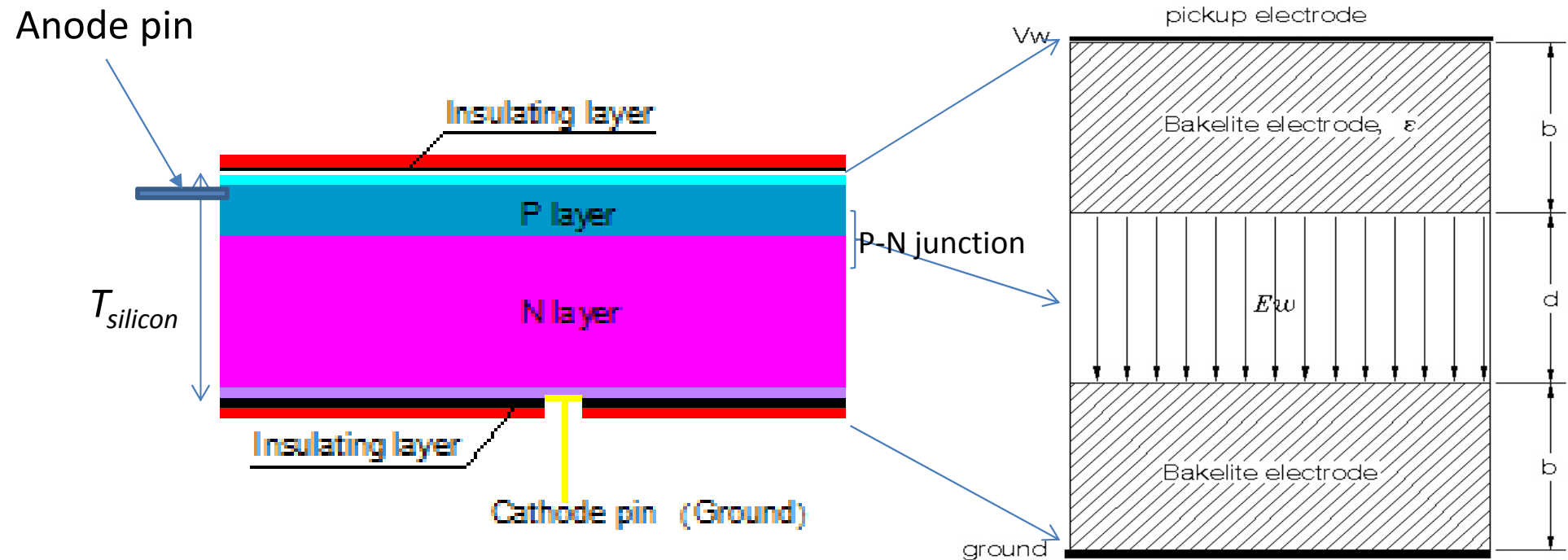http://www.slac.stanford.edu/econf/C0604032/papers/0201.PDF

The difference between RPC and APD is: for the former gas avalanche taking place in the high electric field region, for the latter both electron and ion can produce avalanche, but because the electron/ion is moving in the opposite direction, two induced signals will be added together. Therefore the basic signal formation mechanism should be similar.

If we readout on anode we should set the anode electrode to V_w, set all others to ground, then calculate the weighting field.
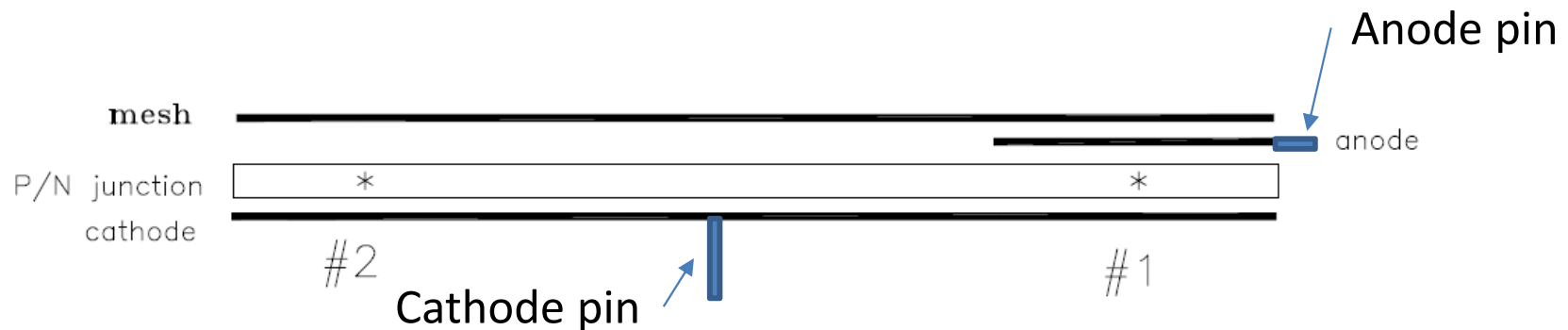
Since the anode surface P-type doping density is lower (see slide 23), its resistivity is high, the effective anode area is limited to a small region next to the anode pin, we model this as illustrated in above sketch. For the avalanche #1, the weighting field is normal there, so the induced signal looks normal, timing is no strange. But for the avalanche #2, the weighting field formed by anode and all other grounded electrodes is distorted from parallel geometry, quantitatively we can understand why the induced signal is much latter and its leading edge slope is much slower.

Similarity of APD & RPC weighting field

Anode pin

Insulating layer

P layer

P-N junction

$T_{silicon}$

N layer

Insulating layer

Cathode pin (Ground)

pickup electrode

Vw

Bakelite electrode, ε

b

E_w

d

Bakelite electrode

b

ground

The similarity between these two illustrations is very clear: the P-N junction → Gas gap; other silicon material → Bakelite electrodes.
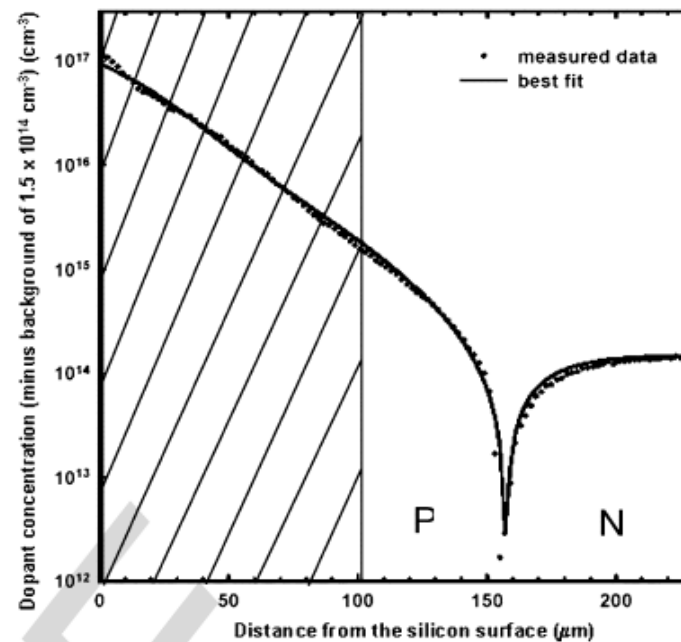
Doping profile

The doping profile is extracted from RMD IEEE NS October, 2006 paper. We add a thin layer of high density doping to each side of the APD: P side 10^{19} (will change it to **10^{17}**), N side 10^{18} (will change it to **10^{21}**).
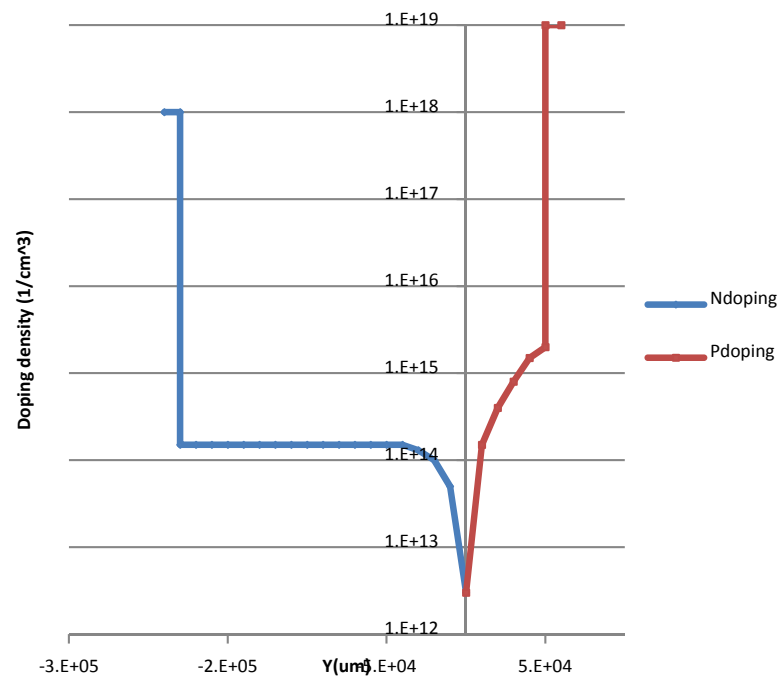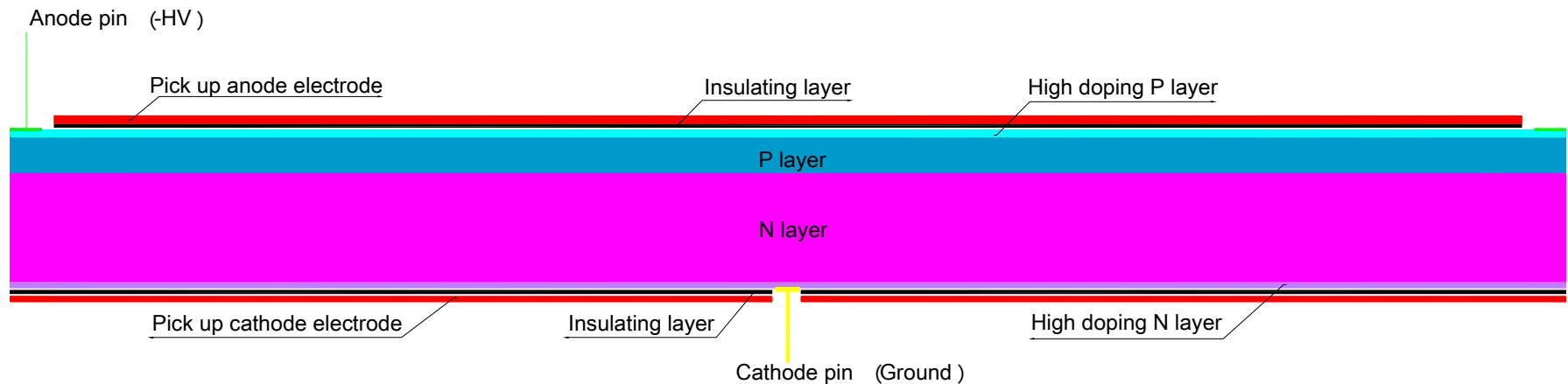
Measured APD doping profile

Anode side resistivity is much higher than cathode side due to doping density difference, only small region around the anode readout pin can efficiently collecting signal, it will rapidly decrease as shown on slide #17.

Suggested improvement to the RMD APD

Anode pin (-HV)

Pick up anode electrode   Insulating layer   High doping P layer

P layer

N layer

Pick up cathode electrode   Insulating layer   High doping N layer

Cathode pin (Ground)

In this design HV electrodes are isolated from signal pick up electrodes.
Based on this idea RMD immediately developed large area mesh APD device, which greatly improve the signal uniformity and reduce time walk effect.