Optical characterization of semiconductor Detectors: An introduction to TCT (Transient Current Technique)

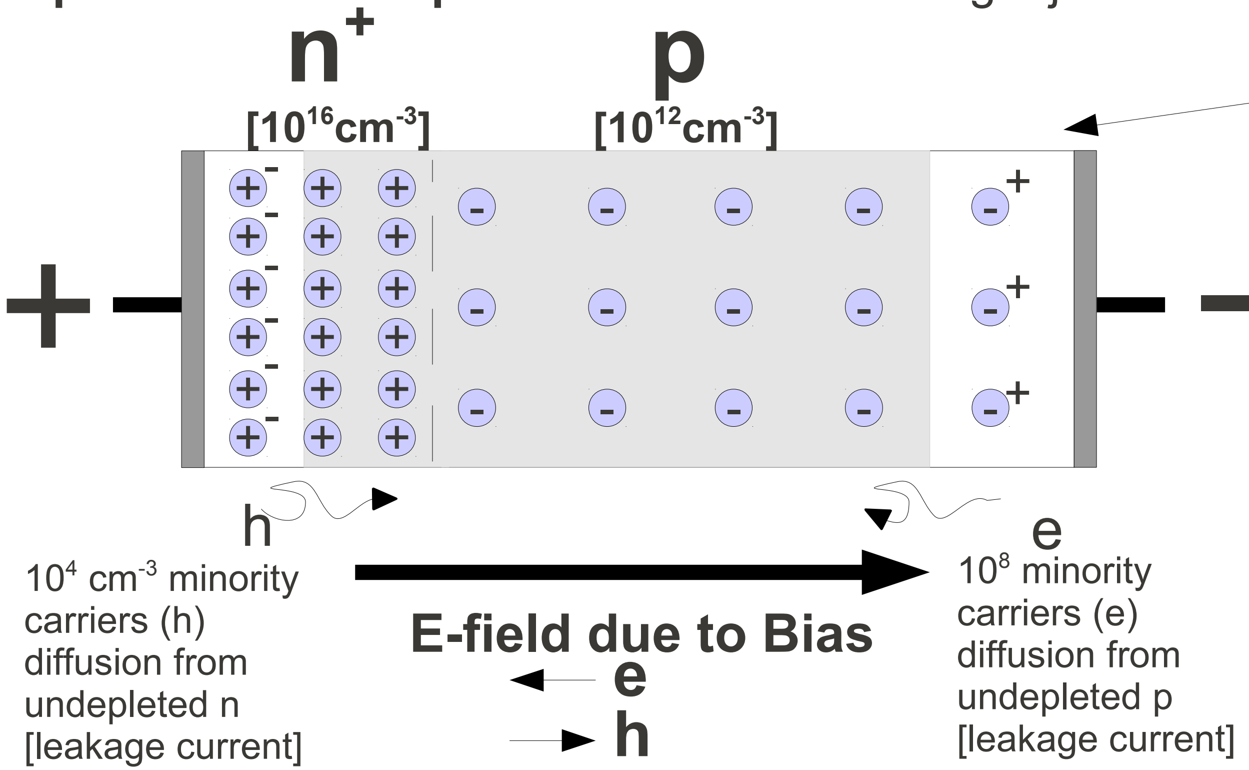
Marcos Fernandez Garcia - Santander, 8th January 2019

Reminder of useful concepts

- Number of free thermally generated charge carriers in intrinsic Si prevents usage as a solid state detector: **n_i~10^{10} cm^{-3}** vs **10^4 e-h pairs** produced by a **MIP** in 300 μm of Si.
  - Si atomic density is ~10^{22} cm^{-3} → 1 in 10^{12} atoms loose an electron at RT

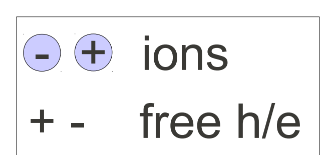
- **Mass action law** (valid for doped/undoped material) relates number of charge carriers of each type in equilibrium: $n \cdot p = n_i^2$ .Out of equilibrium, generation-recombination processes will try to get back to this condition.

- Problem: deplete intrinsic Si bulk of charge carriers → not possible. However a bulk of **doped Si can be depleted**. Trick is done using a junction of ***n*** and p-***doped*** Si.



Here you are! The most basic semiconductor detector

Majority	Minority
N_n~10^{16}	$p_n=10^{20}/10^{16}=10^4<<n_n$
p_p~10^{12}	$n_p=10^{20}/10^{12}=10^8<<p_p$



Reminder of useful formulae

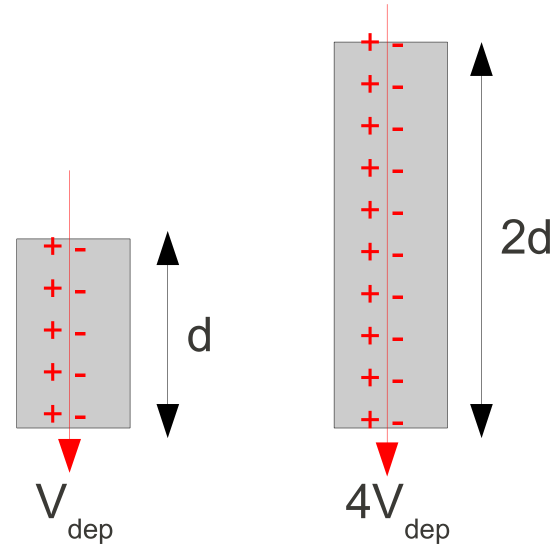
$$-\frac{d^2\Phi(x)}{dx^2} = \frac{\rho_{el}}{\epsilon\epsilon_0} = \frac{eN_{eff}}{\epsilon\epsilon_0}$$

- Poisson equation because this is an electrostatics problem

$$V_{dep} = \frac{eN_a}{2\,\epsilon\,\epsilon_0} d^2$$

- If we increase the thickness by factor 2 (to collect more charge) we need to apply four times the depletion voltage!

- Doping concentration can be calculated, once thickness is known



- Capacitance is inversely proportional to depleted thickness

$$W(U) = \sqrt{\frac{2\,\epsilon\,\epsilon_0}{eN_a}(U + U_{bi})}$$

- Depleted width increases as the square root of voltage

What is TCT?

What is TCT?

TCT is a tool to characterize semiconductor detectors

TCT can **answer** the following **question**

TCT can **answer** the following (unlikely) **question**

TCT can **answer** the following (unlikely) **question** that you may pose yourself

What does an electron see...

What does an electron see

when it is traveling inside a detector?

It **sees**:

1) other electrons traveling

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1) other electrons traveling

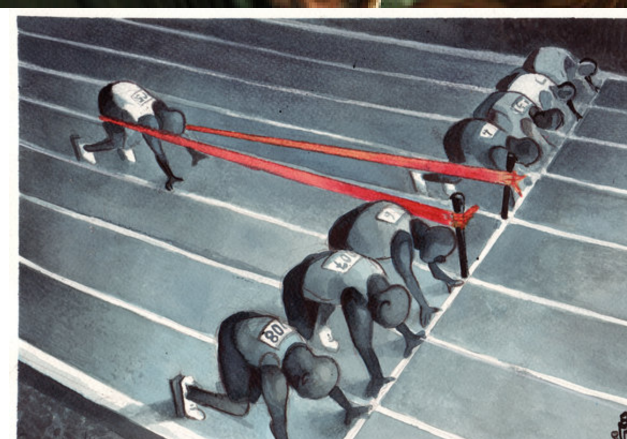
2) Silicon lattice

It **sees**:

1) other electrons traveling

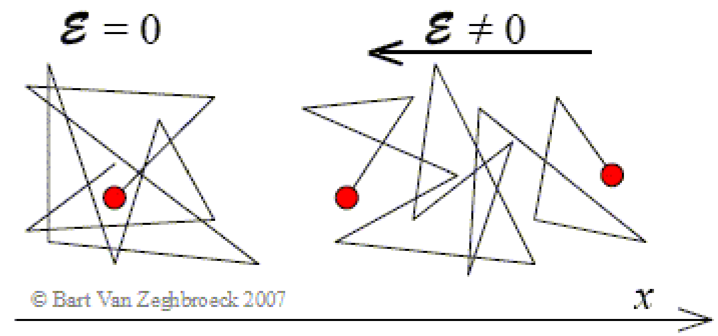
2) Silicon lattice

3) Some doping

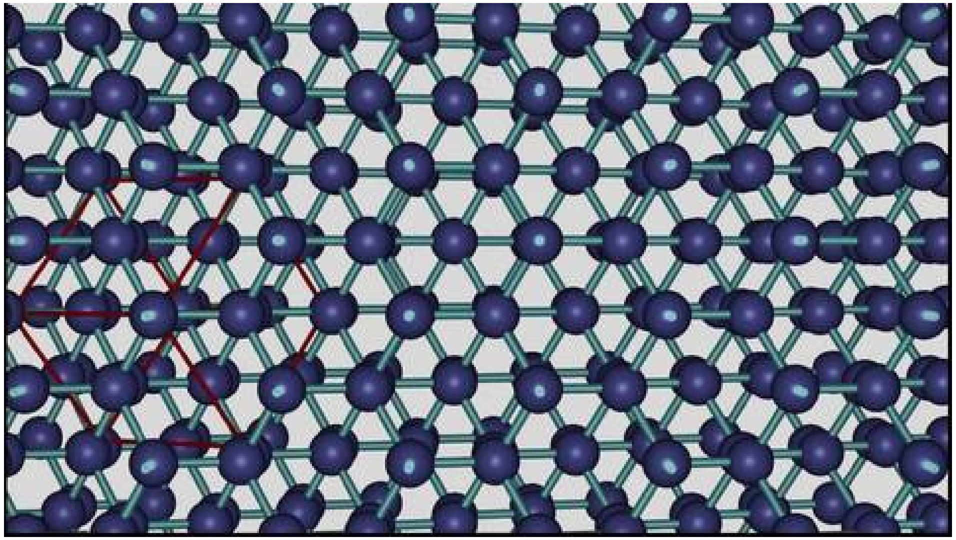


It **sees**:

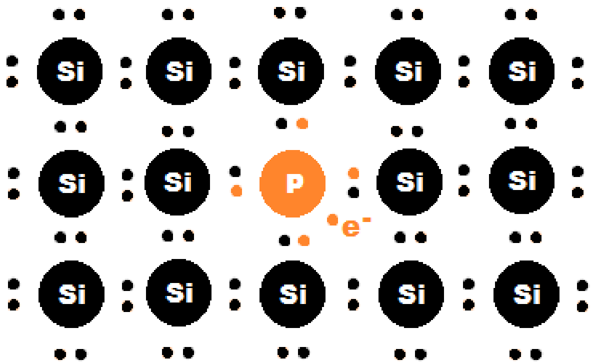
1) other electrons traveling



2) Silicon lattice



3) Some doping



It **feels**:

1) an electric field

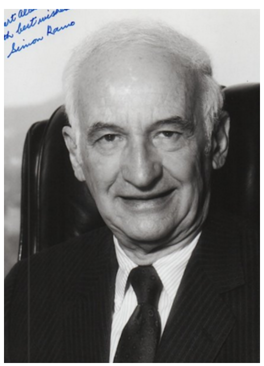
TCT (Transient Current Technique) gives us information of the **electric field** the carriers **feel** during their trip across a silicon detector

And **why** is this **important**? Because if you know the electric field inside your device, you know everything about it. And the **E-field** of a detector embedded in a radiation field **changes** alongside the life of the detector. We can **measure** these changes using **TCT**.

Ramo's theorem: signal formation

In a **roller coaster** the slope of the tracks determines the speed of the train. If we measure the velocity of a wagon as a function of time we could infer the shape of the roller coaster.

In TCT, the **signal** we measure **is the current** induced by the movement of carriers



This man (**Simon Ramo**, 1913-2016) demonstrated that the induced current in a system of electrodes can be calculated considering the **drift velocity** of the carrier... **weighted** by a magnitude (so-called weighting field) that depends on the position of the particle.

In a **2 electrode system**, the **velocity profile** corresponds to the **E-field profile** (diode~roller coaster)

$$I(t) = q_e v_{drift} E_W$$

q_e is the electron charge
v_{drift} is the drfit velocity of the carrier
E_w is the weighting or Ramo field

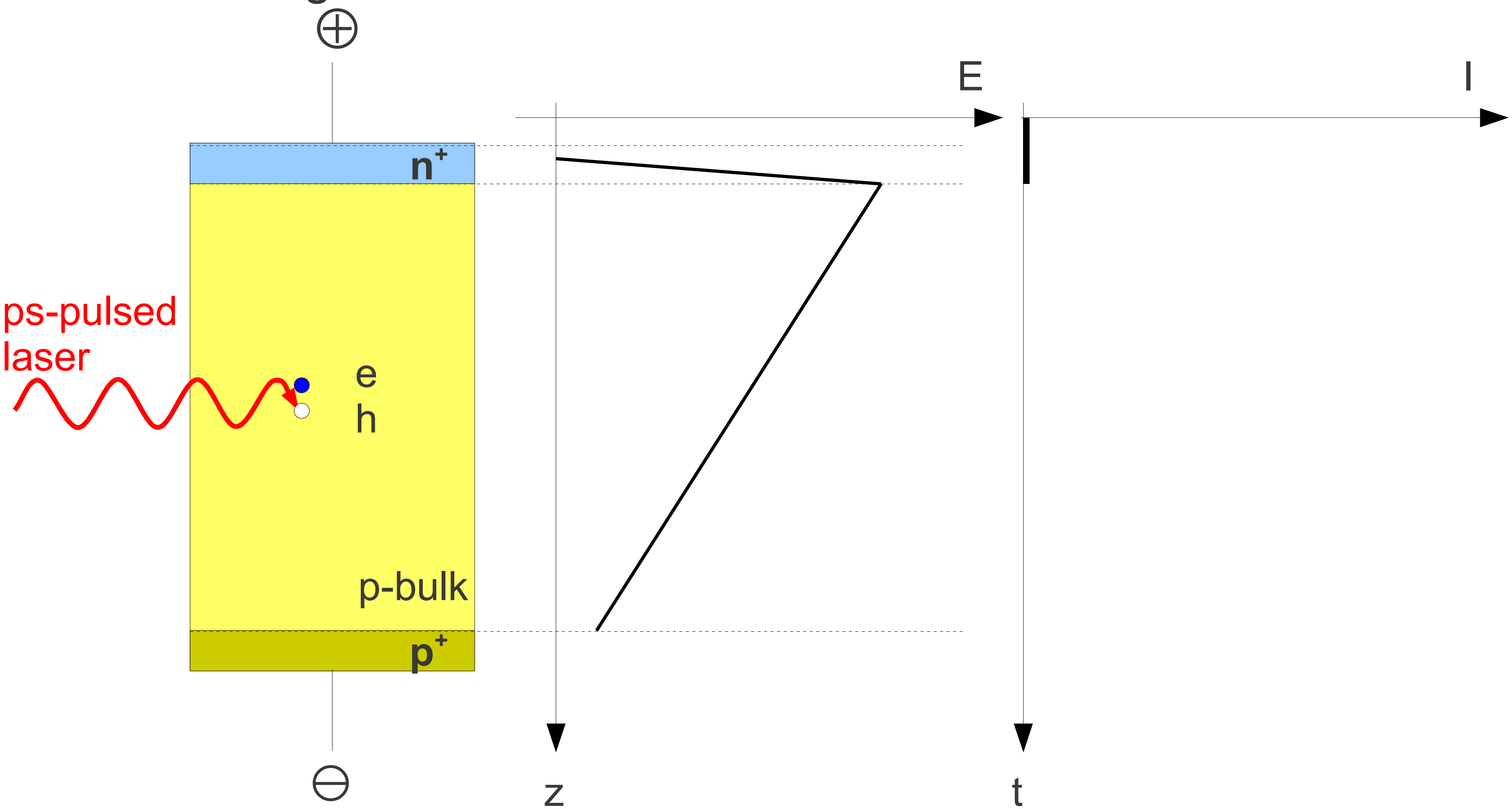
The **drift velocity** of a carrier is, for small fields, **linear with the intensity of the field** (see backup slides)**.** Therefore **the "shape" of the induced current** will tell us something about **the shape of the E-field** the carriers see.

What is TCT?

(finally!)

TCT: Transient Current Technique

Allows to probe the space charge of a detector by measuring transport of induced charge carriers

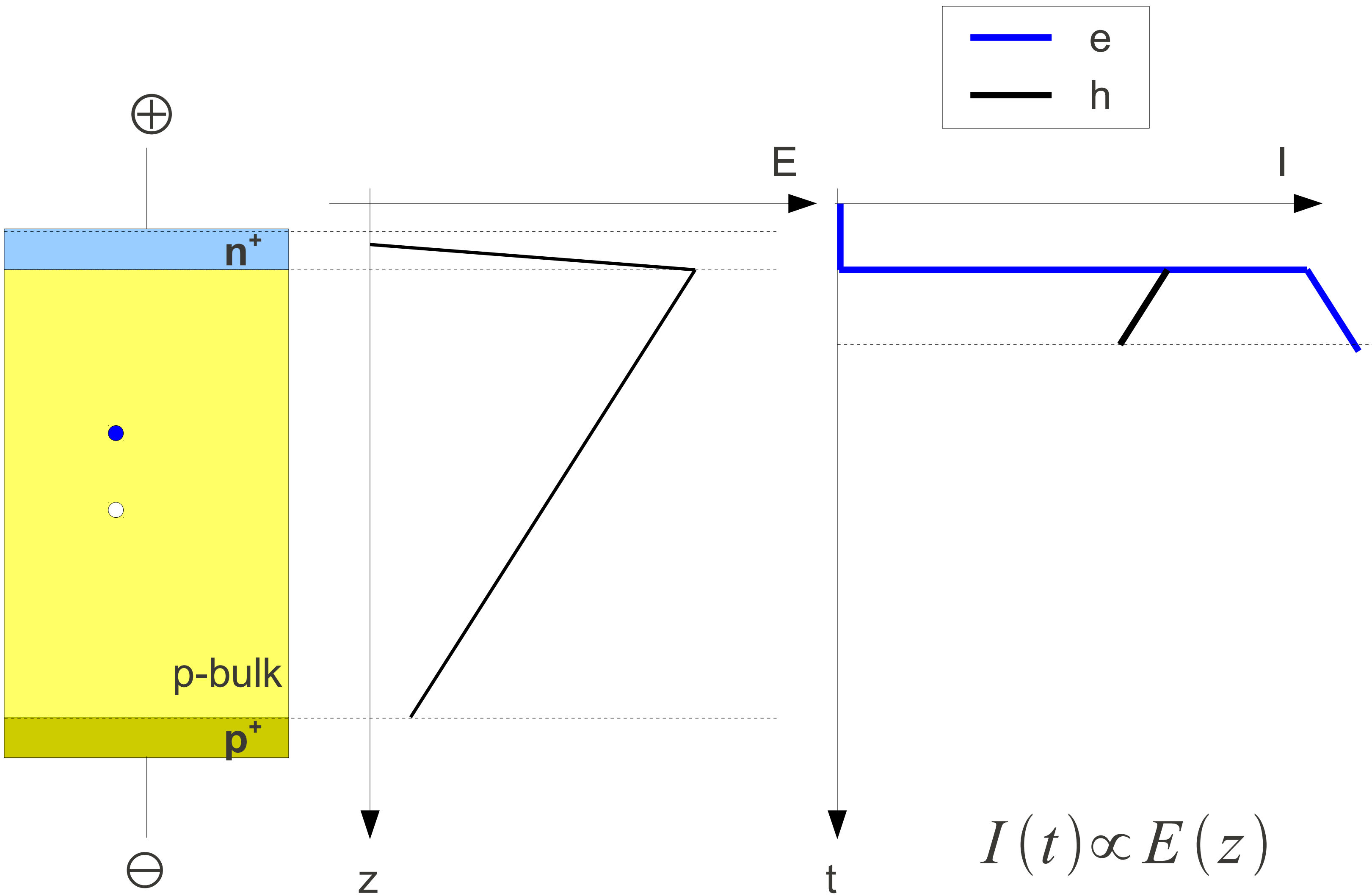


$$I(t) = N_{eh} A q_e v_{drift} E_W \propto v_{drift} = \mu(E)E \Rightarrow I(t) \propto E(z)$$

Assumption: overdepleted, non-irradiated diode

t = -0 ns

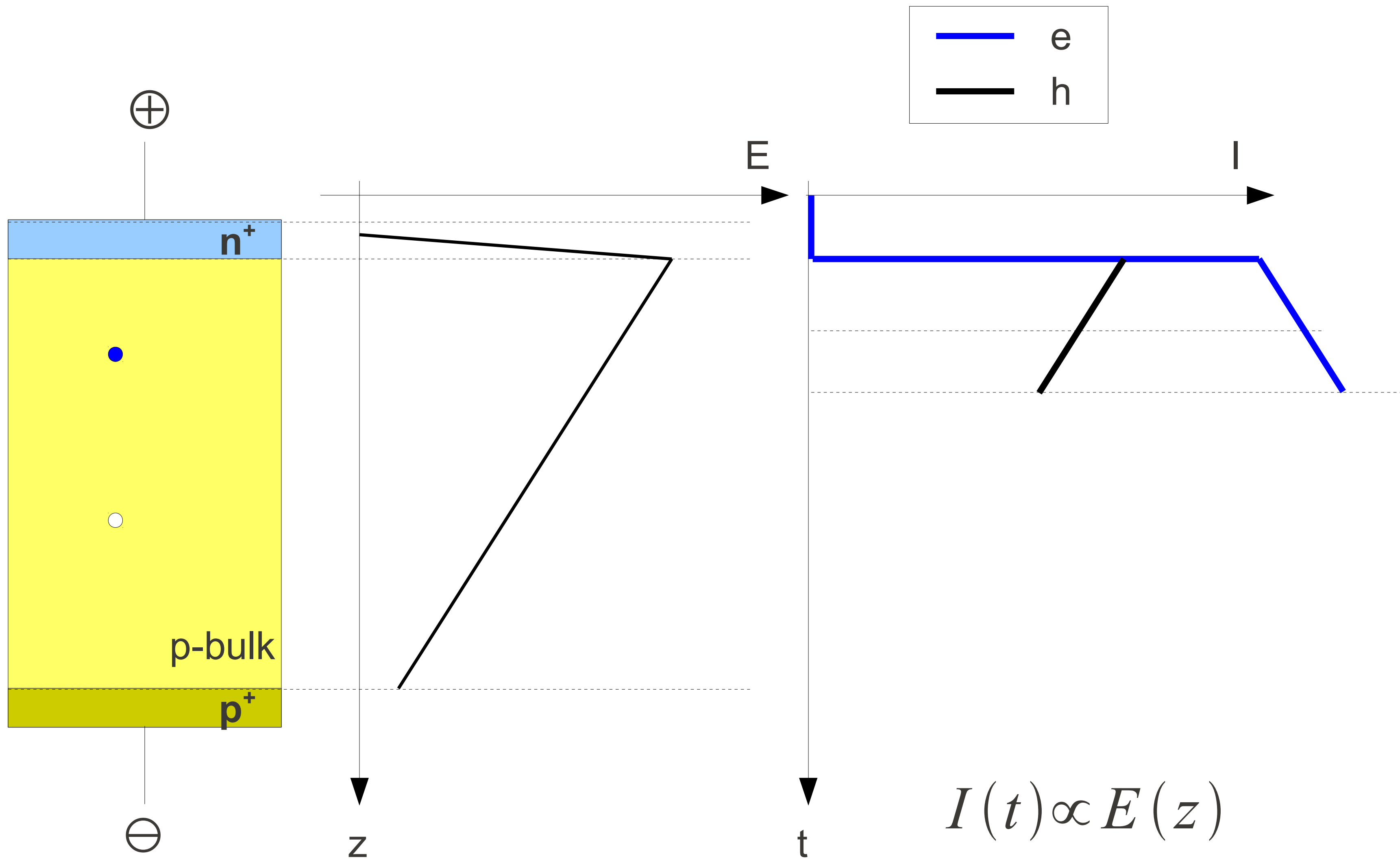
TCT: Transient Current Technique



$$I(t) \propto E(z)$$

t = 1 ns

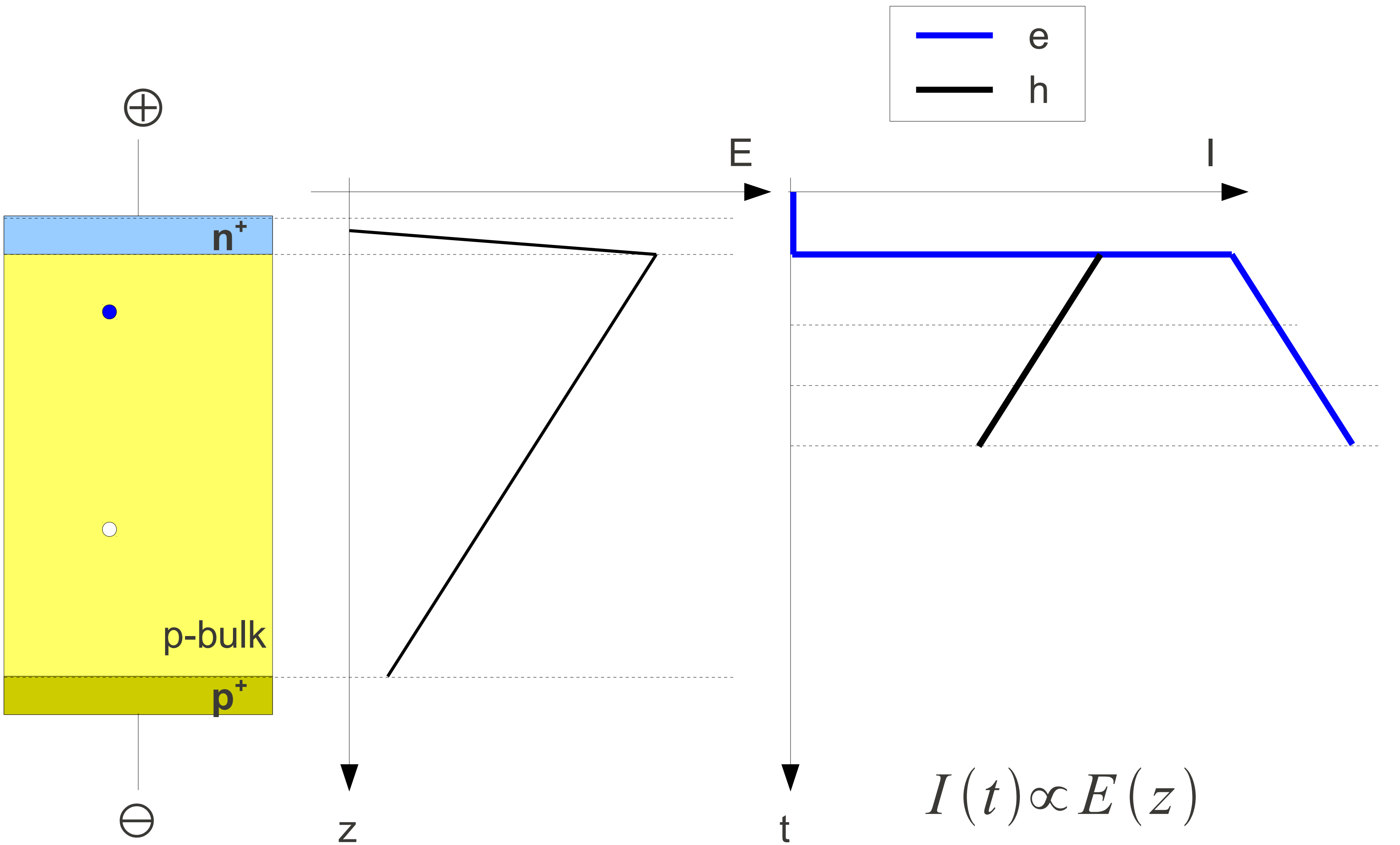
TCT: Transient Current Technique



$$I(t) \propto E(z)$$

t = 2 ns

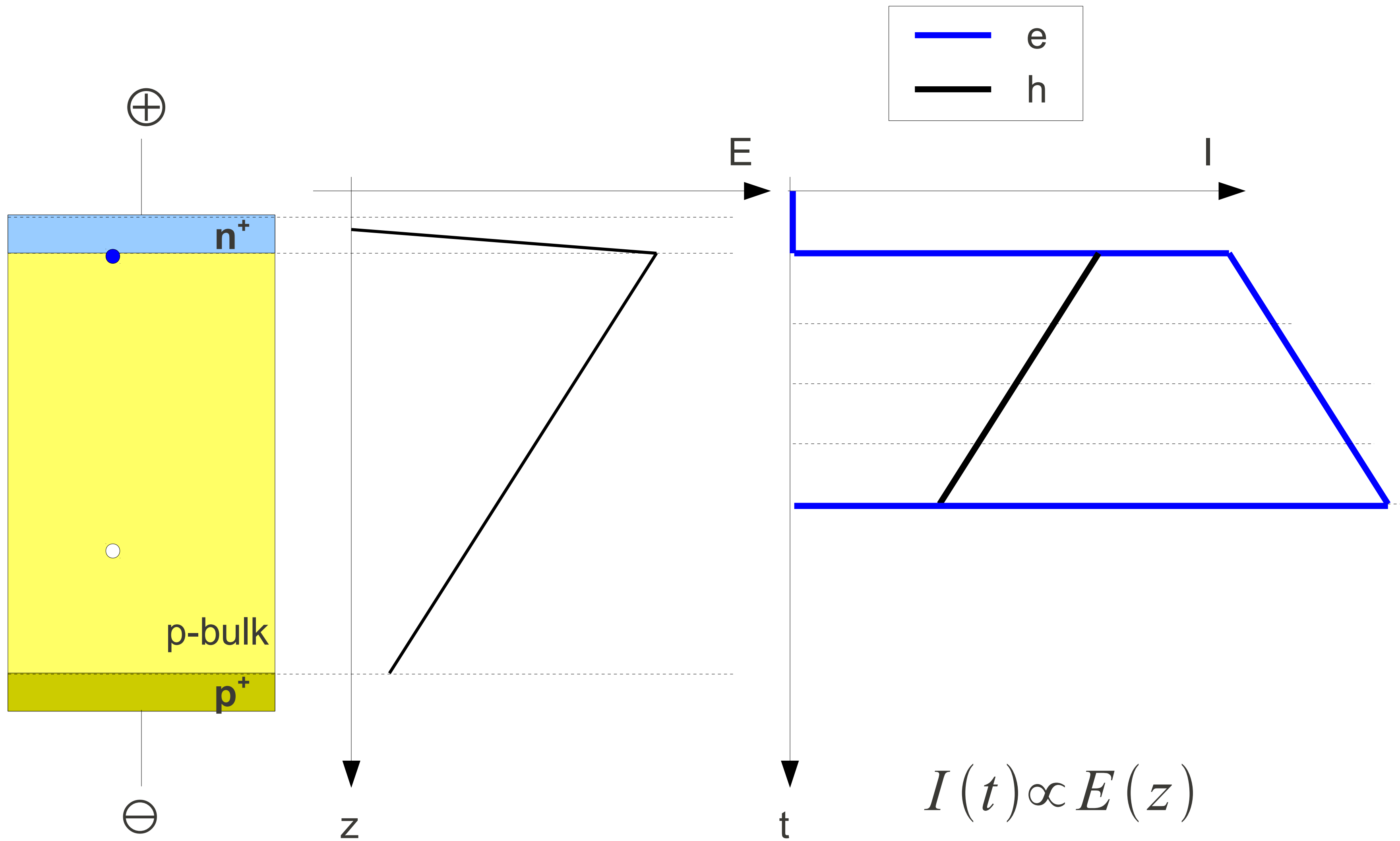
TCT: Transient Current Technique



$$I(t) \propto E(z)$$

t = 3 ns

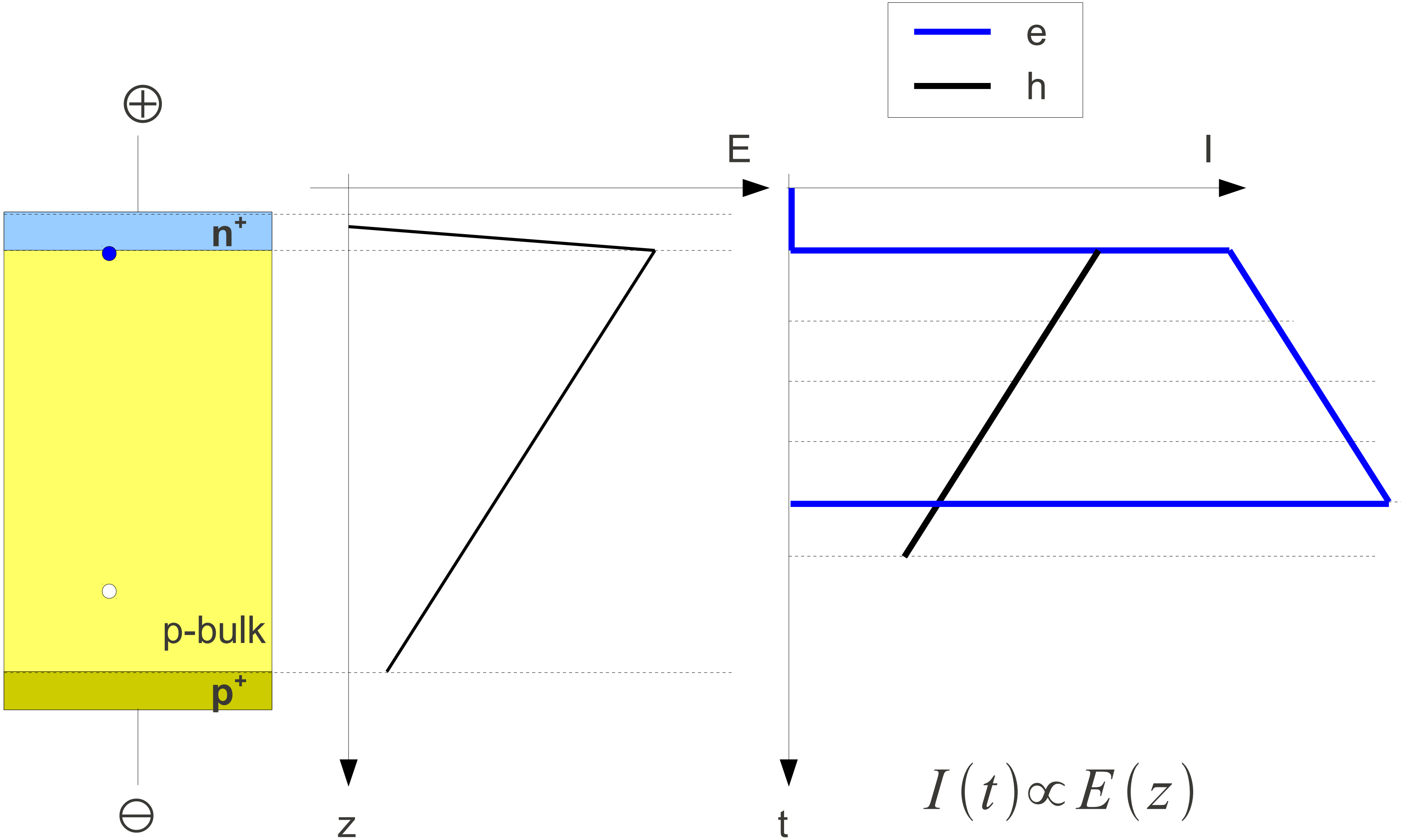
TCT: Transient Current Technique



$$I(t) \propto E(z)$$

t = 4 ns

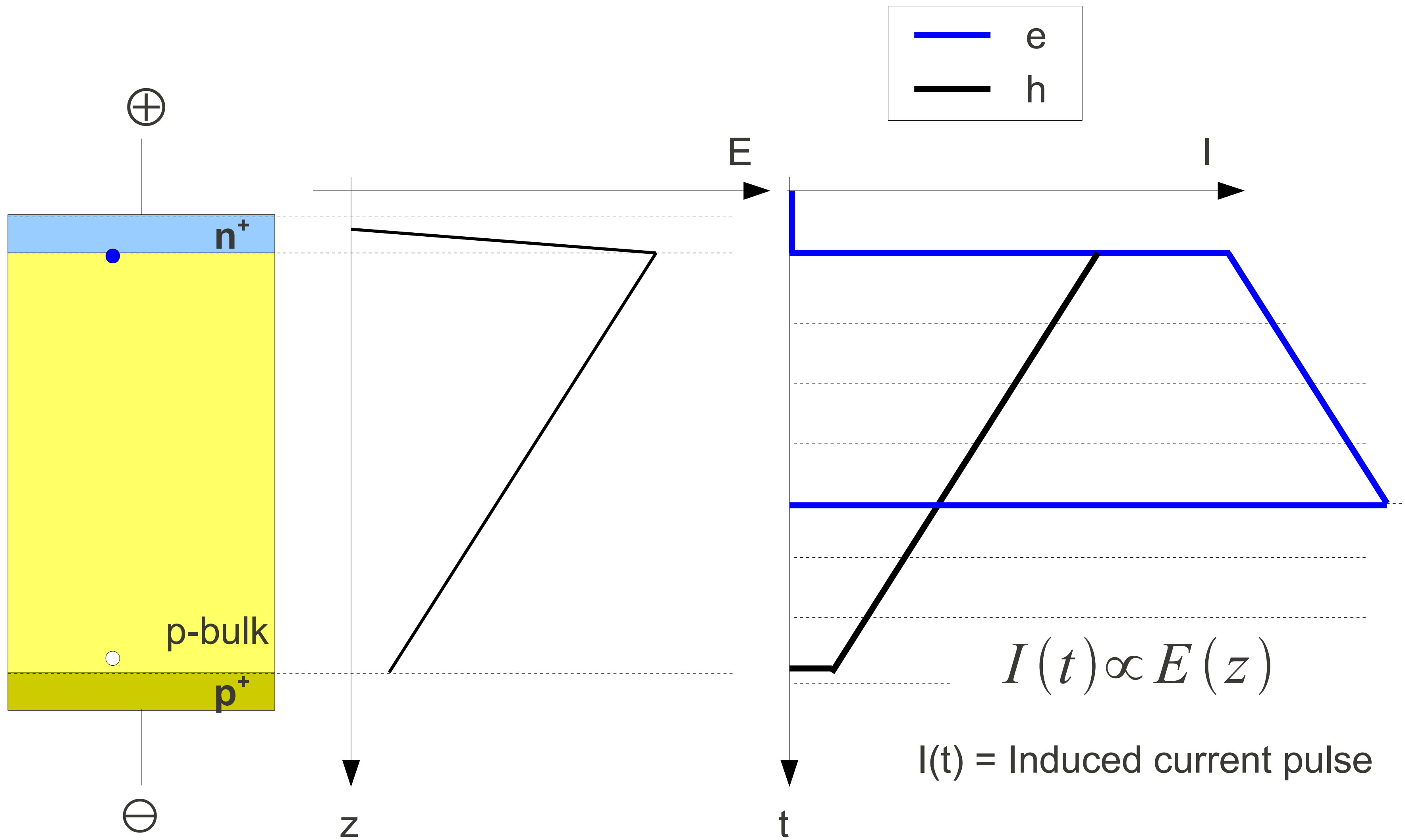
TCT: Transient Current Technique



$$I(t) \propto E(z)$$

t = 6 ns

TCT: Transient Current Technique

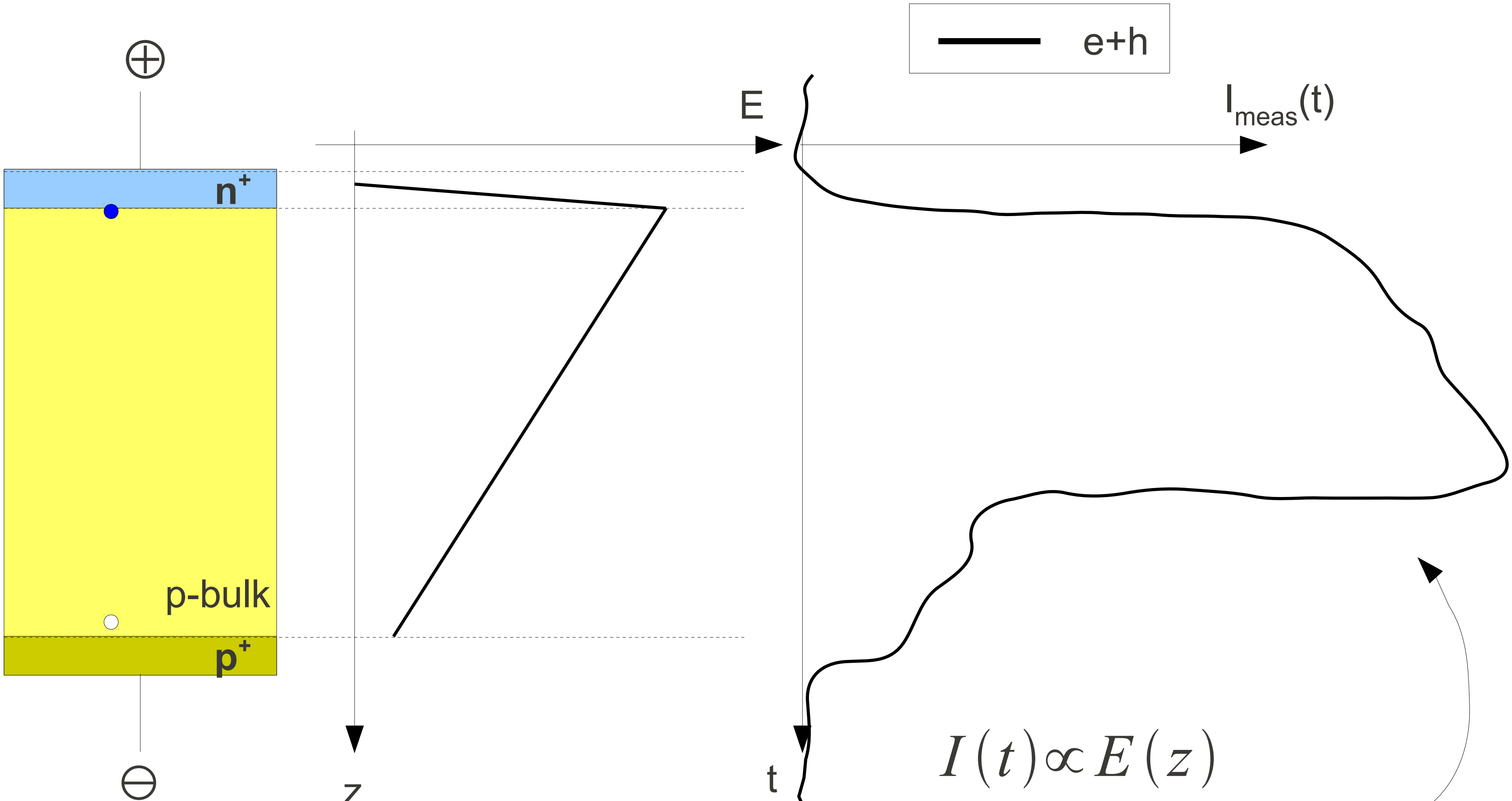


$$I(t) \propto E(z)$$

I(t) = Induced current pulse

t = 12 ns

TCT: Transient Current Technique



$$I(t) \propto E(z)$$

Measured pulse shows a "picture" of the electric field the carriers encountered during drift.

For an **irradiated** detector, the picture gets **distorted** due to **trapping** of charge carriers. Carriers do not "**see**" the full E-field profile.

Measured pulse convolutes:

1) EM noise
2) $RC_{detector}$ (low pass filtering)
3) Amplifier transfer function

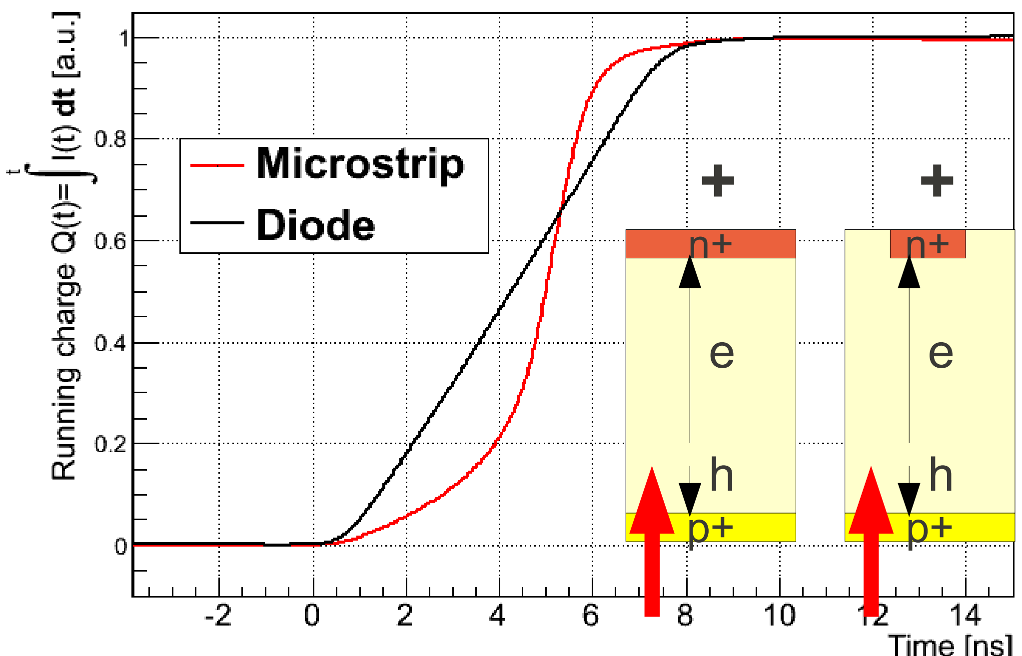
Sensing weighting field effects

- **Weighting field** is not a physical field, **cannot** be measured. It can be calculated by solving Laplace's equation (ρ=0) setting the collecting electrode to 1 V and all the rest to 0V.

- Mathematically, the charge induced by a particle moving from position 1 → 2 can be expressed as the difference of the weighting potential at these 2 points: $Q=e[\Phi(r_2)-\Phi(r_1)]$

- By measuring the induced current in red back illumination we can picture the weighting field of the detector.

  → At t=0 the carrier is at the back and it did not induce any current.
  → At t=τ the carrier is at r



We can plot

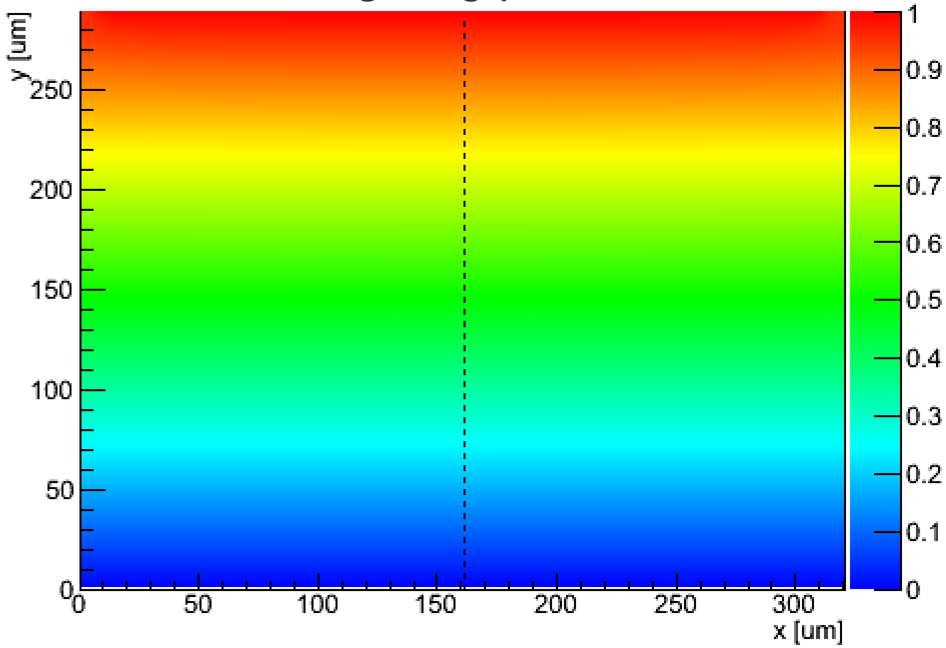
$$Q(\tau)=e(\phi_W(\tau)-\phi_W(0))=e(\phi_W(\tau)-0)=e\,\phi_W(\tau)=\int_0^\tau I(t)\,dt$$

Induced charge in a diode does not depend on the position of the carriers. However, for a microstrip, most of the charge for a strip is induced near the strip

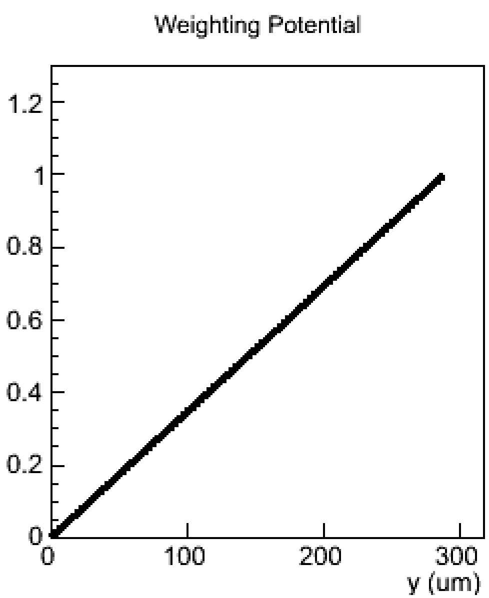
DIODE

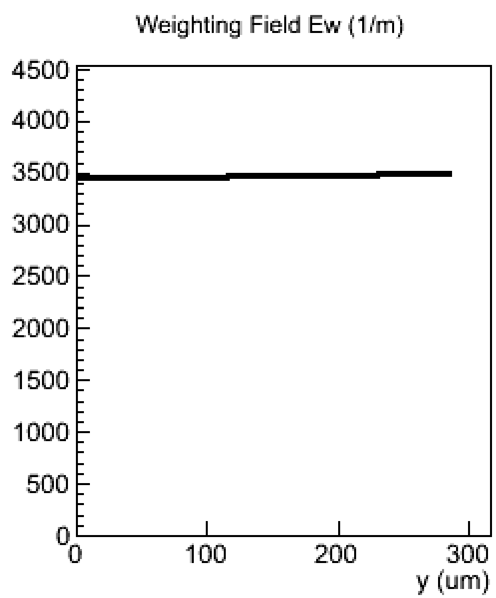
300 μm thick

Weighting potential



Weighting **potential** is **linear** function of depth

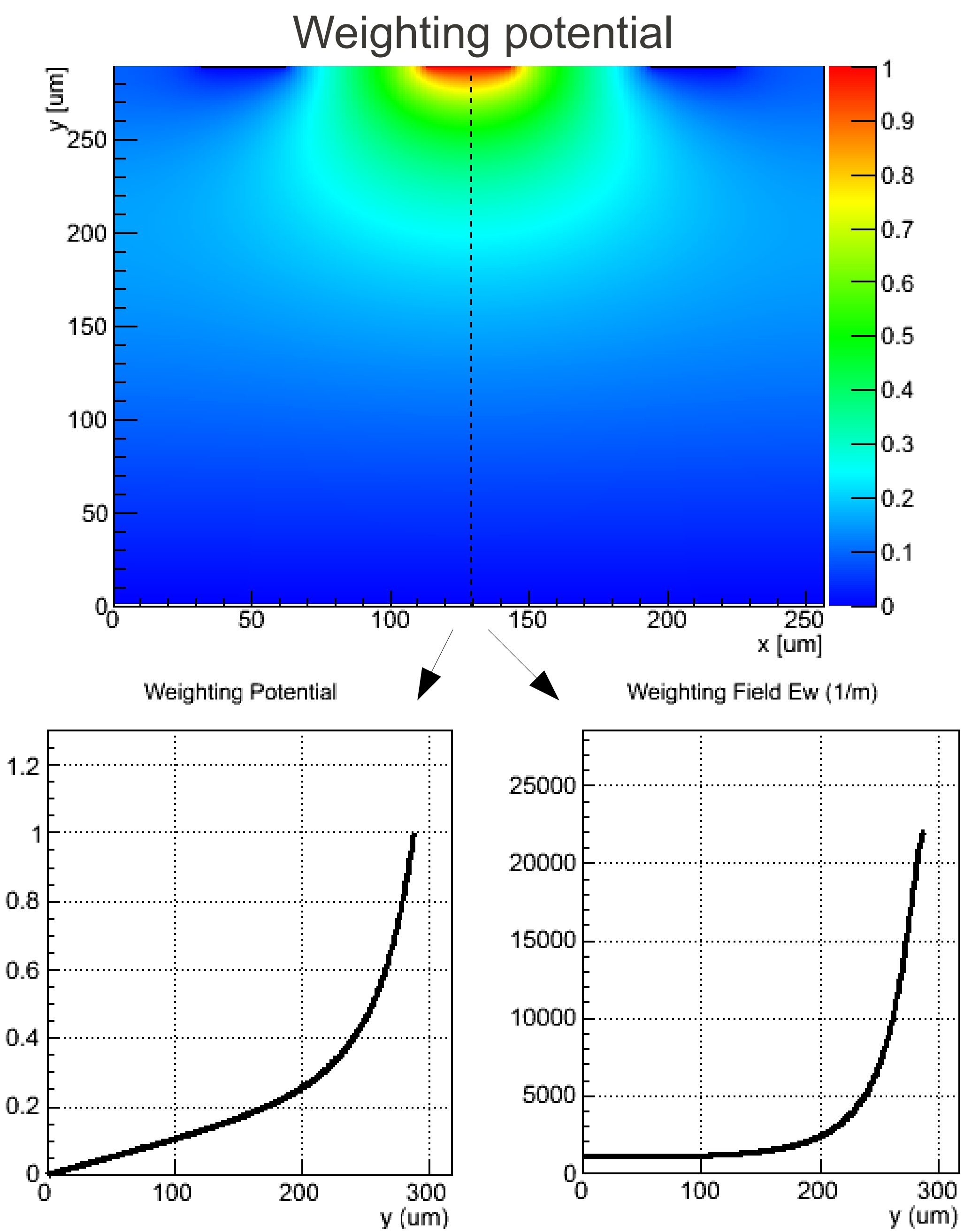




Weighting **field** is a **constant**

Microstrip (collecting electrode)

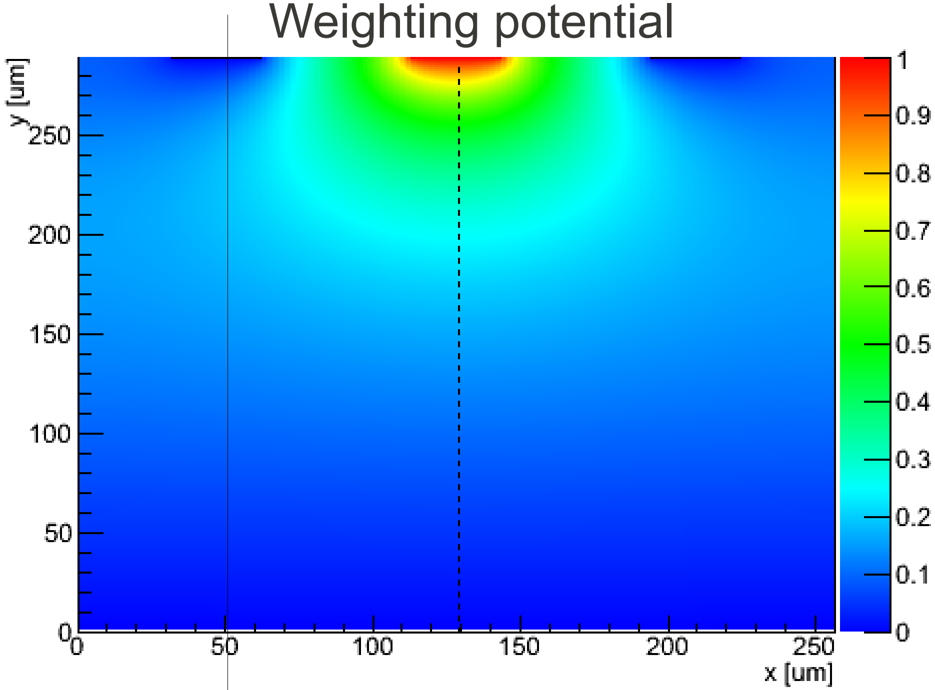
300 μm thick, 3 strips (w=30 μm, p=80 μm)



Microstrip (neighbor electrode)

300 μm thick, 3 strips (w=30 μm, p=80 μm)

Weighting potential



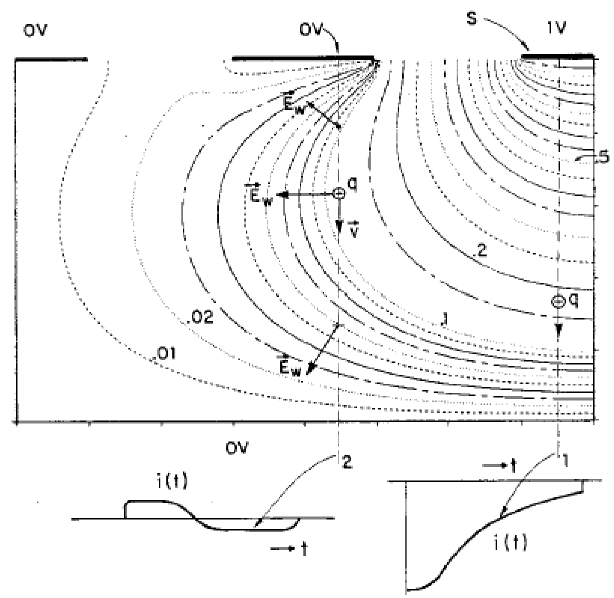
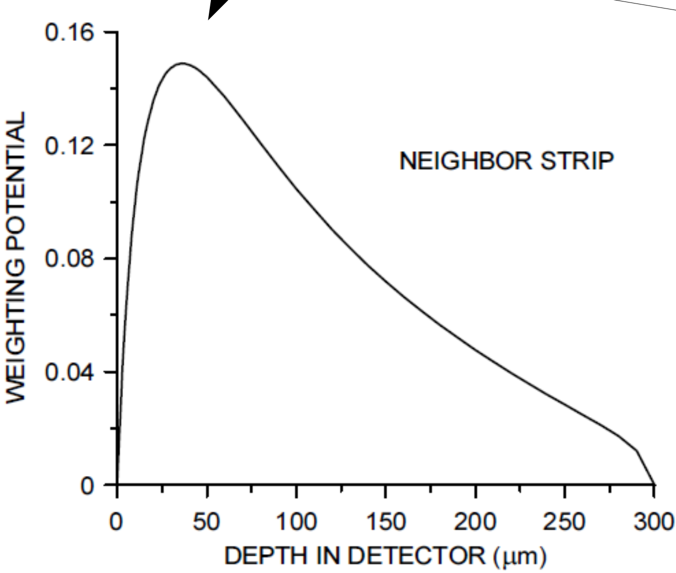
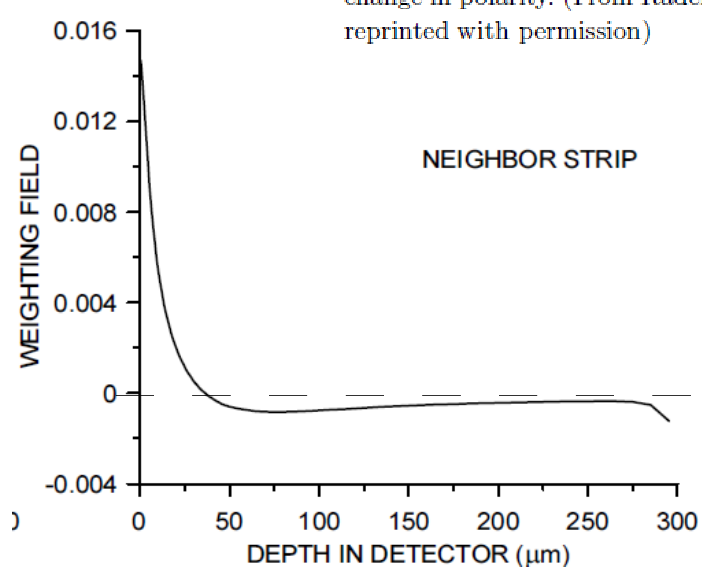


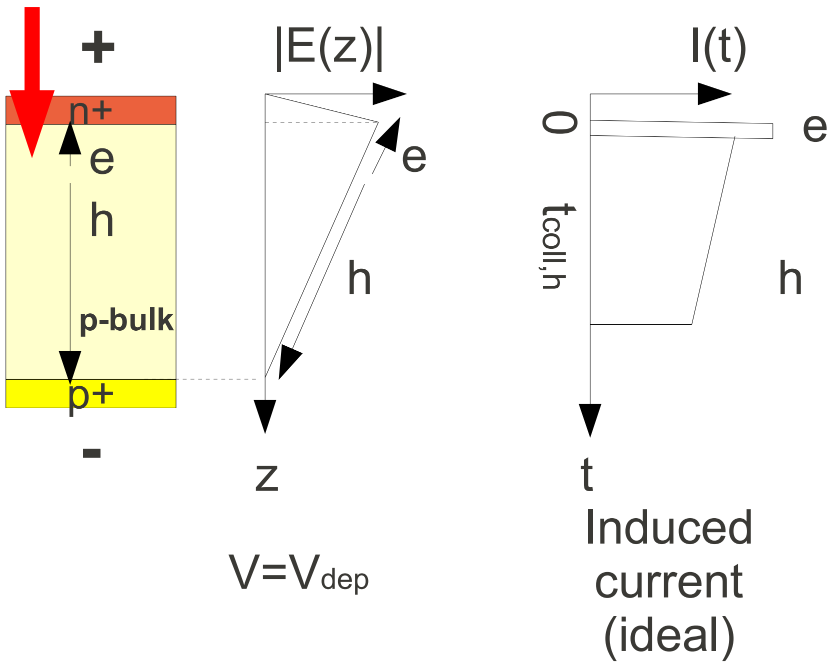
FIG. 2.31. The weighting field in a strip detector. The measurement electrode is the right-most strip. The induced current is shown for a charge terminating on the measurement electrode (right) and the neighbor electrode (left), showing the change in polarity. (From Radeka 1988. ©Annual Reviews www.annualreviews.org, reprinted with permission)



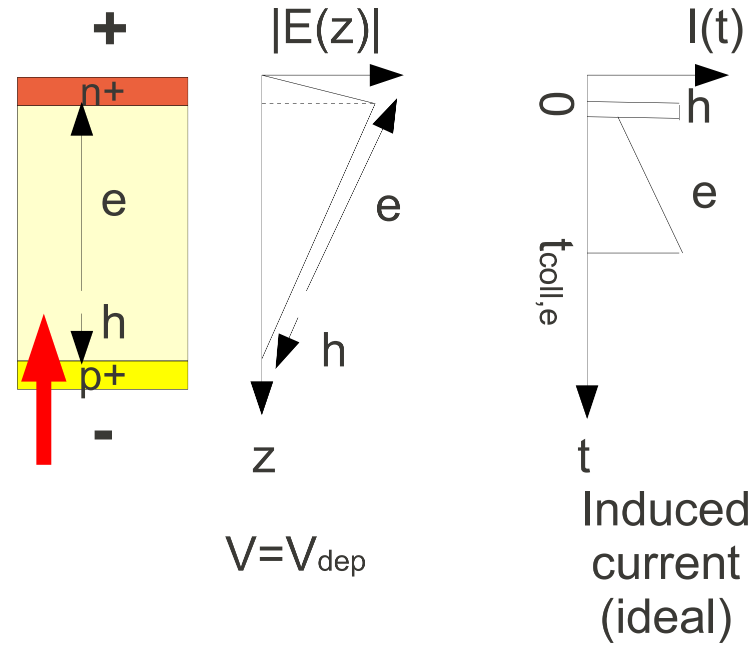


Transient Current Techniques

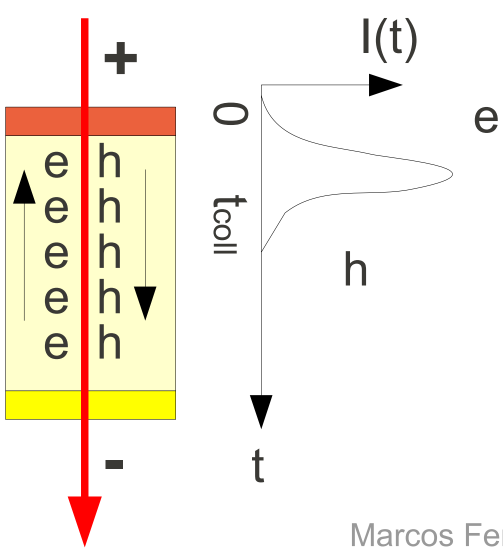
Top Red TCT (h injection)



Bottom Red TCT (e injection)



IR TCT

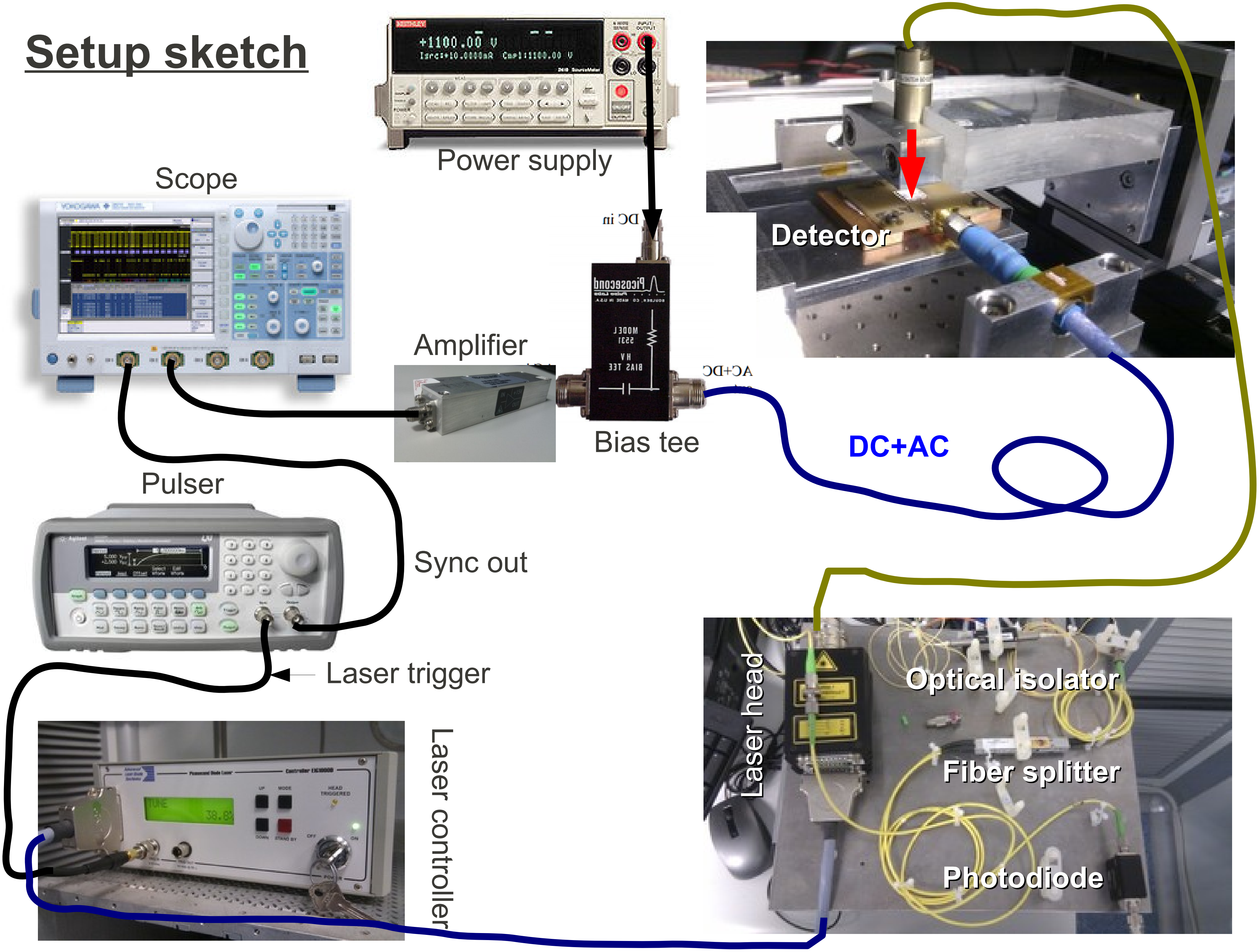


- TCT is a direct application of Ramo's theorem (diode):

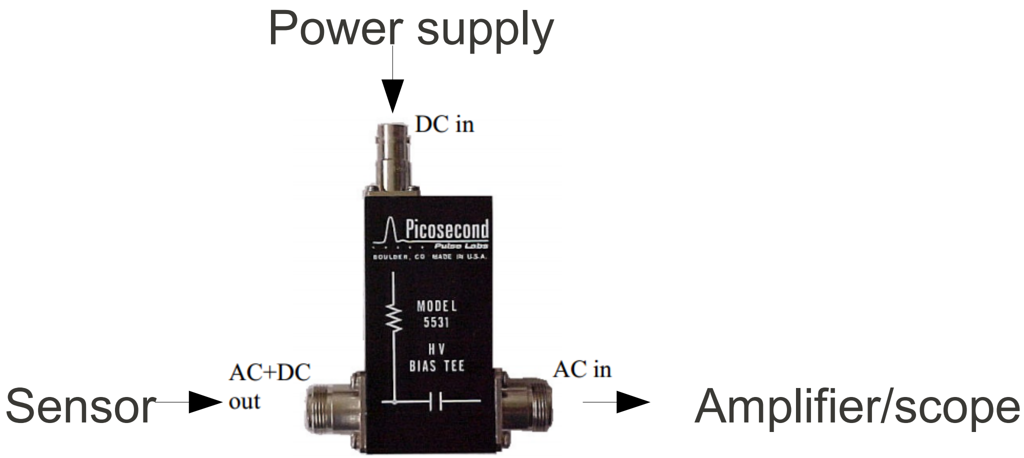
$$\begin{cases} I(t) \propto v_{drift}(t)\dfrac{1}{d} \\ v_{drift}(t) \propto E(z(t)) \end{cases}$$

- Red TCT offers a "**picture**" of the electric field the carriers "see" along the drift. However for heavily irradiated detectors, charge is trapped before crossing the whole bulk, and then we see a **"cropped"** picture of the field. **Edge-TCT** is a **solution** for that.

Setup sketch



Components: electronics



Bias Tee: allows biasing & readout using 1 cable. HV for the sensor is decoupled from AC response

Specs:

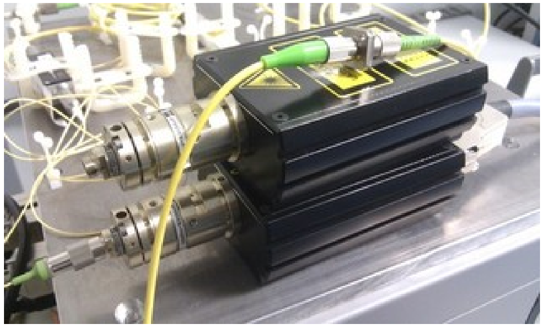
3 kΩ resistance → ~1V drop irradiated detectors
20 mA max DC input
Risetime (10-90%)<45 ps
BW: 750 kHz-10 GHz → High Low freq cut
50Ω terminated
CAREFUL: Mind the connections

Current amplifier: provides output voltage proportional to input voltage

Specs: Miteq 1660

Gain ~60dB dB (×1000)
BW: 10kHz-1.3 GHz
Bias voltage:15V, current 0.135 A
CAREFUL: Max. output voltage 1V

Components: optics



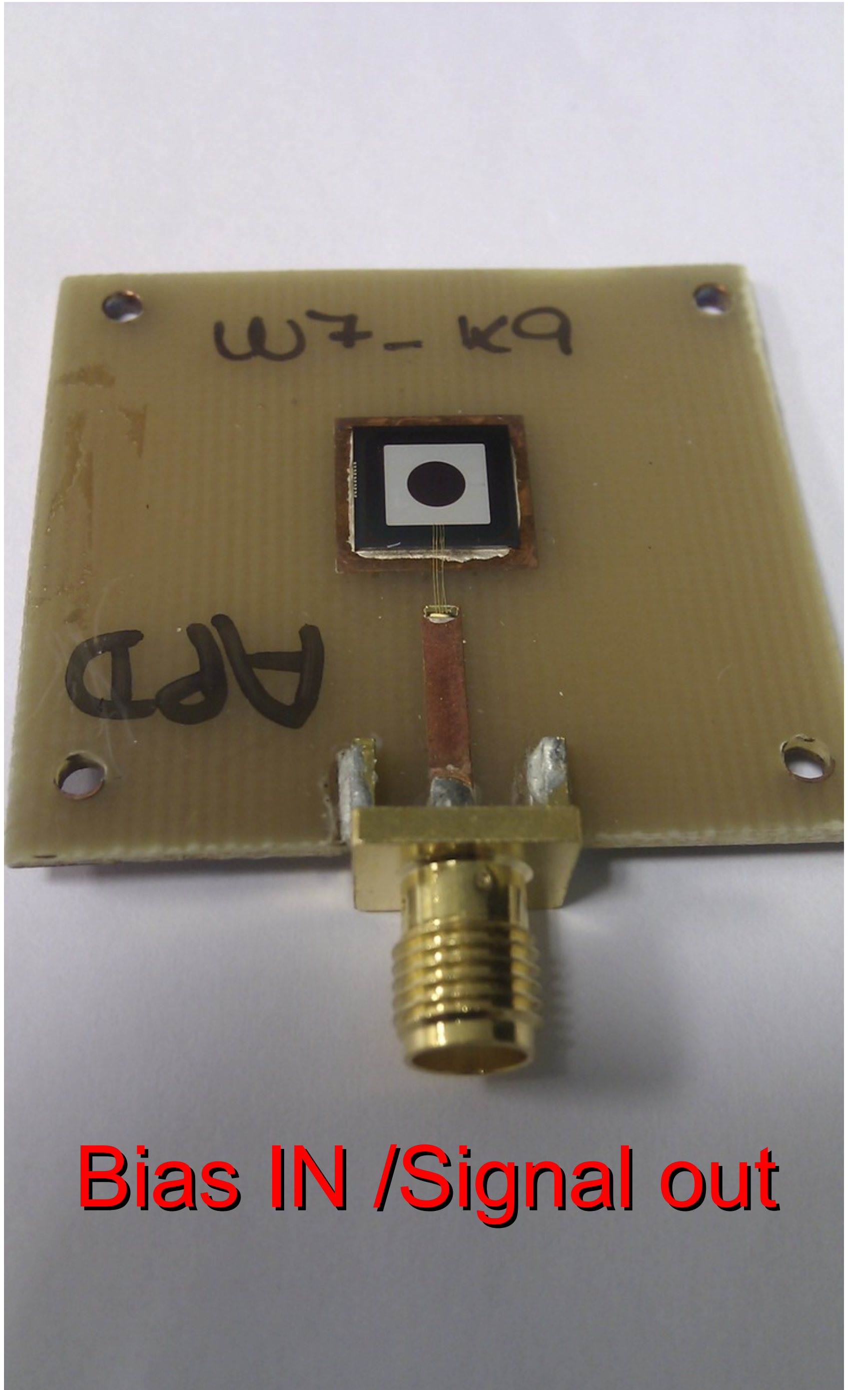
ps pulsed diode Laser: controller + optical head

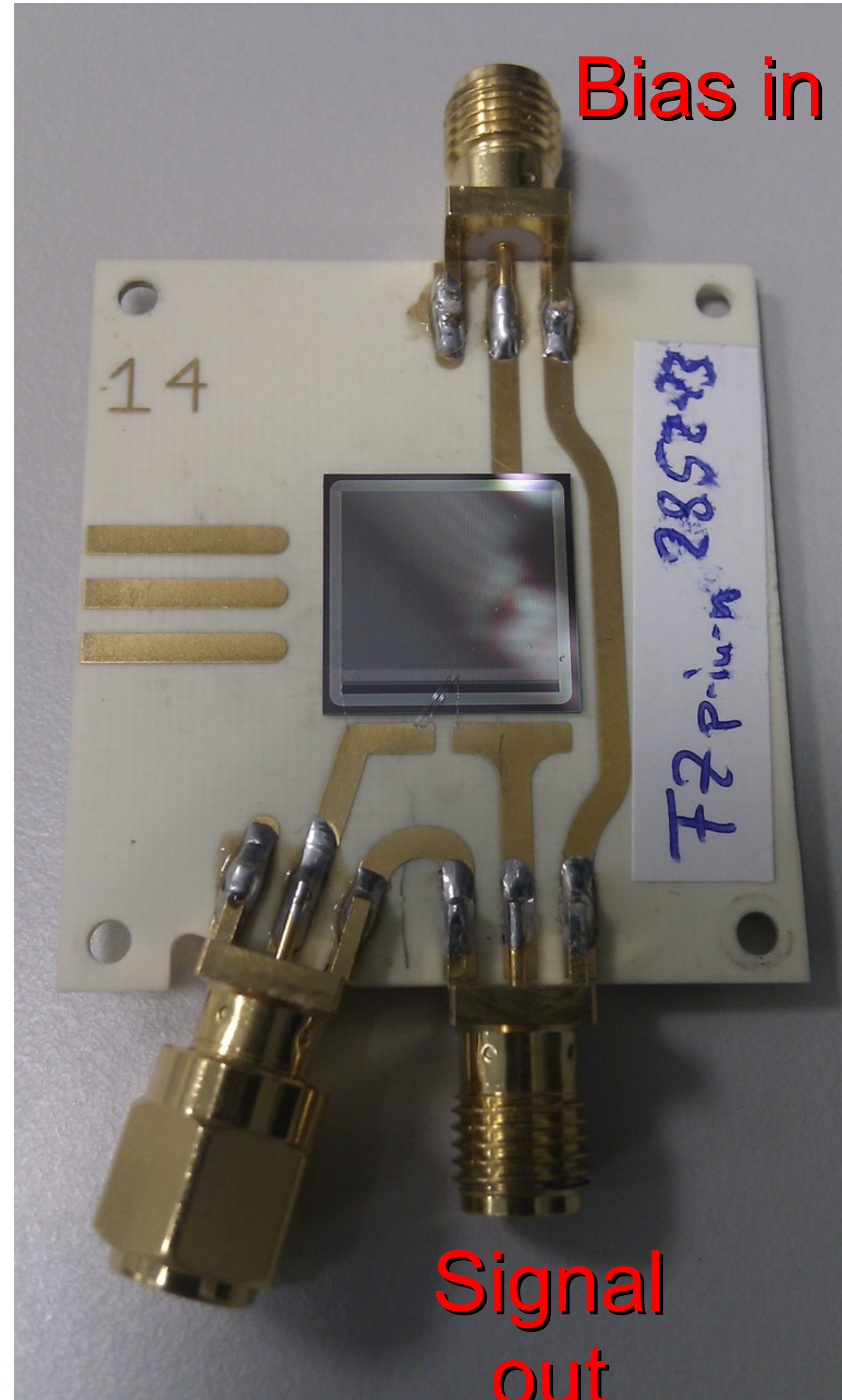
· 670 (1060) nm, 50 ps FWHM
· ↑ TUNE setting leads to higher power, shorter pulse width but longer tail
· Constant pulse energy~10 pJ /pulse
· Pulse power = 10 pJ/50ps=200 mW /pulse
· Average pulse power = pulse power × freq=nW-μW

Optical monitor “photodiode”: measured output current per pulse is linearly proportional to the input optical power.

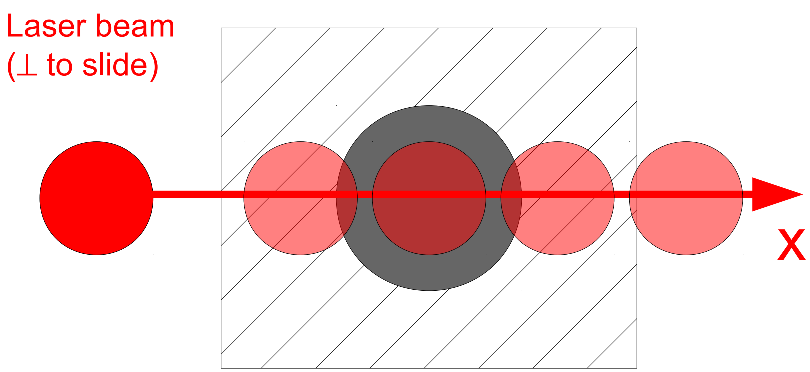
Range: 800-1700nm
Responsitivity: 0.77 A/W
BW: 1.2 GHz
V_{OUT}=0-3.5 V (50 Ω)
Damage Threshold=70 mW

Components: detectors





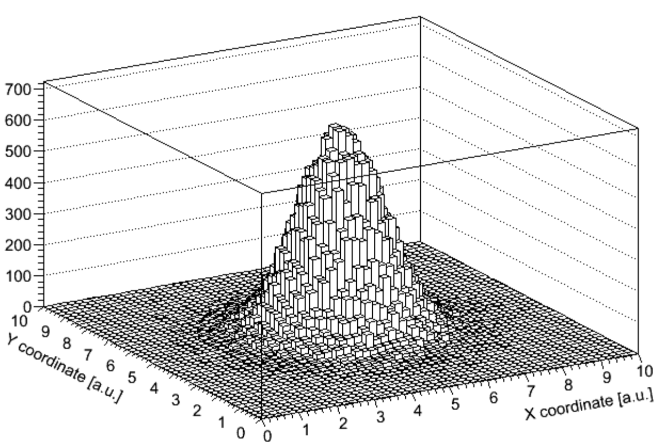
Experiment 1:calculating the waist of the beam: knife edge technique



To calculate the beam waist, the beam is swept along a line that intercepts the opening in the electrode. The impinging beam intensity follows a Gaussian distribution.
If one absorbed photon produces an e-h pair then, after the drift, the collected charge will be *e* (=integral of the induced current pulse).
If we inject a gaussian distribution of photons, the collected charge will display a gaussian shape in x.

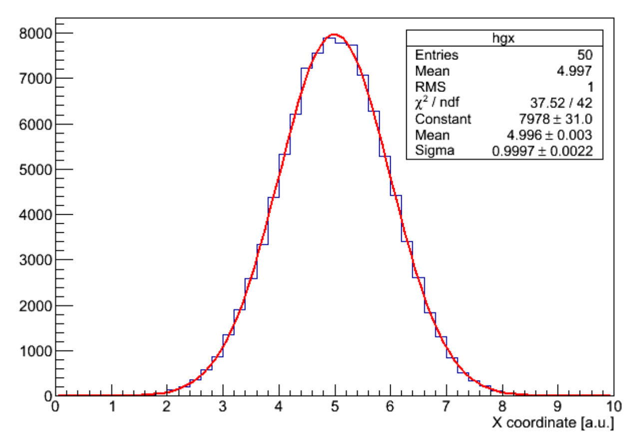
1D integral of 2D gaussian is a gaussian
1D integral of a gaussian is the error function

Sweeping the beam over the detector an error function is reproduced

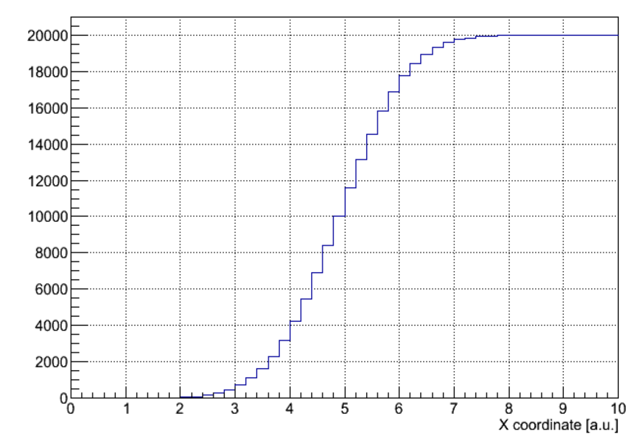


$$G(x,y)=e^{\frac{-(x-\mu_x)^2}{2\sigma_x^2}}\,e^{\frac{-(y-\mu_y)^2}{2\sigma_y^2}}$$

$$\mu_x=\mu_y=5.;\sigma_x=\sigma_y=1.$$



$$G(x)=\int_{-\infty}^{\infty} e^{\frac{-(x-\mu_x)^2}{2\sigma_x^2}}\,e^{\frac{-(y-\mu_y)^2}{2\sigma_y^2}}\,dy$$



$$\mathrm{Erf}(t)=\int_{-\infty}^{t} e^{\frac{-(x-\mu_x)^2}{2\sigma_x^2}}\,dx$$

Analysis (I)

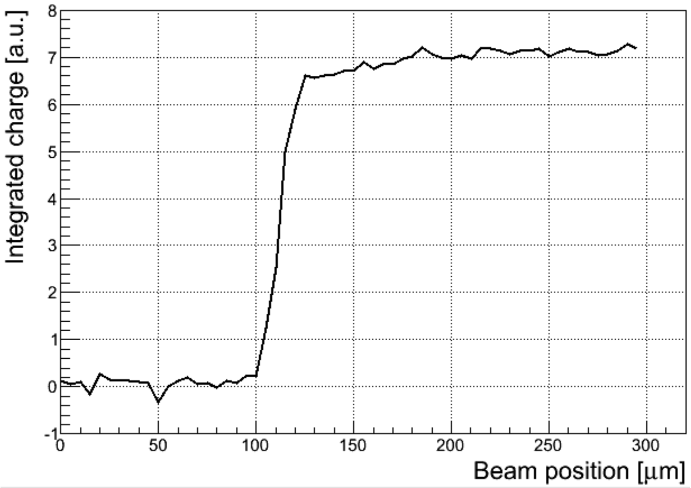
Consider the following root cheat-sheet

`root -l file1.root`	Start root and already connect a file to this session
`TTree *t1=(TTree*) _file0->Get("edge")`	Get pointer to tree called "edge". Refer to this tree from now on as t1
`t1->Draw("Vmax:Vbias","","l")`	Draw a XY graph of maximum amplitude vs bias voltage
`t1->Draw("Q50:Vbias","Vmax>0.1","l")`	Plot charge vs bias voltage, with condition on variable Vmax
`t1->Draw("BlineRMS")`	Histogram the baseline noise (no XY plot)
`t1->Draw("volt-BlineMean:time")`	Draw all waveforms in a file (DC offset removed)
`t1->Draw("volt-BlineMean:time-tleft")`	Same as above but center plots in time=0
`t1->Draw("volt-BlineMean:time","Vbias %50==0")`	Draw waveforms with bias value modulo 50
`t1->Draw("Q50:Vbias","","l")`	Draw charge vs bias voltage, use a line to link points

```
t1->Draw("Sum$((volt-BlineMean)*((time-tleft)>0.&&(time-tleft)<25)):Vbias","","l")
```
Calculating the charge in an arbitrary time range. Link values with a line

Now try to plot the charge vs the shifting position. Let's fit it to an Error Function → (next slide)

Analysis (II)

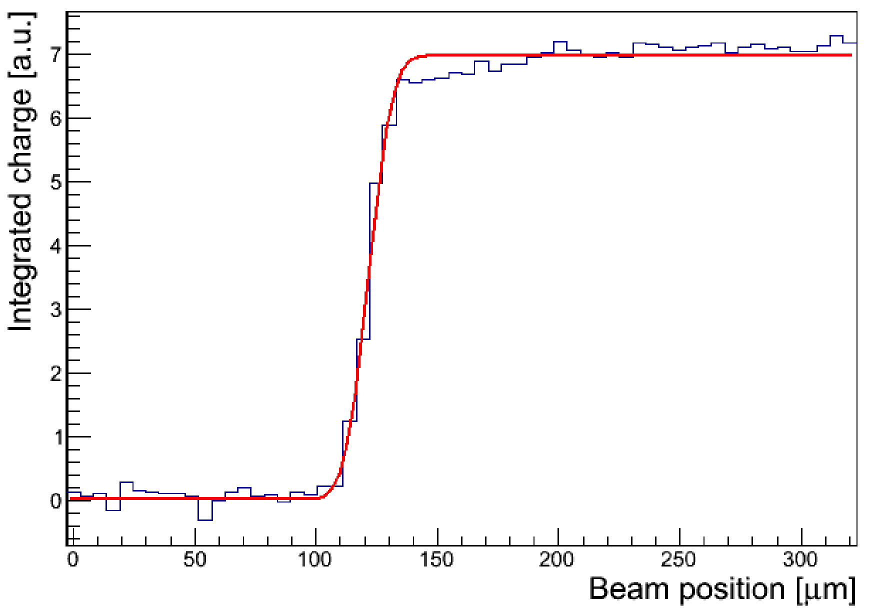


HOWTO convert the 2D graphic into a histogram (after a Draw command):
[carefull with copy/paste to include "" quotes!!!!]

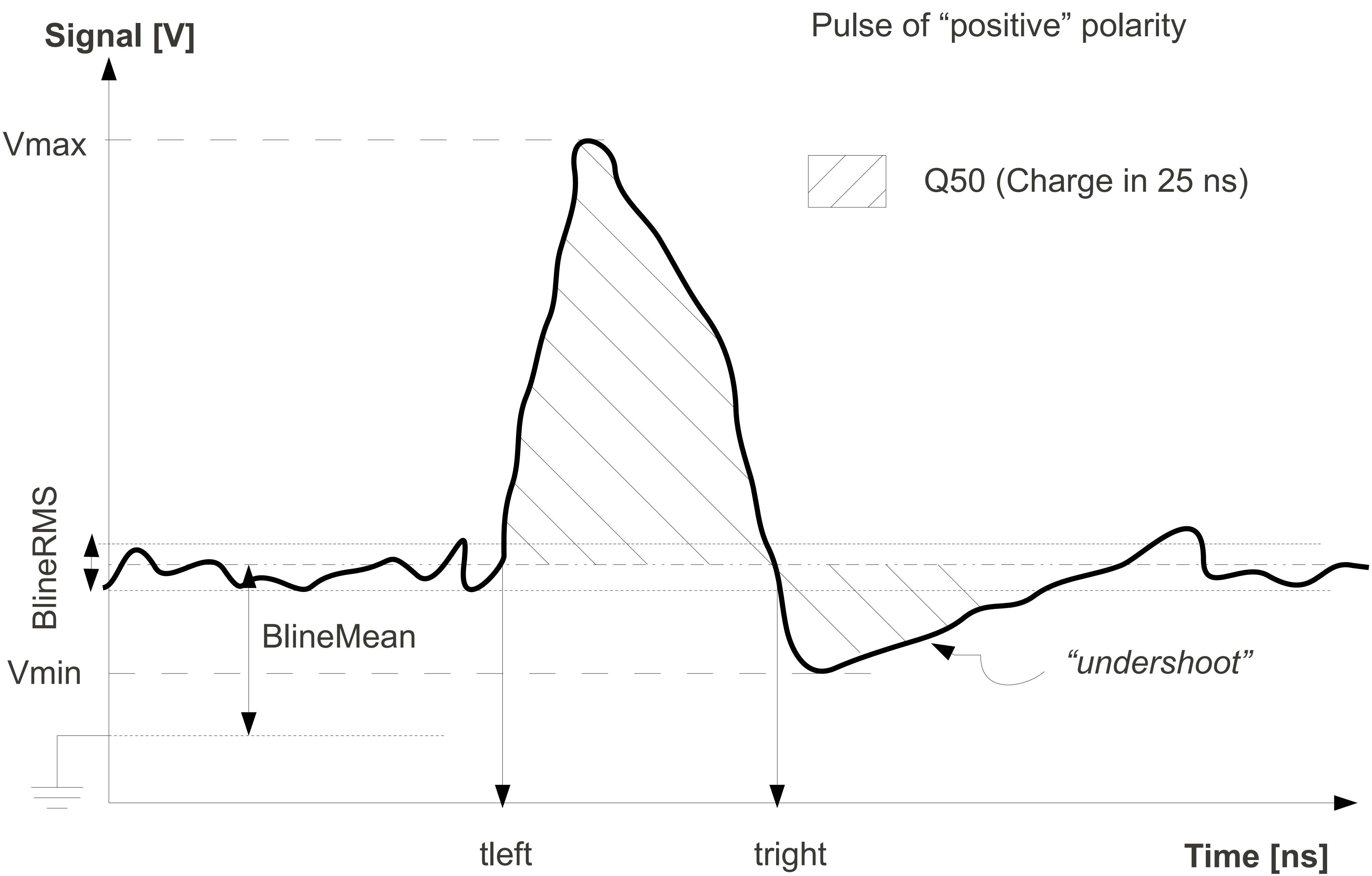
```
Int_t nent= tree->GetSelectedRows();  //Tells the number of drawn elements
Double_t *q=tree->GetV1();
Double_t *x=tree->GetV2();
Double_t Xmax=htemp->GetXaxis()->GetXmax() , Xmin=htemp->GetXaxis()->GetXmin();
Xmin=Xmin-0.5*(Xmax-Xmin)/nent ;Xmax=Xmax+0.5*(Xmax-Xmin)/nent
TH1D *h1=new TH1D( "h1","h1",nent,Xmin,Xmax );
for (Int_t il=0;il<nent;il++) h1->SetBinContent(il+1,q[il])
```

Estimate proper fitting values for the Error Function

```
h1->Draw();
TF1 *f1=new TF1("f1","[0]+0.5*[1]*(1.0+TMath::Erf((x-[2]/(1.414213562*[3]))))",Xmin,Xmax);
f1->SetParameters(val1 ,val2 , val3 , val4 ) // YOU HAVE TO FIND THESE
f1->Draw("same");  //IF YOU ARE HAPPY WITH THE PARAMETERS, PROCEED TO THE NEXT LINE
h1->Fit(f1)
```



Some tree variables...



EXTRA INFO

Why choosing low energy photons for detector testing?

- Detectors need to be optimized for Minimum Ionizing Particles (MIPs) detection. Standard detector characterization procedure would be to use **radioactive sources** (Sr90, for instance) and finally **test beams** (bunched beams, real scale system test).

- Best measurement conditions met with lasers:

  Reproducibility*:* no fluctuations in deposited energy → averaging possible → S/N improvement

  Choice of absorption length by varying laser wavelength

  High spatial resolution: microfocused beams down to few μm allow for fine resolution scans.

  Decoupling of charge carriers possible: by illuminating top or bottom sides of a reverse biased diode

  Easy ***synchronization*** of laser with DAQ

- Visible/IR ps-pulsed lasers commercially available. Red laser "scratches" the surface, IR penetrates. Laser pulse width << ns needed (standard drift in 300 mm Si $\leq$10 ns)

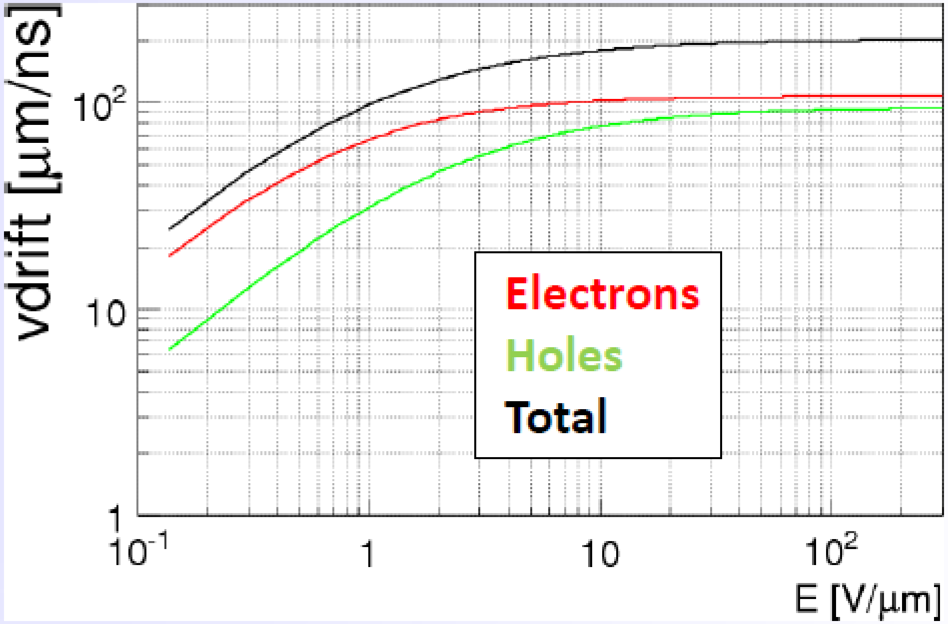
- Fast electronics needed to time-resolve e/h induced currents. Measured current pulses contain information on drift velocity, electric field configuration, trapping times...

Transient Current Technique

- Time resolved induced current can be calculated using Ramo theorem

$$I(t) = -q\vec{v}\overrightarrow{E_W}$$

where $\vec{v} = \vec{v}(E)$ is the drift velocity, E is the electric field and $\overrightarrow{E_W}$ the so-called weighting field



Electric field determines the charge trajectory and the velocity of the particle. It changes:

With bias voltage

Strip geometry

Irradiation of the detector

Electric field for typical detectors:

Pad diode: linear electric field (~capacitor)

Strip detector: peaked near the electrodes, linear in the center

Weighting field is the derivative of the weighting potential U_W. This potential determines how charge couples to an electrode: $Q = q(U_w(2) - U_w(1))$ (induced charge by a carrier moving from position 1 to 2)

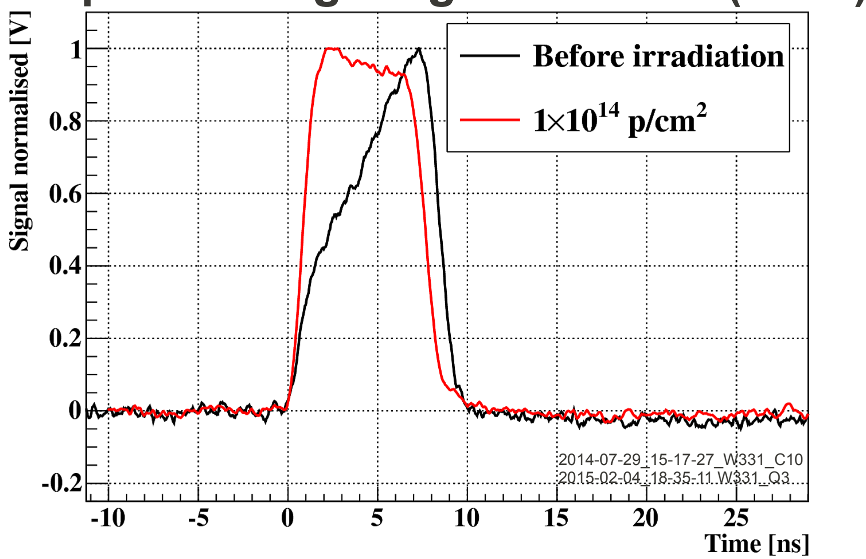
Weighting field for typical detectors:

Pad diode: constant

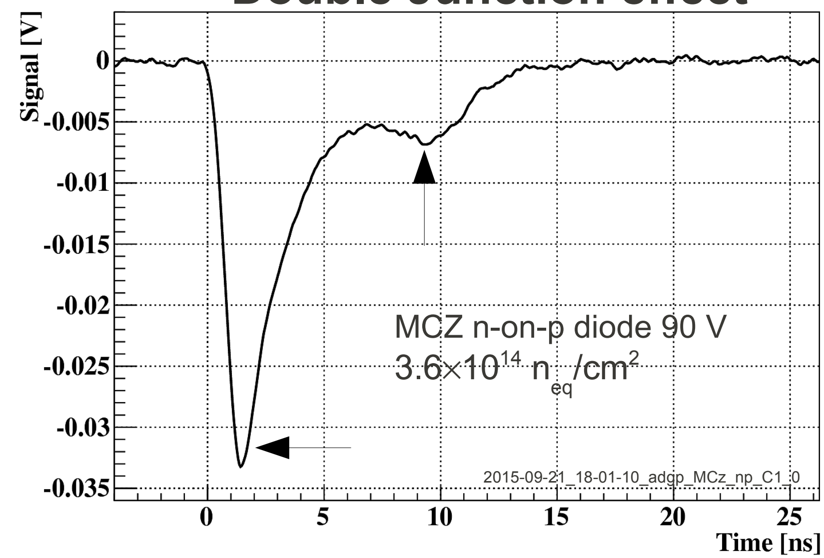
Strip detector: very asymmetric. Peaked near the collection electrode

Examples of TCT performance: measured waveforms

Space Charge Sign Inversion (SCSI)

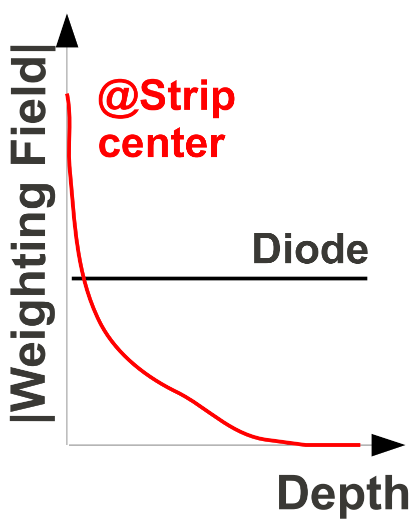


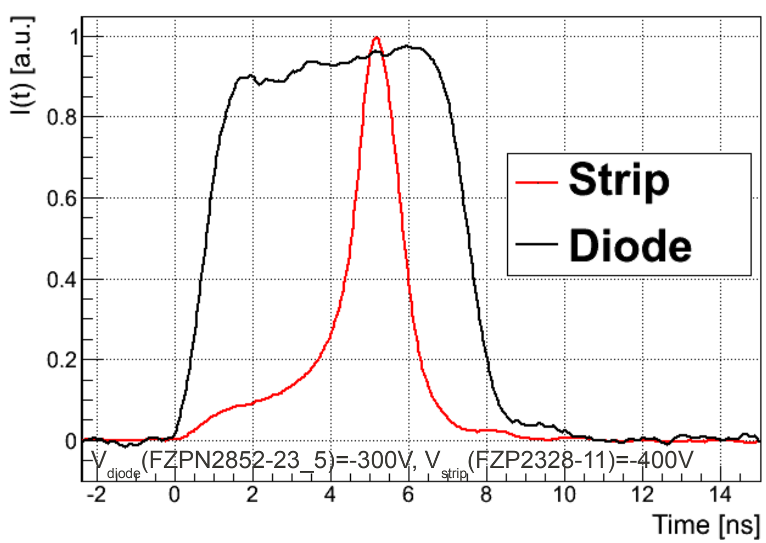
Double Junction effect

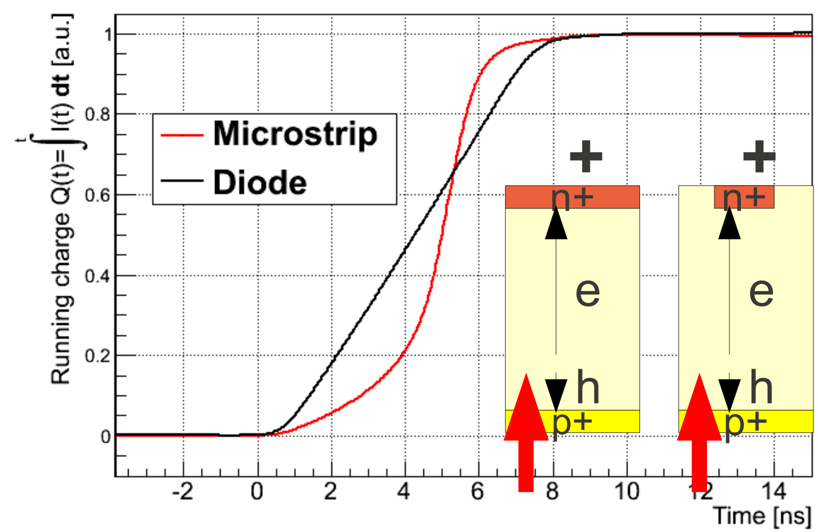


Difference between strip and diode (**bottom red** injection)

Most of the charge for a strip is induced near the strip → **Weighting field**







Experiment 2: charge collection versus voltage

Not covered in this practicum

For each pulse of a voltage scan we can calculate the collected charge
We then plot this charge versus the bias voltage
Explain why does the charge saturate?
Try to explain the output of the following root commands:

```
root -l measurement.root
TTree *tree=(TTree *) _file0->Get("edge");
tree->Draw("volt:time");
tree->Draw("BlineMean");
tree->Draw("volt-BlineMean:time");
tree->Draw("Sum$((volt-BlineMean)):Vbias","","l");
tree->Draw("Sum$((volt-BlineMean)*(time>tleft&&time<tleft+25.0)):Vbias","","l");
```

TOTAL INDUCED CHARGE BY AN e-h PAIR

2.5.2 *Parallel plate geometry with uniform field*

A semiconductor detector with very large overbias can be approximated by a uniform field. The bias voltage V_b is applied across the electrode spacing d. The electric field

$$E = \frac{V_b}{d} \tag{2.68}$$

determines the motion of a charge carrier in the detector. The carrier's velocity

$$v = \mu E = \mu \frac{V_b}{d} \; . \tag{2.69}$$

The weighting field is obtained by applying unit potential to the collection electrode and grounding the other:

$$E_Q = \frac{1}{d} \; , \tag{2.70}$$

so the induced current

$$i = qvE_Q = q\mu \frac{V_b}{d}\frac{1}{d} = q\mu \frac{V_b}{d^2} \; . \tag{2.71}$$

Since both the electric field and the weighting field are uniform throughout the detector, the current is constant until the charge reaches its terminal electrode.

Next, assume an electron–hole pair formed at coordinate x from the positive electrode. The collection time for the electron

$$t_{ce} = \frac{x}{v_e} = \frac{xd}{\mu_e V_b} \tag{2.74}$$

and the collection time for the hole

$$t_{ch} = \frac{d-x}{v_h} = \frac{(d-x)d}{\mu_h V_b} \; . \tag{2.75}$$

Since electrons and holes move in opposite directions, they induce current of the same sign at a given electrode, despite their opposite charge. The induced charge due to the motion of the electron

The induced charge

$Q = it_c$

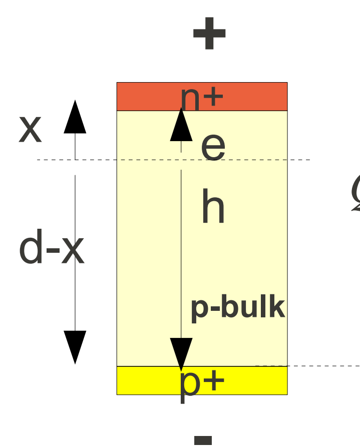
$$Q_e = e\mu_e \frac{V_b}{d^2}\frac{xd}{\mu_e V_b} = e\frac{x}{d} \; . \tag{2.76}$$

Correspondingly, the hole contributes

$$Q_h = e\mu_h \frac{V_b}{d^2}\frac{(d-x)d}{\mu_h V_b} = e\left(1 - \frac{x}{d}\right) \; . \tag{2.77}$$

[Spieler pg- 75-76]

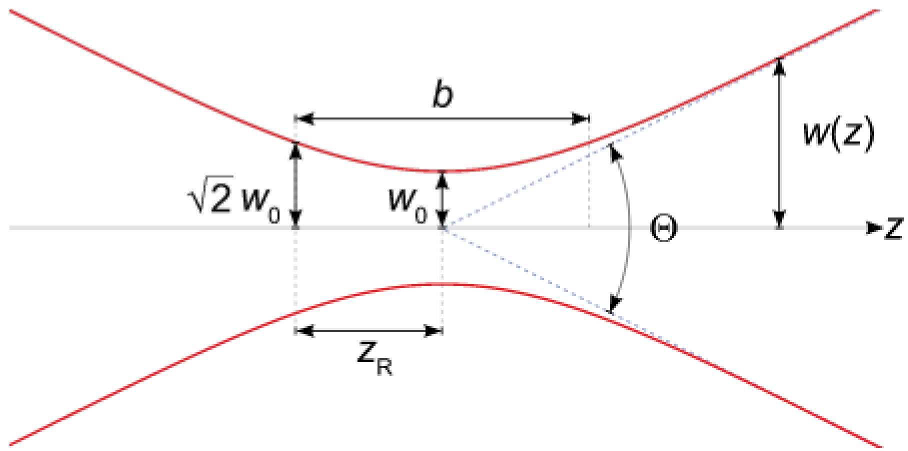
The charge induced by an e-h pair produced at a distance x from the electrodes will be e and not 2e !



$$Q_{tot} = Q_h(x) + Q_e(x) = $$
$$= q\frac{d-x}{d} + q\frac{x}{d} = q$$

Gaussian beam propagation

Many lasers emit beams that approximate Gaussian profiles: their transverse E-field and intensity are well described by Gaussian functions. Refraction does not destroy Gaussian properties.



w_0=beam width or waist (z=0 @ waist)
z_R=Rayleigh length: $w(z_R)=\sqrt{2}w_0$
b = 2 z_R depth of focus

Spot size increases from the waist, linearly for $z \gg z_R$

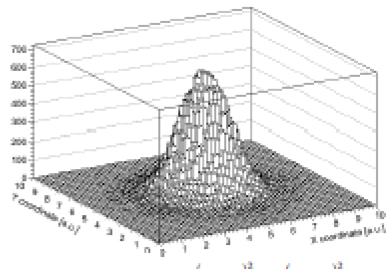
$$w(z)=w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}$$

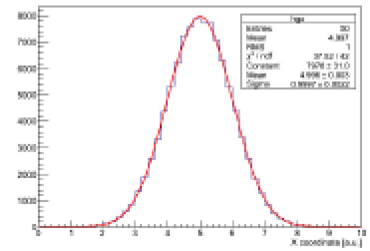
Beam **divergence**

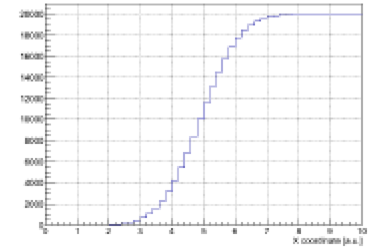
$$\theta\sim\frac{\lambda}{\pi w_0} \quad (\theta \text{ in radians})$$

Rayleigh length and **beam waist** are related by:

$$z_R=\frac{\pi w_0^2}{\lambda}$$







```
{
  TF2 *fgxy = new TF2("fgxy","[0]*TMath::Gaus(x,[1],[2])*TMath::Gaus(y,[3],[4])",0,10,0,10);


  //Create 2D histogram according to TF2
  fgxy->SetParameters(1,5,1,5,1);

  TH2D *hgxy = new TH2D("hgxy","G(x,y)",50,0.,10.,50.,0.,10.);
  hgxy->FillRandom("fgxy",100000);

  //Create 1D histogram where Y-integral will be stored
  TH1D *hgx=new TH1D("hgx","hgx",hgxy->GetNbinsX(),hgxy->GetXaxis()->GetXmin(),hgxy->GetXaxis()->GetXmax());

  //Fill 1D histo with slice integrals
  Int_t iY = hgxy->GetNbinsY();

  for ( Int_t ix=1;ix<=hgxy->GetNbinsX(); ix++ ) hgx->SetBinContent( ix , hgxy->Integral(ix,ix,1,iY,"width") );
  gStyle->SetOptFit(1);
  hgx->Draw();
  hgx->GetXaxis()->SetTitle("X coordinate [a.u.]");

  //Integral of a 1D gaussian
  TH1D *herf=hgx->Clone("herf"); herf->Reset();
  for ( Int_t ix=1;ix<=hgx->GetNbinsX(); ix++ ) herf->SetBinContent( ix , hgx->Integral(1,ix,"width") );
  herf->Draw();
  herf->GetXaxis()->SetTitle("X coordinate [a.u.]");
}
```

RED focusing

Mind the double offset to the vertical holder !!!!