R&D of scCVD Diamond Beam Loss Monitors for the LHC

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Outline

- **Idea and motivation**
  for cryogenic diamond Beam Loss Monitors (BLMs) for the LHC

- **Details of measuring set-up**
  for diamond characterization via TCT

- **The Plasma Effect**
  for heavy ionizing particles in scCVD diamonds

- **Raw measurements and derived charge-carrier properties**
  for scCVD diamonds

- **Conclusion**
Idea and Motivation

- Place BLMs as close to the beam as possible
  → Detector operation at 1.9 K, within the cold mass

- Choose detector material
  → Candidates are: CVD diamond, silicon, liquid He

- Diamonds not tested yet at ultra-cold temperatures
  → Interesting!

- Characterize scCVD diamonds at cryogenic temperatures with gaseous He cooling
  → Start at RT, decrease stepwise down to 67 K with liquid He cooling
  → Start at 1.9 K, increase slowly to 60 K
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"Diamonds Are a Girl's Best Friend!"
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“Diamonds Are a Girl's Best Friend!”

DONE!

First test this week!
Why Diamond

Pros:

➢ High band gap (5.5 eV)
  → Very high breakdown field > 1e7 V/cm
  → Very high resistivity > 1e11 Ω cm
  → Very low leakage current ≤ 1 pA

➢ Low dielectric constant (5.7)
  → Low capacitance
    → Low noise

➢ High displacement energy (43 eV/atom)
  → Radiation hard

Cons:

➢ High pair creation energy (13.5 eV)
  → Less signal (but less noise!)
Details of Measuring Set-up

- The Transient-Current Technique (TCT) measurement:
  
  - measure the transient current
  1) $\alpha$ particles impinge on top side
  2) Create eh-pairs close to electrode
  3) Electric field separates charges
  4) Drifting charges induce current

  - Pos. (neg.) bias → Measure $e^{-}$ ($h^{+}$)

  - Use ultra-fast 2 GHz, 40 dB, 200 ps rise time current amplifier (cividec)

  - Use broad-band 3 GHz scope (LeCroy)

  - Use RF components
Details of Measuring Set-up

- **SETTINGS:**
  - TCT in vacuum
  - Temp: 67 K - 300 K, bias ≤ 600 V
  - Read-out from HV-side
  - Use collimator (avoid edge-effects)
FACTS:

→ αs produce high density charge cloud
→ Outer charges screen inner ones
→ E-Field decreases inside the plasma
→ Increased E-Field decreases lifetime of plasma
Plasma Effect at 295 K

Clear evidence for plasma effect at room temp.

start of drift
plasma phase
pure drift phase
collection phase

$\tau_{\text{plasma}}$

time in ns
Difficulties

Average pulses! S2N much worse for single pulse!

Difficult to further decrease voltage as S2N decreases!
TCT Hole Pulses

295 K

150 K

110 K

80 K
TCT Hole Pulses

What does explain both features?

- 295 K
- 150 K
- 110 K
Below ~150 K:

- Field-free region within plasma cloud → immediate trapping and increased recombination
- Detrapping if $E_{\text{trap}} / kT$ large enough
- Distinguish 2 types of trapping!

\[
\tau_{\text{plasma}} \ll \tau_{\text{drift}}
\]

From Ramo-Theorem:

\[
i(t) = i_{\text{not-trapped}}(t) + i_{\text{released}}(t) = \frac{e}{d} \sum_{i, \text{not-trapped}} v_i(t-t_i^{\text{start}}) + \frac{e}{d} \sum_{i, \text{released}} v_i(t-t_i^{\text{detrap}}); \]

\[
Q_{\text{released}}(t) = Q_{\text{trapped}}(1 - \exp(-t/\tau_{\text{detrap}}));
\]
Trapping/Detrapping at 110 K

Detrapping time few ns
Trapping/Detrapping at 80 K

Detrapping time
~10 ns
Analysis of TCT Pulses

- Four phases:
  1) Start of drift
  2) Current saturation
  3) Collection at electrode
  4) Tail

- Fit $\text{Erfc}(t)$ to rising/falling edge:
  → 50% levels mark start/end time
  → Derive drift mobility and velocity

- Fit $1-\exp(-t/\tau_p)$ to saturation:
  → $\tau_p$ is plasma lifetime

- Fit $\exp(-t/\tau)$ to tail:
  → Tail formed by cable effects, amplifier bandwidth limits, diffusion

![Graph showing TCT pulse analysis](image)
Hole Mobility and Velocity

\[
v_{dr} = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_{sat}}}\]

**Fits yield:**

\[
\begin{align*}
\mu_{0,h}^{295\,K} &= 2278 \pm 110 \, \text{cm}^2/\text{Vs} \\
v_{sat}^{295\,K} &= 11.8 \cdot 10^6 \pm 0.8 \cdot 10^6 \, \text{cm/s} \\
\mu_{0,h}^{67\,K} &= 7300 \pm 1850 \, \text{cm}^2/\text{Vs} \\
v_{sat}^{67\,K} &= 13.4 \cdot 10^6 \pm 1.4 \cdot 10^6 \, \text{cm/s}
\end{align*}
\]

- Mobility \(\mu_h\) and avg. drift velocity \(<v_{\text{drift}}>\) at RT as expected
- \(\mu_h\) increases down to 67 K (\(\rightarrow <v_{\text{drift}}>\) increases as well)
  - \(\rightarrow\) no onset of impurity scattering
- \(v_{sat}\) \(\sim\) constant with temperature
Hole Mobility and Velocity

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**Integrated Charge**

- Charge constant in range 140 K to 300 K
- Steep drop from 140K down to 67 K
  - plasma associated trapping and recombination

Sanity check:
- corrected charge = 50 fC
  - 4.6 MeV alpha (coating of source!)
    - Pair creation energy = 14.7 eV
    - Literature: 13.5 eV
  - OK
Detrapping Time Constant

\[ \tau_{\text{detrap}} = \frac{E_{\text{trap}}}{k_B T} e^{\frac{\sigma N v_{\text{th}}(T)}{k_B T}} \]

- Plot \( \ln(\tau_{\text{detrap}}) \) vs \( 1/T \), do line fit:
  - \( E_{\text{trap}}^h \approx 40 \text{ meV} \pm 10 \text{ meV} \)
  - lowest shallow trap
  - investigate further energy levels of traps via Thermally Stimulated Current technique

In contact with Uni Hamburg
Conclusion

- TCT offers eminent possibility to characterize detectors

- Temperature dependence of
  - drift mobility and velocity
  - total charge
  - trapping-detrapping mechanism
  - pulse shape
  in scCVD diamonds

- Plasma associated trapping reduces total charge yield at T < 150 K

→ $Q_{\text{signal}} \rightarrow 0$ for T $\rightarrow 1.9$ K ??
Cosmic Muons in scCVD

- Use charge-sensitive amplifier here
- No sign of charge degradation (20\% with αs at 100K)
- Work in progress!
Outlook

- Paper in preparation

- Simulate pulse shapes
  including plasma effect and trapping-detrapping mechanism

- TCT with β-source (this summer)
  → test MIP-like signal with diamond
  → density of charge cloud much smaller
    → no (little) plasma effect expected

- Beam tests at 1.9 K

- TCT with irradiated samples
  → compare scCVD diamond with Si detectors
  → expect better performance for scCVDs!
Energy Loss in Diamond

Bragg curve simulator

5.5 MeV α through diamond

http://www.nist.gov/pml/data/star/index.cfm
Pulse shape changes drastically with temperature!

Volt: -400v
Q: h+
Two Contributions to Signal

from Ramo-Theorem:

\[ i(t) = i_{\text{non-trapped}}(t) + i_{\text{released}}(t) = \frac{e}{d} \sum_{i, \text{not-trapped}} v_i(t - t_{i \text{start}}) + \frac{e}{d} \sum_{i, \text{released}} v_i(t - t_{i \text{detrap}}); \]

\[ Q_{\text{released}}(t) = Q_{\text{trapped}}(1 - \exp(-t / \tau_{\text{detrap}})); \]

\[ Q_{\text{not-trapped}} = Q_{\alpha-\text{induced}} - Q_{\text{trapped}} \]
Detrapping vs. T

The graph shows the relationship between detrapping time $\tau_{\text{detrap}}$ in ns and temperature in K. The curves are labeled with different voltages: -100v, -150v, -200v, -250v, -300v, -350v, and -400v. As the temperature increases, the detrapping time decreases for all voltage levels.
Pulse shape at 67 K

-400v
-350v
-300v
-250v
-200v
-150v

Temp: 67k
Q: h+
At full band width

At reduced band width

Reduced band width fakes shorter transient time