



华中师范大学



中国科学院近代物理研究所  
Institute of Modern Physics, Chinese Academy of Sciences



# NνDEX 实验 $SeF_6/SF_6$ 气体中离子 漂移性质研究

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2024年5月 COUSP2024 四川 西昌

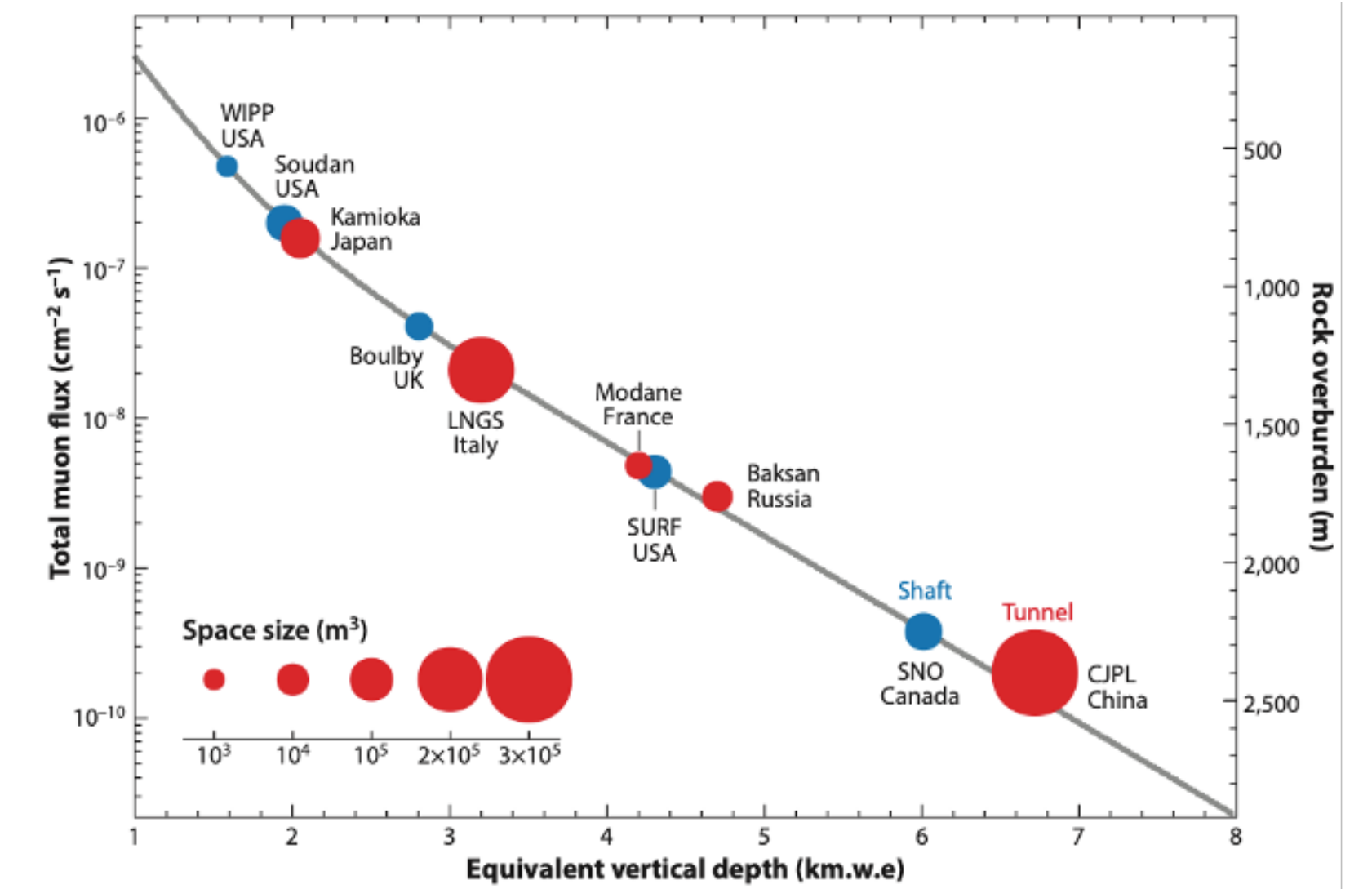
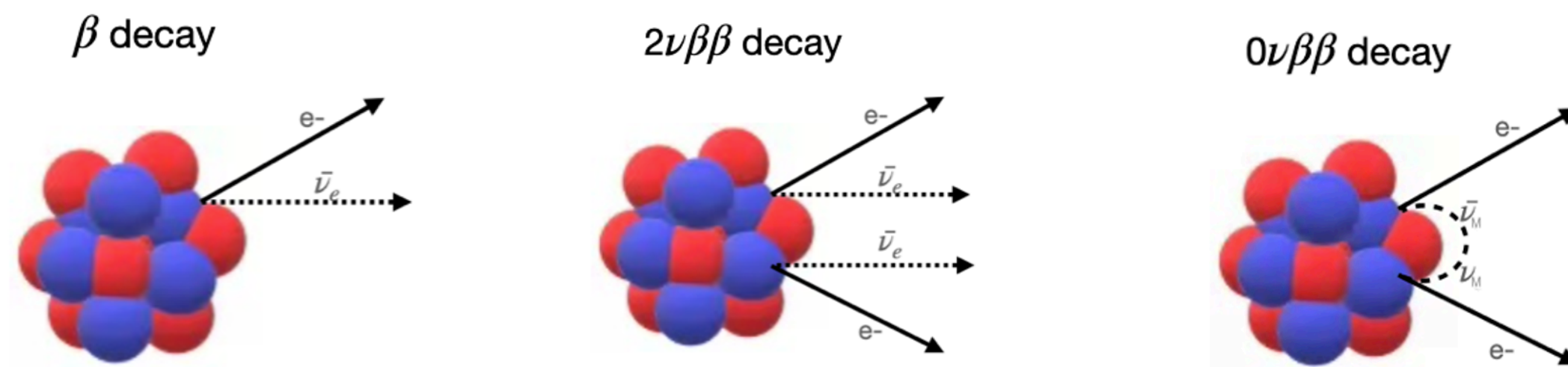
# 主要内容

- 利用离子时间投影室寻找无中微子双贝塔衰变
- 离子漂移速度测量（六氟化硫、空气）
  - 基于N<sub>2</sub>DEx电荷探测与读出单元
    - 结构设计
    - 结果
- 总结
- 基于屏栅电离室和独立前放
  - 电离室结构
  - 结果

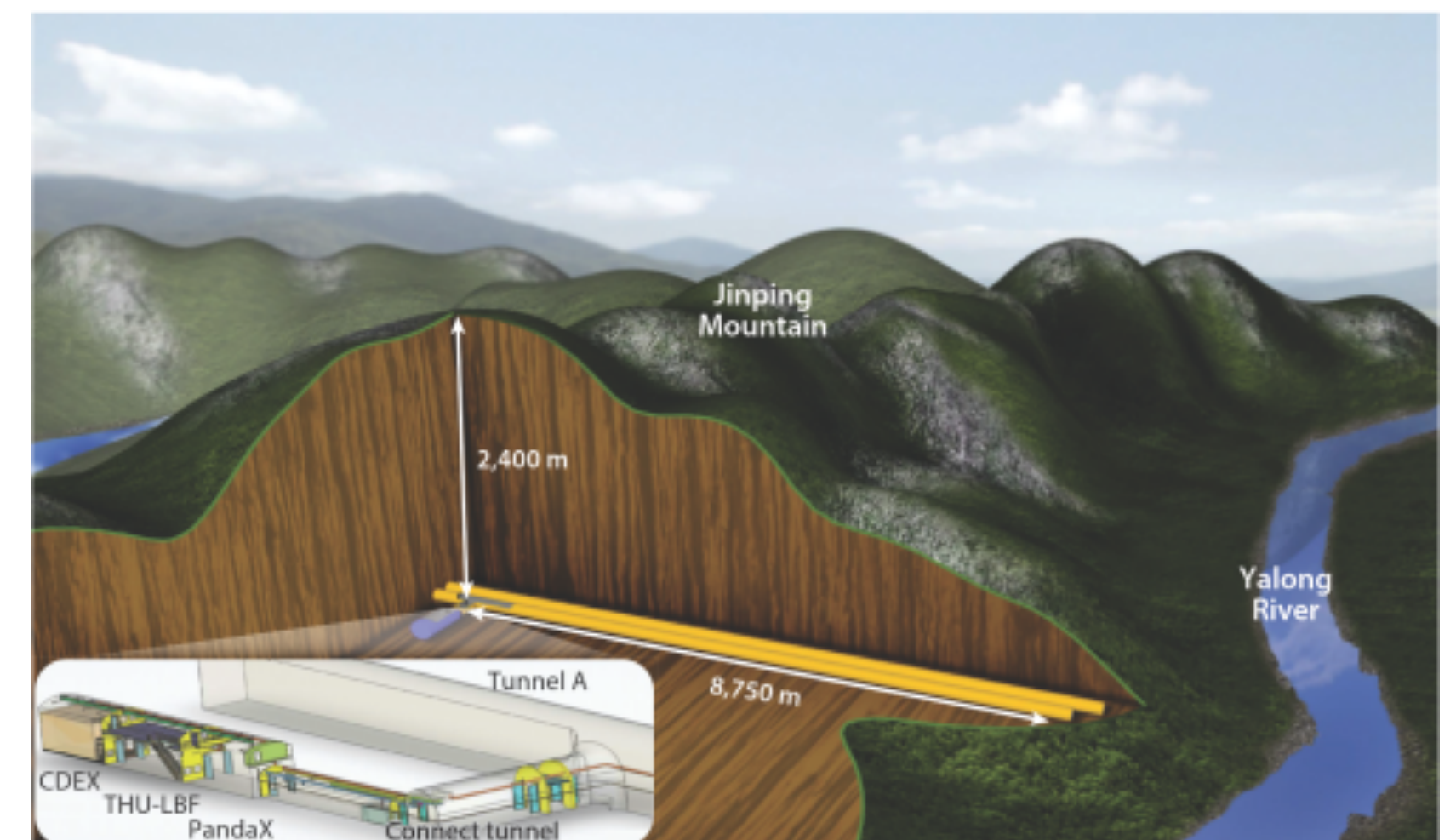
# 离子时间投影室寻找无中微子双贝塔衰变

锦屏地下实验室与NνDEX实验

马约拉纳中微子  $\longleftrightarrow 0\nu\beta\beta$



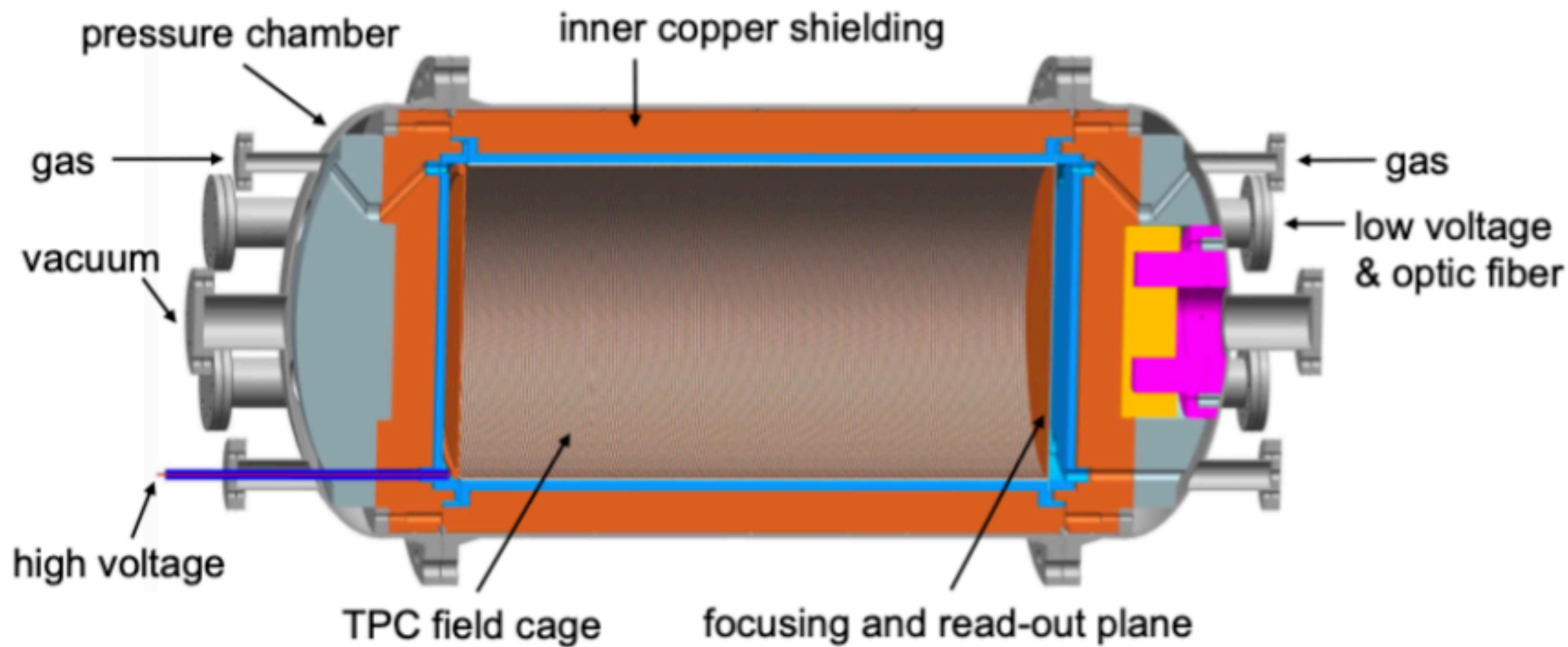
- NνDEX: **No neutrino Double-beta-decay Experiment**
- 锦屏地下实验室：世界上最深的地下实验室
- 气体TPC  
事例几何特征鉴别信号和本底





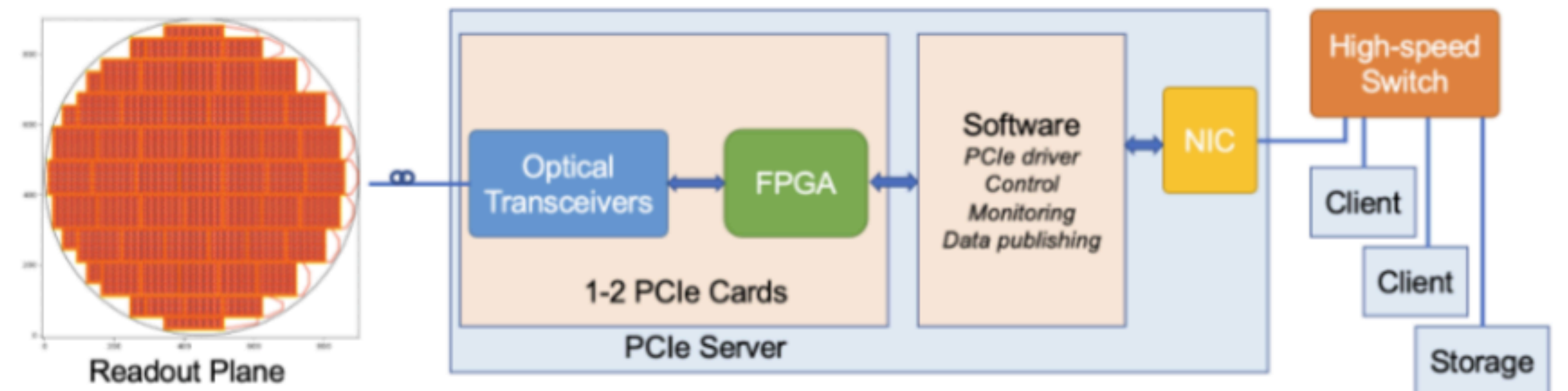
# 离子时间投影室寻找无中微子双贝塔衰变

## 锦屏地下实验室与NUDEX实验



$^{82}\text{Se}$ 高Q值 ( $^{82}\text{SeF}_6$ ) 以及靶电负性  
10倍大气压高纯六氟化硒 (剧毒、强腐蚀性)  
通过直接探测的离子信号来重建 $0\nu\beta\beta$ 过程中电子信息

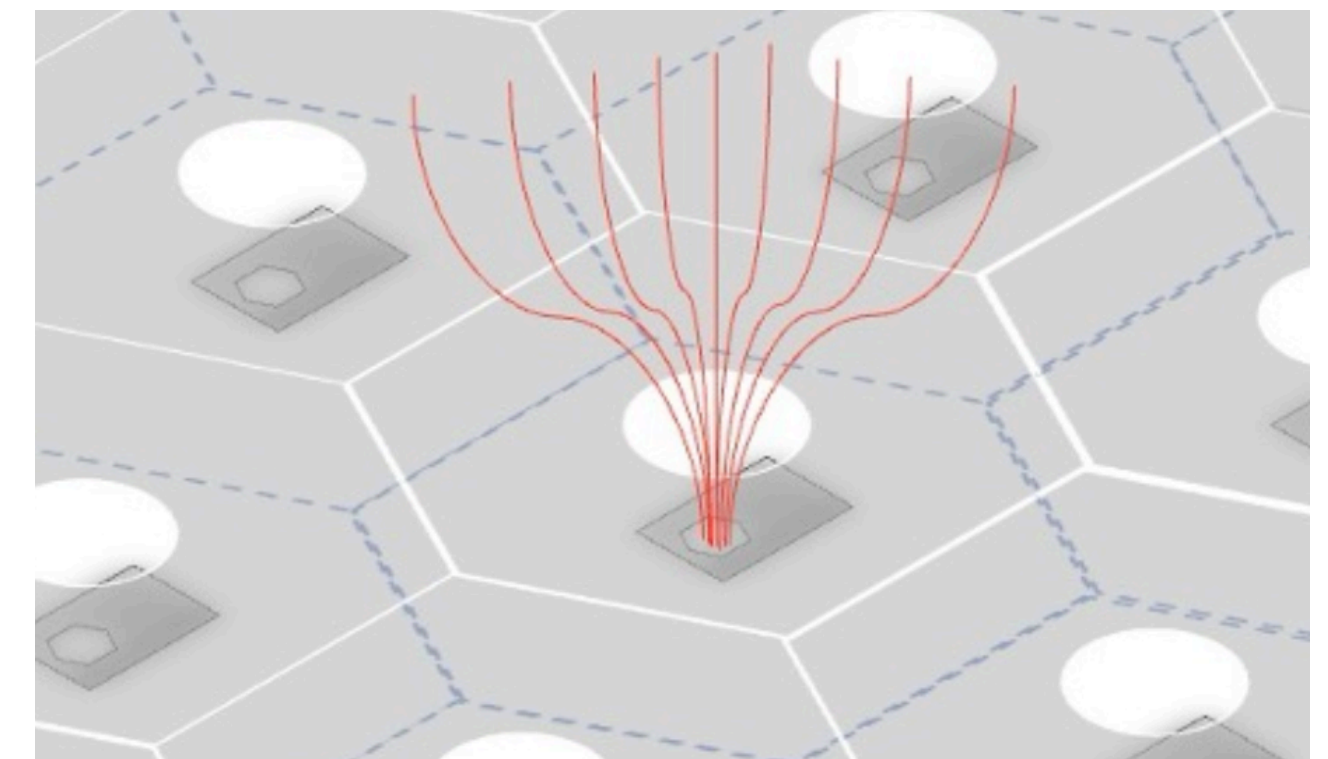
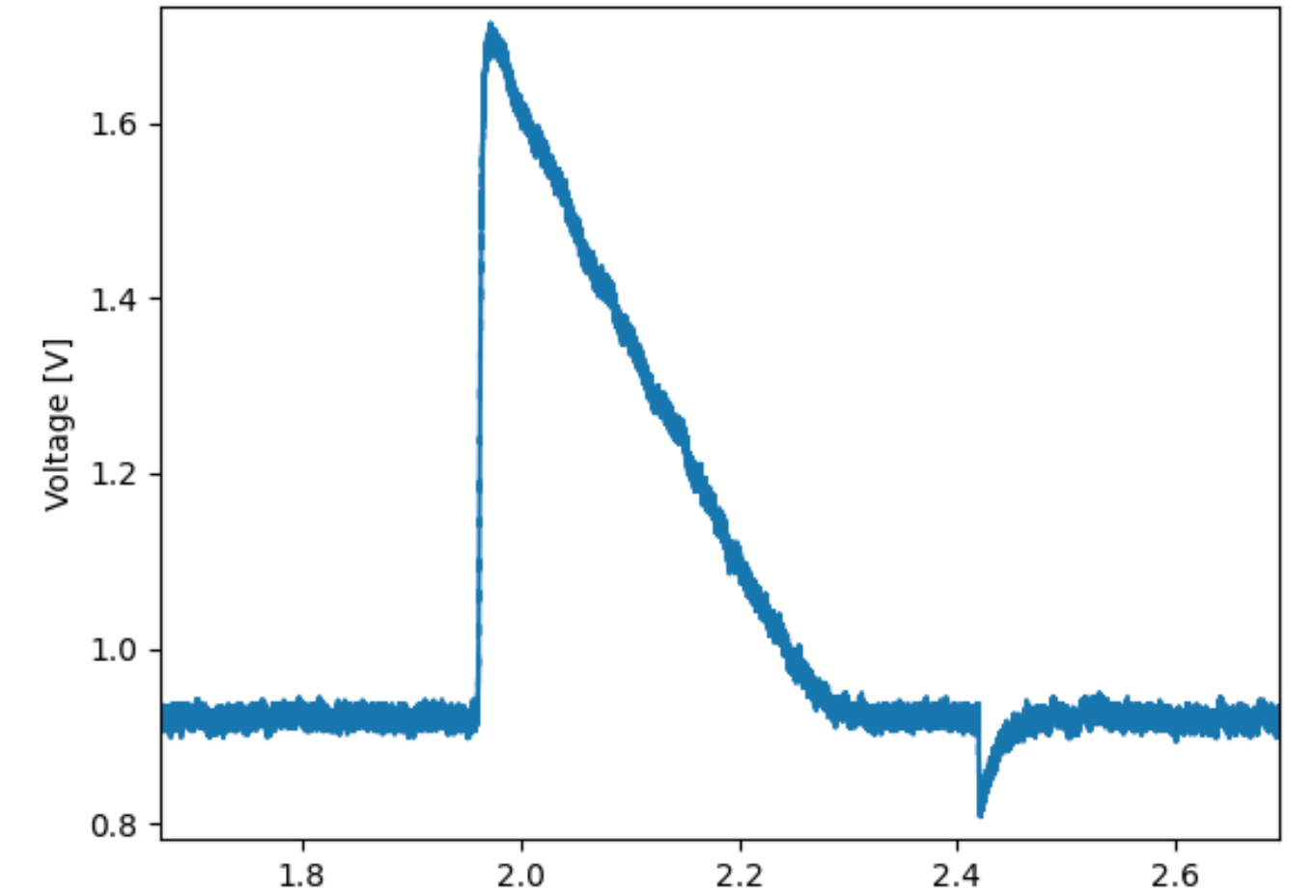
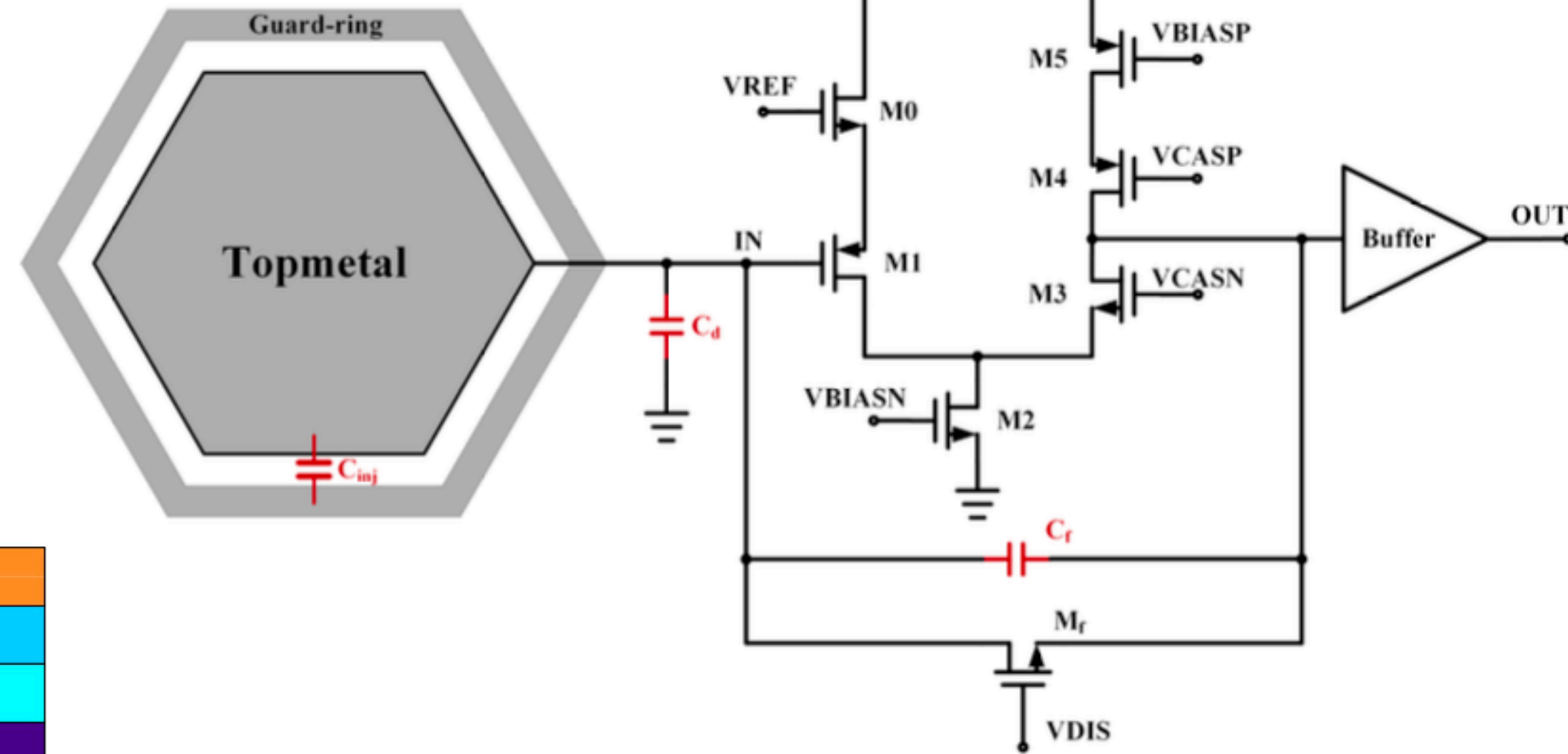
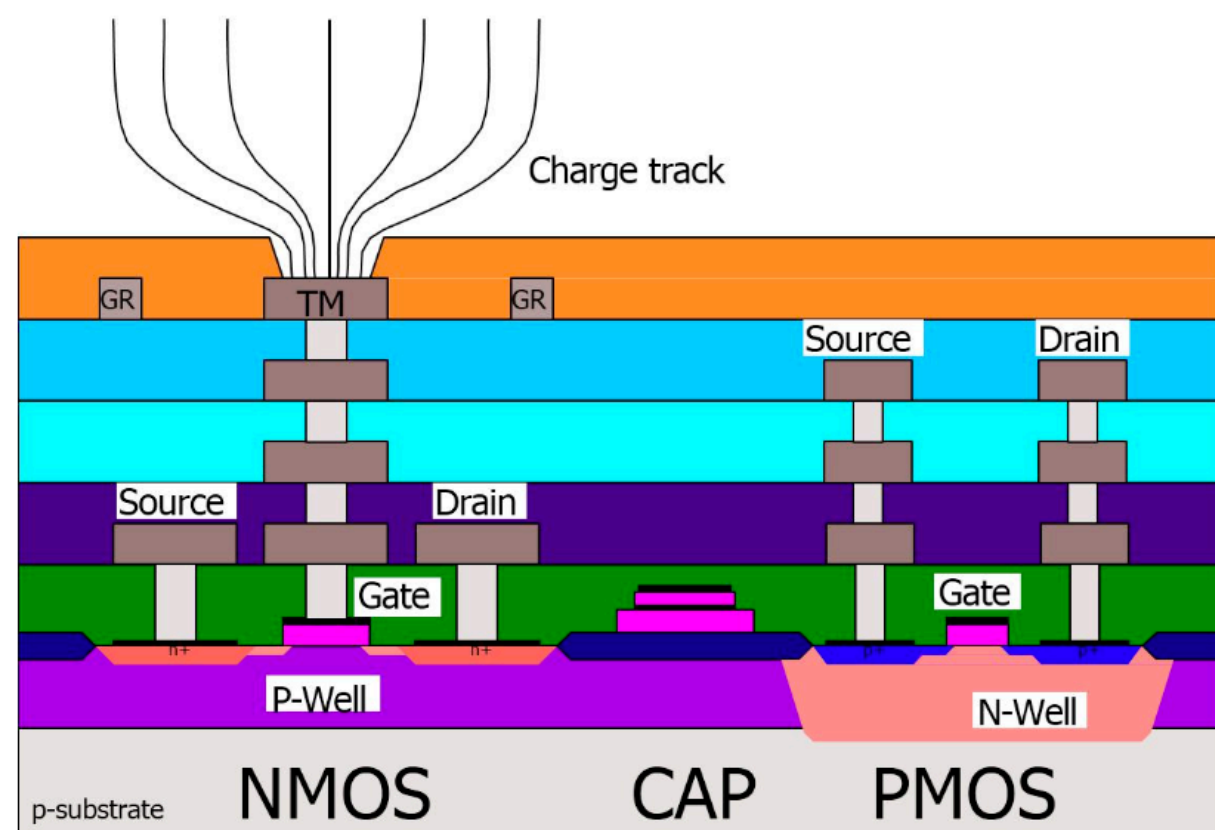
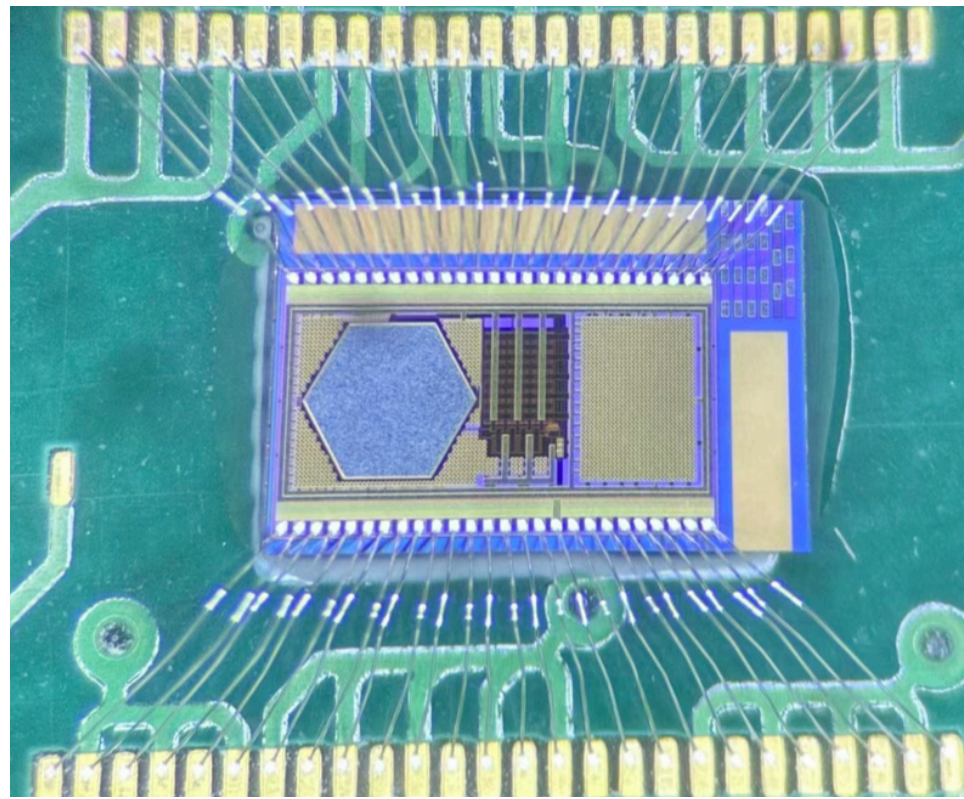
Topmetal芯片实现无雪崩放大收集离子信号  
万路读出-一万路芯片阵列





# 离子时间投影室寻找无中微子双贝塔衰变

## Topmetal-S芯片

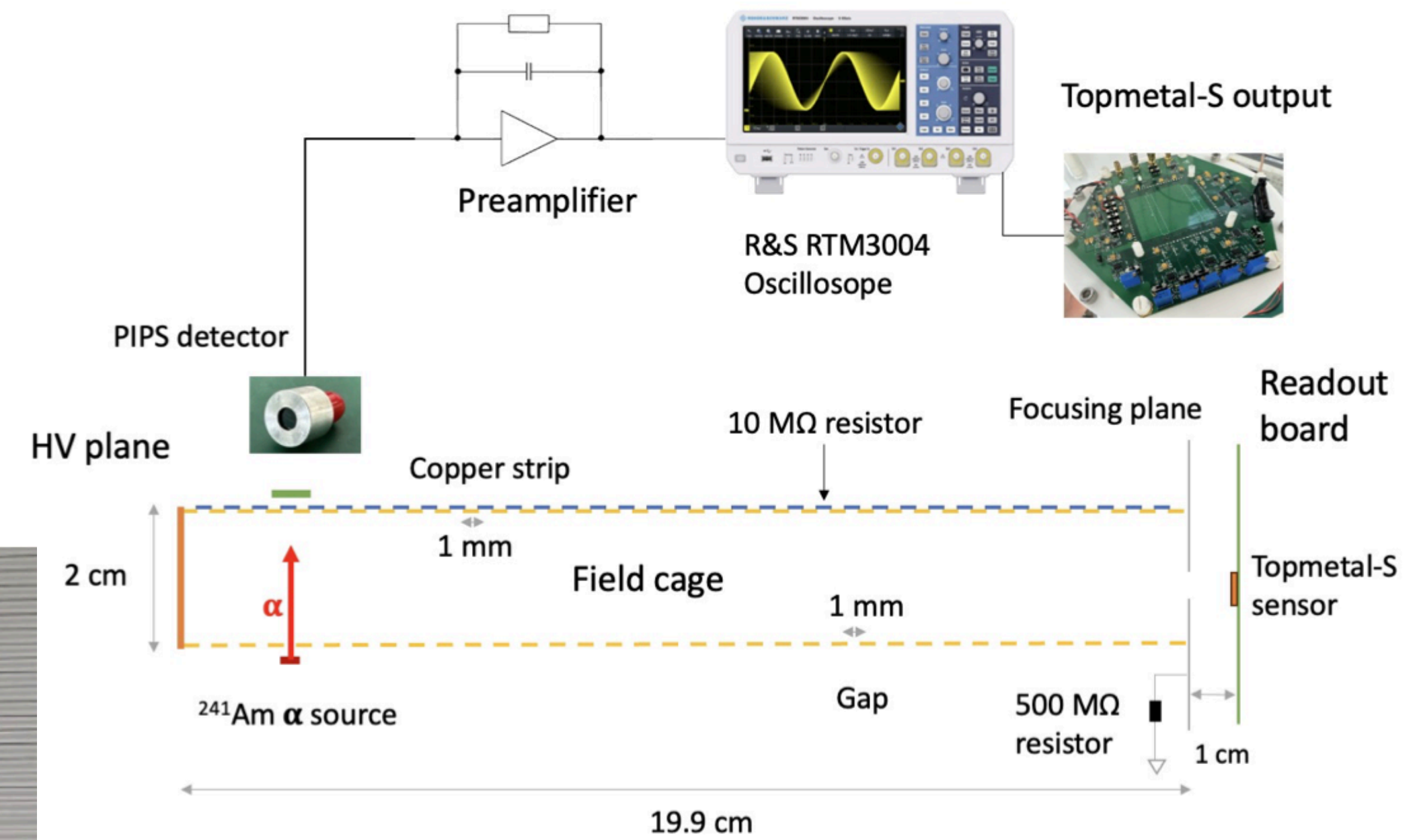
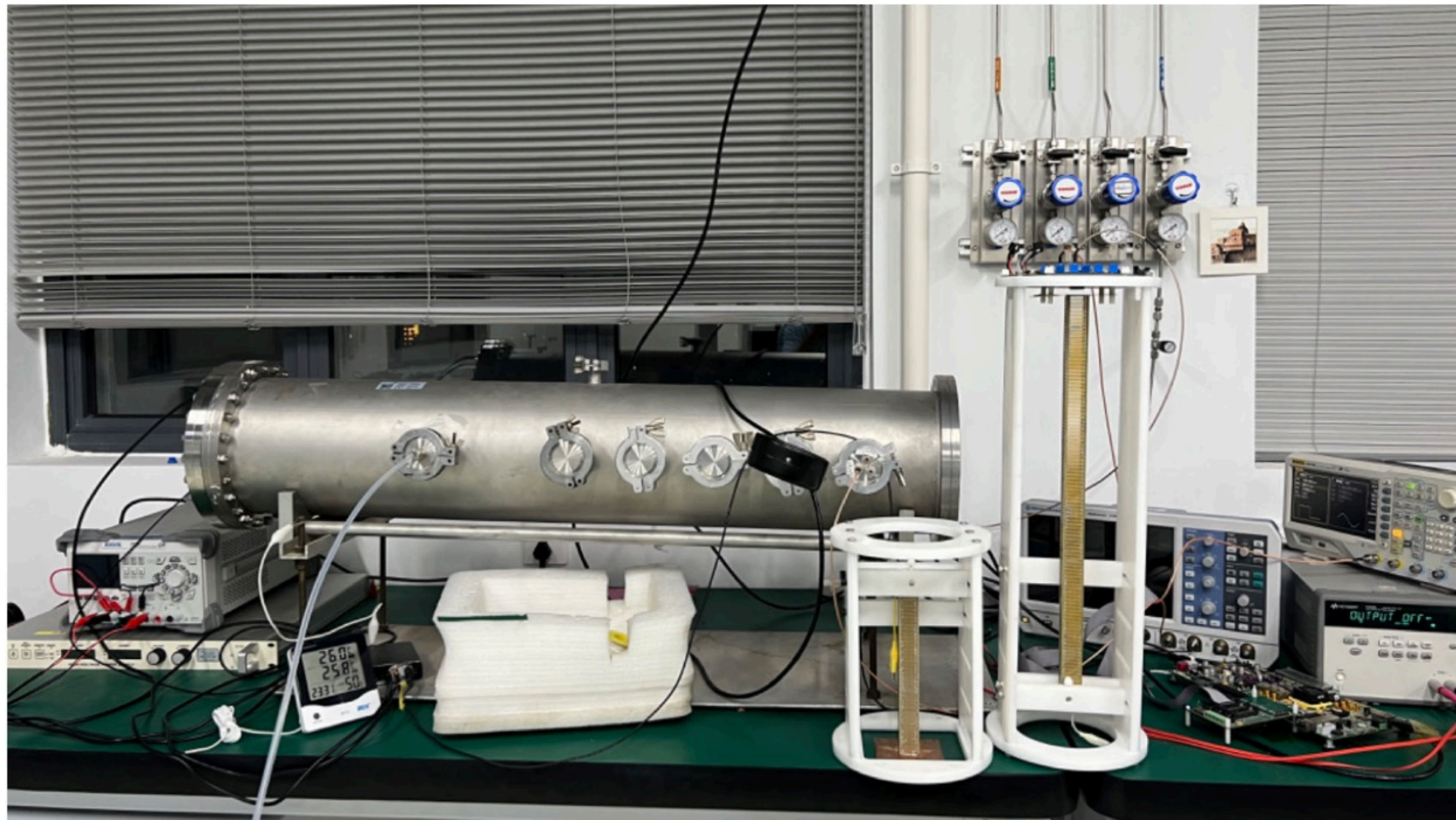




# 离子漂移速度测量

## 基于NLDEX电荷探测与读出单元

JINST 19 C04004 (2024)



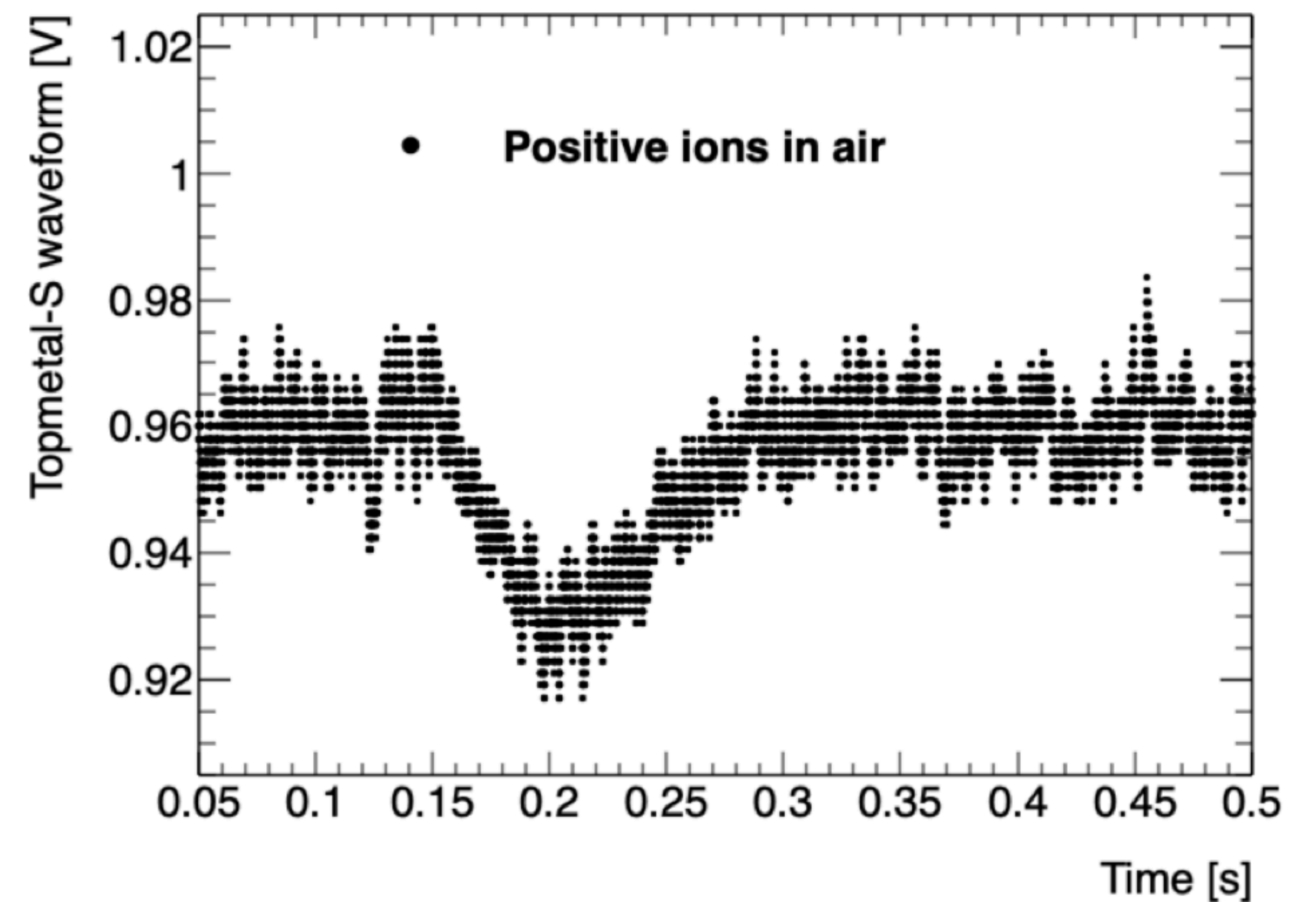
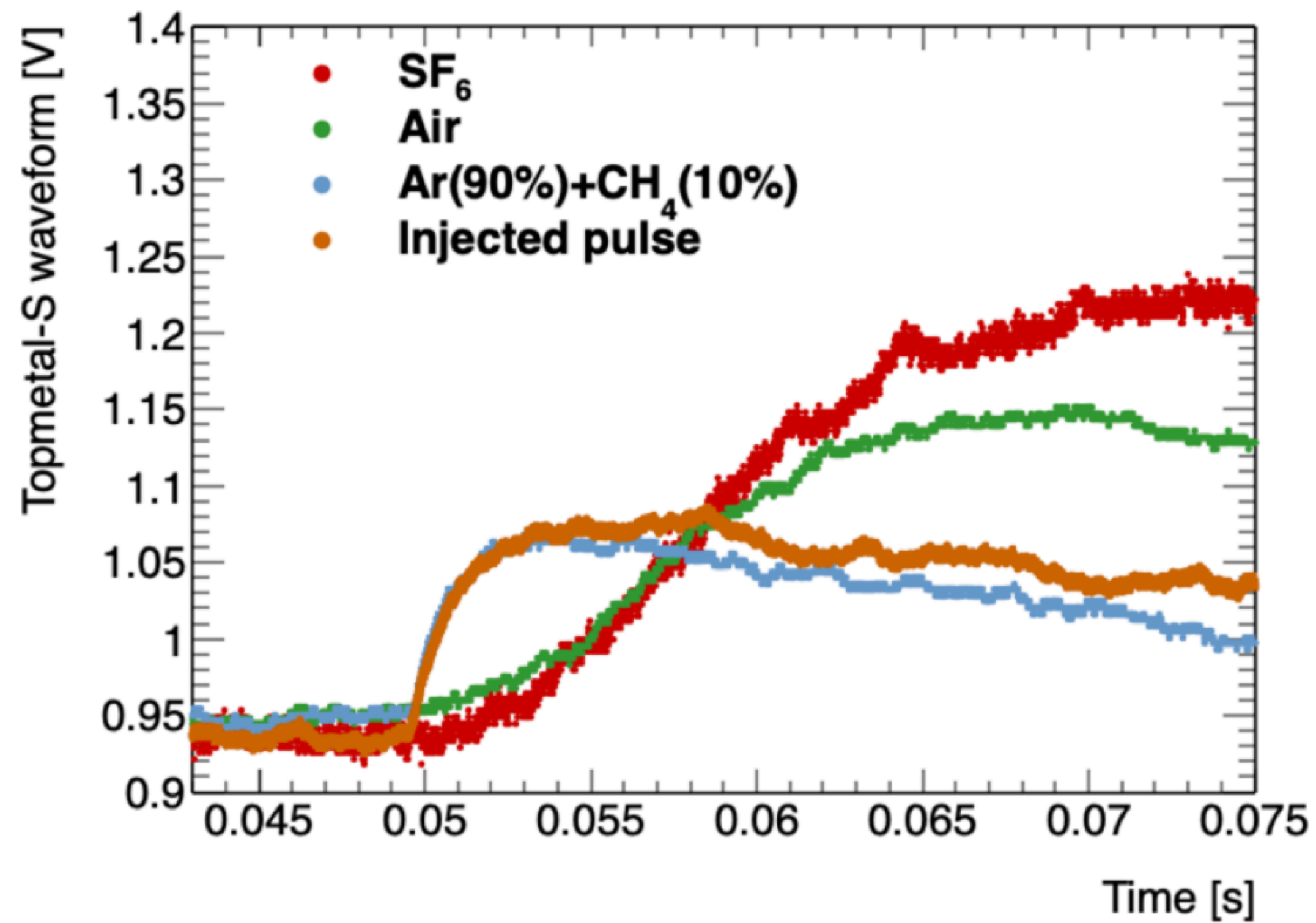
- 气体：29% 氧气+ 71% 氮气（近似干燥空气），测试过程保持微弱流气。
- 温度和湿度保持相对恒定，气压略大于武汉当地气压。



# 离子漂移速度测量

## Topmetal-S芯片对信号的响应

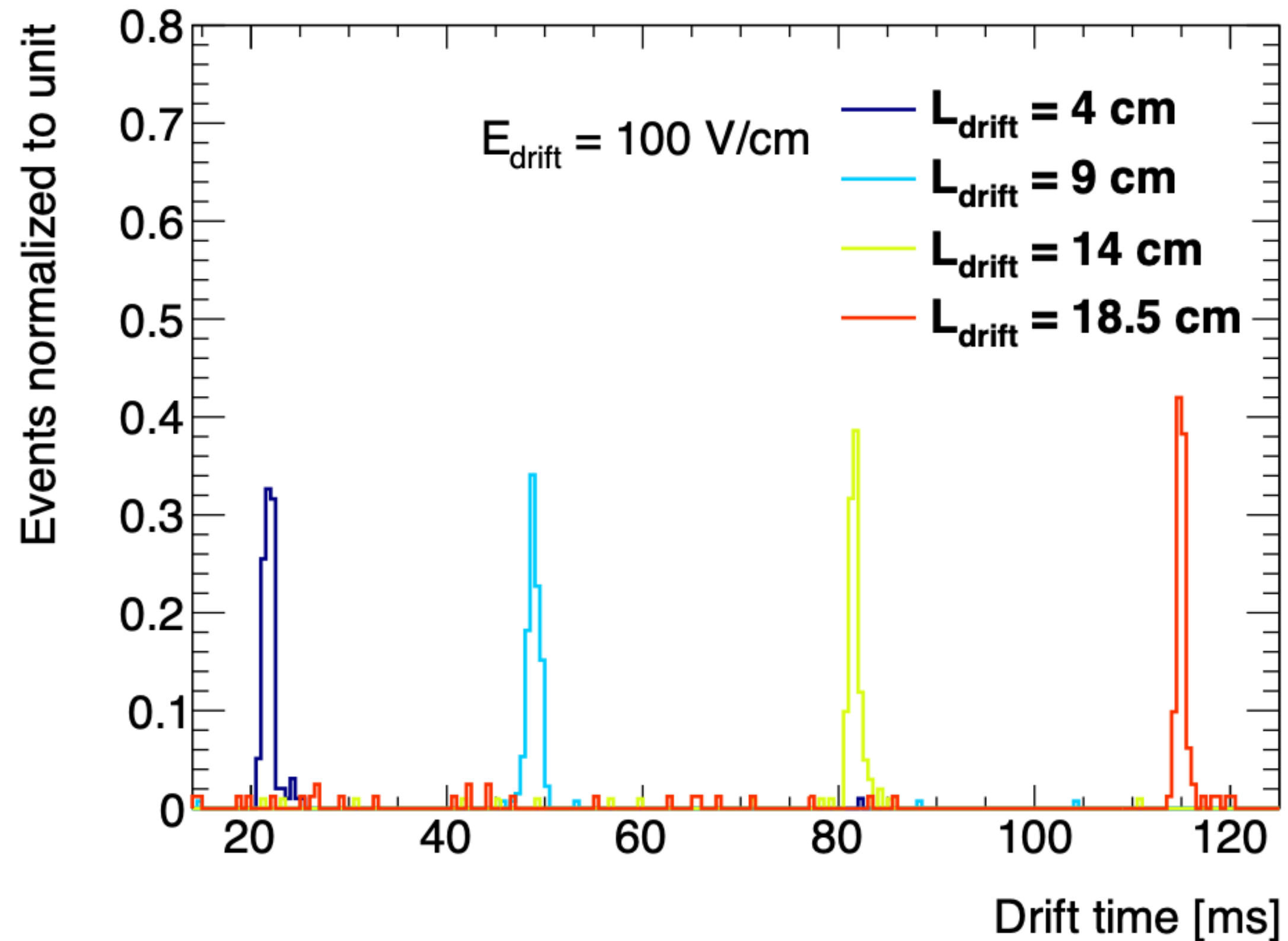
- 芯片对负离子/电子和对正离子响应不对称。



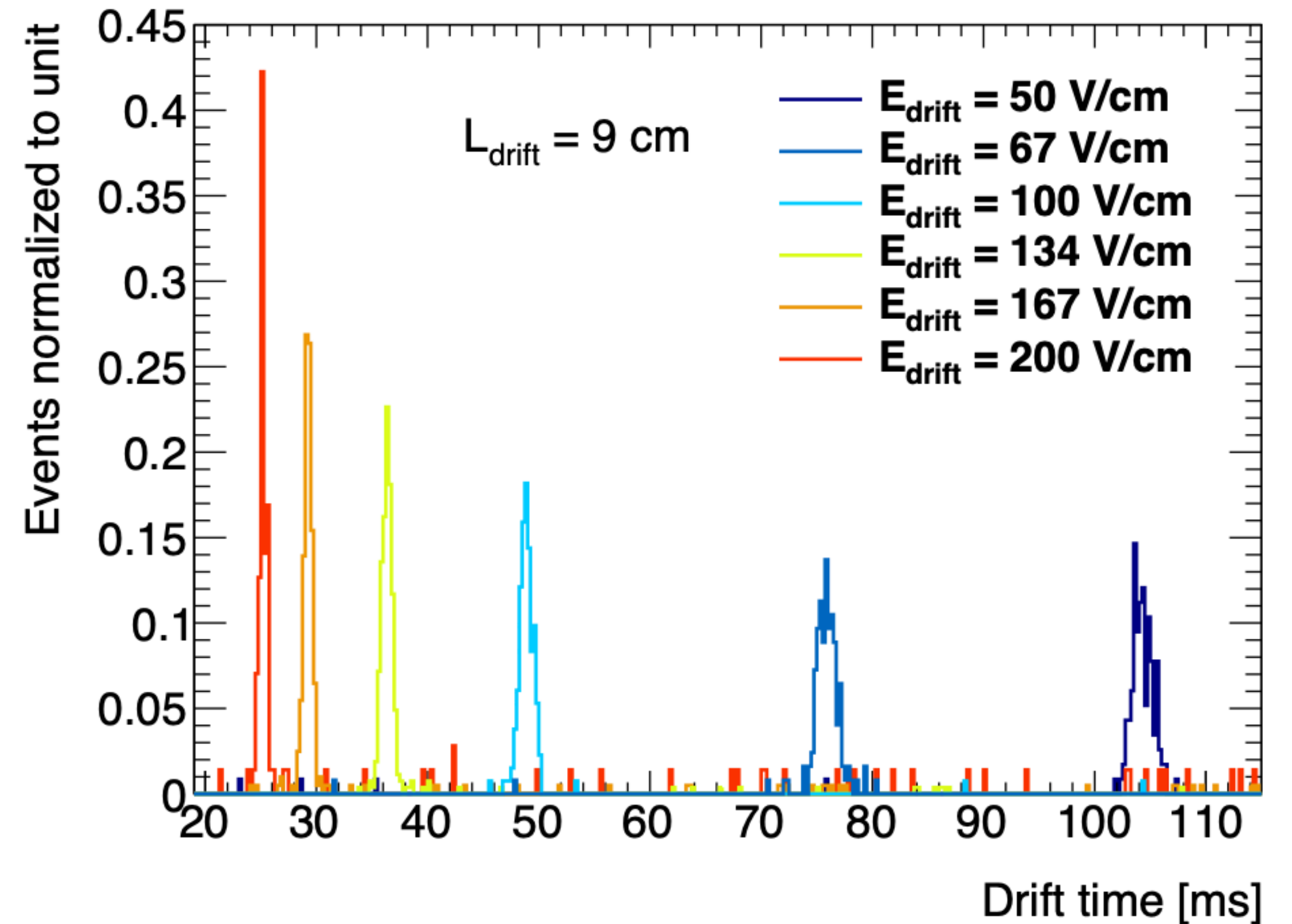


# 离子漂移速度测量

## 漂移时间



- 四个不同位置，六个不同电场强度。

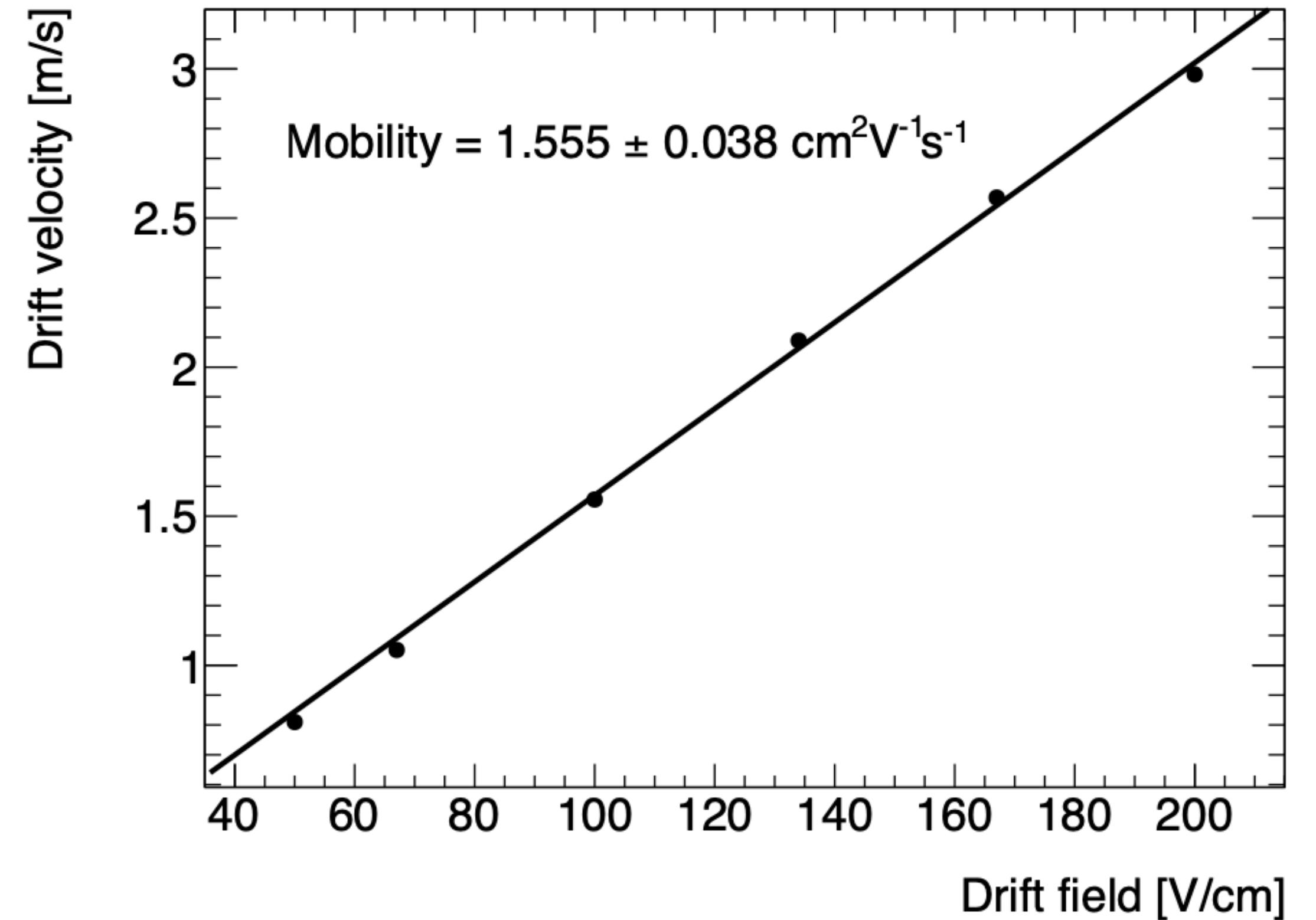
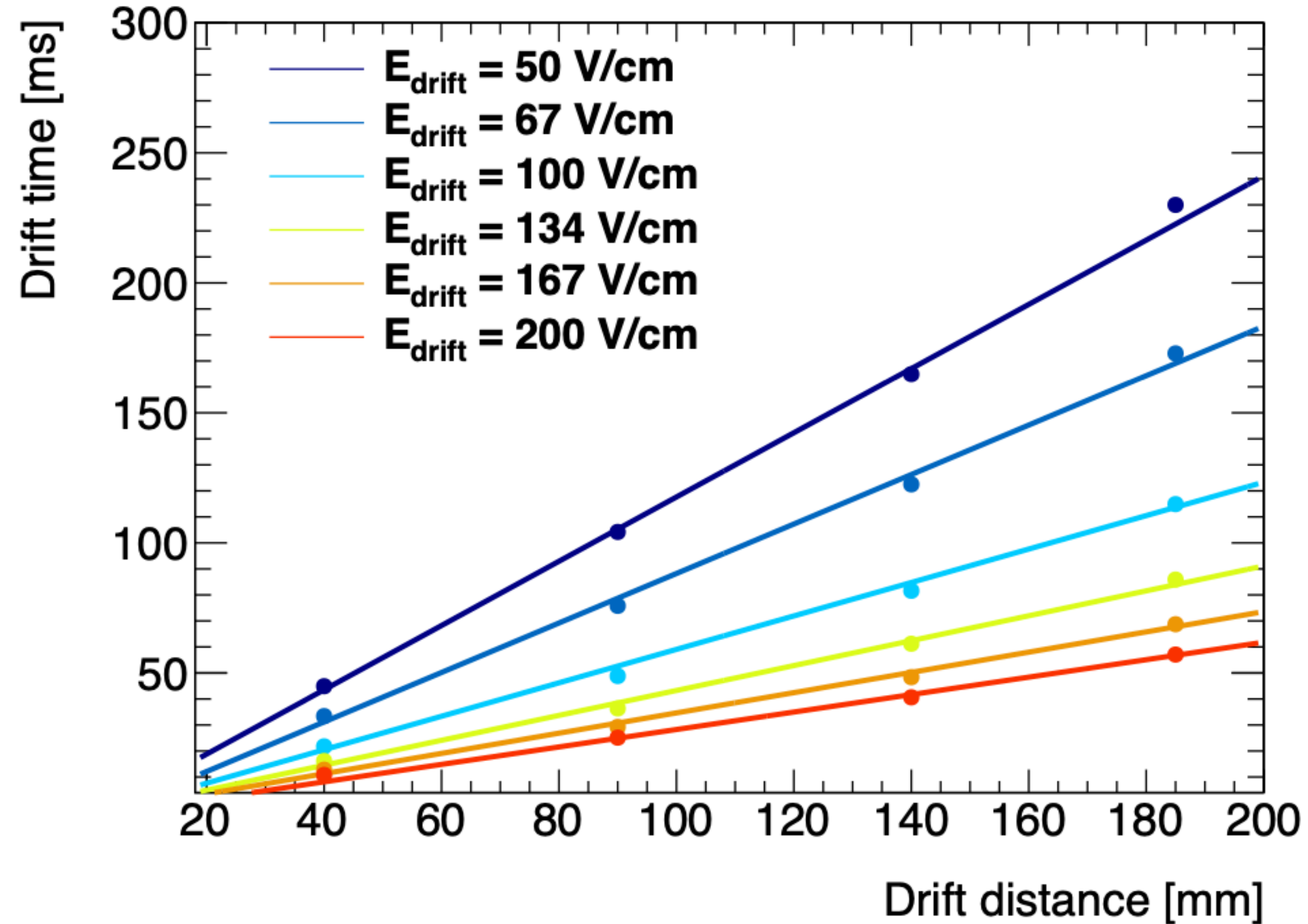


- 由于场笼间距以及高压纹波，电压无法加到很大

# 离子漂移速度测量

## 漂移速度和迁移率

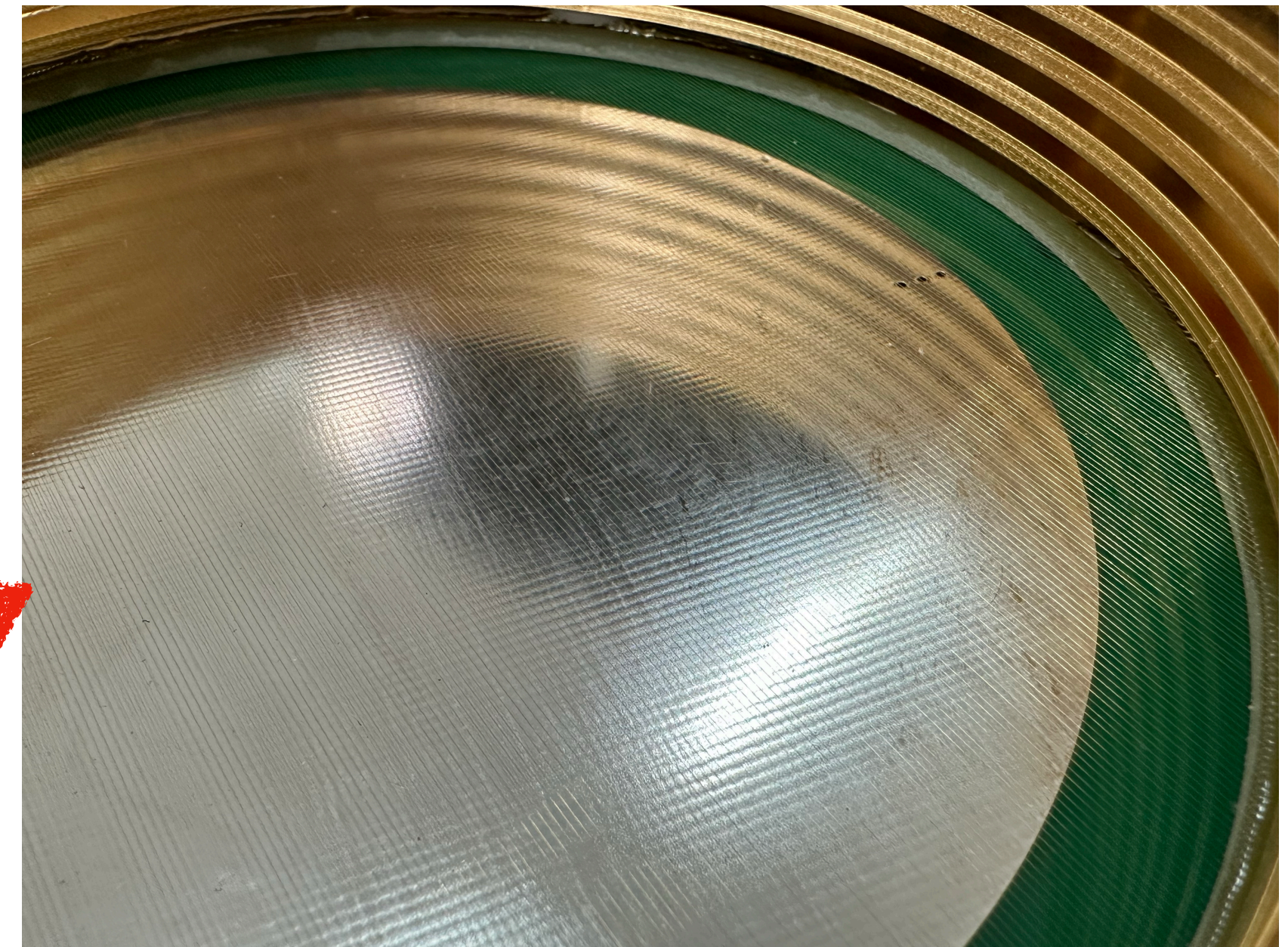
- 漂移速度：拟合距离-时间曲线
- 迁移率：拟合速度-电场强度曲线





# 屏栅电离室设计

## 基本结构

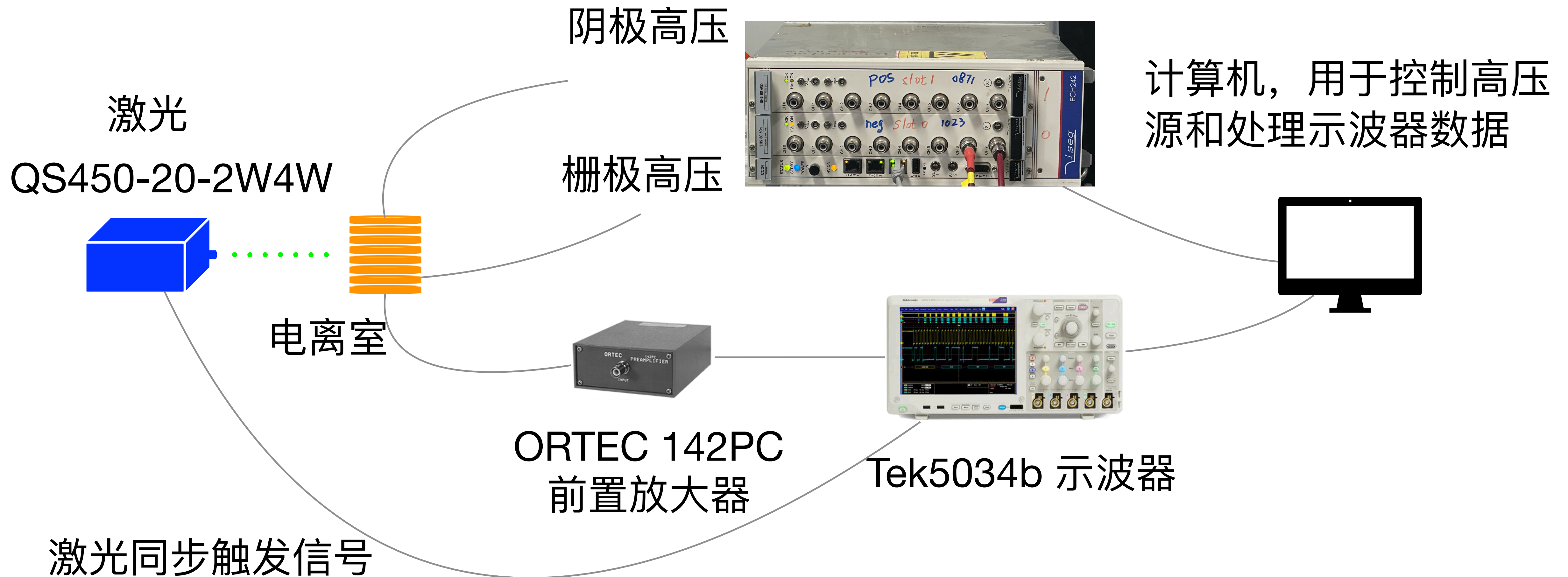


- 阴极与栅极间距3.6 cm，栅极与阳极间距2 mm。
- 场笼铜环之间焊接10 M $\Omega$ 电阻以确保场均匀



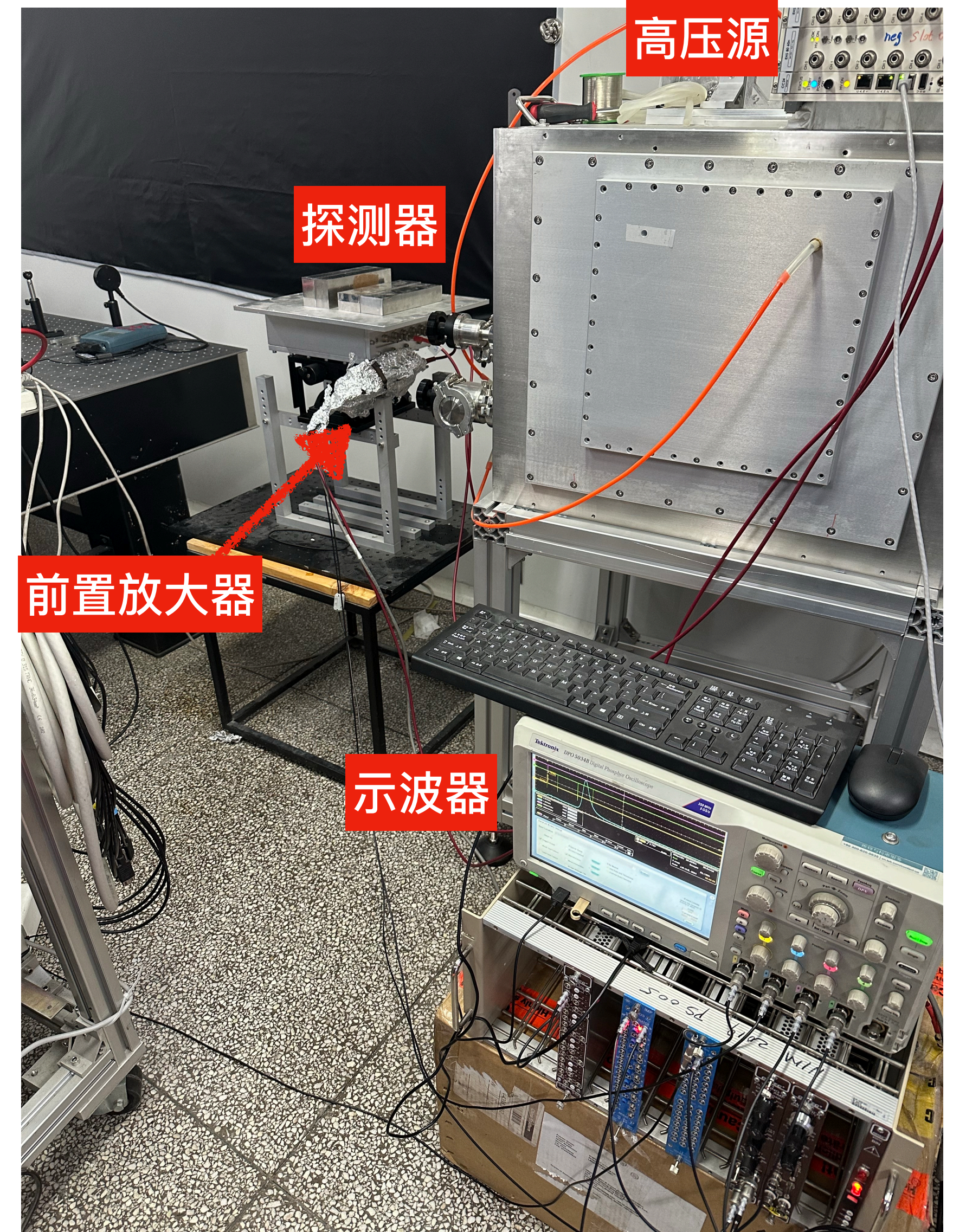
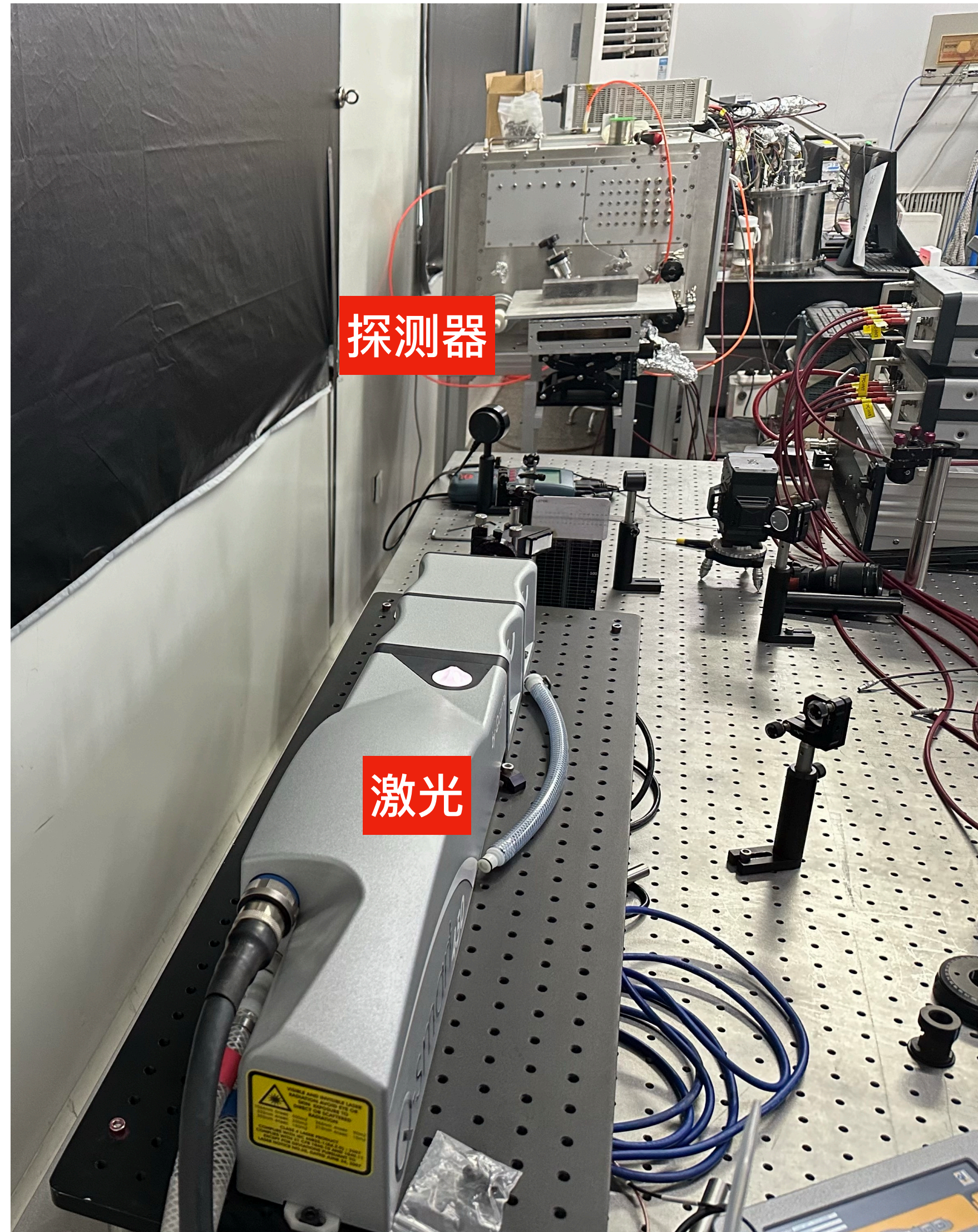
# 离子漂移速度测量

高压源 ISEG EHS8060 n/p





# 离子漂移速度测量

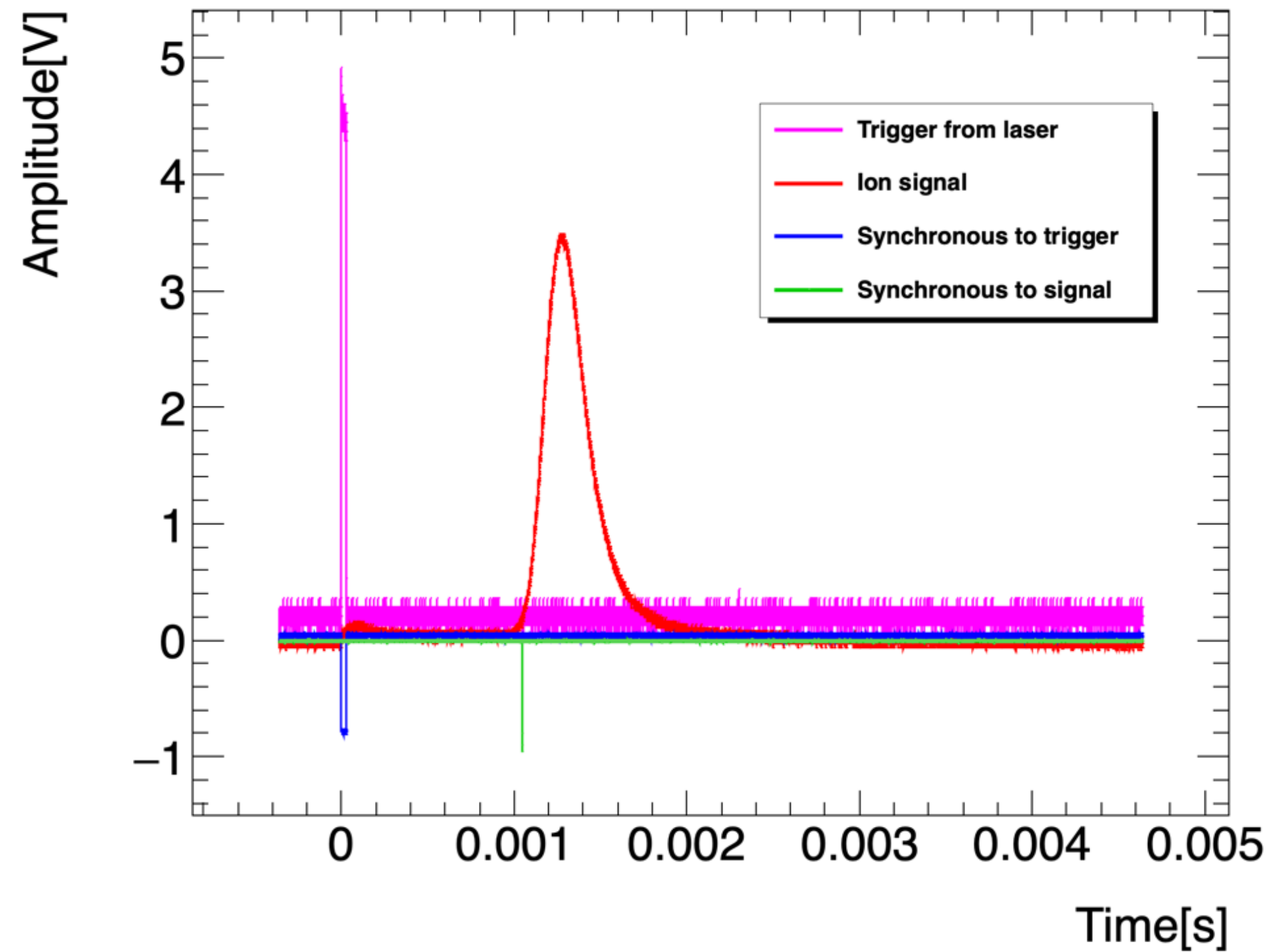




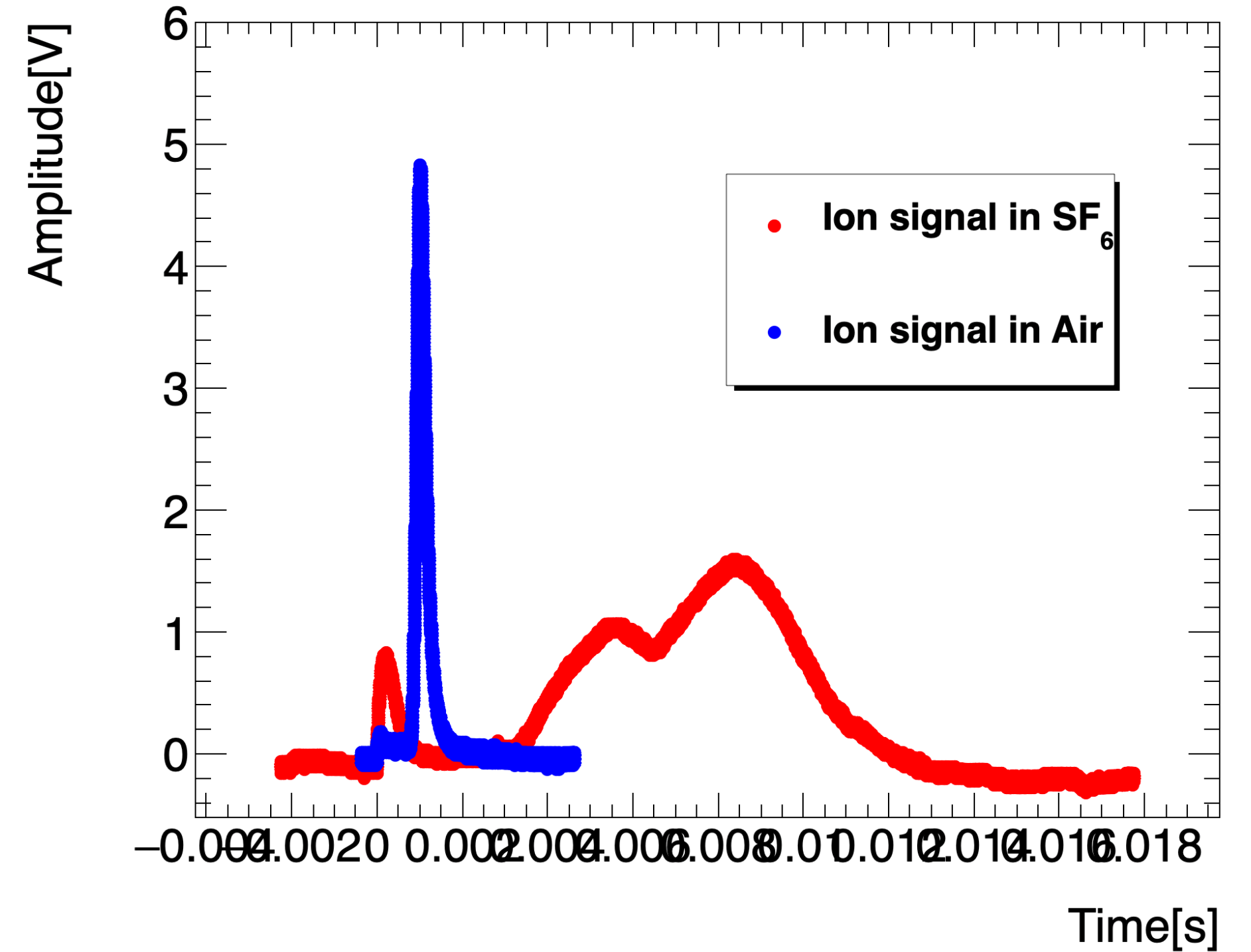
# 离子漂移速度测量

## 测量方法

空气中离子信号波形示例



相近的漂移电场下的不同气体离子波形信号



- 时间 ( $\Delta t$ ) : 两个不同位置下信号时间差
- 距离 ( $\Delta d$ ) : 利用升降平台调整的两个位置间距



# 离子漂移速度测量

分析方法

空气

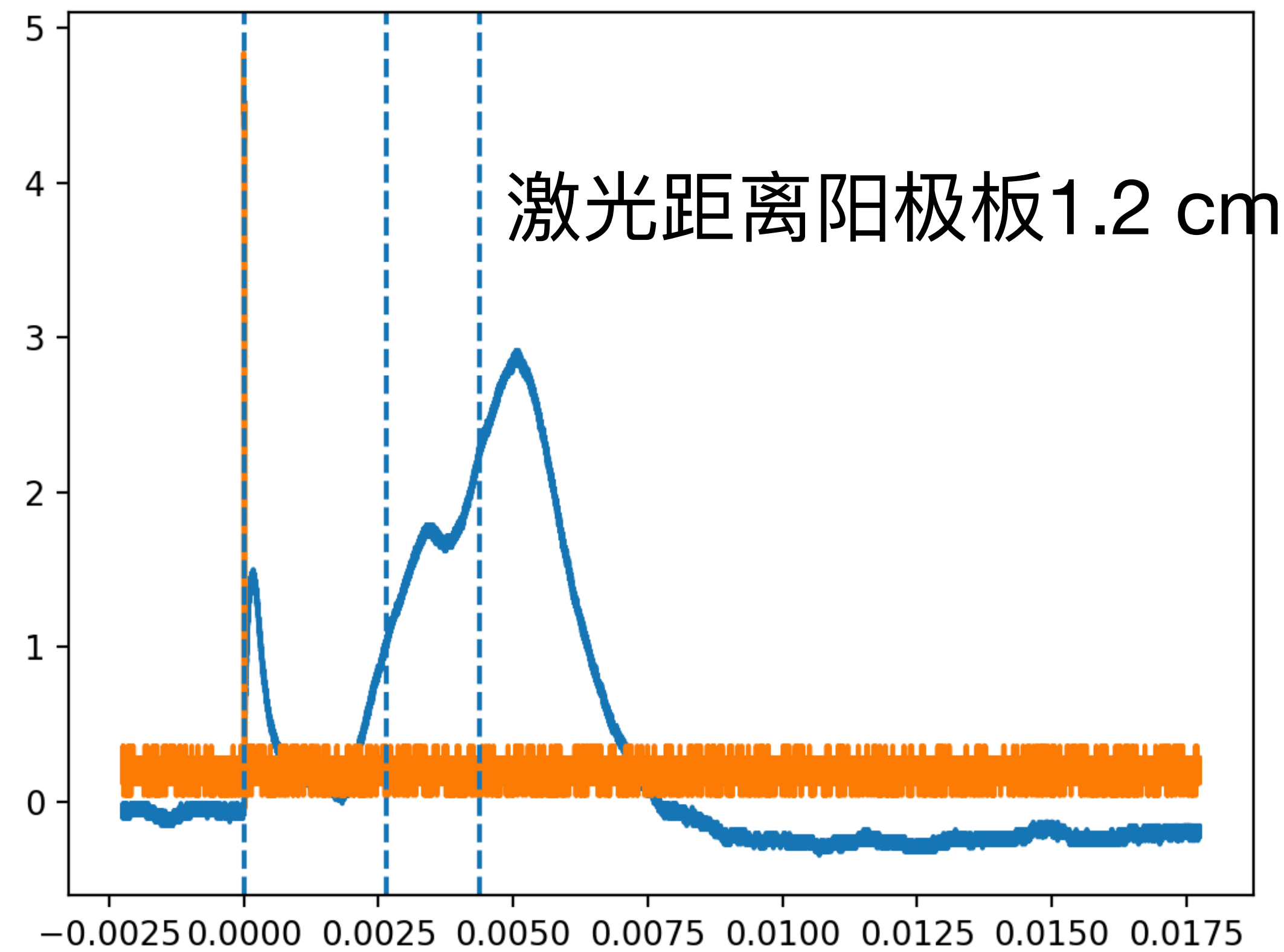
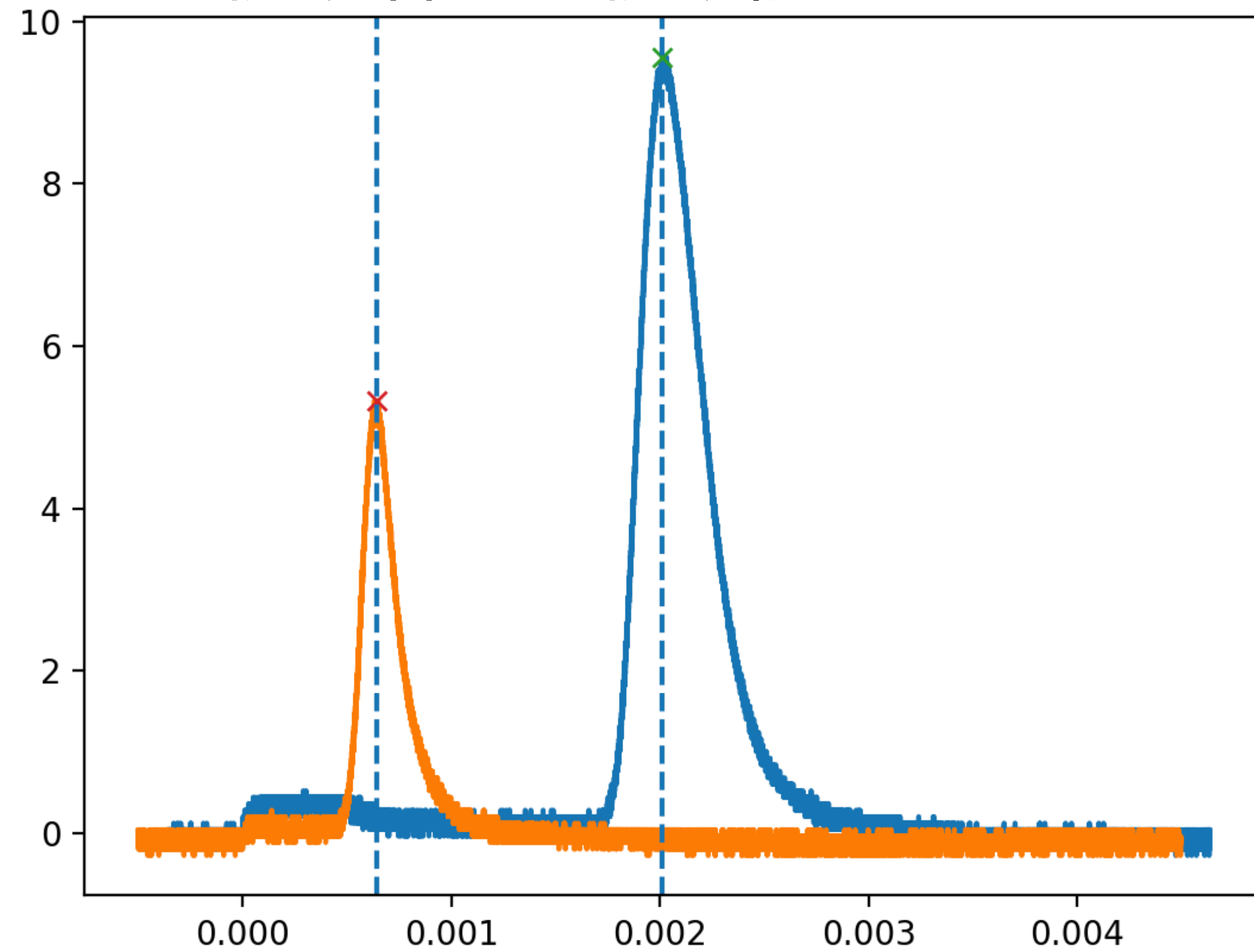
六氟化硫

移动后

移动前

触发时间

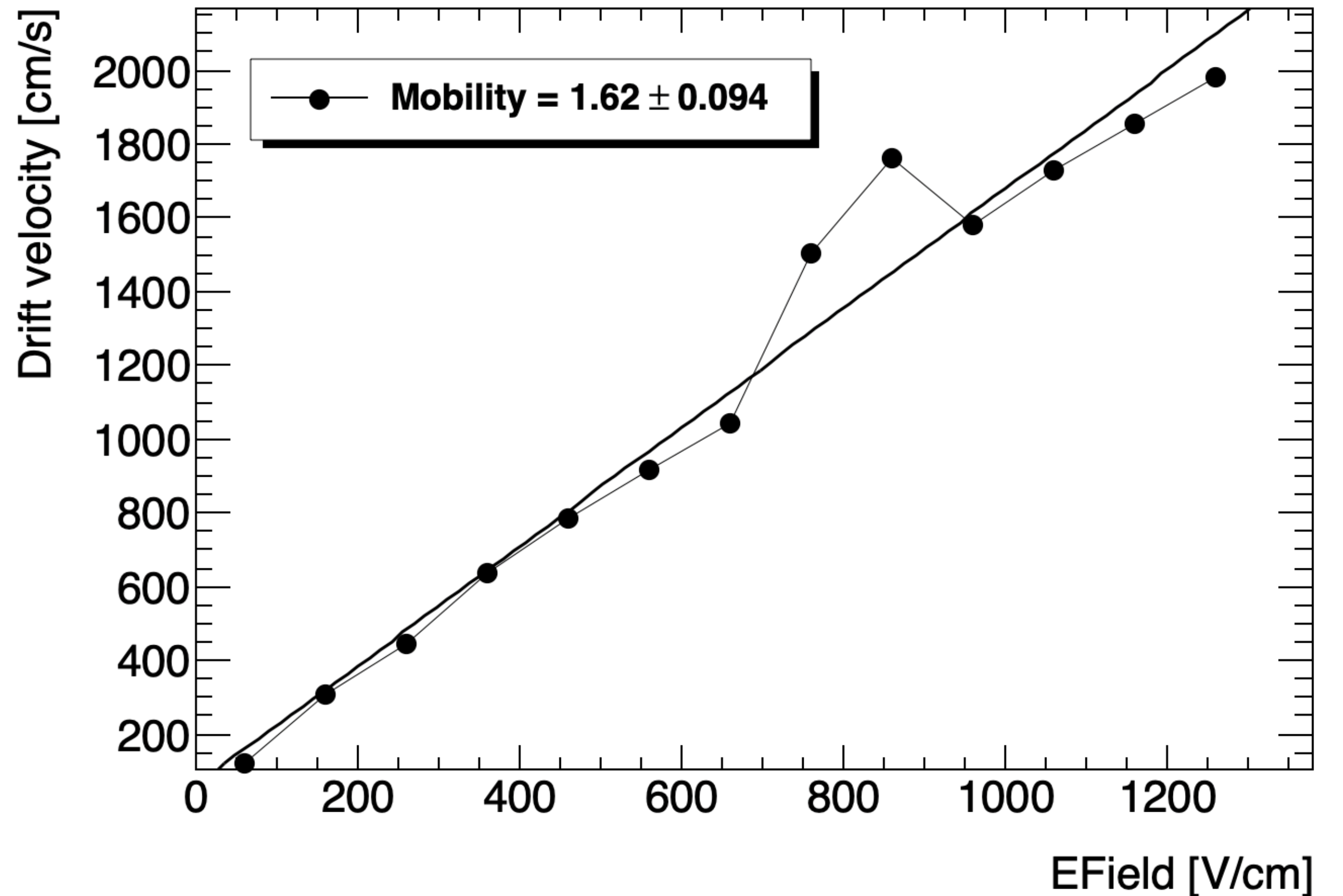
激光距离阳极板1.2 cm



# 离子漂移速度测量

## 迁移率结果

- 空气中电负性气体主要有水蒸气和氧气。但是二者不容易分开，所以空气的迁移率受环境影响很大。
- 在兰州测试条件（气压840 mbar, 293 K）下，空气的迁移率大约为  $1.62 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$

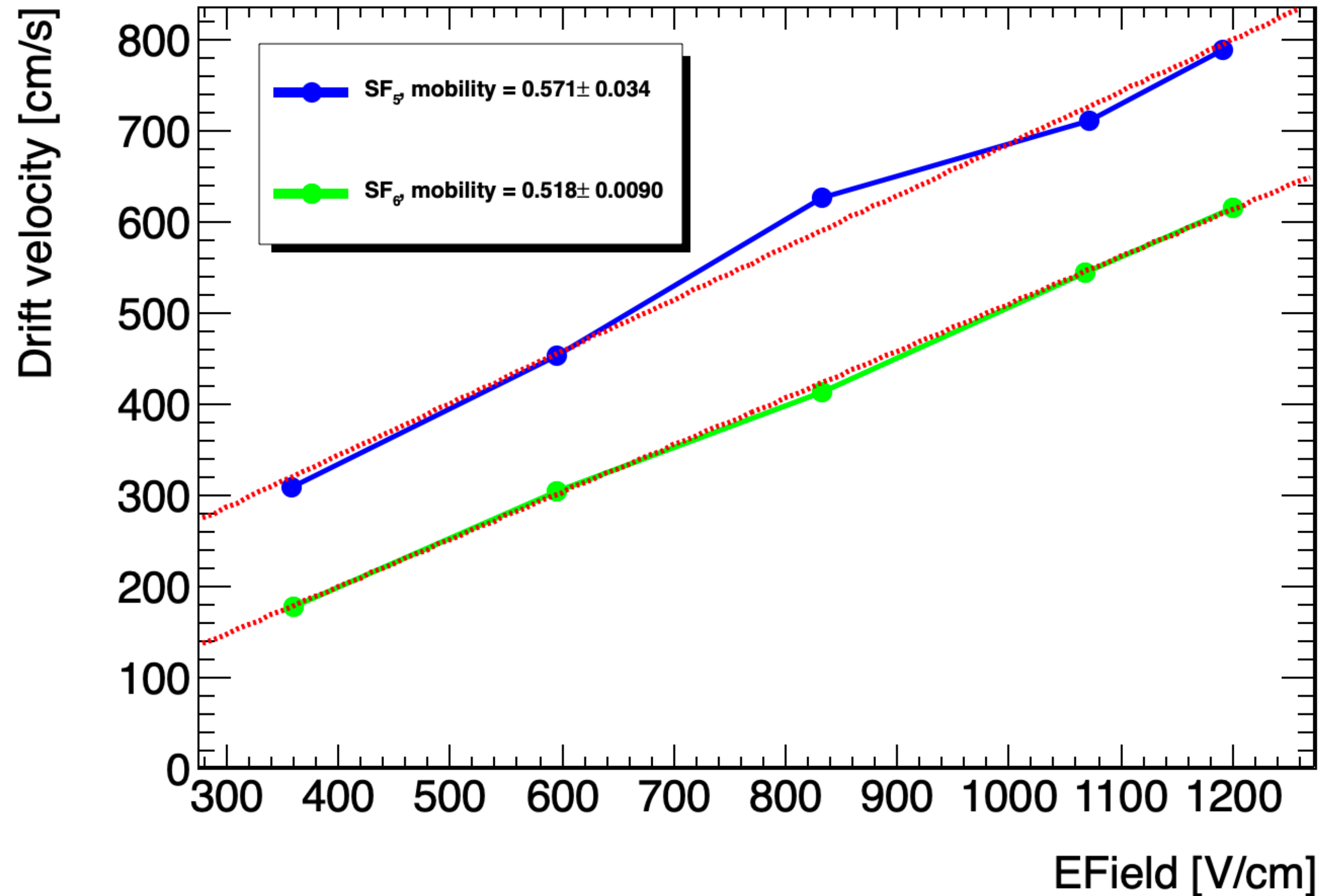




# 离子漂移速度测量

## 迁移率结果

- 六氟化硫中 $SF_5^-$ 与 $SF_6^-$ 为主要离子
- $SF_5^-$ 离子迁移率为 $0.57 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$  (**0.595**)
- $SF_6^-$ 离子迁移率为 $0.52 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$  (**0.542**)



P. L. Patterson; Mobilities of Negative Ions in  $SF_6$ . *J. Chem. Phys.* 15 July 1970; 53 (2): 696–704. <https://doi.org/10.1063/1.1674047>



# 总结

- 利用N $\nu$ DEx电荷探测与读出单元研究了Topmetal-S芯片对的空气和SF6气体中离子信号的响应，以及空气中负离子的迁移率，与文献相符。
- 利用激光，我们成功在小型电离室里面看到了离子信号并测量了空气和SF6中离子迁移率，与文献相符。
- 在屏栅电离室中测量的 $SF_5^-$ 离子迁移率为 $0.57 \text{ cm}^2 \cdot V^{-1} \cdot s^{-1}$ ， $SF_6^-$ 离子迁移率为 $0.52 \text{ cm}^2 \cdot V^{-1} \cdot s^{-1}$ ，后续将进一步细化误差分析。
- 下一步将进行扩散系数、法诺因子、重组率等研究，以及 $SeF_6$ 气体的研究。



**Backup**

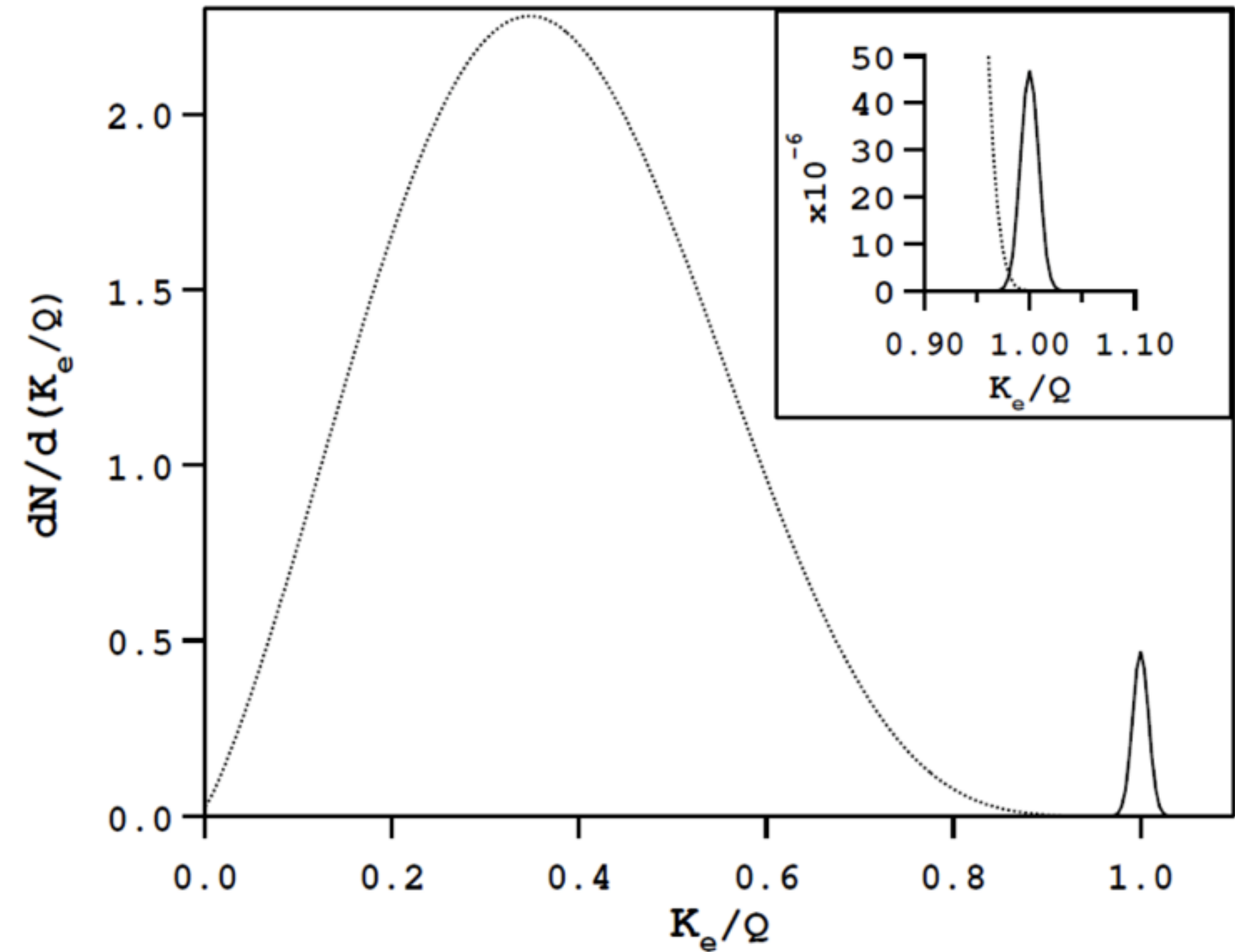


# 无中微子双贝塔衰变实验半衰期灵敏度

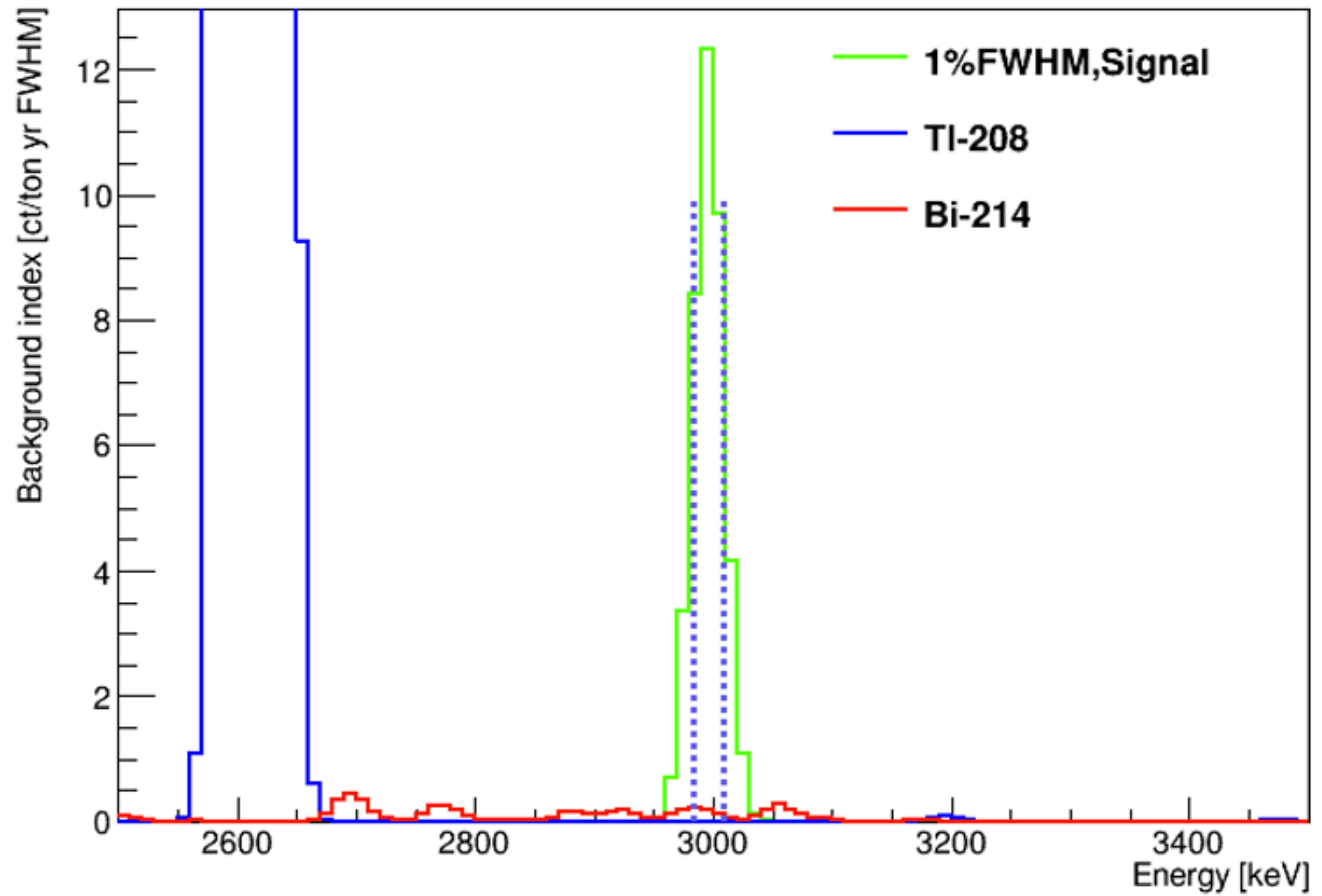
- 信号在双贝塔衰变Q值附近

- $T_{1/2}^{0\nu 2\beta} \propto \begin{cases} aMt(\text{无本底}) \\ a\epsilon\sqrt{\frac{Mt}{B\Delta E}}(\text{有本底}) \end{cases}$

- 已知半衰期下限大于 $10^{26}$ 年  
(arXiv:1605.02889)

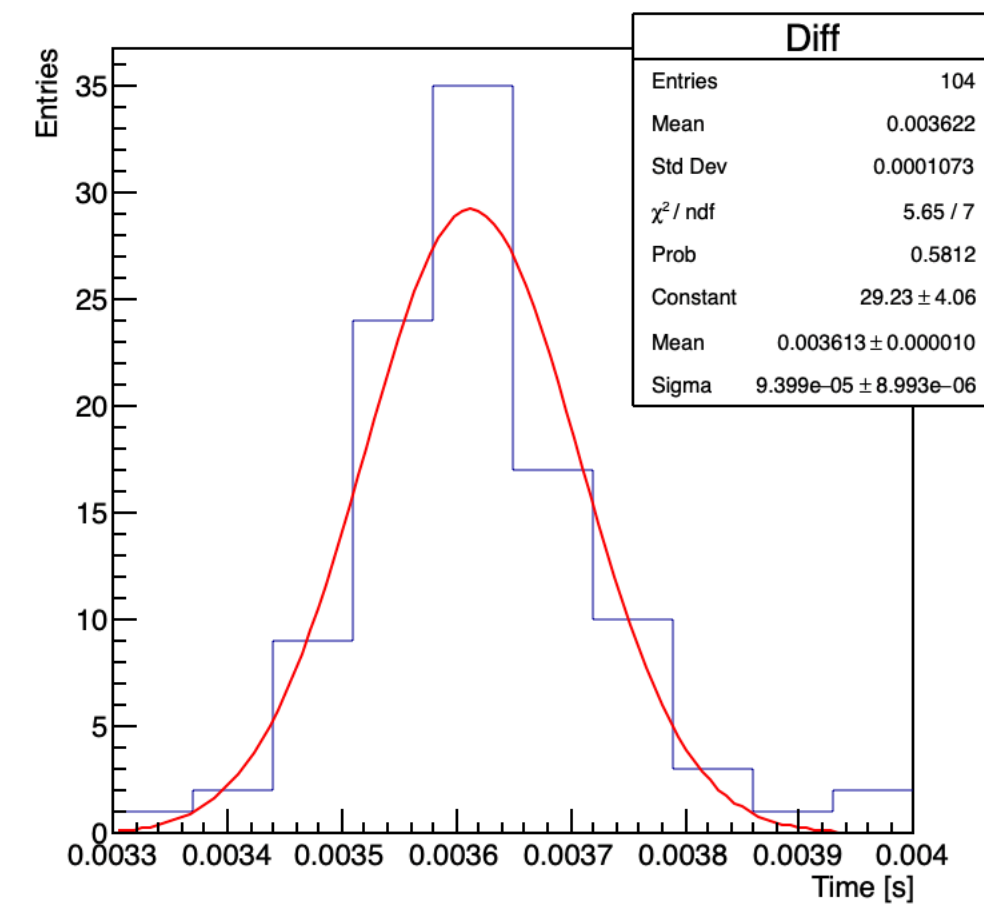
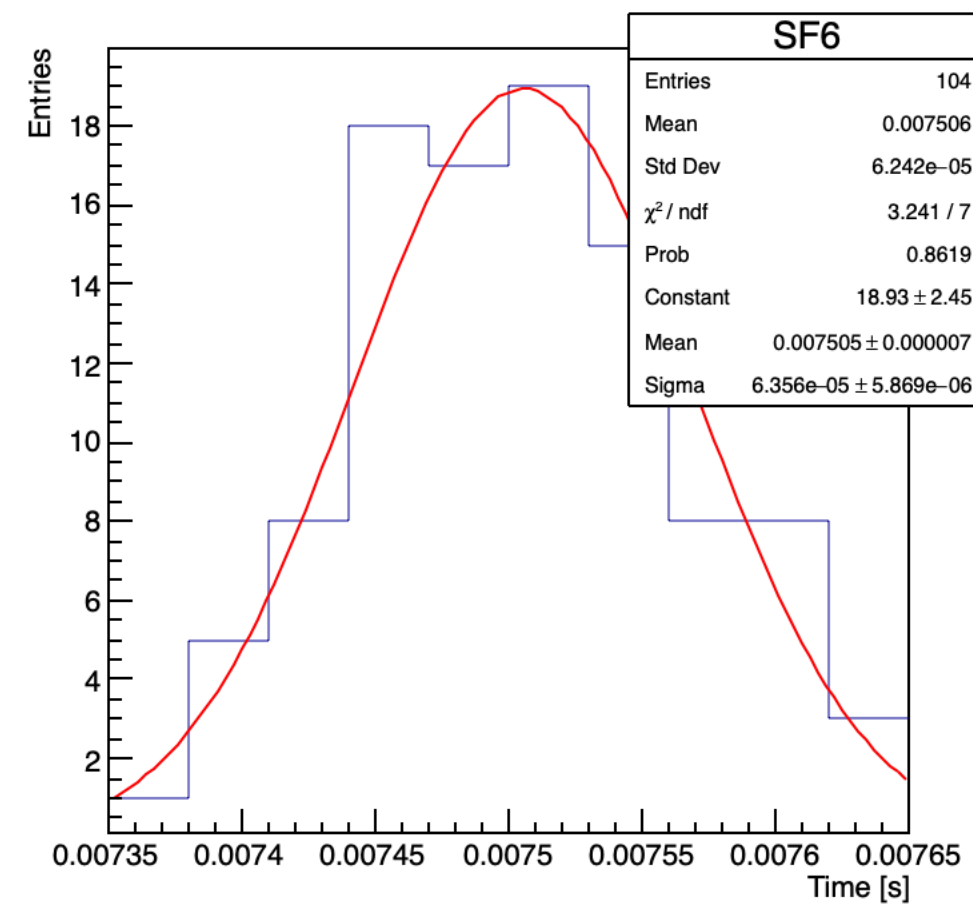
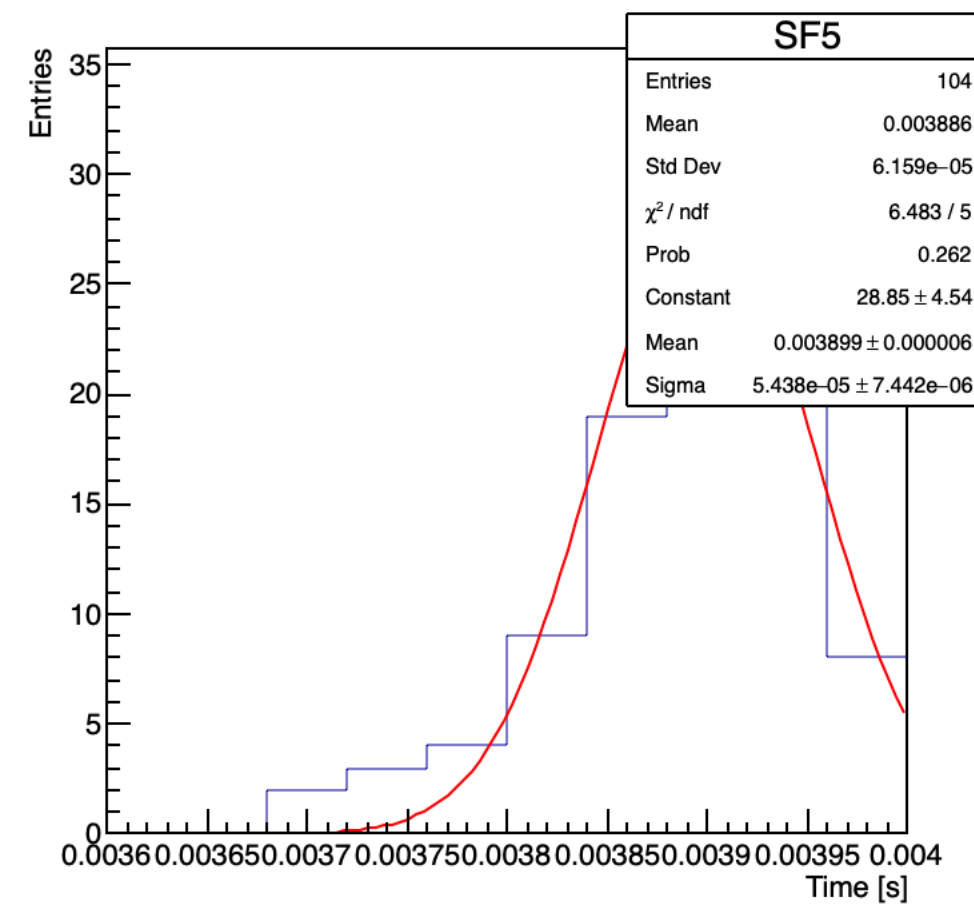




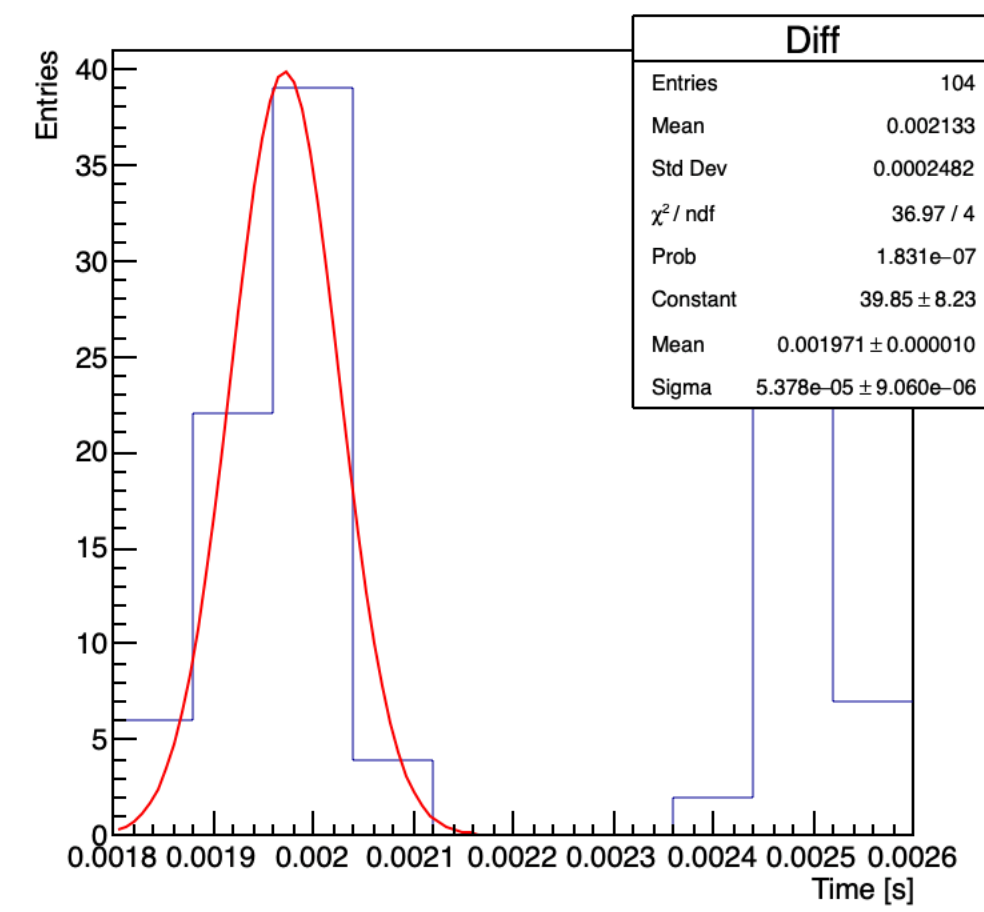
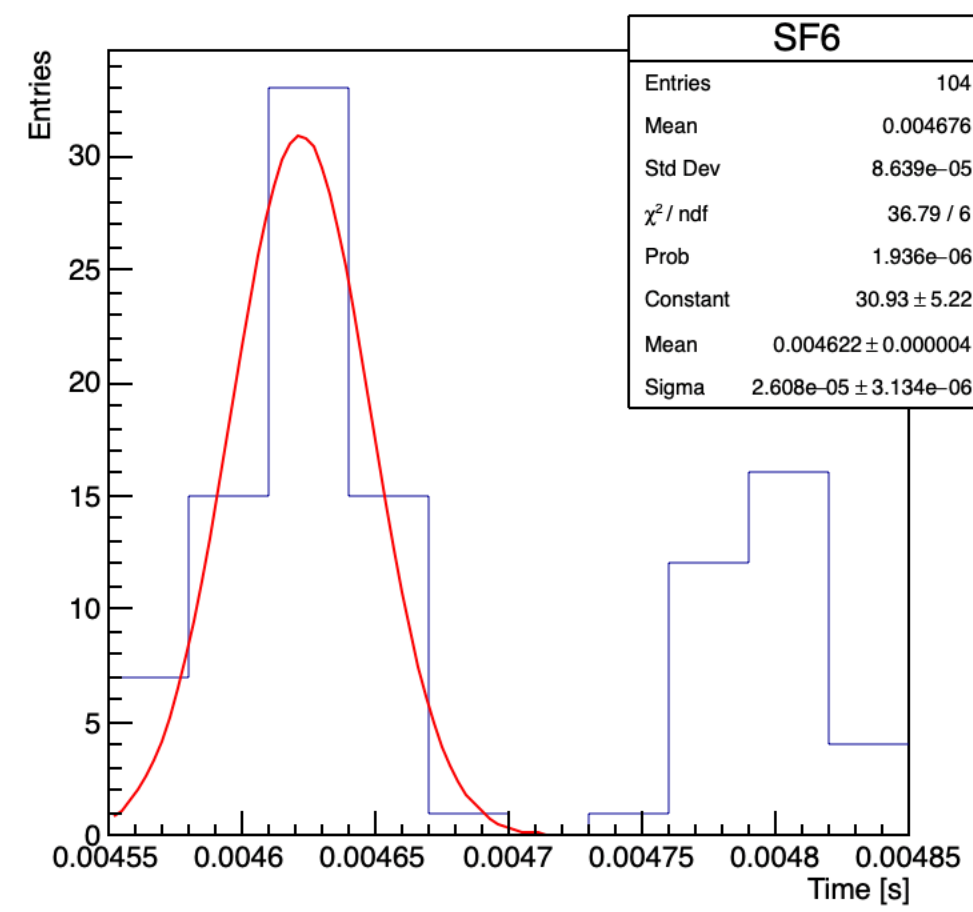
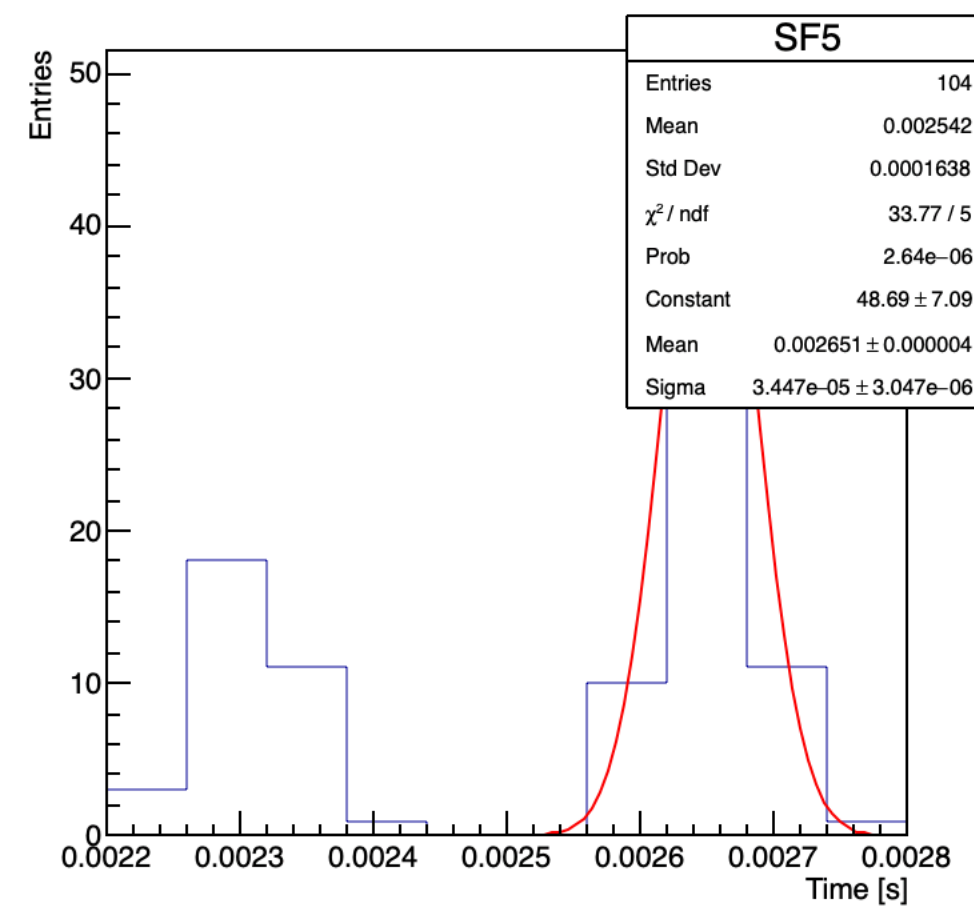




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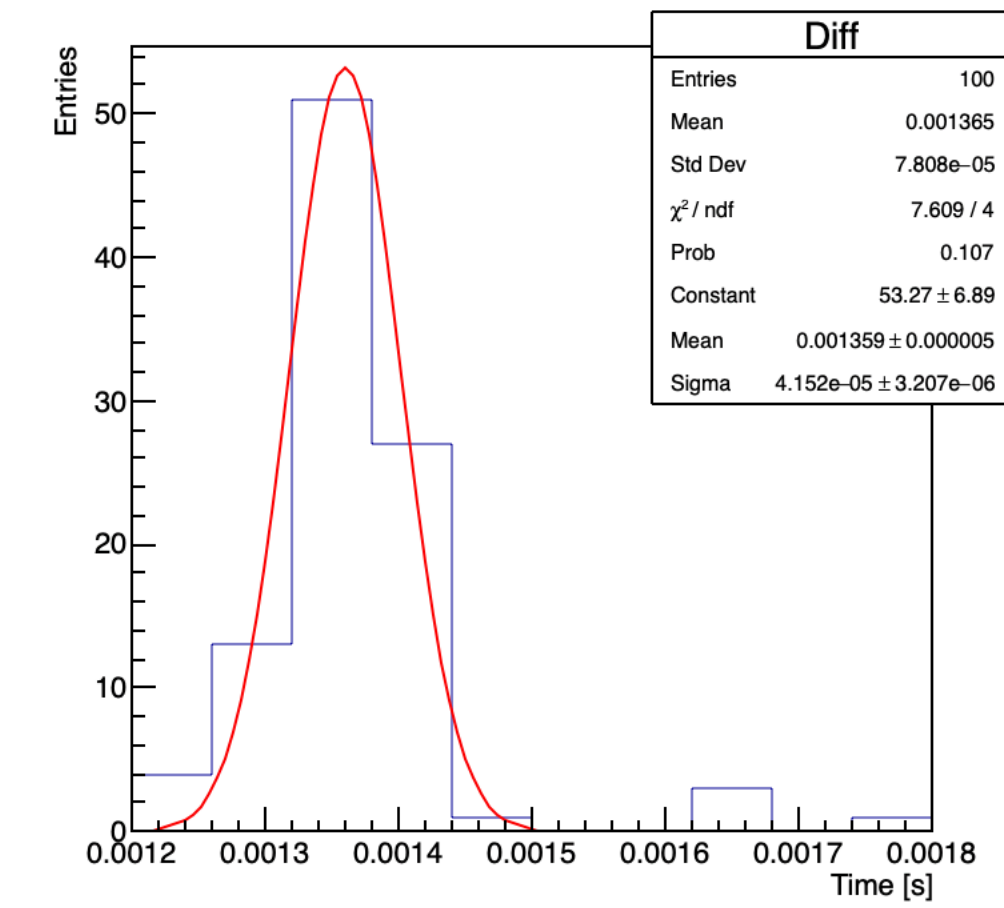
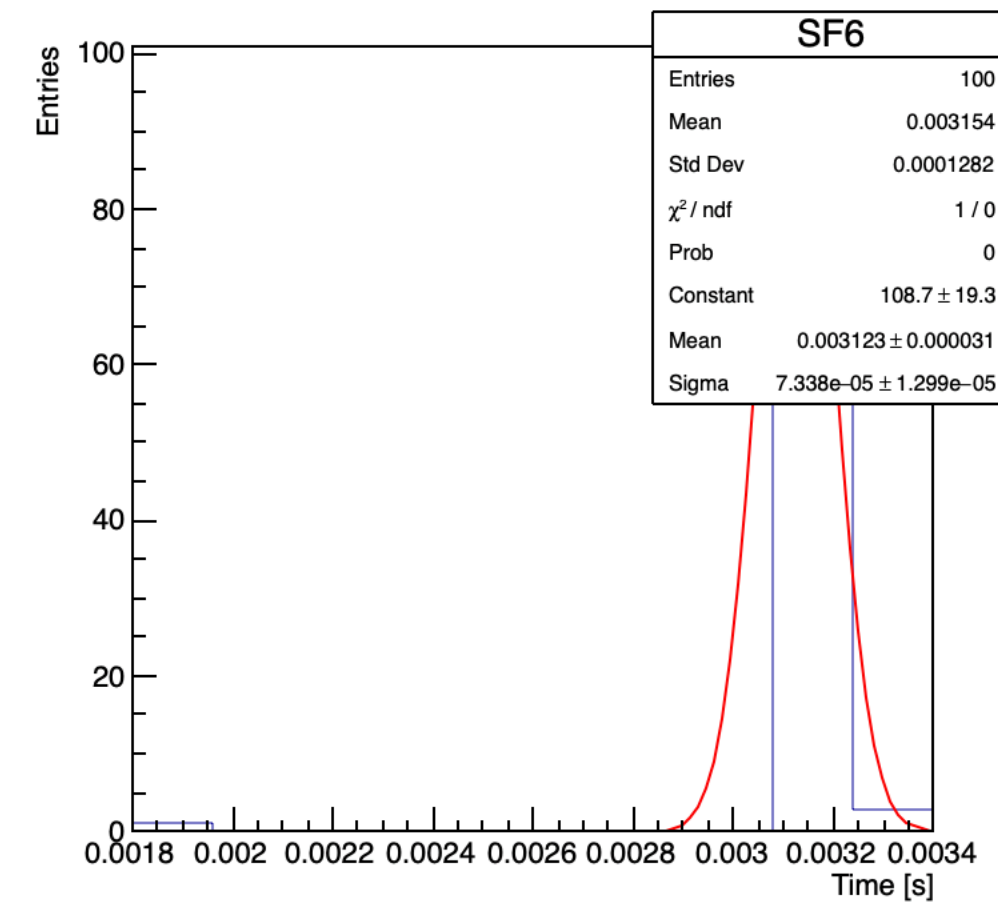
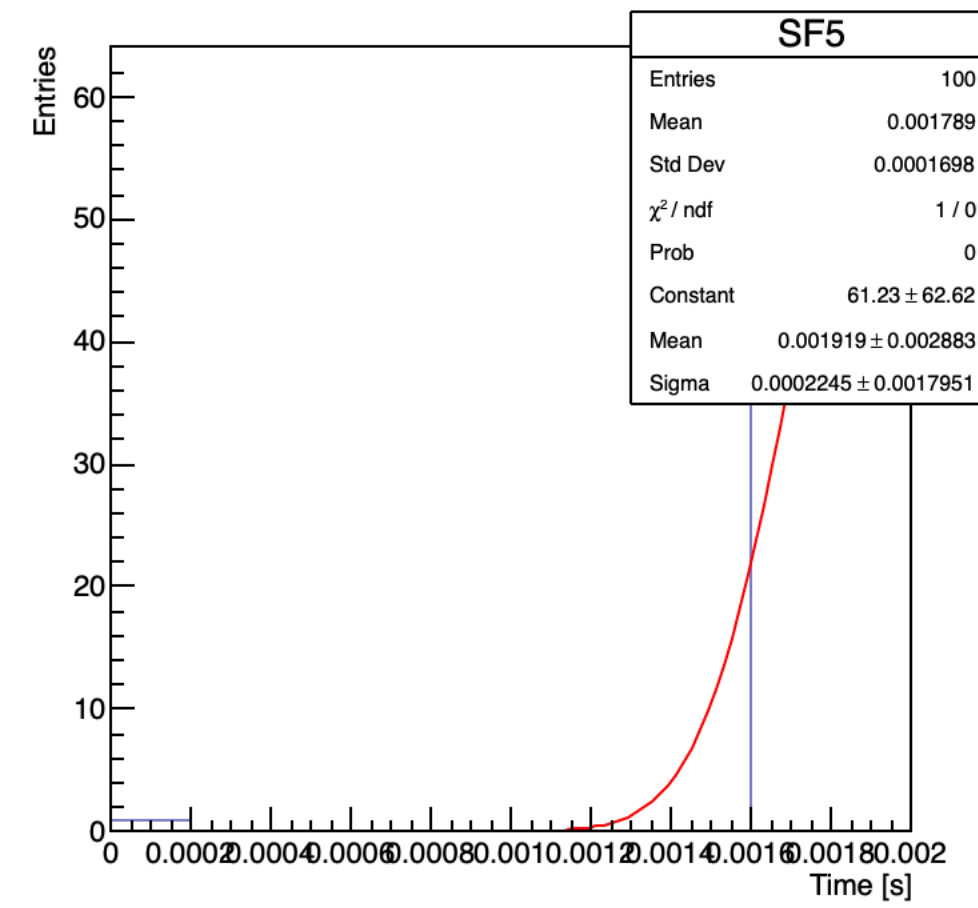


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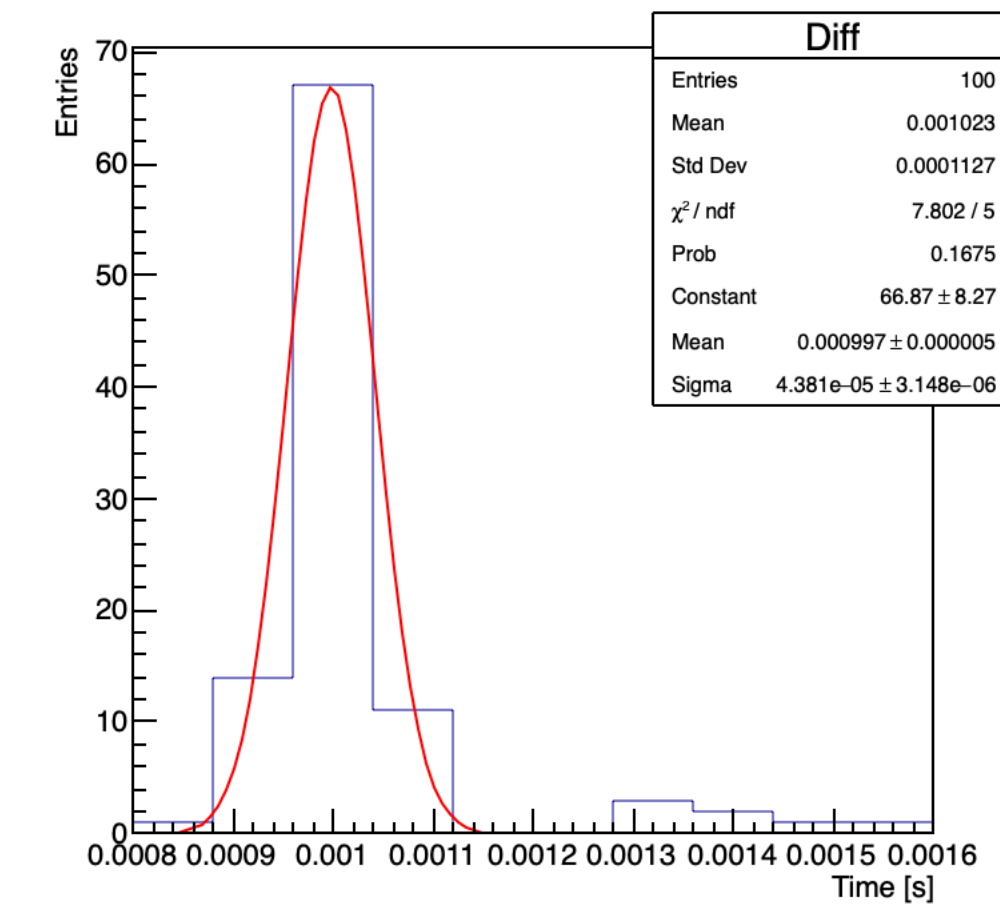
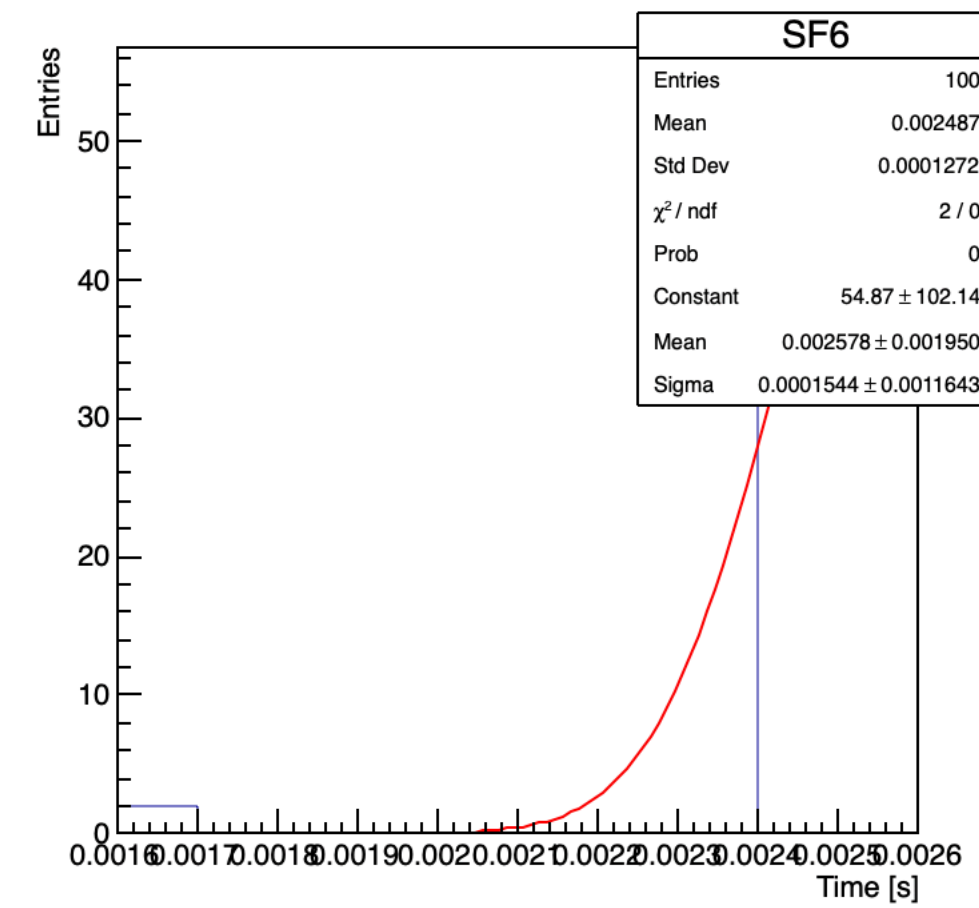
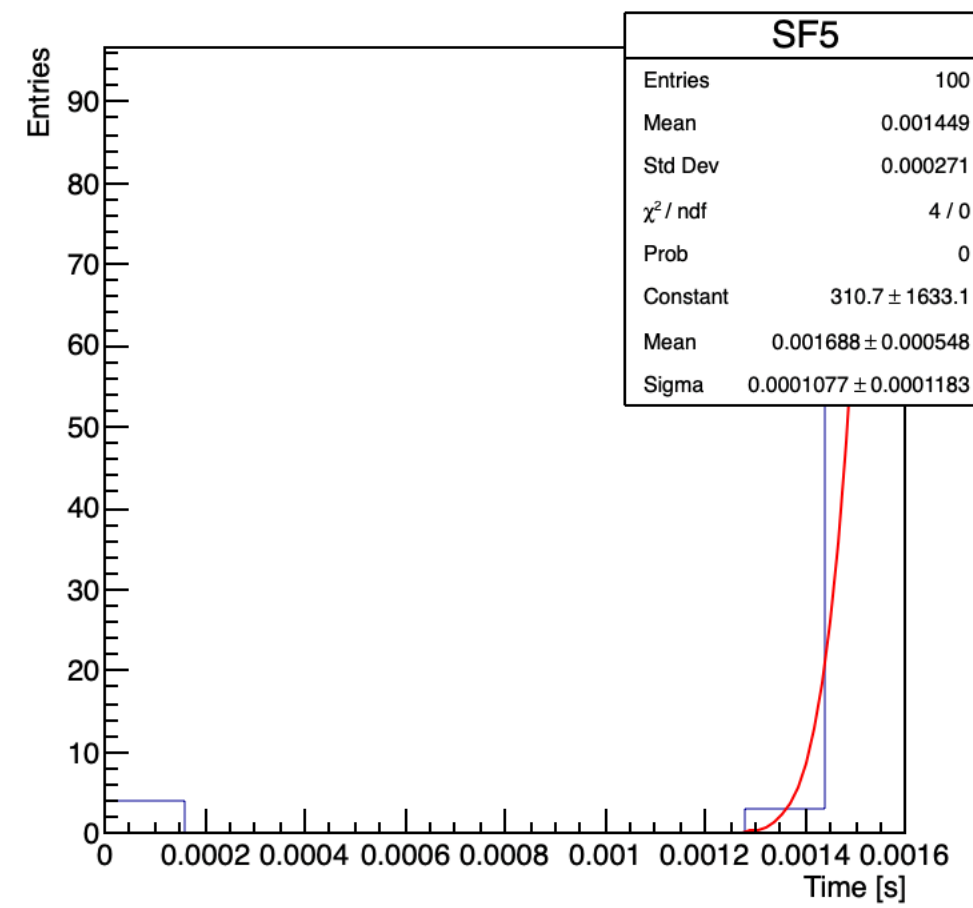




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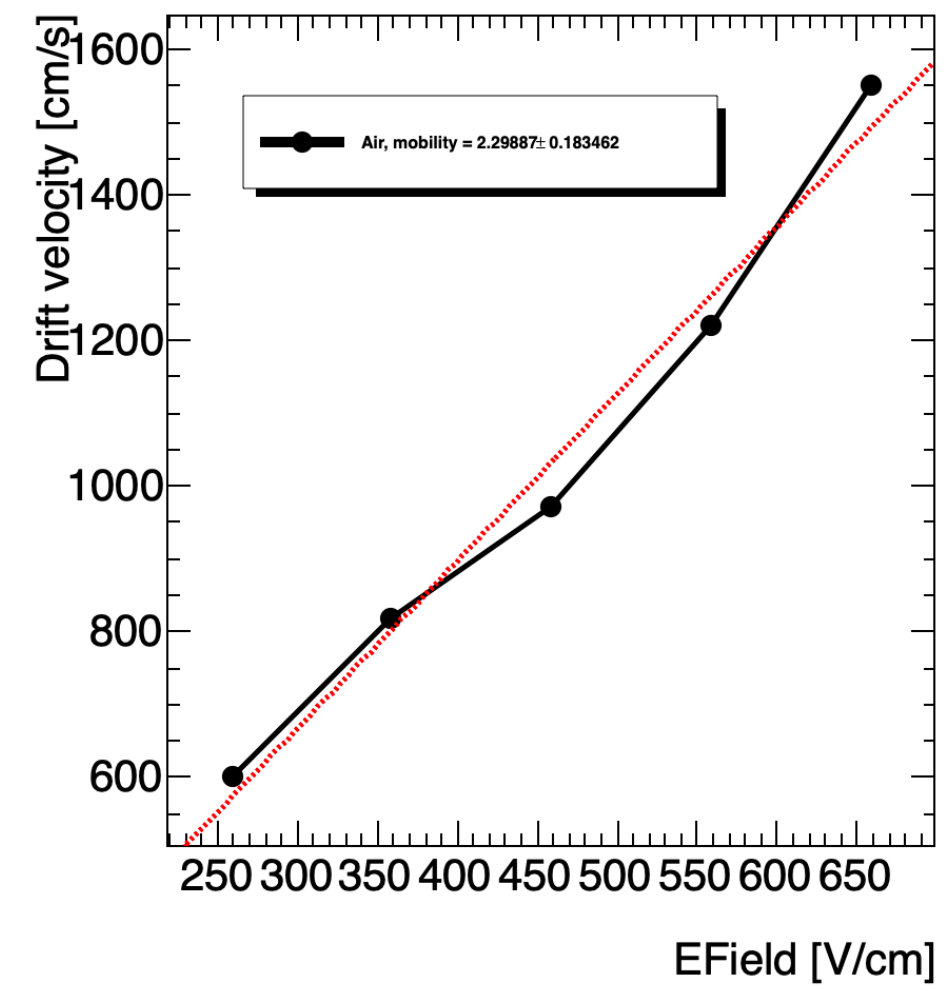
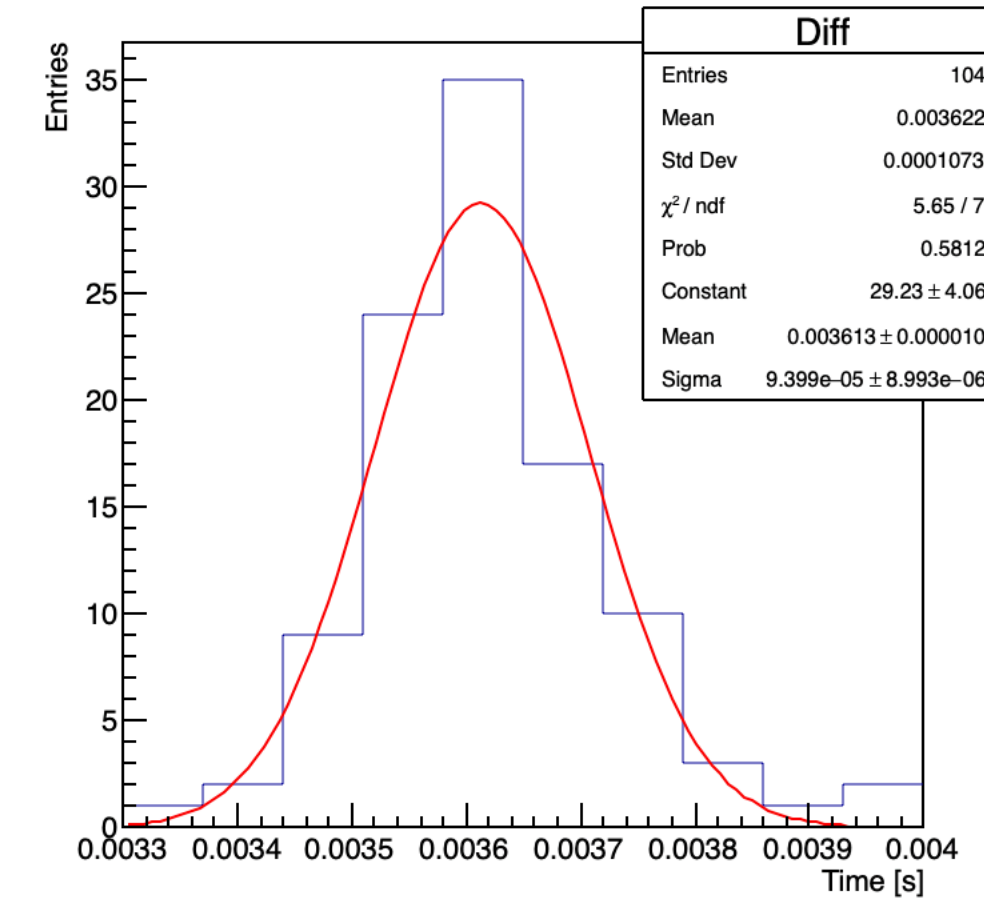
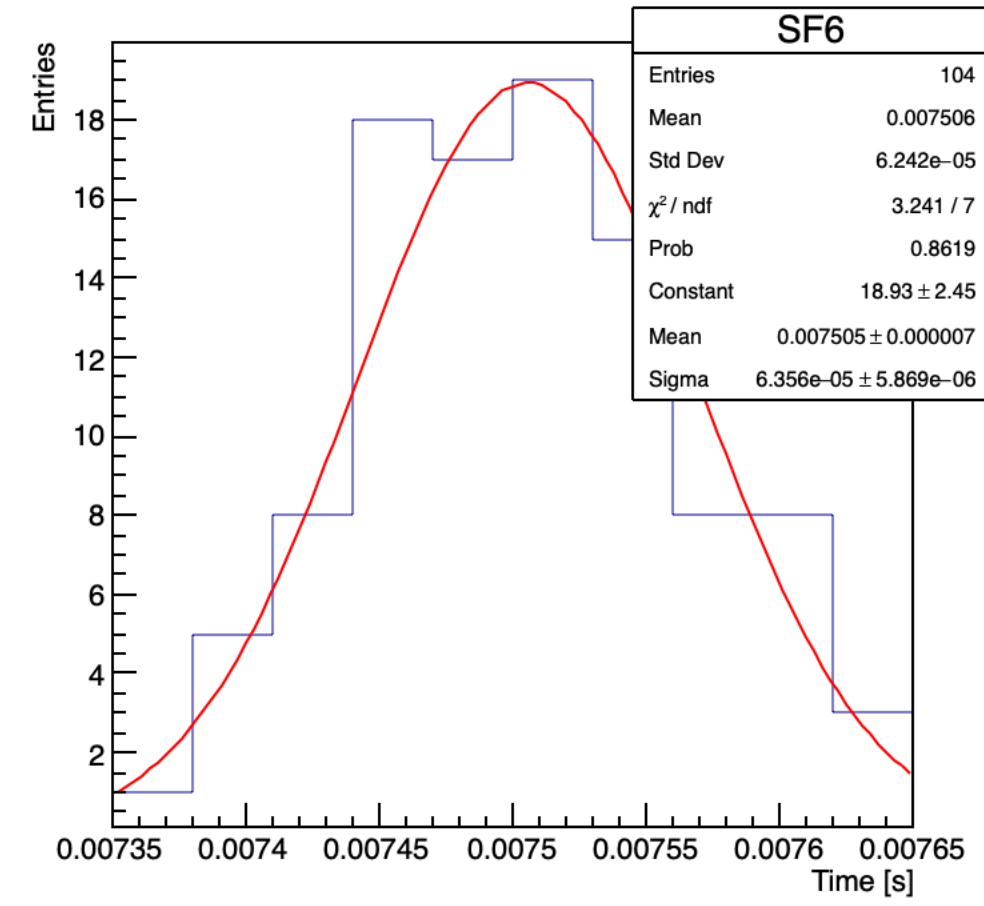
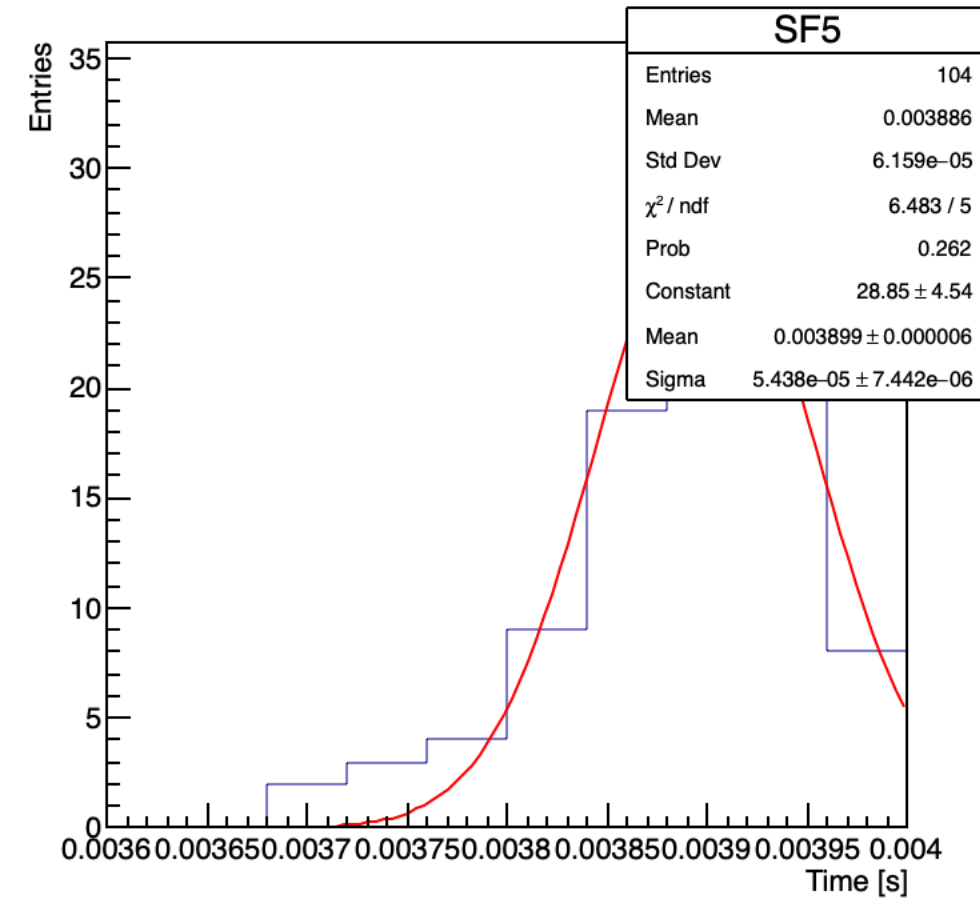


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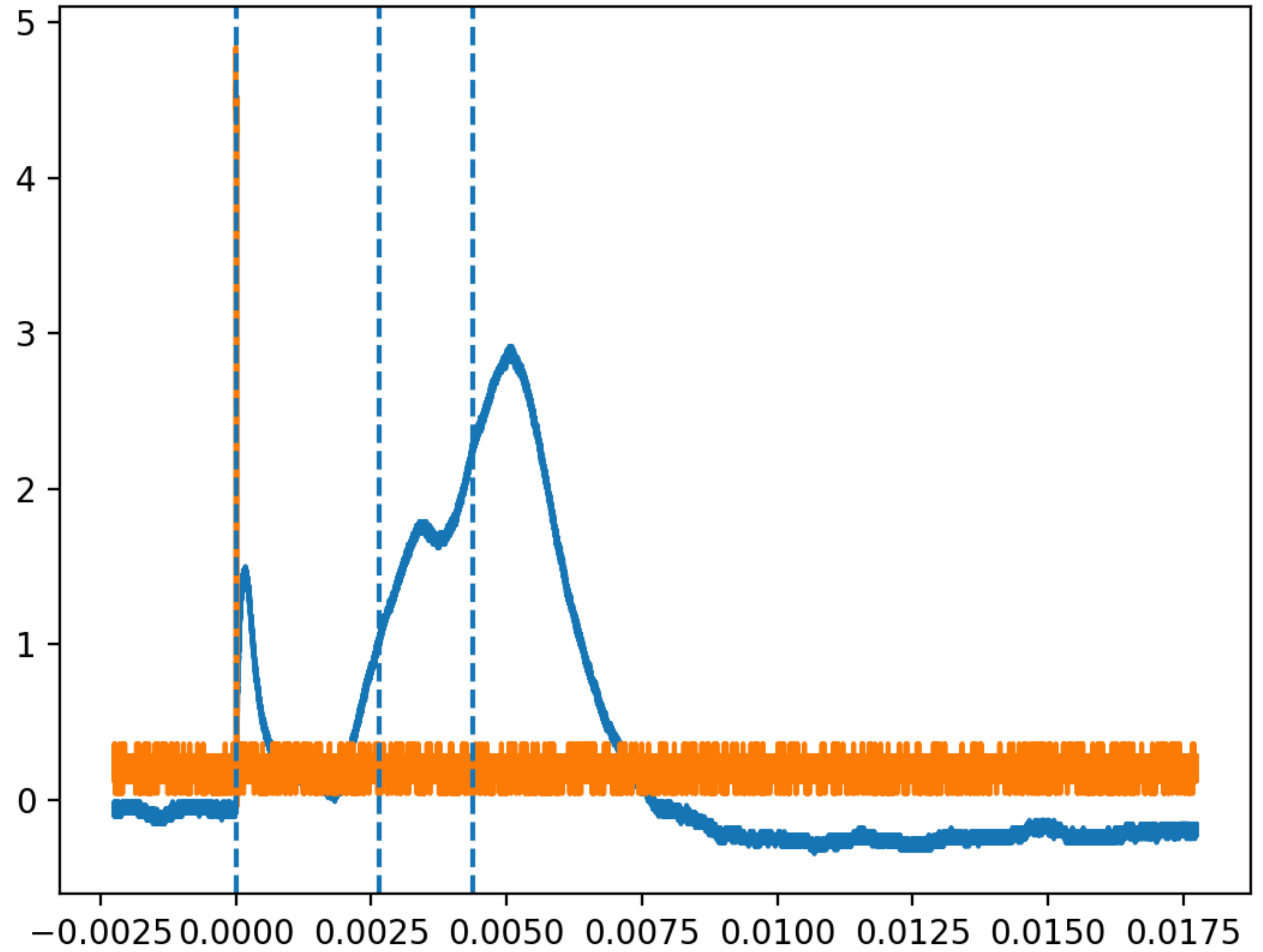


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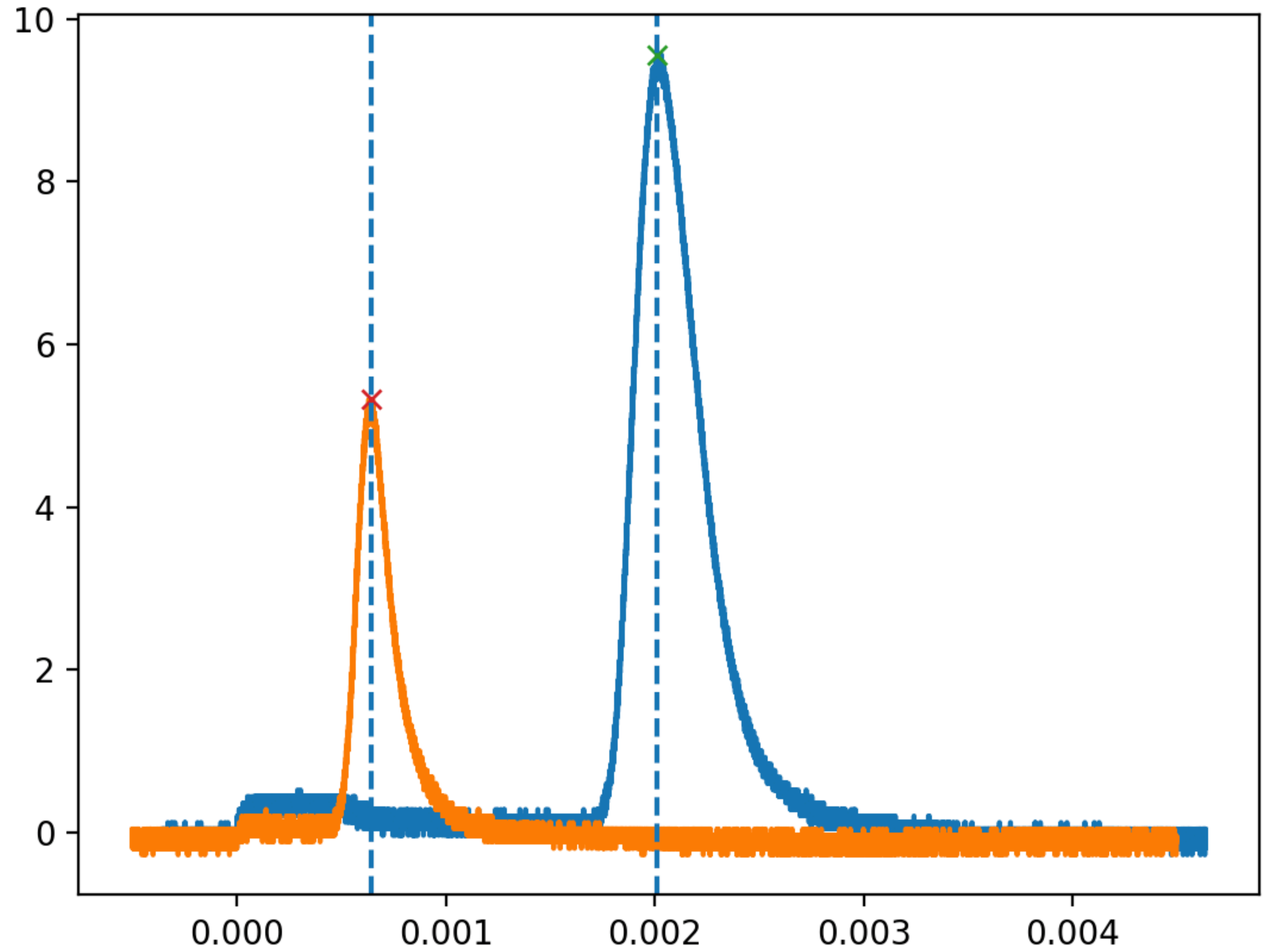


# SF6 analysis example





# Air analysis example



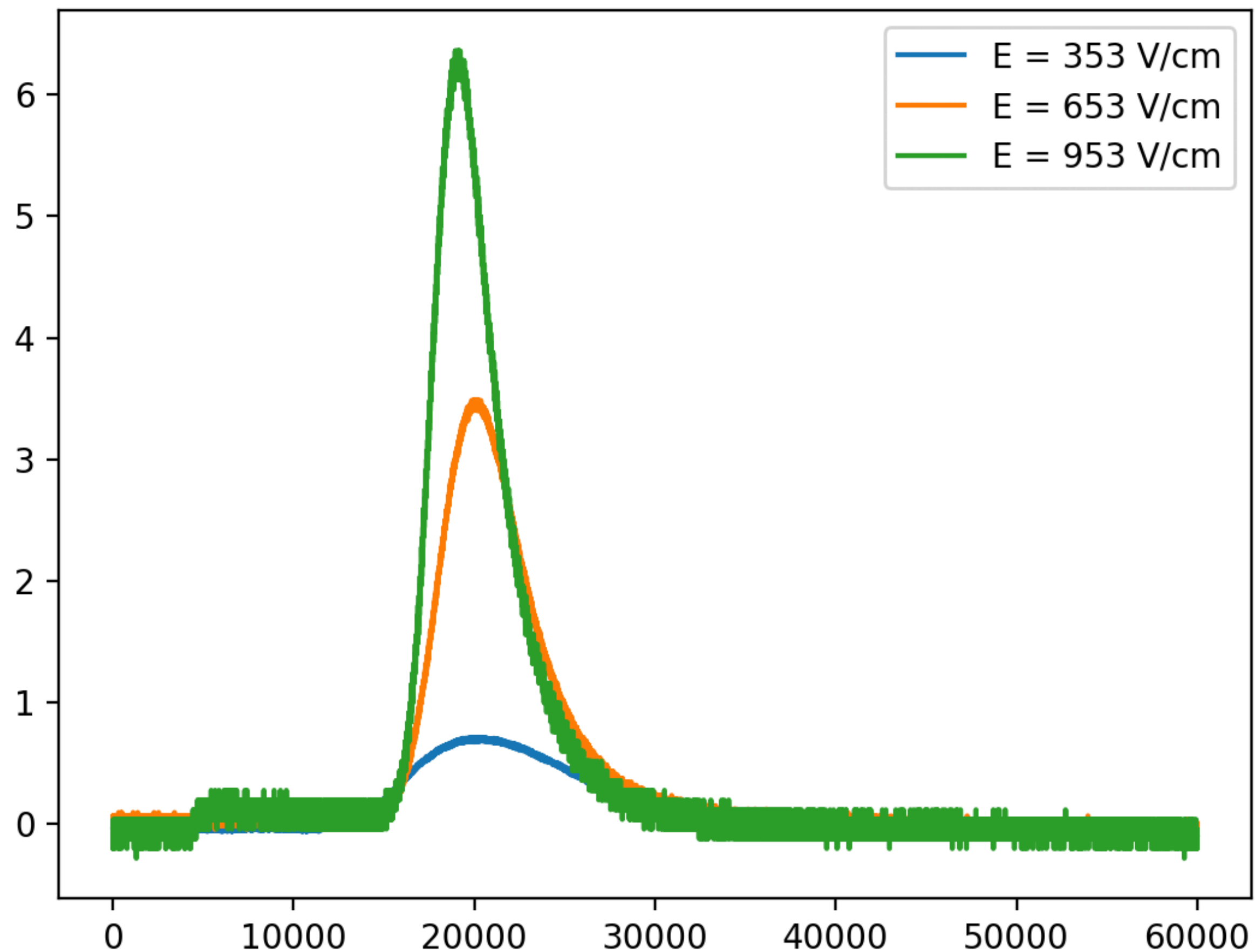


# 离子漂移速度测量

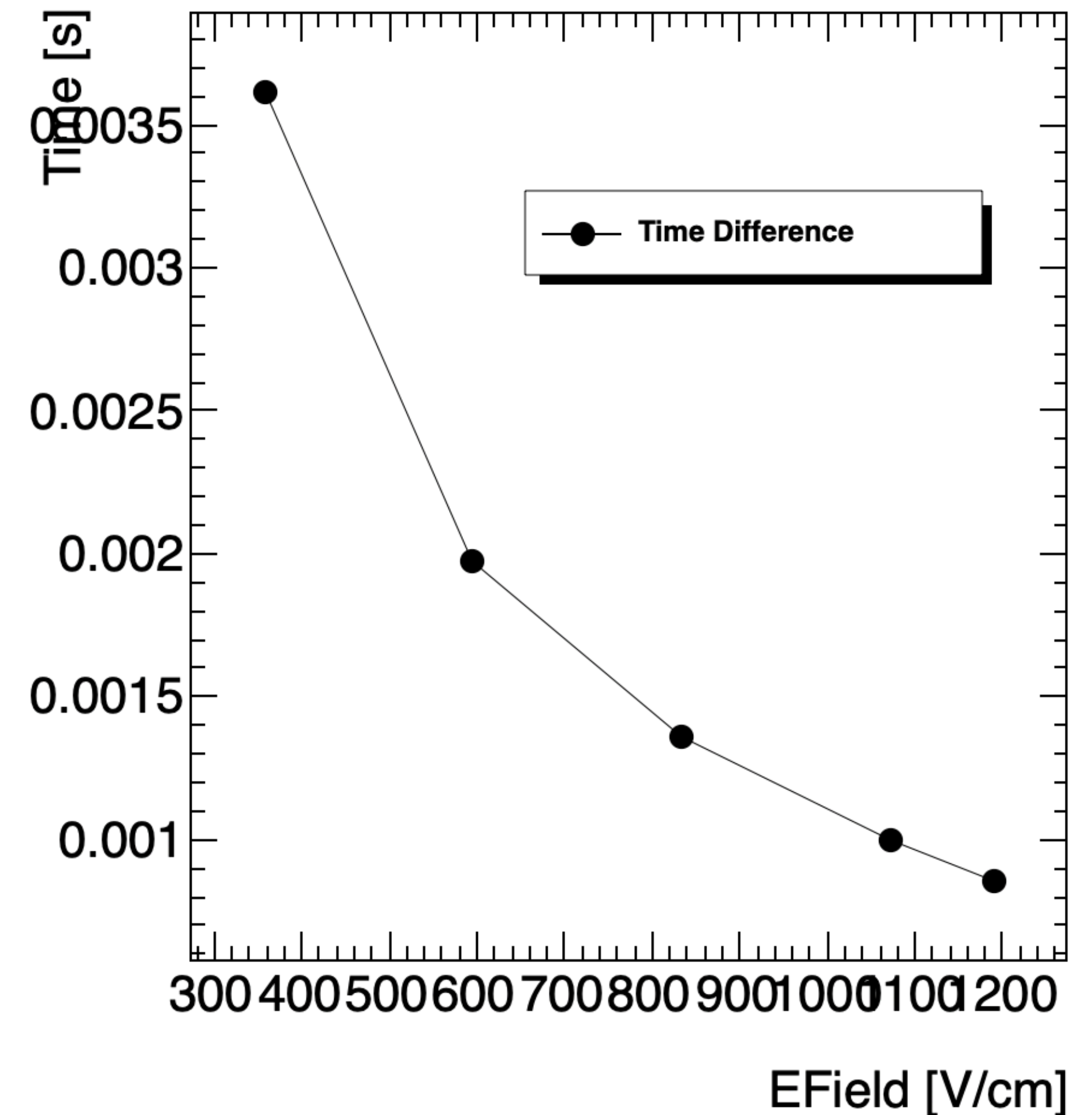
## 迁移率与离子扩散

$$\sigma_t^2 = \frac{2D_L}{v_d^3} z + b$$

空气中不同电场下的离子波形对比

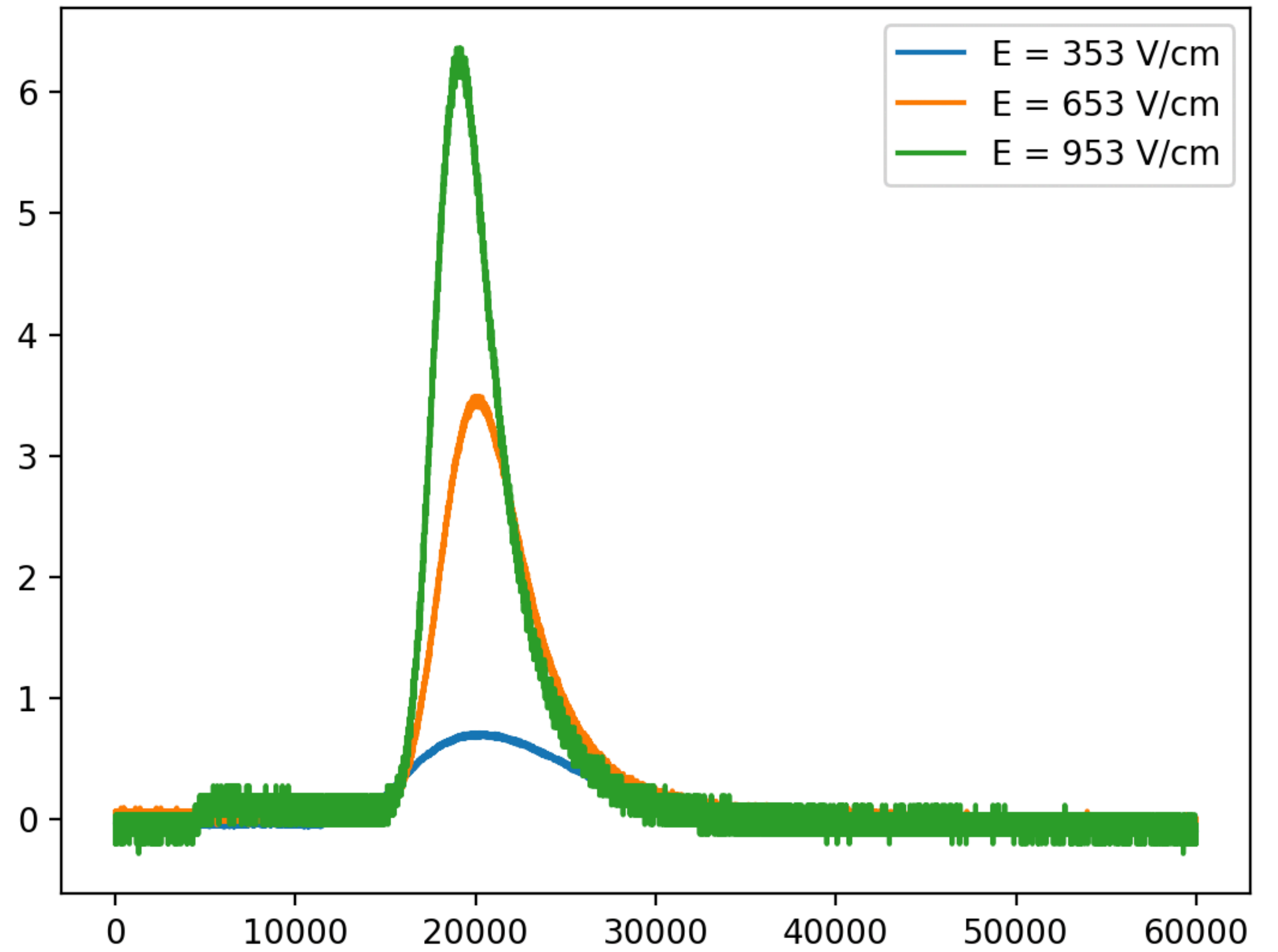
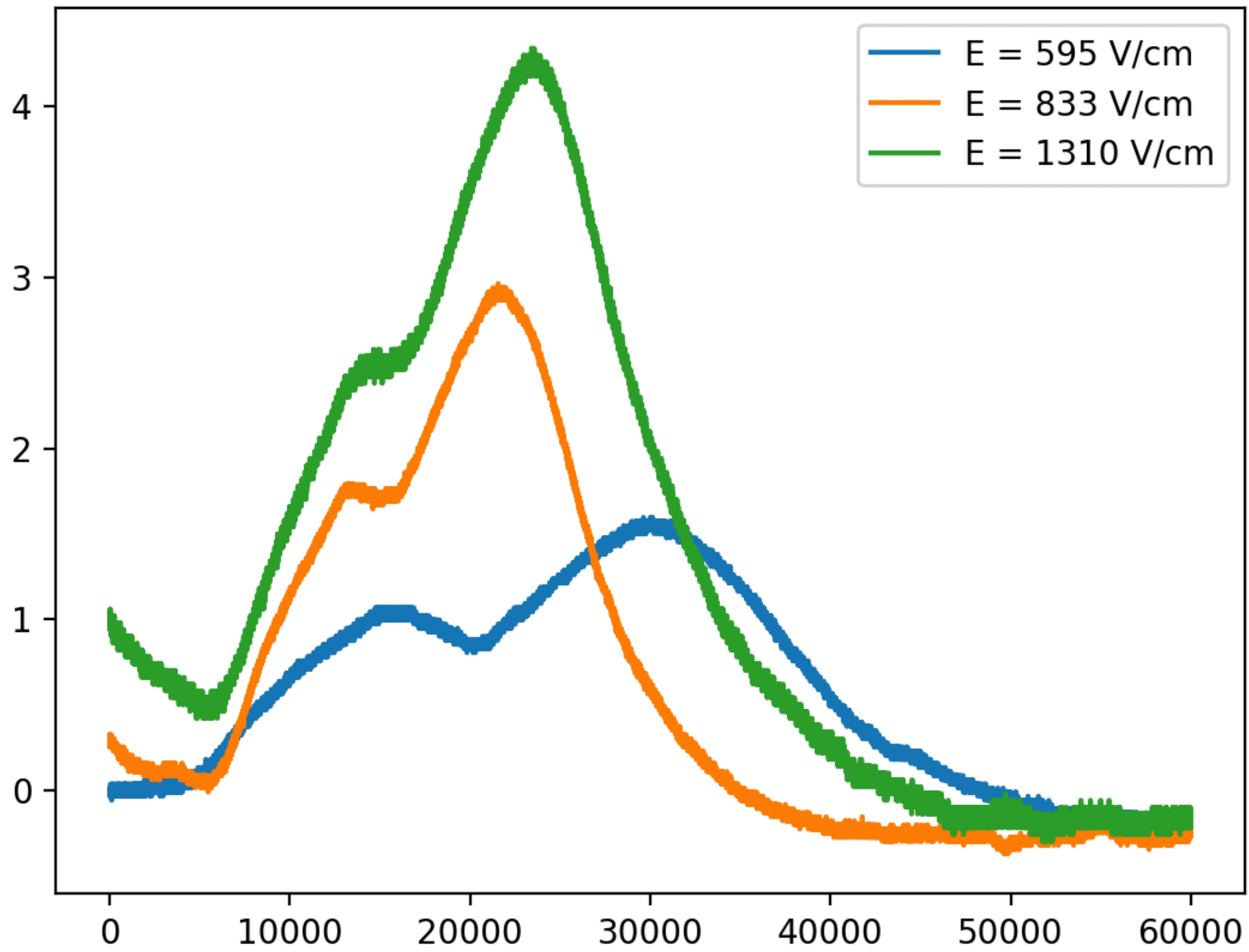


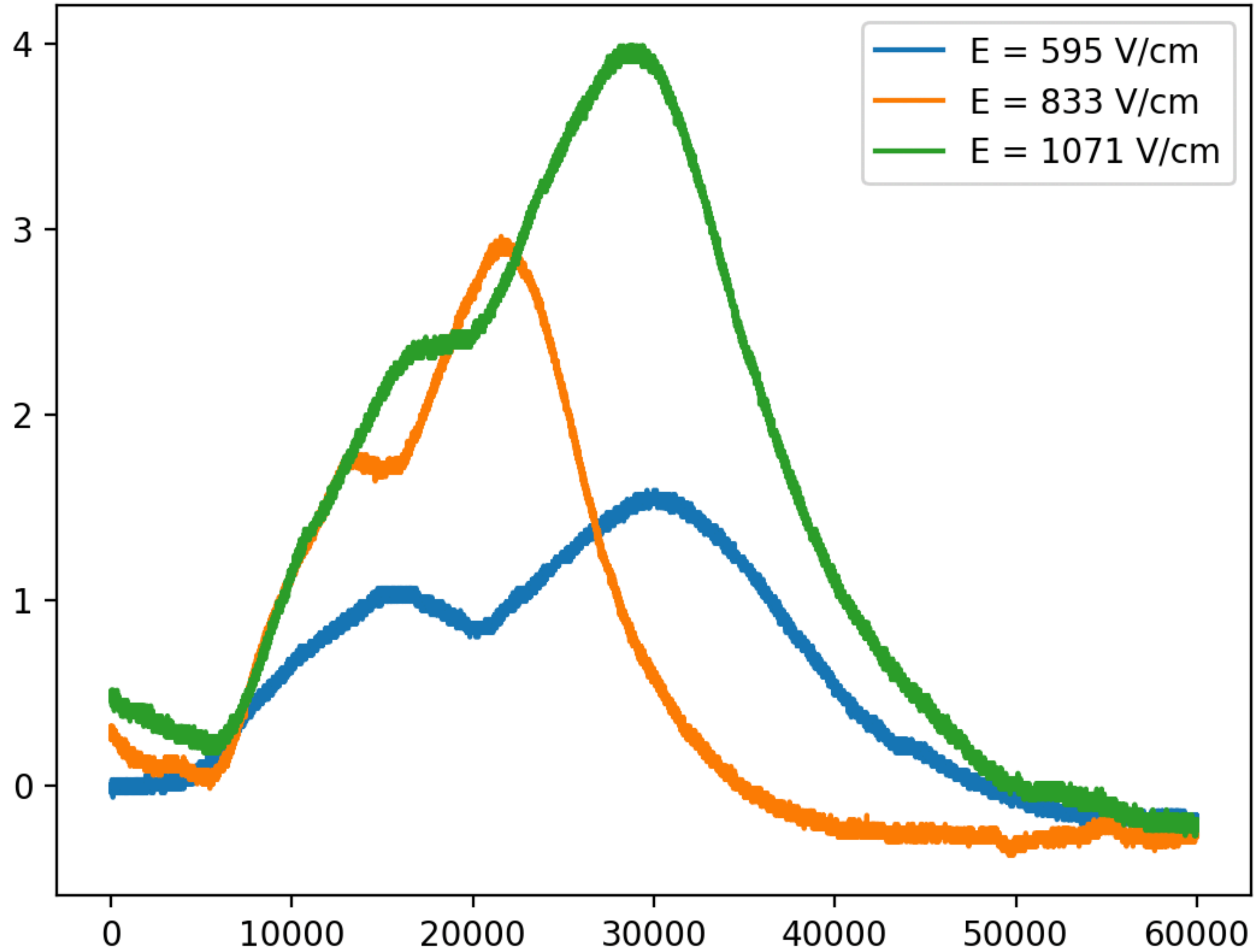
六氟化硫中两种离子时间差





# Waveform with different E-field

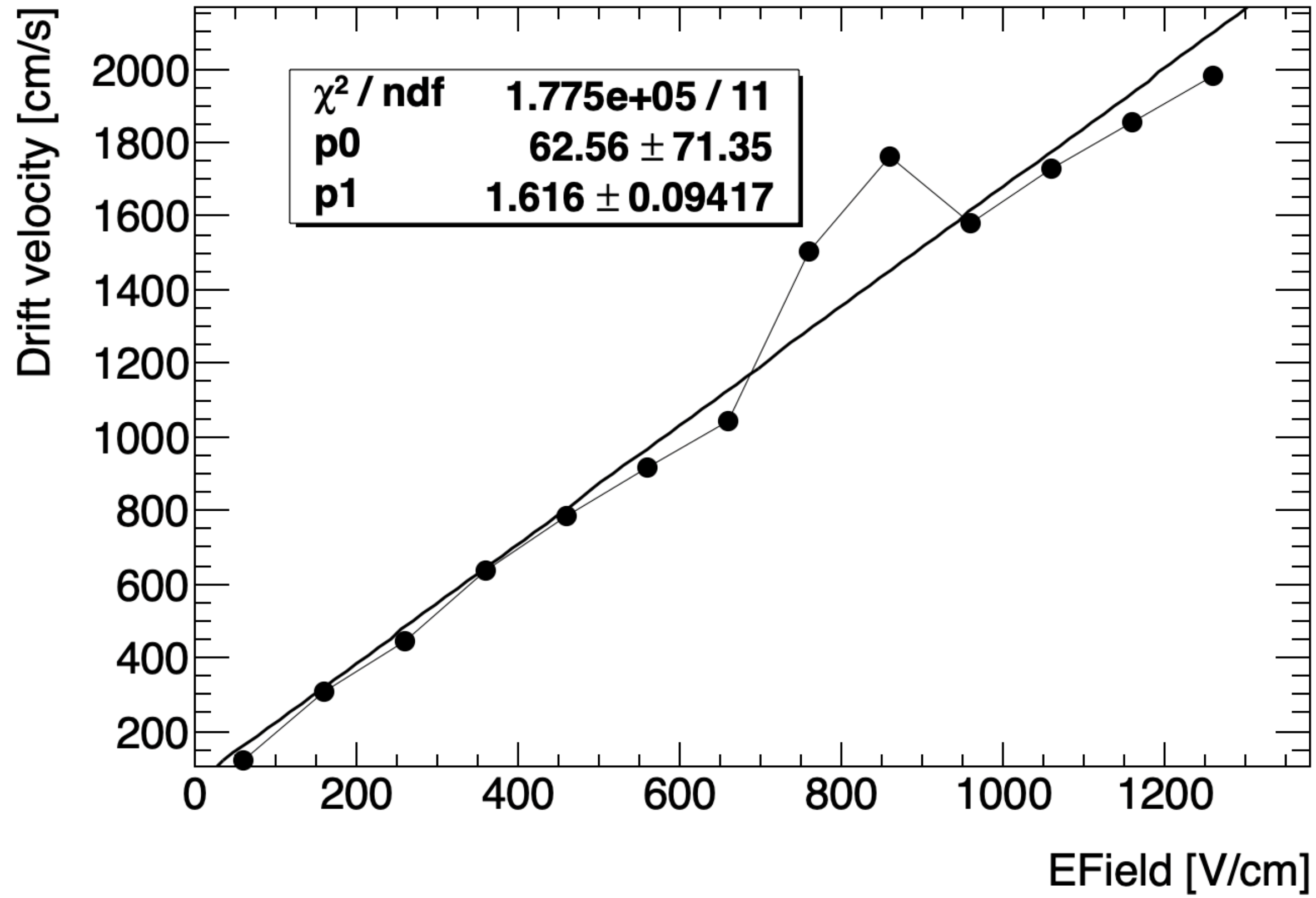




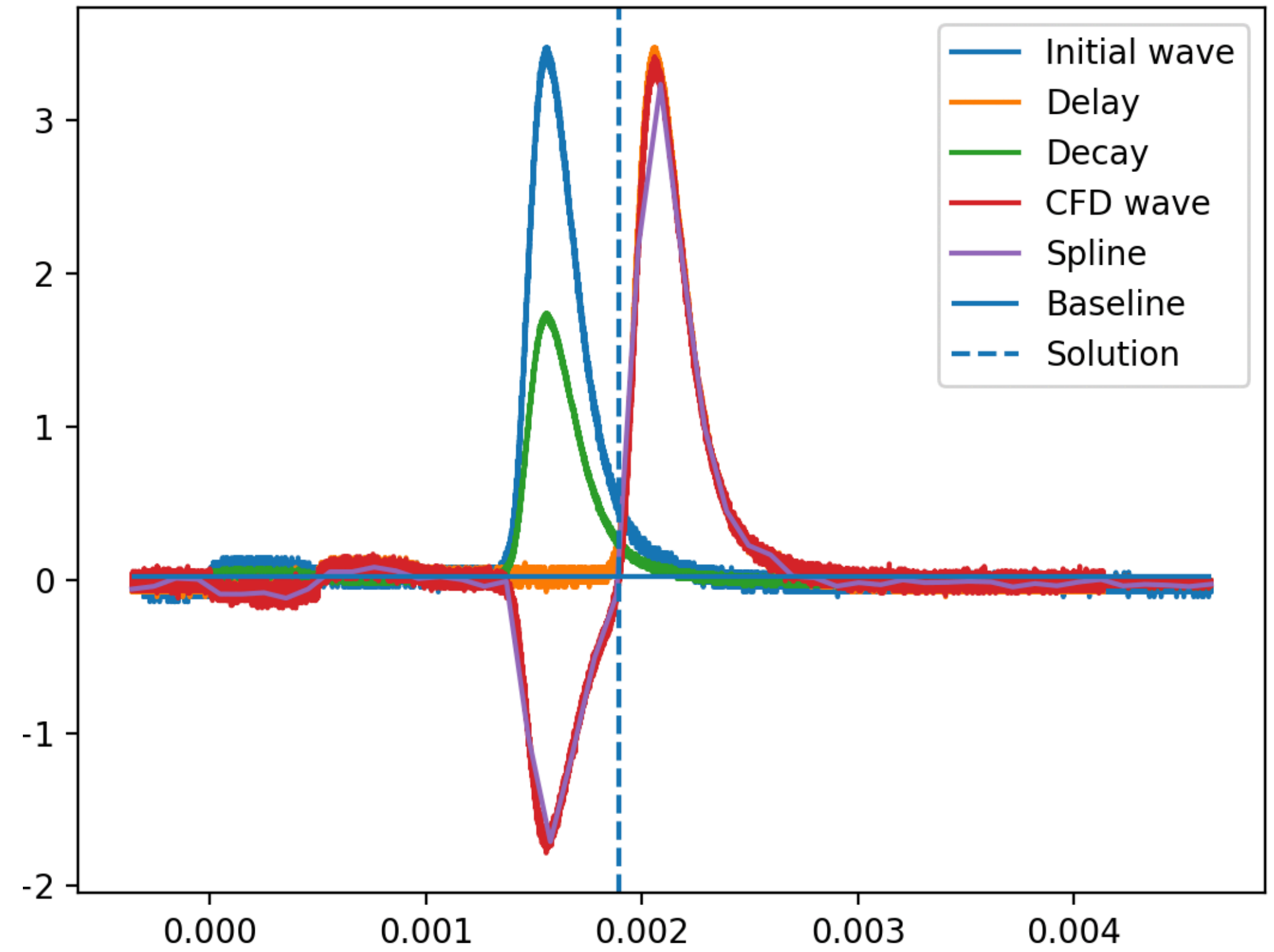
Seems the same leading edge with different E field?  
Even slower for the last peak with higher E field



### CFD result



### CFD\_test



The result could be better than finding peaks. But how to define the delay time and decay amplitude is quite important.

### Leading edge

