DEMIURGOS R&D project

DEtector of Matrix Isolated Unreactive Rare Gas Organized in Solid

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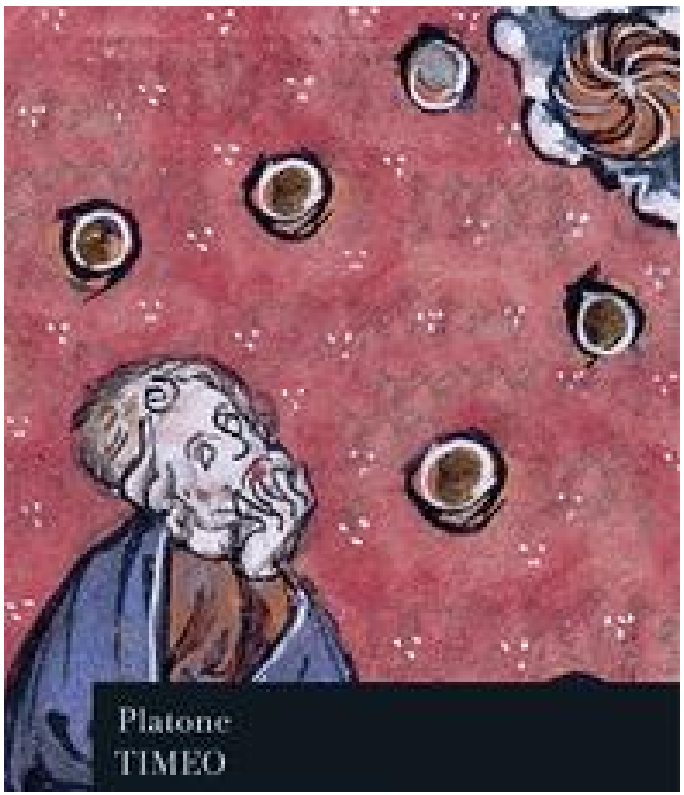
DEMIURGOS EXPERIMENT

Outline: R&D INFN (V committee) project on a novel kind of PARTICLE DETECTOR with a low energy threshold intended for events with feeble interacton based on Large Crystals of Rare Gases both *Doped* and *Undoped*.



Possible application fields:

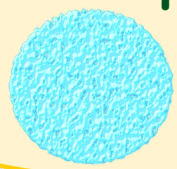
- Light Dark Matter searches;
- Neutrino coherent scattering;
- EDM cryogenic doped crystals;
- medical (MRI/NMR) hyperpolarized ^{131}Xe and Ne;

1. DEMIURGOS idea
2. Experimental part and results
3. Conclusions

The DEMIURGOS idea

Particle detector:

Rare gas crystals undoped



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In-vacuum single electron detection

+

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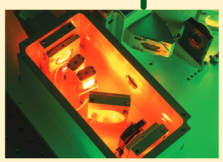
Further lowering energy threshold →

Doping

+ Laser probe



Fields:

Cryogenics and low temperature technologies + Solid State (rare gas crystals) + high efficiency/low dark count rate Electrons sensors + Dopants energy levels + tunable/narrow bandwidth Laser systems

Rare gas crystals properties

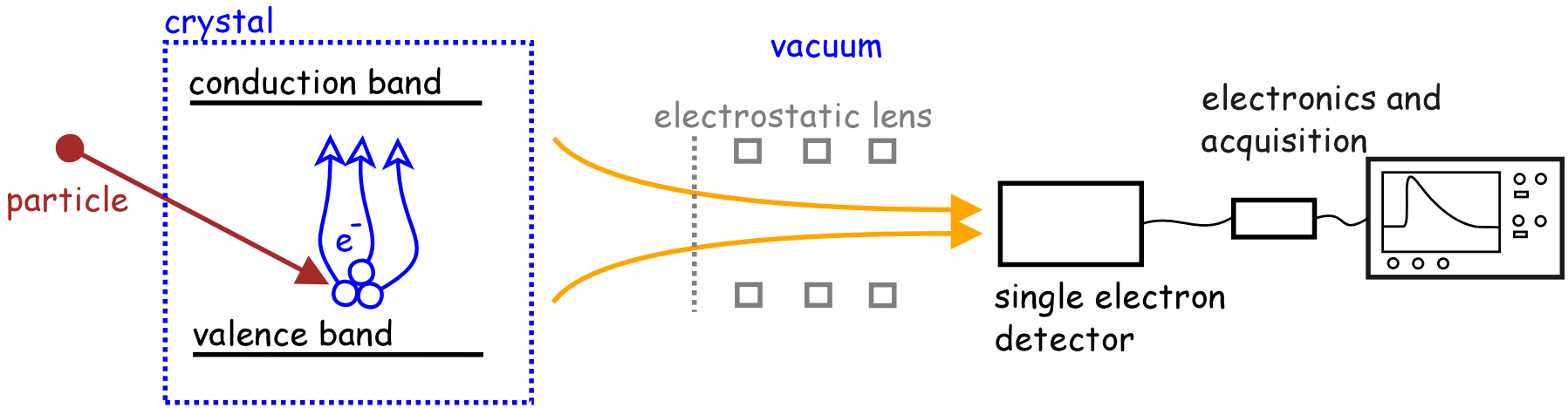
Why Rare Gases crystals?

- Matrix Isolation Spectroscopy: Pimentel in the 50's→ studies of free radicals-unstable-transient species (absorption-emission spectroscopy);
- closed-shell & simple structure (ccp);
- low interacting environment → low line broadening;
  - feeble interaction host host;
  - feeble interaction host guest;
- the species can be accumulated in the matrix over many minutes → high density;
- large interstitial space → good doping;
- (some) have positive V_0 → good signal;
- low melting temperature → difficult of growing and manipulate;

Some parameters

matrix	Z	ρ_{solid} (g/cm^3)	a (pm)	R_{VdW} (pm)	T_m (K)	T_b (K)	μ_e (cm^2/Vs)
Neon	10	1.444	443	158	24.5	27	600
Argon	18	1.623	525	71	84	87.3	1000
Kripton	36	2.826	570	88	116	119.9	3700
Xenon	54	3.54	620	108	161	165	4500

Scheme in undoped matrices



Features:

- Particle direct ionization
- Electrons drift
- Solid-vacuum interface charge extraction
- In-vacuum charge signal
- Furthermore UV fluorescence

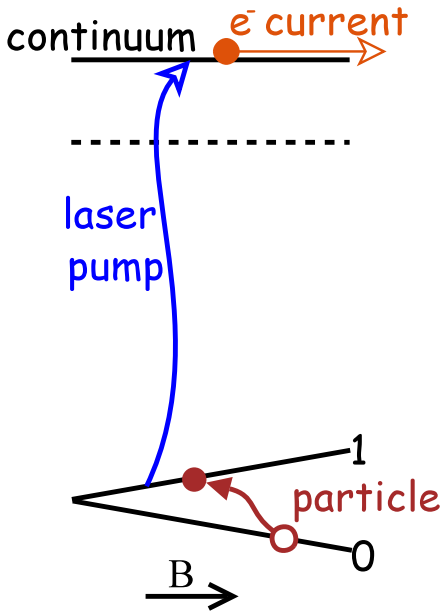
$\Rightarrow E_{th} \sim 100\,\text{eV}$

- Ne$\rightarrow m_W \sim 100\text{MeV}/c^2$
- Ar$\rightarrow m_W \sim 300\text{MeV}/c^2$
- Xe$\rightarrow m_W \sim 500\text{MeV}/c^2$

- nuclear recoil;
- solid-vacuum extraction;

- high gain e^- detector;
- low dark count e^- sensors;

Scheme in doped matrices



Features:

- Internal energy levels
- Incident energy is absorbed
- laser induced ionization LII from excited level
- solid-vacuum electron extraction
- in-vacuum charge signal
- up-conversion efficiency $\eta = \sigma_{13}\tau_1\phi_L \rightarrow \sim 1$

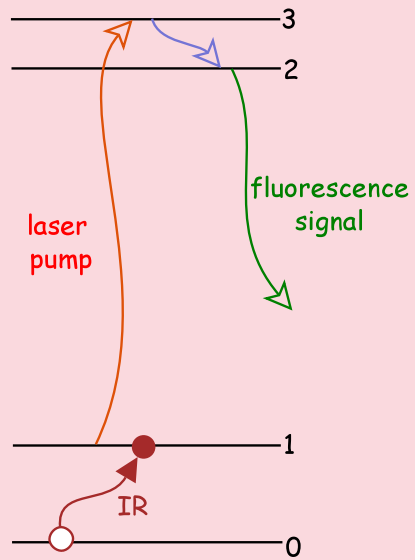
$\Rightarrow E_{th}$:sub-eV

Possible application: Dark Matter Axion

- axion mass: m_a tuned to the 0→1 transition (E_1-E_0);
- Zeeman transition $0 \rightarrow 1$: $\Delta E \sim \mu_B \mathbf{B} \sim$ (10-1000)meV for $\mathbf{B}<$Tesla;
- $K_B T < \Delta E$ required;
- $R_a \propto m_a^2 V_s N_s \tau_a$

V_s:sample volume; N_s:electron density; m_a and τ_a: mass and coherence time of axion

Bloembergen IRQC!



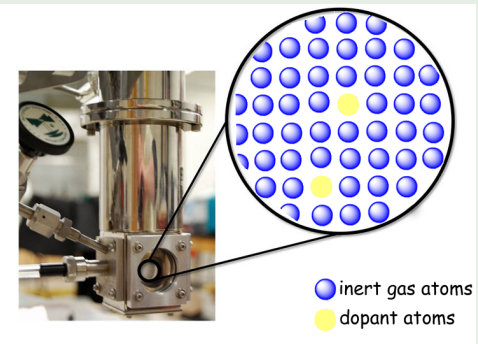
Crystal growth

Two methods:

- Vapour deposition

Films ($\sim cm^3$)

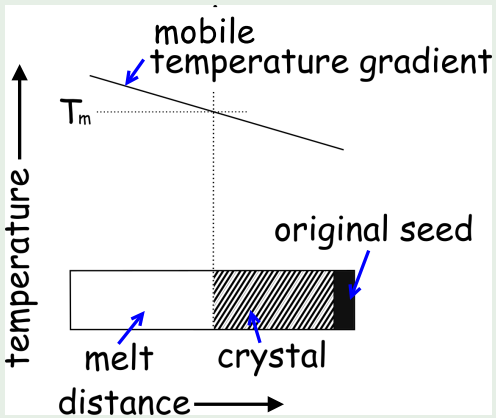
- spray deposition through nozzle;
- easy doping;
- pulse tube He cryocooler @4K;
- $P_{chamber} \sim 10^{-8}$ mbar;
- $P_{growth} \sim 10^{-5}$ mbar;
- time of growth$\sim 1\,cm^3/2$ hours;
- annealing;



- Liquid freezing

Large crystals ($\sim$litres)

- Bridgman-Stockbarger technique;
- low temperature system:
  - cryogenic liquids;
  - pulse tube refrigerators;
- fine tuning temperature control;
- time of growth$\sim 1\,dm^3/5$ hours;



criticism: single crystal VS polycrystalline structure [M. L. Klein, J. A. Venables "Rare Gas Solids" Springer (1984);J. Yoo, et al. JINST 10, 08011 (2015)]

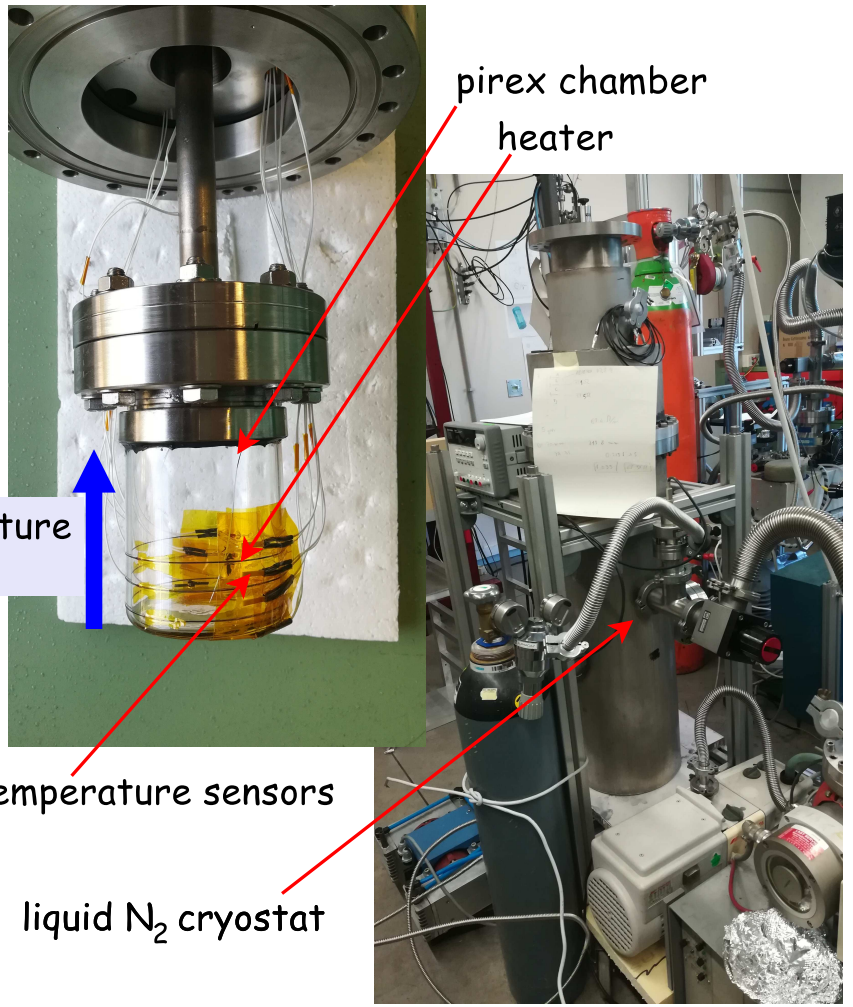
Large crystal: pyrex chamber

Modified Bridgman-Stockbarger technique

- temperature gradient;
- slow cooling;

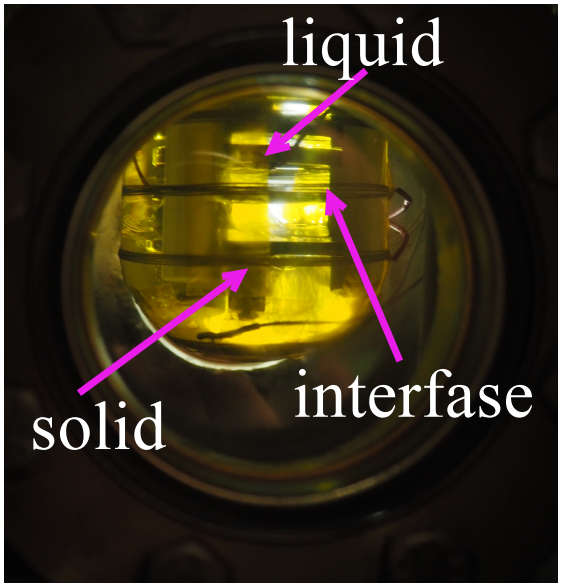
Pyrex chamber

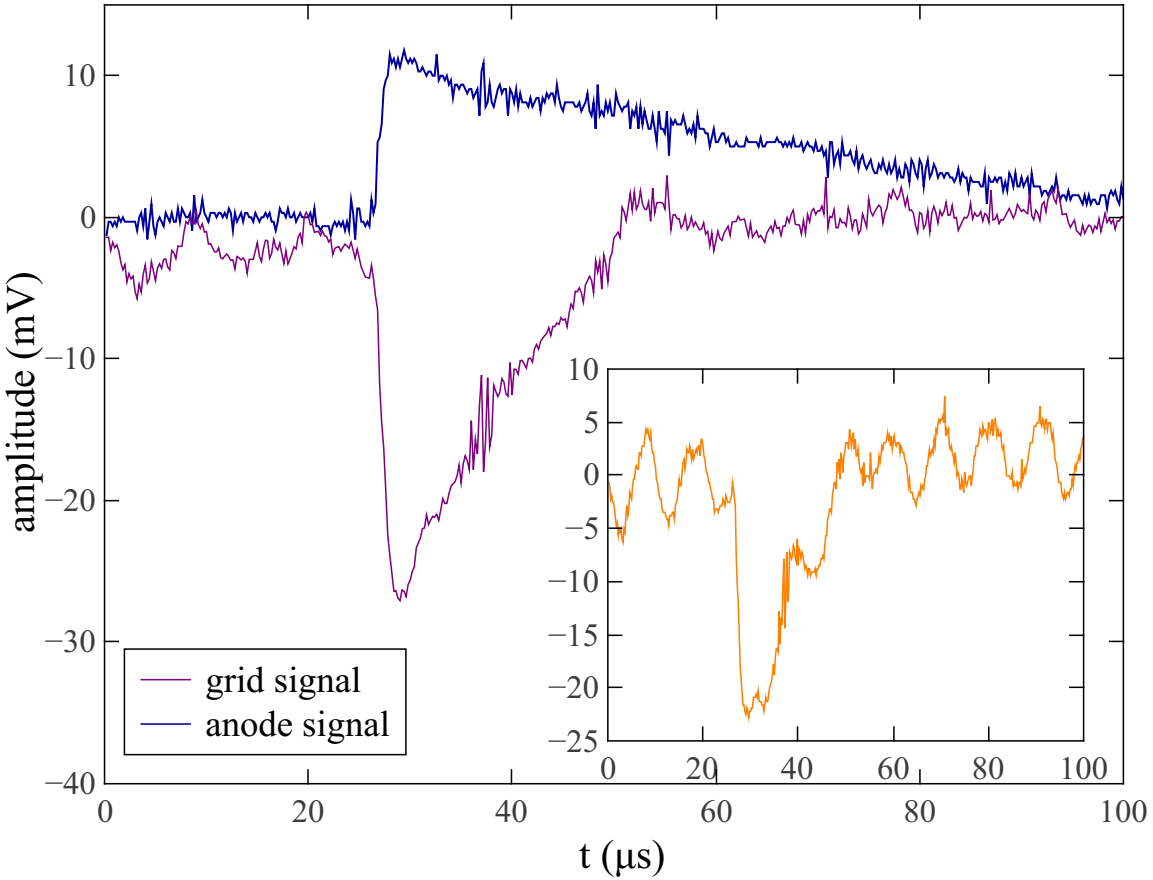
- transparent holder;
- pyrex thermal conductivity$\sim 10^{-1}$ Wm/K @10K;
- multi heater + PT100 sensors;
- temperature gradient (1K/cm);
- fine control;
- l-N_2 cryostat (T>80 K);
- Labview controlled;

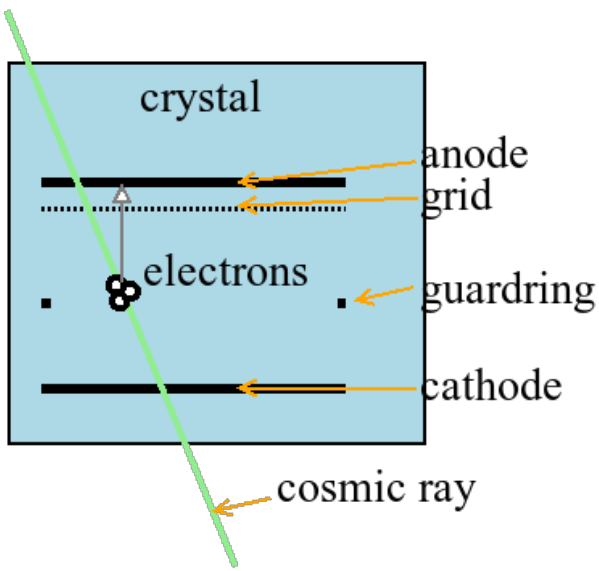


Temperature gradient velocity: 1 K/h

Large Xenon growth and Cosmic Rays detection







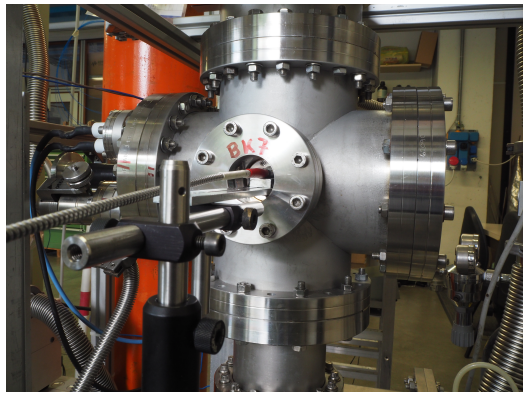
large Xenon crystal

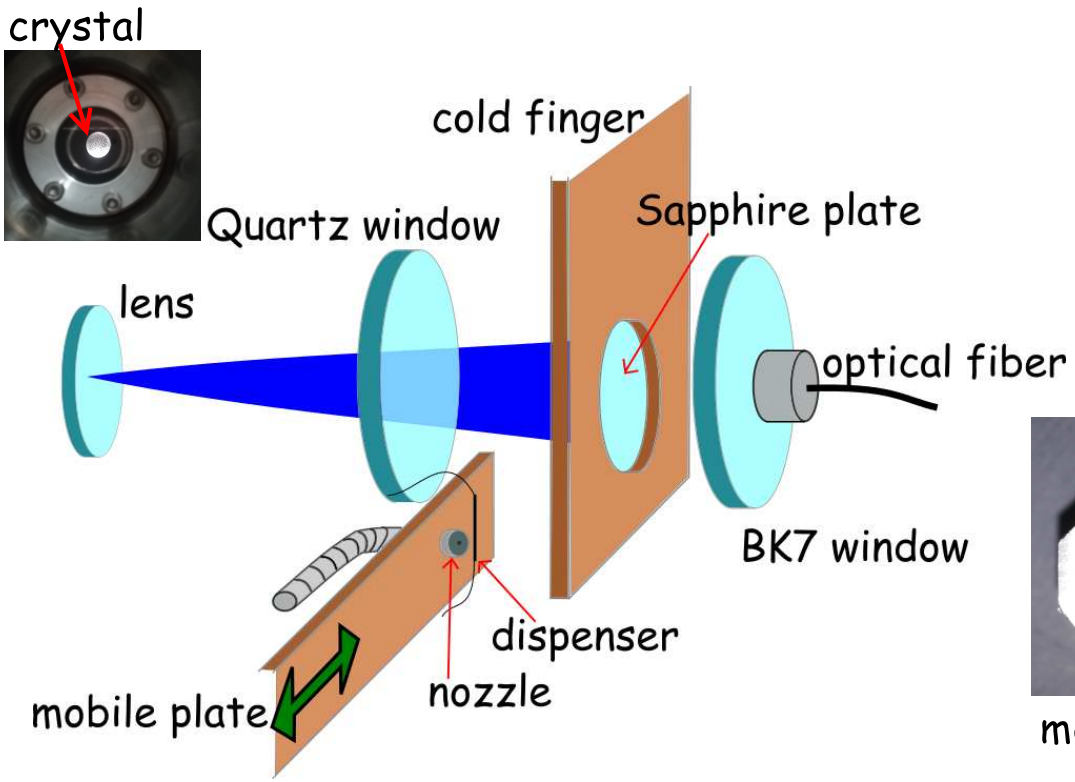
- Bridgman Stockbarger technique;
- volume$\sim$150 cm^3;
- mass$\sim$0.5 kg;

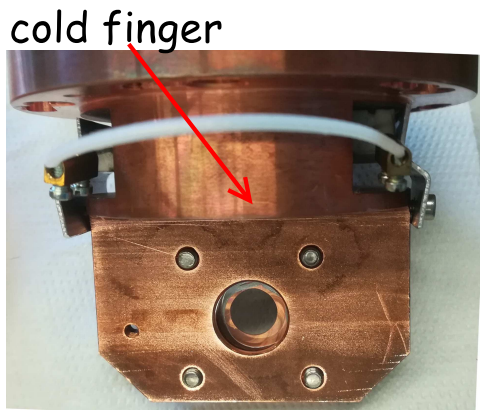
Doped films: apparatus

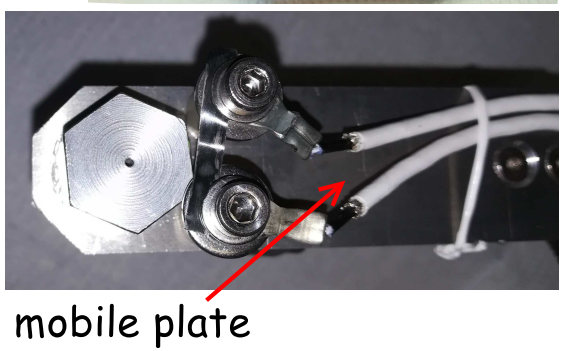
Apparatus:

- thin films (∼mm thickness);
- transmission measurements (UV-IR):
  - absorption spectroscopy;
  - emission spectroscopy;





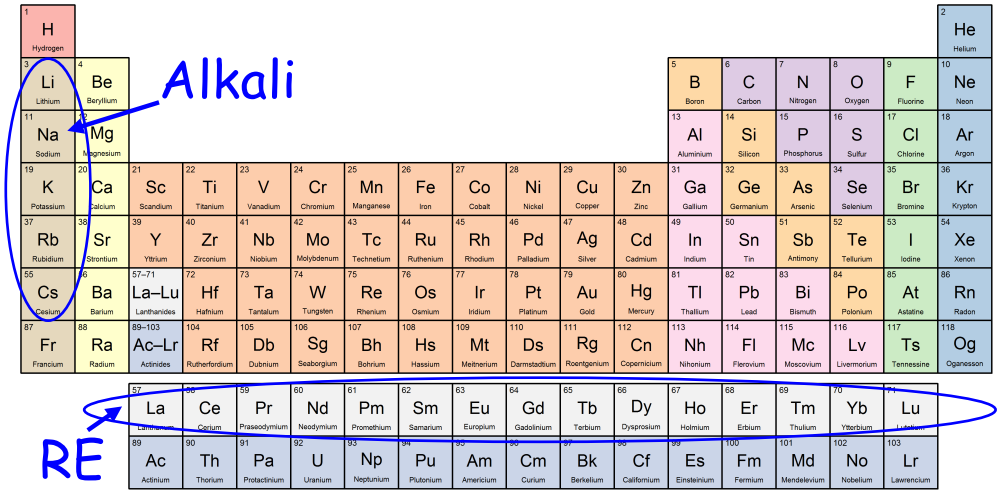




Matrix Isolation and possible dopants

Requests:

- narrow line-width;
- photo-ionization steep;
- low interaction with matrix;
- long lifetime;



Possibilities:

Alkali

element	E_{ioniz} (eV)	λ_{ioniz} (nm)
Li	5.39	230
Na	5.13	241
K	4.34	285
Rb	4.17	297
Cs	3.89	318

Rare Earth (RE)

element	E_{ioniz} (eV)	λ_{ioniz} (nm)
Pr	5.47	226
Nd	5.52	224
Sm	5.64	219
Ho	6.02	205
Er	6.10	203

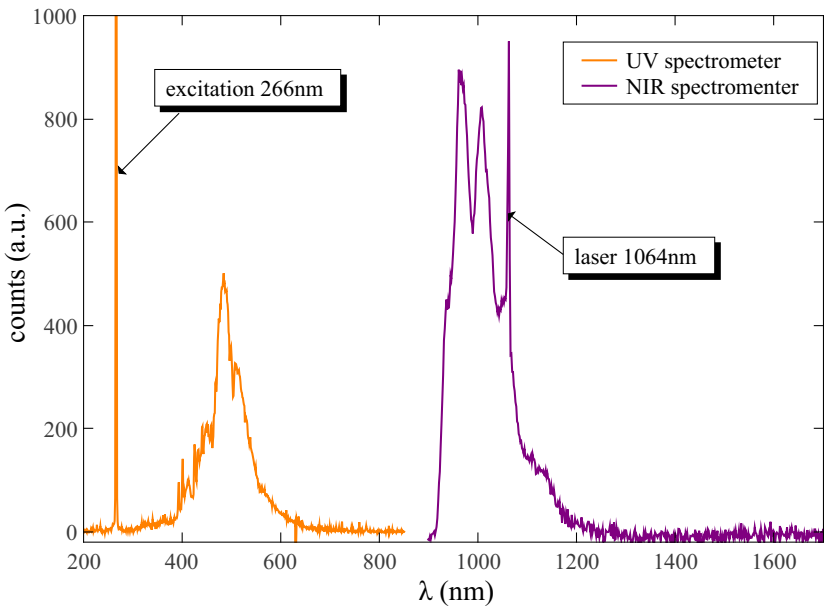
Possible problems:

• clustering; • line broadening; • impurity; • interstitial/substitutional sites;

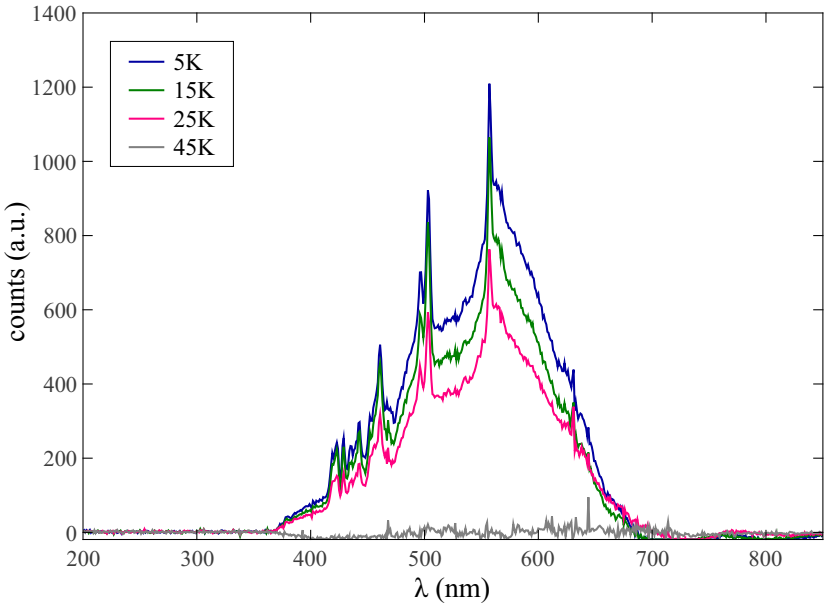
[S. Upadhyay, et al. Phys. Rev. Lett. 117, 175301 (2016);I. Gerhardt, et al. J. Chem. Phys. 137, 014507 (2012)]

An example: Argon Samarium-light signals

- Emission spectrum



- Absorptium spectrum



Features:

- excitation with UV pulses;
- broadband emission @ $\sim$500 nm;
- Sm emission lines at @ $\sim$1 μm;
- long lifetime;

Features:

- halogen lamp excitation;
- Sm lines superimposed to the broadband absorption;
- no temperature dependence;

Summary

DEMIURGOS activity:

- R&D particle detector:
  - low energy threshold and large volume;
  - RG crystals + single e^- detector in vacuum;

Pure crystals

- large crystals:scalability study;
- cosmic rays detection in large Xe;

Doped crystals

- Rare-earth doping studies;
- absorption-emission spectrum;

some references:

- A.F. Borghesani, et al., Particle detection through the quantum counter concept in YAG:Er^{3+} *App. Phys. Let.* 107 193501 (2015)
- F. Chiossi, et al., A new technique for infrared scintillation measurements *NIM A* 855, 13-15 (2017)
- M. Guarise, et al., Experimental setup for the growth of solid crystals of inert gases for particle detection *Rev. Sci. Instrum.* 88, 113303 (2017)
- C. Braggio, et al., Axion dark matter detection by laser induced fluorescence in rare-earth doped materials *Sci. Rep.* 7, 15168 (2017)
- M. Guarise, et al., Novel approaches in low energy threshold detectors for Dark Matter searches *Nucl. Instrum. Methods Phys. Res. A* 61313 (2018);
- M. Guarise, et al., Particle detection in rare gas solids: DEMIURGOS experiment *Nucl. Instrum. Methods Phys. Res. A 162434* (2019);

The end

Thanks for your attention!

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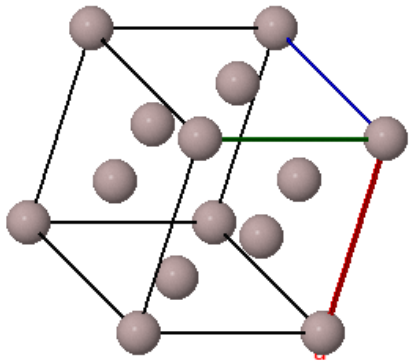
Backup slides

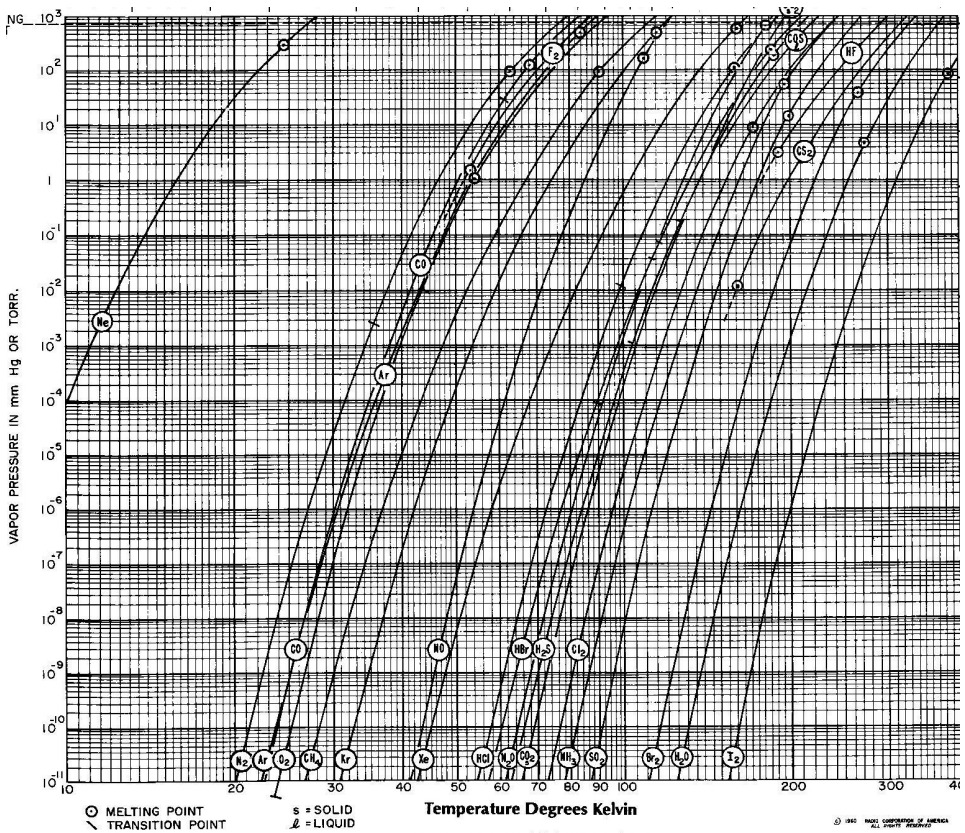
Others Rare gas crystals properties

Parameters

matrix	E_{gap} (eV)	V_0(eV)	μ_e(cm^2/ Vs)
Ne	∼21.6	+1.1	600
Ar	∼14.3	+0.3	1000
Kr	∼ 11.7	-0.2	3700
Xe	∼9.3	-0.4@50 K	4500
para − H_2		+2	

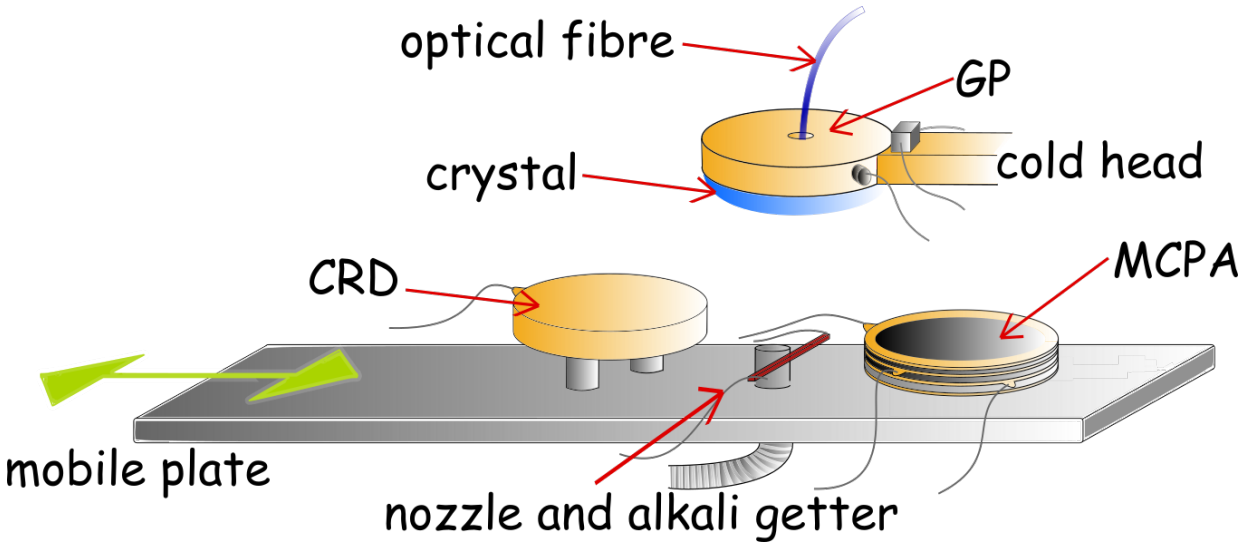


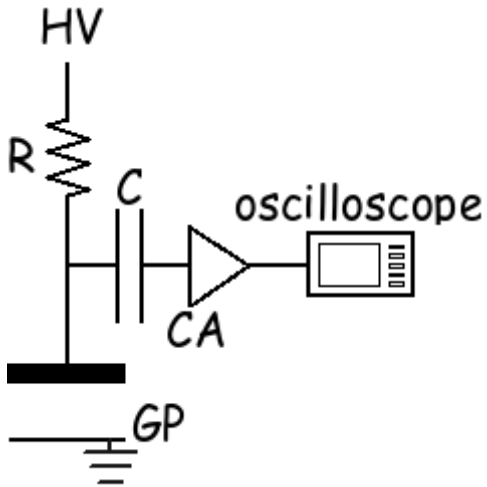
Furthermore, vapor pressure @ low temperature is very low! Worst case: Neon is 10^{-7} mbar at 8 K!!!



In solid Argon no space charge problem up to 3000 β/mm^{2}s [V. Brisson et al, Phys. Script. Vol. 23, 688-68, (1981)]

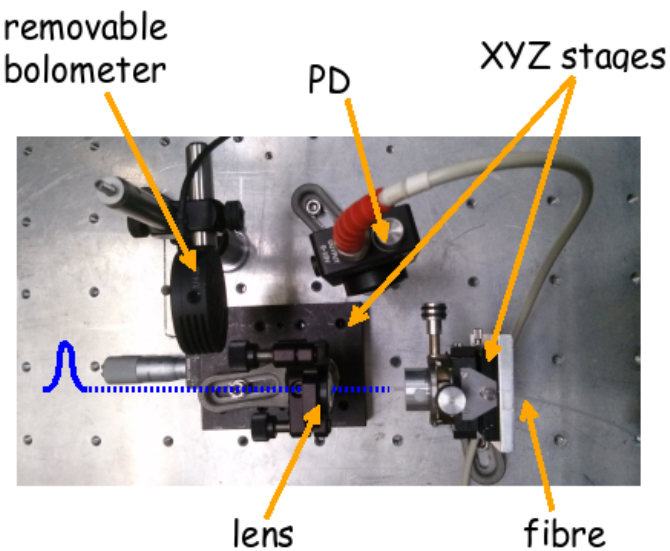
Electrons injection, extraction & collection from a Neon crystal: apparatus



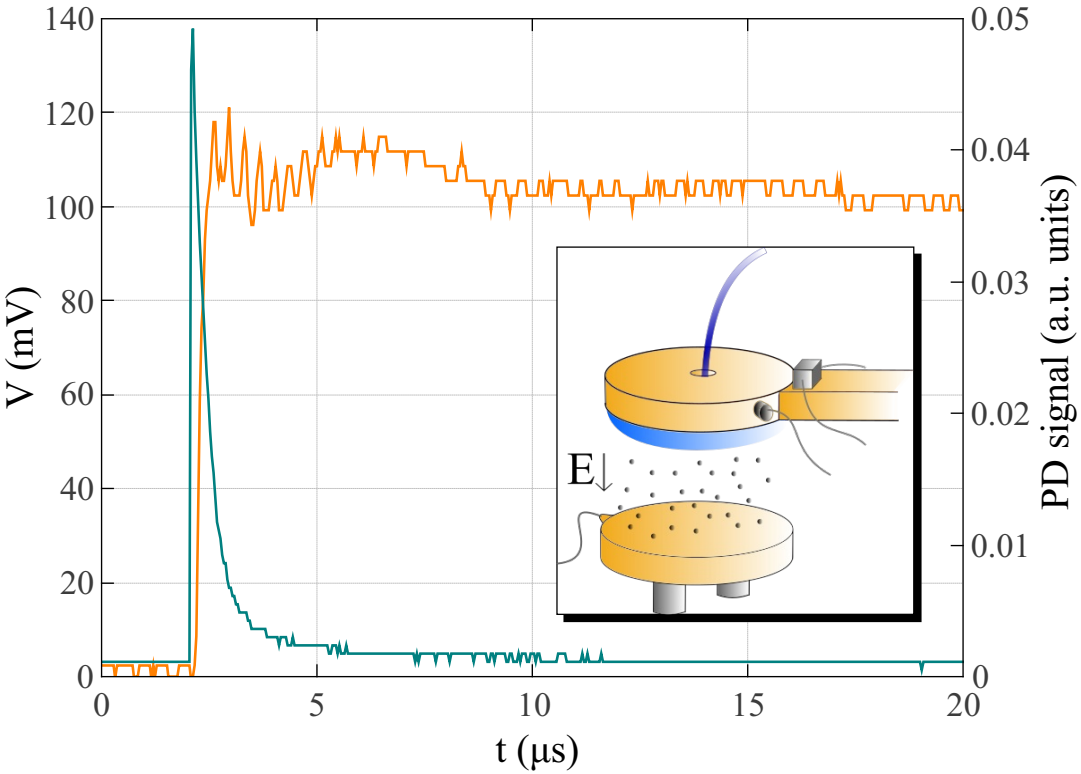


Characteristics

- Au photocathode in the cold head;
- fused silica fibre;
- 10 ns laser pulses @ 266 nm (trigger);
- energy up to 1 mJ;
- charge receiver disk or microchannel plate assembly;

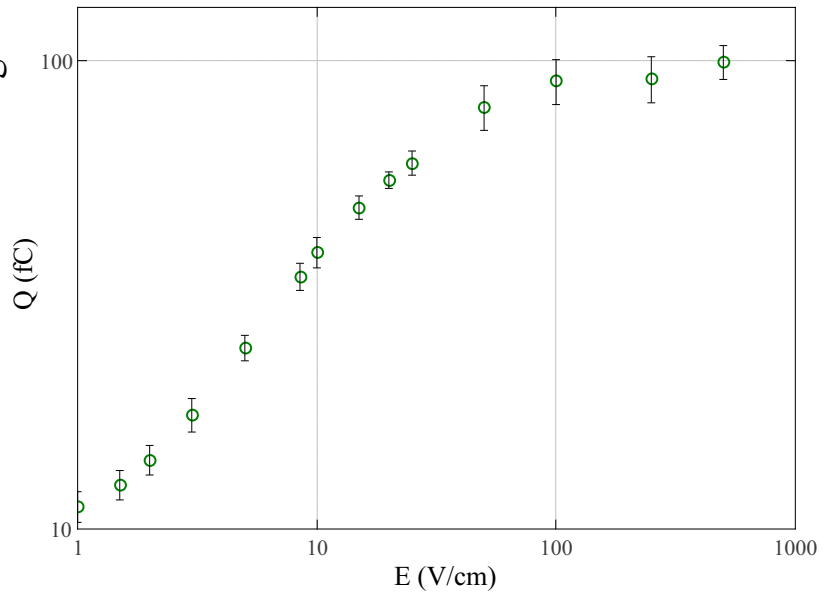


Electrons extraction from a Neon crystal: signal



Measurements:

photoelectrons injection and emission in 2 mm thickness Ne for different electric field applied



long time (hours) stability signal ⇒ no space charge effect! ⇒ no trapping sites! ⇒ high quality crystals!

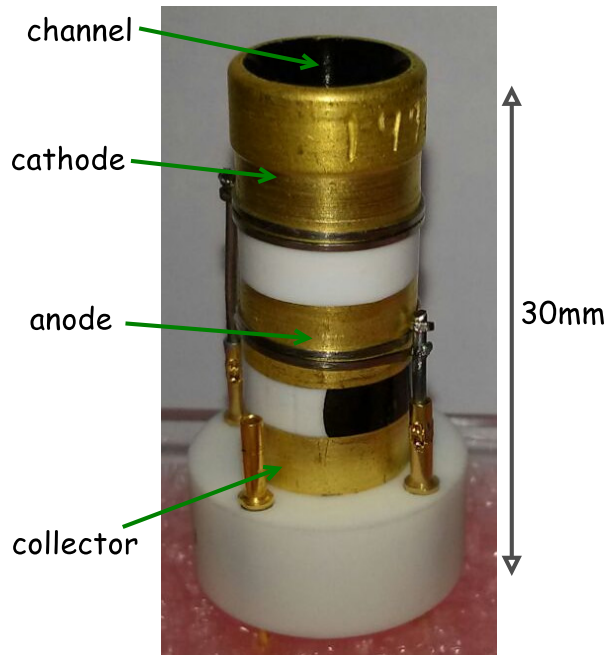
Single electron detection technology

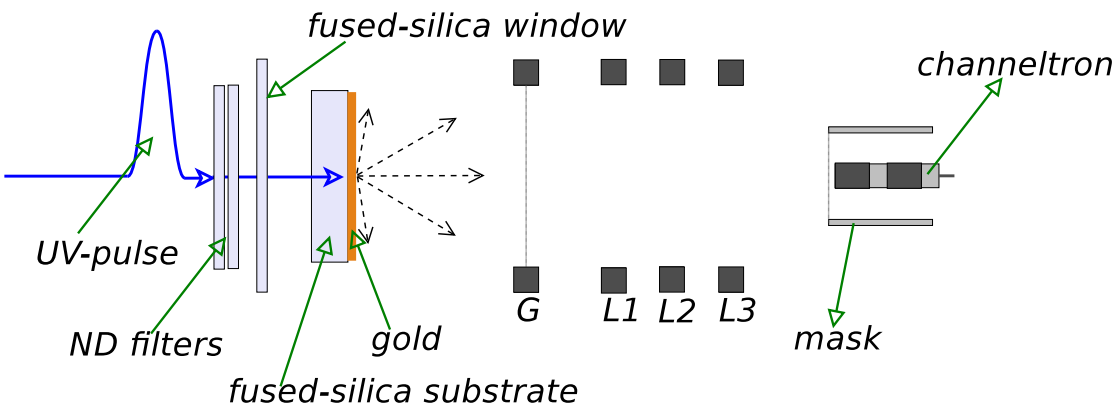
In-vacuum single electron detection using channeltron (CEM) or microchannel plate (MCP)

Our tests with CEM sensor:

- model: 5901 Magnum;
- photoelectrons generated by UV pulses in gold;
- electrostatic lens (3 rings + 1 grid);
- single electron detection;

dark count measured$\sim$ 120 mHz





sensor	*Max Gain*	*Channels*
MCP	10^8	$\sim 10^5 \mathrm{cm}^{-2}$
CEM	10^7	1

MCPs have much problems at low

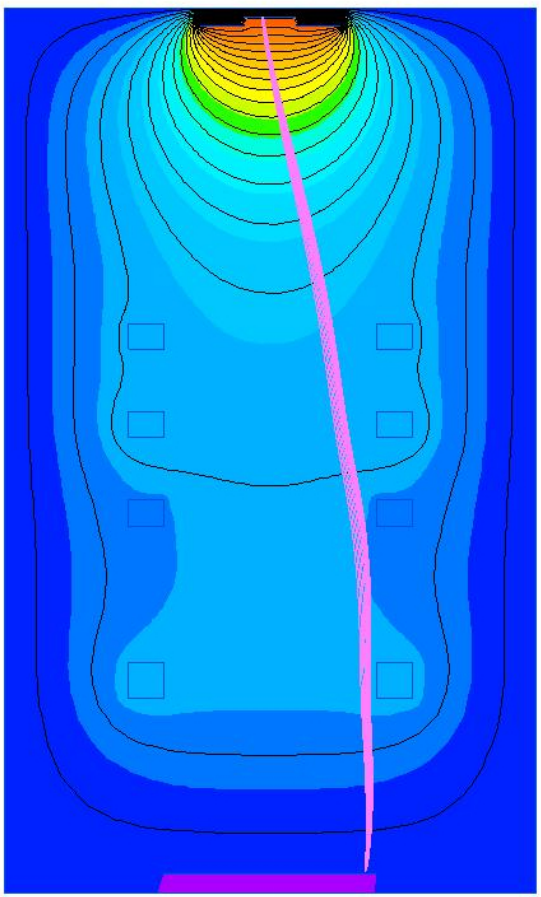
temperature!

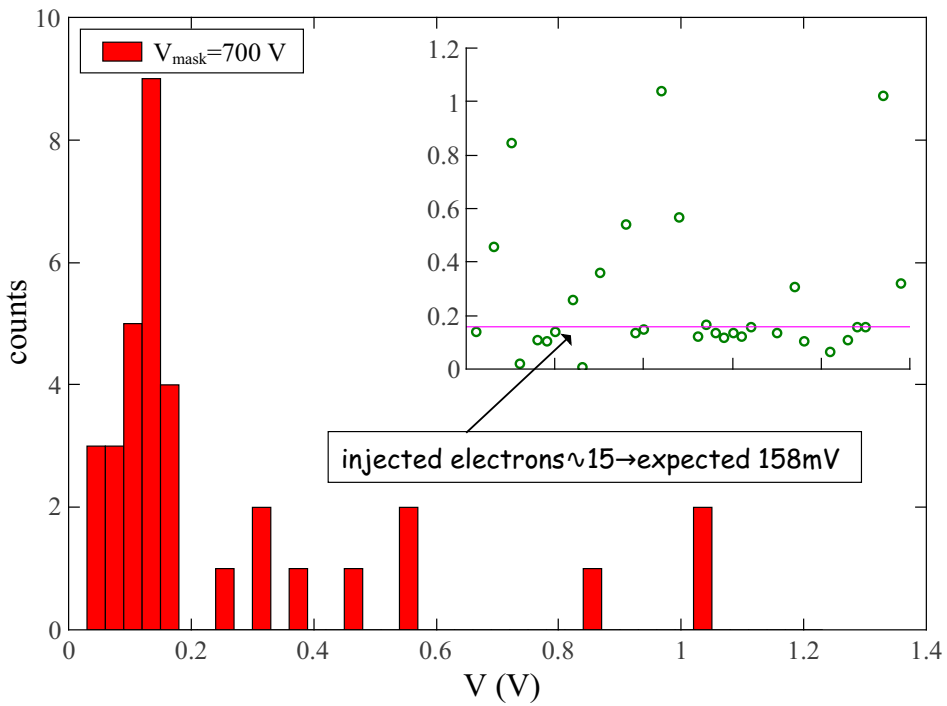
Electrostatic lens and CEM test

Some tests at room temperature...

Finite element simulation of the electrostatic lens that couple crystal and CEM

measure of bunches of electrons at room temperature





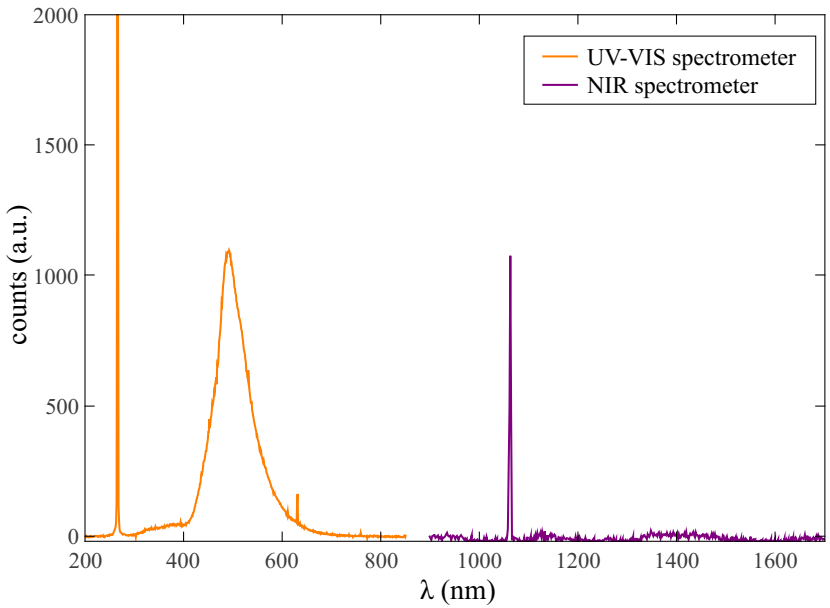
Neon Neodymium: light signal

Excitation:

- 266 nm laser pulses (4.66 eV);
- length ∼10 ns;
- energy ∼1 mJ;
- rate ∼1 Hz;

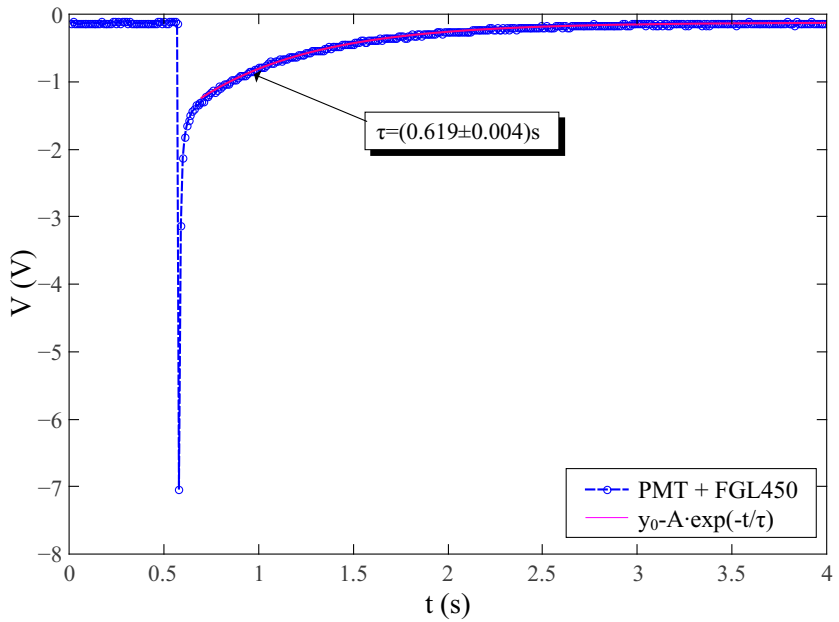
Detection:

- UV spectrometer;
- VIS spectrometer;
- NIR spectrometer;
- PMT+pass-band filter;



Emission spectrum

broad band emission @ ∼500 nm



Signal lifetime

τ ∼0.6 s