SDD detectors to test the Pauli Exclusion Principle for electrons with the VIP2 experiment

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on behalf of the VIP-2 collaboration

Fundamental physics with exotic atoms and radiation detectors

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1. Why we could expect a violation of the PEP

O. Greenberg, one of the pioneers of parastatistic studies, says that a possible violation of the PEP could be due to:

"Possible external motivations for violation of statistics include:

(a) violation of CPT,
(b) violation of locality
(c) violation of Lorentz invariance,
(d) extra space dimensions,
(e) discrete space and/or time and
(f) noncommutative spacetime.".

O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

2. How it is possible to investigate the PEP with VIP2

In Quantum Mechanics the PEP can be formalized starting from two fundamental principles:

1) All states, including those related to identical particles, are described in terms of wave functions

2) Bosonic and fermionic states have a different behavior in relation to the application of the exchange transformation (permutation) of identical particles: the former are symmetrical and the latter are anti-symmetrical

This superselection rule "does not appear as a necessary feature of the quantum-mechanical description of nature".

Messiah A.M.L. and Greenberg O.W.; *Physics Review* 1964, 136, B248.

States of mixed symmetry could, therefore, in principle, exist !!!

Possible existence of particle states that follow a different statistic than the fermionic or bosonic one.

2. How it is possible to investigate the PEP with VIP2

A small violation of PEP in atoms can be described in Quantum Mechanics as proposed by Greenberg in **O.W. Greenberg, Nucl. Phys. B (Proc. Suppl.)6, 83–89(1989):**

"Whenever an electron is captured by an atom, a new state is formed that can have a certain probability of being a mixed symmetry state. This state is highly excited and from its decay one could observe a possible transition prohibited by the PEP."

The Messiah-Greenberg superselection rule prevents transitions among states with different symmetry.

The experimental method of VIP2 is based on the application of a DC current to a copper bar.

Newly-injected electrons can interact with copper atoms in an open quantum system which fulfill the Messiah-Greenberg superselection rule.

2. How it is possible to investigate the PEP with VIP2

Experimental goal: Search for X-rays from PEP violating transitions

Energy transition Kα allowed: **8.05 keV in Cu**

PEP forbidden Kα energy transition: **~ 7.74 keV in Cu**

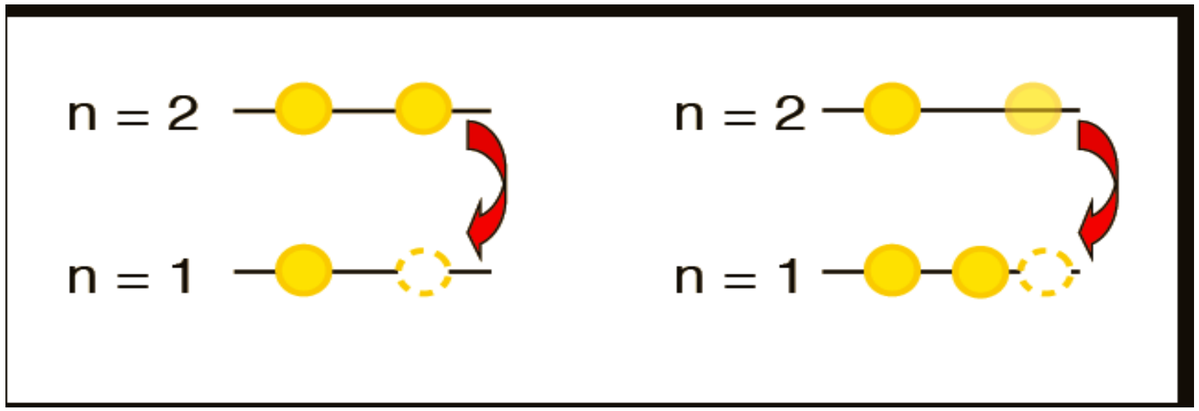
C. Curceanu, L. De Paolis et al., "Evaluation of the X-ray transition energy for the Pauli-principle-violating atomic transitions in several elements by using Dirac-Fock method", 2013, INFN-13-21/LNF.

MULTICONFIGURATIONAL DIRAC-FOCK METHOD

Software for muon atoms adapted to non-antisymmetric electrons

Parameter optimization through a self-consistent process

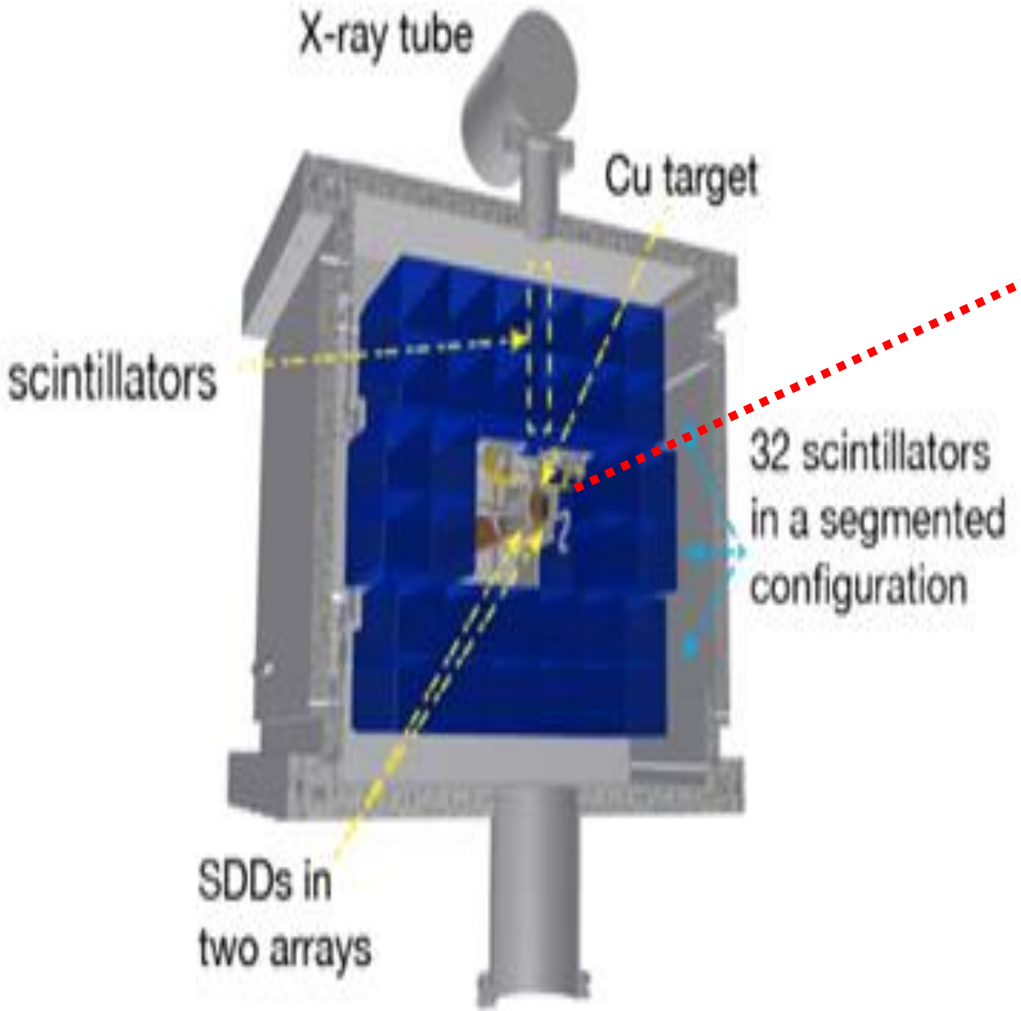
It takes into account: relativistic and radiative corrections, lamb-shift, Breit operator, ...



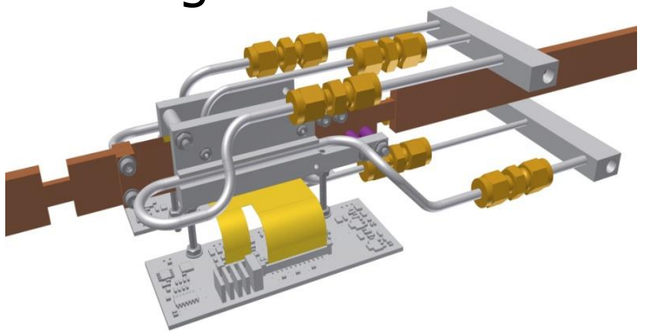
An e- in any level n>2 make a transition to level 2P.
The non-Paulian transition to level 1S produces the emission of a PEP violating X-ray.

The VIP2 experiment: purpose and apparatus.

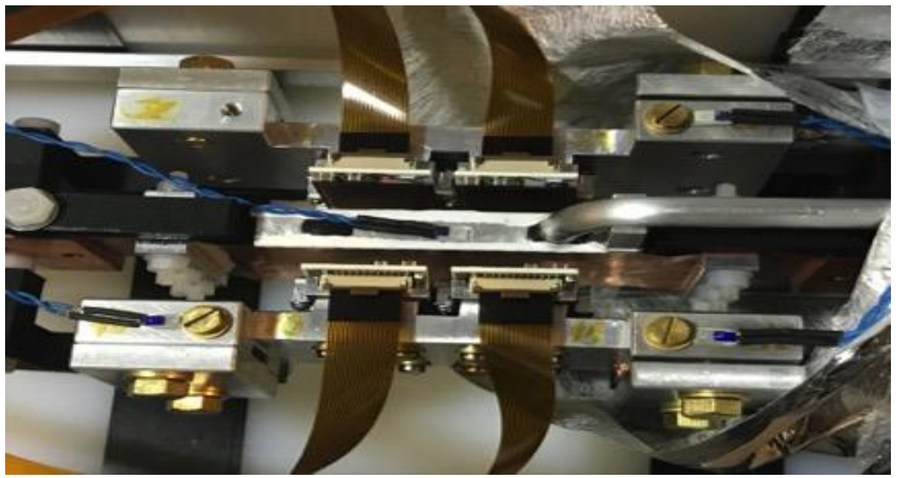
Schematization of the VIP2 chamber:



Target of VIP2



Characteristics of the target: the 2 strips (7 cm x 2 cm x 25 µm) are connected to an external generator by 2 thin copper bars.



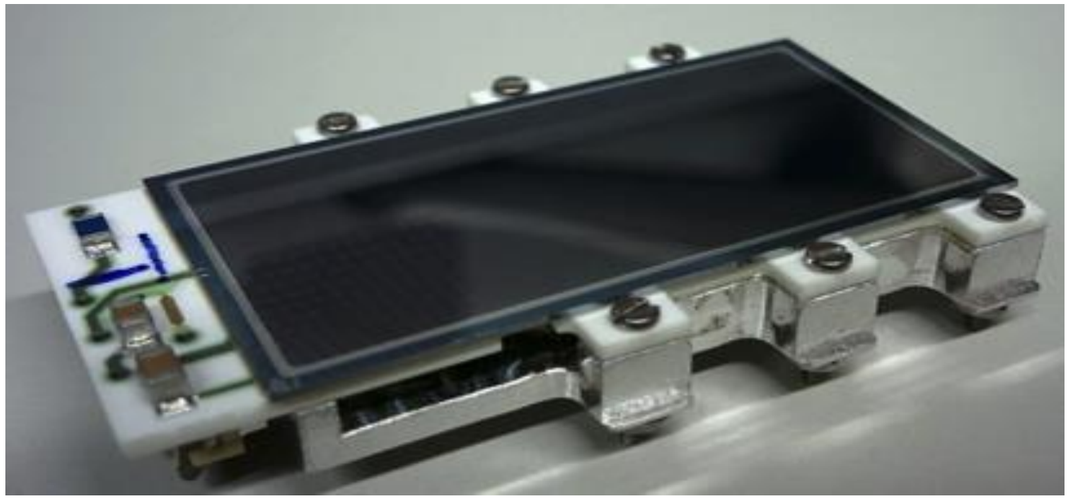
Due to the Joule effect, the current(100 A) is heating the target to 20 ° C. A water circuit cools them so that the temperature of the SDDs does not increase by more than 2K.

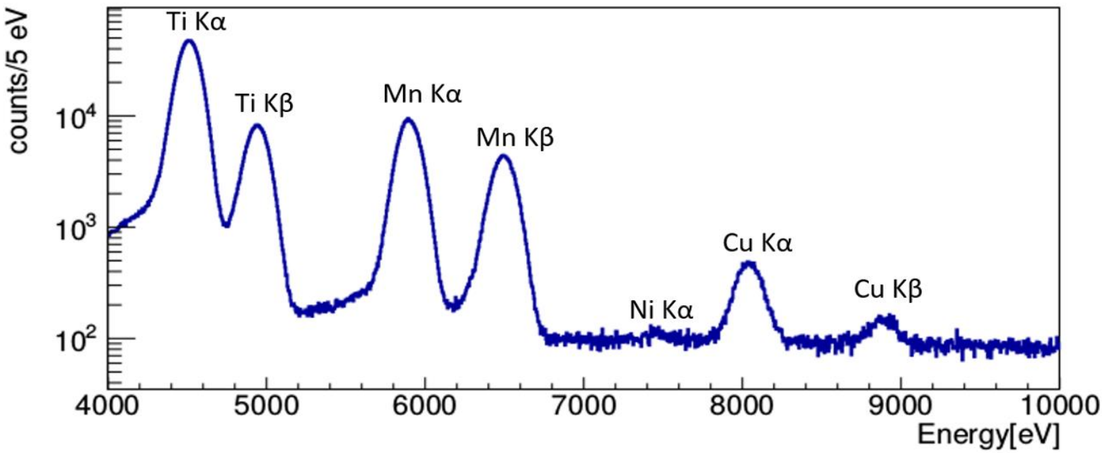
The VIP2 experiment: Silicon Drift Detectors (SDDs)

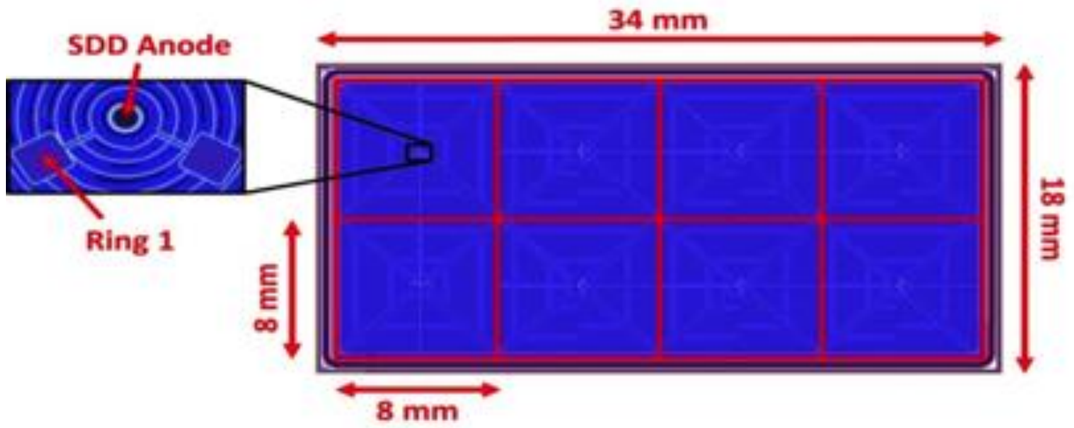
In the VIP2 apparatus, detectors are organized in 4 arrays, each consisting of 2 x 4 SDDs, for a total of 32 detector installed in the apparatus and placed two each side of the target.

Each SDD cell has an active area of 64 mm^2 and a thickness of 450 μm.

The SDD detectors are cooled to T≈ 110 K by a liquid Argon circuit, thus providing a resolution of **170 eV at 8 KeV** and a **detection efficiency > 95 %** in that energy region.

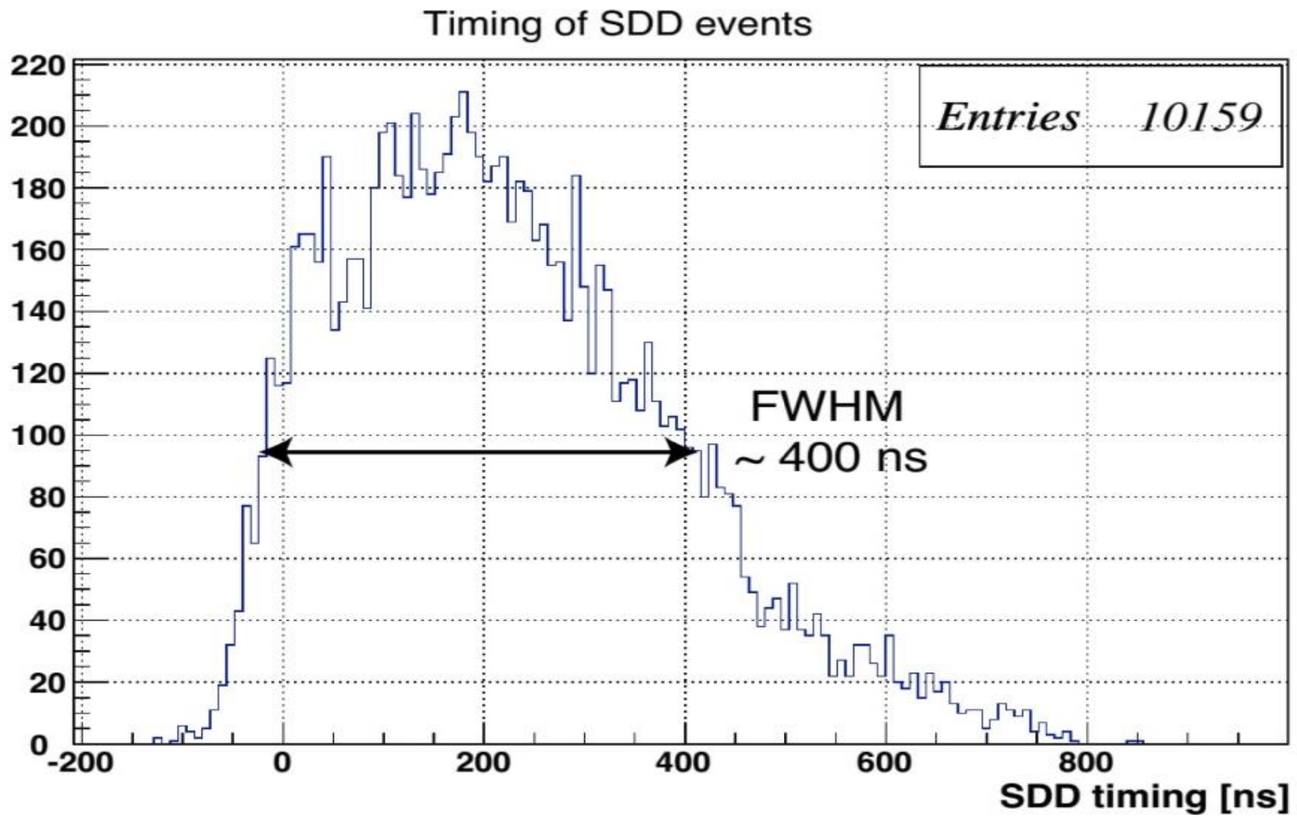






The VIP2 experiment: Silicon Drift Detectors (SDDs)

The SDD detectors provide information on radiation energy and **timing**.



SDDs provide a timing resolution of **400 ns (FWHM)**, tested at Stefan Meyer Institute of Vienna using plastic scintillators

A VETO SYSTEM WAS INSTALLED IN THE VIP2 APPARATUS, WHICH TAKE ADVANTAGE FROM SDD TEMPORAL RESPONSE TO DISCRIMINATE THE BACKGOUND EVENTS

SDD detectors are the main key to the upgrade of VIP to VIP2. They provide:

- An energy resolution half of the previously used Charge Coupled Devices (CCDs)
- A halving of the Region Of Interest (ROI) for PEP-violating Kα transition in copper
- A timing resolution sufficient for veto system implementation to reduce background

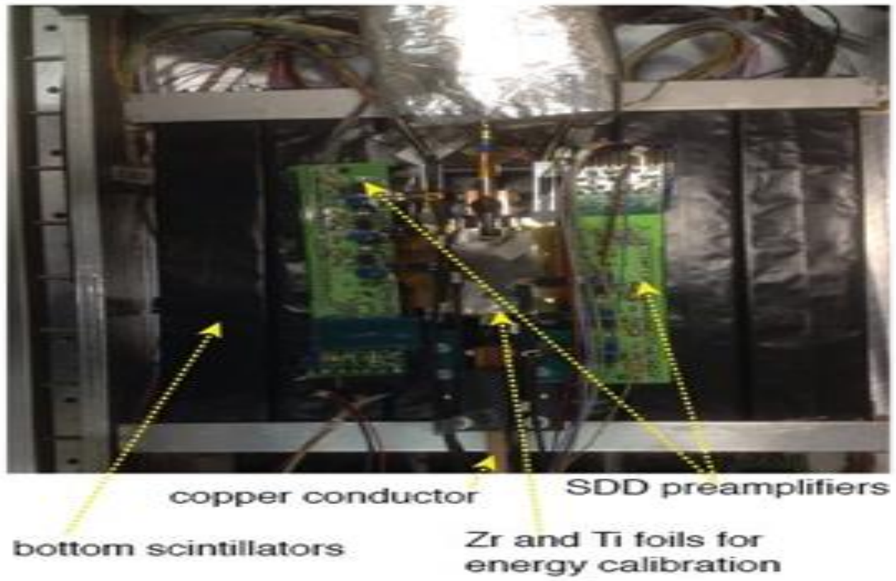
The VIP2 experiment: the VETO system

Used to select incident events with high energy RC unshielded from rock and environmental background.

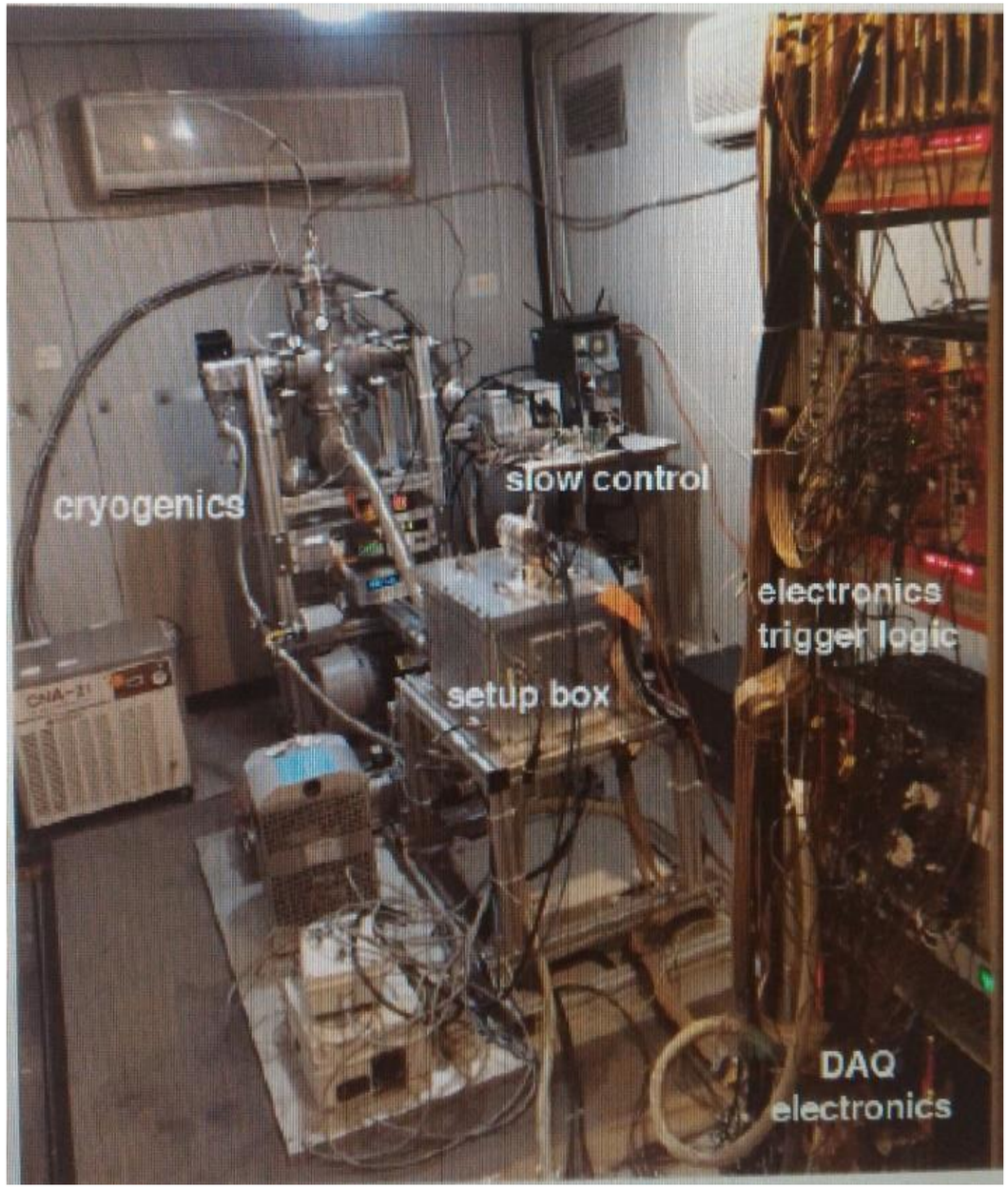
Composed of 32 plastic scintillators measuring $45\,cm \times 3\,cm \times 3\,cm$ and covering a solid angle > 90% compared to the target.

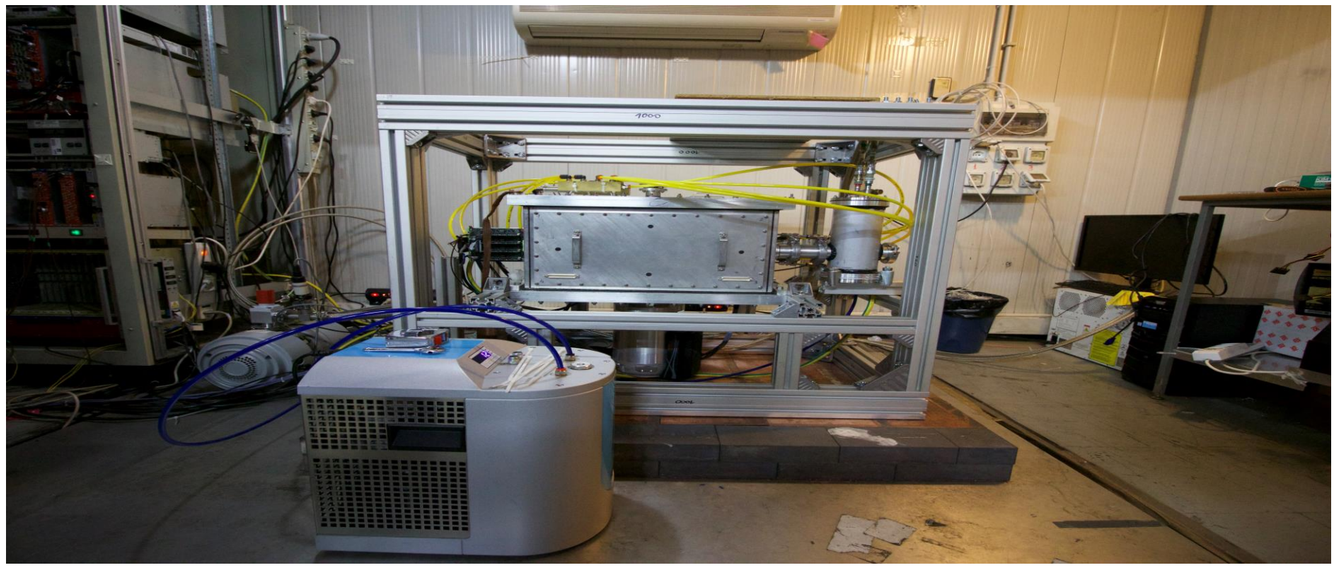
They are read by pairs of SiPM (with $3 \times 3\,cm^2$ of active surface each) located at both ends.

THE ACTIVE SHIELD ALLOWS TO REDUCE THE BACKGROUND IN THE RANGE OF INTEREST FOR A VIOLATION X-RAY OF ABOUT 1 ORDER OF GRANDNESS



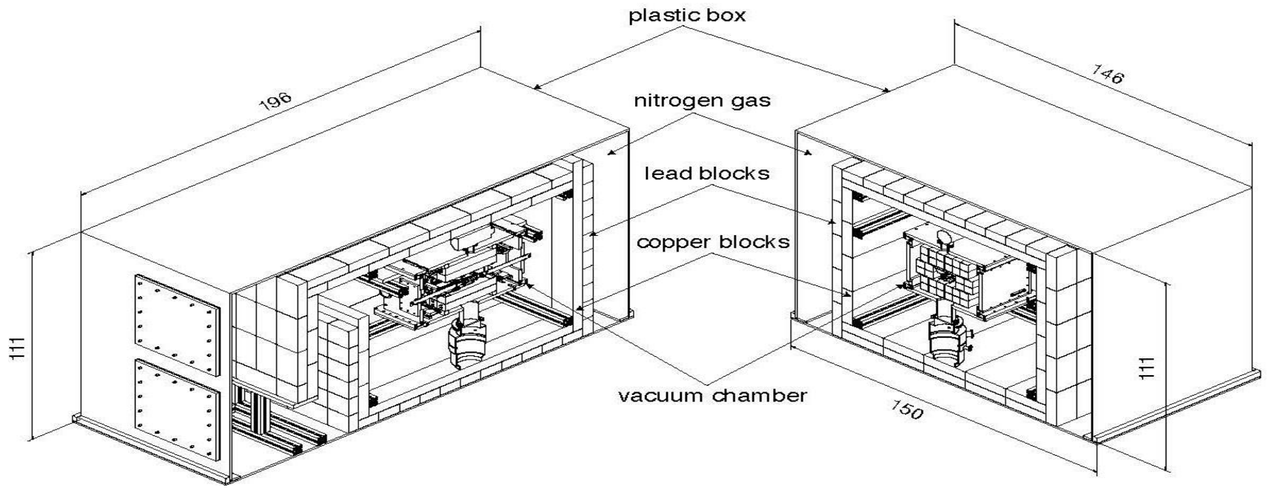
The VIP-2 experiment: photos of the apparatus





Passive shield of VIP-2 apparatus installed in 2018

In November 2018 the final configuration of the VIP-2 experimental apparatus was completed with the passive shielding, made of two layers of lead and copper blocks.

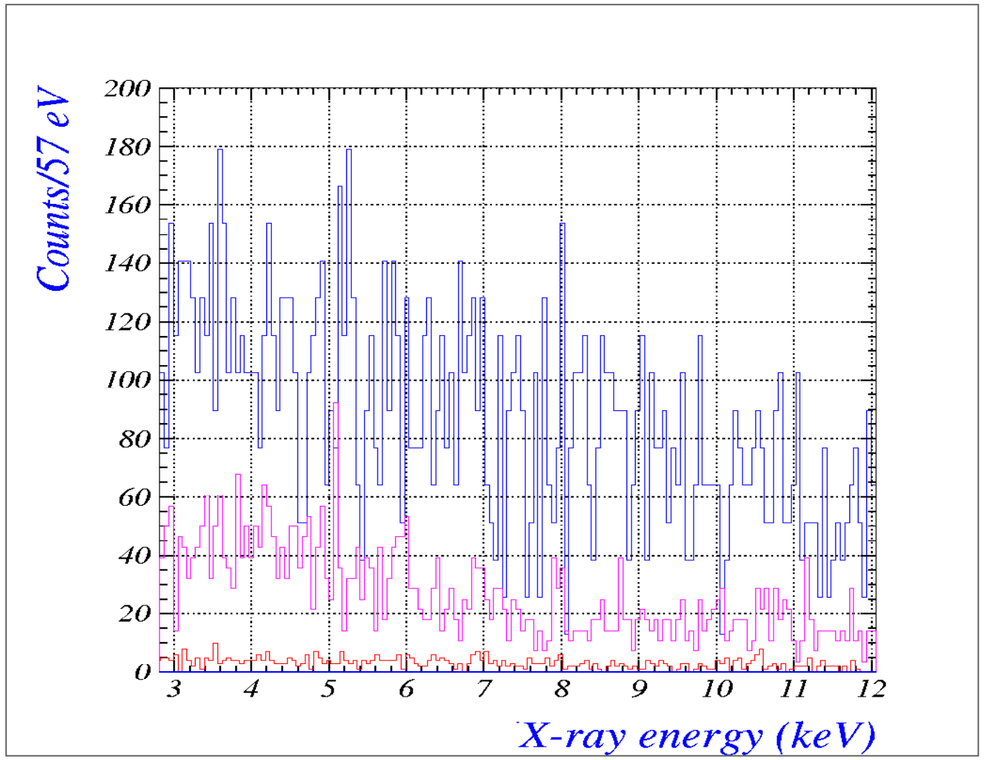


The passive shield will kill most of the background due to environmental gamma radiation.

The VIP-2 experiment: location.

The experiment is taking place at National Laboratories of Gran Sasso (LNGS), an extremely low background environment inside the Gran Sasso mountain: overburden corresponding to a minimum thickness of 3100 m w.e.

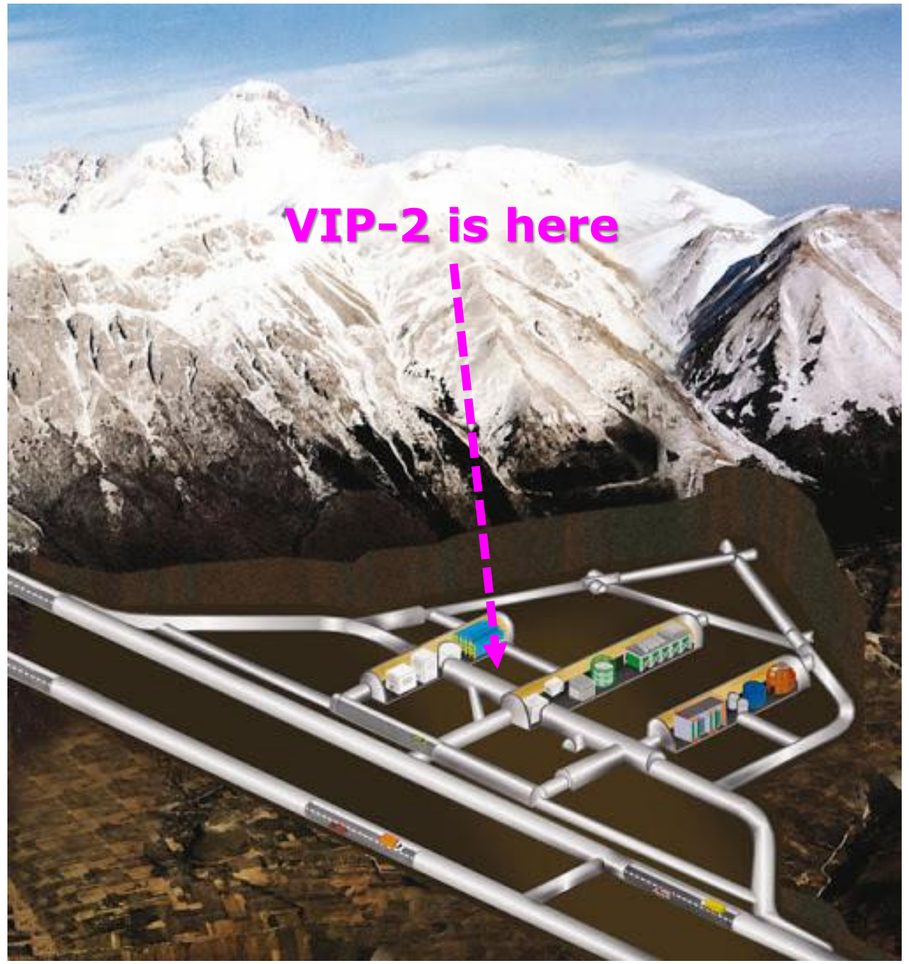
Graphic result of a test done with 2 CCD and normalized distribution



— LNF no sh.

— LNF with sh.

— LNGS with sh.



The background is reducted by a factor ≈ 20

The VIP-2 experiment: Improvements and goal

Improvements made compared to VIP:

- More compact system → improves acceptance
- New target → 2 strip 7 cm x 2 cm x 25 μm
- Different cooling system for target (water)
- Current flowing into the target > 100 A
- New detectors SDD with better resolution and higher efficiency, cooled with liquid Argon (110 K).
- Veto system with plastic scintillators read by SiPM (Silicon Photomultiplier) reducing background in ROI of one order of magnitude.

FUTURE GOAL

$$\frac{\beta^2}{2} < 4.7 \times 10^{-29} \rightarrow 10^{-31}$$

DATA TAKING: 3-4 YEARS

Progresses in the VIP-2 experiment

The VIP2 experiment is presently in data taking at LNGS!!!

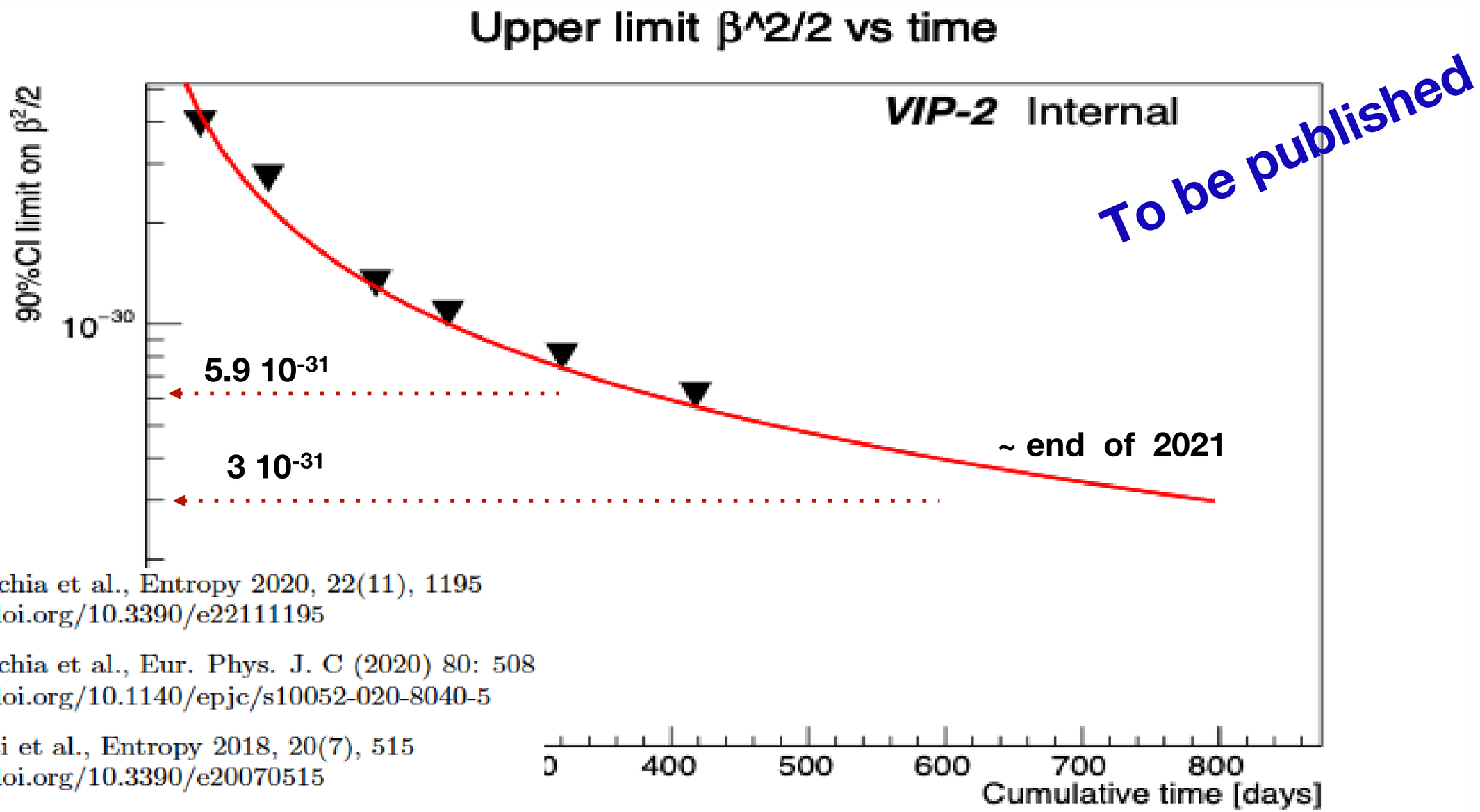
Meanwhile, us collaboration is actively analyzing data and improving data analysis systems and procedure:

- **Regular data taking** is still going on by **alternating periods** of data taking with current (**100 A**) and without current (**0 A**).
- An **optimization of the Slow Control system** was performed which allow to completely control from remote data taking and experimental parameters
- A **continuous energy calibration** is performed on the detectors to reach high precision spectra.
- **New data analyses methods are being studied and improved**:
  - Frequentistic modified analysis
  - Refined Bayesian analyses

  } → to extract the limit on PEP probability violation

  - Test PEP in bulk matter and semi-analytical Monte Carlo methods to simulate the signal of the VIP-2 experiment

VIP-2 Sensitivity projection against time



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THANK YOU FROM VIP2 COLLABORATION AND FROM THE PEP-VIOLATING ELECTRON