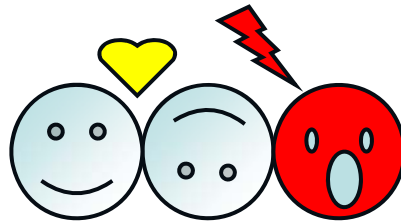


***New experimental limit on the
Pauli Exclusion principle violation
by electrons (the VIP experiment)***



Catalina Curceanu, LNF-INFN
On behalf of the VIP collaboration

DISCRETE08, Valencia 11-16 December 2008

THE VIP COLLABORATION

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PEP lacks a clear, intuitive explanation

... Already in my original paper I stressed the circumstance that I was unable to give a logical reason for the exclusion principle or to deduce it from more general assumptions.

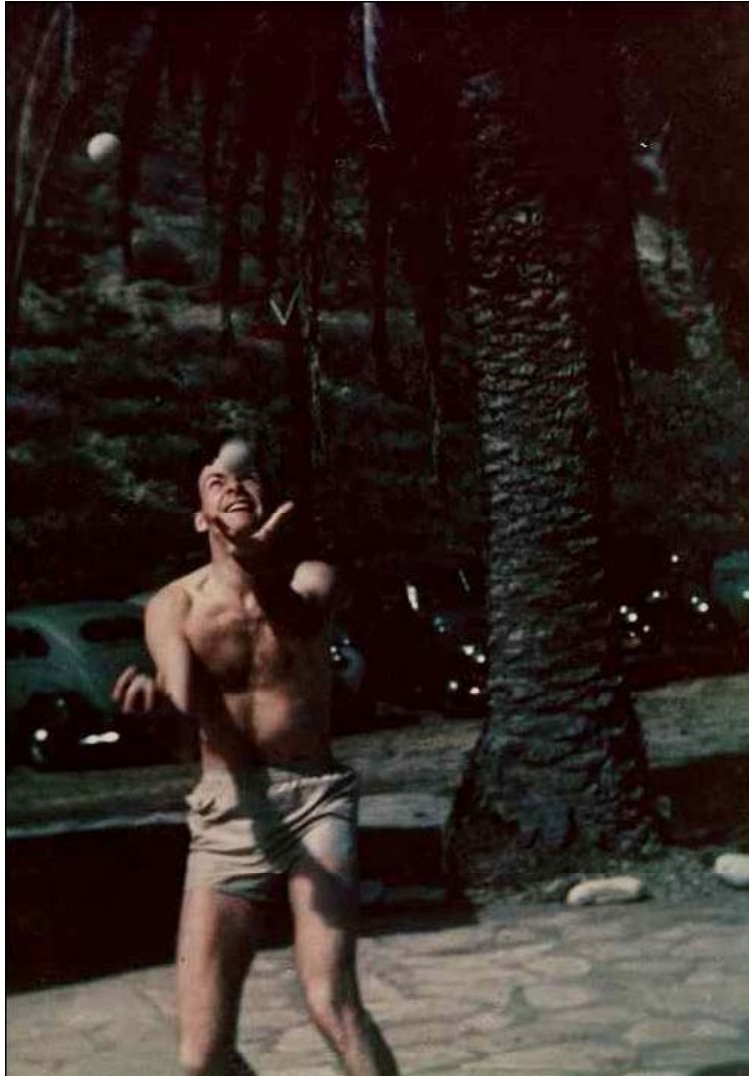
I had always the feeling and I still have it today, that this is a deficiency.

... The impression that the shadow of some incompleteness [falls] here on the bright light of success of the new quantum mechanics seems to me unavoidable.

W. Pauli, Nobel lecture 1945 (50 years from his death – 15 december)



Feynman Lectures on Physics



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This brings up an interesting question: Why is it that particles with half-integral spin are Fermi particles (...) whereas particles with integral spin are Bose particles (...)?

We apologize for the fact that we can not give you an elementary explanation.

An explanation has been worked out by Pauli from complicated arguments from quantum field theory and relativity. He has shown that the two must necessarily go together, but we have not been able to find a way to reproduce his arguments on an elementary level. It appears to be one of the few places in physics where there is a rule which can be stated very simply, but for which no one has found a simple and easy explanation. (...)

This probably means that we do not have a complete understanding of the fundamental principle involved. For the moment, you will just have to take it as one of the rules of the world

*At the root of the Exclusion Principle:
proof of spin-statistics theorem by Lüders and Zumino*

Postulates:

- I. The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)
- II. Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality - microcausality)
- III. The vacuum is the state of lowest energy
- IV. The metric of the Hilbert space is positive definite
- V. The vacuum is not identically annihilated by a field

From these postulates it follows that (pseudo)scalar fields commute and spinor fields anticommute.

(G. Lüders and B. Zumino, Phys. Rev. **110** (1958) 1450)

Theories of Violation of Statistics

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

“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. Of these (a) seems unlikely because the quon theory which obeys CPT allows violations, (b) seems likely because if locality is satisfied we can prove the spin-statistics connection and there will be no violations, (c), (d), (e) and (f) seem possible.....

Hopefully either violation will be found experimentally or our theoretical efforts will lead to understanding of why only Bose and Fermi statistics occur in Nature.”

***VIP is an experiment to test the Pauli
Exclusion Principle (PEP) for electrons in a
clean environment (LNGS).***

Goal of VIP

The VIP experiment has the scientific goal of reducing by four orders of magnitude the limits on the probability of a possible violations of the Pauli exclusion principle for the electrons

From:

$$\beta^2 / 2 \leq 1.7 \cdot 10^{-26} (> 95\% \text{ C.L.})$$

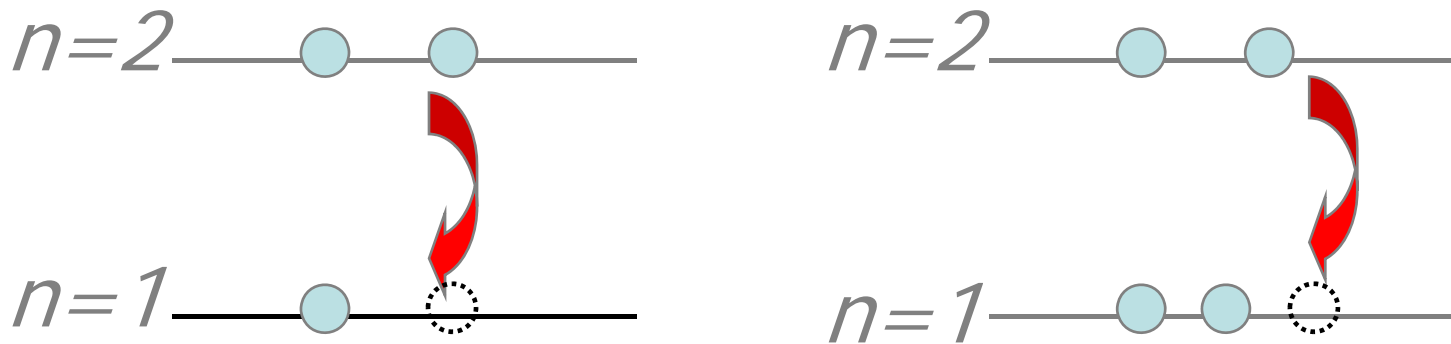
(Ramberg & Snow -1990)

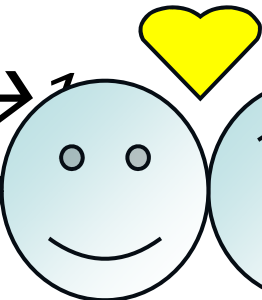
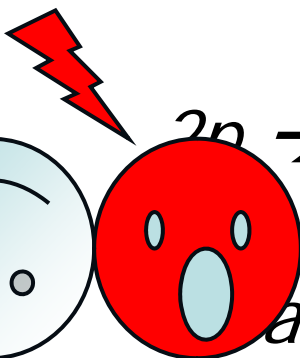
to

$$\beta^2 / 2 \leq 10^{-30}$$

Experimental method

Search for anomalous X-ray transitions



Normal $2p \rightarrow 1s$ transition  $2p \rightarrow 1s$ transition violating Pauli principle 

8.05 keV in Cu

~ 7.7 keV in Cu

Transition energies of the anomalous X-rays in Copper

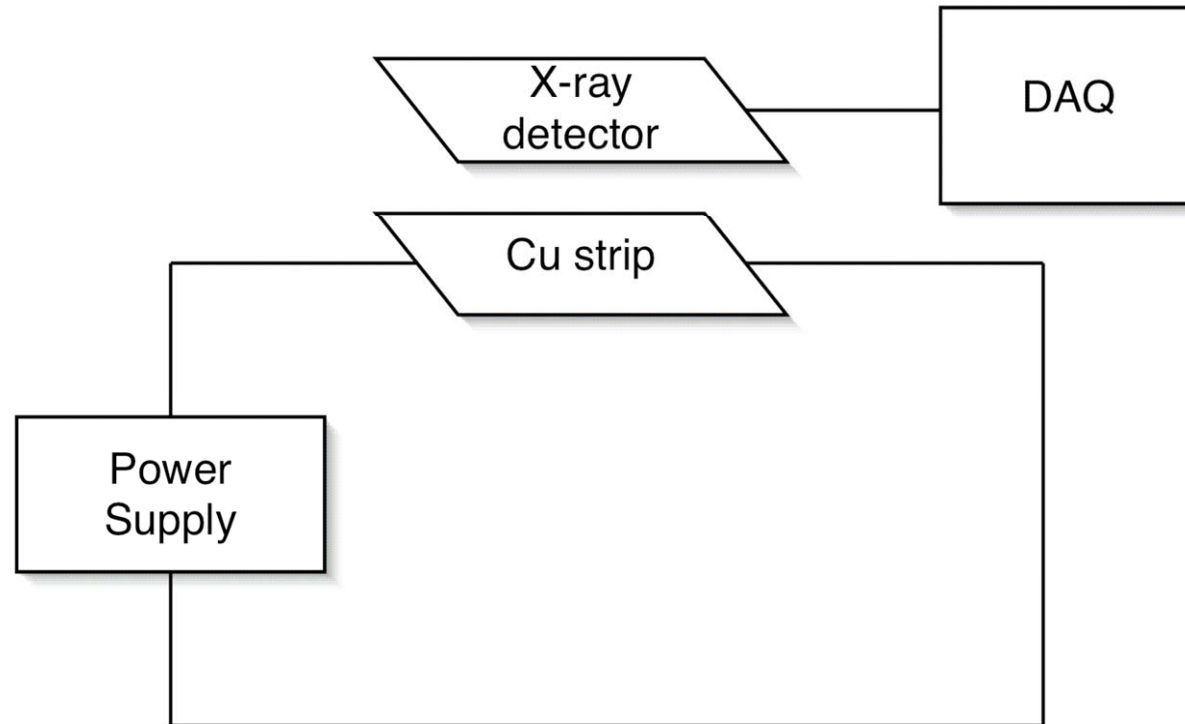
Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)
Multiconfiguration Dirac-Fock approach

core: $(1s)^2(2s)^2(3s)^2(2p^*)^2(3p^*)^2(2p)^4(3p)^4(3d^*)^4(3d)$

| Transition | Initial en. | Final en. | Transition energy | Radiative transition rate (s ⁻¹) | Multipole order | |
|-----------------------|-------------|-----------|-------------------|--|-----------------|--------------|
| $2p_{1/2} - 1s_{1/2}$ | -45799 | -53528 | 7729 | 2.63E+14 | E1 | } K_α |
| $2p_{3/2} - 1s_{1/2}$ | -45780 | -53528 | 7748 | 2.56E+14 | E1+M2 | |
| $3p_{1/2} - 1s_{1/2}$ | -44998 | -53528 | 8530 | 2.78E+13 | E1 | } K_β |
| $3p_{3/2} - 1s_{1/2}$ | -44996 | -53528 | 8532 | 2.68E+13 | E1+M2 | |

• Normal copper: ~ **8040 eV** ($2p \rightarrow 1s$)

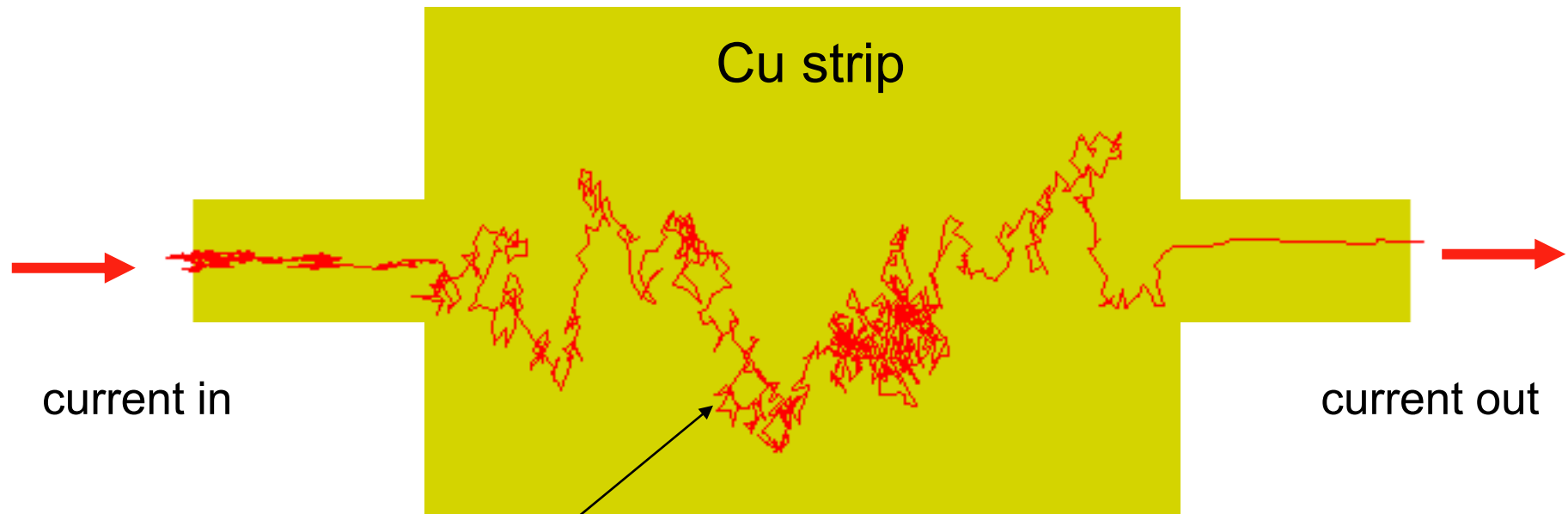
The (previous) Ramberg & Snow experiment



(Experiment performed in the Muon building at Fermilab)

E. Ramberg and G. A. Snow, Phys. Lett. **B238** (1990) 438

random walk of the conduction electrons in the copper strip



current in

current out

electrons may be captured by copper atoms in the strip

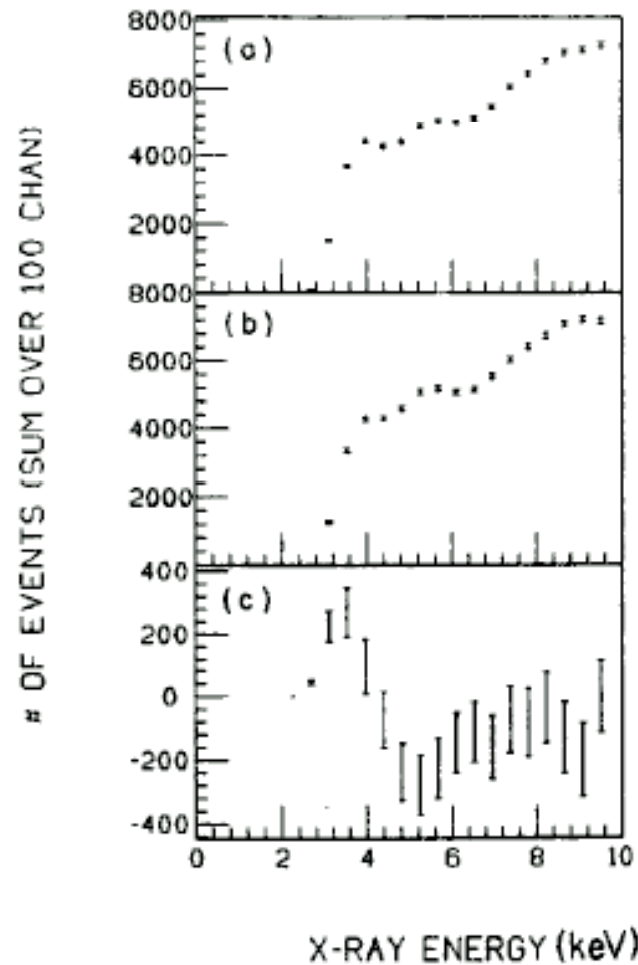


Fig. 2. (a) Number of triggers summed over 100 ADC channels, plotted versus equivalent X-ray energy with current-on in copper strip below X-ray counter. (Note the points are separated by 50 channels, so that only every other point is statistically independent). (b) Same as (a) but with no current passing through an identical strip of copper. (c) Difference between (a) and (b) after normalization at the 9.5 keV point.

Ramberg & Snow calculation

$$N_x \geq \frac{1}{2} \beta^2 N_{new} \frac{N_{int}}{10} =$$
$$= \frac{\beta^2 (\Sigma I \Delta t) D}{e \mu \rho z \sigma}$$

$$\int_T I(t) dt = 15.44 \cdot 10^6 \text{ C}$$

$$D = 0.025 \text{ m}$$

$$\mu = 3.9 \cdot 10^{-8} \text{ m}$$

$$\rho = 8.96 \cdot 10^3 \text{ kg} \cdot \text{m}^{-3}$$

$$\sigma = 10 \text{ m}^2 \cdot \text{kg}^{-1}$$

$$z = 1.5 \cdot 10^{-3} \text{ m}$$

$$N_x \geq \beta^2 (0.90 \cdot 10^{28})$$

$$\beta^2 / 2 \leq 1.7 \cdot 10^{-26} (> 95\% \text{ C.L.})$$

The parameter β

Ignatiev & Kuzmin model \rightarrow creation and destruction operators connect 3 states

- the vacuum state $|0\rangle$
- the single occupancy state $|1\rangle$
- the non-standard double occupancy state $|2\rangle$

through the following relations:

$$\begin{array}{ll} a^+|0\rangle = |1\rangle & a|0\rangle = 0 \\ a^+|1\rangle = \beta|2\rangle & a|1\rangle = |0\rangle \\ a^+|2\rangle = 0 & a|2\rangle = \beta|1\rangle \end{array}$$

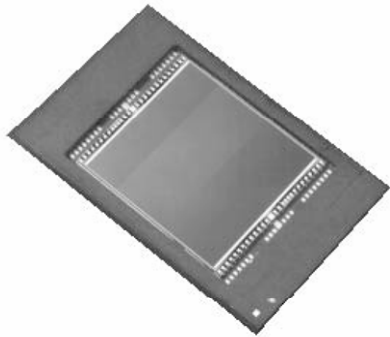
The parameter β quantifies the degree of violation in the transition $|1\rangle \rightarrow |2\rangle$. It is very small and for $\beta \rightarrow 0$ we can have the Fermi - Dirac statistic again.

The VIP experiment

VIP is a much improved version of the RS experiment:

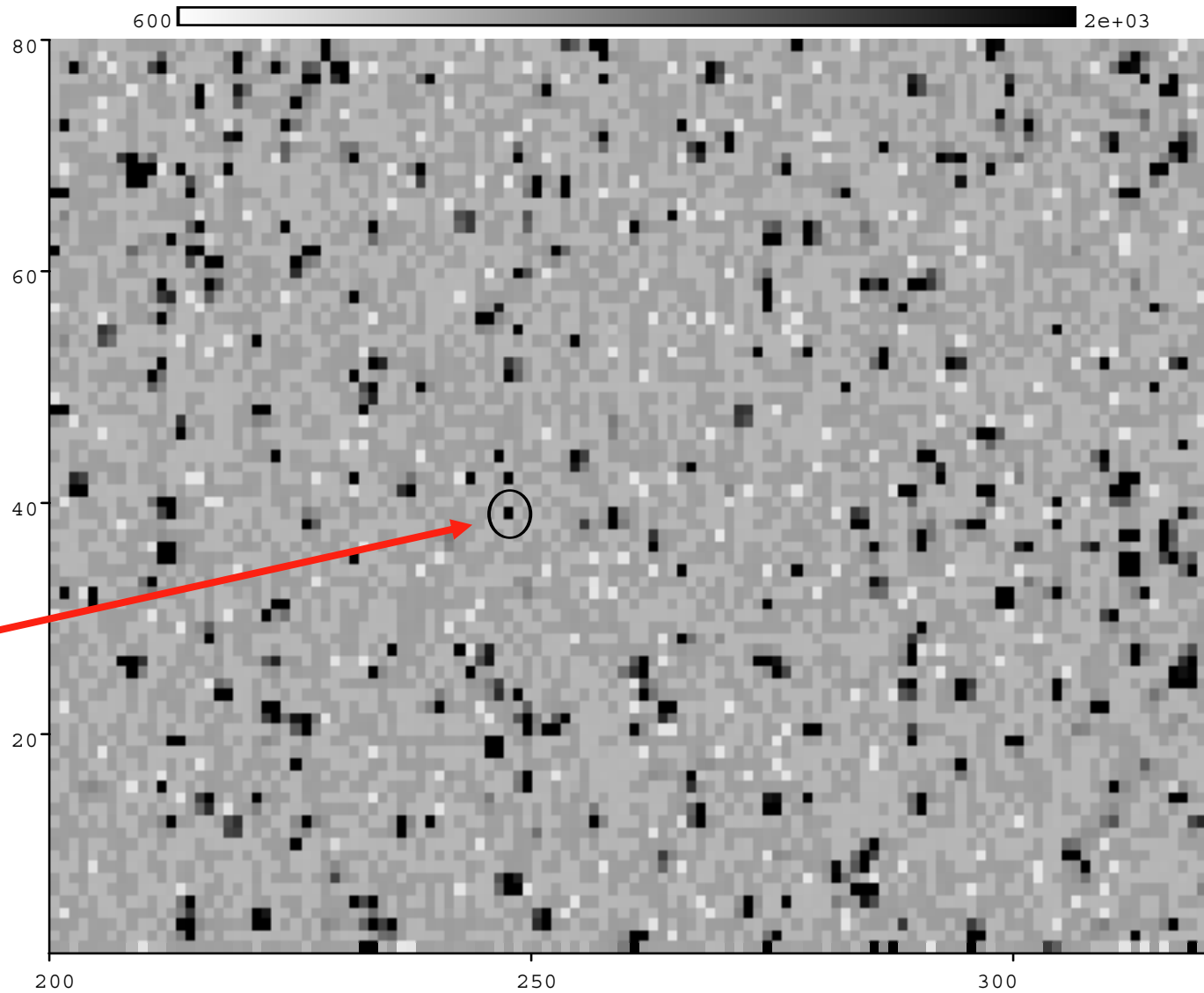
1. sensitive, large-area, X-ray detectors
2. clean, low-background experimental area (LNGS)
3. large “electron reservoir”

CCD's, the "secret weapon" of the VIP experiment ...



EEV CCD55
(1252 x 1152 pixels,
22.5 μm x 22.5 μm)

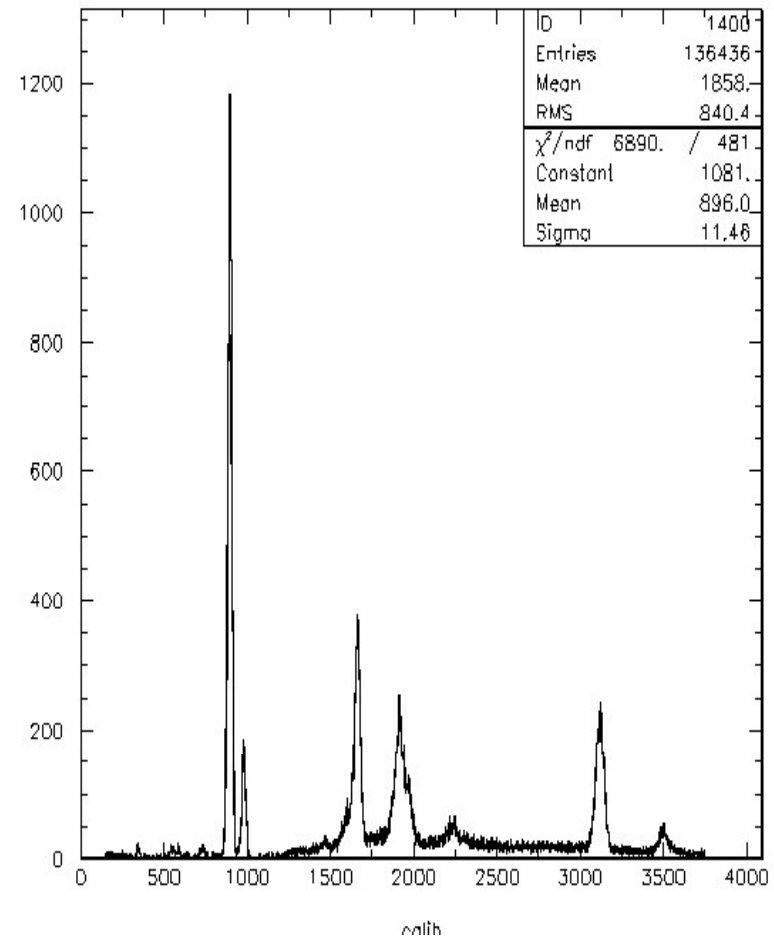
single pixel event,
X-ray photon



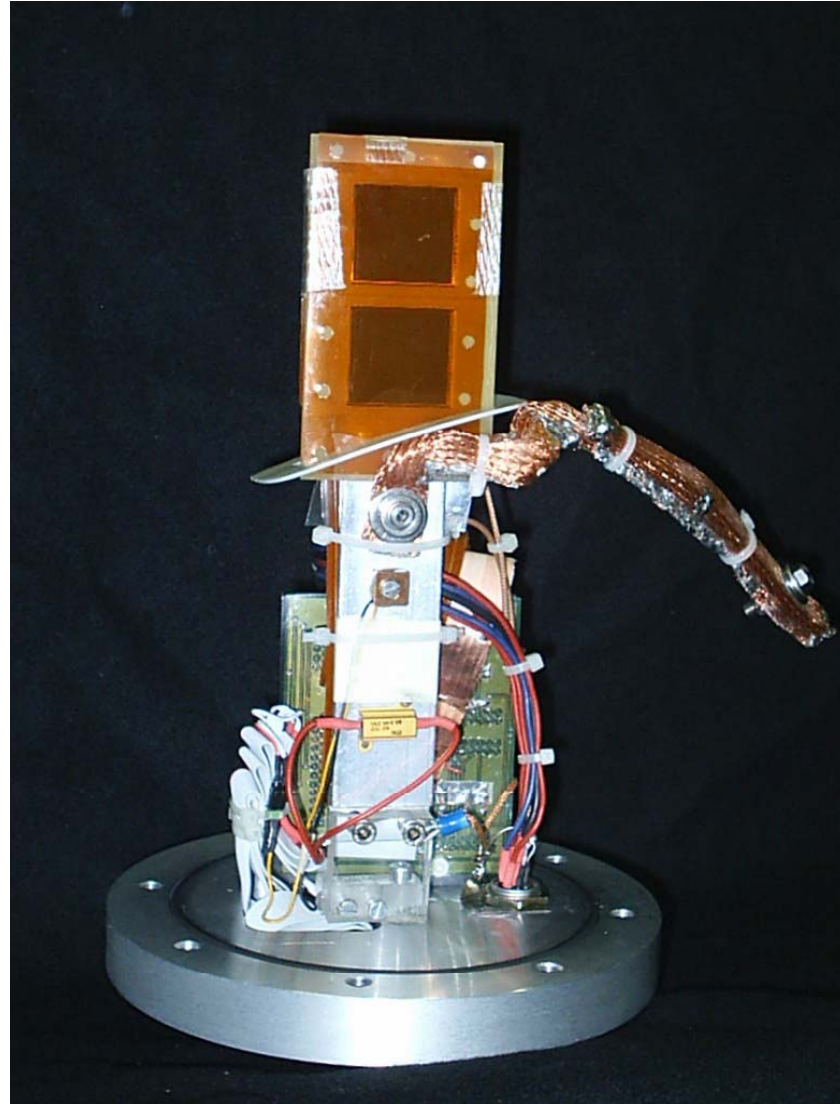
(for details on data analysis see Ishiwatari et al, NIM A556 (2006) 509)

CCD's have

- high efficiency
- exceptional energy resolution in the soft X-ray domain (≈ 1 KeV - 20 KeV)
- extremely high background rejection



2 CCD test setup: the CCD-55's and part of the readout electronics



Experimental activities since October 2004 (approval)

- ❑ ***November-December 2004: measurements with a 2-CCD test setup in the laboratory, with and without shielding;***
- ❑ ***End of December 2004: transportation and installation of the test setup at LNGS and first tests***
- ❑ ***21 February 2005 – 28 March 2005: 5 weeks of DAQ with shielding with the test setup at LNGS;***
- ❑ ***Spring-Autumn 2005: built components of the VIP setup; tests and assembly of the VIP apparatus at LNF;***
- ❑ ***21 November – 13 December 2005: 3 weeks of VIP DAQ at LNF;***
- ❑ ***Autumn 2005 – beginning 2006: preparation of the experimental site at LNGS;***
- ❑ ***February 2006: transportation and installation of the definitive VIP setup at LNGS and first measurements without shielding;***
- ❑ ***April 2006: installation of the final shielding for the VIP setup and start DAQ, with and without current.***

Test site and final location:

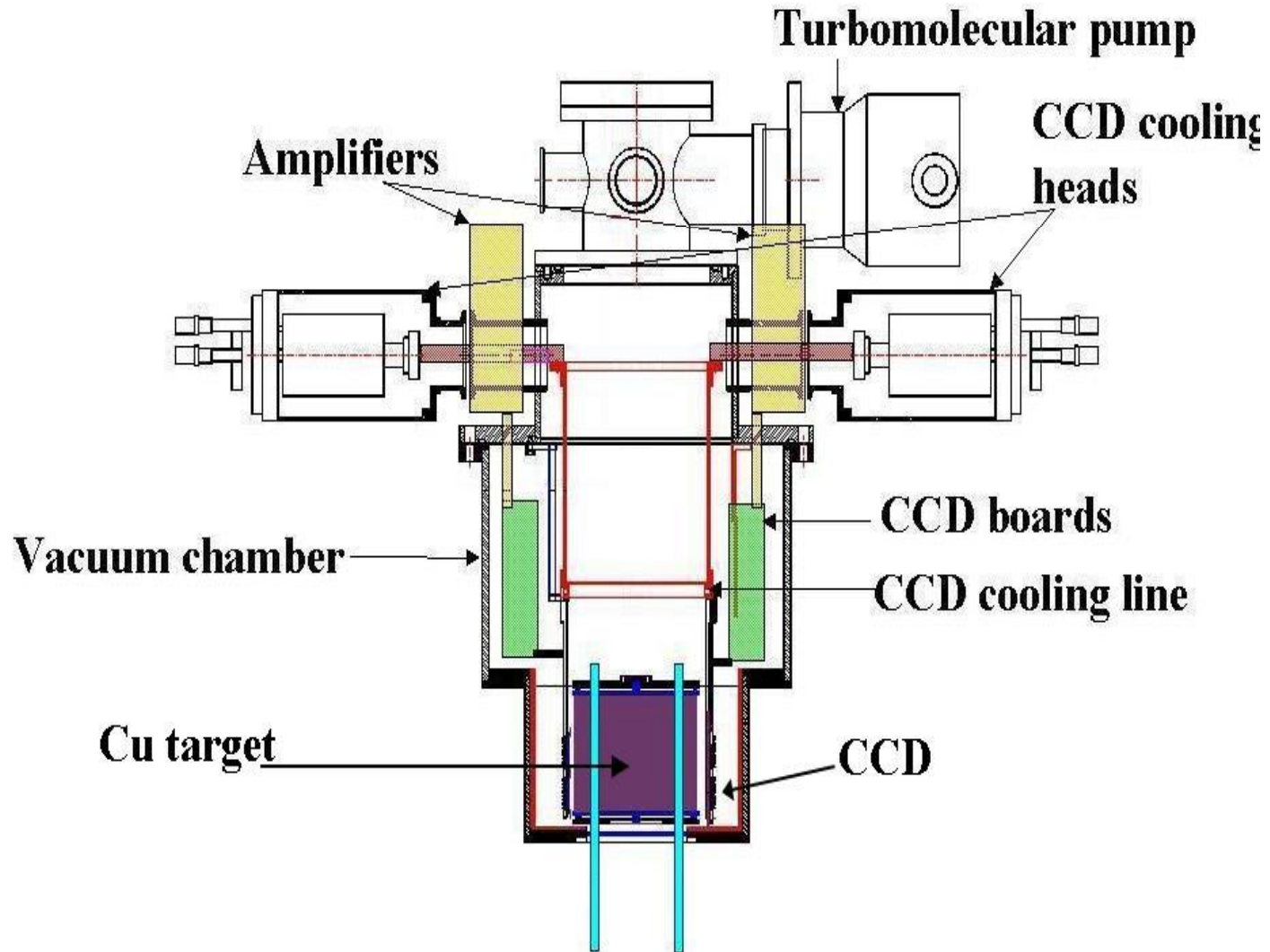
**Laboratori Nazionali del Gran Sasso,
Istituto Nazionale di Fisica Nucleare**



LNGS



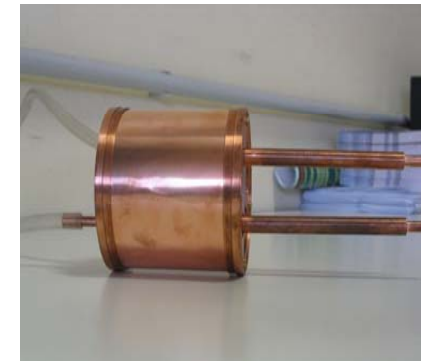
The VIP setup



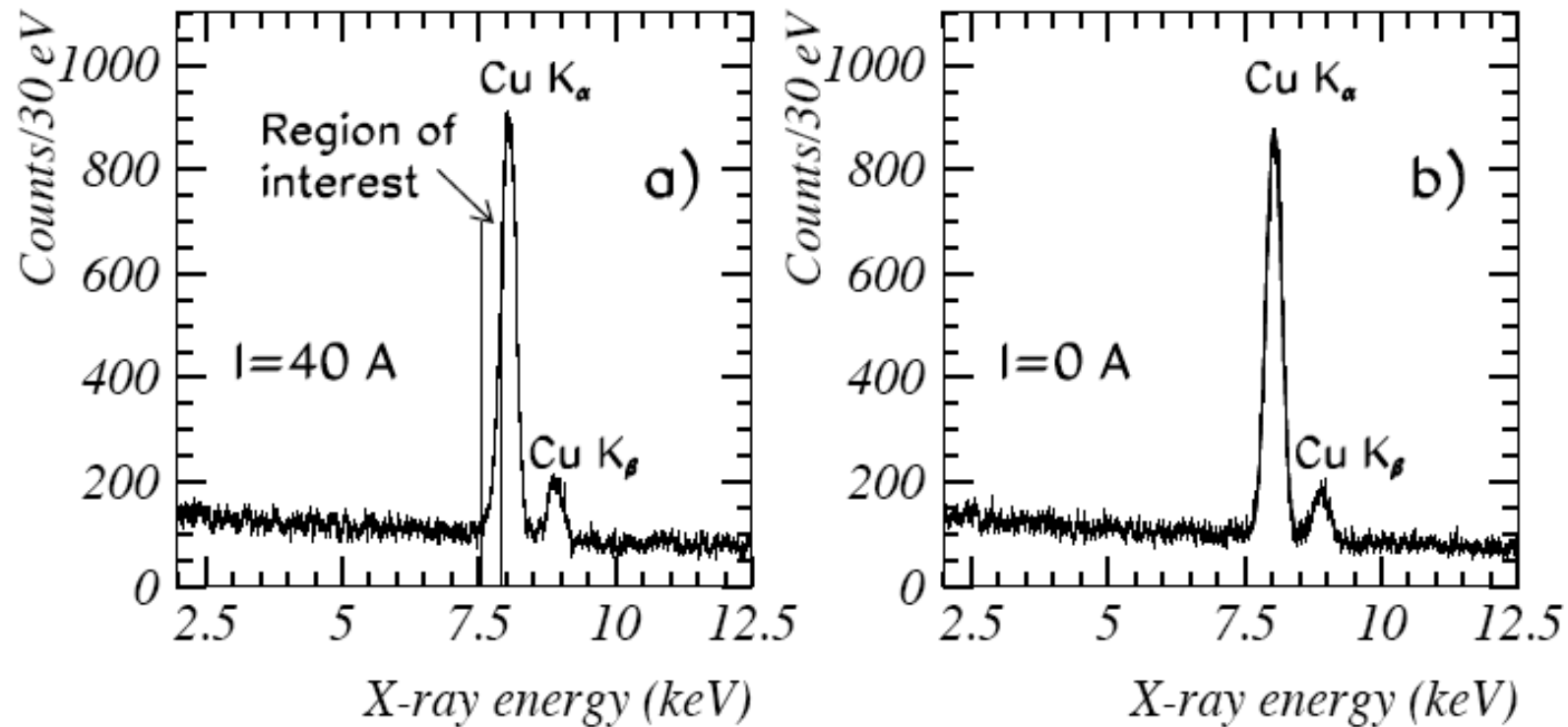
The VIP setup



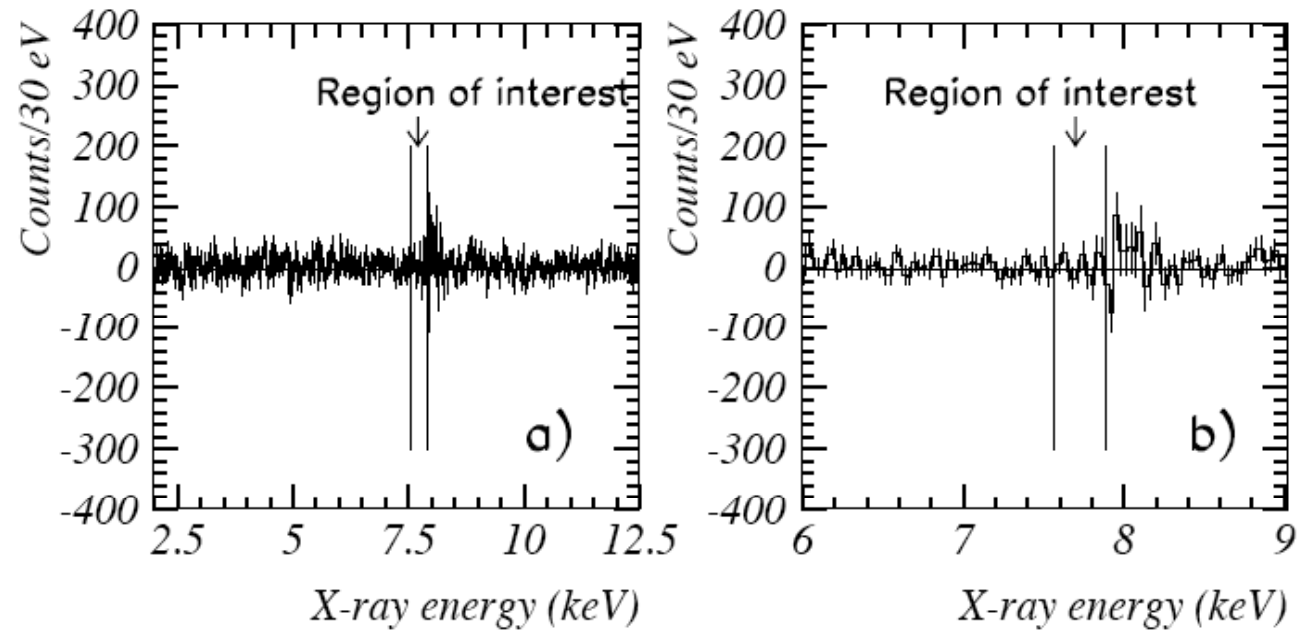
Cu Target



Final setup has been used for preliminary measurements at the LNF-Frascati laboratory – 21 nov. 2005 - 13 dec. 2005



subtracted spectra (“current” - “no current”)



First results

@ $I=40A \rightarrow N_x = 2721 \pm 52$

@ $I=0A \rightarrow N_x = 2742 \pm 52$

$$N_x \geq 4.9 \times 10^{29} \beta^2$$

We get for the PEP violating

$$\beta^2 / 2 \leq 4.5 \times 10^{-30} \quad (99.7\% \text{ C.L.})$$

Phys. Lett. B 641 (2006) 18

Factor 40 of improvement of the limit obtained by
Ramberg and Snow

Echos:

Papers about VIP result in:

-Pro-Physik and Frankfurter Allgemeine Zeitung, 20 Sept. 2006, N. 219

Pauli-Verbot überprüft

Elektronen erfüllen das Ausschließungsprinzip mit hoher Wahrscheinlichkeit.

Die quantenmechanische Beschreibung von Teilchen mit identischen Eigenschaften kennt zwei Möglichkeiten: Vertauscht man zwei der Teilchen miteinander, so bleibt die Wellenfunktion der Teilchen entweder unverändert oder sie wechselt ihr Vorzeichen. Im ersten Fall hat man es mit Bosonen zu tun, im zweiten mit Fermionen, zu denen die Elektronen gehören. Die Antisymmetrie der elektronischen Wellenfunktion hat zur Folge, dass sich niemals zwei Elektronen im gleichen Quantenzustand befinden sollten. Dieses von Wolfgang Pauli aufgestellte Verbot ist eine der Grundsäulen der Physik. Forscher in Italien haben das Pauli-Verbot jetzt mit großer Genauigkeit überprüft.

.....

Inzwischen hat die VIP-Kollaboration ihr Experiment unter die Erde verlegt und im Gran Sasso Laboratorium aufgebaut. Hier, durch 1400 Meter dickes Felsgestein von der kosmischen Strahlung abgeschirmt, sollen die Röntgenmessungen mit und ohne elektrischen Strom jeweils ein Jahr lang durchgeführt werden. Die Forscher hoffen, dadurch die Wahrscheinlichkeit für die Verletzung des Pauli-Verbots auf 10⁻³⁰ bis 10⁻³¹ genau testen zu können. Dieser Bereich ist deswegen interessant, weil sich hier alternative Theorien zum Standardmodell überprüfen lassen, die eine Verletzung des Pauli-Verbots erlauben.

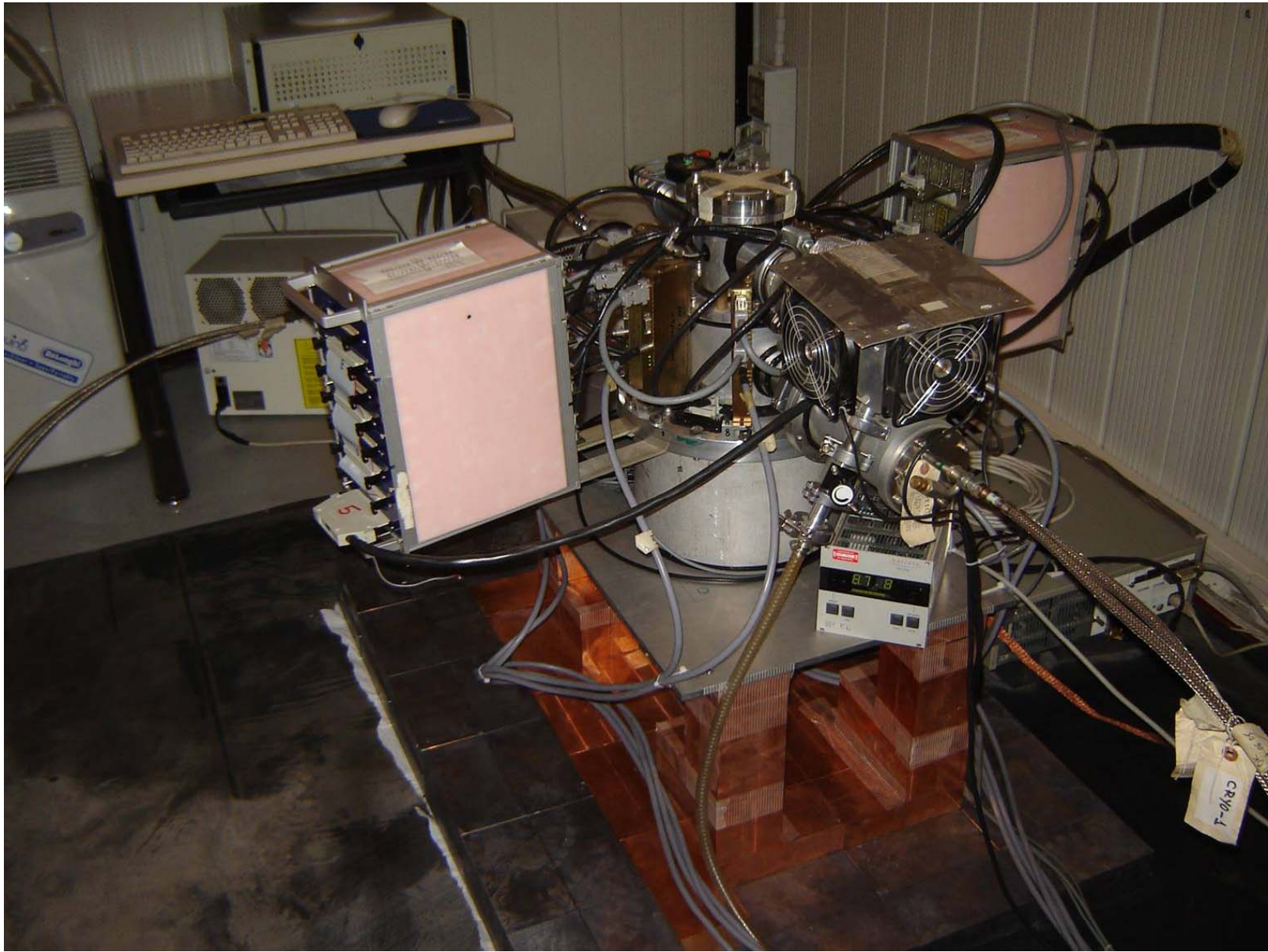
Rainer Scharf

Final setup at LNGS February 2006









Shielding installation in April 2006





VIP Experiment at LNGS Thu Apr 13 2006 12:19:35



Preliminary LNGS results

L. Sperandio Ph. D. Thesis

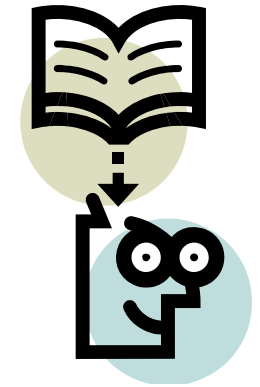
$$\beta^2/2 < 5.7 \times 10^{-29}$$

VIP setup at Gran Sasso

The VIP measurement will continue until early 2009 in the Gran Sasso-INFN underground laboratory, for bringing the limit of violation of the Pauli principle for electrons into the 10^{-29} ; -30 region, which is of particular interest, for all those theories related to the possible PEP violation coming from new physics.



Interpretation of VIP data



The interpretation of this class of experiments is often the hardest part.

In the face of the importance of the Pauli Exclusion Principle, there are only few and incomplete theoretical constructs that allow for a violation.

*At the root of the Exclusion Principle:
proof of spin-statistics theorem by Lüders and Zumino*

Postulates:

- I. The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)
- II. Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality - microcausality)
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From these postulates it follows that (pseudo)scalar fields commute and spinor fields anticommute.

(G. Lüders and B. Zumino, Phys. Rev. **110** (1958) 1450)

Theoretical and experimental aspects of the spin-statistics connection and related symmetries

*Stazione Marittima Conference Center
Trieste, Italy
21-25 october 2008*

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<http://www.ts.infn.it/eventi/spinstat2008/home.html>

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e-mail: spinstat2008@ts.infn.it

Organized by I.N.F.N. and by the University of Trieste, Italy

The workshop will focus on the spin-statistics connection and on related symmetries, both from the theoretical and from the experimental point of view. The workshop will bring together experimentalists, theorists, and philosophers to survey work done during the past years that challenges the traditional views of these issues. The workshop will also explore connections with rapidly developing fields such as other fundamental symmetries, supersymmetry and

2009:

Feasibility test for VIP2

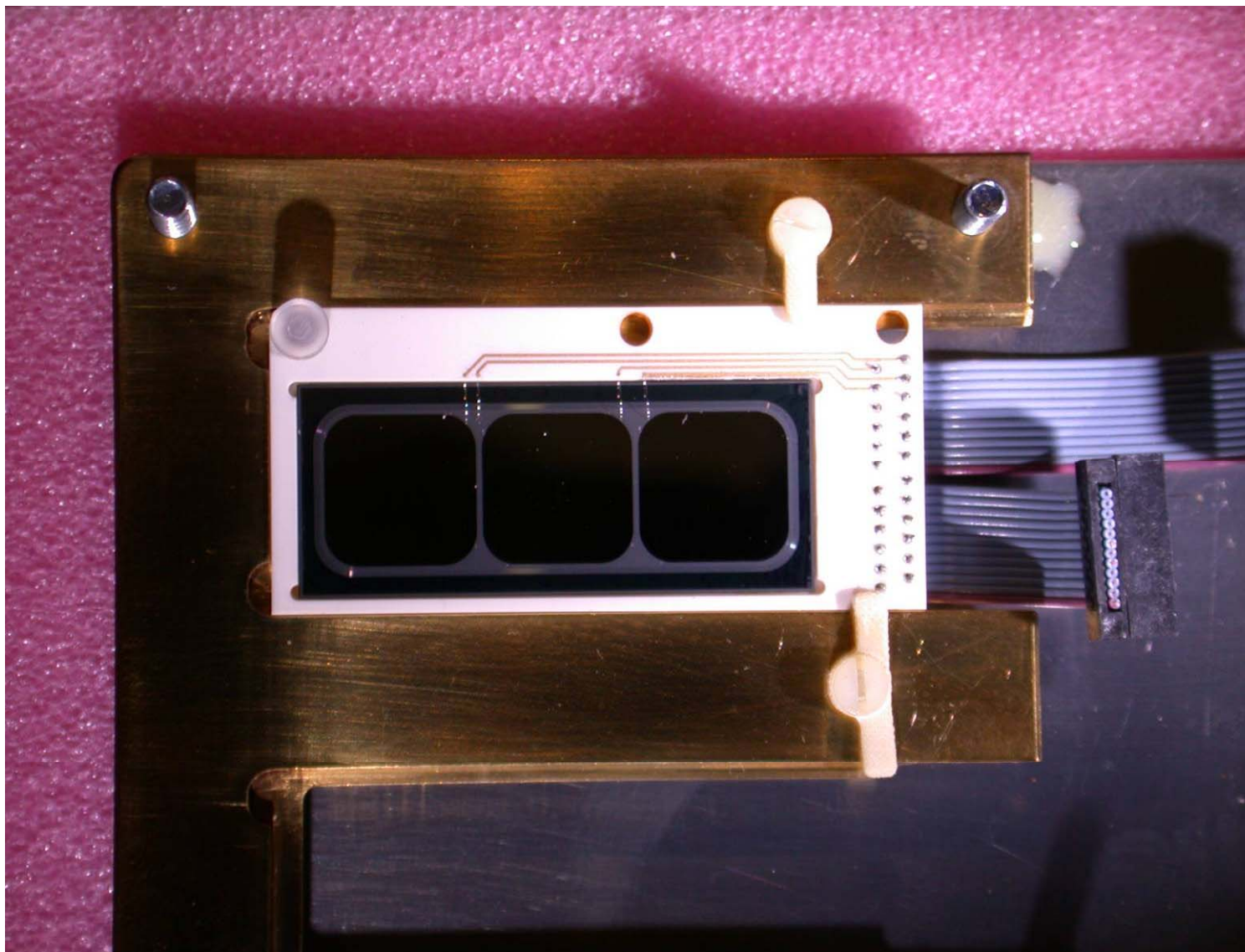
CCD -> SDD detectors

(triggerable) – active shielding

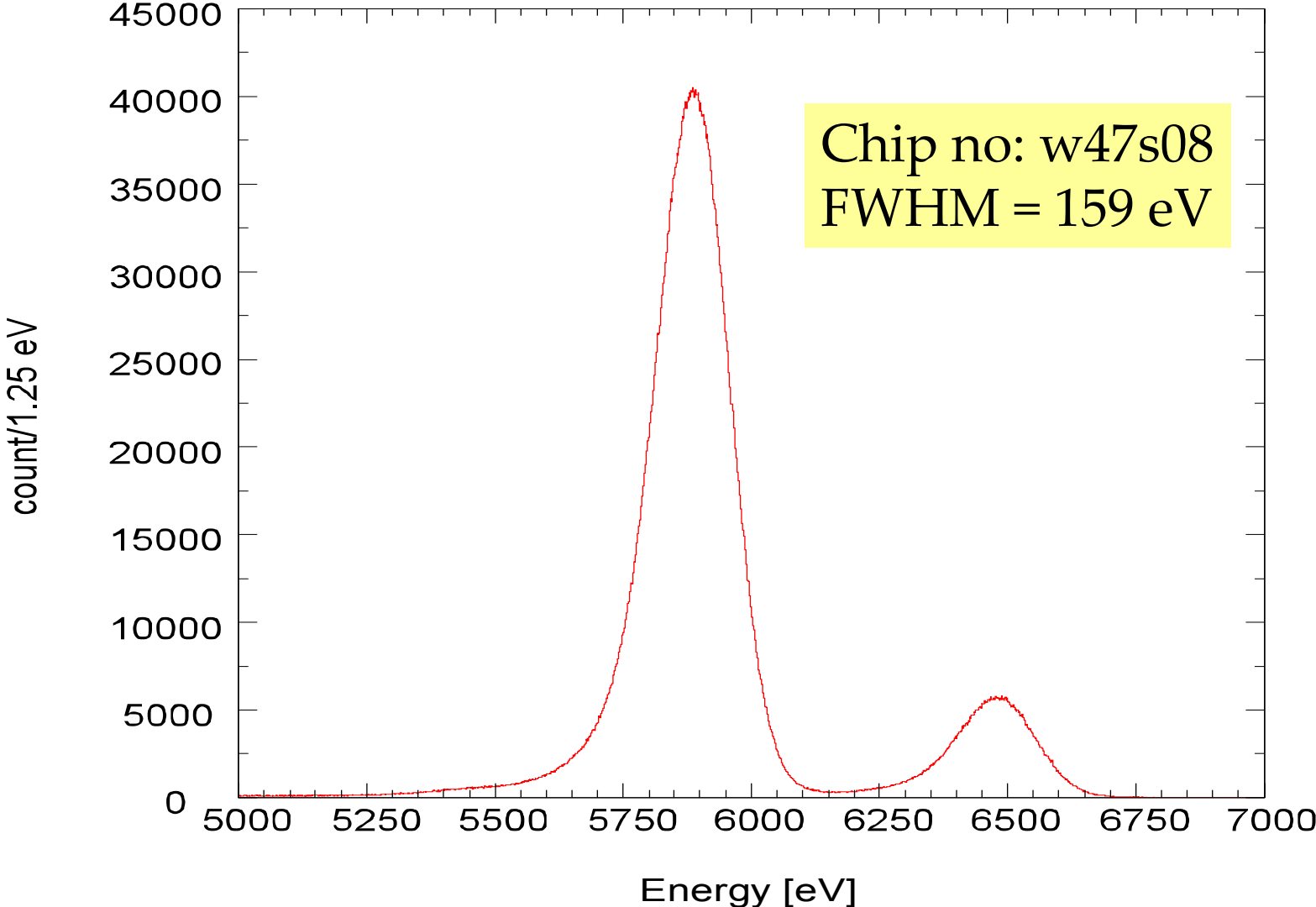
? Background reduction?

All invited to join!!!

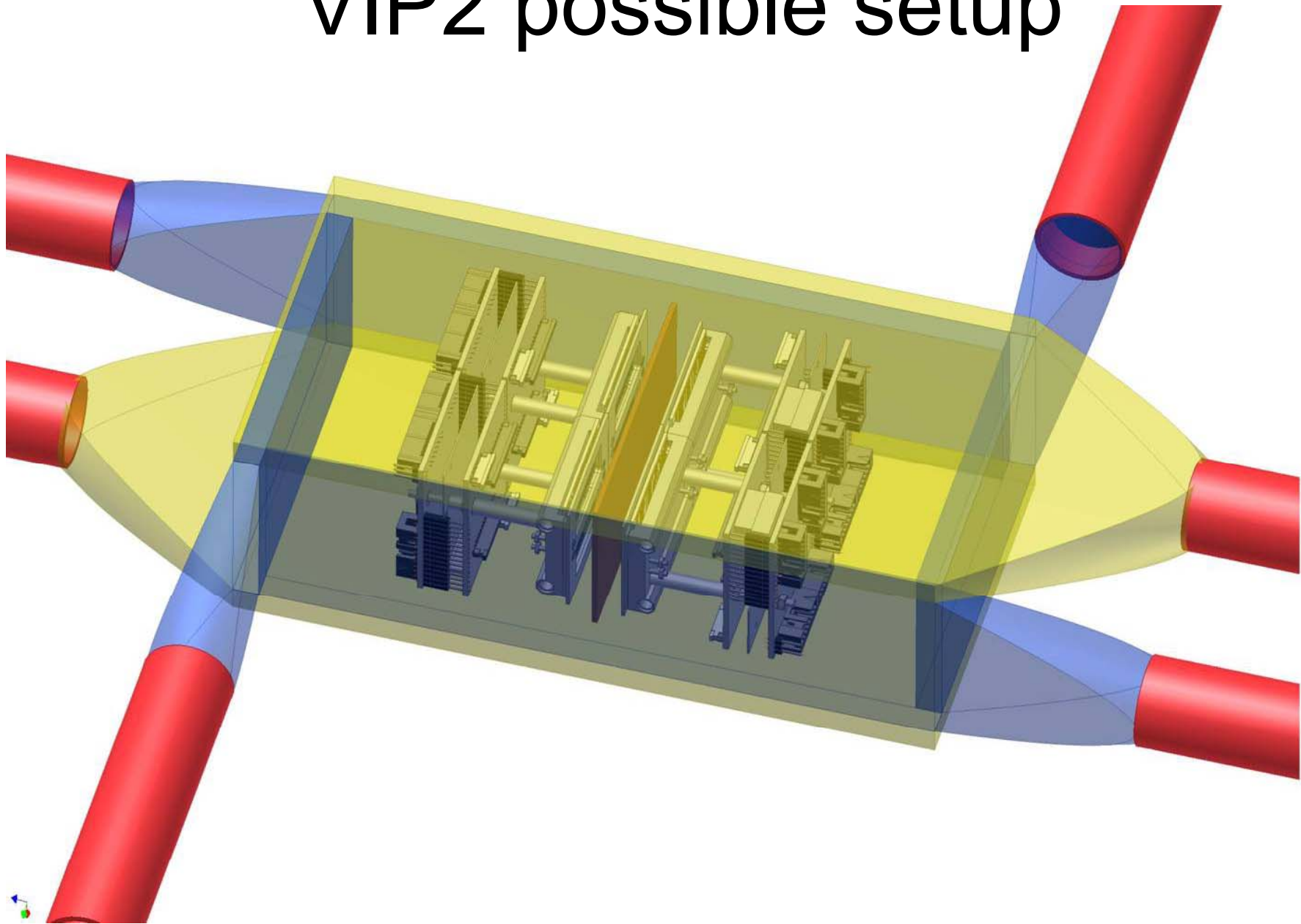
SDD mounted in ceramic frame



SDD energy resolution



VIP2 possible setup



<http://www.Inf.infn.it/esperimenti/vip>

petrascu@Inf.infn.it