The VOXES experiment

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1 Introduction

The possibility to perform very high resolution measurements of the X rays emitted in various processes is becoming a priority in many fields of fundamental science, from particle and nuclear physics to quantum mechanics, as well as in astronomy and in many applications using the synchrotron light sources or X-FEL beams, in biology, medicine and industry. The X-ray detection systems are presently passing through a remarkable fast development process, with new type of detectors being constantly realized, having steadily improved performances in terms of efficiency, energy resolution and costs. In spite of the fast evolving radiation detectors market, the aim of having accessible large area X-ray detector systems, able to achieve eV energy resolution for energies going from few keV up to tens of keV, and capable to measure not only well-collimated sources, but also the extended ones is still to be reached. The VOXES experiment plans to realize the first prototype of a system capable to measure, with eV energy resolution, X rays from 2-3 keV up to tens of keV, working also with extended sources (non point-like, uncollimated) and in high background environments.

2 State of art

Silicon and, more generally, solid state detectors, such as Silicon Drift Detectors (SDDs) or Charged Coupled Devices (CCDs), have been intensively used as position and energy sensitive detectors. Recently, their use as large area spectroscopic detectors has been explored in the framework of the DEAR and SIDDHARTA experiments [1, 2, 3, 4, 5], with lot of success. However, when used for precision transition lines widths measurements these devices are limited by their intrinsic resolution related to the Fano Factor [6, 7, 8] and to the electronic noises. Such detectors have resolutions at 6 keV energy of about 120 eV (FWHM) at best. In the past, experiments performed at the PSI laboratory measuring pionic atoms [9] pioneered the possibility to combine these type of detectors (CCDs) with crystals, to enhance the energy resolution using Bragg reflection principle. The used crystals were of silicon type and the energy range achievable to the system was limited to few keV, due to the crystal structure. Moreover, the capacity of these systems to work with extended sources was rather limited, due to the rigidity of the crystals. Other type of high resolution detectors being presently under development are the Transition Edge Sensors (TES). The achievable energy resolution is excellent (few eV at 6 keV), but the active area is still very small [10]. Moreover, the cost of these detectors is prohibitively high and their use rather laborious, due to the large complex cryogenic system needed to reach the operational temperature of 1 K. In these conditions, a new methodology to overcome these problems comes from the development, in the last decade, of the Higly Annealed Pyrolitic Graphite crystals (HAPG, [11]), which were proven to be able to perform measurements of X rays from few keV up to tens of keV energy with energy resolutions of $\Delta E/E < 10^{-3}$, when combined with standard CCD detectors. Thanks to their intrinsic properties like high reflectivity, efficiency and spatial resolution, these crystals proved to be an ideal solution for focusing soft X rays on position sensing detectors [12] ; in addition, their high flexibility allows to build them with ad-hoc geometries leading to the possibility to reach, through the optimisation of their curvature radius, length, thickness and mosaicity, high collection angles and efficiencies.

3 The VOXES experiment

The VOXES project started its activities in July 2016, with the goal to realize the first prototype of a high resolution and high precision von Hamos X-ray spectrometer for a broad energy range, using Highly Annealed Pyrolitic Graphite (HAPG) crystals combined with fast and triggerable position detectors. The aim is to deliver a cost effective system having an energy resolution at the level of eV for X rays energies from about 2 keV up to tens of keV, able to perform sub-eV precision measurements. For the first time, moreover, the system will work as well with extended X rays sources (i.e. not punctiform, nor collimated). The VOXES system will be qualified by performing real measurements of exotic atoms at the PSI laboratory and/or DAΦNE and/or J-PARC laboratories. There are many applications of the proposed spectrometer, going from fundamental physics (precision measurements of exotic atoms at DAΦNE collider and J-PARC, precision measurement of the K^- mass, quantum mechanics tests) to synchrotron radiation and X-FEL applications, astronomy, medicine and industry.

3.1 Wavelength Dispersive X-ray spectroscopy with HAPG in von Hamos configuration

Highly Annealed Pyrolitic Graphite (HAPG) is a mosaic crystal, consisting in a large number of nearly perfect small crystallites. The unique structure of HAPG crystals enables them to be highly efficient in diffraction in an energy range between 2 keV and several tens of keV. Furthermore, thin HAPG crystal films can be easily bent, allowing the production of ad-hoc optimized shapes. The diffraction properties influencing the energy resolution of HAPG films are determined by the mosaicity and the intrinsic width of Bragg reflection. Mosaicity makes it possible that even for a fixed incidence angle on the crystal surface, an energetic distribution of photons can be reflected, because each photon of this energetic distribution can find a crystallite plane at the right Bragg angle (see Fig. 1).

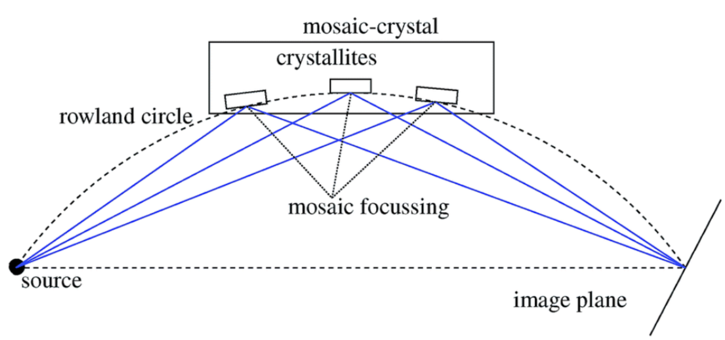

Figure 1: *Mosaic focusing for a flat mosaic crystal; due to the mosaic structure, there are crystallites appropriately oriented and positioned* [13].

The width of the energetic distribution depends on the mosaic spread. The mosaicity is also responsible for the dramatic increase of the integrated reflectivity in comparison to perfect crystals in an energy range between 2 keV and several tens of keV [13]. The idea to combine the dispersion of a flat crystal with the focusing properties of cilindrically bent crystals was put forward from von

Hamos in 1933, in the so called von Hamos spectrometer (see Fig. 2), and has already proven its high-resolution capabilities [14, 15] and excellent focusing properties [12].

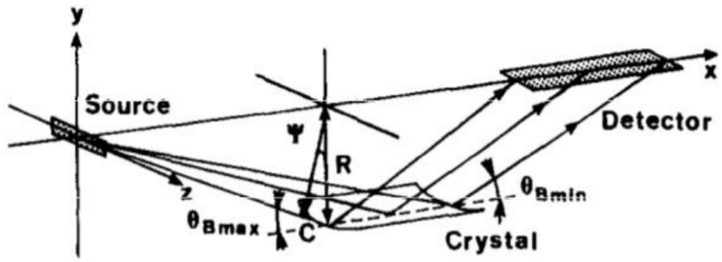

Figure 2: *Schematic drawing of the von Hamos spectrometer geometrical principle of operation. The crystal is curved around the x-axis. The figure is not to scale* [15].

However, in all these experiments the crystals have been used to focus very small and collimated sources. In the past an attempt to use silicon crystals for wider sources has been carried out where the pionic hydrogen and deuterium X-ray lines have been measured, but these lines are in the very small range of 2.4-3.1 keV and the system had a very small efficiency. Another proposal has also been put forward in 2002 [16], still with non-HAPG crystals, but it ended with the conclusion that also for efficiency reason the measurement would need a very long data taking period. The VOXES project will exploit the high collection efficiency of the HAPG crystals and their versatile geometry in order to realize a high resolution X-ray detector for a broad energy range for extended sources.

4 The VOXES group activities

The first phase of the research activity during the first year of the project, started in July 2016, is devoted to a single VH unit (crystal + position detector) design, construction and tests, aiming to characterize and optimize the system to obtain the largest possible acceptance (source size) and energy resolution, which will have an impact on the final prototype spectrometer and on the target cell dimensions and detectors arrangement. In this phase commercial silicon strip detector (MYTHEN2 [17]) is used. The system will be characterized in the laboratory, using targets activated by an X-ray tube. In the second phase of the project, to be realized in the second year, the construction and test of the final VOXES system prototype will be realized. The mechanical part and the detector geometry assembly will be performed by LNF in collaboration with the Stefan Meyer Institute (SMI) of Vienna. The measurement of pionic atoms X-ray lines will be performed on the $\pi - M1$ line at the Paul Scherrer Institue in Villigen (PSI) and it will represent the final goal of the whole project.

4.1 Laboratory activities

In the year 2017, the following activities have been performed in the VOXES laboratory:

- *Von Hamos and Semi Von Hamos configuration evaluation*: In order to improve the dynamic range of the spectrometer, the possibility to use a modified version of the Von Hamos configuration has been investigated (from now on called "semi" von Hamos). In this configuration, the position detector is rotated of an angle θ with respect to the cilindrically bent crystal axis (see fig. 3); in this particular configuration the illuminated surface portion of the position detector scales following the $S(\theta) = \frac{S(0)}{cos(\theta)}$ equation, being θ the angle by wich the detector is rotated and $S(\theta)$ the illuminated portion of the detector surface at a given angle. In this way, for a given position detector length, a wider energy range of photons can be measured in the same Bragg spectrum (see fig. 4). This configuration has been then used for all the performed measurements.

- *First measurement of the $Cu(K_\alpha)$ lines with the single unit prototype*: the first prototype of the spectrometer, equipped in a $206,7\,mm\,\rho$, $100\,\mu m$ thick HAPG crystal, and optimized to measure the $Cu(K_\alpha)$ lines at $\simeq\ 8\,keV$, have been tested and characterized. The best obtained resolution, using a point-like source, is of $4,19\,eV$ (see fig. 9).

- *Design and realization of a new mechanical setup for multiline measurements porpouses*: A new mechanical setup has been designed and realized thanks to the Stefan Meyer Institute (SMI, Vienna) staff. The new setup, consisting in a set of parallel rails with movable stages, allow precise positioning of all the spectrometer components for all energy ranges. For a given energy and crystal radius, crystal and position detector can be placed according to the Von Hamos configuration (see fig. 6).

- *First measurements of $Cu(K_\alpha)$ and $Fe(K_\alpha)$ lines*: A first characterization of the new prototype, using a $103,4\,mm\,\rho$, $100\,\mu m$ thick HAPG crystal, has been performed measuring $Cu(K_\alpha)$ and $Fe(K_\alpha)$ lines. Using a set of 2 slits to collimate the X-rays emitted from the target, photons coming from a non point-like sources with dimensions of $700\,\mu m$ have been successfully measured with resolutions of few eV (see fig. 7 and fig. 8).

- *Multi element spectrum*: Exploiting the wider dynamic range achievable with the "semi" Von Hamos configuration, a first attempt to simultaneously measure lines coming from different material has been done. A first spectrum, using a $103,4\,mm\,\rho$, $100\,\mu m$ thick HAPG crystal, has been acquired using a CuZnNi foil target. The first obtained spectrum is shown in fig. 9.

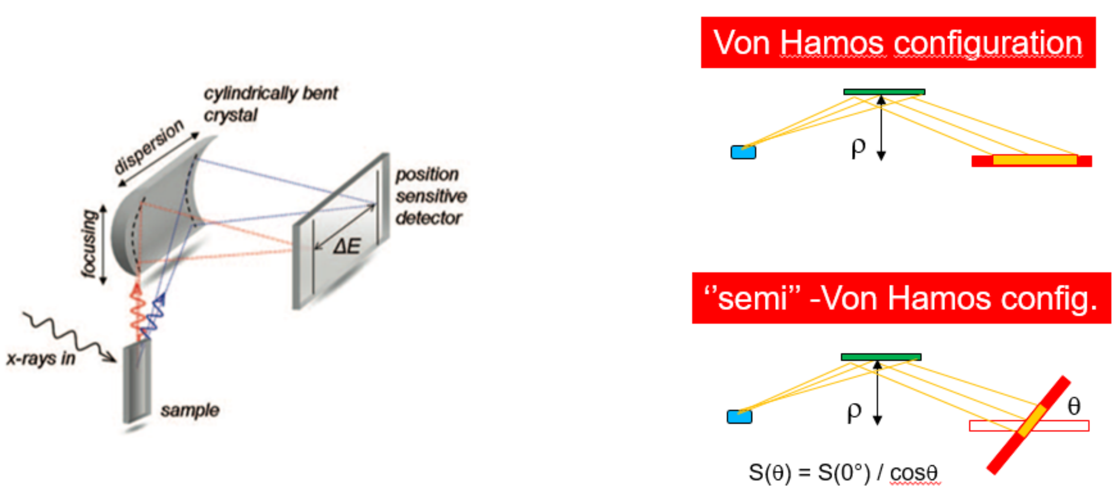

Figure 3: *Schematics of the Von Hamos and the "semi" Von Hamos configuration.*

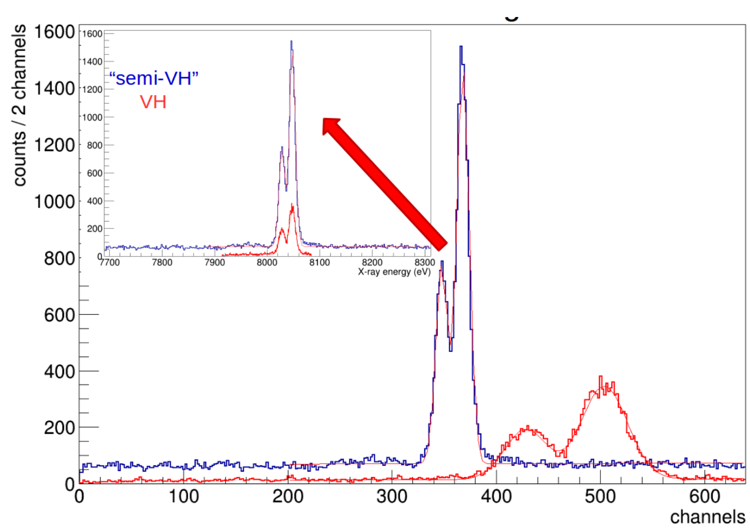

Figure 4: *3D rendering of the new multiline spectrometer prototype. For a given energy and crystal radius, crystal and position detector can be placed according to the Von Hamos configuration.*

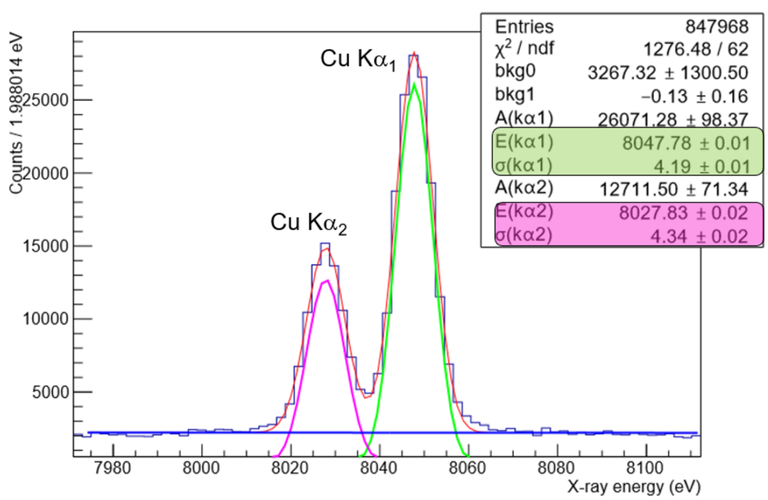

Figure 5: *Best resolution $Cu(K_\alpha)$ lines spectrum obtained with a* $206,7\,mm\,\rho$*,* $100\,\mu m$ *thick HAPG crystal using a point-like source.*

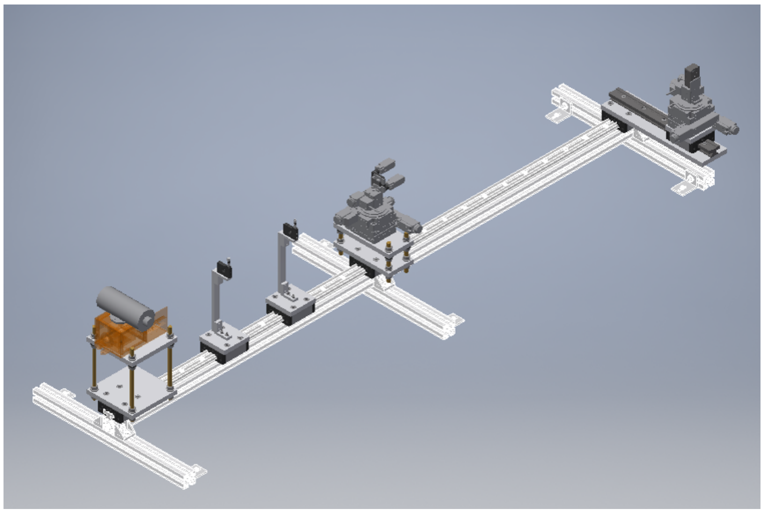

Figure 6: *3D rendering of the new multiline spectrometer prototype. For a given energy and crystal radius, crystal and position detector can be placed according to the Von Hamos configuration.*

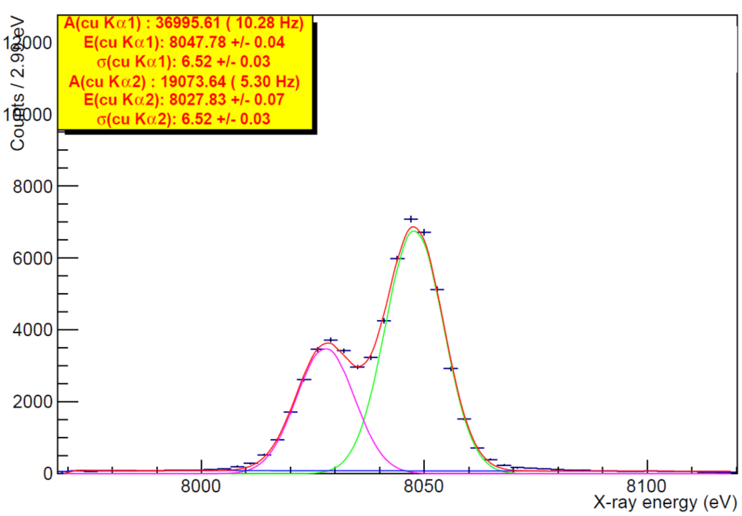

Figure 7: *Best resolution* $Cu(K_\alpha)$ *lines spectrum obtained with a* $103,4\,mm\,\rho$*,* $100\,\mu m$ *thick HAPG crystal using a* $700\,\mu m$ *size source.*

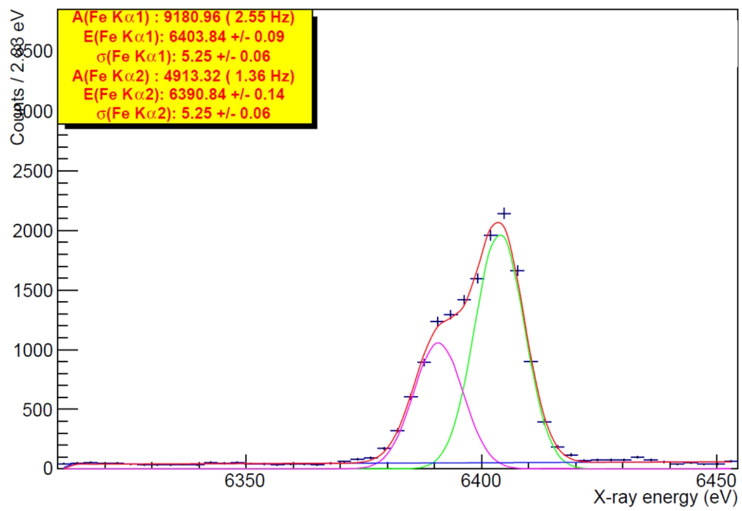

Figure 8: *Best resolution* $Fe(K_\alpha)$ *lines spectrum obtained with a* $103,4\,mm\,\rho$*,* $100\,\mu m$ *thick HAPG crystal using a* $700\,\mu m$ *size source.*

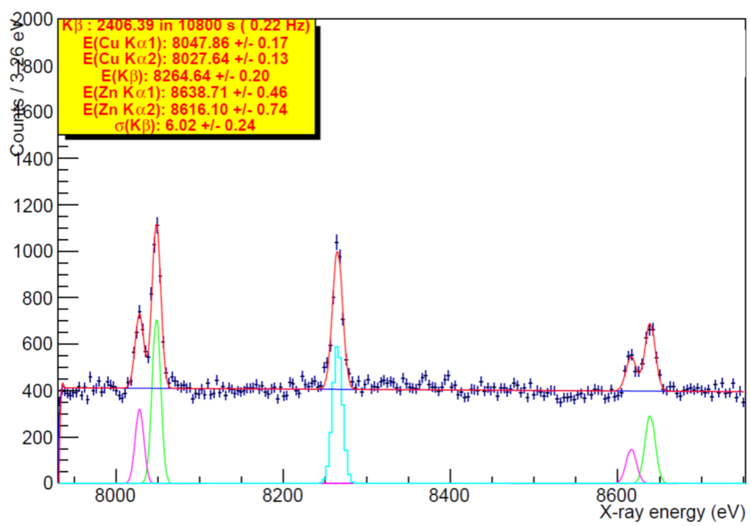

Figure 9: *CuZnNi target spectrum obtained with a* $103,4\,mm\,\rho$*,* $100\,\mu m$ *thick HAPG crystal in "semi" Von Hamos configuration.*

5 External institutes and collaborations

The following institutes are participating to the VOXES project, having the duties stated below:

- LNF-INFN, Coordinating Unit, will coordinate the whole project, and will be directly involved in all phases of the project; it will be responsible for DAQ and Slow Control, for the detector assembly (first and second prototype) for the tests measurements in laboratory and on beam;
- SMI-Vienna is responsible for the realisation of the cryogenic and vacuum systems, and will collaborate to the mechanics design and realisation, to detector system assembly and tests;
- LNF-INFN unit will collaborate with OPTIGRAPH company to optimize and realize the HAPG crystals, being responsible for this operation and for the data analysis and with Milan Polytechnic for the readout electronics.
- Politecnico di Milano (PoliMi) and Fondazione Bruno Kessler (FBK), are involved in the project for future developments of very fast and precise position detectors and electronics.

6 List of Conference Talks and Publications by LNF group members Year 2017

1. A. Scordo, *VOXES, a new high resolution X-ray spectrometer for low yield measurements in high background environments*,
   2nd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics,
   4-11 June 2017, Krakow, Poland
2. A. Scordo, *Development of a high precision X-ray spectrometer for diffused sources with HAPG crystals in the 2-20 keV range: the VOXES experiment.* ,
   ICXOM24, 25-29 Semptember 2017, Trieste, Italy
3. A. Scordo, *Development of a high precision X-ray spectrometer for diffused sources with HAPG crystals in the 2-20 keV range: the VOXES experiment.* ,
   ASTRA, 23-27 October 2017, Trento, Italy
4. A. Scordo, *Development of a high precision X-ray spectrometer for diffused sources with HAPG crystals in the 2-20 keV range: the VOXES experiment.* ,
   HNP2017, 18-22 December 2017, Tokyo, Japan
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