XLab Frascati: XlabF LNF

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Since the beginning of 21st century, at the Frascati's National laboratories (LNF) a team with dedicated research program on selected topics of channeling physics has been working within the projects of the INFN CSN1/CSN5 commissions. This activity has collected the researches in a wide spectrum of fundamental and applied physics dealing with interaction of beams and radiations in media, and over time became the basis for the creation of a specialised laboratory, so-called *"XLab Frascati"*, in 2010.

XLab Frascati (XlabF LNF) is *a unique Italian laboratory* dedicated to the design, manufacture and characterisation of X-ray and neutron polycapillary optics (polyCO)[1]. Involved in several national and international projects and collaborations dedicated to the research on electromagnetic interactions of charged and neutral beams and radiations in various external fields, in the experimental part of its activity XlabF is focused on the use of the optics for desktop X-ray analysis in various applied areas, such as cultural heritage, innovative materials, medical diagnostics, pharmacology, beam diagnostics, detectors characterisation, etc. The laboratory experimental activities aim in particular to analyse novel optics evaluating them for various experimental schemes to be applied in different X-ray techniques such as X-ray diffraction (XRD), X-ray fluorescence (XRF and TXRF - total reflection X-ray fluorescence) and X-ray imaging. The final result of our studies is in designing as well as developing dedicated instrumental prototypes and new X-ray desktop facilities for advanced X-ray techniques.

Recently, our investigations in polyCO physics have been extended for both experimental and theoretical studies on the features of soft X-ray propagation in micro-channel plates (MCPs). Theoretical part of our activity is related to various channeling based studies on fine peculiarities of relativistic leptons and hadrons scattering/motion in crystals and other multichannel structures formed in extreme laser and plasma fields and in solids as well, and to many possible novel physics/application ideas.

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[1] *In the world there are two companies, in USA and Germany, created by Kumakhov & Dabagov, which are specialised just in manufacturing the polyCO optics*

1 Facilities @ XlabF

Presently, three facility stations (RXR, XENA, PXRDS) are open to our users: their combined work allows optimising and matching various analysis, while two more stations are actually in realisation and in commissioning (CTS and Soft-XRF).

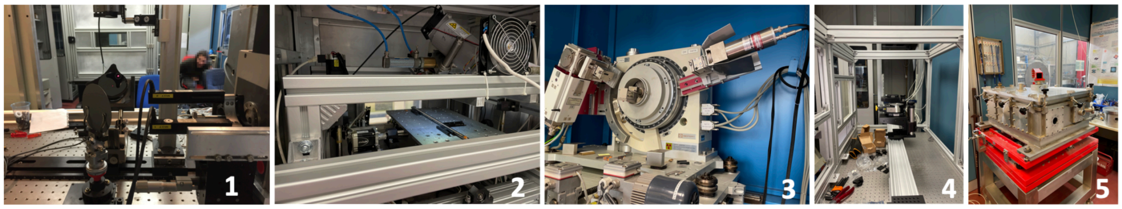


Figure 1: *Pictures of XlabF stations.*

1. **XENA** (X-ray Experimental station for Non-destructive Analysis) is operative (Fig. 1.1). It is equipped with three X-ray Oxford Apogee tubes (W, Mo and Cu anodes), a set of mechanical components and motors for lens alignment and scanning, and an optical table providing many geometrical setup possibilities. At the beginning, being the unique experimental station, it was used for all the different X-ray analysis performed at the laboratory. Today, XENA is a facility dedicated exclusively to imaging, tomography and characterisation of X-ray devices such as novel sources, optics - diffractive crystals and vibrating optics - and detectors.
2. **RXR** (Rainbow X-Ray) is an optimised system of XENA for 2D/3D XRF micro-imaging and TXRF (Fig. 1.2). It is equipped with two detectors of different energy efficiency, in order to measure a full spectrum ranging from 800 eV to 25 keV. RXR works in confocal mode: the source is coupled with a full-lens, and both the detectors are combined with dedicated half-lenses. RXR is also equipped with an optional vacuum chamber for measurements in the low energies range. This vacuum chamber has the possibility of inserting a polyCO for TXRF analysis.
3. **PXRDS** (X-ray Diffractometer Station) is a $\Theta/2\Theta$ ”Seifert - XRD 3003” diffractometer (Fig. 1.3). The instrument has a remarkable mechanical stability, high precision and a variety of possible configurations. The diffractometer is a 2200W Power System with a CuK_α anode target, 1×12 mm beam, while the goniometer, placed in a vertical position, has a high precision thanks to the use of stepper motors with micro-step movement which ensures an angular resolution greater than 0.001°.
4. **CTS** (Computed Tomography Station) is a measuring station for high precision tomography (Fig. 1.4). Developed as part of a *Premiale* project, the station, equipped with a microfocusing source (4 μm on the anode), high precision mechanics and high-resolution CCD detector (10.4 μm per pixel), through the phase retrieval technique CTS resolution is estimated in 600-700 nm per voxel. CTS is currently in the installation and commissioning step.
5. **Soft-XRF** (Soft X-Ray Fluorescence) is the new fluorescence station for studying the organic materials (Fig. 1.5). The main characteristics of this instrument is a high vacuum chamber, a 6-axis manipulator for positioning and a windowless detector necessary for revealing low atomic number elements, such as Carbon, Oxygen, Nitrogen and Fluorine.

2 Activity in 2020

2.1 Volume Photography

During 2020, the XlabF team studied various samples from different application areas (Cultural Heritage, Forestry Sciences) using X-ray fluorescence and tomography techniques [1–4].

@ Cultural Heritage Samples. In collaboration with Universitá di Roma "Tor Vergata", the Casanatense Library (for Manuscript 92), the Ragusa Foundation and the Pigorini Museum (emakimono 142 838 and painted roll n.142 846), we studied the ink present in few ancient artefacts. The objective of the work was the determination of chemical components of the inks present within several areas of two different sample typologies from an ancient manuscript and some Buddhist scrolls (Fig. 2). We aimed in extracting semi-quantitative results following a methodology that was primarily tested on an XRF standard, apart from the qualitative recognition of the elements constituting the inks. Reporting the experimental results achieved on both the artefacts, we have studied the XRF emissions, obtaining element concentration (in %), that allowed confirming the hypotheses came from the bibliographic history of the artefacts. The latter is very important for fine-tuning the further restoration procedure.

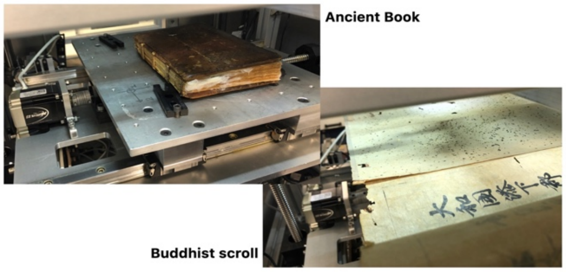


Figure 2: *Pictures of two artefacts studied by XRF Spectroscopy housed in the RXR facility: The Ancient Book (up left picture) and the Buddhist scroll (bottom right picture).*

@ Forestry Research Samples. In collaboration with Universitá of Viterbo "Tuscia" we analysed tree samples from known UNESCO sites to evaluate the presence of atmospheric pollutants, such as Pb, Cu and other heavy metals, and to study the biology of these trees. Tomographic studies were also conducted on the tree bark samples that aimed in reconstructing the cell morphology of

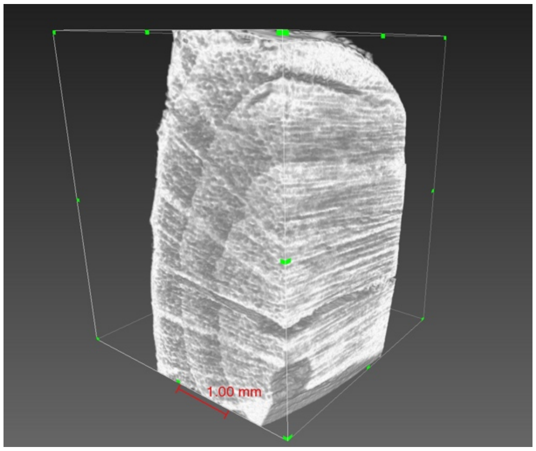


Figure 3: *μCT scan of an aleppo pine bark. The image shows the bark and wood anatomical details, as hollow cells along the longitudinal plane of the sample. The resolution achieved is less than $20 \times 20 \times 20\ \mu m^3$.*

the tree growth area (Fig. 3). Finally, based on high resolution X-ray imaging, which enabled us to investigate the density composition (pollutant dependent) of various examined tree samples as a function of radiation penetration depth, we performed the evolutionary analysis of trees. As a result of our studies, we have developed a new absorption technique adapted for dedicated studies of various tree samples.

2.2 Fermilab Muon g-2

Starting from 2012 our team has been strongly involved in performing both experimental and theoretical activities within the international Fermilab collaboration g-2. First prototype of the advanced laser-based calibration scheme to be used in combination with the calorimeter system at the Fermilab muon g-2 facility for extremely precise measurements of the muon anomaly with a total uncertainty of 1.6×10^{-10} (0.14 ppm), which includes a 0.10 ppm statistical error and about 0.07 ppm systematic uncertainties both on the muon anomalous precession angular velocity ω_a and on the magnetic field measurement with the proton Larmor precession angular velocity ω_p, has been realised at XlabF LNF and successfully tested at BTF LNF using a 450 MeV electron beam impinging on a small subset of the final g-2 lead-fluoride crystal calorimeter system.

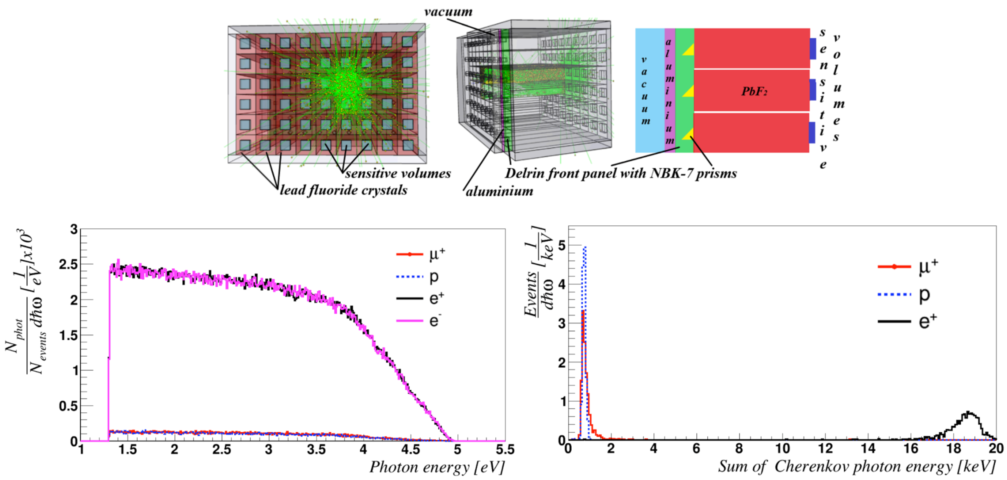


Figure 4: *The picture of the calorimeter structure hit by positron using Geant4 visualisation tools (green tracks are Cherenkov photons or other neutral particles). Left - back surface of the calorimeter with SiPMs; center - side view of the calorimeter; right - schema of the calorimeter: the vacuum chamber, the Al exit of vacuum chamber, the front panel (with NBK-7 glass prisms implanted in the panel), PbF_2 crystals, sensitive volumes. Geant4 simulation of Cherenkov photons collection by sensitive volumes at the back calorimeter surface: sum of energy of Cherenkov photons generated by 3 GeV muons (red line), protons (blue dashed line) and positrons (black line) in PbF_2.*

In 2020 we have continued our activity within a shift program to complete Run1 and to start Run2 in a remote regime [5–8]. We have continued theoretical studies on charged particles interaction with a complex of lead fluoride calorimeter that results also in radiation emission, namely, Cherenkov Radiation (ChR). The existing softwares for computing energy depositions processes by positrons, electrons, protons and muons are general and not adapted for purposes of the muon g-2 experiment (Fig. 4). We created a new code within the Geant4 simulation toolkit that reflects necessary aspects for comparing future experimental and simulated data. Finally, we have written two independent codes (in collaboration with our colleagues from MEPhI and Tor Vergata Universities) to simulate a full-size electromagnetic calorimeter for the muon g-2 experiment.

2.3 Channeling Related Studies

@ Photonuclear Reactions by Channeling Radiation. The research for newly developing branch of nuclear physics, the nuclear photonics, since the beginning has been accompanied by the studies on intense MeV photon sources. One of the possible solutions, which we have proposed, is in the use of channeling radiation (CR) as a photon source [9]. The CR spectrum for moderate energy (sub-GeV - several GeV) electrons is characterised by a sharp maximum at photon energies up to several MeV, which is enough to excite separate nuclear levels as well as (γ, n) reaction for light Be and D nuclei. This maximum may even reach the region of giant dipole resonance for heavier nuclei. At equal radiator thickness CR flux may exceed in more than one order that of bremsstrahlung (B). Thus, CR can be efficiently utilised in studying photonuclear reactions as well as in generating pulsed neutron beams at sub-GeV electron accelerators (Fig. 5). The latter is illustrated by detailed calculations of the neutrons yield from the light D and Be targets irradiated by CR. Nontrivial dependence of neutrons yield on both the energy of incident electron beam and its alignment with respect to the crystal channeling planes is revealed. Our analysis has demonstrated that the use of CR instead of B for equal thickness targets to study photonuclear reactions opens up important advantages.

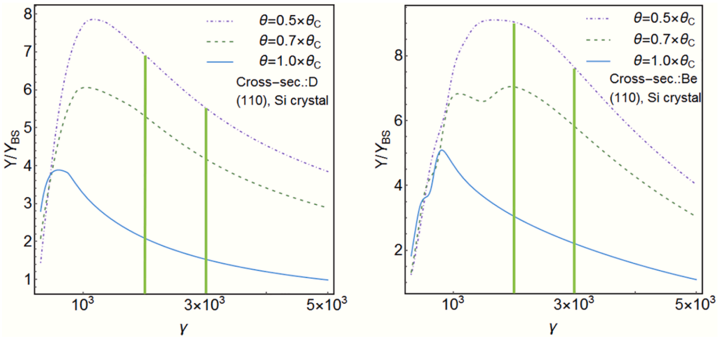


Figure 5: *The ratios of (γ_{CR}, n) yield Y to (γ_B, n) yield Y_B for D target (left) and for Be target (right) for three values of incident angles of electron beam with respect to (110) Si crystal planes plotted as a function of electrons relativistic factor.*

@ Cherenkov-Channeling Radiation by Protons and Muons. We have theoretically studied some features for generation of principally new type of radiation, so-called mixed Cherenkov-Channeling Radiation (ChCR) (Fig. 6) [10, 11]. The earlier developed theory for relativistic electrons have been presently applied to the radiation emission by protons at medical accelerators. This type of radiation can be observed at proton channeling in optically transparent crystals that is accompanied by CR, and can be proposed as alternative to conventional ChR. ChCR photons are emitted at large angles with respect to the projectile momentum and close to the Cherenkov ones as well. It is shown that the ChCR intensity can essentially exceed the ChR one. Applying the numerical methods, the quantitative characteristics of ChCR for selected crystals as well as their distinctive peculiarities are analysed. Our studies suggest the use of ChR by channeled protons, ChCR, at modern medical accelerators without essential facility modifications.

We also analysed ChR by relativistic muons, positive and negative, channeled in optically transparent diamond (C) and silicon (Si) crystals, ChCR, in comparison with ordinary ChR. We have shown that the maxima of spectral angular distributions for both types of radiation are revealed at the derivative extrema for the media refractive index, while, due to the difference in scattering of positively and negatively charged particles at crystal channeling, the number of Cherenkov photons emitted by channeled positive muons might be over the one for negative muons.

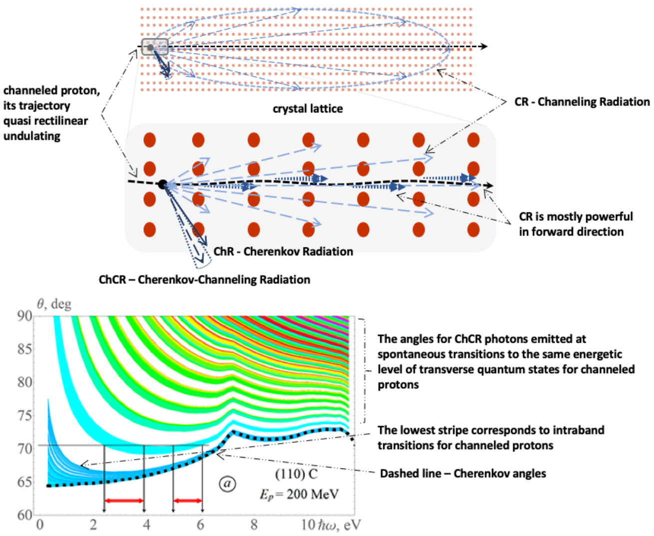


Figure 6: *Scheme for Cherenkov Radiation at channeling conditions - Cherenkov-Channeling Radiation (ChCR)*

ChR by quasi free projectiles is described as one limiting approximation of a general expression for ChR by channeled projectiles, ChCR, which takes into account non-zero derivative of the refractive index. The last may result in essential increase of radiation intensity.

@ Optical Lattice Channeling - Laser Channeling. Charged particle beams might reveal bound motion, known as channeling, in specially structured electromagnetic fields of various origins. Features of channeling motion in crystals are well established. Indeed, both classical and quantum theories of crystal channeling are well known, most of the features were experimentally proved. In this work we continue our studies on interaction of charged beams in crossed laser fields, so-called *"optical lattices"* (OLs). Namely, we analyse a zone structure of channeled motion for a particle in optical lattice formed by superposition of electromagnetic fields. The particle energy spectrum in a single channel is considered. Strong difference of the energy spectrum for a channeled particle in optical lattices from those in crystals is shown [12]. The projectile energy spectrum in the OL channel differs significantly from the spectrum in the crystal channel. Main discrepancy of

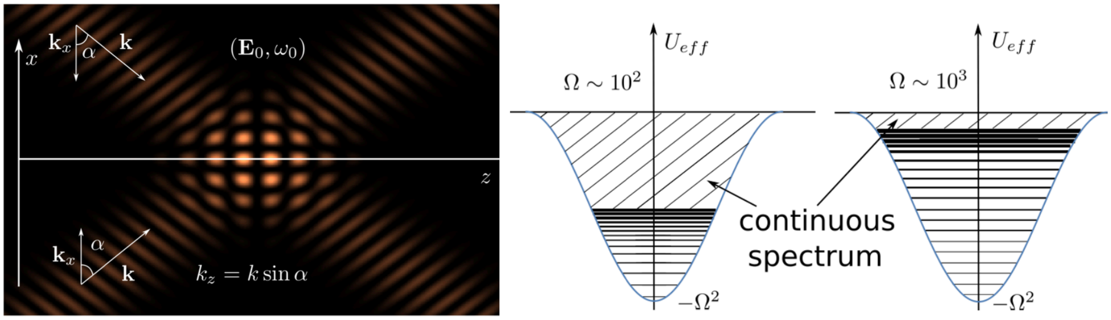


Figure 7: *(left) General scheme of examined system. The 0z axis coincides with the channel axis. The periodical effective potential is formed in the transverse Ox direction. (right) A zone structure corresponding to two different values of the dimensionless frequency. Increasing dimensionless frequency decreases the exertion of a zone structure.*

the energy spectrum for high-energy particle in OL from those in a crystal lattice is in the state number independence on the particle longitudinal energy (Fig. 7). For high-energy particle in the field of OL the state number is only defined by both particle charge and field parameters/geometry. Thus, for a microwave laser of the intensity $I_0 > 10^{10}\, W/cm^2$ the number of discrete transverse states for projectile motion could be very large $N_{max} > 10^2$.

@ Crystal Bassed Positron Source. The results of our continued studies, since the time of the project CSN5 POSSO (POSitron SOurce), for the positron production in the crystal assisted radiator-converter approach (*"hybrid solution"*) are brief analysed in 2020 for $10 \div 50$ MeV electrons. Computer simulations have been performed for both coherent (CB) and incoherent bremsstrahlung (B) in Si and Ge crystal radiators that successfully irradiate the W amorphous converter to release the electron-positron pairs. The positron stopping calculations in a thick convertor allow the optimal converter thickness for the maximum positron yield to be determined, and moreover, the energy spectra for emitted positron beams to be drawn for optimal converter thickness. The results of our recent investigations on the future positron sources based on B of initial electron beams in various substances prove the feasibility for substitution of amorphous radiators by crystalline ones (Fig. 8). For highly relativistic electrons $E \geq 200$ MeV CR in aligned crystals provides much higher photon fluxes than B, while for relativistic electrons of moderate energies $E \approx 10 \div 200$ MeV CB can be utilised as more powerful radiation source for electron-positron pair production [13].

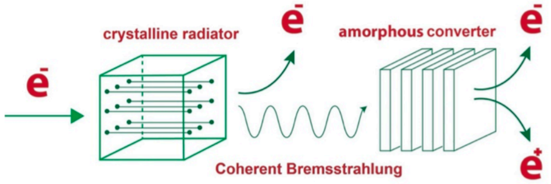
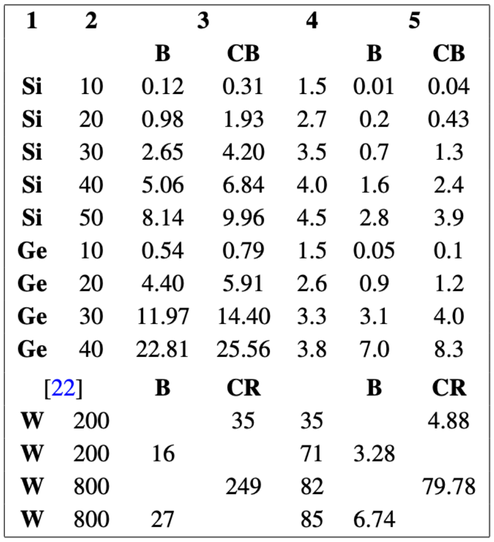


Figure 8: *The scheme of a hybrid positron source using CB by a primary electron beam. Table 1: Total yield of positrons produced by <100> CB of* $10 \div 50$ *MeV electrons in different radiators. 1: the radiator (10* μm *thickness); 2: the electron energy, MeV; 3 (two columns): the total yield of positrons per electron in 0.04 mm W converter,* $(\times 10^{-5})$*; 4: the W converter optimal thickness, mm; 5 (two columns): the total yield of positrons per electron in W converter of optimal thickness,* $(\times 10^{-3})$*.*



1	**2**	**3**		**4**	**5**	
		B	**CB**		**B**	**CB**
Si	10	0.12	0.31	1.5	0.01	0.04
Si	20	0.98	1.93	2.7	0.2	0.43
Si	30	2.65	4.20	3.5	0.7	1.3
Si	40	5.06	6.84	4.0	1.6	2.4
Si	50	8.14	9.96	4.5	2.8	3.9
Ge	10	0.54	0.79	1.5	0.05	0.1
Ge	20	4.40	5.91	2.6	0.9	1.2
Ge	30	11.97	14.40	3.3	3.1	4.0
Ge	40	22.81	25.56	3.8	7.0	8.3
[22]		**B**	**CR**		**B**	**CR**
W	200		35	35		4.88
W	200	16		71	3.28	
W	800		249	82		79.78
W	800	27		85	6.74	

@ X-Ray Focusing by Bent Microchannel Plates. Synchrotron radiation sources have been used to study the focusing properties and angular distribution of X-ray radiation at the exit of spherically bent MCPs. In our recent study, theoretical and experimental, we have shown how soft X-ray radiation at energies up to 1.5 keV can be focused by spherically bent MCPs with curvature radii R of 30 mm and 50 mm. For these devices, a focus spot is detectable at a distance between the detector and the MCP of less than R/2, with a maximum focusing efficiency up to 23% of the flux illuminating a MCP sample (Fig. 9). The soft X-ray radiation collected at the exit of microchannels of spherically bent MCPs are analysed in the framework of a wave approximation. A theoretical model for the wave propagation in micro- and nano- X-ray guides, which we previously proposed and developed, has been successfully introduced to explain the experimental results on radiation transmission by MCP. Experimental data and simulations of propagating radiation represent a clear

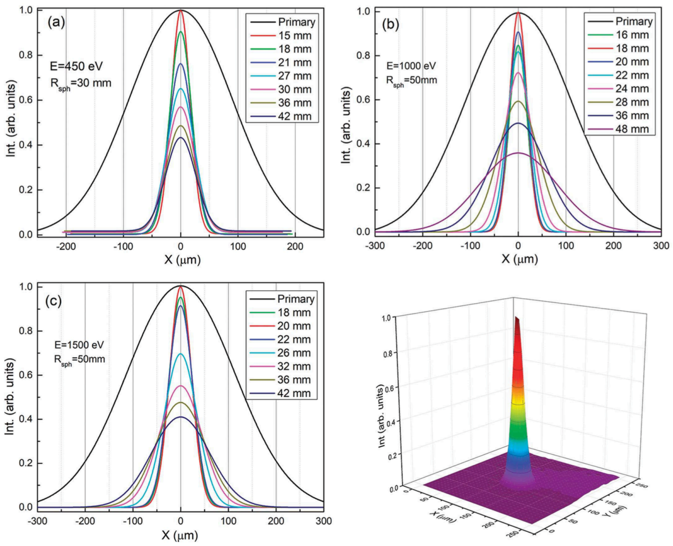


Figure 9: *Comparison of profiles and spot sizes (FWHM) of radiation collected by MCPs with two different radii of curvature at different energies: (a) 450 eV Elettra, (b) 1000 eV BESSY and (c) 1500 eV BESSY. Profiles are normalised to the incident photon flux. Panel (d) shows a 3D profile of focused radiation at 450 eV.*

confirmation of the wave channeling phenomenon for the radiation in spherically bent MCPs [14]. This kind of polycapillary optical system based on totally different fabrication technology might be of special interest for future light sources [15].

3 New Projects (submitted)

1. **MicroSpeX**: Sviluppo e validazione di un micro Spettrometro all-in-one per raggi X (microSpeX)

   DTC Lazio - Progetti RSI - Bando Fase II Role of XlabF: *Project Coordinator*

   The project objective is the development of an all-in-one instrument able to carry out both micro-XRD and micro-XRF analyses of different samples (paintings, old manufacts, ancient books, pigments , etc.) coming from museums, libraries as well as archeological sites.
2. **DAX**: Diffraction Analyzer by X-ray

   R4I - 2021 INFN Role of XlabF: *Project Coordinator*

   The DAX project intends to engineer and validate, with tests on samples from selected application areas, a bench prototype capable of performing micro-diffractometry and micro-fluorescence X, thanks to the implementation of miniaturised X-ray optics such as polycapillary optics.
3. **ALTERNATIVES**: ANTIBACTERIAL, UV-SHIELDING AND ANTI-FLAME COATINGS BASED ON CELLULOSE FIBERS, ENZYMES AND LIGNIN FOR ADVANCED TEXTILES AND INNOVATIVE PAPERS

   BBI Call - Horizon 2020 Role of XlabF: *Materials characterisation*

   This project proposal, entitled ”Antibacterial, UV-shielding and anti-fLame coaTings based on cEllulose fibeRs, eNzymes and lignin for Advanced TextIles and innoVativE paperS - ALTERNATIVES”, has as main objective the design, preparation, testing, and validation for the development of a new and market-oriented coating formulation, composed of bio-based and renewable materials deriving from the European biomass and supply chain.
4. **ZEPHYRUS**: Zero Emission Processes for HYdrogen production via Reversible Use of Sorbents

Bando Regione Lazio - Gruppi di Ricerca 2021 Role of XlabF: *Materials characterisation*

ZEPHYRUS aims to develop technologies that will form the backbone of the future energy system by placing Lazio as a leader. There is no technology with greater commercial potential; lower environmental impacts and greenhouse gas emissions; improved resource efficiency, social acceptance and cross-fertilisation with many sectors over the use of waste for biofuel and electricity production.

5. **MATRIX**: Mapping pollution in natural Archives of Tree RIngs by X-ray techniques

   Bando PRIN 2021 Role of XlabF: *Project Coordinator*

   The MATRIX project will realise a novel methodology, based on X-ray techniques, for the analysis of elements connected to pollution found into natural archives, tree-rings and leaves, and in particulate matter as a potential vector of pollutants in air and precipitation (snow/rain).

4 List of Lectures & Talks by LNF Authors

1. S.B. Dabagov, Channeling highlights, lessons and directions, ACN 2020 - ARIES Workshop on Application of Crystals and Nanotubes for beam acceleration and manipulation, 10-11 March 2020, Lausanne (Switzerland) - *invited, remote*
2. S.B. Dabagov, Radiation Based Technologies for Medical Applications.
   PhD Workshop at Uni Surrey (London), 16 March 2020, London (UK) - *invited, remote*
3. G. Guglielmotti, ”Application of polycapillary optics to x-ray fluorescence for advanced spectroscopy and microscopy studies”, SPIE - Advances in Laboratory-based X-Ray Sources, Optics, and Applications VIII, San Diego (19-24 August 2020), USA - *oral, remote*
4. S.B. Dabagov, Advanced Channeling Technologies: Strong External Electromagnetic Fields to Guide Charged & Neutral Beams.
   Lectures 1-2: Ordered Structures to Handle Relativistic Charged Beams. Crystal and Amorphous Body: Advantages for the Ordered Systems.
   Lecture 3: Laser-Plasma based Channeling Phenomena.
   Lectures 4-5: Capillary Structures for X-ray Optics: How the Curvature Helps to Control X-rays. PolyCapillary X-ray Microscopy and Tomography: Instruments to Solve the Math Tasks.
   Lectures at NRNU MEPhI, October-November 2020, Moscow (Russia) - *invited, remote*
5. S.B. Dabagov, Advanced Channeling Technologies: Strong External Electromagnetic Fields to Guide Charged & Neutral Beams.
   Lecture at SFU, 6 November 2020, Rostov-on-Don (Russia) - *invited, remote*
6. S.B. Dabagov, Channeling: from Crystal to Capillary Guides.
   PhD Lecture at Uni Tor Vergata, 12 November 2020, Rome (Italy) - *invited, remote*
7. D. Hampai, Advanced in X-ray Studies: Optics Applications
   PhD Lecture at Uni Tor Vergata, 19 November 2020, Rome (Italy) - *invited, remote*
8. V. Guglielmotti, Principles of X-ray Diffraction and X-ray Fluorescence and their application to real case studies analysed at XlabF.
   PhD Lecture at Uni Tor Vergata, 26 November 2020, Rome (Italy) - *invited, remote*

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