MULTI-DISCIPLINARY PHYSICS WITH MEV ION BEAMS AT THE LABORATORI NAZIONALI DI LEGNARO USING THE CN AND AN2000 ACCELERATORS

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Abstract

The paper provides updates and statistics of the activity carried out in the last decades at the Laboratori Nazionali di Legnaro (LNL) of the Istituto Nazionale di Fisica Nucleare (INFN) with the 2.0 MV AN2000 and 6.0 MV CN Van de Graaff accelerators in multi-disciplinary research.

1. INTRODUCTION

Low energy, high brilliance light ions electrostatic accelerators (with ion energies in the approximate range from 0.2 to about 10 MeV) are being extensively used since many years for research in interdisciplinary fields such as material analysis, modification and irradiation in semiconductor, opto-electronic, mechanical and quantum applications and precision medicine, radiation biology and dosimetry studies. Light ion beams (^{1}H, ^{2}H, ^{3}He, ^{4}He) are used in a wide range of intensities from single particle irradiation to tens of eμA, depending on the specific application, with collimated beams of mm size and focussed ion beams with micrometer size.

The rapid developments in materials science in terms of preparation, modification and characterization methodologies for nano-structured materials, new quantum and low dimensional materials, novel sensors and micro- and nano-devices require continuous improvement of the analytical tools (including both accelerators and experimental end-stations) to guarantee the highest spatial resolution, accuracy and sensitivity and an unprecedented capability to control individual ions position at the sub-micrometer scale and the LET distribution. Exploitation of ultraprecise single ion implantation/irradiation is the basis of a next generation of advanced materials and micro/nano-devices. The precise positional control of energetic single ions (keV, MeV or even GeV) at micrometric, nanometric or even atomic scale offers a wide range of emerging applications in fields as diverse as quantum technology, novel detectors, single photon sources and detectors, biomedicine and materials science. This e.g. includes investigating single ion irradiated novel topological materials (2D materials and nano-wires), biological cells or nano-assembling qubits in ultrapure solid-state crystal by deterministic single ion implantation.

Europe has a broad diversity of ion beam centres with manifold research interests and complementary technological features which condition the available ions and the accessible energy ranges. The accelerators at the National Laboratories of Legnaro are recognized as user-oriented research facilities comprising several MeV ion accelerators dedicated to multi-disciplinary research and in particular to Ion beam Analysis and ion irradiation

The MeV ion beam's analytical capabilities, including Rutherford and not-Rutherford Elastic Back-Scattering spectrometry (RBS and EBS), channelling techniques, Nuclear Reaction Analysis (NRA), Elastic Recoil Detection Analysis (ERDA), Particle Induced X-ray Emission (PIXE) and Particle-Induced Gamma Emission (PIGE) offer a wide range of "non-destructive" ion beam methods for high sensitivity and high-resolution materials analysis in many physical, chemical and medical disciplines [1]. A complete view of sample composition can be obtained nowadays by detecting X, gamma and particle simultaneously.

Recent developments in accelerator-based research, such as nuclear microprobe and nanoprobe techniques, and precision targeting with single ion are of growing interest to many research groups working in interdisciplinary fields like quantum materials and sensors, environmental physics, geology, radiation biology, radiation detectors and dosimeters technology, Micro Electrical Mechanical Systems (MEMS) fabrication and biological sensors.

An increasing demand to test the radiation hardness of microcircuits and satellite components subject to ionizing radiation exposure is fostered by the telecommunication industry and space missions' preparation projects.

On the other side, light ions accelerators are successfully used with D, Be and Li-based solid nuclear targets to provide fast neutrons using several MeV protons and deuterons with the $^{7}Li(p,n)^{7}Be$, $^{7}Li(d,n)^{8}Be$, $^{9}Be(p,n)^{9}B$, $^{9}Be(d,n)^{10}B$ reactions as well as energetic protons (~ 15MeV), using the large cross section $^{2}H(^{3}He,p)^{4}He$ nuclear reaction at energies below 1 MeV. Such produced neutrons and protons are being used to study the radiation hardness and single event upset (SEU) in electronic micro-devices and to develop and test new radiation detectors and biological sensors preferably in air.

All these potentialities offered by the MeV electrostatic accelerators are exploited at the LNL confirming the unquestioned laboratory's vocation to be a national resource for Ion Beam Analysis and Ion Beam Modification and irradiation of materials.

The activity carried out with the two Van de Graaff AN2000 and CN accelerators is summarised in the following section.

2. THE VAN DE GRAAFF AN2000 AND CN FACILITIES

The Laboratori Nazionali of Legnaro are an European ion beam research infrastructure with solid programs in nuclear physics and astrophysics with stable and radio-active ion beams, and extensive projects in neutron physics, materials analysis, modification and irradiation with ion beams, and applications in environmental physics, cultural heritage, radiation biology and quantum technologies. The laboratory is equipped with 5 accelerators and a pretty large inventory of interdisciplinary research equipment originally developed in the last six decades. There are five accelerator facilities at LNL: (i) two MeV single-end Van de Graaff accelerators (AN2000 2.2 MV and CN 6.0MV) dedicated to interdisciplinary studies, (ii) one 14.5 MV Tandem accelerator for ions from $^{1}H^{+}$ (~28.2 MeV/A) to $^{197}Au^{16+}$ (~ 1.2 MeV/A), (iii) one linac (ALPI) using rf superconducting cavity accelerator technology for a great variety of ions and energies in the range approximately 7 to 22 MeV/A, (iv) a recently installed 70 MeV, 700µA proton cyclotron.

The AN2000 and CN Van de Graaff accelerators are mainly used in applications of nuclear physics and interdisciplinary studies. All research projects are evaluated and approved by the international Program Advisory Committee of the LNL twice a year. On the average, the user's request exceeds the available beam-time by about 30% for each accelerator.

2.1. AN2000 accelerator

The AN2000 Van de Graaff accelerator, operative in the 1970s, was upgraded in 1990s with the installation of a micro-probe facility capable to focus 2.0 MeV proton beams down to about 1.5 µm spot size in high vacuum. The system is based on the "Oxford" triplet focussing optics and scanning setup. The capabilities of the micro-probe are being exploited mainly for the analysis of semiconductors, detector materials, archaeological samples, geological and nuclear waste related materials and aerosol micro-particles through the micro-PIXE, micro-EBS, and micro-NRA techniques. This facility is also being used for single event experiments consisting of hitting with micrometric precision a given specimen with a predefined number (even one) of projectiles and evaluating on-line the electric charge (IBIC) or light (IBIL) developed from the impact point and/or to study off-line the localized radiation damage and defect generation. Among the systems studied with these techniques it is worth mentioning the continuous effort to study and test new solid-state detectors and to investigate the mechanism of interaction of single particles on microchip devices such as flash memories. In the recent years a system for single ion implantation has been installed for sub-micrometer achromatic precision targeting of devices and materials with the available beams. The system is based on special engineered double micro-collimators and high accuracy nano-positioners for the device under test. It offers the possibility to perform multiple irradiations (at different ions and energies) at fixed position to create individual electro-optical defects and defects arrays in semiconductors. It also allows to irradiate with high position precision low-dimensional quantum materials.

Another application with the micro-probe is Ion Beam Writing (IBW) on synthetic diamond specimens to generate buried graphitic electrically conductive paths with proton and α-particles beams of variable energy, to prepare diamond-based micro-devices and biological micro-sensors.

Besides the micro-probe beam line, there are other three beam lines equipped with scattering chambers for complete Ion Beam Analysis (IBA) including EBS, EBS-Channelling, ERDA, NRA, PIXE and ion-luminescence studies and nuclear cross section measurements with collimated beams.

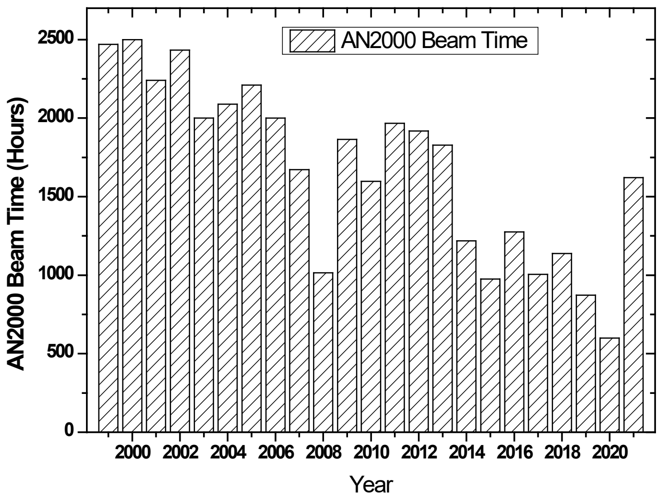

FIG. 1. Yearly beam-time hours delivered on user's targets by the AN2000 accelerator in the past 23 years.

The yearly beam-time on target of the AN2000 in the last two decades is presented in Fig. 1. The research groups accessing the AN2000 facility range from about 15 to 20 per year from Italian and foreign Universities and Research Centres. The decreasing trend of the beam-time provided to user's shown in Fig. 1 is due in great part to the increasing need of servicing and special maintenance of the accelerator and in part to the reduction of personnel for the development of new instrumentation.

Most of the research activity carried out in the AN2000 Laboratory is of analytical nature: PIXE and micro-PIXE analysis, EBS, NRA, ERDA (for stoichiometry analysis and depth profiling of hydrogen and deuterium) are performed routinely with the continuous $^{1}H^{+}$, $^{4}He^{+}$ and $^{3}He^{+}$ beams in the energy range from 200 keV to 2.2 MeV on a great variety of materials and thin films. The subdivision for the last 12 years of the beam-time in the various application fields is shown in Figure 2. As it can be noticed, IBA and micro-probe applications represent a significative amount of the beam time yearly allocation to the users. In recent years the irradiation experiments on satellite components and materials and on new quantum materials are gaining increasing interest. The AN2000 accelerator is also used to perform training of students and young researchers with particular attention to promote Ion Beam Analysis and a quantum-ready workforce.

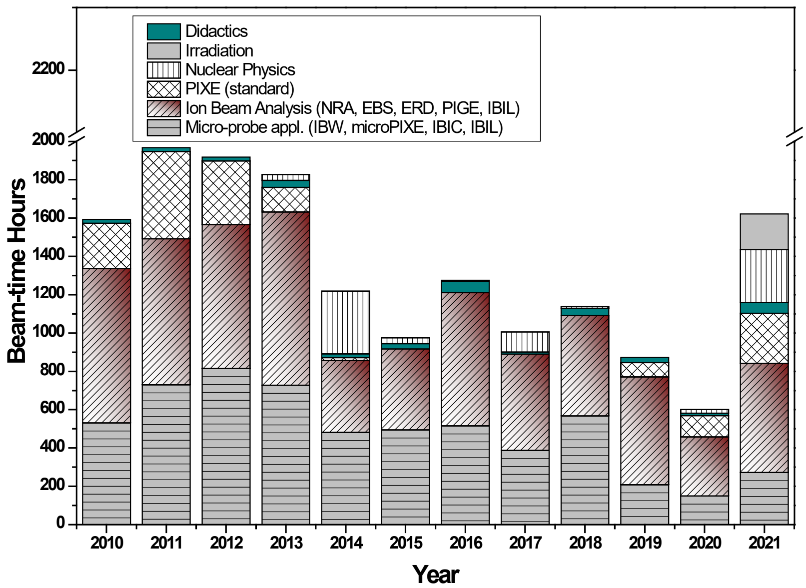

FIG. 2. Yearly beam-time hours delivered on user's targets by the AN2000 accelerator in the past 12 years subdivided in main application fields.

2.2. CN accelerator.

The CN accelerator is operative since 1961. The terminal voltage can be varied from about 1.0 to 6.0 MV allowing for a maximum energy of about 12 MeV for the double charged particles. The ion beams available are $^{1}H^{+}$, $^{1}H_2^{+}$, $^{2}H^{+}$, $^{3}He^{+}$, $^{3}He^{++}$, $^{4}He^{+}$, $^{4}He^{++}$, $^{15,14}N^{+}$ either pulsed or continuous. The original pulsing system of the CN provides 3 MHz repetition rate with bunch duration of about 1-2 ns. A new system has been installed, coupled to the original system, to allow for repetition rates at frequency lower than 3MHz by synchronous beam deflection: the supplementary pulsing system is able to suppress a fraction of main beam pulses by deflecting the unwanted ones toward a beam-dumper placed along the beamline. In such way it is possible to get a secondary pulsed beam with variable frequency down to few hundreds' kHz, well suited to carry out neutron TOF experiment in nuclear astrophysics and detector and dosimeters tests.

The shielding of the CN laboratory infrastructure allows the irradiation of Be and Li-based targets with proton and deuteron beams with currents of order of few μA to produce well characterized MeV neutrons beams using three beamlines. Pulsed beams and thin targets permit to produce quasi-monochromatic MeV neutron pulses with ns duration. In addition, a calibrated beam shaping facility for thermal neutrons based on Be target is also available [3-4].

The available beams allow to perform radiation biology studies, dosimeter calibrations and original development of tissue equivalent proportional counters for oncological hadron-therapy and BNCT.

The CN accelerator is complementary to the AN2000 for the analytical purposes: EBS, EBS Channelling, and NRA, PIXE and PIGE are accomplished routinely spanning the entire available energy and particle range using two scattering chambers of which one provides complete simultaneous data acquisition from 6 detectors comprising 1 Si(Li) detector for PIXE, 1 HpGe detector for PIGE and 4 silicon detectors for simultaneous EBS and NRA using in-situ variable stopping foils, to provide maximum flexibility in (d,p), (d,α), (^{3}He,p), (^{3}He,α) NRA. The sample holder is specifically designed for automated analysis of a large number of samples in environmental and materials science studies.

A new facility for large area MeV proton irradiation is also available for irradiating exposed components on satellites in geo-stationary orbits with doses in the range 10^{9} to 10^{16} cm^{-2}.

The research groups accessing the CN facility range from about 15 to 20 per year from Italian and foreign Universities and Research Centres.

The number of beam-time hours per year and the subdivision of the beam-time in the various application fields of the CN in the last 12 years is shown in Fig. 3. As it can be seen, on the average, about 1100 hours are provided to users yearly. Neutron applications, micro- nano- dosimetry, nuclear cross section measurements, IBA and device irradiation represent the most significative fraction of the beam-time yearly allocated to the CN users. The CN accelerator is also used to perform training of students and young researchers in nuclear physics and material science.

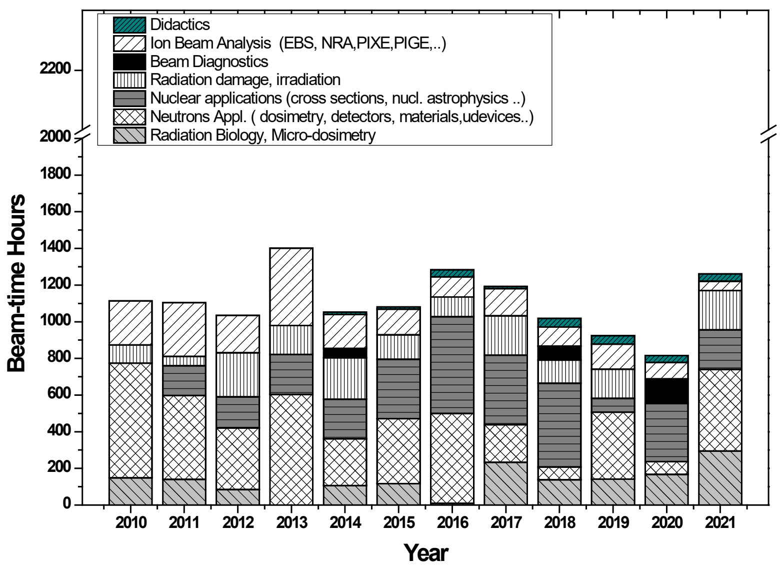

FIG. 3. Yearly beam-time hours delivered on user's targets by the CN accelerator in the past 12 years subdivided in main application fields.

3. CONCLUSIONS AND PERSPECTIVES

The multi-disciplinary and user-oriented nature of LNL is clearly documented by the attraction that the two Van de Graaff MeV accelerators, although quite old, exert on many users involved in academic and applied research in different disciplines of interest not only of INFN but also of a wider multi-disciplinary community. This accounts for an average of about 2500 beam-time hours per year (excluded didactics and servicing) provided by the two accelerators.

Future developments in MeV accelerators at LNL, should take into account the above reported main activities currently carried out by the users willing to do physics with small accelerators at the Legnaro Laboratories and to access the infrastructures in the future to bring innovation and potential return of investment through academic and UE projects and industrial collaborations.

Without entering into the fine details of the daily issues in operating the two accelerators and equipment thereof, which are caused by the considerable age of the two infrastructures (more than 50 years old), we may state that the substantial upgrade of both accelerators and of part the infrastructures and ancillary instrumentation is now mandatory to keep international competitiveness.

The high level of the scientific activity carried out at the AN2000 and CN laboratories is attested by the remarkable number of publications on international journals yearly published by the research teams accessing the two Legnaro infrastructures. Further details might be found in the LNL Annual Report [5], in particular in the "Interdisciplinary physics and instrumentations" section.

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