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ACCELERATOR MACHINES AND EXPERIMENTAL ACTIVITIES IN THE ENEA FRASCATI PARTICLE ACCELERATORS AND MEDICAL APPLICATION LABORATORY*

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Abstract

In the ENEA Frascati research centre the APAM (Particle Accelerators and Medical Application) laboratory is devoted to the development of particle accelerators for medical applications. Two main facilities are operative.

The TOP-IMPLART proton accelerator is a pulsed fully linear machine aimed at active intensity modulated proton therapy with a final energy of 150 MeV. The machine offers two beam extraction points: one at 3-7 MeV, on a vertical line, and the other one at 35 MeV, the maximum energy currently available, with a pulse current up to 35 μA, on the horizontal line.

The REX source consists of an electron standing wave LINAC generating a beam in the energy range of 3 to 5 MeV with a pulsed current of 0.2 A. This source can generate Bremsstrahlung X-ray beams using suitable converters (Pb, W, Ta).

This paper describes the experimental results of satellite activities performed in these facilities in the fields of biology, dosimetry, electronics, PIXE spectroscopy and preservation of cultural heritage artifacts.

INTRODUCTION

Two irradiation machines are currently in operation in the APAM (Particle Accelerators and Medical Application) laboratory of the Frascati ENEA research centre: one is the medium-energy proton accelerator TOP-IMPLART (Terapia Oncologica con Protoni – Intensity Modulation Proton Linear Accelerator Radio Therapy) [1] and the other is the REX (Removable target Electron X-ray) radiation source [2].

Both of these facilities were realized as part of programs aimed at the research and development of compact particle accelerators for medical application and are also used in experimental irradiation campaigns in various sectors.

This article refers the experimental activities carried out in collaboration with other national research institutes and centers within various scientific programs.

The two acceleration machines and some recent applications are described in the next paragraphs.

PARTICLE ACCELERATORS AT ENEA FRASCATI RESEARCH CENTER

Proton Accelerator

The TOP-IMPLART proton accelerator is a machine designed for clinical purposes and financed by the local government of the Regione Lazio. The program is carried out by ENEA in collaboration with the Italian Institute of Health (ISS) and the Oncological IFO Hospital.

It is a fully linear accelerator under construction, composed of a commercial injector produced by ACCSYS-HITACHI operating at the RF frequency of 425 MHz (consisting of a duoplasmatron source, a 3 MeV RFQ and a 7 MeV DTL) followed by accelerating units operating at 2997.92 MHz. The final energy of the accelerator will be 150 MeV. Figure 1 shows the overview scheme of the TOP-IMPLART accelerator in its final layout. As can be seen, the low-energy acceleration section consists of the injector module and a vertical transport line (VL) mainly devoted to radiobiology experiments. The energy of the particle beams extracted from the vertical terminal is selectable between 3 and 7 MeV [3].

The medium energy acceleration section, up to 71 MeV, consists of Side Coupled Drift Tube Linac (SCDTL) acceleration modules while the high energy section, over 71 MeV, is composed by Coupled Cavity Linac (CCL) modules.

Currently only the first 4 SCDTL modules of the TOP-IMPLART system are installed and in operation allowing proton beam acceleration up to 35 MeV along the horizontal line (HL) [4].

The output beam has a temporal structure with a pulse duration of 15-80 μs in the injector and 1-4 μs at the output of the high frequency section. The typical repetition frequency is 20 Hz (50 Hz maximum). The pulse current can be varied from 0.1 to 35 μA by changing the voltage on an electrostatic lens placed in the injector.

During the operation the beam current, injected in the high frequency linac and then extracted from it, is measured by two commercial current transformers.

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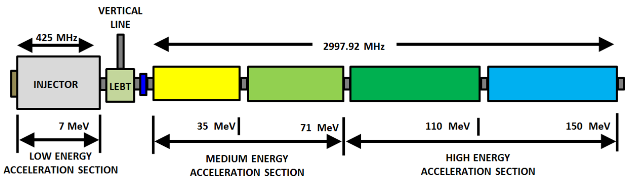

Figure 1: Schematic drawing of the TOP-IMPLART accelerator in its final layout.

They are positioned along the beam line and are used to detect intensity greater than 5 μA in a non-interceptive way. However a large part of the experiments require pulse current lower than the sensitivity of such diagnostics tools. For this reason a suitable small ionization chamber is used to measure charge pulses below to 0.3 pC. The size (FWHM) of the beam at the linac output is less than 1 mm in x and 2.5 mm in y. For experiments requiring irradiations of larger targets the beam is spread in air.

Figure 2 shows the extraction and measurement points of the TOP-IMPLART proton beams.

Figure 2: The vertical extraction line of the low energy proton beam (left) and the medium energy extraction point with the second ACCT device and the integral ionization chamber (right).

Electron Accelerator

The REX source of radiations allows the use of accelerated electron beams and X-rays.

The facility is based on a machine developed in the 1990s [5] and recently modernized and adapted for the current needs of the laboratory.

It is composed of an electron linear accelerator reaching a maximum energy of 5 MeV and an in-vacuum transport line that ends with a titanium window (50 μm thick). A special electrons/X-rays conversion system can be positioned after the electrons extraction terminal: it is a steel section housing a switchable target and an in-air lead collimator. In the REX source, the Bremsstrahlung X-ray beams are generated by Pb or W or Ta conversion targets.

The facility is equipped with a lead irradiation chamber housing the samples to be exposed to ionizing radiation. Within this shielded volume, the dosimetric characterization of the radiation beams is performed with a plane-parallel ionization chamber (model IBA PPC05) that can be moved by a remote control system. Figure 3 shows the REX setup scheme. The inside of the REX irradiation chamber is shown in Figure 4.

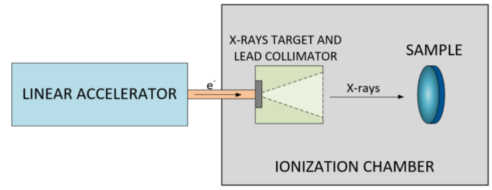

Figure 3: Scheme of the REX setup for samples to be irradiated with electrons or X-rays.

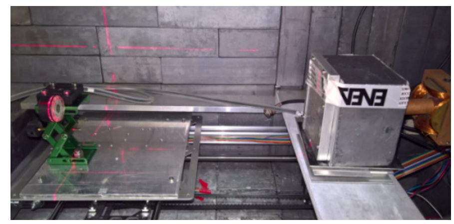
Figure 4: The inside of the REX irradiation chamber.

EXPERIMENTAL ACTIVITIES

Experimental Campaigns with the TOP-IMPLART Proton Beam

The TOP-IMPLART accelerator, given its characteristics described above, is adapted for irradiation in different applied research experiments conducted by external laboratories: the variable energy proton beam is available for exposure campaigns using different operative set-ups also during the current construction phase of the machine. According to the purpose of the experiments, the proton beam is extracted from the VL or from the HL and the samples to be irradiated can be positioned immediately after the beam exit in air or at the distance allowing the appropriate spread of the spot with the desired uniformity.

On the VL quantitative evaluation of the biological damage studies are performed on specific in-vitro cell lines using Petri dishes suitable for irradiation from below [3]. Furthermore non-invasive and non-destructive elemental studies of materials are conducted in the field of Cultural Heritage diagnostics [6]. These experiments require different setups in terms of beam size and charge on target.

For radiobiological studies the beam spot has been made homogeneous on an area of 133 mm^2 combining, along the transport path, a gold scatterer and specific collimators with a 50 μm Kapton exit window. Cell surviving curves of V79 and CHO cells lines have been retrieved by 5 MeV protons in a dose range 0.2-8 Gy with a dose rate of 2 Gy/min, a pulse duration of 13 μsec and a repetition frequency of 10 Hz.

Elemental analysis (PIXE) experiments was carried out using a specific VL terminal ending with a Berillium window 7 μm thick. In the selected configuration the beam spot is reduced to 0.07 mm^2. The proton energy was varied from 2.75 to 5.85 MeV to perform stratigraphic analysis of material layers at different depths. The repetition frequency in PIXE experiments was set to 60 Hz to optimize the response of the RX detector in terms of the signal/noise ratio. The pulse current was 0.2 μA for both experiments.

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An upgrading of the VL irradiation setup is being implemented with the installation of an on-line energy and dose measurement system based on a silicon detector and of a multiple sample-holder with remote controlled movement to allow irradiation of a number of samples.

The proton beam currently available along the HL can have, at the output of the machine, an energy of 35 MeV, operating with all 4 accelerating structures SCDTL switched-on, or 27 MeV operating with 3 SCDTL and transporting the accelerated beam along the last module off. Two ionization chambers are used to monitor the beam in air: an integral ionization chamber (working range 10^0 - 10^2 pC), joined to the extraction segment and a double (XY) multistrip ionization chamber. The first is devoted to measure the monitor units of the irradiation and turn-off the beam when a preset amount of particle charge is reached (equivalently when a specific dose is delivered); the second one is used to monitor the beam in terms of shape and intensity. The beam has been used for wide spectrum of applications (in-vivo radiobiology for space applications [7, 8], in-vitro radiobiology experiments of clinical interest [9], dosimetric detectors characterization [10-13], high energy PIXE [14]). The main parameters of the different experiments carried out on the HL are summarized in Table 1.

Table 1: Main Parameters of Experiments Performed on the TOP-IMPLART Accelerator Horizontal Line

MeV	Experiments	Main operative parameters
27	*in-vitro* cells	Dose range= 1 ÷ 8 Gy
11 - 27	*in-vivo* Mice	Dose= 2 Gy
27 – 35	Alanine dosimeters Silicon dosimeters Diamond dosimeters MOSFET dosimeters Photo-luminescent LiF	Dose rate= 2 ÷ 16 Gy/min
18	ceramic, gypsum, pigments and antique metal coins	Charge= 3.5 pC Current= 0.2 μA

The experiments are conducted 1-1.8 m far from the accelerator in order to obtain a uniform spot (better than 5%) on target. Only for PIXE measurements the samples are positioned at a distance of 1.5 cm from the linac exit.

In-vitro cells (U-251 human glioblastoma) irradiation are carried out using 16.5 x 49 mm^2 slide flasks inserted in a sample holder displaced in a stepwise fashion in front of a 17x17 mm^2 beam collimator in order to cover the all sample holder surface. In this case, the required beam homogeneity on the collimator area is obtained spreading the beam by means of a 120 μm lead scatterer (positioned at accelerator exit) and 2 m of air.

In-vivo irradiation of mice (for immune response of particular organs of small animals in space applications) are performed with a typical dose of 2 Gy using a specific collimator to set up the treatment field on the mouse body. The irradiations of mice have been done in two different phases of the accelerator development using only the SCDTL-1 structure (11 MeV proton energy) first and then using the SCDTL-3 structure (27 MeV proton energy) [7].

For the irradiation of different dose sensors a multiple-detector holder has been realized. The entire layout is positioned at a distance of 1.8 m from the linac. The beam spread in air has a uniformity better than 4% on a circular area with 16 mm of diameter defined by a collimator. The measurements with different type of dosimeters show a beam reproducibility around 2%.

18 MeV protons have been used at SCDTL-2 output for high energy PIXE measurements [14] on different types of samples working at a repetition frequency of 20 Hz.

Future experiments consisting in the irradiation of soft-core microcontroller implemented into an FPGA are planned by using the current maximum available energy (35 MeV) with a fluence of 10^{11} prot/cm^2. The aim is to measure the SEU rate and verify the core reliability limits for space applications.

Experimental Campaigns in the REX Facility

The REX irradiation facility is currently used for demonstration campaigns of materials treatment: studies of specimens of historical and cultural interest [15, 16], for insect sterilization treatments [17] and for analysis of the tungsten damage for nuclear applications [18] are carried out. In the framework of projects aimed to conservation of cultural heritage, the X-ray beams produced by the REX source are used to verify the effectiveness of the treatments for the biodegradation removal from wood, canvas and parchment. The experiments demonstrate that the irradiations killed the contaminant bacteria and xylophagous insects with no damage of substrates.

Moreover, for entomologic applications in the field of the technique of the sterile insect (ordinarily employed on male insects through nuclear facilities), the X-rays produced by the REX source were used to sterilize the mosquito female specimens.

In the materials for nuclear fusion field, electron beams are directly used to create a matrix of defects within tungsten lattices for hydrogen isotopes retention studies.

Table 2 shows some parameters of the REX source configurations used for the described applications.

Table 2: Main Parameters of Experiments Performed with the REX Source

Radiation	Experiments
X-rays 1.1 MeV uniformity= 5 ÷ 10%	Paper, wood, canvas, parchment Dose rate of about 2 Gy/min Distance source/sample= 5 ÷ 20 cm
X-Rays 1.1 MeV uniformity= 5%	Aedes albopictus Dose rate = 1 Gy/min Distance source/sample= 10 cm
Electrons 4.8 MeV uniformity= 3%	Tungsten water-cooled sample holder Average current= 0.18 A

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