EXPERIMENTAL ACTIVITY IN THE ENEA-FRASCATI IRRADIATION FACILITY WITH 3-7 MeV PROTONS

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Abstract

A variable energy (3-7 MeV) and pulsed current (0.1 – 100 μA) proton beam has been made available for different applications (radiobiology experiments, detectors development, material studies) in an irradiation facility at ENEA-Frascati based on the 7 MeV injector of the proton-therapy linac under realization in the framework of the TOP-IMPLART Project. It is a 425 MHz linear accelerator consisting in a 3 MeV RFQ followed by a DTL up to 7 MeV (PL-7 ACCSYSHITACHI model) followed by an horizontal and a vertical beam transport line. The latter one is particularly suitable for radiobiology in vitro studies allowing to irradiate besides cell monolayers also cell growing in suspension culture. The paper describes the facility and the recent results of the experimental activity.

TOP-IMPLART AT ENEA-FRASCATI

A 7 MeV RF proton linear accelerator is in operation at ENEA-Frascati as the injector of a protontherapy linac under developing in the framework the TOP (Oncological Therapy with Protons)-IMPLART (Intensity Modulated Proton Linear Accelerator for RadioTherapy) Project launched by ENEA in collaboration with Italian National Institute of Health (ISS) and Regina Elena National Cancer Institute-IFO-Rome [1]. Aim of the project is a construction of protontherapy centre based a proton accelerator consisting of a sequence of linear proton accelerators up to the final energy of 230 MeV to be housed at IFO. The realization of the first section up to 150 MeV has been funded by Regione Lazio and is under assembly in a 30 m long, 3 m wide bunker at ENEA-Frascati (fig.1) for the full proton beam characterization and dosimetric validation before the relocation to IFO. The proton beam will also be used for radiobiology experiments devoted to the developments of "in vivo" and "in vitro" models for the study of cellular mechanisms involved in the carcinogenesis process. The radiobiology experiments will also allow a biological characterization of the beams in terms of the Relative Biological Effectiveness (RBE), cell survival, time to repair, cell proliferative activity and bone resorption after treatment.

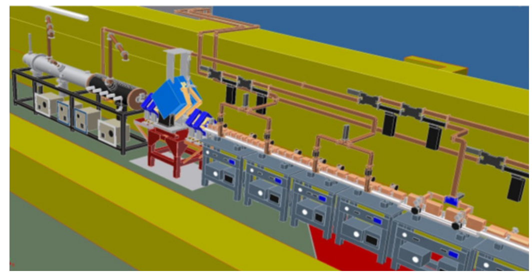

Figure 1: TOP-IMPLART layout at ENEA-Frascati.

The lowest energy part of the accelerator is a commercial 7 MeV proton injector, a PL7 AccSys-Hitachi model consisting of a DuoPlasmatron Source, a 3 MeV RFQ and a DTL (up to 7 MeV) both operating at the frequency of 425 MHz (Fig 2a). It was customized by adding to the standard high current PL7 model two elements for its use as injector for the ENEA low current protontherapy linac: a beam aperture can be inserted to reduce the pulse current to the levels required by protontherapy (from mA to μA scale) and the possibility to vary the beam current also pulse by pulse pulsing the power supply of an einzel lens following the proton source. The injector is able to give a continuously variable energy beam from 2.7 to 7.1 MeV by varying the relative phase and/or the radiofrequency input power level of the DTL.

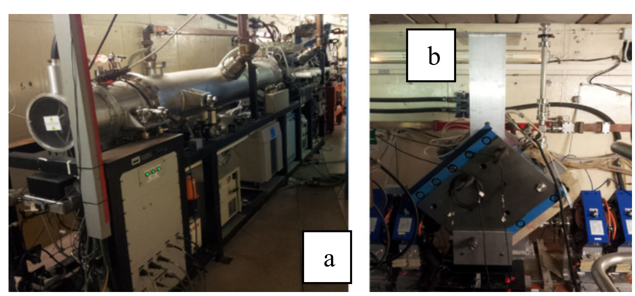

Figure 2: view of the structures of the 3 – 7MeV facility: a) Injector, RFQ and DTL sub-systems. b) vertical and horizontal transport lines.

In the ENEA-Frascati setup the injector is followed by a transport line with four quadrupoles for matching the 7 MeV beam in the transverse planes with the following accelerating structures. A dedicated radiobiology vertical beam line has been implemented using a 90° vertical bending magnet placed between the two couples of quadrupoles (fig.2b).

The proton beam can be also extracted in air in an horizontal point along the transport line before the second pair of quadrupoles for satellite experiments with a high fluence horizontal beam.

All of these characteristics make the TOP-IMPLART injector available for different applications. In the following recent results of the experimental activity performed with low energy (3-7 MeV) proton beams are described: two different experimental campaigns have been done with low and high proton fluences, along the vertical and horizontal beam pipe, as depicted below.

LOW FLUENCE PROTON BEAM

Low energy protons are particularly effective in inducing biological effects [2]. For the study of *in vitro* models of cellular mechanisms involved in the carcinogenesis process development, cells irradiation with proton fluences under 10^6 protons/cm^2 and a uniformity around 10% are required. The TOP-IMPLART low energy vertical beam line has been arranged in order to meet these requirements: a 2 μm thick Au scatterer is positioned after an Al collimator (2 mm diameter) in order to make uniform the particle beam on an area of 13 mm of diameter after a drift of 69 cm. Protons finally cross the vacuum/air interface composed by a 50 μm Kapton window. The use of a beam pointing upwards allows disregarding the cell distribution deformation due to gravity in horizontal beam lines. The beam energy is measured with high accuracy with the magnet used as a spectrometer and the machine operation is monitored during the irradiation measuring the current intercepted by the collimator.

Radiobiology Experiments

A campaign of radiobiology experiments has started on Chinese Hamster V79 cells for cell killing induction studies in a dose interval up to 10 Gy at different beam energies and dose rates. The dose rate can be varied varying the pulse length (i.e. the charge for pulse) and the dose is set varying the irradiation time.

The first irradiations have been made with 5 MeV protons on the cells (LET= 7,7 keV/μm) at different doses in a range 0.5-8 Gy. Cells were seeded with their culture liquid (thickness of about 6 μm) on a mylar sheet of 50 μm and positioned within a cylindrical sample holder with a diameter of 13 mm (Fig. 3-right), standing directly on the beam line terminal. The proton energy in vacuum was 6.2 MeV corresponding to a current of 278 A in the vertical bending magnet.

For the dosimetry control during the whole experimental stage GafChromic films EBT3 was suitably calibrated at LNL Laboratories with proton beams of the same characteristics at the entrance of the active layer of the EBT3 film [3]. Experimental parameters of the V79 irradiation are summarized in table 1.

Table 1: Beam Characteristics during V79 Cells Irradiation

MeV	prot / cm^2	μA	μs	Hz	Gy/ min
5	10^5÷ 10^6	0.16	13	6.25	2

After irradiation the cells were detached from the Petri dish mylar foil, counted, diluted and plated at the appropriate concentrations for survival evaluation. The dose response curve obtained was characterized by an initial shoulder followed by a straight portion, that can be well fitted by a linear-quadratic function of the dose ($S = \exp(-\alpha D-\beta D^2)$). The obtained results were found in very good agreement with literature data.

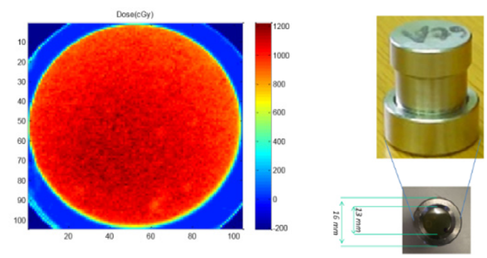

Figure 3: left) Spatial dose distribution on Gaf-Chromic EBT3 film: the irradiated area has a uniformity of 90%; right) Sample holder for cells.

HIGH FLUENCE PROTON BEAM

High fluences proton beams, over 10^{10} protons/cm^2, are extracted along the horizontal line and used on experiments for material studies. In the following results of trials addressed to the development of a LiF particle detector and to realize porous silicon for Micro-Electro-Mechanical-Systems (MEMS) are described.

LiF-Detectors Development

In the last years, lithium fluoride (LiF) crystals and thin films have been proposed and tested as solid-state x-ray and neutron imaging detectors, based on the optical reading of the photoluminescence (PL) of radiation-induced visible-emitting electronic defects, known as colour centres (CCs). Moreover, LiF is a well-known thermoluminescent dosimeter material and it is sensitive to any kind of ionising radiation [4]. For these reasons proton beams of 3 MeV and 7 MeV energy were used to irradiate at room temperature (RT) LiF crystals and 1 μm thick LiF films, in the fluence range from 10^{11} to 10^{15} protons/cm^2. The irradiation of LiF induces the formation of primary and aggregate CCs, which are stable at RT. By a fluorescence optical microscope equipped with a cooled s-CMOS camera, it was possible to record the transversal proton beam intensity profile by acquiring the PL image of irradiated LiF (inset of Fig. 4). It showed an interesting linear behaviour with fluence covering several orders of magnitude of fluence range (Fig. 4).

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The sensitivity of the optical reading techniques and the high emission efficiency provided encouraging results, which are under study in order to optimize the LiF film-based detectors characteristics related to their PL response on selected fluence intervals, for dosimetry and imaging applications in protontherapy.

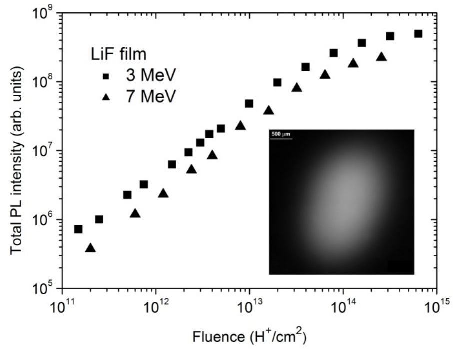

Figure 4: Integrated visible photoluminescence signal as a function of the 3 and 7 MeV proton fluence in irradiated 1 μm thick LiF films grown on a glass substrate.

Porous Silicon

The irradiation of silicon with ion beams of different species, energies and fluences is the principal technique used in the semiconductor industry to alter its electronic properties (doping). Proton beams are particularly interesting for bulk micromachining applications, in particular in conjunction with the formation of porous silicon. It has been discovered that porous silicon does not form in silicon areas irradiated with a given dose of protons [5]. It is known that porous silicon formation is highly dependent on the doping type and level.

Protons of 1.8 MeV (degrading the beam energy placing an aluminum foil in front of the sample) has been used to experiment silicon bulk micromachining with uniform proton beam and a hard metal mask to transfer patterns on silicon. Experiments were carried on 1-10 Ohm*cm, p-type silicon samples (cut in square chips of 1.5 x 1.5 cm^2) doped with Boron with orientation (100).

The implant mask consists of 500μm wide fingers, separated by 500μm gap, is 200μm thick and made of Molybdenum. The fluencies were in the 10^{14} – 10^{15} protons/cm^2 range. After exposure the porous silicon layer has been grown in an electrochemical cell under galvanostatic regime in IPA: HF=1:1 mixture. The morphology of the processed samples has been analyzed with FESEM (Field Emission Scanning Electron Microscope). Figure 5 shows the cross section of the porous silicon grown in a position corresponding to the edge of one finger. The image has been taken with an angle of 67° and, thus the real thickness of the section between the cursor is 31μm, that corresponds to the stopping range for 1.8MeV protons in silicon. Porous silicon appears lighter than silicon and with a rough surface texture. The image clearly shows that the irradiated area is not converted into porous silicon up to a distance from the surface, corresponding to the stopping range. Porous silicon grows from the surface in the non-exposed areas and proceeds vertically (following the implantation profile) up to the depth of the implanted layer. Once the implanted layer has been reached, porous silicon grows isotropically extending below the exposed area.

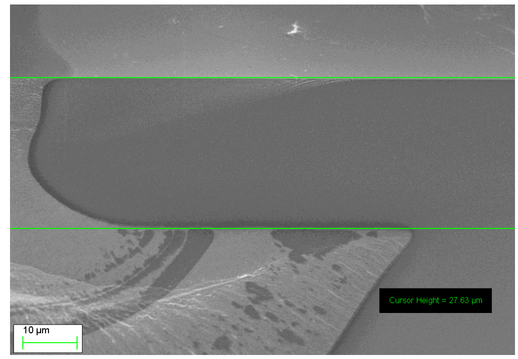

Figure 5: Cross sectional image of exposed silicon sample after porous silicon formation. Porous silicon appears lighter with a rough texture.

Once the porous silicon layer has been removed with a KOH (potassium hydroxide) etch, the transferred pattern becomes evident. The isolated fingers corresponds to irradiated areas and the areas between them corresponds to the porous areas etched away.

This technology is particularly interesting for the realization of MEMS and for the machining of silicon interposers for advanced packaging applications.

CONCLUSIONS

In this work we illustrate the experimental activity with the low energy (3-7 MeV) beam produced by the TOP-IMPLART injector. The facility shows great versatility because of it can work with variable particle fluencies being suitable on different applications as demonstrated describing some recent results of irradiation experiments on several topics: radiobiology trials, detectors development and material studies.

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