THE PROTON BEAM FACILITY OPTIS FOR THE THERAPY OF OCULAR TUMOURS

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ABSTRACT

OPTIS stands for Opthalmological Proton Therapy Installation SIN. The method to treat ocular tumours with a proton beam was developed in Boston, USA, and was introduced in Western Europe by the Swiss Institute for Nuclear Research SIN (today PSI, Paul Scherrer Institute). 72 MeV protons from one of our Injector Cyclotrons are used regularly during one weak monthly for the OPTIS program. Since 1984 more than 600 patients have been treated. OPTIS is a collaboration between PSI and Ophtalmological Hospital of Lausanne University.

The proton beam for OPTIS has to fulfil several special requirements. Besides this, the success of the therapy program depends very much on the availability of a stable, reproducible and well controlled beam. In this paper, the technical aspects of the beam preparation and control are described. The layout and the characteristics of the beam transport line are given together with the main steps of the set-up procedure. The basic ideas of the control and safety system of OPTIS are outlined and the essential details of this system are also given.

INTRODUCTION

The aim of radiotherapy is to sterilize all cells of a tumour with minimal damage to normal cells in its neighbourhood. By using a high energy proton beam for the irradiation of ocular tumours, one comes close to this goal: protons penetrating tissue loose their energy by ionization in a way that the energy loss rises by a factor of three to four just before a sharp stop (Bragg peak). The scattering of the protons within the tissue is much smaller than with usual radiations (e.g. electrons). The sharp stop of the Bragg peak allows to fit the depth of the irradiated volume to the depth of the tumour in the eye by adjusting the proton energy resp. the range in tissue. The low scattering allows to limit laterally the irradiated volume by the use of proper collimators. The energy of 72 MeV is ideally suited to the treatment of ocular tumours: After energy losses through the scattering foils, air, etc. the useful maximum range at the eye is 31. 5mm in tissue. This is sufficient for all tumours of the ocular cavity; a higher energy would not have any advantage but would lead to a broadening of the Bragg peak.

Pioneer in the proton therapy of the eye was the group at Boston/Harvard in the USA. In the Harvard Cyclotron Laboratory in Cambridge, Mass., proton therapy started in 1961 using the beam of the 160 MeV synchrocyclotron for programs in collaboration with hospitals in Boston. The number of the patients rose rapidly and it was recommended [1)] that other laboratories in the USA and Europe start with similar programs soon.

In 1982 the installation of the OPTIS facility using the 72 MeV proton beam of the Injector I-Cyclotron at SIN was decided. The decision was made in regard of two facts: first, in 1984 the new Injector II was planned to take over the duty of injecting 72 MeV protons in the Ring Cyclotron during three weeks of four, leaving enough time for other activities with Injector I. On the other hand, the Eye Hospital in Lausanne (Switzerland) had great experience in the treatment of ocular tumours, most of which are intraocular melanomas, and was much interested in the introduction of proton therapy. As a consequence, a very fruitful collaboration was established: OPTIS is run under the medical direction of the Ophtalmological Hospital of the University of Lausanne[2,3)].

Injector I [4)] of PSI is a compact four-sector isochronous cyclotron with two operation modes: one with the fixed frequency of 50.6 MHz for the injection of a 72 MeV proton beam into the 590 MeV Ring Cyclotron, the other with the variable frequency of 4 to 17 MHz to accelerate protons and various light ions to serve low energy physics experiments. Injector I serves also for the production of radioisotopes. All this tasks are performed in a 4-week-rythm: after two weeks physics experiments follows a week in injection mode, the fourth week being reserved during daytime for OPTIS and at night for isotope production. In spite of this complex operation schedule, an excellent stability and reproducibility of the OPTIS beam could be achieved. OPTIS can be operated both in the fixed frequency and in the variable energy mode. The Injector I-Cyclotron, in operation since 1974, was built by Philips, Endhoven (The Netherlands).

LAYOUT AND BEAM TRANSPORT TO OPTIS

The first beam experiments for OPTIS were carried out during 1983 in one of the experiment areas, where later the therapy unit was definitely installed. The situation of OPTIS with respect to the Injector I-Cyclotron is shown in Fig. 1.

The distance along the beamline between the cyclotron and the treatment point of OPTIS is about 38 m. The beamline consists of 3 bending-, 11 quadrupole- (1 triplet and 4 dou-

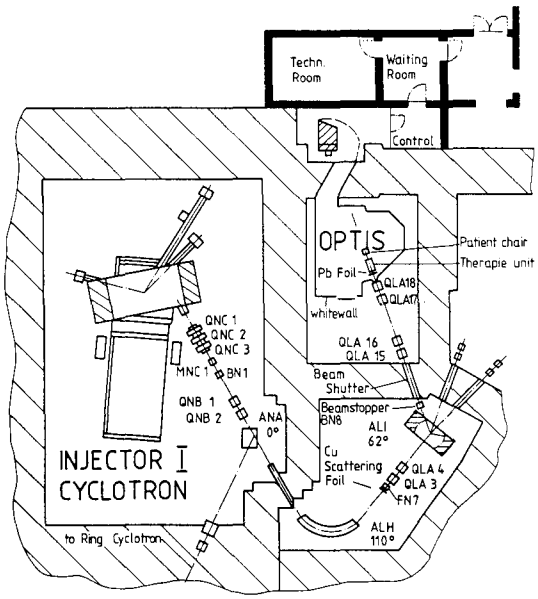

Fig. 1: Layout of the OPTIS beamline.

blets) and 6 steering magnets as well as of standard diagnostics elements[5]: profile monitors, beam stoppers, slits, ionization chambers and a non-intercepting beam current measuring device. For the transformation of the experimental beamline into a therapy line for OPTIS no major changes had to be made. The beam optics is simple and unsensitive to the starting conditions, fulfilling one of the requirements for a safe routine operation. It was designed with the help of our version of the well known computer code TRANSPORT[6,7]. The optics is shown in Fig. 2.

The first part of the beam optics is for all 72 MeV proton beams of Injector I the same, which differ only in the intensity of the respective beam current: up to 200 μA for the injection mode, 80 μA for isotope production and 0.5 to 0.6 μA for OPTIS. The value for OPTIS was chosen in regard to a safe and comfortable beam intensity control. The emittance of all these beams lies between 2 and 4 pimmrad and the energy spread is about 300 keV. By the quadrupole triplet QNC1/2/3 a horizontal and a vertical waist are produced, and the doublet QNB1/2 shapes the beam for the following analysing magnet ALH.

To reduce the beam intensity by a factor of 0.1 for OPTIS, a copper scattering foil was installed close to the focus of ALH. The 0.4 mm Cu foil, mounted on a frame, can be pneumatically put in and out of the beam. It is a most important element in the safety system of OPTIS. The loss of intensity on the foil is roughly 90 percent. The horizontal divergence of the scattered beam is limited by the movable slit FN7 to protect the vacuum chamber of the following doublet QLA3/4, which produces a double waist in front of ALI, a switching magnet distributing the low energy beams in different experiment areas. A graphite collimator of 30 mm diameter between the exit from ALI and the beam stopper BN8 limits the beam divergence in both phase planes. During the OPTIS runs the beam stands on BN8 which is pneumatically moved in and out of the beam according to the commands of the OPTIS control system. Inside the OPTIS vault, the doublet QLA15/16 transports a large beam to the last doublet QLA17/18 which produces a very sharp double waist. This waist is at the location of the entrance collimator of the therapy unit of OPTIS. Between QLA18 and the collimator the beam exits the vacuum system by a 0.05 mm capton window.

BEAM HANDLING WITHIN THE THERAPY UNIT

The therapy unit[8] is shown in Fig. 3. The 5 mm opening of the entrance collimator together with a 0.9 mm thick lead scatterer foil mounted on it define a secondary point source of the scattered beam, which traverses an air filled tube with four collimators of different openings and arrives at the treatment location 1430 cm downstream with a homogeneous flux of 10^8 protons cm^{-2} s^{-1} within a diameter of 34 mm. This is essential for the safety, since any mismatch of the beam optics would result only in the reduction of intensity but would have no effect on the spatial dose distribution. The final collimator at the treatment location is shaped to the profile of the tumour.

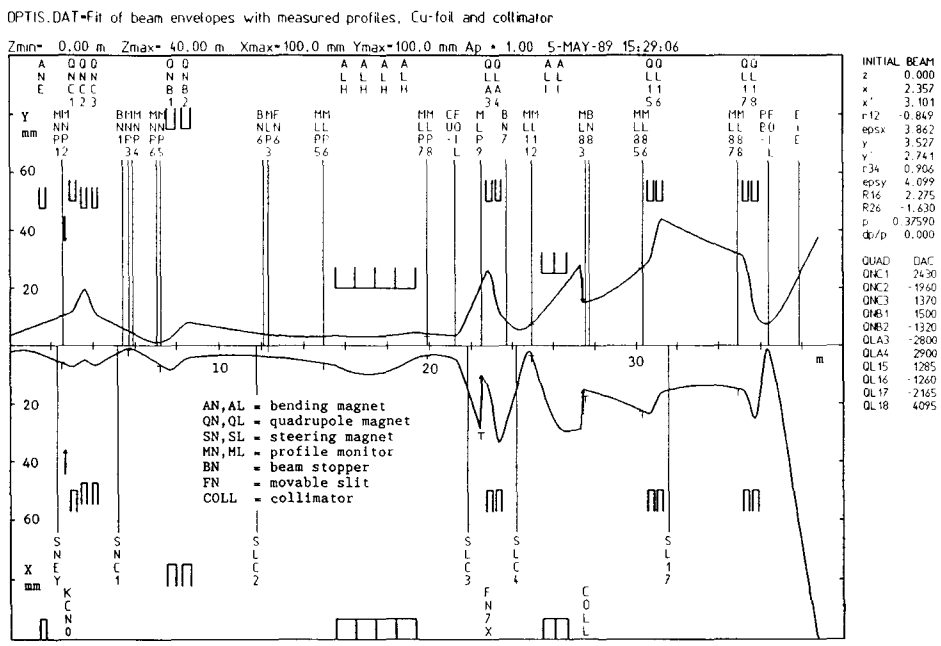

Fig. 2: Envelopes of the OPTIS beam. For the calculation of the envelopes, the beam profiles as measured during an arbitrary OPTIS run are fitted with the phase ellipses as free parameters of the beam extracted from the cyclotron. The Cu foil and the limiting apertures are taken in account.

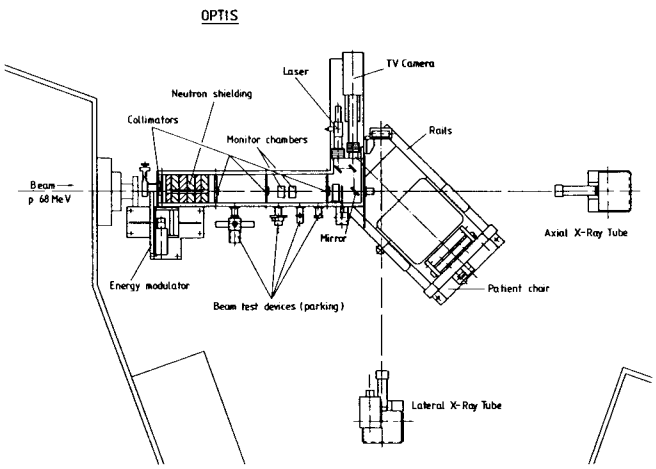

Fig. 3: Therapy unit of the OPTIS facility.

The energy modulation system shifts and modulates the beam energy in order to produce any wanted individual depth-dose distribution. The main requirement is a constant dose over the whole depth range of the tumour to achieve the same biological effect throughout the tumour volume. The principle of the system is outlined in Fig. 4. The aluminium profiles mounted on a wheel modulate the energy with a frequency of about 400 s^{-1}. The copper screens mounted on the same wheel stop the low energy protons thus producing a lower surface dose if wanted. The depth of reduced dose can be chosen by mounting one of our 11 copper screen sets of different length. A fixed absorber of continuously adjustable thickness allows to shift the whole depth-dose distribution toward lower ranges. Since it introduces distortion of the constant distribution as well, we need 4 sets of modulators to cover the domain of maximum ranges from 4 to 31.5 mm in tissue, allowing for full-width distortion of max. 10 percent. The modulation system produces additional scattering especially at high energy reduction, i.e. small ranges in tissue. Placing it upstream to the first collimator we can avoid the effects on the spatial distribution at the expense of additional losses in beam intensity. We need an average of 50 nA incident proton beam to get a treatment fraction dose of 15 Gy within 20 seconds. To protect the body of the patient down to 2 mSv in a full treatment course of 60 Gy in 4 fractions, a neutron shielding is mounted inside the beam tube.

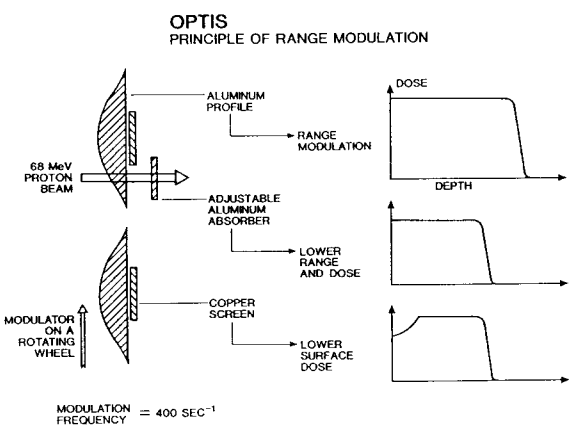

Fig. 4: OPTIS principle of range modulation.

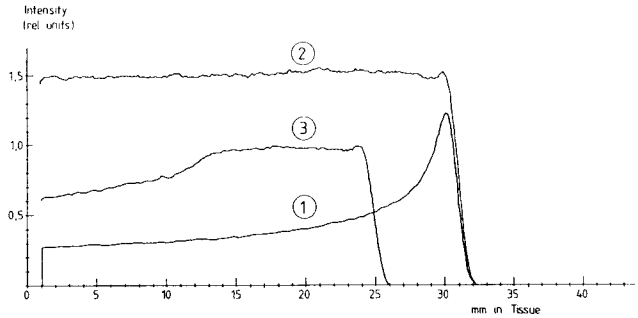

Fig. 5: Measured depth dose distributions
Curve 1: Undisturbed Bragg peak
Curve 2: Modulated Bragg peak
Curve 3: Modulated distribution shifted to lower range with reduced surface dose.

SET-UP PROCEDURE

To achieve a reproducible proton beam for OPTIS, it is essential, in addition to the reliability of all elements involved, that the set-up procedure will be followed rigorously step-by-step. After having set the interlock system in the proper mode, the magnet coils are set to standard values by a computer program. The set-up of the cyclotron is straightforward. An important safety requirement for OPTIS is to ensure that the intensity of the extracted beam can not go beyond the specified level. This is done by limiting the beam size in the center of the cyclotron vertically by a collimator, mounted on the body of the ion source, and horizontally by a phase slit in the first orbit[4]. In addition to these, the ion source, which is of the Lambertson-PIG-type with heated cathode, as described in ref. 4), is equipped with a pair of vertically deflecting plates which can be biased with 2 kV each. The intensity of the extracted beam, as measured on the non-intercepting current monitor MNC1 is controlled by the voltage of Plate 1 (Plate 2 is normally grounded) by means of a feed-back program [9] which keeps the proton current constant. Plate 2 serves as a very fast shut-off element: an interlock- resp. 'therapy stop' signal closes a contact in the power supply and the beam will be deflected. The deflector plate of the ion source is thus a most important safety element of OPTIS.

As the next step in the set-up, the beam optics as characterized above will be established. We dispose of a fine automatic centering code working with a simple matrix algorithm, with the help of which the deviations of the beam positions as measured on the profile monitors will be corrected by the coordinated steering magnets within a few minutes[10]. When the beam is ready on the beam stopper BN7, the Cu foil is put in, the width of the profile MLP9 is controlled and the beam is brought to BN8. The set-up of the last part of the beamline which is inside the OPTIS vault can be made only with the collaboration of the operators of the Main Control Room with the OPTIS crew. Since there are no profile monitors after QLA18, the final optimization is made by maximizing the current on a diode at the location of the eye. The OPTIS crew is responsable for the accomplishment of the prescribed function tests.

CONTROL AND SAFETY SYSTEM OF OPTIS

Our Personnel Safety System 'PSA' protects persons working at PSI by preventing them to enter an experiment area

as long as the beam is there: entrance is possible only when the signal 'closed' of the beam shutter resp. that of the beam stopper in front of it have been received. Accordingly, the beam may be let in an area only after the thorough control (by a key system) that nobody is in the vault and that the heavy shielding door is closed.

The Machine Interlock System of PSI protects not the people but the elements of the three cyclotrons and of the respective beamlines from damages of whatever origin during a run. It is divided in sections between two beam stopper devices. The Machine Interlock is part of our Main Control System [11] and is based on programmable CAMAC modules. According to the actual operation mode, various Interlock Modes can be programmed so that only the sections where the beam should go will be sharply controlled.

A dedicated OPTIS Control System[12] has to fit between the two systems outlined above to fulfil the special requirements, partly in contradiction to the standard system, namely:

- the safety required for patient treatment is much stronger than the protection provided by the Machine Interlock System
- the access of the personnel must be much faster than allowed by the PSA system, the PSA access control is therefore replaced by a special set of warning devices and rules of behaviour for the crew members.

The OPTIS Control System consists of two sections: a section located at the therapy area controlling mainly the elements and functions of the therapy unit, the status of which is signalized for the therapy crew, and a section located in the Main Control Room watching over the conditions of the 'OPTIS Beam Allowed' status. The detailed informations about these are displayed on a screen for the operators in the Main Control Room; only a single sum signal is sent over to the therapy crew to the local control rack.

The main tasks of the OPTIS Control System are:

- control and carry out the 'beam on'/ 'beam off' commands of the therapy crew
- control the dose delivery to the patient
- enable calibration measurements and biology experiments without patient in slightly changed but still strictly defined conditions.

To ensure the maximum possible safety for the patient, several elements of the system are supervised with two- resp. threefold redundance. An example is the Cu scattering foil, which is secured by a key: for all interlock modes except for OPTIS, the key must be stuck in the console of the Main Control Room. In the 'OPTIS' mode, the foil has to be put in the beam by pulling the key out of the console to be allowed to transport the beam to the stopper BN8 but not further; to get the permission for therapy irradiation, the key has to be stuck in the local control rack of OPTIS and turned properly, its position being watched by both parts of the OPTIS Control System, the Machine Interlock System, and also by the 'PSA'. After having received the key, the OPTIS crew has taken over also the responsability for moving the beam stopper BN8 out or into the beam and the operators of the Main Control Room have no access to the stopper until the key will be returned.

The local part of the OPTIS Control System has two modes of operation: the 'therapy' and the 'measurement' modes. In the 'therapy' mode, no vetos can be bridged. The OPTIS operator gives the 'therapy start' command by pushing a button. This command acts only when all vetos have been resetted before: it opens the beam shutter KNA2 and the stopper BN8 and lets the beam in the area, i.e. to the patient until the 'therapy stop' signal shuts it off.

The 'therapy stop' signal is given normally by a 'scaler stop' veto of the readout electronics after the radiation dose wanted is delivered. It acts simultaneously on the deflector Plate 2 of the ion source, the beam stopper BN8 and the beam shutter KNA2. The beam will be deflected within 20 ms but will be given free and comes back automatically to BN8 as soon as stopper and shutter are closed. For safety redundance, the status of the deflector plate and the beam are watched independently so that if the beam is not deflected after the stop command the cyclotron RF and the arc current of the ion source are shut off within 65 ms.

OUTLOOK

In view of the good results of the treatment[3] and because of the advantages a dedicated 'eye machine' would offer, as pointed out already a few years ago[1], preliminary studies with cost estimate with regard of such a machine were carried out[13,14] but no decision was made yet.

ACKNOWLEDGEMENT

The very reliable OPTIS beam is the result of a remarkable teamwork and the engagement of many people involved, whereby we particularly appreciate the contributions of the Injector I-(S. Drack, P. Meyer, J. Pokorny, P. van der Starre), Control- and Operation Groups.

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