High Energy Accelerator Technology in Radiology

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Abstract

Radiation treatment of cancer dates back about 100 years. Today, mega-voltage electron accelerators are used routinely to irradiate many kinds of tumours. About two thirds of all cancer patients receive at least some radiation. More recently, other kinds of particles have come into use, some already on a more or less routine basis: neutrons, pions, protons and other light ions. Experience with some of these particles at PSI is described. As an illustration, a concept for advanced accelerator-based therapy is described; it consists of a 2.5 MeV RFQ injector, a 70 MeV linac, a 250 MeV H^- synchrotron, and a 2.1 GeV electron ring operated as a synchrotron light source. Possible niches for high energy technology are identified.

INTRODUCTION

At present, about two out of three cancer patients receive at least some radiation[1]. In the longer term, there is concern throughout Europe, and in particular in the EEC countries, about the growing human toll of the disease, and the increasing strain that it is placing on health and welfare facilities. In 1985 about three-quarters of a million people died of it in the EEC alone. Given present-day costs, improved (and cheaper) treatment methods are becoming increasingly important.

One promising line of attack involves the use of accelerators. PSI, with its expertise in all the fields involved in this multi-disciplinary effort, and its national and international contacts, is very well placed to contribute to the R & D effort, and to some degree to routine treatments. However, the main goal is to develop hardware and techniques that can be transferred to the lower-technology environment of hospitals, clinics, etc., not only in the developed world.

THE PIOTRON - IRRADIATION WITH Π^-S

One of the most technologically advanced forms of therapy is irradiation with negative π^-s, which has been tried at all three pion factories: PSI, LAMPF & TRIUMF. The principle of the technique is that as a π^- comes to rest in tissue, it will react with one of the heavier nuclei $(C, N, O\ldots)$. If the π^-s can be brought to rest in a tumour, the reaction products will preferentially irradiate the tumour. At PSI about 500 patients have been treated, starting in 1980 with a superficial melanoma case.

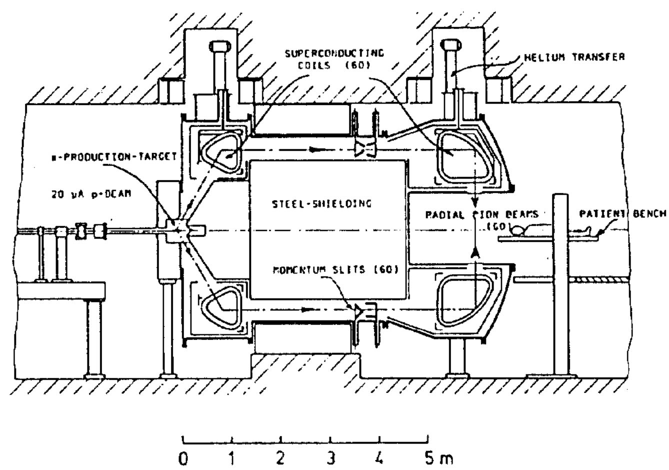

Figure 1: The Piotron at PSI

The beam-line, the most sophisticated yet built, is known as the 'Piotron', and is shown in Figure 1. A full description can be found in references[2,3]. In brief, a beam of up to 20 μA of 600 MeV protons from the PSI Main Ring impinges on the π^- production target. Among the many particles produced, π^-s at near 60° are collected and deflected parallel to the axis of the Piotron by a toroidal arrangement of super-conducting coils. After passing through the momentum slits, the π^- beams are bent by a second toroid, towards the patient, who is supported within a water bolus.

With appropriate selection of the rigidity, and hence the range, of the π^-s, most of them will some to rest near the focus, forming a 'hot spot' 40-50 mm in diameter. Treatment consists of moving the patient inside the water bolus in such a way that the hot spot is scanned through the tumour, sparing as much as possible the healthy tissues nearby.

The technique has been tried on many tumours, and is almost routine for large (typically some kg) abdominal sarcomas of complicated shape. The usual dose is 33 π^- Gy delivered in 20 fractions. The 5-year local control rate is 60% for the sarcoma cases, which cannot for various reasons be treated by conventional radiation, chemotherapy or surgery. There are however some drawbacks:

- About 10^5 protons at 600 MeV are required to deliver 1 π^- to the tumour; this corresponds to about 0.5

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Gy-kg per minute at 20 μA.

- The RBE under treatment conditions is not as high as expected from the very early studies made at low dose rates to low doses, usually on plants, in the π^- beams that were available before the advent of the pion factories.

The RBE has in any case been less useful than the ability to make the dose distribution conform to the tumour shape.

OPTIS – TREATMENT OF RETINAL MELANOMAS

Optis, the 72 MeV PSI beam-line dedicated to the treatment of retinal melanomas, is a simpler device, based on earlier work in the USA. It is based on the principle that a heavy particle, as it comes to the end of its range in matter, deposits an increasing amount of energy per unit track length – the so-called Bragg peak. Eye tumours are typically 15 mm thick as seen by the protons, each of which will therefore deposit a few tens of MeV in the tumour.

The proton beam from injector 1 is shaped to match the tumour by a combination of scattering, collimation and range shifting. The dose is 60 Gy (cobalt equivalent), delivered in four fractions of 15-30 seconds each by a nA beam. This technique is well suited to routine therapy, as evidenced by the 200 or so patients treated in 12 weeks of operation each year. Some results are shown in Figure 2.

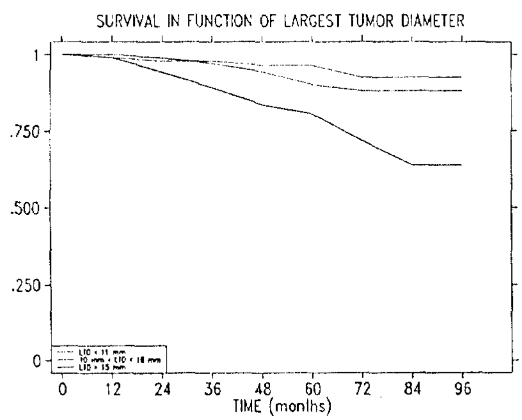

Figure 2: Some results of retinal melanoma irradiation.

PROTON IRRADIATION OF LARGE TUMOURS

A great deal has been learned from a decade's experience of treating some 500 patients in the Piotron, especially about 3-dimensional treatment planning. Much of this experience is being applied to proton irradiation of large tumours – the Proton Therapy Project (PTP). Scanning is done magnetically, by range shifting, and by moving the patient, in that order. Installation of the device has begun.

The proton beam spot is significantly sharper than the π^- beam spot in the Piotron. One can therefore match the treatment volume more precisely, sparing better the healthy tissue near the tumour. It is felt that this will more than compensate for the lower RBE of protons as compared to π^-s. In consequence, the proton beam is expected to be as good or better than the π^- beam.

At PSI the protons are made by slowing down 600 MeV particles from the Main Ring. An accelerator of the size needed to produce beams at the 200-250 MeV required, although a large and expensive device, would be within the budget of a large hospital if sufficiently good results could be demonstrated.

EXPERIENCE AT UPPSALA

Biological experiments and radiotherapy with 185 MeV protons from the synchrocyclotron at what is now the The Svedberg Laboratory (TSL) began in the 1950's. The accelerator, now rebuilt, can be operated at fixed frequency to deliver 100 MeV protons, or with variable frequency up to nearly 200 MeV.

A treatment room equipped with a narrow proton beam unit for therapy of small intracranial targets is in operation at TSL. Patients are seated in front of a fixed horizontal beam line. Titanium markers permanently implanted in the patient's *tabula externa* are used for the precise location of the patient with X-rays for each treatment fraction. To date, 14 patients have been treated with 100 MeV protons, most for arterio-venous malformations. In addition, 20 eye melanoma cases have been treated with 72 MeV protons, using a technique very similar to the PSI one discussed above.

BORON NEUTRON CAPTURE THERAPY (BNCT)

This is a promising technique for the treatment of gliomas and other brain tumours, and for certain other cancers[4]. It is based on the large cross-section (4 kbarn) for thermal neutron capture by ^{10}B: if the latter is concentrated in a tumour, the tumour cells will be preferentially irradiated by the short-range reaction products; healthy tissue nearby will be largely spared.

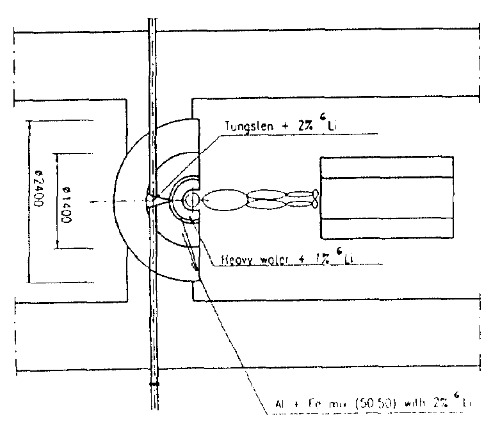

Figure 3: A possible BNCT layout

Concentrations of $\sim$ 30 ppm$_w$ of ^{10}B in the tumour, and neutron fluxes of 10^9 cm^{-2} s^{-1} at keV energies are needed, for a total treatment time of a few hours, fractionated as required. Because reactors face such problems of public acceptance, accelerator-produced neutrons are very attractive. A dedicated spallation source, based on a 100μA proton beam from Injector 2, is under intensive study at PSI; a possible layout is shown in Figure 3.

A POSSIBILITY FOR THE FUTURE

Table 1 lists some parameters of a possible accelerator complex which is described elsewhere[5]. It consists of several parts:

1. A 2.5 MeV RFQ injector, intended for
   (a) Feeding the 70 MeV injector linac
   (b) Low energy BNCT, neutrons being produced by the ^{7}Li(p,n)^{7}Be reaction
2. A 70 MeV linac, intended for
   (a) Feeding the synchrotron
   (b) Nuclide production, as at PSI today
   (c) Eye irradiation, again as at PSI today
   (d) BNCT, in a double-patient facility, using spallation neutrons
3. A 250 MeV H$^-$ synchrotron, intended for the irradiation of large, deep-seated tumours in five beam-lines, three of which are equipped with gantries in which patients can be irradiated isocentrically. One beam-line is available for experiments.
4. (In a later option, if required by future radiological developments.) A 2.1 GeV electron ring, built on a different level and intended for the generation of keV X-rays for imaging and treatment. The ring might also be able to accelerate carbon ions, in the first instance for intracranial irradiations.

The facility, able to treat several thousand patients each year, would cost about as much as a jumbo-jet; it would be small enough to be installed at a large university hospital, or at PSI. A related study is under way in Italy, by the Progetto Adroterapia ('TERA') group at the Como campus of the University of Milan.

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Table 1: Accelerator Specifications for a Medical Facility

RFQ Injector					
Energy	2.5	MeV			
Beam Current (pulse)	20-30	mA			
Linac			Synchrotron		
Energy	70	MeV	Particle type: H$^-$		
Beam Current (pulse)	40	mA	Energy	60-250	MeV
Energy Spread (FWHM)	$\pm$0.1	%	Intensity	10^{11}	p/s
Emittance (normalized rms)	0.15π	mm.mrad	Extraction time	30	μsec
Max beam pulse width	215	μsec	Repetition rate	5	Hz
Pulse repetition rate	1-120	Hz	Accelerator diameter	16	m
Max average beam current	1000	μA	Power consumption	100	kW
Accelerator weight	7.5	ton			
Accelerator length	ca 25	m	Particle type: $^{12}C^{6+}$		
Input power			Ring diameter	20	m
at 100 μA average current	100	kW	Dipole field	1.3	T
at 1000 μA average current	650	kW	Max energy	260	MeV/A