ACCELERATION OF NITROGEN IONS TO 7 GEV IN THE PRINCETON PARTICLE ACCELERATOR

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Abstract

Nitrogen ions in charge state N^{5+} and N^{6+} have been accelerated in the Princeton Particle Accelerator (PPA) to 4 and 7 GeV respectively. An external N^{5+} beam of 3×10^5 particles/sec has been obtained while the N^{6+} beam was about 2×10^5 particles/sec. The measured total charge-changing cross section of N^{5+} was found to decrease from 5×10^{-17} cm^2/molecule at 0.6 MeV/amu to 3×10^{-18} cm^2/molecule at 40 MeV/amu. Calculation shows that an improvement in vacuum from 2.2×10^{-7} Torr to 1×10^{-7} would increase the N^{5+} beam by at least tenfold. Rough measurements of the N^{6+} total cross section indicate that it is smaller than the N^{5+} at the higher energies. Some initial experimental results on the properties of the 4 GeV beam are presented.

1. Introduction

Until recently the scientific interest in accelerated heavy ions has been confined to the 10 MeV/nucleon range, and below, since it is in this energy regime where traditional nuclear structure physicists feel most at home. The regime of 100-1000 MeV/nucleon, and higher, has long been of keen interest to cosmic ray physicists studying high energy heavy ions, but lacking intense sources of accelerated particles progress has been slow in this field. Recently a vigorous biomedical interest in heavy ions has arisen because of the prediction that ions of nitrogen, or neon, with sufficient energy to penetrate tissue to depth of 10-20 cm would be markedly superior to X rays in treating cancer. For this an energy of about 300-600 MeV/nucleon is necessary. Figure 1 summarizes, very schematically, the energy and ion species requirements for various fields of interest.

Because of the wide range of energy and nuclear species desired by the experimenters the accelerator designer is presented with a rather challenging problem. We have chosen to concentrate, for the time being, on nitrogen because that is probably the heaviest particle which our present vacuum will transmit with a tolerably low attenuation. Also, nitrogen is close to being the ideal particle for the cancer therapy studies which are our major, current interest. A suitable source of fully stripped neon would probably make that particle available with sufficient intensity to be very interesting.

A heavy ion synchrotron may be operated in any one of several modes depending on the final charge state to be accelerated and the manner of achieving that charge state. This fact presents the designer with both opportunities and challenges. There are opportunities to use various combinations of ion sources, preacceleration, stripping, post-stripping acceleration, and stripping after acceleration in the synchrotron followed by storage and final acceleration. The challenge arises from the large number and range of possible parameters which must be rationalized. While it might be possible to attempt a general analysis of these problems, as a practical matter one must start from the status quo which, in the case of the PPA, means a 4 MV electrostatic injector with scant space for an ion source and a system originally designed for the acceleration of protons, deuterons and α-particles. The following discussion will therefore be largely concerned with the problems we faced and our particular solutions.

2. Various Possible Modes of Heavy Ion Acceleration in a Synchrotron

The present types of ion sources produce ion charge states which correspond to the removal of rarely more that a few electrons; charge states as high as 10+ have been obtained only for krypton and some heavier elements, although with relatively low yields. Different modes of ion acceleration in a synchrotron have to be used to cover the desired energy range up to the upper limit, which is determined by the ratio q/m of a fully stripped ion and by the magnetic rigidity $B \cdot \rho$. The final ion energy is variable over a wide range, step-wise by changing the charge state q at injection, and between the charge steps, by continuously varying the peak magnetic field. The following modes of operation can be used, depending on the desired charge state in the final state of the acceleration:

Mode (a) Acceleration in a constant charge state, as produced in the source, through the injector preaccelerator and through the synchrotron to ejection.

Mode (b) Stripping of the preaccelerated particles before injection into the synchrotron

Mode (c) As in Mode (a), but followed by extraction out of the synchrotron, partial stripping, temporary storage in a d.c. storage ring and subsequent reacceleration in the main ring (Omnitron proposal)[1].

Mode (d) As in Mode (b), but followed by extraction, a second, 100% stripping, storage and subsequent reacceleration in the main ring to maximum energy.

Advancing from Mode (a) to Mode (d) the peak available energy increased toward the upper limit set by the top magnetic field.

3. Synchrotron Vacuum Requirements

In the course of the acceleration ions will be lost through the interactions with the molecules of the residual gas in the vacuum chamber. One of the interactions, multiple small-angle scattering which leads to a gradual increase of the phase space occupied by the beam, will be relatively less important than in a proton synchrotron; fully stripped ions may represent an exception. Losses due to charge-changing collisions are the main cause of concern. The beam transmission or the relative number of ions surviving in the synchrotron after a time t is given by the Omnitron formula,

$$\frac{n}{n_o} = \exp\left[-10^{27}\cdot p\cdot\int_0^t \sigma(\beta)\beta dt\right] \qquad (1)$$

where p is the pressure in Torr, and $\sigma(\beta)$, in cm^2 per molecule, is the sum of all cross sections for single and multiple charge changes as a function of $\beta = v/c$. An exact calculation of the pressure p, which would allow a certain beam transmission n/n_o, requires a knowledge of the residual gas composition and of all charge change cross sections. As there are no available experimental data for high energy heavy ions, empirical expressions and extrapolations for $\sigma(\beta)$ have to be used. Standard procedures have been described in several PPA internal reports. The residual gas in the present vacuum chamber consists mostly of water vapor and some nitrogen and CO, but in order to simplify the calculations a pure nitrogen background was assumed. The results obtained for the required pressures should be on the conservative side because one may expect that the cross sections for a nitrogen molecule would be somewhat larger than those for a water molecule. Calculations were performed for a few different ion species in the operating Modes (a) and (b). Assuming an average time constant of the beam decay equal to the acceleration time, and a beam transmission of 1/e, vacuum requirements are calculated to be as follows:

Table I

N^{2+} stripped to N^{5+}; Mode (b): $p = 3\text{-}5 \times 10^{-8}$ Torr

N^{2+} stripped to N^{6+}; Mode (b): $p = 4\text{-}6 \times 10^{-8}$ Torr

N^{2+} stripped to N^{7+}; Mode (b): $p = 1\text{-}2 \times 10^{-7}$ Torr

N^{3+} stripped to N^{7+}; Mode (b): $p = 2\text{-}3 \times 10^{-7}$ Torr

Xe^{4+}, Xe^{5+}, U^{7+} ; Mode (a): $p = 1\text{-}2 \times 10^{-9}$ Torr

When accelerating N^{5+} and N^{6+} beams, however, a pressure higher by a factor of two can be tolerated in practice because the injected beam is at least an order of magnitude more intense than the N^{7+} beam.

4. Ion Source and Stripping

A small, low power PIG source was developed to fit into the space available in the present Van de Graff terminal[2]. Its main feature is a pulsed 4 kG magnetic field. When operated with nitrogen gas a total accelerated current of 1.5 mA is obtained at the base of the Van de Graaff, with 7% in N^{2+} and 0.8% in N^{3+}. Very small amounts of N^{4+} and even smaller of N^{5+} are observed. Although the direct acceleration of N^{2+} and N^{3+} components would yield ions with energies of up to a few hundred MeV/nucleon, such a mode cannot be used with the present vacuum chamber because a vacuum in the low 10^{-8} Torr range would be required. Instead of that, the beam from the Van de Graaff is first separated in an ExB separator and then the N^{2+} or N^{3+} component is stripped in a 10 $\mu g/cm^2$ carbon foil. The selected thickness is a compromise between the requirement that the equilibrium distribution of charge states be reached and that the handling be easy on one side and the desire for the smallest possible scattering and subsequent deterioration of beam qualities on the other. At an accelerating voltage of 4 MV in the Van de Graaff the following equilibrium charge distributions have been obtained. Our results compare very well with those of Reynolds, Wyly, and Zucker[3] who have made similar measurements.

Table II

Initial Charge State	Equilibrium charge distribution, in µamp, after stripping			
	N^{4+}	N^{5+}	N^{6+}	N^{7+}
N^{2+}	8.4	16.5	6.7	0.33
N^{3+}	0.16	1.1	0.8	0.12

5. RF System Modification

The accelerating system has four drift tubes and four cavities which, taken together, cover, for proton acceleration, the range 2.4 to 29.8 MHz. Crossover from drift tube to cavity occurs at 5.8 MHz. An extended frequency range from 1.2 to 29.8 MHz is needed to accommodate the lower charge to mass ratio of deuterons, α-particles and a variety of heavy ions. The method chosen was to leave unchanged the crossover frequency and the high power cavity system while extending the low frequency limit from 2.4 to 1.2 MHz and doubling the peak voltage capability of the drift tubes from a maximum of 8 kV station to about 16 kV station. These modifications were achieved by using new ferrites for the drift tube resonator tanks (Tohoku ACI200-R) and by using for the final amplifier stages larger tetrodes (4 CW 25000), new power supplies, drivers, as well as transistor banks for biasing the ferrites.

6. Parameter Programming

Programming the various accelerator parameters for selected ion variety, selected charge state from the source, selected charge state from the stripper, etc., was carried out on a Hewlett-Packard computer. The program provides complete information on parameters for the injection and acceleration cycle, parameters which are manually fed into the synchrotron while a certain amount of fine tuning by hand is still done by the operator. A small on-line computer which was in process of being connected to the machine is, unfortunately, no longer with us. This computer was intended to correct injection parameters by means of minimum field and pole face winding trimming and had performed well on tests with the proton beam. Table III gives a few typical parameters for possible modes of injection and acceleration of nitrogen.

Table III

Initial Charge State	Stripped Charge State	Frequency Swing (MHz)	Field KGauss	E_{Total} BeV	h^*
N^{2+}	N^{5+}	1.60-29.6	.331-8	.008-4	12
N^{2+}	N^{6+}	1.60-29.6	.278-6.7	.008-4	12
N^{2+}	N^{5+}	1.33-29.6	.331-11	.008-7.3	10
N^{2+}	N^{6+}	1.33-29.6	.278-9	.008-7.3	10
N^{3+}	N^{6+}	1.30-29.6	.338-13.9	.012-12.5	8
N^{3+}	N^{7+}	1.30-27.4	.29-13.9	.012-16.7	8

*Harmonic Number

Our initial success on July 16, 1971, was with the first mode N^{2+} to N^{5+}. On September 15 we successfully accelerated N^{6+} to 7 GeV.

7. Beam Monitoring

Three varieties of beam monitoring devices are presently available: fluorescent and electronic flags, capacitive pickup electrodes, and photomultiplier-scintillator detectors.

(a) Flags are used for initial beam finding and orbit determination at injection.

(b) The same electrostatic beam pickup electrodes which were used for monitoring the proton beam are used for the heavy ion program. New FET amplifiers with low noise, about 3 μV rms, allow us to observe the beam down to about 10^5 particles/pulse (N^{5+}).

(c) A few milliseconds after injection the beam has become so weak, because of attenuation by charge-changing collisions, that beam monitoring for tuning purposes must be done by two scintillator-photomultiplier probes. This combination of diagnostic tools allows us to inject, capture and accelerate the beam in spite of the fact that the intensity is presently six orders of magnitude lower than that of the proton beam.

Figure 2 shows a typical oscilloscope picture of the scintillator probe signal as a function of time. The signal amplitude is primarily a function of the energy lost in the probe and therefore of the dE/dx for a single particle. If two or more particles should pass through the scintillator within a fraction of a microsecond the amplitude shows quantum jumps the probability of which increases with beam current. Of course the number of discrete pulses per unit time is also a function of beam current. The rising and falling amplitude corresponds to the nitrogen ions penetrating deeper and deeper into the 6 mm scintillation probe finally passing all the way through. By the use of an inner and outer probe it becomes easy to fine tune the RF program. Actually the inner probe is used almost exclusively since for N^{5+} the loss of an electron, leading to N^{6+}, is by far the most probable cause of beam attenuation and such an increase in net charge causes the particle to move in radially where it is detected.

8. Injection Line Modifications

The nitrogen beam from the Van de Graaff, containing all charge states, is passed through a crossed electric-magnetic field separator which transmits only N^{2+}. After passage through a 3 m radius deflector the beam is sent through a 10 μg/cm^2 carbon foil mounted on tungsten mesh. The emerging beam, now enriched in N^{5+}, N^{6+} and N^{7+} is sent through an electrostatic inflector, 2.4 m in radius, which can be adjusted to transmit and inject a single charge state into the synchrotron. There are additional electrostatic deflector plates, magnetic dipoles and electrostatic quadrupoles to focus and direct the beam.

Due to slightly poorer injection energy regulation than we had for protons (± 800 V) it was necessary to choose a rate of magnetic field rise at injection time which permits only five-turn injection (45 μsec). Eventually we expect to double this to ten turns which corresponds to an injection time of about 90 μsec. According to our experience with protons we should achieve a factor of two more beam.

9. Capture Efficiency

Capture efficiency calculations have been performed using standard theory with the result that about 20% of the injected beam should end up in phase stable buckets. This is essentially the same as we compute, and observe, for protons.

10. Vacuum Chamber

The original PPA chamber consisted largely of a fibre glass and epoxy resin skin supported by laminated metal ribs attached to a stainless steel front wall which also served as a pole piece spacer. Some chambers have vapor barriers of thin, stainless steel inner liners while others have thin sheets of glass incorporated in the outer coating. Twenty-three, six inch oil diffusion pumps were used to pump the system to 2 x 10^{-6} Torr, a pressure quite adequate for protons. Most of the residual gas was found by mass spectrometer analysis to be water vapor. A series of tests demonstrated that the epoxy-fibre glass walls are slightly permeable to water vapor and helium. Essentially the same chamber is now used for heavy ion acceleration. In order to reach our present average pressure of 2.0 x 10^{-7} Torr we instituted a program of replacing all rubber O-rings by metal gaskets, or Viton, and, most importantly, by installing liquid nitrogen "cold fingers" throughout the system. We are also replacing eight of the old CVC pumps by faster Varian pumps. We are currently planning on doubling the area of cold fingers and expect to halve the pressure to essentially 10^{-7} Torr, or better.

We have built, and installed, two ceramic chambers which, on test stand, reached $8 \pm 3 \times 10^{-10}$ Torr using a single oil diffusion pump. The ceramic chambers in the synchrotron average about 3×10^{-8} Torr without being thermally outgassed and without liquid nitrogen cold fingers.

Looking towards the future we hope to replace all epoxy chambers by ceramic chambers, to eliminate all organic matter and to substitute sputter ion pumps for the oil diffusion pumps. If this is done we are confident of reaching 10^{-9} Torr.

11. Performance of PPA as an Accelerator of N^{5+}

An external beam of 3.9 GeV (280 MeV/amu) N^{5+} ions has been produced at a maximum current of 3×10^5 particles/sec (2.7×10^4/pulse) and a long time average of 4×10^4/sec. The N^{5+} beam injected into the synchrotron had an energy of 7.0 MeV (0.5 MeV/amu) and an intensity of about 8×10^8 particles/pulse. Assuming about 10% capture efficiency the beam, before suffering gas attenuation, contained about 8×10^7 particles/pulse. Since the internal beam is probably about five times the external the circulating beam must have been about 1.35×10^5 particles/pulse at 4 GeV. Thus the attenuation from capture time to 4 GeV is about a factor of 600. Circulating beam signals, as seen on the electrostatic pickup plates, allowed us to make preliminary measurements of the attenuation of the beam as a function of time up to 500 MeV total (35.8 MeV/amu). Curve (a) of Figure 3 gives the observed data while Curve (c) depicts the deduced total charge-changing cross section of N^{5+} as a function of energy. The dip in total cross section at 15 MeV may or may not be real. The dotted curve gives the predicted variation of cross section based on the observations of MacDonald and Martin[4]) who studied oxygen ions travelling in nitrogen. The most interesting and significant feature of our data is the rapid drop in total cross section at energies above 30 MeV (2.1 MeV/amu). Based on the observed currents above 1 GeV we can state that σ_{Tot} must continue its rapid decrease up to at least 3.9 GeV (280 MeV/amu).

It is clear that an improvement in the vacuum would lead to a substantial decrease in beam attenuation of N^{5+}. Curve (b) was derived from (a) by assuming a vacuum of 1×10^{-7} Torr rather than the present 2.2×10^{-7} Torr. A beam increase of at least a factor of ten should result. It is apparent from Table I that even our present vacuum is entirely adequate for N^{7+}; the attenuation would be no more than 1/e. Unfortunately our present N^{7+} current is too small to tune on unless we use He^{2+} as a "tuning" gas in the initial stages of acceleration when the beam energy is too low to activate the scintillation counters. When we do, eventually, accelerate N^{7+} we will reach 1.1 GeV/nucleon or 15.4 GeV total.

We have recently, successfully accelerated N^{6+} to 7 GeV with an external current in the range of 2×10^5/sec. The attenuation from capture to 7 GeV appears to be substantially less than for N^{5+}. Since both N^{5+} and N^{6+} were injected at the same energy, 7.0 MeV, the smaller attenuation observed for N^{6+} must be intrinsic to the more fully stripped state of N^{6+}.

12. Extracted Beam

An external beam is obtained by use of the same resonant extraction system which was used for protons, deuterons and α-particles. About 20-50% of the internal beam is extracted and transmitted 24 m to the bombardment cave. The focal spot obtained with protons was approximately 6 mm in diameter, a figure which should be independent of q/m of the particle even though to date we have not done this well with nitrogen. A spill time of 8 msec was customary with protons, with a concurrent 10% momentum spread due to our sine wave top. While the same spill properties should be attainable with nitrogen we have limited the spill to 2 msec in order to limit the energy spread to ± 1%. A flat top, magnet power supply exists which, if employed, would yield a 50 msec spill with top flat to 0.1%.

13. Some Preliminary Experiments at 4 GeV

One of the first things to establish in connection with our cancer therapy studies is the depth dose profile of the beam. Figure 4 shows data taken by the Columbia Radiological Laboratory using two, thin ionization chambers filled with tissue-equivalent gas. The steeply rising dose near the end of the range is due, of course, to the Bragg peak which results from the q^2/v^2 variation of dE/dx with charge and velocity. Nuclear interactions occurring along the path of the ion cause both attenuation of the nitrogen beam and a background of secondary fragmentation particles, both charged and uncharged, which contribute to the measured dose. Thus the dose data shown in Figure 4 include nuclear attenuation and secondary nuclear particles as well as the primary ionization by the nitrogen ion. The small plateau to the right of the peak is almost certainly due to nuclear fragmentation particles. That this plateau is quite small and the Bragg peak is quite high lends support to our belief that heavy ion therapy holds great promise. Initial experiments on the inactivation of hamster cells by 4 GeV nitrogen ions shows distinctly the higher lethality of the Bragg peak and an entrance lethality comparable with X rays.

We have measured the nuclear attenuation length in polyethylene and find it to be 15.4 ± 3.8 cm, a quantity consistent with expectation assuming a cross section which varies as $A^{2/3}$ (A = atomic number). The cross section for producing the radioactive nucleus ^{11}C has been measured to be 103 ± 9 mb.

Secondary charged particles emitted at 13° from a platinum target bombarded by 4 GeV nitrogen ions have been observed as a function of momentum and time-of-flight. Preliminary analysis indicate a rather surprisingly copious production of α-particles, ^{3}He, ^{3}H and deuterons relative to protons.

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References

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4) J. R. Macdonald, F. W. Martin, Experimental Electron Transfer Cross Sections for Collisions of Oxygen Ions in Argon, Nitrogen and Helium at Energies from 7 to 40 MeV (Private Communication)

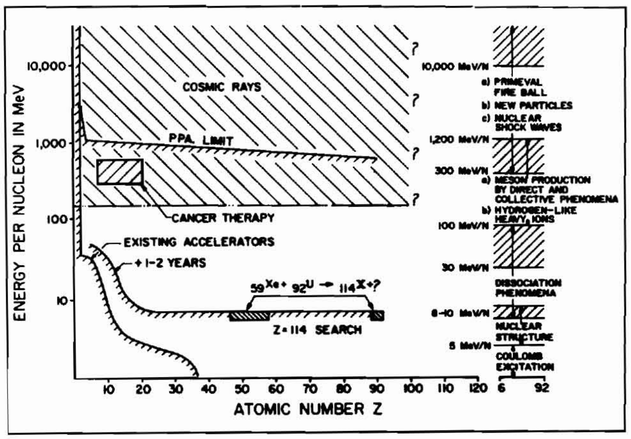

Figure 1: RANGE OF NUCLEAR SPECIES AND ENERGIES REQUIRED FOR VARIOUS FIELDS OF INTEREST

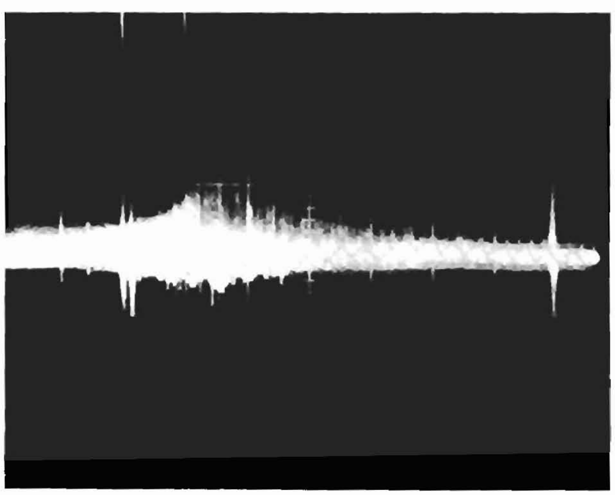

Figure 2: SCINTILLATOR PROBE BEAM SIGNAL 3.5 MSEC/DIV

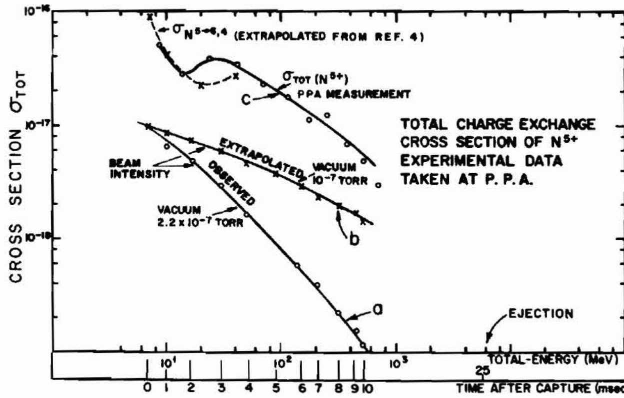

Figure 3: TOTAL CHARGE-CHANGING CROSS SECTION FOR N^{5+} AS FUNCTION OF ENERGY: Curve (a) Observed attenuation of beam as function of time after capture at a pressure of 2.2×10^{-7} Torr; Curve (b) Predicted beam current of N^{5+} assuming a vacuum of 1×10^{-7} Torr; Curve (c) Charge-changing cross section of N^{5+} as function of energy as derived from (a)

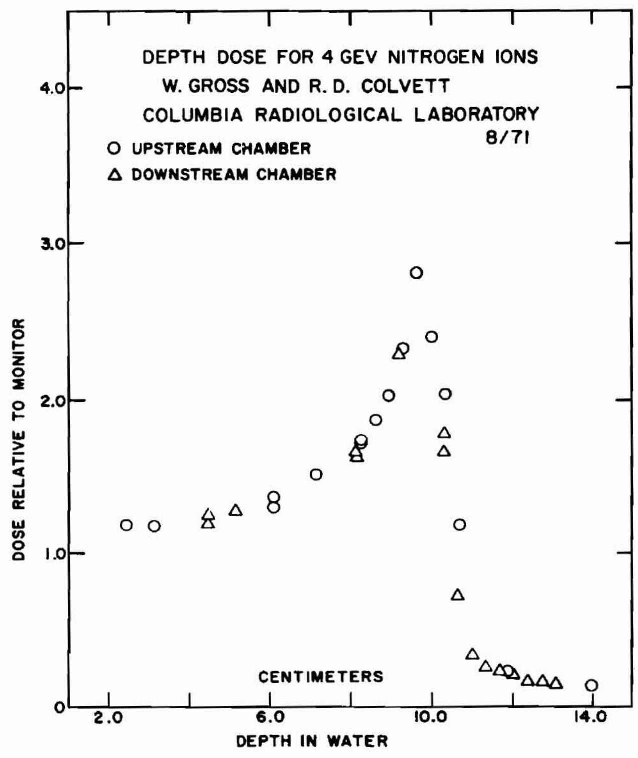

Figure 4: DEPTH DOSE PROFILE OF 4 GEV NITROGEN BEAM AS MEASURED IN A TISSUE EQUIVALENT IONIZATION CHAMBER. Note: The nominal energy of 4 GeV was reduced to 3.4 GeV by intervening material

DISCUSSION

R. WIDERØE: What was the dose-rate at the Bragg-peak for the present intensity and what do you think you can reach in the near future?

M.G. WHITE: At our present current we deliver 1 - 2 rads/min. We expect to reach 20 - 100 rads/min with improvements now being installed. Eventually we should be able to reach 1000 - 5000 rads/min with a 10^{-9} vacuum and a new ion source now being built.

It is interesting to note that, to reduce all survival of a 1 cm^3 tumor to the 10^{-10} level one needs, according to calculations by P. Todd, about 10^9 nitrogen ions. He also shows that for π^- therapy a somewhat larger number would be necessary. Nitrogen ions, being easy to produce compared with π^- particles, may prove to be more practicable and economical. Even so, it is important to carry to completion fundamental biomedical experiments on both particles before reaching any biomedical, engineering or economic conclusions.

R. WIDERØE: For medical reasons we cannot use a Bragg-curve which is very steep with a very high peak extending only over a small depth. We need a plateau with an extension in depth of perhaps 2 - 5 cm or more. Now the steep peak can easily be changed by using a variable absorber thickness before the body to be irradiated, or by smearing out the energy of the ions by extracting at various times.

This is only to mention that (opposite to most uses) $\Delta E/E$ must not be made too small and not developed in this direction for medical uses.

M.G. WHITE: I agree. Where possible, it would be preferable to range-scan by varying the synchrotron energy since the use of absorbers will introduce a small background of neutrons, protons, etc., due to nuclear interactions in the absorber.

V.P. DZHELEPOV: What intensity of heavy ions, such as Xenon, could you achieve at your accelerator?

M.G. WHITE: Assuming 10^{-9} torr vacuum, the PPA can reach, in principle, about 10^{10} to 10^{11} particle/sec for Xenon. Heavier ions need ion-source development.