ION OPTICAL DESIGN OF THE BRF-FNAL-SAIC-UW PET ACCELERATOR

D.J. Larson, D. Sun, P.E. Young
SAIC, 4161 Campus Point Ct., San Diego, CA 92121
F.M. Bieniosek, J.-F. Ostiguy, R.J. Pasquinelli, M. Popovic, C.W. Schmidt
Fermilab, P.O. Box 500, Batavia, IL 60510 USA*

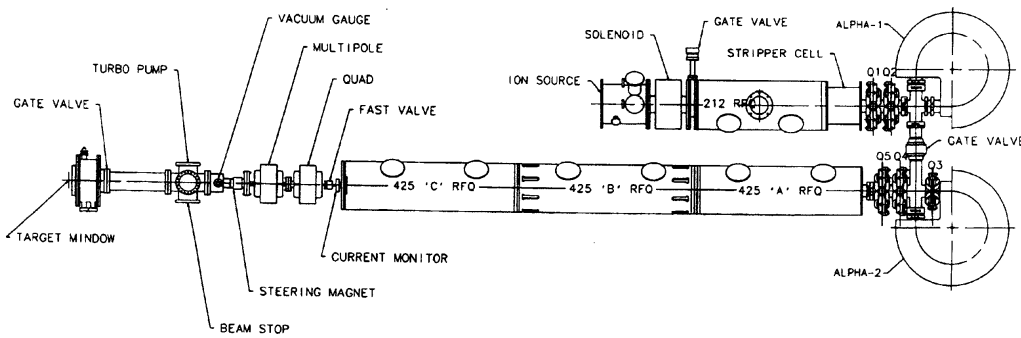

Figure 1. The PET Accelerator. Scale - Dipoles Have 30.48-cm Bend Radius.

Abstract

Production of positron emitting radioactive isotopes ^{18}F, ^{15}O, ^{11}C and ^{13}N for use in positron emission tomography is important for medical imaging. The present state of the production art is to use cyclotrons to accelerate deuterons to an energy range in the 10's of MeV and impinge the deuterons on appropriate targets. An alternative approach is to use a cascade of RFQ's to accelerate ^3He ions to 10-MeV as the bombarding particles. Due to the lower background radiation, a ^3He accelerator requires far less shielding than a cyclotron, in addition to other advantages. This paper will discuss briefly the end to end ion optics design of an RFQ based ^3He PET accelerator. Emphasis will be on the medium energy beam transport (MEBT) portion. The MEBT required a solution to the difficult problem of matching two RFQ's while allowing room for a gas jet stripper. Our solution to this problem could be modified to allow a match between high power RFQ's and linacs, a problem faced by several possible future accelerators.

1 INTRODUCTION

The ^3He PET Accelerator[1] is shown in Figure 1. In order to get sufficient ^3He beam current out of the source, $^3He^+$ is accelerated in the source to 20-keV. A low energy beam transport (LEBT) section matches the $^3He^+$ beam into an initial 212.5-MHz RFQ wherein it is accelerated to 1-MeV. Since $^3He^{++}$ is needed for the latter acceleration stages (to keep length manageable) a MEBT section strips and focuses the beam prior to entering the subsequent RFQ's. (At 1-MeV beam energy efficient stripping is possible using a gas jet stripper.) The $^3He^{++}$ beam is then accelerated in three 425-MHz RFQ's to a final beam energy of 10.5-MeV. A high energy beam transport (HEBT) section flattens and focuses the beam onto the PET production target.

*Operated by the Universities Research Association Inc, under contract with the U.S. Department of Energy.

In the absence of an all encompassing accelerator code, the optics of the PET accelerator was designed using a number of complimentary codes. Each section, source, LEBT, 212.5-MHz RFQ, MEBT, 425-MHz RFQ and HEBT, was studied with a design tool most applicable to that section, and a careful matching was done to translate the output of one code into the input of the next.

This report only highlights the design philosophy of the PET accelerator. For more detailed information on various beam sections the reader is referred to PET collaboration internal reports.[2]

2 ION SOURCE, LEBT & 212.5 MHz RFQ

The ion source has been studied by the ray tracing code EGUN (by Herrmannsfeldt of SLAC), and is consistent with experiments. The plasma temperature was varied until EGUN produced an emittance equal to what was measured at the end of the LEBT. The distance between the source plasma and the extraction electrode was varied within know tolerance until the current output from EGUN matched the measured current output of the source. The EGUN study was done up to the point where electron neutralization of the space charge is expected to begin.

Since the beam is unbunched in the LEBT, the LEBT has been studied with TRACE 2-D. The design followed from a detailed analysis of emittance measurements done in July, 1996. The emittance measurements were done for a variety of solenoid settings, and a consistent modeling of the LEBT was obtained for this set of measurements. The model which obtained the closest fit to the data implied that the beam was highly space charge neutralized, and that the beam at the exit of the source was close to a waist. The EGUN runs are consistent with a waist at the source exit.

The Pre-stripper RFQ Design was performed during a previous phase of the project using PARMTEQ, which is a space charge inclusive, particle tracking code.

3 MEBT DESIGN

The MEBT, which matches the beam out of the 212.5-MHz RFQ and into the 425-MHz RFQ string, has proven to be the most challenging portion of the accelerator to design and implement. Due to space and vacuum constraints, a design based on a near-symmetric, 540-degree isochronous triple focus bend has been adopted. The output of the 212.5-MHz RFQ is a small (~2-mm radius), tightly bunched, rapidly debunching beam. The input to the 425-MHz RFQ requires that the beam be even smaller (~1-mm radius), be tightly bunched and be converging in one transverse plane while diverging in the other. High current (28-mA average in the macro pulse) makes space charge concerns important. The chosen MEBT design appears in Figure 2.

3.1 Design Principles and Codes Used

The first guiding principle for the MEBT design is that of isochronicity. By developing a design for the MEBT that is isochronous at an energy of 1-MeV, all particles will traverse the MEBT region in the same amount of time. Since the particles are tightly bunched when they leave the 212.5-MHz RFQ, the beam is equally bunched when it enters the 425-MHz RFQ. Isochronicity requires that there be a great deal of dispersion in a long bending region, since it is dispersion in a bend region that leads to higher momentum particles traversing a longer path, and it is this longer path that allows them to have the same transit time. Computer analysis could only achieve the condition of isochronicity if 540 degrees of bending was accomplished. The design of a 540-degree bend also led to a condition where the overall PET accelerator was shortened by folding; this is important to keep the total device size manageable.

The second guiding principle is that of symmetry. Having a triple waist in the center of the drift between two double focusing (n = 0.53) 270-degree dipole bends (the cross-over arm) ensures that the beam evolution in each dipole is a mirror image of the other. Since the longitudinal phase space is also symmetric about that point, this leads to a condition where the dispersion and the dispersion gradient are both zero as the beam leaves the second 270-degree magnet. This symmetry also leads to cancellation of some higher order optics effects.

The third guiding principle is that of tunability. The fringe field behavior of the magnets and the amount of space charge neutralization (caused by trapped electrons in the beam) can not be known exactly in advance. To allow for operation in the presence of these uncertainties seven tunable electromagnetic quadrupoles were designed into the system.

The fourth guiding principle is separability. While not totally separable, the two quadrupoles placed in the cross-over arm are in a region of high dispersion and have a predominant effect on the longitudinal optics, with only a small effect on the transverse optics.

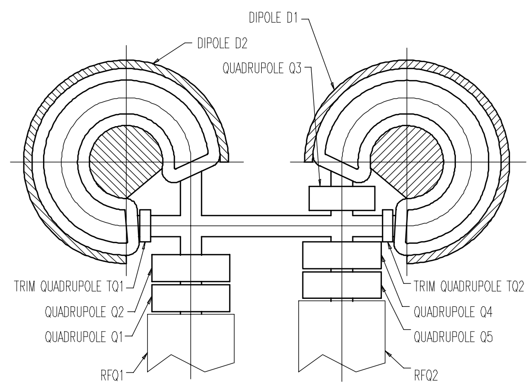

Figure 2. PET MEBT layout.

The MEBT has been studied in great detail using TRANSPORT, TRACE 3-D, and SCAT. TRANSPORT was used to check the zero space charge limit of the design, while TRACE 3-D and SCAT (a 2D code) were used to check space charge inclusive operation. Of these codes, only TRACE 3-D had all the features desired. The TRACE 3-D output for the MEBT design is shown in Figure 3.

3.2 Space Charge

A major concern of the device design was the self space charge of the ^{3}He beam. Analysis indicated that full space charge forces would lead to severe emittance dilution for a gaussian beam distribution, and would also lead to focal point shift as a function of beam current. In the worst (gaussian) case, 40-50% of the beam was predicted to be lost due to space charge emittance growth, and a pulse to pulse and intra pulse current consistency of 5% would be required to adequately control the position of the final focal point. It was realized in advance that the beam distribution might be quasi-parabolic or quasi-uniform and this would alleviate the problem of emittance growth. It was also realized that electron neutralization might off set the problems of space charge entirely.

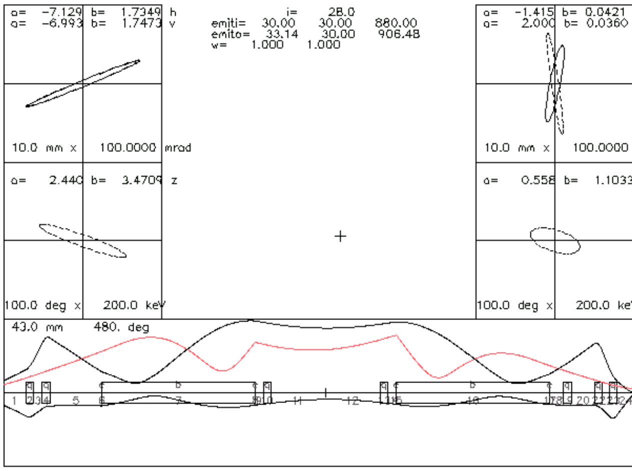

Figure 3. TRACE 3-D Output Graphics - MEBT Design.

3.3 Tolerances

An important issue in the MEBT development was a specification of tolerances for the magnetic components in the system. One of the basic rules of thumb for accelerator design is violated in the MEBT design, in that beam half size varies from under one-mm to 43-mm as the beam evolves throughout the MEBT. A usual rule of thumb is to keep the beam within a factor of 10 in size during traversal through a system. But this rule comes about because of the role of magnetic field errors. A small error in field where the beam is large contributes a relatively large angular error to the beam phase space, creating emittance dilution. Awareness of this danger led to a careful consideration of field quality in each of the MEBT components. Analysis and tracking studies indicated that the 270-degree dipoles were particularly prone to causing emittance growth. This led to a field tolerance of plus or minus 1.6-Gauss out of the 4.1-kG dipole field for the good field region of the dipole. This led in turn to a four conic section shim requirement on the dipole pole face[3], with the pole face machined to half mil accuracy.

Magnetic tolerances for the quadrupoles[3] were not as severe, with a 10-G field error being allowable. (This is because of the relatively short length of these quadrupoles.) Tolerances for tilt, role, yaw and transverse misalignment were also derived; none of these tolerances proved difficult to implement.

3.4 MEBT Operation

While MEBT operation has been demonstrated with values close to the nominal design values for magnetic excitation, experiment has proven the utility of the tunable devices. Emittance scans done at the end of the MEBT show output MEBT horizontal emittance varying between 30 π mm-mr (90% beam, normalized) to 200 π mm-mr depending upon the settings of the quadrupoles in the cross-over arm. (This shows the effect of dispersion varying as a function of cross-over arm quadrupole strength.) While the nominal settings of the cross-over arm quadrupoles are zero (the edge angles of the 270-degree magnets are designed to arrange this) experimental operation of these quadrupoles requires significant excitation. Variations between the design nominal values and experimental values for the remaining MEBT quadrupoles were also observed.

The most telling success of the MEBT operation is in the beam transmission through the first downstream RFQ. Transmission is in excess of 60%. At no point in the experimental operation is space charge causing deleterious effects. For more information on MEBT operation, see our companion paper[4].

4 425-MHz RFQ STRING AND HEBT

The Post-stripper RFQ string was designed using PARMTEQ. For our application it is best to use several RFQ's to reach the design energy of 10.5-MeV. (Conflicting modes are more difficult to suppress as length is increased. Also, as a practical matter, commercial construction of the vanes is limited by the length of material that can be machined in a single piece.) We have modified the PARMTEQ code so that a direct particle tracking could be performed in the short regions between each of the three RFQ's. Extensive studies of the RFQ string were done with many different scenarios. Current, emittance, particle number, and random seeds were all varied.

The HEBT for the PET accelerator has a function of delivering the 10.5-MeV He^3 beam to a target window. The HEBT line consists of drifts, a quadrupole, and a multipole magnet. The quadrupole, and the quadrupole component of the multipole, provide appropriate focusing to match the beam to the target. The higher order fields of the multipole have been used to arrange a more uniform beam density at the target window, lowering the peak target heating. The HEBT was designed using TURTLE.

REFERENCES

[1] Ralph Pasquinelli, et al., `A 3He++ RFQ Accelerator for the Production of PET Isotopes', PAC-97, 9B.09.

[2] PET collaboration internal reports: D.J. Larson, `LEBT 96'; `MEBT 95'; `MEBT 96'; and `HEBT 96' and D. Sun, `Report on End to End Simulation of RFQ A, B and C'; all reports can be obtained from the office of the PET project manager, Ralph Pasquinelli.

[3] N. Chester, et al., `Magnet Development for the BRF Positron Emission Tomography Accelerator', PAC-97, 2P.09.

[4] F.M. Bieniosek, et al., `Charge Stripper and MEBT for the 3He RFQ Accelerator', PAC-97, 7P.111.