DESIGN AND OPERATION OF PET RADIO FREQUENCY QUADRUPOLES

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Abstract

The PET isotope production accelerator built by a collaboration of BRF, FNAL, SAIC, and UW consists of four RFQ's to accelerate $^{3}He^{2+}$ ions to 10.5 MeV for production of radioactive ^{18}F, ^{11}C, ^{15}O and ^{13}N isotopes. The design, tuning, and operational results are presented.

1 STATUS OF PET RFQ'S

The PET (Positron Emission Tomography) accelerator has been built to accelerate $^{3}He^{2+}$ ions for production of radioactive ^{18}F, $^{11}C11$, ^{15}O and ^{13}N isotopes. The accelerator consists of an ion source, four RFQ's, a charge stripper, and beam transport system (Figure 1) [1]. The ion source generates 20 keV $^{3}He^{+}$ ions. The $^{3}He^{+}$ ions are accelerated to 1 MeV through the first RFQ (pre-stripper RFQ) operating at 212.5 MHz. After exiting the first RFQ, $^{3}He^{+}$ ions are stripped off the second electrons by a charge stripper. Then $^{3}He^{2+}$ ions go through the MEBT transport system (consisting of two 270 degree bending magnets and five quadrupole magnets) to enter a three RFQ string (post-stripper RFQ's) operating at 425 MHz. $^{3}He^{2+}$ ions are accelerated from 1 MeV to 10.54 MeV by these RFQ's (5.05 MeV at the end of RFQ A, 8.025 MeV at the end of RFQ B and 10.54 MeV at the end of RFQ C.)

This accelerator was originally designed and built by SAIC to accelerate $^{3}He^{2+}$ to 8 MeV using three RFQ's (one pre-stripper and two post-stripper RFQ's) The accelerator was operated by SAIC and delivered 2.5 mA $^{3}He^{2+}$ current at 1% duty factor before the project stopped in 1992 [2].

In 1995, the project was re-started. The designed final energy has been increased to 10.5 MeV. At higher energy, the beam loss is less when $^{3}He^{2+}$ ions passing through a thin foil window in the target area and the yield of isotope production is higher. A new post-stripper RFQ (RFQ C) has been added to the previous RFQ's to accelerate $^{3}He^{2+}$ from 8 MeV to 10.5 MeV. Water leaks caused by corrosion in cooling channels of vanes were found in all previous RFQ's. Therefore vanes of the two existing post-stripper RFQ's have been replaced with new ones and have been re-tuned. The whole pre-stripper RFQ will be replaced later with a new one. All cooling channels are now coated with a thin layer of Teflon to prevent corrosion.

2 DESIGN PARAMETERS

The design of pre-stripper RFQ has been reported before [3]. It is a segmented four vane structure with a rectangular "window" cut out in the middle of each vane. This structure reduces the dimensional requirement of resonant frequency of quadrupole mode and move it to below both dipole modes. Recent simulation showed that transmission of this RFQ is ~60-65% for input current of 20-25 mA. So the contour of new vanes of pre-stripper RFQ has been modified to improve the transmission to 80-85%. The three post-stripper RFQ's are all traditional four vane RFQ's (not segmented) and have acceleration section only. The transverse curvature of vane tip is constant. There is no rf tuner in the cavity since the designed tuning method dose not require any extra tuner. Computer codes MAFIA and SUPERFISH are used to calculate the theoretical Q, power and other rf properties. The basic parameters are listed in Table 1. Since RFQ B and C are similar to A, only parameters of pre-stripper RFQ and post-stripper RFQ A are listed in Table 1.

Table 1. Design Parameters of PET RFQ's

	pre-stripper	post-stripper A
Particle	$^{3}He^{+}$	$^{3}He^{++}$
f_0 (MHz)	212.5	425
Aperture (cm)	0.25	0.18
Modulation	1.78	2.1
Input energy (MeV)	0.02	1.0
Output Energy (MeV)	1.0	5.05
Voltage (kV)	57.0	58.4
Max. Field (MV/m)	32.2	39.9
Q_0 (MAFIA)	7600	9500
Power (kW)	59.0	63.0
Pulse Width (µs)	70	70
Rep. Rate (Hz)	360	360
Inject Current (mA)	25	28
Transmission	80%	90%
Length (cm)	103.9	137.1

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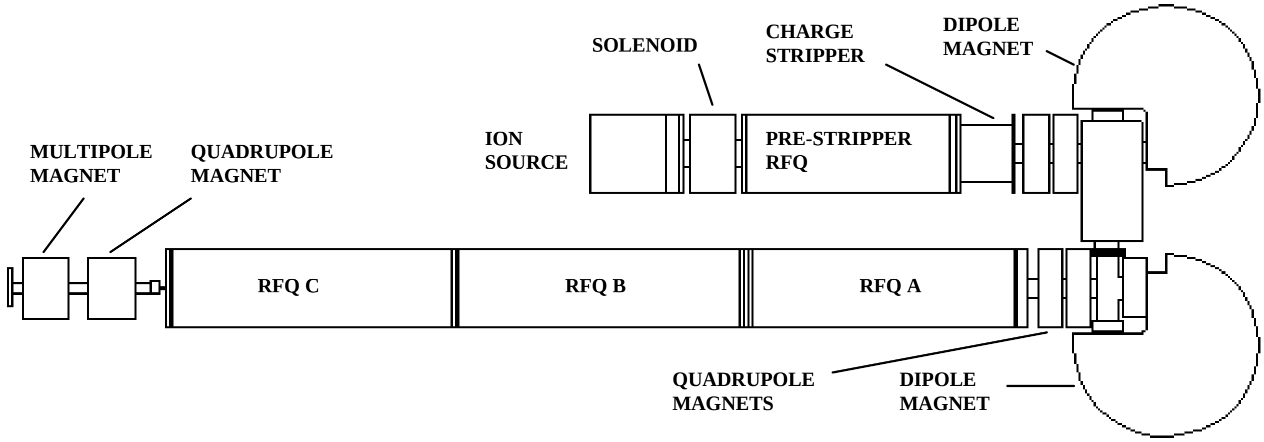


Figure 1 PET ACCELERATOR

3. SIMULATION RESULTS

Simulation of particle transport through pre-stripper RFQ and three post-stripper RFQ's are performed using PARMTEQ. The results are listed in Table 2 and 3. Two versions of PARMTEQ were used: SAIC version (denoted as SAIC in Table 2 and 3) and the version used in ANL (originally written at Chalk River Laboratory) which has the option to use 2 or 8 potential terms (denoted as ANL (2-term) or ANL (8-term) in Table 2 and 3.)

Shown in Table 2 is the simulation results of particles through pre-stripper RFQ which is performed separately from other three post-stripper RFQ's.

Transport of particles through the string of three post-stripper RFQ's is simulated from entrance of RFQ A to the end of RFQ C (end to end simulation.) There is a plate with aperture of 0.635 cm between each RFQ, so the RFQ's are not coupled. This plate and the space between the end of vanes and this plate create a gap of 1.16 cm long between each RFQ. In end to end simulation, a drift space of 2.16 cm between each RFQ was used which represents the above mentioned 1.16 cm gap as well as other end effect of each RFQ. Simulation results show that beam loss in RFQ B and C is mainly due to this 2.16 cm drift space between each RFQ since beam becomes mismatched to next RFQ after such a drift space. Shown in Figure 2 is the total transmission at the end of RFQ C versus length of drift spaces between each two RFQ's. One can see the beam loss in RFQ B and C is small if there is no drift space in between.

Although the design for post-stripper RFQ's is based on the transverse emittance of 0.0019 π cm-rad, simulations are also done with various transverse emittance, currents and number of particles. Shown in Figure 3 is the total transmission at the end of RFQ C versus various transverse emittance.

Table 2. Simulation Result of Transmission of 212.5 MHz RFQ (input current 25 mA, transverse emittance: 0.016 (x), 0.016 (y) π cm-rad)

	existing pre-striper rfq	modified pre-stripper rfq
SAIC	0.59	0.80
ANL (2-term)	0.66	0.87
ANL (8-term)	0.32	0.65

Table 3. Simulation Results of Total Transmission of RFQ A, B and C (input current 28 mA, emittance: 0.0019 (x), 0.0019 (y), 0.0091 (z) πcm-rad and 65° phase spread)

	End of A	End of B	End of C
SAIC	0.865	0.655	0.600
ANL (2-term)	0.990	0.518	0.333
ANL (8-term)	0.960	0.545	0.485

4. EXPERIMENTAL DATA AND OPERATIONAL RESULTS

4.1 Tuning

All RFQ's were tuned by mechanically adjusting each vane using equally spaced screws. For three recent-tuned post-stripper RFQ's, the final field balance is tuned to a level that the average dipole components is less than 2% for RFQ A and B, and less than 1% for RFQ C. Resonant frequency of these RFQ's are tuned to ~425.3 MHz at room temperature. The operating frequency of 425 MHz is achieved by controlling the differential temperature between vanes and cavity.

The unloaded Q's of RFQ's are: 6100 (pre-stripper RFQ), 7667 (RFQ A), 8900 (RFQ B), and 8900 (RFQ C) while the unloaded Q's given by MAFIA code is 7300 (pre-stripper RFQ) and 9500 (post-stripper RFQ's).

There are 12 rf pickup loops in each of post-stripper RFQ's. In each quadrant there are three of them: one is at middle of the RFQ, other two are at ~15 cm from each end of the RFQ. They can be used to monitor the field unbalance which may occur during operation or other problems such as electrical breakdown. So far we have used these probes to check if the field balance changed after the vane is heated and the frequency is adjusted to 425.0 MHz. No significant change of field balance has been observed.

4.2 Operational Results

There are four RF power amplifier systems, one for each RFQ. Each amplifier system consists of a solid state amplifier with maximum power of 850 W, a Burle 7651 tube amplifier with maximum power of 4 kW and a Burle 4616 tube amplifier with maximum power of 200 kW.

The pre-stripper RFQ has been operated for a long time (even with small leaks in water cooling channels of vanes.) This RFQ was run (without beam) up to power level of 135 kW without sparking problem. Higher power levels are possible but were not tried, since 135 kW is already more than needed. This RFQ is normally operated at 100-110 kW level with beam load of 20-24 kW. The threshold of power level to accelerate beam is about 80 kW. The emittance at entrance of this RFQ is 0.024 - 0.03 π cm-rad which is larger than the value used to guide the design. So far output current of 16 mA has been measured while the current out of ion-source is 24 mA. This result is in agreement with recent results of PARMTEQ simulation.

RFQ A, B and C are still being commissioned. Output current of 12 mA at the end of RFQ A and 6 mA at end of RFQ C have been measured while the input current at the entrance of RFQ A is about 20 mA (measured at the exit of MEBT system.). This result is close to the transmission predicted by PARMTEQ simulation for a beam with emittance of 0.0030 π cm-rad. The measured emittance of input beam at entrance of RFQ A is indeed 0.0030-0.0040 π cm-rad which is larger than the value (0.0019 π cm-rad) used to guide the design. To get the above mentioned output current, RFQ A is operated at power level of 100-110 kW while RFQ B and C are operated at power level of 80-90 kW. These power levels are also in agreement with results of PARMTEQ and MAFIA simulation.

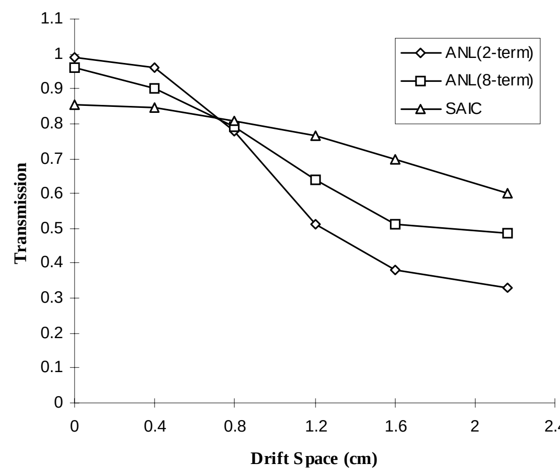
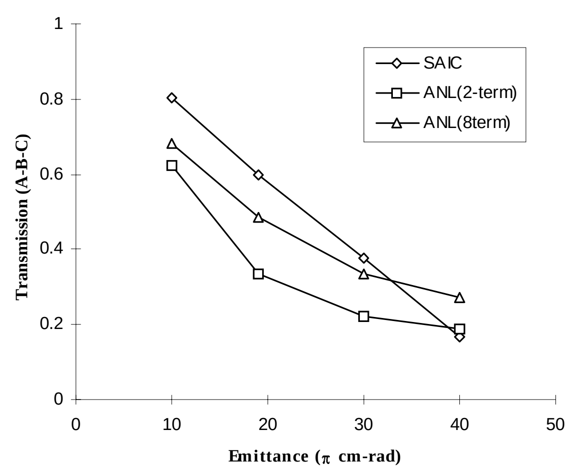


Figure 2. Transmission (A-B-C) vs. Drift Space



Figuer 3. Transmission (A-B-C) vs. Emittance

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