MULTI-CAVITY PROTON CYCLOTRON ACCELERATOR*

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Abstract

A detailed analysis is presented of a new concept for a high current, high gradient proton beam accelerator in a normal conducting (i.e., room temperature) structure. The structure consists of a cascade of RF cavities in a nearly uniform axial magnetic field. The proton energy gain mechanism relies upon cyclotron resonance acceleration in each cavity. In order to check the concept and determine its limits, a design is presented of a four-cavity electron counterpart test accelerator under construction that will mimic parameters of the multi-cavity proton accelerator.

MOTIVATION

There is interest [1] in high intensity proton drivers for various applications including neutron production, waste transmutation, energy production in sub-critical nuclear reactors and others. For these applications, a compact (25 m), high energy (~1 Gev), high intensity (~10-100 MW) source of protons could be appealing. One possibility is presented here: a high intensity proton source based on a multi cavity cyclotron accelerator [2-6].

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MULTI-CAVITY PROTON CYCLOTRON ACCELERATOR

The multi-cavity proton cyclotron accelerator (MCPCA) consists of a cascade of RF cavities embedded in a nearly uniform axial magnetic field The operating mode for each cavity is rotating TE_{111}, and the resonant frequencies differ in adjacent cavities by a fixed frequency Δf. Protons injected into the first cavity at intervals of $\Delta T = 1/\Delta f$ or integer multiples thereof can experience continuous energy gain throughout the structure provided the relative phases of the fields in each cavity are properly adjusted.

As protons can make a substantial number of orbital turns in each cavity, the voltage gain can be much larger than the product of the peak electric field and the cavity length. This gives the opportunity to have the cavity surface fields well below breakdown and multipactor limits. Also since the protons are heavily constrained to follow spiral orbits in the strong magnetic field, no further focussing magnets are needed in the acceleration section which simplifies the design of the accelerator.

Additionally it was discovered that this acceleration mechanism can be sustained for exceptionally wide injection angles in the first cavity, e.g. two RF cycles in the example below. This is highly significant in that it allows operation with high duty factor (~13%) and low peak proton current (< 1 A), thereby mitigating against issues from high space charge while allowing high average proton current (~100 mA).

Shown in Fig. 1 is a schematic of the accelerator concept. The diagram showns the proton beam passing through the cascade of cavities (8 in this example), then emerging on trajectories that fan out in the diverging magnetic field. The trajectories scan azimuthally at the gyrofrequency of the protons. This allows the very substantial beam power to be "self-scanned" over a large internal surface area of, for example, a spallation target for use with a sub-critical reactor or an assembly of spent fuel rods.

The proton beam analyzed had a duty factor of 1/7.5 corresponding to an injection phase of 720°. For an average current of 122 mA this corresponds to a peak current of 915 mA (at 1000 keV). The parameters for the cavities are listed in Table 1. For this example, the cavity frequency separation is Δf = 8 MHz. The final energy

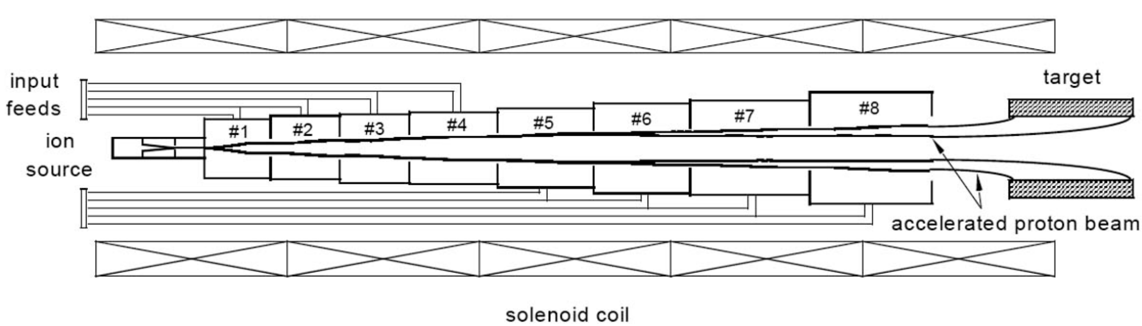

Figure 1: Schematic of the multi-cavity proton cyclotron accelerator with eight cavities in this example.

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of the beam is 952.7 MeV which corresponds to an average gradient of 37.9 MV/m. Note that this includes the 20 cm drift tunnels between the cavities. The duty cycle assumed was 1/7.5. Loaded Q_L's for all the cavities were of the order $2.7\text{-}6.3\times10^4$.

Table 1: Parameters for 122 mA, 8 Cavity MCPCA

Stage	Cavity freq. (MHz)	Cavity radius (cm)	Cavity length (m)	RF power input (MW)	Peak surface field (MV/m)	Mean energy gain (MeV)
1	120	92	2.06	18.0	7.2	63.6
2	112	98	2.23	15.0	4.0	92.9
3	104	106	2.39	15.5	4.8	80.9
4	96	110	2.81	18.5	4.9	96.1
5	88	120	3.07	24.0	5.1	124.3
6	80	132	3.38	23.0	4.1	135.3
7	72	144	3.92	30.0	4.2	177.0
8	64	172	3.89	30.0	3.9	182.7
total			25.15	174		952.7

The magnetic field profile and evolution of the energy gain are shown in Fig. 2 for the case in Table 1. The field variation is about ±2% about a mean value of 8.1 T. The dependence of spreads in the rms relativistic energy factor, γ, and the axial velocity, β_z, with axial distance in the MCPCA is shown in Fig.3. The oscillatory nature of the spreads is evidence for the stabilizing effects of the RF and static magnetic fields.

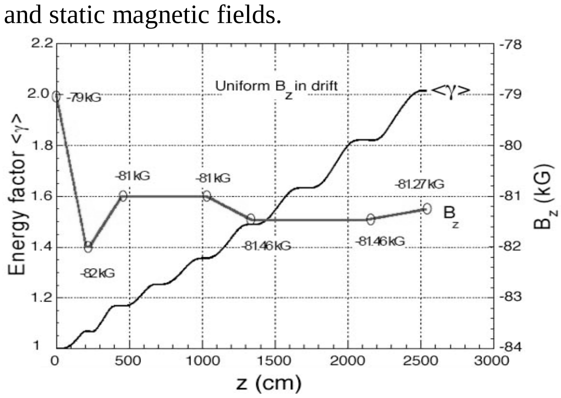

Figure 2: Magnetic field profile and evolution of average proton energy gain for example of 1/1.75 duty cycle.

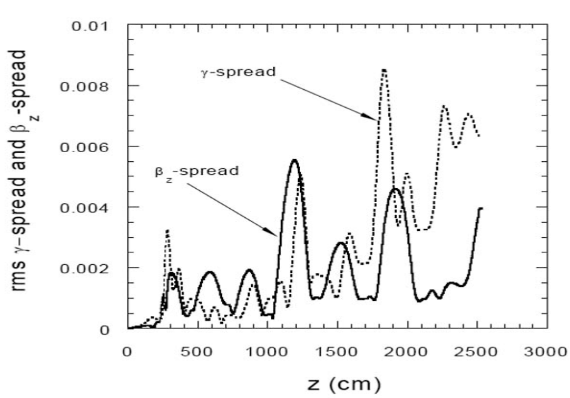

Figure 3: Dependence of average normalized transverse $<\beta_\perp>$ and axial velocity $<\beta_z>$.

ELECTRON COUNTERPART

The purpose of the electron model is to act as a counterpart to the proton device. Much the relevant physics can be tested in a simpler, less expensive device. Parameters of the device are set to mimic as much as possible the parameters of the proton accelerator, such as electron acceleration to ~511 keV (γ =2), corresponding to ~938 MeV (γ =2) for protons. Injected beam velocities are similar with electrons at 11 keV (β =0.63) and protons at 1000 keV (β = 0.046). The exceptions to the parameter similarity are in the RF power and magnetic fields. For the proton case, average RF and beam powers are 174 and 116 MW; while for the 50 µA electron case these values are 1.4 and 0.025 kW. The axial magnetic field for the proton case is 8.1 T, while for the electron example is 0.155 T.

To demonstrate the operation of the multi-cavity concept a four-cavity electron device was chosen. The beam current and initial voltage were chosen to have approximately the same β and space charge as for the proton case. The operating mode for the RF was rotating TE_{111} in all four cavities. The cavity dimensions and beam tunnel apertures with RF parameters in Table 2 were chosen to minimize excitation of adjacent cavities. Field maps of the cavities are shown in Fig. 4 showing such excitation to be minimal.

Table 2: Simulation Parameters for the Four-cavity Electron Counterpart.

cavity	f_{TE111} GHz	R mm	L mm	a mm	Q	P W	dU keV
1	2.4	45.37	104	16.3	24300	207	119
2	2.1	51.21	119	22.8	26000	420	123
3	1.8	59.24	139	28.4	28500	367	105
4	1.5	70.05	174	33.6	30800	426	147
totals			536			1420	494

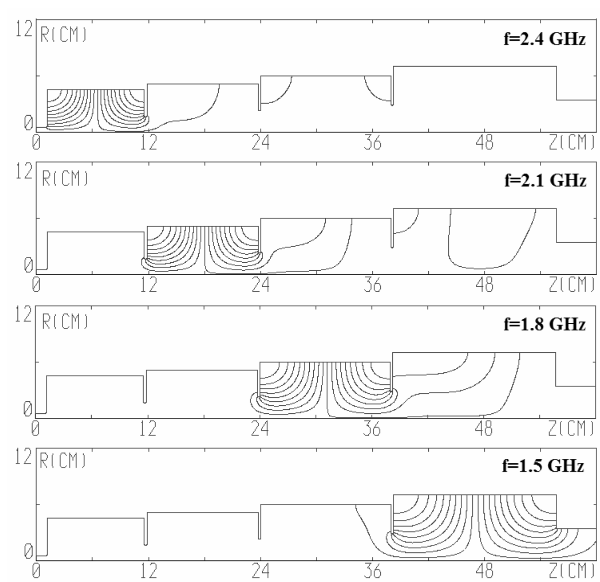

Figure 4: Field maps for cavities in the electron counterpart, showing small coupling between cavities.

The energy spread for the four cavity device, shown in Fig. 5, is seen to be weakly dependent on the injection phase angle up to 200° where the energy spread is shown to be ≤ 7%.

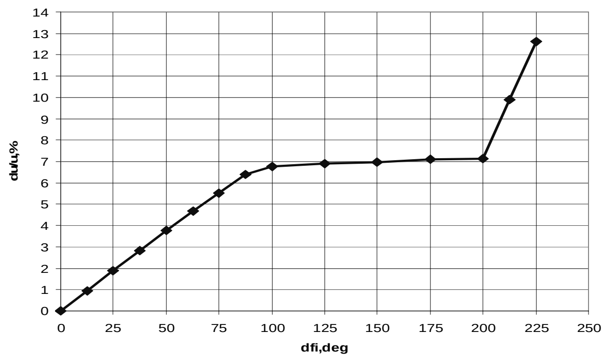

Figure 5: Energy spread $(U_{max}-U_{min})/2U_{average}\times100\%$. dependence on width of the injected phase window.

Simulations of the energy gain and beam radius are shown in Fig 6. The final energy was ~510 keV with an energy spread of ±30 keV. The beam radius grew to a maximum of 2.5 cm..

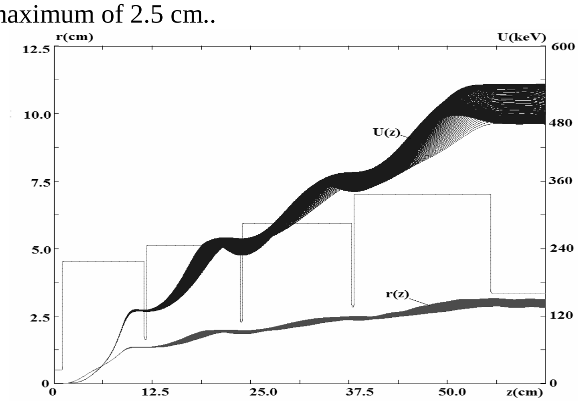

Figure 6: Calculated energy gain and beam radius in the electron equivalent model showing final beam energy of ~494 keV and a final beam radius of 2.5 cm. The outline shows the location and size of the four cavities in the model.

An engineering design for the experiment is underway, based on the calculations shown here.

SUMMARY

A design for a multi-cavity proton cyclotron accelerator has been developed. The design utilizes a cascade of 8 cavities to produce a 952 Mev (γ ~ 2), 122 mA beam. The energy spread (6 Mev) and velocity spread (0.004c) are both low. The average acceleration gradient, including the drift tunnels is 39.7 MV/m for the 25.2 m long device. An electron equivalent utilizing a four cavity structure to produce a 510 keV, 50 µA beam is to be built to test the multi cavity concept, including dependence of final mean energy and energy spread on injection phase width window, growth of energy and velocity spreads and relative phase angles of the cavities.

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