MULTI-CAVITY PROTON CYCLOTRON ACCELERATOR: AN ELECTRON COUNTERPART*

M.A. LaPointe, Department of Physics, Yale University, New Haven, CT 06520, USA
S.V. Shchelkunov, Department of Physics, Yale University, New Haven, CT 06520, USA
J.L. Hirshfield, Department of Physics, Yale University, New Haven, CT 06520, USA
and Omega-P, Inc., New Haven, CT 06511, USA
V.P. Yakovlev, Omega-P, Inc., New Haven, CT 06511, USA
and Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Abstract

A novel multi-cavity multi-frequency proton cyclotron accelerator has been proposed. By utilizing cyclotron autoresonance, a compact (25m), eight cavity, 1 GeV proton accelerator has been simulated. A four cavity electron counterpart is under construction to test the mechanism of the multi-cavity setup including phase acceptance, energy gain, and growth of energy spread and emittance at parameters that correspond to the proton case. The electron counterpart consists of four sequential cavities driven by phase synchronous RF sources at 1.5, 1.8, 2.1 and 2.4 GHz. Each cavity operates in the rotating TE_{111} mode and includes two feeds to drive the rotating mode and two RF pickoffs for diagnostics. The electron beam source is a Kimball Physics BaO cathode which operates at -1200V and <50 microamps. The beam is collected on either a Faraday cup or is imaged with a phosphor screen. Details of the setup and initial results from cold tests of the four cavity electron counterpart will be presented.

INTRODUCTION

The interest in high-intensity proton drivers is for various applications, encompassing but not limited to, nuclear waste transmutation, controlled fission in sub-critical reactors [1], ion implantation for materials development, proton therapy, radioisotope production for medical purposes, and fundamental discovery science. A proton source that is compact (<25m), has high intensity (10-100 MW) and final kinetic energy of ~1 GeV might be an appealing choice to addresses some of the aforementioned needs. Already, one possibility has been proposed by some of us, which employees a mechanism for multi-cavity cyclotron nearly-autoresonance acceleration [2]. Below we report on further development of these ideas, and in particular on progress in building of an electron cavity structure that is to act as a counterpart to a proton accelerator to test the basic principles in a simpler and less expensive way.

The operating principles behind the accelerator are described in [3]. To re-state briefly, the device is a cascade of RF cavities immersed in a nearly uniform axial magnetic field. The operating mode for each cavity is rotating TE_{111}, and the resonant frequencies in adjacent cavities differ by a fixed interval Δf, chosen to preserve synchronous cyclotron acceleration of particles, whose effective mass increases as they proceed along the structure. A schematic of a proton device is in Fig. 1.

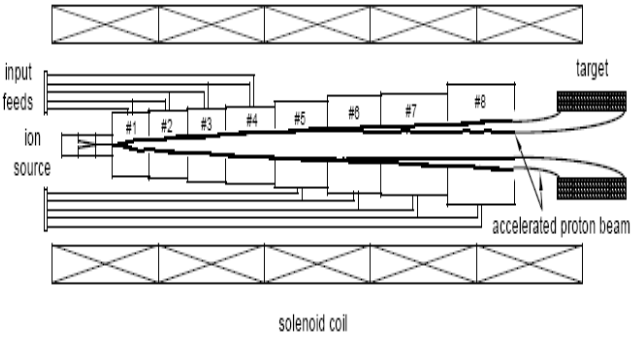

Figure 1: Schematic of the multi-cavity proton cyclotron accelerator with eight cavities.

The proton beam that has been analyzed had a pulse duty factor of 2/15 corresponding to an injection angle of 720°, and a peak current of 920 mA and an initial kinetic energy of ~1MeV. The parameters are listed in Table 1; the cavity frequency separations are Δf =8 MHz. Cavities are separated by 20 cm long drift tunnels, with the entire chain residing in an 8.1 T guide field.

Table 1: Parameters of Proton-Accelerator see Ref. [3]

stage	cavity freq. (MHz)	cavity radius (cm)	cavity length (m)	RF power input (MW)	Peak surface field (MV/m)	Energy gain (MeV)
1	120	92	2.0	18	7.2	64
2	112	98	2.23	15	4	93
3	104	106	2.39	15.5	4.8	81
4	96	110	2.81	18.5	4.9	96
5	88	120	3.07	24	5.1	124.3
6	80	132	3.38	23	4.1	135.3
7	72	144	3.92	30	4.2	177
8	64	172	3.89	30	3.9	183
total			25.15	174		953

---

*Work supported by DoE, Office of High Energy Physics
US patent 6,914,396 B1; Symons, Hirshfield, & Wang, July 5, 2005
sergey.shchelkunov@gmail.com

ELECTRON COUNTERPART: OVERVIEW OF DESIGN AND STATUS

The electron counterpart is shown in Fig. 2. The cavity chain was designed to mimic the parameters of the proton device, accelerating electrons to $\gamma \sim 2$ (511 keV *vs* 938 MeV). Other parameters matched were low beam loading and normalized injection velocity β (0.04 *vs* 0.06).

The electron source is a custom built gun based on a Kimball Physics BaO cathode unit (Fig. 3); the gun performance was simulated by the SAM code [4]. It will operate at a cathode voltage of ~1 kV; the focusing electrode (biased at 1.2 kV) is to help to control the emission current (between 10-30 μA).

The beam current is chosen to be small to avoid beam loading of the cavities, and thus to simplify the requirements on the cavities themselves (i.e., no need to adjust their frequencies and *Q*-factors to compensate for beam loading), and to the RF-power sources, since only power losses are to cavity walls; this lowers the cost of RF amplifiers considerably.

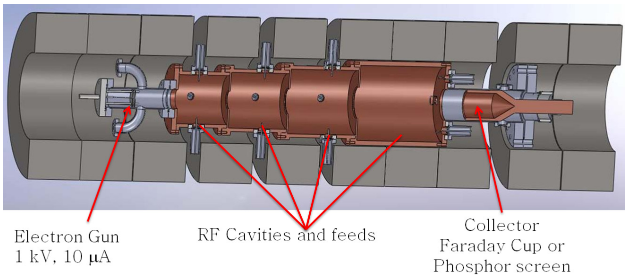

Figure 2: Solid model of the 4-cavity e-counterpart.

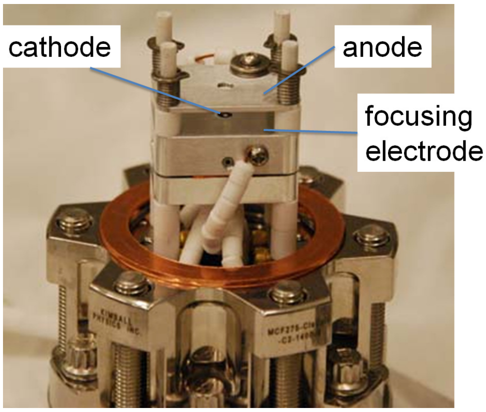

Figure 3: Electron source.

The cavities (Fig. 4, left) are presently manufactured and are undergoing tuning procedures. Initial measurements confirmed that the frequencies and *Q*-factors are within expected ranges. The frequencies will be further tuned by increasing the inner diameters slightly; the *Q*-factors will be adjusted by controlling the penetration depth of the antennas or areas of the loops. Provisions to make these adjustments were incorporated into the design.

Four phase-locked RF-sources are to be used to feed the four cavities. A master oscillator operates at 300 MHz to provide seed power to four frequency multipliers followed by amplifiers, each of whose power can be adjusted by controlling their input powers. To control the amplitudes and phases, attenuators and phase-shifters are installed before each amplifier. The frequency multipliers deliver power at 2.4, 2.1, 1.8, and 1.5 GHz. Each amplifier provides about 500 W.

The cavities (together with the beam collector/analyzer) are immersed in a solenoidal magnetic field with an average strength of 1.6 kG (see Fig. 5).

After the interaction, the electron beam will be delivered to a either a phosphor screen or a faraday cup with an iris. By varying the magnetic field and knowing the parameters of the system, one may predict and measure the expected particle distribution profile resulting from the motion of the accelerated e-beam in the varying field. The results of these comparisons should deliver necessary information to draw conclusions as to the efficacy of the acceleration mechanism, acceptance window, and optimum relative phasing of the cavities.

Cold tests of the machined cavities have begun. Initial measurement results are shown in Table 2. All cavities were initially designed to resonate about 8-10 MHz above the design frequency to allow for precise final machining to tune the cavities. Once final tuning is made the gun, cavities and collector will be assembled and installed inside the solenoid. First acceleration tests are expected to begin in the early Summer 2012.

Table 2: Cold Test Parameters of Assembled Cavity Chain

Cavity	Design *f* (GHz)	Measured *f* (GHz)	*Q*
1	2.400	2.4069	1035
2	2.100	2.1078	1240
3	1.800	1.8102	935
4	1.500	1.5092	1174

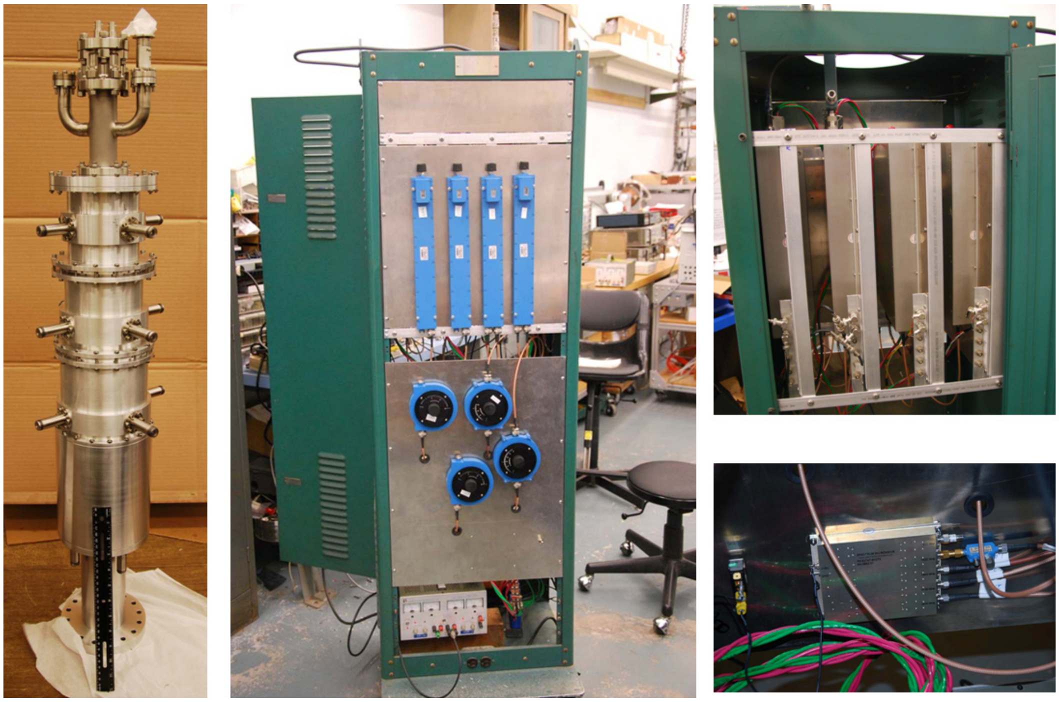

Figure 4: Photos of the cavity chain (left), and an ensemble of four phase-locked RF-sources (and auxiliary components) to feed the electron counterpart with power at four different frequencies.

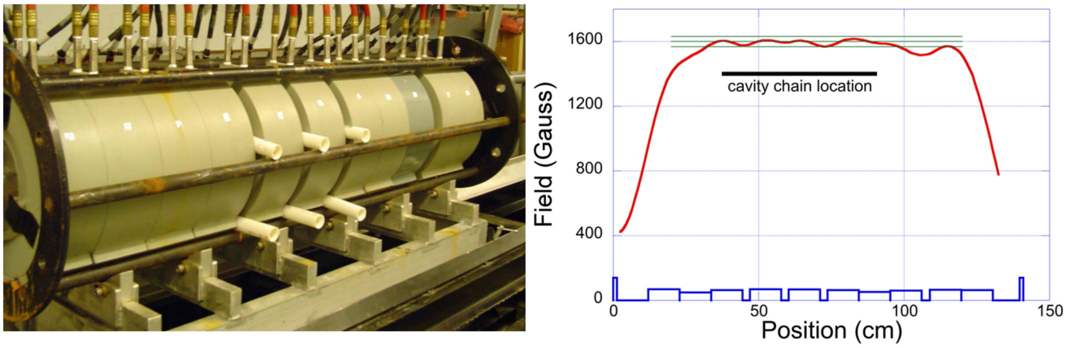

Figure 5: The magnet system shown was tested at the operating field and achieved the 1.6 kG over the interaction region. Peak-to-peak ripple due to the necessary gaps in the solenoids is less than ±2% over the full interaction region.

REFERENCES

[1] "The Future Path for Advanced Spent Fuel Treatment and Transmutation Research: Report to Congress…". Office of Nuclear Energy Science and Tech., US Dep. of Energy, Jan. 2003.

[2] J. L. Hirshfield et al., Proc. of 11th Int. Conf. on Emerging Nuclear Energy Systems, Sep/29-Oct/4, 2002, pp. 92-100 (2003) and references therein.

[3] M. A. LaPointe et al., Proc. of PAC09, Vancouver, BC, Canada, pp. 3045-3047 (2009) and references therein.

[4] D. G. Myakishev et al., 1992 Hamburg. Int. J. Mod. Phys. A (Proc. Suppl.) 2B (1993), v. 2, pp. 915-917.