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FAST CYCLING FFA PERMANENT MAGNET SYNCHROTRON*

D. Trbojevic†, S. Brooks, J.S, Berg, M. Blaskiewicz, BNL, Upton, NY, USA

Abstract

We present a novel concept of the Fixed-Field-Alternating (FFA) small racetrack proton accelerator 10x6 size, with kinetic energy range between 30-250 MeV made of permanent magnets. The horizontal and vertical tunes are fixed within the energy range, as the magnets The combined function magnets have additional sextupole and octupole multipoles the chromatic corrections, providing very fast cycling with a frequency of 1.3 KHz. The injector is 30 MeV commercially available cyclotron with RF frequency of 65 MHz. The permanent magnet synchrotron RF frequency is 390 MHz and acceleration uses the phase jump scheme.

INTRODUCTION

This is a proposal based on the existing patent on permanent magnet Fixed Field Alternating Gradient accelerator [1]. This is a Non-Scaling Fixed Field Alternating (FFA) gradient accelerator with fixed vertical and horizontal tunes with an estimated RF power of 400 kW.

The proposal follows the successful commissioning of the Cornell Brookhaven Electron Test Accelerator (CBETA) [2-7]. The electrons were transported though the single beam line from the superconducting accelerator starting with energy of 36 MeV and finishing with 150 MeV, passing 4 times through the linac in acceleration mode and 4 times in decelerating mode making full energy recovery.

This is a proposal of an extraordinary synchrotron as acceleration time does not depend on limited speed of magnet response. The acceleration cycle is imitated only by the RF. In the present design the accelerator cycle frequency is 1.3 kHz. This represents at the same time a proof of principle for the future proton drivers – an essential element in a chain of synchrotrons in any collider. The proposal uses permanent combined function magnets lay out in a racetrack and occupying a very small area of 10 x 6 m. The proton beam is accelerated in a kinetic energy range between 10 MeV and 250 MeV with three Pill Box cavities with synchronous voltage of 25 kV. The total number of turns is ~3600.

The synchrotron permanent magnets are significantly smaller than warm iron synchrotron magnets. This specific energy range is very important for the proton cancer therapy and recent FLASH cancer radiation therapy [8]. The FLASH therapy occurs when the large radiation dose is delivered in controlled way during a very short time ~100 ms. The other possible applications are the fast-cycling synchrotrons for protons, muons, or other hadron drivers like the Proton Driven Fusion systems and colliders.

APPLICATION FOR 'FLASH' THERAPY

The 'FLASH' cancer therapy is a relatively new possibility in treating the cancer tumours if the radiation is required. Multiple biological studies and even few patients' treatments around the world in recent years confirmed significant improvements in the cancer treatment results by delivering the radiation dose *in much shorter time intervals* — fractions of a second as opposed to minutes — and in far fewer fractions or even a single fraction and therefore at dose rates that are thousands of times higher [9]. All cancer particle radiation facilities in the world are presently not capable of delivering the radiation dose within 100 ms as it is very difficult to get such a fast response from the magnets in such a short time. The cyclotron-based proton therapy facilities have an additional problem with necessary energy degraders as the proton energy from the cyclotrons is fixed ~230 MeV. The degraders significantly reduce the intensity of the beam and enhance the beam size-emittance. The fast-cycling FFA synchrotron, made of permanent magnets, can extract very fast the required proton energies for the patient's treatment and can transport all energies without changing the magnetic field. In addition, the delivery system-gantry is made as well of permanent magnets and can accurately transport protons of all energy range between 70-250 MeV to the patients.

FFA FAST CYCLING SYNCHROTRON

The proton therapy accelerator from 10 MeV to 250 MeV is designed using the racetrack lattice made of Non-Scaling Fixed Field Alternating Gradient (FFA) arcs and two parallel straight sections. The layout of the accelerator is shown in Fig. 1.

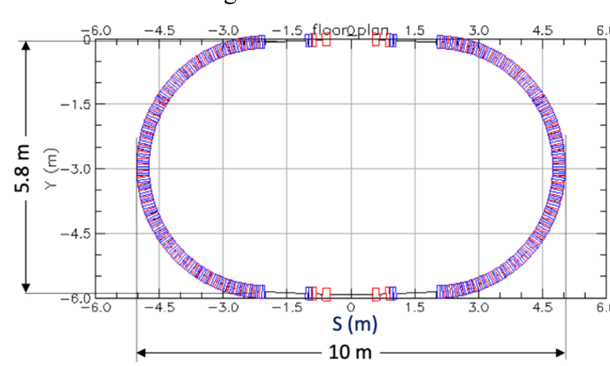

Figure 1: Layout of the Fast-Cycling FFA synchrotron.

The injector for this accelerator could be one of the 10-30 MeV cyclotrons available on the market (CYCLONE 10/2) [10]. The racetrack accelerator magnets in the arcs

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†dejan@bnl.gov

are combined function magnets with additional sextupole, octupole and decapole multipoles. The dipole bending field at the central energy where the beam orbit is purely circular, is E_{kCENT}=3.4 MeV is B_{CENT}=0.304 T, while the Neodymium Iron Boron magnetic residual induction is B_r=1.3 T. The radial orbit offsets *‘D_{xMAX}’* in the NS-FFAG arcs are between -4.05mm< x_{max} < 9.63 mm (for the kinetic energy range between 10 MeV < E_k < 250 MeV or momentum offset range between -68.2% < $\Delta p/p_{CENT}$ < 68.2%). The straight sections have proton orbits of all energies merged in a single orbit with zero radial offsets as it was successfully shown in the CBETA project. The straight sections in the racetrack are on two opposite sides. One is used one for acceleration, where the three RF cavities are placed, while the second one is used for the single turn proton injection and extraction with injection/extraction kickers and septa. The permanent magnets accelerator should reduce overall and operating cost. It fits into a very small area of 6 x 10 m space. The betatron functions, orbits, and dispersion functions of the FFA synchrotron are shown in Fig. 2.

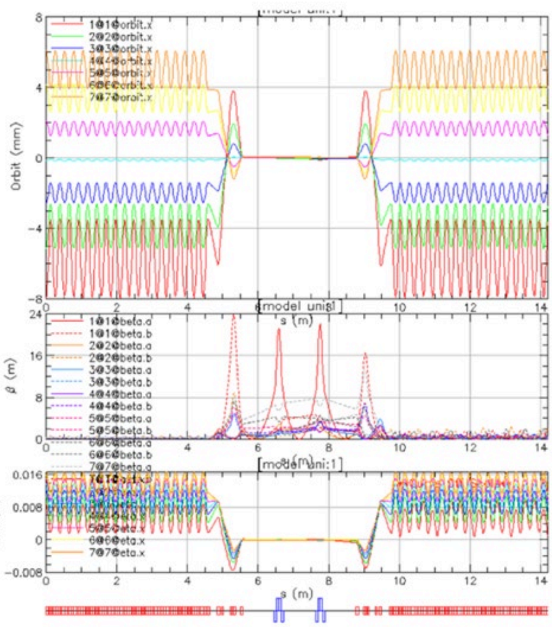

Figure 2: Orbit offsets (top), Betatron functions (middle) and the dispersion functions for energies between 10 and 250 MeV in the Fast-Cycling FFA synchrotron.

Fixed Betatron Tunes in 10-250 MeV Range

The major novelty presented in this report are the fixed betatron tunes in the very large proton kinetic energy range of 10-250 MeV or as shown above $\Delta p/p$=±68.2 %. The tune dependence on kinetic energy is shown in Fig. 3. Previously in the linear magnetic field dependence of the FFA lattice designs the tune variation between the lowest and the highest energy is between 0.304 < $\nu_{x,y}$ < 0.38. This is a new extraordinary, fixed field accelerator not reported by anyone else. This dependence removes crossing multiple resonances with increase of the beam emittance or beam loss.

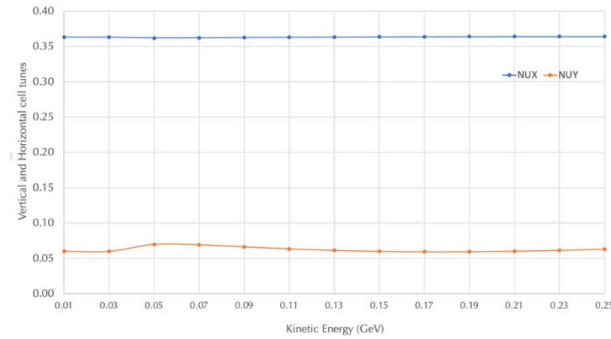

Figure 3: Tune dependence on kinetic energy in the fast-cycling FFA synchrotron.

Permanent Magnet Design for the Accelerator

The initial design of the permanent magnets with non-linear magnetic field dependence along the transverse plane. The focusing and defocusing magnets are shown in Fig. 4.

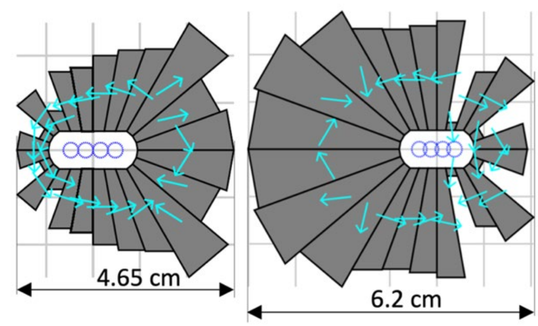

Figure 4: Non-linear focusing (left) and defocusing (right) permanent magnet design for the fast-cycling FFA synchrotron.

Extraction and Injection into the Synchrotron

The injector for the fast-cycling synchrotron could be commercially available 10-30 MeV cyclotrons with frequency of 42 MHz and provides 120 mA. This makes $1.8\text{x}10^7$ protons per bunch. As the synchrotron accelerates 30 bunches this makes per each synchrotron cycle $N_{PROTONS}$ = 1.15 x 10^8 x 30 = 5.4 x 10^7.

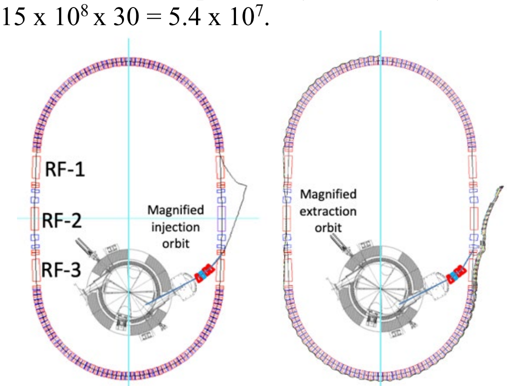

Figure 5: Injection, extraction, and the RF cavities layout in the fast-cycling synchrotron with a injector cyclotron.

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To achieve the 3.8×10^{11} protons for FLASH therapy it is required to run the synchrotron per one FLASH treatment $N = 3.8 \times 10^{11}/3.23 \times 10^{9} \sim 700$. The total time for the FLASH treatment is $t_{FLASH} = 700 \times 898$ ms = 632 ms! The layout of the extraction and injection devices with the three RF cavities is shown in Fig. 5.

Acceleration in the Fast-Cycling Synchrotron

Protons are accelerated in a non-relativistic energy range and their flight path around the accelerator's circumference varying very much as shown in Fig. 6.

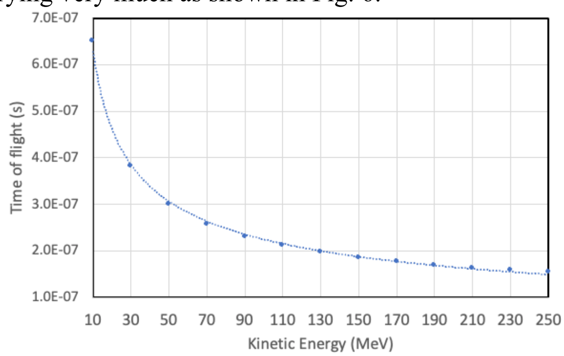

Figure 6: Proton's time of flight dependence on kinetic energy in the fast-cycling synchrotron circumference.

To accommodate a difference in the proton path length or time of flight and provide the synchronous acceleration there were different proposed solutions like the Harmonic Number Jump where the beam is accelerated by a pre-programmed RF voltage and the profile is being always kept constant across the width of the cavity with all orbits could simultaneously be occupied by beam. We adopted frequency-modulated rf systems. The harmonic number h is constant, and the *RF* frequency increases in proportion to the particle speed $c\beta$. This implies h =4, 5, and 6 and minimum frequencies between about 4.2 and 8.7 MHz. The properties of ferrites yield an upper limit for the range of frequencies at about 50 MHz.

We selected the Phase Jump Acceleration (PJA) method following a previous proposal by D. Boussard [11] with the pill box cavities. Acceleration is performed by adjusting the RF phase each turn.

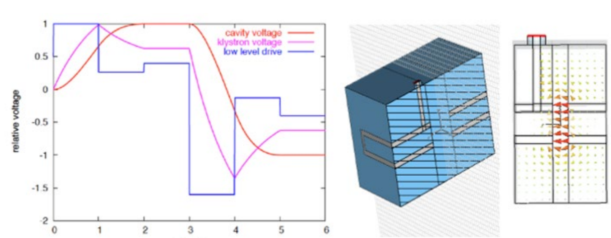

Figure 7: The full cycle with the cavity voltage (red) during the phase jump acceleration. The klystron voltage in shown in pink, while the low-level RF drive is shown in blue color.

We have modeled an RF cavity for proton acceleration to 250 MeV, the value changes from injection 0.1448 to 0.6136 and the cavity impedance varies by a factor of three. At top energy R/Q = 33 throughout the cycle Q=50 and f_{RF} = 390 MHz, and the exponential decay time for the field is 43 ns. *There is 80 ns time to change the cavity frequency when there is no beam.* The bunch train fills almost quarter of the ring at the injection. The RF frequency needs to be in a high range, ~370-395 MHz, because of the required large number of RF cycles between the passages of bunches, to achieve higher values of Q. The basic idea is to accelerate a train of bunches with a gap. During the gap the RF phase is adjusted so that when next the bunch train arrives, the phase is correct for acceleration. The challenge is to find a low-level RF drive signal, which causes the cavity voltage to reach a certain target value during the gap. The solution by M. Blaskiewicz (BNL) is presented in Fig. 7. As each cycle is 783 µs long this makes for the total time of treatment $t_{TREATMENT}$=116x783 µs = 90 ms with the synchrotron cycle of 1.3 kHz. The variation of the frequency during acceleration is shown in Fig. 8.

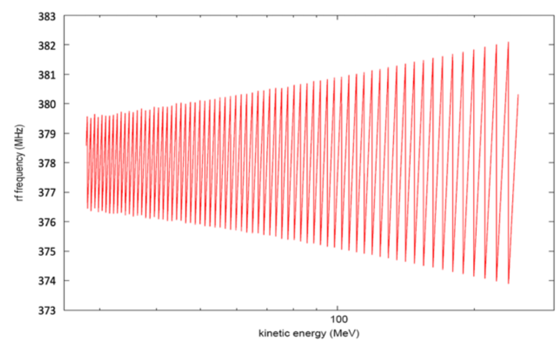

Figure 8: RF frequency and phases changes during the proton acceleration from 30 to 250 MeV. The central frequency is 390 MHz.

If the synchronous voltage is 22 kV a total number of turns required to accelerate protons is $N = (E_{max}-E_{min})/N_{cav}*V_{synch} = (250-10)10^{6}/(3*20*10^{3}) = 4000$. The total stored energy in the cavity is related to the amplitude V_{RF} of the RF voltage as: $U = V_{ac}^{2}/(2\omega_r(R/Q))$ where ω_r is the angular resonant frequency, Q is the quality factor, and R is the resistance. A total power for one RF driver is 100 kW, for 3 cavities this makes 300 kW for the total power.

CONCLUSION

The 10-250 MeV fast cycling proton synchrotron with cycling of 1.3 kHz is the fastest synchrotron proposed so far. The other existing synchrotron rates are in a range are 15- 60 Hz. In proton acceleration within the non-relativistic energy range the main problem is the limitation on the speed due to magnetic field response to the change of energy. This limitation is now eliminated by using the permanent magnets for the same energy range. The Fast-cycling permanent magnet synchrotron with 6 x10 m area is the best possible synchrotron for the cancer proton FLASH radiation therapy. It is cost efficient, does not require electrical power, magnets are very small and light. This proof of principle accelerator would enable new areas of research using the same principle but building the magnets with multi-layer superconducting wires.

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