15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPR46

FLASH PROTON THERAPY FACILITY DESIGN WITH PERMANENT MAGNET*

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Abstract

We present a design of the proton FLASH radiation therapy facility using the Brag peak to be built at Stony Brook University Hospital at the Radiation Oncology Department. It includes an injector using a commercially available injector cyclotron (10-30 MeV), fixed field alternating (FFA) gradient beam lines, permanent magnet Fixed Field Alternating Gradient non-scaling variable transverse field fast-cycling synchrotron accelerator with unprecedent kinetic energy range between 10-250 MeV, and a permanent magnet delivery system the FFA gantry. This facility removes limitations of the present proton cancer therapy facilities allowing FLASH radiation to be performed with **40 Gy/s** in **100 ms**. This allows treatment with the FLASH therapy without **magnet adjustments** for any proton kinetic energy between 70-250 MeV. The proposal is based on already experimentally proven FFA concept at the Energy Recovery linac 'CBETA' built and commissioned at Cornell University [1-8].

INTRODUCTION

The hadron-ion cancer radiation therapy deposits the energy in the body at the site of the cancerous tumor. Most of the energy is deposited at the Bragg peak. The position of the tumor in the body defines the proton energy required to propagate through the body and precisely deposits the energy. In radiation therapy ion energies can be adjusted allowing the spread-out Bragg peak to reach deep seated tumors inside of the body. The modern systems like VARIAN-ProBeam 360^{o}, IBA Proteus^{R}, Hitachi synchrotron proton accelerator etc. use pencil beam scanning to allow precise and fully conformal dose distribution. In hadron therapy protons or carbon ions propagate through the body modifying biological structures due to direct ionization leading to the single or double-strand DNA break-ups. Today's treatments of about 60-80 Gy are delivered to the patients usually over a couple of weeks, with the dose fractionation of ~2 Gy per dose. On the trajectories of ions there are secondary particles and ionization of molecules with radiation damage in the path of the order of few nanometers. Photons and electrons create significant doses to the surrounding tissues. The 'FLASH' cancer therapy is a relatively new possibility in treating the cancerous tumors if radiation is required. Recent multiple biological studies around the world, mostly in animals with few patient treatments, showed that by delivering ultra-high radiation dose in much shorter time intervals there is significant improvements in sparing healthy tissues [9, 10]. The radiation fractions are delivered in a part of a second (100 ms) 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. The proton FLASH therapy requirements are 40 Gy/s with respect to 0.01 Gy/s in conventional RT. To obtain the dose of 40 Gy/s in 100 ms for a volume of 1000 ml (10x10x10 cm) this becomes 4 Gray in 100 ms. If we take 3.8×10^{11} protons or 60 nC to be delivered in 100 ms, then this is equivalent to 600 nA. It is not yet clear why the high FLASH radiation spares the healthy tissue, but it looks like that radiochemical depletion of oxygen occurs inducing tissue radio resistance [11]. This proposal removes limitations of the existing proton therapy facilities. It delivers protons with required energies in a very short time without changing the magnetic field. It is made of permanent magnets except in the spot scanning part. The facility includes: (1) Injector cyclotron commercially available with a maximum kinetic energy of 10, 16.5 or 30 MeV, (2) Fast-cycling permanent magnet synchrotron with kinetic energy range between 10-250 MeV, (3) Permanent magnets transfer beam lines with proton kinetic energy range 70-250 MeV, and (4) the Permanent magnet gantry with energy range 70-250 MeV as shown in Fig. 1.

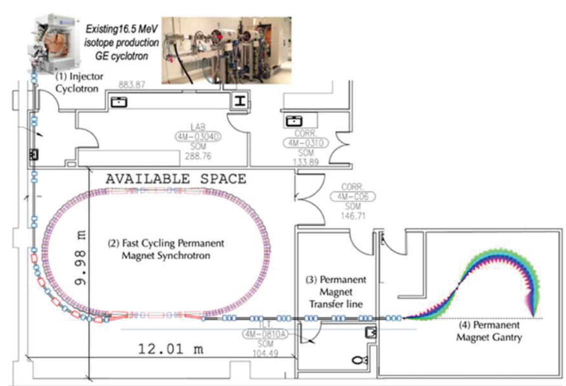

Figure 1: Layout of the proton FLASH therapy facility

LIMITATIONS IN PRESENT FACILITIES

Major limitations at any existing cancer hadron radiation therapy system or facility are the variable magnetic field requirements for different energy settings. It is hard to adjust the magnetic field within the short time (hysteresis) required for FLASH. The cyclotron-based treatment centers required energy degraders as a single 230-250 MeV energy is extracted. At low energies only 1% of the initial beam is delivered to the patient. The beam size – emittance is always significantly enlarged. The synchrotrons are

* This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy
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presently cycling with low frequencies and using the slow extraction of the beam towards the patients requiring too long for FLASH. For synchrocyclotrons (MEVION and IBA S2C2) the spot scanning has serious problems. It is unlikely that synchrocyclotrons would be the eventual technology of choice for a pure spot-scanning FLASH proton therapy system [12]. At present, for AVO system the repetition rate of 200 Hz is simply too slow to enable delivery to anything but small volumes. The pulse repetition frequency of 200 Hz makes it possible to irradiate only 20 separate energy layers within a time window of 100 ms. An increase in this rate by a factor of >500 would be necessary [12] for spot-scanned FLASH delivery to a 1-liter volume. The present synchrotron design assumes RF frequency of 500 Hz (already tested at Rutherford Laboratory in UK).. A quotation from the reference [12]: "In the future, rapid energy variation will demand **beam delivery systems with large energy acceptance**; rather than adjust the magnet settings for each energy layer, the beam dispersion is limited by a suitable beam-optical arrangement and sufficient aperture within the magnets and vacuum system provided to obtain a large energy acceptance." This is the main argument for using the presented FLASH facility design with the energy range between 70-250 MeV without magnet adjustments.

MAJOR CBETA ACCOMPLISHMENTS

The CBETA project successfully commissioned four turn Energy Recovery (ERL) superconducting linac by using a single FFA beam line. For the first time there were four electron energies of 42, 78, 112, and 150 MeV transported through the single FFA beam line during acceleration and three energies of 150, 112, and 78 MeV during deceleration. Here are the major accomplishments from the fixed field accelerators point of view: (1) Full proof of principle for the non-scaling FFA's, (2) Merging multiple energy orbits into a single straight-line orbit, and (3) Development of the new permanent magnet technology as shown in Fig. 2.

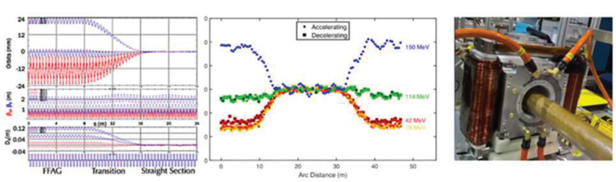

Figure 2: Major accomplishments of the CBETA project from the FFA side: predicted orbits (left), measured orbits (right) and building superb-quality permanent magnets.

LAYOUT OF THE PROPOSED FACILITY

The proposed layout of the proton FLASH therapy facility is shown in Fig. 1. There are includes a commercially available injector cyclotron with the maximum extraction energy with the range between 10 and 30 MEV. Cyclotron injectors are presented in Table 1. The RF Resonant cyclotron frequencies in proposed injector cyclotrons are within a range between 27.2 – 85 MHz with extracted current within the range 200-1200 μA. The injection porch of the synchrotron length depends on the selection of the injector cyclotron. The layout of the injection cyclotron with the fast-cycling synchrotron is shown in Fig. 1 and Fig. 3. To get enough beam intensity to perform FLASH treatment there are necessary beam merging's or stackings to be performed. As the proton energy acceptance in the fast-cycling synchrotron is between 10 and 250 MeV there are few possible ways to raise the beam intensity. There were already reports on beam merging in the scaling FFA [12] with injection energy of slightly different values as shown in Fig. 3. Time of flight during one turn in the synchrotron at the injection energies from cyclotrons, as shown in Fig. 3, are: $\tau_{(10\ \mathrm{MeV})}$=690.9 ns, $\tau_{(14\ \mathrm{MeV})}$=585.7 ns, $\tau_{(16.5\ \mathrm{MeV})}$=540.6 ns, $\tau_{(19\ \mathrm{MeV})}$=504.8 ns, $\tau_{(30\ \mathrm{MeV})}$=405.2 ns.

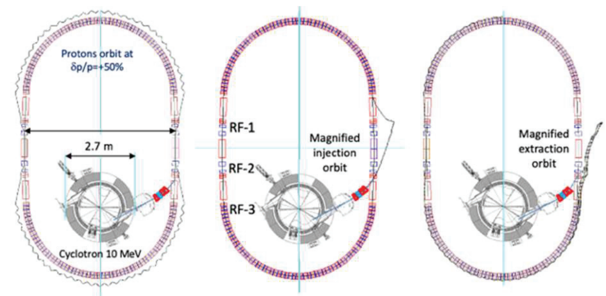

Figure 3: Magnified orbit offset for three different cases in the fast-cycling synchrotron @ the maximum proton energy of 250 MeV(left), at the injection (middle) and at the extraction (right).

The proton time-of-flight dependence on kinetic energy is shown in Fig.4.

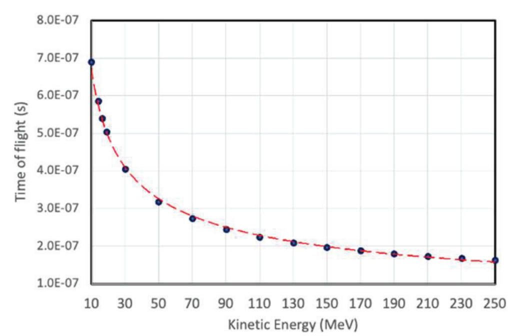

Figure 4: Time of flight dependence on kinetic energy.

The slip stacking is another possible solution to enhance the proton intensity from the injection cyclotron as schematically presented in Fig. 5.

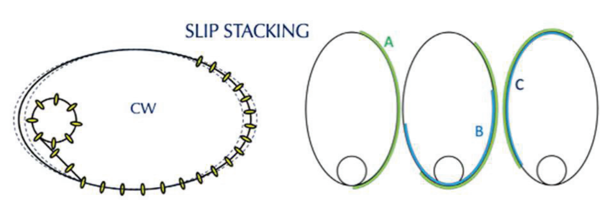

Figure 5: Slip tacking in the fast-cycling synchrotron.

In the half of the synchrotron ring there is a place for 18 bunches from the cyclotron TR-19 one of the possible injection cyclotrons as shown in Table 1. An additional capability of stacking multiple bunched injected from the

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cyclotron is possible at FFA's as the momentum acceptance is very large ss previously reported [12]. The bunch merging technique from 3→1 or 6→1 is also another possibility.

Table 1: Possible Injector Cyclotrons

	ACSI	GE	TR-19	IBA	Units
Max Energy	14	16.5	19	30	MeV
RF frequency	85	27.2	73.2	63.96	MHz
Current	400	200	400	1200	μA
Charge/Treatm.	60	60	60	80	nC
#inj. turns	4	4	4	2	#
RF/turn	29.7	29.7	29.7	44.55	kV
	FLAH Treatment Options				
Turn duration	585.7	540.6	504.8	405.1	ns
Charge/turn	0.234	0.101	0.151	0.486	nC
# Proton./turn	1.46	6.3	9.43	30.3	$*10^8$
Charge/injection	0.937	0.432	0.808	0.972	nC
Mach. Cycles	65	139	100	62	#
Cycle rate	540	540	540	810	Hz
#Proton/treatm.	0.95	0.876	0.943	1.88	$*10^{11}$
Treatment time	120	257	185	76.6	ms

Details of the fast-cycling synchrotron are shown at this conference [13]. Fixed tune dependence on energy is main new FFA capability allows beam to make multiple passes ~3600, through the possible systematic resonances as the same FFA cell repeats multiple times (66 cells). The tune dependence on momentum is shown in Fig. 6.

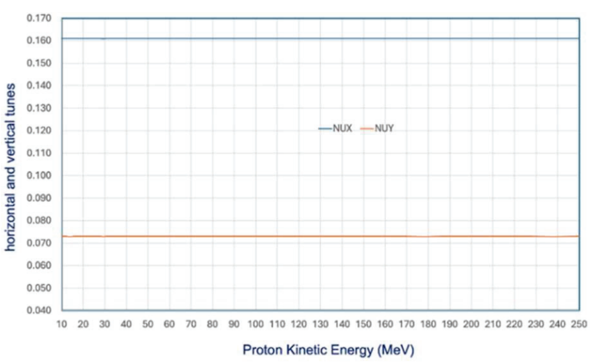

Figure 6: Tune dependence on proton kinetic energy.

Merging orbits of the multiple energy beams into a single orbit is shown in one of the first example of the fast-cycling synchrotron in Fig. 7.

Permanent Magnet Proton Gantry

The last part of the proposed FLASH facility is the permanent magnet proton gantry with a possibility to transport the proton beams with multiple energies in a range between 70-250 MeV to the focusing point at the patient. The gantry is isocentric and rotates around the horizontal axis. The gantry's elements are placed in a single plane. The plane, as shown in Fig. 8, assumes the gantry in upward position or 90° with respect to the horizontal plane. The gantry is comprised of three parts: The first part labelled as ***A***, bends the proton beam in this case upward is an achromatic and orbits with higher energies are shown in the lower part. At the end of the part **A** all orbits merge into a point. The orbits continue upward but the bending is reversed, and the elements in the second part labelled as ***B,*** repeat the half of the part ***A***. The last part ***C*** bends in the same direction using the last elements combined function permanents magnets to focus the beam at the point on the x-axis.

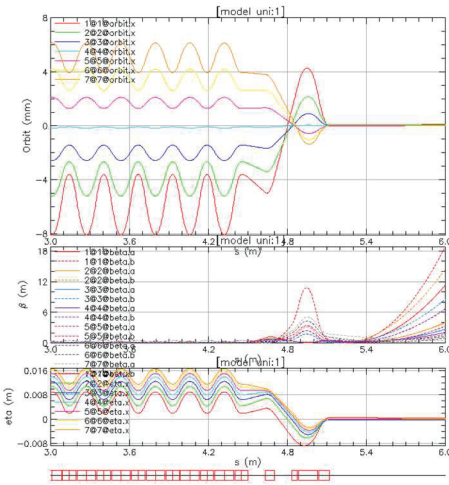

Figure 7: Multiple energy arc orbits merging into one.

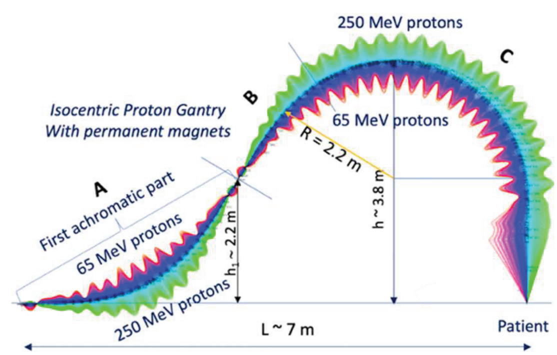

Figure 8: Permanent Magnet Gantry1

SUMMARY

- The **cost** of the FLASH radiation therapy facility **is significantly reduced** (~$40M with respect to ~$160M).
- **Simplified operation** as there is not a need to change the magnet settings for different proton energies.
- A significant **reduction of the power consumption** as the permanent magnets do not require electrical power. Exceptions are the correction magnets and RF power amplifiers.
- Significant **reduction on radiation shielding** as the beam losses in synchrotron if any are controlled.
- Significant **reduction of the magnet sizes and weights**. The **gantry weight is significantly reduced.**

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