15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC69

PERMANENT MAGNET ELECTRON ENERGY SYNCHROTRON 2.5 - 18 GEV WITH FIXED BETATRON TUNES*

D. Trbojevic†, S. Brooks, J.S. Berg, F. Meot, BNL, Upton, NY, USA
G. Hoffstaetter, BNL Cornell University-CLASS, Ithaca, NY, USA

Abstract

We are presenting a design of a 2.5-18 GeV electron synchrotron accelerator made of permanent non-linear combined function magnets with fixed betatron tunes. It is based on the successfully commissioned CBETA Energy Recovery Linac where we used a single return beam line based on Fixed Field Alternating gradient (FFA) principle [1-8]. The 2.5 GeV injection energy electrons come from the Recirculating Linear Accelerator (RLA) with 350-400 MeV linac and a single FFA linear combined function magnet beam line to return electrons to the linac. The electron collision energy uses the same single beam line avoiding the RF accelerating cavities during selected number of turns.

INTRODUCTION

The permanent combined function magnets were successfully used at Fermilab antiproton recycler ring [9, 10]. We present a design of the permanent magnet fast cycling synchrotron to accelerate electrons from 3-18 GeV placed in the Relativistic Heavy Ion Collider (RHIC) tunnel at Brookhaven National Laboratory (BNL). Previously the non-scaling FFA's with the linear transverse magnetic field dependence were considered in the Energy Recovery Linac (ERL) using 1.5 GeV superconducting linac. The transverse linear magnetic field in the combined function permanent magnets is replaced with the non-linear dependence to produce fixed betatron tunes in both planes. If a combination of the fixed betatron tunes and isochronous condition in the arcs are achieved with betatron function matched to the linac additional number of passes through the linac could be possible and the spreaders and combiners might be eliminated. The time of flight could be adjusted with the additional chicanes. To preserve electron polarization during acceleration the number of passes through the arcs needs to be limited requiring higher linac energy. This proposal is very well connected to energy reduction and sustainability using the permanent magnets.

ESSENTIALS OF THE CONCEPT

The injection FFA accelerator is an Energy Recovery Linac type like the successfully commissioned CBETA ERL. The maximum injector linac energy is connected to the energy range of the designed injector RLA. If the non-linear non-scaling FFA is used the energy range could be 6 times of the energy of the first pass though the accelerating structure. As the injection energy of the large ring accelerator is 2.5 GeV the injection gain in energy of the injector would be N=2.5/6 GeV=350–400 MeV (this could be either superconducting linac or the warm or 77K linac would work as well) as shown in Fig. 1. If the superconducting linac is selected the time of flight and M_{56} need to be precisely controlled either by using the spreaders and combiners or chicane with the isochronous arcs. The linac betatron matching to the multi-pass single permanent magnet arcs is provided by adiabatic reduction of the bending angle at the end of the arc with enhancement of the distance between the arc triplets using the power law as shown later in the article. The main accelerator is also an RLA synchrotron made of combined function permanent non-linear FFA magnets. It allows multiple turns during acceleration. The number of passes through the arcs is limited by the electron polarization loss. But this is an RLA in CW mode. There are two possible modes of operation: one with sending the electron bunches after the collisions with ions to the dump downstream of the collisions or store them after collisions for few hundred of turns and replenish them from the FFA accelerator adjusting the CW electrons by using the gap in the injector (shutting off the laser at the cathode of the injector gun). The gap in the 360-bunch configuration in both cases must exist due to abort gap.

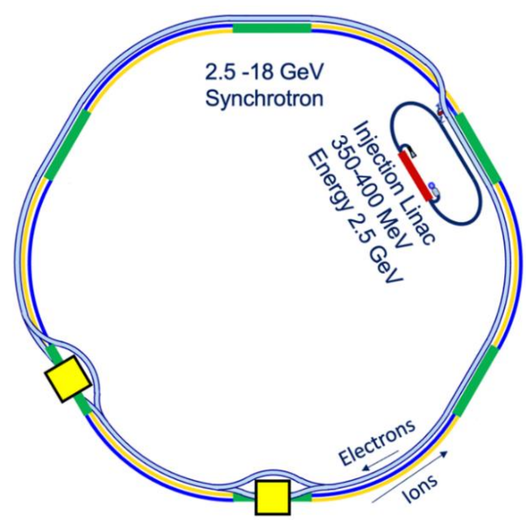

Figure 1: Layout of a possible solution with two non-scaling non-linear FFA permanent magnet RLA's. The injector with 350-400 MeV linac accelerates the beam to 2.5 GeV and the large RAL FFA accelerates from 2.5 to 18 GeV.

* This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
†dejan@bnl.gov

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC69

The injector is an RLA with matched betatron functions as shown in Fig. 2.

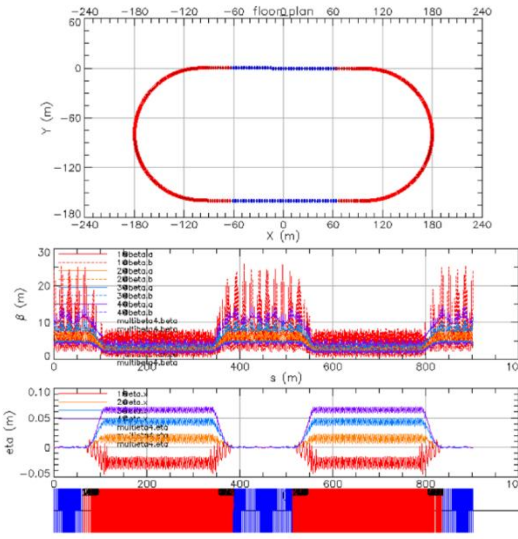

Figure 2: Schematic of the RLA accelerator from 350-400 MeV up to 2.5 GeV with non-linear non-scaling FFA's.

The betatron functions matching is shown in Fig. 3.

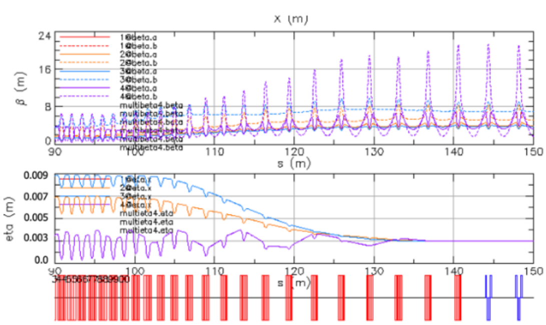

Figure 3: The betatron functions from the arc (left) are adiabatically merged to the straight section with larger distance between the FFA's triplets to accommodate space linac cavities.

It is important to note that the betatron function matching is valid for the whole energy range. As the linac modules raise the energy the betatron functions change in the following drift to the value corresponding to the higher energy. A possible placement of the cavities in the straight section is shown in Fig. 4.

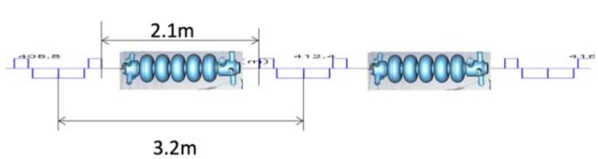

Figure 4: A possible placement of the cavities in the straight section.

Large 18 GeV RLA with Non-Linear FFA

The accelerator is placed in the existing RHIC tunnel following six arcs with six straight sections. The merging to the straight section is done adiabatically as shown previously in the injector example. The basic cell is made of the triplet magnets. Two focusing ***F*** and a single the defocusing magnet ***D*** combined function magnets. The drifts space between the ***F*** and ***D*** magnet is *LD2*=6 cm and a drift between the ***F*** magnets is the same *LD3*= 6 cm. The focusing combined function magnet length is L_{QF}=39.5 cm with non-linear transverse magnetic fields including multipoles up to the 14th pole. The bending fields at the reference orbit at energy of 8 GeV are both B_{QF}= B_{BD} =–7.73E-002 T. The gradient of the focusing magnets is G_{QF}= -50.83 T/m. There are 192 cells in each arc. The bending angle of each arc θ_{ARC}= 0.93240864 rad is defined by RHIC geometry with the arc length of l_{ARC}= 356.30044 m. The defocusing combined function magnet has a length of l_{BD}=88.573 cm and the gradient of G_{BD}= 38.52 T/m. The betatron tune dependence on energy in focusing magnet is shown in Fig. 5.

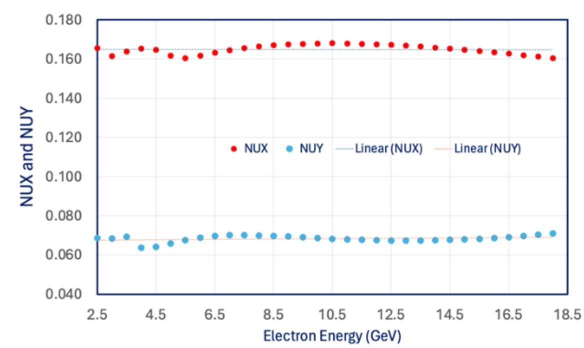

Figure 5: Betatron tune dependence on energy (F magnet preliminary data).

The maximum orbit offsets in the ***F*** magnets are shown in Fig. 6.

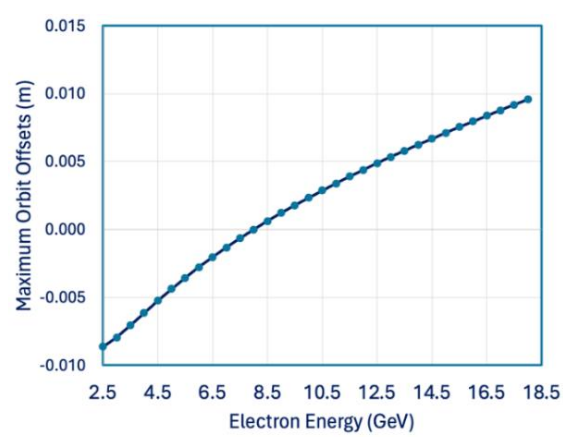

Figure 6: Maximum Orbit offsets in the F magnet.

Possibility of Multiple Ways for Beam Collisions

- Polarized electron gun provides enough charge per bunch for a single collision between ions and electrons.

This CW mode of possible collider operation would be performed from the beginning of the electron accelerator complex. The large intensity polarized electron beam bunches are produced in the gun. They are accelerated by

15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC69

injection linac with the beam colliding structure of 360 buckets filled with electron bunches such to produce the same length of the abort gap as in the RHIC ion bunches. The acceleration is continuous in the CW mode and follows with the large non-linear FFA placed in the RHIC tunnel reaching the energy of 18 GeV. The beam extraction is provided by a set of small permanent magnet dipoles within the last arc before the Interaction Point (IP) as shown in Fig. 7. All non-linear combined function magnets are open gap magnets to allow synchrotron radiation to tangentially escape. The same dipole magnets have open aperture and can be inserted into the larger drift space. The triplet structure end of last FFA arc has larger drifts between the triplets adiabatically enhanced. This creates the larger orbit offsets to allow extraction permanent Halbach type dipole to slide tangentially inside of the over the wide aperture extraction pipe. The position of the extraction Halbach permanent dipoles depends on what energy needs to be extracted for collisions with ions. After electrons collide, they are removed to the beam dump.

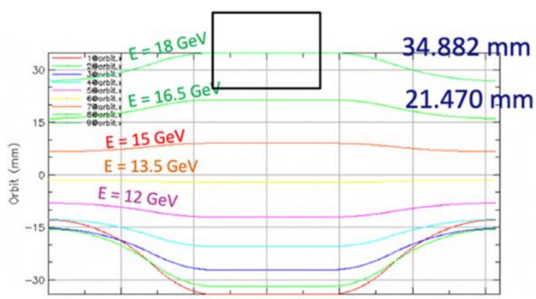

Figure 7: Extraction of the electron beam.

- Merging of the electron beams in the injector is required to obtain enough charge per bunch intensity for collisions.

The electron merging, shown in Fig.8, is in a similar injector was previously shown [11].

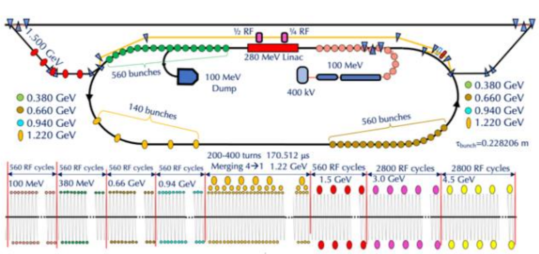

Figure 8: Merging of electron beams in the injector [11]. Previously shown merging example.

- Single non-linear and non-scaling FFA used as an accelerator and the storage ring at the same time.

This mode requires two separate RF systems: one for acceleration in the non-linear FFA permanent magnet synchrotron and the other in a separate extraction straight section line for collisions with ions. The electron beam is extracted as shown in Fig. 7 and after colliding with ions is brought back to the FFA accelerator to the same circulating orbit. This orbit avoids the accelerating RF at the location of the FFA accelerator. This is accomplished by the same way as for the electron beam extraction. The loss of energy during multiple passes of the 'stored' beam is replenished by the RF system placed at the collision straight line. The FFA RAL accelerator can operate CW mode a similar way as the PSI cyclotron. This is possible due to the fixed magnetic field and separate different energy orbits. As multiple high electron charge beams pass through the same beam pipe the problem of coherent synchrotron radiation and beam wall interaction needs to be investigated.

SUMMARY

An attempt to reduce use of electrical power towards sustainability of accelerators is presented. The fast-cycling synchrotrons made of permanent magnets using permanent magnets with non-linear magnetic field with the fixed betatron tunes allow reduction of the size of the linac and use of the multiple passes to achieve the required collision energy of 18 GeV in this case. Significant reduction of electrical power is achieved as it would be needed only for the correction magnets and the RF systems. The requirement for two rings, one for acceleration and one for the storage, could be reduced by using a single non-linear FFA accelerating and storage ring at the same time. The size of the permanent magnets is significantly smaller than electro iron magnets and they do not require ramping of the current simplifying significantly the operation. A problem of the permanent magnet material degradation due to radiation needs to be investigated although the permanent combined function magnets at Fermilab antiproton recycler ring operated successfully; although their design was based on iron dominated magnets.

REFERENCES

[1] D. Trbojevic, J. S. Berg, M. Blaskiewicz and S. J. Brooks, "Fast Cycling FFA Permanent Magnet Synchrotron", in *proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 126-129, doi:10.18429/JACoW-IPAC2022-MOPOST029

[2] D. Trbojevic, "Non-Scaling Fixed Field Alternating Gradient Permanent Magnet Cancer Therapy Accelerator," United States Patent Application Publication and No. US 2014/0252994 A1, Sep. 11, 2014.

[3] A. Bartnik et al., "First Multipass Superconducting Linear Accelerator with Energy Recovery," *Phys. Rev. Lett.*, vol. 125, pp. 044803, Jul. 2020. doi:10.1103/physrevlett.125.0 44803

[4] C. Gulliford *et al.*, "Measurement of the per cavity energy recovery efficiency in the single turn Cornell-Brookhaven ERL Test Accelerator configuration," *Phys. Rev. Accel. Beams*, vol. 24, pp. 010101, Jan. 2021. doi:10.1103/physrevaccelbeams.24.010101

[5] S. Brooks *et al.*, "Permanent magnets for the return loop of the Cornell-Brookhaven energy recovery linac test accelerator," *Phys. Rev. Accel. Beams*, vol. 23, p. 112401, Nov. 2020. doi:10.1103/physrevaccelbeams.23.112401

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC69

[6] D. Trbojevic *et al.,* "CBETA Project Report," CLASSE, Ithaca, New York, USA, Rep. NYSERDA contract No. 102192, Mar. 2020.

[7] D. Trbojevic *et al.*, "Multi pass Energy Recovery Linac Design with a Single Fixed Field Magnet Return Line," in *Proc. ICAP2018*, Key West, Florida, USA, Oct. 2018, pp. 191-195. doi: 10.18429/JACoW-ICAP2018-TUPAF09

[8] K. E. Dietrick *et al.*, "Novel "Straight Merger for Energy Recovery Linacs," in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 702-705. doi:10.18429/JACoW-LINAC2018-THPO010

[9] M. Hu, "The Fermilab Recycler Ring", in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper MOPA006, pp. 30-32.

[10] J. T. Volk, "Experience with permanent magnets at the Fermilab recycler ring", *IEEE Open J. Instrum.*, vol. 6, no. 08, pp. T08003, Aug. 2011. doi:10.1088/1748-0221/6/08/t08003

[11] D. Trbojevic *et al*., "Permanent Magnet Future Electron Ion Colliders at RHIC and LHeC", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1401-1404. doi: 10.18429/JACoW-IPAC2021-TUPAB028