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MULTI PASS ENERGY RECOVERY LINAC DESIGN WITH A SINGLE FIXED FIELD MAGNET RETURN LINE*

D. Trbojevic†, J. Scott Berg, Stephen Brooks, Francois Meot, Nicholaos Tsoupas
BNL, Upton, NY, USA
William Lou, Cornell University (CLASSE), Ithaca, NY, USA

Abstract

We present a new approach of the Energy Recovery Linac Design for the future projects: PERLE (Powerful Energy Recovery Linac for Experiments), LHeC/FCCeH and eRHIC. The concept uses superconducting linacs and a single fixed field beam line with multiple energy passes of electron beams. This represents an update to the existing CBETA (Cornell University Brookhaven National Laboratory ERL Test Accelerator) where the superconducting linac uses a single fixed field magnet beam line with four energy passes during acceleration and four passes during the energy recovery. To match the single fixed field beam line to the linac the CBETA uses the spreaders and combiners on both sides of the linac, while the new concept eliminates them. The arc cells from the single fixed field beam line are connected to the linac with adiabatic transition arcs wher cells increase in length. The orbits of different energies merge into a single orbit through the interleaved linac within the straight sections as in the CBETA project. The betatron functions from the arcs are matched to the linac. The time of flight of different electron energies is corrected for the central orbits by additional correction magnet controlled induced beam oscillations.

INTRODUCTION

The Energy Recovery Linacs (ERLs) and Recirculating Linacs (RAL) are considered to be a part of the future Electron Ion Colliders in several world programs: LHeC (CERN) [1], FCC eh [2], eRHIC(BNL) [3], ELIC (Jefferson Lab) [4] and EIC@HIAF (China) [5]. A proposal presented in this report describes a solution of ERL where the electron beam is brought back to the linac with a single large energy acceptance beam line using a concept of linear fixed field alternating (FFA) gradient. The concept of the FFA beam transport with large momentum acceptance is not a novelty. There are three experimentally confirmed proof-of-principles: EMMA-Electron Model for Many Applications [6], ATF (Accelerator Test Facility) [7] experiment with 12 FFA cells, and Fractional Arc Test of the Cornell University-Brookhaven National Laboratory ERL Test Accelerator-CBETA [8]. A comparison of these three examples are compiled and shown by Stephen Brooks [9] in Fig. 1 and in Table 1.

We present a new concept of the ERLs where the large momentum acceptance linear FFA magnet beam lines bring

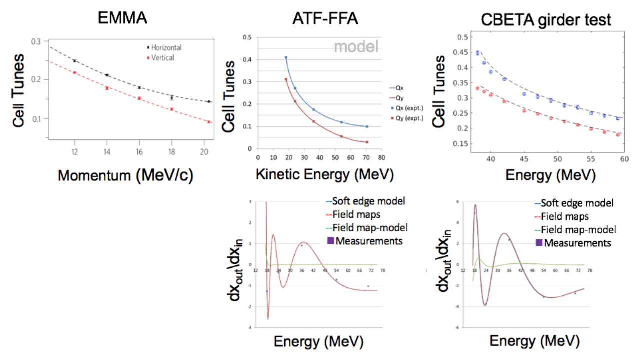

Figure 1: Comparisons on tune dependence on Energy in the three FFA examples.

the electron beam back to the superconducting linac without spreaders and combiners. In multiple passes through the ERLs the acceleration of electrons generated by the linac is too fast to consider any return beam line by using fast cycling magnets. With the large momentum acceptance linear FFA gradient magnets this can be achieved. The first test of the concept will be achieved in 2019 by the ERL CBETA at Cornell University. There are many advantages and simplifications: 1) the replacement of multiple returning beam lines with a single beam line reduces the cost and complications; 2) established technology of the Halbach type permanent magnets used at CBETA project will confirm the reduction of cost and simplification of the beam lines; the magnet aperture remains to be very small while transporting multiple energy beams. In the present study the superconducting linac is made of 5-6 cavity cells, each separated with small permanent FFA triplets. The same type of triplet cells con-

Table 1: EMMA-ATF-CBETA Comparisons

Parameter	**EMMA**	**ATF-FFA**	**CBETA girder**	**CBETA Future**
Energy (MeV)	10–20	18–71	37.5–59	41–150
Mom. ratio	1.953	3.837	1.553	3.572
ρ of curv. (m)	2.637	2.014	5.0879	5.0879
Avrg. dip. (T)	0.026	0.118	0.0983	0.0983
Total angle (°)	360.0	40.0	20.0	280.0
Oper. mode	ring	Tr. line	Tr. Line	ERL
Acceleration?	YES	none	none	linac
Lattice	Doublet	~FODO	Doublet	Doublet
Cell Length (m)	0.395	0.234	0.444	0.444
Cell per turn	42	54	72	107.5
Length (m)	16.57	1.406	1.776	47.73

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† dejan@bnl.gov

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tinues towards the FFA arc but with an adiabatic reduction of the cell lengths. The betatron and dispersion functions for each energy are adiabatically matched to the corresponding functions of the arc FFA cells.

Recently the National Academy of Sciences released a study of "An Assessment of U.S.Based Electron Ion-Collider Science." ... "The principal goals of the study were to evaluate the significance of the science that would be enabled by the construction of an EIC, its benefits to U.S. leadership in nuclear physics, and the benefits to other fields of science of a U.S.-based EIC." ... "Several presentations to the committee specifically addressed the challenges and **necessary innovations** in accelerator science needed for constructing an EIC capable of addressing the most important science questions" ... "To reach the performance goals of the proposed EIC conceptual designs, a number of accelerator advances are required. Several of these advances are common to all EIC designs and include the following: advanced magnet designs, strong hadron beam cooling, **high current multi turn ERL technology**, crab cavity operation with hadron beams, the generation of polarized 3He beams, and development and benchmarking of simulation tools. The successful implementation of an EIC requires the successful validation of these key concepts through high-fidelity simulations and demonstration experiments. The following subsections review these enabling technologies, the present state of the art, and required research and development to meet EIC facility specifications and realize EIC science: **Energy Recovery Linacs**." ... "The ERLs required for electron cooling are at scales much larger than supported by present-day experience, so a number of accelerator physics and technology challenges still need to be overcome with focused R&D and great attention to detailed simulations. The challenges center around the following three major areas: 1. Achieving high electron source brightness 2. Maintaining high beam brightness through the accelerator transport-beam dynamics of an unprecedented number of spatially superposed bunches in the SRF linacs; very precise phase and amplitude control 3. Dealing with unprecedented beam currents in SRF linacs (halo mitigation, beam breakup instabilities, higher order mode dissipation). Many of these R&D issues are being investigated vigorously in dedicated test facilities under construction and commissioning in laboratories around the world. Specifically, the 4-pass Fixed Field Alternating Gradient R&D loop for eRHIC, see Box 4.2 **CBETA and Fixed Field Alternating Gradient Optics** for Electron Acceleration, it could illuminate key issues including multi-turn beam-breakup instability thresholds for proof of possible cavity designs, halo and mitigation, beam-ion effects, and operational challenges such as instrumentation and stability of multi-turn beams". The suggestions obtained in the National Academy of Sciences report emphasize theimportance of the CBETA project and further developments towards improvements of the concept.

The presented study is divided into couple of sections: first section describes the arc cell design to allow transport of multiple energy electrons; the second section describes a design of the long straight section to be used for the placement of the linac superconductiong cavities. Acceleration of electrons through the linac requires use of the "normalized to betatron functions" as the momentum changes along the length of the linac. To make the matching conditions on both sides of the linac the triplet quadrupoles strength along the linac needs to be adjusted accordingly. The adiabatic transition from the arc FFA cells towards the linac is explained in the next section. Overall solution with orbits, betatron functions, dispersion function is shown in the fourth section. The time of flight adjustment is described in the fifth section while the summary and conclusions are shown in the sixth section.

LINEAR FIXED FIELD ALTERNATING (FFA) GRADIENT ARCS

The principle of the linear FFA gradient acceleration has been previously described in details [10] and [11]. The main idea of the principle is to keep the value of dispersion function $\Delta x = D_x \cdot \delta p/p$ as low as possible or to have a control of the 'dispersion action' $\mathcal{H} = (D_x/\sqrt{\beta})^2 + (D'_x\sqrt{\beta} + \alpha D_x/\sqrt{\beta})^2$. The accelerator physics program 'Bmad' [12] is used throughout this study. The main arc FFA cell design is shown in Fig. 2. Figure 3 shows few arc cells with betatron functions and orbits.

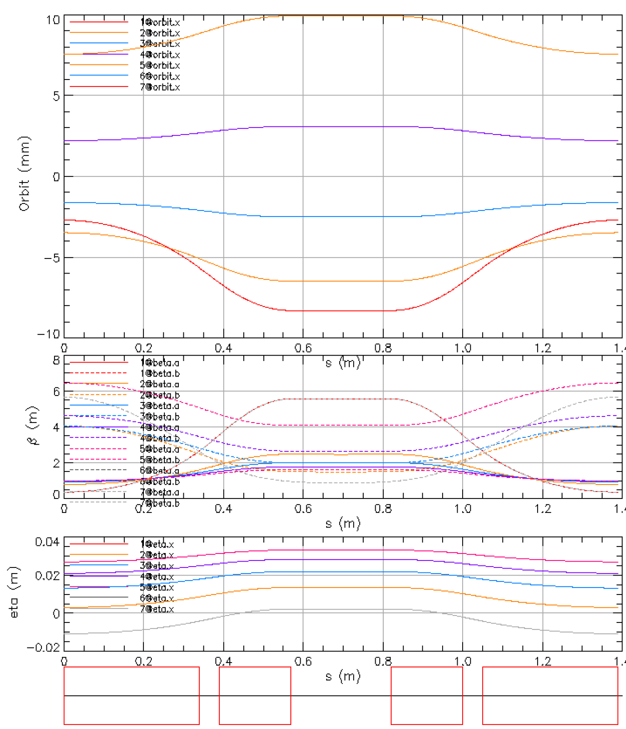

Figure 2: Lattice functions and orbits in the linear FFA arc cell.

STRAIGHT SECTION

The linear FFA racetrack design has two straight sections on opposites sides connected to the two arcs with the adi-

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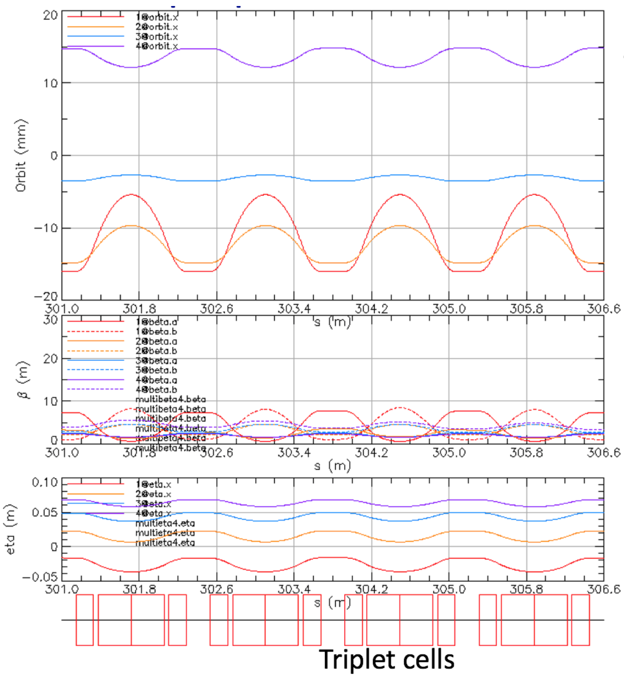

Figure 3: Lattice functions and orbits in few basic linear FFA arc cells.

abatic transitions. A problem of the RF straight section is solved in two steps: First, the straight section is designed with 42 cells made of the triplet quadrupoles and drifts without RF cavities matched to the FFA gradient arcs with adiabatic transitions. The second step was done by retuning the 42 triplets with the 1.7 m superconducting 5 cell cavities placed with 3.2-meter long cells, making the total length of each straight section equal to 134.2 m. The accelerator physics code `Bmad` has two ways to present the acceleration through the linac: `lcavity` and `rfcavity` where the `lcavity` represents the accelerating cavity without constant reference energy, while the `rfcavity` is the storage ring cavity with constant reference energy without acceleration. The transverse trajectory in `Bmad` through an `lcavity` is modeled using equations developed by Rosenzweig and Serafini [13] modified to give the correct phase-space area at non ultra-relativistic energies. First step in the the ERL design is to create the straight section with long enough drifts between the triplet quadrupoles to allow placement of the superconducting RF 5 cell modules. The lattice functions of the straight section cell are shown in Fig. 4. The adiabatic transition from the arc FFA cell to the straight section is shown in details in the next section. The second step in the straight section design is to introduce the 1.7 m long cavity modules of in the available 2.1 m long drift space. The 42 triplet quadrupoles are the variables with constraints related to the 6 different energies: the first energy is the lowest energy from the injector getting into the straight section. All other betatron function of initial and end values of the linac are already obtained in the results from the step one described above. The triplet quadrupole matching for the

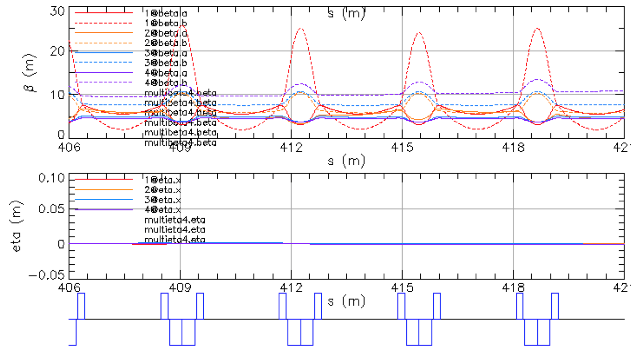

Figure 4: Lattice functions and orbits in the straight section cells.

six energies, or in the `Bmad` program corresponding six "universes," is possible as there are 12 constraints on both sides of the linac of the $\beta_x, \beta_y, \alpha_x$, and α_y with 42x3 variables of the triplet gradients.

ADIABATIC TRANSITION

A transition from the linear FFA arc cells to the straight section requires that electron orbits of all energies merge into a single obit without any orbit offsets. In addition the lattice and dispersion functions are matched on both sides. This is accomplished with adiabatic reduction of dipole field down to zero. The combined function magnet properties remain the same but the bending magnetic field is being adiabatically reduced to zero. A problem of merging all arc orbits into a single straight section orbit with the lattice functions was solved previously in the former electron ion collider eRHIC design. The adiabatic function was a polynomial of the third order. The CBETA project follows S. Berg [14] optimized adiabatic dependence as shown in Eq. (1):

$$f_T(x) = \frac{1}{2} + (x - \frac{1}{2}) = \sum_{k=0} a_k \binom{2k}{k} x^k (1-x)^k. \quad (1)$$

The adiabatic transition in this design is different as the length of the cells is adiabatiacally increased from the 1.3889 m FFA arc value to the 3.2 m. Details of the adiabatic transition are shown in Fig. 5. The superconducting cavity placement in the straight section is shown in Fig. 6.

RACETRACK ERL WITH LINEAR FFA

The complete layout of the ERL racetrack with the betatron functions in shown in Fig. 7.

The orbit merging in the racetrack from the arc cells through the adiabatic transition cells is shown in Fig. 8.

TIME OF FLIGHT CORRECTION

Th most important parameter of the ERL is the electron bunch arrival to the linac as the acceleration is at the top of the sinusoidal RF function. The energy recovery requires a change of the RF phase so the bunches arrive at the bottom of the sinusoidal RF function. This phase flip occurs after

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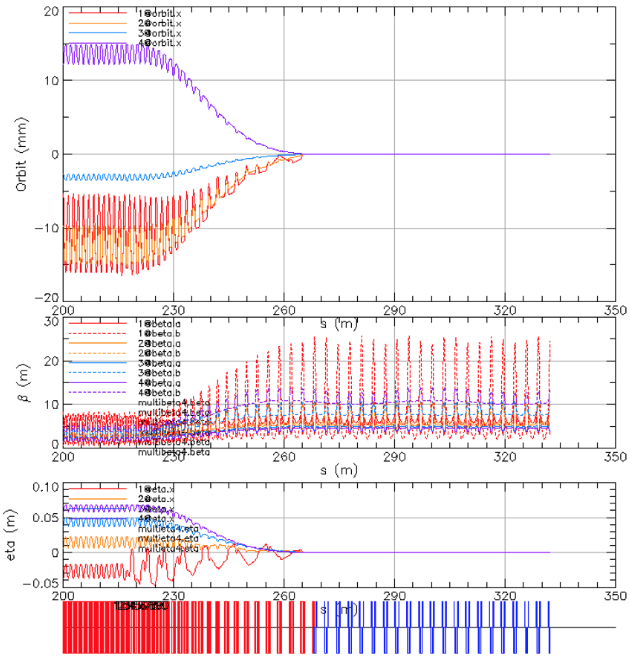

Figure 5: Lattice functions and orbits in the adiabatic transition and straight section cells.

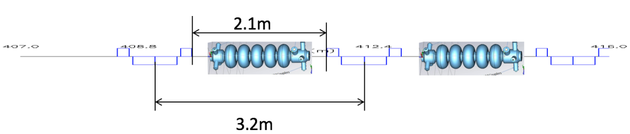

Figure 6: The superconductivity RF modules placement in the straight section.

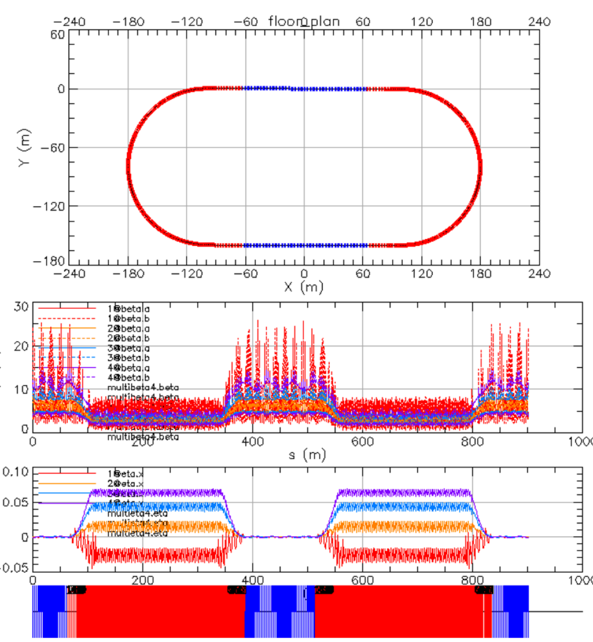

Figure 7: Lattice functions and orbits in the basic straight section cell.

the collisions. The electrons are extracted form the adiabatic transition part brought to the collisions with a separate beam

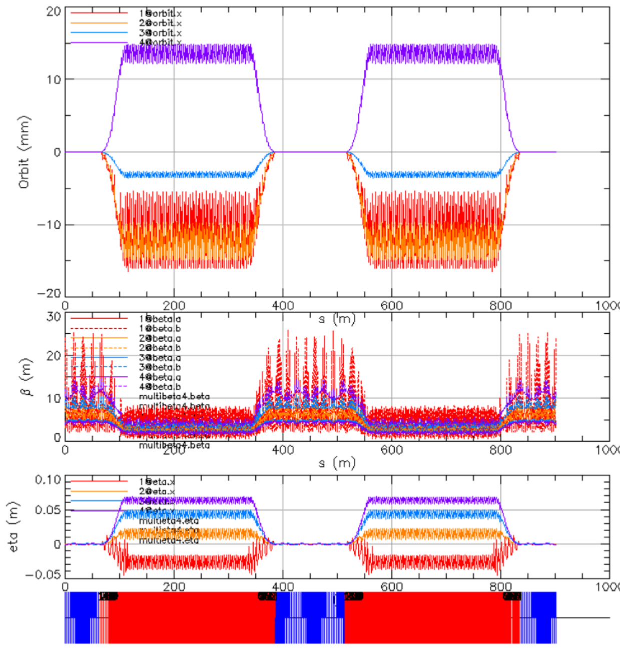

Figure 8: Orbits and dispersion merging from the arc cells to the straight section for different energies in the racetrack.

line to ions and brought back by the separate beam line with an 0.5 phase difference at the highest energy. The FFA gradient arcs have a parabolic function with respect to the time of flight. The lowest energy has the same value of the time of flight as the highest energy while the medium energies correspond to the minimum of the parabolic function. The orbits in the FFA arc cells oscillate around the middle "central" energy as shown in Fig. 3. The main idea of the time of flight correction is that the central orbit can become longer if additional oscillations are introduced to the mostly circular orbit. This was first tested by using two correction dipoles with opposite kicks. This produced the same time of flight after the first attempt. More sophisticated method of time of flight correction was developed by Stephen Brooks and soon will be shown in different publication. The main idea is to use dependence of FFA arc cell of the tunes with respect to energy and choose correctors at positions where the betatron phases are equal to zero and make additional oscillation to the orbits. Results of the path length corrections are shown in Fig. 9.

CONCLUSION

We have shown an example of ERL with the multi-turn single beam line returning the beam to the linac. The arc FFA gradient cells are made of triplet combined function magnets with a 1.3889 m long cells. The arc FFA gradient cells are matched to the straight sections with adiabatic transition cells where the length of the cells is increasing gradually up to 3.2 m, according to the to the function shown in Eq. (1). The matching was done in two steps: the first step is to match the straight section cells made of triplet magnets separated by the drifts. The second step in matching is to introduce in

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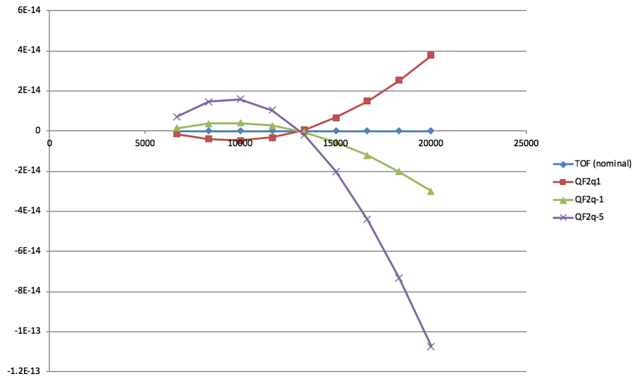

Figure 9: Stephen Brooks method of time of flight correction.

one of the straight sections 1.7 m long superconducting RF modules and then redo the matching of the betatron functions. The beginning and end of the straight section corresponds to the two values of energy where after each pass energy steps are equal to 1.25 GeV. The previously found initial conditions correspond to specific energy. There are many advantages of this proposal especially for the future Electron Ion Colliders: the previous splitter and combiner beam lines used to match the linac without any quadrupoles where necessary to to the time of flight correction and betatron function matching. They are eliminated by introduction of the triplet magnets between the RF superconducting modules.

REFERENCES

[1] LHeC Study Group, J. L. Abelleira Fernandez *et al.* "A Large Hadron Electron Collider at CERN", *Journal of Physics G: Nuclear and Particle Physics*, vol. 39, no. 7, July 2012, pp. 075001. doi:10.1088/0954-3899/39/7/075001

[2] FCC eh: http://lhec.web.cern.ch

[3] eRHIC Design Study, "An Electron Ion Collider at BNL", arXiv:1409.1633, 2014.

[4] ELIC: https://casa.jlab.org/overview.shtml

[5] EIC@HIAF, http://snst-hu.lzu.edu.cn/wiki/index.php/Eic

[6] S. Machida *et al.*, "Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA", *Nature Physics*, Jan 2012. doi:10.1038/nphys2179

[7] R. C. Johnson (ed.), "Small Accelerator, Big Promise", https://www.eetimes.com/document.asp?doc_id=1332173

[8] CBETA, https://www.classe.cornell.edu/CBETA_PM/

[9] Stephen Brooks, "CBETA Magnet Production", presented at FFA'18 in Kyoto, Japan, Sep 2018. https://indico.rcnp.osaka-u.ac.jp/event/1143/contributions/1213/

[10] D. Trbojevic, E. D. Courant, and A. Garren, HEMC'99 Workshop, Montauk, New York, October 1999.

[11] D. Trbojevic, E. D. Courant, and M. Blaskiewicz, *Phys. Rev. Spec. Topics Accelerators and Beams*, vol. 8, pp. 050101, 2005.

[12] D. Sagan, *Bmad manual*, https://www.classe.cornell.edu/bmad/manual.html

[13] J. Rosenzweig and L. Serafini, "Transverse particle motion in radio-frequency linear accelerators", *Phys Rev* E, vol. 49, p. 1599, 1994. doi:10.1103/PhysRevE.49.1599

[14] J. S. Berg, https://indico.bnl.gov/event/2764/contributions/7146/attachments/6425/7812/JSBerg-170909.pdf