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R. Gamage
Old Dominion University

T. Satogata
Old Dominion University

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BUNCH SPLITTING SIMULATIONS FOR THE JLEIC ION COLLIDER RING *

R. Gamage[†1] and T. Satogata[1,2]
[1] Center for Accelerator Science, Old Dominion University, Norfolk VA, USA
[2] Thomas Jefferson National Accelerator Facility, Newport News VA, USA

Abstract

We describe the bunch splitting strategies for the proposed JLEIC ion collider ring at Jefferson Lab. This complex requires an unprecedented 9:6832 bunch splitting, performed in several stages. We outline the problem and current results, optimized with ESME including general parameterization of 1:2 bunch splitting for JLEIC parameters.

INTRODUCTION

The proposed JLEIC (Jefferson Lab Electron-Ion Collider, formerly MEIC) is designed to meet science program program outlined in the EIC white paper [1] and the priorities set forth in the 2015 DOE long range plan for nuclear science [2]. A recent iteration of this facility's technical design is detailed in [3, 4].

The JLEIC design achieves high luminosities in its design CM energy range of 15-65 GeV with large collision frequency, short bunches, and modest bunch charges. Though this strategy has been successful at B-factories, the JLEIC design requires substantially shorter hadron bunch lengths σ_z in higher RF frequency f_{RF} than any previous collider. These differences are itemized in Table 1; RHIC parameters are for rebucketed Au ions at 100 GeV/u.

Table 1: Hadron Collider Longitudinal Parameters

Parameter	JLEIC	RHIC	HERA-p	LHC
f_{RF} [MHz]	953	196	208	400
σ_z [cm]	1	25	25	7.6
λ_{RF} [cm]	31	153	144	75
V_{RF} [MV]	19	6	2.4	12
Circumf [km]	2.15	3.83	6.34	26.6
h	6832	3833	4400	35640
E [GeV]	100	100/u	920	7000

Table 10.1 of [4] indicates a need for a gymnastic that converts hadron bunches in an h=9, 1.25 MHz injection and ramping RF system to bunches in an h=6832, 952.6 MHz storage RF system. A debunch/rebunch scheme would require unrealistically low longitudinal impedances to avoid coasting beam instabilities, and would create uniform polarization of all bunches. Controlled bunch expansion [5] may mitigate some instabilities but does not provide even intensity distribution of final bunches.

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† Author email: bgama002@odu.edu

Here we explore the parameter space of 1:2 bunch splitting [6] for JLEIC, and evaluate multiple 1:2 bunch splits using ESME [7] to evaluate initial RF voltage and longitudinal emittance requirements for such a scheme. These are preliminary investigations, but they provide a prototype for further studies.

SINGLE SPLIT OPTIMIZATION

Several factors must be optimized when designing a bunch splitting strategy, and tradeoffs must be made. This section uses JLEIC parameters to discuss and evaluate a hypothetical first 1:2 split from $h = 9$ to $h = 18$, which can then be scaled for higher splits.

The splitting time T_{split} must be long enough (typically many synchrotron periods T_s) to make the process effectively adiabatic and preserve longitudinal emittance within desired tolerances. The split time, however, should not be longer than necessary. For $h = 9$ and RF voltage $V_{rf,h=9} = 100$ kV in [4], $T_s \equiv T_{s,h=9}$ =10500 turns or 76 ms.

The splitting RF voltage is given by assuming bucket areas scale as the split. This gives $V_{rf,h=18} = 2V_{rf,h=9}$, preserves bucket height, and gives $T_{s,h=9} = 2T_{s,h=18}$.

With these parameters, we performed ESME simulations of 1:2 splits with split times T_{split}/T_s ranging from 10 to 200, and the initial bunch emittances ranging from 2.5% to 50% of the RF bucket. This gives information to optimize split time for a given initial longitudinal emittance and emittance growth tolerance. Results are shown in Figs. 1 and 2. Note the different emittance growth factor scales, where 1.0 indicates a perfect split with no net emittance growth.

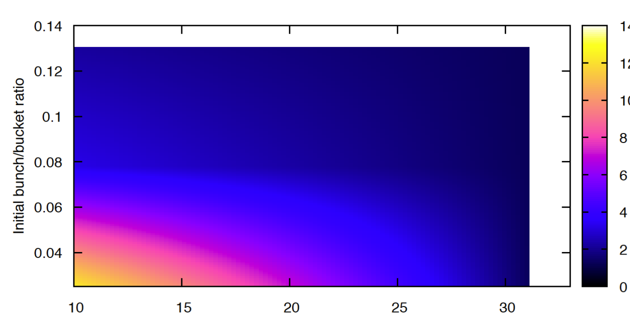

Figure 1: JLEIC 1:2 split emittance growth, $T_{split}/T_s < 30$.

Figure 1 shows that split times of $10 - 30$ T_s create considerable longitudinal emittance growth unless the initial bunch is over 10% of the bucket area. Naive expectations might consider this split time to be "adiabatic enough", but even split times of 30 T_s cause more than 20% emittance

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growth per split. This is not a product of the lower harmonic choice $h = 9$ for T_s, as $30\ T_{s,h=9} = 60\ T_{s,h=18}$ here.

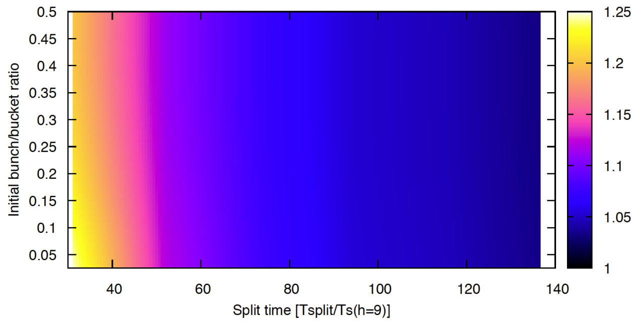

Figure 2: JLEIC 1:2 split emittance growth, $T_{split}/T_s > 30$.

Figure 2 shows that split times of 100 T_s or more are needed to constrain emittance growth to below 5% per split. This result appears robust against a wide variety of initial bunch emittances, and will be used to preserve emittance growth for simulations of multiple bunch splits. It has significant implications for simulation time with realistic distributions. A genetic algorithm optimization [8] will also be performed to determine the Pareto optimal front for various RF voltage ratios and alternative split parameterizations.

MULTIPLE 1:2 SPLITTING SIMULATIONS

We used the philosophy and results of the previous section to study multiple bunch splits needed by JLEIC. Table 10.1 of [4] shows that bunches go from $h = 9$ to $h = 6832$, so we need about 9-10 1:2 splits. The numerology is closer if one of the splits is 1:3, as this gives a final number of bunches of $2^8 \times 3 \times 9 = 6912$. We ignore this detail here and concentrate on simulating the end-to-end process of eight 1:2 splits.

RF voltage doubles with every split to maintain a constant bunch/bucket area ratio, bucket height, and bunch momentum spread. Figure 3 shows the RF voltages used for this simulation, on a logarithmic scale to make the voltage doubling scheme clear. Voltage ramps are presently piecewise linear as in traditional 1:2 split schemes [6]. Additional RF manipulations may be used to lower higher harmonic voltages, but at the expense of tradeoffs between bunch/bucket ratio and momentum spread.

The maximum RF voltage in Fig. 3 is consistent with [4], but at the expense of requiring a small (10 kV) initial h=9 RF voltage in this voltage doubling scheme. This is small for conventional RF control but may be achieved with suitable counterphasing of multiple cavities.

The initial bunch/bucket area ratio 0.1, suitably large for modest emittance growth with reasonable split times for initial simulations but small enough to respect the (unusually small) required bunch ratio of $\sigma_z/\lambda_{RF} = 1/31$ in Table 1.

With an initial distribution of 20,000 particles, the final buckets end up with approximately 39 particles each, assuming each split evenly divides the bunch in half. For the initial split, the voltage ramp time was adjusted to get an adiabatic split, which was used in the following splits since the

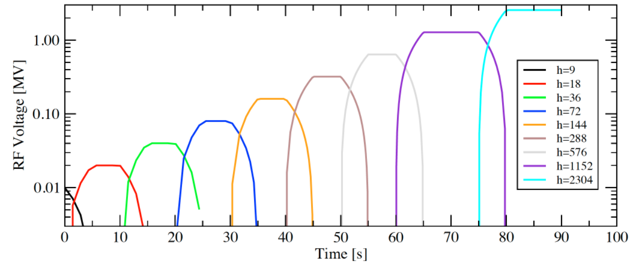

Figure 3: RF voltages used for initial JLEIC multiple 1:2 splitting simulations, showing voltage doubling with each successive harmonic.

synchrotron oscillation period goes down with increasing voltage. ESME does not have parallel computational capabilities so adding particles and track time for the ring causes the simulation times to go up considerably. It is important to verify that the bunches are evenly divided and have a bi Gaussian distribution after splitting before moving to the proceeding split so that following each split all the bunches have almost the same number of macro particles.

The large variation of synchrotron periods during multiple splitting simulations initially caused some problems when we used ESME's adaptive time step integrator, as the scaling was set by the initial long h=9 synchrotron period. Full simulations are therefore done with non-adaptive integration steps. This improves the fidelity of the simulation at the expense of compute time. However, on a 2.7 GHz Intel Core i7 Mac, simulations with 20k macroparticles take about a factor of 50 times longer than the wall clock tracking time, or about 1.5h for 80 seconds of tracking.

SIMULATION RESULTS

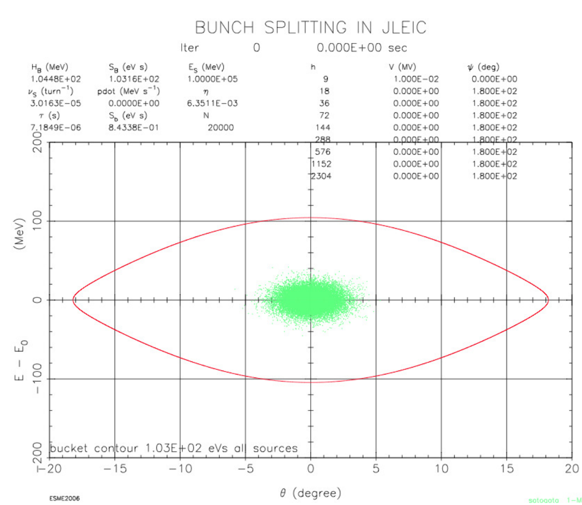

Figure 4: Initial bunch distribution with h=9 and 20k particles.

Figure 4 shows the initial parabolic bunch distribution for h=9 in this simulation, with an RMS bunch height of about 3×10^{-4} and bunch/bucket area ratio of 0.1.

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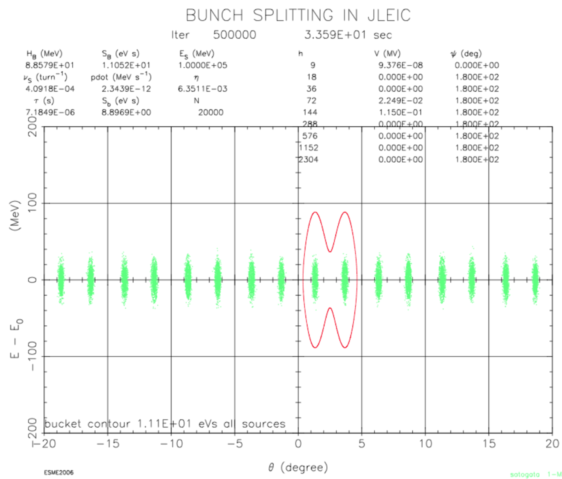

Figure 5: Bunch distribution during fourth bunch splitting from h=72 to h=144.

Figure 5 shows particle distributions in the middle of the splitting process, from $h = 72$ to $h = 144$. Bucket and bunch heights are consistent with initial distributions, and bunch/bucket area ratios are still approximately 0.1.

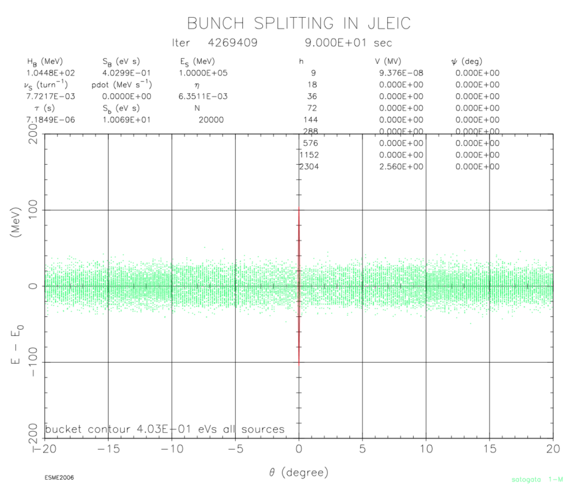

Figure 6: Bunch distribution after final bunch splitting from from h=1152 to h=2304.

Figure 6 shows the final distribution after splitting to $h = 2304$, showing a quasi-coasting, high frequency structure. Bunch intensity distributions and emittances are nearly equal, and show little sign of emittance dilution in eight 1:2 splits.

FUTURE STUDIES

The JLEIC hadron bunch formation strategy is still being developed, including alternate considerations of higher harmonic numbers and different splitting strategies. Some splitting may occur in the ion Booster ring [9]; impedances and space charge effects will be included as necessary.

A 2^n bunch splitting scheme seems prohibitively costly with regards to RF requirements, but low harmonic voltage requirements appear to be modest. Work is ongoing at Jefferson Lab to develop harmonic QWR cavities for a harmonic kicker [10] for the JLEIC electron cooler. That work drives a single resonating cavity at odd harmonics. With some R&D this concept may be extended to even harmonics suitable for bunch splitting [9].

This scheme requires fine control of RF parameters over a broad range of RF parameters, particularly drive voltages and frequencies. RF control loop constraints will be considered to include requirements on control of non-merge harmonics through the entire splitting process. Requirements on the flatness of the final bunch intensity distribution will drive both RF control and impedance constraints, as even small drive of nearby harmonics may create substantial bunch intensity variation.

CONCLUSIONS

We have identified the requirements for bunch splitting for short hadron bunch formation for the JLEIC ion collider ring at Jefferson Lab. Initial studies led to a parameterization of longitudinal emittance growth versus initial bunch size and split time for 1:2 RF splits, which show that split times should be over 100 times the lower harmonic synchrotron period to limit longitudinal emittance growth below 5% per split. 2^8 successive splits were simulated for realistic JLEIC design parameters using ESME, showing reasonable simulation time and bunch parameter behavior. This infrastructure will be used to further study the bunch formation problem in the JLEIC booster and ion collider ring, including realistic impedances and other longitudinal bunch manipulations.

ACKNOWLEDGMENTS

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