

Modeling HIF relevant longitudinal dynamics in UMER



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ABSTRACT

The foremost challenge for Heavy-Ion Fusion (HIF) is achieving sufficiently low emittances and small energy spreads in the presence of intense space-charge, to achieve the high deposition densities necessary for pellet ignition. The University of Maryland Electron Ring (UMER) uses intense low-energy electron beams to access the scaled physics of HIF drivers. In particular, the long path-length propagation in UMER presents an opportunity to study, at realistic scales, the longitudinal beam dynamics and manipulations required for such a driver. With the use of induction modules, as in the ion machines such as NDCX-II, the resulting bunch dynamics show evidence of space-charge waves excited by an initial mismatch between the detailed initial beam distribution at the bunch ends and the applied focusing waveforms, persisting with multiple damped reflections propagating along the bunch flat-top. Using the induction module we are able to suppress space-charge waves with great accuracy, at amplitudes that include wave steepening prior to the formation of solitary wave trains. The longitudinal dynamics largely dominates when no containment fields are applied, coupling through the natural chromaticity of the ring even within the first turn. After subsequent turns, the bunch elongates and wraps the circumference of the machine multiple times; eventually reaching a point of instability that has also been shown through simulation, obtaining excellent agreement when the detailed longitudinal dynamics of the experiment are carefully incorporated into the model.

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1. Introduction

The ion beams considered for the heavy-ion fusion approach to Inertial Fusion Energy (IFE) require longitudinal beam shaping that includes a combination of confinement, compression and acceleration of the bunch using highly non-linear tailored waveforms [1].

Applying the necessary waveforms (E_z vs. t) needed to counteract the longitudinal space-charge forces and shape these intense beams requires a detailed understanding of the longitudinal distribution throughout the beams lifetime during the focusing schedule.

Induction accelerators, in particular, linacs have been able to attain these high intensities by employing wideband induction modules to manipulate the longitudinal velocity distribution along the beam [3–7]. The Neutralized Drift Compression Experiment (NDCX-II) at Lawrence Berkeley National Laboratory will use induction modules to longitudinally confine, compress and accelerate an intense ion beam in order to obtain a sub nanosecond pulse for warm dense matter (WDM) and inertial fusion energy studies, using a longitudinal focusing schedule derived from careful simulation prescriptions [3].

A machine like NDCX-II represents a major step in progress toward higher energy machines, but construction of a driver-scale experiment will require a greatly expanded program. In the interim, a promising approach to the cost-effective exploration in this area of beam physics has been demonstrated in the University of Maryland Electron Ring (UMER); which makes extensive use of a scaled ring topology to access the physics of intense beams over long path-lengths. UMER has demonstrated the ability to access kilometer-scale propagation distances ($> 3 \times 10^4$ alternating gradient periods) whereas existing linear machines have generally been limited to hundreds of meters in length [8].

The typical UMER beam has an average energy of 10 keV, $1 \mu\text{m}$ transverse emittance, and a variable current in the range of 0.55–100 mA [9]. We inject a long (100 ns) approximately rectangular flat-top beam that fills approximately half the ring and employ induction modules to focus the beam ends to keep the overall beam confined.

In this paper, we briefly review recent studies investigated at UMER, as well as some of the previously published work.

2. Longitudinal dynamics within the 1st turn

The longitudinal dynamics of a space-charge-dominated beam that is long compared to the pipe diameter can be adequately

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characterized using the one-dimensional cold fluid theory [10]. This approximation is valid because the beam is generally found to have a very low longitudinal thermal velocity as a result of accelerative cooling from the source [2]. The beam is injected with constant line-charge density and constant velocity, such that the self-fields push particles in the beam-ends away from the central region at a rate of $2c_s$ in the beam frame; where c_s is the longitudinal space-charge wave speed, $c_s = \sqrt{qg\lambda_0/4\pi\epsilon_0\gamma_0^5m}$, q is the electron charge, m is the electron mass, γ_0 is the Lorentz factor, ϵ_0 is the permittivity of free space and the variable g is the geometry factor accounting for the pipe shielding of the longitudinal self-fields [10–13].

A particle at the leading edge of the beam (either at the head or tail), undergoes an energy gain or loss of $\Delta E = 2mc_s(v_0 + c_s)$ where the line-charge density goes to zero at the edges of the beam [14]. The velocity, v_0 , is the injected beam velocity defined in the mid region of the bunch. In a circular machine, these variations in energy or momentum causes a displacement in both the equilibrium orbit through the dispersion function and a shift in the betatron frequency (or tune) through the natural chromaticity [15–19]. The natural chromaticity, η , to first order is an average of all chromatic aberrations in the lattice from dipole and quadrupole elements [15]. Using the natural chromaticity we approximate the tune shift, $\Delta\nu$, at the leading edges of the head and tail from the resulting energy shifts. The analytical longitudinal space charge wave speed is 1.28×10^6 m/s for the 21 mA beam and thus the calculated tune shift at the edges would be ± 0.347 using

$$\Delta\nu = \eta \frac{\Delta p}{p_0} \approx \pm \eta \frac{2c_s}{v_0} \quad (1)$$

where Δp is the change in momentum at the head or tail of the beam and p_0 is the injected momentum. The equation also assumes the beam is non-relativistic. Using an experimental technique presented in Ref. [20,21] we have measured the tune-shifts induced at the edges of the beam from the longitudinal expansion of the bunch within the first turn when no confinement fields are applied.

Fig. 1 illustrates the measurements of tune-shift at four different beam position monitors (BPMs) located around the ring. Note that betatron frequency decrease at the head of the bunch from the increasing particle energy and the betatron frequency increase at the tail of the bunch from the decreasing particle energy.

Comparisons between measurements and calculations, presented earlier using the chromaticity formulation, are consistent

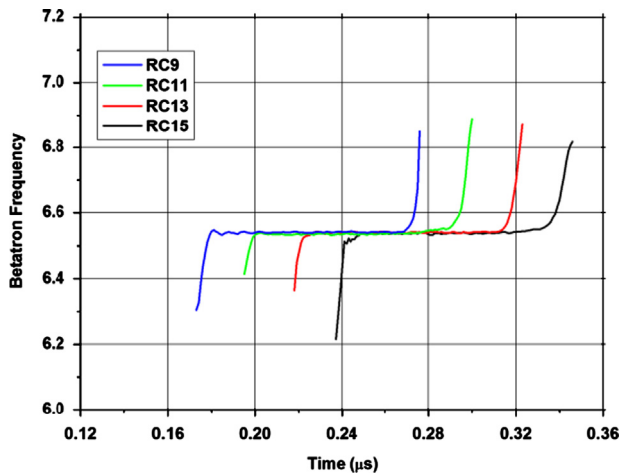


Fig. 1. Horizontal betatron frequency as a function of beam length, measured using beam position monitors located at RC9, RC11, RC13 and RC15 [20]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

and show good agreement for both the beam head and tail [21]. The beam head has a minimum measurable frequency of 6.216 ± 0.1 and the tail has a maximum measurable frequency of 6.888 ± 0.1 . The beam tail is 0.3% from the calculated value and the beam head is 6.6% from the calculated value.

3. Longitudinal dynamics over multiple turns

Without external fields to counteract the longitudinal space-charge forces, the bunch will continue to elongate, overlapping itself and wrapping several times around the ring [22,23]. At certain operating conditions, we noticed an instability develop that has been shown to be dependent on both the line-charge density and overall length of the bunch [24]. Fig. 2 illustrates the measured current profile using the wall current monitor at RC10. Note the onset of the instability at $16.5 \mu\text{s}$ for the 6 mA bunch injected at a length of 100 ns.

4. Longitudinal confinement of a rectangular bunch

With the use of suitable applied fields, the bunch propagates for hundreds of turns while maintaining an approximate rectangular profile. In this form of confinement, the beam is longitudinally captured using periodically pulsed “ear” fields applied to the edges of the beam, at a burst frequency of 1.013 MHz. Fig. 3, a “mountain range” plot, illustrates the measured current profile, over the first 200 turns.

As a byproduct of the confinement, space-charge waves are induced at the edges of the bunch from the resulting mismatch between the applied fields and self-field of the beam. These waves have been shown to sustain multiple reflections at the confined beam edges, eventually dampening in amplitude over the containment lifetime [8]. The reflections occur at the edges of the beam due to the boundary conditions imposed by the confined edges. This situation is similar to a pulse propagating down a shorted transmission line, where the polarity of the pulse voltage flips polarity but the polarity of the current pulse remains the same.

5. Suppression of space-charge waves

To attenuate space-charge waves, we use a technique developed at UMD that suppresses the modulations simultaneously in both density and velocity space. The experiment presented accomplishes

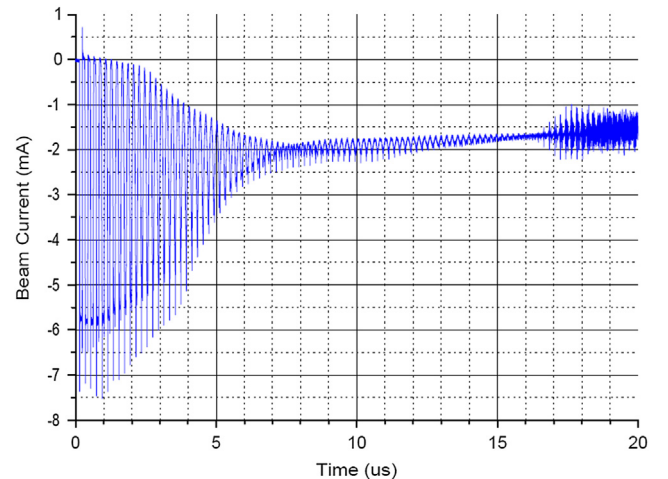


Fig. 2. Measured current profile using the RC10 wall current monitor, for the 6 mA 100 ns bunch. Note the onset of the instability at $16.5 \mu\text{s}$.

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