

RELATIVISTIC KLYSTRON TWO-BEAM ACCELERATOR SIMULATION CODE DEVELOPMENT

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Abstract

We present recent work on the development and testing of a 3-D simulation code for relativistic klystron two-beam accelerators (RK-TBAs). This code builds on our previous experience with 1-D and 2 1/2-D relativistic klystron simulators. We adopt a new approach utilizing symplectic integration techniques to push particles, coupled to a circuit equation framework that advances fields in the cavities. Space charge and current effects are calculated using an electrostatic PIC algorithm.

1 INTRODUCTION

Current development of relativistic klystrons for two-beam accelerator applications [1] demand a high degree of simulation detail. These devices are long (extraction sections of tens to hundreds of meters), employ both solenoid and quadrupole focusing elements, and may use detuned RF output structures for longitudinal stability. In the LLNL/LBNL RK-TBA design, the beam receives periodic re-acceleration from induction cells, followed by energy extraction in the output RF structures. The beam phase space cycles rapidly through a sequence of different states, and there exist numerous instabilities that ultimately limit the device's RF power extraction efficiency. The breaking of azimuthal symmetry in the transport lines and RF cavities, and the high degree of longitudinal bunching, necessitate a fully 3-D simulation capability. For a short device, a 3-D electromagnetic particle-in-cell (PIC) code would be an appropriate simulation tool. However, these new devices are quite long, so that full PIC studies become exceedingly expensive and impractical for beamline design.

We are building a simulation code that incorporates well established symplectic tracking techniques for single particle motion [2] and an electrostatic beam frame PIC algorithm, with a circuit equation solver for the cavity modes.

In section 2 of this paper, we describe the general framework and formalism used by the code. In section 3, we present results from the simulation of transport through a beamline comprised of magnetic quadrupoles, induction accelerating cells, and an RF output cavity.

2 CODE FORMALISM

The code uses a Hamiltonian framework to advance the positions and canonical momenta of the particles. The equations of motion for particles following a given design orbit (or fiducial) are solved exactly. All other particles are advanced by tracking their deviations in phase

space about the fiducial. Deviations in transverse position and canonical momenta, arrival time, and energy all are tracked to 3rd order. Likewise, external fields are included as scalar and vector potentials, represented as 4th order Taylor series expansions about their values along the fiducial. Fringe fields and overlapping beamline elements are included automatically. Effects arising from self-fields are calculated by an electrostatic PIC solver in the beam's rest frame.

2.1 Particle Tracking

The total Hamiltonian is represented in the form

$$H_{\text{tot}} = H_{\text{kin}} + H_{\text{ex}} + H_{\text{self}}$$

where H_{kin} is the kinetic portion describing single particle motion in the absence of all fields, H_{ex} is the contribution to single particle motion from external electromagnetic fields, and H_{self} is the contribution from self-fields. The transfer maps due to the kinetic and external field sectors are calculated together, resulting in a total map for single particle motion. The map due to self-fields is then calculated separately.

These two separate mappings are applied to the particle phase space coordinates by using split operator techniques¹. The prescription to advance the particles, which is accurate through 2nd order over the step size (t), is to apply the two mappings in an interleaved manner, viz.

$$M_{\text{total}}(t) = M_{\text{single}}(t/2) M_{\text{self}}(t) M_{\text{single}}(t/2).$$

Here M_{single} is the resultant single particle map, while M_{self} is the map from the self-field impulse. In terms of computational expense, calculating the map due to self-fields is by far the most costly step in this procedure. To increase the efficiency in the computation, we use as large a step size as possible, while maintaining sufficient accuracy (as determined, for example, by verifying that the

¹Split operator techniques are based on splitting the Hamiltonian into pieces that can be solved exactly (or through some desired order of accuracy), and then combining the separate maps to produce an approximate map for the full Hamiltonian. Split operator symplectic integration algorithms (including the well known leap-frog algorithm of plasma physics simulations) are widely used in the treatment of Hamiltonian systems [3 4 5].

results do not change significantly when the step size is further decreased.)

The self-fields are determined by numerically solving Poisson's equation on a 3-D Cartesian grid in the beam's rest frame. Standard fast Fourier transform techniques are used [6, 7]. For an accurate representation of the 3-D fields from a bunched beam, we must use grid sizes of up to $64 \times 64 \times 512$ nodes, as well as $10^5 - 10^6$ macroparticles. Even with this many particles, noise effects in the fields remain an issue.

2.2 Circuit Equation for RF Cavities

The RF structures are modeled by a decomposition of fields into the vacuum modes. Associated with each mode is a characteristic circuit equation describing the evolution of amplitude and phase. The beam-cavity interaction is modeled by specifying a small set of parameters: the mode frequency (ω_0), the loaded Q (Q_L) of the mode, the $[r/Q]$ of the mode, the driving frequency of the beam (ω), and the overlap of the beam current density with the mode (i_b). The cavity voltage (V_c) then evolves according to

$$\dot{V}_c + \frac{\omega_0}{Q_L} \dot{V}_c + \omega_0^2 V_c = \omega_0 \left[\frac{r}{Q} \right] i_b$$

where the overdots indicate time derivatives. We assume that both the current and the cavity voltage oscillate at the same frequency (ω), and that amplitude variations in both occur on a much longer time scale than $1/\omega$. Then, solving for steady state voltage levels, we find that

$$V_c = i_b Q_L \left[\frac{r}{Q} \right] \cos\psi \cos(\psi + \omega t)$$

where ψ is the tuning angle, defined by $\psi = Q_L \left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0} \right)$.

This formalism is used to study the beam dynamics in both the RF output and the induction cell cavities. Besides the fundamental mode in the in the RF output structures, attention is paid to longitudinal modes in the induction cells, as well as transverse beam-breakup (BBU) modes in both cavities. The BBU modes have been identified as the cause of transverse instabilities which eventually limit the net efficiency of the RK-TBA. The longitudinal mode in the induction cell cavity has been studied [8] as a source of beam energy loss as it can couple to the fundamental harmonic of the RF beam current.

3 SIMULATION RESULTS

We present results of simulation through a section of a hypothetical RKTBA extraction section. The beamline is comprised of permanent magnet quadrupoles, induction cell acceleration cavities, and standing wave output structures. The parameters are shown in Table 1.

The RF output structure extracts 180 MW from the beam as it passes through, corresponding to a 300 kV drop in the beam voltage. There are five induction reacceleration cells per meter, each providing 60 kV to

the beam. In this way, the beam energy is kept steady, period by period. Here, we attempt to model the steady-state behavior of the beam through the section.

Table 1 Parameters of RKTBA extraction section

Beam Parameters	
Average energy	3.88 MeV
DC current	600 A
RF current, frequency	1200 A, 11.424 GHz
FODO Lattice	
Lattice period	0.20 m
Phase advance / period (s_0)	72°
Occupancy factor	0.5
Induction Cell Parameters	
Cell Voltage	60 kV
RF Structure Parameters	
Frequency	11.424 GHz
Q_L	80
Steady-state output power	180 MW

The choice of a 1 m betatron period corresponds to the spacing between RF output structures. This *betatron node* scheme significantly reduces the transverse instability growth rate associated with the cavities. In Figure 1 we show the evolution of the transverse phase space through a 1 m section of the beamline. The transverse phase space distribution is seen to remain stationary, with only a small number of particles leaving the core to form a halo.

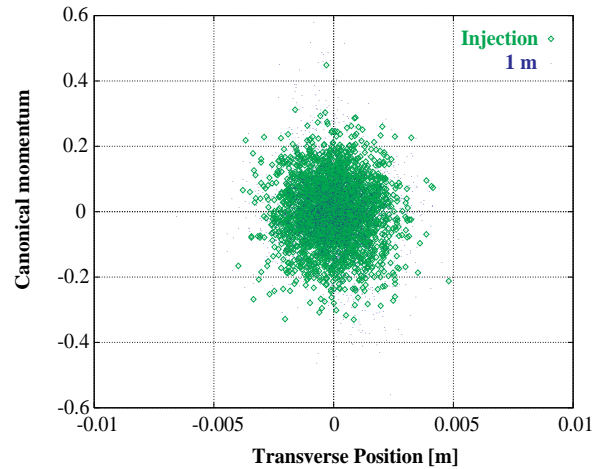


Fig. 1 Transverse phase space evolution

The beam upon injection was strongly bunched at the 11.424 GHz frequency, but was not otherwise matched in its longitudinal phase space. Longitudinal space charge forces act to debunch the beam, while the RF output structure can be phased to provide some focusing. Figure 2 shows the evolution of the longitudinal phase space as the beam passes through 1 m of beamline. The increase in energy spread due to space charge is readily apparent,

with nonlinearities due to the nonuniform (gaussian) distribution.

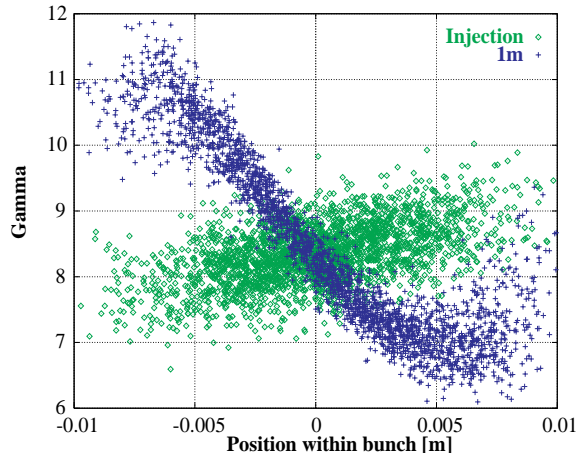


Fig. 2 Longitudinal phase space evolution

4 CONCLUSIONS

We have begun work on a new simulation code for relativistic klystron two-beam accelerators. This code tracks the full six dimensional phase space of the beam, and incorporates fields self-consistently. More work on transient power evolution in the RF cavities is being performed. Benchmarking of the code will concentrate simulations of transport, RF power extraction, and debunching effects in upcoming 35 GHz experiments.

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