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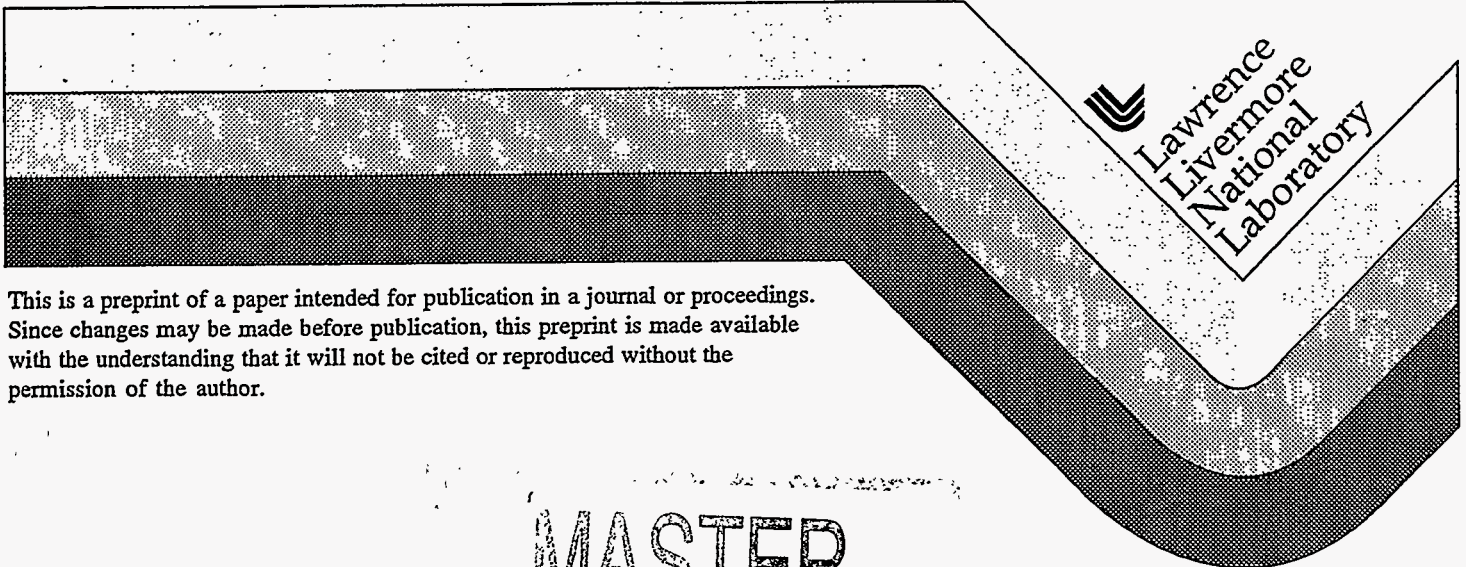
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RELATIVISTIC KLYSTRON TWO-BEAM ACCELERATOR STUDIES AT THE RTA TEST FACILITY*

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Abstract

A prototype rf power source based on the Relativistic Klystron Two-Beam Accelerator (RK-TBA) concept is being constructed at the Lawrence Berkeley National Laboratory to study physics, engineering, and costing issues. The prototype, called the RTA, is described and compared to a full scale design appropriate for driving the Next Linear Collider (NLC). Specific details of the induction core test and pulsed power system are presented. Details of the 1-MeV, 1.2-kA induction gun currently under construction are described.

Introduction

For several years a Lawrence Berkeley National Laboratory (LBNL) and Lawrence Livermore National Laboratory (LLNL) collaboration has studied rf power sources based on the RK-TBA concept [1]. This effort has included both experiments [2] and theoretical studies. A preliminary design study for a rf power source using the RK-TBA concept suitable for an rf power source upgrade of the NLC collider design (TBNLC) has been published [3]. The design specifically addressed issues related to cost, efficiency, and technical issues. For a 1.5-TeV center-of-mass energy design, the rf power source is comprised of 76 subunits, each about 340 m in length with 150 extraction structures generating 360 MW per structure. Estimated conversion efficiency of wall plug energy to rf energy for this source could be greater than 40%. Theory and simulations showed acceptable drive beam stability through the relativistic klystron, and no insurmountable technological issues were uncovered.

We have established the RTA test facility [4] at LBNL to verify the analysis used in the design study. The principle effort is constructing a rf power source prototype where all major components of the TBNLC rf power source will be tested. The different sections of the RTA are described in Table 1. Due to fiscal constraints, the RTA will have only 8 rf extraction structures. Table 2 is a comparison between the pertinent parameters for TBNLC and the RTA. The pulsed power system and induction cells in the extraction section will be similar for both machines, allowing a demonstration of the wall-plug power to drive beam power conversion efficiency and establishing a basis for costing of the components.

Table 1.
RTA Accelerator Sections

Section	Beam Energy[†] (MeV)	Current[†] (kA)	rf current[†] (kA)	Section Length (m)
Electron gun	1	1.2	0	3
Accelerator	2.8	1.2	0	8
Chopper	2.8	0.6	0.5	1
Adiabatic compressor	4	0.6	1.1	4
Extraction section	4	0.6	1.1	8
Diagnostic section	0	-	-	2

† Beam parameters at the end of the section.

Table 2
Comparison between RTA and the TBNLC.

Parameter	RTA	TBNLC
Pulse Duration		
Flat-top	200 ns	200 ns
Rise Time	100 ns	100 ns
Current		
Pre-chopper	1.2 kA	1.2 kA
Extraction Sec.(dc)	600 A	600 A
Extraction Sec.(rf)	1.1 kA	1.1 kA
Beam Energy		
Injector	1 MeV	1 MeV
Chopper	2.8 MeV	2.5 MeV
Extraction	4.0 MeV	10.0 MeV
Bunch Compression	240° to 110°	240° to 70°
Beam transport in the Extraction Section		
Betatron Period	1 m	2 m
Lattice Period	20 cm	33.3 cm
Phase Advance	72°	60°
Occupancy	0.5	0.48
Pole Tip Field	870 G	812 G
Beam Diameter	8 mm	4 mm
RF Power		
Frequency	11.4 GHz	11.4 GHz
Power/Structure	180 MW	360 MW
Structures	SW &TW	3-cell TW
Output Spacing	1 m	2 m

Pulsed Power System

Conversion of wall plug power into induction drive beam power is a significant factor in the rf power source efficiency. The efficiency of a TBA induction accelerator depends on several factors. Beam transport dynamics will determine the size of the beam pipe. The rf power requirement determines the pulse duration, beam current, accelerating gradient, and repetition rate. Once these factors are established, the outer

radius and material of the core can be calculated from: $\Delta V \cdot \Delta t = \Delta B \cdot A \cdot F_p$, where ΔV is cell voltage swing, Δt is pulse duration, ΔB is core flux swing, A is core cross section, and F_p is core material packing factor. The core volume increases nearly as the radius squared, so smaller, more efficient and lower cost induction cells can normally be obtained by using higher ΔB materials and minimizing the inner radius.
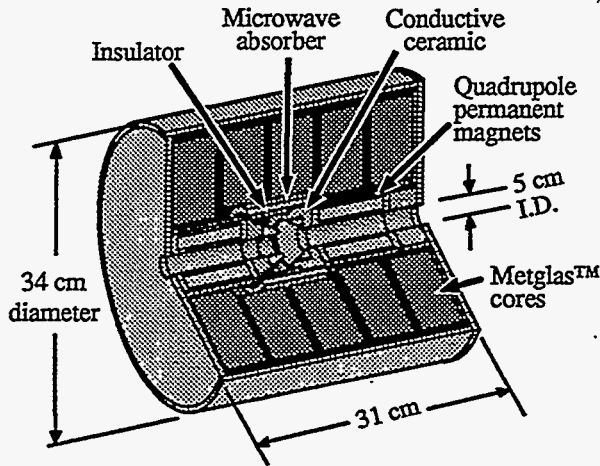

Fig. 2. A proposed RK-TBA induction cell design illustrating longitudinal core segmentation.

Several core materials have been tested at the RTA Test Facility [5]. Two METGLAS® alloys, 2605SC and 2714AS, have been selected for use in the RTA. The alloy 2605SC has a ΔB of ~2.5 T with a core loss of ~ 2 kJ/m^3 for a 400 ns pulse and 20 μm thick ribbon. The alloy 2714AS has a lower ΔB, ~1.1 T, but a much lower core loss of ~ 150 J/m^3 with 18 μm ribbon. The core tests are performed with the expected pulse shape and duration for accurate loss measurements. For our TBNLC geometry, the low core loss 2714AS can achieve a conversion efficiency of wall plug power to drive beam power of 59%, a substantial improvement over 2605SC.
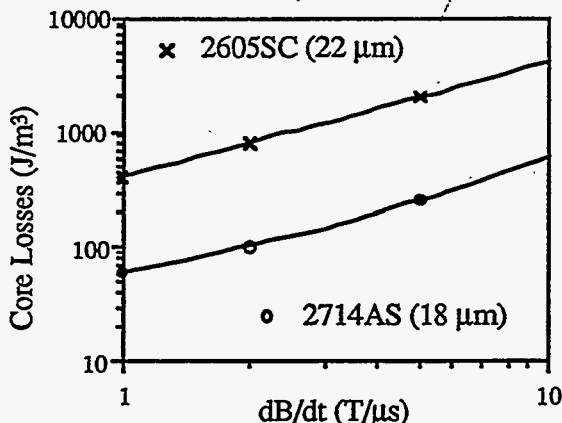

Fig. 3. Core loss for different rates of magnetic flux change.

The modest repetition rate (120 Hz) and current rise time (100 ns) envisioned for the NLC permit the use of a simple, and cost effective thyratron driven modulator. The total

induction cell core is segmented longitudinally into smaller cores each individually driven at 20 kV or less. Driving at this voltage level avoids a separate step-up transformer and allows for switching with fast inexpensive single-gap tubes. Length of the induction cell, thus number of cores per cell, is set by geometrical constraints due to extraction structures, magnet positions, etc. The TBNLC design in Fig. 2 has five cores per cell while the RTA has three cores.

Beam energy flatness is an important issue affecting beam transport and rf phase variation. The current required to drive the cores is nonlinear for a constant amplitude voltage pulse since the inductance of the core decreases as saturatiion of the material is approached. The effect is more pronounced for high aspect ratio ($\Delta r/\Delta z$) cores due to non-uniform saturation starting at the inner radius propagating outward. This effect is shown in Fig. 4 where the voltage pulse has ~200 ns of flat top during which the drive current increases non-linearly. The generated voltage amplitude can be kept constant, within bounds, as the material approaches saturation by tapering the impedance of the PFN stages. Our PFN will consist of many coupled L-C stages.

We have been testing pulsed power prototypes using a 3-core injector cells. In the prototype we have used EEV CX1538 and TRITON F-232 thyratron tubes. The injector cell design calls for 14 kV/core or 40 kV/cell. Early test performed using CX1538 tube did not yeild rise times below 100 ns, however a pretrigger applied to an additional grid on the tube gave performance (see Fig. 4) close to the design (100 ns rise time, 200 ns flat-top). The F-232 tube has lower internal inductance as well as a higher di/dt rating. It also gave performance close to the design criteria.
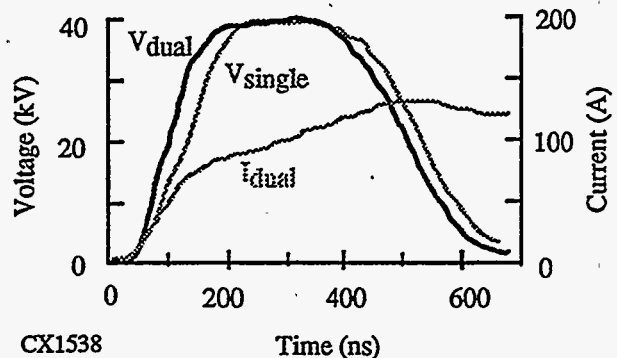

Fig. 4. Injector cell voltage and current driven by a prototype pulsed power unit. The V_{single} trace shows the voltage waveform with a single trigger. The rise time (10% to 90%) was about 150 ns with a voltage flat top of 120 ns. With a pretrigger to an additional grid on the tube we were able to get the rise time to down to 100 ns and obtain a voltage flat top of 180 ns (shown in V_{dual}). The I_{dual} trace shows the PFN current for the dual trigger case.

Injector

The injector consists of two sections, a 1-MV, 1.2-kA induction electron source, referred to as the gun, followed by several induction accelerator cells to boost the energy to 2.8 MeV. Two goals of the design are minimizing electrical field stresses in the gun and realizing the lowest

possible emittance growth. Gun induction cores are segmented radially to reduce the individual aspect ratios with each driven separately at about 14 kV. Components of the induction cells for the gun are in fabrication.
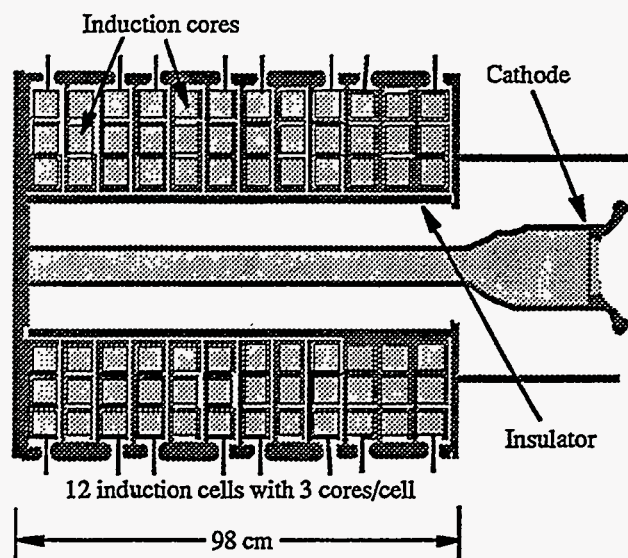

Fig. 4. Schematic of the cathode-half of the RTA electron gun. This section provides 0.5 MV of the guns potential.

A novel feature of the gun design is the insulator, a single, 30 cm ID, PYREX® tube with no intermediate electrodes. Average gradient along the insulator at the operating voltage of 500 kV is ~ 5.1 kV/cm. Maximum fields at the triple points, intersection of insulator, vacuum, and metal, are less than 3.5 kV/cm. Maximum surface fields in the cathode half of the gun are about 85 kV/cm. Our design allows for the addition of intermediate electrodes and/or substitution of a ceramic insulator to offset the increased risk associated with this approach.

The focusing solenoidal field profile must be optimized for the injector to control the beam radius while minimizing emittance growth. A new electrode package and larger dispenser cathode will likely be required for the desired low emittance 1.2-kA, 1-MeV electron beam. The design goal is for beam radius less than 5 mm and horizontal normalized edge emittance less than 250 π-mm-mr at the end of the injector. Alignment of the solenoids is critical to avoid corkscrew motion and emittance growth. Incorporating homogenizer rings [6] with the solenoids could reduce the need for correction coils and simplify alignment.

Experience operating other induction accelerators has shown that careful alignment of the solenoids may not be sufficient to reduce the amplitude of the corkscrew motion [7] to the 0.5 mm desired for the RTA injector. We plan to use a time independent steering algorithm developed at LLNL to control steering coils on the solenoids. The algorithm corrects for the Fourier component at the cyclotron wavelength of the field error.

Beam Dynamics and RF Power Extraction Issues

Beam dynamics issues related to longitudinal and transverse stability, modulation, and transport have been presented in detail elsewhere [3, 8]. A brief description of these issues is given here. Initial beam modulation is accomplished with a transverse chopping technique. After this modulator section, an adiabatic compressor, a system of idler cavities and induction accelerator modules, is used to bunch the beam and further accelerate it to an average energy of 4 MeV. The lower frequency component of the transverse beam breakup instability is controlled by Landau damping. Control of the higher frequency component, excited in the rf cavities, is accomplished with the focusing system in a technique that we refer to as the "Betatron Node" scheme. The rf extraction structures are appropriately detuned to compensate for space charge and energy spread effects so that the longitudinal current distribution is stable.

After the adiabatic compressor, the beam enters the extraction section. where beam energy is periodically converted into rf energy (via extraction cavities) and restored to its initial value (via induction modules). Both traveling wave (TW) and standing wave (SW) structures are being considered for the extraction section of the RTA. The TBNLC design [9] uses TW structures to reduce the surface fields associated with generating 360 MW per structure. RTA is designed to generate 180 MW per structure. Thus, inductively detuned SW cavities are a practical alternative.

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