Title

Relativistic-Klystron Two-Beam Accelerator as a Power Source for a 1 Tev Next Linear Collider - A Systems Study

Author

Yu, S.

Publication Date

2008-09-18

LBL-36232
UC-414

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

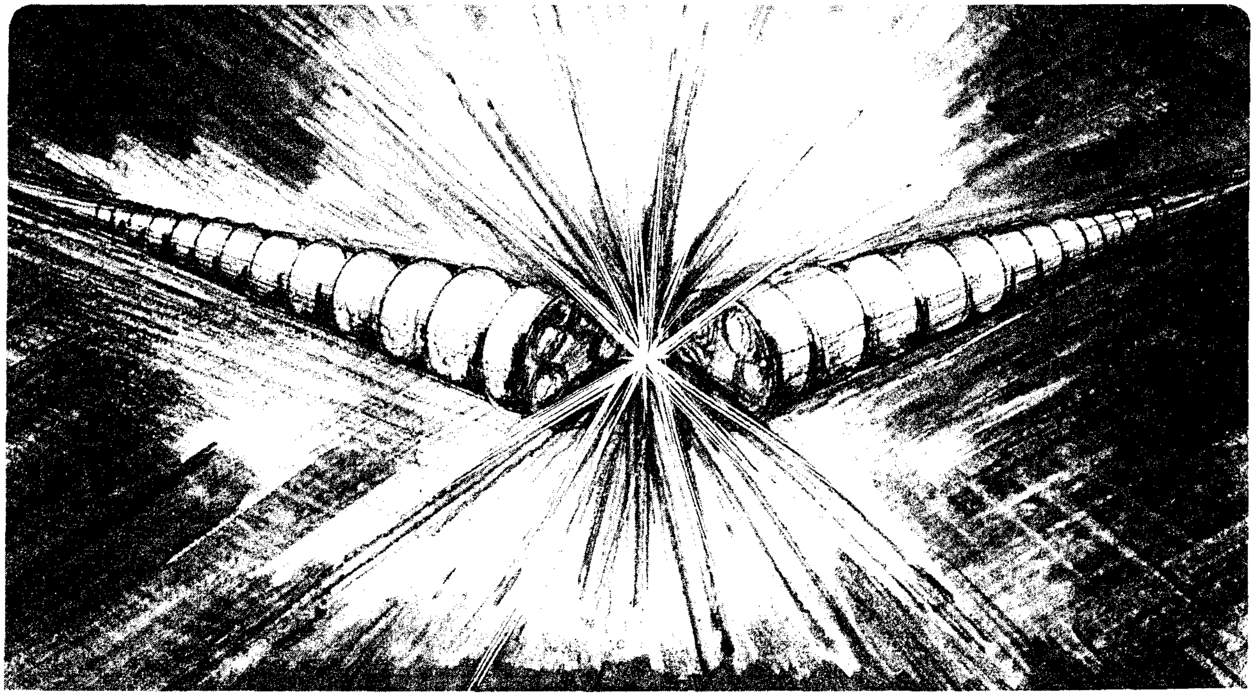
Accelerator & Fusion
Research Division

Presented at the LINAC '94 conference, Tsukuba, Ibaraki,
August 21–26, 1994, and to be published in the Proceedings

Relativistic-Klystron Two-Beam-Accelerator as a Power Source for a 1 TeV Next Linear Collider — A Systems Study

S. Yu, F. Deadrick, N. Goffeney, E. Henestroza, T. Houck, H. Li,
C. Peters, L. Reginato, A. Sessler, D. Vanecek, and G. Westenskow

October 1994



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

RELATIVISTIC-KLYSTRON TWO-BEAM-ACCELERATOR AS A POWER SOURCE FOR A 1 TEV NEXT LINEAR COLLIDER — A SYSTEMS STUDY*

S. Yu[1], F. Deadrick[2], N. Goffeney[1], E. Henestroza[1], T. Houck[2], H. Li[1], C. Peters[1],
L. Reginato[1], A. Sessler[1], D. Vanecek[1], G. Westenskow[2]

[1]Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720
and
[2]Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

Abstract

A physics, engineering, and costing study has been conducted to explore the feasibility of a relativistic-klystron two-beam-accelerator system as a power source candidate for a 1 TeV linear collider. We present a point design example which has acceptable transverse and longitudinal beam stability properties. Preliminary 'bottom-up' cost estimate yields the full power source system at less than 1 billion dollars. The overall efficiency for rf production is estimated to be 36%.

Introduction

As a power source candidate for linear colliders, two-beam-accelerators [1] (TBA) have the inherent advantage of very high efficiency for power conversion from drive beam to rf. In addition, induction-linac-based TBA's have favorable scalings with high frequencies (≥ 11.4 GHz) and high accelerating gradients (≥ 100 MV/m). Recent reacceleration experiments [2] have successfully demonstrated bunched beam transport through 2 reacceleration induction cells and 3 traveling-wave extraction cavities for a total rf output of over 200 MW. The phase and amplitude were shown to be stable over a significant portion of the beam pulse.

The technical challenges for making TBA's into realizable power sources lie in the dynamics of the drive-beam which must propagate over long distances. In particular, the beam-break-up instability through a long multi-cavity relativistic-klystron version (RK-TBA) is known to be severe. While BBU suppression techniques have been successfully demonstrated for a few cavities, a scenario with acceptable BBU control over many traveling-wave cavities must be constructed. Similarly, the longitudinal stability of the rf bunches over a multi-cavity TBA must be demonstrated. In addition to technical feasibility, a case for economic attractiveness is no less essential for the viability of the TBA as a power source.

With these general considerations in mind, we propose a new version of the RK-TBA which has acceptable longitudinal and transverse beam stability, as well as low cost and high efficiency. A systems study, including physics and engineering designs, as well as 'bottom-up' costing, has been conducted for a point design example with the RK-TBA as a power source for a 1 TeV center-of-mass linear collider [3].

RK-TBA Architecture

To generate an unloaded gradient of 100 MV/m in the high-gradient structures, the TBA must supply 360 MW of rf power at 11.4 GHz every 2 meters. The output rf field is specified to have a 100 ns linear rise followed by 200 ns flat-top. The repetition rate is 120 Hz. To power a 15 km long collider (7.5 km for each arm), we propose an architecture with 50 RK-TBA units, each 300 m long, operating at an average drive beam energy of 10 MeV, with an average current of 600 amps over the duration of the pulse, and a reacceleration gradient of 300 kV/m.

The front end of each RK-TBA unit consists of a 1.5 kA injector, followed by an rf chopper at 2.5 MeV, and an 'adiabatic capture' unit in which the chopped beam (average current 600 A) is accelerated to 10 MeV and further bunched with idler cavities in preparation for injection into the main TBA. To enhance the efficiency of the TBA system, an 'after-burner' at the end of the main TBA continues to extract rf power through 12 successive output cavities before depositing the spent beam (average beam energy < 3 MeV) at the beam dump. The overall efficiency (drive-beam to rf) of each RK-TBA unit is 90%. The 10% loss is shared among the beam loss on the chopper (3.7%), beam dump (2.8%), and rf generated in the induction cells (3.5%).

The new RK-TBA design is based on the technology of long-pulse (~ microseconds) induction machines that have been studied over the last 18 years for heavy ion fusion applications [4]. The magnetic material used in this design is Metglas, which can accomodate a large flux swing of nearly 3 T before saturation. The induction cores can therefore be made quite compact. Commercial applications of this material over the last few years have led to dramatic reductions in the cost of Metglas. The small Metglas cores, when combined with low field (800 Gauss) permanent magnets for qudrupole focusing,

---

* Work supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the US Department of Energy under contract(s) No. AC03-76SF00098 at Berkeley and W-7405-ENG-48 at Livermore.

and small beam pipes (5 cm diameter), have led to a compact induction cell design whose transverse diameter is about 34 cm — much smaller than any of the previously known induction cell designs. A schematic of a 2-m module which is repeated ~150 times in the main TBA is shown in Figure 1.

The pulse power for the induction cells is a low voltage system. The induction cores consist of small 20 kV units, powered by pulse forming networks (PFN's) switched by ceramic thyratrons. Power is fed into the PFN's via DC power supplies and command-resonant-charging systems. The low voltage design bypasses step-up transformers with associated losses. The main losses in this system are associated with core currents in the induction cells. The overall efficiency of the pulse power system (wall plug to drive-beam) is estimated to be 40%.

The rf extraction cavities are located every 2 meters. Present designs center around traveling-wave structures with 3 inductively detuned rf cells, with an inner radius of 8 mm. A pair of iris-waveguide structures in the last cell are matched for power extraction.

Beam Dynamics

Longitudinally, beams will debunch because of space-charge and rf-induced energy spread. To counter these debunching effects, the rf output cavities are inductively detuned. This is accomplished by making the phase velocity of the 3-cell traveling-wave-structure faster than the velocity of the particles ($v_p = 1.33$ c). The particle bunch lags behind the decelerating crest of the wave, and the energy loss becomes phase dependent, with the particles at the bunch tail losing the least energy. Kinematics lead to a 'catching up' of the tail with the bunch front and subsequent synchrotron oscillation in stable rf buckets. 1-D PIC simulations with a coupled cavity circuit model [5] show stable propagation through 150 cavities (Figure 2). For comparison, cavities with no inductive detuning are shown to result in particle debunching after a few cavities.

A key design feature of the present TBA is that the betatron period is exactly equal to the spacing between adjacent output cavities. This 'betatron-node' scheme leads to minimal beam offset at the rf cavities. Excitation of the HEM_{11} mode at 14 GHz is drastically reduced as a result. Transverse dynamics have been modeled with a beam-breakup code [6] that includes both cumulative and regenerative effects, and the results are shown in Figure 3. Past experiences in the design of induction accelerators have shown that BBU growth of 4 to 5 e-folds is acceptable. The cavity parameters for these simulations were obtained from URMEL and MAFIA. For an 8-mm radius cells, a natural de-Qing of the dipole mode occurs because of the coupling to the TE_{11} mode in the beam pipe.

The betatron-node scheme imposes constraints on the accuracy of the focusing fields and beam energy. Sensitivity studies to this point indicate that without feedback the field errors must be less than 0.3% and energy variations from head to tail must have comparable accuracies. These requirements can be relaxed hopefully with feedback.

There is another low frequency BBU mode associated with the induction gaps that must be controlled. The relatively low current of 600 Amps, combined with the Landau damping that occurs naturally because of the energy spread in the rf buckets, have led again to simulated BBU growth of about 4 e-folds (see Figure 4). To achieve this low growth, the induction gaps were designed for maximal dipole de-Qing, using the induction cavity design code AMOS [7].

RK-TBA Costing

A first engineering and costing exercise for the full TBA system has been performed. The electrical design includes all components starting from the AC power distribution system, to the DC power supplies, the command resonant charging system, the pulse forming networks, and the induction cores. Racks and installation, as well as instrumentation and control, were included in this exercise. The mechanical design and costing includes details of the induction cells, rf structures, vacuum, alignment, and utilities. Costs were estimated with a 'bottom-up' approach, assuming mass production procedures for fabrication and assembly. Our preliminary cost estimate for the TBA-based power source for a 1 TeV cm linear collider is $882M. This estimate does not include conventional facilities, ED&I, or any institutional overhead. The overall efficiency of the system (wall plug to rf) is estimated to be 36%.

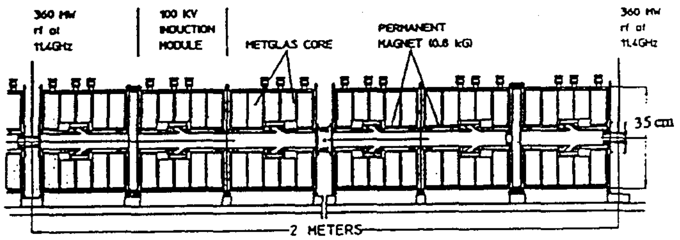


Fig. 1 2-m module in the main TBA.

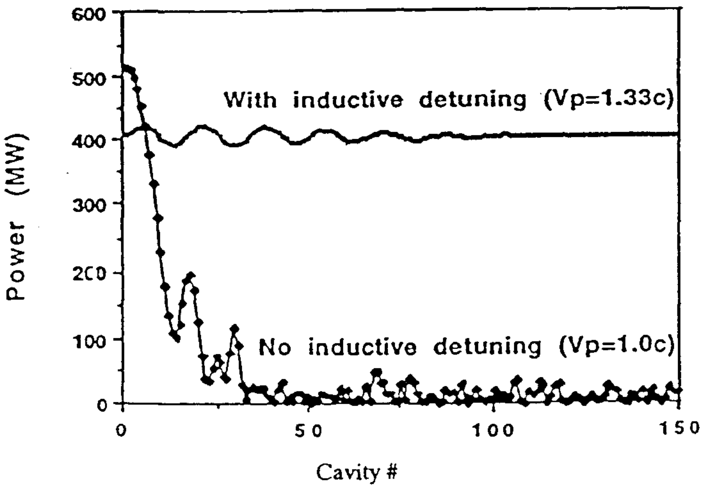


Fig. 2 Power extraction from 150-cavities in one unit of RK-TBA.

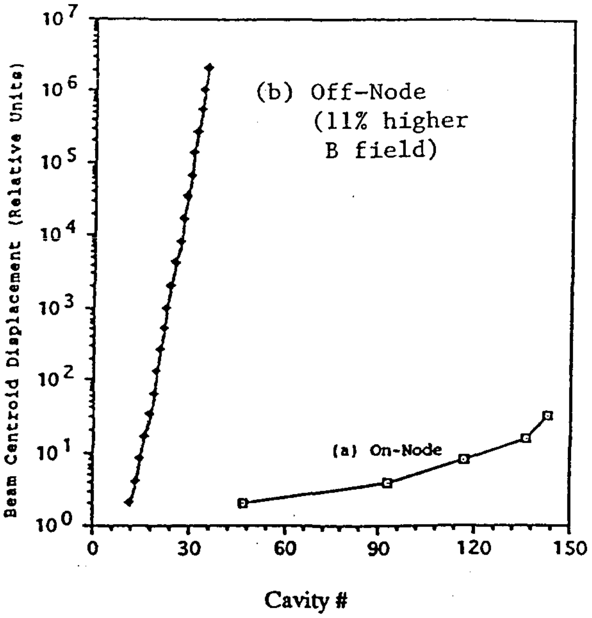


Fig. 3 Effect of the 'betatron-node' scheme on the BBU growth at 14 GHz.

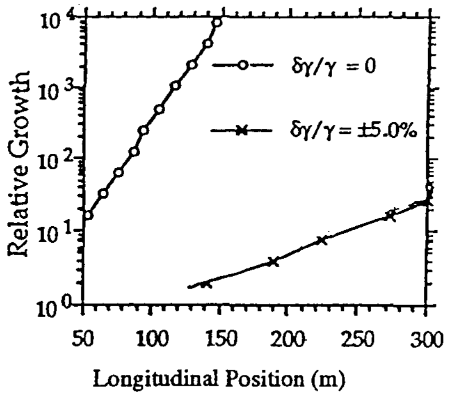


Fig. 4 Low frequency BBU growth, with and without Landau damping.

References

1. A.M. Sessler and S.S. Yu, "Relativistic Klystron Two-Beam Accelerator," Phys. Rev. Lett., 58, No. 23 pp. 2439-2442 (1987).
2. G.A. Westenskow and T.L. Houck, "Results of the Reacceleration Experiment: Experimental Study of the Relativistic Klystron Two-Beam Accelerator Concept," Proceedings of the 10th International Conference on High Power Particles Beams, San Diego, CA, June 20-24, 1994.
3. R.H. Siemann, "Overview of Linear Collider Designs," Proceedings of the 1993 Partical Accelerator Conference, Washington, D.C., May17-20, 1993, pp. 532-536.
4. W. J. Hogan, R. Bangerter, and G.L. Kulcinski, "Energy from Inertial Fusion", Physics Today, 42, 9 (1992), pp. 42-50.;
   T. Fessenden and C. Fong, editors, "Induction Linac Systems Experiments Conceptual Design Report", LBL document PUB-5324, (1992).
5. R.D. Ryne and S.S. Yu, "Relativistic Klystron Simulations Using RKTW2D," Proceedings of the 1990 Linear Accelerator Conference, Albuquerque, New Mexico, September 10-14, 1990, pp. 177-179.
6. T.L. Houck, G.A. Westenskow, and S.S. Yu, "BBU Code Development for High-Power Microwave Generators," Proceedings of the 1992 Linear Accelerator Conf., pp. 495-497.
7. J.F. DeFord, G. D. Craig, and R.R. McLead, "The AMOS (Azimuthal Mode Simulator) Code". 1989, PAC Conference, Chicago, IL.