PROPOSAL TO USE PIVAIR AS A 30 GHZ HIGH-POWER GENERATOR

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Abstract

The Two-Beam Accelerator (TBA) is under active study both at Lawrence Berkeley National Laboratory (LBNL) and at CERN. In the TBA, an extremely intense low-energy electron beam is bunched at the desired operating frequency and, upon passing through resonant cavities, it generates radio-frequency (RF) power for accelerating the main beam. Among the different approaches to the production of a suitable drive-beam, the use of a free-electron laser has been proposed. Recently at CEA-CESTA, encouraging results in this direction have been obtained. To extend this work, we propose the use of the induction accelerator "PIVAIR" at CESTA (7.2 MeV, 3 kA) as a test stand for high power RF structure experiments at 30 GHz. Our research program for PIVAIR includes:

1 Production of a drive beam current profile designed to compensate beam loading,
2 High power tests of a CLIC Transfer Structure,
3 Tests of the 30 GHz RK-CLIC components.

1 INTRODUCTION

As a power source candidate for linear colliders, the highly developed klystron technology provides reliable and economic RF power at frequencies of order 3-12 GHz, but its extension to higher frequencies represents a difficult task. As alternatives to klystron technology, the TBA, suggested by A. Sessler at Lawrence Berkeley National Laboratory (LBNL) [1], is under active study both at LBNL [2] and at CERN, where the project bears the name Compact LInear Collider (CLIC) [3]. For multi-TeV TBA designs, both groups are considering operating frequencies around 30 GHz. Among the many technological difficulties in the TBA approach, the production of a suitable drive beam (DB) constitutes a major challenge. The research program outlined in the present document is devoted to a scheme of generating such a beam, based on the bunching that naturally occurs in a Free-Electron Laser (FEL) powered by an induction accelerator capable of producing kiloampere currents of electrons with energies in the several MeV range.

In a series of experiments performed at CEA/CESTA with the LELIA induction linac, the capacity of a FEL, powered by an induction accelerator, to generate an intense bunched beam has been demonstrated [4]. The next step, which is being pursued actively at CESTA, is the extraction of the bunched beam and its propagation into a resonant cavity [5]. The aim is to demonstrate the ability of this scheme to generate the required amounts of RF power by the passage of the bunched beam through the extraction cavity [6]. Although this program is proceeding as planned, a major difficulty must be surmounted, namely the tendency of a tightly bunched beam to debunch under the influence of longitudinal space charge forces. In the case of LELIA, the usual relativistic factor $\gamma = 5.3$, whereas at the nominal energy of the PIVAIR accelerator, $\gamma = 15.1$, and the correspondingly increased debunching distance is roughly an order of magnitude greater.

We propose here a continuation of the TBA R&D in a 4-year experimental program. This proposition is in fact a testbed for high frequency and high power RF acceleration. Many tests of interest are planned, thanks to the powerful PIVAIR accelerator [7], which is a unique tool capable of producing a bunched beam with specifications very close to the final DB for both TBA designs: CLIC and RK-TBA.

2 EXPERIMENTAL PROGRAM

The PIVAIR accelerator delivers a 3 kA, 7.2 MeV low emittance electron beam which will be transported to a high gain FEL amplifier operating at 30 GHz. A similar experiment was performed in the past at Lawrence Livermore National Laboratory at a beam energy of 6 MeV [8]. In the wiggler magnet, the beam undergoes the FEL process and becomes bunched at the resonant frequency. The interaction is stopped at a length where the bunching is maximum. The bunched beam is then ready to be used for various tests.

To compensate for transient beam loading effects in the accelerating cells, the front end of the current must be ramped with a profile adapted to produce the desired power extraction from the transfer cavity (TC). This shaping of the front end of the beam is necessary for the FEL to remain a viable candidate for DB production.

The PIVAIR energy is high enough to ensure bunched beam propagation through one or more TC. High power operation of the TC would permit us to test its operating limits. The breakdown threshold, dark current capture threshold, and maximum gradient are measurements of prime importance.

The RK-CLIC scheme is an extension to 30 GHz of the work in progress at LBNL for the RK-TBA project at 11.4 GHz. Idler and open cavities are its basic components. The coupling is stronger than in the other scheme and a re-acceleration of the electron beam is necessary by means of an induction cell. Tests of beam transport, high output power production, compact induction modules are proposed.

3 THE PIVAIR INDUCTION LINAC

A photograph of PIVAIR is displayed in Fig. 1. The high voltage pulse generator of the injector was developed by Pulse Science Incorporated (PSI) for the Dual Axis Radiographic Hydro-Test Facility (DARHT) and the diode was designed by Los Alamos National Laboratory (LANL). It is a single shot device whose repetition rate is once every 5 minutes. A 3 kA, 3.6 MeV electron beam is extracted from a velvet cathode with excellent reproducibility. Upon exiting the injector, the electron beam is accelerated to 7.2 MeV by 16 induction cells, which are fed by external high voltage generators producing 250kV, 75 ns pulses with 1% voltage spread. Each generator drives two induction cells. The beam energy spread is less than 1% over 60 ns and the normalized edge emittance is 1000 π-mm-mrad. PIVAIR has an excellent reliability when operating at 7.2 MeV.

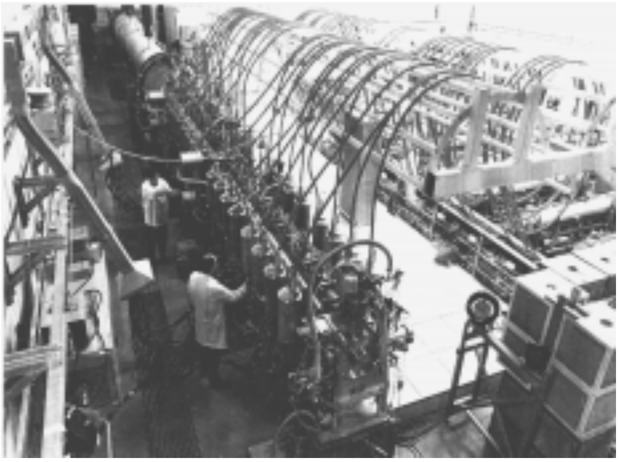

Figure 1: Photograph of the PIVAIR facility.

4 THE FEL AMPLIFIER AT 30 GHZ

In the proposed experiment the wiggler is a pulsed bifilar helix. The external EM wave is produced by a 30 GHz microwave source such as a magnetron or traveling-wave tube. Since the FEL efficiency varies slowly with the wiggler period, the length required to reach saturation does too. We choose a wiggler period short enough for the total length of the wiggler to be reasonable (a few meters).

FEL numerical simulations are performed using the code SOLITUDE. We present here the results obtained for a 7 m long wiggler with 6 adiabatic entrance periods, at 7.2 MeV. For these calculations, the beam current and beam radius have been chosen to be 1 kA and 1cm, respectively, while the waveguide diameter was 60 mm. Power levels close to 1 GW are expected at resonance for B_w = 1900 G. In Fig. 2, we have plotted the power as a function of the interaction length showing that saturation occurs at period 27 (5.40 m). The bunching is maximum just before this point with a maximum bunching parameter (average over the electrons phase in the longitudinal phase space) of 0.5. Consequently, the wiggler length should be around 5 meters to obtain the maximum bunching.

The beam is adiabatically extracted to remove the transverse momentum imparted by the wiggler field. Simulation with PARMELA indicates that the beam remains bunched at a significant level for a distance greater than 3 m permitting all the DB tests.

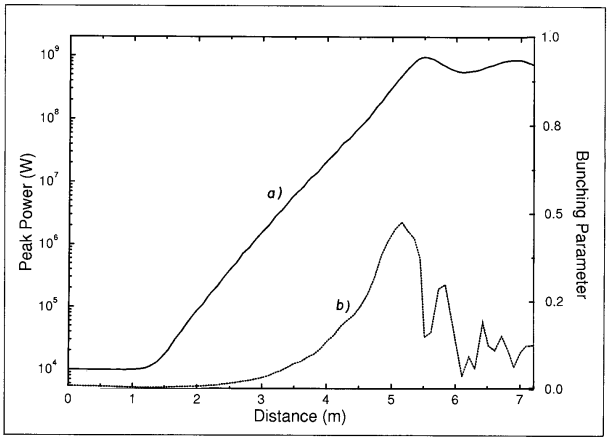

Figure 2: FEL simulations with the code SOLITUDE for the best resonant magnetic field (1900 G): a) power vs. z and b) bunching parameter vs. z.

5 PRODUCTION OF THE BEAM CURRENT PROFILE

Ramping of the current profile is a necessary requirement in any system that seeks to produce usable RF power to drive multi-bunch, high-gradient accelerating structures. Without any profiling, the transient response of the accelerating structure will cause an intolerable energy spread in the accelerated pulse train. By including an initial ramp to the drive beam, the transient filling of the accelerating structure will be accomplished before the main beam arrives, and constant transfer of energy will occur over the entire pulse train.

We propose the use of a pulsed quadrupole and a beam scraper to induce a ramped current profile. The quadrupole field is produced by a stripline device [9]. Initially, the beam is defocused in one plane by the quadrupole at the aperture position, and only a part of the total current is allowed to pass. As the quadrupole field decreases, the beam is more and more focused, until at zero field all the current is transported through the aperture. The quadrupole is pulsed and decays over a duration corresponding to the desired current ramp.

6 HIGH POWER OF A CTS

The multi-kiloamp PIVAIR beam current opens up interesting possibilities for testing future CTS. These would allow us to test both the extremely high field effects and long pulse periods that are required for multi-TeV colliders. At present, three CTS parameters sets have been studied in detail with MAFIA (See Table 1).

The electron beam requirements for full-field tests are easily calculated using the expression for structure output power.

$$P = \frac{(r/Q) q_d^2 \omega}{2d}$$

where q_d is the beam charge passing through the structure during the drain time

$$d = (s/c)(1/\beta_g - 1)$$

The charge is supposed to be concentrated in infinitely short bunches spaced by $g=c/f=1$cm (f=30 GHz). The necessary beam charge per drain time is obtained from the above expression as:

$$q_d = \sqrt{\frac{2dP}{(r/Q)\omega}}$$

Furthermore, the charge per bunch (for a train of delta-function drive bunches) is obtained as $q_b = 2q_d/fd$. The Fourier analysis of a beam with these infinitely short bunches spaced in time by $1/f$ yields a peak current component at f of $I=2fq_b$. Note that the CTSs are tuned to the frequency component at f = 30 GHz. Assuming a RF current bunching factor of 0.6 at 30 GHz, the required PIVAIR beam DC current amplitude becomes $2fq_b/0.6$. Numerical values for the three drive beam cases are summed up in the table.

	1 TeV Single DB	1 TeV Multi DB	3 TeV Multi DB
CTS output power: P (MW)	550	309	600
CTS length: s (m)	0.92	1.028	1.028
Drain time: d (ns)	5	5.14	5.14
Relative group velocity: β_g	0.38	0.4	0.4
Beam charge / d: q_d (nC)	2325	673	798
r/Q of CTS (circuit Ω)	5.2	51.4	51.4
CTS peak deceleration (MV)	1.18	2.5	3.87
FEL mean current (A) (for delta-function)	465	123	155
Peak 30 GHz FEL current (A)	930	247	310
FEL mean current: (A) (for I_{rf} = 0.6 at 30 GHz)	1550	411	517

Table 1: CTS parameters for different DB possibilities.

7 RK-CLIC STUDIES

The existing effort at LBNL seeks to realize the RK-TBA concept by construction and successful operation of a full-scale, prototype device [10]. This will be a 11.42 GHz version and will test all the key components and design elements of a complete system. PIVAIR operated as a test stand will provide a valuable resource in the effort to examine beam dynamics and to test designs of beamline components for a high frequency RK-TBA.

A key point in the beam dynamics of an RK-TBA is the stability of the bunching against space charge forces and longitudinal impedances. The RF cavities are designed to be 'inductively detuned' to provide a net re-bunching force on the beam as it travels through the structure, and to maintain stable synchrotron (longitudinal) oscillation. The cavities themselves are designed to act upon the beam to maintain stable bunches.

The induction cells may take on a very compact design, increasing the efficiency of the re-acceleration units. However, decreasing the beampipe diameter tends to increase the transverse impedance and peak surface electric field in the induction modules. Innovation is required in the cell geometry, induction core material, and high gradient insulation. These may all be tested at PIVAIR.

The RF cavities are the centerpiece in any RK-TBA system. Their microwave properties are crucial to the generation of useful power by the drive beam. The idler, standing-wave (SW) and travelling-wave (TW) output cavities all have unique interactions with the beam that need to be measured and analyzed experimentally. Important tests that need to be performed include: generation of high output power , high-voltage holdoff, low Q, longitudinal impedance characterization.

8 CONCLUSION

The PIVAIR accelerator is a useful research tool, capable of providing an intense high-quality electron beam of energy 7.2 MeV. This machine may be used in a variety of scientific and technological projects, among which figures prominently the generation of high-power, high-frequency microwaves. A major application of these consists in powering the next generation of linear colliders which will operate at high frequencies, such as 30 GHz. In the present project, we propose to use PIVAIR in conjunction with a FEL to produce an intense bunched beam, and to test structures designed to extract power at 30 GHz from such a beam.

Some of the technical aspects of our proposal have been contributed by members of different groups. We express to them our thanks, and acknowledge the helpful remarks offered by members of the CLIC collaboration and the RKTBA group.

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