EUROPEAN LABORATORY FOR PARTICLE PHYSICS
CERN - PS Division

CERN PS/91-41 (DI)
3 September 1991

Two-Beam Accelerators for High Energies

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Abstract

After an introduction to the Two-Beam Accelerator (TBA) concept for linear colliders the various approaches to generate the rf power based on this concept are summarized and the status of the work sketched.

Invited paper at the 1991 Meeting of the Division of Particles and Fields of the American Physical Society, PF91

Vancouver, BC, 18-22 August 1991

Geneva, September 1991

TWO-BEAM ACCELERATORS FOR HIGH ENERGIES

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ABSTRACT

After an introduction to the Two-Beam Accelerator (TBA) concept for linear colliders the various approaches to generate the rf power based on this concept are summarized and the status of the work sketched.

1. Introduction

Linear colliders for high energy will require accelerating gradients E_a of 0.1 GeV/m or more to obtain energies in the TeV range with a reasonable length of the accelerator. Amongst all approaches[1] the one based on a normal conducting radio-frequency (rf) linear accelerator (linac) with a resonant frequency one order of magnitude above actual linacs (1 to 3 GHz), promises to lead to a real project[2]. The choice of a very high frequency is mandatory as the required total peak rf power $P_p \sim f^{-1/2}$, and the average power $P_a \sim f^{-2}$, for a fixed gradient. The high gradient also implies a high rf peak power per unit length (0.2 to 1 GW/m) as $E_a \sim (dP_p/ds)^{1/2}$. The rf power generators must be capable of delivering this power with a high efficiency in order to keep the power drawn from the grid within reasonable bounds. Their number should be limited to a few large units, they should be as simple as possible for cost reasons, and have a high reliability and low maintenance cost. The TBA, proposed in 1982[3], seems to be a promising approach where a high-intensity but low-energy, bunched drive beam runs along the whole linac or at least a large fraction of it. This beam periodically interacts with either rf cavities, travelling-wave (TW) rf structures or wiggler magnets. It excites electro-magnetic fields in these rf devices or amplifies the e-m field in the wiggler via single-pass free-electron laser (FEL) action. Hence, the drive beam is decelerated and beam energy is converted into electro-magnetic energy; the latter is then coupled out and led by waveguides to the main linac which accelerates a beam of lower intensity to much higher energy.

The paper briefly summarizes the main TBA approaches and their specific problems. The general layout of linear colliders and the issues common to all approaches, such as damping rings, final focus and general beam dynamics are treated elsewhere[4].

2. Linear Accelerator powered by Relativistic Klystrons

In this device[5] a pulsed relativistic electron beam of GW power, produced by a linear magnetic-induction accelerator, is transformed into a train of short pulses by bunching it via velocity modulation with the help of a cavity excited with the desired frequency f and followed by a set of passive cavities. This train is then decelerated by the extraction cavity and/or a TW structure. Since only part of the beam energy is deposited there, in principle, the beam can be re-accelerated by induction units and energy could be extracted repeatedly. Since the beam will eventually degrade, a number of relativistic klystrons will be required along each linac. The first experimental setup comprised the induction linac and a relativistic klystron. It provided a power of 170 MW for 40 ns at 11.4 GHz with a 1.3 MeV, 630 A beam as input. The maximum total power achieved was 290 MW. A 26 cm long TW accelerating structure was coupled to this device and, for 80 MW at input, a gradient of 84 MV/m was measured with a probing low energy (35 keV) electron beam[6]. Bunch train generation by transverse chopping is now being studied allowing for a higher energy beam (>3 MeV) and promising a higher efficiency[7]. Further studies will be needed to simplify the whole device, improve the phase stability across the rf pulse and prevent beam degradation of the drive beam during transport through many structures, induction gaps and the small diameter (below cutoff for f) beam pipe.

3. Linear Accelerator powered by FELs

In order to illustrate the principle[3], a possible layout[8] is described. The drive beam pulse is generated also by an induction accelerator. It is prebunched by FEL interaction in a wiggler magnet and then injected into the first extraction wiggler where it amplifies via FEL an e-m wave (TE waveguide mode) launched by means of a low-power klystron. The rf power is extracted by a coupler from the waveguide at the end of the wiggler and the beam re-accelerated by an induction unit. Extraction wigglers and re-acceleration units could repeat about 100 times until the beam is degraded and a new beam has to be created. One such set (injector plus 100 FEL and accelerator units) is foreseen to power a 0.1 TeV subsection of the main linac[8]. In the first experiments, combining an induction linac driven FEL and a seven-cavity copper test structure, accelerating gradients of 180 MV/m were obtained during a 3.1 MW, 15 ns rf pulse from the FEL at 35 GHz[9]. In another test stand, the induction linac injected a 0.5 kA, 0.76 MeV electron beam into a 2 m long solenoid wiggler magnet, and rf power in excess of 10 MW at 9.4 GHz for 50 ns was obtained from this FEL[10]. In order to overcome significant problems associated with the coupling out of the TE waveguide mode, it is proposed[11] to replace the interaction waveguide with an overmoded cavity where a standing wave is excited by FEL interaction with the drive beam. This cavity is side-coupled to an accelerating cavity of the main linac. The stored energy of the coupled system is periodically exchanged between the two cavities, the drive beam *replenishing* via FEL what is lost to the main beam. This method also lowers the output peak rf power, which reduces the risk of breakdowns. Only theoretical work has been done on this beat coupling approach concentrating on the phase and amplitude oscillations in the rf output owing to jitter in the drive beam energy and current[11]. The amplitude of these oscillations must be limited in order to keep the energy of the main beam within the momentum acceptance of the final focus system. It is difficult for induction linacs to meet the tolerance on the drive beam energy jitter (<1%). Shaping the drive beam pulse should help.

4. Linear Accelerator powered by Transfer Structures

In this scheme[12], very similar to that discussed under point 2 and the approach adopted for CERN Linear Collider (CLIC) studies, a very high energy (≈5 GeV) drive beam periodically deposits energy in 0.5 m long 30 GHz travelling-wave (TW) "transfer" structures. From each of the latter a 40 MW 11 ns rf pulse is fed to each of the four accelerating (80 MV/m) TW structures of the main linac. The drive beam creates via the coupling holes of the transfer structure a TE_{10} backward wave in the output waveguide. The distance between the axes of the two linacs is <1 m such that the linacs can be housed in a relatively small tunnel. The drive beam consists of four trains of 11 bunches. The bunch-to-bunch distance is 1 cm corresponding to λ(30 GHz). Spacing between the heads of the trains corresponds to one wavelength of 350 MHz so that the trains can be periodically re-accelerated by 350 MHz superconducting cavities, as developed for LEP, providing ≈5 MV/m and powered by standard 1 MW cw klystrons. These 350 MHz cavities are grouped in strings every two to three km such that the number of access points to the linac is kept to the minimum. All this yields a very compact design. The high energy drive beam is an excellent phase reference, avoiding all problems with phase stability brought about by the unavoidable low energy of the drive beam in the other approaches using induction accelerators.

A test facility (CTF) is being constructed at CERN to study the generation of the e^- bunches (160 nC per bunch, σ_s=1 mm) required by the CLIC drive beam, and to generate MW 11 ns long rf pulses to test 30 GHz accelerating and transfer structures. The S-band rf gun with a laser driven photocathode has already provided 40 nC in a 8 ns long pulse. Photocathodes (CsI and Na_2 KSb) have reached peak quantum efficiencies exceeding 1%. A newly designed overmoded, circular transfer structure has a large diameter (16 mm) reducing considerably the resistive wall effects. Detailed model measurements at 9 GHz have confirmed the design. A main linac accelerating section containing the required 80 cells has been completed including cooling and vacuum manifolds; it is ready for tests in CTF. One of the disadvantages of the high operating frequency (30 GHz), apart from the tight mechanical tolerances of the accelerating sections, is the strong wakefields created by the main beam, which react back on the beam and can destroy it. In order to control the transverse wakefield effect, the quadrupoles and sections must be aligned with a 1 µm, and 5 µm tolerance respectively using the beam itself as reference (pre-alignment of about 0.2 mm over 100 m seems possible. A micro-movement test facility has shown that displacements of typical accelerator components can be achieved at a level of 1 μm. Microwave quadrupoles and beam position pick-ups are being studied, and extensive simulations of longitudinal and transverse beam dynamics have been done. The latter show that the trajectory correction procedure needs a further refinement in order to reduce the emittance blow-up to ≈25%, from the present intolerable level of 60% for 1 TeV final beam energy. The nominal luminosity is 10^{33} $cm^{-2}s^{-1}$ at 1 TeV per beam with beam dimensions of 12 nm x 60 nm at the final focus and zero crossing angle in single bunch operation; the repetition rate is 1.7 kHz. A recent study shows that the same luminosity can be obtained at 0.25 TeV per beam, which will pave the way for a staged approach for CLIC. More details can be found in recent progress reports[13].

Acknowledgement

I am grateful to S. Hiramatsu, M.A. Makowski, A.M. Sessler and my colleagues of the CLIC Study Group for kindly providing information for the preparation of this summary. Thanks are due to D.J. Warner and I. Wilson for critical reading of the manuscript and for useful suggestions.

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