THE ARGONNE WAKEFIELD ACCELERATOR*

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Abstract The Argonne Wakefield Accelerator (AWA) is a proposed new facility for advanced accelerator research, with a particular emphasis on studies of high gradient wakefield techniques. A novel high current short pulse L-Band photocathode gun and preaccelerator will provide electron bunches at 30 MeV for the initial phase of the program. The eventual addition of a 100-150 MeV drive linac will form the basis for a 1 GeV demonstration wakefield accelerator.

Introduction

Wakefield acceleration is a promising technology for use in future linear colliders. Based on the success of proof-of-principle experiments conducted at Argonne's Advanced Accelerator Test Facility (AATF), a new facility, the AWA, has been designed to study wakefield devices producing gradients in excess of 100 MeV/m [1], as well as for high precision measurements of beam coupling impedances. The first phase of the AWA features a laser photocathode gun capable of producing 100 nC 10 ps bunches, a preaccelerator to boost the beam energy to 30 MeV, and a wakefield measurement system.

A long term goal is the demonstration of a true high energy wakefield accelerator. The proposed design requires the addition of further linac sections to increase the beam energy to 100-150 MeV. A train of bunches will then be used to drive an 850 MeV Cherenkov wakefield accelerator (CWFA) [2], to provide a final beam energy of 1 GeV. The AWA program will examine all critical features needed for practical wakefield accelerators.

Photocathode Electron Source

Previous work on photocathode sources has been directed toward extremely bright, high repetition rate devices. The requirements of the AWA source, however, are significantly different. The need for 100 nC, 10 ps bunches is driven by the goal of attaining 100 MV/m scale accelerating fields in wakefield devices, but the maximum tolerable transverse emittance is much larger, so that even with its much larger charge/pulse, the AWA source brightness is an order of magnitude smaller than guns developed at LANL and BNL. The desired repetition rate is also much lower (30 Hz). These parameters have the effect of greatly relaxing many of the demands on the source components.

The role of the gun cavity is to accelerate the electrons from the photocathode to relativistic energies sufficiently rapidly that longitudinal and transverse space charge blowup of the beam is minimized. The problem of cavity design is one of maximizing the accelerating gradient at the photocathode,

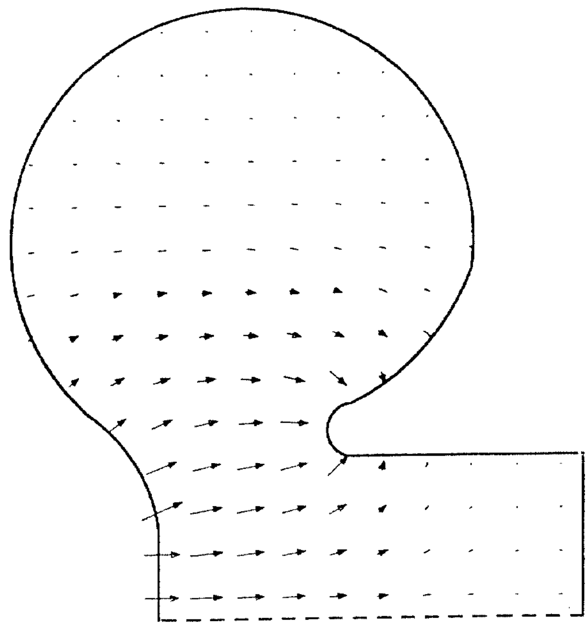

Figure 1: $r-z$ plot of the AWA gun cavity and electric field vectors.

subject to the constraints of operating frequency, available drive power, stored energy, and peak surface fields.

The cavity is shown in figure 1, with the electric field vectors for the fundamental mode superposed. The nearly circular cross sectional shape is graded smoothly to a flat photocathode region and to a nosecone which serves to concentrate the fields at the photocathode. The fields and other cavity parameters were calculated using the frequency-domain codes URMEL and SUPERFISH. The cavity geometry was iteratively adjusted to obtain the desired frequency (1300 MHz) and sufficient accelerating field at the photocathode (92 MV/m peak at 1.5 MW input power). The Q of this cavity is 15500.

A prototype gun cavity was constructed based on this design. Results from low power bench tests were found to agree well with the calculated frequency and Q, once the proper surface resistivity was taken into account. Following usual practice, the rf coupling slot dimensions were determined empirically by minimizing the reflected power in the attached waveguide.

In order to better control space charge effects in the gun, the present design calls for forming the electron bunch using a concave laser wavefront, generated by passing the laser pulse through a stepped optical element, like a stack of quartz optical flats of decreasing radii. The effect of the curved wavefront is to considerably reduce the instantaneous charge density and hence the space charge forces at the photocathode, at the expense of an initially longer pulse. The electrons are

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produced with a strong positive correlation between angular divergence and initial radial position, and between radial position and time. If allowed to drift, the electrons at larger radii tend to axially lag those at smaller radii, thus effectively compressing the bunch. A solenoid downstream of the gun is used to control the transverse size of the bunch and permits matching to the aperture of the preaccelerator.

Beam dynamics in the photocathode gun were modelled using a version of the PARMELA code specially modified by us to handle photoelectron emission produced by a nonplanar laser wavefront. Increased computational accuracy was obtained through the use of an adaptive space charge mesh. The cavity fields computed by URMEL were normalized to the input power level and converted to a form readable by PARMELA, which then was used to follow the bunch through the cavity. Space charge forces were calculated at each time step. The transmission and bunch length were optimized with respect to injection phase, etc. For a laser pulse duration of 2 ps, wavefront sagitta of 0.51 cm (17 ps), 1 cm spot radius, and 100 nC total charge, we find that at the end of the gun cavity, when the electrons emitted last have caught up with those emitted earlier, a FWHM of 0.25 cm (8 ps) is obtained. The bunch energy is 1.9 MeV at the end of the gun.

For the current design, we have chosen Yttrium over higher quantum efficiency materials for our photocathode because of its less stringent vacuum and preparation requirements. The quantum efficiency of Yttrium at 266 nm is 5×10^{-4} [3], thus in order to generate a 100 nC electron pulse, a laser capable of producing at least 1 mJ per pulse is required.

There are several commercially available, off the shelf laser sytems which will satisfy our requirements. Since the pulse to pulse amplitude fluctuation cannot be easily controlled by the laser itself, an amplitude noise reduction system will be needed to reduce the fluctuation to $< 2\%$.

Preaccelerator

The design goals of the preaccelerator differ from many existing linacs only in the magnitude of the beam currents involved. Wakefields, which will be used constructively elsewhere in the facility, are a potential source of problems in the preaccelerator and drive linac, and suggest deviations from typical linac designs. In particular, the aperture is much larger than usual to minimize the effects of parasitic wakefields in the structure. Design of the preaccelerator proceeded iteratively, optimizing the accelerating properties (Q, shunt impedance, group velocity) computed using URMEL, while minimizing transverse wakes as calculated by TBCI.

The photocathode and the preaccelerator will share a common klystron with an output of 25 MW (for $3-6\ \mu s$) at a frequency of 1.3 GHz. The photocathode will require < 3 MW, leaving at least 22 MW available for the preaccelerator.

The original preaccelerator design [1] called for an iris-loaded standing wave structure operating in a $\pi/2$ mode. In this scheme the cavity consists of 16 cells, each 5.78 cm in length, resulting in a total length of 1.04 meters. Each cell is 10.0 cm in radius, and each iris is 5.08 cm in radius, with a length of .5 cm. Note that this is a much larger iris radius than traditional L-band linacs normally use. This cavity was computed to have a Q of ~ 18600, a shunt impedance/unit length of 29.1 $M\Omega/m$, and a group velocity of 0.136 c. This option would provide an accelerating gradient of 13 MV/m. A four cell prototype cavity was constructed and bench tested, and excellent agreement with the parameters as computed by URMEL was obtained.

It now appears that by doubling the length of this cavity, operating in a travelling wave mode, and using rf recirculation to increase the effective shunt impedance, a net energy gain of 28 MeV in the preaccelerator stage can be obtained.

Wakefield Measurements

The AWA drive linac, with its high instantaneous current and short bunch capabilities, will provide a unique tool for many lines of research. The gun and preaccelerator will serve initially as the source of drive and witness beams for a wakefield measurement device based on the design used at the AATF [4]. This will permit continuity of the AATF experimental program while at the same time extending the measurement capabilities beyond those presently available.

A witness beam is formed by generating a small laser pulse 3 1/8 rf cycles ahead of the main laser pulse which generates the drive bunch, so that besides leading the drive bunch in time, the witness will be accelerated to about half the driver energy. (This technique of forming the witness beam differs from that presently used at the AATF, where a degrader forms the second bunch.) The two bunches are separated magnetically to pass down different beamlines and then recombined to pass on collinear or parallel trajectories through the wakefield device under test. The length of the low energy line is varied using a trombone section to provide a continuously adjustable driver-witness delay of up to 2.5 ns. After passage through the test device, the energy and deflection of the two beams are measured using a magnetic spectrometer.

The majority of the beamline magnets, the trombone stage, and the spectrometer will be recycled from the AATF. Use of this technique in conjunction with the AWA front end should yield a factor of 25 improvement in sensitivity over the AATF from the larger available drive charge alone. The shorter drive and witness bunches will also more than double the maximum wakefield frequency accessible, beyond 30 GHz. Although intended to be used with the AWA front end, the design is flexible enough to accommodate higher energy bunches from the drive linac, should wakefield measurements at larger energies with long delays be desirable.

Phase I Experimental Program

The source parameters for the AWA will allow accelerating gradients of ~ 200 MV/m to be obtained in 20 GHz CWFA structures. The CWFA devices to be used in the 1 GeV demonstration accelerator can be thus be tested and optimized in a realistic operating environment prior to the completion of the drive linac. This includes studies of the effects of dielectric nonlinearity and anisotropy [5], deflecting mode suppressor schemes, and possible two-beam accelerator options (to be discussed below). A variety of other measurements are also planned for the AWA program.

High sensitivity studies of longitudinal and transverse beam couplings of pickups, cavities, and other conventional accelerator components will be possible with the new facility. Scaling from the performance of the AATF, the AWA should permit measurements of transverse and longitudinal wake potentials in these devices at the level of ~ 50 V/nC.

It is well known that the use of drive bunches with asymmetric longitudinal profiles can improve the transformer ratio in wakefield devices, although this effect has yet to be studied experimentally. Shaped drive pulses may be generated in the AWA gun by appropriate shaping of the laser pulse. The AWA will offer the opportunity to develop and evaluate this technique.

The availability of beams from the AWA will permit the work on beam-plasma interactions begun at the AATF [6] to be continued. It is estimated that the electron pulse corresponding to the AWA design would drive accelerating gradients in a plasma of density $n_e \simeq 10^{14}$ cm^{-3} of > 250 MeV/m with 30 MeV initial beam energy and > 1 GeV/m at 150 MeV, concomitant with drive beam self-pinches $\sim$ 300 μm.

Experiments with high power laser klystrons would use the beam from the preaccelerator as a basis for microwave sources in the 30 GHz - 1 THz region. Of particular interest is the use of dielectric Cherenkov waveguides for this purpose [7], although plasma based coherent radiation sources are also under consideration.

1 GeV Wakefield Accelerator

Linear wakefield devices are in general limited to transformer ratios < 2, with practical considerations reducing this further to perhaps 1.2. The AWA will use a train of 4-5 drive bunches to produce an effective transformer ratio ~ 6.

A drive linac will be added to the phase I gun and preaccelerator. By using three more linac tanks identical to the preaccelerator a final drive beam energy $\simeq 120$ MeV can be obtained. Since the increased rigidity of the beam in the later cavities will render it less sensitive to parasitic wakes, a smaller iris size may be used to increase the shunt impedance and consequently the beam energy.

The train of drive bunches and the witness bunch will be generated by optical splitting of the laser pulse. The inter-bunch energy differences (from beam loading and phasing) will be utilized to magnetically separate the bunches for injection into the wakefield accelerator sections.

There are currently two options under study for the wakefield accelerator proper. The classical scheme involves drive and witness bunches travelling on collinear trajectories through dielectric loaded structures. Transverse wakefield effects on the witness bunch are eliminated through the use of mode suppressors [8], while head-tail instability effects in the drive bunch can be controlled (but not entirely suppressed) through the use of external focussing elements.

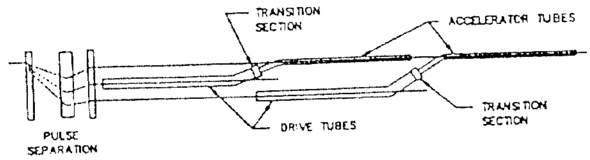

Figure 2: Coupled wake tube accelerator (CWTA).

An alternative method is the coupled wake tube accelerator (CWTA) [1], shown in figure 2. The wakefield generated by the drive beam in a large bore dielectric structure is fed through a quarter-wave transformer to a smaller radius tube with the same fundamental frequency. The witness bunch is then injected into the smaller tube at the appropriate phase. The larger drive tube reduces the BBU effects on the drive bunch, while the noncollinear witness and driver trajectories yield considerable simplification of the staging optics. The smaller accelerating tube also compresses the wakefield, giving larger peak fields than in the drive tube.

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