DIELECTRIC WAKEFIELD ACCELERATOR TO DRIVE THE FUTURE FEL LIGHT SOURCE

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Abstract

X-ray free-electron lasers (FELs) are expensive instruments and the accelerator holds the largest portion of the cost of the entire facility. Using a high-energy gain dielectric wake-field accelerator (DWA) instead of the conventional accelerator may facilitate reduction of the facility size and significant cost saving. We show that a collinear dielectric wake-field accelerator can, in principle, accelerate low charge and high peak current electron bunches to a few GeV energy with up to 100 kHz bunch repetition rate. Several such accelerators can share the same tunnel and same CW superconducting linac (operating with a few MHz bunch repetition rate) whose sole purpose is feeding the DWAs with wake producing low energy, high charge electron bunches with a desirable periodicity. Then, ten or more x-ray FELs can operate independently, each using its own linac. In this paper, we present an initial case study of a single stage 850 GHz DWA based on a quartz tube with a ~100MV/m loaded gradient sufficient to accelerate a 50 pC main electron beam to 2.4 GeV at a 100 kHz bunch repetition rate in just under 30 meters.

INTRODUCTION

A number of FEL facilities are in operation around the world and more have been planned [1, 2]. While tremendously effective in providing extreme photon fluxes, these machines can only accommodate a small number of users at a time. To address this limitation, multi-user, multi-FEL facilities have been recently proposed (i.e., see for example [3]). The prevailing paradigm is to use a CW SRF linac to provide electron bunches of a few GeV at a 1 MHz repetition rate. to feed a switchyard of ten or more FELs, each operating at about 100 kHz, at the end of the linac. Here we propose a new approach where a CW SRF linac of much lower energy (100’s MeV) but still high 1 MHz repetition rate is used to feed a switchyard of ten or more DWA linacs + FELs. In other words, the switchyard has been moved to the beginning of the main linacs. While the facility still uses a, SRF linac, its size (and, thus, cost) has been shrunk significantly; a 100’s of MeV compared to few GeV.

High gradient DWA structure is a key to our proposal. Fortunately, advanced accelerator studies aimed at a future high energy collider, have been showing impressive results achieving multiple GV/m energy gradients in various wake-field acceleration schemes [4, 5].

A DWA SCHEME FOR FEL

In a collinear dielectric wakefield accelerator, the fields generated by a leading, high-charge drive bunch (either a single drive bunch or a train of drive bunches) is used to accelerate a trailing, low-charge main bunch which contains a relatively small amount of charge. The collinear configuration has the two beams traversing the accelerator along the same trajectory so that the energy is directly transferred from the drive bunch radiation to the trailing main bunch. The most commonly used DWA structure is very simple - a cylindrical, dielectric tube with an axial vacuum channel is inserted into a metal outer jacket. The dielectric constant and the inner and outer radii of the dielectric tube are chosen to adjust the fundamental monopole mode (TM_{01}) frequency excited by the passing beam. The phase velocity of the mode will equal the beam velocity ~c.

The overall facility layout is shown in Figure 1. The scheme consists of 10 parallel DWAs (30m long, 2.4 GeV, with an 80% fill factor) sharing one drive beam. The 200MeV, 1MHz drive beam consisting with 1.6 nC, 3.3 ps shaped bunches is generated by L-band CW superconducting linac. The switch yard distributes electron bunches to the ten DWAs on the rotating basis such as the repetition rate of each DWA is 100kHz. The main reason behind the choice of the beam repetition rate is to keep the average rf power dissipation of the accelerating structure at a manageable level, as discussed at the end of the paper. The drive bunch has a longitudinally shaped profile for the purpose of increasing the transformer ratio, which is defined as the ratio of the maximum accelerating field behind the drive over the maximum decelerating field inside the bunch. For a finite length, longitudinal symmetric bunch, the transformer ratio TR can never exceed factor of 2. A way to increase the transformer ratio TR above this limit is to use a bunch or a bunch train which has a double triangular temporal profile shown in Fig. 1. It can be implemented using bunch shaping via an emittance exchange (EEX) beamline as discussed in [6, 7]. The effective acceleration length for each beamline is 24 m. This is the distance travelled where the drive beam has lost 83% of its energy. We assume an 80% fill factor; a reasonable number considering the beam optics and diagnostics in the beamline. In terms of beam breakup control, particularly for the DWA, quadrupole channels are the most effective approach.

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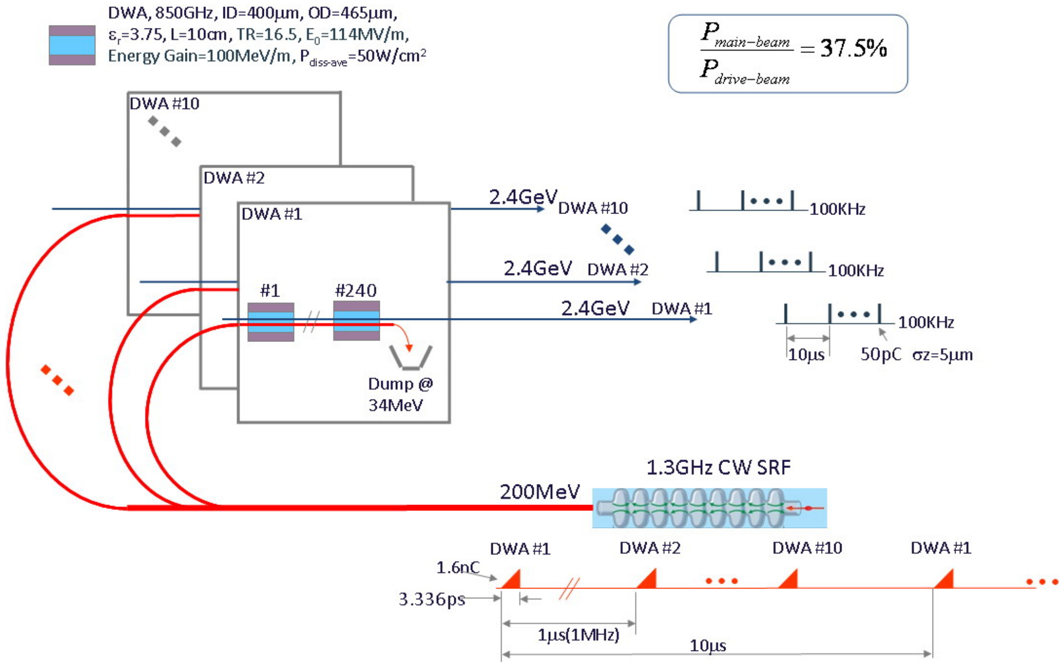

Figure 1. A schematic of the FEL light source facility showing CW superconducting linac, transport lines and an array of dielectric wakefield accelerators. Essential electron beam and accelerator parameters are shown.

Each DWA has 240 10-cm long, low-cost quartz based structures, but the actual length of the individual structures has not been decided yet. In principle, it can be of any length insofar as the electron beam control requirement is satisfied. All quartz tubes have a small 400 micron hole, critical for achieving a high gradient acceleration using a relatively modest 1.6 nC drive bunch. Obviously, stable propagation of drive bunches with 200 MeV energy through this hole along the entire DWA possess significant challenge that is going to be addressed in the future R&D.

The transformer ratio is 16.5 in our straw man design. The peak gradient behind the drive bunch is 114MV/m which means the drive bunch energy loss is, 114/16.5=6.9MeV/m. All the values are calculated with four longitudinal modes included, but the dominat contribution is from the fundamental mode because the structure was intentionally designed to minimize the loss factor of all high order modes (HOM). This is very important for the drive bunch to achieve a high transformer ratio, as well as to mitigate the self wake inside the main beam (the main beam has much shorter bunch length which is prone to excite HOMs).

Two major factors were considered in the choice of the main bunch parameters: 1) to minimize beam loading the main bunch charge was made as high as possible without causing a serious drop in the net gradient; 2) to maximize beam brightness we kept the charge as low as possible to yield small energy spread and a short bunch. A short bunch makes it easier to minimize the energy spread. The self wake from the main beam depends on the wakefield structure, is proportional to the charge, and inversely proportional to the bunch length. In the collinear wakefield acceleration scheme, both the drive and main beam share the same beam channel. In general, while the structure is optimized to maintain a single mode excitation for drive beam, multiple modes are excited by the main beam due to its shorter bunch length. But the self wake inside the main beam will converge very fast because loss factor of HOMs become negligible after the first few modes. 50 pC/ bunch and 5 μm bunch length (*r.m.s.*) are chosen in the design is to allow a reasonable beam loading and ~1.2 kA peak current. Another critical parameter of an accelerator is the efficiency. The overall efficiency of the proposed scheme can be roughly estimated by cascading the efficiencies of each subsystem, for example, klystron AC-to-RF efficiency, RF-to-drive beam efficiency, and drive-to-main beam efficiency, etc. The drive-to-main beam efficiency, 37.5%, can be obtained using the parameters in the layout. If we assume 50% efficiency for each of other subsystems, the overall wall plug efficiency is around 5~10% with consideration of power consumption from the cooling, magnets, and infrastructure, etc.

BEAMLOADING AND ENERGY SPREAD

In a collinear wakefield acceleration scheme, the structure radius, *a*, is chosen to be small so that the drive beam excites a strong wakefield. However, because the bunch length of the main bunch is shorter than that of the drive, the main beam self wake (deceleration) can be severe so single bunch beam loading must be considered. Figure 2 shows the overall wakefield plot with a main bunch trailing behind the drive bunch. Due to the main beam's short bunch length (~5um, *r.m.s*), we included 10 modes in the calculation even though only the first 5 modes contribute to the main beam wakefield. Based on calculations, ~10 MeV centroid (i.e. mathematical expectation) energy loss per 10-cm long structure is obtained and the induced correlated energy spread of a monoenergetic injected beam (i.e. standard deviation) is ~150 keV. Considering the same rate of acceleration through the entire linac we calculate~1.5% energy spread in the bunch at the end of the linac. This is inconsistent with the FEL operation, but may be manageable since this energy spread is correlated along the electron bunch. Further studies will address this issue, in particular, means to reduce energy spread and also possibilities of utilization of the correlated energy spread using tapered undulator in the FELs.

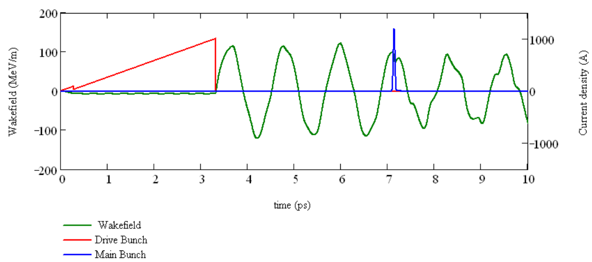

Figure 2: Wakefield due to drive and main bunches.

For example, one way to reduce the beam loading and, thus, the correlated energy spread, would be to increase the bunch length of the main beam. One could imagine accelerating a long bunch length main beam through the accelerator and then compressing it before the entrance to the FEL. A question that also needs to be studied is to what extent the effect of the increased energy spread can be offset by running off crest through the part of the DWA.

THERMAL ESTIMATION AND COOLING

Note that in the ~THz regime, the rf attenuation is very high so that the wakefield power will be exhausted in 10 cm. This means that the rf packet generated by a drive bunch is only 333 ps long. The single layer DLA structure has a low electric field in the dielectric (Es ~1.7Ea, where Ea is the accelerating field) but a high magnetic field on the metal surface. Therefore, the rf power is mostly dissipated in the copper surface and dielectric losses contribute little for the low loss materials considered here.

Two types of thermal issues were considered when designing the accelerator: rf pulsed heating and average thermal heating. Pulse heating is an instantaneous phenomenon occurring primarily within a skin depth of the metallic surface. Rf pulse heating usually is not an issue for wakefield accelerators due to the short rf pulse length from the drive bunch. The temperature rise from rf pulse heating is only 17 ºC (conditions: 100 MV/m of the loaded gradient corresponding to 680 kA/m peak magnetic field at the copper surface, 100 ps square pulse length (to simulate the 333 ps heavily attenuated pulse)).

Average thermal heating is a temperature rise in the volume of the accelerating structure due to rf power dissipation. This is the main factor limiting repetition rate of the conventional s-band and x-band high energy gradient accelerators. Fortunately, the problem is much less severe in the DWA because of a small amount of energy used to excite the wakefileds and a short period of time that the wakefield remains inside of the structure (results of the short structure, high group velocity, and high loss in THz range). Calculations based on the parameters in Fig. 1 show that the average power load from the wakefiled on the copper tube holding the dielectric tube is ~ 50 W/cm^2. This power can be easily handled by conventional water cooling providing less than 0.5 ºC temperature rise across the copper as seen in Figure 3.

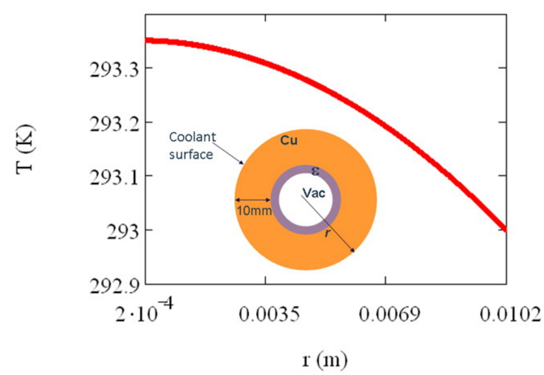

Figure 3: Estimated temperature rise from the dielectric surface to the 293ºK cooling surface.

SUMMARY

It has been shown that the collinear dielectric wakefield accelerator is a viable candidate for an accelerator for a light source facility with multiple FELs. It is reasonably compact, inexpensive, and can support FEL producing up to 10^5 x-ray pulses per sec. The straw man design considered here established the feasibility of this approach, but left many unanswered questions for future R&D.

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