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STUDY OF A DIELECTRIC DISK STRUCTURE FOR SHORT PULSE TWO-BEAM ACCELERATION

J. Shao[1,*], C. Jing[1,2], J. Power[1], M. Conde[1], and D. Doran[1]
[1]Argonne National Laboratory, Lemont, IL 60439, USA
[2]Euclid Techlabs LLC, Bolingbrook, IL 60440, USA

Abstract

Argonne Flexible Linear Collider (AFLC), a proposed 3 TeV electron-positron linear collider based on two-beam acceleration (TBA) scheme, applies a short pulse length (~20 ns) to obtain a high accelerating gradient (267 MV/m) and a compact footprint (~18 km). The baseline design of the main accelerator section adopts 26 GHz K-band traveling-wave dielectric-loaded accelerators (DLA) with an rf to beam efficiency $\eta_{rf-beam}$ of 27%. Recently, an alternative structure which is similar to a metallic disk-loaded one but with dielectric disks, noted as dielectric disk accelerator (DDA), has been investigated and optimized, leading to ~45% improvement in $\eta_{rf-beam}$. To demonstrate the key technologies, an X-band prototype structure has been designed and will be tested at Argonne Wakefield Accelerator (AWA) facility with a 300 MW metallic power extractor. Detailed comparison between K-band DLA and DDA for AFLC main accelerator as well as the preliminary design of the X-band DDA prototype will be presented in this paper.

INTRODUCTION

Future TeV colliders in general require high construction and operation cost. To reduce the former by building a compact machine, much attention has been devoted to the research of high gradient accelerating structures. As the rf breakdown rate is exponentially proportional to the rf pulse length [1], AFLC proposes to apply a pulse length around 20 ns to achieve a loaded accelerating gradient of 267 MV/m, corresponding to 80 MeV energy gain in a 0.3 m long main accelerator unit [2]. To efficiently accelerate the main beam with such a short pulse, a 26 GHz DLA with a high group velocity (0.11 c) has been selected as the baseline design of the main accelerator section [2]. After optimization, the rf to beam efficiency is 27% and the wall to beam efficiency $\eta_{AC-beam}$ is ~9%.

In order to reduce the operation cost by increasing $\eta_{rf-beam}$, several alternative types of the main accelerator have been studied at AWA. Among the candidates, the DDA structure was first investigated in the 1950s, when researchers theoretically proved that DDA could achieve higher shunt impedance and higher group velocity than metallic disk-loaded ones [3]. An experiment by the same group also demonstrated an acceleration gradient of 2.6 MV/m with a clamped assembly [3]. For short pulse TBA in AFLC, simulation results show that $\eta_{rf-beam}$ can be significantly increased by ~45% after optimizing the disk thickness t and the dielectric constant ϵ_r of DDA. In addition to its higher efficiency, DDA is also easier for machining and tuning compared with DLA, especially for high frequency and constant gradient structures. An X-band prototype has been designed to test the key technologies of DDA, including the brazing between copper and dielectric, the machining and tuning method, the multipacting and charging effect, and the resistance to high surface electric field. The prototype will be driven by an X-band metallic power extractor at AWA with a maximum power of 300 MW and a pulse length of ~10 ns.

* jshao@anl.gov

K-BAND DDA FOR AFLC

The global repetition of AFLC is designed to be 5 Hz and the local repetition within the 100 μs giant beam pulse is 20. The main beam train has a duration t_m of 14.4 ns, consisting of 187×0.5 nC bunches. The main bunches are launched every other 26 GHz rf cycle to mitigate the beam loading effect, resulting in a beam current I_m of 6.5 A. The average main beam power is 28 MW, same as the CLIC project. Each main accelerator unit is driven by a 0.3 m long 26 GHz dielectric power extractor which extracts rf power from a 1.3 GHz drive beam. The drive beam loses 95% of its energy in 38 power extractors before dumping. The power extractor has a group velocity of 0.25 c, a quality factor of 2950, and r/Q of 9.8 kΩ/m. More details of the AFLC design can be found in Ref. [2].

In the main accelerator optimization, the parameters of the main beam and the design of the power extractor are fixed; the charge, the energy, and the bunch number of the drive beam have been adjusted to meet the output power P_{rf} and the pulse length t_{rf} requirements as following.

The energy gain of the accelerator unit is set to 80 MeV and can be expressed as

$$u = \sqrt{2P\eta_{wg}Z_aL_a}\frac{1-e^{\tau_a}}{\sqrt{\tau_a}} - Z_aI_mL_a(1-\frac{1-e^{\tau_a}}{\tau_a}) \quad (1)$$

where η_{wg} is the waveguide efficiency considering rf loss, Z_a, L_a, and τ_a are the shunt impedance, the length, and the attenuation parameter of the accelerator, respectively.

The pulse length of the generated rf power from the power extractor follows

$$t_{rf} = t_m + \frac{L_a}{v_{g,a}} - \frac{L_a}{c} \quad (2)$$

where $v_{g,a}$ is the group velocity of the accelerator. The rising and falling time caused by the limited coupler bandwidth are not taken into consideration.

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For simplicity and clarity in comparison, the accelerating structures are designed to be the constant impedance type with a fixed length of 0.3 m. The aperture size is set to be ϕ3 mm. The dielectric loss tangent is assumed to be material independent and is fixed at 1×10^{-4}. In addition, the beam loading compensation is not taken into account when calculating the efficiency.

The section view of DLA and a single cell in DDA are illustrated in Fig. 1. DLA applies a uniform dielectric tube with copper coating on the outer wall; DDA applies similar design as the well-developed metallic disk-loaded structure but with dielectric disks.

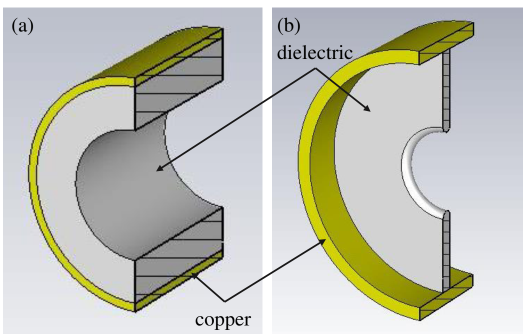

Figure 1: The section view of structures. (a) DLA; (b) A single cell of DDA.

DLA works at π mode in which the electric field on axis has uniform amplitude and linear phase. DDA can work at an arbitrary mode depending on the boundary condition. For comparison in this paper, DDA is designed to be operated in $2\pi/3$ mode. For given aperture size and length, ϵ_r is the only adjustable parameter in DLA. In contrast, DDA can optimize both ϵ_r and t, as shown in Fig. 2. With a high dielectric constant (ϵ_r ≥50) and a thin disk (t=0.5 mm), the $\eta_{rf-beam}$ of DDA is ~50% higher than that of the optimized DLA.

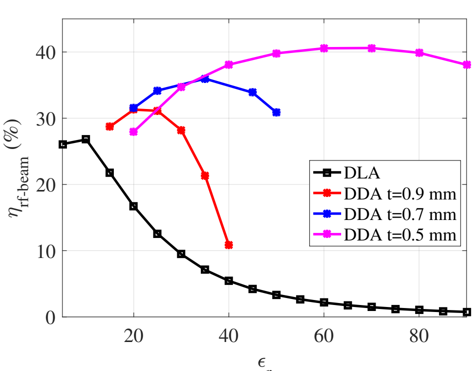

Figure 2: $\eta_{rf-beam}$ as a function of the dielectric constant in different structures.

In reality, material with a dielectric constant of 50 and a loss tangent of 5×10^{-4} is commercially available (D-50 Ba-Ti from SKYWORKS). A detailed comparison of the optimized DDA with this material and the AFLC baseline DLA is listed in Table 1.

Table 1: Comparison Between the Optimized K-band DLA and DDA

	DLA	DDA
Dielectric outer diameter	4.99 mm	9.23 mm
Dielectric long. dimension	300 mm	0.5 mm
Dielectric trans. thickness	1 mm	3.12 mm
Dielectric constant	9.8	50
Dielectric loss tangent	1×10^{-4}	5×10^{-4}
Group velocity	0.11 c	0.16 c
Quality factor	2295	6430
r/Q	21.8 kΩ/m	32.5 kΩ/m
r	50.0 MΩ/m	208.8 MΩ/m
Required input power	1.22 GW	0.96 GW
$\eta_{rf-beam}$	27%	39%
$\eta_{AC-beam}$ [1]	~9%	~13%
E_{max} [2]	365 MV/m	660 MV/m
Beam loading parameter	15.5%	17.1%

DDA has several remarkable advantages over DLA for short pulse TBA in AFLC. 1. High efficiency: The wall to main beam efficiency of AFLC can be increased by ~45%, while the beam loading parameter remains below 20%. 2. Simple machining: The dielectric disks in DDA are easier for machining than the high-aspect-ratio dielectric tube in DLA. 3. Easy tuning: DDA can be tuned with the standard method developed for metallic disk-loaded structure; DLA requires more complicated and delicate methods [4]. 4. Constant gradient structure: For linear collider, constant gradient structures are more favorable than constant impedance ones for efficiency concerns. Similar to metallic disk-loaded structures, DDA can apply tapered iris for each individual cell to obtain a constant gradient. In contrast, the whole tube of DLA has to be tapered which is much more difficult for machining and tuning.

In spite of the outstanding merits, DDA has three major issues to be addressed by high power testing prototypes. 1. The brazing between the dielectric disk and the copper jacket requires careful design and tests to avoid field enhancement at the dielectric-metal-vacuum joint. 2. The surface electric field is enhanced on the iris, which may lead to rf breakdown. 3. The multipacting and charging effect of the specific material remains unknown.

X-BAND DDA PROTOTYPE

Currently, several power extractors are available at AWA to provide short rf pulse for high power tests, including the 55 MW K-band dielectric one [5], the 105 MW X-band di-

[1] Assume the wall power to klystron efficiency to be 55%, the klystron to drive beam efficiency to be 86%, the drive beam to K-band rf efficiency to be 77%, and the K-band waveguide loss to be 5%.

[2] Maximum unloaded surface electric field. Apply elliptical rounding to the iris of DDA.

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electric one [6], and the 300 MW X-band metallic one [5]. The last one has been chosen to drive the prototype due to its highest power.

The design of a single cell in the X-band traveling-wave DDA prototype is illustrated in Fig. 3. It operates at 11.7 GHz and $2\pi/3$ mode. In order to study the resistance to rf breakdown in the regime of 600-700 MV/m, a long nose-cone has been added onto the disk to remarkably enhance the electric field. A groove has also been added to the copper jacket to hold the dielectric disk.

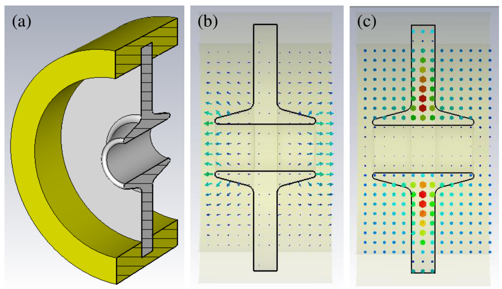

Figure 3: A single cell of the X-band DDA prototype. (a) Section view; (b) Electric field distribution; (c) Magnetic field distribution.

The detailed parameters of a single cell of the prototype are listed in Table 2.

Table 2: Parameters of the X-band DDA Prototype

Parameter	value
Disk thickness	1.5 mm
Aperture	ϕ3 mm
Group velocity	16.5%
Quality factor	4040
r/Q	22.4 kΩ/m
E_{max}/E_0	7.1
E_{max} (200 MW input)	580 MV/m
E_{max} (300 MW input)	710 MV/m

The prototype consists of 6 normal cells and 2 matching ones, as illustrated in Fig 4. The total length of the normal cells is ~51 mm and the filling time is ~1 ns.

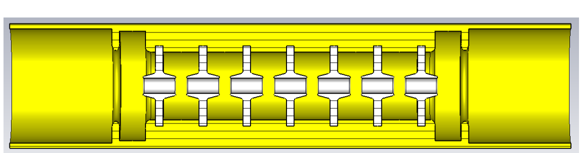

Figure 4: Section view of the X-band DDA prototype without couplers.

The -10 dB bandwidth of the structure together with the SLAC-type coupler is ~300 MHz, adequate for the ~10 ns input rf pulse. The amplitude and the phase of the on-axis electric field are illustrated in Fig. 5.

The X-band DDA prototype is currently under engineering design and the high power test will be performed soon.

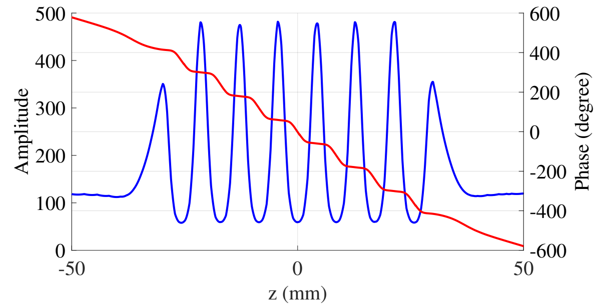

Figure 5: Distribution of the amplitude (blue) and the phase (red) of the on-axis electric field in the X-band DDA prototype. The power is fed from the left.

CONCLUSION

Dielectric disk accelerator is a promising structure for short pulse two-beam acceleration. By optimizing the disk thickness and the dielectric constant, the wall power to main beam efficiency of AFLC has been improved by ~45%, reaching ~13%. Further improvement by operating the DDA at other modes is currently under investigation. DDA also has the merits of simpler machining and tuning compared with DLA. An X-band prototype, driven by a 300 MW metallic power extractor at AWA, has been designed to test the key technologies of DDA. Research to further improve the TBA efficiency by main beam bunch shaping with the emittance exchange beam line [7] is also ongoing at AWA.

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