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A PORTABLE X-RAY SOURCE BASED ON THE DIELECTRIC ACCELERATOR

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Abstract

The portable low energy accelerator based X-ray sources have attractive applications in the non-destructive examination as a replacement of radiological gamma isotope sources. We are developing an inexpensive ultra-compact dielectric accelerator technology for low energy electron beams. The portability in the realm of this proposal is unprecedented ~ 1 *ft*^{3} volume with ~ 50 *lbs* of weight. The use of ceramics makes the transverse size of the accelerating waveguide comparable to that of a pencil. Because of this size reduction, additional weight reduction of shielding becomes possible. The article will report on the progress of this project.

INTRODUCTION

Modern mobile cargo inspection systems utilize a similar, few - MeV electron linear accelerator (linac) and are truck mounted: the RF power system (magnetron, modulator and cooler) for a conventional accelerator weighs at least 500kg and the accelerating structure with shielding and X-ray target weighs at least another 500kg. The ultimate goal is to make the system almost two orders of magnitude lighter at the expense of beam power. This corresponds to going down from the truck mounted system's 1 kW electron beam to about 20 W beam power. The kinetic energy of the beam has to stay at 1-4 MeV level to allow production of high energy x-rays (hence deep penetration), so the current is allowed to be low, 10-50 μA. To achieve 1-4 MeV beam energy relatively high peak power RF is needed. Going to high frequency, the weight and volume of the structure can be reduced, scaled by approximately $1/f^2$. In this project, we focus on a light weight solution for a ~ 10 GHz source because much higher peak power is available, manufacturing tolerances are reasonable, cell to cell coupling is not a problem with the tuning procedures developed, and our proposed solution is truly compact. We propose the use of an X-band 200 – 250 kW peak air traffic control radar magnetron as the power source for our compact accelerator. The average power of this magnetron is only ~220 W due to its low duty cycle. Magnetron efficiency is on the order of 40% which means that modulator will consume ~ 600W. Including the overhead for cooling etc, the 1 kW total power budget can be provided for 1 hour with a compact ~7 kg Li-ion battery. The parameters of a *minimum weight 1 MeV accelerator* seem to be in-line with the desired 1 ft^3 / 50 lbs target, provided that a light weight accelerating structure can be demonstrated (see Fig.1 as an illustration of the portable accelerator based X-ray source). This condition on the light weight accelerating structure is a key one. Recent approaches to compact accelerator development [1, 2] took the same route reducing the system weight as outlined above. However, they used a traditional iris-loaded copper structure, arriving to a ~50 kg "x-ray head" unit that only includes accelerator and x-ray target with collimator. As the weight could not be reduced further due to the weight of accelerating structure and its shielding, the design evolved to a three module, "man-portable" system – "battery", "modulator" and "x-ray" head. Each unit ~ 50 kg heavy, but can be moved around and setup by two technicians. The x-ray head weight is essentially fixed, hence there is no incentive to minimize weight of the other two units and instead the beam power is maximized, while keeping other units also weight at around 50 kg. If a light weight accelerating structure can be made, the "battery" and "modulator" can be re-optimized for lower weight (consequently lower power), but the whole system can be merged into one portable unit.

Figure 1: Artistic view of a portable accelerator based radiation source.

THE DIELECTRIC ACCELERATOR

Recently Euclid designed and patented an inexpensive ultra-compact accelerating structure based on a waveguide partially loaded with dielectric [3] – dielectric loaded accelerator (DLA) and a hybrid dielectric – iris – loaded waveguide (Hybrid DLA - HDLA). The use of high permittivity ceramics reduces the transverse size of the cavity significantly (Figure 2), making the accelerating structure thickness comparable to the thickness of a pencil. Typical X-band cavity has OD ~ 5 cm, while DLA ~ 1 cm, area-wise size is reduced ~ 25 times at the expense of small length reduction. This results not only in a sizeable weight reduction of the structure itself, but even more importantly, a reduction of the volume to be contained in lead, i.e. OD of lead shield.

Dielectric loaded accelerating structures were proposed half century ago, but the idea did not gain attraction because of concerns that electron beam would charge the ceramic structure. The enabling factor for the proposed

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approach is that for the case of a minimum weight accelerator, the beam current is a miniscule 10-50 µA, manageable for ceramic structures. The recent experimental investigation (see Fig. 3) reveals that the electrons on the ceramic surface will be rapidly dissipated once the longitudinal electric field of accelerating field (e.g. TM01 mode) applied.

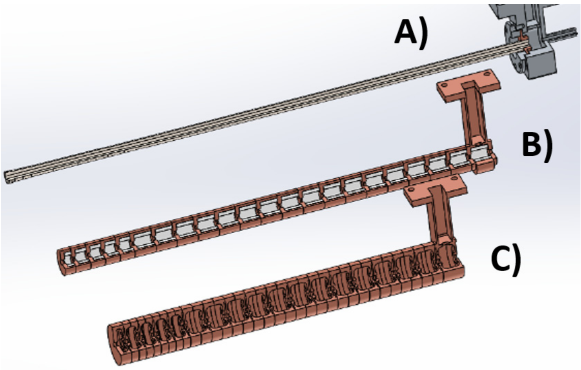
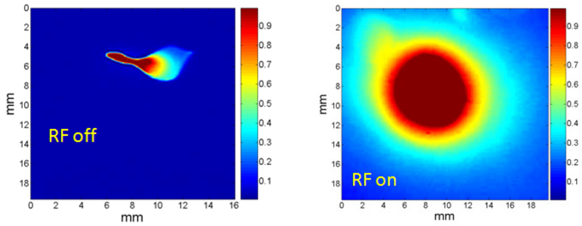


Figure 2: a) DLA b) Hybrid - HDLA and c) All-metal structure on the same scale.



(a) (b)

Figure 3: The beam out of the DLA structure when (a) RF drive is off. (b) RF drive is on.

Figure 4 illustrates a concept of a standing wave low energy DLA structure. The dielectric tube has a uniform beam aperture but is divided into three axial segments. The outer diameter (OD) and length of each of these sections is selected to match the increasing velocity of the accelerating particles. To keep the dielectric surface at constant ground potential the dielectric structure is metalized with a thin copper layer. A metal-ceramic braze joint at the ends is applied to connect to vacuum flanges and provide the vacuum seal.

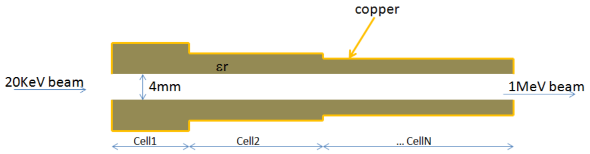


Figure 4: Illustration of a low beta 9.4 GHz π mode standing wave dielectric accelerator.

Table 1 shows the parameters we are aiming for. Figure 5 shows the profile of the accelerating field. The beam aperture of the DLA is uniform but the outer diameter varies in several sections according to the accelerated electron velocity. The injected beam is a 20keV DC beam. The simulation shows that around 40% of the beam is bunched and accelerated to 1MeV after 32cm of acceleration. It is worth to point out that a ~500Gauss solenoid field applied in the simulation. The beam capture rate is ~11% without the external solenoid field applied.

Table 1**:** Tentative Parameters of for the Developed DLA (subject to change with other practical constrains)

Input energy	20 keV
Input current	10 mA
Number of cells	6
Total Length	32.70 cm
Total power	253.0 kW
Mean energy after this Section	1.01MeV
Dielectric constant	16.7
ID	4.0 mm
Max. OD	11.5 mm

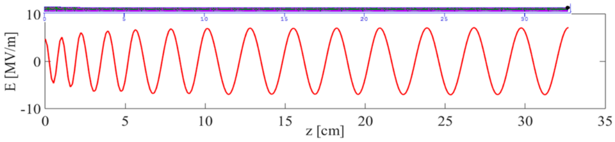


Figure 5: Simulated accelerating field profile of the 1MeV dielectric accelerator.

THE DLA ENGINEERING DESIGN

As shown in Fig. 6, a Field Emission cathode needs to be integrated as a part of RF coupler design so that it can be powered by the same RF drive as the accelerator. It provides a bunched beam, therefore has a higher efficiency. It also eliminates the need of heater in a thermionic electron source (saving the battery).

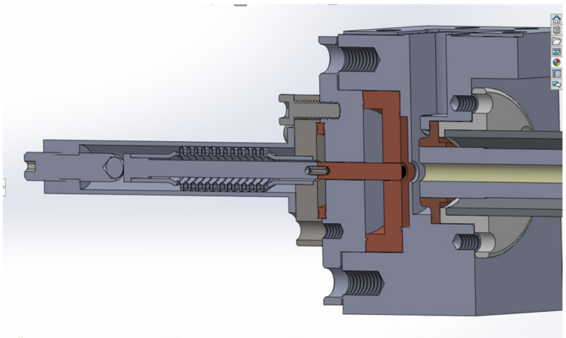


Figure 6: The 3D engineering design of the 1MeV DLA.

Euclid developed an X-band FE cathode gun two years ago [4], in which a spring was used to prevent the rf leakage through the gap between the cathode plug and its receptacle hole on the gun body. However the spring is too soft for that size (a few mm) which is easy to be distorted during the assembly thus vulnerable to rf breakdowns. Therefore, we plan to use a choke in place of spring in the 1MeV accelerator design. A knife edge is designed for sealing the rf. The uniqueness of this design is the no need of brazing. The rf coupler is made of stainless steel then plated with copper for raising the quality factor. The dielectric tube is metalized and soldered to a copper gasket. A stainless steel flange presses the copper gasket against the rf coupler to seal the vacuum and rf.

THE PREVIOUS RESULTS AND NEXT

A pilot low energy DLA test was conducted to evaluate the design. Figure 7 shows the beam test setup in the Euclid facility. The vacuum was ~4e-7 Torr during the test and 60kW rf power was fed into the structure to boost the available 100KeV DC beam to 500KeV in a ~10cm long DLA with a capture rate of 40%. No RF breakdown occurred during the test but the multipactor persisted. Using a permanent magnet solenoid, the multipactor was significantly suppressed by a few hours of conditioning. Based on the displacement after the Steering coil at two different current settings, we estimate the kinetic beam energy is 459KeV, which is very close to the 500KeV in the simulation. Beam current is well preserved when RF is on.

All the knowledge and experiences gained from the previous test have been used to improve the 1MeV DLA design. The needed hardware for the 1MeV portable X-ray source is under fabrication. We expecet to have the first test by fall 2018.

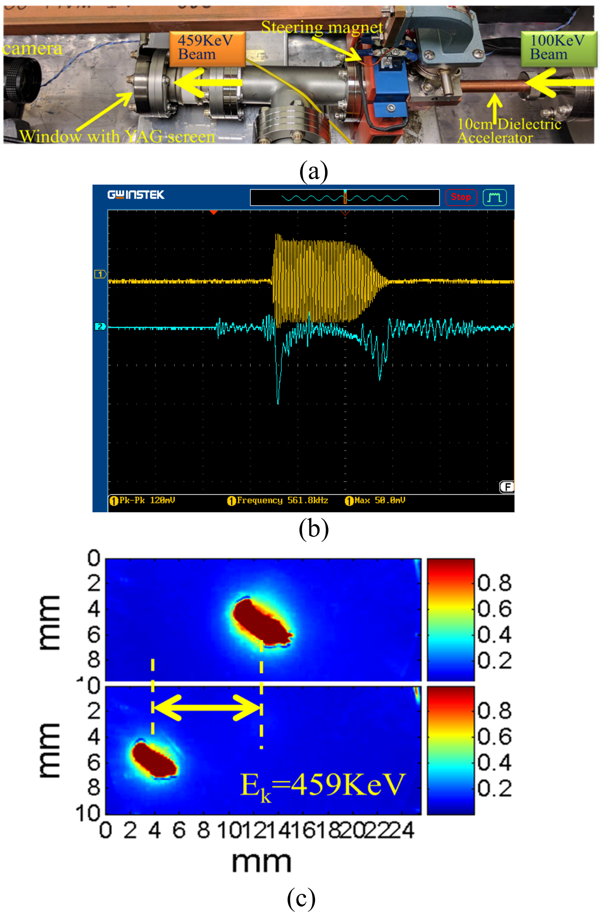


Figure 7: (a) The beam test set up of the dielectric accelerator at Euclid. (b) rf traces: yellow—the forwarded rf pulse after the frequency down-conversion; blue—the reflected rf pulse after a diode rectification. (c)Beam image at the downstream YAG with two different steering coil currents.

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