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# A CONCEPTUAL DESIGN OF A COMPACT WAKEFIELD ACCELERATOR FOR A HIGH REPETITION RATE MULTI USER X-RAY FREE-ELECTRON LASER FACILITY*

A. Zholents†, S. Doran, W. Jansma, M. Kasa, R. Kustom, A. Nassiri, J. Power, S. Sorsher, N. Strelnikov, K. Suthar, E. Trakhtenberg, I. Vasserman, G. Waldschmidt, J. Xu,
Argonne National Laboratory, Lemont, IL, USA
S.S. Baturin, the University of Chicago, PSD Enrico Fermi Institute, Chicago, IL,USA
H. Perez, Illinois Institute of Technology,Chicago, IL,USA

*Abstract*

A preliminary design of a collinear wakefield accelerator is described. It is assumed that the array of such accelerators will play a central role in a free-electron laser-based x-ray user facility under consideration at Argonne National Laboratory [1].

## FACILITY DESCRIPTION

Fig.1 shows a schematic of a multi-user hard x-ray facility. There are five major components: the drive bunch accelerator (DBA), the switch yard, the array of collinear wakefield accelerators (CWAs), the array of the free-electron lasers (FELs), and the array of x-ray beamlines and experimental end stations.

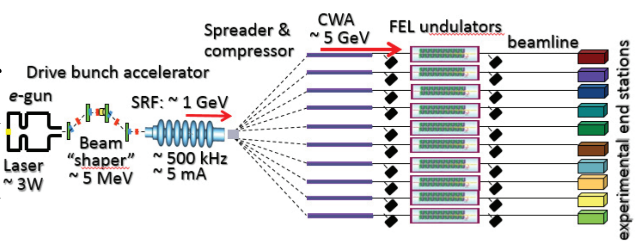


Figure 1: A schematic of the facility showing up to ten individual CWAs, FEls and beamlines.

Each CWA employs a Čerenkov radiation of a ~ 10 nC drive bunch in a retarded media formed by a corrugated waveguide to create ~ 100 MV/m accelerating field for the ~ 0.3 nC charge witness bunch that follows behind. Both the drive and the witness bunches are supplied by the DBA whose components are a high-charge, high repetition rate photocathode electron gun, a beam "shaper," and a CW superconducting rf linear accelerator (linac). The beam "shaper" beamline is used to prepare a sharply asymmetric electron charge distribution along the bunch length, which is critical for CWA efficiency. After obtaining ~1 GeV at the end of the linac, the pairs of the drive and witness bunches are directed in up to ten CWAs employing spreader beamlines and are further compressed in the process. In the CWAs, the drive bunches are decelerated to ~200 MeV and the witness bunches are accelerated to ~5 GeV. In the next step, drive bunches proceed into the dumps and the witness bunches proceed into their respective FELs where they subsequently produce x-ray pulses with many gigawatts of a peak power. All CWAs and downstream FELs can be individually tuned. The maximum possible bunch repetition rate in the CWA determined by the ability to cool the corrugated waveguide is ~50 kHz. Therefore, the maximum bunch repetition rate in the DBA is ~500 kHz and the maximum average beam current is ~5 mA. The operation of SRF linac at 800 MeV with an average beam current of six milliamperes during 800 microseconds RF pulse had been demonstrated [2]. Although this is already a large current, the electron gun and the injector of the DBA has to produce an even larger current to compensate for inevitable particle losses during bunch shaping [3]. Therefore, optimal shaping techniques remains the focus of active research with the goal of minimizing these losses [4]. In this paper we report only on the work related to the design of the CWA.

## DESIGN OF THE COLLINEAR WAKEFIELD ACCELERATOR

For the CWA to be an efficient accelerator, the maximum accelerating field behind the drive bunch, $\max|E_+|$, must be much higher than the maximum decelerating field inside the drive bunch, $\max|E_-|$, in which case the energy obtained by the witness bunch by the time the drive bunch is completely depleted of its energy will be higher than the initial energy of the drive bunch by a factor $R = \max|E_+|/\max|E_-|$ known as a transformer ratio. This is accomplished by using the drive bunch with an asymmetric electron distribution along the bunch length [5] and an example of a such distribution is shown in Fig.2. It was pointed out in [6] that the highest transformer ration equal to $R \simeq \sqrt{1 + k^2 l^2}$ is obtained by using the electron distribution that produces an identical decelerating field for all electrons inside the drive bunch and by using the waveguide where a fundamental axial mode dominates all other wakefield modes excited by the drive bunch. Here $k = 2\pi/\lambda$ is the wave vector and $\lambda$ is the wavelength of the fundamental axial wakefield mode of the corrugated waveguide, and $l$ is the base of the electron density distribu-

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† azholents@anl.gov

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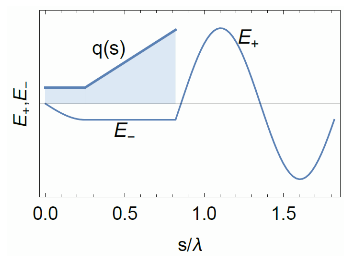


Figure 2: Electron charge distribution $q(s)$ proposed in [5] shown as a filled area; the corresponding accelerating and decelerating field shown by the blue curve.

tion shown in Fig.2. It is also important to have a constant $E_-$ in as much the long part of the bunch length as possible and to let the majority of the electrons to lose their energies with the same rate.

The same study [6] also shows that the high transformer ratio always bound to a simultaneous reduction of $\max|E_+|$, i.e.

$$\max|E_+| \lesssim \frac{4\kappa_{\|}|Q|}{R}, \quad \text{when } R > 2\,, \tag{1}$$

where $Q$ is the total charge of the drive bunch and $\kappa_{\|}$ is the loss factor of the point particle per unit length of the corrugated waveguide.

Moreover, in any CWA there is a threshold $Q$ above which the drive bunch cannot be stably decelerated all the way down to a small fraction of its initial energy due to the onset of a beam breakup instability (BBU) caused by the transverse wakefield. The stability condition was recently studied in [7] where it was shown that the CWA has to be embedded into the quadrupole wiggler with alternating focusing and defocusing quadrupoles (shown in Fig. 3) in order to be able to decelerate bunches with the large $Q$ and to deliver a large $\max|E_+|$.

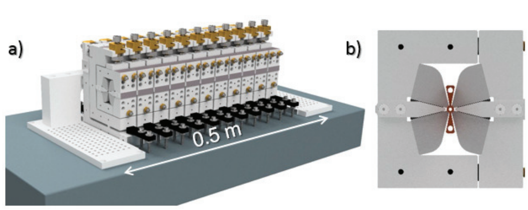


Figure 3: An accelerator module and a front view on the permanent magnet quadrupole and the vacuum chamber.

The drive bunch also has to be prepared with the energy chirp satisfying the condition writen below, and the relative value of this chirp has to be maintained during its deceleration as described in [7].

$$\left|\frac{\Delta\gamma}{\gamma}\right| \gtrsim 3\frac{a_m}{ka^2}\frac{\max|E_+|}{cB_0}. \tag{2}$$

Here $\gamma$ is the beam energy and $\Delta\gamma$ is the head-to-tail energy variation, where the head has higher energy, $B_0$ is the quadrupole's pole tip magnetic field, $a_m$ is the quadrupole's bore radius, $a$ is the corrugated waveguide's bore radius, and $c$ is the speed of light. However, even if drive bunches with a very large $\Delta\gamma/\gamma$ can be delivered by DBA, it does not necessary guarantee that the high $\max|E_+|$ will be obtainied as one deduces from Eq. (2). This is because a large $\Delta\gamma$ results in appearance of a low enregy electrons in the bunch tail and the over-focusing of those low energy electrons by the quadrupole wiggler may cause their losses (see, [7] for more detail). Therefore, a practical limit for $\Delta\gamma/\gamma$ is $\sim (10-15)\%$ in which case a practical limit for $\max|E_+|$ calculated using $a$=1mm, $a_m$=1.5 mm and $B_0 \approx 1.5$ T lies in the range of (70-100) MV/m depending on the choice for $k$.

Fig.3 shows a 0.5 m long CWA module that contains a copper vacuum chamber with a 2 mm ID corrugated waveguide and a high magnetic field gradient quadrupole wiggler. Fig.4 shows a design of the vacuum chamber with the corrugated waveguide in the middle and cooling water channels above and below. We note that cooling efficiency largely defines the bunch repetition in CWA. Indeed, a predicted heat load from wakefields produced by the drive and witness bunches propagating the waveguide at a 50 kHz bunch repetition rate is ~20 W per linear centimeter of the waveguide. Calculations show that this power can be dissipated without excessive temperature rise and temperature variation in the chamber (see, Fig.4), but no much extra margin is left.

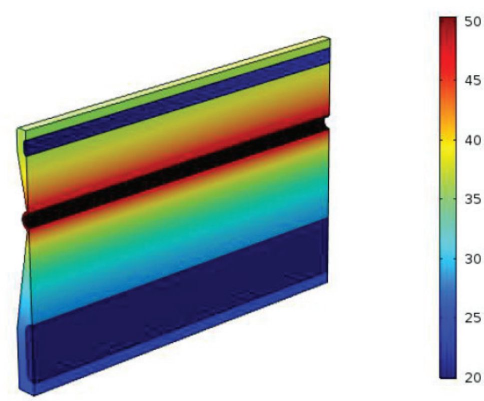


Figure 4: The vacuum chamber with the corrugated waveg-uide (half of the chamber is shown). The temperature distri-bution is shown in degrees Celsius.

Figure 5 shows a preliminary design of the corrugated waveg-uide. The fundamental axial wakefield mode of this structure is 220 GHz. Fig.6 shows the calculated wake potential ex-cited in this waveguide by the 10 nC electron bunch with a charge distribution shown in Fig.2 and with $l$=1.3 mm.

We pursued several ways of making the vacuum chamber with the corrugated waveguide shown above and one possibil-ity is to assemble it from two halves. Fig.7 shows a segment of a fabricated one half of the corrugated waveguide viewed through a high resolution microscope. In order to gain the experience with the corrugated structures and establish a corresp -ondence between calculations and measurements, we

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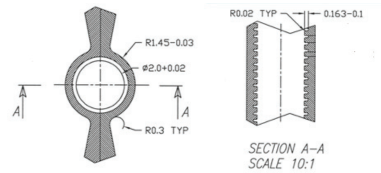


Figure 5: The design of the corrugated waveguide.

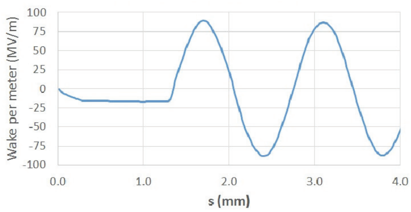


Figure 6: The wake potential function for 10 nC drive bunch calculated with ECHO code [8].

plan to build several structures scaled to ~21 GHz frequency, some with deliberate errors, and test them at the Argonne Wakefield Accelerator facility [9]. A report discussing this activity is given in [10].

The quadrupole wiggler was designed with the bore radius $a_m$=1.5 mm and the peak magnetic field gradient $G$=0.96 T/mm. Two quadrupoles representing one wiggler period were built and characterized. Fig.8 shows the quadrupoles on the magnetic measurement bench. Results of the magnetic measurements demonstrating the capability to determine the quadrupole's magnetic centers with a precision better than 1$\mu$m and other details are given in [11].

## CONCLUSION

The work on the design of the structure-based compact wakefield accelerator is progressing very well in Argonne National Laboratory. Advances have been made in the theoretical understanding of the performance limits, design and characterization of the corrugated waveguide, design and characterization of the quadrupole wiggler and overall assembly of the accelerator module. New results are expected soon.

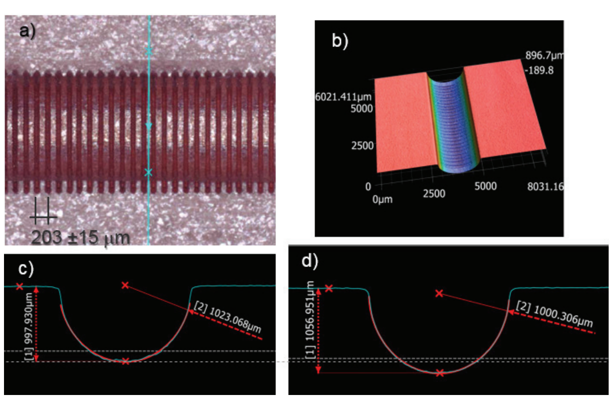


Figure 7: A segment of one half of the corrugated waveguide: a) image under the microscope, b) digital rendering, c) cross-sectional profile through a raised tooth marked by the light blue line in a), and d) cross-sectional profile through a groove.

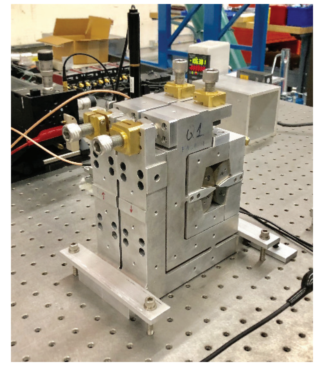

Figure 8: Two quadrupoles representing one quadrupole wiggler period on the magnetic measurement bench.

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