ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS055

ENERGY MODULATION OF ELECTRON BEAM IN CORRUGATED DIELECTRIC WAVEGUIDE

A. Lyapin, K. Lekomtsev, S. T. Boogert, S. M. Gibson, JAI at Royal Holloway, University of London, Egham, Surrey, UK
A. Aryshev, N. Terunuma, J. Urakawa, KEK: High Energy Research Organisation, Tsukuba, Ibaraki, Japan
A. A. Tishchenko, National Nuclear University MEPhI, Moscow, Russia

Abstract

Energy modulated electron beams have a wide range of applications in accelerator physics, for example they can serve as drivers in resonant wakefield acceleration schemes. A strong wakefield induced energy modulation can be produced using a dielectric lined waveguide [1], the resultant micro-bunched beam is capable of producing coherent terahertz radiation. We report on observation of energy modulation due to self-wakefields in a few picosecond duration and 1 nC charge electron bunches of LUCX facility at KEK. To produce the modulation, we used a corrugated dielectric waveguide with an inner radius of 2 mm and a period of corrugation of 10 mm. In this case, the period of corrugation is longer than the wavelength of the main accelerating mode. We show electromagnetic simulations of on-axis electric fields leading to an optimisation of the corrugation period allowing to enhance the accelerating/decelerating fields compared to dielectric lined waveguides with a constant inner radius.

DWA ACCELERATION EXPERIMENTS AT LUCX

Experimental Setup

In our experiments, the beam is first accelerated to up to 8 MeV in a 3.6 cell S-band RF gun, see Fig. 1. It then passes through the experimental chamber. The linac structure downstream is offline during our experiments, although it can produce wakefields, so a baseline measurement without a dielectric structure introduced in the beam path is usually taken with every data set. The RF gun introduces a time-energy correlation in the beam, resulting in a small energy modulation along the beam contained within the same RF bucket and resolved by the energy spectrometer consisting of a bending magnet and a YAG screen. The difference in energy between bunches of different parts of the same bunch, is simply transformed into a distance on screen. The screen can be calibrated, for example by changing the magnetic field by a known amount.

The structure used in the experiments is shown in Fig. 2. It is made of stacked up dielectric discs, where smaller inner diameter disks are used for corrugation irises. The disks are loaded in a copper sleeve which is mounted to a manipulator stage within the vacuum chamber, and can be retrieved completely for reference measurements. The dimensions are shown in Table 1: the aperture of the structure is wide enough to allow most of the particles in the beam to pass through without any parasitic interactions even at the relatively low beam energy we had in our experiments.

Table 1: Parameters of the Corrugation

Parameter	Value [mm]
r_1	2.0
r_2	2.2
r_3	2.7
L	60

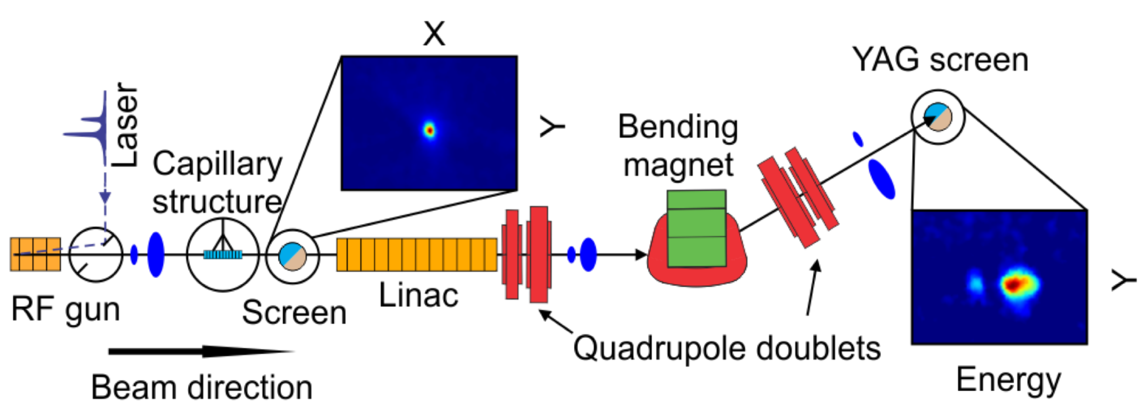

Figure 1: LUCX facility and DWA experiment.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS055

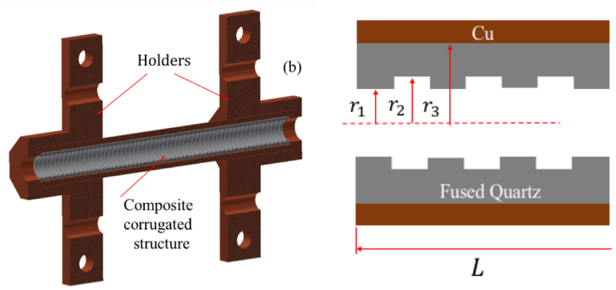

Figure 2: Grated structure a) in its holder sleeve and b) shown schematically.

Energy Modulation Measurements

We previously reported on using 2 short, mm-spaced drive and witness bunches [2]. Their spacing was scanned around the wavelength of the fundamental accelerating mode of the capillary, both with and without corrugation. We observed acceleration, but with the fs pulse laser the bunch charge was limited (20 and 6 pC for the drive and witness respectively). Therefore, our 2-bunch acceleration/deceleration measurements showed a modest gradient of about 170 keV/m.

The work is currently proceeding in 2 directions: increasing the number of available bunches for resonant acceleration and employing a different, higher power, but longer ns duration pulsed laser producing around 3 nC bunches. The latter was the subject of the last (Dec. 2018) measurement campaign. The results are still being quantified, but it is clear that there is an effect on the energy spectrum of the bunch, which is consistent with a higher accelerating gradient. Essentially, the structures worked as a de-chirper, compressing the energy spread, Fig. 3. The bunching effect is more pronounced in case of the corrugated structure. Compared to the measurements presented in [2], there was also a significant change to the structure, in that the corrugation period had been made longer, 10 mm, the reason for which is discussed in the next section.

DWA SIMULATIONS

Further simulation work continued to assess any possible advantages of both introducing a corrugation and using resonant excitation with multiple bunches. Simulations were performed with a Particle-in-Cell code VSim [3], which is designed to run computationally intensive electromagnetic simulations in the presence of complex dielectric, magnetic, or metallic shapes. However, the drive beam was represented by corresponding drive field in order to speed up the simulations and to eliminate numeric Cherenkov noise caused by the mesh size limited resolution at high frequencies [4].

Corrugated vs Flat Capillary

The discussion on the usefulness of the corrugation continues: initially, the corrugation was expected to give a significant improvement of the accelerating field as Smith-Purcell effect would potentially enhance the Cherenkov radiation from the drive beam. Seemingly, the effect we observe already bears a strong resemblance of the Smith-Purcell mechanism even in a flat structure. This may be due to the reflection of the radiated fields from the outer dielectric-conductor boundary, which causes a structured, modal composition of the resulting wake field (as opposed to an infinite dielectric with a capillary producing a broad spectrum). Both theoretical and simulation work are in progress to confirm this understanding. As part of this effort, an interesting conclusion had been reached: longer (compared to the capillary's self-resonance wavelength) corrugation periods give better enhancement to the accelerating gradient, Fig. 4.

An interesting insight one gets considering how the fields behave along the structure, Fig. 5. The accelerating field oscillates around a (slightly higher than in a flat structure, as shown in previous figure) average value. The peak field evolves with the same periodicity, equal to the period of corrugation, moving towards the drive bunch and then resetting. This may explain the better performance of the corrugated structure as a de-chirper in the experiment.

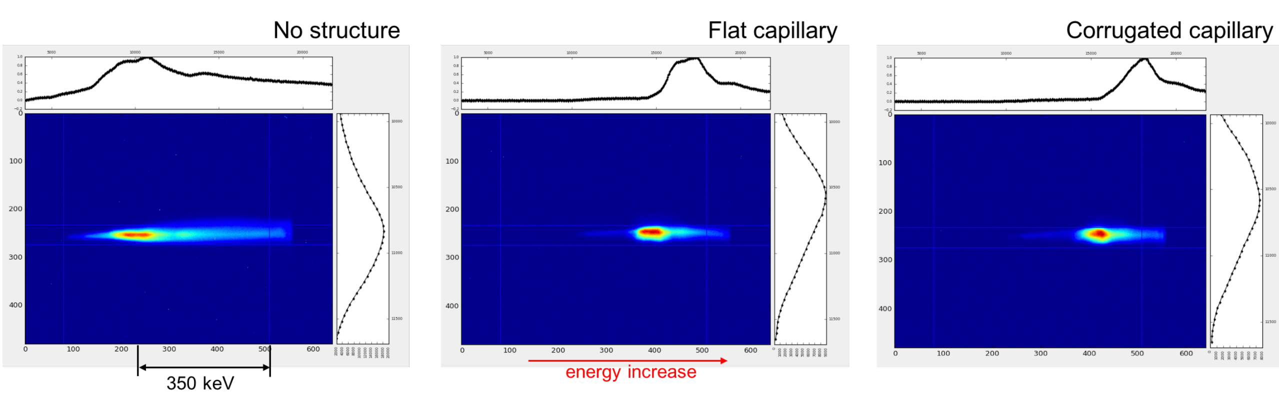

Figure 3: Energy modulation measurements: baseline measurement with no structure (left), flat capillary (middle), corrugated capillary (right).

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS055

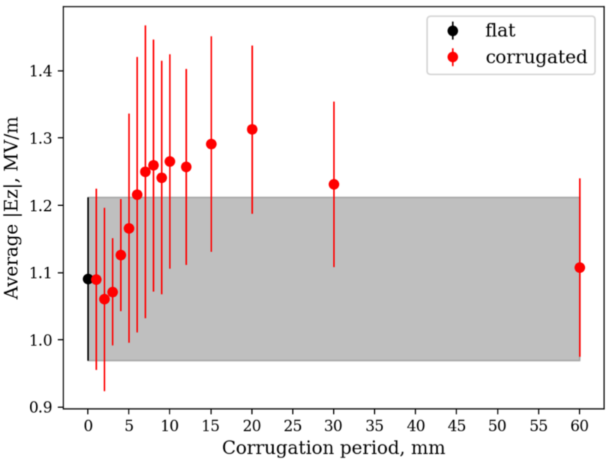

Figure 4: Average accelerating field on axis vs corrugation period.

Resonant Excitation

Resonant excitation, when several drive bunches excite the wake, can potentially lead to higher accelerating gradients. For us it is especially valuable as would allow us to achieve larger, easier to resolve, energy modulation even at low bunch charge, at present inevitable with fs bunches.

Simulations were done for up to 4 bunches, in this instance using FACET II beam parameters, see Table 2 and Fig. 6. There is a clear increment to the accelerating field with every added bunch, However, at 4 bunches the corrugated structure starts going into saturation, while the flat one experiences seemingly linear increments. However, it is early to draw conclusions as equidistant bunches where used in simulations, while it may not be optimal for the corrugated structure.

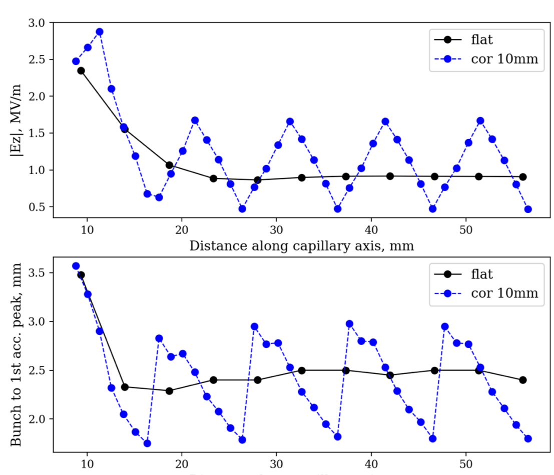

Figure 5: Accelerating field (top) and delay of the peak accelerating field with respect to the drive bunch (bottom) along the structure.

- There is an advantage in using corrugated structures vs flat ones in terms of the accelerating gradient. It is smaller than expected, possibly because there is no modification to the actual mechanism of the excitation.

Table 2: Parameters of the Resonant Excitation

Bunches	**Charge [nC]**	σ_z **[mm]**
1	5	0.3
2	1.67, 5	0.2, 0.3
3	1.67, 3.33, 5	0.2, 0.25, 0.3
4	1.25, 2.5, 3.75, 5	0.2, 0.233, 0.266, 0.3

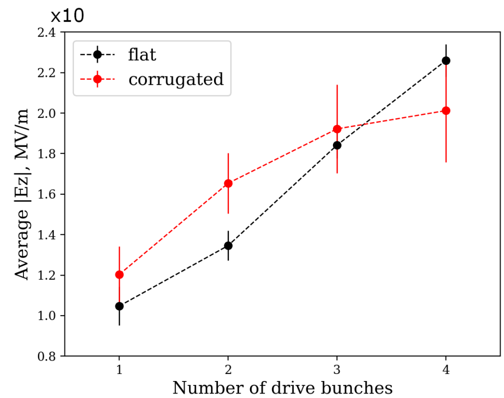

Figure 6: Scaling of the accelerating gradient in case of resonant excitation.

CONCLUSION

What we show here is obviously work in progress, however, there are some important, even though preliminary, conclusions that can be drawn:

- Longer than fundamental wavelength corrugation period causes longitudinal oscillations, which may be beneficial to both acceleration and bunching.
- Resonant excitation in combination with fs spaced bunches and smaller capillary radii seems to be the way forward for this experiment as laser technology progresses towards shorter higher power bursts that can be used for producing suitable longer higher intensity bunch trains.

REFERENCES

[1] S. Antipov *et al.*, “Experimental observation of energy modulation in electron beams passing though terahertz dielectric wakefield structures”, *Phys. Rev. Lett.*, vol. 108, p. 144801, 2012.

[2] K. Lekomtsev *et al.*, “Driver-witness electron beam acceleration in dielectric mm-scale capillaries”, *Phys. Rev. Accel. Beams*, vol. 21, p. 051301, 2018.

[3] C. Nieter and J.R. Cary, “VORPAL: a versatile plasma simulation code”, *Journal of Computational Physics*, vol. 196, no. 2, p. 448, 2004.

[4] A.D. Greenwood *et al.*, “On the elimination of numerical Cerenkov radiation in PIC simulations”, *Journal of Computational Physics*, vol. 196, no. 2, p. 665, 2004.