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ACTIVE CONTROL OF THE ENERGY CHIRP OF A RELATIVISTIC ELECTRON BEAM AT THE ARGONNE WAKEFIELD ACCELERATOR

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Abstract

A very high electron peak current is needed in many applications of modern electron accelerators. To achieve this high current, a large energy chirp must be imposed on the bunch so that the electrons will compress when they pass through a chicane. In existing linear accelerators (LINACs), this energy chirp is imposed by accelerating the beam off-crest from the peak fields of the RF cavities, which increases the total length and power requirements of the LINAC. A novel concept known as the Transverse Deflecting Cavity Based Chirper (TCBC) [1] can be used to actively impose a large energy chirp onto an electron beam in an accelerator, without the need for off-crest acceleration. The TCBC consists of 3 transverse deflecting cavities, which together impose an energy chirp while cancelling out the transverse deflection. An experiment is being developed to demonstrate this concept at the Argonne Wakefield Accelerator (AWA) facility [2]. Here we explain the concept, show preliminary simulations of the experiment, and report on progress related to implementation of the experiment at AWA.

INTRODUCTION

In conventional linear accelerators, energy chirps are imposed on the particle beam by controlling the phase of the RF accelerating cavities. Typically, the particle beam interacts with the cavity when the oscillating electric field of the cavity is off-crest, so that the peak field is diminished but there is an energy slew imparted on the bunch. This energy slew is needed so that the bunch will compress to high currents when it passes through a series of magnetic chicanes, this is especially important for free electron lasers, which must have very high electron beam current to function properly [3].

This method of chirping and compressing the electron beam works but is inefficient. By accelerating off-crest, the total RF power, colling, and total length of the machine increase by ~10%, which translates to a comparable increase in the total cost of the machine. For new proposed XFELs such as the MaRIE XFEL [4], the total cost will be ~$2B, so this cost increase translates to ~$100M.

A novel concept has been proposed to actively chirp the electron beam, which allows the bulk accelerators to be operated on crest [1]. This concept uses a set of equally space transverse deflecting cavities (TDCs). A TDC gives a transverse kick κ to the electron beam, $\Delta x' = \kappa\tau$, where τ is the time delay of a particle from the centre of the bunch (this assumes the RF phase of the cavity is perfect), and κ is proportional to the square root of the power in the cavity. This kick is seen in the right side of Fig. 1: the beam stays at a constant energy but is kicked transversely.

By the time the beam drifts to the 2nd cavity the beam has a correlation between the time τ and the transverse coordinate x. A TDC also gives an energy kick that is proportional to the transverse coordinate of the particle: $\Delta E = \kappa x$. The second cavity is reversed with kick -2κ, because of this the transverse kick is reversed at the second cavity. In addition, because the bunch has an $x - \tau$ correlation at the second cavity, it picks up the desired $E - \tau$ correlation at the second cavity.

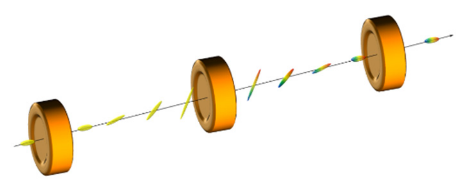

Figure 1: Illustration of our concept. Red colours indicate higher energy, and blue colours indicate lower energy. The beam enters from the left and exits to the right.

In the drift from the second cavity the $x - \tau$ correlation is removed. The third cavity has the same kick κ as the first cavity and removes the $x' - \tau$ correlation.

This concept has been demonstrated analytically and numerically using ELEGANT [1, 5], but still needs to be demonstrated experimentally.

EXPERIMENTAL PLAN

In October 2023, a collaboration started between LANL and ANL to demonstrate this concept experimentally. The project will last for three years, ending in September 2026. The goal of the project is to demonstrate the concept by inducing a chirp of at least 350 keV, and to develop a deeper understanding of the limits on the concept from timing jitter, nonlinearity and space charge through experimentation and 3D simulation. The demonstration will take place at the Argonne Wakefield Accelerator (AWA) [2]. AWA is a state-of-the-art electron accelerator that can accelerate high quality electron beams to 40 MeV with a wide

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variety of achievable beam parameters. We have selected a set of beam parameters and a set of TCAV locations for the experiment at AWA, these are shown in Table 1.

Table 1: Experimental Parameters

Parameter	Value
Beam Energy	40 MeV
Bunch Charge	0.1-1 nC
Bunch Length	5-10 ps
Center Cavity Power	9.80 MW
RMS Espread from chirp	350 keV

The experiment will reside in zone 3B and zone 5 of the AWA beamline, with 2 of the TCAVs in zone 3B and one of the TCAVs in zone 5. A final TCAV in zone 5 will be used as a diagnostic, and provide detailed diagnostics of the longitudinal phase space of the beam.

The diagnostic TCAV and one of the TCAVs used in the experiment will come from existing TCAVs at AWA. The other 2 TCAVs are currently being fabricated by Dymenso LLC in San Fransico, CA [6].

The plan is to complete the fabrication of the cavities by January 2025, and to start testing them at AWA shortly after. By spring of 2025, the plan is to begin installation of the cavities in the AWA beamline.

LOCATIONS OF TCAVS AT AWA

The locations of the TCAVs in the experiment have been selected and are shown in Fig. 2. Because of experimental necessity, the TCAVs are not equally spaced from each other: TCAV1 and TCAV2 are separated by 2.4 m, while TCAV2 and TCAV3 are separated by 3.9 m.

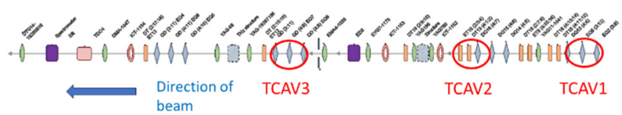

Figure 2: Location of the TCAVs in the planned experiment.

The difference in drift lengths between the TCAVs can be dealt with in 2 different ways: either quadrupoles can be used to make the effective drift length between the TCAVs the same, or by having different power levels in the first and third TCAV. We will explore both options, but our baseline design will have different powers in the first and third TCAVs. When the cavities are evenly spaced, the central cavity must have 4 times the power of the first and third cavities, so that the central cavity has -2 times the kick κ of the outer cavities. For our experimental design the three cavities have 3.63, 9.8, and 1.5 MW, respectively.

The total power needed between the 3 experimental TCAVs is 14.94 MW. This leaves 5 MW available to operate the final diagnostic TCAV in zone 5.

Fig. 3 shows an analytical calculation of the evolution of the transverse RMS size of the bunch (called x in this analysis), and the energy spread in our planned experiment. The x RMS size begins to increase dramatically after the first TCAV because of the transverse kick. After the second TCAV, this RMS spread in x is reversed because the second TCAV has the opposite phase from the first TCAV. The energy spread increases dramatically in the second TCAV and does not go away at the end of the line, this is from the chirp imparted to the electron bunch.

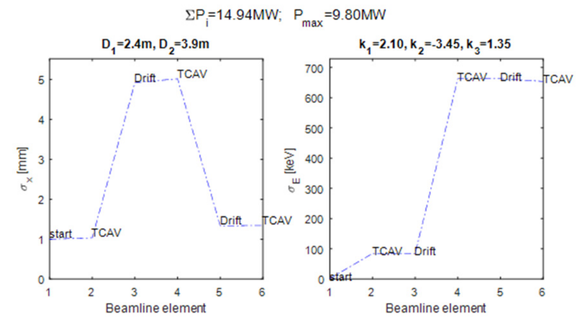

Figure 3: Evolution of the RMS transverse size (x) and energy spread in our planned experiment.

The TCAVs and the RF windows that pump power into the TCAVs should be able to handle the peak power of 10 MW. However, if for some reason we are not able to achieve this peak power than we will be able to run the experiment at a lower power. We have a lower power design where the three cavities have 1.83, 4.98, and 0.76 MW of RF power, respectively, and the final RMS energy spread from the induced chirp is 350 keV. This is still much greater than the random energy spread in AWA of ~2 keV, and large enough to easily measure in the diagnostic TCAV.

CAVITY MODELING AND RF PROBE DESIGN

The TCAVs at AWA, including the one that will be used in the experiment were designed and built at Tsinghua University in Beijing [7]. We have based the design of the 2 new cavities almost completely on the Tsinghua design, with a few small modifications. The new cavities are being fabricated by Dymenso LLC in San Fransico, CA.

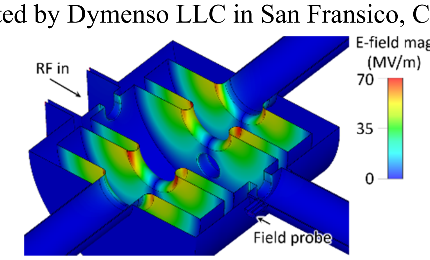

Figure 4: CST simulation, showing E-field on the surface for an input RF power of 10 MW, of the TCAVs being constructed by Dymenso LLC [6], with a design based on [7].

The cavities were modelled using CST Microwave Studio [8], see Fig. 4. Small adjustments were made to the inner radius of the cavities to ensure that the cavity operating frequency would be set at 1300 MHz. To do this, the CST simulation was set so that the model predicted 1300.3 MHz. This difference was included because the machine shop will fabricate the part at room temperature,

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but the experiment will operate at a nominal temperature of 35°C.

The tuning divots were modified slightly compared to the Tsinghua design. The diameter of the divots were increased from 20 mm to 30 mm. In addition, the number of divots was increased from 10 in the old design, so that there are now 22 divots total. The total frequency tuning range was modelled with the CST Microwave Studio. It was found that the frequency could be tuned by ±0.5 MHz. In addition, the allowable tolerances of the internal cavity dimensions were modelled using CST Microwave Studio. The internal diameters of the cavity must be set to 0.001", while most other inner dimensions are set to 0.002". Doing this gives a frequency error of +0.20/-0.26 MHz, which is less than the amount that can be adjusted by the tuning divots (this is a maximum error, not an RMS error).

AWA is designing a new Low Level RF (LLRF) system, which will decrease the RF timing jitter below the current value of 5-10 ps. This is important for our experiment, because an RF phase offset of when the electron beam interacts with the TCAVs will lead to a transverse shift in beam location.

To further reduce timing jitter, we have added an RF probe (Fig. 5) for the 2 new cavities that are being manufactured. This will allow for a feedback system to be incorporated to further reduce timing jitter. The probe was designed so that it will pick up 10 Watts of power when the cavity is at the maximum power of 10 MW input.

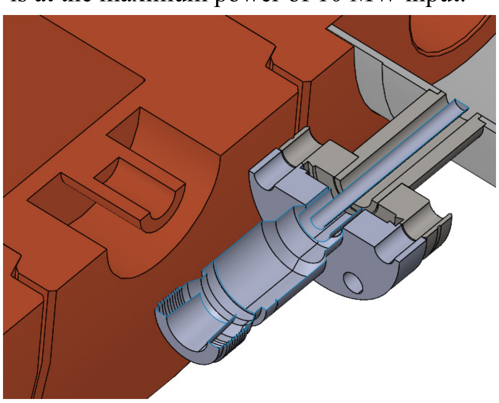

Figure 5: Model of the probe that will be used to measure cavity phase and power.

FUTURE WORK

The experiment will be modelled using the numerical particle physics code General Particle Tracer (GPT) [9]. GPT will be used because it can calculate the effects of 3D space charge on the experiment. It has been used to model the AWA facility for several years and provided good agreement with experiment. In addition, CST Microwave Studio will be used to calculate nonlinear effects in the TDC. We will model the entire experiment, including the TDC diagnostic at the end of the experiment.

The cavities are planned to be completed by January 2025. After this they will be tested at the AWA facility. Soon after this, we will begin setting up the experiment by installing the TCAVs.

CONCLUSION

An experiment has been designed to demonstrate the TCBC concept [1] at AWA. The locations of the TDCs have been selected, the power budget has been worked out, and the 2 additional cavities needed for the project have been designed and are in the process of being fabricated. The TCBC concept has the potential to reduce machine length and cost of large linear accelerators by ~5%, which translates into savings of 100s of millions of dollars.

ACKNOWLEDGEMENTS

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