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EXPERIMENTAL TEST OF SEMICONDUCTOR DECHIRPER*

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Abstract

We report the observation of de-chirping of a linearly chirped (in energy) electron bunch by its passage through a 4 inch long rectangular waveguide loaded with two silicon bars 0.25 inch thick and 0.5 inch wide. Silicon being a semiconductor has a conductivity that allows it to drain the charge fast in case if some electrons get intercepted by the dechirper. At the same time the conductivity is low enough for the skin depth to be large (on the order of 1 cm) making the silicon loaded waveguide a slow wave structure supporting wakefields that dechirp the beam.

INTRODUCTION

The free electron laser (FEL) is considered to be the main candidate for a short wavelength (UV to X-ray), short pulse (femto- to attosecond) light source. Demands on the electron beam needed to drive this class of FELs have become more and more challenging, including high repetition rate (~ MHz), high peak current (a few kA), and low emittance (sub-micron normalized emittance) [1].

Short pulses (subpicosecond) are central to many of the next generation light source initiatives that are typical of modern linear accelerators. At the same time, at the output of the last compressor the electron beam will be left with a small chirp to compensate for wakefield effects through the rest of the accelerating stages [2, 3]. Although relatively small, this energy spread needs to be compensated using a specially designed device. The use of a Cherenkov dielectric wakefield compensation scheme ("silencer") to correct the correlated energy distribution (chirp) of a short, low emittance electron bunch was originally suggested in references [4, 5]. This technology using an adjustable dielectric compensating structure can be applied to a soft X-ray FEL SRF linac. We study dielectric loaded accelerating structures as chirp compensating devices. The first dielectric loaded dechirper was demonstrated at Accelerator Test Facility (ATF) of Brookhaven [6]. At the same time a standard iris-loaded structure was proposed as a dechirper for NGLS [8]. We demonstrated a tunable (via aperture size) planar chirp compensating structure that can accommodate various scenarios for beam chirp at the accelerator facility recently [8]. In this paper we present experimental results from Accelerator Test Facility (ATF) of Brookhaven National Laboratory (BNL) where a tunable semiconductor-based dechirper was tested.

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TUNABLE CHIRP CORRECTOR

Short bunches with high peak currents in the kA range are desirable for applications like FEL. They are obtained by compression of the energy-chirped beam in a chicane. Compressed beam after chicane carries residual chirp – energy variation along the beam. For successful lasing of the FEL this chirp has to be removed. A passive device, dechirper, was suggested to remove this residual chirp [4, 5]. Nearly every new FEL project entertains the idea of using dechirper for chirp correction.

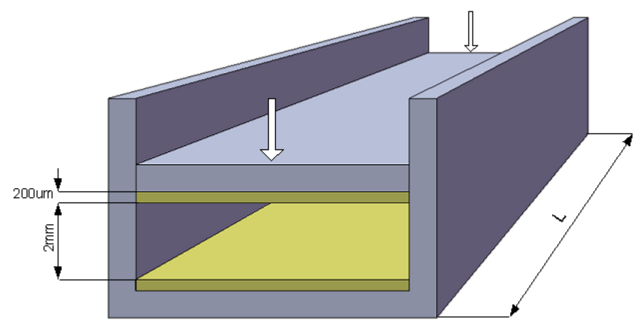

Figure 1: Conceptual design of a tunable dielectric loaded rectangular chirp corrector.

Figure 1 shows a photo and a schematic of a *tunable* dechirper. It is a dielectric loaded waveguide. Alternatively it can be corrugate wall waveguide. High current electron beam passing through such structure generates wakefield (cherenkov radiation). Spectrum of such wakefield is shown on Figure 2. Most importantly there is a wake inside the beam itself: the head decelerates the tail (Figure 3).

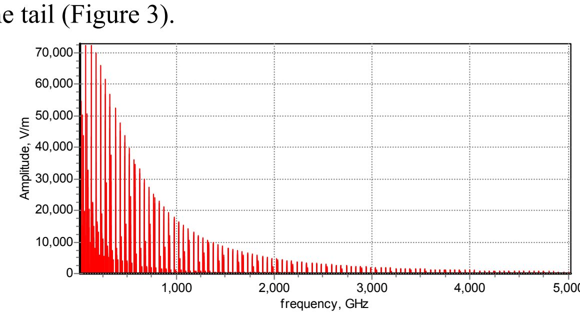

Figure 2: Spectrum of modes excited by the σz = 10 micron gaussian beam (equivalent to the rising edge of the quasi-rectangular beam) inside the 1 mm thick alumina plates, 600 micron gap structure.

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If most of the excited modes have wavelengths longer than the length of the beam the decelerating field inside the drive beam will be quasi-linear [8]. This allows multimode structures to operate at smaller apertures hence higher dechirping gradients than single mode structures like corrugated metallic ones. By making the gap between the dechirper plates smaller the decelerating gradient can be increased. At some point when the gap is too small and the presense of high frequency modes is significant the decelerating field ceases to be quasi-linear (Figure 4).

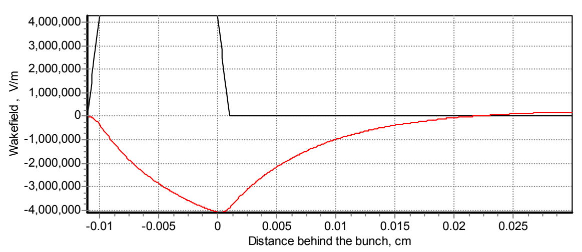

Figure 3: Almost linear decelerating field generated inside the quasi-rectangular beam passing through the 1 mm thick alumina plates, 600 micron gap structure.

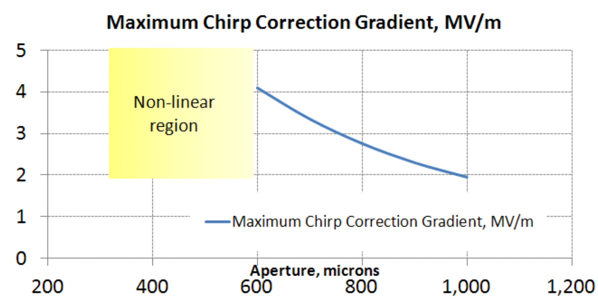

Figure 4: Chirp correction gradient as a function of the aperture size for a tunable dechirper consisting of 1 mm thick alumina plates.

EXPERIMENT WITH SEMICONDUCTOR DECHIRPER

Even though we had not seen effects related to dielectric charging in our experiments at a maximum repetition rate of 10 Hz, there is a valid concern that dielectric may become charged when the repetition rate is >1 kHz. For this reason we turned to semiconductors which combine properties of dielectrics and conductors. For example, graphite which is semiconductor is used for collimators at the LHC. Its conductivity is high enough (7×10^5 S/m) or equivalently its resistivity (146 μOhm × cm) is low enough to drain the intercepted charge at a MHz rate. However its skin depth very small (~few microns), hence the wake inside the collimator is a typical resistive wake. For a multimode dechirper we want a material that has a skin depth of few mm yet sizable conductivity. Silicon is a commonly used semiconductor material and is available with different conductivity values that can be attained by doping. For this experiment we used a high resistivity silicon (5kOhm × cm) that has skin depth of about 35 mm. This is sufficient for Cherenkov wake generation in a waveguide loaded with this material.

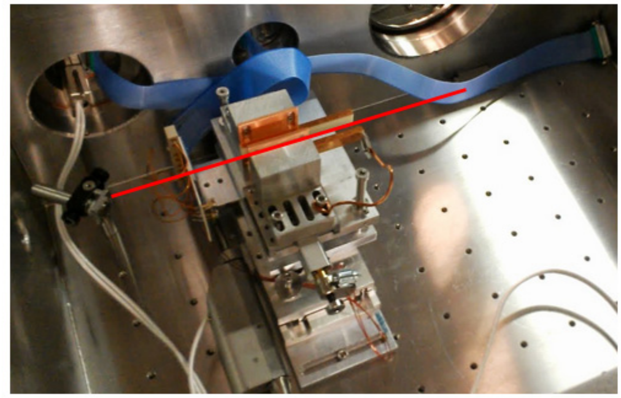

Figure 5: Chirp corrector in the ATF beamline. The beam path is marked with a red line.

What can we say about the charge drainage? It depends on a number of parameters like the electron penetration depth into different materials and their conductivity properties. This topic deserves a separate study. As of now we can say the following: a well proven graphite working at MHz repetition rates is about 7 orders of magnitude better (faster to discharge) than high resistivity silicon. And silicon is about 8 orders of magnitude faster to discharge than alumina (conductivity 1×10^{12} Ohm × cm) which works without any charging problems at a 10 Hz repetition rate. We can conclude conservatively that high resistivity silicon will be able to drain the intercepted charge at rates of about 100 kHz.

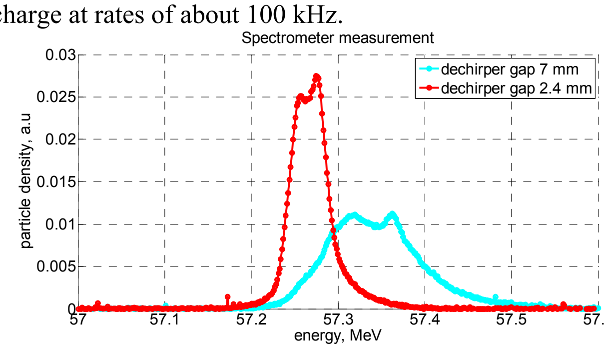

Figure 6: Energy spectra of the beam passing through a dechirper with gap sizes: 7 and 2.4 mm. The energy spread reduction is observed.

The semiconductor dechirper test was performed at the Accelerator Test Facility at Brookhaven National Laboratory. The experimental layout Figure 5 was virtually identical to the previous experiment [8]. For this experiment, the electron bunch was accelerated off-crest in the linac to an energy of about 60 MeV with a positive energy chirp. A mask located between the two opposite sign dipole magnets (inside the dog leg) at a point with a large energy dispersion was used to obtain a peak current distribution with a quasi-rectangular profile. The length of the rectangle was approximately 300 μm and the total charge of the electron bunch after the mask was 90 pC. The electron bunch length was measured by the

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interferometer using coherent transition radiation (CTR) from a foil located downstream of the second magnet. As the beam passes the dechirper it generates a wake. When blades are sufficiently far away (7 mm) the wake is weak and the beam is not affected. As the blades are closed to 2.4 mm the wake is strong and quasi-linear and the chirp is compensated (energy spread is reduced) (Figure 6). The dip feature on a curve (Figure 6) comes from CSR effects in the dogleg upstream.

SUMMARY AND PLANS

We performed a set of experimental studies at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory of chirp corrector, a passive device that reduces the energy spread of the chirped beam. In 2012 we performed a first demonstration with the dielectric loaded round waveguide. In 2013 we demonstrated tunable dechirper based on rectangular dielectric-loaded waveguide. Recently we successfully tested a semiconductor-loaded waveguide that can act as a beam collimator as well. In this experiment a 300 um long quasi-rectangular beam was transmitted through a semiconductor loaded rectangular waveguide with variable aperture. As the aperture gap was made smaller the energy spread of the beam also became smaller manifesting a reduction in energy spread.

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