DESIGN AND FABRICATION OF AN X-BAND TRAVELING WAVE DEFLECTION MODE CAVITY FOR LONGITUDINAL CHARACTERIZATION OF ULTRA-SHORT ELECTRON BEAM PULSES*

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Abstract

An X-band Traveling wave Deflector mode cavity (XTD) has been developed at Radiabeam Technologies to perform longitudinal characterization of the sub-picosecond ultra-relativistic electron beams. The device is optimized for the 100 MeV electron beam parameters at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory, and is scalable to higher energies. An XTD is designed to operate at 11.424 GHz, and features short filling time, femtosecond resolution, and a small footprint. RF design, fabrication procedure, and commissioning plans are presented. An experimental program at ATF to utilize the deflector for compressed beam characterization is discussed, including proposed measurements of the phase space filamentation due to non-linear processes in a chicane compressor.

INTRODUCTION

Some of the most compelling and demanding applications in high-energy electron beam-based physics, such as linear colliders, X-ray free-electron lasers, inverse Compton scattering (ICS) sources, and excitation of wakefields in plasma for future high energy physics accelerators now require sub-picosecond pulses. The creation of ultra-short pulses presently relies on the use of RF photocathode electron guns. To achieve sub picosecond pulses, advanced photoinjector facilities employ compression techniques such as magnetic chicane bunch compressors [1] or velocity bunching [2] schemes. These methods require intricate transverse and longitudinal diagnostics in order to successfully compress the beams without degrading their quality. Hence, a better experimental utilization of fast beams relies on improving resolution and capabilities of fast longitudinal diagnostics.

RF deflecting cavity is being recognized as a robust solution for diagnosing the characteristics of 10's of femtosecond-class electron beams, that is drawing increasing attention in the ultra-fast beam community. An S-band deflector, termed LOLA IV and built in the late 1960's [3] has been recently resurrected for use on the SPPS beamline at SLAC [4]. More compact standing wave deflecting mode cavities have been developed by the INFN-UCLA collaboration for the SPARC project [5] and the UCLA Neptune Lab [6]. Based on this experience, RadiaBeam is developing an X-band Traveling wave Deflecting mode cavity (XTD) to be utilized for direct longitudinal phase space measurements of compressed electron beams. The XTD surpasses the state-of-the-art in deflecting cavities by taking advantage of the greater efficiency and compactness of X-band RF structures; which naturally allows extension of the technique to very high energies, necessary for next generation light sources and linear colliders.

Deflecting cavity operates in a dipole mode: an ultra-short beam (ps duration or less) traverses a device near the zero-crossing phase of the RF wave, thus deflecting the front (earlier time) components of the beam differentially with respect to the trailing components, with an approximately linear time-slew. As a result, a certain temporal slice of the beam can be imaged if the differential kick over the relevant time period must give, after drifting the beam to a detector plane, a differential beam displacement that exceeds the betatron beam size at this point. Of course, the beam transport between deflection and detection may be more complex than a simple drift, and may include, for example, bending in the non-deflection plane.

The transverse pattern of the TM_{11} deflecting magnetic fields in the cavity are also shown in Figure 1. This pattern in which the transverse magnetic field is approximately constant near the axis, corresponds to a longitudinal electric field that vanishes on-axis. In a pill-box cavity, these are the only components of the electromagnetic field that exist; in the presence of irises that allow the beam passage, there is also a transverse electric field which has the effect of adding in phase to the total deflecting kick.

The capabilities of this type of measurement system can be straightforwardly extended to the measurement of longitudinal phase space, when a bend dipole is placed

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downstream of the deflector to disperse the momenta of the beam along the non-deflecting axis. Thus, one may expect that the longitudinal phase space will be displayed, subject to uncertainty introduced by the finite betatron beam size, at the post-dipole detector. The implementation of this type of measurement at ATF-BNL photoinjector is discussed in the experimental plans section.

DESIGN CONSIDERATIONS

The overall design philosophy of the X-band RF deflector is set by the need to maximize the RF deflection of a particle with a given arrival time Δt different from the design particle. As the deflection observed at the detector screen is given by,

$$\Delta x_d = \omega_{RF} \Delta t \sqrt{\beta_d \beta_f} \left(\frac{eV_0}{E} \right) \sin\left(\Delta \psi_\beta\right), \qquad (1)$$

where β_d, β_f are the beta-functions at the deflector and screen, respectively, ω_{RF} is the RF frequency, V_0 is the RF voltage, E is the beam energy, and $\Delta\psi_\beta$ is the phase advance between deflector and detector (naturally chosen to be near $\pi/2$). For a clear measurement, a meaningful deflection value must exceed the betatron beam size of $\sigma_\beta = \sqrt{\beta_f \varepsilon}$, where ε is the geometric emittance. To satisfy this condition, even when, as in some applications under consideration, Δt is of the order of 10 fsec, large β_d is desired. The upper limit of β_d is defined by the aperture acceptance of the X-band cavity.

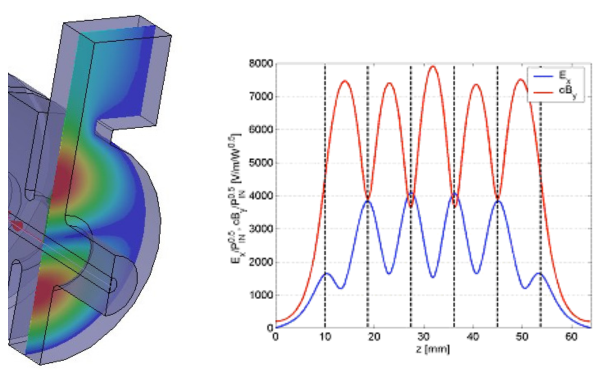

Figure 1: An HFSS model of the deflecting mode excitation (left), and transverse electric and magnetic fields amplitudes for 3-cell numerical XTD model (right).

Additionally, Eq. 1 explicitly shows the advantages of high frequency (ω_{RF}), and a high RF voltage (V_0) values. To achieve a higher voltage, it is natural to increase the length of the deflector, which can only be accomplished straightforwardly by use of a traveling wave device. As in a traveling wave RF linac, an optimum length of a deflector structure is just over one RF attenuation length. Finally, we note the explicit energy dependence in Eq. 1 favours low beam-energy operation, even with the natural damping of beam size (through emittance) as $E^{-1/2}$.

The RF design of the XTD was initially specified by examining the single cell and a short structure behaviour using the commercial 3D electromagnetic modelling code HFSS v10.0. The results of the short structure analysis were extrapolated to the behaviour of the whole device, and the final design parameters are shown in Table 1. The field balance for a model structure comprised of three full cells and two coupling cells is displayed in Figure 1. The transverse electric field is, as expected, lower in the coupling cells, and nearly balanced in the interior cells. The transverse magnetic field is more balanced due to the mode profile: it does not notably penetrate into the beam tubes.

Table 1: XTD design performance

Parameter	Value
Field amplitude, $\sqrt{E/P^{1/2}}$	8.48 kV/mW$^{1/2}$
Group velocity, v_g	0.0267c
Attenuation factor, α	0.66 m^{-1}
Cavity length, L_T	0.46 m
Number of cells, N	53
Power ratio, P_{out}/P_{in}	0.55

FABRICATION AND TUNING

The XTD is currently in the final stages of fabrication with one last prototype scheduled for brazing prior to completion of the final XTD structure. The entire device is fabricated from OFE 101 F68 Class1 Cu, with the exception of the SS tuning pins, water fittings, SLAC crush seal style RF flanges and vacuum flanges.

Proper handling and cleaning procedures are critical to the successful operation of any RF cavity and detailed travelers have been utilized to document the fabrication of the device, from raw material to final leak testing. Each copper component is also subjected to a modified version of the SLAC C01 cleaning procedure prior to braze. All fabrication will be performed with CNC lathes and mills, with a revised asymmetric waveguide taper eliminating the need for EDM processing. Non-sulfur containing cutting fluids will be employed to ensure UHV compatibility.

The mechanical design and fabrication of the XTD structure was informed and guided by tolerancing studies performed in HFSS. All dimensional deviations encountered in the manufacturing of the device will be overcome by the incorporation of tuning pins (Figure 2). These pins allow for a total of 15 MHz of resonant frequency modification per cell by means of dimple tuning. Each cell includes 'mode separation' geometries whose alignment is accomplished with the incorporation of a clocking grove on the outer diameter of each cell. Axial alignment of each cell is also built into the cell geometry.

The main structure of the XTD device is composed of 50 identical cells. Thus, to verify cell geometries by conventional metrological means such as with a CMM, would be expensive and time consuming. Therefore a more cost effective, time effective and informative QA process of measuring each cell frequency has been developed. This single cell RF test stand is precisely measured only once by a CMM and simulated with HFSS. All of the repeating 'main' cells in the structure will then be measured to verify its resonant frequency and overall conformance to fabrication tolerances.

All brazing of the XTD structure will take place in a Hydrogen furnace, using preformed braze filler when possible. All graphite and SS fixturing for the final prototype is currently in fabrication. Cu Coupons will travel with the assembly during furnace braze for future metallographic analysis.

Verification of the tuning procedure and algorithm will be performed on the final prototype under the contract with SLAC, utilizing the experience and infrastructure developed for the NLC X-band accelerating structures R&D program. This procedure will then be repeated on the final assembly prior to crating and delivery to the Accelerator Test Facility at Brookhaven National Laboratories.

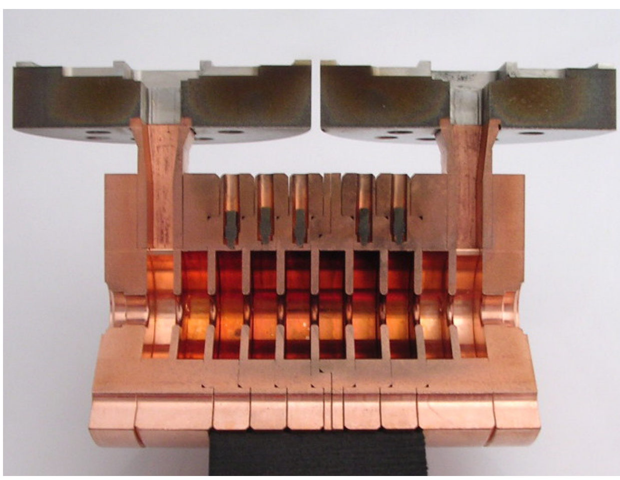

Figure 2: A cross-section of deflecting cavity prototype.

EXPERIMENTAL PLANS

XTD commissioning and initial experiments will be performed at Accelerator Test Facility at BNL in Fall of 2008. A numerical simulations of the XTD performance with ELEGANT [7] indicate the device longitudinal resolution less than 10 fs for ATF beam parameters. The beam experiments will be performed in collaboration with UCLA, and will include a direct phase space mapping experiment (Figure 3), when the beam is imaged behind the horizontal bending magnet, while deflected vertically in the XTD. As a result a detailed map of the longitudinal phase space will be available. The experiment will be performed after the ATF-UCLA chicane beam compressor [8], to study a longitudinal phase space fragmentation due to non-linear effects in the strongly compressed beam.

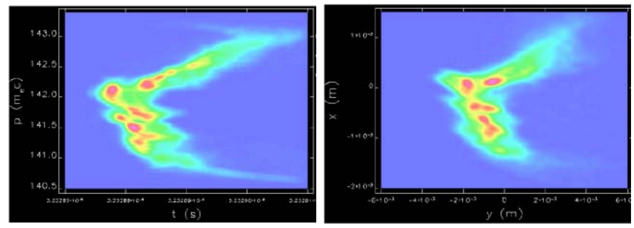

Figure 3: Numerical (ELEGANT) model of ATF XTD experiment: a post-compressor beam longitudinal phase space in (p,t)-coordinates (left); and a corresponding (x,y) map after the XTD and a bending dipole (right).

CONCLUSION

The X-band travelling wave deflection cavity is a promising tool for high resolution longitudinal diagnostic of ultra-fast beams, and is currently in the final stage of development at RadiaBeam Technologies. The device use can be extended to very high energies due to compactness and efficiency of the X-band approach. In the experimental stage of the project XTD will be used to perform a study of the physics of compressed beam with the unprecedented level of details.

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