A Proposal to the Brookhaven Accelerator Test Facility

for

ELECTRON BEAM PULSE COMPRESSION-BASED PHYSICS AT THE BROOKHAVEN ATF

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1. Electron beam pulse compression: scientific and technical interest.

This proposal seeks support for experiments to be performed using a compressed electron beam pulse derived from a magnetic chicane-based pulse compression system currently under construction at UCLA for the Brookhaven National Laboratory Accelerator Test Facility (BNL ATF). This compressor will serve several experimental purposes, both immediate and long-term. The immediate purpose, from the UCLA point-of-view, is to install a state-of-the-art compression system, an effort funded by the Office of Naval Research (ONR), which springs technically from earlier efforts at the UCLA Neptune laboratory and Fermilab/DESY. Upon completion, we intend to use it to test the as yet poorly understood physics of the compression process, such as emittance growth due to non-inertial space-charge, and related phenomenon of coherent synchrotron radiation generation. From both UCLA and BNL view points, then, the compressor will allow an important test of a critical beam physics issue, the effect of these compressor-derived effects on the gain of self-amplified spontaneous emission free-electron lasers (SASE-FELs). This FEL work, already supported nationwide by the VISA collaboration and at BNL/SUNY-Stonybrook by ONR, more directly addresses the issues surrounding the generation of very short wavelength FELs such as the LCLS than previous work at lower beam energy and current. In addition, the long-range benefit of this work is the addition to the ATF infrastructure of a state-of-the-art bunch compression, thus allowing an expansion of experimental possibilities at this national user facility.

From a basic beam physics viewpoint, the physical effects we propose to study as a direct result of compressor implementation are fundamental aspects of these space-charge dominated systems under transverse acceleration. It is necessary, in order to make experimental progress in use of these beams, to thoroughly explore these effects, which have little in the way of compelling measurements to allow their understanding. Of course, the applications of these beams, specifically in the generation of coherent radiation from high gain free-electron lasers, provides even larger motivation for the beam physics field. For next generation SASE-FELs it will be necessary to use pulse compressors to raise the peak electron beam current, but in the process of compression, the quality of the electron beam’s transverse phase space may be degraded to the point where there is no improvement in gain. This proposal seeks dedicated beam time at the ATF to make experimental tests of the physical processes relevant to pulse compression, and the concommitant transverse phase-space degrading collective effects which occur in bend magnets. After establishment of the beam physics effects associated with the compressor itself, we will then use the compressed beam in the VISA undulator to test the physics of ultra-high gain FELs with such a beam as a driver. This experiment will also be performed within the structure of the VISA collaboration. We note in this regard that all of the listed experimenters, with the exception of R. Agutsson, are presently members of the VISA collaboration.

2. Experimental work plan

The proposed experiment consists of the following main tasks, many of which are already completed:

a) Simulation of ATF beam optics using TRACE-3D and PARMELA, to produce an optimized compressor design, consistent with the constraints of the ATF beamlines. This is complete, and discussed below.
b) Further three-dimensional coherent synchrotron radiation simulations (TREDI and ELEGANT) to aid in understanding non-inertial space-charge effects.
c) Electromagnetic design and simulation of optimized chicane magnets (complete, discussed below)
d) Engineering and shop design of magnets; design of vacuum vessel for chicane transport (complete, discussed below).
e) Machining, winding, finishing testing and support of magnets (nearly complete).
f) Experimental measurement of pulse compression and coherent synchrotron radiation at ATF.
g) Experimental measurement of emittance growth during compression at ATF.
h) Experimental measurement of ultra-high gain FEL performance with VISA.

To describe the rationale and necessary technical background behind the technical tasks listed above, we first must review the overall motivation for the work we have proposed. To this end, we note first that compression of electron beams from the picosecond to subpicosecond regime is a subject of intense interest to the FEL and advanced accelerator communities, as the demand for shorter pulse lengths, and high currents, drives research forward. Methods such as velocity compression and chicane compression have been in use for some years, but their applicability to systems in which the beam is very bright — has high current and low emittance, are not guaranteed. Several physics effects have been identified which may cause the degradation of beam emittance during compression, such as non-inertial space-charge, and the related far-field phenomenon of coherent synchrotron radiation emission. These mechanisms are very poorly understood from the analytical and computational points-of-view, but their understanding is critical to the success of many future FEL and linear collider projects.

Because of this, a number of laboratories, including UCLA, have begun to experimentally investigate the processes of chicane-induced compression and emittance growth during compression. This technique requires an rf linac-based source, such as the UCLA Neptune photoinjector or the ATF photoinjector, with an optimally designed chicane magnet system. In the linac, a correlated chirp in energy and time is imparted by accelerating the bunch ahead of the rf crest. The purpose of the chicane is to remove this correlation through the differential path lengths of the off-energy particles, thus compressing the beam. At UCLA, the compressor has been built and implemented at the Neptune advanced accelerator lab (see Fig. 1), and runs at 13-16 MeV. Initial experiments on this system are presently underway, with the eventual goal of running very low charge bunches with length shorter than 40 microns (130 fsec) for plasma beatwave acceleration experiments. We will also be investigating the phase space-transformation properties in general of the beam as it undergoes compression, in particular space charge effects on the transformation. These effects include compression degradation from longitudinal space charge, and emittance growth from both rectilinear (velocity fields) and non-inertial (acceleration fields) transverse space charge. The non-inertial effects are not large compared to the more well understood rectilinear effects at 16 MeV, and thus many of the most compelling questions surrounding the future use of compressors for FELs and linear colliders cannot be answered at UCLA.

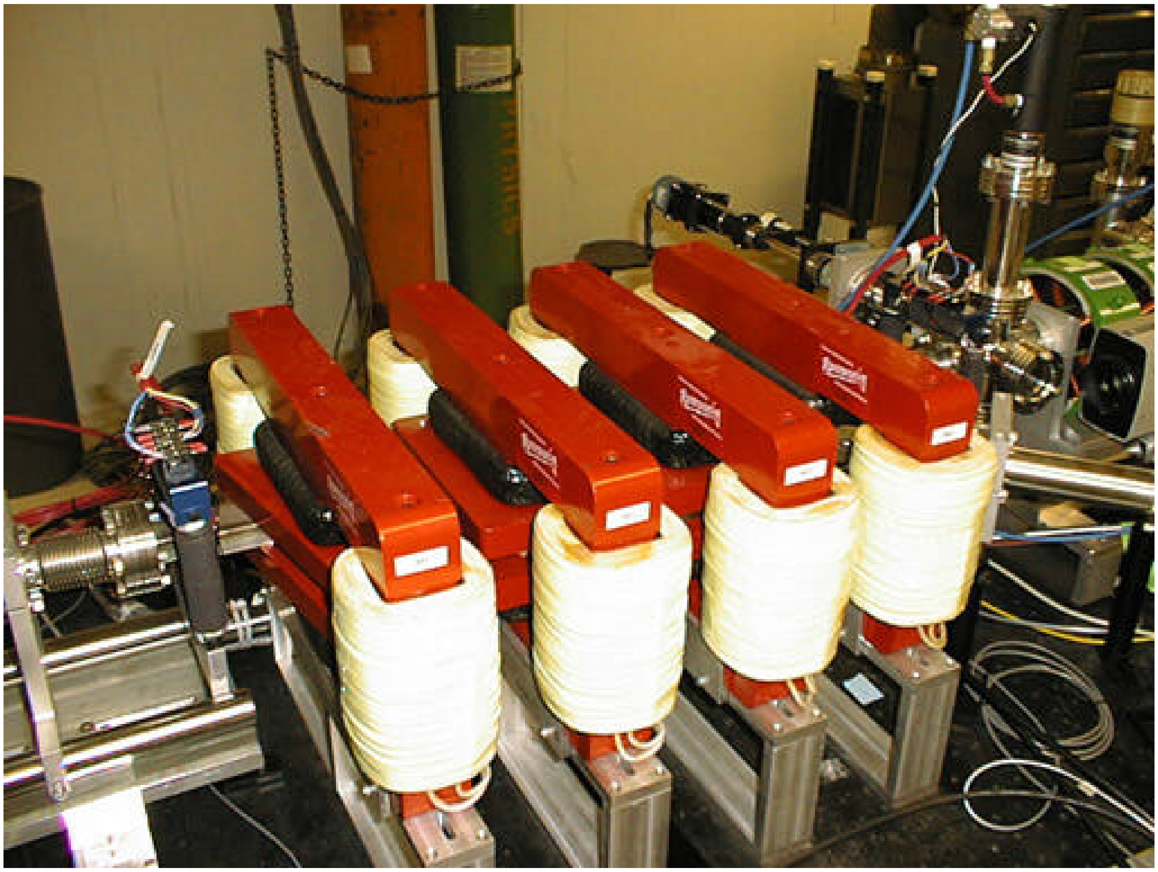

Figure 1. Chicane compressor magnets, along with large aperture vacuum vessel, built at UCLA for the Neptune Laboratory

Thus we have proposed to the ONR to build a chicane compressor appropriate for use at 70-80 MeV to be installed and used at the BNL ATF, and this proposal has been funded for nearly a year. This higher energy system allows compression in TRACE 3D simulations of a precompressed (using velocity compression in the gun) 150 pC beam from 0.5 mm FWHM (1.65 psec) to 23 μm, or a factor of over twenty, which is three times better than can be achieved at Neptune. The fact that the emittance growth in this system is predicted by rectilinear space charge analysis allows a cleaner measurement of the emittance growh due to coherent acceleration fields (the near field of the coherent synchrotron radiation, CSR). For the case shown in Figure 2, the emittance growth due to is estimated from the O'Shea-Dowell model to be between 5 and 10 mm-mrad, or an order of magnitude better than a well-tuned ATF beam. The signal due to coherent synchrotron radiation (synchrotron wakes) in the sub-mm regime will be large in the ATF case, allowing comparison of the computational results to experiments in a way independent of emittance measurements. This experimental arrangement is much closer to the applications of interest, and thus is able to give more relevant information on the phase-space density degrading properties of the compressor.

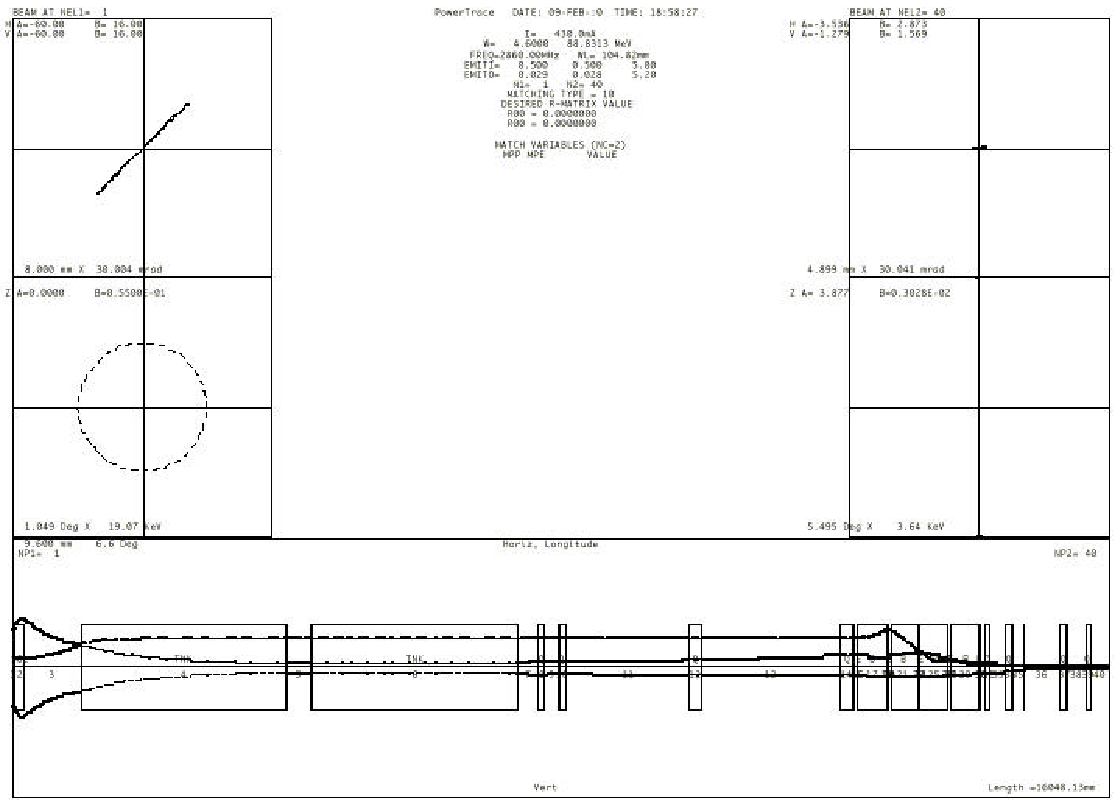

Figure 2. TRACE 3D simulation of the ATF beamline from gun exit through chicane for 150 pC beam. Bunch length is given by heavy line above envelope axis, and can be seen to rapidly compress inside of the chicane.

In addition to being able to make measurements on the fundamental beam physics of compression, the ATF has two beamlines which have undulators installed on them. This will allow the use of the highly compressed beams to drive SASE FEL experiments, measurements which are planned by Prof. Ilan Ben-Zvi (BNL/ SUNY-Stonybrook), under ongoing ONR support. The FEL process itself is perhaps the most sensitive diagnostic of phase space density one can use to probe a beam — if the beam is degraded in energy spread or emittance, it does not lase. The types of degradations one may expect from the compression process produce highly correlated, non-thermal phase space distributions. It is therefore not easy to predict analytically or computationally what the performance of the FEL will be, and direct experiments addressing this issue become all the more critical. This type of experiment is discussed below.

We now review the preliminary work which has gone into this project to date. The use of the ATF beamlines, in which there is non-trivial dispersion (>80 cm) and a tight aperture (1” beampipe), restricts the passable energy spread without clipping to 0.5% FWHM. This constraint means that the initial energy spread including chirp must be kept small by using the shortest of beams available from the ATF. We have used the conservative value of 1.65 psec FWHM at 150 pC to perform a design “envelope” covering the most extreme compression cases. The TRACE3D simulations, which include space-charge in a “water-bag” three-dimensional envelope model, have been run using essentially the same magnetic field as the chicane magnets builts at UCLA (Figure 1) for the Neptune laboratory, B=2.1 kG.

The magnets for the ATF compressor are of course much larger in footprint than the Neptune magnets, but are be similar, using horizontally focusing initial and final edges of the magnet array to roughly equalize the strong vertical and horizontal focusing of the chicane. These magnet edges are set at 20 degrees, which is the same as the nominal bend angle. The final design of the magnets has been done with a 3D magnetostatic code (AMPERES) simulations, an example of which is shown in Fig. 3. This code was employed to minimize the weight of the magnets while simultaneously insuring that the iron used does not saturate. The magnets are machined in the UCLA shops and coated and wound in local job shops under UCLA supervision, so that quality control is guaranteed.

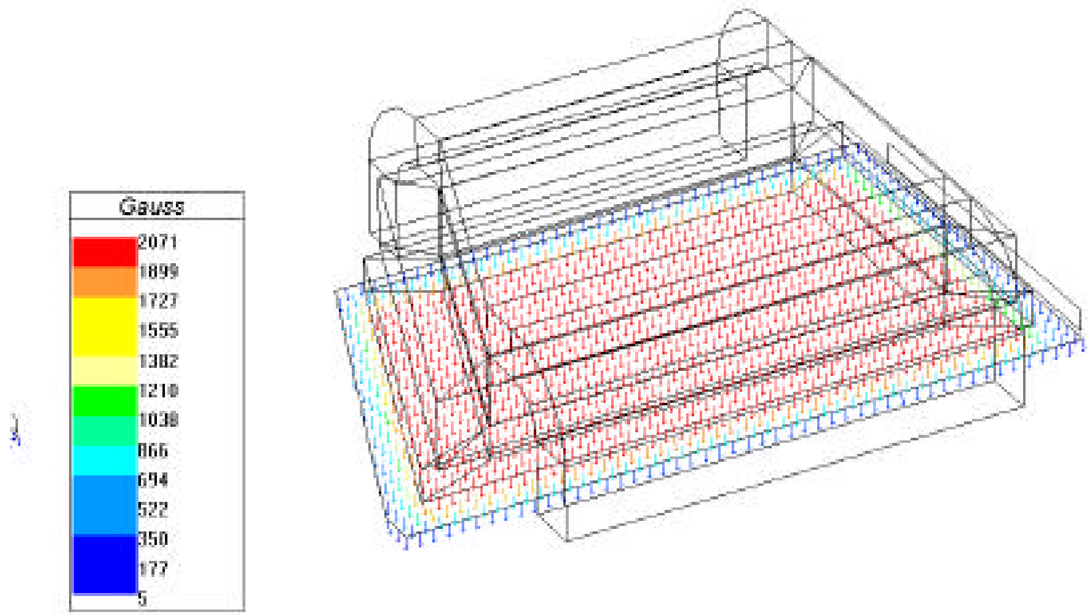

Figure 3. Arrow plot from AMPERES simulation of ATF chicane end magnet.

A vacuum vessel for this chicane has been designed at UCLA after including input from the demands of the beam optics, the ATF staff, and mechanical considerations. The vessel, which has design based on the successfully deployed Neptune chicane vacuum system, inserted into the four chicane magnets, is shown in Figure 4.

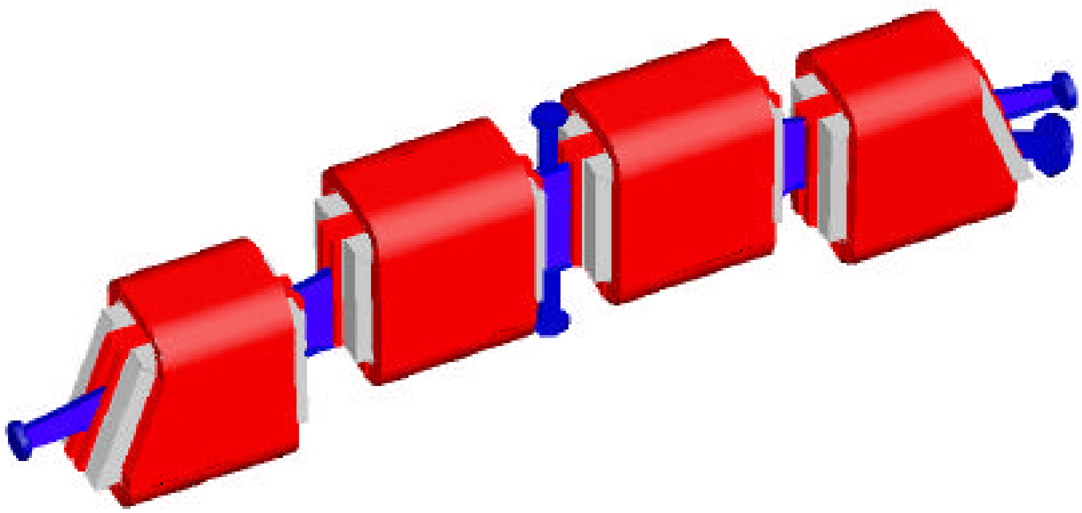

Figure 4. 3D rendering of chicane magnets and vacuum vessel (viewed from below).

The magnets shown in Figs. 3 and 4 have now finished their final stages of machining, and are being coated and wound (with air-cooled 8 gauge enamel-coated copper wire). The magnets use a maximum excitation current of 14 A and have a resistance of 4.25 Ohms. They will be each have separate power supplies to allow for correct trimming of the fields. The magnets are designed with modular construction in order to ease the installation into the ATF linac bunker, as discussed below. Installation of the chicane and vacuum vessel into the ATF beamline is foreseen for September or October of 2000.

The experimental plan for the time before and after installation of the chicane is now described in more detail.

a) Simulation of beam optics. At UCLA, the first step in performing a space-charge dominated beam dynamics simulation is to use TRACE3D, as described above. This allows the overall envelope behavior to be deduced, as shown in Fig. 2, up to and including the performance of a compressor. Figure 2 includes the effects of acceleration and focusing in the rf linac sections of the ATF, as well as the chicane magnets and nearby matching optics. The TRACE3D simulations form the basis of setting up PARMELA simulations. The UCLA version of PARMELA has been extensively modified, to include longitudinal wake-fields, and to allow better handling of the point-to-point space-charge evaluation routine needed to model space-charge self-consistently in an asymmetric beam. It also has much improved phase-space diagnostics, so that the beam dynamics can be understood and optimized straightforwardly. TRACE3D and PARMELA have been used, in cooperation with BNL personnel running TRANSPORT, to specify the beam optics which will allow matching of the high rms divergence (see Fig. 2) of the beam at exit of the compressor to the rest of the ATF. The magnetic and optical characteristics of the chicane compressor system as designed are summarized in Table 1. Only the most extreme case of compression is quoted — other cases with larger charge and smaller compression have also been studied. Note that in general the compression will be significantly smaller for initially larger pulse lengths (typically accompanying larger charges).

Beam Energy	71 MeV
Beam Charge	0.15 nC
Energy spread	0.5% FWHM
Nominal linac rf phase	17 degrees
Bend angle	20 degrees
Magnetic field	2.1 kG
Initial pulse length	0.5 mm FWHM
Final pulse length	>0.023 mm FWHM
TRANSPORT R_{56}	0.63 mm/(δp/p%)
RMS normalized emittance growth	5 – 10 mm-mrad

Table 1. Chicane optics and magnet parameters.

b) Further code development: Unfortunately, even our version of PARMELA cannot be used to predict well the influence of non-inertial space-charge terms in the fields (all of the emittance growth seen in Figure 2 is due to rectilinear, or velocity, fields). In fact, PARMELA predicts small (~1 mm-mrad) emittance growth in that case. The quoted emittance growths in Table 1 are larger estimates based on a semi-analytical approximation. To improve our predictive modeling, we have begun to use two new codes, a new three-dimensional Lienard-Wiechert code called TREDI, and ELEGANT, a code which calculates CSR effects. TREDI has been bench-marked on an analytical calculation of an effect of collective beam fields in bend magnets — the diamagnetic effect of beams in undulators[1]— with excellent results. We have begun to use this code on the problem at hand, the chicane, which can be seen to be merely a version of the undulator with more dramatic bends. An initial field calculation for the case of a chicane magnet (at 10 MeV) was also benchmarked against an analytical model (and alternative computational model) due to R. Li[2] of Jefferson Lab, as shown in Figs. 5 and 6. From TREDI we will be able to calculate predictions for two experimental measurements: the degree of emittance growth during compression, and the power radiated coherently by the beam as synchrotron radiation.

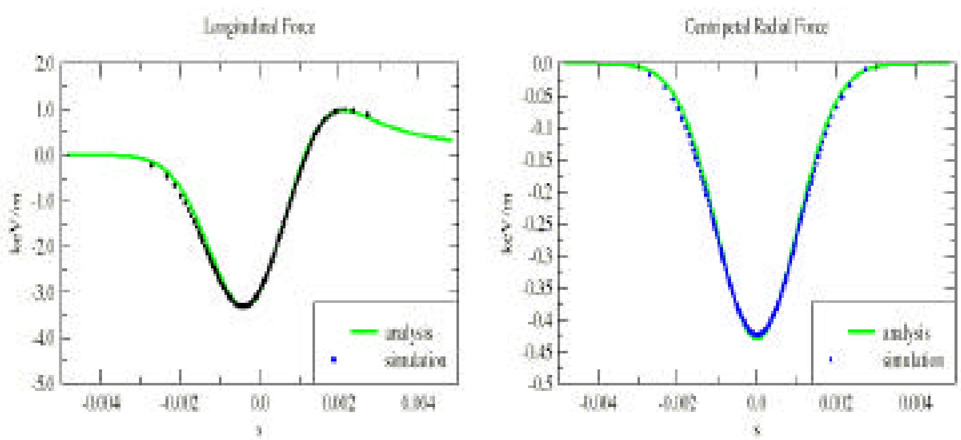

Figure 5. Predicted transverse and longitudinal synchrotron “wakes” in 10 MeV bend. (from R. Li, JLAB).

[1] "Diamagnetic Fields Due to Finite Dimension Intense Beams in High-Gain Free-Electron Lasers", J. Rosenzweig and P. Musumeci *Physical Review E – Rapid Communication* **58**, R2737 (1998).

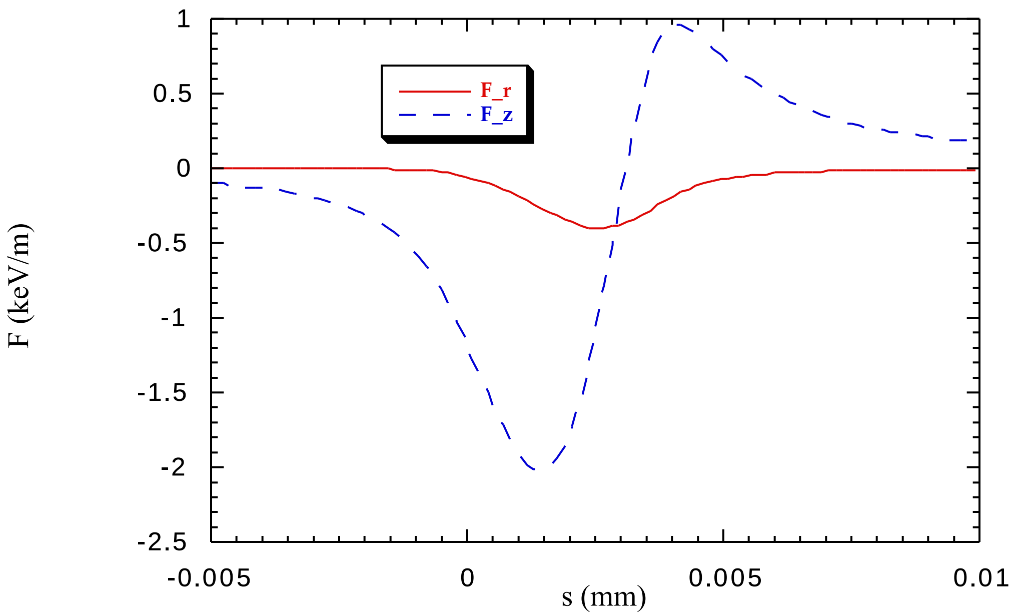

Figure 6. UCLA TREDI simulation of identical 10 MeV case given in Figure 5.

The Lenard-Wiechert approach of TREDI is somewhat computationally intensive, and is challenging to implement at 70 MeV, a task we are presently undertaking. In addition, we have begun collaboration with Paul Emma of SLAC on modeling of the LCLS with a CSR code written by M. Borland of the APS, termed ELEGANT. We are now beginning to use ELEGANT for simulating CSR effects in the chicane. Soon, ELEGANT will be upgraded to include velocity fields as well as acceleration fields, and at this point we will rely on it as our main simulation tool for this experiment.

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[2] "Progress on the Study of CSR Effects", R. Li, to be published in *The Physics of High Brightness Beams"* Eds. J. Rosenzweig and L. Serafini (Worlkd Scientific, 2000).

c) Electromagnetic design and simulation of optimized chicane magnets: complete, see above.

d) Engineering and shop design of magnets; design of vacuum vessel for chicane transport: The magnets have been engineered in consultation with the UCLA shop, which has not only produced the dipole magnets shown in Figure 1, but also a new generation of Neptune chicane dipoles, precision quadrupoles and steering magnets (see Figure 5) now in use at UCLA, DESY, Fermilab, and Brookhaven. We have incorporated the vacuum vessel into the design in consultation with ATF personnel, to insure maximum aperature (14 mm) in the narrow dimension, while obeying constraints due to the magnetic circuit and gap, as well as mechanical deflection under vacuum (<10 microns). Both magnets and vessel have been designed with modular pieces for ease of assembly. The vessel has also been designed with metal gasket knife-edge seals to allow high bake-out temperatures, and vacuum consistent with the rest of the ATF injection line.

e) Machining, winding, finishing testing and support of magnets: The construction of the chicane magnets, as indicated above, is nearly complete. The precision machining of yoke and pole pieces for UCLA magnets is performed with the aid of a computer controlled CNC cutting machine. The magnets are finished and wound at local job shops. After construction, we will undertake a complete field mapping and saturation test on the magnets before shipping them from UCLA to BNL in the summer of 2000. The stands and alignment rails to be used inside of the ATF are presently under final design, pending discussions with ATF engineers. The present status of the design is shown in Fig. 7. Note the access port at the upper right hand corner of the vessel to allow measurement of CSR from the exit of magnet 3 and entrance of magnet 4.

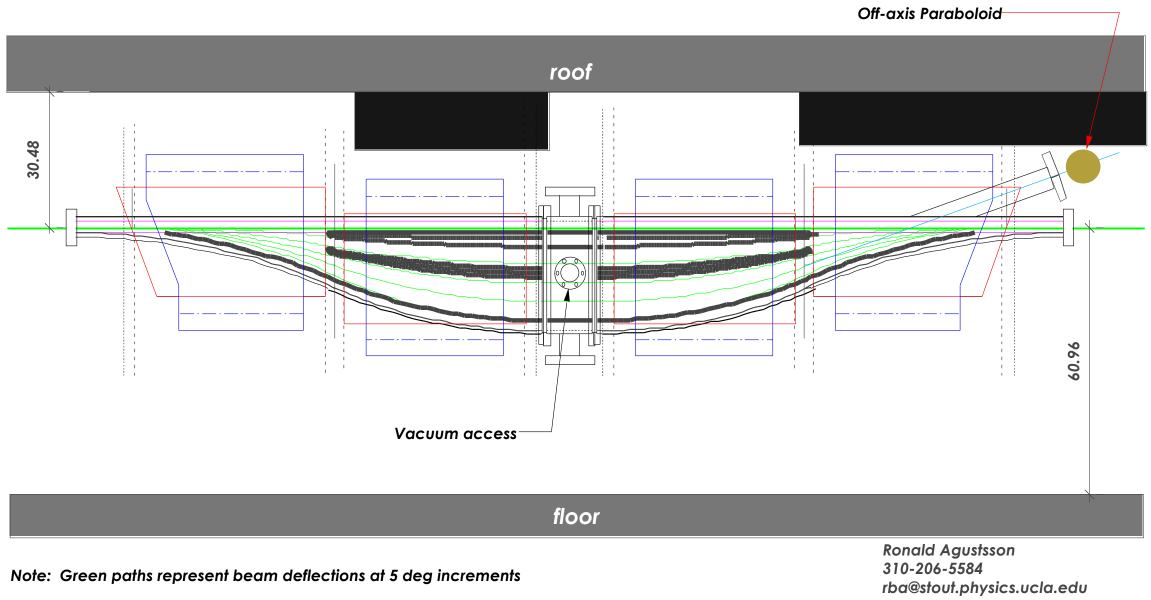

Figure 7. Side view of chicane magnets and vacuum vessel in ATF injection line bunker.

The previous development of chicane dipoles, precision quadrupoles and steering magnets at UCLA has necessitated the building of numerous Hall probe test stands for measuring magnetic field profiles. Numerous power supplies are available for energizing the magnets, as is a degaussing supply for studying the elimination of remanant fields.

f) Experimental measurement of pulse compression and coherent transition radiation at ATF: While we have developed many methods for the measurement of bunch charge, emittance and pulse length at UCLA, it will not be necessary to bring all of these to the ATF, as this facility has developed more energy-appropriate methods of their own to measure these quantities. We will therefore use the ATF infrastructure for measurements and data acquisition where possible, in determining emittance growth as a function of charge. On the other hand, at BNL pulse length is now typically measured using a linac phasing and momentum spectrum technique which cannot be used with a compressor. At UCLA, however, we have developed, in collaboration with Prof. Uwe Happek of the University of Georgia, a pulse length measurement system based on coherent transition radiation, as shown schematically in Figure 8.

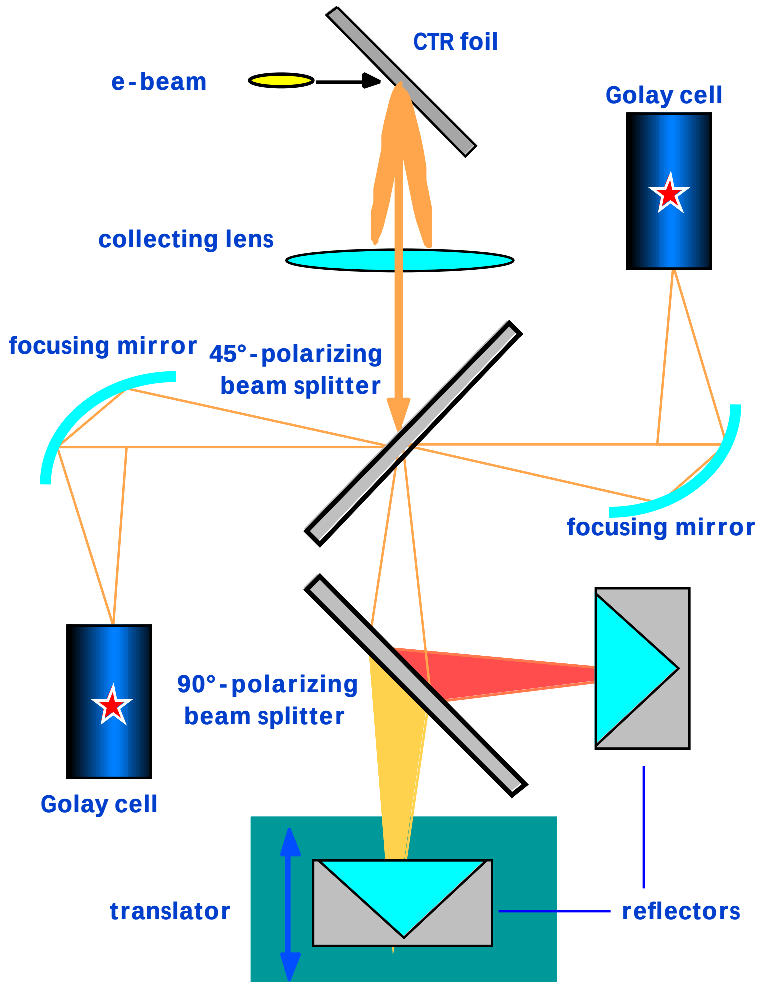

Figure 8. The UCLA coherent transition radiation-based interferometer.

This measurement system is based on collection of the coherent transition radiation (CTR) emitted at a 45 degree foil. Half of the coherent radiation is then sent into a reference detector, and half into a polarizing Michelson interferometer. Autocorrelations of the CTR, and thus, because the coherent portion of the radiation intensity is porportional to the instantaneous current, the beam profile itself is made possible in this way. An example of the data obtained from the CTR interferometer is shown in Fig. 9. The non-unipolar autocorrelation displayed arises by the filtering of long wavelength radiation by the effects of diffraction in the collecting optics and the interferometer. This problem has been taken out of the data in analysis using a time-domain fitting procedure developed at UCLA[3]. This type of measurement is now routine at several laboratories worldwide.

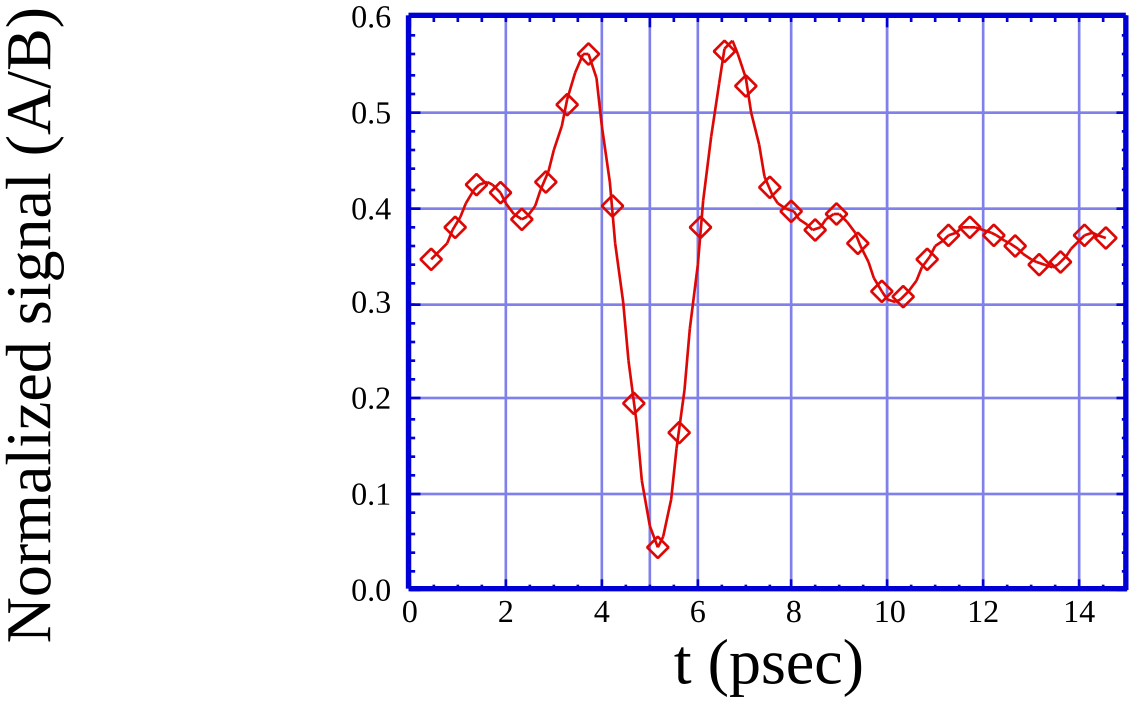

Figure 9. Autocorrelation of beam-derived CTR data from Neptune photoinjector using interferometer of Fig. 8.

We propose to bring the UCLA CTR interferometer to measure coherent synchrotron radiation (CSR) with this device, as a way of measuring the bunch length, and completing the experimental picture of non-inertial space-charge and related radiative effects during the compression process. The CSR will be observed at either the off-axis port shown in Fig. 7, or by use of a downstream mirror. The Golay cells will be easily sensitive to the predicted CSR values, which can be two orders of magnitude larger than those observe in CTR measurements at UCLA. The minimum resolvable bunch length of this device is 100 microns FWHM (due to the wire grid spacing in the transmission polarizers),

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[3] "Bunch length measurement of picosecond electron beam from a photoinjector using coherent transition radiation" A. Murokh, J. Rosenzweig, *et al.*, *Nuclear Instruments and Methods A* **410,** 549 (1998).

however. We thus will be able to obtain a calibrated measurement of compression to this level, but must work harder to resolve shorter pulse lengths. We will initially use a total power measurement at the straight-through port, which will be calibrated to the interferometric measurement at longer wavelengths.

We also plan to develop new beam splitter techniques with Happek in order to extend the resolution of the interferometer itself to shorter bunch lengths. This is also important in that we need to eventually resolve the shorter wavelengths of CSR in order to compare with theoretical model calculations. One can see that measurements of CSR and pulse length are in fact not at all separate in this system.

g) Experimental measurement of emittance growth during compression at ATF. This measurement will be performed using the standard quadrupole scanning system in use at the ATF, with pulse length calibration obtained from the CSR system.

h) Experimental measurement of ultra-high gain FEL performance with VISA. The end-game of all of these studies is to provide a high quality compressed beam to the experimental beamlines of the ATF. The most compelling use of such beams on presently installed experiments is undoubtedly VISA, which will benefit enormously from the higher beam brightness the compressor should provide. This is shown in Fig. 11, which displays GENESIS (3D time-dependent FEL code) simulations of the expected gain due to a beam compressed to a (slightly derated) 35 micron FWHM bunch length, for 5 and 10 mm-mrad cases, respectively. The distance to saturation is shortened from the standard VISA design of slightly below 4 m, to between 2.3 and 3 m. These gain curves display curious artifacts, however, due to slippage, which is over 150 microns in this case, much longer than the beam. Thus direct measurement of slippage effects is possible, *e.g.* the effect seen in the 10 mm-mrad case where the beam head saturates first, and the tail last, leading to a much “softer” saturation profile. While this experiment is obviously of high importance to the FEL community, it is predicated on the success of the previous measurements, and on the development of good beam transport from the compressor to the experiment in the presence of a relatively large energy spread. It is thus foreseen that this phase of experimentation will not begin in this ATF experimental cycle (before 7/2001).

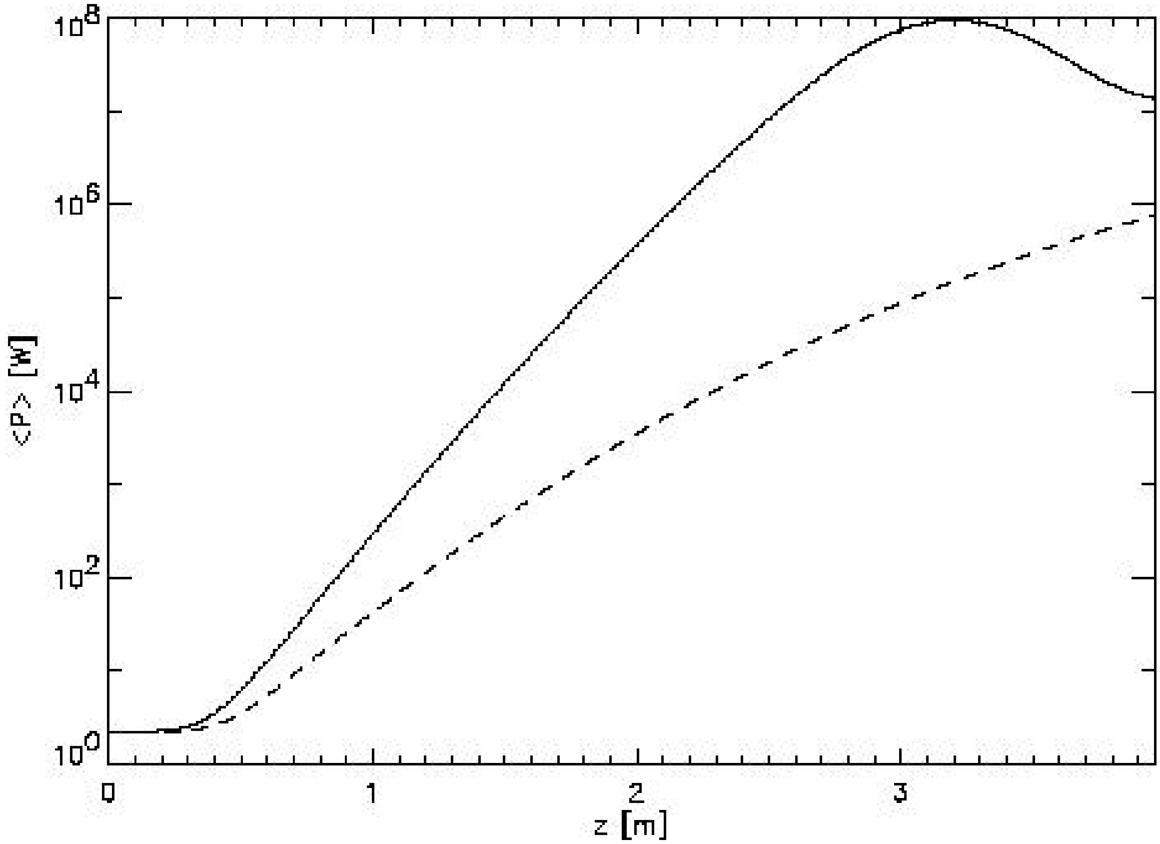

Figure 11. GENESIS (3D time-dependent FEL code) simulations of the expected gain due to a 150 pC beam compressed to a 35 micron FWHM bunch length, for 5 (solid line) and 10 (dashed line) mm-mrad cases, respectively.

3. Estimated beam time needed for the experiment

It is presently foreseen that the compressor will be installed by the end of October 2000. From November 2000 to the end of June 2001, we anticipate that we will need 20 ATF shifts, or an average of 2.5 per month for compressor studies. At the end of these studies, a coordinated proposal for further beam time will be made with the VISA collaboration.

4. Suggested location on the ATF experimental floor/interference with existing equipment

The exact layout of the beamline between the end of the linac to the bend out of the injector bunker is being coordinated at present with the ATF personnel, as it is being upgraded in several ways, including the addition of the compressor.

5. Needs for equipment and/or manpower from the ATF

The ATF is providing engineering support, as well as collaboration of physicists, to this project. At present we are coordinating the vacuum design, supports, and alignment systems. We are also collaborating on optics issues related to implementation of the compressor. The ATF is of course expected to take the lead role in directing our installation of compressor hardware. When the experiments are running, we expect ATF support in basic beam measurements such as the emittance and charge.

6. Ability of collaboration to carry out the experiment

Financially, this experiment is fully funded through the next 12 months by ONR. This funding supports R. Agutsson and a portion of the PI (Rosenzweig), as well as all hardware and travel. The other UCLA members of this collaboration are supported by the VISA collaboration, which is funded by BES as a component of the LCLS program. The UCLA team consists of a number of experimentalists who have developed hardware and performed experiments in high brightness beam physics and SASE FELs in the recent past. Two of the UCLA members of the collaboration are now stationed at BNL full time, A. Murokh (graduate student), and A. Tremaine (post-doc, VISA experiment manager). R. Agutsson will be also heavily involved in installation at BNL. The experiment is being directed by the spokesman, J. Rosenzweig.