Accomplishments Achieved Under DOE Grant Number 
DE-FG03-92ER40693
The Physics of Gain Mechanisms in Self-Amplified
Spontaneous Emission Free Electron Lasers
PI: Prof. James Rosenzweig

Overview
As stated above, a broad range of investigations into SASE FELs and high brightness beams were proposed 3 years ago at a preceding grant renewal point. We have accomplished the majority of the stated physics goals, and added other areas of investigation, extending well beyond the scope of the original proposal as the research developed and new opportunities came into view.

We review the results in high brightness beam and beam-based radiation physics that have been obtained under this grant’s support in the following sections, by topic:

- Experiments on ultra-short beam creation and coherent radiation generation at UCLA-designed and built chicane compressor at the BNL ATF.
- UCLA-performed SASE FEL experiments at VISA, also located at the ATF.
- Initial velocity bunching experiments at the UCLA Neptune Lab.
- Velocity bunching experiments performed at the LLNL PLEIADES inverse-Compton-scattering experiment injector. Use of compressed ultra-short beams in ICS experiments.
- Development and use of high gradient permanent-magnet quadrupole-based final focus systems at PLEIADES, to create ultra-small beam spots for ICS and other applications.

These topics will form the background for discussing progress in: computational and theoretical studies, student training, publications, and technology development. We report the progress towards new experimental facilities (advanced injector and diagnostic development at SLAC and INFN), in the context the following section, as lays the groundwork for the discussion of proposed future experiments.

BNL Compressor Experiments

The chicane compressor at the BNL ATF has been installed in the high-energy beam line after the injector. Significant delays as well as cost increases were encountered in this project because of BNL safety approval demands. The increases in costs were born partially by the DoE BES grant that nominally funds on-campus FEL work, and also by donations of labor and diagnostic equipment from collaborators INFN-LNF (Frascati). Initial data was obtained in late 2004 from this experiment.

The compression experiments at ATF have focused on creation of very short (~20-25 micron rms) beam pulses, and on testing the effects of coherent synchrotron radiation (CSR) and of coherent edge radiation (CER) emitted from such short beams. Both of these radiation effects are under investigation for their link to a new form of microbunching instability. The UCLA effort
has indeed identified the link between this instability, which may greatly impact the performance of compressors in short wavelength FELs such as the LCLS, and the FEL instability itself. A theoretical study of the comparison between these two instabilities\textsuperscript{1} has been published in Physical Review STAB. The microbunching instability is found to have both high gain and low gain regimes which are similar to those corresponding to the FEL, but much stronger. The CSR instability may assert itself in less than a bending period — and can strongly filament the beam’s longitudinal phase space.

The closely related CER effect\textsuperscript{2,3,4} has not yet been observed in the short wavelength regime that is relevant to modern FELs, and where contributions to CSR instability may be relevant. In addition, because of the CER power dependence on the bunch length, it may be used in a non-destructive beam monitoring scheme. To examine the physics of CER from compressed beams, we have put together a measurement program based on filtered cryogenic detectors for the copious 15-1000 micron radiation expected from the compressor. In order to model the experiment, a start-to-end simulation (PARMELA-Elegant) has been put together which allows the general behavior of the system to be predicted.

Figure 1. Cutaway of rendered engineering drawing of the UCLA-built ATF compressor, showing alignment and supports; vacuum vessel with central diagnostic chamber and coherent edge radiation port (upper right).

Figure 2. Magnet testing stand at UCLA for field quality in ATF chicane (left) and results of the field measurement for one end magnet (right).
The compression process creates sub-25 micron long beams by use of the magnetic chicane, shown in Fig. 1. This device was conceived of, designed and constructed at UCLA. It has initial and final horizontally-focusing edge-angles to mitigate the strong natural vertical-focusing of the chicane that would otherwise lead to excessive charge-density inside of the chicane. The magnets were fully modeled with the 3D magnetostatic code AMPERES, and field-quality rigorously tested on campus (Fig. 2). A custom vacuum-vessel was designed and constructed, which allows beam diagnosis in chicane-on and –off configurations; and, features a dedicated coherent synchrotron radiation port. All of these systems, along with their power supplies and safety interlocks, are now working at the ATF. It may be deduced from the sophistication of the hardware layout shown in Fig. 1 that this was an extremely technically challenging project, that had to satisfy many demands (field, alignment, diagnostics, safety) of being placed in a cutting edge national lab user facility.

The modeling of the beam dynamics in the chicane system was undertaken first by ELEGANT, with the usual PARMELA-modeled beam particles at accelerator exit used as input. The design performance is typified by the results shown in Fig. 3, which predicts that a 60 MeV, 55 A (0.3 nC) beam will be compressed to 1.6 kA peak. Accompanying this compression, ELEGANT indicates that the vertical (bend-plane) normalized rms emittance increases from 1.5 to 6 mm-mrad due to coherent synchrotron-radiation (CSR) effects. There are considerable doubts about this prediction; however, as the validity of the 1D CSR model in ELEGANT is not guaranteed. Further, there are no velocity-fields (space-charge) in ELEGANT, which may also be a significant oversight. Improvement of the computational model is discussed at the end of this section.

One critical aspect of the coherent synchrotron radiation has yet to be measured — the CER effect at short wavelengths. When a charged particle encounters a fast changing magnetic field (edge), it emits an enhanced radiation-spectrum that is similar to transition radiation (TR). In order for CER to be significant the field change must occur on a scale much shorter than a radiation formation length. Thus for long wavelengths (see the 0.1-1 mm cases in Fig. 4) the radiation appears at the detection window in our experiment as a TR pattern while at shorter wavelengths (e.g. the 1 µm case in Fig. 4), the spectrum is not distinguishable from synchrotron radiation. In addition, it is expected that the CER wavelength dependence in this spectral region will differ from that of CSR in a systematic way, having enhanced long wavelength components.
Figure 3. ELEGANT simulation of the longitudinal phase space in the ATF chicane, with input 50 A beam from PARMELA (left) and output 1.6 kA compressed beam (right).

![Figure 3](image1.jpg)

Figure 4. Calculated CER angular spectrum at output port in BNL ATF compressor experiment.

![Figure 4](image2.jpg)

Figure 5. Example of simulated CSR spectrum from FieldEye, post-processor of TREDI.

![Figure 5](image3.jpg)

In order to model the experiment more rigorously, a start-to-end simulation (PARMELA-TREDI) has been put together which allows calculation of the fields. The simulation of CER using TREDI is accomplished by direct calculation of the fields using a Lienard-Wiechert approach. With TREDI and a new post-processor, FieldEye, we can calculate both near field (see Fig. 5) effects, and the flux of radiated fields at the CSR/CER port. This work is now being undertaken by a team at UCLA including Michael Fairchild and Alessandro Flacco (from Univ. Milan), who work in collaboration with M. Quattromini and L. Giannessi of ENEA.
In order to observe CER phenomena, we use a cold bolometer to detect long-wavelength photons efficiently. Initial runs have shown that the collected edge radiation to be enhanced only when the bunch is run near the correct linac phase for compression, as is shown in Fig. 6. In addition, the data have the correct spectral dependence, with a flat long wavelength response, and a roll-off at the appropriate wavelength corresponding to three times the rms bunch length (Fig. 6). Finally, we note that the radiation is confirmed to have predominantly radial polarization.

For measurement of phase space effects, we look first at the momentum spectrum, which is directly affected by collective radiative fields. We observe (Fig. 7) a strong breakup of the momentum distribution in the spectrometer at the phase of full compression. This physical signature is now being studied using TREDI simulations.

For studying transverse effects, we have employed transverse phase space tomography (pioneered at BNL, and implemented on this experiment by UCLA scientist Feng Zhou), which should have allowed follow-on studies of the transverse phase-space filamentation observed at the UCLA Neptune Lab. As shown in Fig. 8, a vertical (bend plane of chicane) bifurcation has been observed in the ATF experiments, where the beam energy is a factor of 5 higher. This
indicates that the velocity fields, which were dominant in the Neptune experiment, still impact the ATF measurements.

**Figure 8.** Reconstructed transverse beam phase spaces of beams at under-, near full-, full- and over-compression at -14°, -18°, -19°, and -22° RF off-crest phase, respectively; top plots are x-x' (non-bending plane), and bottom plots are y-y' (bend plane); the abscissa axis is x (y), and the ordinate axis is x' (y'); the bunch charge is 200 pC.

**Second-generation VISA Experiments at BNL**

The UCLA role in SASE FEL experiments is aimed at improving the fundamental understanding of these systems as producers of tunable, high intensity radiation. The experimental, computational, and conceptual tools needed for SASE FEL experiments are enhanced by general high brightness electron beam studies, such as the compressor experiments described above, in which the PBPL has great strength. As such, the cross-fertilization between the beam physics and light source aspects of the PBPL program — which is a microcosm of this same process going on in the labs in the context of the X-ray SASE FEL (SLAC NLC and LCLS; DESY TESLA and TESLA FEL) has been of incalculable value. Nowhere is depth of the connections within our program more apparent than in the VISA experiment at BNL. This experiment has been divided historically into two components: VISA I, supported by DoE BES and LCLS, and VISA II, supported along with the UCLA/BNL compressor, by this grant, a now defunct grant from ONR, and some small recent (June 2005) support from NSF.

**Historical background: VISA I**

In the original BNL/LLNL/SLAC/UCLA collaboration to study the SASE process in the visible to near-IR, UCLA was responsible for most FEL and beam diagnostics, played a key role in experimental running, and has been the lead institute in data analysis and modeling. In this experiment, using a multiplexed array of 8 intra-undulator optical and electron beam diagnostics, we have measured exponential gain in excess of 10^8, with a power gain length of 18.7 cm, leading to saturation before the end of the 4 m undulator. While other SASE FEL experiments had reported saturation of SASE, they were accomplished in systems which did not employ both high brightness beams and strong focusing, as in VISA. These systems (LEUTL at Argonne, and
TTF-FEL at DESY) thus had much longer gain lengths, and very long undulators, even
discounting for their higher operation energy. The results of the VISA experiment have been
summarized in three papers in the Physical Review\textsuperscript{13,8,9}.

**Chirped Pulse SASE FEL: VISA II**

While many of the fundamental physics questions concerning SASE FEL have been addressed, a
number linger, in particular in the area of ultra-short pulse operation. The physics of ultra-short
pulse FELs is of high importance\textsuperscript{10} as the users of light sources are increasingly demanding
shorter duration (10 fs pulses) X-ray pulse to probe molecular dynamics and processes at atomic
time scales\textsuperscript{11,12}. Short pulse FELs can be seen as a challenge in electron beam compression, in
that one may attempt to directly produce short FEL pulses. Alternatively, a chirped-energy
electron beam could be employed to make a chirped FEL pulse, which is then filtered or
compressed. The previous sections work addresses aspects the former scheme; we now discuss
the work at VISA which explores the latter approach.

One of the schemes for using a chirped beam in a two stage SASE FEL is shown in Fig. 9,
where the stages are separated by a monochromator, which picks out a very short section of the
light to amplify in the second stage. Theoretical studies of chirped SASE FELs show that the
effect of the electron beam energy chirping on the FEL gain is small if the radiation frequency
change in a cooperation length is small compared to the natural FEL line-width. However, this
result, and the microscopic physics rationale behind it, has not been verified experimentally. It is
this scenario that has motivated our studies of chirped FEL systems thus far. In addition to
application to SASE systems, we also note that the manipulation and compression of chirped
beams will play a central role in future seeded amplifiers.

![Figure 9](image_url)

**Figure 9.** Scheme for using a chirped beam in a two stage SASE FEL, where the stages are separated by a
monochromator, which picks out a very short time-slice of the light to amplify in the second stage.

At the ATF, because of the bend-line encountered after the injector, use of a chirped beam is
also a very technically challenging experiment in nonlinear beam-dynamics. These effects led to
the fortuitous compression of the beam in the original VISA experiment. For the current
experimental scenario, however, one must linearize the transport of the off-momentum beam-
particles in order to preserve the time-energy chirp, through correct deployment of sextupoles.
This technique has been extensively studied in the context of both UCLA Neptune and BNL
ATF work recently\textsuperscript{13}. The needed sextupole magnets have been constructed at UCLA, installed at
the ATF, and deployed in initial beam dynamics studies as well as SASE FEL runs.

The linearization of the transport, along with moderate (factor of 3) negative $R_{56}$ compression
in the bend-line, allows for the creation of chirped pulses with 2% total relative bandwidth. This
is the maximum which can be accepted into the bend-line aperture. Full modeling of the experiment using start-to-end simulations with PARMELA-ELEGANT-GENESIS has identified a promising scenario for the experiment, as shown in Figs. 10 and 11. It can be seen that in this case a gain of over six orders of magnitude is possible in the VISA undulator, thus allowing a robust probing of the electron beam/radiation system.

Figure 10. PARMELA-ELEGANT simulations of the beam before and after bend transport, showing conversion of the initial chirped distribution, by compression (including linearization with sextupoles) and collimation, producing over 150 A beam at the VISA undulator.

Figure 11. GENESIS simulation of VISA II chirped beam (Fig. 10) output vs. distance along the undulator.

In order to recommission the VISA SASE-FEL, studies without sextupole correction were initially performed, with very high gain (>10^7, just past the onset of saturation) observed. The wavelength spectrum (see Fig. 12) shows a surprising 15% full width, which cannot arise from the energy spread nor the natural on-axis bandwidth due to the optical pulse length (bandwidth of ~4-5%). This bandwidth is well excess of what has been previously observed. With such
compelling results, this mode of operation became the focus of much experimental and computational study. These efforts have led to a recent publication in *Physical Review Letters*.\(^\text{14}\)

![Figure 12.](image)

This experiment has a complicated longitudinal phase-space which has been studied through start-to-end simulation at UCLA (Fig. 13). The experiment has a small, highly compressed region (beam current > 300 A), that is in saturated gain by the end of the undulator. There is more compression than in the VISA I in this case because the initial beam-chirp was quite large, and nonlinear compression is allowed over a large energy-band of the beam. It is now understood that the beam radiates as it undertakes large transverse-oscillations in the undulator with large angles associated with strong focusing. These oscillations, along with the small size of the beam in the undulator, allow coupling to off-axis radiation, which can give a large red-shift in wavelength, following the FEL resonance condition \( \lambda_r = \frac{\lambda_0}{2\gamma^2} \left[ 1 + \frac{1}{2} K^2 + (\psi \theta)^2 \right] \). The energy spread plays a negligible role in the frequency spectrum in this experiment; when the electron energies are set to be equal in the GENESIS simulations, no notable difference in the spectrum is found.

![Figure 13.](image)
The production of the measured bandwidth's anomalous aspects through off-axis emission is correlated to oscillations in rms beam size. A bi-Gaussian transverse distribution of radiators with rms widths \( \sigma_{x,c} \) and \( \sigma_{y,c} \) may emit coherently into angles as large as \( \theta_c \equiv (\lambda_c/4\pi)\sqrt{\sigma_{x,c}^2 + \sigma_{y,c}^2} \). For the beam sizes indicated in Fig. 14, this prediction yields \( \theta_c \) in the range of 1.7–2.5–mrad, consistent with the observed emission angles. On the other hand, Fig. 14 shows that when the transverse beam size is smallest (the maximum coherent angle is largest) the bandwidth rapidly decreases. This behavior is accompanied in simulations by a notable increase in the gain. The connection between the gain and bandwidth variations is that the near-axis, short wavelength mode gain is enhanced by the increase in beam density when the transverse beam size (beam radius defined as \( \sqrt{\sigma_{x,c} \sigma_{y,c}} \) ) is small, resulting in “gain guiding”\(^{15} \). However, the red-shifted mode gain is not as strongly enhanced, due to its wider angular emission, and the radiation bandwidth diminishes. As the FEL enters the onset of saturation, gain guiding is no longer effective, and the ratio of on-axis radiation to that of higher order modes is reduced. The FEL enters a final, pronounced period of bandwidth growth, yielding the observed state of large spectral spread.

We thus see that the off-axis radiation effects are critical to understand the wavelength spectrum of the FEL. Further, these spectra both depend in an intricate and specific way on the beam phase space. Indeed, the undulator has been proposed many times as a beam diagnostic, and these results support the utility of beam-produced radiation as a signature of the beam properties. The ability to uncover the results of complex beam dynamics, along with the simulation tools to model the dynamics, has broad benefits in accelerator science in general. As we discuss below, the information obtained from the undulator output can be increased by further analysis of the radiation.

To begin with the most direct extension of our radiation measurements, we discuss the development at UCLA of a diagnostic termed “double-differential spectrum”, or DDS. This measurement gives the differential-frequency and angular spectrum, \( \frac{d^2 I}{d\Omega d\Omega} \), which is fortuitously the result of many classical theoretical treatments\(^{16} \). Examples of this measurement are shown in
Fig. 15, which shows the expected quadratic dependence of $\omega$ on emission angle $\theta$. These measurements give additional insight into the mechanism for such anomalous, yet robust, broadening of the FEL signal. Thus, as in the original VISA [13] experiment, the mixture of precision beam and radiation diagnostics, in combination with rigorous, benchmarked start-to-end simulations, is allowing us to develop a detailed picture of the complex beam physics involved in the current experiments.

![Figure 15. Double-differential spectrum (DDS) measurement at second-generation VISA experiments.](image)

The physics behind the far-field structures may be even more subtle than those observable in the DDS system, which expects a symmetric angular spectrum, can reveal. We have observed, as seen in Fig. 16, decidedly asymmetric far-field radiation patterns. We are at present attempting to understand how these patterns arise. One recent suggestion is that the light is in a different type of eigenmode than usual, one that has so-called orbital angular momentum $l$. These Laguerre-Gaussian states have cork-screw, instead of approximately parallel phase-fronts, which have a defined orbital (around the $z$-axis) angular-momentum $l$. The intensity profiles of these modes, as well as the modes mixed with a standard Gaussian fundamental-mode, are shown in Fig. 15. It can be seen that the half-Gaussian, half $l=1$ mode looks very much like the profiles in Fig. 14.

![Figure 16. Far-field intensity profile from VISA high energy-spread experiment, with (right) and without (left) alignment laser to show center.](image)
If such modes are really present in the high energy-spread, nonlinear compressed-beam version of VISA, we may convert them to a mode with the signature of a standard Hermite-Gaussian by use of a pair of cylindrical lenses. It is planned to do this in the next round of VISA experiments. We suspect that these modes arise from the known transverse ($x$) slewing of the energy, which causes a slewing in the phase across the radiated pulse.

The preparations for the VISA II high gain, chirped-beam SASE-FEL experiment are, from the beam viewpoint, complete. Measurements in summer 2005 will attempt to gain an understanding of the longitudinal-transport correction using sextupoles. These studies will combine longitudinal CTR-measurements with examination of linear and nonlinear dispersion. In addition, seeding experiments, which are of critical importance to future high average power amplifiers such as those being planned for ERLs, are now being undertaken. The finishing of the BNL experiments in both compression and FEL study areas are discussed further in the proposed work section of this proposal.

**Figure 17.** (left) Phase fronts associated with states of definite $l$, with their associated (center) intensity profiles and (right) intensity profile when mixed with a Gaussian mode (from [31]).
Velocity bunching studies at Neptune

While magnetic compression schemes have proven successful in increasing the beam current, their impact on the transverse phase space has been shown not to be benign. When performing the compression at low energy, both velocity-field and centrifugal space-charge forces are not yet strongly suppressed by the relativistic cancellation of electric and magnetic fields, and their emittance-damaging effect becomes significant, especially in bending trajectories. In the case of compression at higher energy, one has to deal with deleterious effects of coherent synchrotron radiation (CSR) on the longitudinal as well as the transverse phase space\textsuperscript{18,19,20}. An alternative scheme which may preserve the transverse phase space quality while compressing the beam to sub-ps bunch length has been proposed by Serafini and Ferrario (SF)\textsuperscript{21}. This scheme, commonly known as “velocity bunching” — as opposed to the path-length dependence of magnetic compression systems — is an extension of the commonly employed technique of RF rectilinear-compression. This method has been typically used to bunch dc electron-sources at kinetic energies in the 100’s of keV range, but when applied to the RF photoinjector system, the bunching occurs at energies around several MeV. As bending is not needed in this system, one may avoid the phase space degrading effects observed in magnetic compression experiments on photoinjector-derived beams. With the compression occurring at low energy, where the transverse beam dynamics are space-charge dominated, special care must be taken to preserve the transverse emittance. The emittance compensation process is based upon precise control of the transverse beam (plasma) oscillations, allowing near complete cancellation of the space-charge derived emittance growth. The simultaneous action of velocity bunching and emittance compensation was initially studied theoretically by SF; it has been examined further using simulations and experiments in two different scenarios by PBPL. This work was a central component of the last renewal proposal for this grant.

It should be emphasized that velocity bunching allows for the compression to occur early in the acceleration process, and at lower energy than magnetic compression. This attribute plays a strong motivating role for the implementation of velocity bunching in the two applications discussed in below. In the first, to the ORION photoinjector, we have proposed use of velocity bunching to compress bunches emitted from an S-band RF gun, using a high gradient, short S-band linac section as a buncher. This scheme, which operates in a ballistic bunching regime where the compression occurs mainly in a drift, is needed to shorten the bunch length from one characteristic of S-band, to one scaled appropriately to the X-band linacs that give most of the acceleration at ORION. One may control the phase spread of the beam at the lowest possible energy (~5 MeV), thus mitigating the beam’s final energy spread. This scenario, which is critical to the ORION mission, is discussed further below. For now, we note that it provides a conceptual framework for the Neptune experiments. An alternative scenario, which we term phase space rotation, is relevant to experiments we have performed at LLNL, and corresponds closely to the original SF proposal. This type of velocity bunching was recently studied as well at BNL SDL\textsuperscript{22}.

The use of ballistic bunching was initially undertaken at the ATF, with bunching observed in a 1.6 cell S-band RF gun, when the electron beam is launched from the cathode at phases far off crest\textsuperscript{23} — in standard RF gun phase convention, far below 90°. This scheme has been shown to produce modest compression, and is based on both phase space rotation within the gun, and ballistic bunching after the gun. Furthermore, it is consistent with achieving low emittance. The
use of this type of velocity bunching is limited, however, by the constraints simultaneously placed on photo-emission, acceleration, focusing, and space-charge handling. Thus the ORION scenario, with the added freedom of a short bunching linac, is attractive.

The Neptune photoinjector\textsuperscript{24} and associated measurement capabilities\textsuperscript{25} are well suited for ballistic compression studies (Fig. 18). The photoelectrons generated in the gun are accelerated by the RF fields of peak on-axis amplitude \(\sim 80\) MV/m, and are transversely focused into the PWT linac entrance using the emittance compensation solenoid. At this point the beam can be energy-chirped for ballistic bunching inside the 8-cell, 42 cm long, S-band PWT RF cavity that is adjusted to run forward of crest. Downstream of the linac there is a CTR pulse length measurement system, as in the chicane tests. The final two chicane magnets are used as a 45° spectrometer. For the ballistic bunching experiments, a quadrupole and a Ce:YAG screen are used in the bend line, for "slice"-emittance measurements employing quad scanning.

**Figure 18.** Schematic layout of the Neptune ballistic bunching experiment.

**Figure 19.** Autocorrelation of optimally compressed beam in Neptune ballistic bunching experiment.

The investigations that were undertaken at Neptune were mainly centered on measurement of the bunch length using CTR interferometry. Parametric studies of linac electric field amplitude in the bunching linac were performed, allowing determination of the best compressing phase for different acceleration gradients. The presence of strong beam chirping means that one may use a dipole to select a portion of the beam with relatively small energy spread, thus allowing longitudinal beam slice measurements. In this way, the emittance of the central slice of the
electron beam was studied via quad scan techniques. As the phase of the RF accelerating wave in the PWT approached the optimum compression conditions, emittance growth was observed. Three-dimensional simulations that agree well with the experimental results were performed, but with some subtlety in interpretation needed.

Because one compresses with ballistic bunching by running the PWT far from crest (near the zero-crossing), the final bunch length is not as strongly limited by RF nonlinearity as in magnetic compression, where the beam manipulations require application of RF fields having strong longitudinal curvature near to the wave crest. For a case with approximately $Q = 250$ pC of charge, injected 70 degrees off crest in the PWT cavity (optimal compression), the CTR autocorrelation data are shown in Fig. 19. The fit to the data gives an rms pulse length of 0.39 ps. It is worth noting the compressed beam is shorter than that achieved (over 0.6 ps) using magnetic compression at Neptune with comparable beam charge and slightly shorter initial bunch length\textsuperscript{26}. It is also interesting to see that the Neptune beam was compressed to a length 35% shorter than achieved in the BNL SDL velocity bunching experiments; further, the compression factor (12-15) is much larger than in the SDL measurements (approximately 3).

As the total energy spread of the beam without post-acceleration to much higher energy is +/-25% at Neptune, full quad scans were not viable, as they would have been dominated by chromatic effects. Instead, the beam was horizontally bent, and a quadrupole scanning of the vertical emittance of the central slice (found by the mean energy) was performed. The results of this effort are shown in Fig. 20. Also shown are the detailed predictions of 3D modeling using start-to-end PARMELA/TREDI simulations, which agree well with experimental results.

![Figure 20. Emittance growth during compression, experimental results from quadrupole scan, and TREDI multiparticle simulations of compression and measurement system.](image)

These observed and simulated emittance growth were perhaps not due to the expectations of strong compression, leading to longitudinal cross-over (wave-breaking), previous to the bend. One predicted aspect of the bend is that because it has a negative $R_{56}$, the beam should cease compressing in the bend. In fact, this is only true if one looks at the projected beam distribution. When one includes the strong correlations between $x$ and $z$ in the bend, it can be seen that the beam’s local density is strongly enhanced for certain conditions where the beam does not reach longitudinal cross-over before the bend. This effect can be clearly observed in TREDI, as is shown in Fig. 21. It can be seen that higher energy electrons that are behind in $s$ (the beam direction) actually catch up to those forward, lower energy electrons in $z$, thus giving rise to the
increase in beam density. It is, surprisingly, this increased density that drives the observed onset of strong emittance growth, not space-charge effects upstream of the dipole. This anomalous density compression mechanism was an unexpected by-product of the experiments.

These experiments thus showed very robust pulse shortening from the ballistic bunching process. In addition, they produced a novel effect of anomalous density-enhancement in the attempt to measure the emittance growth due to velocity bunching. As we had no control over the emittance compensation process after bunching (no external focusing or post-acceleration), this was not a strong set-back. Control of emittance growth during the phase space rotation type of velocity bunching scheme was undertaken at LLNL. The measurements described here, as well as those taken at LLNL described in below, and relevant computational studies, have been published in *PRSTAB*.27

![Figure 21. Cartesian configuration space x-z projections for a beam accelerated 70 degrees off crest in the PWT linac at three different locations along the Neptune beam line: before the dipole (first column), at the anomalous compression point 12 cm inside the dipole (second column) and after the crossover (third column). The top line has equal scale on x and z axes. An arrow shows the beam propagation direction. The bottom pictures are zoomed versions of the top ones with expanded axes. Particles with higher energy (blue) that were in the tail of the beam overcome the lower energy particles (red) in the front.](image)

**LLNL velocity bunching experiments**

UCLA PBPL has been deeply involved in the 4th generation light-source experiment at LLNL, termed PLEIADES (Picosecond Laser-Electron InterAction for Dynamic Evaluation of Structures), since its inception. The focus of this project is the development of a time-synchronized collision of the 30 fs, 10-100 TW laser pulse from Falcon at LLNL with an intense low-emittance electron beam from a 30-100 MeV linac, to produce an intense, tunable, sub-100 fs to ps pulses of X-rays in the 10 to 100 keV spectral region via inverse-Compton scattering (ICS). The resulting X-ray beam, which exhibits world-class characteristics as a dynamic material probe, is now being utilized in unique experiments on high-Z material diffraction. In the near future, such bright, ultrafast high energy x-rays will enable pump-probe experiments on
laser-excited materials, such as shock compressed or laser heated metals. Importantly, it will develop new X-ray probing techniques of time-resolved dynamics in metals excited or shocked by a laser, and provide new techniques for fundamental materials science experiments. These techniques are relevant to the LCLS (the same wavelength region is easily accessed with low energy beams), fusion, stockpile stewardship, and ultimately many branches of nanoscience.

In terms of beam physics, PLEIADES has already been deployed as a test-bed for advanced techniques in manipulating electron beams at the fs time and the micron length scales. UCLA-led experiments have been completed which demonstrated the utility of the velocity bunching process\(^29\) for creating sub-ps beam pulses. We have also demonstrated the world’s most powerful installed permanent magnet quadrupoles (PMQs) in creating the ultra-small transverse spot sizes needed in the ICS final focus. As such, the PLEIADES ICS X-ray source is an example of an emerging class of cross-disciplinary scientific tools, where the physics of the tool itself is as challenging as the experiments performed with it. PLEIADES has produced notable results mentioned above in basic beam physics, and also already shown more ICS photons (over \(10^7\)) per pulse than any short-pulse source previously measured\(^30,31\).

We now review the progress in the UCLA beam physics studies at the PLEIADES experiment. We note that in this experiment, UCLA fabricated the RF gun, a bypass chicane system, and many of the longitudinal and transverse beam diagnostics in the PLEIADES system. We have also designed the cutting-edge approach to beam handling in this system — one must compress the beam to well-sub psec, and keep the energy spread and emittances low, at 1 nC, and relatively low energy (~50 MeV), then focus it to ultra-small spots. These combined goals are reached through velocity bunching, and use of ultra-short focal-length final-focus system. We begin with a discussion of the velocity bunching experiments.

![HOMDYN simulation of the bunch length and relative energy spread in the velocity bunching scheme implemented at PLEIADES. The bunch charge in this case is 250 pC.](image)

As chicane compression has produced such unexpected phase-space artifacts in experiments performed in a number of different regimes, it is obvious that we choose velocity bunching for this relatively low-energy experiment. The form of velocity bunching that we employ at LLNL is
quite close to that of the original SF proposal — what we term phase-space rotation, in which the beam is continuously exposed to RF fields, being injected near the traveling wave zero-crossing at roughly 4 MeV, and slipping back in phase until it reaches near the maximum in acceleration field, where the energy spread is minimized by both acceleration and rephasing of the linac sections. These manipulations are shown in the HOMDYN simulations given in Fig. 22. They are distinct from the ballistic bunching scenario measured at Neptune.

In order to understand this velocity-bunching effect, we refer to the longitudinal phase-space maps shown in Fig. 23, corresponding to an idealized, approximate Hamiltonian analysis of the longitudinal dynamics in the PLEIADES linac. The beam injected at the zero-crossing is compressed by a factor of over 15 in peak current through a phase-space rotation of approximately one-quarter of a synchrotron oscillation.

The results of a PLEIADES test of the full phase-space rotation scheme are shown in Fig. 24. This CTR measurement of pulse length shows an rms beam duration of 0.33 ps, a bit longer than predicted by simulation. This represents a factor of over 12 in compression; is nearly a factor of two shorter than that achieved at Neptune using chicane experiments; and, is at the limit of the resolution of the CTR device.

In subsequent experiments, the fact that independently-powered solenoids exist around each length of the traveling-wave linac section allowed an exploration of the emittance-compensation process during velocity bunching. The beam plasma-driven oscillations in the beam size and emittance are speeded up as the beam is compressed to higher densities, and the beam’s plasma-frequency is raised relative to a non-compressed case. The solenoids are raised in strength to compensate for this density increase as the beam traverses the accelerator.
The experimental tuning of the solenoids allowed an optimized beam to be created with an emittance increase of a factor of two. This beam was then subsequently used in the PLEIADES final focus, where the spot size was limited also by chromatic aberrations. Nevertheless, X-ray photons were produced using this beam, as is shown in the CCD images given in Fig. 26, however, with a factor of 4 less yield. Because of the pulse compression, however, the brightness of the X-ray source was increased by a factor of three by use of velocity bunching. One of the limitations on use of velocity bunching at PLEIADES was chromatic aberrations in the beam final focus system which are caused by the additional energy spread induced by the compression process. This effect was later mitigated by use of a novel final focus system, as discussed in the following section.

The results of the LLNL velocity bunching experimental studies have been published jointly with the Neptune results in PRSTAB.
Ultra-short Focal Length ICS Final Focus System

In order to make full use of the velocity-bunched beams, even with good emittance-compensation and preservation, we must still face difficulties in implementing a powerful enough final focus system. This innovative approach to solving this problem we have used, employing ultra-short focal-length optics, has general applicability in advanced electron-beam physics applications based on the photoinjector\textsuperscript{32}. These applications, for example, include driving a PWFA\textsuperscript{33} as well as providing an electron beam for an ICS X-ray source\textsuperscript{34} — any use that depends on production of very dense beams.

These applications require shorter bunch-lengths $\sigma_z$ and lower transverse-emittances $\varepsilon_{x,y}$, which drives one to employ methods such as optimized velocity-bunching. Much less emphasis has been placed, however, on the need to scale the beam focal-systems down along with the relevant length scales — $\sigma_z$, $\varepsilon_{x,y}$. The length scale of the focal system is clearly set by the minimum “$\beta$-function”, $\beta^*_s$, which is related to the beam size at focus by $\sigma^*_s = \sqrt{\beta^*_s \varepsilon_s}$.

In focusing to the smallest $\beta^*_s$ in an ICS interaction region one must simultaneously avoid chromatic-aberrations due to energy spread, and emittance growth due to residual space-charge effects in the beam if it is expanded for final focusing. Assuming one uses relatively weak normal-conducting electromagnetic-quads, the final spot-size (in the absence of an elaborate, energy-compensated final-focus system) is limited by chromatic aberrations. These observations are illustrated by the following relation governing the ratio of final spot size $\sigma^*$ to initial $\sigma_0$:\textsuperscript{35}

$$\frac{\sigma^*}{\sigma_0} = \sqrt{1 + \left(\frac{\beta_0}{\beta_s}\right)^2 \left(\frac{\sigma_{y,p}}{\sigma_0}\right)^2} \equiv \frac{\sigma^*_{y,p}}{\sigma_{y,p}} \frac{\sigma_{y,p}}{\sigma_0}.$$  

When the initial $\beta$-function, $\beta_0 = \sigma_0^2 / \varepsilon$, is larger than the effective focal length $f$ of the final focus system, strong reduction of the beam size is possible, up until the chromatic aberrations begin to dominate, $\beta_0 / f = p / \sigma_{y,p}$, at which point the emittance grows rapidly and demagnification is limited to approximately twice the rms energy spread.

At PLEIADES\textsuperscript{36,37}, with the present generation of relatively large aperture quads that UCLA employs the minimum value of $f$ (effective focal length for a triplet) is roughly 50 cm, gives a minimum $\sigma^* \approx 30 \text{ m}$ for $1 \text{ m}$. This spot size estimate, which has been verified in PARMELA simulations, is unacceptably large for the ICS. In addition, by allowing the beam to expand in this scenario, space-charge forces will increase the emittance, giving an even larger final spot size. This consideration also precludes more elaborate approaches to elimination of chromatic aberrations. At low energy, transport and final-focusing systems must be compact, and short focal-lengths are highly desirable.

It is well known that permanent-magnet quadrupoles (PMQ) and superconducting quads (SCQ) may achieve the highest gradients, and thus shortest focal-lengths. For such short magnets as PLEIADES demands, the SCQ is not practical. On the other hand, tunability is a large issue when dealing with PMQs. In the linear-collider main-accelerator application, a serious effort has been underway for several years to design a moderate strength, but tunable magnet.

The need for extremely large field-gradients makes the introduction of significant gradient-tuning into a PMQ very challenging. We have therefore adopted an alternative scheme that sidesteps these difficulties, by tuning the strength of the final-focus array (a generalization of a
quadrupole triplet) only through the longitudinal positioning of the individual PMQs. In this way, the issue of tunability is separated from both that of alignment, and that of achieving the highest gradient. Additionally, one may access field gradients that are extremely large, by using an optimum, static intra-magnet configuration. Such a magnet configuration, also introduced originally by Halbach\(^{38}\), is shown in the simulation model displayed in Fig. 27. The pure permanent-magnet geometry consists of 16 sections of permanent magnet pieces. This sectioned magnet configuration has been studied by the CLIC LC group, and has been implemented at CESR in the CLEO detector mini-beta system\(^{39}\).

![Figure 27.](image)

This geometry is known to allow one to obtain field gradients that are given by

\[ B' = 2B \left( \frac{1}{r_1} - \frac{1}{r_2} \right), \]

where \( B_r \) is the remnant field of the PM material, and \( r_1( r_2) \) are the inner (outer) PM material radius. For the favored material NdFeB, \( B_r = 1.22 \) T, and thus a 2.5 mm inner radius produces approximately 600 T/m. This scaling was born out by the RADIA\(^{40}\) 3D magnetostatic simulations corresponding to the magnetization geometry shown in Fig. 27, where the gradient for these conditions was found to be 560 T/m.

Although we have referred to the final-focus scheme as an adjustable generalized triplet, in practice it is not run near standard triplet settings — FDDF. Instead, we have found that the final quadrupole should have approximately equal strength with the inner quad. Thus we employed beam optics in this final-focus system based on equal strength PMQs consist of three independently positionable units, in an FDDFF array; the final two magnets are twice the length of the first. In this way, the strong modulation of the beam size in the system can be dealt with.

The details of the beam optics performance expected from such a system, with 3 PMQs of 1(2) cm length and 560 T/m gradient have been studied with simulations, including TRACE3D\(^{31}\) (Fig. 28) and ELEGANT\(^{42}\). The demagnification is strong, from 400 \( \mu \)m to approximately 5(6) \( \mu \)m rms (x,y). The vertical beam size \( \sigma_y \) is more limited than \( \sigma_x \) by chromatic aberration-induced emittance growth, because the maximum vertical beam-size in the system is larger. Distortions in the phase space are notable in the ELEGANT output shown in Fig. 29. The ELEGANT simulations do not yet contain information on the multipole content of the PMQs, which is in any case very small in the Halbach design — the fields display no significant nonlinearity (from the optics view-point) until one exceeds 80% of the physical aperture.
The method of tuning a focusing system, by changing the distance between modular quadrupole units, is easy to understand in terms of the concepts of alternating gradient focusing—increasing the distance between focusing and defocusing units generally increases the focal power. As described, the final-focus system based on the PMQ array has three adjustable parameters associated with PMQ placement in $z$, and a number of additional parameters associated with the upstream quads. In practice, we have found that the upstream Twiss parameters may be measured using a quad scan. Then, TRACE3D allows one to estimate the correct setup of the system for final tuning, giving an algorithm that has been shown to be successful in experiments over a wide range in energies.

The design of the PMQ lenses themselves involves a number of interdependent considerations, such as overall gradient strength, effective length, radiation/temperature/reverse-field induced demagnetization, tolerances, sorting of PM pieces, mounting, centerline and gradient correction. The design chosen has been based on 3D simulations performed with the code RADIA. The PM material chosen is NdFeB, because of its higher remnant field ($B_r = 1.22$ T) and intrinsic coercivity ($H_{ci} = 21$ kOe) compared with SmCo. Fabrication of all quads from a single assembly allows control of relative roll, which must be kept to less than 0.5 degrees.

Because of the small size of the quadrupoles, and the required resolution, magnetic measurements were challenging. Hall probes were used to obtain an overall estimate of the field.
gradient. For centerline location and linearity, however, we have relied on pulsed wire measurements. This measurement system allows us to calibrate the first integral of the field in the PMQ to that of a known magnet, and to scan with ~5 micron precision the field profile.

The implementation of the PMQ system on PLEIADES required that general problems associated with the application of this focusing system be solved. This project was quite difficult, exceeding even that of the BNL compressor. A mechanically simple design (see Fig. 31) was chosen to comply with experimental requirements. Computer controlled custom vacuum linear motion feedthroughs were utilized to control quadrupole longitudinal position, which was precisely constrained by a rail system. Motion of the PMQs is controlled by stepper motors and LabVIEW software. The entire magnet axis of the system was aligned by use of the pulsed wire system and optical techniques. Other features of the assembly include a ceramic ablation disc at the front of the assembly to protect the magnets from misaligned laser damage, and a scintillating disc at the beam entrance side of the assembly for locating mis-steered electron beams.

The UCLA adjustable PMQ final focus system was recently installed on the PLEIADES beamline, and run to reliably produce ~15 micron beam spots. An example of this performance is shown in Fig. 100, which displays the optical transition radiation (OTR) spot at a polished cube, along with the FALCON laser spot. The OTR diagnostic provides the signal for the spatial

---

**Figure 31.** The adjustable PMQ final focus assembly before (left) and after (right) installation at PLEIADES.

**Figure 32.** (Left) Image of electron beam showing a 16x20 µm spot (from OTR), and laser (from attenuated reflection); (Right) X-ray spot on CCD using PMQ final focus, with enhanced output.
alignment, and streak-camera based temporal alignment systems, as well as the spot-size measurements. Figure 32 shows an electron beam spot of 16x20 µm, and a laser which is similar in size. In fact, because the laser is a bit larger than the electron beam now, the gain in X-ray flux due to this final focus system in going from a 50 µm beam to the present focus (factor of ~8-10) was not as pronounced, and increasing by only a factor of 4-5.

\[
\begin{align*}
\epsilon_n &= 12.9 \text{ (mm mrad)}, & \epsilon_n &= 16.3 \text{ (mm mrad)}, \\
\beta_y &= 1.79 \text{ mm}, & \beta_y &= 1.62 \text{ mm}, \\
\sigma_{\text{min}} &= 14.2 \mu\text{m}, & \sigma_{\text{min}} &= 15.2 \mu\text{m}
\end{align*}
\]

Figure 33. Quad scan of the final focus beam at LLNL PLEIADIES, moving entire PMQ assembly together.

We noted that in the first round of tests, the measured electron beams were somewhat larger than expected. Part of this size comes from large emittance input to the final focus, and some due to emittance growth within the final focus. The most important effect, however was the inherent resolution of the optical system used to observe the beam’s OTR image. It was determined by both examination of the optics system, and fitting of the quad scan assuming a minimum beam size as a fit parameter (added in squares with the actual beam size), that the resolvable beam size was near 15 microns. Present and future work at LLNL PLEIADIES will feature better resolution optics; the final focus system will also be deployed, as intended with velocity bunched beams.

The tunable PMQ final focus system is part of the thesis work of UCLA student Jay Lim. The initial work written up in an article that has been published in *PRSTAB*. The development of this unique scientific tool has caused considerable notice in the field; a similar system has been adopted at the Neptune ICS experiment, and is under study for adoption at SLAC and LBNL experiments. The technology itself has also been licensed by UCLA to RadiaBeam Technologies for commercial development.

---


“Light’s angular momentum” Miles Padgett, Johannes Courtial, and Les Allen, Physics Today (May 2004)


40 http://www.esrf.fr/machine/groups/insertion_devices/Codes/Radia/Radia.html

41 http://iapdipc.physik.uni-frankfurt.de/Texte/TRACE3D.html
