MONITORING AND MANIPULATION OF SUB-PICOSECOND BEAMS*

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Abstract

In cutting-edge applications such as advanced accelerators and free-electron lasers, very high brightness beams of duration shorter than a picosecond are required. Further, these applications demand specific types of longitudinal beam profiles, such as pulse trains, and ramped pulses. The production of such types of beams present challenges both in technique, and in the instrumentation required to verify the method employed. The techniques for producing such short beams which have received the most investigation in recent years include chicane compression, and modulation via free-electron laser mechanism and its inverse. We discuss the principles and relevant single particle and collective effects which impact their performance. We review progress in implementing these schemes, as well as newer concepts such as relativistic velocity bunching and use of negative R_{56} compressors. We also discussed the chal-enges in diagnosing these state–of-the-art beam systems.

1 USES OF SUB-PICOSECOND BEAMS

There are numerous applications driving the development of sub-picosecond electron beams at the present time. These applications are principally derived from the fields of ad-vanced accelerators[1] and ultra-fast radiation[2] sources. Not only are these beams required to have ultra-short time duration, they also typically possess *high brightness*, defined to be the ratio of the peak current to the transverse phase space area, $B_e = 2I/\varepsilon_n^2$.

Within the applications mentioned above, the characteristics of the beams vary quite widely. In the field of advanced accelerators, the end goal is to provide beams of high energy, accelerated at a high rate (0.1 to many GV/m), having attributes consistent with high luminosity when brought into collision at a linear collider final focus. It is straightforward to deduce how this implies very high beam brightness. It is implicit in the assumption of large electric fields that the accelerator be operated at short wavelength λ (*i.e.* shorter than any standard technology, or sub-cm), in order to give favourable beam dynamics, and also to limit stored electromagnetic (EM) energy and power use. These types of short wavelength accelerator concepts fall into two categories. In *direct EM acceleration*, the “rf” wavelength is that of the laser or other short wavelength power source. In such cases, the accelerating beam pulse in the device is short compared to the wave period, and thus may be in the sub-femtosecond range. When dealing with such a concept, the injected are generally envisioned to be *microbunched* pulse trains formed by modulating the distribution of a longer (psec) pulse. Each micropulse typically needs to contain a relatively small charge (pC), and low normalized emittance ($\varepsilon_n < 10^{-7}$ m-rad).

At wavelengths closer to those presently used in linear collider research (far IR to mm), there is an additional role played by the beam, that of the power source itself. Accelerators powered by short-pulse, ultra-relativistic *driver* beams are termed *wakefield accelerators.* These devices use a high impedance environment (plasma; metallic or diel-ectric structure) to extract large peak power out the beam. The medium in this case is chosen to be resonant in the above-indicated wavelength range, where there are no attractive alternative power sources. The beam current must have spectral content at the wavelength ranges. This means, again, that either short (compared to the wavelength) pulses, or pulse trains modulated at the resonant wavelength can be employed. Additionally, one finds the *transformer ratio* (the ratio of the peak accelerating field behind the driver to the peak decelerating field inside the driver) may be enhanced by using a specially tailored current profile[3] — a long ($>>\lambda$), gentle rise followed by a sharp fall ($<<\lambda$). We will discuss the creation of such “ramped” pulses below.

In the beam-plasma interaction, it should be noted that the extracted radiation is considered to be in *plasmon* form, due to the existence of free-charges supporting the wave. Generalized plasma wakefields are driven also by powerful short pulse or resonant beatwave[4] lasers. This can be considered a form of mode-conversion. In most cases of wakefield acceleration, the injected beam is not a pulse train, but a single pulse measuring <100 fsec.

Radiation sources based on short pulse, high brightness beams also fall into two main categories: self-amplified, spontaneous emission free-electron lasers (SASE FELs)[1], and Thomson scattering sources[5] based on the collision of high power laser pulses with relavistic electron beams. In the case of the SASE FEL, the beam must be intense and cold, in order for the collective instability with converts electron energy into coherent EM radiation to strongly assert itself. High interest now exists in constructing an X-ray SASE FEL in the wavelength region of one Angstrom (*e.g.* the LCLS or TESLA-FEL), which requires beam energy in excess of 10 GeV. As the gain length in a FEL scales[6] as $(B_e/\gamma)^{1/3}$, at high energy one must use a very bright electron beam in order to avoid an excessively long undulator. In practice, the demands of SASE FEL operation imply a peak current of several kA, and $\varepsilon_n < 10^{-6}$ m-rad. With typical beam charge in a pulse <1 nC, this implies an rms pulse length of 100 fsec or less. To obtain such high current pulses, compression techniques must be applied at intermediate energies (0.2 -5 GeV).

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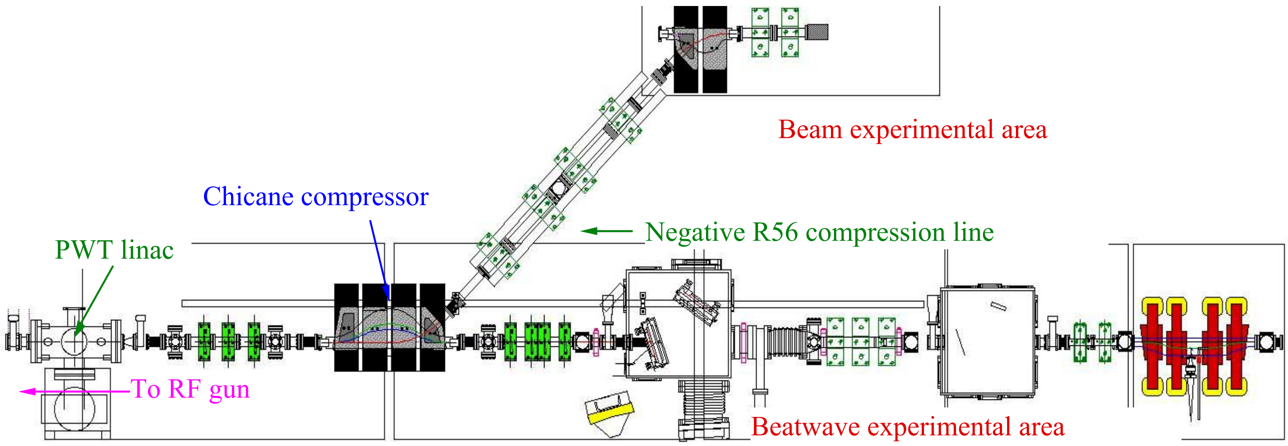

Figure 1: UCLA Neptune laboratory beamline, with post-acceleration linac, chicane compressor, S-bend negative R56 compression line (installed fall of 2001), and experimental areas shown.

The application of ultra-short electron beam pulses in Thomson scattering x-ray production devices is similar to high energy physics collisions, in the sense that high peak luminosity is needed to create sub-psec radiation pulses with large numbers of photons. Thus one must focus the colliding electron and laser pulses as tightly as possible, while maintaining large electron beam charge, and laser pulse energy. The demand on the beam is clearly again for high brightness, but at much lower energy (20-30 MeV for an IR laser, to obtain LCLS-like x-ray wavelengths. In this case, scattering at 90^o incidence has been proposed to make fsec-psec x-ray pulses. The timing synchronization of these collisions is similar to the injection requirements of advanced accelerators, and is well sub-picosecond.

2 RF PHOTOINJECTOR SOURCES

The rf photoinjector[7] is now the ubiquitous technology employed to produce short electron pulses. In such devices, the electron beam is created by illuminating a photocathode embedded in a high-field rf cavity with a short-pulse laser. This allows a high charge, short pulse photoelectron beam to be emitted, and accelerated to relativistic velocity in a very short distance ($<<\lambda_{rf}$).

As high energy laser pulses are available at the sub-100 fsec level, in principle, it is possible to produce photo-electron beam pulses with this characteristic time structure. Several effects interfere with this approach, however. First, one must have a photocathode with a response faster than 100 fsec, which is possible with relatively low quantum efficiency (QE) metallic cathodes, but which may not be for high QE semiconductors (e.g. Cs_2Te). More systematic problems arise due to dynamical effects during acceleration, however. During the initial capture and acceleration of the photoelectrons, the spatio-temporal dependence of the rf fields produce longitudinal compression (known as velocity compression, or phase focusing). The time duration of a pulse is typically shortened by over 15% due to this effect[8].

Phase focusing is opposed by the action of collective effects[8] — longitudinal space-charge and wakefields, which are especially strong at low energy, near the cathode. As one obtains low emittance from photoinjectors by relying on *emittance compensation*, where the transverse beam plasma frequency $k_p = \sqrt{4\pi r_e n_b / \beta^2\gamma^3}$ is such that one transverse plasma oscillation occurs during the initial acceleration and drift up to the linac[11] (see the layout example in Fig. 1) entrance. As the longitudinal plasma frequency scales with the transverse, while remaining slightly smaller, the beam has a tendency to debunch under the influence of space-charge forces. This effect tends to be stronger for shorter pulse lengths, and thus there is a limit to how high the beam current, and thus the beam brightness which can extracted from a photoinjector.

3 MAGNETIC COMPRESSORS

In order surmount the difficulties which are encountered in creating sub-psec electron pulses from photoinjectors, many laboratories have implemented magnetic compressor systems, in which correlated momentum spreads induced by running off crest in the photoinjector linac can be used in concert with the path length dependence on momentum in bending systems. Two examples of such systems are dis-played in Fig. 1, which shows the layout of the UCLA Neptune Lab photoinjector[9]. The chicane compressor[10] shown after the PWT linac is designed to compress beams with a negative $(\delta z_i, \delta p_i)$ correlation, or chirp, obtained by running the beam "forward" of rf crest. The chicane accom-plishes this through its large, positive value of the TRANSPORT parameter $R_{56} \equiv \partial(\delta z_f)/\partial(\delta p_i / p_0)$, *i.e.* high δp particles traverse the chicane in shorter path length.

There is also a (soon to be installed) negative R_{56} com-pression line, which has a dog-leg geometry, and allows another experimental (beam-only) area at Neptune in addition to the inline (laser acceleration) area. In this case, compression occurs when the beam is placed "back" of rf crest, to impart a positive $(\delta z_i, \delta p_i)$ chirp.

Powerful chicane compression has been demonstrated at many labs, including Neptune, where a 4-5 psec beam shortened to 0.5 psec (rms)[11]. The phase space picture of chicane compression is illustrated in Fig. 2. It can be seen that at optimal compression, the linear correlation between the original (at the cathode!) and final longitudinal position vanishes, $R_{11} \equiv \partial(\delta z_f)/\partial(\delta z_i)=0$, and only the quadratic component of the phase-energy correlation due to rf curva-ture is left after the chicane. The projection of this final phase space gives a ramped beam, but with a fast rise and a slow fall time, the reverse of that needed for generating a large transformer ratio in a wakefield accelerator.

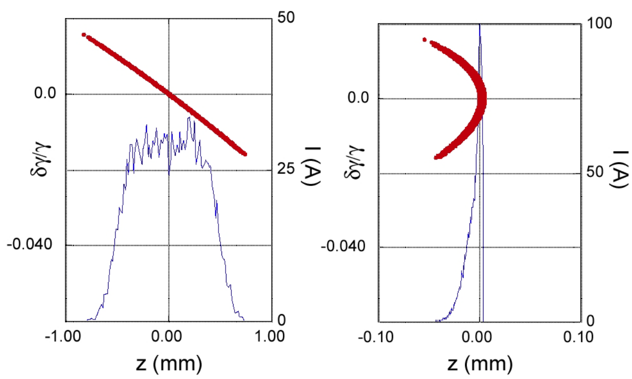

Figure 2. Initial (after linac) and final (after chicane) phase space and current distributions, from PARMELA simulation of Neptune photoinjector/chicane.

The condition that $R_{11} = 0$ also means that to lowest order (and ignoring longitudinal space-charge and wakes), timing injection jitter with respect to the rf "clock" vanishes[10]. Thus one may use a chicane to lock the photoelectrons to the rf system timing. For applications such as Thomson scattering, one must then also lock the high power laser to the rf clock, and a proposal to do this with an electro-optic “chicane” has been proposed[12].

The chicane can also used to make the electron beam orthogonal to the rf clock, which is the condition $R_{11} = 1$, by removing the phase focusing occurring in the rf gun. This is accomplished by running the beam back of rf crest in the linac to apply phase defocusing. Thus one may recover the initial laser pulse profile and timing in originally exciting the photocathode. This technique has been studied in the context of using the Neptune beatwave (10.3, 10.6 μm) laser, the Mars system, to impart a modulation on the photocathode drive laser by electro-optic methods. The $R_{11} = 1$ condition not only guarantees that the modulated photoelecton beam emitted has the correct periodicity to inject into the plasma beatwave accelerator (PBWA) experiment, but also that the PBWA and the electron pulse train may be synchronized. This method may of course also be applied to synchronization in Thomson scattering systems, where one uses the same laser system to drive the cathode and the Thomson interaction region, but at the price of using a longer, non-compressed pulse.

It should be noted that the generation of pulse trains by the FEL or IFEL mechanism is also based on continuous chicane-like transformations. This form of magnetic comp-ression has successfully produced few micron (fsec) pulses which were then synchronously injected into an IFEL section in the STELLA experiment[13]. It is notable that the synchronization of buncher and accelerating IFEL (with laser power in each section derived from the same 10.6 μm system) was maintained over 30 minute periods.

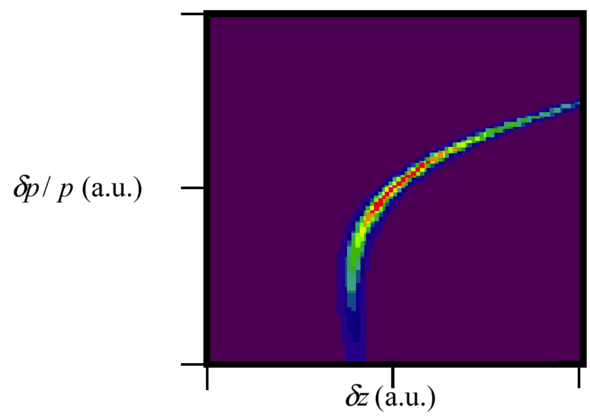

Figure 3: Phase space distribution of electron beam compressed using negative in ORION design simulation.

While chicane compression is used widely and success-fully, and is a critical enabling technique in current FEL[14] and wakefield[15] experiments, it is degraded by the col-lective forces in beams. This is true of the transverse phase space, where the velocity fields (space-charge) and acceleration fields (noninertial space-charge, and coherent synchrotron radiation, or CSR) can produce strong emittance growth during compression[16]. These effects are under intensive scrutiny at photoinjectors such as Neptune[11].

In addition longitudinal self-forces tend to oppose the chirp needed in a positive R_{56} compressor. This situation indicates that negative R_{56} systems, such as the Neptune dog-leg beamline shown in Fig. 1, may be of interest for compression, as collective longitudinal forces actually add to the needed positive $(\delta z_i, \delta p_i)$ chirp, enhancing the efficiency of compression. This dog-leg geometry is quite generally used, and relies on the dispersion going through zero in the mid-point between bends. It forms the basis of the experimental beamlines at the BNL ATF, and is under study for use at the ORION lab being designed for SLAC[17].

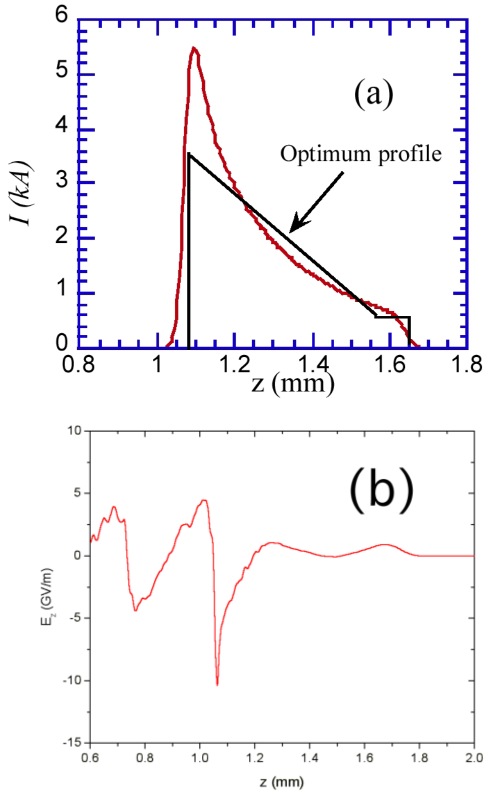

Figure 4: (a) Current profile of 4 nC beam phase space shown in Fig. 3, with optimum theoretical profile for driving wakes; (b) PIC simulated wake-fields generated by beam in a $n_o = 2 \times 10^{16}$ cm^{-3} plasma, at ORION.

In addition, one may produce a beam with the correctly-oriented ramped current profile for high transformer ratio wakefield generation, as shown in Fig. 3. By not comp-letely cancelling the linear correlation of the distribution, a long, nearly optimized ramped pulse may be produced.

The current profile associated with the phase space in Fig. 3, and a comparison of it to the optimized current profile for producing large transformer ratio, are shown in Fig. 4(a). This beam has been used as input to simulation of a proposed plasma wakefield accelerator experiment at ORION, with the result shown in Fig. 4(b).

The negative aspects of compression arising from bending particle trajectories are of great concern, as the present designs for X-ray SASE FELs rely this manipulation, but must avoid transverse emittance dilution. To avoid these effects, Serafini and Ferrario have recently proposed[18] a velocity bunching scheme in which the beam undergoes standard injection and emittance compensation before the first post-acceleration linac section. In this section, which is designed to operate at a phase velocity slightly less than *c*, the beam is injected paraphase at 5-7 MeV, and undergoes one quarter of a synchrotron oscillation in the linac, ending up with a strong (> a factor of 10) compression.

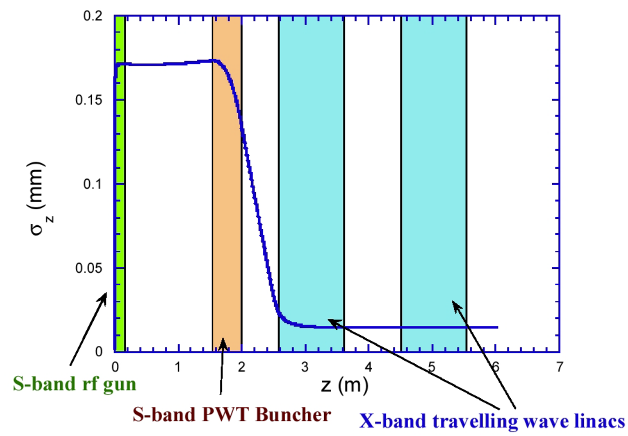

Figure 5: Simulation of velocity compression of 10 pC beam in the ORION injector, from HOMDYN.

This scheme is also interesting from the viewpoint of compression at ORION, as the pulse naturally obtained from the high gradient S-band 1.6 cell gun has a significant phase spread in the NLCTA X-band post acceleration linacs (25°). Because of this the beam will have excessive energy spread for laser acceleration experiments, and will be challenging to compress unless a precompression scheme is employed. A simple variation on the above velocity bunching scenario uses a short, high gradient PWT linac (the first two rf structures are the same as Neptune), run paraphase, to give a bunching "kick" followed by a drift, and freezing of the longitudinal dynamics. A simulation of this scheme for ORION has been performed with the code HOMDYN, and shown in Fig. 5, for a 10 pC beam, giving a final rms length of 16 μm.

4 SUB-PSEC PULSE MEASUREMENTS

The measurement of sub-psec electron beams presents great challenges to the experimenter. Time domain optical signals can be obtained from prompt incoherent processes such as Cerenkov and transition radiation. This light can then be input to a streak camera to give the temporal structure of the beam, and additional information (*e.g.* profile, energy spectrum) in the non-streak dimension. This is a powerful method of time-resolving beam properties[19] but has resolution limited to 0.25-0.5 psec[20].

In order to do better than this limit, methods based on coherent signals such as coherent transition radiation (CTR) have been developed. In the time domain, the CTR signal from a foil can be autocorrelated using, for example, a Martin-Puplett interferometer, as is done at Neptune and other labs. This method suffers from the fact that the CTR is not efficiently produced or propagated at long wave-lengths due to finite foil size effects[21]. Thus the auto-correlated CTR pulse which is does not reproduce the beam current profile, and to derive the pulse length fitting algorithms have to be employed[22]

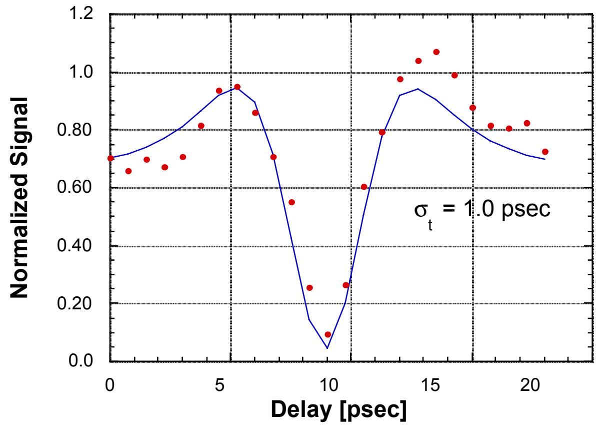

Figure 6: Autocorrelation of compressed beam at Neptune, with time-domain fit to data.

An example of such a measurement made at Neptune along with the time-domain fit of the autocorrelation is shown in Fig. 6. Beams as short as 0.5 psec rms have been measured at Neptune with this method[11], with the inherent resolution (0.2 psec) limited by the interferometer beam splitters.

To diagnose temporal structures of microbunched beams using CTR, one measures the frequency spectrum, with observation of the lines at the fundamental modulation frequency and, in the case of strong bunching, harmonics. This method was introduced in the context of IFELs[16], and SASE FELs[23], and has found wide application14].

One of the limitations of CTR interferometry and some spectral measurements is that they take many pulses to make a determination of pulse length. This has been circumvented by use of a multichannel sub-mm wave polychromator[20] in experiments performed by a Tohoku-Tokyo collaboration. By measurement of the single-shot spectrum, one can invert the spectrum, adjusting for the long wavelength CTR suppression, and using the Kramers-Kronig relation, to reconstruct the pulse[24]. A variant of this scheme has been proposed for measuring the single shot beatwave modulated beam spectrum at Neptune. In this case, a polychromator with wavelength detection centered around the beatwave (330 μm) will be employed[10].

Time-resolved measurements of beam properties at high energy may be performed by "beam streaking" using a deflecting mode cavity, as proposed by Wang[25]. This scheme may allow time-resolved beam diagnosis at the 10 fsec level in the LCLS[26]. This type of scheme is also under study for use at ORION, where determination of details of beam profiles such as that of Fig. 4(a) is critical to the success of the wakefield acceleration program.

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