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EXTREME PULSE COMPRESSION FOR IMPULSIVE IONIZATION OF VALENCE WAVEPACKETS

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Abstract

We show how a chicane with anomalous dispersion can be used to compress an electron beam into a narrow, high-current, spike by exploiting the intrinsic chirp created by collective effects. We explore the limits of compression in a linearized model and then apply these beams to impulsively pump valence electrons. In the limit of an ultrashort electron beam, the valence electron wave-packet is accelerated so rapidly that the excited state forms an image of the bound state, allowing for unique insight into the structure of the electronic states of a molecule.

INTRODUCTION

The transverse space-charge field of a relativistic electron beam can be compressed into a high intensity impulse which is capable of driving novel quantum phenomena [1]. Compared to a conventional laser, it has shorter and stronger fields because the beam current supports deeply sub-wavelength foci. The space-charge field is also uniquely broadband, such that it can generate complicated superposition states with non-trivial ultrafast dynamics.

In the limit of a very short, intense beam, the space-charge field can impulsively ionize a valence electron by kicking it to high momentum before it has time to scatter. This creates a complex superposition of energy eigenstates with the simple (length-gauge) interpretation of a translation in momentum space. The impulsively ionized electrons can be recorded on a spectrometer to directly track the bound-state dynamics [2–4]

The space-charge field must meet three main conditions to drive impulsive ionization: first, the current spike should be shorter than the Bohr period $\tau << 2\pi/\omega$; second, the integrated kick should be larger than ionization energy $(q_e/m_e)A = \int (q_e/m_e)Edt \approx q_e Z_0 Q/(m_e 4\pi\sigma_r) >> \sqrt{(2\hbar\omega/m_e)}$; and finally, the pulse contrast must be large so that the pre-pulse does not tunnel ionize the electron before the spike arrives [5]. For a typical valence binding energy of $\hbar\omega$ =5 eV, the Bohr period is $2\pi\times125$ as, implying that the current spike must be compressed to very short lengths. This does not necessarily imply large currents, because we can tightly focus σ_r, but in practice σ_r<25 µm is undesirable because it becomes difficult to image the ionized electrons with better resolution. Therefore the peak current of this pulse will be of order 50 kA, indicting the importance collective effects during the formation and transport of an impulsive electron beam.

In this proceeding we will consider the creation and transport of ultrashort, high intensity current spikes for impulsive ionization (see Fig. 1). First we will use an analytical 1D model [6] to describe the space-charge driven de-bunching of a high current spike. Then we will consider the design of a chicane with positive R_{56} to re-compress the space-charge chirp [7].

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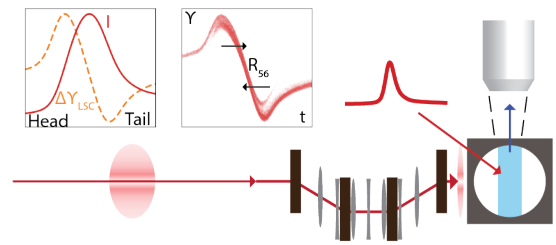

Figure 1: Cartoon of bunch compression for impulsive ionization. Left: during beam transport, the current profile (solid) drives a high-frequency longitudinal space charge wake (dashed). Right: the LSC chirp can be compressed by an anamolous chicane and used to impulsively ionize a gas jet. The collected spectrum will form an image of the bound state momentum density.

Longitudinal Space Charge

A short current spike propagating in free space will rapidly gain energy spread and then slowly decompress under the influence of longitudinal space charge. We can describe this process self-consistently in 1D by using the model first introduced by Chao [6].

Let us start by considering the longitudinal space charge (LSC) impedance Z [8] for a beam of radius r_b in a pipe radius r_p with $\xi_b = kr_b/\gamma$, $\xi_p = kr_p/\gamma$:

$$Z(k) = \frac{iZ_0}{\pi\gamma r_b}\frac{1}{\xi_b}\left(1 - \xi_b\left(K_1(\xi_b) + K_0(\xi_p)\frac{I_1(\xi_b)}{I_0(\xi_p)}\right)\right) \quad (1)$$

$$\approx -ik\frac{Z_0}{4\pi\gamma^2}\left(\Gamma - \frac{1}{2} + \ln(\xi_b/2)\right), \quad (2)$$

where $\Gamma \approx 0.577$ is Euler's constant and the approximation holds for $\xi_b << 1$ and $r_b << r_p$. Since the logarithm varies slowly with k over the range of interest, then we can fairly neglect it by setting $\xi_b \approx 2\pi r_b/\gamma\sigma_z$ for a current spike of length σ_z. Then the Fourier transform of the impedance tells us that LSC is proportional to the derivative of the current profile.

Bending magnets can greatly increase the beam impedance. For CSR of a short spike ($\sigma_z << s_L = R\phi^3/24$) the force is also proportional to the derivative of the current profile [9]. Of particular interest is the impedance travelling through a short-wavelength undulator. In this case the increased impedance can be understood as a reduction in the cancellation of the electric and magnetic

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forces due to the slowing of the average beam velocity $\gamma \rightarrow \langle \gamma_z \rangle = \gamma/\sqrt{1+K^2/2}$ [10].

These approximations for the 1D LSC are valid provided the current spike is long in its rest frame: $r_b << \gamma\sigma_z$ and that the electron beam is much larger than the single-period diffraction $r_b >> \sqrt{\lambda_u \sigma_z}/2\pi$. For a typical $r_b \approx 25\,\mu$m, $\gamma \approx 10000$, $\lambda_u \approx 3$ cm then we find our theory is valid for current spikes with 2.5 nm $<< \sigma_z <<$ 0.9 mm.

If we model the beam as a cylinder of radius r_b with a parabolic current profile $I(t) = I_0(1 - t^2/\tau^2)$ of half-width τ, then the LSC forces will be linear in t. The parabolic distribution can be related to other distributions by matching the rms parameter $\sigma_z = c\tau/\sqrt{5}$. Then the space charge interaction is characterized by a perveance κ:

$$\partial_z \gamma \approx \frac{qZ_0 I_0}{4\pi mc^3 \gamma_z^2 \tau}\left(\log\left(\frac{2\gamma_z c\tau}{a}\right) - \frac{1}{2}\right)\frac{t}{\tau} \quad (3)$$

$$= \frac{3Nr_c}{5^{3/2}\gamma_z^2 \sigma_z^3}\left(\log\left(\frac{2\gamma_z c\tau}{a}\right) - \frac{1}{2}\right) t \quad (4)$$

$$= \kappa^2 t\ , \quad (5)$$

where r_c is the classical electron radius I_0 the peak current and N the number of electrons.

In addition to the longitudinal space charge, we consider the dispersion of free space $R_{56} = L/\gamma^2$. Like LSC, this increases inside an undulator by $\gamma \rightarrow \langle \gamma_z \rangle$.

All together these dynamics are described by a non-conserved Hamiltonian $H = \left(\delta^2/2\gamma_z^3 - t\kappa^2/2\right)$ in terms of position t and momentum $\delta = \langle \gamma_z \rangle - \langle \gamma_{ref} \rangle$. The dynamics admit the familiar invariant, which we can call longitudinal emittance: $\epsilon_z = \langle t \rangle^2 \langle \delta \rangle^2 - \langle t\delta \rangle^2$.

By placing particles in a shell following the single-particle phase space ellipse, one can create a parabolic stationary current profile (analogous to a K-V distribution), such that the model is self-consistent (neglecting, of course 3D effects like [11]).

A solution to this system is given in [6]. The space-charge force acts to continuously grow the energy spread until the beam is suitably debunched, at which point the energy spread of the beam saturates. Starting from a waist, the beams we are considering will double their bunch lengths in a characteristic distance $s \approx \frac{2\gamma_z^3 \sigma_z}{\sqrt{\sigma_\delta^2 + \gamma_z (400\,\text{nm}/\sigma_z)}}$, (where the rms quantities are the values at the waist). In a typical case $\sigma_z \approx 50$ nm, $s \approx \gamma_z^{5/2}\sigma_z/2$.

To give a concrete example, we use Fig. 2 to plot the propagation of an intense 4 GeV electron beam through either 20 m of free space or 20 m $K = 4$ undulators (relevant for LCLS-II SXR undulators). For simplicity, we consider a fixed current of 50 kA ($\sigma_\delta = 0.5$ %), although this is too weak to impulsively ionize the shortest pulses in our plot.

During the free space drift, the bunch energy spread increases, but the bunch doesn't have a chance to lengthen. Only for the shortest input pulses is 20 m long enough to lengthen the pulse. Once the pulse starts lengthening, the energy spread will decrease since the beam blows out before it has a chance to chirp. The undulators speed up the dynamics so that we can see this more clearly. For the beam passing through the undulators we see a minimum pulse length of 200 as.

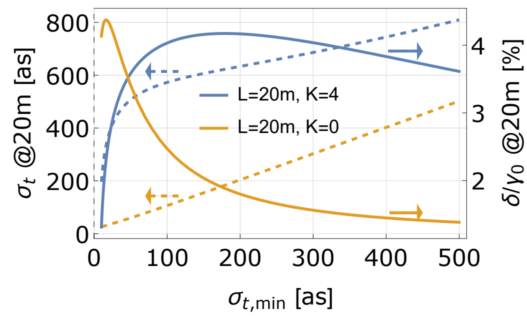

Figure 2: Pulse length and energy spread of a 4 GeV, 50 kA beam after 20 m of drift. In free space, the bunch remains short, but gains energy spread. In an undulator, the bunch rapidly lengths and is limited to $\sigma_t > 200$ as at 20 m.

These results suggest that the beam should be compressed to its final waist very close to the point where it will be used. Otherwise it will blow up to several percent energy spread and eventually decompress.

Bunch Compression

Generating such a short, high-intensity beam is difficult to do by directly compressing the beam from an S-band photo-injector. The beam that emerges from the gun several ps long, such that RF (and later wakefields) will introduce correlations which increase the projected longitudinal emittance. Consequently, at full compression (with reasonable energy spread) the bunch is typically 1-10 fs long for a wide range of compression schemes [12–14]. To compress more tightly, we choose to operate only on a small portion in the middle of a longer electron bunch. In this central slice, the longitudinal emittance can be lower by almost an order of magnitude.

To take a concrete example, we work with the beam from a start-to-end simulation of the LCLS beamline [1] in which a shaped laser-heater pulse is used to seed the microbunching instability [15]. After propagation through the doglegs, this produces a 2 fs current spike similar to those we use for attosecond lasing [16]. The short current spike naturally generates high-frequency chirp through longitudinal space-charge.

To compress LSC chirp we need to design a chicane with "anomalous dispersion" (positive R_{56}) [7]. We can accomplish this by using quadrupoles to invert the beam in the middle of four-dipole chicane (analogous chirped pulse compression in a laser [17]).

The design we choose is shown in Fig. 3. The heart of the design are the 7 quadrupole magnets used to control the sign of the dispersion inside the chicane. The quadrupoles are set symmetrically around center of the chicane. Their strengths are chosen so that the outer quadrupoles flip the sign of

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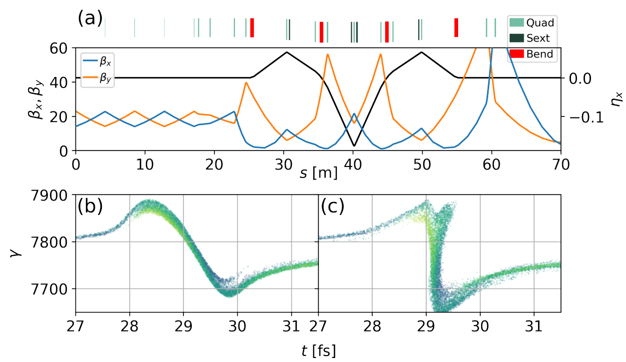

Figure 3: (a) Chicane design. (b) Sample of longitudinal phase space at the start of chicane, colored by x-angle (p_x/p_z) (c) Sample of longitudinal phase space at the end of the beamline, colored by *initial* x-angle (same as in (b)).

the dispersion before the first (and after the last) interior bend, while the middle triplet is used to again flip the sign of the dispersion so that the two halves do not cancel. The overall length of the chicane (30 m) is chosen to keep the beta functions from pinching too hard (we achieve β_{min} =0.6 m, β_{max} <100 m).

The resulting beamline exhibits strong non-linearities (T_{566} and U_{566} are the biggest culprits, followed by T_{561} and T_{562}). To compensate, we introduce a set of sextupole magnets at locations of high dispersion, and then optimize their strengths to reduce the lattice non-linearity. After compensation, the chicane optics do not contribute to bunch lengthening. Instead, the bunch length is dominated by the incoming phase space.

We illustrate the compression in Fig. 3(b,c). We can see that the final bunch length is strongly correlated with the initial beam angle due to strong longitudinal-transverse correlations. These correlations originate from CSR in the upstream BC2 compression chicane. In principle, the sextupoles can be used to remove some of these incoming correlations, but since this is a dynamic process it would require an attosecond bunch length diagnostic.

Note that transport through this chicane and to the sample is modeled in Elegant before being exported to GPT to calculate the space-charge field. Elegant's CSR model shows that CSR energy loss plays little role in the compression because it largely occurs after the spike has formed, but it does lead to an increase in the rms emittance $(\epsilon_{nx}, \epsilon_{ny})$ from (1.1 × 0.4 µm) to (1.4 × 0.4 µm). Elegant's CSR model, however, is 1D and here we weakly satisfy Derbenev criteria in the 3rd bend (i.e. approach equality) such that 3D calculations may slightly differ from those presented here. We expect this to have a small influence on the emittance growth.

The resulting transverse space-charge field is shown as a function of time for a fixed point in space in Fig. 4. Within a few micron area around this point, the field is roughly uniform (and x-polarized). Within this region we can achieve a 75 as rms duration with a pre-pulse contrast >20.

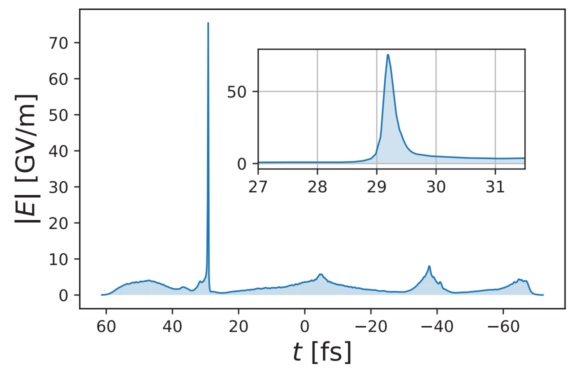

Figure 4: Transverse space charge field after compression. The inset matches the field of view in Fig. 3. The attosecond spike has a large contrast over the pre-pulse.

CONCLUSION

In this proceedings we have discussed the compression of an ultrelativstic electron beam to attosecond pulse widths. As an explicit example, we simulate the compression of a 4 GeV electron beam at the LCLS facility to <100 as pulse width. Our compression scheme uses a chicane with anomalous R_{56} to compress the high-frequency chirp generated by longitudinal space charge.

We use a generic 1D model to discuss the compressed beam propagation. We show that for few GeV electron beams an attosecond current spike will naturally decompress and grow to 5% energy spread over a few tens of meters.

Our work illustrates a possible scenario to realize impulsive ionization of valence electrons, and it suggests that we can push the limits of extreme beam compression to enable novel attosecond and strong-field science.

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