EXPRESSION OF INTEREST: Instabilities Associated with Compression of Electron Beams – Causes and Cures

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SUMMARY OF IDEA

Sources of bright electron beams generate the electrons in packets, or “bunches”, and a train of bunches forms the beam. One use of such beams is to drive free-electron lasers (FELs), wherein a periodic array of magnets causes the electrons to undulate and thereby emit light. For the light to be both bright and coherent, essentially all of the electrons in each bunch need to undulate in lock step. To do so, they must all fit inside the optical mode of the FEL system. Thus, each bunch must reside in a compact phase-space volume. This is especially true for short-wavelength FELs, e.g., x-ray FELs (XFELs).

To form a compact longitudinal phase space, each bunch passes through a series of dipole magnets that compresses it to short, sub-mm lengths. The curved trajectories lead to radiation that is coherent, and thus intense, at wavelengths comparable to the bunch length. This “coherent synchrotron radiation” (CSR) from the tail of the bunch can catch up to the head. One potential consequence is an instability that forms fine structure, or “microbunching”, that can mix quickly and lead to growth of the beam’s phase space. The effect is so severe that, e.g., it can preclude XFELs from lasing. Accordingly, a cure is needed.

A potential cure may be to “flatten” the beam prior to compression, i.e., to distend its transverse phase space in the bend plane so the CSR decoheres. This EOI concerns doing a systematic, quantitative study of compression-induced microbunching and beam-brightness degradation versus the flatness of the beam entering the compressor. The outcome will not only answer whether this technique can cure the instability, but also provide a more complete understanding of how a beam self-consistently behaves during compression.

STATEMENT OF THE PROBLEM

The problem proposed for study, both experimentally and theoretically, is the complicated dynamics associated with compressing a relativistic electron beam to short bunch lengths. The idea is to accelerate the bunch off the RF crest so the electrons in the tail gain a preferentially higher energy than those in the head. A bunch compressor comprises a set of dipole magnets through which the higher-energy electrons follow shorter trajectories. The tail thereby catches up to the head, resulting in a shorter bunch in keeping with a rotated longitudinal phase space.

This simple picture, however, can be thwarted by the presence of intense coherent synchrotron radiation (CSR) emitted by the bunch as it curves through the compressor. CSR from the tail of the bunch can catch up to the head, with concomitant deceleration of the tail and acceleration of the head. The energy spread thereby grows, and the bunch emerges with a correlated head-to-tail "warp". Even more serious, however, is the possibility of a CSR-induced instability that will form fine structure, or "microbunching", in the bunch. In short-wavelength free-electron lasers (FELs), the presence of microbunching seriously threatens to impede, or even prohibit, lasing. This matter was highlighted in a special workshop held just this January in Berlin, Germany. Designers of x-ray FELs organized the workshop because they are concerned that the microbunching phenomenon is a potential showstopper. Accordingly, a cure is needed.

The matter of CSR-induced microbunching is not yet well understood, although there are some indications that the physics is similar to that of self-amplified spontaneous emission that arises in connection with passage of high-quality electron beams through magnetic undulators. An embryonic theory developed at DESY suggests the gain length of the instability scales as the -4/3 power of the beam brightness in the bend plane. The theoretical prediction would seem to be qualitatively true in that poor beam quality (a big beam) in the bend plane should decohere most of the electrons and thereby reduce the strength of the synchrotron radiation.

The indications from theory suggest a cure for CSR-induced microbunching. If one can make the beam "flat" in the bend plane before it enters the compressor, then one can hope for a very long gain length and little-to-no microbunching. In this context, "flat" means the beam brightness (specifically, the emittance) in the bend plane is much greater than in the orthogonal plane.

The electron injector at Fermilab is presently the only one configured to produce flat beams. It also has a bunch compressor in the beam line. Thus, with the proper diagnostics, one can quantitatively study the influence of bunch compression on the overall phase space, and on the detailed structure of the beam. Plus, one can measure the coherent synchrotron radiation directly. A key diagnostic, shortly to be on hand at Fermilab, is highlighted in the Procedural Plan below.

The product of this proposed effort would ideally be a complete understanding of the microbunching instability. Measurements of microbunching as a function of beam flatness will be compared to similar parametric studies done with existing simulation codes and to theory. It will answer the question as to whether compressing a flat beam can cure the phenomenon. A "yes" answer would provide an important design option for accelerators of high-brightness electron beams, such as those involving short-wavelength FELs.

PROCEDURAL PLAN

Producing bright flat beams with the Fermilab high-brightness electron injector [1] is now routine [2]. The principal motivation is to achieve maximum flatness with the best possible beam quality, an achievement that could simplify or eliminate the electron damping ring inherent in designs of future linear colliders. One can span all geometries of the transverse phase space, from round through the highest flatness achievable (presently a ratio of x-to-y beam quality ~50).

A photocathode is the source of 1-10 nC electron bunches. After acceleration and without compression, the bunch length is ~3 mm (at 1 nC). With compression this length reduces to ~0.3 mm. A dipole magnet at the end of the beamline serves as an energy spectrometer. Each electron is deflected according to its energy and strikes an optical-transition-radiation (OTR) viewer monitored by a CCD camera. Thus, the energy spread and any structure (e.g., microbunching) it may have can be measured. Microbunching of compressed round bunches has been reproducibly observed at other laboratories [3] and with the Fermilab injector. Attempts at Fermilab to compress flat beams suggest the effects of CSR are then suppressed, but these attempts have only been cursory. The output beam energy is low, ~15 MeV, so space charge is a complication. Simulations nevertheless indicate that CSR will dominate round-beam dynamics in the compressor [4]. Moreover, because the injector produces high-brightness beams, resolving modest compression-induced growth of the beam's phase space is feasible.

Careful, systematic study requires precision beam diagnostics. One example is a Michelson interferometer [5] that analyzes coherent transition radiation (CTR) generated from passage of the electron beam through a thin foil. The coherent radiation spans wavelengths corresponding to the bunch length and scale lengths associated with charge-density variations. Prof. Uwe Happek has already designed the interferometer, pictured in Fig. 1, and it will be installed on the photoinjector beamline shortly. Moreover, Happek's follow-on plan is to build a multichannel vacuum interferometer for the photoinjector that would enable measurements on single bunches, in contrast to multibunch-averaged measurements that typify present capabilities.

The beam line is equipped with a six-way cross immediately following the bunch compressor. The cross has a CTR foil in place that can be remotely moved in and out of the beam path. By reconfiguring the foil mount so a mirror can be added, one can also measure directly the CSR emitted as the bunch passes through the last dipole magnet of the compressor. CSR will be strongest there, and thus one can correlate the CSR power spectrum with the CTR spectrum from the foil. *Presently the beam transits the*

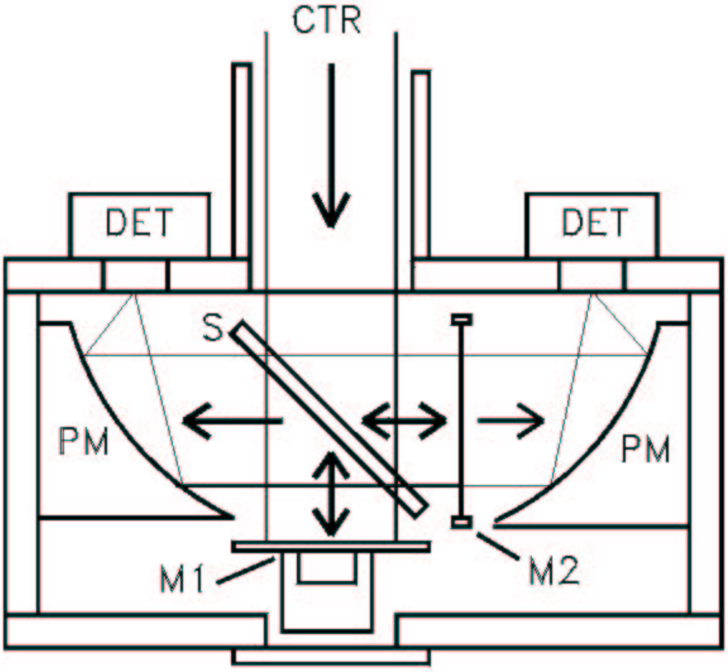

Figure 1. Michelson interferometer being procured for use at FNPL in measuring the electron beam's longitudinal density profile. Dimensions are 30 cm x 15 cm x 15 cm. CTR = coherent transition radiation, S = beam splitter, M1 = mirror on translation stage, M2 = fixed, semi-transparent mirror, PM = off-axis parabolic mirror, DET = detector module.

compressor before the round-to-flat transformation is complete; the hardware will have to be rearranged to correct this for a proper experimental study.

The interferometer directly yields the autocorrelation signal of the coherent radiation. By applying a Fourier transform and doing a Kramers-Kronig analysis of the result, one can extract the longitudinal density distribution of the bunch charge [6]. Details of the density distribution are accessible within the bandwidth of the device. The interferometer to be installed has an inherent bandwidth in the range 20-3,300 μm. The vacuum window for viewing the CTR foil imposes another constraint. The transmission of a crystalline quartz window cuts off at ~100 μm; a silicon or diamond window cuts off at ~20 μm. The plan is to start with the quartz window since it is known to be robust under vacuum. Later a silicon window might be tried, though a diamond window might be better in that it is perhaps more robust. It is also very expensive (~30 k$ for a 2-inch diamond window). The payoff of accessing shorter wavelengths is the ability to resolve finer details of the density structure (finer microbunching).

Plans are also to develop an innovative electro-optic diagnostic. Electro-optic (EO) sampling is a noninvasive technique offering picosecond time resolution of the electric field at the EO material [7,8]. It is based on the Pockels effect. When an electric field is applied to a certain class of crystals the refractive-index ellipsoid is modified, and as a result retardation (phase shift) is introduced between two orthogonally polarized components of a pulse of light traversing the crystal. This retardation can be detected by observing the change in the polarization of the transmitted light. By using short laser pulses and varying the delay between the "probe" pulse and the pulse that produced the electron bunch -- the "pump" pulse -- one can sample the time-dependence of the electric field. In principle the EO technique permits direct time-domain measurements of both beam-induced wakefields and the electric field from a single bunch itself.

Dr. Yang Xi has been considering a design centered on a cylindrically symmetric EO material mounted to the interior of a beam tube that has specially designed ports for the laser light. She is still in process of fleshing out the idea. Were it successful as presently conceived, the diagnostic would provide both longitudinal and transverse density profiles for a single bunch, as well as serve as a beam-position monitor.

In addition to the aforementioned energy spectrometer, the injector has a suite of diagnostics to measure root-mean-square properties of the beam's phase space. It will be used to decipher the extent to which the phase-space volume increases as a consequence of bunch compression. Accordingly, the experiment provides numerous means by which to cross-reference the measurements and thereby lend more credence to the conclusions. A future possibility is to add a deflecting-mode cavity, presently under development at Fermilab for unrelated purposes, to project the longitudinal density distribution onto a viewer. Doing so would provide an interesting check of the interferometric results.

The overarching plan of the experiment involves two categories of investigation. First is the influence of the transverse phase-space geometry on the microbunching instability. Second is the influence of the details of the beam's phase space upon entry to the compressor on that at the exit of the compressor. By adjusting the laser that drives the photocathode, one can systematically change the phase space of the beam. For example, by modulating the laser pulse, one might purposely seed the microbunching instability.

An intriguing idea involves using the microbunching instability to enhance modulations purposely applied to the beam prior to compression, and then sending the strongly modulated beam through a FEL system [9]. The payoff could be more compact short-wavelength FELs. Accordingly, not only would the proposed procedure yield information on curing the instability, but also it may hint at the feasibility of using it for compact light sources.

In addition to the experiments, simulations also will be done. These simulations are inherently based on the Lienard-Wiechert 4-potential that accounts for retardation effects from the finite speed of light. Accordingly, because they involve integrating over the history of the beam, simulations involving CSR are much slower and much more memory intensive than are standard N-body codes. To develop a fast code, one makes what are hoped to be judicious simplifying approximations. One example is to ignore the transverse component of the CSR wakefield because it is often much less than the longitudinal component. A penalty of approximations is that they limit the general applicability of the code.

There are now several “fast” simulation codes concerning CSR in bunch compressors and its influence on the beam’s phase space. Two that run on personal computers are ELEGANT [10] and TraFiC4 [11]. Both are in the public domain. I recently purchased a Beowulf cluster of personal computers for use in doing beam simulations at Northern Illinois University, and I hired a postdoc, Ioannis Sideris, to concentrate principally on simulations. Thus, we are positioned to do computational parametric studies.

Presently the most comprehensive code is that of Rui Li at Jefferson Laboratory [12]. It is a macroparticle code that runs on a mainframe computer, and aside from incorporating a finite size of the macroparticles, contains no approximations. Dr. Li and I have previously collaborated on CSR and other studies, and she would like to collaborate on this proposed work. In addition, there is a good possibility for collaboration with Bob Warnock (SLAC) and Jim Ellison (Professor of Mathematics at the University of New Mexico) on the development of a new CSR code based on Vlasov’s equation for bunch-compression simulations. They, along with Marco Venturini, have recently applied a Vlasov-based code to study CSR bursts in synchrotrons and storage rings.

In summary, the top-level plan and procedure is to do, all in parallel, experiments involving parametric studies of the dynamics of bunch compression, simulations to guide and interpret the experiments, and an improved analytic theory (especially concerning the microbunching instability) to tie things together into a coherent picture and to provide scaling laws.

ESTIMATED RESOURCE REQUIREMENTS

Michelson interferometer of Fig. 1: already purchased (soon to be installed)
Mirror installation downstream of compressor for direct observation of CSR
Multichannel vacuum interferometer: 80 k$ (firmer estimate TBD)
Electro-optic diagnostic: 20 k$ (firmer estimate TBD)
Reconfiguration of beamline to place skew-quad triplets upstream of the compressor (not needed for experiments on seeding of the microbunch instability)
Beam time: 1,000 hours (6 months of single-shift operation)

Concerning funds for the diagnostics, the intent is to provide them mostly from external research grants to NIU and the University of Georgia, none of which are yet in hand. A sizeable NICADD contribution would no doubt expedite their development.

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