SUMMARY OF COTR EFFECTS

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Abstract

Coherent Transition Radiation in the visible regime (COTR) has become a serious issue for FEL-Linacs disturbing the measurement of beam profiles by OTR screens up to a level where this diagnostics becomes totally impossible. In this paper we summarize the measured COTR effects from LCLS, FLASH and other machines and the investigations done so far into the dependence of the effect on beam and machine parameters. The status of the theoretical background and understanding of its origin will be discussed as well as proposals and experiences with possible remedies.

INTRODUCTION

The observation of Optical Transition Radiation (OTR) from metallic screens is a wide spread and attractive method for transverse beam profile measurements at linear accelerators. OTR monitors are technologically rather simple; besides the screen a commercial CCD camera with appropriate optics is required. Up to very high γ, the spatial resolution is not limited by the radiation process itself but by diffraction in the optical system and the resolution of the camera [1]. OTR monitors have become common devices for single shot transverse beam profiling, for emittance measurements and beam matching. They typically use visible or (very) near infrared radiation for which a large variety of silicon based CCD cameras is available and the metallic OTR screen shows perfect reflectivity. The method however relies on the fact that transition radiation at these wavelengths is emitted incoherently by individual bunch particles with random phase correlations. Only in this case, the intensity distribution reflects the (longitudinally integrated) charge distribution in the transverse plane. As soon as a noteworthy fraction of the observed OTR is radiated coherently from the entire bunch or parts of it, the measured profiles are completely dominated by interference effects and thus useless for beam profiling. Coherent Optical Transition Radiation (COTR) is emitted if either the overall bunch length is comparable to a few visible wavelengths ($\sigma_t \approx 1$ fs) or if there are longitudinal microstructures inside the bunch on the same length scale. Since the ratio of coherent to incoherent intensity scales with the number of particles in the bunch N times $|F_L|^2$, the longitudinal form factor squared, even small micro-modulations can create dramatic effects and completely compromise OTR monitoring. Significant coherent radiation in the visible regime has first been observed at the bright, low emittance electron beams for FELs and has become as serious issue for the applicability of OTR monitors at such machines. In this paper, we will summarize the experimental observations made at various facilities, briefly outline the basis of the present theoretical understanding of the underlying microbunching process and finally present a few new concepts how to circumvent the diagnostic problems.

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UNEXPECTED PHYSICS AT LCLS

COTR at visible wavelengths has first been observed from the density modulated beam of a SASE-FEL operating at 530 nm [2] and is used as a diagnostic tool for the ultra-short electron bunches emerging from laser-plasma acceleration [3]. In both cases, the microstructures are intended effects and the resulting coherent radiation gives valuable information about those. The main subject of this paper are the uncontrolled and unwanted COTR phenomena as first observed and investigated at the LCLS [4, 5]. At LCLS, the electron bunch from the photo-injector enter the main linac at about 135 MeV through an achromatic bend DL1 ("dogleg") and is further compressed by two bunch compressors (BC1 and BC2) at 250 MeV and 4.3 GeV (Fig. 1). During beam emittance studies downstream of BC1, clear indications for COTR were observed not only for extreme compressions, where very sharp temporal spikes in the charge profile could be expected, but also for uncompressed bunches of 2.4 ps rms length. The intensity of the coherent light turned out to be extremely sensitive to the setting of the quadrupole (QB) between the two DL1 dipoles, reaching its maximum value for QB making a DL1 a perfect linear achromat (Fig. 2). For uncompressed bunches with typically $\sigma_t = 50$ fs and $q = 250$ pC, the COTR intensity exceeded the incoherent value by about a factor of 4 while for compressed bunches a factor of more than 100 was observed. Further downstream after BC2, the enhancement factor reached 5 orders of magnitude.

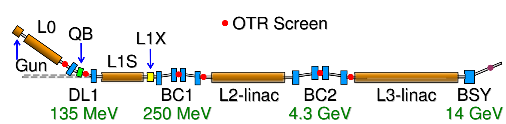


Figure 1: Schematic layout of the LCLS linac

OTR images observed under these conditions (Fig. 3) are characterized by pronounced intensity and shape fluctuations from shot-to-shot quite often locally saturating the imaging system. In consequence, any OTR based beam profile and emittance measurements downstream DL1 turned out to be impossible.

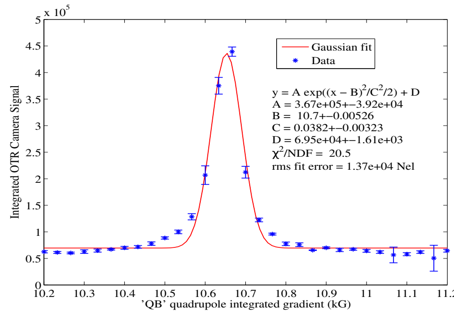


Figure 2: Integrated CTR intensity observed at LCLS after DL1 as function of QB quadrupole strength [5].

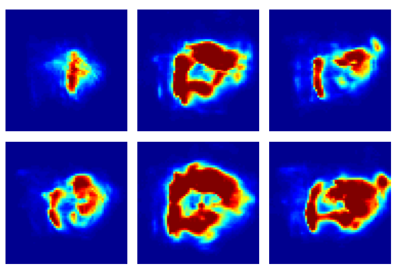


Figure 3: Single shot OTR images observed at LCLS downstream BC1 (courtesy H. Loos).

MICROBUNCHING INSTABILITY

For bunches much longer than optical wavelengths, the presence of coherent radiation in the visible region is a consequence of collective effects leading to a normally undesired generation and amplification of microstructures inside the bunch which is discussed in literature as microbunching instability. The beam of a high gain free electron laser linac is especially prone to create such effects since it combines high charge density with magnetic bunch compressors which act as effective amplifiers and wavelengths shifters for the micro-structures. The basic mechanisms can be described in a simple one dimensional model [6]. An initial energy modulation in front of a magnetic bunch compressor is transformed into a longitudinal density modulation due to the non-vanishing R_{56}. The resulting depth of the density modulation critically depends on R_{56} and the intrinsic (local) energy spread σ_γ/γ. In the one dimensional model with no energy chirp, the most effective transformation takes place for a wavelength $\lambda = 2\pi R_{56}\sigma_\gamma/\gamma$. Modulations with shorter wavelengths are rapidly washed out.

The source of the initial energy modulation can be manifold. It could be a primordial modulation generated in the electron source or be created upstream of the chicane by the longitudinal space charge impedance. If the bunches are very strongly compressed in the chicanes, Coherent Synchrotron Radiation (CSR) acts as an additional source for further amplification of the microbunching [7]. For a quantitative understanding of the observed COTR intensity, the transverse structure (emittance) of the beam and the influence of dispersion (R_{16}) and R_{51} and R_{52} have to be taken into account as well as the three dimensional form factor for the radiation process. In this way, the striking dependence of the COTR intensity on the chicane optics shown in Fig. 2 could be fully explained [8].

COTR EFFECTS AT FLASH

Bunch preparation and compression in the linac of the free electron laser FLASH has much in common with the situation at LCLS. As shown in Fig. 4, electron bunches are produces by a photo injector and compressed in two subsequent magnetic chicanes at about 150 MeV and 500 MeV. After the final acceleration to at maximum 1.2 GeV, a achromatic lateral displacement ("dogleg") is used for energy collimation. Before 2010, FLASH used a so called "roll-over" compression scheme where the curvature of the longitudinal phase space before compression led to a sharp leading current spike followed by a long tail. Since 2010, the longitudinal phase space can be linearized using an additional 3rd harmonic (3.9 GHz) super conducting resonator (ACC39) leading to a much more homogeneous and extended current distribution in the compressed bunches. A variety of OTR based diagnostics is used at FLASH, not only transverse profiling and emittance measurements. The most important longitudinal diagnostics is a transverse deflecting RF structure (TDS) which is used to measure the longitudinal current profile with high resolution and, in conjunction with a dispersive magnet, to image the longitudinal phase space. Before 2010, the TDS was located right in front of the energy collimator, at present it is installed directly in front of the FEL undulators at the very end of the linac.

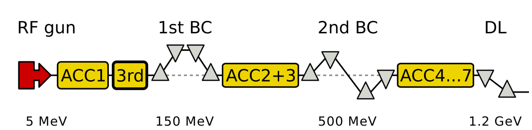


Figure 4: Outline of the FLASH linac

Prior to the installation and use of ACC39, no serious deterioration of the OTR diagnostics by coherence effects was observed. To investigate this in more detail, we measured the spectral distribution of the CTR light in the visible and NIR region from a port at the location of the TDS screen in front of the "dogleg" chicane. Measurements where done for bunches in normal FEL operation conditions which was by then non-linearized compression in both magnetic chicanes, and for "uncompressed" bunches passing the magnetic chicanes wit no linear energy chirp gained in ACC1 (on-crest operation). For normal FEL operation (Fig. 5a), the intensity and spectral distribution in the visible region was in fact in good agreement with purely incoherent radiation. Above about 1 μm, an excess of coherent emission could be observed reaching about a factor of 80 at 1.6 μm. It can not be excluded, that this excess is due to the sharp leading current spike and thus no indication for additional microbunching effects. For uncompressed bunches the situation was different. These bunches should not have sharp structures from the compression process, nevertheless excessive coherent radiation down to the visible region was observed. The intensity of the radiation could be dramatically increased by reducing the R_{56} of the magnetic chicanes. For the smallest R_{56} which could be used, coherent radiation extended down to the UV cut-off of the spectrometer optics.

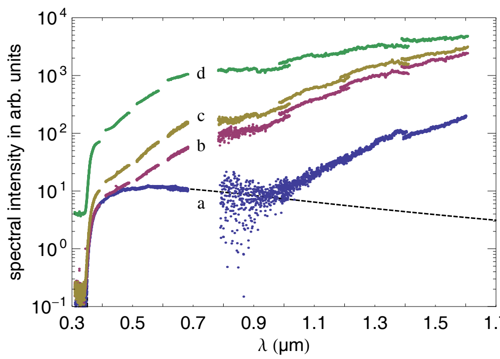


Figure 5: CTR spectra in the VIS and NIR regime observed at FLASH in front of the energy collimator. a) normal FEL operation (non-linear compression), b) - d) on-crest operation of ACC1 with different strengths of the compressor chicanes [9].

For two of the machine settings, we were able to complete the spectra by measurements using a grating bases FIR spectrometer which showed that the CTR from microbunched on-crest bunches peaks at about 10 µm [10].

The COTR situation at FLASH changed after the installation of ACC39 and the simultaneous upstream shift of the TDS and its screens behind the energy collimating chicane. The TDS transforms the longitudinal profile into the vertical by applying a time dependent streak voltage. The resulting distribution can be imaged either directly, thus mapping the longitudinal density as function of the horizontal coordinate or after passing a dipole magnet with a bending angle of 10 deg, mapping the longitudinal density vs. energy deviation (longitudinal phase space). It turned out, that under normal machine operation conditions, the straight screen cannot be used due to very severe COTR effects which critically depend on the detailed setting of the phases of ACC1 and ACC39 defining the energy chirp in front of the first bunch compressor [11]. Fig. 6 shows images of streaked bunches without dispersion applied for two slightly different phases of ACC1. While in one case imaging seems to be undisturbed, the second case shows all the COTR typical symptoms: excessive intensity saturating the camera, extreme shot to shot fluctuations and structure dominated by interference effects.

Imaging the phase space after the dispersive section on the other hand shows no indications for COTR effects; Fig. 7 shows a typical phase space image for a highly compressed bunch. It is free from COTR effects but clearly reveals a microstructure along the bunch with a typical modulation length of about 20 fs (6 µm).

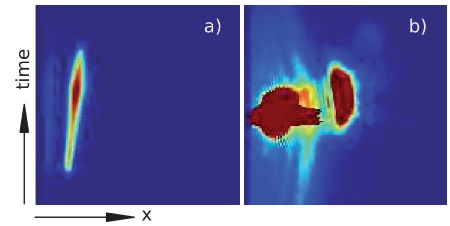


Figure 6: Images of a TDS streaked electron bunch at FLASH. While a) seems to be free from COTR effects, b) is COTR dominated. Between a) and b) the phase of the accelerating module ACC1 in front of the first compressor chicane was changed by 0.5 deg.

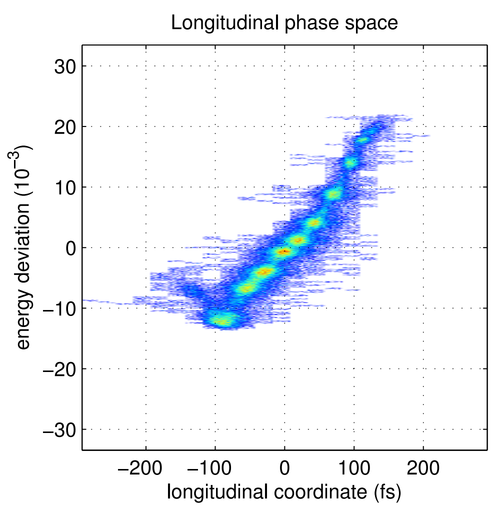


Figure 7: Longitudinal phase space of a compressed electron bunch at FLASH imaged using the transverse deflecting structure (TDS) and a dispersive dipole. The bunch exhibits substructure in energy and longitudinal coordinate at a scale of 20 fs but produces no COTR effects.

The reason for the obvious strong suppression of COTR effects after the dipole bend is the strong R_{51} and R_{52} which very efficiently wipes out the optical wavelength structures of the bunch.

To further investigate the situation and especially the role of the collimator chicane, we measured the CTR spectra in the VIS and NIR regime (Fig. 8) for three compression settings (Fig. 9). All bunch shapes show a similar spectral distributions, all of them leaking into the range of CCD cameras. The intensity depends dramatically on the details of the phase space distribution. A simple simulation including the linear optics of the“dogleg” and a realistic normalized emittance of 1 mm mrad explains the cut-off of around $\lambda = 600$ nm but leaves many details to be investigated.

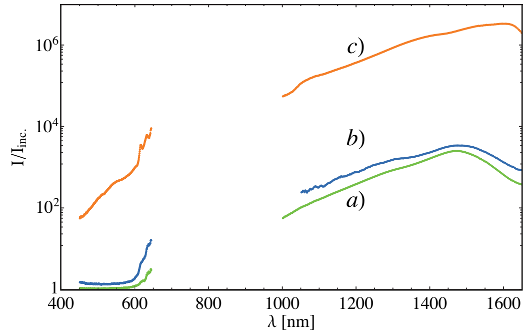


Figure 8: CTR spectra in the VIS and NIR regime observed at FLASH for three different compression modes: a) on-crest, b) moderate compression, c) partially overcompressed. The longitudinal phase space distribution of these settings is shown in Fig. 9.

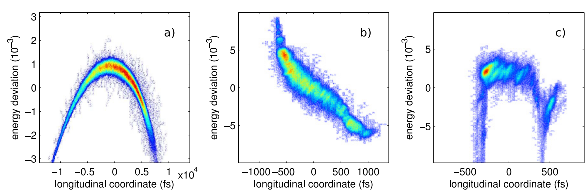


Figure 9: The longitudinal phase space for the three compression settings used for Fig. 8.

COTR AT OTHER FACILITIES

COTR effects impeding beam diagnostics has been reported from various facilities meanwhile though not very many details have been published. One decisive detail seems to be nature of the electron source, all positive reports on COTR have been made at machines using laser driven photo-injectors. Besides LCLS and FLASH, three other facilities report positively about the observation of COTR:

- APS (Argonne) [12] attributed to microbunching.
- NLCTA (SLAC) [13] attributed to microbunching
- FERMI (Elettra) [14] potentially due to a very short current spike

The situation found at facilities using thermionic guns is different, no clear indications for COTR from microbunching have been observed so far:

- APS (Argonne) [12] no microbunching when thermionic gun is used
- SCSS (SPring8) [15] no indication for COTR during operation
- SACLA (SPring8) [15] COTR seen during commissioning, but probably due to short spike

Despite the fact the all facilities use similar beam parameters like emittance and energy spread, photo injector produced bunches seem to be more prone to develop microbunching instabilities than those from thermionic guns. The situation at APS is especially interesting and pointing in this direction since the same accelerator has been operated with both types of sources.

ALTERNATIVE CONCEPTS AND OTR RESCUE PLANS

If screen based beam profile monitors fail due to COTR effects, wire scanners can be used to measure the transverse profile of the beam. At LCLS, all transverse monitoring and emittance measurements between DL1 and dump are now based on wire scanners. Nevertheless, the striking simplicity and single shot capability of the imaging technique makes it interesting to think about alternative concepts and ideas to avoid the COTR problems. One obvious idea is to adapt the machine optics such, that microbunching instabilities are avoided. Unfortunately, the parameter space optimized for FEL operation more or less coincides with optimal microbunching conditions. Nevertheless, choosing for instance the compression sequence properly, minimizing LSC and CSR effects, could help to mitigate the problem or shift it into a harmless wavelength regime. One very powerful method is the use of a laser heater to artificially increase the uncorrelated energy spread of the beam [16, 17]. At LCLS, such a device has been installed and is used routinely. During normal operation, the energy spread is increased from few keV to 20 keV [18]. At this level, the gain length for FEL operation is optimized and COTR is suppressed considerably (Fig. 10). But nevertheless it is not suppressed to a level, where OTR diagnostics would be possible, it still overrides the incoherent radiation by at least a factor 5.

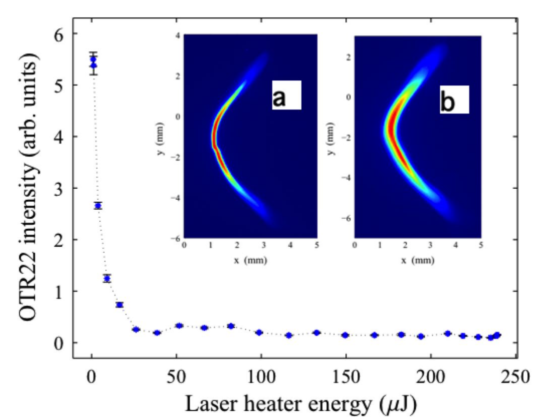
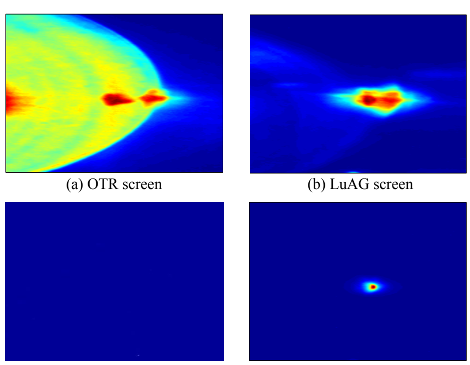


Figure 10: COTR intensity as function of laser heater power at LCLS. The phase space for no heating (a) and normal operation heating (b) are shown in the inset.

Besides changing the beam properties, several ideas have been developed to improve on the imaging diagnostics side to solve the problem. One possibility would be to do the imaging at much shorter wavelengths since with typical energy spreads and emittance, the COTR falls off very rapidly beyond the visible regime. Proposals for UV or even EUV (20 nm) TR monitors [19, 20] have been made and are under investigation now. Another interesting idea is to use scintillating screens instead of transition radiation. Scintillation is a ionization based secondary light emission process of statistic nature and thus completely insensitive to the longitudinal structure of the bunch. Under normal conditions, scintillating screens are inferior in resolution to transition radiation but optimized screen geometry and material [21] promises room for improvements. An actual overview on the field of scintillators for beam diagnostics is given at this conference [22]. It should be mentioned, that CTR is not restricted to metallic screens but as well produced at the vacuum-crystal boundary of the scintillating screen. Coherent emission is not restricted to transition radiation but enhances similarly optical synchrotron radiation from bending magnets and quadrupoles. Care has to be taken concerning the imaging geometry to prevent all potentially very intense radiation, COTR and COSR, from reaching the imaging system. Besides to assure this by an appropriate geometry, it can as well be separated out in time. CTR and CSR are instantaneous processes happening at the time scale of the bunch duration. Scintillation on the other side is based on excited atoms, the emission process is delayed by typically several hundred nanoseconds. Using a fast gated camera, it could be demonstrated [23], that the surface COTR from a scintillating screen could be completely blocked and an undisturbed bunch image observed even under severe COTR conditions (Fig. 11).



(a) OTR screen (b) LuAG screen

(c) OTR screen, +100ns delay (d) LuAG screen, +100ns delay

Figure 11: Imaging electron bunches at FLASH using a scintillator screen and fast gated intensified camera [23]. The prompt OTR image (a) exhibits severe COTR/COSR effects as does the prompt image from the scintillator (LuAG) screen (b) which is dominated by surface COTR. With a gate delay of 100 ns, the OTR image vanishes completely while the scintillator afterglow reveals the true bunch shape.

The method has the drawback of requiring an expensive camera, resolution and optimized geometry are still under investigation.

CONCLUSIONS

COTR has become as serious issue during the past years for the image based diagnostics at high brightness electron linacs for FELs. In many cases, it makes the use of standard OTR screens impossible. Investigations into the spectral content of the radiation have shown that coherent radiation in the visible regime is just the short wavelength tail of an extremely broadband spectrum caused by a self amplifying microbunching effect in these machines. From the existing experience, thermionic guns seem to be less prone to support microbunching instabilities than photo emission based sources. Due to the extreme level of the COTR intensity, remedies and circumventions are tough and alternative concepts for transverse beam profiling have to be found. Several promising concepts are presently under study.

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