FIRST EXPERIMENTAL MEASUREMENTS OF THE CAUSTIC NATURE OF TRAJECTORIES IN BUNCH COMPRESSORS

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Abstract
Advancements in the theory describing density perturbations in accelerated charge particle beams, known as caustics, has been gathering interest over the past few years. This proceeding describes the first experimental measurements of the caustic nature of charged particle trajectories in a particle accelerator. Caustics by their nature are discontinuities that result from small continuous perturbations of an input. Under certain conditions, small density modulations will reliably produce striking changes in the corresponding output current profile. These current modulations can shift along the bunch with varying higher-order longitudinal dispersion. The MAX IV linac double-bend achromats provide the perfect test bed for experimentally verifying how the caustic lines evolve. The natural amplification of small perturbations makes caustics an attractive diagnostic tool, and effective tool for characterise the bunch compressors. This approach also allows us to modify and improve the longitudinal charge profile, removing current spikes or creating tailor shaped current profiles.

INTRODUCTION
Caustics are the coalescence of trajectories forming points, lines or surfaces of greatly enhanced charge density. Often referred to as 'natural focusing' [1], caustics are the envelope of particle trajectories. Figure 1 illustrates a caustic line forming where multiple electron trajectories coalesce. Longitudinal dispersion that can be used to compress a chirped bunch, can lead to caustics evidenced by current spikes at the head or tail, or both the head and tail of a bunch.

A caustic expression has been derived based upon the approach presented in reference [2]. This parametric expression describes the longitudinal position of the caustics for a given set of control parameters, R56, T566, and U566 (i.e. the first-, second-, and third-order longitudinal dispersion);

\[
\tilde{z}(z_i) = -z_i - \frac{R56\delta(z_i)}{2} + \frac{U5666\delta'(z_i)}{2} + \frac{\delta(z_i)}{2\delta'(z_i)}
\]

\[
T566(z_i) = \frac{1}{2\delta'(z_i)} \left( -R56 - \frac{1}{\delta'(z_i)} - 3U5666\delta'(z_i) \right)
\]

where \(\delta(z_i)\) is the shape of the initial longitudinal phase space distribution (or chirp), often described by a high-order polynomial and \(\delta'(z_i)\) is the derivative with respect to \(z_i\).

When a bunch is subjected to strong bunch compression, often the compressed bunch will exhibit a single-spike [3–5] or double-horned [6–10] current profile. These current spikes are detrimental to FEL performance, leading to greater CSR which can increase the horizontal projected emittance [11–13].

Figure 1: Illustration of a caustic line (red, bold), which is the envelope of particle trajectories (blue) which are focused and defocused by beam optics. Each trajectory that contributes to the caustic, makes a tangent to the caustic line.

In this paper, we present the preliminary work done for measuring of the caustic nature of electron trajectories passing through a dispersive region. The experimental setup is described and some initial results presented.

General Layout of the MAX IV Linac

The MAX IV facility consists of a 300 m S-band linac [14], that provides both full energy and top-up injection to two storage rings (1.5 and 3 GeV) and is a high brightness driver for a short pulse facility (SPF) [4]. Plans are also under way for an Soft X-ray Laser (SXL) beamline fed by the same linac [15]. A 1.6 cell photo cathode gun capable of producing an emittance of 0.4 mm mrad [4] is used for the SPF and for the measurements shown in the next sections. A schematic layout of the linac can be seen in Fig. 2.

Bunch Compressors

Bunch compression is shared across two double-bend achromats. The double achromat is characterized by a positive \(R56\) value, and therefore necessitates acceleration on the falling slope of the RF crest. The double achromat design also has a positive \(T566\) value which is naturally close to the optimal \(T566\) for linearization of the longitudinal phase space. As such, these achromat designs are called “self-linearizing”, and avoid the need for a harmonic linearizing cavity [16, 17]. Two weak sextupoles are located in each bunch compressor, positioned in the middle of the achromat where the horizontal dispersion is greatest. These sextupoles
allow for fine tuning of the $T_{566}$. For most operating conditions (i.e. RF phases), the optimal $T_{566}$ is less than the natural $T_{566}$ of the achromat. The sextupoles allow for $T_{566}$ to be reduced for optimal linearization of the longitudinal phase space. The experimental measurements presented in this paper concern BC1, and therefore the optics and parameters of only BC1 are shown in Fig. 3. For the details of BC2, see reference [16].

It can be noted that whilst the second-order transverse dispersion does not go to zero at the end of the first achromat, the two achromats making up the bunch compressor exhibit a symmetry whilst bending in the opposite direction (see Fig. 2), and this allows for the second-order transverse dispersion to go to zero at the end of the compressor.

**ZERO-CROSSING METHOD**

A transverse deflecting cavity is currently planned to be installed at the end of the MAX IV linac this summer [18]. In the meantime, in order to probe the longitudinal phase space and current profile, a modified version of the zero-crossing method was used [17, 19, 20], which allows for measurement of femto-second bunches and give an indication of the current profile shape. The bunch was accelerated off-crest in the main linac, and viewed on a screen at maximum dispersion. (b) first- and second-order dispersion properties along BC1.

Figure 3: Optics through BC1. (a) horizontal and vertical beta functions, as well as the horizontal dispersion. (b) first- and second-order dispersion properties along BC1.

Varying the achromat sextupole strengths, varies the $T_{566}$ value linearly, whilst keeping $R_{56}$ constant. By scanning through the range of sextupole strengths, the current profile can be measured on the YAG screen to give an indication of the longitudinal charge profile.

**LONGITUDINAL WAKEFIELDS**

The longitudinal wakefields encountered after BC1 induce an additional energy spread in the bunch which will impact the zero-crossing method results [21]. As the energy spread induced by wakefields is dependent upon the bunch length and charge profile shape, we have not attempted correct for this, but rather opted to include conservative error bars to encompassing the effect of wakefields.

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once the phase space has curved to the point where the tail of the bunch passes the origin (e.g. the red curve in Fig. 4a).

When the phase space distribution is multi-valued in $z$, this leads to an artificial increase in the width of the measured current profile. Figure 4b illustrates why this is the case. Ideally, particles at the same longitudinal position, $z$, should be mapped to the same position on the screen in BC2. However the grey portions of the curve have higher energies than their counterparts of the same longitudinal position, and are therefore mapped to larger values in $x$ on the screen. This makes the distribution broader than it ought to be, and the uncertainty becomes larger for increasing curvature of the phase space distribution. This uncertainty, plus the influence of longitudinal wakefields, are responsible for the offset between the theoretical and experiential results shown in the following section.

RESULTS AND DISCUSSION

By tuning the sextupoles to over- or under-linearize the longitudinal phase space, the position of the current peak can be shifted towards either the head or the tail of the bunch. A detailed explanation of how the sextupoles influence the current profile shape can be found in Reference [2]. Figure 5 shows the current profiles for two sextupole settings, producing a linearly-rising, and a linearly-falling profile.

![Figure 5: Current profiles obtained for two different settings for the BC1 sextupoles; a) $k_2 = 11 \text{ m}^{-3}$ and b) $k_2 = 33 \text{ m}^{-3}$.](image)

Figure 6 shows the evaluation of the caustic line from the YAG screen projections. Good agreement can be seen between the shape of the theoretical expression and the experimental data. However the theoretical and the experimental data are offset by $14 \mu m$. This is most likely due to the imprecision of the longitudinal phase space distribution from longitudinal to transverse position mentioned above. The analytical expression (red curve in Fig. 6) was calculated using the known values of $R_{56}$ and $T_{566}$, and through fitting $c_1$ and $c_2$ to the experimental data.

For $T_{566}$ values where Eq. (1) is undefined, caustic current spikes are not expected to appear. Over these regions, the longitudinal phase space is considered well linearized, resulting in a short bunch with a symmetrical current profile.

OUTLOOK

Transverse deflecting Structures (TDS) have proven immensely valuable when it comes to measuring longitudinal phase space distributions [22]. Facilities such as SLAC [23], FERMI@Elettra [24] and SwissFEL [25] have all demonstrated the usefulness of transverse deflecting cavities. MAX IV has plans under way to install a TDS in at diagnostics beamline at the end of the linac [18]. Once installed, measurements such as the ones presented in this paper, can be repeated with improved temporal resolution and accuracy. It is also expected that the offset visible in Fig. 6 would not be seen with TDS measurements. In addition to the TDS, an up-grade of the photocathode electron gun is being planned [26], which is expected to improve the beam quality and will allow for increased repetition rate.

The production and control of linearly ramped current profiles shown in this paper, is of interest for plasma-based acceleration schemes [27]. The positive or negative ramped profiles of driver beams creates efficient drives the plasma wave [28–30], and negative gradient linearly ramped witness bunches allows for efficient extraction of energy from the wave, as well as minimizes energy spread [30,31].

Finally caustics has also been applied to longitudinal phase space management of recirculation machines [32] for optimal acceleration and energy recovery.

CONCLUSION

Preliminary results show good agreement in shape between the experimental data and the theory of caustics forming in particle trajectories. An offset between the theoretical expression and the experimental data is observed, which can be accounted for by the indirect mapping of longitudinal position to the measured transverse position on the screen when there is curvature in the longitudinal phase space distribution shape. In addition to validating the caustic expressions, these measurements demonstrate the effectiveness of optical linearization of the MAX IV bunch compressors.

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REFERENCES


