

# ELECTRON-MAGNETIC-PHASE MIXING IN A LINAC-DRIVEN FEL TO SUPPRESS MICROBUNCHING IN THE OPTICAL REGIME AND BELOW

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## Abstract

Control of microbunching instability is a fundamental requirement in modern high brightness electron linacs, in order to prevent malfunction of beam optical diagnostics and contamination in the generation of coherent radiation, such as free electron lasers. We present experimental control and suppression of microbunching instability-induced optical transition radiation by means of particles' longitudinal phase mixing in a magnetic chicane. In presence of phase mixing, the intensity of the beam-emitted coherent optical transition radiation is reduced by one order of magnitude and brought to the same level provided, alternatively, by beam heating. The experimental results are in agreement with particle tracking and analytical evaluations of the instability gain. A discussion of applications of magnetic phase mixing to the generation of quasi-cold high-brightness ultra-relativistic electron beams is finally given.

## BACKGROUND

The strength of the microbunching instability is usually quantified by its spectral gain, which is the ratio of the final to the initial bunching. When only longitudinal space charge (LSC) force is considered, the gain can be evaluated by [1]:

$$G(k) = Ck |R_{56}| \frac{I}{\gamma_A} \frac{|Z(k)|}{Z_0} \exp\left(-\frac{1}{2} C^2 k^2 R_{56}^2 \sigma_{\delta,0}^2\right), \quad (1)$$

where  $C$  is the electron bunch length compression factor provided by one magnetic insertion with momentum compaction  $R_{56}$ ,  $k$  is the wave number of the energy modulation induced upstream of the compressor by the LSC impedance  $Z(k)$ ,  $\gamma$  is the beam's relativistic Lorentz factor at the compressor,  $\sigma_{\delta,0}$  is the beam fractional incoherent energy spread just before compression,  $Z_0 = 377 \Omega$  and  $I_A = 17045$  A. The gain is the relative amplification factor of the initial density modulation and a gain smaller than 1 means that the additional modulation due to collective effects is smaller than the modulation associated to the initial bunching. A maximum gain as large as  $10^2$  to  $10^4$  is common in linac-driven FELs and peaks at initial wavelengths around few tens of micron [2]. Large bunching is accompanied by large energy modulation with analogous spectral content. The final energy modulation may act on the FEL process as large local (slice) energy spread that, depending also on the spatial scale of the cooperative FEL process, may reduce the FEL output power and/or enlarge the FEL

spectral bandwidth [3,4]. A "laser heater" (LH) system was first proposed in [5] to counteract those disrupting effects. In a LH, the electrons interact with an external infra-red laser pulse in a short undulator, at beam energies typically around 100 MeV. As a consequence of the interaction, the electron beam incoherent energy spread is increased and the microbunching gain suppressed, as suggested by Eq.1. A LH is routinely adopted at LCLS [6] and FERMI [7] FEL facilities where, in standard operating conditions,  $\sim 20$  keV and  $\sim 7$  keV, respectively, are added to the 1–3 keV beam incoherent energy spread (all rms values). When the LH is turned off, a high instability gain leads to large coherent optical transition radiation (COTR) signal at screen targets intercepting the time-compressed beam for diagnostic purposes. Coherent optical transition radiation (COTR) emission limits the utility of beam profile imaging systems [8]. This can be recovered by the LH action which is able to reduce the OTR intensity to the incoherent emission level [3]. The OTR intensity is thus an indicator of the strength of the instability at optical wavelengths. In our experiment, we made use of this relationship, finding agreement of the OTR intensity behavior with numerical and analytical predictions for the instability gain.

## EXPERIMENTAL SET UP

Initially proposed in [9] as an alternative to the beam heating process described above, phase mixing has the advantage of relying on a relatively simple and robust system, *i.e.*, a four dipoles, non-isochronous magnetic chicane (hereafter named "mixing chicane") installed at intermediate linac energies. The idea consists in smoothing the electron bunch current and energy distribution by forcing the electrons to "rotate" in the longitudinal phase space  $(z, \delta)$ , where  $z$  is the particle's longitudinal coordinate along the bunch and  $\delta$  is the particle's fractional energy deviation. The rotation is actually a phase slip, primarily induced by the first order momentum compaction ( $R_{56}$ ) of the mixing chicane that couples to the  $(z, \delta)$  correlation established by the upstream instability at its characteristic (short) wavelength scale. The experiment was carried out at the FERMI S-band linac, which is sketched in Fig.1, and it has been reported in [10]. A 500 pC, 2.8 ps rms long electron bunch was photo-injected into the linac and time-compressed by a factor 12 in a magnetic chicane (BC1) at 0.27 GeV. The second magnetic compressor (BC2) was used as the mixing chicane. The beam was then accelerated to the energy of 1.23 GeV. In general, phase mixing should not affect the bunch length  $\sigma_z$ . This implies

that the correlated fractional energy spread  $\sigma_\delta$  evaluated on the bunch length scale (linear energy chirp) has to be small enough to ensure  $R_{56}\sigma_\delta \ll \sigma_z$ . Bunch length compression in the mixing chicane has also to be avoided because, defeating its scope, it would enhance the total instability gain at short wavelengths, as it happens in a two-stage compression scheme with respect to the one-stage [11]. If the electron bunch were time-compressed in the early stage(s) of the accelerator, the total chirp at the mixing chicane would be a resultant of the linear energy chirp required for previous magnetic compression, the energy spread induced by the RF curvature, the action of linac longitudinal wakefield and adiabatic damping due to acceleration. The latter two contributions tend to reduce the former. The linac wakefield and the RF curvature add quadratic and cubic energy chirp to the beam longitudinal phase space. In order to remove the linear chirp at the BC2 location, the RF phase of two upstream S-band accelerating structures, L3 in Fig. 1, was scanned and set 50 deg off the phase of maximum energy gain. That value gave the minimum horizontal beam size in the middle of BC2, measured with a beam profile imaging system. The residual correlated energy spread, now dominated by a quadratic energy chirp, was lowered to 0.1% rms level. With this linac set up and 90 mrad bending angle in BC2, the ELEGANT code [12] predicts ~10% bunch length variation at the exit of the mixing chicane relative to ~1 ps full width bunch duration at its entrance.



Figure 1. Sketch of the FERMI linac (not to scale) for the phase mixing experiment [10].

## EXPERIMENTAL RESULTS

At the linac's end, an OTR-based beam profile imaging system was used to measure the beam transverse sizes and the beam spot's OTR intensity as the BC2 bending angle was varied in the range 0–90 mrad;  $|R_{56}|$  was varying in the range 0–46 mm. During the scan, the beam sizes were kept almost constant at the observation point by tuning upstream quadrupole magnets. The effect of CSR emission in BC2 on the beam transverse emittance was counteracted with a manipulation of the beam optics across the chicane [13]. The projected emittance was not varying by more than 10% at the linac's end over the entire BC2 angles' range. The OTR intensity, integrated over the region occupied by the beam spot and averaged over many shots, is shown in Fig.2 vs. the  $|R_{56}|$  in BC2, with and without the LH action. When turned on, the LH provided approximately 50 keV rms incoherent energy spread to the uncompressed beam. Such a strong beam heating was used on purpose since, as discussed below, the analytical model ensures total suppression of microbunching at optical wavelengths and shorter. When

the LH was off the OTR intensity increases sharply even for small values of  $|R_{56}|$ ; it then drops for values equal or larger than 9.1 mm. At  $|R_{56}| = 27.8$  mm, the OTR intensity was the same as in the presence of beam heating.

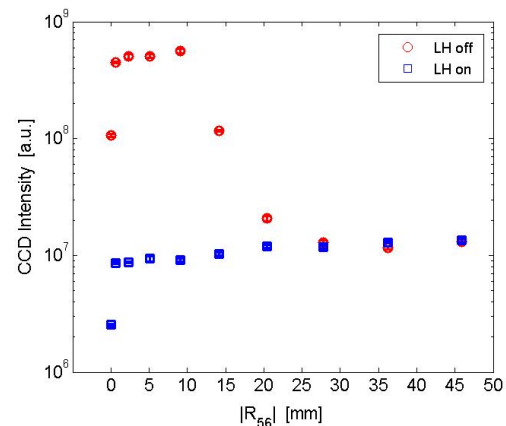


Figure 2. Integrated OTR intensity at the FERMI linac's end as function of  $|R_{56}|$  in BC2 [10].

## ANALYTICAL VERIFICATION

For the case of LH off, we computed the microbunching instability gain at the end of the FERMI linac, at the optical wavelength of 550 nm vs.  $|R_{56}|$  in BC2, starting from shot noise and on the basis of the linear theory developed in [1,14,15], for a beam with 1  $\mu\text{m}$  transverse normalized emittance and initial 2 keV rms incoherent energy spread. The gain is shown in Fig.3. The behavior of the instability gain is in agreement with that of the OTR intensity in Fig.2 as the instability gain at the optical wavelength of 550 nm is suppressed by the same  $|R_{56}| \approx 20$  mm that causes drop of the OTR intensity to the incoherent level. Other two wavelengths at the extremes of the optical range are considered in Fig.3 to show that, depending on the wavelength of interest, the instability gain is suppressed by a different value of  $R_{56}$ . As far as the *peak* gain is concerned, namely its maximum value evaluated over the entire spectrum, the analytical model predicts an increase of up to two orders of magnitude as  $|R_{56}|$  in BC2 moves from 0 to 46 mm. However, as the momentum compaction is increased and phase mixing becomes more effective, the wavelength of maximum gain red-shifts from 1.1  $\mu\text{m}$  to 7.1  $\mu\text{m}$ . This trend is shown in Fig.4. Consequently, the amount of phase mixing can be tuned through the mixing chicane's bending angle to bring the instability gain far enough from the spectral range of interest. With LH on, the optical gain is strongly suppressed for any  $|R_{56}|$  in BC2 in the range 0–46 mm and the peak gain is shifted to initial (i.e., uncompressed) wavelengths longer than hundreds of micron (not shown). The experimental behavior of the OTR intensity, as outlined in Fig.3, confirms the analytical prediction of Fig.4. This confirmation together with our finding that the instability gain can be controlled with BC2, are the principle results of our study.

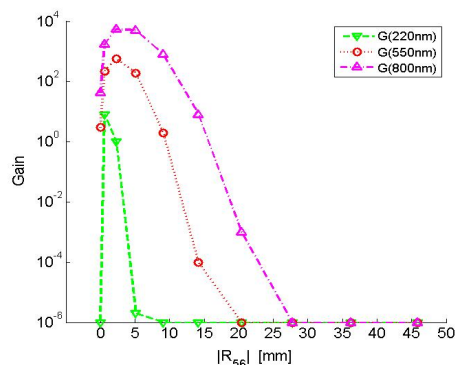


Figure 3. Analytical evaluation of the microbunching instability gain at the FERMI linac's end as function of the momentum compaction,  $|R_{56}|$ , in the mixing chicane (BC2); LH is off [10].

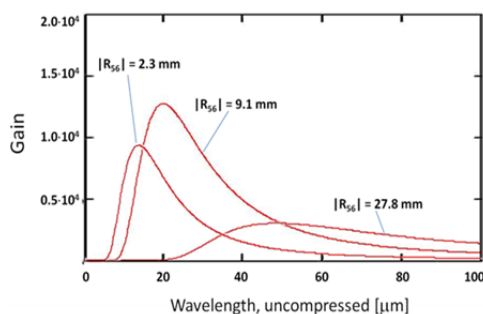


Figure 4. Analytical evaluation of the microbunching instability gain as function of the *initial* modulation wavelength, for three values of  $|R_{56}|$  in BC2 [10].

## APPLICATION TO FELS

Since the phase mixing takes advantage of the microbunching instability to minimize its impact on the beam *final* longitudinal phase space, the adoption of a mixing chicane at the beginning of the linac, where the bunching has not grown enough yet, inhibits the electrons' phase slip and is therefore ineffective. Phase mixing at late linac stage smoothes the longitudinal phase space, but the final slice energy spread remains of the same order as the (possibly large) energy modulation amplitude accumulated up to that point. We thus conclude that phase mixing should take place at an intermediate linac longitudinal coordinate – let us call it  $\bar{s}$  – to be most effective. Roughly speaking, for an FEL to be efficient we impose that the energy modulation amplitude accumulated up to  $\bar{s}$  and normalized to the *final* linac energy, be smaller than the so-called FEL parameter,  $\rho$  [16]. We then require that the energy modulation amplitude from  $\bar{s}$  to the undulator be smaller than that accumulated upstream of the mixing chicane:  $\Delta\gamma(\bar{s} \rightarrow s_f) < \Delta\gamma(s_i \rightarrow \bar{s}) < \gamma(s_f)\rho$ , with  $\gamma$  the relativistic Lorentz factor. If such an  $\bar{s}$  exists, depending on several electron beam and machine parameters, an increase of the slice energy spread will be allowed along the beam line, but not to the extent that it overwhelms the

FEL normalized energy bandwidth. For the FERMI moderate one-stage compression, we found that there is no further growth of the instability after phase mixing. The final slice energy spread is then expected to be approximately 100 keV rms (the maximum energy modulation amplitude accumulated up to BC2), which is close to that measured at FERMI during standard operation of the LH [17].

## ACKNOWLEDGMENTS

The authors are indebted to: L. Badano who provided the calibration curves to compute the OTR integrated intensity; M. Veronese, for instructive discussions about COTR; E. Allaria, who inspired the software tool used for data collection; M. Venturini for instructive discussions on topics covered by this article, and M. Cornacchia, J. Wu, G. Penco and R. Bosch, for careful reading and suggestions. We thank the FERMI commissioning team for the time available to carry out the reported measurements.

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