Burst mode MHz repetition rate inverse free electron laser acceleration

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The capability of accelerating electron bunches at high repetition rate is one of the key performance criteria for all high average power particle accelerator applications. High gradient laser-driven acceleration holds the potential for greatly reducing size and costs of future machines, but typically requires very high peak laser powers. On the other hand, MHz pulse trains of TW-class laser beams are much beyond the state of the art, so that laser recycling and recirculation is a necessary step to bridge that gap. In this experiment we demonstrate for the first time an inverse free electron laser accelerator (IFEL) operating within an active optical cavity showing the ability to laser-accelerate electron bunch trains in burst mode at > 20 MHz repetition rate. The experimental setup, synchronization challenges and acceleration results are presented. It is found that careful control of the dispersive properties of the cavity is required in order to sustain high accelerating gradients over many passes in the laser pulse train.

DOI: [10.1103/PhysRevAccelBeams.23.051301](https://doi.org/10.1103/PhysRevAccelBeams.23.051301)**I. INTRODUCTION**

The last decade has seen major advances in high gradient laser-driven particle acceleration mostly using plasma wakefield, but also dielectric structure, laser-generated THz-driven or even vacuum interactions [1–4]. Nevertheless, the scalability of laser-driven particle accelerators remains fundamentally linked to the progress in the development of high average power high peak power lasers. While there are few scientific applications where operating at low repetition rates would be acceptable and even desired in some cases, any power-hungry, industrial or medical deployment will require to scale up the accelerated beam average current/power to levels which put demands on the drive power essentially beyond the reach of current laser technology. For example, assuming 100 fs–1 ps pulse lengths, the average power of a modest 10 TW laser driven system, minimum requirement for a typical laser employed in high gradient laser acceleration experiments, at 100 KHz

repetition rate would be a 0.1–1 MW, whereas the state-of-the-art is at the 1 kW level.

Among all laser-driven particle accelerators, the inverse free electron laser (IFEL) has many important characteristic advantages which can ultimately enable very high repetition operation. In an IFEL copropagating electron and laser beams interact inside a strongly tapered magnetic undulator [5,6]. The energy exchange is assisted by varying the undulator parameters (tapering) so that the resonance condition is satisfied while the electron energy increases along the undulator [7]. While very high output energies are hindered by the synchrotron losses associated with the wiggling trajectory, given the present status of magnetic undulator and laser technology, the IFEL is ideally suited to reach few GeV beam energies well matched for compact soft x-ray free electron lasers and gamma-ray Compton sources [8]. In addition, since IFEL acceleration is mainly determined by the static magnetic field profile in the undulator, the accelerated beam longitudinal phase space can be fully controlled by properly designing the interaction, resulting in small energy spread, and, even in presence of large laser energy jitters, much reduced output energy fluctuations, especially compared to other laser acceleration schemes which rely on nonlinear effects. Many of these properties have been demonstrated by a series of experiments at BNL which, utilizing an intense CO₂ laser

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pulse and a strongly tapered helical geometry undulator, achieved high accelerating gradient (> 100 MV/m), energy spread below 1.5% and even smaller final energy fluctuations, significantly reduced compared to the jitter in drive laser intensity [9]. Utilizing a cascade buncher scheme, capture fractions larger than 90% were also demonstrated [10]. Finally, as the IFEL process is fully reversible [11], it has been recognized recently that the IFEL can be reconfigured as a decelerator with great potential for application in very high efficiency tunable light sources, as was recently demonstrated in the NOCIBUR experiment which showed electron-optical conversion efficiency of $> 30\%$ [12] at $10\ \mu\text{m}$ wavelength.

In the context of the high repetition rate discussion, the most important property of the IFEL accelerator is its far-field free space interaction nature. There is no medium or nearby boundary, so the energy in the isolated electromagnetic wave-particle system is conserved, and very high gradients can be sustained without a risk of material breakdown; a single IFEL stage can easily be made up to few meters long, thus providing continuous interaction over extended length with a freely diffracting laser beam; repetition rate is simply limited by availability of laser power as no thermal load or plasma recombination time pose any restrictions on how fast the process can be iterated; lastly, absorption of energy from the electron beam is the only effect of the interaction which influence the radiation propagation. Therefore, the unique opportunity exist to recycle the same laser pulse multiple times in order to enable high repetition rate IFEL acceleration.

Recirculating high power CW laser cavities have been developed for other nondestructive laser applications in accelerator technology such as for example inverse Compton scattering (ICS) [13–15]. The most successful approach being the high-Q Fabry-Perot laser cavity [16] which on the other hand presents several drawbacks for the IFEL as each laser pulse carries only a relatively small energy and there are several challenges associated with combining such supercavity with the extended geometry (long Rayleigh ranges and multi-meter cavity lengths) of the IFEL scheme. A robust alternative approach is to include a laser amplifier inside the cavity to compensate for losses. While nonlinear effects and dispersion limit the suitability of solid-state laser amplifiers for this application, CO_2 gas lasers allow for direct amplification of picosecond pulses as recently demonstrated in the recirculating ICS BNL experiment [17]. Even operating in pulse-burst regime, embedding the IFEL undulator in an optical cavity would allow us to reduce the average laser power requirements by 1-2 orders of magnitude depending on how many passes can be supported for a single laser shot.

In the present paper, we explore the suitability of an active cavity toward the development of a high repetition rate IFEL accelerator. In particular, we demonstrate the capability for an IFEL to operate in burst mode at MHz

repetition rates in an experiment at the Accelerator Test Facility at BNL by embedding the Rubicon undulator in an laser cavity where a CO_2 amplifier is used to compensate for the roundtrip losses (which include the energy lost to the accelerating beam). A 50 ns spaced electron bunch train was produced by the photocathode drive laser and injected in the undulator. The laser cavity length was carefully tuned (at the sub-picosecond level) to match the electron repetition rate and acceleration of multiple electron bunches was detected at the energy spectrometer.

The experiment constitutes the first proof-of-principle test of a recirculating laser acceleration concept and required addressing many key issues such as the design of a long recirculating cavity to accommodate e-beam (focusing quadrupoles, steering magnets, prebuncher and IFEL undulator) as well as laser (refocusing mirrors, CO_2 amplifier, vacuum windows) optics elements and the synchronization of electron and laser bunches to achieve an efficient operation essential for repetition rate multiplication. In the end, obtaining IFEL acceleration with the highest energy laser pulses turned out to be challenging due to the pulse splitting effect in multipass CO_2 amplifier as verified by measuring a sizable acceleration signal at injection delays off the synchronized cavity roundtrip by integer numbers of pulse splitting temporal intervals. The measurements presented here with the help of simulations allowed a deeper understanding of the cavity recirculation dynamics, validating the laser pulse evolution simulations, so that this effect can in principle be corrected in future designs.

The paper is organized as follow. We first describe the details of the laser cavity, we then discuss how we achieved synchronization and timing, show the experimental acceleration results and discuss the challenges associated with laser pulse degradation inside the active cavity, before drawing conclusions and future outlook.

II. LASER CAVITY

The experimental setup is shown in Fig. 1 and a list of experimental parameters is reported in Table 1.

Referring to Fig. 1 for the layout of the CO_2 optical cavity, the two $f = 250$ cm off-axis parabolic (OAP) mirrors close to confocal position define the cavity mode in the IFEL beamline. The distance L between these mirrors is adjusted to 5200 mm in order to match the design Rayleigh range (50 cm) and focal size (1.2 mm) at the waist inside the undulator and simultaneously the size of the collimated beam at the laser amplifier to fit into its 20 mm inter-electrode distance. While the choice of reflecting OAP mirrors has important advantages over a lens-based design, is prompt to transverse profile distortions which were carefully addressed using a low power optical diagnostic setup (also depicted in Fig. 1). A pulse-kicker would select a pulse in the cavity and redirect it to a

FIG. 1. Layout of high repetition rate IFEL experiment. A 50 MeV beam is injected into the ATF beamline 2 via dipole (on the right-hand side), focused in the matching section into the prebuncher and redirected into IFEL helical undulator. A laser beam is injected into the CO₂ optical active cavity where it is amplified and introduced into the electron beamline just upstream of the dipole to co-propagate with the electron beam. An accelerated e-beam is refocused onto the magnetic spectrometer diagnostic screen and disposed, whereas the laser beam is recirculated and reamplified to interact with the subsequent bunch within the electron beam pulse train. The laser cavity length is set to approximately 14.7 m (49 ns), and an optical delay stage is introduced to achieve beam-laser synchronization throughout the duration of the pulse train.

camera to image the beam focus and a pinhole were used to ensure that the mode quality was not degrading.

The CO₂ amplification is performed in two 60-cm long discharge sections which are simultaneously triggered. The system includes four amplifier- and beamline- optical windows that separate vacuum or gas volumes from ambient atmosphere. We initially considered ZnSe windows which can be antireflection (AR) coated to minimize the cavity losses, but the large nonlinear coefficient and the low damage threshold of ZnSe would put a severe limitation in the energy and intensity of the recirculating laser pulses. Therefore, we selected to use for the window material uncoated NaCl salt. NaCl has 2 orders of magnitude lower nonlinear refractive index than ZnSe, but AR coating technology is not readily available for NaCl resulting in an additional Fresnel reflection loss at each window surface.

An input seed from the main CO₂ amplifier at ATF [18] is injected into the cavity via reflection from a NaCl window at a small angle to preserve the input polarization.

TABLE I. Parameters for the HD-IFEL experiment.

Parameter	Value
Initial electron beam energy	55 MeV
Initial beam energy spread ($\frac{\Delta E}{E}$)	0.0015
electron beam emittance ($\epsilon_{x,y}$)	2 mm-mrad
electron beam waist ($\sigma_{x,y}$)	100 μ m
electron bunch length	1 ps
electron beam current	100 A
Laser wavelength	9.2 μ m
Rayleigh range	0.7 m
Laser waist	1.4 mm
Laser waist position (from undulator entrance)	0.1825 m
Laser Energy (Full train)	8 J
Laser FWHM	2 ps
Cavity period	49.0196 ns

With 1 J of a seed pulse energy transported from the ATF picosecond CO₂ laser system and 4% reflectivity on the salt window surface, a pulse with 40 mJ energy can be actually injected into the amplifier cavity. This pulse is amplified on each pass by the local amplifier producing a pulse train peaking near the 15th pass (see Fig. 2) at a maximum pulse energy of 300 mJ. The small signal gain in laser amplifier sections is 1%/cm for the first pass and then gradually drops as the pulse energy grows (e.g., $\sim 0.5\%$ /cm around the peak of pulse). Note that the cavity injection window (bottom left corner in Fig. 1) could be swapped out with a full solid copper mirror to allow the use of a much higher energy pulse to establish alignment, and synchronization of the first pass in the cavity as discussed below.

The helical undulator requires a circular polarization laser pulse. Unlike linear polarization, where Brewster

FIG. 2. (a) Sample scope trace of the pulse train as measured by the photodiode (red) and analytical fit used in the analysis (blue). In the inset (b) the 14th and 15th pulse of pulse train (red) and relative fit (blue) yield a cavity period of 49.02 ns. The reference signal from the photodiode on the laser master oscillator (yellow) and its sinusoidal fit (green) are also shown. The period of the laser oscillator signal (12.2549 ns) is exactly 1/4 of the roundtrip of the IFEL cavity. The x-axis is shifted so that zero corresponds to the peak of the train.

windows can be used to minimize losses, in the case of circular polarization reflection beams at the level of 4% at each window surface are inevitable, more than doubling total roundtrip loss to the order of 45%. The other source of optical energy loss were due to the restrictions of the electron beam pipe set by the limited aperture of the magnets employed in the experiments (focusing quadrupoles and undulators). Although the losses are fully recovered in the amplifier, they reduce the overall length and peak energy of the pulse train. More importantly, as will be discussed later, the introduction of the NaCl windows increased the propagation distance through non-linear material each round trip enhancing the pulse splitting in the amplification process which would ultimately limit the intensity of the drive laser and hence the performances of the IFEL acceleration.

The pulse train evolution shown in Fig. 2 is measured in absence of interaction with electron beam. Nevertheless, it is not expected that the dynamics will be significantly modified by the acceleration process. Even assuming 100 pC per bunch loaded into the IFEL accelerator the energy absorbed per pass will be less than 1 mJ adding < 0.3% additional losses per cavity roundtrip. This effect is negligible in the present setup, but will be important in future designs where losses are minimized. In this case the pulse dynamics in the cavity should be calculated self-consistently including the energy exchange between laser and electrons [19].

III. IFEL ACCELERATION

The IFEL accelerator uses a retuned version of the Rubicon helical undulator, previously employed in other IFEL experiment at ATF [9]. As in previous instances of the Rubicon IFEL setups, a prebuncher undulator is used to maximize the fraction of the electron beam injected into the stable ponderomotive accelerating bucket [20,21]. For this experiment the tapering was designed for an initial resonant accelerating phase, $\theta_{r0} = -\pi/4$, assuming a drive laser pulse with energy of 250 mJ and a 3 ps pulse length. The variation of the normalized magnetic field amplitude K along the undulator has been obtained imposing the condition of constant bucket area for the ponderomotive potential in longitudinal phase space. This tapering choice differs from previous IFEL designs [6] where the resonant phase θ_r had been chosen as a fixed value in the interaction. Nevertheless, there is no fundamental reason preventing adjusting this important parameter along the undulator [7] which can in fact be finely adjusted in order to compensate for particle detrapping along an IFEL undulator.

The study of detrapping and individual particle dynamics in the ponderomotive potential requires self-consistent three dimensional numerical simulations. However, the effect can be treated in one dimensional approximation noting that the probability for particle detrapping [22] is simply proportional to the rate of change of the area

FIG. 3. (a) Rubicon IFEL period and normalized undulator parameter tapering profile (top) and corresponding resonant energy and resonant phase along the undulator (bottom). (b) Electron beam spectra for no laser (blue, scaled by 1/2), linear polarization (red) and circular polarization (yellow) with seed laser energy 270 mJ.

enclosed in the separatrix. Therefore, the most direct way to ensure that the initially trapped electrons remain in the bucket is to design the undulator tapering so that the stable bucket area remains constant throughout the interaction. In the approximation that the bucket area is proportional to $\frac{1-\sin\theta_r}{1+\sin\theta_r}$, this allows us to write a condition for the resonant phase in terms of the undulator K , undulator wave number k_w and normalized vector potential for the laser K_l :

$$\sin(\theta_r) = \frac{\sqrt{KK_l} - \sqrt{k_w}J_0}{\sqrt{KK_l} + \sqrt{k_w}J_0} \quad (1)$$

where $J_0 = \sqrt{\frac{K_0 K_0}{k_w 0} \frac{1-\sin(\theta_{r0})}{1+\sin(\theta_{r0})}}$ is the initial bucket area.

Inserting Eq. (1) into the tapering design equation [8], together with the Rubicon period profile (which is already predetermined since the undulator has been already built), we can numerically solve for the variation of the undulator normalized parameter K . The solution is reported in Fig. 3(a) and was adopted in the experiment by retuning the gap between the permanent magnets along the undulator.

Prior to running in multibunch/cavity mode, the NaCl injection window was replaced by a solid mirror to redirect the entire input CO₂ pulse to the undulator and a single electron bunch was injected in the undulator. This allowed us to benchmark the operation of the IFEL accelerator with the new tapering design and obtain a reference electron spectrum which is shown in Fig. 3(b). Images with no laser and with a linearly polarized laser pulse are also shown for reference. The strong modulation in output energy has been explained previously as nonresonant IFEL interaction [12] and is due to the fact that even in this ideal case particle detrapping still occurs as some particles (at the transverse and longitudinal tails of the beam distribution) experience a drive laser intensity still below the tapering design value. As discussed below, the issue of a lower-than-design laser

FIG. 4. Normalized maximum and average output energy for the Rubicon undulator tapering tune used in the recirculated IFEL experiment as a function of input laser pulse energy.

intensity will turn out to be critical in the recirculating experiment.

To better understand what happens when the IFEL is driven by lower energy laser pulses, we also performed 3D particle tracking simulations of the system and show the results in Fig. 4. The maximum and average relativistic gamma factor of the IFEL output beam is shown for a range of input laser energy from 50 to 300 mJ. This plot provides the following information. First of all, a small acceleration signal is present even at the lowest pulse energy, which can be exploited for synchronization purposes. While the average energy is gradually increasing (corresponding to the fact that more particles are trapped and accelerated in the ponderomotive potential), it is clear by looking at the maximum energy curve that a threshold laser power needs to be provided in order to maintain acceleration over the entire undulator length. The same plot also shows that the variation in the IFEL maximum energy once the input laser energy is larger than 150 mJ is less than 4%, indicating that multiple laser pulses in the cavity can be used for maximum acceleration.

IV. TIMING AND SYNCHRONIZATION

The design cavity roundtrip period is 49.0196 ns, equal to the fourth subharmonic of the ATF master oscillator period, 12.2549 ns which is used to generate the electron beam at the cathode.

Coarse adjustment (at the ns-level) of the cavity length has been achieved by matching a photodiode signal of the pulse train to a reference signal from the master oscillator. The cavity length can be measured and adjusted at the picosecond level by Fourier analyzing the pulse train envelope, Fig. 2. Picosecond level timing is established by monitoring electron beam controlled transmission of the mid-IR pulse through a Ge crystal [23]. In detail, the transmission of CO₂ through Ge can be truncated by the prompt electron-hole plasma formation induced by the passage of the relativistic electron beam in the crystal.

FIG. 5. (top) IFEL-induced rms energy modulation on the injected bunch (σ_γ) when varying the external delay stage at 1st, 2nd, 5th, 7th and 12th pass, showing a 2 ps drift of the optimal timing over 12 passes. (bottom) Maximized IFEL energy modulation at the 5th pass, showing a 6% fraction of the initial beam accelerated to the final IFEL output energy.

Watching for onset of this truncation allows us to synchronize beams to the accuracy at or below the e-bunch duration.

Timing between laser and e-bunch is then further optimized by tuning the optical delay for the incoming CO₂ pulse to maximize the IFEL energy modulation using the first pulse of the pulse train (typically ~ 20 – 40 mJ). The cavity length can then be probed to subpicosecond precision by stepping the electron beam timing in integer numbers of cavity periods. Provided that the cavity roundtrip delay is accurate to within few picoseconds, fine timing at each pass can be established by adjusting the external delay stage again to maximize the IFEL energy modulation (see Fig. 5). This measurement allows to estimate the accuracy in the synchronization of the recirculating laser pulses. Clear IFEL interaction is observed over more than 12 passes in the cavity, and this measurement can be used to provide an upper bound for the cavity roundtrip length using the convolution of the laser and electron pulse lengths (2.2 ps) divided by 12 (i.e., < 200 fs).

V. HIGH REPETITION RATE IFEL OPERATION

Once the laser is injected in the active recirculating 20 MHz cavity, we were able to demonstrate high repetition rate IFEL operation taking advantage of the ATF linac capability to run in multibunch burst mode. The ATF

photoinjector drive laser system had been originally designed to allow the operation of the linac with long trains and this has been successfully done in the past [24], but for this proof-of-principle demonstration experiment we limited the length of the train to a small number of equally spaced electron bunches to simplify operation and diagnostics.

A sequence of three UV laser pulses is obtained activating a Pockel cell every fourth pulse from the master oscillator train. The master oscillator frequency 81.6 MHz is an exact submultiple (factor of 35) of the radio frequency driving the accelerator (2.856 GHz) so that each electron beam is phase-locked and experiences the same rf accelerating field. The resulting temporal spacing between the three UV pulses is 49.02 ns, matched to the cavity roundtrip time. The timing of the laser within the 4 μ s long high power rf pulse is chosen such that the photoelectrons generated when the UV illuminates the cathode are accelerated on the rising edge of the rf pulse, where beam loading helped to maintain constant energy for the three bunches. The bunch train is then accelerated in the linac and injected into the IFEL synchronous with the recirculating CO₂ pulse.

Figure 6 shows the images obtained at the spectrometer when three electron bunches were injected into the undulator temporally overlapped with the 7-9th passes of the

laser pulse train. The combined energy spectrum is compared for reference with the single bunch case. Image analysis (i.e., projecting along the energy axis with background subtraction) shows approximately a factor of three increase in the accelerated charge. For a more quantitative comparison it is useful to look at the normalized energy distributions shown in the lowest graph of Fig. 6. Here the differences between the multibunch and single bunch spectra are more evident and we can actually observe a degrade in performance for the multibunch case. This is due to time-dependent effects in the particle loading in the IFEL accelerator associated with the fact that in the bunch train case, each bunch has a slightly larger charge and pulse length (250 pC, 2.5 ps) than the single bunch case (100 pC, 1 ps). Note that for the 9th pass the energy in the laser pulse is still below 100 mJ so much below the IFEL tapering design value. This results in a large energy spread and extremely small fraction of accelerated particles in agreement with simulations.

VI. PARASITIC SELF-MODULATION OF A CO₂ LASER PULSE

To summarize, satisfactory operation of the IFEL accelerator has been observed only when the design laser pulse intensity was used, that is, in the single pass configuration obtained replacing the injection window with a solid copper mirror. After switching to the cavity configuration, as we step the e-beam delay to move toward the peak of the laser pulse train, we consistently failed to increase the IFEL energy modulation above what reported in Fig. 6.

Various reasons have been initially considered for the degradation of the IFEL performances for the later pulses in the train, including possible drift in the laser pointing due to mechanical fluctuations, degradation of the mode profile and/or polarization purity at later passes. Nevertheless, the pulse-selective optical diagnostic introduced to monitor the spatial profile and alignment of the laser over multiple passes did not show significant changes. Similarly, we evaluated the depolarization effects due to the NaCl windows and multiple mirror reflections. Some of the windows in the cavity designs have been angled vertically in order to compensate and distribute the Fresnel losses in the two planes. Still, the s- and p-pol losses in each cavity roundtrip differ by < 3%, and the pulse polarization gradually becomes elliptical. Nevertheless, the horizontal to vertical polarization ratio is estimated to be 1 : 1.5 around 15th pass, which is not sufficient to explain why the IFEL energy modulation degrades when we synchronize the electron bunch with the highest energy pulses in the pulse train.

In order to understand the poor acceleration performances reported in Fig. 6, we need to take a closer look at the pulse evolution in the recirculating cavity with the help of laser pulse dynamics simulations [25]. In the end, it turned out that a strong degradation of the pulse length was occurring during recirculation. This was attributed to the spectral

FIG. 6. Spectrometer images for single bunch (a) and three bunches (b) injected in the IFEL. Note that the gain is adjusted to maximize the dynamic range and avoid saturation of the images. (c) Charge normalized energy histograms for single bunch (red) and three bunch (blue). We also show for comparison the single bunch spectra scaled by a factor of three (red dashed) (d) Spectra corresponding to (a) and (b) are also shown normalized to unity for reference.

FIG. 7. Pulse train build up in ideal cavity with isotopic gain broadening (top) and in actual cavity with nonlinear effects in windows included (bottom). The zero of the time-axis corresponds to the trigger of the pumping discharge in the amplifier. The injection time for the first pass corresponds to $0.7 \mu\text{s}$ on this scale. The temporal profiles of the corresponding pulses at the peak of the pulse train are also shown.

structure from the roto-vibrational lines of CO_2 molecules. During the design phase, isotopic line broadening had been suggested to smooth the gain spectrum and sustain the amplification of $< 5 \text{ ps}$ long pulses over multiple passes. This is shown in Fig. 7. When we include in the simulation the nonlinear effects associated with the propagation in the vacuum windows, the situation drastically change. The experimental constraints and the resulting cavity implementation, in particular the insertion of relatively thick NaCl windows which significantly increased the nonlinear effects, prevented from reaching the design operating condition and the resulting gain spectrum was significantly modulated. This resulted in severe pulse splitting after multiple passes in the amplifier [see Fig. 7(b)]. The 40 GHz rotational line separation in a CO_2 gain spectrum converts to the 25 ps time interval seen in the plots on the right. Note that for these simulations we assumed a transform-limited 2 ps input pulse spectrum which has a strong mismatch with the modulated gain spectrum, resulting in a reduced spectrum-averaged

FIG. 8. IFEL energy modulation varying external delay for 6th pass (blue) 8th pass (red) 12th pass (yellow) and 16th pass (green) showing peaks in the IFEL energy modulation at regular time intervals corresponding to the CO_2 rotational line separation (indicated by the vertical lines in the plot). Note that timing was continuously varied, but only electron spectra appreciably different from the laser-off shots are reported in the figure.

gain during the first passes in simulations. This is not observed in the experiment (compare with Fig. 2 since the input laser pulse coming from the upstream CO_2 amplifiers has a spectrum which better matches the gain spectrum thus enabling relatively high amplification immediately from the first passes).

An experimental validation of these simulations was obtained using the electron beam to monitor the laser intensity at the temporal interval characteristic of pulse-splitting for CO_2 amplification (see Fig. 8). In short, at 25 ps from the main pulse we should have recorded a null signal on the IFEL spectrometer as we were far away in time from the main CO_2 pulse. Conversely, after moving the delay line, a measurable IFEL acceleration signal reappeared at regular time-intervals for the later passes in the optical cavity. For the 16th pass we observed IFEL modulation at a temporal distance corresponding to four CO_2 time-interval indicating severe pulse-splitting in agreement with the predictions. This implies that only a portion of the laser energy in each pulse was available for acceleration and that the peak power was clamped at a level much lower than expected. In other words, even though the pulse energy was increasing along the train, the laser intensity overlapping with an electron bunch did not, ultimately limiting the performance of the IFEL accelerator.

VII. CONCLUSIONS AND FUTURE OUTLOOK

The experiment presented in this paper demonstrated the feasibility of very high repetition rate (20 MHz) in burst mode laser acceleration by the inverse free electron laser mechanism. This achievement takes full advantage of the far field vacuum characteristics of the IFEL acceleration scheme and is a stepping stone toward high average power laser-driven acceleration. The importance of controlling the evolution of the laser pulse in the optical cavity has been highlighted as laser pulse splitting ultimately limited the accelerator performances.

There are several possibilities to overcome the pulse splitting problem. In principle a cavity redesign which would minimize the losses and use thinner windows and a larger spot size could be used in order to limit the nonlinear effects. Another idea is to use a lower energy cavity early in the amplification chain to generate a sufficiently long pulse train to drive the IFEL undulator in single pass mode. The train can be for example extracted from a preamplifier through a semitransparent output coupler and then further amplified in a final amplifier. In addition, independent triggering of the amplifiers offers additional freedom in extending the gain time span to produce a quasi-flat-top laser pulse train. All of these options will be evaluated in future versions of this experiment.

Finally, in order to reach multi-GeV level energies with an IFEL accelerator, one could consider moving toward shorter wavelength laser as it is desirable to keep undulator magnetic period lengths at a reasonable size (below 10 cm).

As the high intensity required to achieve large accelerating gradients prevents the use of solid-state amplifiers inside the cavity (unless a complicated stretcher-amplifier-compressor-accelerator design is worked out). An interesting solution, which will be the subject of future investigations, will be to use a TESSA (i.e., reverse IFEL) amplifier to extract or recovery energy from a relativistic electron beam.

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