ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP054

NANOSECOND PULSE ENHANCEMENT IN NARROW LINEWIDTH CAVITY FOR STEADY-STATE MICROBUNCHING

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Abstract

In steady-state microbunching (SSMB), nanosecond laser pulse with megawatt average power is required. We build up a theoretic model to simulate the enhancement process of such pulse in narrow linewidth (e.g. kHz level) cavity for this demand, which shows that a mode-locked mechanism in frequency domain should be considered. Simulations indicate that such pulse can be enhanced sufficiently under this condition. And we also propose some experimental schematics to realize it.

INTRODUCTION

In SSMB, nanosecond pulse laser field with megawatt average power is required [1]. To our knowledge, such power level is difficult and expensive to achieve with direct generation methods. In another hand, power enhancement by an optical cavity has been studied intensively in both cw and ultrashort pulse case last few decades, and 7.5kW [2] and 670kW [3] intracavity average power has been realized respectively. Also, enhancement of nanosecond laser pulse [4] has been studied theoretically and experimentally, which illustrate that such pulse can be sufficiently enhanced with the condition that the pulse linewidth is narrower than or comparable to that of the cavity. However, the linewidth of the cavity used for SSMB is narrower than ordinary one under same finesse because of its larger round trip length, which indicate that a nanosecond pulse hardly can be enhanced by such cavity.

In this paper, we propose a kind of nanosecond pulse with comb structure in frequency domain, which can be sufficiently enhanced in such narrow linewidth cavity. Using the model of pulsed multi-beam interference we numerically analyze the enhancement process of a nanosecond pulse in a travelling wave narrow linewidth cavity, which indicate that the pulse with any time duration can be sufficiently enhanced by this method. We also propose some schemes to generate such pulse.

MODEL OF NANOSECOND PULSE ENHANCEMENT FOR SSMB

Figure 1 shows the schematic of the enhancement cavity for SSMB. Here, a standard bowtie travelling wave ring cavity is chosen, whose advantages have been discussed already in detail [5].

To quantify the enhancement process, pulsed multi-beam interference model should be considered. However, two differents should be noticed here. Frist, the transmissions occur at every mirror. Second, the reflectivity and transmission of input coupler should be different from other mirrors because of the requirement for impedance matching.

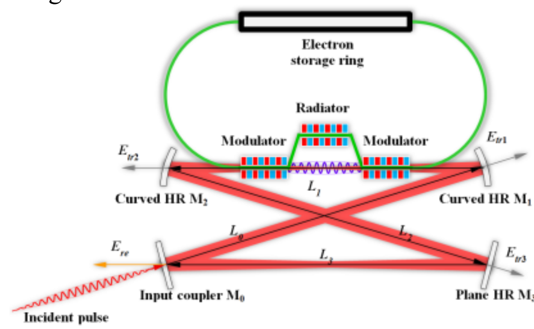

Figure 1: Schematic of SSMB with standard bowtie ring cavity.

To quantify the enhancement process, pulsed multi-beam interference model should be considered. However, two differents should be noticed here. Frist, the transmissions occur at M_1, M_2 and M_3. Second, the reflectivity and transmission of input coupler M_0 should be different from M_1-M_3 because of the requirement for impedance matching. Then, the model is modified as follow,

$$E_{re} = \left[\sqrt{R_0}\cdot E(t) + T_0 \sum_{n=1}^{\infty}\left(-\sqrt{R_0}\right)^{n-1}\left(-\sqrt{R}\right)^{3n} E\left(t - \frac{nL}{c}\right) e^{in\delta}\right] e^{i(\omega t - kz)} \quad (1)$$

$$E_{tr1} = \left[\sqrt{T_0 T}\sum_{n=0}^{\infty}\left(-\sqrt{R_0}\right)^{n}\left(-\sqrt{R}\right)^{3n} E\left(t - \frac{nL+L_0}{c}\right) e^{in\delta}\right] e^{i(\omega t - kz)} \quad (2)$$

$$E_{tr2} = \left[\sqrt{T_0 T}\sum_{n=0}^{\infty}\left(-\sqrt{R_0}\right)^{n}\left(-\sqrt{R}\right)^{3n+1} E\left(t - \frac{(2n+1)L}{2c}\right) e^{in\delta}\right] e^{i(\omega t - kz)} \quad (3)$$

$$E_{tr3} = \left[\sqrt{T_0 T}\sum_{n=0}^{\infty}\left(-\sqrt{R_0}\right)^{n}\left(-\sqrt{R}\right)^{3n+2} E\left(t - \frac{(n+1)L-L_3}{c}\right) e^{in\delta}\right] e^{i(\omega t - kz)} \quad (4)$$

$$E_{in} = \sqrt{T_0}\sum_{n=0}^{\infty}\left(-\sqrt{R_0}\right)^{n}\left(-\sqrt{R}\right)^{3n} E\left(t - \frac{z}{c} - \frac{nL}{c}\right) e^{i\left(\omega\left(t-\frac{z}{c}-\frac{nL}{c}\right) - kz - n\delta\right)} \quad (5)$$

Where, E_{re}, E_{in} represent reflection and intracavity field. E_{tr1}, E_{tr2} and E_{tr3} are the transmission fields from M_1 to M_3. c and z is the speed of light and the position in the cavity along the direction of the beam propagation, and the origin of z is set at M_0. L_0 -L_3 is the distance between two mirrors. $L=L_0+L_1+L_2+L_3$, is the round trip length of the cavity and δ is the corresponding phase shift. R_0, T_0 is the reflectivity and transmittance of M_0, and R, T is that of

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39th Free Electron Laser Conf. FEL2019, Hamburg, Germany JACoW Publishing
ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP054

M_1, M_2 and M_3. k, ω is the wave vector and frequency of incident pulse. Then the electric field can be expressed as $E(t,z) = E(t)e^{i(\omega t - kz)}$.

SIMULATION OF THE TRADITIONAL NANOSECOND PULSE ENHANCEMENT

Nanosecond pulse is generated by Q switching method usually, which have transform limited linewidth of megahertz level. Such pulse can't be enhanced in high Q cavity obviously, because this kind of cavities always has linewidth of kilohertz level or even narrower.

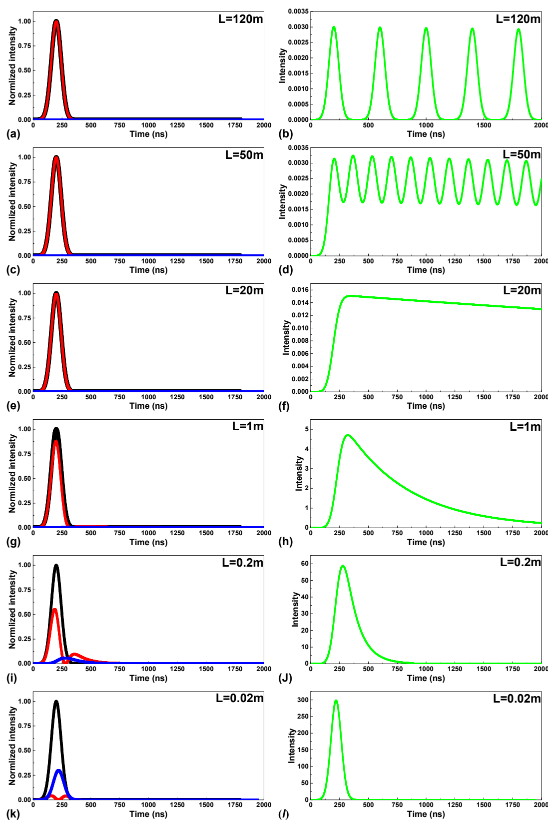

Figure 2: Simulation of traditional nanosecond pulse enhancement in different cavity length.

Assume that the incident pulse is the gaussian and the duration is 100ns with normalized amplitude. The simulation conditions are chosen as following: laser wavelength λ is set to 1064nm, mirror reflectivity R and transmittance T are set to 0.999 and 0.001, and for impedance matching the condition of $T_0 = 3T$ has been used. Cavity lengths L are set to 120m, 50m, 20m, 1m, 0.2m, and 0.02m respectively, we calculate the intensity of E_{re}, E_{tr2}, and E_{in} for revealing the enhancement process.

Figure 2 shows the results. We can understand the process in time domain: when the cavity length is long (e. g. 120m and 50m, which is longer than the pulse length cτ≈30m), the different part of laser filed can't overlap. When the cavity length gets shorter than the pulse length (e. g. 20m, 1m, 0.2m and 0.02m), the laser filed superposition occurs. The shorter the cavity length is, the more the superposition times are, and then we get the stronger enhancement. In addition, the longer cavity length (e. g. 20m, 1m and 0.2m) induce the broaden of pulse duration, which can be understood as the superposition of the pulse end to end.

In another hand, this process also can be understood with a simple picture in frequency domain. First, the linewidth of the Gaussian pulse is always transform limited because no chirp arises, for 100ns duration the ideal linewidth Δv_p is 4.4MHz. Following above simulation parameters, the different cavity length lead to different free spectral range (FSR) and cavity linewidth (Δv), Table 1 shows these results. Comparing Δv with Δv_p we can see that when the cavity linewidth is bigger than the pulse the sufficient enhancement occurs, which can be seem as the cavity has enough capacity to hold the pulse in frequency domain.

Table 1: FSR and Δv with Different Cavity Length Comparing the Pulse Linewidth.

	120 m	**50m**	**20m**	**1m**	**0.2m**	**0.02m**
FSR (MHz)	2.498	5.996	14.990	299.790	1498.962	17989.623
Δv (kHz)	2.388	5.731	14.328	286.567	1432.838	14328.379
$\Delta v/\Delta v_i$	0.0005	0.0013	0.0033	0.0651	0.3256	3.2564

SIMULATION OF MODE-LOCKED NANOSECOND PULSE ENHANCEMENT

Comb structure in frequency domain has been used to generate ultrashort pulse with duration down to femtosecond. For realizing such ultrashort pulse millions of discrete lines have been used. On the other hand, a few lines produce the pulse with duration much longer. This physical picture can be easily understood by Fourier transform mechanism. We choose appropriate quantity of the discrete lines, besides the linewidth of single line is equal to or narrower than the cavity and the spacing between each other is equal to the cavity FSR. Such pulse train should be able to be enhancement in the cavity.

Here, the round trip cavity length is set to 120m, leading 2.5MHz in FSR. And other conditions are same as above, which bring the cavity linewidth of 2.39kHz. We assume that a pulse with 39 discrete lines, whose spacing and linewidth match the cavity's. The envelope and line shape are Gaussian and Lorentzian respectively. The pulse train structure in frequency and time domain are shown in Figs. 3 (a) and (b). Using the enhancement model above we obtain the reflection, transmission and intracavity field intensity, which are shown in Figs. 3 (c) and (d). We can see that the reflection is almost vanished, which means the impedance matching achieve, and the enhancement factor is about 332. These results indicate such kind of pulse can be enhancement sufficiently.

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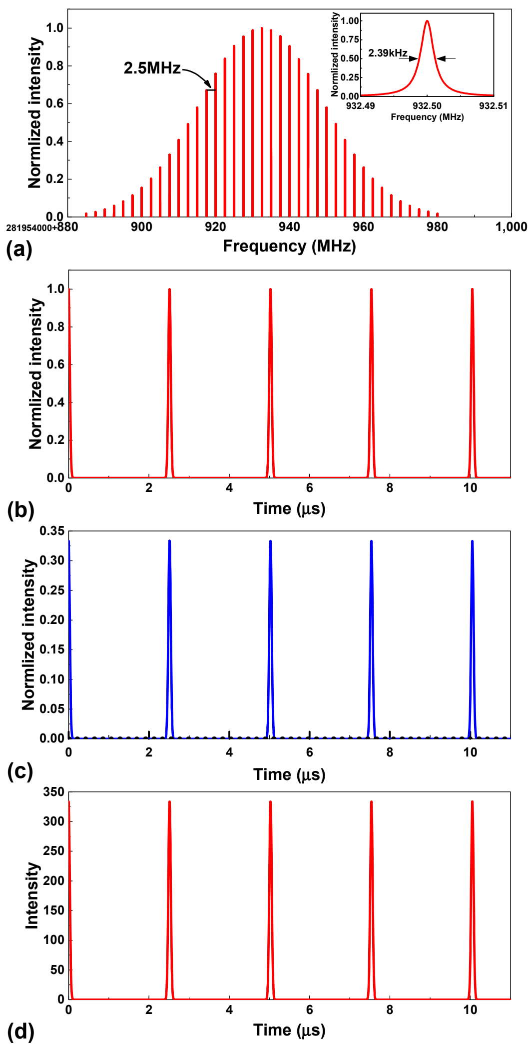

Figure 3: Simulation of mode-locked ns pulse enhancement. The structure of (a) frequency and (b) time domain of the pulse; (c) the reflection (black dot line) and transmission (blue solid line) intensity of the cavity; (d) intracavity intensity.

GENERATION OF THE MODE-LOCKED NANOSECOND PULSE

To realize the enhancement of mode-locked nanosecond pulse two aspects should be considered carefully. First, in the given narrow linewidth cavity the pulse which can be sufficient enhanced in has certain structure in frequency and time domain, which means for generation such pulse one should obtain the cavity structure firstly. And such cavity structure may be decided by other requirements, e.g. the dimensions of modulator and radiator for electron beam. Second, the number of the discrete lines (or modes) decides the pulse duration directly, so the technic which can generate the lines with a given numbers have to be developed.

Two candidate methods based on narrow linewidth cw laser may be feasible. The first one base on coherent combination. The second one produces many sidebands and then filter out the superfluous lines to obtain such pulse. The phase locking technic (e.g. PDH method) is required in both methods for locking the cavity and laser source.

CONCLUSIONS

We propose a kind of nanosecond pulse generated by mode locking process, which can be sufficiently enhancement in high Q long (narrow linewidth) cavity. Comparing with traditional nanosecond pulse, e.g. generated by Q switching, such pulse is fully coherent, which is just suitable for the application in SSMB.

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