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AN EFFICIENT OPTIMISATION OF A BURST MODE-OPERATED FABRY-PEROT CAVITY FOR COMPTON LIGHT SOURCES

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Abstract

The burst mode operation of a Fabry-Perot cavity (FPC) allows for the generation of a high-intensity photon beam in inverse Compton scattering (ICS) sources. The geometry and burst mode parameters of the FPC can be optimised to maximise the scattered photon flux. A novel optimisation method is presented, significantly improving processing speed and accuracy. The FPC's dimensions, mirror requirements, and effective energy can be obtained from the electron beam parameters at the interaction point. A multi-objective optimization algorithm was used to derive the geometrical parameters of the FPC; this brought orders of magnitude increase in computation speed if compared to the nominal Monte Carlo-based approaches. The burst mode parameters of the FPC were obtained by maximizing the effective energy of the laser pulse in the FPC. The impact of optical losses and thermal lensing on the FPC parameters is addressed. Preliminary parameters of an ICS source implementing this novel optimisation are presented. The source could reach high-performance photon beams for high-energy applications.

INTRODUCTION

Fabry-Pérot cavities are widely used to generate high-intensity photons from inverse Compton scattering [1]. FPCs are operated in one of two regimes: permanent or pulsed. Most ICS setups use the first option, which matches the high repetition rate requirements for storage ring sources.

More recently, FPCs operated in the pulsed regime have been considered for linac-based ICS sources [2], since both require a lower repetition rate than storage ring or energy-recovery linac designs. In burst mode, FPCs can achieve an effective gain 2 or 3 orders of magnitude larger than for the permanent mode.

This paper addresses the optimisation of an FPC's geometry and burst-mode parameters from [3]. Significant improvements were made relating to the runtime and efficiency of the optimisation.

THEORY

The mechanism of optical enhancement in FPCs can be described in terms of the temporal patterns of the electron and laser pulses in the cavity. N_p laser pulses are stacked in the FPC and interact with N_e electron bunches. Prior to the interaction, N_0 laser pulses are injected to provide an initial circulating laser power. A schematic of the interaction between the electron train and the laser pulses stored in the FPC is shown in Fig. 1.

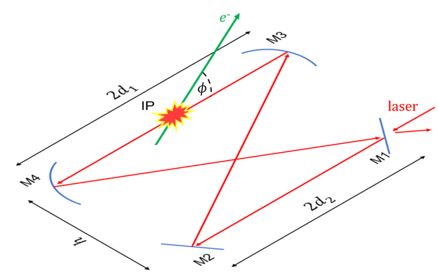

Figure 1: Layout of the ICS interaction of the input electron train with the laser pulses stored in the four-mirror planar Fabry-Pérot cavity. The electron beam enters the cavity plane with a crossing angle ϕ.

Given a small electron recoil, identical time separation between the electron and the laser pulses and no change in both the laser's pulse energy, $\mathscr{E}_0$, and the bunch charge, Q, the total scattered photon flux from ICS, $\mathscr{F}$, can be determined from

$$\mathscr{F} = \sigma_C \frac{f_{\text{rep}} Q N_b \mathscr{E}_{\text{tot}}}{2\pi (ehc/\lambda)\sigma_{\gamma,y}\sqrt{\sigma_{\gamma,x}^2 + \sigma_{\gamma,z}^2 \tan^2(\phi/2)}}, \quad (1)$$

where σ_C is the Compton cross section, e the elementary charge, h Planck's constant, c the speed of light in vacuum, λ the laser wavelength, ϕ the crossing angle between the electron and laser beam, $\mathscr{E}_{\text{tot}}$ the laser effective energy, and σ_γ the source *rms* spot size at the interaction point (IP) [3]. To maximise the total flux, the FPC should provide the maximum $\mathscr{E}_{\text{tot}}$ and the smallest laser waist size at the IP. The first condition depends mainly on the optimisation of the burst mode parameters provided by the input laser, while the second depends on the optimisation of the cavity geometry.

The circulating laser-beam energy determines $\mathscr{E}_{\text{tot}}$. It is a function of $\mathscr{E}_0$, N_0, N_p, N_e, and the cavity finesse, F,

$$\mathscr{E}_{\text{tot}} = \epsilon\left(N_p, N_0, N_e, F\right) N_p \mathscr{E}_0, \quad (2)$$

where ϵ is the effective gain, and $N_p \mathscr{E}_0$ is the laser macropulse energy delivered to the FPC, in the following called U. The effective gain is a cavity-dependent parameter. Its linear dependence to $\mathscr{E}_{\text{tot}}$ makes it relevant for the maximisation of the scattered photon flux. The optimum value for N_0 can be derived from $\partial\epsilon/\partial N_0 = 0$.

Given a high optical power, thermal lensing effects in the cavity mirrors must be considered, as they change their focal length, which can prevent the FPC from reaching a small

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waist size at the IP. For standard optics used in FPCs, the main contribution to thermal lensing is from the temperature dependence of the refractive index of the mirror substrate, dn/dT. Under this condition, the thermal lensing effect can be quantified by f_{thermal}, the thermally-induced focal length:

$$f_{\text{thermal}} = \frac{2\pi\kappa}{1.3b\,(dn/dT)\,l}\frac{w^2}{P} = \frac{1}{m_0}\frac{w^2}{P}, \tag{3}$$

where P and w are the laser beam power and waist incident on the mirror, b is the absorption coefficient of the material, κ the thermal conductivity, and l the thickness of the material [4]. Note that the terms in the first fraction only depend on the substrate material, and can be expressed in terms of a constant, m_0 [5].

The goal of both the previous seminal study from [3] and this paper was to optimise a burst mode FPC to provide the largest flux with state-of-the-art technology. This was achieved by optimising both the geometry and burst mode parameters of the FPC.

BURST PARAMETER OPTIMISATION

The burst mode parameters are represented by the initial and total number of laser pulses injected in the cavity, N_0 and N_p, respectively. These parameters, along with the cavity finesse were tuned to maximise $\mathscr{E}_{\text{tot}}$.

A parametric scan of F against laser-defining parameters was performed to assess the finesse's impact on the optimisation results. It was found that more laser pulses can be stored in an FPC with a large F (due to the smaller losses in the cavity). However, cavities with large F require precise laser matching and mirror tuning, which has been shown to be challenging. Nevertheless, relaxing the technical requirements of the FPC by reducing F leads to an increase in the power requirements of the input laser. The performance of FPCs with $F > 1000$ was therefore optimized and compared.

Review of the Previous Studies

In the previous study [3], ϵ was obtained from the numerical maximisation of its formula. The only input required was the number of electron bunches per train. The effective energy was obtained by multiplying ϵ with the maximum U allowed by the cavity geometry. This optimisation is adequate if the cavity round-trip length L_{RT} is fixed and $\mathscr{E}_0$ is treated as a free variable. However, e.g., in X-band-based linacs [6], where GHz repetition rates are used, the cm-long L_{RT} suggested the use of a subharmonic of the pulse repetition rate to increase the distance between the IP and the nearest mirrors, allowing for a larger U. Furthermore, $\mathscr{E}_0$ is fixed by the input laser, and was therefore treated as a constant in the present optimisation.

Novel Method

To establish a dependence between $\mathscr{E}_{\text{tot}}$ and N_p, a scan of the maximised ϵ against N_p was performed, given a maximum F. To obtain curves for $\mathscr{E}_{\text{tot}}$, each ϵ was then multiplied

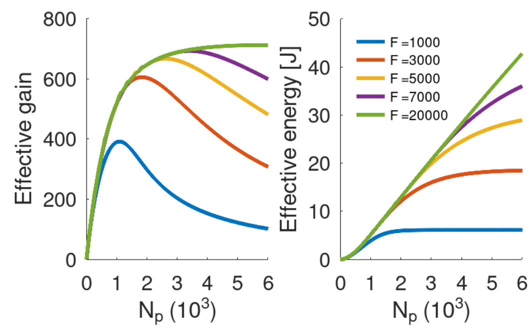

Figure 2: Scans of the optimised effective gain (left) and effective energy (right) against the total number of laser pulses injected, for a range of values of the maximum cavity finesse. The number of electron bunches per train is 1000, and the laser micropulse energy is 10 µJ.

by its corresponding N_p, and a fixed $\mathscr{E}_0$. Plots for $N_e = 1000$ and $\mathscr{E}_0 = 10\,\mu\text{J}$ are shown in Fig. 2.

A local maximum is reached for ϵ, which, for a large enough F, is constant. However, for any F, $\mathscr{E}_{\text{tot}}$ continues to increase with N_p past the point of maximum ϵ. This constitutes a major issue in the previous study. If one wants to obtain the largest possible flux $\mathscr{F}$ from the burst mode parameters of an input laser, the maximisation of ϵ will provide a smaller $\mathscr{E}_{\text{tot}}$ than the global maximum of $\mathscr{E}_{\text{tot}}$.

By setting a limit on the maximum F, one can see that $\mathscr{E}_{\text{tot}}$ plateaus with increasing N_p, with relative changes smaller than 1%. The burst mode parameters should, therefore, be taken at the onset of the plateau. One would then adjust the geometry optimisation to allow for the U obtained from the burst mode optimisation. For example, given a maximum $F = 1000$, the $\mathscr{E}_{\text{tot}}$ corresponding to the maximum ϵ is lower than the global maximum of $\mathscr{E}_{\text{tot}}$ by 40%, with a corresponding change in flux. Note that this difference in flux increases with the set maximum F.

CAVITY GEOMETRY OPTIMISATION

A planar bow-tie configuration was chosen because it provides increased stability compared to other designs [7]. A geometrical optimisation of the cavity was performed, simultaneously varying the distance between the planar ($2d_2$) and spherical mirrors ($2d_1$), the cavity height (h), and radius of curvature (R) of the spherical mirrors. The mirror diameter was set to a standard value of 0.59 cm. The dimensions are shown in Fig. 1.

The only input required for the geometry optimisation is the cavity round-trip length L_{RT}. The limits of the optimisation are three constraints: (1) prevent the optical beam on a mirror from being eclipsed by another mirror, $h - \Phi > h\,|d_1 - d_2|\,/\,(d_1 + d_2)$; (2) set the maximum fluence on each mirror, $2U/\,(\pi w_s w_t)$, smaller than the laser-induced damage threshold [8]; and (3) constrain the absolute value of the FPC's ABCD matrix's trace to be smaller than 2, to ensure stability.

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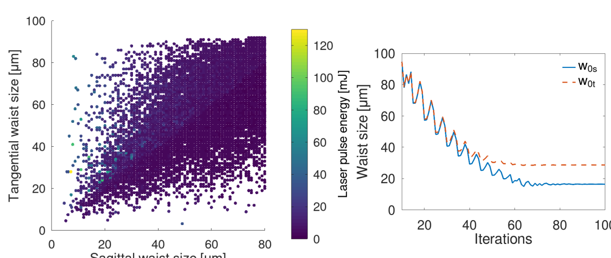
Review of the Previous Studies

In the previous study, the geometrical parameters were randomly varied in the range $[0, L_{RT}/4]$, and the largest flux solution within the constraints was selected. This Monte-Carlo-based technique, however, does not guarantee that a global optimum is reached. Furthermore, over 10 million iterations were required to reach convergence, corresponding to a significant computation runtime. A plot of the values for waist size at the IP and burst energy from a set of stable geometries is shown in Fig. 3a.

Novel Method

The optimisation was rewritten as a merit function minimized using the simplex algorithm. As shown in Fig. 3b, the number of iterations required to reach convergence was decreased to 100. The computation runtime was reduced by more than four orders of magnitude compared to the Monte-Carlo technique. Note that this optimisation does not claim to be global; however, a global optimum can be approached by running the algorithm in parallel from randomised starting points.

The merit function required careful weighting to fulfill the cavity constraints, e.g., maximising flux while keeping the laser waist sizes within a realistic range. Given identical constraints and objectives, the results obtained with the simplex method corresponded to those from the Monte-Carlo method.



(a) (b)

Figure 3: Representation of the Monte-Carlo (a) and simplex (b) method of optimisation. Each of the 50000 points from the Monte-Carlo optimisation corresponds to a possible FPC geometry. Less than 100 iterations were required for the simplex optimisation to converge.

IMPACT OF THERMAL EFFECTS

The thermal lensing effect was implemented in the optimization of the FPC geometry by adding the contribution from Eq. (3) to the mirror ABCD matrices. Fused silica substrates with $m_0 = 4.19 \times 10^{-12}\,\mathrm{m\,W^{-1}}$ were assumed for the FPC mirrors [9].

A decrease of up to 83% in flux was observed when introducing thermal lensing to set-ups optimised without the effect. However, the impact from thermal lensing was cancelled when the geometrical parameters were tuned by the optimisation to account for the thermal focal lengths.

FPC PARAMETERS FOR AN ICS SOURCE

The present optimisation was used to compute the burst parameters and FPC geometry suitable for an ICS source implementing an X-band linac driven by an S-band photoinjector. The setup was optimised to provide a 240 MeV electron beam colliding with a laser with a 515 nm wavelength [6]. This promises high intensity, small bandwidth 2 MeV photon beams suitable for nuclear resonance fluorescence (NRF) experiments [10].

In the setup, the electron gun produces a multi-bunch beam with a bunch spacing equal to 3 GHz. A cavity with a round-trip length matching a 3 GHz spacing corresponds to $L_{RT} = 10$ cm, which is too small for practical use. Therefore, a sub-harmonic of the rep-rate was used to increase L_{RT} to 1 m. The geometrical parameters obtained from the optimisation allowed for a maximum U of 42.0 mJ and sagittal and tangential waist sizes at the IP of 8.6/13.4 µm. For 1000 bunches per train and a maximum $F = 1000$, $\mathscr{E}_{tot} = 6$ J was determined from the burst mode optimisation.

Considering a train repetition rate of 100 Hz, the total flux obtained from this source would be in the order of 10^{13} photons per second. This value corresponds to the requirements set by the NRF-based detection of clandestine material [11].

FURTHER WORK

A ray-tracing model of the FPC should be implemented to realistically evaluate the impact of losses and thermal effects in the cavity for different mirror materials. Another relevant study would be computing the geometry optimisation using Kostenbauder matrices, which consider dispersive effects for both the spatial and temporal coordinates [12].

CONCLUSIONS

Burst-mode FPCs perfectly match the multi-bunch operation of high-gradient linacs in the X-band, promising very high-flux ICS photon sources. A novel optimisation technique of a burst-mode-operated Fabry-Pérot cavity is presented. The optimisation is based on previous studies, of which we improved methodology and objectives, significantly increasing the efficiency and reducing the runtime. A multi-dimensional, multi-objective optimisation was set up with the primary goal of maximising the scattered photon flux of the ICS source. This was achieved by maximising the effective energy provided by the cavity, which led to an increase in the total flux by over 40%. The novel geometry optimisation was shown to be faster by more than four orders of magnitude than the initial Monte-Carlo-based approach. A theoretical study of thermal lensing concluded that standard mirror substrates and coatings can be used for burst mode FPCs, with minimal impact on the laser waist size at the IP, given that the effects are implemented in the geometry optimisation. The present considerations can be used to design high-intensity linac-based ICS sources.

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