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# COHERENT STACKING SCHEME FOR INVERSE-COMPTON SCATTERING AT MHZ REPETITION RATES *

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*Abstract*

An experiment to produce 1 MeV gamma rays via Compton back-scattering of infrared photons on 250 MeV electron bunches is currently in preparation at the Fermilab Accelerator Science & Technology (FAST) facility. To increase the gamma-ray flux the energy of the infrared laser pulses are planned to be amplified within the interaction region using a resonant cavity. This passive amplifier composed of a Fabry-Perot cavity will allow the laser pulse bunches to coherently and constructively stack. Our estimates, based on theoretical models, show that the laser pulse energy can be increased from approximately 1-2 mJ at the exit of the last active amplifier to 5-12 mJ at the interaction point when the laser repetition rate is set at the nominal value of 3 MHz. This paper details the cavity design option(s) and associated wave-optic simulations.

## INTRODUCTION

Laser beams can be amplified in optical enhancement cavities (EC) that contain no active light amplification medium. In our design the EC is a Fabry-Perot type resonator consisting of two mirrors facing each other with the same curvature radius. The laser pulses to be amplified (seeding laser) enter the EC through a relatively low reflectivity coupling mirror where it coherently overlaps with the laser pulse that bounces inside the cavity. It was shown that the amplification factor of these cavities is only limited by the loses due to the mirrors [1]. Amplification factors of several thousands were obtained with high reflectivity mirrors [2, 3].

Systematic studies of non-linear optical processes were in the past the main driver for building EC's [4]. The cavity amplification factor is only slightly lowered by placing crystals with non-linear optical properties at at the location of beam waist due to their low conversion efficiency. More recently these cavities became attractive for building high brightness light sources due to their high enhancement factor, power tunability, capability to tailor the seeding laser before entering the EC and ultra high vacuum compatibility.

Our project is to build a gamma-ray source based on inverse Compton scattering (ICS) of infrared (IR) photons with 250 MeV electrons produced at Fermilab FAST facility. An overview of this project can be found at [5]. The photocathode of the electron linac is illuminated with UV laser pulses obtained from an IR phase-locked laser after two conversion stages. The substantial fraction of the unused IR intensity is increased to an estimated 1 mJ/pulse in two linear amplifying stages and sent to ICS area. The interaction area is schematically shown in Fig. 1. The energy of the IR pulses is further increased in the resonator consisting of the concave mirrors $M_3$ and $M_4$.

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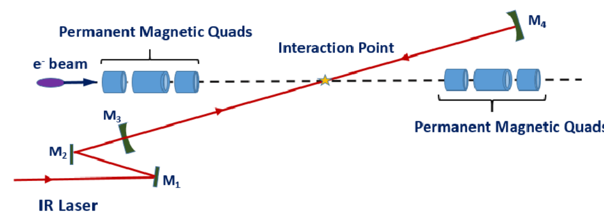


Figure 1: Simplified view of the interaction region. The enhancement cavity (EC) consists of the concave mirrors $M_3$ and $M_4$. The angle between electron beam direction of propagation and EC axis is about $5^0$. Optical elements for laser beam matching, feed-back components and the additional Herriott cell are not shown.

This contribution contains a theoretical analysis of the EC gain in Section 2, simulation results obtained with Synchrotron Radiation Workshop (SRW) code [6] in Section 3 and conclusions.

## ENHANCEMENT CAVITY GAIN

The oscillator of the laser system at Fermilab FAST electron linac generates about 3 ps long pulses with central wavelength $\lambda$ = 1054 nm and repetition rate 81 MHz. From each subset of 81 pulses 3 equally spaced bunches are selected to be further amplified. The laser repetition rate at EC entrance is 3 MHz and the estimated bunch energy is at least 1 mJ.

The coherence between the laser pulses that penetrate the EC and the laser pulse which is bouncing inside the resonator is crucial for any significant amplification. The coherence condition implies that the effective length of the EC should be:

$$L_{eff} = \frac{c}{2f_{rep}} \quad (1)$$

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With laser repetion rate $f_{rep} = 3$ MHz the effective length of the EC is 50 m. For practical reasons the vacuum chamber which hosts the EC must be much shorter. Our choice for the resonator length is $L = 1$ m and so the laser pulse inside the EC performs $N = 50$ round trips between two consecutive overlaps with the external laser pulses. These round trips include $N = 50$ reflections on each of the two resonators mirrors.

The maximum amplification factor of the EC, defined as the ratio between the intensity of the pulse inside the cavity and the intensity of the seeding laser when steady state is achieved, depends on the loses caused by mirrors provided all coherence and beam matching conditions are fulfilled [1]:

$$A \equiv \frac{I_{cav}}{I_{Laser}} = \frac{T_1}{(1-a)^2} \qquad (2)$$

where $T_1$ is the intensity transmission coefficient of the coupling mirror and $a$ is the loss-factor of the cavity. In the case of a Fabry-Perot resonator $a = (R_1 R_2)^{\frac{N}{2}}$ where $R_1$ and $R_2$ are the intensity reflection coefficients.

To maximize amplification factor we choose mirrors available commercially with very high reflection coefficients of $R_1 = 0.9999$ and $R_2 = 0.99995$. The reflectivity of the coupling mirror $R_1$ must be somewhat lower in order to comply with an experimental constraint which limits the cavity filling time to less than about 0.4 ms. An amplification factor of about 7.1 can be achieved with seeding laser $f_{rep} = 3$ MHz. This value can be largely increased if the number of round-trips $N$ is decreased by increasing laser $f_{rep}$. For example by increasing $f_{rep}$ from 3 to 9 MHz the amplification factor increases to 69.5. An additional amplification factor of 2 can be obtained by coupling the Fabry-Perot resonator with a Herriott cell [7]. In this case the gain is higher because $2N - 1$ reflections occur on higher reflectivity mirror and only one on the coupling mirror compared with the previous case when the $2N$ reflections are evenly shared by the two mirrors.

Since the brightness of the gamma-ray source strongly depends on its transverse size, the EC also has the role to focus the laser pulse such that the beam waist at interaction point, $w_0 \approx 30$ $\mu$m matches the transverse size of the electron beam for optimal Compton interaction rate. To obtain such a low beam beam waist, $w_0 = \frac{\lambda}{2\pi}\sqrt{L(2R-L)} \approx 30$ $\mu$m [8], the cavity design should be very close to a concentric configuration: $R \approx \frac{L}{2} = 0.5$ m. The accuracy of mirrors curvature radius should be at least $\delta R/R \sim 10^{-3}$.

## SIMULATIONS

The simulations presented here were performed with the SRW code version 3.96. The component of the SRW code mostly used for these simulations is the numerical propagator, mostly based on Fourier-optics, of a gaussian beam wavefront through a configuration containing several optical elements,

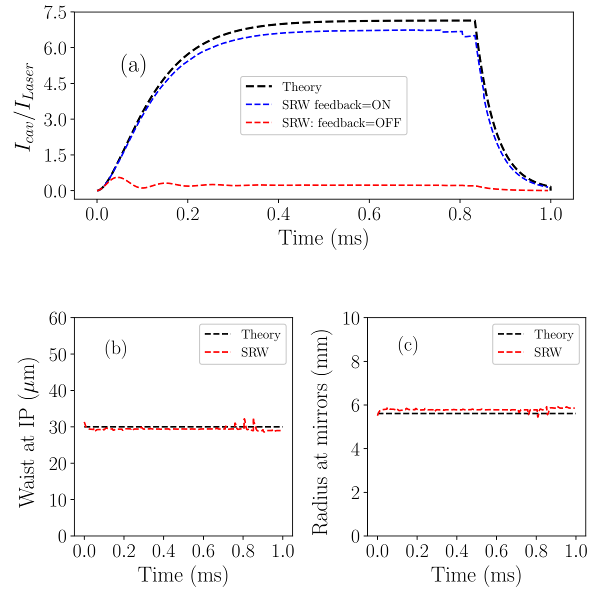


Figure 2: (a) SRW simulations of the amplification factor when phase correction procedure (feedback) is turned on and off. Results from a theoretical model are also shown. The seeding laser is turned off at $t \approx 0.85$ ms. (b) SRW simulation of the spot size at cavity center with phase correction procedure turned on. Expected value is also shown. (c) The same for the spot size at either of the two mirrors.

The simulations presented here include two simplifying assumptions in order to bring the computational time within manageable limits:

1. The seeding laser pulse is assumed monochromatic. This assumption is motivated by using a phase-locked laser and the PDH feedback system which locks the EC to to the laser central frequency. The eventual phase slippage from pulse to pulse caused by the carrier-envelope frequency $\omega_{CE}$ [9] is ignored.

2. The $N = 50$ round trips of the pulse inside the EC performed between the arrival of consecutive seeding laser pulses are reduced to a single round trip. To maintain the same cavity loss-factor and the same gain the reflectivity of the coupling mirror is replaced by: $R_1 \rightarrow R_{1eff} = R_1^{N/2} R_2^{N/2-1}$.

The seeding laser wavefront is propagated with SRW a distance of 0.5 m from generation point to the coupling mirror $M_1$ where a small fraction $T_1 = 10^{-4}$ penetrates inside the EC. The radiation is further propagated to the high reflectivity mirror $M_2$ and back to $M_1$ where, just after reflection, it is overlapped with the fraction of the seeding laser which travels through $M_1$. Although the distance between the two mirrors is an integer multiple of $\frac{\lambda}{2}$ there is a small mismatch between the phases of the two overlapping waves due to numerical inaccuracies. In these simulations the phase

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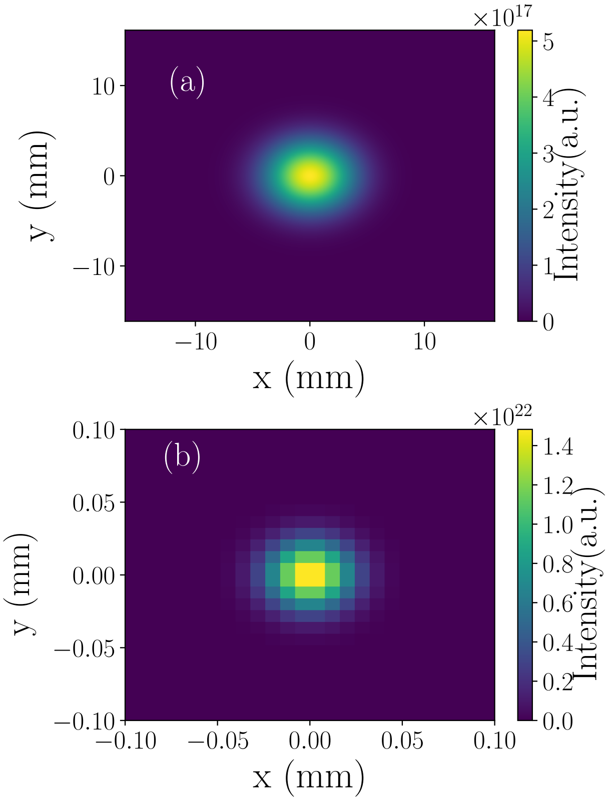


Figure 3: (a) SRW simulation of laser pulse transverse projection image at the first mirror. (b) Same for the spot at beam waist located at the center of the cavity.

mismatch is about 10 mrad rms and it can be corrected by slightly adjusting the travel distance between the two mirrors. This phase correction procedure acts is a similar manner as the feedback system in the real device. Figure 2 (a) shows the evaluation of the EC amplification factor with and without the phase correction procedure. These plots show that the feedback system is mandatory for the real EC. Although small, the phase mismatch causes a 6 % decrease of the amplification factor because, like in the real case, the phase correction is applied after the waves overlap. The low transmission of the coupling mirror $M_1$ is desirable to minimize the cavity loss-factor but it also increases the cavity fill up time. In our case maximum fill up time is dictated by the seeding laser pulse train length and cannot exceed 0.4 ms.

The transverse beam radius at mirrors and at the cavity center are shown in Fig. 2 (b) and (c). They are very close to expected values. The differences are caused by the apperture at the center of the cavity intended to block the peripheral portion of the wavefront more affected by numerical noise. The diameter of this aperture is 4.0 times larger than the expected beam radius and makes the beam waist to be slightly smaller than the theoretical value. As a consequence the beam radius at mirrors is slightly (2-3 %) higher. Transverse intensity distributions at mirrors and cavity center are shown in Fig. 3 when simulations were performed with 6.25 $\mu$m × 6.25 $\mu$m grid cell size. Other quantities like laser pulse energy, stored power and pulse duration play no role in these simulations.

In practice phase fluctuations of the beam inside the EC are primarily caused by mechanical vibrations of the two mirrors. To estimate this effect the distance between the mirrors is assumed to vary periodically: $d = d_0 + a \cdot \cos \omega t$ where $d_0$ is the nominal distance and $a$ and $\omega$ are amplitude and frequency of the perturbation. The mechanical vibrations were measured and we assumed conservatively that $a = 0.3$ $\mu$m and $\frac{\omega}{2\pi} = 1$ kHz. The amplification factor decreased by less than 1 % compared with the case when phase mismatch was entirely due to numerical noise.

These simulations also allowed us to estimate the impact of the seeding laser matching conditions. In particular, matching of the wavefront curvature radius of the seeding laser and the laser pulse inside the EC is extremely important: a 4 % mismatch causes a 70 % reduction of the amplification factor. Matching the transverse size of the two waves is far less important. In this case a mismatch of about 20 % causes an amplification reduction of about 5 %.

## CONCLUSIONS

The design of high gain passive enhancement cavities requires understanding and mitigation of several physical processes that could drastically reduce the amplification factor of these devices. SRW code is a useful simulation tool to evaluate how cavity performances are affected by the lack of coherence between the seeding laser and the amplified wave and by the approximate fulfillment of the matching conditions between seeding laser and the resonator.

Our simulations performed with SRW show that cavity amplification factor can reach at least 90 % of the theoretical predicted value if phase mismatch between the two interfering waves is lower than 10 mrad rms. The feedback system should normally compensate the phase drift caused by mechanical vibrations with little cost, < 10 %, for the overall amplification factor if laser repetition rate is 3 MHz or higher. More importantly, the seeding laser wavefront curvature radius needs to be controlled within 1 % resolution to obtain energy gain of at least 90 % from maximum value.

The cavity amplification factor can be greatly increased, up to several thousands, if the number of reflections on the relatively low reflectivity coupling mirror is reduced. This can be accomplished by coupling the cavity to a Herriott cell or by increasing the seeding laser repetition rate.

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