USE OF MONOCAPILLARY X-RAY OPTICS AS A MEANS TO REDUCE LINEWIDTH AND FLUCTUATIONS IN SASE FELS

A. Lin and G. Travish, UCLA Department of Physics & Astronomy, Los Angeles, CA 90095, USA

Abstract

The Self Amplified Spontaneous Emission (SASE) operation of high-gain Free Electron Lasers (FELs) allows for amplification from noise when no suitable seed sources are available. While SASE FELs can achieve high powers and short radiation pulses within the X-ray region, they are hindered by large linewidths and fluctuations in amplitude and temporal profiles. Various approaches have been proposed to clean up the spontaneous emission and produce better effective seed signals. This paper presents the use of monocapillary X-ray optics as an alternative to current methods to improve SASE operation. A monocapillary tube placed at the beginning stages of the undulator can reduce the bandwidth and enhance a narrow band of the spontaneous emission amplified by the FEL. Monocapillary tubes guide radiation due to total external reflection, and the critical angle of the guiding is dependent on the frequency of the radiation (and indirectly on the surface profile and materials). These properties allow for the selection of desired frequencies which are reflected back towards the axis, while all other frequencies are lost through diffraction. The effectiveness of the monocapillary tube was simulated using a simple model for the X-ray mirror. LCLS-like parameters in the hard X-ray regions were simulated and the results are presented.

INTRODUCTION

The radiation produced within a SASE free electron laser is temporally and spectrally noisy, due in part to the incoherence of the shot noise responsible for starting the process. It is beneficial to have the startup radiation be filtered prior to the amplification and bunching processes within the undulator. Current schemes, such as the HXRSS on the Linac Coherent Light Source (LCLS) use a monochrometer to clean-up the radiation after a fixed length of the undulator, and then reintroduces this radiation to the electron bunch later as an effective seeding mechanism [1]. This so-called self seeding process is effective and does give positive results, but the process introduces additional complexity, length and operational constraints. By introducing a finite monocapillary tube, placed at the start of the undulator, it may be possible to effectively clean up the radiation without the redirection of the electron beam and without the use of chicanes. A monocapillary tube, often made of glass due to the surface quality achievable, is a type of cylindrical waveguide whose guiding is based on the principle of total external reflection. The reflectivity of monocapillaries is a function of the frequency of the radiation being guided and the angle at which the radiation impinges on the surface of the tube (Fig. 1). Because the energy of the radiation is dependent on its frequency, the tube can be used to select and preferentially guide certain frequencies of the spontaneous radiation, whose bandwidth is otherwise large. In some SASE applications, it may also be possible to use incident angle filtering. The work presented here is a first attempt to understand this *in situ* filtering and model the process using a numerical code.

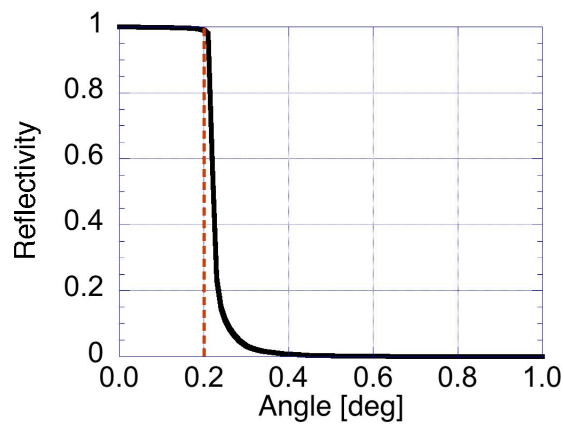


Figure 1: The reflectivity of a silica monocapillary tube over an angular spread at 8 keV. There is a sharp dropoff in the function at $\theta = 0.2\,^\circ$, indicating the critical angle of guiding.

MONOCAPILLARY TUBES

Reflection of an electromagnetic wave occurs at the boundary between two regions of differing indices of refraction. Total internal reflection occurs when the first medium has a greater reflective index than the second medium and the incident angle is greater than the critical angle. The value of the critical angle is directly determined from Snell′s law. Because of this, total internal reflection is often used to guide electromagnetic radiation, as seen with optical waveguides and fiber optic cables. However, this method of guiding is not possible for hard X-rays since the refractive indices of all materials are less than unity. The Drude model provides a simple formulation:

$$n(\omega)^2 = 1 - \frac{\omega_p^2}{\omega^2} \tag{1}$$

where

$$\omega_p^2 = \frac{e^2 n_e}{\epsilon_0 m_e} \tag{2}$$

ISBN 978-3-95450-123-6

The Drude model can be applied here because at X-ray wavelengths, all materials are essentially a sea of free electrons, and appear as plasmas [2]. Thus in order to guide hard X-rays, total external reflection is used. Like total internal reflection, total external reflection occurs when radiation crosses the boundary of two media, with the second medium having a smaller index of refraction. This condition can only be fulfilled if the radiation is first traveling through a vacuum, $n = 1$, and is incident on the walls of a monocapillary tube, $n < 1$. The critical angle of guiding of a monocapillary tube is small and an overestimate is given by:

$$\theta_c = \frac{\omega_p}{\omega} = 1 \tag{3}$$

More sophisticated models as well as databases of measured quantities allow for the calculation of reflectivity as a function of the critical angle. For radiation with wavelength of 1.5 angstrom, the critical angle is 3.75 mrad for most materials (Fig. 1). The critical angle can be enhanced by using bi-layered and multilayered monocapillary tubes [3].

START-UP WITH MONOCAPILLARY TUBES

The concept of using monocapillary tubes in SASE FELs involves placing a monocapillary tube at the early stages of the FEL, to allow the guiding a narrow band of the spontaneous emission. The radiation from this first part of the FEL then acts a seed for the second segment of the undulator, where normal high-gain amplification occurs, but now with a filtered SASE signal (Fig. 2). In general, the emission from the first part of the undulator is both broad-band (Eq. 4) and large-angle (Eq. 5):

$$\frac{\Delta\omega}{\omega} \sim \frac{1}{N_u} \tag{4}$$

$$\phi \sim \frac{1}{N_u} \tag{5}$$

with N_u being the number of undulator periods. Since monocapillary tubes guide only a narrow-band and narrow angular spread of x-ray photons, at energies of interest (e.g. $\sim$<8 keV), this lensing is rather effective [4]. Thus, by inserting this monocapillary tube, the photon flux near and on-axis will be enhanced for a small bandwidth. To be effective, the tube has to have several bounces, just as in fiber optics (Fig. 3). The crisscrossing of the X-ray signal from multiple bounces may produce several undesired effects [5]. On the other hand, the crisscrossing helps to mix the spatial and temporal variations from the spikes analogous to reverse slippage.

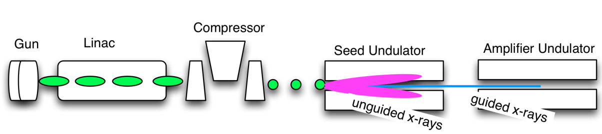


Figure 2: A cartoon of an FEL amplifier showing two sections of an undulator, the first acting as a seed to the second. Radiation within the seed undulator is emitted at a diffraction angle $\theta \ll 1$. A monocapillary tube would reflect radiation with $\theta < \theta_c$ back towards the axis of the undulator.

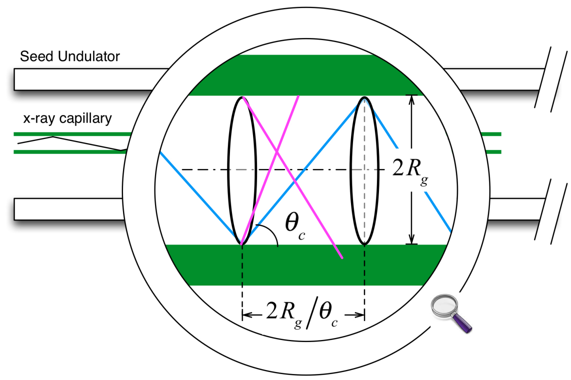


Figure 3: The guiding utilized to achieve the self-seeding is shown along with relevant geometry. Radiation within experiences multiple bounces to increase selectivity.

There are some important areas to consider: bandwidth, coherence, and mode competition.

Bandwidth

The FEL parameter, ρ, is typically a few times 10^{-3}. Diffractive and refractive X-ray optics have natural line widths of about 10^{-3}. This can be increased through coatings, but it can also be narrowed through coatings. Still, these numbers are similar. The impact of the altered spontaneous emission spectrum, even if modest, may have a dramatic influence over the first few gain lengths as the bunching evolution is sensitive here. The interplay between the guided signal and the resulting bandwidth must be studied.

Coherence

For the longitudinal coherence, the capillary may not have a strong influence on the evolution. Normally, the longitudinal coherence builds through slippage over a coherence length. With a capillary there is the possibility of "mixing" the radiation in a way not well accounted for just by slippage (i.e. radiation from further back in the bunch can reflect back towards further ahead of the bunch). So, simulations may have to be used to understand the coherence effects of the guided radiation.

Mode Competition

If the guided signal is not of sufficient amplitude to overwhelm the general SASE signal, the FEL may amplify two or more modes. Establishing the correct capillary parameters to assure a large guided signal is one path to avoiding multi-mode operation; other approaches may be possible.

ISBN 978-3-95450-123-6

MODELING OF THE START-UP PROCESS

A monocapillary tube can be modeled as a simple waveguide with lossy boundaries. A highly simplified case has a perfect reflecting boundary within the critical angle and a narrow bandwidth and zero reflectivity otherwise:

$$R = \begin{cases} 1 & \theta < \theta_c\,, \quad \omega = \omega_r \pm \frac{\Delta\omega}{\omega} \\ 0 & \theta \geq \theta_c\,, \quad \omega \neq \omega_r \pm \frac{\Delta\omega}{\omega} \end{cases} \tag{6}$$

A simple condition for the tube to influence the bunching factor of the electron beam is that the power of the guided radiation must be large enough to overcome the effective SASE power. Thus, the minimum length of the tube can be estimated to be on the order of the gain length. The diameter of the tube, though unrealistic in practice, can be set to the electron beam diameter, to assure that the tube interacts with the radiation.

To model the monocapillary tube and its effect on the emitted radiation, simulations were performed in Genesis 1.3, a time-dependent three-dimensional FEL code. Genesis 1.3 was selected due to its ability to study the time evolution of a SASE FEL, a crucial element in FEL startup, as well as source code availability.

Genesis 1.3 maps the electron beam distribution and the radiative field onto a radial and Cartesian mesh, respectively, and then uses computational integration methods to solve the self-consistent FEL equations [6]. To reduce the high memory requirements that normal time-dependent simulations require, Genesis discretizes the electron beam and radiation fields into slices in *t*, and allows for these slices to influence subsequent slices to account for slippage. By modifying the behavior of the boundary conditions, a monocapillary tube with prescribed angular and energy acceptances was simulated.

The code's calculation of the diffraction angle was modified from using the entire mesh to only including a thin ring that represented the radiation impinging on the walls of the tube (Fig. 4). Since the calculation of the diffraction angle requires the standard deviation of all the field points, field points that did not lie on this ring were temporally given a value of zero to remove their contributions to the standard deviation. The values of the diffraction angle were then stored into an array which determined the type of boundary condition applied to the fields at each longitudinal integration step. If the angle was greater than that of the tubes acceptance, the boundary condition was set to a Dirchelet boundary; if less, the Neumann boundary was enforced. The Neumann boundary was calculated by summing together the field magnitudes of the points located directly on the edges of the tube and the points located one meshpoint prior to these edges. This reflecting boundary condition included a loss factor which represented the finite reflectivity of the tube.

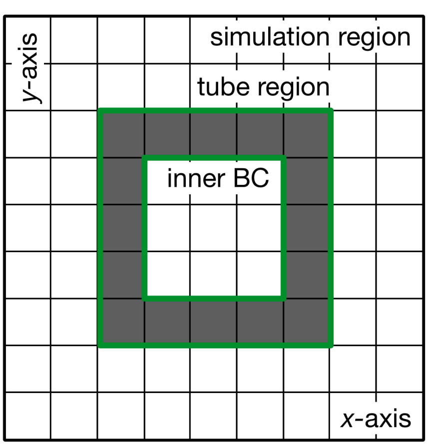


Figure 4: Discretization of the tube onto the Cartesian mesh in Genesis 1.3. The tube is centered around the radiation field.

AN LCLS-LIKE CASE

The LCLS represents a challenging benchmark for this self-seeding scheme: the high energy beam (≈14 GeV) implies a low divergence angle for the radiation and the small FEL parameter ($\sim 10^{-3}$) implies a narrow line width (Table 1).

Table 1: Simulation Parameters

Parameter	Value
Undulator Type	Planar
Peak Current	3400 A
Undulator Period Length	3 cm
Radiation Wavelength	1.5 Å
Simulated Undulator Length	60 m
Electron Beam Energy	13.6 GeV
RMS Diffraction Angle	~6.8 μrad

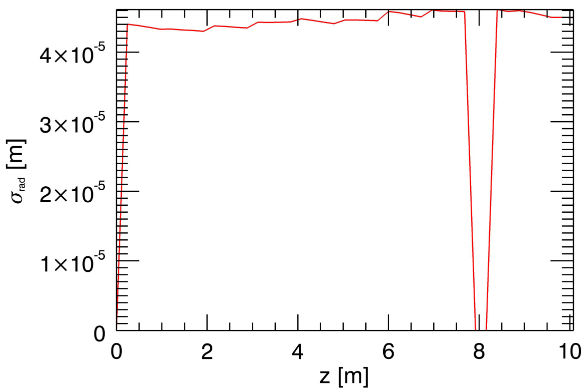
An unphysical tube (Table 2) was chosen to yield a strong effect: a realistic tube would have to be much shorter and have a larger diameter. The tube was chosen to be roughly twice the power gain length (20 m), and have a diameter equal to the beam size (34 m).

Table 2: Tube Values

Parameter	Value
Width	34 μm
Height	34 μm
Length	20 m
Critical Angle	3.75 mrad

Using the modified Genesis 1.3 code described above, results thus far show guiding of the radiation by the tube as compared to the free space case (Fig 5). Little to no impact on the FEL start-up process has been observed with this overly simplified model. Wavelength and angle selectivity will be implemented in future work.

ISBN 978-3-95450-123-6



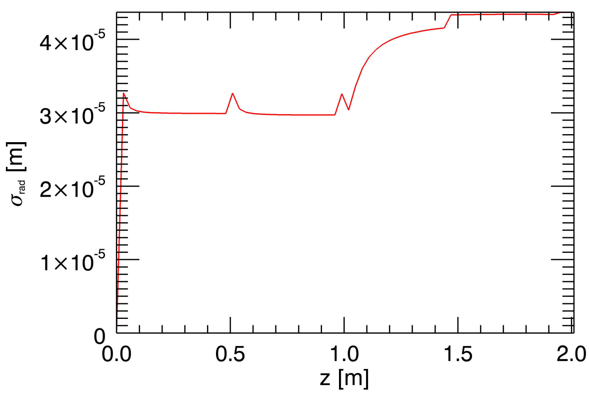


Figure 5: (Top) Guiding without the effect of the monocapillary tube. Simulated for 10 meters. (Bottom) Guiding with the effect of the tube, simulated over 2 meters. The radiation field is constrained by the tube. Discontinuities in both graphs are errors due to missing slices in post-processing.

FUTURE WORK

The present model of self-seeding with monocapillary tubes is lacking in a number of aspects. Future work will include spectral filtering; reflectivity as a function of frequency; and circular geometry. In addition to a more realistic model, additional FEL parameter sets will be considered. Finally, an experiment will be proposed at an existing facility.

ACKNOWLEDGMENT

The authors gratefully acknowledge assistance and insight from Gabriel Marcus and David Schiller. The authors also wish to thank all group members who have contributed towards this paper.

REFERENCES

[1] J. Amann, *et al.*, "Demonstration of self-seeding in a hard X-ray free-electron laser", Nature Photonics, March 2012.

[2] G. Travish, *et al.*,"Guiding of X-rays from Inverse Compton Scattering as a means to enhance flux and brightness", Nuclear Instruments and Methods in Physics Research A, Vol. 608, 2009.

[3] B.L. Henke, E.M. Gullikson, and J.C. Davis. X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000 eV, Z=1-92, Atomic Data and Nuclear Data Tables Vol. 54 (no.2), 181-342 (July 1993).

[4] F. R. Sugiro, *et al.*, "Beam collimation with polycapillary x-ray optics for high contrast high resolution monochromatic imaging", Medical Physics, Vol. 31, No.12, Dec. 2004.

[5] S. D. Padiyar, *et al.*., "Beam Collimation using Polycapillary X-ray optics for Large Area Diffrcation Applictions", Advances in X-ray Analysis, Vol. 43, 2000.

[6] S. Reiche, "Numerical Studies for a Single Pass High Gain Free-Electron Laser", PhD Thesis, DESY report: DESY-Thesis-2000-012, 2000.

ISBN 978-3-95450-123-6