GAS-FILLED CELL AS A NARROW BANDWIDTH BANDPASS FILTER IN THE VUV WAVELENGTH RANGE

G. Geloni*, European XFEL GmbH, Hamburg, Germany
V. Kocharyan and E. Saldin, DESY, Hamburg, Germany

Abstract

We propose a method for spectrally filtering radiation in the VUV wavelength range by means of a monochromator constituted by a cell filled with a resonantly absorbing rare gas. Around particular wavelengths, the gas exhibits narrow-bandwidth absorbing resonances following the Fano profile. Within the photon energy range 60 eV-65 eV, the correlation index of the Fano profiles for the photoionization spectra in He is equal to unity, meaning that the minimum of the cross-section is exactly zero. For sufficiently large column density in the gas cell, the spectrum of the incoming radiation will be attenuated by the background cross-section of many orders of magnitude, except for those wavelengths close to the point where the cross-section is zero. Remarkable advantages of a gas monochromator based on this principle are simplicity, efficiency and narrow-bandwidth. A gas monochromator installed in the experimental hall of a VUV SASE FEL facility would enable the delivery of a single-mode VUV laser beam. The design is identical to that of existing gas attenuator systems for VUV or X-ray FELs. We present feasibility study and exemplifications for the FLASH facility in the VUV regime. **These proceedings are based on the article [1], to which we address the interested reader for further information and references.**

INTRODUCTION

A large portion of experiments using VUV radiation are presently carried out at synchrotron radiation facilities and VUV SASE FELs. A high-resolution VUV monochromator is an important element of such facilities. Photoabsorption spectra of Helium are often used for calibration of these monochromators. In fact, as is well-known, the transmittance spectrum in the Helium gas exhibits narrow-bandwidth absorbing resonances down to a few meV, which follow the Fano profile.

Here we propose a novel method for spectral filtering based on a remarkable feature of the Fano interference phenomenon for Helium. In particular, within the photon energy range between 60 eV and 65 eV, the correlation index of the Fano profile for the photo-ionization spectra in Helium is equal to unity, meaning that the minimum of the cross-section is strictly zero. We suggest the exploitation of this feature for filtering purposes, using a windowless gas-filled cell equipped with differential pumping. In fact, for a sufficiently large column density, the spectrum of the incoming radiation will be attenuated by the background cross section of many orders of magnitude, except for those wavelengths near the point where the cross-section is zero. In this paper we concentrate on physics issues. The design features of a gas monochromator system based on this principle should not differ too much from the gas attenuator systems at XFELs.

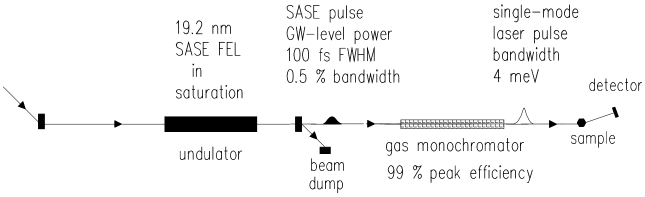

Figure 1: Scheme of the gas monochromator for VUV SASE FEL sources

A remarkable advantage of gas monochromators based on the above principle is simplicity. In fact, such a device would use no optical components, and therefore there are no problem with alignment, heat loading and beam wavefront perturbations. Moreover, the peak efficiency of a gas monochromator would be close to 100%. Also, a very narrow bandwidth would be granted. Such a device, installed at any VUV SASE FEL facility would enable the delivery of single-mode VUV laser beams. In this case, the shapes of the single-shot spectra after the monochromator can be identified with the gas-cell transmittance calculated from first principles, and do not depend on the detailed intensity distribution of modes of the incoming spectrum.

We present a feasibility study and exemplifications for the FLASH SASE FEL in the VUV regime. The applicability of the gas monochromator setup is obviously not restricted to VUV SASE FEL facilities. Synchrotron radiation facilities may benefit from this scheme as well.

SPECTRAL FILTERING TECHNIQUE BASED ON THE USE OF A GAS CELL

The output radiation pulses from SASE FEL exhibit poor longitudinal coherence. While a single-shot spectrum consists of many spikes, or modes, the average spectrum is constituted by a smooth distribution with a FWHM typically corresponding to about 1% in the VUV wavelength range. The bandwidth of the VUV beam can be thus further reduced by using a gas monochromator. A schematic

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* gianluca.geloni@xfel.eu

representation of the setup is shown in Fig. 1. Each spike in the spectrum has an average width of about $0.03\% - 0.04\%$ for wavelengths around 20 nm, and is thus larger than the bandwidth of the gas monochromator, which allows for a few meV bandwidth. This fact enables the delivery of single-mode VUV laser beams. The shape of the single shot spectra after the gas monochromator can be described in terms of the transmittance of the gas cell, and does not depend on the details of the intensity distribution of the spikes in the incoming spectrum. It is therefore possible to properly define amplitude and phase for a single-shot spectrum after the monochromator and, hence the single-shot radiation pulse shape in the time domain.

The working principle of the gas monochromator is based on the characteristic of the photo-absorption cross-sections for Helium at energies below the second ionization threshold. In general, the interaction with a soft X-ray electromagnetic pulse has an ionizing effect for the atom. A first ionization threshold, where the remaining electron in the ion is found in the state with principal quantum number $n = 1$, is found at 24.6 eV, while a second ionization threshold with $n = 2$ is found at 65.4 eV. Therefore, after interaction with a photon with energy between these two thresholds, one finds the Helium ion in the ground state $1s$, and a free electron with kinetic energy equal to the photon energy diminished of 24.6 eV. This single open channel can be reached either directly or via decay of a doubly excited state, the well-known autoionizing state. In this case only one channel is open in the continuum, meaning that the final state is the Helium ion in the ground state. The two paths towards this channels interfere and one is left with Fano lines obeying:

$$\sigma = \sigma_b \frac{(q+\mathcal{E})^2}{1+\mathcal{E}^2} \ , \tag{1}$$

where $\sigma_b = \sigma_b(\lambda)$ is the background cross-section

$$\begin{aligned} \sigma_b(\lambda) \quad = \quad & -0.05504 - 1.3624 \cdot 10^{-4}\lambda \\ & +3.3822 \cdot 10^{-5}\lambda^2 \ , \end{aligned} \tag{2}$$

given in Megabarn ($1\mathrm{Mb} = 10^{-18}\mathrm{cm}^2$), q is known as the asymmetry index, while the reduced energy $\mathcal{E}$ is defined as

$$\mathcal{E} = \frac{2(E_R - hc/\lambda)}{\Gamma} \ , \tag{3}$$

E_R being the energy of the resonance, with a width Γ. Note that there is always one energy value around the resonance, at $\mathcal{E} = -q$, where $\sigma = 0$. Around that energy value, radiation can pass through the gas cell almost without attenuation. In fact, the photoabsorption cross section σ is linked to the light attenuation through a gas medium of column density $n_0 l$, l being the length of the cell and n_0 the gas density, via the Beer-Lambert law:

$$I(\omega) = I_0 \exp[-n_0 l \sigma(\omega)] \ , \tag{4}$$

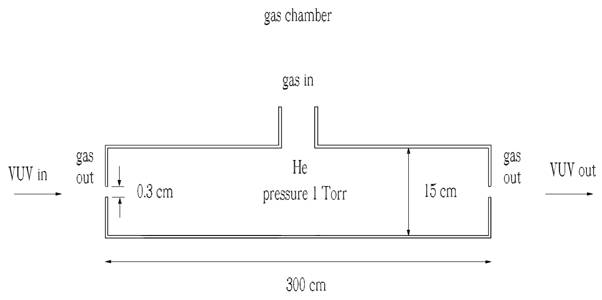

Figure 2: Schematic of the gas cell

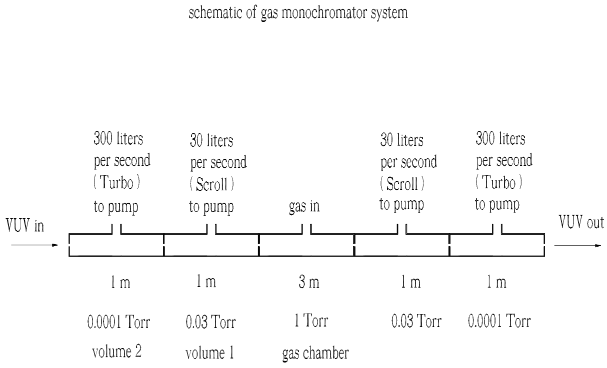

Figure 3: Schematic of the differential pumping system

where I_0 is the incident intensity, and $I(\omega)$ is the attenuated intensity of the transmitted light at frequency ω. By inspecting Eq. (4) it can be seen that when the column density is increased, radiation is attenuated at all frequencies except at $\mathcal{E} = -q$. As a result, in the case of the Helium gas, and for energies below the second ionization threshold an increase in the gas density transforms the gas cell into a bandpass filter.

AMPLITUDE AND PHASE OF THE GAS CELL TRANSMITTANCE

If a monochromatic electromagnetic pulse of intensity I_0 and frequency ω impinges on a cell of length l, filled with a gas with density n_0, the transmitted intensity obeys the Beer-Lambert law, Eq. (4). As a result, the modulus of the transmissivity can be defined as

$$|T| = \exp[-n_0 l \sigma/2] \ , \tag{5}$$

where $\sigma(\omega)$ follows a Fano profile convolved with the Doppler-broadening profile. In this article we will assume that the gas used in the monochromator is Helium, and that the energy of the FEL photons is within the range between 60 eV and 65 eV. These requirements ensure that the cross-section has a zero for $\mathcal{E} = -q$. In order to obtain a pass-band filter, one needs to increase the gas pressure so to ab-

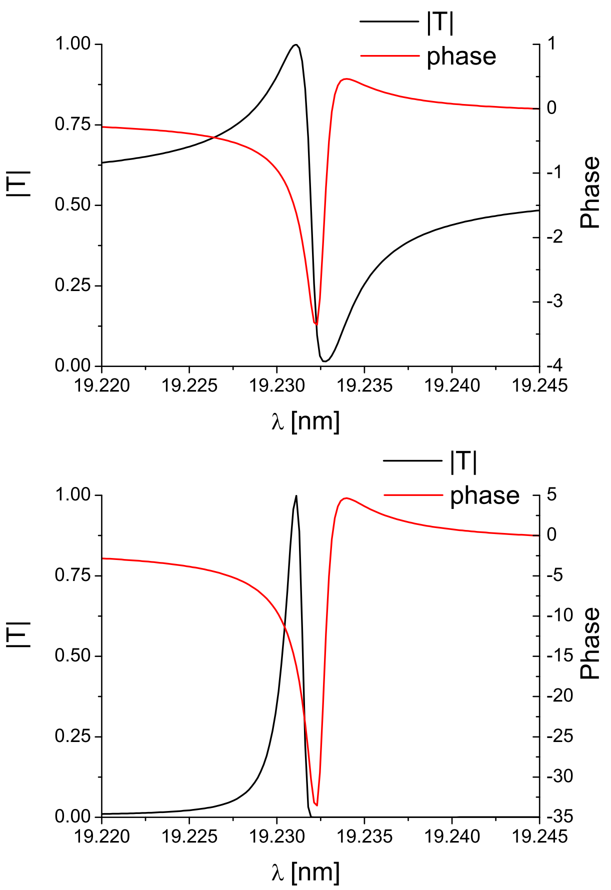

Figure 4: Modulus and phase of the transmissivity of Helium around the $n = 4$ line of the $(sp, 2n+)\ ^1P_0$ Rydberg series. The modulus has been calculated according to Eq. (5), while the phase is recovered with the help of the Kramers-Kroning relation according to Eq. (7). The upper plot refers to a column density $n_0 l = 10^{18}\mathrm{cm}^{-2}$. The lower plot refers to a column density $n_0 l = 10^{19}\mathrm{cm}^{-2}$.

sorb radiation outside a small bandwidth around the point where $\mathcal{E} = -q$. The pressure in the gas cell is limited by capabilities of the differential pumping system, and cannot exceed a few Torr in the present design. Fig. 2 and Fig. 3 show the schematic of the gas cell, and its integration in the differential pumping system. The length of the gas cell is between 3 m and 5 m, Fig. 2, and cannot be easily increased due to space limitations. Even with these limitations on length and pressure, the gas cell can provide a very large attenuation coefficient. For example, at a cell length of 3 m and a pressure of 1 Torr the column density is $n_0 l \sim 10^{19}\mathrm{cm}^{-2}$, and the spectrum of the incoming radiation is attenuated by the background cross section of about 40 dB.

Let us consider the third $(n = 4)$ resonant line of the $(sp, 2n+)\ ^1P_0$ Rydberg series for Helium, and let us calculate its cross-section with the help of[1] Eq. (1) and Eq. (2). The modulus of the transmissivity can be found with the help of Eq. (5). In order to exemplify the effects of the pressure increase, we select two values for the column-density: $n_0 l = 10^{18}\mathrm{cm}^{-2}$, and $n_0 l = 10^{19}\mathrm{cm}^{-2}$. Since $|T|$ is known, it is possible to use the Kramers-Kroning relations to recover the phase. In fact one can write

$$\ln[T(\omega)] = \ln[|T(\omega)|] + i\Phi(\omega) = -nl\sigma/2 + i\Phi(\omega) \ . \quad (6)$$

Note that $T^*(\omega) = T(-\omega)$ implies that $|T(\omega)| = |T(-\omega)|$ and that $\Phi(\omega) = -\Phi(-\omega)$. Therefore, using Eq. (6) one also has that $\ln[T(\omega)]^* = \ln[T(-\omega)]$. Then, application of Titchmarsh theorem shows that the analyticity of $\ln[|T(\Omega)|]$ on the upper complex Ω-plane implies that

$$\Phi(\omega) = -\frac{2\omega}{\pi}\mathcal{P}\int_0^\infty \frac{\ln[T(\omega')]}{\omega'^2 - \omega^2} d\omega' \ . \quad (7)$$

A direct use of Eq. (7), with $|T|$ given as in Eq. (5), yields back the phase $\Phi(\omega)$. By this, one tacitly assumes that $\ln[T(\Omega)]$ is analytical on the upper complex Ω-plane. This fact, however, is immediately granted because σ is proportional to the imaginary part of the refractive index of the medium, and it is well known that the refractive index must obey the Kramers-Kroning relation Eq. (7). We therefore used Eq. (7) in order to recover the phase of the transmittance. More specifically, we took advantage of a publicly available Matlab script which serves exactly to that end (see references in [1]). The final result in terms of modulus and phase of the transmissivity T is shown in Fig. 4 for the case $n_0 l = 10^{18}\mathrm{cm}^{-2}$, upper plot and $n_0 l = 10^{19}\mathrm{cm}^{-2}$, lower plot. One can see that an increase in the gas density of a factor 10 transforms the filter in Fig. 4 upper plot, into the few meV bandpass filter in Fig. 4 lower plot.

The example studied here for the $n = 4$ resonance case corresponds to a pass-band filter with a 2.1 meV FWHM-bandwidth. Such bandwidth is narrower than that of a typical FEL mode, and this enables the delivery of single-mode VUV laser beams. Note that the knowledge of modulus and phase of the transmittance allows for the characterization of the single-mode output both in modulus and phase. This is an obvious advantage for scientists wishing to model the interaction between single-mode VUV pulses and matter.

SIMULATIONS OF GAS MONOCHROMATOR OPERATION AT FLASH

In this section we present a feasibility study of our scheme. We demonstrate the potential of our technique using as an example the parameters for the FLASH facility in the VUV region, although our setup can be exploited by other FEL and synchrotron radiation facilities in the same photon energy range. The main parameters used are listed in Table 1. Full 3D simulations have been performed in order to confirm the scheme feasibility. The simulations

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[1] In actual simulations we will also account for Doppler broadening effects. For simplicity we do not account for them here.

Table 1: Parameters for the nominal pulse mode of operation used in this paper.

	Units	
Undulator period	mm	27.3
K parameter (rms)		0.89
Wavelength (fundamental)	nm	20
Charge	nC	0.5
Electron beam energy	MeV	560

are performed with the code GENESIS 1.3, which uses as input the beam parameters obtained in start to end simulations. Simulated current profile, horizontal and vertical normalized emittances, energy profile and rms energy spread profile were used. The focusing system along the FLASH undulator consists of doublets between each undulator segment. In our simulations we implemented a FODO focusing structure with an average betatron of about 10 m.

In the following we will consider, as an example, the third autoionization profile for $n = 4$ for the $(sp, 2n+)$ autoionizing series of Helium. Other resonances are considered in [1]. FLASH is tuned at saturation, so that the SASE average bandwidth overlaps the third resonance.

Fig. 5 shows the output spectra and power for a column density $n_0 l = 10^{19}\mathrm{cm}^{-2}$. Note that if the gas pressure is decreased, the filter ceases to behave as a bandstop filter. In the case under study, the resonance width is only 2.1 meV FWHM. The shot-to-shot fluctuations in the profiles of both intensity and spectrum are almost absent (although, for a single mode, we have a power fluctuation near to 100%) and, as discussed above, we basically deal with a single-mode laser pulse. Except for the amplitude, the characteristics of the single-mode pulse are fixed by the filter transmittance and not by the SASE spectra, which changes from shot to shot.

In the previous example we considered the case where FLASH was tuned at saturation, so that the SASE average bandwidth overlapped with one resonance at a time, $n = 4$ in our case. However, beyond saturation the bandwidth of the SASE spectrum continues to increase, due to a deterioration of the coherence time. It is therefore possible to set (see [1]) the operating point of FLASH well after saturation, that is after six active undulator modules, corresponding to a magnetic length of 30 m. In this way the SASE spectrum can be made overlap two (or, in principle, more) resonances, yielding a doublet (or, in principle, a multiplet) structure.

CONCLUSIONS

We propose a new method to obtain a spectral filter in the VUV wavelength range using the Fano interference phenomenon for the VUV photo absorption spectra of Helium. Our gas monochromator combines a very narrow bandwidth, down to a few meV and a very high peak efficiency of 99% with a much-needed experimental simplicity. No optical elements nor alignment are required. The applicability of our scheme is limited to the wavelength range around 20 nm. In this range, however it is possible to completely define the output VUV pulse characteristics, both in modulus and phase. This opens up the possibility of full characterization of the VUV radiation pulse in the time domain, which constitutes a powerful advantage for materials scientists wishing to model radiation-matter interactions.

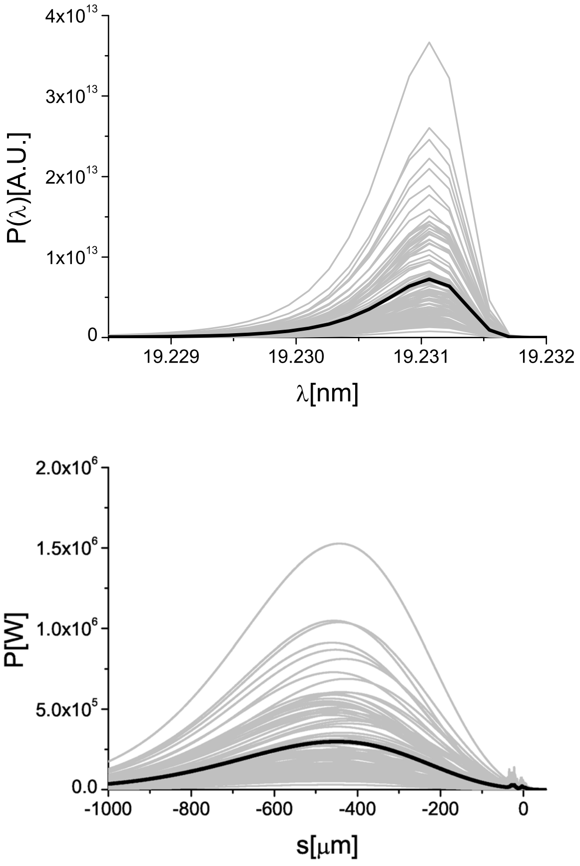

Figure 5: Third resonance mode of operation. Pulse spectrum (upper plot) and power (lower plot) after the gas cell. Grey lines refer to single shot realizations, the black line refers to an average over one hundred realizations. Plots refer to a column density of $n_0 l = 10^{19}\mathrm{cm}^{-2}$.

REFERENCES

[1] G. Geloni, V. Kocharyan and E. Saldin, ”Gas-filled cell as a narrow bandwidth bandpass filter in the VUV wavelength range”, DESY 11-055, http: //arxiv.org/abs/1104.1879