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A COMPACT WATER WINDOW X-RAY SOURCE BASED ON INVERSE COMPTON SCATTERING

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Abstract

X-rays in the water window (2.33 nm to 4.40 nm wavelength) can be used to provide high quality images of wet biological samples. Given the limited availability of current generation light sources in this energy range, table-top water window X-ray sources have been proposed as alternatives. We present start-to-end simulations in RF-Track of a water window X-ray source based on inverse Compton scattering. A brazing-free electron gun with a maximum beam energy of 6 MeV is considered, providing photon energies covering the full water window range. Performance estimates for the gun operating with copper and caesium telluride cathodes are presented. The caesium telluride cathode, combined with a burst mode Fabry-Pérot cavity, allows for an increase in flux by orders of magnitude compared to single bunch copper cathode operation. A beamline of 1 m was determined to be sufficient to produce a high photon flux. Additionally, an improved flux formula is proposed, based on the Q-Gaussian assumption.

INTRODUCTION

The water window is defined for photon energies between 282 eV and 533 eV. This region allow for high quality images of wet biological samples [1]. Until recently, water window imaging experiments have been mostly performed at large-scale photon sources. Emerging technologies and growing interest have encouraged the development of table-top soft X-ray sources in the water window [2].

In inverse Compton scattering (ICS), narrow bandwidth and high intensity X-rays pulses are generated through the interaction of a charged particle and a laser pulse [3]. Due to their increased energy tunability and small footprint, ICS sources can be used as a driver for table-top water window microscopes. Linac-based ICS sources can benefit from developments in high gradient acceleration and high repetition rate injectors developed in the context of the Compact Linear Collider (CLIC) and CompactLight (XLS) [4, 5]. A test installation in the CLIC Test Facility 2 (CTF2) is herein considered for a potential compact water window source.

THE CTF2 BEAMLINE

The electron injector intended for AWAKE Run 2c is currently tested and commissioned at CTF2. A prototype S-band standing wave 1.5 cell RF-gun is already in operation. The electron gun was designed and fabricated with brazing-free technology and commissioned by INFN Frascati [6]. A schematic diagram of the current set-up, equipped to function as an ICS source, is shown in Fig. 1. A mJ laser pulse is frequency-quadrupled and sent to the copper cathode of the electron gun, producing bunches at a fixed repetition rate. After the bunch is accelerated by the gun, a double coil solenoid magnet focuses the beam to a viewport chamber, where it is imaged through a YAG:Ce screen and CMOS camera. Further downstream, a magnetic spectrometer is used to measure the momentum of the electron beam. Lastly, a Faraday cup is installed for bunch charge readings. For the ICS experiment, a vacuum chamber housing the X-ray detector will be installed between the spectrometer and the Faraday cup. An in-vacuum detector (microchannel plate) was chosen due to the near 100% absorption of water window X-rays in air.

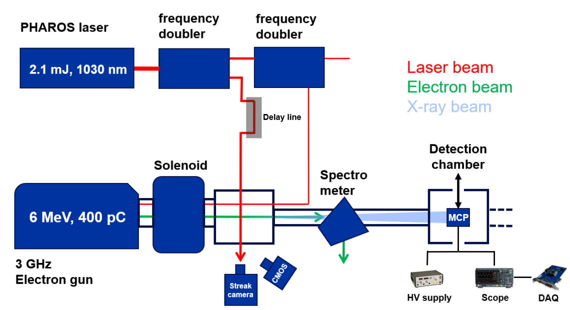

Figure 1: Schematic diagram of the set-up for the ICS experiment.

Electron Beam Parameters

The CTF2 gun is able to provide single electron bunches with repetition frequencies between 0.83 and 10 Hz. The copper cathode currently installed allows for a near equal work function and laser photon energy, which leads to a decreased thermal emittance compared to a caesium telluride (CsTe) cathode. A nominal bunch charge of 400 pC can be extracted from the cathode. The gun has a gradient of up to 120 MV/m, with a maximum electron beam energy of 6 MeV. The typical measured energy spread is 2‰. The bunch length has not yet been measured, however simulations predict a value up to 2 ps for the smallest laser pulse duration of 113 fs RMS.

Laser Beam Parameters

For each cathode configuration, one laser is used for both bunch extraction and ICS interaction. In the current copper set-up, a femtosecond ytterbium-doped potassium gadolinium tungstate (Yb:KGW) laser (PHAROS, Light Conver-

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sion) is used. The laser sends 1030 nm pulses, with a maximum pulse energy of 2.1 mJ and a minimum RMS pulse length of 113 fs. Using a system of parabolic mirrors with holes, the crossing angle between the electron and laser beam can be reduced to close to 0°. The schematic diagram in Fig. 1 shows the actual experimental set-up, where due to spatial constraints a 90° crossing angle is used.

For the CsTe cathode set-up, a 1047 nm OneFive GENKI laser was considered, producing trains of up to 100,000 laser pulses with a 10 Hz repetition rate and 4 ps pulse length. The pulse energy of 9.3 µJ requires the use of a CsTe cathode with a quantum efficiency several orders of magnitude larger than the 10^{-4} value for copper. Due to its use of multibunch electron and laser pulses, the new configuration allows for the integration of an optical enhancement cavity at the interaction point, which can lead to a significant increase in the ICS photon output [7]. For both lasers, a 10 µm sigma laser spot was assumed at the interaction point (IP) of the laser and the electron beam.

Interaction Region

Assuming a linear Compton regime, round Gaussian intensity profiles, and neglecting the hourglass effect, the number of photons scattered through ICS from the interaction of a photon and charged particle bunch in a head-on collision can be obtained from

$$N_\gamma = \sigma_T \frac{N_e N_{\text{laser}}}{2\pi\sigma_y\sigma_x}, \quad (1)$$

where σ_T is the Thomson cross section, N_e is the number of charged particles per bunch, N_{laser} is the number of laser photons per pulse, and σ_i with $i = x, y$ is the convolution of the charged particle and laser transverse size at the IP [3].

In order to maximise the scattered flux from Eq. (1), a strongly focused collision of high density particle bunches is required. To achieve this, the electron beam transport was designed using the particle tracking code RF-Track [8].

RF-TRACK SIMULATION OF ICS

A start-to-end optimisation of the CTF2 beamline was done with RF-Track. This is a tracking code developed at CERN to simulate beam transport under the simultaneous effect of space-charge forces and wakefields. The ability to simulate ICS has been recently implemented and benchmarked against CAIN [9], the standard code used for ICS simulations [10]. RF-Track allows for tracking the electron beam from its generation at the cathode, up to the interaction point. The scattered photons can then be simulated in the same pass, and tracked up to a detection screen.

The optimisation was performed using the simplex algorithm, which minimised a merit function dependent on flux. The laser RMS spot on the cathode and RF phase were reduced to minimise the emittance. The RF gradient was set to its maximum possible value in order to minimise the collection angle of the scattered photons. Lastly, the solenoid field was tuned to obtain a small electron beam waist size at the IP. To reduce background, an upper limit on the maximum electron spot of 10% of the beam pipe aperture was set. The IP was fixed at 0.57 m from the cathode, where a diagnostics screen can be placed for temporal and spatial alignment. The following optimisation assumes a 0° crossing angle.

OPTIMISED BEAM PARAMETERS

The optimised input parameters for the copper cathode are shown in Table 1, along with the relevant electron beam parameters at the IP. The electron beam RMS spot, bunch length, transverse and 4D emittance are tracked in Fig. 2.

Table 1: Optimised Parameters of the Electron Beam from the Copper Cathode

Parameter	100 pC	200 pC	300 pC	400 pC
RF phase [deg]	-19.5	-11.5	-21.0	-26
RF gradient [MV/m]	120	120	120	120
Solenoid field [T]	0.350	0.355	0.350	0.336
Laser RMS spot [µm]	438	482	502	567
Beam energy [MeV]	5.77	5.84	5.77	5.75
Emittance [mm mrad]	1.88	2.77	4.00	6.14
Max e^- RMS spot [mm]	1.27	1.68	1.78	1.80
Min e^- RMS spot [µm]	42	46	61	94
RMS bunch length [ps]	0.4	0.6	0.8	1.1
Total flux [ph/s]	1.4e5	3.5e5	3.7e5	2.9e5

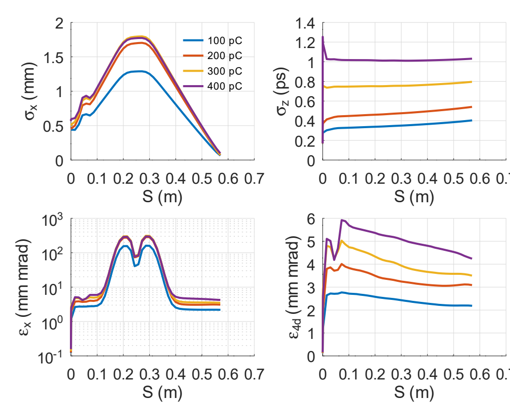

Figure 2: Tracking of the electron beam RMS spot, bunch length, transverse and 4D normalised emittance for the current copper cathode-based injector. The optimisation was done independently for four distinct bunch charges.

The optimised laser spot was increased linearly with the bunch charge, in order to mitigate space charge effects. The optimal RF phase ranged from −10° to −20° with respect to the on-crest phase. The emittance, RMS spot and bunch length of the electron bunch at the IP scaled with the bunch charge. Note that the maximum photon flux was not obtained at the maximum bunch charge of 400 pC, but at 300 pC. This indicates that there is a space charge-induced limit on the achievable flux with respect to the bunch charge. Note that

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for this set-up, photons with a Compton edge of 630 eV are obtained. To reach the water window, the gun gradient can be slightly decreased, as for the optimisation the maximum gun gradient of 120 MV/m was assumed.

A difference between the CsTe and Cu cathode configurations comes from the RMS bunch length, which is increased to 3 ps for CsTe due to the longer pulse length of the OneFive laser system. Due to the 100 times smaller laser pulse energy, and given similar electron bunch charges generated, the number of photons scattered per bunch at the IP is reduced to a few hundred. However, the OneFive laser and CsTe cathode allow for multi-bunch electron operation. For a nominal value of 80 bunches per train, the photon flux corresponds to the values obtained in the copper configuration.

The multibunch operation further allows for the implementation of a Fabry-Pérot cavity (FPC) at the interaction point. Assuming 80 electron bunch trains, limiting the cavity finesse to 1,000, and using 20,000 laser pulse bursts, a maximum circulating laser energy available for the ICS interaction, or effective energy, of 0.5 J could be obtained, using the optimisation described in [11]. The cavity finesse was limited in order to ease the requirements for laser matching and mirror tuning. By comparison, the configuration with no FPC, where each electron bunch interacts with only one laser pulse, had an effective energy of 7.5×10^{-4} J. The addition of an FPC leads to an increase in the total photon flux to 10^8 ph/s, which corresponds to typical requirements for water window imaging [2].

ELECTRON BEAM SHAPING

A non-Gaussian transverse beam shape was obtained for the optimised electron beam profile at the IP. Figure 3 indicates that the maximum achievable flux is obtained with a heavy tail distribution, which is well described by a Q-Gaussian distribution [12]. Simulations showed that the Q-Gaussian profile is caused by space charge forces, which induce an electron beam halo. The beam halo was also observed experimentally at the IP [13]. The photon flux was therefore maximised by increasing the electron beam core density through beam shaping under space charge forces.

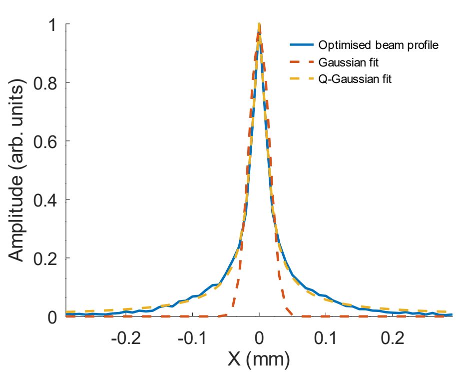

Figure 3: Gaussian and Q-Gaussian fit of the optimised electron beam distribution at the IP. The Q-Gaussian fit parameters are $q = 2.6$ and $\beta = 6117$.

The beam halo of the optimised beam accounts for 80% of the bunch population. Due to the distribution of the beam halo around the centre of the electron bunch, the sigma electron spot size increased. From Eq. (1), which assumes Gaussian bunches, this would entail a reduction in flux. As seen in Fig. 3, the bunch centre is Gaussian and has a high particle density. This indicates that in order to maximise the flux of an ICS source, instead of searching for the smallest electron spot, the beam distribution corresponding to the highest density interaction region should be used. More importantly, it was found that maximising the Gaussian flux formula led to a value for the scattered photon flux that was two-times smaller than the one obtained by maximising the flux directly. The direct flux optimisation is a feature exclusive to RF-Track, since it can perform a start-to-end simulation of the electron beamline and simulate the ICS interaction in one pass.

Due to the non-Gaussian shape of the electron beam, the flux value from Eq. (1) differs with respect to the simulation by a factor two. To assess the impact of the realistic bunch, the flux formula [3] was modified to correspond to a head-on collision of a Q-Gaussian beam with a Gaussian one,

$$N_\gamma = \frac{\sigma_T N_e N_{\text{laser}} \sigma^{-4k-1}}{2\pi^2 \beta \sqrt{k}\,\Gamma\left(k-\frac{1}{2}\right)^2} \times \left[k^{k-1/2}\beta^{2k-1}\Gamma\left(\frac{1}{2}-k\right)\Gamma(k)\,{}_1F_1\left(k; k+\frac{1}{2}; \frac{k\beta^2}{\sigma^2}\right) + \sqrt{\pi}\sigma^{2k-1}\Gamma\left(k-\frac{1}{2}\right){}_1F_1\left(\frac{1}{2}; \frac{3}{2}-k; \frac{k\beta^2}{\sigma^2}\right)\right]^2, \quad (2)$$

where $k = 1/(q-1)$, ${}_1F_1$ is the confluent hypergeometric function, Γ is the gamma function, σ is the RMS transverse size of the Gaussian beam, and β and q are fit parameters of the Q-Gaussian distribution. The formula corresponds to $1 < q < 3$, for which the heavy tails observed in simulations and experiment are obtained. Note that for head-on collisions, there is no contribution from the longitudinal distribution. By comparing the result from the modified flux formula with simulations, a difference of less than 9% between the two methods was observed, significantly smaller than for the standard Eq. (1).

CONCLUSION

A start-to-end optimisation of the CTF2 electron beamline for an ICS experiment has been presented. The goals of the optimisation were to maximise the output flux and minimise background. Two cathode configurations were considered for the electron bunch extraction: copper and caesium telluride. The latter, combined with an FPC, can be used to increase the total scattered photon flux to 10^8 ph/s. Additionally, the optimisation of the input parameters of the injector revealed that a transverse electron beam shaping corresponding to a heavy tail Q-Gaussian leads to the maximum achievable flux. Given the cathode to ICS photon detector distance of 1 m, this design represents a competitive alternative for compact water window sources.

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