DEVELOPMENT OF A FOCUSING SYSTEM FOR THE AXSIS PROJECT*

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Abstract

In this paper, we investigate with ASTRA simulations the achievable performances for several focusing systems considered in the AXSIS project [1]. We focus our attention on the requirements in terms of position of the focal point and bunch transverse size at this point. We show that they cannot be fulfilled with a solenoid resistive electro-magnet, but that it is possible when using a solenoid permanent magnet. The use of a quadrupole doublet proves to be adequate to fulfil the requirement on the position of the focal point and be very close to the one on the bunch transverse size, which could possibly be achieved by a further optimization of the parameters of the doublet. Finally, we also investigate the possibility to use an active plasma lens, showing that it could easily fulfil the requirements but that several points must be carefully studied before considering its implementation.

INTRODUCTION

The AXSIS project [1] aims at producing fully coherent few keV attosecond X-ray photon pulses for ultrafast spectroscopy and imaging applications. These photons will be produced through the inverse Compton scattering (ICS) between an infrared (IR) laser pulse and a 15 MeV sub-fs electron bunch accelerated by a dielectric-loaded waveguide (linac) driven by THz pulses [2].

One of the key parts of AXSIS will be the focusing system between the linac exit and the ICS point. It has to transversely focus the bunch at a focal point, located between 30 cm and 1 m away from the linac exit, down to a transverse size around or below 5 µm rms to optimize the ICS process. Its design is challenging due to the following three reasons: the high bunch energy spread (at least 0.5 % rms), its asymmetry (sizes and emittances) between the two transverse planes by a factor of approximately 2 at the linac exit, and the necessity to keep a short bunch length after the linac exit up to the ICS point.

In this paper, we investigate with ASTRA simulations [3] the achievable performances for several focusing systems, considering as an input the bunch properties shown in Table 1. Note that, except for Fig. 1, the positions are given relative to the exit of the linac, which is referred to as 0. The limitations of the different systems, from the beam dynamics and technical point of views, will be exposed. In the first part, we present the results obtained with a solenoid magnet, considering both the possibilities of resistive electro-magnet and permanent magnet. In the second part, the results obtained with a quadrupole doublet are presented. In the third part, we finally introduce preliminary simulation results obtained with an active plasma lens [4, 5].

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Table 1: Input Bunch Properties used for the Simulations

Bunch property	Value at the linac exit
Charge	1 pC
Mean kinetic energy	14.65 MeV
Rms energy spread	82.70 keV
Rms length	1.28 µm (≡ 4.27 fs)
Rms horizontal size	213 µm
Rms vertical size	133 µm
Rms horizontal emittance	0.195 π.mm.mrad
Rms vertical emittance	0.090 π.mm.mrad

CASE OF A SOLENOID MAGNET

To perform the simulations with a solenoid magnet as focusing device at the linac exit, we considered the on-axis field profile shown in Fig. 1. We assumed that the maximum peak field achievable with a resistive solenoid electromagnet is of 0.5 T and the one with a permanent magnet of 1.5 T. We then studied how the distance of the focal point from the linac exit and the bunch transverse sizes at this focal point evolve as a function of the peak field of the solenoid magnet and of its position respective to the linac exit. The results are shown in Fig. 2.

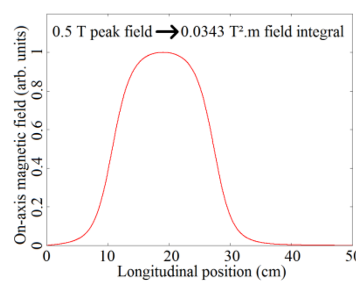

Figure 1: On-axis magnetic field profile considered for the simulations of a solenoid magnet.

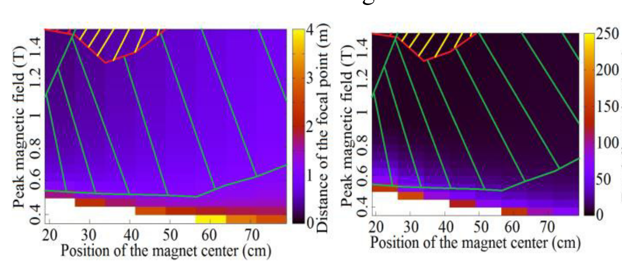

Figure 2: Colour encoded distance of the focal point from the linac exit (left) and rms bunch transverse size at this focal point (right) as a function of the solenoid peak magnetic field and of its position. Green striped area: Requirement on the position of the focal point fulfilled. Red striped area: Requirement on the transverse bunch size at the focal point fulfilled. Yellow striped area: Both requirements fulfilled.

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Figure 2 shows that, under our assumptions, both the requirements on the position of the focal point and on the bunch transverse size at this focal point cannot be achieved with a solenoid resistive electromagnet. Indeed, the focal point can be at best around 1.2 m away from the linac exit and the bunch transverse size is around 18 µm rms in this case. It is shown that for permanent solenoid magnet there is a zone (yellow stripe in Fig. 2) where these two requirements could be simultaneously fulfilled. However, due to their very small tunability, such permanent solenoid magnets will not be considered as a standalone focusing device for the AXSIS project, where tunability is required. But they could still be considered in combination with other (tuneable) focusing devices.

CASE OF A QUADRUPOLE DOUBLET

We then studied the achievable performances with perfect quadrupole magnets, for which transverse gradients up to 50 T/m can be achieved with resistive electromagnets. We chose to first study the case of a symmetric quadrupole doublet, meaning that the two quadrupoles are identical with same absolute field gradients and just inverted polarities, because this layout is of simplest implementation. It is possible to consider only a doublet to achieve a common focal point for the horizontal and vertical transverse directions, because the bunch transverse sizes are different along these directions at the exit of the linac. At least a quadrupole triplet would have been required if they would have been equal. Our protocol has been to fix the distance ΔLQ of the first quadrupole from the linac exit, and then to search for each transverse field gradient which position of the second quadrupole allows obtaining a common focal point for the two transverse directions. Figure 3 shows the obtained results for 10 cm long quadrupoles with 3 cm radii.

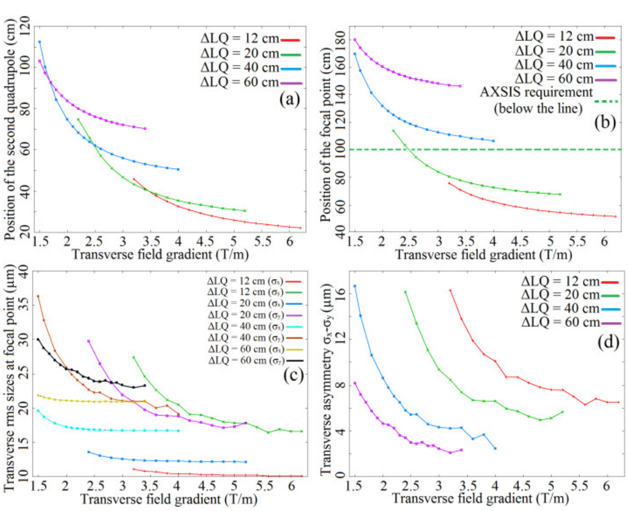

Figure 3: Position of the second quadrupole (a) and of the focal point (b), transverse sizes (c) and asymmetry (d) at the focal point as a function of the transverse gradient, for several distance ΔLQ of the first quadrupole from the linac exit. 10 cm long quadrupoles with 3 cm radii.

It is visible in Fig. 3.a that the range of theoretically usable transverse field gradients is limited. This is due to the fact that above a certain value, function of ΔLQ, the distance required between the two quadrupoles to have a common focal point for the two transverse directions becomes smaller than their lengths, which is mechanically impossible. Figure 3.b shows that the requirement on the position of the focal point can be fulfilled when ΔLQ is sufficiently small (the limit value is located between 20 cm and 40 cm). On the opposite, Fig. 3.c shows that the requirement on the bunch transverse size at the focal point is far from being achieved and that a strong asymmetry, plotted in Fig. 3.d, remains between the two transverse directions contrary the case of a solenoid magnet. In fact, for ΔLQ = 12 cm and a transverse gradient of 5.5 T/m, the achieved bunch transverse size is of 10*16 µm^2 rms.

We performed similar simulations with smaller quadrupole magnets, namely with 5 cm lengths and 1.5 cm radii. These simulations demonstrate that the asymmetry of the bunch transverse size along the two transverse directions is greatly reduced at the focal point by this change while still keeping the position of the focal point within the requirement. Indeed, for ΔLQ = 12 cm and a transverse field gradient of 14.4 T/m, the focal point is 45 cm away from the linac exit and the bunch transverse size is of 11*13 µm^2 rms.

To try achieving the requirement on the bunch transverse size at the focal point, we gave up the constraint of using a symmetric quadrupole doublet. Namely, we still use two mechanically identical quadrupoles but with possibly two different absolute transverse field gradients. The ranges of possible parameters for this case have not been totally explored yet, therefore the result presented in Fig.4 is only preliminary. It shows that using such an asymmetric quadrupole doublet effectively allows significantly decreasing the transverse bunch size and approaching the requirement, while still keeping the position of the focal point within the requirement. Indeed, we obtain 6.0*8.8 µm^2 rms at 32.3 cm from the linac exit. One can note that the asymmetry of the bunch transverse size at the focal point, already observed with a symmetric doublet, has not been eliminated. It seems therefore not possible to correct this asymmetry, already present at the exit of the linac (see Table 1), when using quadrupole magnets as focusing device.

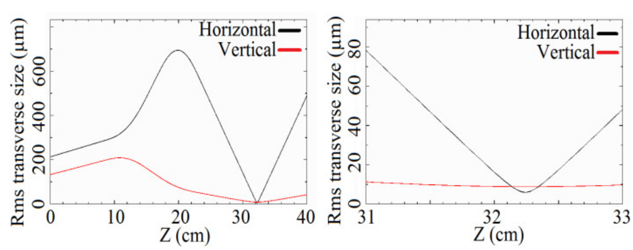

Figure 4: Evolution of the rms bunch transverse size for a quadrupole doublet (5 cm long and 1.5 cm radii magnets). The two magnets are placed 12 cm and 20 cm after the linac exit and respectively have transverse field gradients of -14 T/m and +18.5 T/m.

CASE OF AN ACTIVE PLASMA LENS

We finally studied the achievable performances using an active plasma lens as focusing device [4, 5]. This device is considered because the magnetic field generated by the discharge is azimuthal, cylindrically symmetric and increases linearly with the radius (for a perfect discharge). This leads to a focusing similar to the one of a quadrupole magnet but, contrary to the quadrupole, being the same in every radial direction therefore implying a cylindrically symmetric focusing of the bunch. For performing the first simulations in ASTRA, we fix the length and radius of the chamber to 2 cm and 1 mm. We consider a current of 1 kA flowing through the discharge, leading to a transverse field gradient of 200 T/m. The results are shown in Fig. 5.

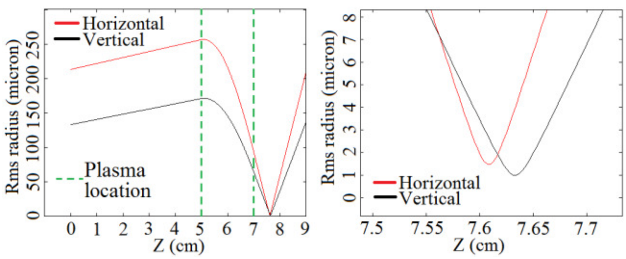

Figure 5: Evolution of the rms bunch transverse size for a perfect active plasma lens (2 cm length and 1 mm radius) located 5 cm after the linac exit and having a 200 T/m transverse field gradient.

It is visible in Fig. 5 that the achievable bunch transverse size at the focal point with an active plasma lens is much lower than the one with conventional magnets, since it is between 1 µm and 2 µm rms, and could fulfil the requirement for AXSIS. However, two problems also appear in Fig. 5. Firstly the position of the focal point is too close from the linac exit, around 7.5 cm, and thus not compatible with the AXSIS requirement. But this can easily be solved by placing the active plasma lens farther away from the linac exit and/or by increasing its focal distance (decrease of field gradient and/or of the length). Secondly, as shown on the right plot of Fig. 5, there is an asymmetry in the position of the focal point for the two transverse directions. This, considering that the focusing is very strong, could lead to a significant asymmetry of the bunch transverse size in the ICS region and is therefore problematic.

This astigmatism is due to the already existing bunch asymmetry at the entrance of the active plasma lens (see left plot of Fig. 5). It can therefore be overcome by placing a solenoid magnet before the active plasma lens, in order to correct the asymmetry and enter the plasma lens with a transversely symmetric bunch. To demonstrate that we perform a simulation with the same active plasma lens than in Fig. 5, just adding before the solenoid magnet which field profile is shown in Fig. 1. The results are shown in Fig. 6 and effectively demonstrate that the addition of a solenoid magnet before the active plasma lens almost totally remove the previously observed astigmatism and delivers a bunch transverse size around 2 µm rms at the focal point (see right plot).

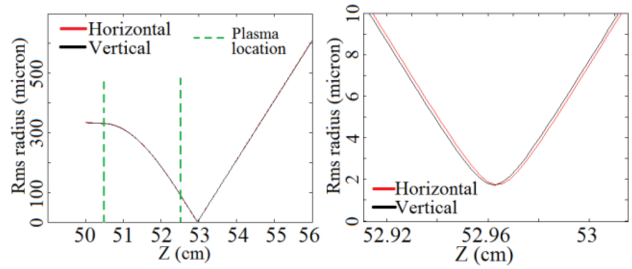

Figure 6: Evolution of the rms bunch transverse size for a perfect active plasma lens (2 cm length and 1 mm radius) located 50.5 cm after the linac exit and having a 200 T/m transverse field gradient. The solenoid magnet which field profile is shown in Fig. 1 has been placed 34 cm after the linac exit with a peak field of 0.5 T.

The use of an active plasma lens, in combination with a solenoid magnet, as focusing device to the ICS point for the AXSIS project is an interesting possibility to consider, because it could easily fulfil the requirement in terms of position of the focal point and bunch transverse size. However, before going on for an eventual implementation, several points must be carefully studied concerning the active plasma lenses: effect of the fringe fields (not included in the present simulations); effect of the non-linearity (the increase of the magnetic field with the radius has been assumed linear, which is not valid far from the lens axis [4]); stability and homogeneity of the magnetic field within one discharge and shot-to-shot reproducibility; mechanical integration in the AXSIS beamline [1] (the very short focal distance may cause trouble for transport of the IR laser to the ICS point and if the IR laser strikes the plasma chamber).

CONCLUSIONS AND PROSPECTS

The AXSIS requirements in terms of position of the focal point and bunch transverse size cannot be fulfilled with a solenoid resistive electro-magnet, but it is possible when using a solenoid permanent magnet. However, due to its poor tunability, it will be considered only in combination with another (tuneable) magnet. The use of a quadrupole doublet, for which the optimization is not yet finished, allows fulfilling the requirement on the position of the focal point and being very close to the one on bunch transverse size. However, a remaining asymmetry of the bunch transverse size along the two transverse directions seems to be unavoidable with this device. The use of an active plasma lens, in combination with a solenoid magnet, could easily fulfil the requirements and looks therefore promising. However, several points must still be carefully studied before considering its implementation.

In this paper, we just look at the focusing performances of the different possible devices. In the next steps of the study, already ongoing, it will be important to look how each device deteriorates the bunch transverse emittance. It will be also important to make the transverse focal point coinciding with the longitudinal one. For this purpose, the simulations of the focusing system will be made in combination with the ones of the linac (see [2]).

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