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RUEDI MICROSCOPY: SOLENOIDS OR QUADRUPOLES?*

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Abstract

RUEDI, the Relativistic Ultrafast Electron Diffraction and Imaging facility for the UK, is a planned facility that will deliver single-shot, time resolved, MeV electrons for imaging and ultrafast (≈ 10 fs) diffraction. The facility naturally separates into two lines, both fed by the same RF gun. The first line is for microscopy and imaging whereas the second is dedicated to diffraction. Microscopy can be done in two ways, the first is by building a line with solenoid lenses and the second is by building the same line with quadrupole lenses. Here, we explore the advantages and disadvantages of both. Starting with a description of how the microscope is built using solenoids and extending this to look at various options with quadrupoles.

INTRODUCTION

RUEDI plans to deliver 20 pC, single-shot, time resolved, electron bunches for imaging and ultrafast (≈ 10 fs) diffraction. These electrons are, initially, planned to be at 2 MeV kinetic energy with the possibility to extend this to higher energies if these become feasible in the future. The facility is divided into two lines, both fed by the same RF gun. The first line is dedicated to microscopy and imaging whereas the second is for diffraction purposes [1]. This paper, together with [2], will be dedicated to microscopy and the initial design of the diffraction line can be found in these proceedings in [3]. Microscopy can be done in two ways, both require lenses for focusing. The first is by building a line with solenoid lenses which are the electron equivalent of magnifying glasses. The second possibility involves building the same line with quadrupole lenses to provide the focusing. The main reason for going with quadrupoles is to go to higher energies, otherwise, it is unlikely to be able to get any microscopy line to operate significantly above a kinetic energy of 3 MeV. Here, we explore some of the advantages and disadvantages of both. We start with a description of how the microscope is built using solenoids and later extend this to look at same line with quadrupoles.

The sample will be between 5 µm and 5 mm in radius and the desired magnification in the range of 650 and 6500. The reason for the two extremes is so as to be able to look at the sample in coarse detail and identify a region of interest and, hence, zoom in on it as much as possible. Beam sizes of 5 µm and 5 mm correspond to β functions of 120 µm and 120 m, respectively, for a 2 MeV operation with a 1 µm normalised emittance.

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GENERAL CONSIDERATIONS

A typical microscopy line can be summarised in the plot shown in Fig. 1. Typically, there are a couple of condenser lens solenoids before the objective lens whose role it is to get the beam as round and as parallel as possible at the sample. These are not shown here as they are considered to be relatively weak in strength and may be replaced by several quadrupoles. The labels h_i, $i = 1, 2, 3, 4$ refer to the original

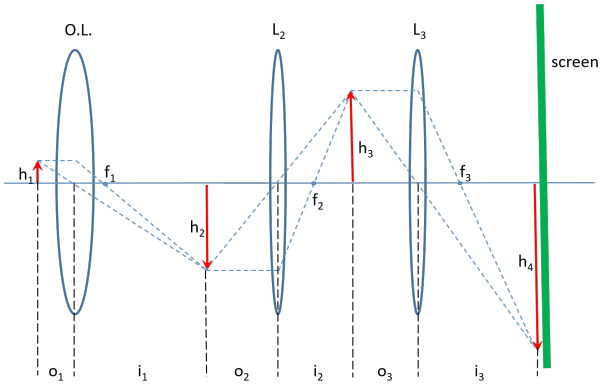

Figure 1: Typical layout of a simple microscopy line with one objective lens solenoid ($O.L. = L_1$) and two projector lens solenoids (L_2 & L_3) and a screen / detector at the end. Nothing is to scale and all labels are described in the text.

sample radius (h_1) and all the subsequent image radii. If we think of the objective lens as a normal lens, we can label all three lenses as $L_1(= O.L.)$, L_2 and L_3 or L_i with $i = 1, 2, 3$. Each lens, labelled by i, has its own focal length f_i, distance of object to the lens centre o_i and distance from the lens centre to the image i_i. Each lens obeys, to first order at least, the thin lens approximation:

$$\frac{1}{f_i} = \frac{1}{o_i} + \frac{1}{i_i}.$$

For the objective lens, this is not really sufficient, however, it gives a good starting indication. Each lens magnifies the object in the usual way with the magnification given by $M_i = \frac{i_i}{o_i} = \frac{h_{i+1}}{h_i}$. The overall magnification is then $M = M_1 \times M_2 \times M_3$. For the purposes of microscopy at RUEDI, the overall magnification will range from 650 to 6500. Therefore, a possible choice is to have $M_1 \approx 35$ and $M_2 = M_3 \approx 14$. If we allow the first projector lens (L_2) to operate over a range of magnifications from 14 to 19, then it should be possible to switch the second projector lens off and have the desired magnification of 650 at the detector / screen at the end of the microscopy line. This is possible because the magnification is not just a function of solenoid strength but also how far away the desired image is. It is also important to get the phase advance in each plane to be π or, equivalently,

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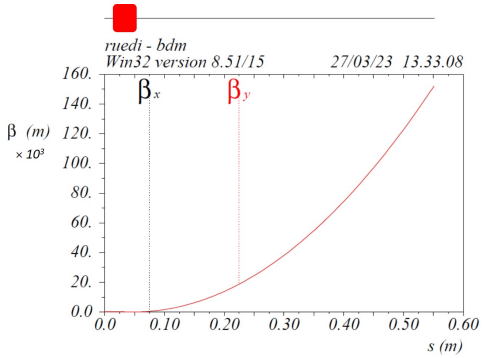

Figure 2: Beta functions for the beam going through and exiting the objective lens solenoid and going through a drift of a fixed length to ensure $R_{12} = R_{34} = 0$. The final values of the β functions correspond to a beam size of 175 mm at 2 MeV, equivalent to a magnification $M_1 = 35$.

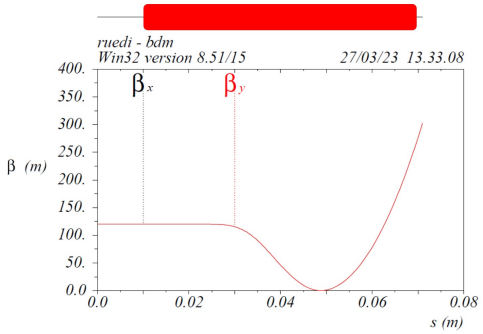

Figure 3: Closeup of the start of the line shown in Fig. 2. The sample is typically located between 1 and 2 cm.

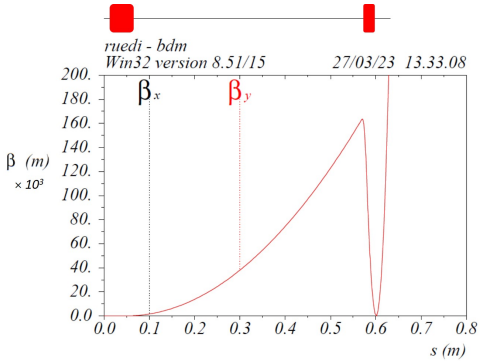

Figure 4: Detailed plot of the β functions for the objective lens and the first projector lens. The β functions after the second focus, at 0.6 m, go up to a magnification of 35×14 as desired.

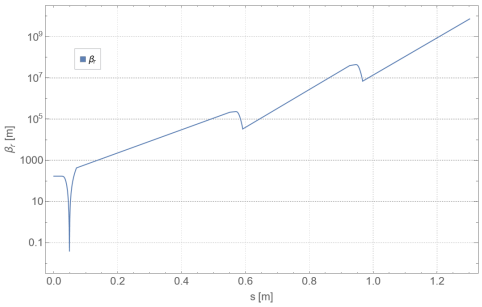

Figure 5: Radial beta function for the entire solenoid microscopy line. The β_r function at the end of the line correspond to a total magnification of $M = 35 \times 14 \times 14 = 6860$ which is slightly larger than the required value of 6500.

$R_{12} = R_{34} = 0$, from the object to the location where the image should be. Therefore, each drift length after the exit of the solenoid corresponds to a particular solenoid strength. The setup of the line using solenoids is detailed in the next section.

SOLENOID MICROSCOPY LINE

The solenoids were modelled in MAD8 by using a series of thin solenoid elements, each with the same length, with varying strengths according to a typical solenoid profile. It is not a requirement to have the correct phase advance between sample or object and subsequent image for each of the lenses individually. However, from the point of view of commissioning it would be beneficial to be able to see things at the correct focus and on all available screens along the way. Therefore, taking this into account, each lens or solenoid was set up individually at first so as to get the correct magnification and phase advance. Figures 2 and 3 show a MAD8 plot of the objective lens together with the downstream drift and a more detailed version of the start of the line.

Given that the two projector lenses are modelled in much the same way as the objective lens, all that is left is to put them together and this is shown in Fig. 4. The full extent of the β function is not shown as this would dwarf the details so this is shown in Fig. 5. From Fig. 5 it can be seen, taking into account that β functions scale according to the square of the beam size, that the beam is magnified a total of slightly over 6500 times. The total length of the line is just over 1.3 m. The peak strengths, at 2 MeV, of the objective and either of the projector lenses are currently 1.3 and 1 T and their lengths are 6 and 3 cm, respectively. The setup of the same line using quadrupoles is detailed in the next section.

QUADRUPOLE MICROSCOPY LINE

The possible quadrupole replacement sections for the microscopy are based on the design of the Shanghai group [4] while trying to keep the parameters realistic and, especially, tunable. Several focusing schemes exist, based on a triplet, quadruplet or quintuplet of quadrupoles to replace one solenoid. Now, the beam has to come to a focus before fanning out to get the magnification and this has to be the same in both transverse planes. Therefore, two constraints are required for the focus in both transverse planes together with an additional one for the β functions being the same at the end of the drift. A further constraint needs to be ap-

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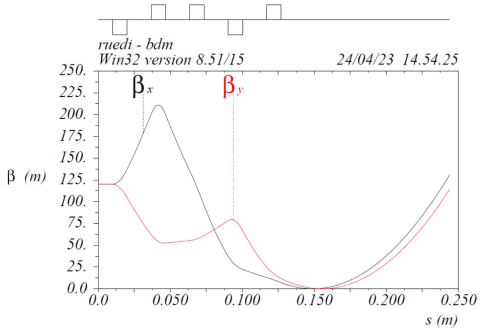

Figure 6: Beta functions for the beam going through and exiting the quintuplet equivalent of the objective lens. The final values of the β functions are not shown but correspond to a beam size of 175 mm at 2 MeV, equivalent to a magnification $M_1 = 35$. The sample is around 1.5 cm.

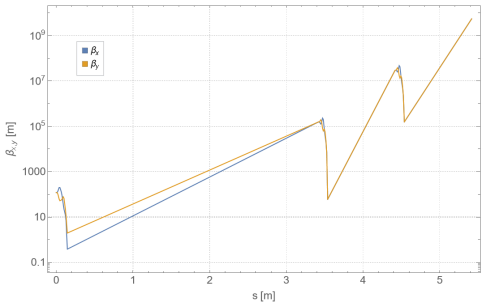

Figure 7: Beta functions for the entire quadrupole microscopy line with the same overall magnification factor as the solenoid line.

plied, in both planes, to ensure the correct phase advance is achieved, or $R_{12} = R_{34} = 0$. This makes a total of five constraints and it is not possible to achieve this consistently with less than five variables. Therefore, the quintuplet focusing scheme was chosen. In order to reduce the overall distance, it is important that the drifts in the quintuplet be as short as possible and the quadrupoles also. The parameters that were chosen were 1 cm long quadrupoles separated by 1 cm long drifts. This is slightly more relaxed dimensions than those found in [4] where the entire quadrupole objective lens is less than 26 mm long and contains five permanent magnet quadrupoles. Each quadrupole is almost as high as 540 T/m. Such challenging parameters are bound to have alignment as well as error implications. With the quintuplet for RUEDI, all three sections of the microscopy line are similar and the quadrupole strengths were all kept below 30 T/m. Figure 6 shows the detail of the start of the line for the objective lens. Hence, we can see the result of putting all three lens systems together in Fig. 7.

CONCLUSIONS

A layout for the RUEDI microscopy line was presented, both using solenoids and quadrupoles. The line with solenoids consists of three lenses, one objective lens and two projectors, with lengths 6, 3, 3 cm and peak strengths 1.3, 1, 1 T, respectively. The overall distance this takes is just over 1.3 m. It was shown that the same line can be made by replacing each solenoid lens with a quintuplet of quadrupoles. In this case, a total of 15 quadrupoles is required. The current specification for these quadrupoles is that they are 1 cm long with an aperture of approximately 1 cm and strengths at or below 30 T/m. For comparison, the main parameters of both options are summarised in table 1.

Table 1: Table highlighting the main differences between the solenoid and the quadrupole options for RUEDI.

RUEDI:	solenoids	quadrupoles
solenoid no.	3	
sol. lengths [cm]	6, 3, 3	
sol. strengths [T]	1.3, 1, 1	
quadrupole no.		15
quad. lengths [cm]		1
quad. strengths [T/m]		30
total length [m]	1.3	5.5
total magnification	6860	6860

The quadrupole strength is reduced by over an order of magnitude from that found in [4] despite that project being at 3 MeV and RUEDI being at 2 MeV kinetic energy. However, the overall length of the quadrupole line is almost 5.5 m and the RUEDI microscopy design is still not complete. For example, the behaviour in the presence of space charge as well as chromatic aberrations still needs to be investigated, for both lines. As far as space charge is concerned, there may be an advantage to ensuring the beam comes to a focus at a slightly different point in the two transverse planes, that way the charge is not concentrated in a point at any time but is twice confined to a line. This would only be possible in the quadrupole case.

The quadrupoles are already very challenging because of how close and short they are. However, ideally, they should be even closer because the rapidity of the beam expansion after the focus depends directly on how tight and strong things can be made at the start. It would also be useful to vary the quadrupole field so as to tune the line. An answer to these stringent requirements could be to use ZEPTO [5, 6] quadrupoles or rotating quadrupoles [7], both of which are tunable but permanent. Maybe also the Halbach quadrupoles used in [8] could be used in order to create an entire microscopy line with a magnification factor of 6500 rather than 30. Making them this short is always going to be a challenge, particularly mechanically.

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