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BEAM DYNAMICS OF THE RUEDI DIFFRACTION BEAMLINE*

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Abstract

RUEDI is a proposed relativistic ultrafast electron diffraction and imaging facility. It will have two beamlines: a diffraction beamline and an imaging beamline. This proceeding discusses the beam dynamics design of the diffraction beamline. The diffraction beamline needs to have the best temporal resolution possible which requires short bunch length and minimal time of arrival jitter at the sample. To achieve this a magnetic bunch compressor operated in a jitter cancelling configuration is used. To achieve compression as well as jitter cancellation the beam's longitudinal space charge forces are used to modify the chirp to compress the beam. The RUEDI diffraction line will operate at 4 MeV meaning that both space charge forces and ballistic effects are significant and need to be accounted for in the design. The diffraction line will be operated in three modes: single-shot, stroboscopic and streaking.

INTRODUCTION

RUEDI (Relativistic Ultrafast Electron Diffraction and Imaging) is a proposed facility to be based at Daresbury Laboratory in the UK [1,2]. RUEDI will have two beamlines: one for imaging [3] and one for diffraction, each optimised for their specific purposes. The two beamlines will share a common electron gun [4]. The layout of RUEDI with the diffraction beamline indicated can be seen in Fig. 1.

The purpose of the diffraction line is to perform pump-probe ultra-fast electron diffraction (UED) measurements with the best possible temporal resolution and a range of different sample types and environments. To achieve good performance, short 10-50 fs, low emittance, electron bunches with small time of arrival jitter will be needed. A large number of different pump laser options will be provided covering a wide range of frequencies, pulse lengths, and powers. To allow for different sample types and environments the sample chamber will be interchangeable. Different chambers will be used for solid samples, liquid and gas jets, and cryogenic samples, for example.

The RUEDI diffraction beamline will operate in three modes: single-shot, stroboscopic and streaking. The specification of the three modes can be seen in Table 1. In both the single-shot and stroboscopic modes a short bunch will be used to probe the sample and then the diffraction pattern will be recorded downstream. The difference between these two modes is the number of electrons that are incident on the sample, and the resultant beam quality. In the single shot mode 10^6 electrons reach the sample, compared to 10^4 electrons for the stroboscopic mode. Irreversible processes can only be investigated in the single-shot mode, as in the stroboscopic mode, images of diffraction patterns need to be accumulated over many shots. However the stroboscopic mode has better momentum and timing resolution. The streaking mode operates very differently to the two other modes. It uses a single long bunch to probe the whole temporal evolution of the dynamics and then uses a Transverse Deflecting Cavity (TDC) to streak the bunch allowing the changes in the diffraction pattern to be seen along one of the transverse axis of the detector [5]. This allows entire processes to be examined in a single-shot, rather than scanning the delay time between pump and probe.

BEAMLINE LAYOUT

The RUEDI diffraction beamline consists of: the RF electron gun, the pre-arc matching quadrupoles, the 4-dipole arc, the pre-sample focusing optics and the post-sample optics. The beamline layout can be seen in Fig. 1. The arc compresses the 4 MeV electron bunch, while cancelling the timing jitter and physically separating the two beamlines. A magnetic arc was chosen over an RF based compression system system as an RF buncher would introduce additional jitter and would not allow the beamlines to be separated.

The electron gun is shared with the imaging beamline and is a 2.5 cell S-band RF electron gun which is being designed to minimize dark current while achieving the required high brightness beams [4]. In single shot and stroboscopic modes the photo-injector (PI) laser will be operated in the blowout regime - with a very short <60 fs pulse length, but larger transverse size. The electron bunch produced rapidly expands to several hundreds of femtoseconds in length under the action of its own space charge forces. This process produces ellipsoid bunches with linear phase spaces and space charge forces [6, 7] which helps with compression and preserving the transverse emittance. In both modes the bunch is created with the same amount of charge and then the number of electrons that reach the sample is adjusted by collimation in the pre-sample focusing optics. In the streaking mode where longer electron bunches are needed a PI laser with a several ps long pulse length and <50 µm transverse diameter will be used. This is similar to the PI laser parameters used for the imaging mode [3].

Following the gun, 4 quadrupoles are used to match the beam into the magnetic arc. This arc has been designed to both compress the bunch and cancel the time of arrival jitter at the sample. It is designed to have variable R56 with the capability to operate with either positive, negative or zero R56 for operational flexibility. The arc also translates

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Table 1: Operating Modes and Desired Design Parameters of the RUEDI Diffraction Beamline

Parameter	Single shot	Stroboscopic	Streaking
Kinetic energy [MeV]	4	4	4
Number of electrons	10^6	10^4-10^5	10^7
Temporal resolution [fs]	50-10	50-10	10
Momentum resolution [Å^{-1}]	0.05-0.15	0.05-0.15	0.05-0.15
Spot size [µm]	200-400	50-100	100

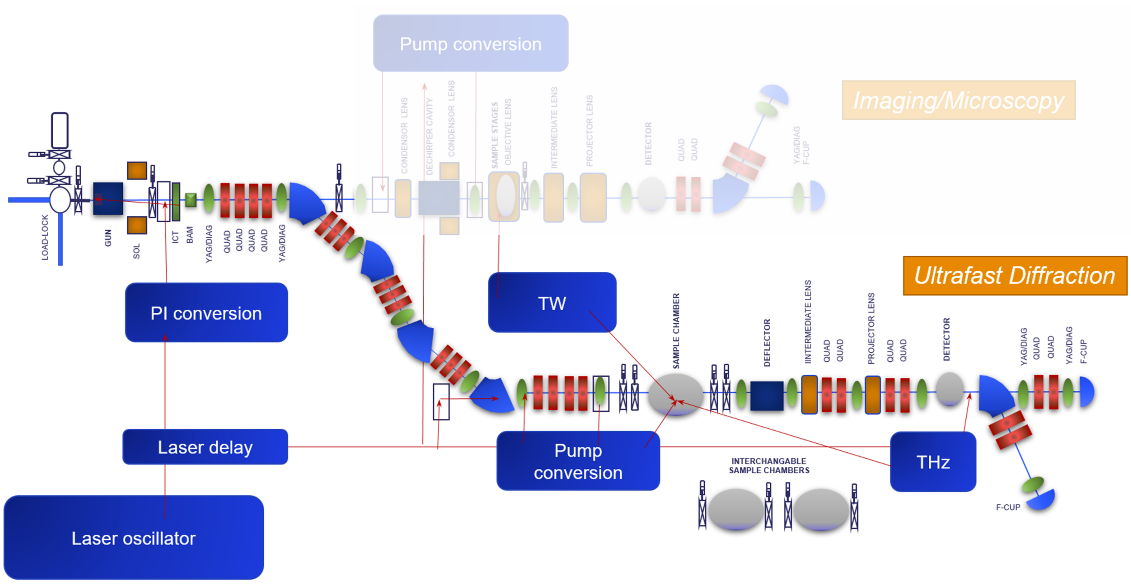

Figure 1: The layout of RUEDI with the diffraction beamline highlighted.

the beamline around 2 m allowing the diffraction beamline to run parallel to the imaging beamline with a shielding wall in between. The shielding wall allows experimental setup to be carried out on the diffraction beamline while the imaging beamline is operating, increasing the efficiency of the machine. A four dipole arc was chosen as it is the simplest arrangement of dipoles that can provide variable R56 whilst physically separating the imaging and diffraction beamlines so that they run parallel to each other.

Following the arc are the pre-sample focusing optics. These consist of four quadrupoles and a collimator. They are used to re-form a round beam, after the asymmetric focusing of the arc, and bring it to a tight focus. The collimator is used to cut the beam to the required size and shape for the sample, and change the number of electrons.

The post-sample optics consist of a number of solenoidal lenses. The first of these (the objective lens) focuses the beam to form the diffraction pattern, and the remaining solenoids magnify the pattern onto the detector. This optics system should allow for variable magnification so that each pattern can be adjusted to the optimal size on the detector and so that specific features in the diffraction pattern can be zoomed in on. These optics can also be bypassed. Two detectors are planned, a high resolution direct electron detector, and a scintillator with a hole in the centre to let the undiffracted beam pass through. A TDC is used in the streaking mode to streak the diffraction pattern, and also used as a bunch length diagnostic. THz diagnostics located in the sample chamber are also planned for bunch length measurements. A second THz station will be located after the detector, which will allow shot by shot time of arrival measurements to be carried out, for experiments which use a detector with a hole.

LONGITUDINAL DYNAMICS: TEMPORAL RESOLUTION, JITTER AND BUNCH COMPRESSION

The temporal resolution, R_t, is the key parameter for the performance of the RUEDI diffraction beamline. It is given by

$$R_t = \sqrt{\Delta t_{electron}^2 + \Delta t_{laser}^2 + \Delta t_{jitter}^2 + \Delta t_{velocity}^2} \quad (1)$$

where $\Delta t_{electron}$ is the electron bunch length, Δt_{laser} is the pump laser pulse length, Δt_{jitter} is the arrival time jitter between the electron bunch and the laser pulse, and $\Delta t_{velocity}$ is the velocity mismatch between the electron bunch and the laser beam (which is negligible at 4 MeV). The diffraction beamline is optimised to minimise the electron bunch length and time of arrival jitter.

To reduce the jitter a common laser source will be used for the both the photoinjector laser and the pump laser. The

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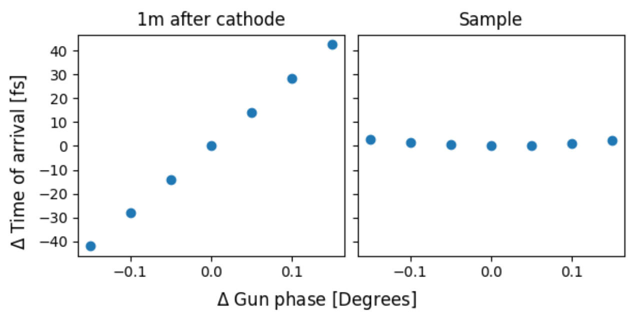

Figure 2: A comparison of the time of arrival at the electron gun exit and at the sample position.

intrinsic synchronisation between these two lasers means that the main timing jitter will come from variation in the time of flight of the electron bunch through the beamline. This jitter mostly originates from the RF in the electron gun. The timing jitter due to the electron gun can be cancelled by tuning the R56 of the beamline to the appropriate value [8]. This works because the jitter leads to a correlated variation in both the energy, and the time of arrival, of the bunch at the gun exit. The R56 of the beamline relates the time of flight through the beamline to the bunch energy. So if the beamline is tuned to have the opposite energy-time of flight relationship to the one at the exit of the electron gun caused by the jitter, then all bunches will arrive at the sample at the same relative time. The arrival time at the gun exit and at the sample after a phase jitter cancelling arc as a function of phase can be seen in Fig. 2. The fact that the timing jitter is fully removed at the sample apart from a small second order contribution can clearly be seen.

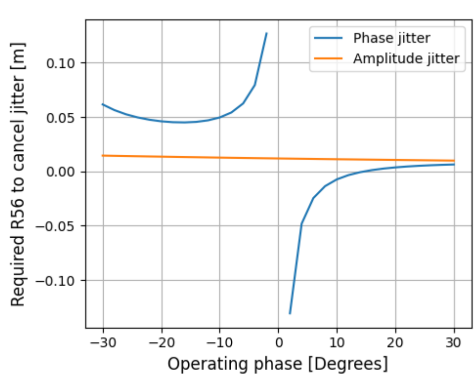

Figure 3: The required R56 for the beamline to cancel the phase and amplitude jitters as a function of gun operating phase for a 2.5 cell electron gun.

However, there are two sources of timing jitter in the electron gun: the amplitude jitter and the phase jitter. These two sources require different beamline R56s to cancel them. The dependence of the required R56 to cancel the jitter for both jitter sources as a function of gun phase can be seen in Fig. 3.

In addition to cancelling the jitter the bunch also needs to be compressed longitudinally. In order to achieve this compression while also cancelling the timing jitter, the space charge forces of the bunch are used to modify the chirp. This changes the time of the flight of the head and tail of the bunch leading to compression while preserving the time of flight of the bunch centroid so jitter cancellation is still maintained. The space charge chirp is tuned by modifying the laser spot size on the cathode.

The low energy of the RUEDI bunch means that it cannot be treated using the ultra-relativistic assumption. Particles of different energies have different velocities leading to a ballistic R56 contribution which acts over the entire beamline, in addition to the magnetic component which changes only in the dipoles. As a result the timing jitter and bunch length only achieve their minimum values at the sample position. In addition the bunch must be over-compressed in the arc and then ballistically re-compressed in the final drift before the sample.

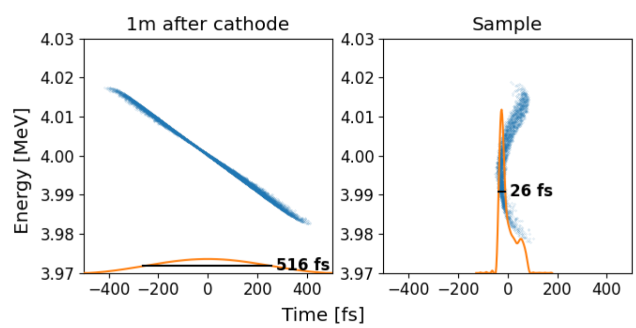

Figure 4: A comparison of the longitudinal phase space at two positions. The orange curve shows the current profile and the FWHM of the bunch is marked.

A comparison of the longitudinal phase space, for a stroboscopic mode, 1 m from the cathode and at the sample showing the compression can be seen in Fig. 4. The compressed bunch has an RMS bunch length of 33 fs and a FWHM bunch length of 26 fs. The compression is limited by the longitudinal phase space curvature due to both the second order longitudinal dispersion of the compressor (T566) and the non-linear space charge forces.

CONCLUSION

The RUEDI diffraction beamline is designed for carrying out pump-probe ultrafast electron diffraction experiments with good temporal resolution. It achieves small temporal resolution by using a four dipole arc to compress the electron bunch while also simultaneously cancelling the timing jitter. The technical design of RUEDI is currently ongoing. As part of the future work full start to end simulations of the beamline from the cathode to the detector with simulated diffraction will be done. As well as a full jitter and misalignment study looking at all contributing factors. Improvements to the design to further reduce the bunch length will also be investigated such as the addition of sextupoles to correct the T566 of the beamline or collimators in the arc to remove the longitudinal phase space non-linearities [9].

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