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STATUS OF THE RUEDI UK NATIONAL FACILITY DESIGN *

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Abstract

RUEDI (Relativistic Ultrafast Electron Diffraction & Imaging) is a recently announced facility which will deliver single-shot, time-resolved, imaging with MeV electrons, and ultrafast electron diffraction down to 10 fs timescales. RUEDI is being designed to enable the following science themes: dynamics of chemical change; materials in extreme conditions; quantum materials; energy generation, storage, and conversion; and in vivo biosciences. RUEDI will to be built at STFC's Daresbury Laboratory in the UK.

INTRODUCTION

The RUEDI project was introduced at IPAC last year [1]. It is a future facility to directly observe and measure fundamental dynamic structural and chemical processes in materials as they happen in real time. The aim of RUEDI is to deliver MeV electron diffraction at timescales down to the sub-10 fs level, in combination with time-resolved MeV electron imaging at slower (ps-scale) timescales with nm-scale resolution. A large variety of laser pump sources and sample environments will be incorporated to enable a wide variety of science to be carried out. RUEDI will be an EPSRC UK national facility, hosted at STFC Daresbury Laboratory.

A two-year design study was funded by the UKRI Infrastructure Fund, running from 2022-2024, with several design reports produced [2-4]. Full funding for RUEDI was announced in March 2024 [5], for £124.4 million, starting circa 2026. This would start a 5-year construction and commissioning programme, before handing over to user operations, for a minimum of 10 years. A further two-year design study will be performed to complete the design before capital funding arrives, this paper presents the status of the design, as presented in the latest design report [4].

The RUEDI design has evolved from the initial intention of a single beamline to provide both the imaging and diffraction modalities, to a split beamline from a single electron source, as presented at last IPAC [1], to the current design of two completely separated beamlines, as shown in Fig. 1. This allows for flexibility to optimise the design of to meet the different requirements of each beamline, in addition to separate operation.

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SCIENCE REQUIREMENTS

Dynamics of Chemical Change

This theme has a wide variety of experiments, which are carried out using pump-probe measurements that will be standard for the RUEDI diffraction line, thus enabling high throughput science. Time resolutions less than 100 fs are required, down to the sub-10 fs level, with a large variety of laser pumps. The experiments will largely be made using stroboscopic electron diffraction in the liquid and gas states, at room to high temperatures.

Energy Generation, Conversion, and Storage

This theme requires single shot and stroboscopic imaging. A range of timescales is needed, from sub-µs with sub-nm spatial resolution for single shot, to ps-scale, with ~10 nm resolution for stroboscopic. An array of laser pumps from NIR to UV (>200 nm) is required.

Biosciences

To study biology requires whole cells to be imaged specifically to determine what is happening within the cell, with spatial resolution less than 0.8 nm required within a single-shot. The MeV-level beam energy will enable liquid cells to be studied, as well as thick samples in liquid nitrogen environments. Biology happens on slow timescales, meaning sub-µs temporal resolution is all that is required. A pump laser is required for either local heating, to act as an electrical stimulus or to open membranes between cells. De-vitrification/vitrification requires a change in temperature of around 250°C, which can be achieved with a 532 nm laser. In general, low pulse energies are required to keep samples below 50°C and laser sources will be in the NIR to UV (> 200 nm) wavelength range, along with THz.

Materials in Extreme Conditions

This theme will enable a variety of unique experiments to be carried out. Most will utilise a TW laser to deliver $>10^{18}$ W.cm^{-2} intensity on the sample and probe them via single-shot electron imaging. Due to the requirements to capture irreversible processes in a single-shot, lower temporal and spatial resolution is required, to the 100 nm and ps scales.

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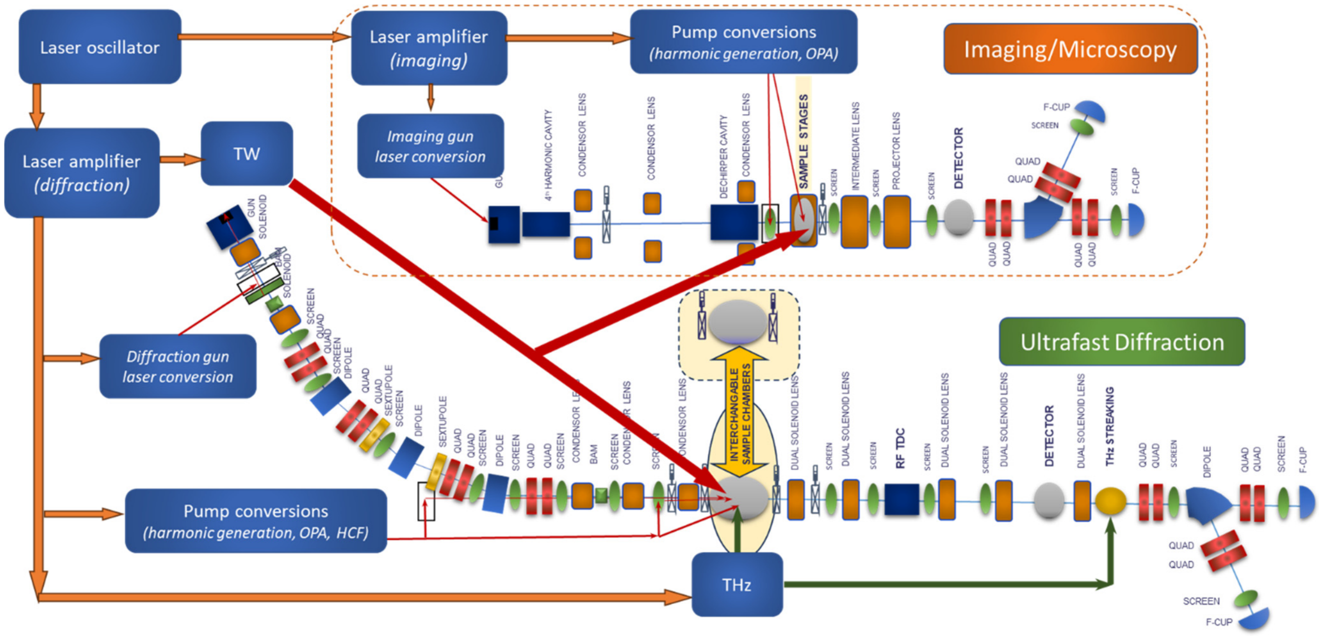

Figure 1: RUEDI schematic layout. RF cavities are shown in dark blue, dipole magnets in blue, quadrupoles in red, solenoidal lenses in orange, and diagnostic stations in green. The sample stations and detectors are shown in grey. The components of the laser system are shown in blue boxes.

Quantum Materials and Processes

To study of quantum materials, a cryogenic chamber will be included on the diffraction line to reach down to mK scale temperatures. This will enable the study of solid samples using stroboscopic diffraction to sub-100 fs resolution, with faster resolution enabling a wider range of dynamics. To pump the samples, it is envisaged that typically THz radiation, or an OPA are used, to enable the wavelength to be scanned and the subsequent behaviour monitored (possibly with appropriate THz detection). To reach the sub-10 fs time resolutions, a HCF laser source might be required.

ULTRAFAST DIFFRACTION BEAMLINE

The proposed design of the RUEDI ultrafast diffraction beamline is shown in Fig. 1. It consists of a 2.4 cell S-band RF electron gun [6], followed by a flexible magnetic transfer line designed to offer the fastest possible temporal resolutions – by simultaneously supressing the source jitter, and allowing variable compression enabling electron bunch lengths on the order of <10 fs – 1 ps to be produced. The magnetic transfer line is based on a triple bend achromat, allowing full control of the R_{56}, and sextupoles for higher order correction. This is a development of the jitter supressing beamlines introduced by [7, 8]. Fig. 2 shows beam dynamics simulations demonstrating jitter and bunch duration both down to less than 10 fs.

Flexible solenoidal-based electron optics follow this, allowing control of spot size and number of electrons onto the sample, and variable magnification post-sample onto the detector. A dedicated suite of ultrafast temporal diagnostics will be made available to diagnose the bunch length and time-of-arrival to the fs-level. These include THz streaking both at-sample and post-detector, an RF transverse deflecting cavity, and RF-cavity based beam arrival monitors. Ref. [9] this conference has more information on the longitudinal diagnostics.

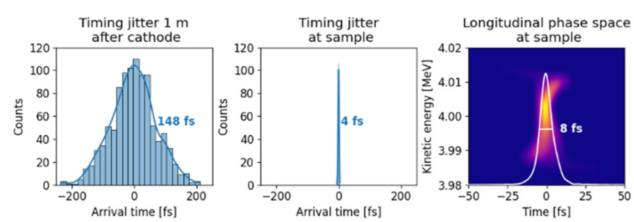

Figure 2: Beam dynamics simulations demonstrating the jitter suppression and bunch compression to the <10 fs timescales.

The sample chamber itself will be interchangeable. In the first stage, three chambers will be made available: one for solid specimens, with a high degree of sample motion control, and diagnostics; one for liquid and gas stage experiments; and a cryogenic chamber enabling temperatures down to the mK level.

IMAGING BEAMLINE

A possible design of the RUEDI imaging beam delivery line is shown in Fig. 3. It consists of an S-band RF electron gun, followed by two further RF cavities – a higher harmonic cavity for lossless monochromation, by linearising the longitudinal phase-space, and a same-harmonic cavity to reduce the beam energy just before the sample. This allows higher brightness beams to be produced from the electron source at higher beam energies, before decelerating to the maximum energy which the objective lens can focus.

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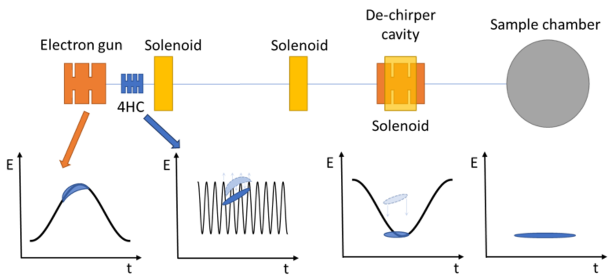

Figure 3: Schematic of a 3xRF cavity imaging injector, showing the longitudinal phase-space manipulation of each cavity.

An alternative would be to use a MeV DC electron source followed by a fast chopper [10] to provide the pulsed beams. The static source would allow for excellent spatial resolution due to the low energy spread and stability, compared to the RF system, but could not reach the ps-scale resolutions with enough electrons to form an image in a single-shot, that RF systems enable.

The sample specimens will be mounted within a solenoidal objective lens (Fig. 4) via a vacuum load-lock system. The saturation limit of the magnetic field in this lens limits the beam energy which can be imaged without increasing the aberrations. The dominant aberrations limiting the spatial resolution are the chromatic terms, which drive the need for low energy spread and stability from the electron source. Pump lasers will be injected into the objective lens, including the high intensity TW laser to enable study of matter in extreme conditions.

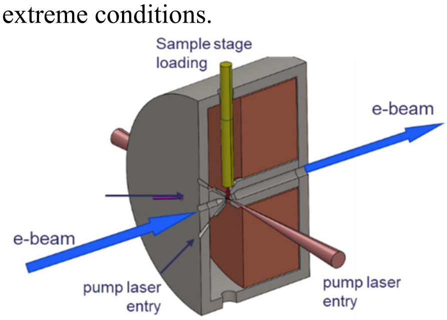

Figure 4: Schematic of a solenoidal objective lens, including sample loading, pump laser entry, and TW laser side-injection.

A number of condenser and intermediate/projector lenses, all solenoidal, will allow for beam manipulation and magnification up to 90,000 times onto the detector. This detector will be a monolithic active pixel direct electron detector, with single electron sensitivity, capable of operating in either high dynamic range mode, or high resolution (16-64 MP) mode, at repetition rates of up to 1 kHz.

The imaging beamline will utilise advances in computational imaging (including dictionary learning, image inpainting, and compressive sensing) to achieve the combination of spatial and temporal resolution required for the science themes, by drastically reducing the number of electrons required to form a single-shot image. nm-scale information will be able to be recovered from a low-dose image where only 20% of the pixels detect an electron.

LASER SYSTEMS

It is proposed to have a common laser oscillator to feed the two beamlines, which is then synchronised with all the other non-laser systems. The amplifier output is split among multiple systems, including the sample pumps, electron probes, and THz diagnostics. An additional amplification stage will produce high intensity TW pulses, which will be transported to both diffraction and imaging lines. Fig. 1 shows an outline of the laser systems and the different interfaces with the electron beamlines.

A large variety of pump laser parameters will be provided, with a range of wavelengths, pulse energies, spot sizes, and durations. Different frequencies will be provided by harmonic generation and OPAs. Laser-generated THz will also be provided as a sample pump, as well as the high intensity TW radiation. Order 10 fs scale pulse durations will be provided on the diffraction line via hollow-core fibre compression. Further pumps, including DUV/VUV generation by soliton emission, and XUV generation, by high harmonic generation could also be provided.

ENVIRONMENTAL SUSTAINABILITY

A full carbon emissions analysis has been produced in [11] with the results outlined in Fig. 5. This examined the manufacture, and the first 10 years of user operation. The main contributor in manufacturing is the concrete required for radiation shielding. Operational carbon greatly outweighs the manufacturing carbon and is largely dominated by the temperature control systems. A large contributor comes out of travel – of both staff, and users, of which long-haul flights to international conferences, dominates.

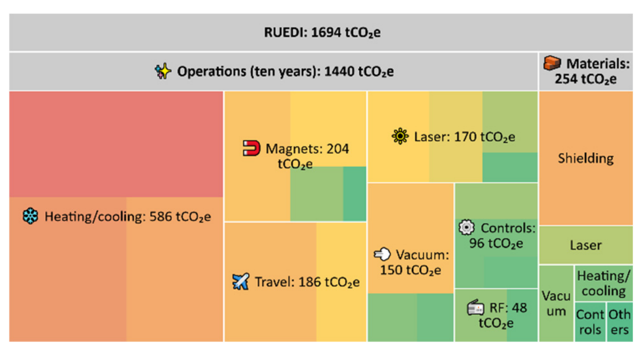

Figure 5: Carbon emissions analysis for manufacture and 10 years of user operation.

DIGITAL TWIN

A full digital twin of the instrument will be developed in parallel with construction of the physical machine. This will be based on a similar development for the CLARA facility [12]. The digital twin would enable: offline software development, machine setup characterisation and optimisation, and operator training before the physical machine is built; virtual user experiments before each user run; and, whilst operational, virtual diagnostics to allow parameters to be predicted online where no physical non-destructive diagnostic devices are available.

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