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Development of the Jyväskylä microbeam facility

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ABSTRACT

A new microbeam facility is being constructed at the 1.7 MV Pelletron Accelerator in Jyväskylä. The facility is designed for easy upgrading and incorporates a number of innovative features. Initially, it is based on a Heidelberg doublet with a design capability of a 3 × 5 μm beamspot at PIXE intensities and later upgraded to nanobeam performance. A thermal-expansion compensated rigid frame mounted on a mechanically isolated floor section is used to support the ion optical components. A compact-post focusing electrostatic deflector is used for high linearity beam scanning. This together with a novel time-stamped data collection (TDC) allows dynamic effects in IBIC, fluorescence bleaching to be studied as well as facilitating multi-resolution image support for low-fluence imaging of cells. The target chamber is fitted with a novel low-cost large working distance optical microscope, extremely compact large solid angle photon detectors as well as conventional secondary electron, PIXE and Scanning Transmission Ion Microscopy (STIM) detectors.

1. Introduction

MeV ion microbeams are powerful tools for biomedical and material research [1–5] e.g. for mapping spatial distributions of trace elements. They have the potential for sub-optical diffraction limit imaging of fluorescent labeled biomolecules [5] and have been used for microfluidics devices in biomedical applications. The DREAM (Development of REsearch with an Accelerator-Microbeam) project in the Accelerator-based materials physics group, University of Jyväskylä, is developing a new microbeam at the 1.7 MV Pelletron accelerator. This will be used for characterisation and modification of materials for biomedical research. In contrast to conventional MeV ion micro- and nanobeam systems which are capable of mapping images in two, or three lateral dimensions, DREAM will be able to map time-dispersive signals. The new microbeam is based around combining the existing setup for Programmable Proximity Aperture Lithography (PPAL) [6–8] with a Heidelberg quadrupole doublet lens [9] and post-focus scanning system. The goals of our work are to develop an instrument for, (i) tissue and cellular level imaging, (ii) extending the lithographic capabilities beyond those of the PPAL technique in MeV ion beam lithography (iii) study of transient Ion Beam Induced Charge (IBIC) effects in semiconductor devices in conjunction with the RADiation Effects Facility (RADEF) program in Jyväskylä. The initial design is anticipated to give a beam spot of 3 × 5 μm, for beam currents of 0.15 nA which is suitable for Particle Induced X-ray Emission (PIXE) analysis of tissue and large cells. The system is designed in a modular way so it can easily be upgraded by exchanging the ion optical elements and sample configuration to achieve focussing to sub-50 nm beam spots for sub-cellular level research. Here we present an overview of the DREAM microbeam project and development of the novel features which include time-stamped data collection and pattern writing system and the low-cost thermally compensated mounting of the ion-optical elements.

2. MeV microbeam line

2.1. Beamline configuration

The schematic of the accelerator microbeam is shown in Fig 1. The beam line consist of three apertures (S1, S2, S3), Faraday cup, beam blanker, a magnetic quadrupole doublet lens. The sample chamber itself contains the post-focusing deflection system, computer-controlled x-y-z sample and PPAL-aperture stages and a long-working distance optical microscope with CCD camera readout. The ion optics are conventional. The primary aperture (S1) is used to reduce the heat-load on the objective aperture (S2) by dumping off-axis beam and for current feedback to control the beam energy. It also defines an upper limit to the beam divergence.

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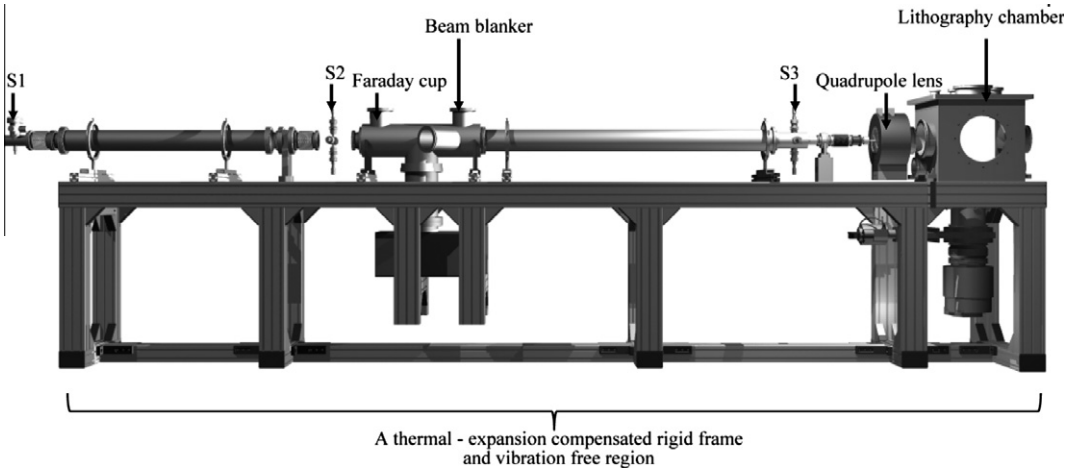

Fig. 1. Major components of the accelerator microbeam line (some components are removed for clarity).

The objective aperture, S2 defines the size of the bright object that is focused by the lens and S3 is a scraper aperture that is used for spatial filtering to control the contribution of lens aberrations on the beam spot size. Faraday cups placed after S2 and behind the target position are used for beam current monitoring.

2.2. Mechanical stability and thermal drift

Mechanical stability is of the utmost concern when working with beams on nm-μm scales. To maintain the positional stability, the beam line after S1 is supported by a rigid framework that supports the ion optical components without flexure (Fig. 1). This is important in low-demagnification systems, such as the dipole used here, because the low demagnification implies that small movements of the objective lead to significant displacement of the image spot compared to that of high demagnification systems. The supports are made from rigid extruded aluminium profiles that are anchored at a single point to a concrete base which is mechanically isolated from the accelerator. A kinematic mounting allows free expansions in the horizontal plane along the beam line. The ion optical components are maintained in at constant horizontal position and relative vertical height horizontal alignment by matched expansion. The room is free of direct sunlight that can cause different temperatures along the support frame. The ambient room temperature was found to vary by ±1.5 °C during the working day. The beam-line is pumped by a shielded ion pump and the sample chamber by a Varian V550 low-vibration turbo pump. Mechanical roughing and backing pumps are located outside of the concrete base-plate.

3. Focusing lens

3.1. Ion-optics

The new system initially uses a Heidleberg quadrupole doublet [9] for focusing the beam on the sample. The lens comprises two 40 mm long quadrupoles with 4 mm pole tip radius. The pole pieces and the yoke are make of Vacoflux 50 [10] which in solid form has a maximum permeability $\mu_r \sim 4500$ and a saturation field of ~2.25 T [11]. A maximum field gradient at the pole tips of 50 kG cm^{-1} at 3A has been estimated [10] which allows focussing of heavy ions such as 6 MeV $^{12}C^{3+}$.

The size of the beam spot is governed by the demagnified size of the object aperture and the Seidel aberrations of the demagnifying optics [9,12]. The image and object distances are 120 and 2200 mm, respectively. Compared to higher-order lenses (triplet, quadruplet), the aberrations for a doublet are relative small. Using tabulated data [9] for a Heidelberg doublet the demagnifications are 2.0 and 10 in the x and y-directions, respectively and measurement of the brightness for 2 MeV $^1H^+$. Then a 6 × 50 μm objective aperture is anticipated to give a 3 × 5.4 μm beamspot of ~0.15 nA including chromatic and spherical aberrations.

3.2. Thermal performance of the lens

Temperature gradients within the lens assembly may lead to changes in the pole-piece alignment due to thermal expansion. The temperature gradients were investigated using an i.r. imaging camera. A dummy beam tube was used for these tests to simulate its effect on cooling. It was found that with 3A excitation current and no additional cooling the temperature of all the pole pieces were 35 ± 0.5 °C and the yoke showed no temperature gradients (Fig. 2). Forced-air cooling directed perpendicular to the lens face reduced the yoke-pole-piece temperature to ~29 °C with no detectable differences in pole-piece temperatures. However, directing the air at 45° to the end face lead to a ~1 °C difference in pole-piece temperature that can be associated with the wind shadow of the beam tube. A worst-case estimate of the associated thermal shift of the pole pieces is less than 0.7 μm. This may degrade the performance of the lens by increasing aberrations. This can be important especially, if a long working distance is used.

4. Sample chamber

Fig. 3 shows the layout of components inside the sample chamber. Recently developments in MeV ion microscopy such

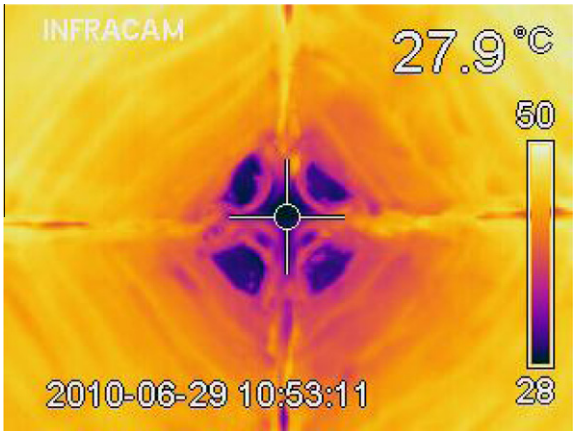

Fig. 2. Thermal imaging view of the lens at a current of 3A in each lens element.