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A novel scheme for electron optics of a high-power microfocus X-ray source for phase contrast imaging

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Abstract

Phase contrast X-ray imaging has huge potential for applications in medical radiography, imaging of biological samples, discrimination within soft tissues, non-destructive testing, environmental science and material science. An important requirement in X-ray phase contrast imaging is the spatial coherence of the source, which can be provided by electron-beam microfocus X-ray sources. To obtain better resolution and to minimize exposure times, the source power needs to be enhanced by increasing the electron-beam power. To circumvent the problem of melting of solid anode at high electron beam power, recently liquid metal jet anodes have been used. But if the power is increased using a straight electron beam, the liquid metal at the e-beam impact point may be evaporated or ionised and may flow towards the electron gun region causing repeated high voltage discharges, erosion of cathode material and metallic coatings on insulation. By bending the electron beam through ~180° or more before impact on the liquid metal jet, the vapor and ions can be prevented from entering the high voltage cathode region. A crucial requirement is that this bending does not affect the size and circular symmetry of the electron beam spot on the target so as not to affect the spatial coherence of the source. To achieve this objective, based on the principle of distortion-less bending of a converging electron beam (B Dikshit et al, *Nucl. Instr. Methods Phys. Res.* A, 596, 300 (2008)), schematic design of a high power 180° bent electron-beam microfocus X-ray source is described in this paper.

Keywords: *Microfocus X-ray sources, X-ray phase contrast imaging, medical radiography*

1. Introduction

X-ray phase contrast imaging offers greatly enhanced image quality over conventional amplitude contrast methods. It has a major potential for applications in medical radiography [1-4] especially for discrimination within soft tissues (cartilage, lungs, breast) and imaging of biological samples with low absorption, non-destructive testing in the microelectronics sector [5-6], environmental science [7], materials science [8] and cultural heritage [9]. Since the phase component of the refractive index is several orders of magnitude higher than the absorption component at X-ray wavelengths, phase change measurements generate very high contrast compared to absorption imaging, resulting in improved spatial resolution. Thus, phase-contrast imaging is superior because of its high contrast as well as high resolution. In addition, as this technique does not require the specimen to be stained, imaging of the internal details of micro-organisms and cells can be carried out without structural damage to the specimen.

A considerable number of recent experiments on X-ray phase contrast imaging have produced some extraordinary images demonstrating greatly enhanced contrast over conventional methods revealing soft tissue discrimination at micrometre scale resolutions. Since cartilage is rendered visible in phase images (as illustrated by Lewis [1]), there is considerable interest in using phase contrast to detect early degenerative changes in cartilage. Non-invasive imaging of cartilage and bone is also important for the development of successful treatments for conditions such as degenerative joint disease and osteoarthritis. Mori et al. [10] demonstrated theeffectiveness of phase information in detecting small fractures that were invisible using conventional techniques. Mollenhauer et al [11] imaged a human knee and an intact ankle joint. They found that the cartilage was not only visible but also provided distinction between morphologically degenerate and non-degenerate cartilage. In addition, the continuing rise in breast cancer incidence together with the difficulty of interpreting mammograms has led to substantial interest in the possible improvements offered by phase contrast techniques for breast cancer detection. Phase contrast has potential in this area since the breast is composed of soft tissues having similar mass absorption coefficients resulting in relatively low contrast in conventional mammograms. Several researchers have imaged breast tissues (Ingaly et al [12], Pisano et al [13] and Arfelli et al [3]) using the X-ray phase contrast technique. In all these studies, the diagnostic information related to breast cancer provided was found to be significantly enhanced relative to conventional imaging. The finding that infiltrating lobular carcinoma was better visualized than absorption imaging is of interest since this is a particularly difficult tumor to detect. Momose et al [14] demonstrated that blood vessels in an excised rat liver could be visualized without contrast agent. The large difference in the refractive index of air and soft tissue makes lungs ideal candidates for phase contrast imaging. Some recent images are truly spectacular, making it clear that phase contrast techniques offer enhanced chest radiographs [1]. Phase-contrast X-ray computed tomography (PCX-CT) has also been reported for three-dimensional observation of organic matter [4]. Similarly, in the semiconductor industry, microprocessors and IC chips require integration of more than 100 million transistors and metal interconnects with line widths of 200 nm and below. As the number of devices increases and the feature sizes become smaller, high resolution imaging is a powerful tool for process diagnostics and control during microstructure manufacturing. Unlike electron microscopy methods, imaging with keV X-rays is capable of penetrating samples several tens of micrometers thick and thus allows non-destructive study of buried nanostructures. However, the advantage of high penetration power is connected with the disadvantage of low absorption (meaning low amplitude contrast). Hence phase information for generating contrast is the method of choice; Neuhausler and Schneider [6] have reported the detection of defects and voids with a resolution of around 60 nm.

The most important requirement in X-ray phase contrast imaging is the spatial coherence of the source, which is available in synchrotron and electron-beam microfocus sources. As synchrotron facilities are too large and costly for routine use in clinical or small laboratory/industrial scale, compact electron-beam microfocus sources provide an excellent alternative for wide spread applications of X-ray phase contrast imaging. Conventionally, microfocus X-ray sources use straight axial type electron guns, in which focusing of the electron beam occurs along both perpendicular directions via a coaxial thin magnetic coil and the electron beam goes in a straight line after exiting from the focusing coil. The electron beam typically of energy 20-80 keV is focused onto a target within a circular area of diameter ~10μm. To get better image resolution (~ 1 μm) and to minimize the exposure time (important for moving objects), the brightness of microfocus X-ray sources must be very high which can be attained by increasing the electron beam power density to the order of 20-50 kW/mm^2. High electron beam power in X-ray source however can lead to melting of the solid anode. To circumvent this problem, liquid metal jet anodes have been recently used in microfocus sources, allowing the power to be increased by an order of magnitude [15]. The increase in power primarily relies on the regenerative nature of the liquid jet which replenishes the material loss from anode. However, with a straight electron beam axis, this increased e-beam power results in significant amount of evaporation of liquid metal and the resulting vapor may travel towards the cathode of electron gun causing repeated high voltage discharges and metal coatings in the insulating parts.

To circumvent this problem, the electron beam can be bent by 180° or more before hitting the liquid metal jet so that vapor and ions do not enter the high voltage cathode region. But it is essential that this bending does not affect the size of the electron beam spot on the jet which otherwise would affect the coherence properties of the source. However, if a uniform magnetic field is applied to bend an initially parallel electron beam (as in commercial transverse type electron guns), the beam is focused *only along one direction* due to geometrical crossover after 90° and 270° rotation (as shown in Fig.1). If a radially converging electron beam of circular cross section is bent by uniform magnetic field before it is focused, the electron beam spot on the target becomes elliptical, affecting the size and symmetry of the e-beam spot.

In this paper, we describe an innovative design of microfocus X-ray source based on the principle of distortion-less bending of a converging electron beam which has been recently published us [17-18]. We apply the principle in electron optics of the liquid metal jet X-ray source to increase the brightness of the source so that neither the coherence of X-ray source is affected nor the performance of the system is affected by possible vapor propagation towards the high voltage electron-emitting cathode.

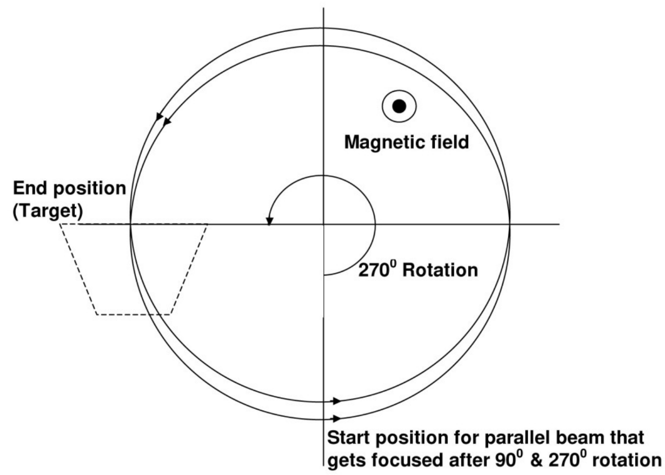

Figure 1. Focusing along one dimension by geometrical crossover in conventional transverse type electron guns

2. Principle of operation of the X-ray source

It has been analytically proven in [16] that the effect of bending on the size and shape of e-beam spot on the target can be completely eliminated by using a radially decreasing magnetic field and a specific radial electron velocity distribution. The spatially varying magnetic field intensity should satisfy

$$B = \frac{mv_{a0}}{eR} \tag{1}$$

where v_{a0} is the axial velocity of the electrons in the beam (which has to be same for all electrons), R is the radial distance from the centre of curvature of the bent beam, m is the electron mass and e is the electronic charge. The initial radial velocity of the electrons within the beam which is bent by an angle α is given by

$$v_{r0} = \frac{-v_{a0}}{\alpha \cos\theta_0} \ln\left(1 + \frac{r_0 \cos\theta_0}{R_0}\right) \tag{2}$$

where R_0 is the radius of curvature of a central ray of the e-beam and (r_0, θ_0) is the initial position of an electron on the cross sectional plane of the beam just before entering the region of magnetic field that causes the bending. In the paraxial case, when the cross-sectional diameter of electron beam is much less than the radius of curvature, equation (2) reduces a circularly symmetric radial velocity distribution as given below,

$$v_{r0} = \frac{-v_{a0} r_0}{\alpha R_0}. \tag{3}$$

Above condition given by Eq-3 can be achieved by using a coaxial thin magnetic lens. The analysis is valid for any angle of bending of the electron beam and is relativistically correct (when *m* is the relativistic mass).

Thus, the basic principle for distortion-less bending of a converging electron beam shows that the effect of bending on the size and shape of the e-beam spot on the target can be completely eliminated through a radially decreasing magnetic field given by Eq-1 and a radial velocity distribution of the electrons agreeing with Eq-3 which is simpler and can easily be implemented. Using this principle, the performance of a typical 270° bent beam axial-type electron gun has already been numerically evaluated by computer simulation of electron trajectories in the radially decreasing magnetic field [17]. This electron gun has been found to offer both the advantages (a) compact high-voltage cathode assembly placed in the geometrical shadow region of the emerging vapour and (b) a circularly symmetric electron beam spot with high power density.

3. Schematic of the proposed high power microfocus X-ray source

The conditions given by Eq-1 and 3 in an microfocus X-ray source can be achieved practically by a conical magnet pole face and a coaxial thin magnetic lens. Based on the above described principle of distortion-less bending, schematic diagram of the proposed high power 180° bent electron beam microfocus X-ray source is shown in figure 2. The x-ray source uses a liquid metal jet as the anode. Although the beam can be focused after any angle of bending, we have chosen to bend the electron beam by 180^0 as it is sufficient for avoidance of the metal vapor and schematically we get more space to place the various subsystems such as liquid metal jet, x-ray optics assembly etc. in the set-up. In this system, equation (1) is satisfied by use of conical pole faces that generate the radially decreasing bending magnetic field and equation (3) is satisfied by use of a thin focusing coil that converges the electron beam. The figure only shows the electron optics in detail. The other parts such as the liquid metal jet system and the X-ray imaging optical arrangements can be made same as described in literature [2, 15].

Of course, an important parameter that might limit the focusability of electron spot in any electron gun (straight or bent beam) is self field due to space charge effect. This effect can be estimated by solving the following beam envelope equation [19],

$$\frac{d^2r}{dz^2} = \frac{eI}{2\pi\varepsilon_0 m(\gamma\beta c)^3 r} \tag{4}$$

where r is the radius of the beam at any axial distance 'z' , $\beta = v/c$ (v is axial velocity and c is velocity of light), $\gamma = 1/\sqrt{1-v^2/c^2}$,
I = Beam current, m = Rest mass of electron,
e = Electronic charge

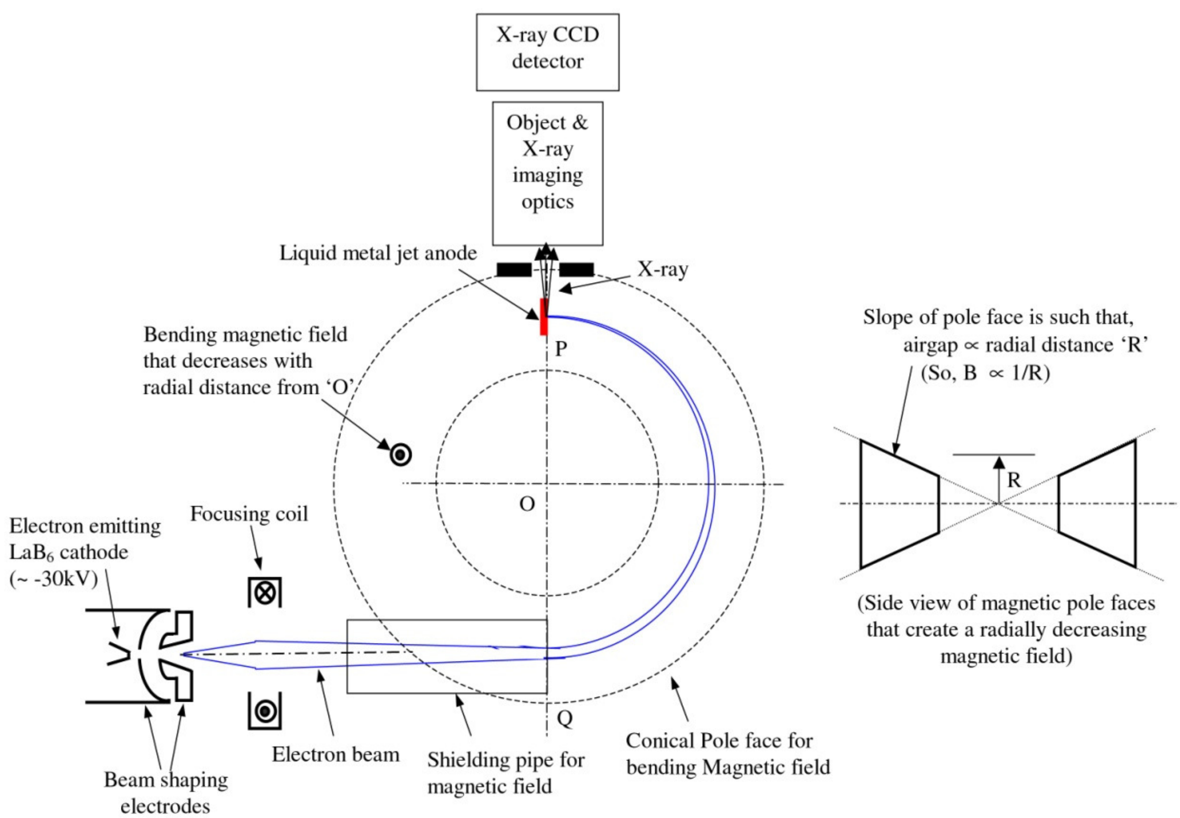

Figure 2. Schematic of the proposed high power microfocus X-ray source using a bent electron beam.

Due to very high voltage and low e-beam current in case of microfocus sources (for instance 50kV, 1-2 mA), space charge effect is found to be negligible and the minimum achievable radius of the beam limited by space charge effect is much less than 1um. So, if we are able to achieve the electron spot diameter <10 um in a straight electron gun, we can also achieve the same spot size in the bent-beam electron gun as we have eliminated the effect of bending on electron spot by specially designed magnetic field.

Thus, the use of above electron beam transportation system offers several advantages, (a) the high-voltage cathode assembly can be placed in the geometrical shadow region of the atomic vapour emerging from the liquid metal jet anode at higher powers (hence avoiding electrical discharge problems) and (b) the compact and circularly symmetric electron beam spot despite the bending of the electron beam so that the source coherence is not affected.

4. Conclusion

To conclude we find that a liquid metal jet micro-focus X-ray source based on the principle of distortion-less bending of electron beam can be operated at very high power which can ultimately result in high contrast and high resolution imaging for medical and industrial applications. State of the art high power microfocus X-ray sources are in demand for medical and industrial applications, and a compact and circular electron beam spot along with trouble free operation of the electron gun through avoidance of the vapor in the high voltage cathode region will be very effective in popularizing phase contrast imaging techniques.

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