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A nanofabricated wirescanner with free standing wires: Design, fabrication and experimental results

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ABSTRACT

Measuring the transverse size of electron beams is of crucial importance in modern accelerators, from large colliders to free electron lasers to storage rings. For this reason several kind of beam instrumentation have been developed such as optical transition radiation screens, scintillating screens, laser scanners and wire scanners. The last ones although providing only a multishot profile in one plane have demonstrated a very high resolution. Wirescanners employ thin wires with typical thickness of the order of tens of microns that are scanned across the beam, whilst ionizing radiation generated from the impact of the electrons with the wires is detected. In this paper we describe a new approach to wirescanners design based on nanofabrication technologies opening new possibilities in term of wire shape, size, material and thickness with potential for sub-micron resolution and increase flexibility for instrumentation designers. We present a device fitted with nanofabricated wires and its fabrication process. We also report the measurements performed on the FERMI FEL electron beam with the goal of providing an online profile measurement without perturbing the FEL.

1. Introduction

It is of primary importance for a large class of accelerators to control the transverse dimension of the beam, both for guaranteeing low emittance as in the free-electron lasers [1] and for meeting the design luminosity as in the colliders facilities [2]. This task is accomplished with the help of transverse profile instrumentation. Through the decades several concepts of transverse profile instrumentation have been explored depending on the specific parameters of the accelerator and the resolution requirements. Two of the most extensively deployed instruments in electron accelerators are imaging screens and wirescanners (WSC). The imaging screens are capable of providing a two dimensional profile in a single shot. Metallic screen emitting transition radiation can reach resolutions of few microns [3] but in the case of short and dense bunches they are often plagued by coherent optical transition radiation (COTR) [4]. Imaging screens based on scintillators have resolution hardly better than 10 μm [5] but COTR mitigating schemes have been developed [6,7]. The wirescanners on the other hand can provide only one dimensional multishot measurements of the beam profile but can reach better resolution than screens. Typical WSC detection is based on measurement of the ionizing radiation dose produced by the electron beam hitting the wires. For high brightness electron beams where the beam sizes are below 100 μm, the wirescanner designer has the possibility to choose amongst wires of different materials, such as tungsten, aluminum and carbon [8–10], and wire diameter, to reach the needed compromise between signal, resolution and mechanical robustness. For a detection based on ionizing radiation the thicker the wire, the larger the atomic number and density of the material the larger the signal. However this also means that a higher radiation dose is released to machine components such as electronic equipment and undulators with an augmented risk of damage. The resolution of a measurement performed with a wire of diameter d corresponds to the r.m.s. of the cylindrical distribution i.e. $d/4$ [10]. In practice the diameter of the wire is typically limited to about 5 μm.

In this paper we describe the fabrication and operation of a novel device manufactured using nanofabrication techniques providing several benefits including the potential for sub-micron resolution, a lower dose rate and the compatibility with the routine operation of an accelerator facility. Measurements of beam profile with this device were performed

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Table 1
Relative ionizing radiation dose of wires.

Type	Dimensions	Material	Rel. Yield
Wire	10 μm diameter	W	929
Wire	5 μm diameter	Al	1
Bridge	$0.5/2/0.5 \times 10$ μm	Ag/SiN/Ag	26.7
Bridge	2×10 μm	SiN	0.84

on the FERMI FEL facility. The basic idea is to nanofabricate thin bridges across a frame. By nanofabrication these structures can be made thinner and narrower than a traditional wire. Moreover using low Z materials, these new devices have a lower impact on electron beam emittance making possible to run measurements during FEL operation.

2. Device design

A 500 μm thick silicon wafer coated on both sides with a 2 μm thick low stress non-stoichiometric silicon nitride (SiN) film has been used as a substrate for the next microfabrication process. After patterning the device design on the SiN coating, the etching of the substrate allowed the release of suspended structures bridged on a 3×9 mm free window. The structures have a rectangular cross section and from now on we will refer to them as nanofabricated wires (NF wires). The resolution that can be seen as the second moment of the uniform distribution of length w is equal to $w/\sqrt{12}$. With nanofabrication the width can made as small as 0.5 μm and thus the resolution can potentially reach 0.15 μm.

The energy loss per unit thickness by bremsstrahlung of a high energy electron beam scales with the square of the atomic number Z of the target material and is linear in its density ρ [11]. For applications in intra-undulator diagnostics, as in the FERMI experiment here presented, the associated lower ionizing dose is a beneficial property since it reduces the risk of damage to the permanent magnets of the undulators. SiN has a low density $\rho(SiN)$ of 3.2 gcm^{-3} and a low effective atomic number which can be calculated according to [12] to be $Z(SiN) = 12.1$ ($Z(Si) = 14$ and that $Z(N) = 7$). The relative yield between wires of different shapes and materials can be calculated. Considering, for example, a SiN NF wire with a width of 10 μm and a thickness of 2 μm the calculated dose is 929 times less than the one generated by a 10 μm cylindrical tungsten wire ($Z(W) = 74$, $\rho(W) = 19.35$ gcm^{-3}). A comparison between cylindrical wires and NF wires can be found in Table 1. A benefit of the NF wires compared to traditional wires is that the ionizing yield can be chosen independently from the desired resolution. In our device, for example, we made a coating of silver (Ag) with thickness of 0.5 μm on both sides of the device. The Ag film increases the device dose emission of about one order of magnitude without changing the resolution.

3. Ionizing radiation simulations

A simulation with the Monte Carlo particle tracking code Fluka [13,14] has been performed to compare the radiation field created by the four wire types described in Table 1. The simulation contains exclusively electromagnetic interactions and tracks electrons and positrons down to a kinetic energy of 20 keV, photons down to 5 keV. The simulated electron beam has a Gaussian profile of $\sigma = 50$ μm and no divergence. It hits the wire centrally at $z = 0$.

For the sake of simplicity, the rest of the simulation space is empty (vacuum). For the evaluation of the radiation field in an actual accelerator, the magnetic lattice and the shape of the vacuum chamber would have to be taken into account. Fig. 1 shows that the electrons provide a fluence of ionizing radiation a few orders of magnitude larger than photons. This gives a more accurate evaluation of the fluence reported in Table 1 where only bremsstrahlung is considered.

Fig. 2 depicts the equivalent dose delivered in the plane orthogonal to the electron beam and set at 10 m downstream the impact point. The simulation evaluates almost the same dose for the 2 μm SiN NF wire and for the 5 μm Aluminum wire. It predicts 7 time higher dose for the Ag/SiN/Ag NF wire and about 160 times higher dose for the 10 μm tungsten wire.

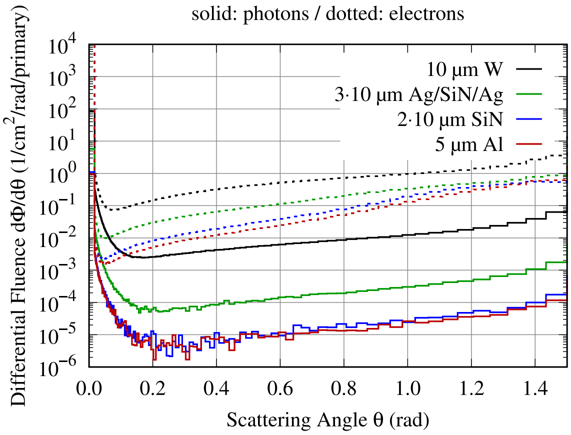

Fig. 1. Differential fluence vs scattering angle for electrons (dotted lines) and photons (solid lines).

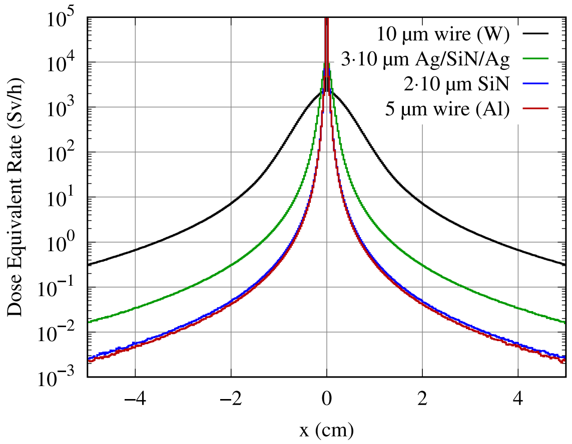

Fig. 2. Cross sectional distribution of ionizing radiation dose for different wires at a distance of 10 m from the impact point.

4. Device fabrication and characterization

The device used in the experiment has been fabricated at IOM-CNR Laboratory in Trieste, Italy. The fabrication process has been completed starting from a double side polished Silicon wafer substrate (500 μm thickness) coated by low pressure chemical vapor deposition (LPCVD) with a low stress SiN film (2 μm) and DC Sputtered chromium (100 nm). Suitable pattern has been produced on coated optical resist (MEGA-POSIT SPR220 1.2) by classical UV lithography process, defining on one side the windowing structure and, on the other one, the bridged wires. The following wet etching protocol allowed to reproduce the pattern on the Cr thin film, exploited as a mask for high aspect ratio inductively coupled plasma reactive ion etching (ICP-RIE) process for the removal of the exposed SiN layer. The sample have been transferred in KOH wet etchant solution (33% in weight, 75 °C) in order to selectively remove the Si substrate and complete the release of the suspended SiN wires. A well set protocol has been implemented in order to dry the samples avoiding to damage the obtained structures. The following metal coating step has been performed by thermal metal evaporation of silver. In order to reduce the stress induced by metal film, the deposition has been done on both sides of the device.