Nuclear Instruments and Methods in Physics Research B 383 (2016) 234–244

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Imaging the attenuation coefficients of magnetically constrained positron beams in matter

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ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 6 July 2016
Accepted 8 July 2016
Available online 7 August 2016

Keywords:
Magnetic field
Positron
Beam
Attenuation
Tomography
Imaging

ABSTRACT

This paper describes a method for tomographically imaging the linear attenuation coefficients (LACs) of positron beams in heterogeneous materials. A β^+ ray emitter such as ^{68}Ga, placed in a uniform 3T static magnetic field, generates a well-defined positron beam that maintains its spatial coherence over an attenuation of more than 10^{-3} while signaling its intensity via the annihilation radiation it generates. A positron emission tomography (PET) system embedded in the magnetic field measures the positron–electron annihilation distribution within objects illuminated by the beam. It's shown that this image can be decomposed into maps of the positron beam's flux and its material-dependent LACs without need for auxiliary measurements or transmission of the beam completely through the object. The initial implementation employs a hybrid PET/magnetic resonance imaging (MRI) scanner developed for medical applications. Mass thicknesses up to 0.55 g/cm^2 at a spatial resolution of a few millimeters have been imaged.

1. Introduction

The attenuation of β^+ rays in matter is a complex process that may involve inelastic electron scattering, elastic nuclear scattering, the formation of positronium, and ultimately, positron–electron annihilation. Measurements related to these interactions can provide useful information on material properties, such as the characterization of defect distributions in solids by means of positron lifetime spectroscopy [1]. Estimates of positron transport characteristics such as their ranges, LACs and stopping powers in known materials are important for practical applications such as PET [2,3], radiation shielding, and dosimetry [4]. The β-ray attenuation properties of a material are conventionally measured by placing uniform samples of varying thickness between a collimated β emission source and detector, and recording the transmission rate versus thickness [5,6]. One could envision extending this direct transmission method to three-dimensional (3D) β-ray transmission tomography, analogous to X-ray CT, but for β^+ rays, an alternative approach is feasible. This paper describes a novel 3D tomographic technique for non-destructively imaging β^+ ray attenuation coefficients in heterogeneous materials, referred to as *positron attenuation tomography* (PAT). It works by magnetically constraining positron beam divergence, and by using a PET camera to detect positron annihilations within the object being imaged rather than their transmission through it. The initial implementation employs a hybrid PET/MRI scanner developed for medical imaging.

An integrated PET/MRI consists of a PET system embedded in the uniform 3T $\mathbf{B}_0$ magnetic field region of an MRI scanner, as indicated schematically in Fig. 1a. When a ~1 MeV β^+ decay source such as ^{68}Ga ($E_{\max} = 1.9$ MeV) is exposed within the field of this magnet, the emitted positrons follow helical paths around the field lines with gyroradii on the order of 1 mm or less due to the action of the Lorentz force, and a non-diverging positron beam is formed parallel to $\mathbf{B}_0$ across the PET's field of view (FOV) [7]. Losses in air are modest (~1%/cm) and thus a vacuum system is not required for beam transport. The PET component can accurately image the annihilation rate along the beam within an object intersecting it by detecting the annihilation radiation generated. Such a material structure is shown in Fig. 1b. The PET image of the annihilations produced by the beam in this object is shown in Fig. 1c. The annihilation rate per unit volume quantified in a voxel of this image, λ, can be understood as the product of the axial positron flux, ϕ_z, and the LAC of the material at that point, μ_z. Further, since the only

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Abbreviations: PET, positron emission tomography; PAT, positron attenuation tomography; MRI, magnetic resonance imaging; CT, computed tomography; LAC, linear attenuation coefficient; FOV, field of view; PS, polystyrene; PE, polyethylene; FWHM, full width at half maximum; BSC, beam softening correction; 3D, three-dimensional.

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http://dx.doi.org/10.1016/j.nimb.2016.07.008
0168-583X/

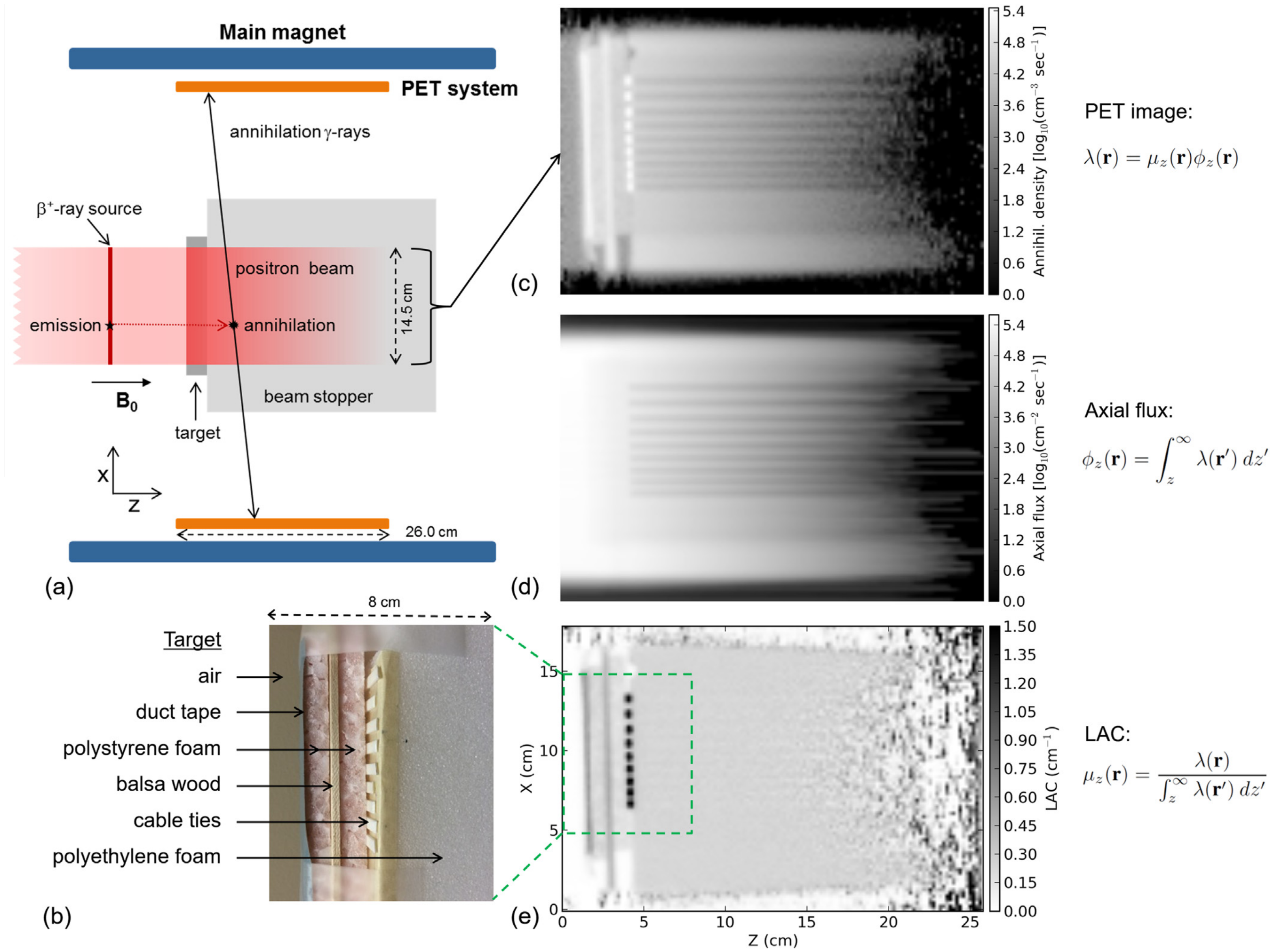

Fig. 1. (a) Schematic of an axial cross-section through the experimental configuration for positron attenuation tomography in a PET/MRI scanner (not to scale). (b) A material structure to be imaged. (c) The PET image of the annihilation rate density in the target and beam stopper. (d) The estimated positron axial flux. (e) The PAT image of the LAC distribution in the structure. The equations describe the relation between these images.

loss mechanism of positrons from the beam is annihilation with an electron, if the beam is fully stopped within the PET's FOV, the positron flux at any point can be estimated from the integral annihilation rate down-beam from that point, as shown in Fig. 1d. These two facts allow the flux and LAC components of the annihilation rate image to be distinguished. The resulting PAT LAC image is shown in Fig. 1e.

This paper begins with a discussion of the theoretical basis of PAT. Its implementation on a commercial PET/MRI system is then described, and LAC images of some example material structures are shown. The spatial coherence of the beam and the variation of the LACs due to beam softening are characterized. The issues of positron backscattering and the dependence of the image on view angle are illustrated. Supporting Monte Carlo simulations are also presented. Finally, some potential extensions and applications of PAT are discussed.

2. Theory

The attenuation of magnetically constrained positrons in matter can be discussed in terms of their axial flux $\phi_z(\mathbf{r})$ and a corresponding linear attenuation coefficient $\mu_z(\mathbf{r})$. In Appendix A it is shown that subject to certain approximations, the velocity integrated transport equation for the positron phase space density can be reduced to:

$$\frac{\partial \phi_z(\mathbf{r})}{\partial z} = -\mu_z(\mathbf{r})\phi_z(\mathbf{r}) \tag{1}$$

with

$$\mu_z(\mathbf{r}) = \frac{\phi(\mathbf{r})}{\phi_z(\mathbf{r})}\left(\frac{\rho_e(\mathbf{r})}{\phi(\mathbf{r})}\int \sigma_{\mathrm{an}}(\mathbf{r}, v)\, v f(\mathbf{r}, \mathbf{v})\, d\mathbf{v}\right). \tag{2}$$

Here $\mathbf{r} = (x, y, z)$ and $\mathbf{v} = (v_x, v_y, v_z)$ are spatial position and velocity vectors respectively, $f(\mathbf{r}, \mathbf{v})$ represents the number of positrons per unit phase space volume at $(\mathbf{r}, \mathbf{v})$, $v = \|\mathbf{v}\|$, $\rho_e(\mathbf{r})$ is the electron density, and the annihilation cross-section σ_{an} is a material property representing an average over electron states present. $\phi_z(\mathbf{r}) = \int v_z f(\mathbf{r}, \mathbf{v}) d\mathbf{v}$ is the net velocity-integrated positron flux in the axial (z) direction, and $\phi(\mathbf{r}) = \int v f(\mathbf{r}, \mathbf{v}) d\mathbf{v}$ is the total velocity-integrated flux. The factor in brackets on the right in (2) is the total flux-weighted average macroscopic annihilation cross-section of the material for the beam, Σ_{an}. In conventional narrow-beam transport scenarios the axial flux is attenuated both by scattering of particles out of the beam and their absorption within it. Here, due to the magnetic confinement, only absorption (annihilation) contributes to beam loss, but this loss is incurred by the total flux rather than just its axial component, resulting in the flux-ratio pre-factor in (2). As a consequence of this magnetic constraint, the material LACs accessible to PAT could differ from those measured by other techniques.