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Accurate 3D modeling of Cable in Conduit Conductor type superconductors by X-ray microtomography

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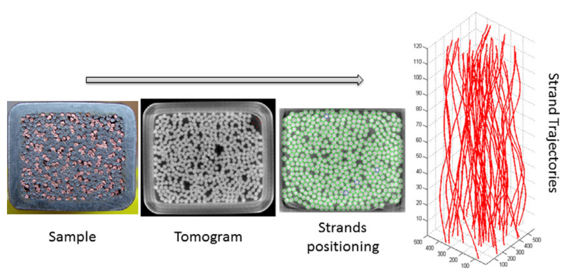
HIGHLIGHTS

- Quality controls monitoring of Cable in Conduit Conductor (CICC) by X-ray tomography.
- High resolution (≈40 μm) X-ray tomography images of CICC section up to 300 mm long.
- Assignment of vast majority of strand trajectories over relevant section of CICC.
- Non-invasive accurate measurements of local void fraction statistics.

GRAPHICAL ABSTRACT



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ABSTRACT

Operation and data acquisition of an X-ray microtomography developed at INFLPR are optimized to produce stacks of 2-D high-resolution tomographic sections of Cable in Conduit Conductor (CICC) type superconductors demanded in major fusion projects. High-resolution images for CCIC samples (486 NbTi&Cu strands of 0.81 mm diameter, jacketed in rectangular stainless steel pipes of $22 \times 26\,\text{mm}^2$) are obtained by a combination of high energy/intensity and small focus spot X-ray source and high resolution/efficiency detector array. The stack of reconstructed slices is then used for quantitative analysis consisting of accurate strand positioning, determination of the local and global void fraction and 3D strand trajectory assignment for relevant fragments of cable (~300 mm). The strand positioning algorithm is based on the application of Gabor Annular filtering followed by local maxima detection. The local void fraction is extensively mapped by employing local segmentation methods at a space resolution of about 50 sub-cells sized to be relevant to the triplet of triplet twisting pattern.

For the strand trajectory assignment part we developed a global algorithm of the linear programing type which provides the vast majority of correct strand trajectories for most practical applications. For carefully manufactured benchmark CCIC samples over 99% of the trajectories are correctly assigned. For production samples the efficiency of the algorithm is around 90%. Trajectory assignment of a high proportion of the strands is a crucial factor for the derivation of statistical properties of the cable such as twisting pattern, cos(θ) or void fraction.

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1. Introduction

Cable-in-Conduit Conductors (CICCs) are complex structures which include superconducting strands, insulation materials and stabilizing parts and therefore require the use of sophisticated modeling techniques to predict their performance. A complete description can be achieved through a multi-physics approach which combines magnetic, mechanic and electrical-thermal models. Reliable modeling depends on precise input data. As local phenomena have a major impact on the large scale magnets behavior, detailed information that account for properties at the level of cable components is needed. Retrieving local information of the 3D CICC structure, in a non-destructive way, is a task well suited for X-ray micro-tomography (μCT) [1,2]. Moreover, μCT is able to provide "as fabricated" instead of "as designed" information and to allow the development of realistic models.

The most important quantitative parameters to be retrieved by μCT are the strand trajectories (in 3D) on a relevant section of the cable and the mapping of the local void fraction. Given that the twisted multifilament structure is strongly impacting on induced currents paths during transient, the collection of real trajectories will stand as the best input possible for realistic electromagnetic modelization of coupling losses. The void fraction distribution is also a strong factor for cable immunity against transverse loads and for hydraulic properties.

2. Methods and materials

The experiments have been carried out on a high resolution X-ray micro-tomography facility in the National Institute for Laser, Plasma and Radiation Physics (INFLPR). Its main component is an open type nanofocus X-ray source with maximum high voltage of 225 kV at 30 W maximum power delivered on a transmission W target deposited on diamond window. In [2] we have tested two possible μCT scanning methods: (i) cone beam configuration (CBCT) associated with a high resolution flat panel detector (XRD 1622 from PerkinElmer) (ii) fan beam configuration (FBCT) with a line sensor based on high detection efficiency individual scintillators (X-Scan-f3-iHE from DT Detection Technology). Quality tomographic image reconstructions are obtained only in the fan beam configuration. Cross sectional slice images are achieved by sampling the line sensor at 10–20 Hz sampling rate as the part continuously rotates 360° in 1–2 min. The current configuration can accommodate samples weighting not more than 7 kg, of max.10 cm in diameter and up to 50 cm in length.

The reconstructed volume is post-processed by proprietary algorithms in order to compensate for the inherent tomography artifacts such as misalignments and beam hardening. The data processing comprises three steps: (i) strands positioning in 2D slices, which is realized by the Gabor Annular wavelet filtering and consists in determining the coordinates of the center of individual strands and their radius; (ii) void fraction calculation and (iii) strand trajectory assignment that is operated in 3D coordinates by correlating the strands of successive slices. Additionally, the space resolution achieved with this technique can provide information about the absolute topology (strand distribution inside jacket, contact statistics etc...) and the structural integrity (i.e. partially thinned by abrasion, heavily deformed or even broken strands) of the CICC.

This methodology is used for the quality control monitoring of NbTi CICC for JT-60SA TF coils. The TF conductor includes 486 strands of 0.81 mm diameter (2/3 NbTi-1/3 copper) wrapped with a thin stainless steel foil (0.1 mm) and compacted into a rectangular stainless steel jacket of $22 \times 26\,\text{mm}^2$ exterior dimensions [3]. The methodology was optimized on a benchmark CCIC sample of 100 mm and then applied to five production samples of 300 mm in length (Fig. 1) extracted from a manufactured TF unit length.

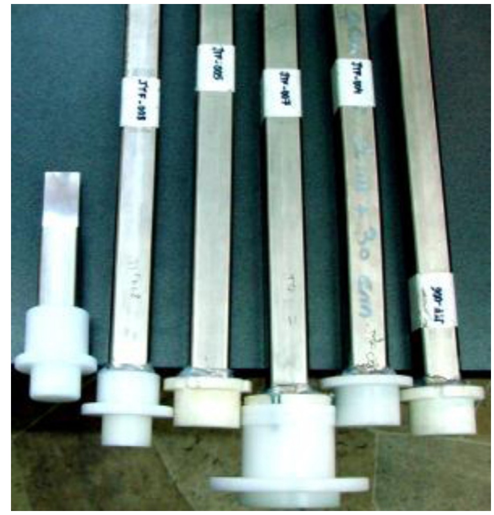

Fig. 1. Photography of the benchmark and the five productions samples with support holders.

3. Results and discussion

The space resolution achieved with this technique (~40 μm) can provide information about the structural integrity of the CCIC samples. All 486 strands are visible and their trajectories can be virtually followed. The cable pattern, the twist pitch sequence as well as strands and voids distribution, the inter-strand and strand to jacket contact regions are identifiable. The complex geometry of the wrapping foil (0.1 mm) and its structural integrity can be clearly revealed. Visually, the quality of tomographic image is slightly improved if grinding can be applied to the cable jacket (Fig. 2). This translates into detection of less spurious strands and, consequently, in better trajectory assignment. However, we estimate that with subsequent improvement of post-processing software the grinding step can be avoided.

3.1. Strand positioning

We pursued three different methods for the automatic strand positioning, which is operated at the slice level: (i) LabView IMAQ method, (ii) Circle detection by Hough Transform and (iii) Circle detection by wavelet filtering (Gabor Annular – GA filter). The

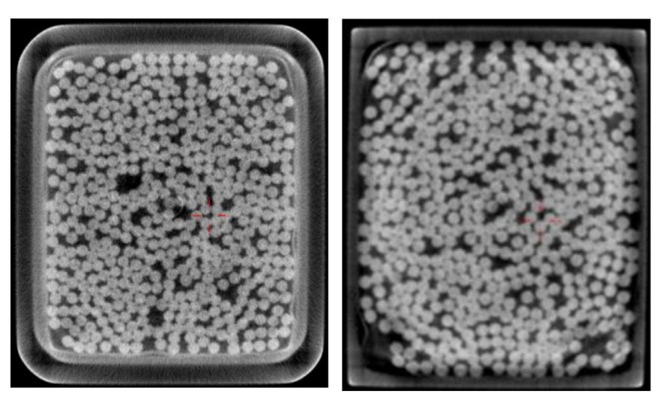

Fig. 2. Importance of jacket grinding (left image) for the tomographic image quality (strand diameter 0.81 mm, jacket exterior dimensions: $22 \times 26\,\text{mm}^2$).