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Characterization of NbTi wires for the electron-ion collider project

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Abstract. The Electron-Ion Collider (EIC) is a proposed particle accelerator to explore the behaviour of the fundamental particles and forces that bind atomic nuclei together. EIC will use several different types of superconducting strands for magnets near the interaction region (IR). In low magnetic fields at beam injection, considerable field errors are generated from magnetization currents in the superconducting strands even having very fine filaments. The accurate magnetization measurement results from those superconducting strands will be critical for the calculation and future correction of magnetic fields for EIC. In this work, we characterized three different superconductor NbTi wires. The magnetization was measured at 4.2 K and 1.9 K in magnetic fields below 1.5 T. The critical current at 4.2 K and in magnetic field down to 5 T were also measured. Other properties that are important for the safety margin of superconducting magnet such as residual-resistance-ratio (RRR), filament diameter, Cu to non-Cu ratio, twist pitch, and mechanical properties at 77 K are also presented.

1. Introduction

The Electron-Ion Collider (EIC) is a proposed machine to explore the behaviour of the fundamental particles and forces that bind atomic nuclei together [1]. In EIC, high energy and highly polarized hadron and electron beams will collide with a centre of mass energy up to 140 GeV to study the internal structure of protons and atomic nuclei [2]. The design and construction of the EIC are underway at Brookhaven National Laboratory (BNL) in collaboration with Thomas Jefferson National Accelerator Facility. The EIC will use several different types of NbTi superconducting wires for large aperture dipole and quadrupole magnets near the interaction region (IR) of the EIC. At beam injection, the magnetic field is usually very low compared with its maximum operating field. This usually creates considerable field errors mainly generated from persistent current in NbTi strands even using very fine filament. The accurate magnetization measurement results from those NbTi strands will be critical for the calculation and future correction of the magnetic fields. Other properties such as critical current, residual-resistance-ratio (RRR), filament diameter, twist pitch length and Cu/non-Cu ratio are also important parameter which impact the magnet design. In addition, the mechanical properties of NbTi wire at cryogenic temperatures are needed for mechanical design of magnet systems.

NbTi, a low Tc superconductor, has been widely used in accelerator magnets, fusion magnets, and magnets for magnetic resonance imaging (MRI). The test method for critical current [3] and other properties is well established [4]. In this paper, we present results from characterization tests of NbTi wire procured for EIC. It is also imperative to note that materials data such as these are valuable as part of the database to serve the community of superconducting magnet designers.

2. Experimental methods

Wires were fabricated by Bruker EAS. The wire diameter is 1.065 mm, with a nominal Cu/non-Cu ratio of 1.6, similar to type 01 strand used in the large hadron collider (LHC) at CERN [5]. For each of the tests described below, except for the mechanical test, three samples were tested from each of three different wires.

Magnetization measurements were performed by a vibrating sample magnetometer (VSM) using a physical property measurement system (PPMS) made by Quantum Design Inc. Small 7-turn coils measuring approximately 6 mm in outer diameter were measured.

Critical Current (I_c) measurements were performed in a 15 T superconducting magnet. Sample wire was wound on a titanium test mandrel [6]. The sample was connected to a test probe using pressure contacts. The maximum allowed current of the probe was 1000 A. The criterion of 0.1 μV/cm was used to determine the I_c with voltage tap length of 50 cm. During the measurement, the sample was immersed in a liquid helium bath. No self-field corrections were made to the measured I_c data.

Residual Resistivity Ratio (RRR) of NbTi wire was defined as the ratio of resistance between 295 K and 10 K. Samples of 150 mm long were connected in series and placed on a G10 plate. A Cernox® temperature sensor was attached to the G10 plate using GE varnish. Resistances were measured by the four-probe method with current of +/- 1 A. 10 K temperature was reached by naturally warming up the system from 4.2 K. The typical warm up rate was about 10 mK per second. Further details of above measurement methods can be found in [6], [7].

The diameters of NbTi filaments were measured from optical micrographs taken from polished wire cross-sections. Micrographs were analysed using ImageJ software. The twist pitch was measured by the incline angle of the filaments, visible after etching away the outer copper stabilizer, with respect to the wire axial direction [6]. The Cu/non-Cu ratio was measured and calculated by copper weight loss after etching by nitric acid solution (HNO_3: H_2O = 1:1) for several hours.

Mechanical properties were tested in liquid nitrogen using a universal test machine (MTS corporation). Aluminium grips designed for testing wires were used as shown in figure 1. A 25 mm clip-on extensometer (Epsilon Technology) calibrated at 77 K was used for strain measurements.

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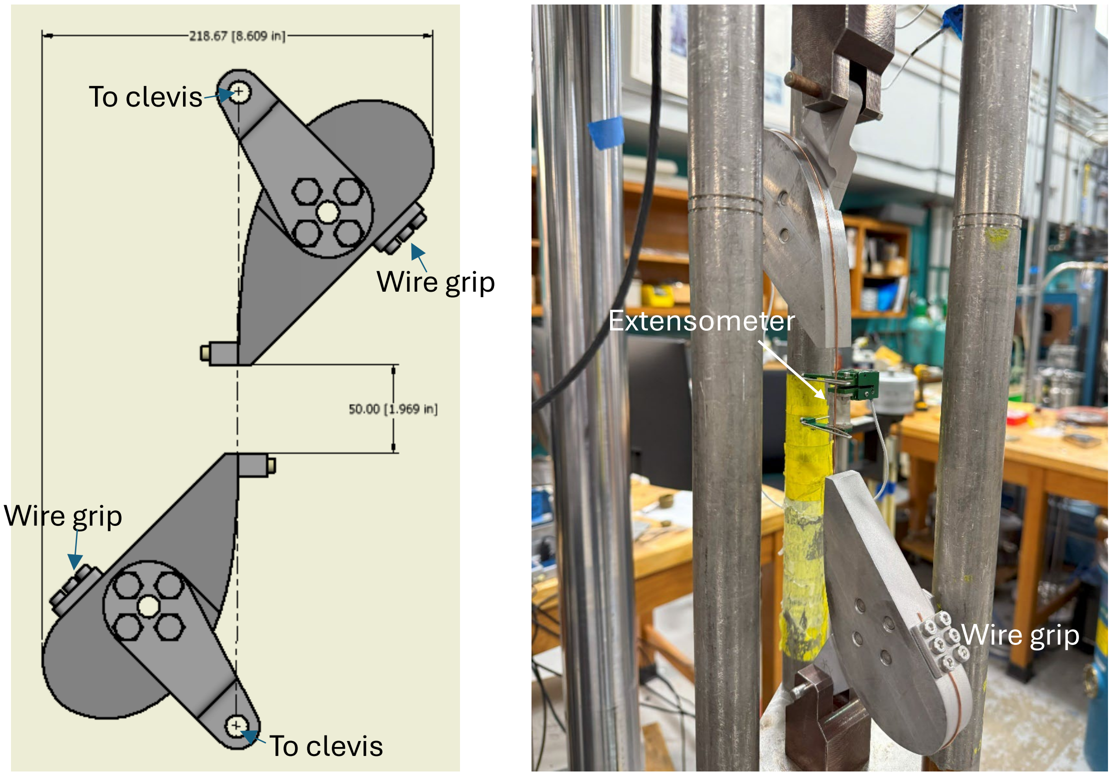

Figure 1. Mechanical testing of NbTi wire. (a) wire grip design. (b) a sample mounted on the grips with an extensometer on the MTS machine.

3. Results and discussions

3.1 Room temperature measurements

Figure 2 shows cross-section micrographs of two types of wires. The individual filaments are clearly resolved in Figure 2(c) and 2(d). After etching away the outer copper stabilizer, the twisting of filaments are revealed as shown in Figure 3. From the observed incline angle α, the twist pitch is calculated. Table 1 summarizes the room temperature measurement results.

Table 1. Geometric characterization of NbTi wire.

Sample ID	Filament diameter (μm)		Cu/non-Cu ratio		Twist pitch (mm)	
	Mean	stdev*	Mean	stdev*	Mean	stdev*
113776AA	9.8	1.5	1.59	0.02	18.7	1.2
114010AA	6.5	1.4	1.67	0.01	19.7	0.6
114052BA	6.5	1.7	1.69	0.01	21.4	1.6

*stdev = Standard Deviation

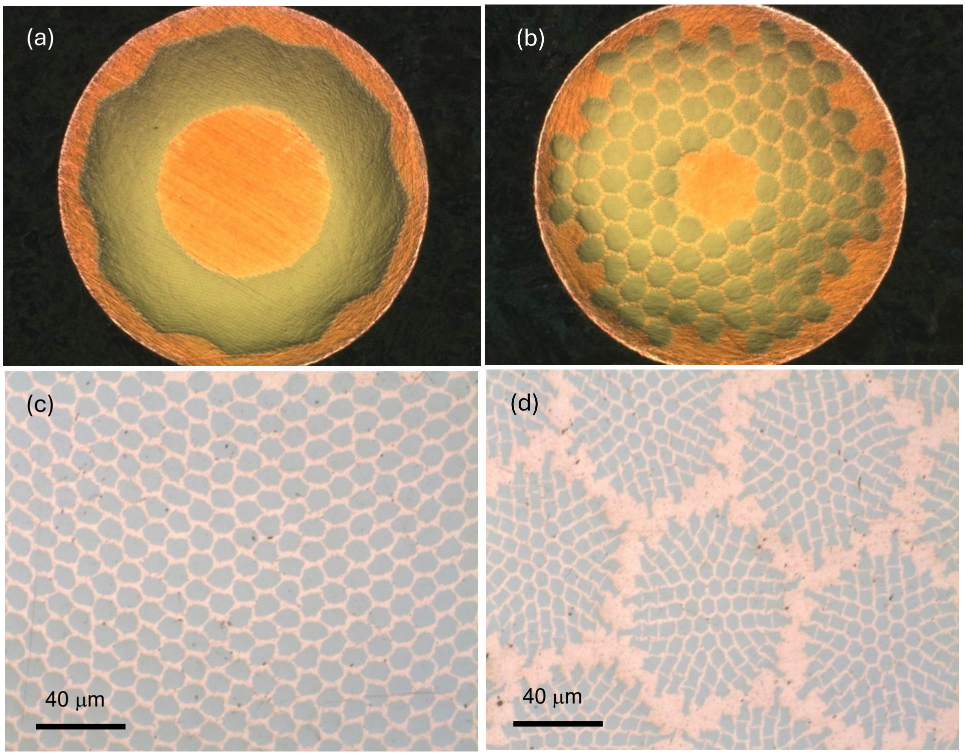

Figure 2. (a) and (b) cross-sections of wires 113776AA and 114010AA respectively. The architecture of 114052BA is the same as 114010AA. (c) and (d) the corresponding high magnification micrographs used to measure filament diameters.

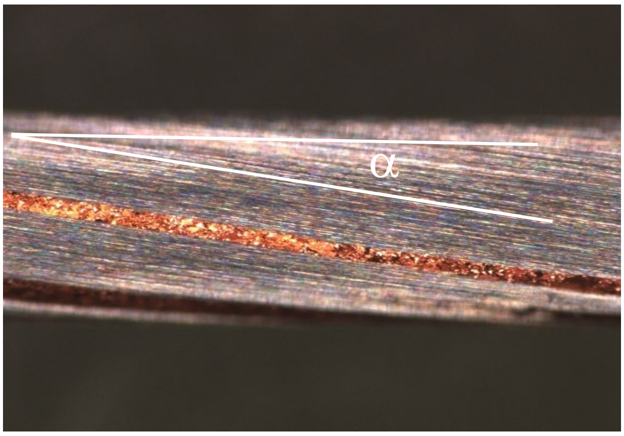

Figure 3. The 113776AA wire after the outer copper stabilizer is removed by nitric acid. The incline angle α is used to calculate twist pitch.

3.2 Critical current and RRR

The I_c and RRR results are shown in Table 2. The RRR values are as expected for LHC strands of > 150 [8]. The variation in I_c among the three tests for each billet is less than 1%. The average I_c is plotted against the applied magnetic field as shown in figure 4. The measured I_c values are slightly greater than the LHC wire specification of > 532 A at 7 T and 4.2 K [9]. The specificatin of LHC wire I_c is also ploted in figure 4 for comparison.

3.3. Magnetization

Figure 5 (a) shows the initial magnetization curves up to 0.5 T for two different wires. Higher magnetization corresponds to the wire with larger filament diameter. For instance, the magnetization at 0.2 T for 113776AA is about 1.3 times larger than that of 114010AA, while the filament of 113776AA is about 1.5 times larger than that of 114010AA (Table 1). Figure 5 (b) compares the 0 – 1.5 T – 0 loops of 114010AA measured at 4.2 K and 1.9 K. The 2 K data from LHC type 01 NbTi strand is reproduced from [10] and plotted as the dash line for reference.

3.4. Stress strain curves

Figure 6 shows three stress strain curves from 114010AA samples at 77 K. An initial load of 50 N is applied to eliminate the error introduced by wire bending. The stess-strain curves can be seen to have a slope change at about 250 MPa. This is attributed to the yielding of Cu in the Cu-NbTi composite wire. Between 250 and 800 MPa, the stress-strain is approximately linear. The apparent modulus can be obtained in this quasilinear region, which is about 33 GPa. The resultant apparent modulus can be roughly explained by the rule of mixture of Cu and NbTi in the composite wire, where modulus of NbTi filaments is about 60 - 70 GPa at room temperature [11] and Cu is yielded at these stress levels. The ultimate tensile strength are about 1.0 GPa. Table 3 summarizes these properties with standard deviations as errors. One of three samples was unloaded from 0.01 to 0.005 strain then reloaded. Prominent hysteresis during the unload-reload is observed. Each test was terminated when the specimen factured which occured outside the extensometer region.

Table 2. Critical current and RRR.

Sample	RRR	7.5 T		7 T		6.5 T		6 T		5.5 T		5.0 T	
		I_c	n	I_c	n	I_c	n	I_c	n	I_c	n	I_c	n
113776AA-1	209	469	26	577	30	688	34	796	38	907	38	>1000	
-2	214	469	28	577	32	688	36	799	39	907	44	>1000	
-3	208	469	25	580	31	688	34	799	39	907	38	>1000	
114010AA-1	280	466	25	563	31	664	29	765	35	865	30	958	30
-2	276	475	26	568	27	673	30	766	31	868	32	961	30
-3	279	466	29	565	29	664	33	766	34	865	35	961	35
114052BA-1	209	448	24	550	28	646	29	742	31	838	32	934	30
-2	201	451	26	550	29	649	30	745	32	841	33	929	Q
-3	204	454	25	553	27	649	29	745	30	841	32	929	31

* Q is quenched before transition.

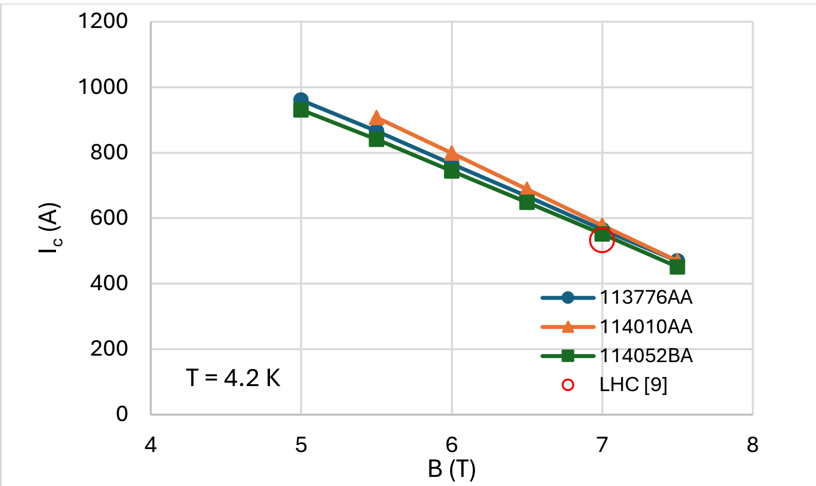

Figure 4. Average I_c versus B of samples from the three wires. Specification of LHC type 01 wire minimum I_c [9] is shown as the empty circle for reference.

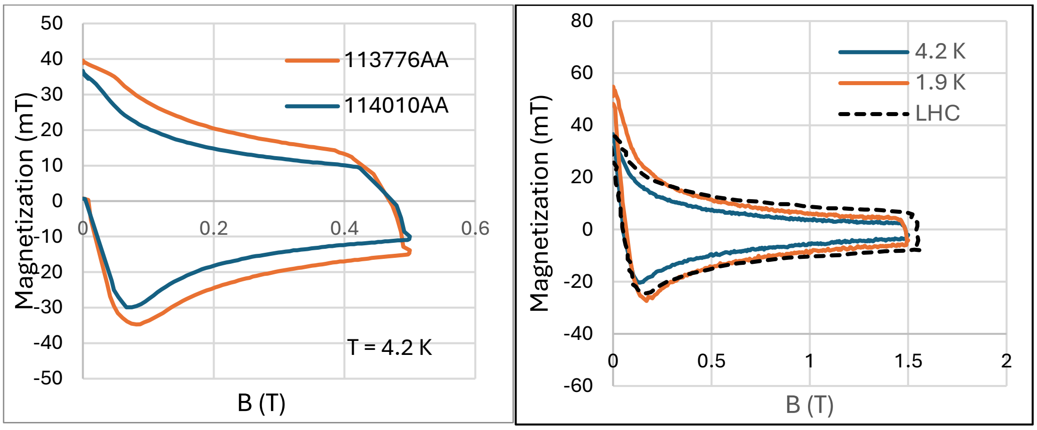

Figure 5. Magnetization versus applied magnetic field: (a) the initial magnetization (0 – 0.5 -0 T) comparison of wires with different designs. A larger filament diameter corresponds to a higher magnetization, (b) 1.5 - 0 -1.5 T at 4.2 K and 1.9 K of 114010AA wire. The magnetization of LHC type 01 wire at 2 K is reproduced from [10] and plotted for comparison.

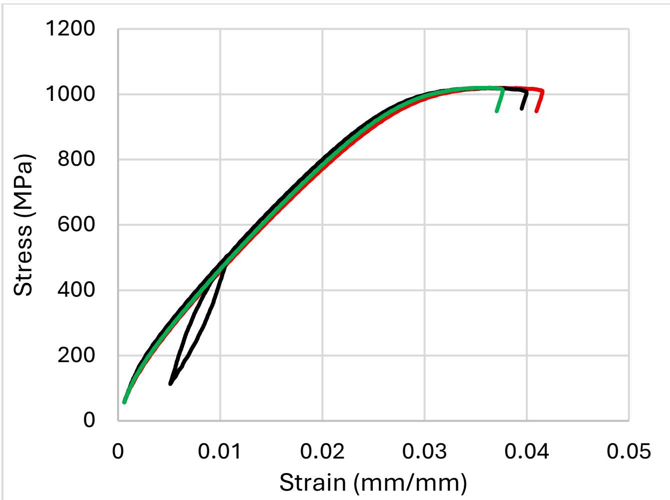

Figure 6. Stress-strain curves of 1114010AA NbTi wires (3) at 77 K.

Table 3. Mechanical properties of NbTi wire at 77 K

ID	# of test	Apparent Modulus* (GPa)	UTS (MPa)	Strain at failure (%)
113776AA	1	33.5	972	3.9
114010AA	3	32.6 ± 0.9	1020 ± 0.4	3.9 ± 0.2
114052BA	2	33.3 ± 0.1	1017 ± 5.5	3.8 ± 0.01

*Apparent modulus is obtained from data between 250 and 800 MPa. The errors presented are standard deviations.

4. Summary of results

In this work, magnetization, critical current, RRR, filament diameter, Cu/non-Cu ratio, twist pitch and the mechanical properties of NbTi wires used for EIC design studies are characterized. Magnetization, I_c at 4.2 K, RRR, filament diameter, twist pitch are comparable to the type 01 wires of the LHC. The magnetization is measured at both 4.2 K and 1.9 K. Larger filament diameter corresponds to higher magnetization. Mechanical testing is performed at 77 K. The ultimate tensile strength is about 1.0 GPa. The apparent modulus between 250 and 800 MPa is 33 GPa.

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