Ion Irradiation facility with Performance Online Monitoring for High Temperature Superconducting Tape

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ABSTRACT

A ultra-compact multi-particle superconducting cyclotron is currently under construction at the China Institute of Atomic Energy (CIAE). It is designed for the irradiation modification of high-temperature superconducting (HTS) tapes and medical isotope 211At production. An ion irradiation facility with online monitoring of temperature and critical current performance for HTS tapes have been designed. The facility comprises the following systems: 1) Beam transport system: A dual-scatterer method is employed to shape the beam, thereby generating a large-area, highly uniform beam spot. This approach yields a uniform beam spot of no less than 4 × 4 cm² at the irradiation terminal, with a uniformity exceeding 90%. 2) Ion irradiation terminal: This terminal features a high-precision roll-to-roll transport system, a high-vacuum system, an efficient cooling system, and a in house developed online monitoring system for temperature and critical current performance. It enables real-time monitoring of temperature changes during the continuous ion irradiation process, as well as real-time, non-destructive measurement of the critical current of HTS tapes. This capability facilitates dynamic research into the relationship between irradiation-induced damage and the degradation of HTS critical current performance. This facility combines advanced accelerator beam technology, high efficiency cooling system, high vacuum technology, and real-time monitoring and diagnostic techniques, providing a stable, efficient, and fully functional comprehensive experimental device for deeply revealing the mechanism of ion irradiation on the micro-defects and critical current performance of HTS tapes. This facility will be presented in detail in the paper.

Overview of the 36MeV LTS cyclotron

The multi-purpose ultra-compact superconducting cyclotron independently developed by the China Institute of Atomic Energy (CIAE) is capable of delivering a 9 MeV@1 mA proton beam and a 36 MeV@50 μA alpha particle beam, serving both industrial irradiation and medical and healthcare applications. In the industrial domain, this accelerator can be used for proton-irradiation-induced artificial pinning modification of superconducting tapes and for studying the mechanisms of alpha-particle-induced soft errors in integrated circuits. In the medical field, it can be applied to the batch production of At-211 radionuclides, PET and SPECT isotopes, as well as to studies of space radiobiological effects.

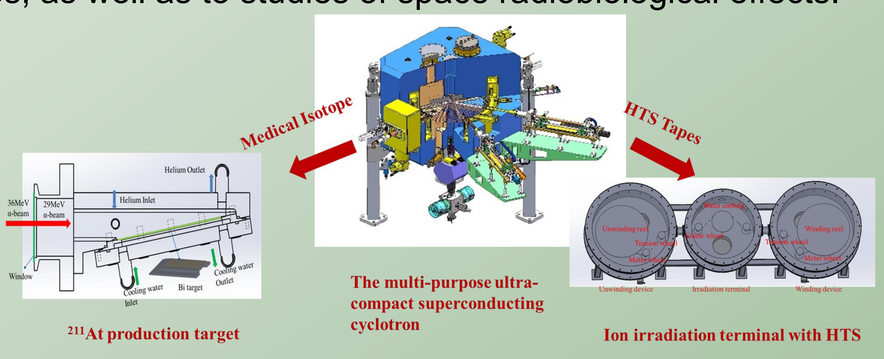

Fig .1 The superconducting cyclotron and applications

Roll-to-Roll Transport System

To achieve coordinated constant-tension and constant-speed control, this work combines a servo motor with a magnetic powder clutch.1）Constant speed: A slip-free length-measuring wheel provides high-frequency feedback. With a ≤10 ms control cycle, closed-loop speed adjustment maintains tape speed fluctuation within ±0.5% in the irradiation zone. At 200 m/h, dynamic recovery time ≤50 ms, eliminating speed-induced fluence non-uniformity.2）Constant tension: A speed-mode strategy with tension limiting is adopted. The unwind shaft uses feedforward speed based on real-time coil diameter; the take-up shaft applies PID correction from speed deviation. A 1 kHz tension sensor triggers speed limiting or active slackening when fluctuations exceed ±5%, preventing tape damage and ensuring synergistic stability.

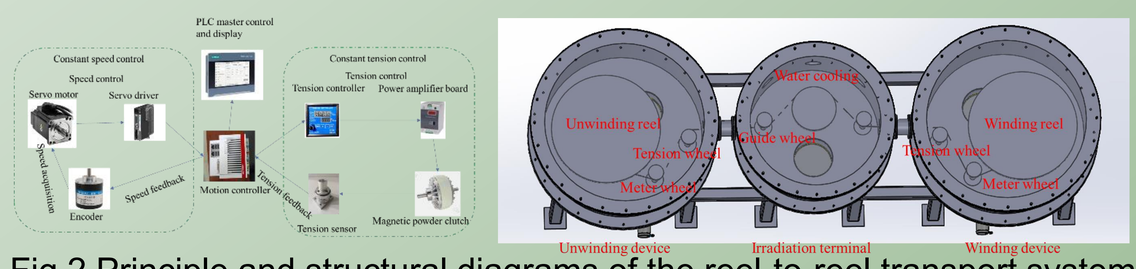

Fig.2 Principle and structural diagrams of the reel-to-reel transport system

Online Temperature Monitoring System

If heat from high-energy ion beam bombardment of superconducting tapes is not promptly removed, the resultant temperature rise causes two adverse effects: (1) annealing that restores irradiation-induced defects, hindering pinning center formation; and (2) heat accumulation leading to tape melting and performance degradation. To address this, a hybrid cooling structure (water-cooled copper block + graphite plate) and a dual-sensor closed-loop temperature control system (PT100 and infrared pyrometer) are designed. When the monitored temperature exceeds a safety threshold, the system automatically adjusts cooling water flow rate, tape speed, or beam fluence rate within the response time, achieving dynamic thermal balance through multi-parameter coordination.

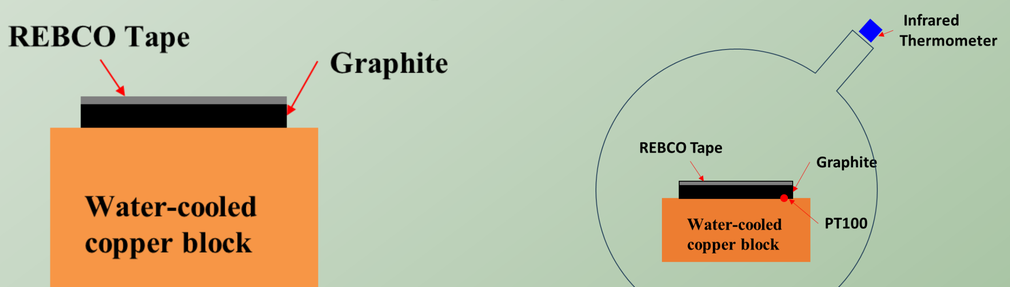

Fig.3 Schematic diagram of the cooling device principle

Online Real-Time Monitoring of Ic

During continuous proton irradiation, the uniformity of irradiation dose along the length direction of the superconducting tape directly determines the stability of its critical performance. However, in engineering production, factors such as beam non-uniformity and non-uniformity in reel-to-reel transport speed are difficult to completely eliminate, which may lead to inhomogeneous critical current (Ic) along the tape length. To address this issue, an online nondestructive real-time critical performance detection module is integrated into the reel-to-reel proton irradiation terminal, which operates synchronously with the irradiation transport system, thereby establishing a closed-loop “irradiation-detection-feedback” engineering system.

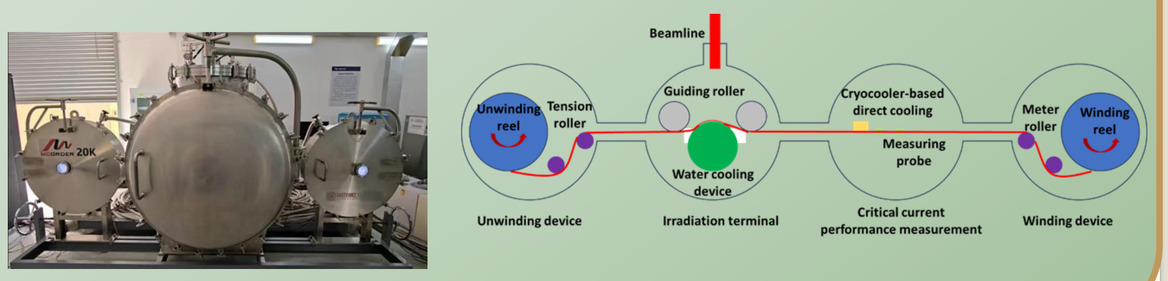

Fig.4 Ic monitoring device and integration with the irradiation terminal

conclusion

To counter REBCO tape performance degradation, a reel-to-reel proton irradiation system with online monitoring was developed using a 36 MeV cyclotron. It provides constant tension/speed control (±0.5% speed fluctuation), double-scatterer beam broadening with 100Hz fluence feedback (fluence deviation ±5%), and composite cooling with dual temperature sensors to suppress annealing. An online magnetization-based critical current module (≤50 ms) enables closed-loop irradiation–characterization–feedback, allowing hundred-meter tape modification to enhance in-field Jc. This elucidates proton pinning mechanisms in doped/non-doped tapes, supporting industrial batch modification.