COMMISSIONING OF THE CHINESE LARGEST SUPERCONDUCTING HIGH-FLUX LINEAR PLASMA DEVICE SWORD

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Abstract

The paper reports status of the linear plasma device SWORD at ASIPP, as an effort to address prominent plasma material interaction issues in current and future fusion devices. A unique goal of SWORD is set to produce hydrogen plasmas with a peak particle flux > 10^{25} m^{-2} s^{-1}, a peak heat flux > 80 MW m^{-2} and a beam size > 20 mm simultaneously. Accordingly, key subsystem designs enabling this goal are described. Encouraging He first plasmas with a flux greater than 10^{24} m^{-2} s^{-1} and a duration greater than 1000 s have been achieved in January 2025.

1. INTRODUCTION

While linear plasma devices (LPDs) have long been exploited to understand plasma surface interactions (PSI) in fusion devices, their particle/heat fluxes are lower than those expected in ITER and DEMO, leaving much uncertainty in extrapolating the results from LPDs to future fusion devices. Magnum-PSI located in DIFFER is the first LPD to produce >10^{24} $m^{-2}s^{-1}$ hydrogen plasmas with a cascade arc source [1]. However, its plasma temperature is typically lower than 5 eV and beam size is smaller than 15 mm [2]. MPEX located in Oak Ridge National laboratory, on the other hand, plans to produce high-density plasmas with a helicon plasma source, followed by electron cyclotron heating and ion cyclotron heating to increase the electron and ion temperatures [3]. However, this project seems to have experienced huge delay as its final design is completed in 2023, which is already 10 years after its start.

Motivated by the great need of high-flux LPDs to qualify plasma facing components to support China's fusion roadmap but with a limited time budget, we have been building the linear plasma device SWORD (Superconducting plasma Wall interactiOn lineaR Device) based on the cascade arc plasma source technology since 2019. Besides design philosophy of Magnum-PSI and MPEX, improved understanding of PSI in fusion devices over the years have shaped our idea of what plasmas we wish to produce with SWORD. As explained in Ref. [4], a unique capability of SWORD will be to produce hydrogen plasmas with a peak particle flux > 10^{25} m^{-2} s^{-1}, a peak heat flux > 80 MW m^{-2} and a beam size > 20 mm simultaneously. This high-level requirement put constraints on the subsystems, as described in the next section.

2. KEY SUBSYSTEMS

2.1 Plasma source system

Fig. 1 shows a schematic drawing of the cascade arc source used in SWORD. Because strong magnetic fields are used to confine plasmas, the beam size is approximately the inner diameter of the discharge channel of the plasma source. For example, the bore size in Magnum-PSI is 7 mm, which results in a typical beam size (full width at half maximum) of ~10 mm. To obtain a 20 mm beam size implies a bore size of 15-20 mm. SWORD will be the first LPD to operate with such a large bore cascade arc plasma source. The gas flow inside the discharge channel obeys the Poiseuille law ($p \propto \Phi^{0.5} d^{-2}$) [5], doubling the bore diameter (d) while maintaining the inlet pressure (p) requires a 16-fold inlet gas flow (Φ). A 2 SLM gas flow that works in Magnum-PSI projects to a 32 SLM gas flow in SWORD. Discharge characteristics of such a large bore cascade arc source are actively being investigated.

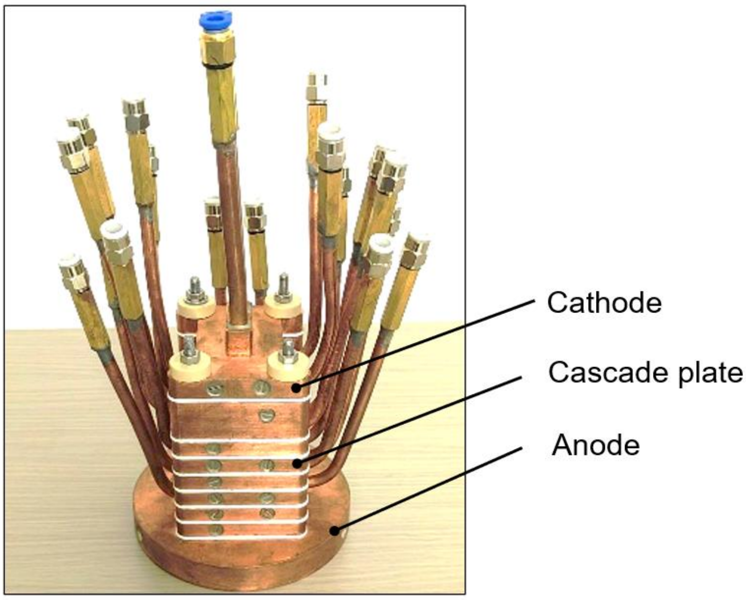

Fig. 1. Photo of the cascade arc source.

2.2 Vacuum system

Differential pumping will be used to pump away the high gas load at the source while maintaining a low neutral pressure near the target. Fig. 2 shows the current design of the vacuum vessel, which is divided into three separate chambers by two gas diaphragms. Each chamber is pumped by its own pump station with a total pump capacity of ~40000 m^3h^{-1}. The design is still being optimized based on gas flow dynamics. Preliminary modelling indicates that the neutral pressure in the target chamber is below 1 Pa with a hydrogen gas flow of 20 SLM.

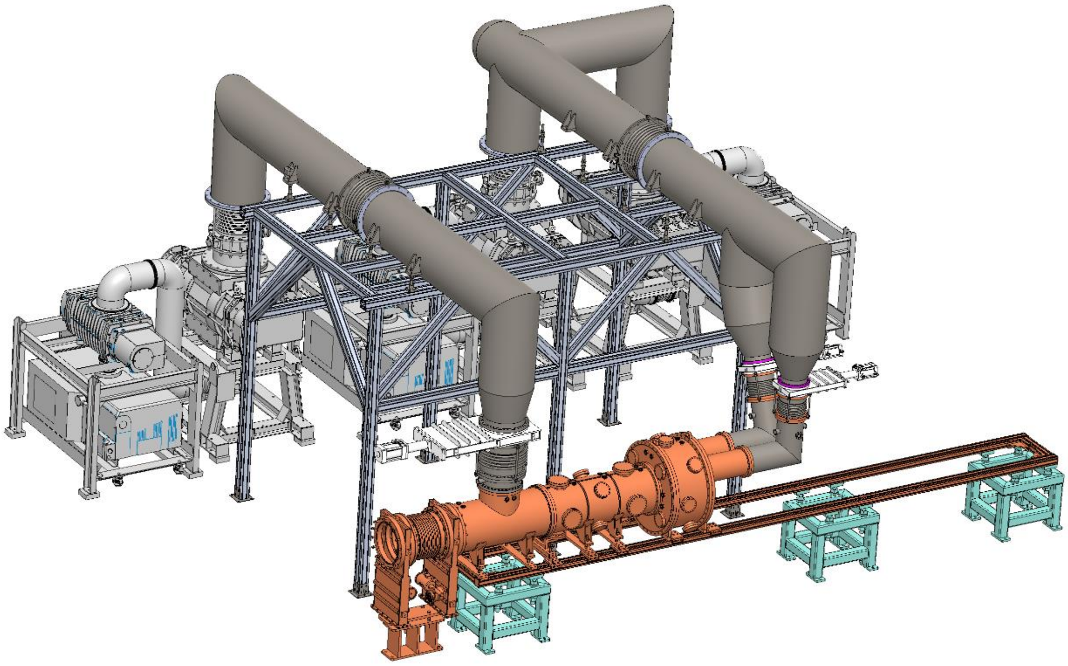

Fig. 2. SWORD vacuum system.

2.3 Superconducting magnet system

The design drawing of the superconducting magnet is shown in Fig. 3. The important dimensions are given in mm. It features a 1210 mm inner bore and 3 T maximum magnetic field, which uniformly spans a volume of ~diameter 120 mm × 1200 mm. NbTi superconducting coils cooled with liquid helium using a zero boil-off system generate the required steady-state high fields. It passed the factory acceptance tests in 2024. However, during on-site testing it quenched after just reaching 3 T. Subsequent tests were run below 0.6 T to avoid further damage. It was then sent back to the manufacturer for repair. The latest estimate is that it will be sent back to us in November 2025.

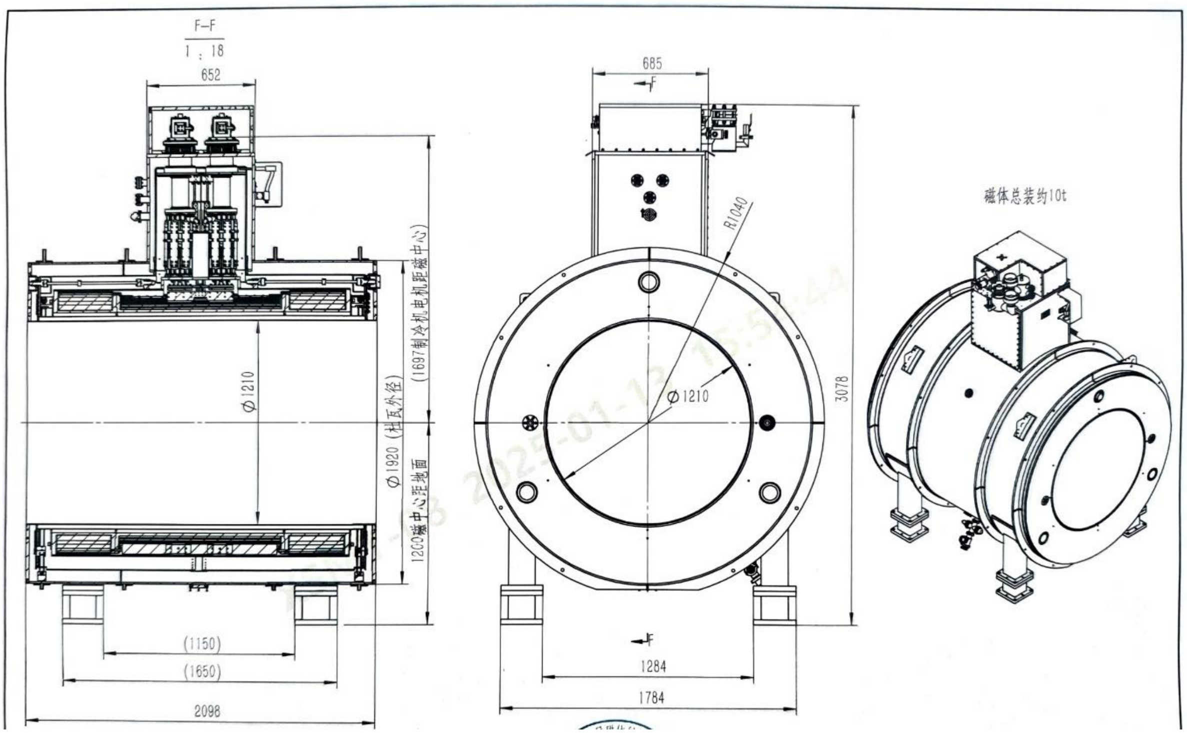

Fig. 3. Design drawing of the superconducting magnet of SWORD.

2.4 Diagnostic system

The large inner bore of the superconducting magnet enables multiple diagnostics in the periscope configuration. The visible light viewing module is illustrated in Fig. 4. It has a focal length of 37 mm, a magnification of 0.08, and a pixel size of $11 \times 11\ \mu m^2$. The lenses are sealed in vacuum to reduce dust and water vapour contamination. Additional diagnostics include Thomson scattering, IR cameras, pyrometer, LIBS, Langmuir probes, optical emission spectroscopy and multiple temperature sensors and pressure gauges.

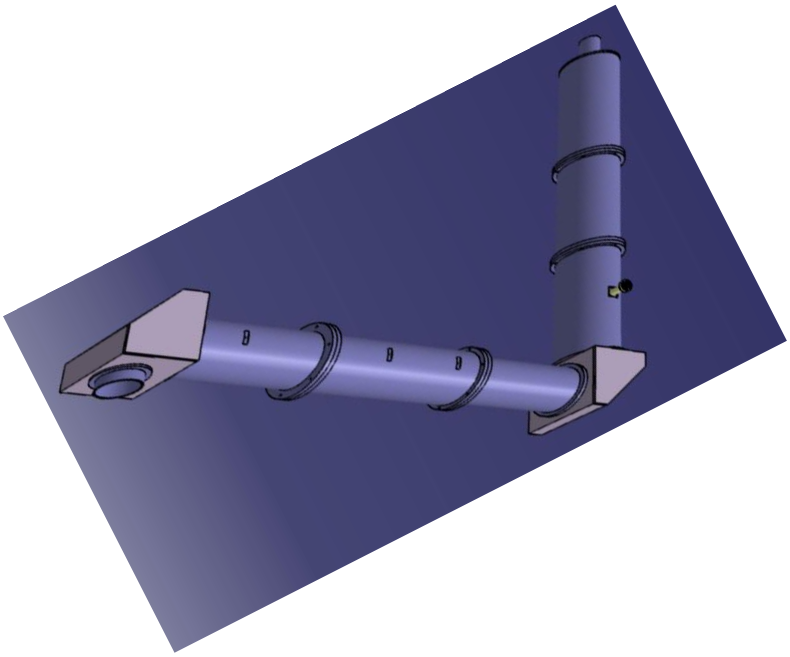

Fig. 4. Design drawing of the visible light viewing module of SWORD.

3. ASSEMBLING AND FIRST PLASMA

The subsystems were assembled in January 2025 (Fig. 5) and obtained its first plasma smoothly. Encouragingly, with only a 0.6 T magnetic field, we achieved >10^{24} m^{-2} s^{-1} and >1000 s He plasma discharges in steady-state [4]. Such high-flux long discharges have only been reported by Magnum-PSI. Note that such discharges were conducted with a 7 mm bore 'standard' cascade arc plasma source and only one pump station was used. When the superconducting magnet returns, we will explore the limit of SWORD and upgrade it accordingly.

Fig. 5. Photo of SWORD in January 2025.

4. CONCLUSION AND OUTLOOK

A superconducting high-flux linear plasma device named SWORD is under commission at ASIPP. Promising first plasma were obtained despite technical issue of the superconducting magnet. Further tests are scheduled to produce hydrogen plasmas in the strongly coupled regime, which is expected to enable unique experiments for exploring detachment physics and quantification of plasma facing materials.

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