**Optimization and Active Stabilization of a Far-Infrared Laser for NSTX-U High Poloidal WavenumberScattering Diagnostics**

**Abstract**

The far-infrared (FIR) laser output beam power and pattern are critical parameters in laser-aided diagnostics, directly influencing the spatial resolution and signal-to-noise ratio of measurements. This work focuses on developing a systematic control method to enhance FIR laser beam quality through optimized mirror alignment and real-time feedback-based precision cavity length tuning. A high-power CO₂ laser, aligned with the waveguide axis using a HeNe reference laser, serves as the pump source. The sensitivity of FIR beam intensity to pump gas pressure and thermal expansion is investigated, revealing that even a 1 μm cavity expansion can significantly degrade output power stability. To address this, a feedback control module has been designed and implemented for active cavity length adjustment, stabilizing the output power at approximately 30 mW. Additionally, maintaining a high formic acid gas pressure (>190 mTorr) within the cavity ensures reliable operation. The optimized FIR laser will be deployed on the NSTX-U high poloidal wavenumber scattering system for studying electron-scale turbulence in tokamak plasmas.

**Section I: Introduction**

Transport is one of the key research topics in fusion plasma physics. In experiments conducted on the NSTX device, electron-scale transport has been observed to exceed neoclassical transport predictions by a significant margin [ref]. This elevated transport can lead to substantial particle and thermal losses, ultimately degrading plasma confinement. Consequently, understanding and controlling electron dynamics is critical for the successful operation of tokamaks. The NSTX-U device, with its distinctive high-beta and low-collisionality conditions, provides an ideal platform for investigating electron-scale turbulence. This study will systematically explore how turbulence characteristics vary with essential parameters such as collisionality, the q-profile, and E×B shear, aiming to identify the mechanisms that govern confinement scaling. An essential diagnostics system in this investigation is the 693 GHz, 8-channel millimeter-wave poloidal scattering system, which will measure electron-scale turbulence across the plasma core to edge (normalized radius from 0.2 to 1) with a poloidal wavenumber range of 7 to ~40 cm−1. This capability enables comprehensive coverage of the predicted electron temperature gradient (ETG) and other electron-scale turbulence spectra.

The system employs an optically pumped far-infrared (FIR) laser using formic acid (HCOOH) vapor as the gain medium, pumped by a 150 W CO₂ laser operating at the 9R20 line (9.27 μm), which generates the 693 GHz FIR signal through rotational transitions. The output beam is coupled into a waveguide and transmitted to launch optics, where adjustable mirrors enable precise beam steering for different measurement configurations. The performance must be maintaining a Gaussian beam profile for optimal waveguide coupling, which depends heavily on the alignment of the FIR cavity optics, including perforated copper mirrors, mesh grids, and dielectric wafers. The misalignment (even minor as 0.1 degree) degrades FIR output beam quality. In addition, the CO2 laser driver delivers heat will change the FIR laser cavity length, which decreases the output power. This work bridges that gap by introducing a repeatable alignment methodology and identifying the dominant factors governing beam pattern and power optimization in FIR systems.

The system utilizes an optically pumped far-infrared (FIR) laser with formic acid (HCOOH) vapor serving as the gain medium. It is pumped by a 150 W CO₂ laser operating at the 9R20 line (9.27 μm), which drives rotational transitions to generate the 693 GHz FIR signal. The output beam is coupled into a waveguide and directed to the launch optics, where adjustable mirrors allow precise beam steering for various measurement configurations. Maintaining a high-quality Gaussian beam profile is critical for efficient waveguide coupling. This depends sensitively on the precise alignment of FIR cavity components, including perforated copper mirrors, mesh grids, and dielectric wafers. Even minor misalignments (as small as 0.1°) can significantly degrade the output beam quality. Additionally, heat from the CO₂ laser can alter the length of the FIR laser cavity, resulting in a drop in output power. This work addresses these challenges by developing a repeatable alignment methodology and identifying the key factors that govern beam pattern and power optimization in FIR systems.

This paper focuses on optimizing the performance of a 693 GHz far-infrared (FIR) laser through precision optics alignment and cavity length feedback control. The system is driven by a CO₂ pump laser, and its output beam quality is important for high poloidal wavenumber scattering diagnostics. Section 2 reviews the FIR laser setup, while Section 3 presents beam pattern optimization by optics alignment. Section 4 details power stabilization through real-time cavity length feedback control and gas pressure tuning. Finally, Section 5 summarizes the implications for improving FIR laser stability and output efficiency.

**Section II: FIR laser setup and beam quality importance**

1. **FIR laser and CO2 laser system overview**
2. **FIR beam output beam power and pattern distortion affected on scattering system (diagnostics degradation)**
3. **NSTX-U FIR laser requirement**

**Section III: Beam pattern optimization by optics alignment**

1. **Principle of laser optics setup**
2. **Non-ideal beam pattern sample**
3. **Alignment process and beam pattern quality improvement**
4. **Please add a short description about the regular alignment duration requirement**

**Section IV: Beam power stabilization**

1. **Beam power decreasing with nature operation (no feedback control)**
2. **Key parameters (beam power): cavity length, gas pressure**
3. **Beam power performance with feedback control module**
4. **Please add a short description about the regular adjustment duration requirement**

**Section V: Summary**

1. **One sentence about high k scattering laser requirement**
2. **Three sentences about optimized beam power and pattern performance**
3. **Summarize the optics alignment method, cavity length adjustment method, and more.**
4. **Impacts on other laser-aided diagnostics.**