Developing Small-Pitch Optical Fiber Positioners for Massively Parallel Spectroscopy

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Topical Group(s):

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☑ (CF3) Dark Matter: Cosmic Probes
☑ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☑ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☑ (CF7) Cosmic Probes of Fundamental Physics
☑ (IF2) Instrumentation: Photon Detectors

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Abstract:

Advances in dark energy, dark matter, inflation, and deviations from general relativity will rely on measuring precision redshifts for large samples of galaxies. Science cases for Stage V dark energy experiments, as outlined in the “Cosmic Visions” reports, would require as many as several hundred million galaxy redshifts. Accumulating that many spectra will require a technical advance in instrumentation. While robotic fiber positioners (FP) have been an integral part of advancing spectroscopic surveys, more cost-effective, smaller-scale robotic fiber positioners are required to provide further increases in multiplex power. Current FP technology permits accumulation of ~5000 spectra simultaneously. Positioners with a pitch (packing space) of 5-6 mm provide the path towards instruments capable of collecting three to four times the number of spectra. This LOI describes R&D, currently in progress, aimed towards developing working “Tilting Spine” FPs, with 5 mm pitch.

Introduction

The Dept. of Energy “Cosmic Visions” program report highlighted the importance of cosmic surveys to the understanding of high energy physics, including, but not limited to, the nature of dark energy, dark matter, inflation, modified gravity, and the number and masses of neutrinos [1]. Cosmic imaging surveys, such as the Sloan Digital Sky Survey, the Dark Energy Survey, and the Rubin Observatory LSST, map an increasing fraction of the Universe to unprecedented depth (limiting magnitude). Correspondingly, operating spectroscopic instruments, such as SDSS [2] and Dark Energy Spectroscopic Instrument [3], have become increasingly multiplexed, now permitting acquisition of precise redshifts of O(20M) galaxies over the course of the experiments’ lifetimes using modest-sized telescopes.

White papers submitted [4] to the Decadal Survey on Astronomy and Astrophysics (Astro 2020) advocate for larger telescopes [5,6] and much more massively-multiplexed spectroscopic instruments [7-10] particularly to follow up LSST imaging with redshift determinations. The scientific ambitions are to measure O(100M) to O(1000M) redshifts. Measuring the redshifts of a billion objects will require an apparatus that can measure more than 20,000 of them in one pointing. The light from each of those objects is collected at the tip of an individual optical fiber that is oriented at the position of the object on the focal surface by a “Fiber Positioner” (FP).

Robotic FPs have been an integral part of the advancement in spectroscopic surveys. They are an economical solution to maximizing the number of spectra that can be collected with a given telescope/instrument combination in a fixed amount of time. Fitting so many positioners on a single focal surface (typical telescope focal surfaces are 0.4 meter to 1 meter in diameter, state-of-the-art FPs are ~ 1 cm in diameter) requires development of much smaller unit positioners. This need is highlighted in the “Cosmic Visions Dark Energy: Small Projects Portfolio” as one the highest-priority R&D directions for astrophysical instrumentation [11]. Among the generic designs for fiber positioners are “Tilting Spines” and “Twirling Posts”. Though there are advantages and disadvantages for each [12], the Tilting Spine design [13] seems to have more potential than the others for a reduction of the pitch to 5 mm or less. A positioner design that enables a pitch of that size would enable simultaneous acquisition of 20,000 to 50,000 spectra depending on the size of the focal surface.

In this note, we briefly describe state-of-the art FP technologies. Then we outline the R&D path our team is undertaking, briefly describing the goals and plan.

STATE-OF-THE ART FIBER POSITIONER TECHNOLOGIES

Three general types of robotic FPs are in use worldwide. The “Twirling Posts” FP designs include for DESI [12] (5000 FPs) with 10.4 mm pitch between neighboring units, and the PSF [14] (2400 FPs) with 8 mm pitch in hex-close-packed configuration. The former uses 4mm diameter brushless geared-motors and the latter uses “wobbly” piezoelectric motors to position the tip of the optical fiber through rotation about 2 axes. Reducing the size (pitch) of Twirling Post technology depends on developing smaller motors and maybe at the feasible limit of the technology. “Starbugs” [15], developed at AAO, are mobile, piezo-controlled “walking” robots with optical fiber(s) through their middle, being used on the TAIPAN Instrument [16] (150 FPs). They are size limited to > 1 cm diameter, but interesting, can easily be made larger and configured as movable IFUs. The third general type of FP is the “Tilting Spine” design [13] originally developed by AAO for FMOS (400 FPs), 4MOST [17] (2436 FPs), and now planned for MSE [5] (4332 FPs). In this design the optical fiber ends at the tip of a thin carbon-fiber rod. The rod is tilted by means of a slip-stick action achieved by bending a piezo-electric tube. Quickly releasing the voltage, the piezo snaps back to straight, leaving the tube at a small angle. Repeating this action in 2D positions the tip of the optical fiber as desired. R&D at AAO for DESpec [18-19] (see Fig. 1) resulted in FPs configurable with a 7 mm pitch.

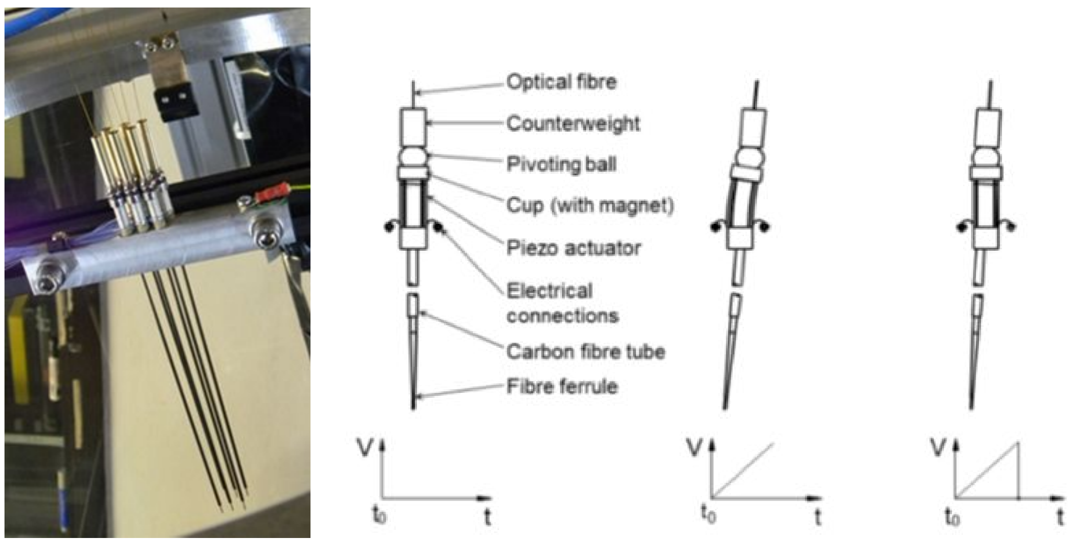

Figure 1. Photograph (AAO) of prototype DESpec Tilting Spine FPs developed by AAO. These are about 10 inches long from counterweight to tip. On the RHS is a diagram illustrating how the FP motion is achieved.

R&D TOWARDS 5mm PITCH OPTICAL FIBER POSITIONERS

A follow-up [20] to the “Cosmic Visions Dark Energy: Small Projects Portfolio” includes a section on FP R&D that outlines the steps and presents them as 4 Milestones: *1)* Prototype the critical components. Complete preliminary designs for fully-functional positioners based upon these components. *2)* Complete first-generation fiber positioner prototypes and performance testing for positioning accuracy. Complete preliminary designs for ferrules. *3)* Construct second generation fiber positioner prototypes, based upon both performance results and assembly lessons from the first-generation prototypes. Conduct performance testing, environmental testing, and lifetime tests of the second-generation prototypes. Test assemblies of fibers in ferrules, and ferrules into positioners. Complete preliminary design for control electronics. *4)* Build and test assemblies of 50 positioners with fibers, including concurrent controllers.

Our group plans to complete the first 3 steps of this plan, including mechanical and optical performance testing, in roughly two years. We’ve had initial successes, obtaining and controlling a DESpec-style FP. Currently we are developing a model of the physics and engineering that makes this device work, and soon will design and build prototype FPs with smaller components and a 5mm pitch. Along the way we’ll also develop some understanding of the smallest possible Tilting Spine design toward the development of an instrument that can perform a survey that provides O(1B) high-resolution spectra.

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