SuMIRe
(Subaru Measurement of Imaging and Redshifts)
– Prime Focus Spectrograph (PFS)

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for the
SuMIRe PFS Collaboration

The Observational Pursuit of Dark Energy after Astro2010
Caltech
October 2010

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Science Surveys

- Dark Energy
- Galaxy evolution
- Low dispersion Galactic Archaeology
- High dispersion Galactic Archaeology – future upgrade?

Requirements Flowdown – Dark Energy

Science Goal	**Science Goal**	**Observing requirement**	**Instrument requirement**	**Instrument performance**
Provide a constraint on *w* to 3%. Measure the growth rate of density fluctuations.	Measure the distance to a mean redshift 1.2 with an accuracy of 0.6%.	• Redshift of the OII doublet at 373 nm from a redshift of 0.7–1.6 • Optimize visibility of OII doublet in OH night sky spectrum • Observe $> 4 \times 10^6$ galaxies	• Wavelength range • Resolution • Signal-Noise Ratio • Number of Fibers • Configuration Time	• λ = 630–970 nm • R = 3500 • Line S/N = 7 • 2,400 fibers • 40 s configuration
	< 2000 hours for DELZ and DEHZ	• Fast observations and high efficiency		
	Measure in 4 independent redshift bins z~1 2% z~3 10%	• > 100,000 galaxies observed • < 1% incorrect redshift • Redshift precision: $\Delta z < 0.001$	• Wavelength range • Resolution • Signal-Noise ratio	• λ = 420–670 nm • R = 1500 • Cont. S/N = 4

Key elements: large aperture telescope, thousands of simultaneous spectra

Survey Density and Exposure Time

$n = 4 \times 10^{-4} / (h^{-1}\text{Mpc})^3$ → Volume Density

$0.7 < z < 1.6$ →

$h=0.71$, $\Omega_\Lambda = 0.73$, $\Omega_M = 0.22$ →

↓

Projected Angular Density — 1245 galaxies / $\deg^2$

Allocation efficiency < 1 →

Successful redshift fraction < 1 →

↓

Required Observed Angular Density — **2132 galaxies / $\deg^2$**

↓

Galaxy number counts →

Magnitude Limit — $R_{AB} < 23$

Instrument parameters, throughput

Required S/N level →

↓

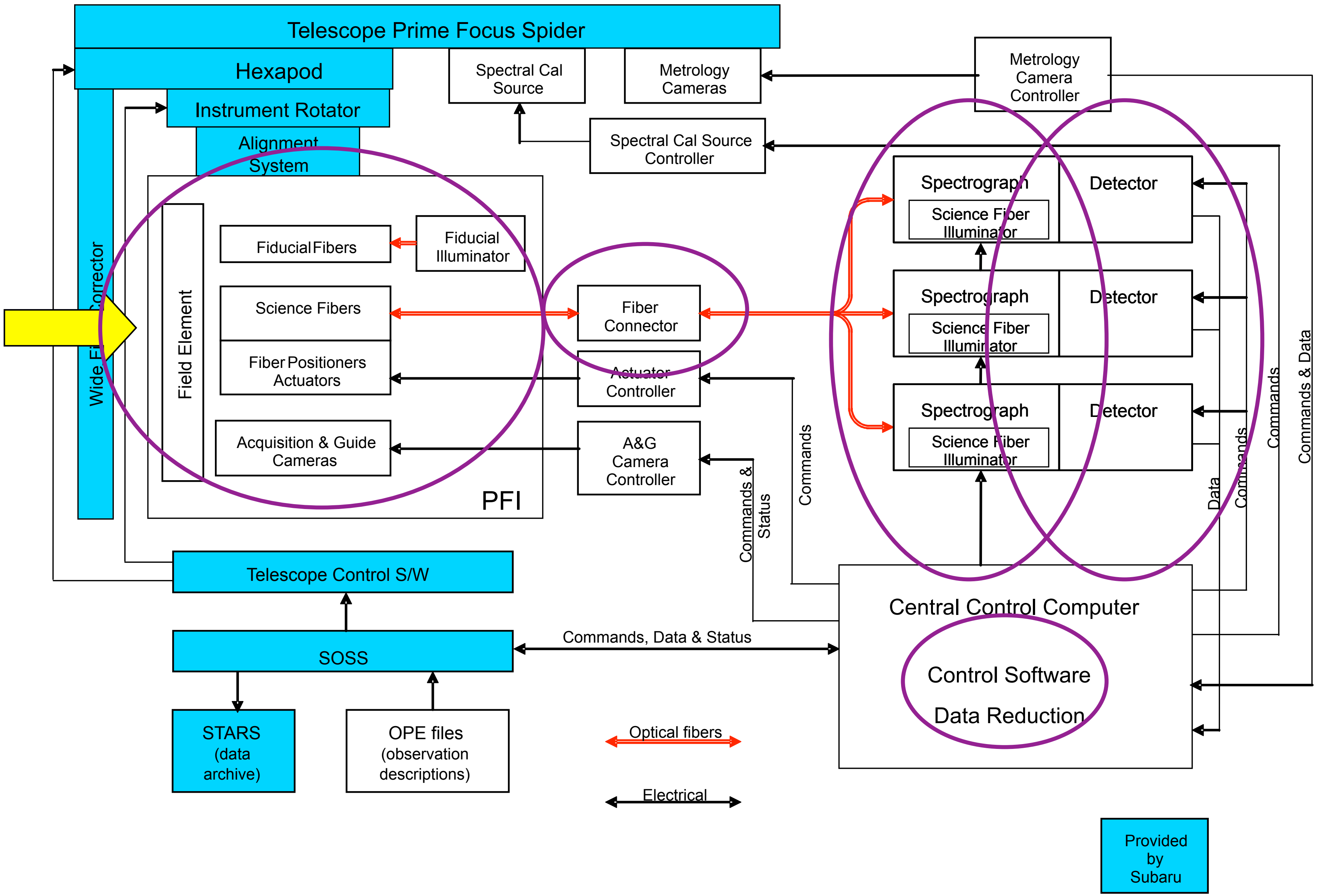
Exposure time — ~ 15 minutes / field

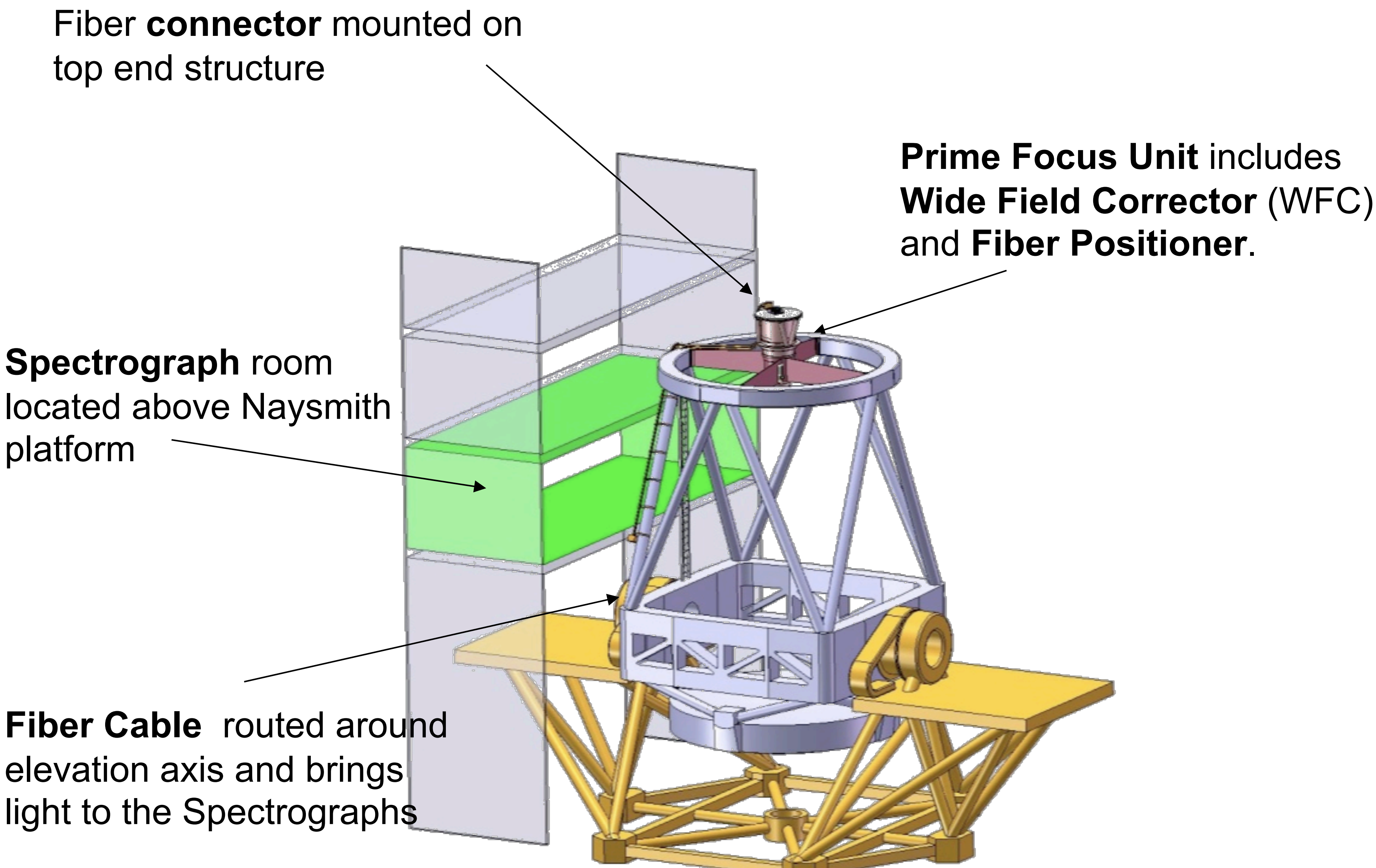
Building blocks

Telescope → Object Selection → Optical routing → Spectrometer

Telescope	Object Selection	Optical routing	Spectrometer
8.2 m aperture Very good seeing Wide Field Corrector for HSC Very stable top end structure	Allows the selection of light from galaxies of interest while rejecting unwanted sky background	Fiber optics or other method relays the light of interest	Disperse the light and detect

System Block Diagram




Fiber **connector** mounted on top end structure
Prime Focus Unit includes **Wide Field Corrector** (WFC) and **Fiber Positioner**.
Spectrograph room located above Naysmith platform
Fiber Cable routed around elevation axis and brings light to the Spectrographs

Subaru Telescope

Photo credit: Steven Beard, UKATC

3rd Floor Spectroscopy Lab

Total weight limit: 10 metric tons.
Maximum weight distribution: 250 kg/m^2.

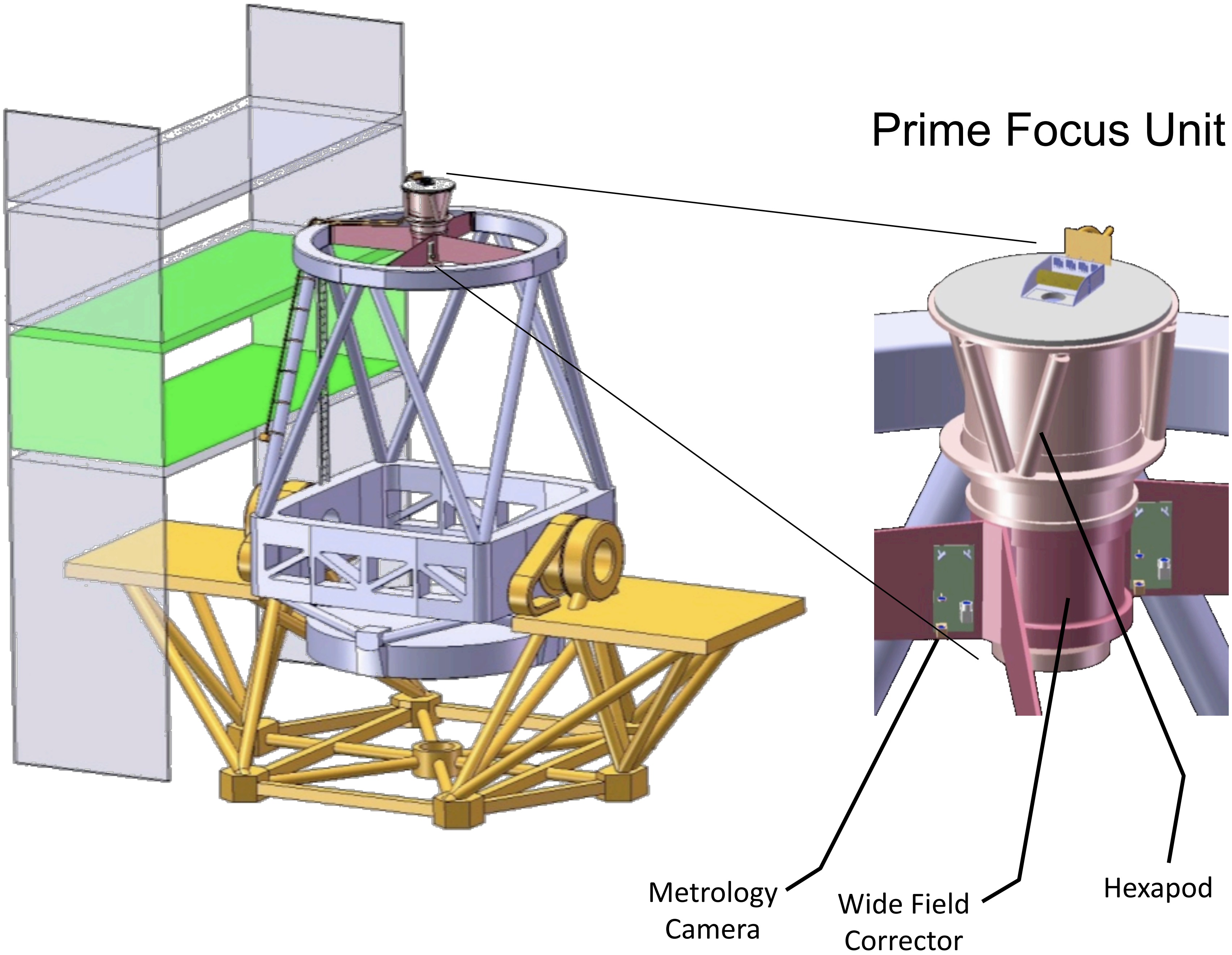
1.8x1.8x2.0m (LxWxH)
Size limit on sub-units

Access hatch

SuprimeCam Prime Focus Unit

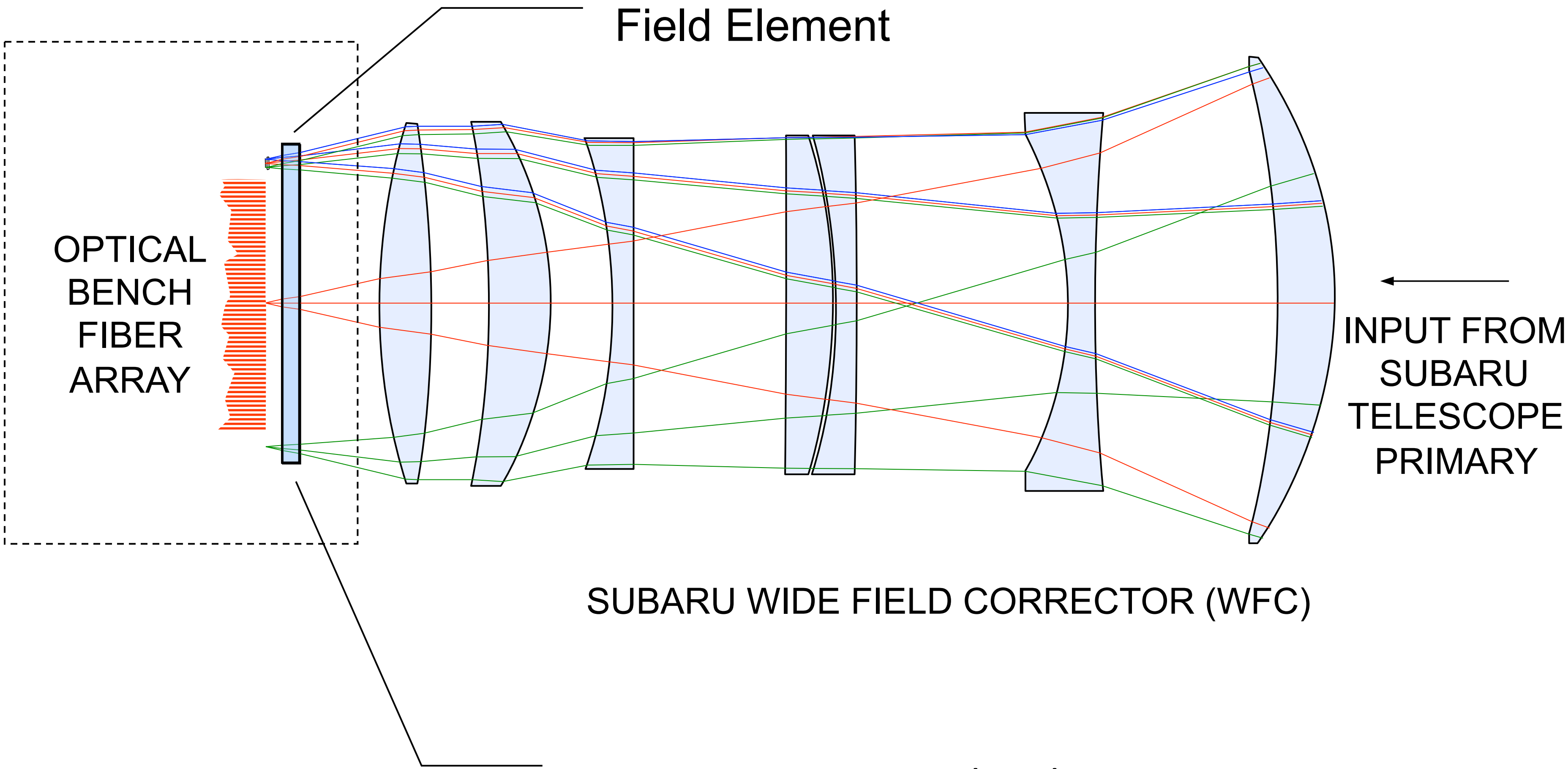
The Subaru Telescope is an ideal location for such an instrument

Photo credit: Steven Beard, UKATC



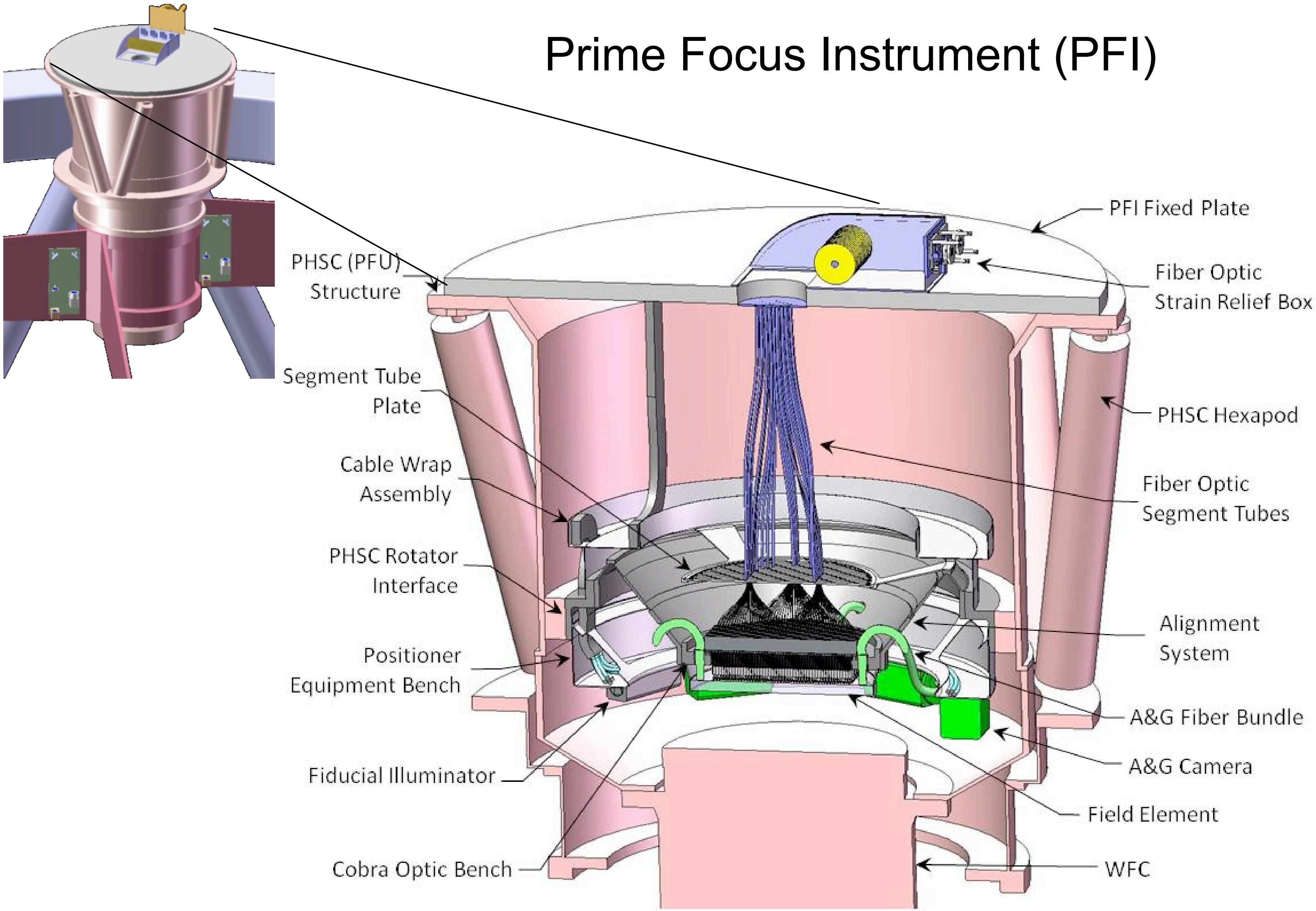
Prime Focus Unit
Metrology Camera
Wide Field Corrector
Hexapod

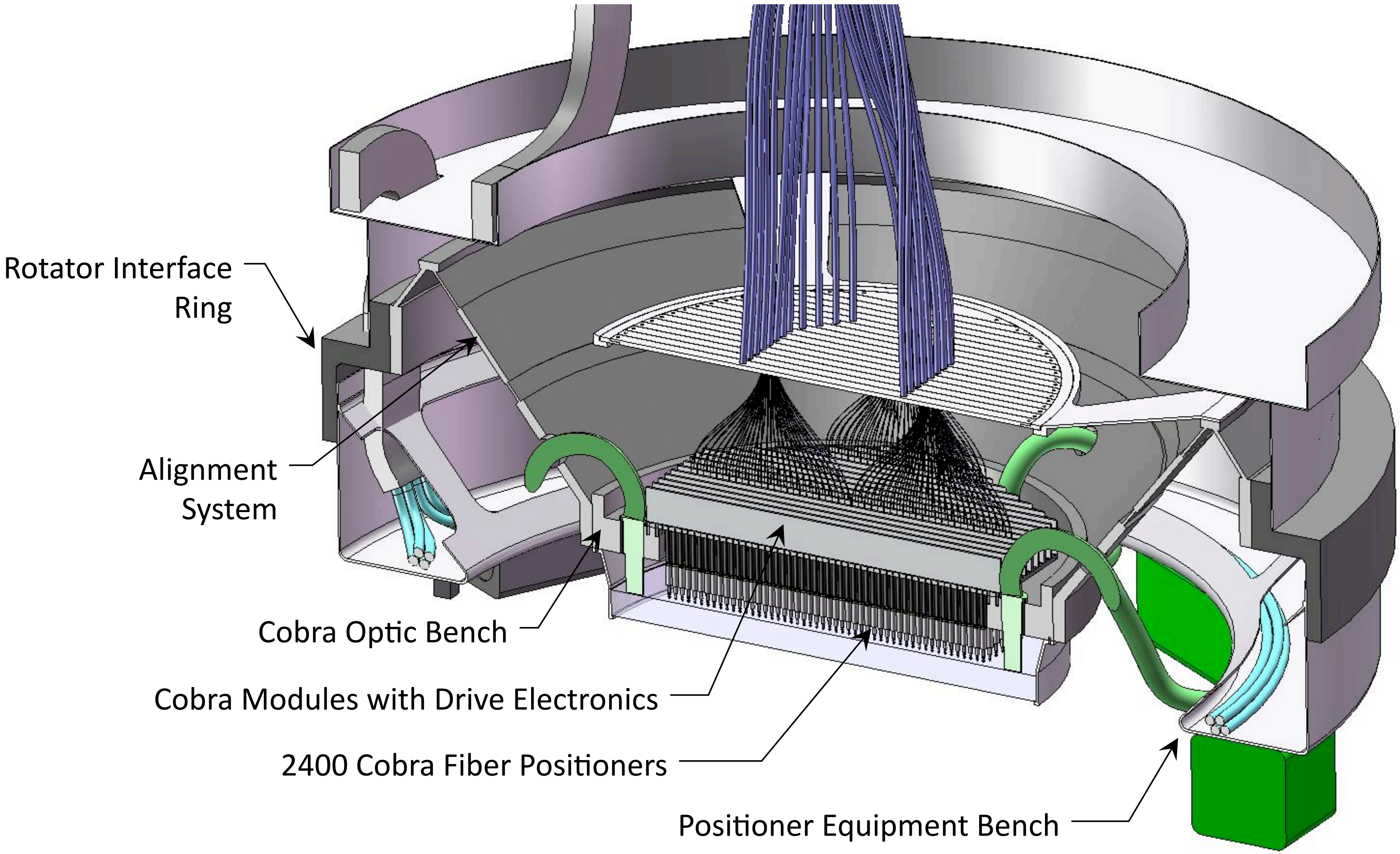
Wide Field Corrector

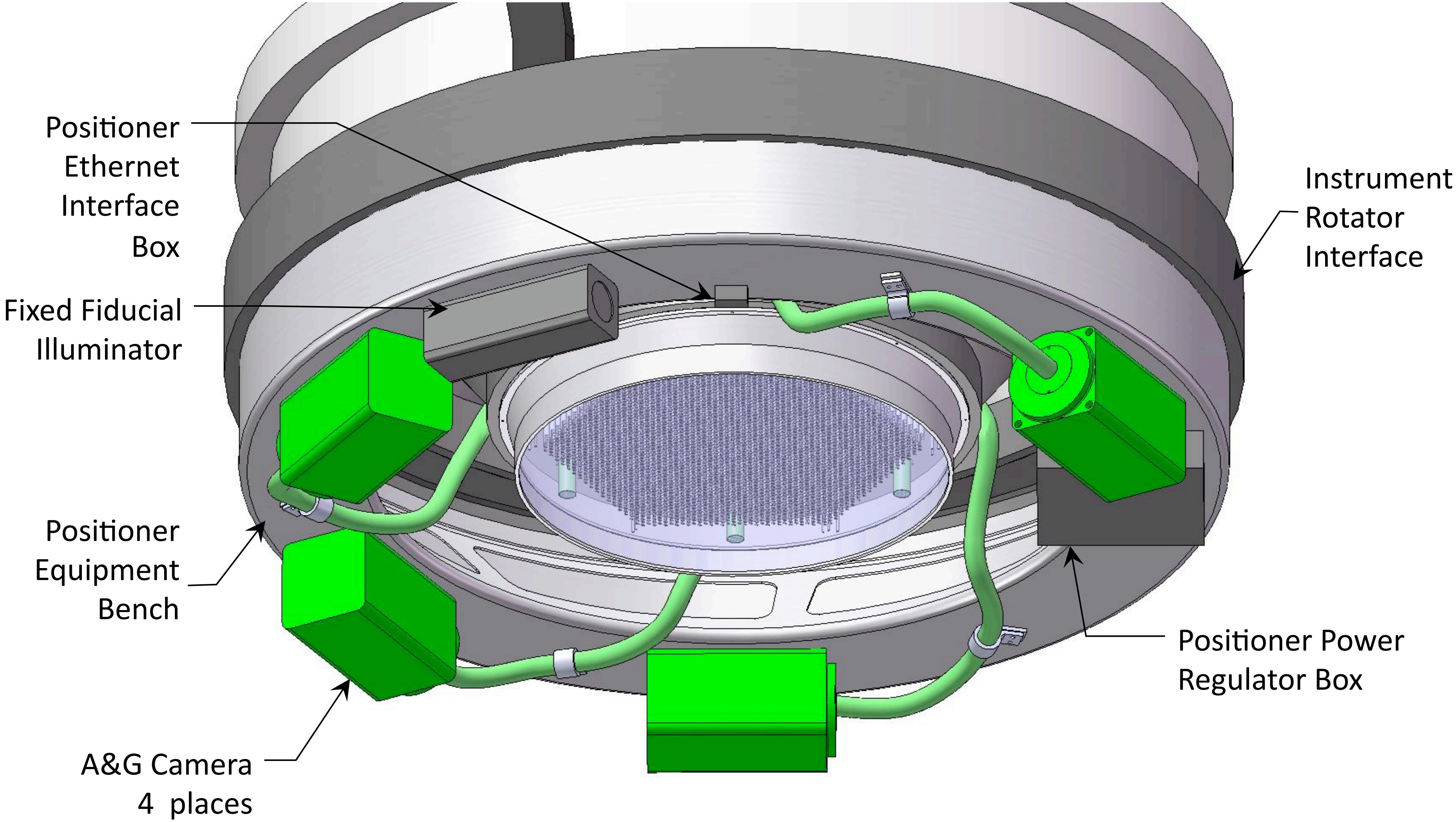


System is vignetted and not telecentric at edge of field

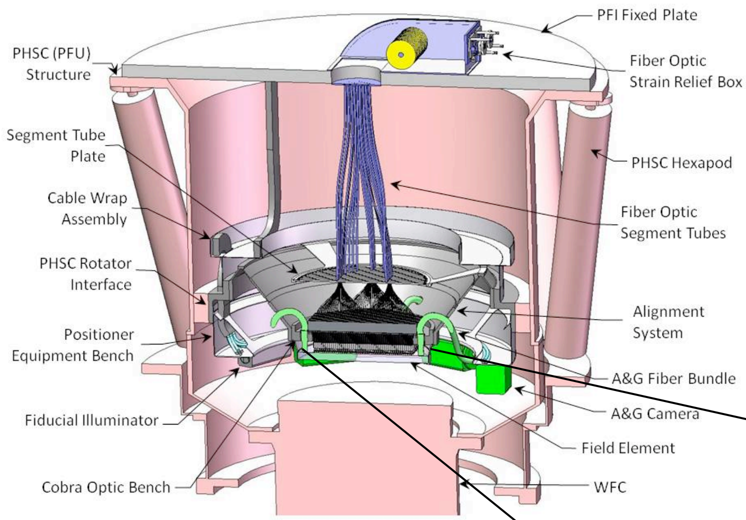
Prime Focus Instrument (PFI)

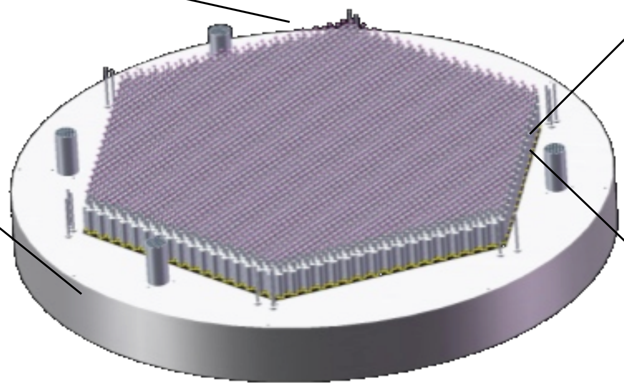



Rotator Interface Ring
Alignment System
Cobra Optic Bench
Cobra Modules with Drive Electronics
2400 Cobra Fiber Positioners
Positioner Equipment Bench


Positioner
Ethernet
Interface
Box
Fixed Fiducial
Illuminator
Instrument
Rotator
Interface
Positioner
Equipment
Bench
Positioner Power
Regulator Box
A&G Camera
4 places

Positioner





Optical Bench with 2400 Positioner Units

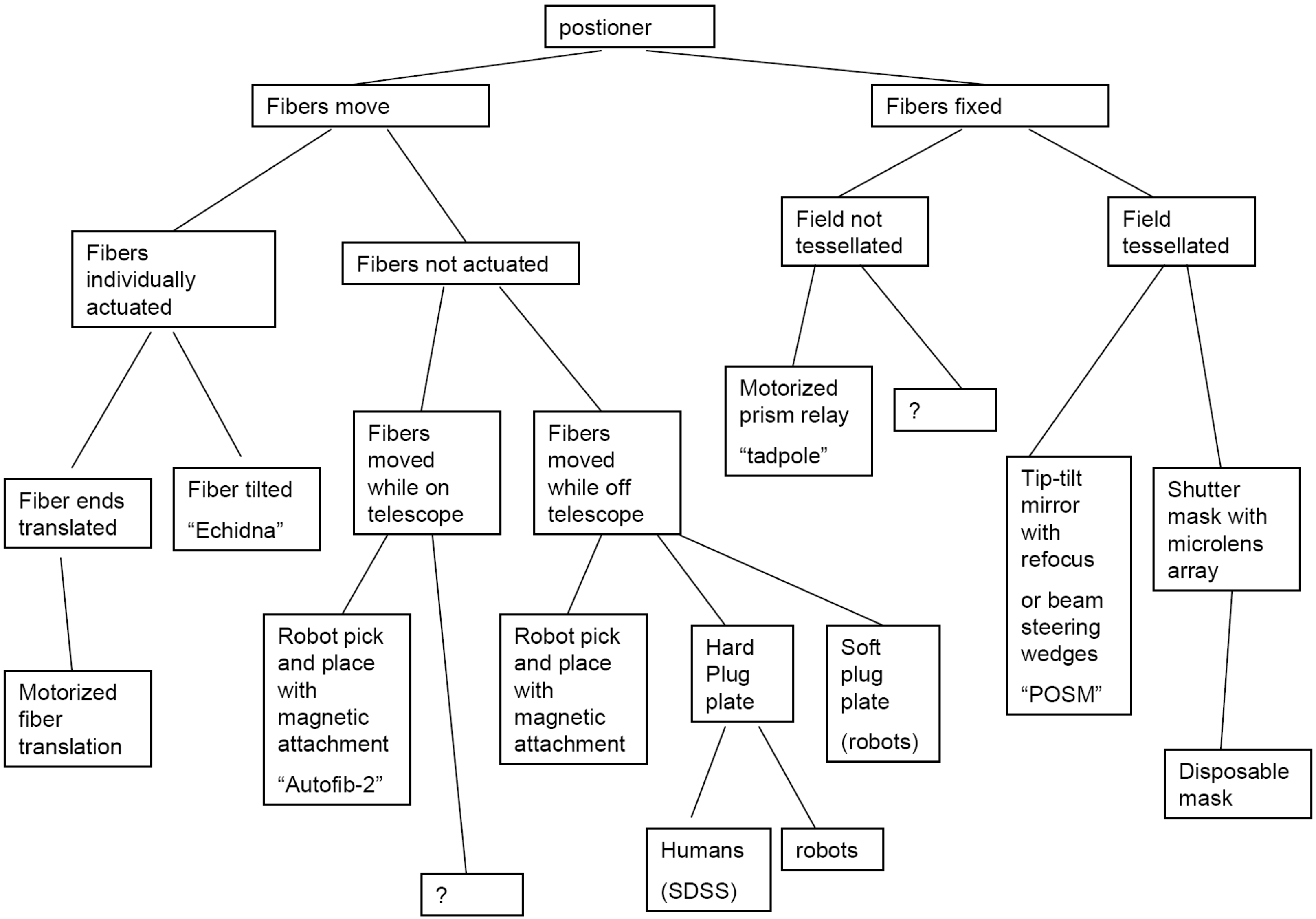
1 Positioner Unit - *Cobra*

Consider the full range of options for object selection.

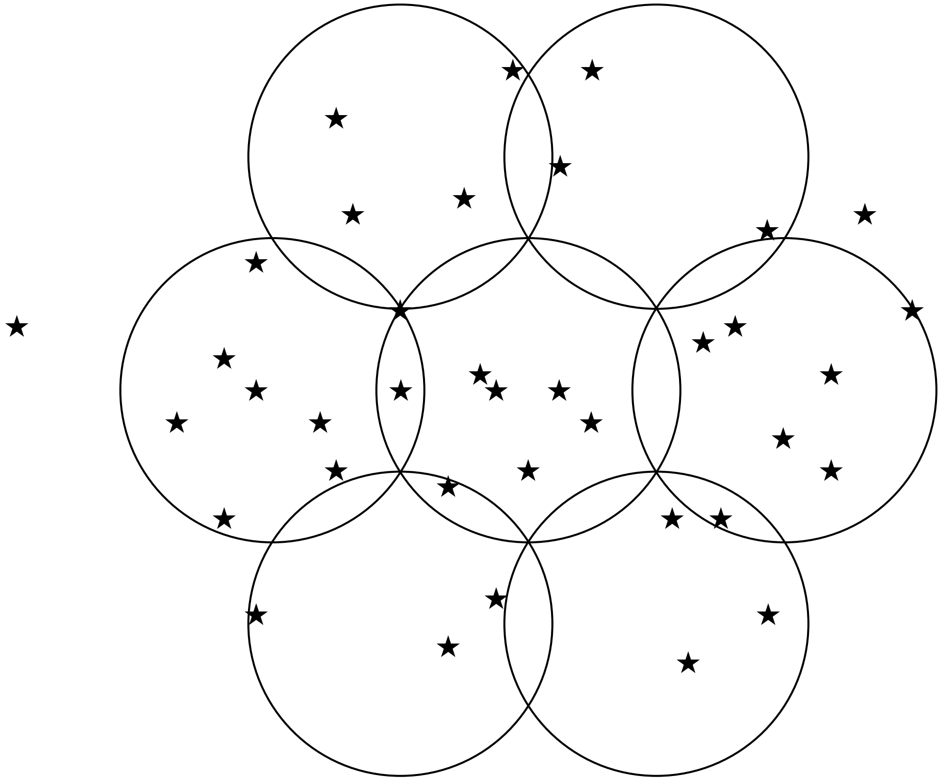
Desired properties:

- Thousands of elements over a large field
- Efficient: fast reconfiguration, high throughput
- Not too expensive!

Tree of positioner alternatives



Patrol Regions



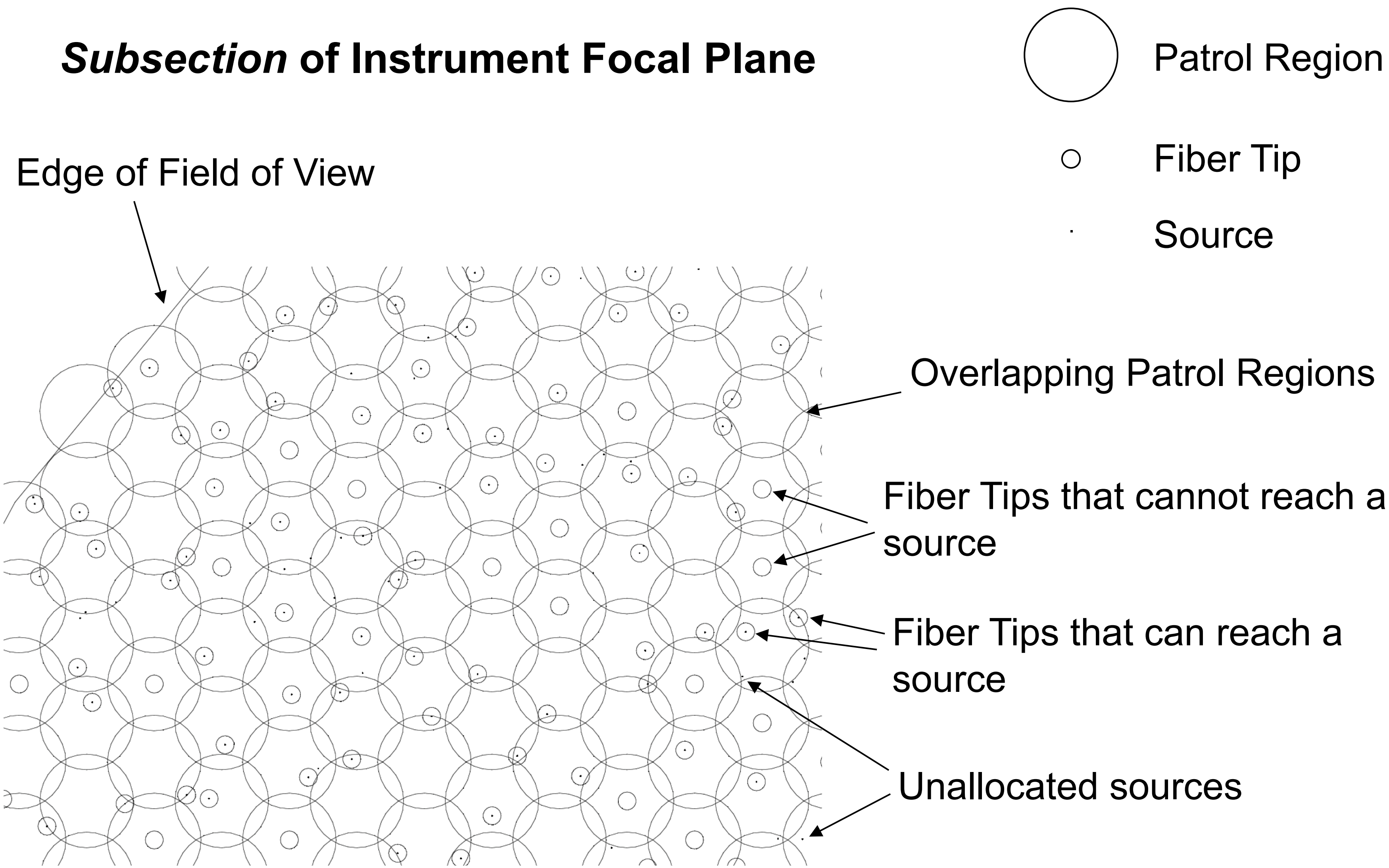
Patrol Region – Area of the focal plane accessible to one fiber (9.5 mm diameter)

Adjacent patrol regions overlap with no gaps

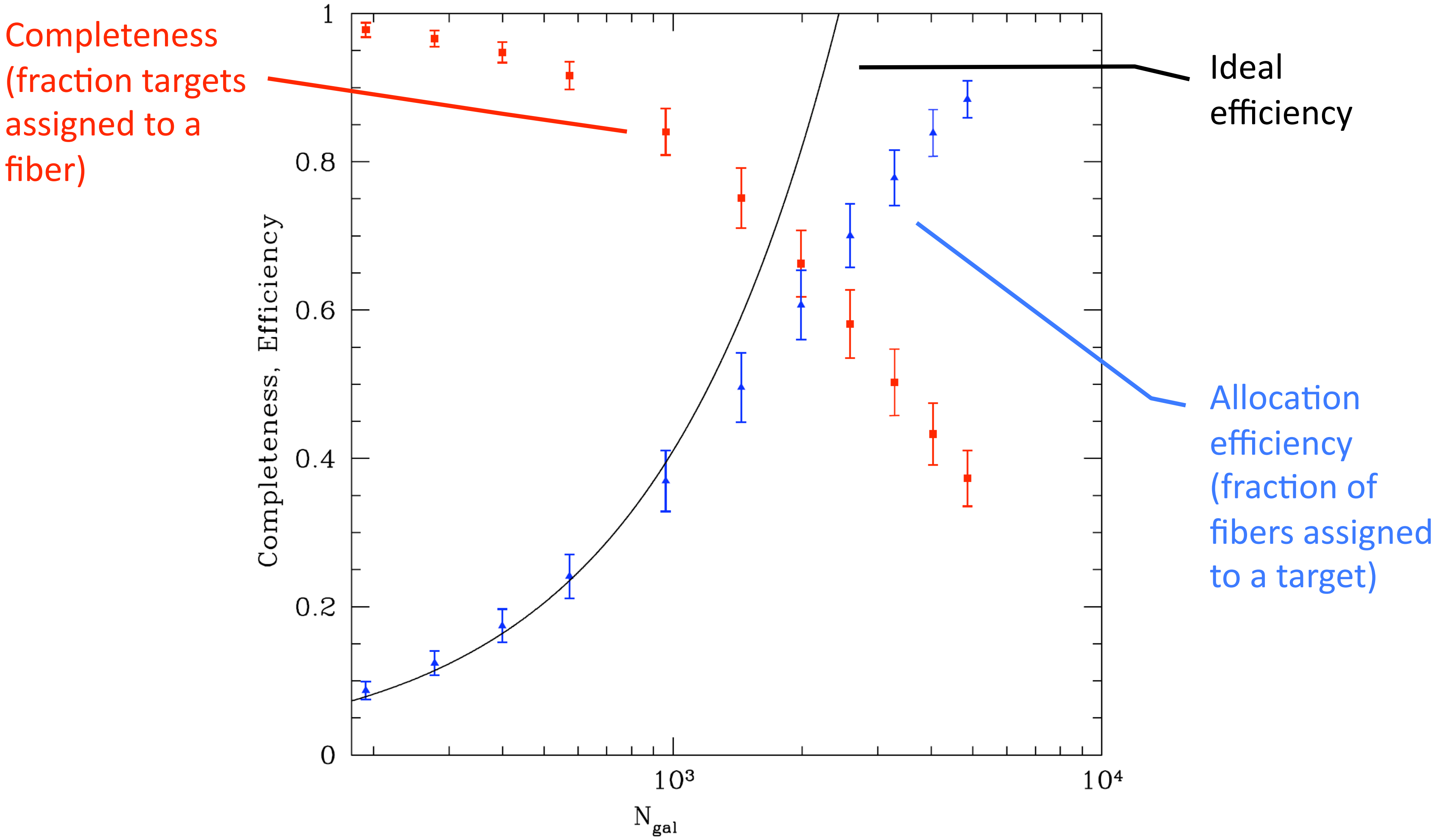
Patrol Region may have zero or may have many potential astronomical targets

Allocation efficiency describes the success rate in assigning targets to fibers

Positioner and Source Allocation



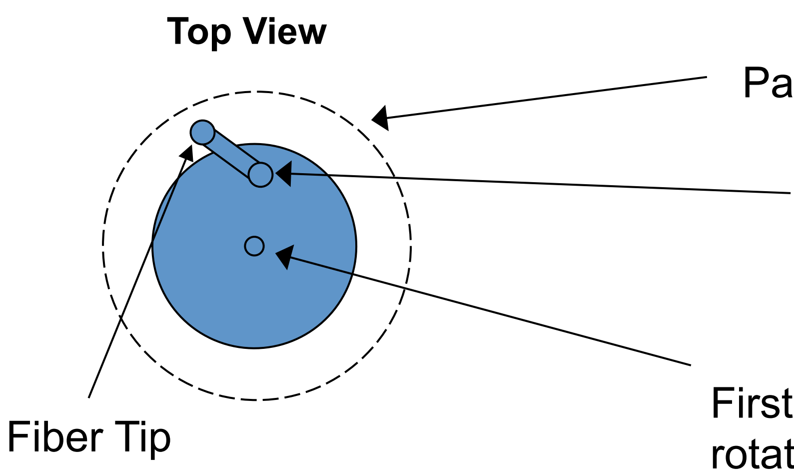
Allocation Efficiency

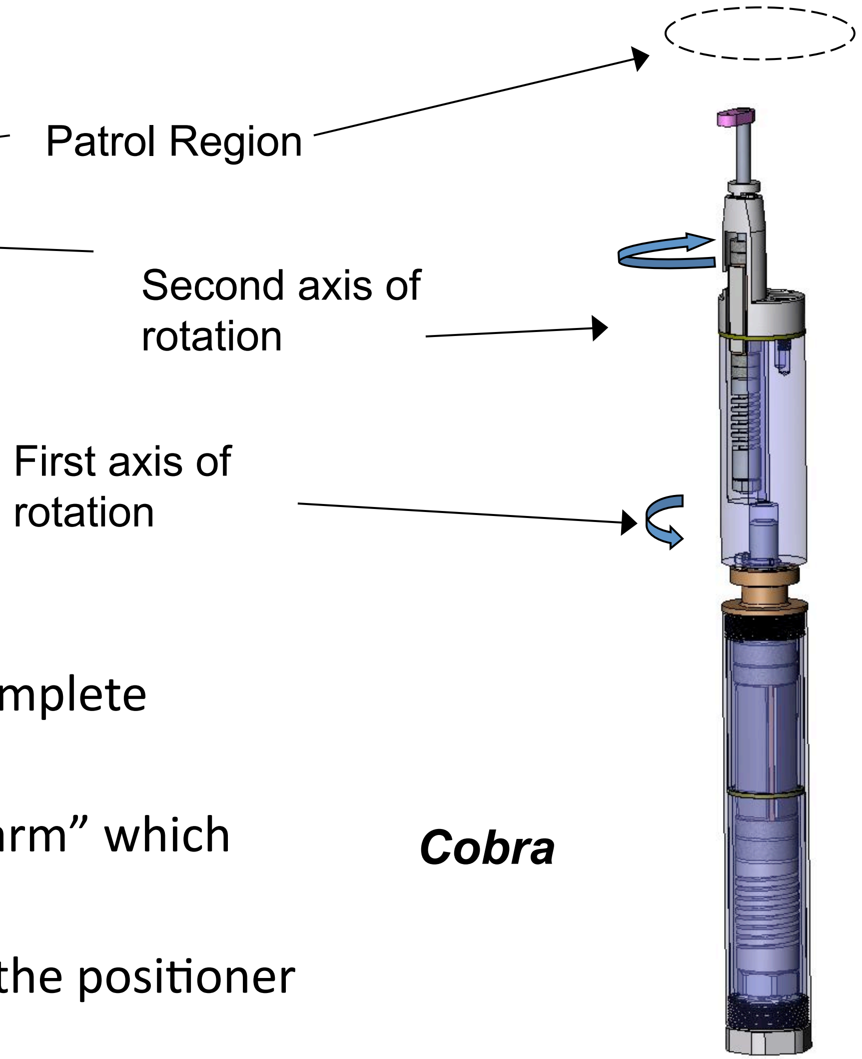


We have simulated a variety of designs and arrived at the following conclusions:

- For low target densities, degree of overlap between patrol regions is unimportant. Important not to have gaps.
- For high target densities, degree of overlap not important – there are many targets in each patrol region to choose from
- For intermediate target densities (target density ~ positioner density) there is some benefit to having larger overlap.

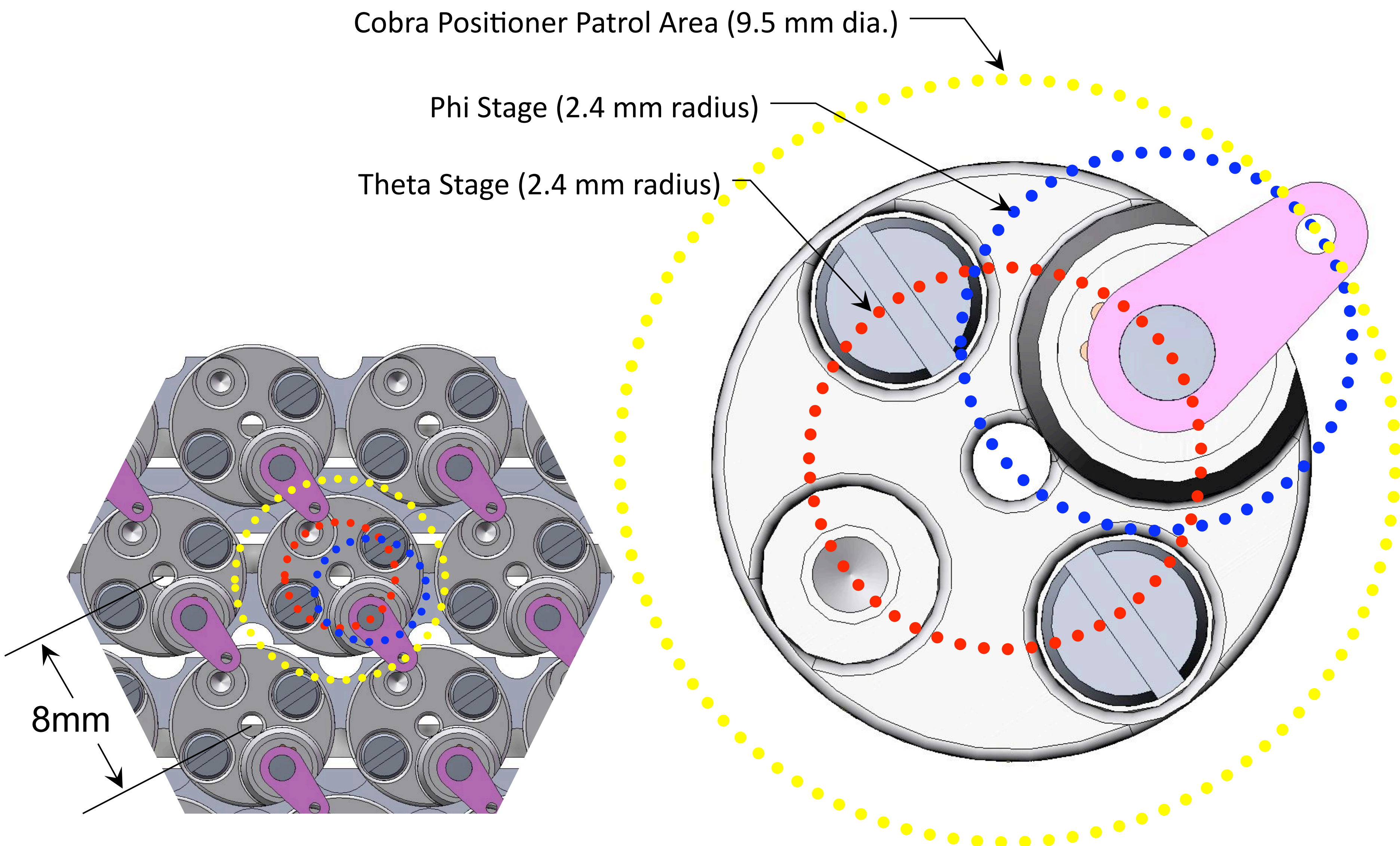
Positioner Element – "Cobra"





- Each motor rotates to provide complete coverage of the patrol region.
- Optical fibers mounted in "fiber arm" which attaches to upper postioner axis:
- Fiber runs through the center of the positioner

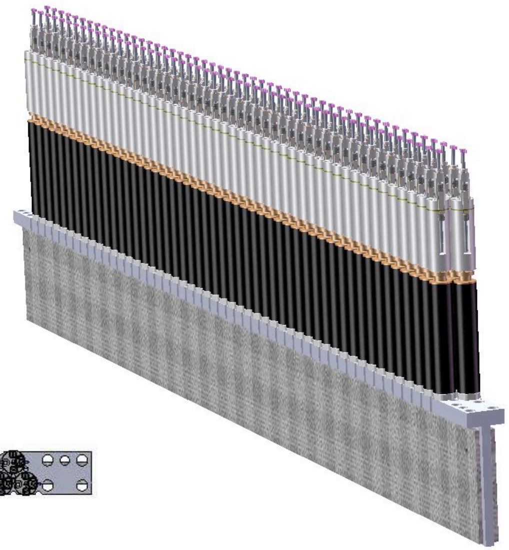
Geometry

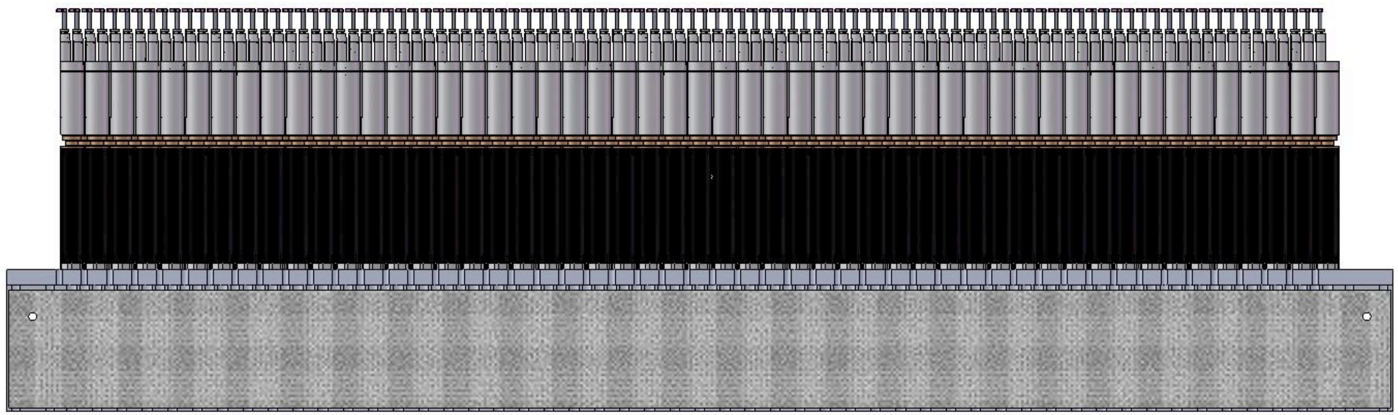


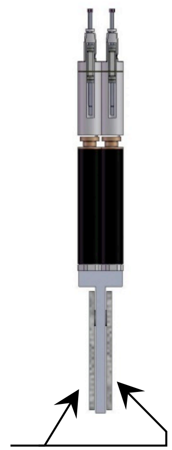
Cobra Positioner Patrol Area (9.5 mm dia.)
Phi Stage (2.4 mm radius)
Theta Stage (2.4 mm radius)
8mm

Module

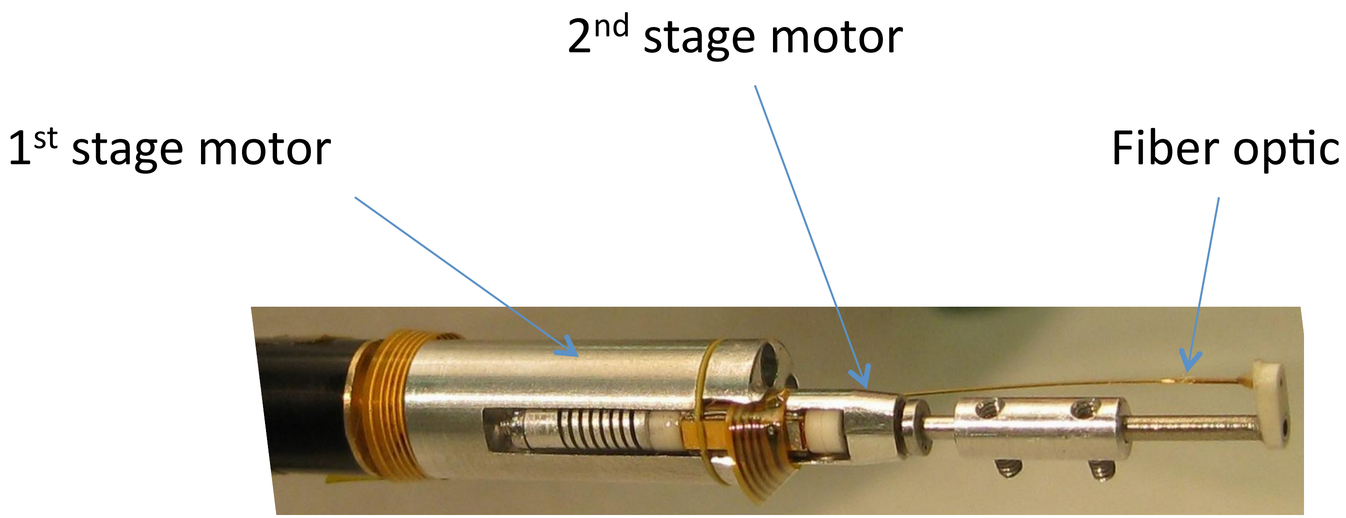
- A module is a subassembly of actuators and drive electronics boards
  - Staggered production
  - Parallel module integration
  - Early mechanical and electrical functional testing
  - Parallel fiber integration to reduce schedule
  - Increases serviceability







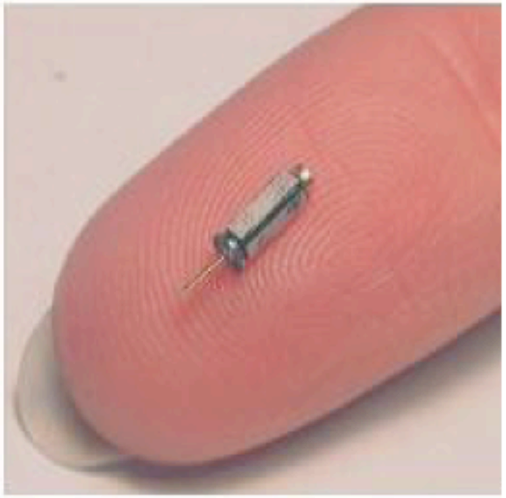
Prototype



- Ceramic friction drive
- Lubrication free, zero backlash
- Journal bearing limits motor side loads
- Hardstops to limit fiber twisting

- 5 um precision of fiber positioning
- Motor movement < 1 sec/iteration

Motors



Commercially available rotating tube motor:

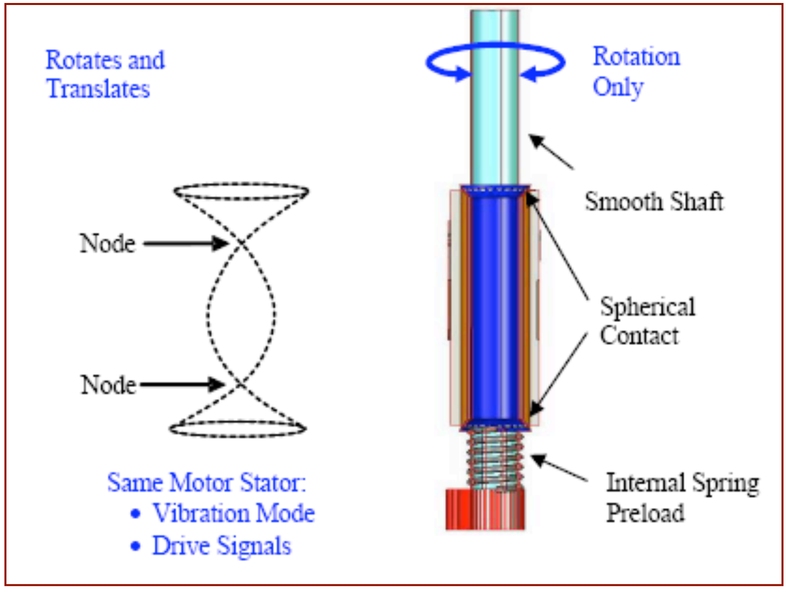
High torque when stationary and unpowered

~ 1 mN-m powered torque

1 mrad resolution

1 – 10 rev/sec speed

- Pairs of PZT plates oscillate in tandem bending
- Drive signals of the two PZT plates are phase shifted by 90 degrees
- This creates a traveling wave on the stator that excites the rotor like a harmonic gearbox to rotate the shaft by extremely small angles



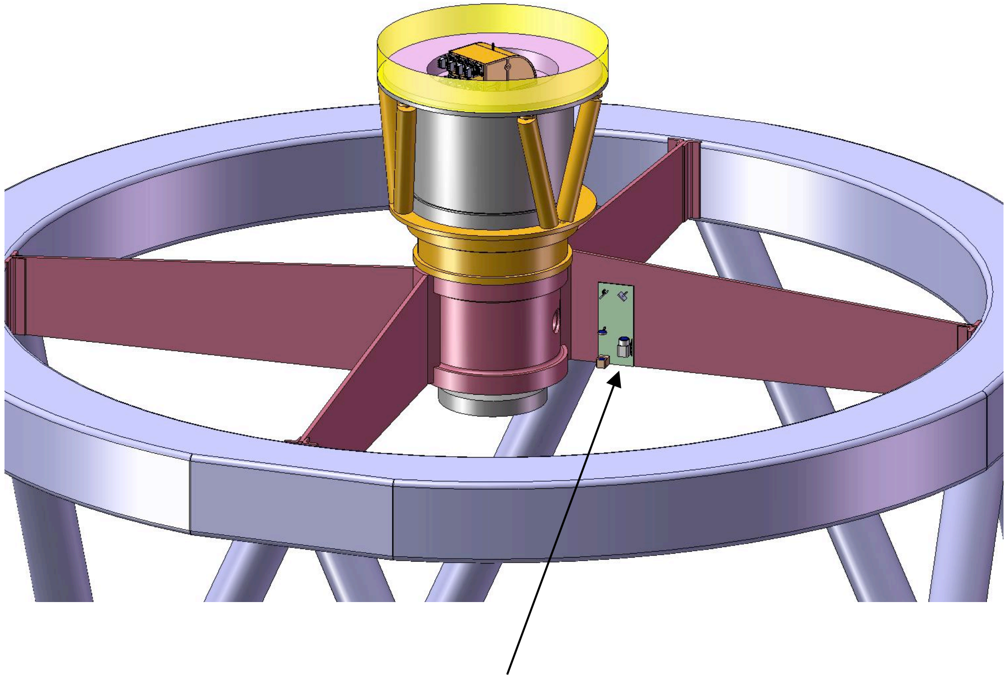
Video clip of prototype

Metrology Camera

- Four camera systems each looking at a ¼ of the focal plane. Located on prime focus support struts looking back at positioner focal plane via primary

- Science fiber positions established relative to fixed fiducial fibers on positioner focal plane

- Each camera will have a 4k by 4k CCD with 15μm pixels. Cameras are defocused to ~ 4 pixels FWHM to allow centroiding to ~ 1/20th of a pixel. Back-illuminated CCDs to allow better centroiding.



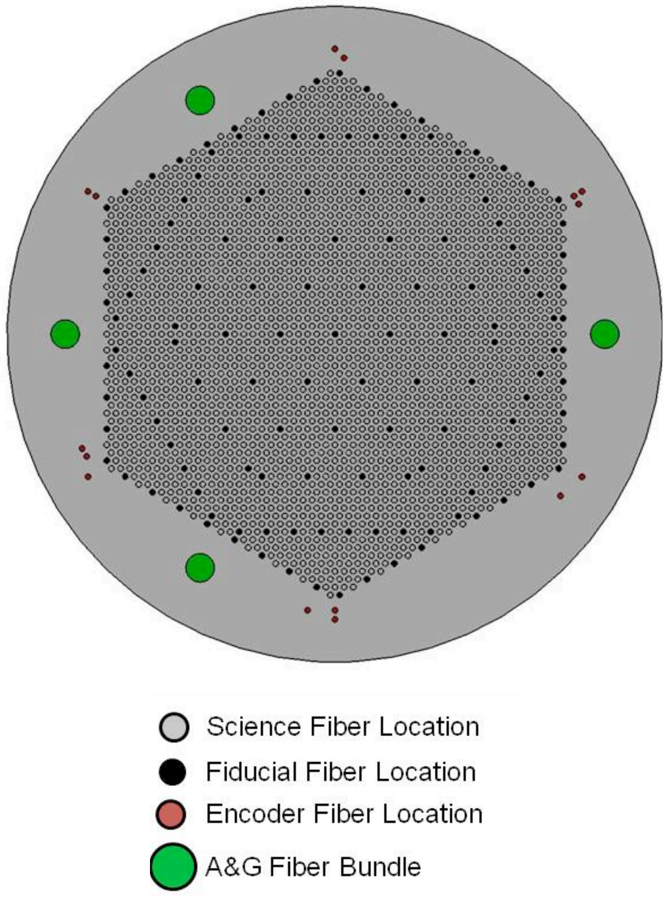
Metrology camera (1 of 4 shown)

Camera positioned 890mm from center of positioner.

Mounting plate provides kinetic mounting points.

System can be installed quickly with repeatable accuracy.

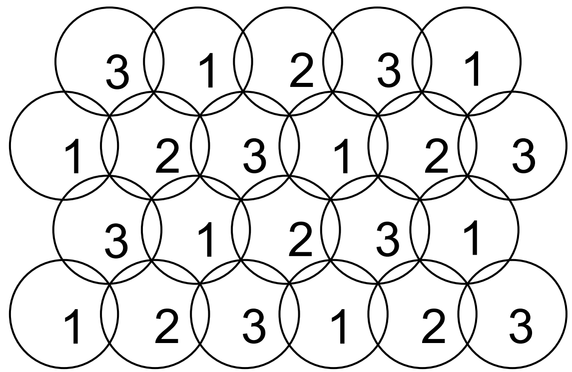
Back-lit fiducial fibers used to establish position of science fibers on positioner plane



Encoder fibers used to establish rotation orientation of positioner

Science fibers are back-lit in a sequence to allow discrimination between fibers in the overlap regions between adjacent fibers, 1/3 at at time.

In one exposure only the fibers marked (1) are illuminated, the next exposure only the ones marked (2) are illuminated, etc.



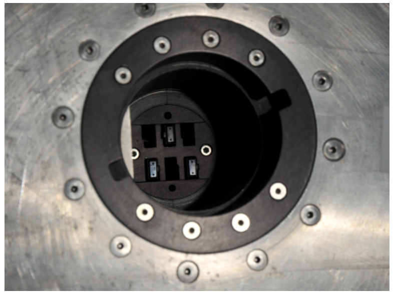
Parallel Configuration

- Positioner configuration – metrology loop: 40 seconds
  - Positioner moves elements in 3 groups of 800
  - Metrology camera views back-illuminated fibers. Fibers are illuminated in 3 groups of 800.
  - Movement, illumination, camera readout, computation in parallel
  - 6 iterations can be completed in < 40 seconds

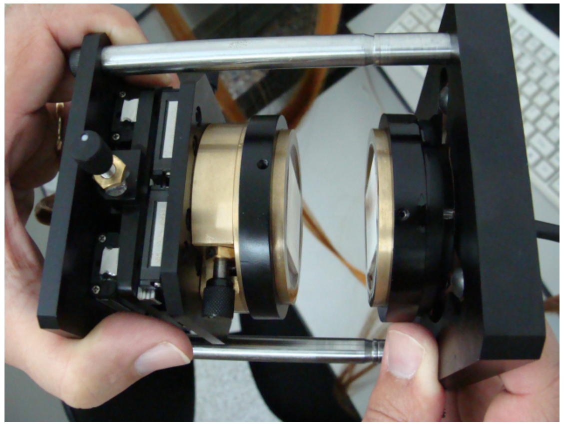
Start Time	Duration (s)	Steps being Taken in Parallel		
0	1	Move A-1		
1	2	Image A-1	Move B-1	
3	2	Compute A-1	Image B-1	Move C-1
5	2	Move A-2	Compute B-1	Image C-1
7	2	Image A-2	Move B-2	Compute C-1
9	2	Compute A-2	Image B-2	Move C-2
11	2	Move A-3	Compute B-2	Image C-2
13	2	Image A-3	Move B-3	Compute C-2
15	2	Compute A-3	Image B-3	Move C-3
17	2	Move A-4	Compute B-3	Image C-3
19	2	Image A-4	Move B-4	Compute C-3
21	2	Compute A-4	Image B-4	Move C-4
23	2	Move A-5	Compute B-4	Image C-4
25	2	Image A-5	Move B-5	Compute C-4
27	2	Compute A-5	Image B-5	Move C-5
29	2	Move A-6	Compute B-5	Image C-5
31	2	Image A-6	Move B-6	Compute C-5
33	2	Compute A-6	Image B-6	Move C-6
35	2		Compute B-6	Image C-6
37	1			Compute C-6
38				

Fiber connector options

APOGEE:
US Conec 30 fiber connectors "ganging" with custom fixture allowing simultaneous mating of 300 fibers.
Wilson et al., 2010

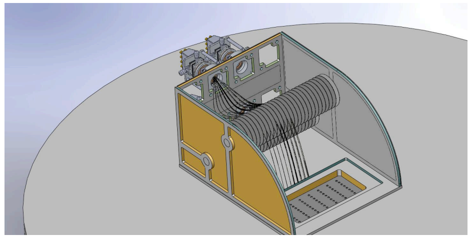


WFMOS team B study:
Custom connector for 800 fibers with simultaneous mating.
De Oliveira, 2008



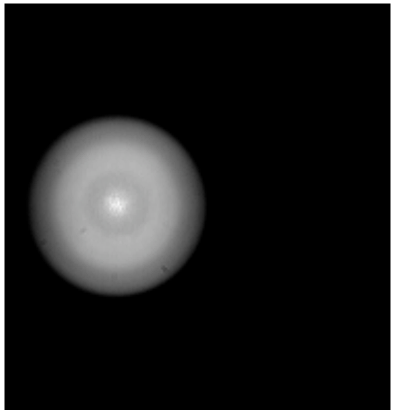
Fiber bending and twisting

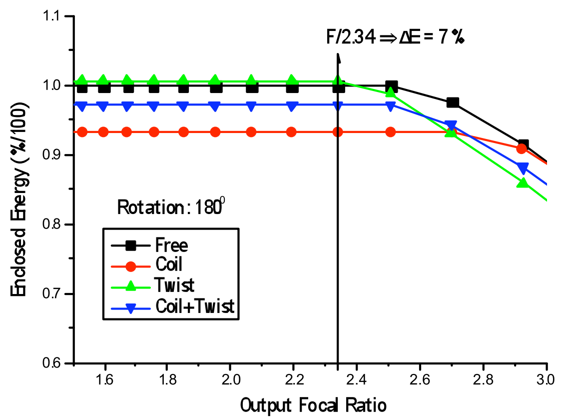
Design features address strain relief in operation of the instrument



C. de Oliveira et al.

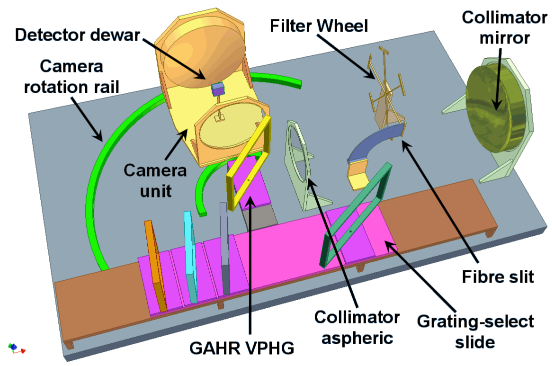
Measurement of Focal ratio degradation (FRD) induced by fiber bending and twisting





Spectrograph options

1) WFMOS Team-B derived:
Flexible spectrographs allowing
up to 2400 simultaneous spectra with resolution of 1500-5000

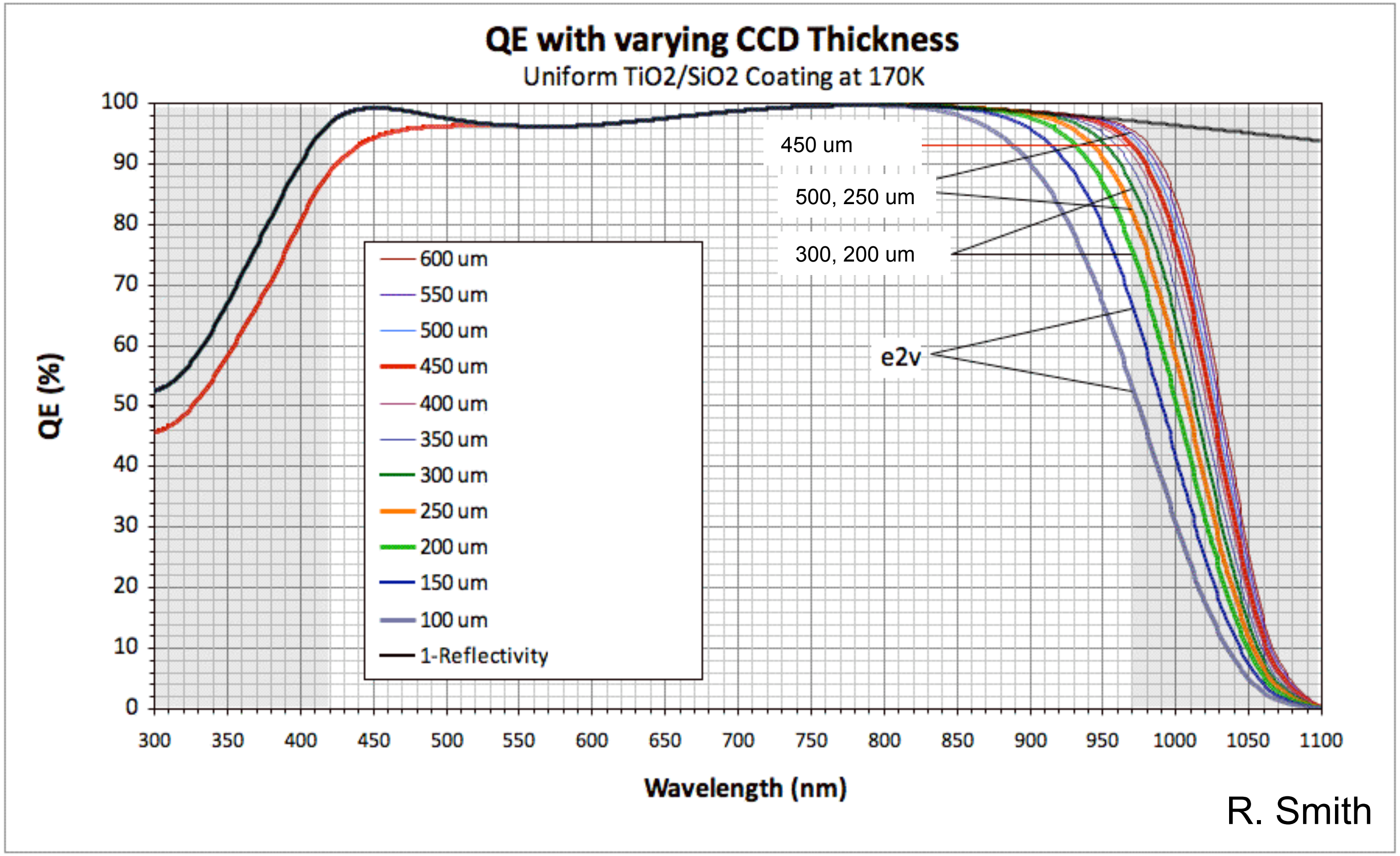


2) Reflecting Schmidt spectrograph
10” beam, f/2.8 collimator
600 fibers/spectrograph
Dichroics allow red-arm + blue-arm
Future expansion capability to near-IR

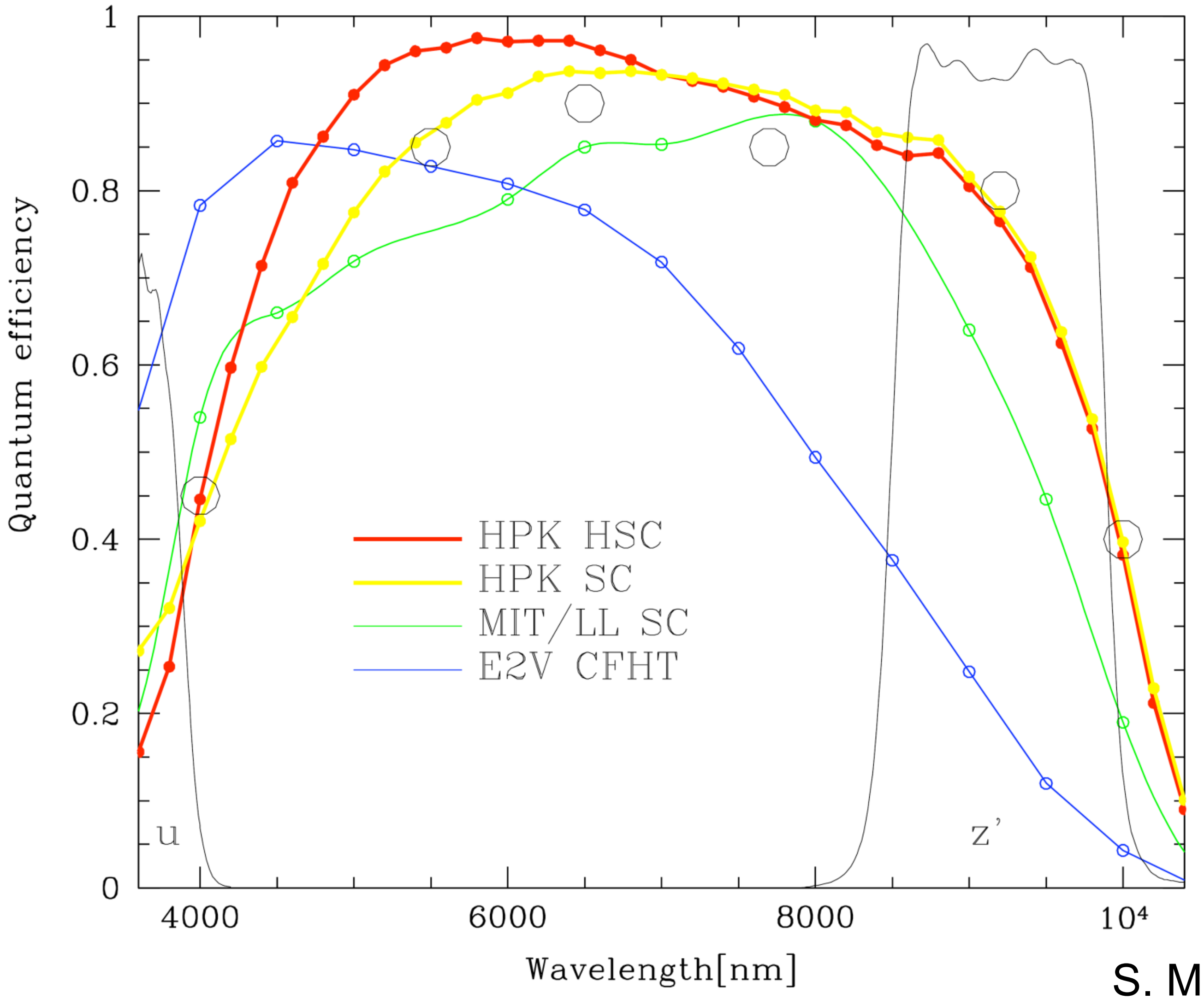
3) Many (10?) fast refracting spectrographs
6” beams

Future expansion for high dispersion (R ~ 20,000) ?

Detector Quantum Efficiency



Detectors – NAOJ – Hammamatsu collaboration



S. Miyazaki

- Key challenge of fiber-fed spectrographs: getting the fiber placed accurately on the astronomical target
  - large field of view
  - large number of fibers
  - smaller diameter fiber

- Our design addresses these challenges:
  - positioner design provides high precision
  - attention to differential mechanical flexure
  - error budgets for mechanical tolerances

Conclusions

The design emphasizes instrument efficiency:

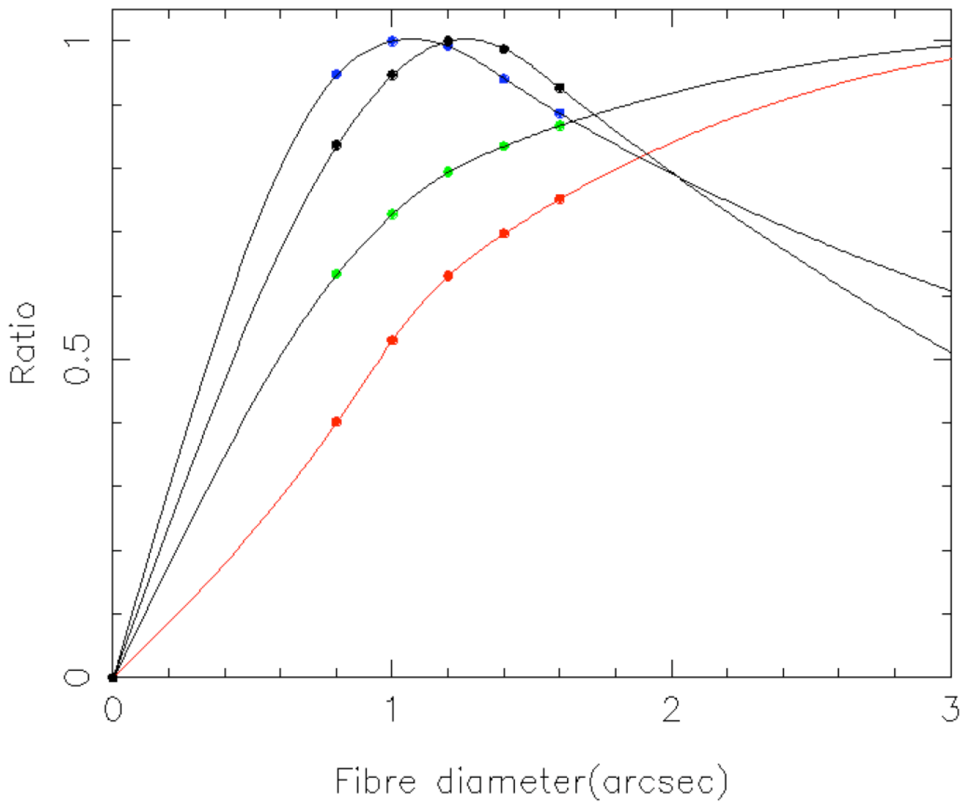
- Fast positioner configuration speed
- Mechanically stiff, robust, & precise positioner system
- High quantum efficiency detectors

We are very excited about starting soon!

BACKUP

Fiber Diameter

We have chosen 1.2 arcsec fiber diameter to maximize survey efficiency



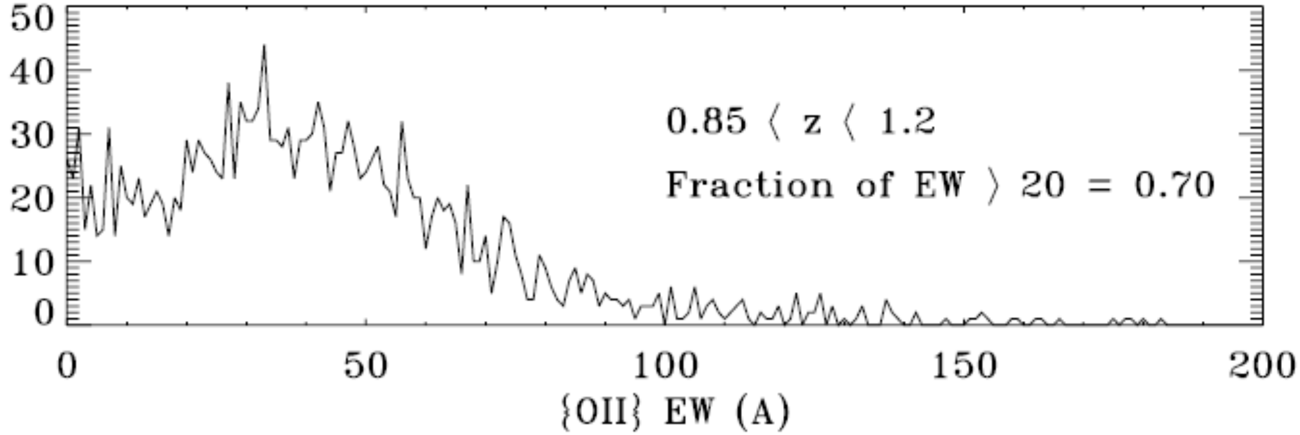
Red: curve-of-growth of flux for stellar objects

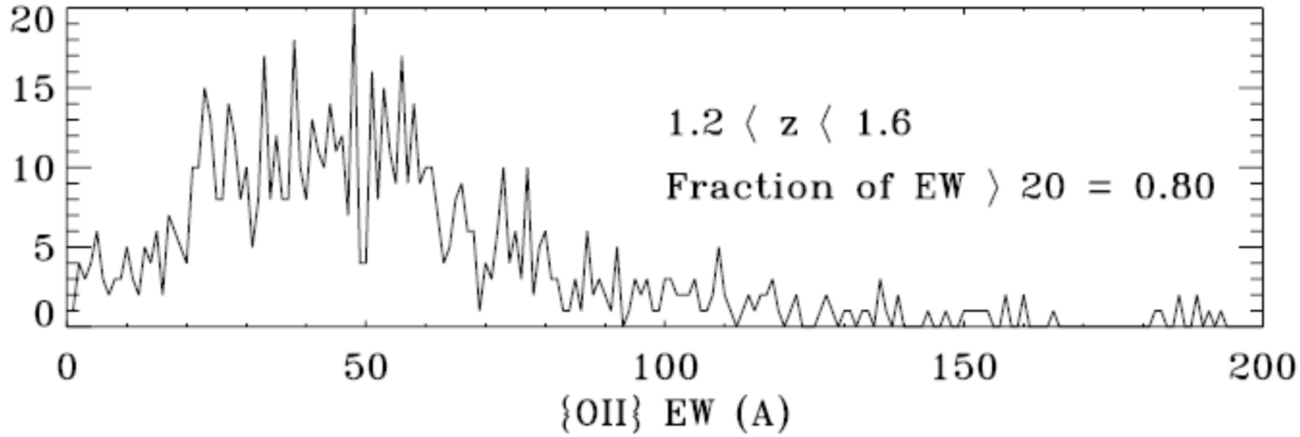
Green: S/N for bright stellar objects

Black: stellar objects with similar mag to sky brightness per sq arcsec.

Blue: S/N for objects 3–4 mags fainter than sky.

Equivalent Width histograms

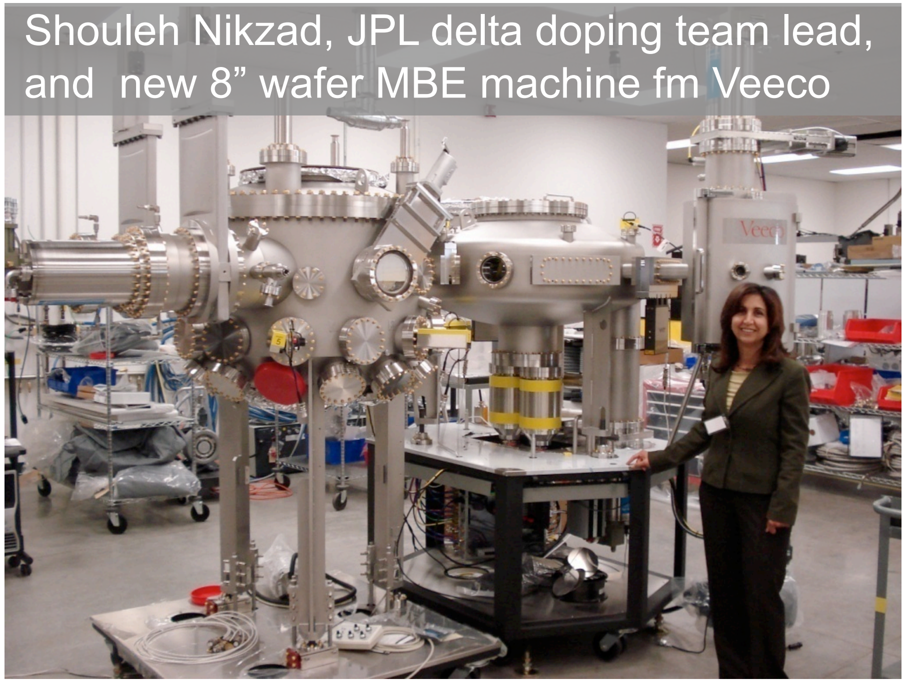


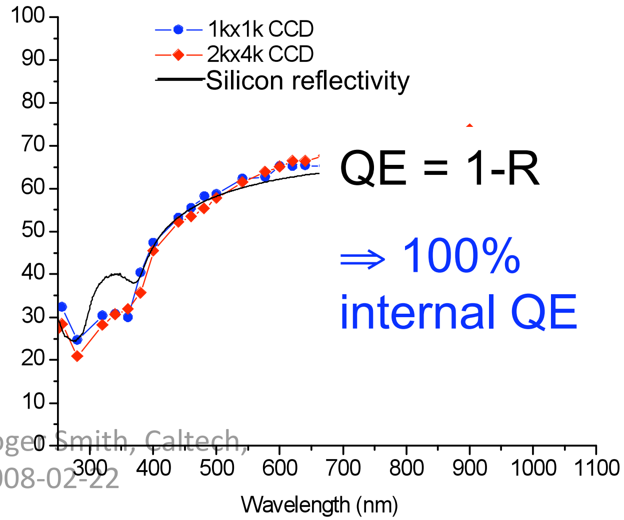


EW = spectral width of continuum that has the same flux as the emission line

Data from Team Keck Redshift Survey (TKRS) (Wirth et al, AJ, 127,3121 (2004))

Delta doping by JPL for high blue QE





- High density mono-atomic dopant layer deposited by MBE.
- Forms conductive backside contact without absorption or backside potential well to trap charge generated near surface.
- Allows high performance AR coating.
- Simpler fabrication process than ISDP+ITO used by LBL.

⇒ **higher yield and higher QE**

Requirements Flowdown – Galactic Archaeology

Low Resolution Survey

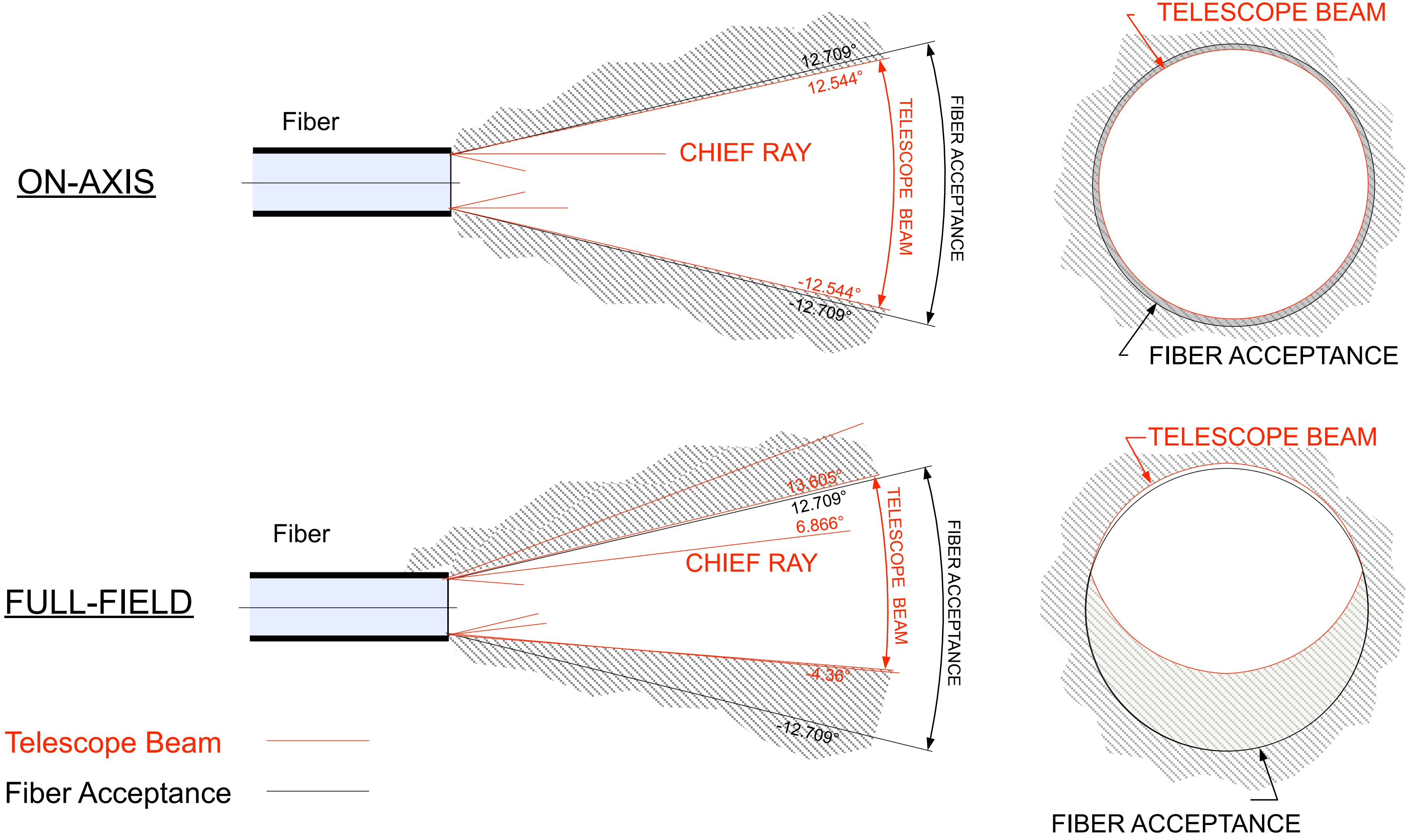
Science Goal	Science Goal	Observing requirement	Instrument requirement	Instrument performance
Measure mass, extent, substructure, of Milky Way dark matter halo Conduct kinematic measurements of dSph candidates to confirm status, measure masses, density profiles Measure the extent, (sub)structure, and kinematics of Milky Way stellar populations	Characterize radial velocity in approximately 30% of substantial stellar streams in the halo. Radial velocity precision of 2 km/s Proxy [Fe/H] measurements to 0.1 dex	• Observe > 3 × 10^6 stars w/ V ≤ 20 • R ~5000 • λ = 480–550 nm and 825–885 nm • Wavelength centering ≥ 0.01 nm • Continuum estimation ≥ 5% • high efficiency	• Number of fibers • Resolution • Wavelength Calibration • Scattered light control • Configuration time	• 2,400 fibers • R = 5000 • λ = 480–554 nm and 818–885 nm • Spectral calibration Lamps emit over λ = 480–544 and 818–885 nm. • Scattered light < 5% • 40 s between observations
	< 2500 hours for GALR and GAHR			

Requirements Flowdown – Galactic Archaeology

High Resolution Survey

Science Goal	**Science Goal**	**Observing requirement**	**Instrument requirement**	**Instrument performance**
Explore the fossil record of chemical evolution of stellar populations in the Milky Way.	Measure metalicity of stars with equivalent widths to better than 5 mÅ	• Observe > 1×10^6 stars w/ V ≤ 17 • R ~20,000 • λ = 480–680 nm • Wavelength centering ≥ 0.01 nm • Continuum estimation ≥ 5%	• Number of fibers • Resolution • Wavelength • calibration • Scattered light • Configuration time	• 2,400 fibers • R = 20,000 • λ = 480–680 nm • Cal lamps: λ = 480–544 & 818–885 nm. • Scattered light < 5% • 40 s between observations
	< 2500 hours for GALR and GAHR	• high efficiency		

Fiber Coupling



Conclusion: Simple, Flat, Field Element Suffices

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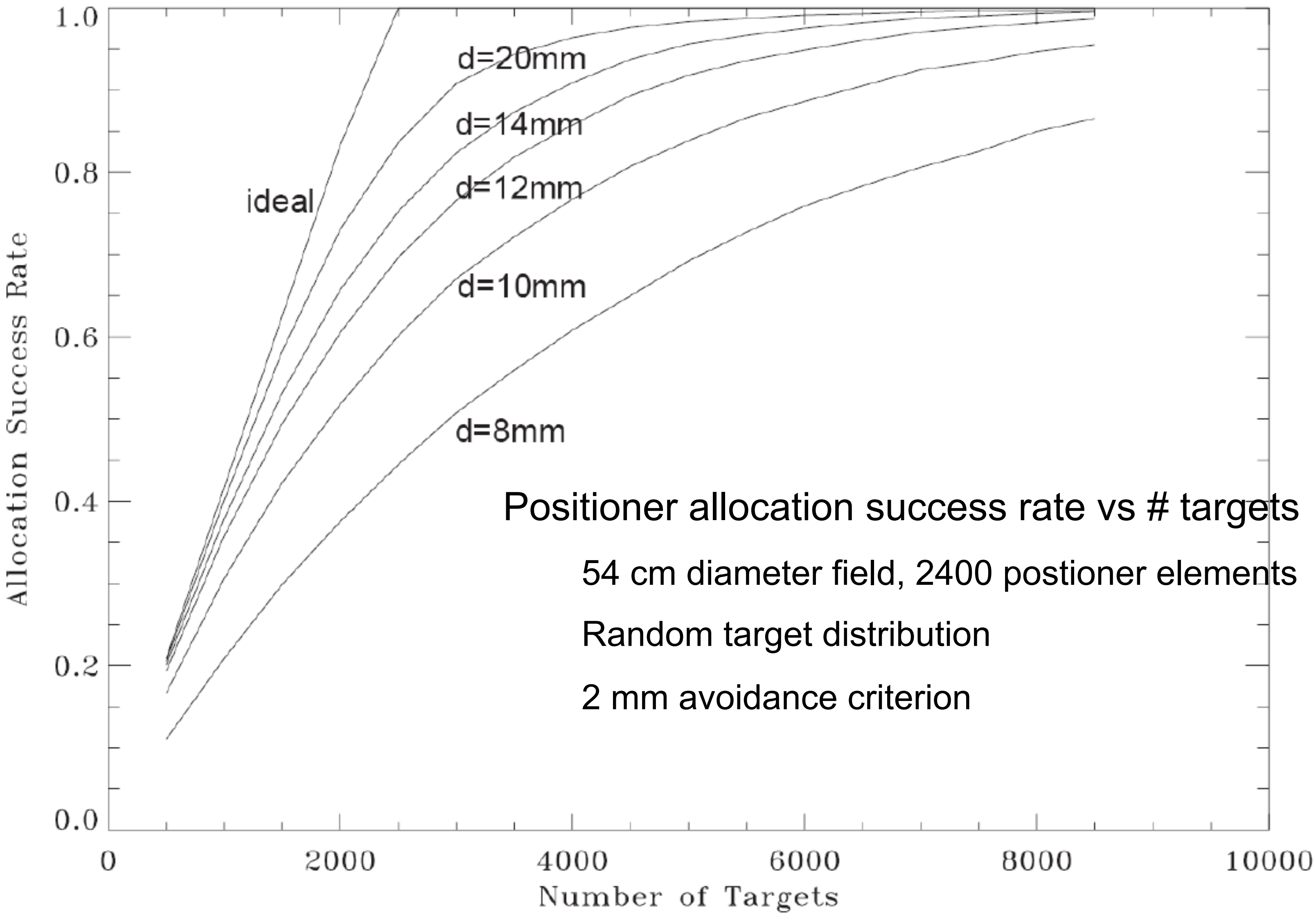
Allocation Efficiency



Positioner allocation success rate vs # targets

54 cm diameter field, 2400 postioner elements

Random target distribution

2 mm avoidance criterion