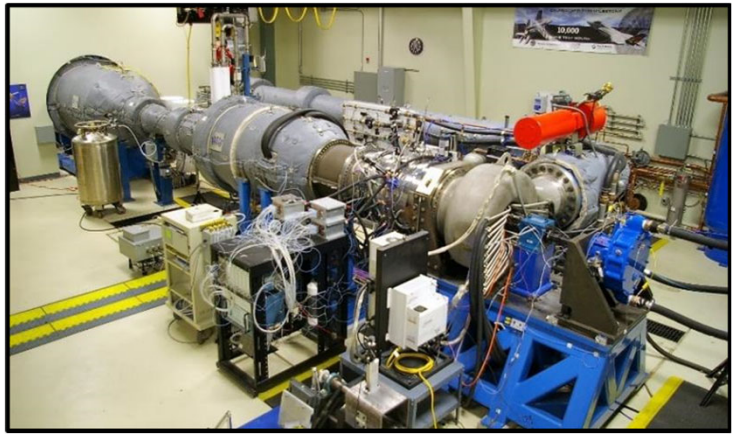
DOE Projects: Cooled Blades and NExT

September 2022 UTSR Update



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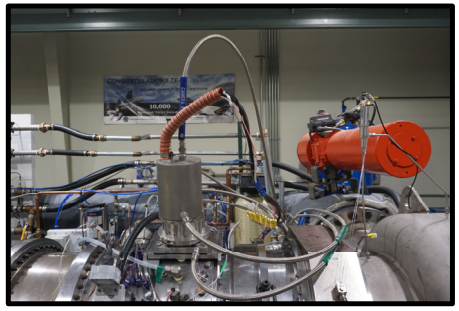
Kelsey McCormack	Pete Wilkins
Chad Schaeffer	Ethan Bonn

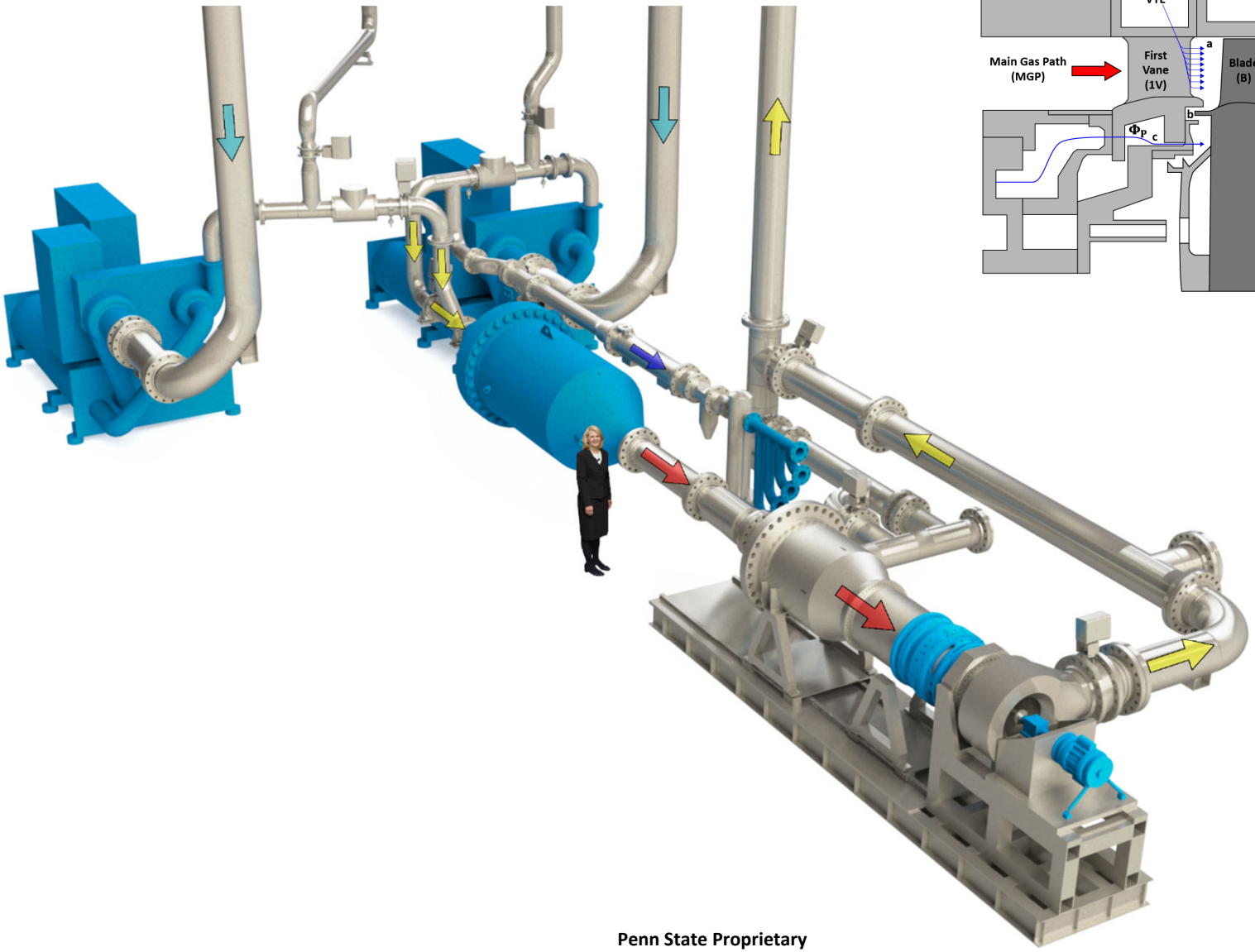
This update provides a summary of recent START 2022 progress made towards supporting two important DOE-NETL funded programs

START:
Facility and Instrumentation



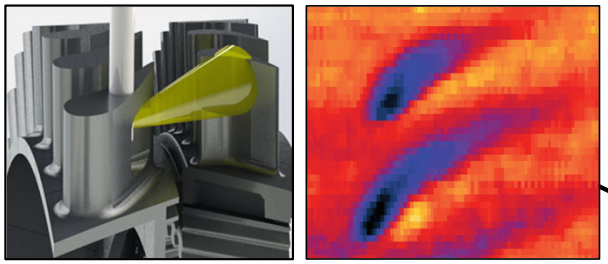
Measurement Improvements:
Durability and Stage Thermal Efficiency

NExT: Manufacturing; Pre-test Predictions and Test Plans

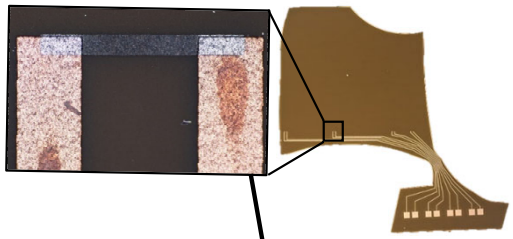


PSU-START integrates a broad suite of measurement techniques to evaluate aerothermal turbine performance

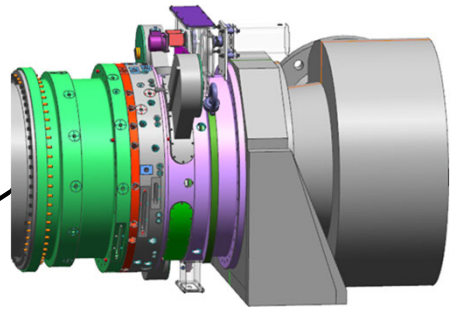
Thermal Imaging



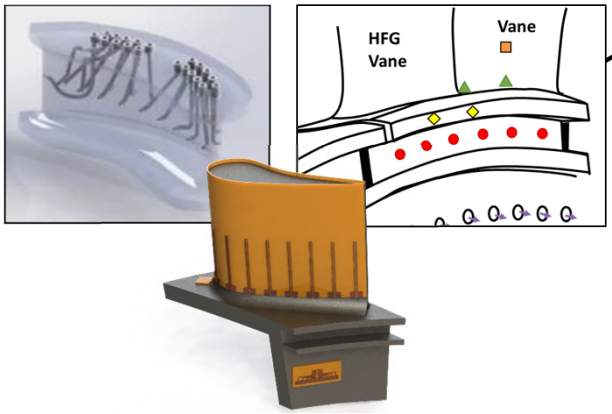
Heat Flux Gauges



Radial & Circ. Traverses



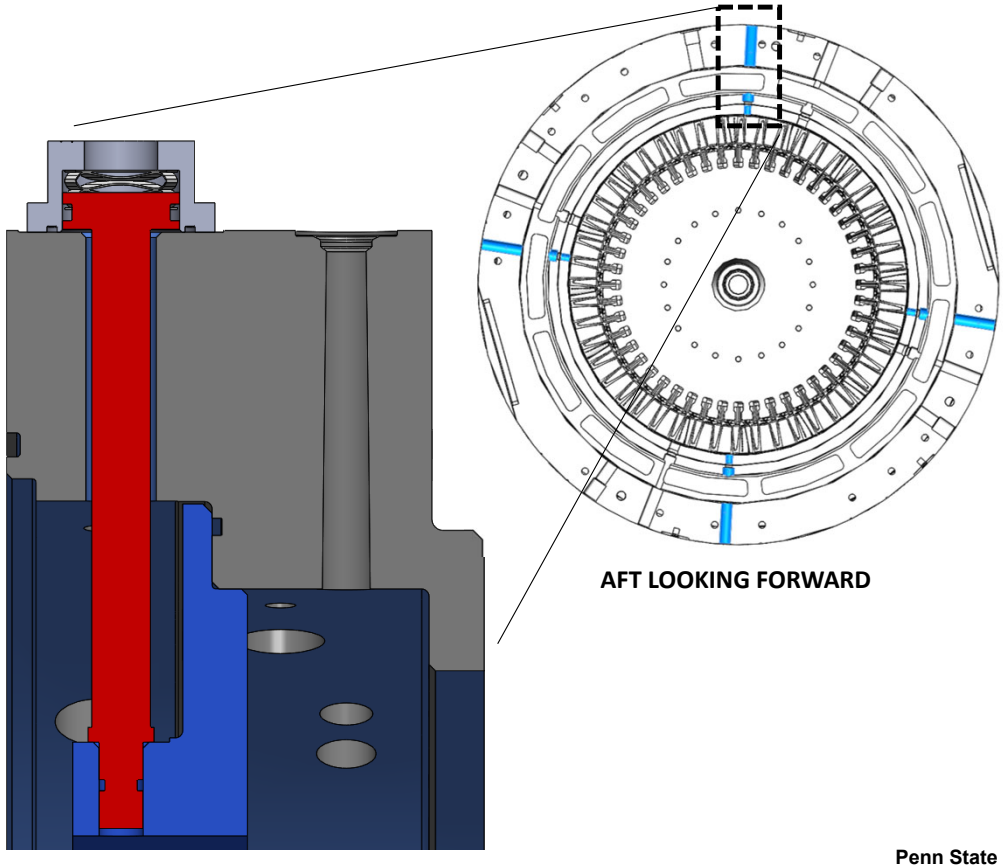
3D Printed Vanes and Blades



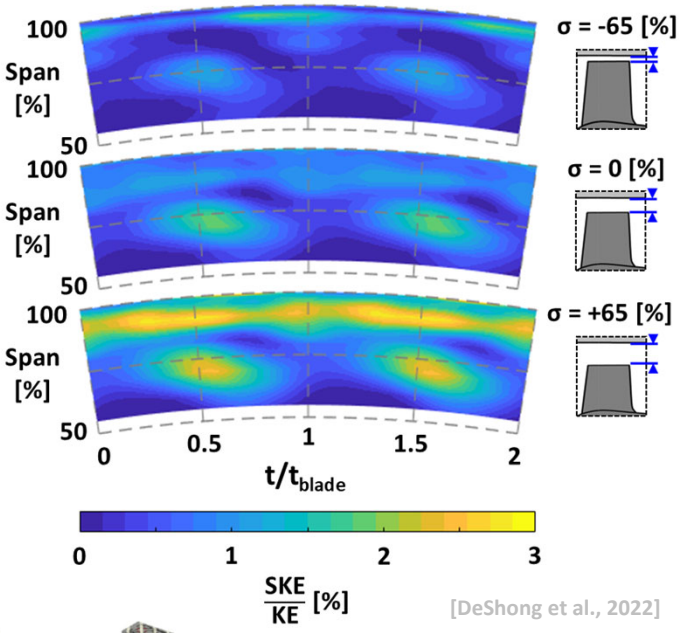
Magnetic Bearing

Advanced instrumentation techniques have also been integrated as standard measurement capabilities for START research programs

Tip Clearance Probes for On-Line Blade-By-Blade Clearance Measurement



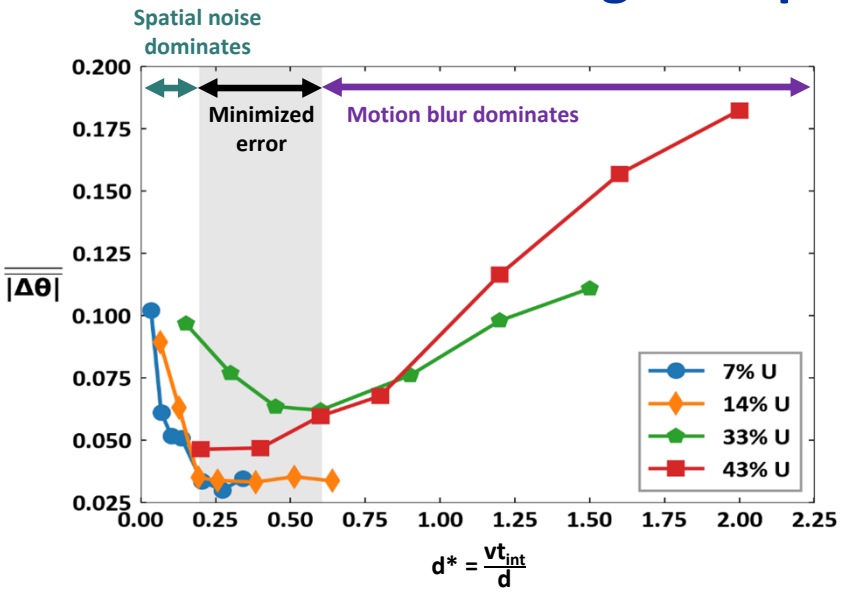
FRAP System for Unsteady Flowfield Measurements

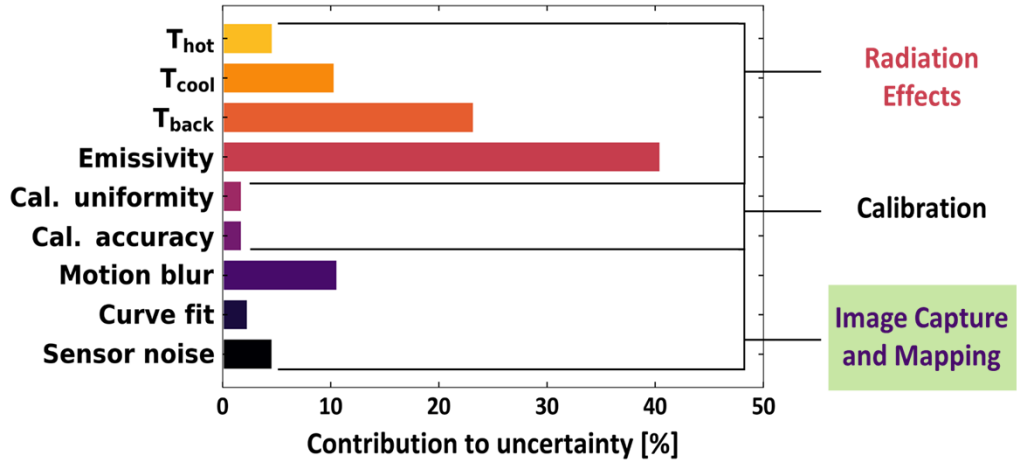


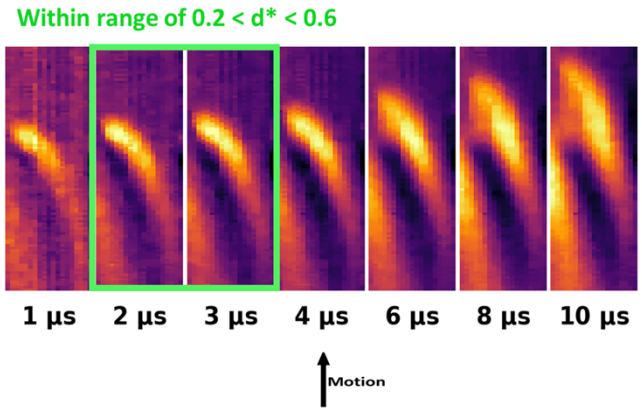
[DeShong et al., 2022]

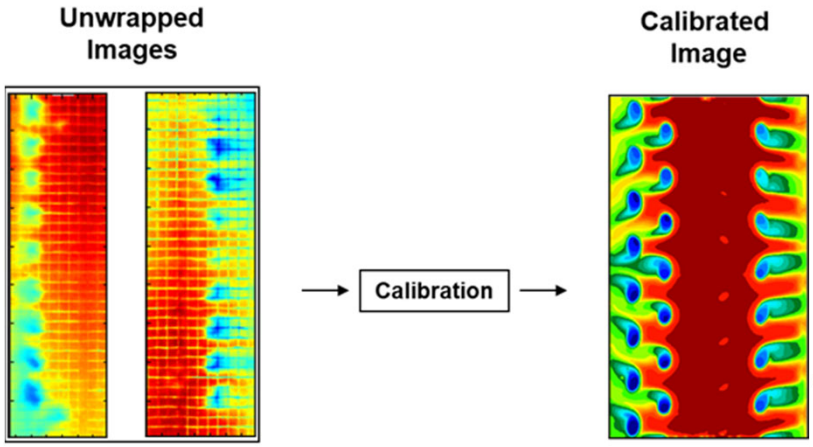
Courtesy of Limmat Scientific

Using a nondimensional parameter, an optimal integration time can be chosen to reduce motion blur at a given speed

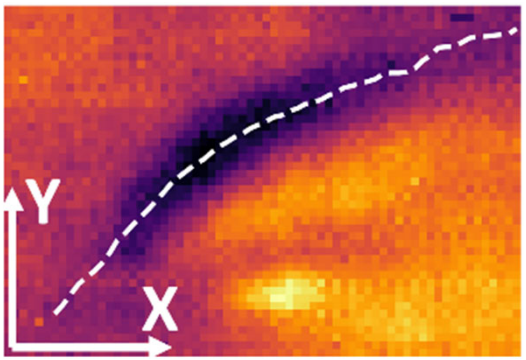




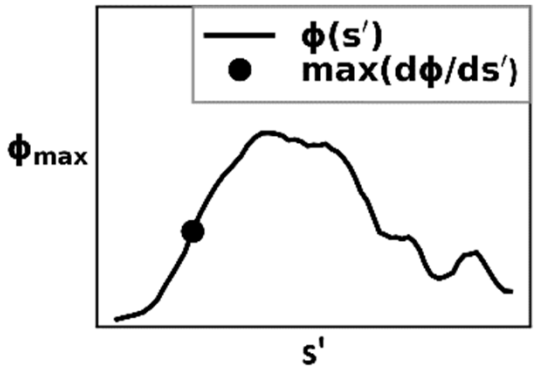




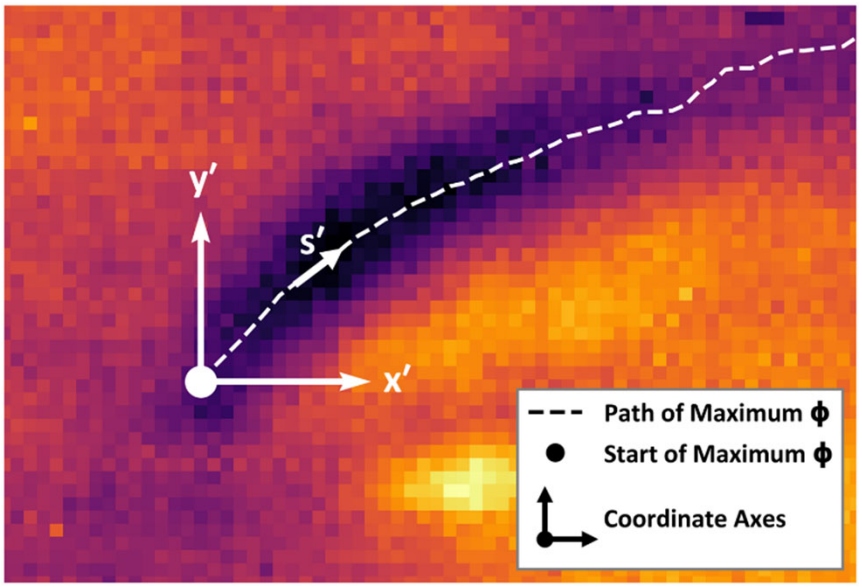
To compare effectiveness results between blades, an objective method was used to establish a coordinate system for each blade for a single hole



Determine path of maximum effectiveness

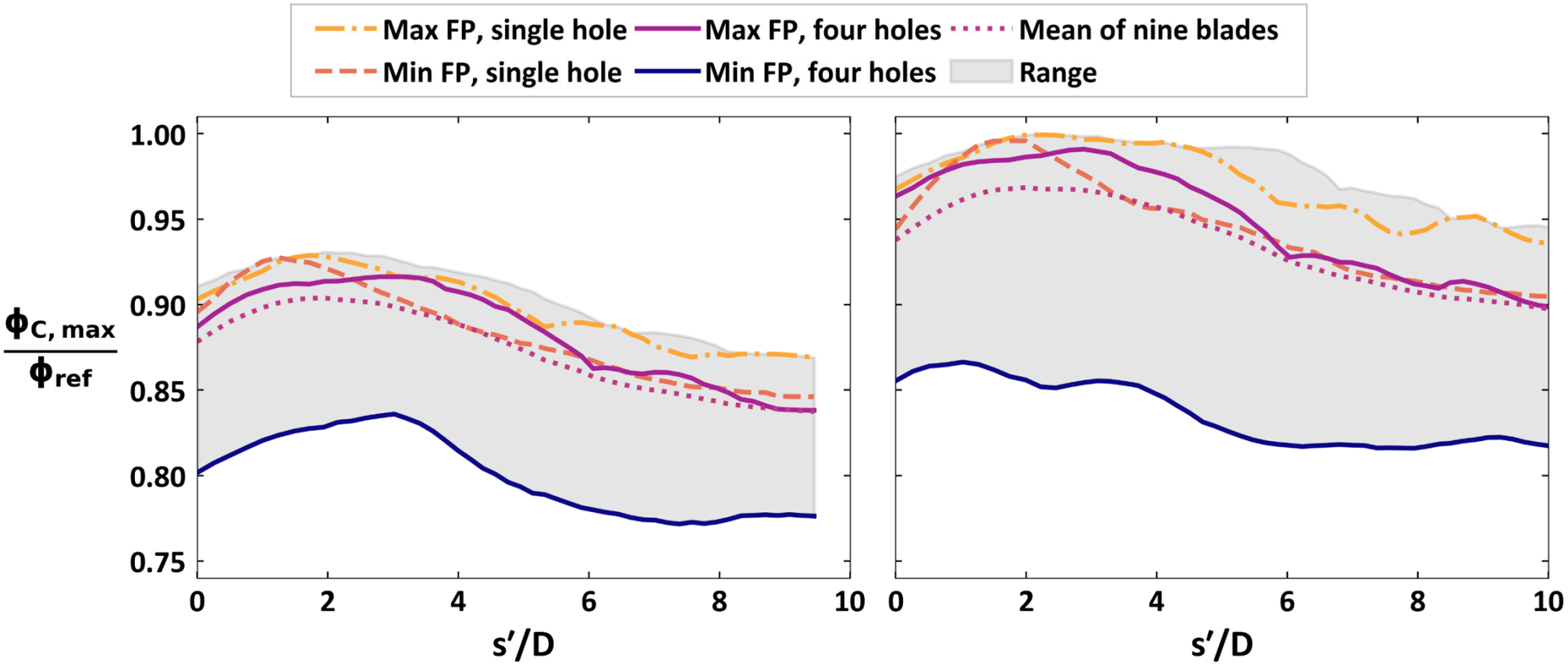


Find location of maximum slope dϕ/ds′



Use location of maximum slope as origin of (x′, y′) coordinates

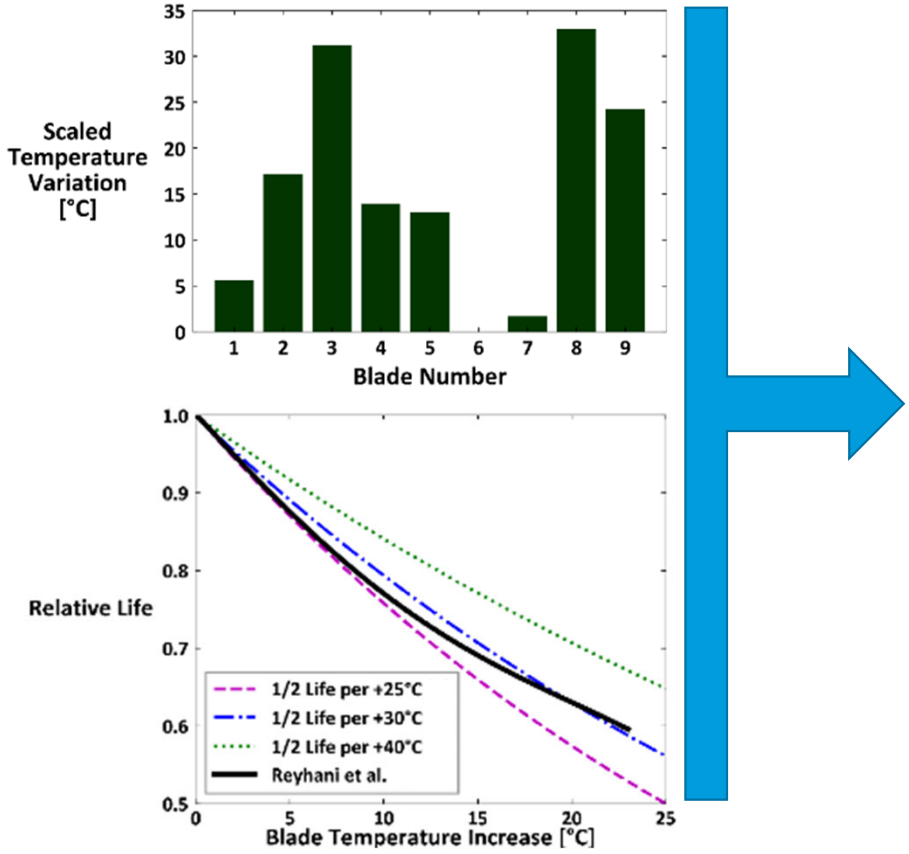
The blade-to-blade variations in effectiveness are up to 15% at the nominal flow case, a wider variation than at the 65% flow case

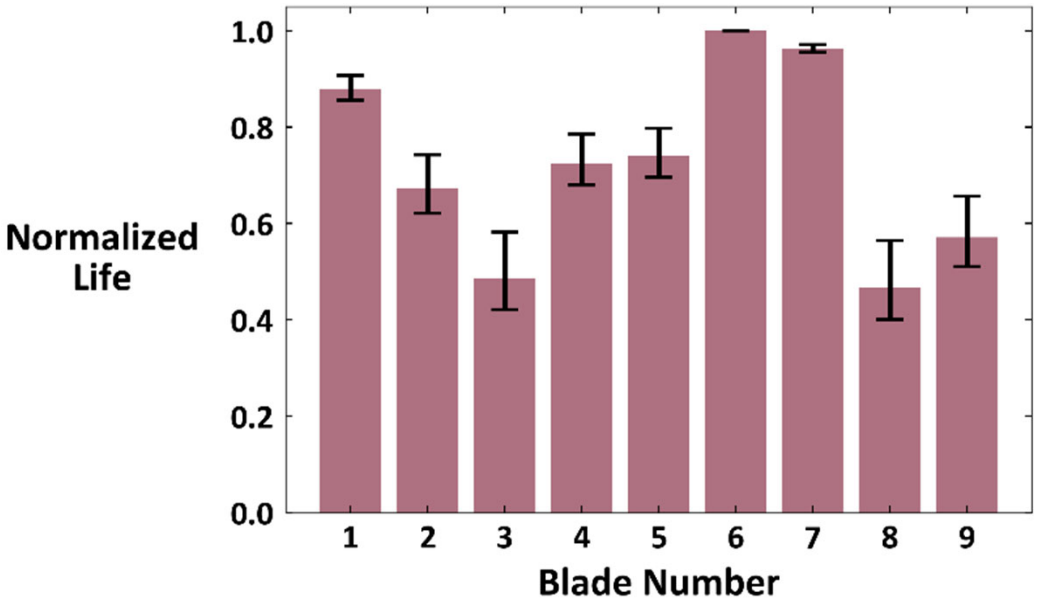


65% cooling flow rate

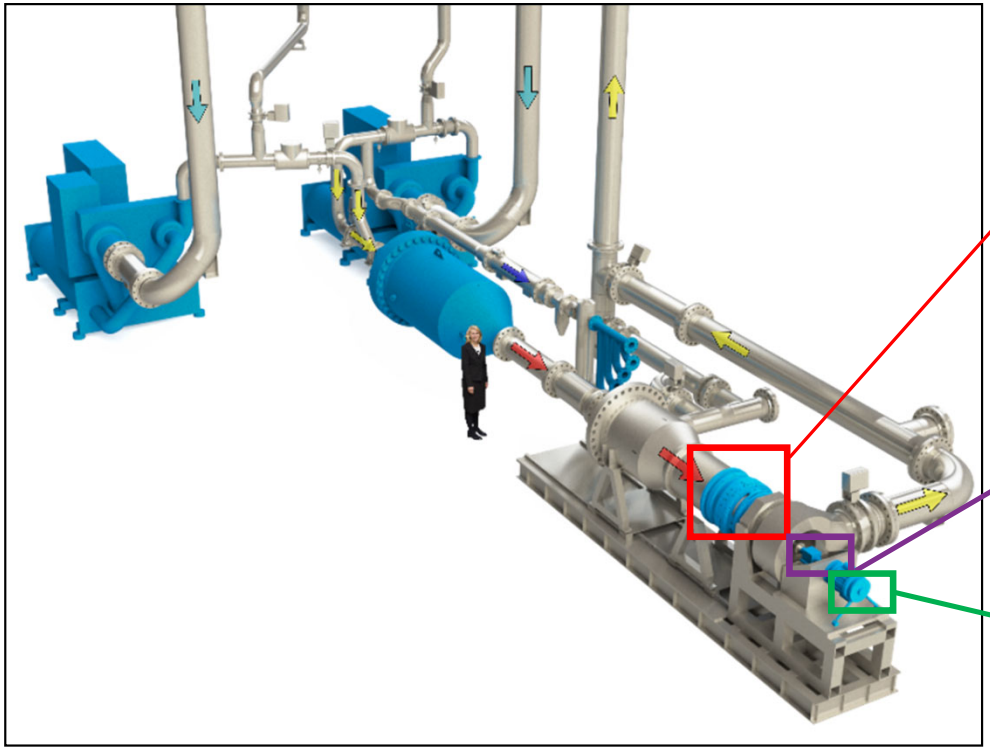
Nominal cooling flow rate

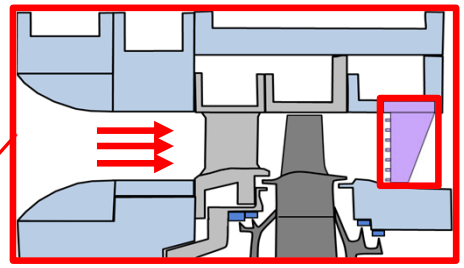
Variations in normalized effectiveness were scaled to engine conditions to show the expected variations in temperature and life

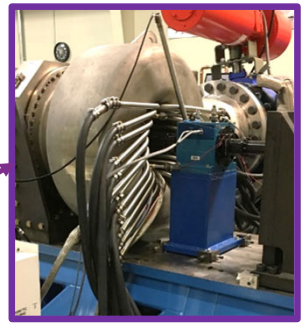




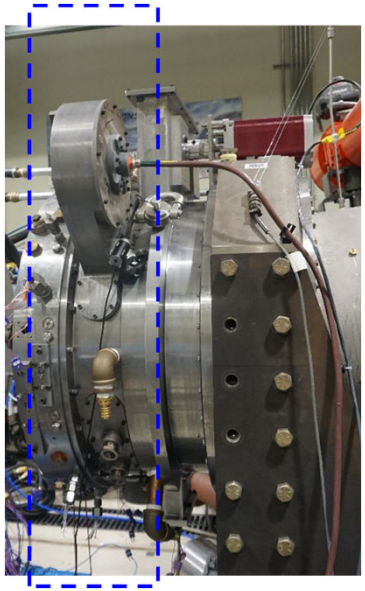
The START Lab at Penn State is a continuous duration single stage test facility with three methods of measuring turbine work

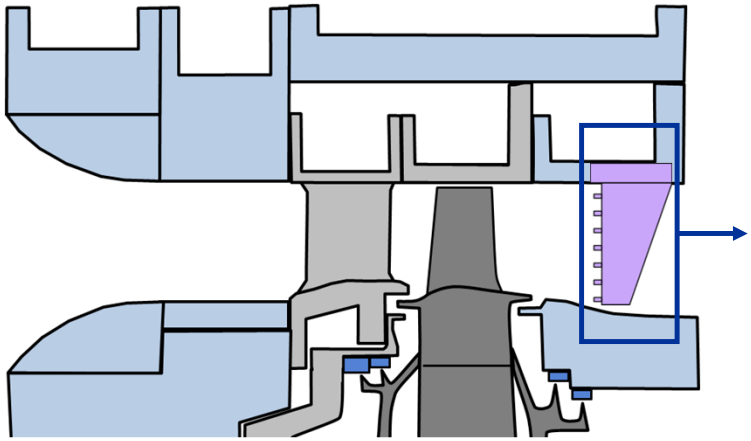


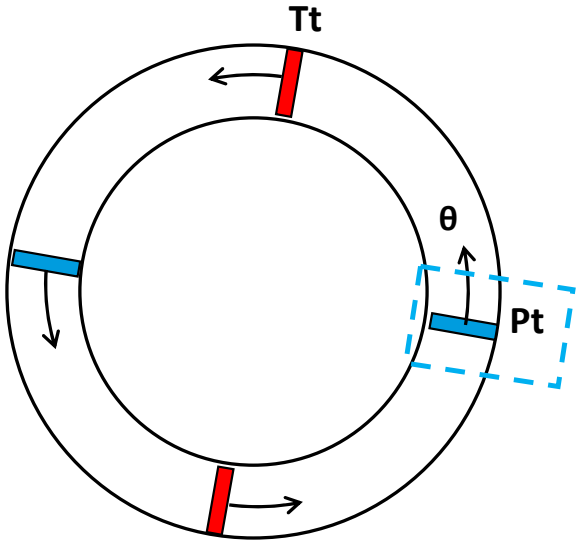


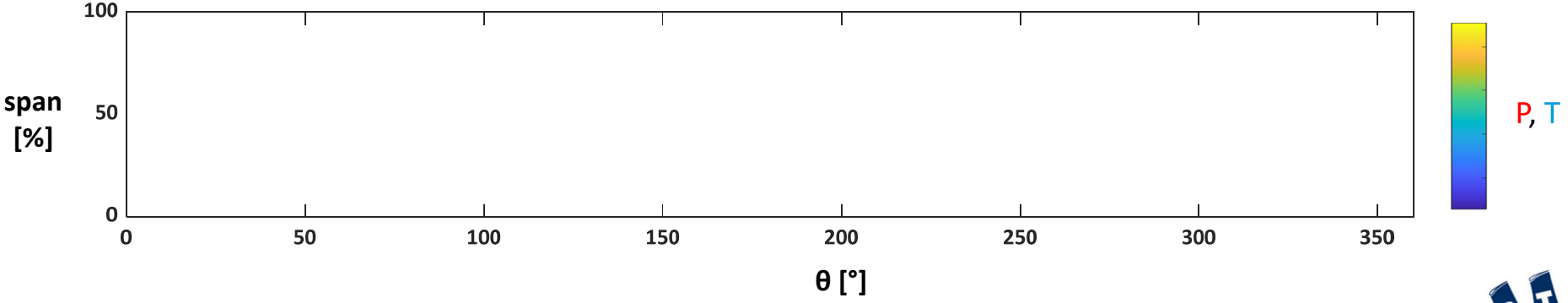


The test turbine facility includes a 360° probe traverse for full-annulus calculations of aero efficiency

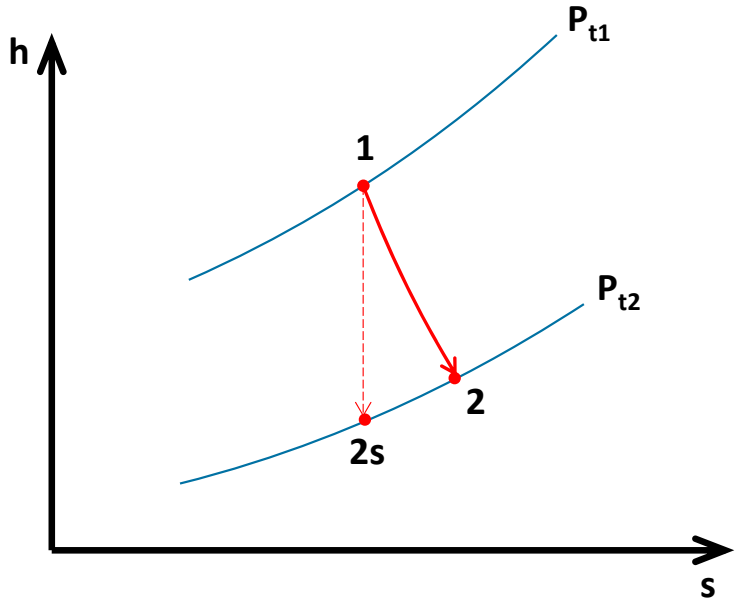


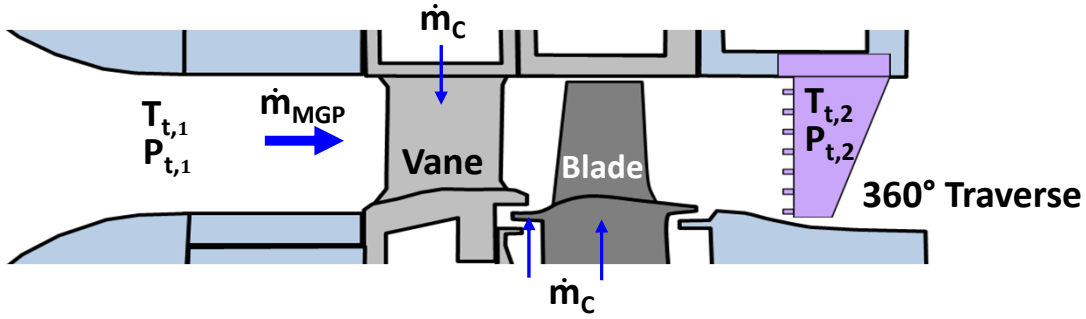






Traversed profiles at the turbine inlet with 360° traverse data at the turbine exit and torque measurements can be used to calculate integrated efficiency





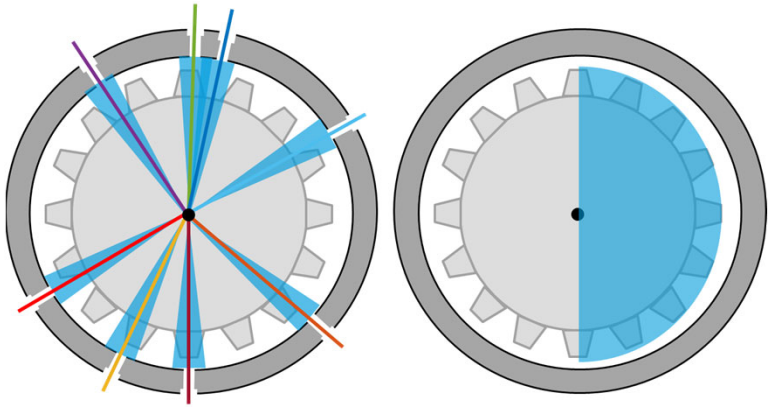
$$h_t = f(P_t, T_t)$$

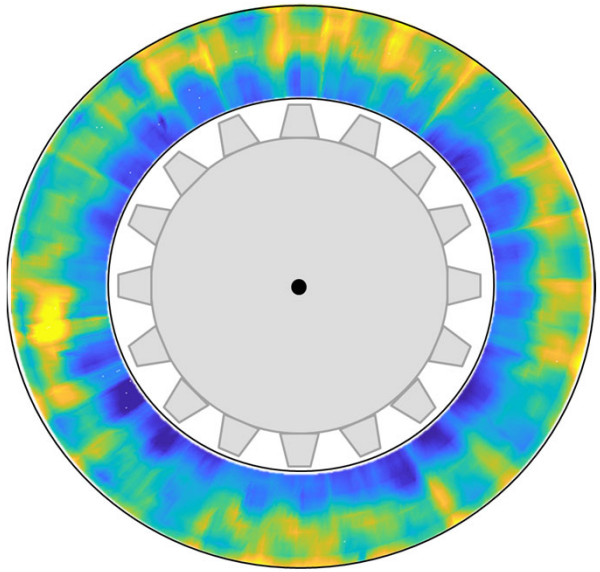
$$\eta = \frac{\text{actual work}}{\text{isentropic work}} = \frac{\Delta H}{\Delta H_S}$$

$$\eta_{aero} = \frac{[\dot{m}_{MGP}h_{MGP,1}+\dot{m}_c h_{c,1}] - [(\dot{m}_{MGP}+\dot{m}_c)h_2]}{[\dot{m}_{MGP}h_{MGP,1}+\dot{m}_c h_{c,1}] - [\dot{m}_{MGP}h_{MGP,2s}+\dot{m}_c h_{c,2s}]}$$

$$\eta_{torque} = \frac{2\pi NT}{[\dot{m}_{MGP}h_{MGP,1}+\dot{m}_c h_{c,1}] - [\dot{m}_{MGP}h_{MGP,2s}+\dot{m}_c h_{c,2s}]}$$

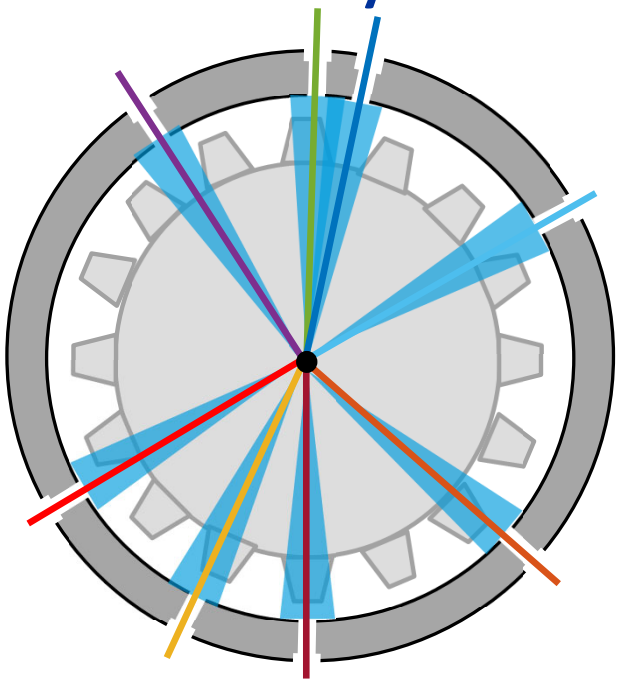
Spatial variations of properties dictate that a full 360° is preferred for efficiency formulations based on both thermodynamic and torque measurements





Temperature differences of only 2°F at the turbine exit plane can result in stage efficiency of > 1pt

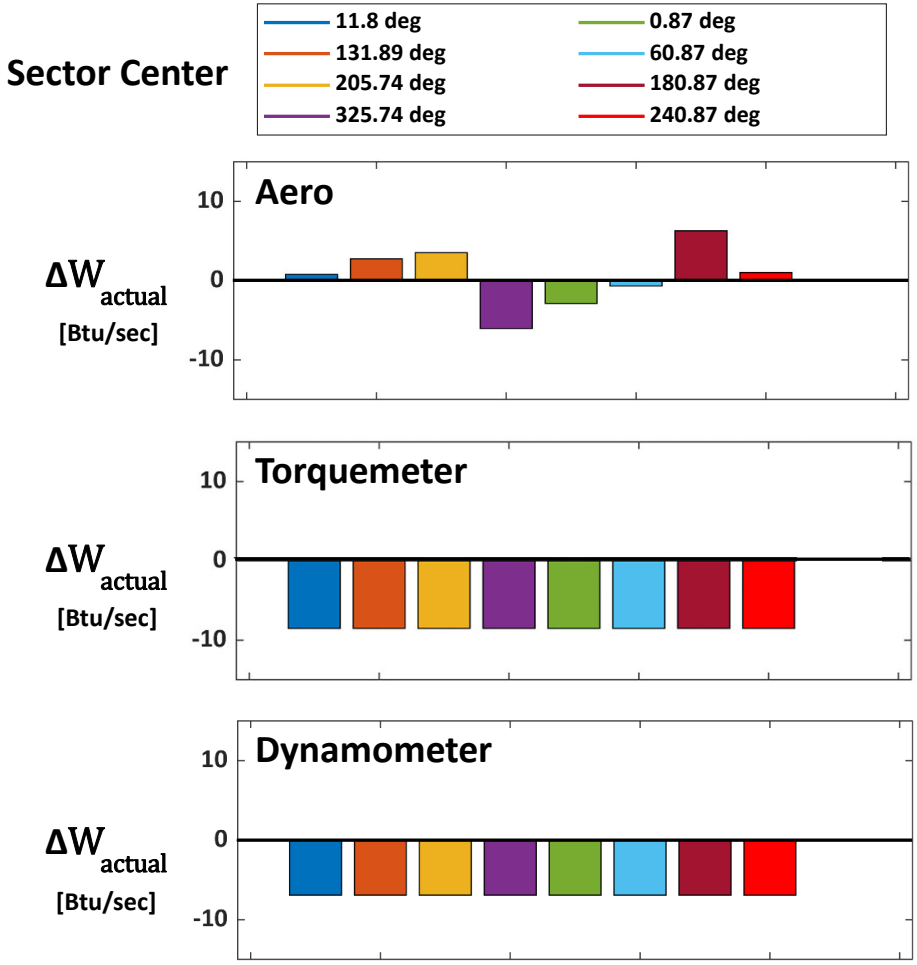
Whereas aero work measurements are dependent on sector size or location, the torquemeter and dynamometer work are not



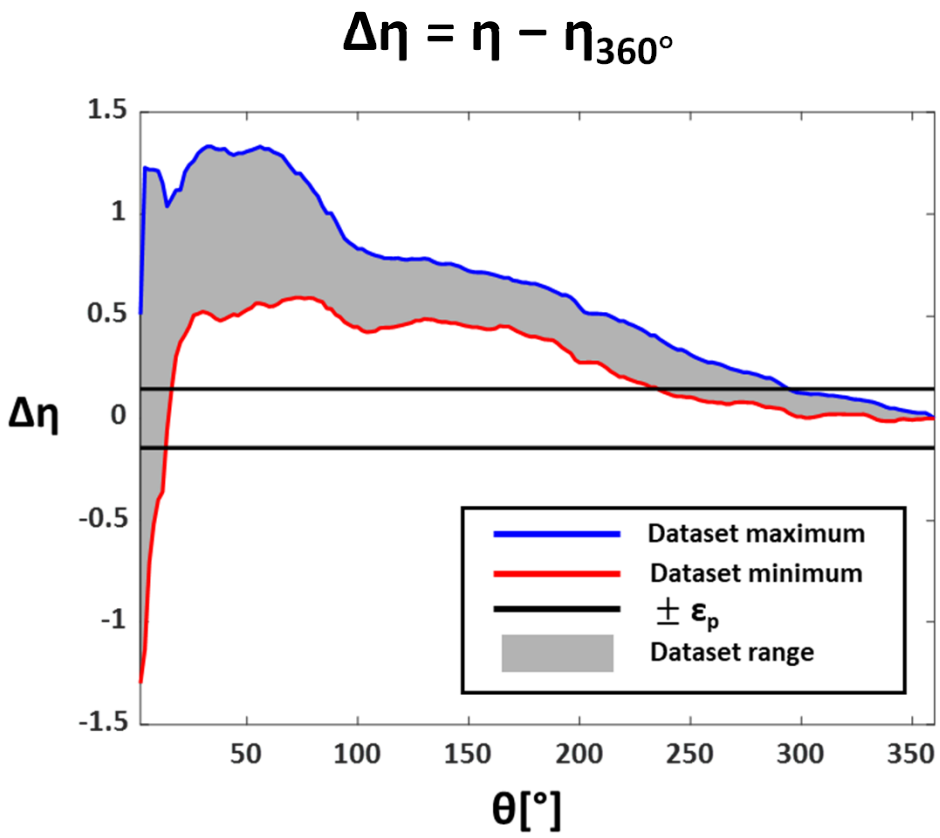
$$\Delta W_{actual} = W_{actual} - W_{actual,aero,360}$$

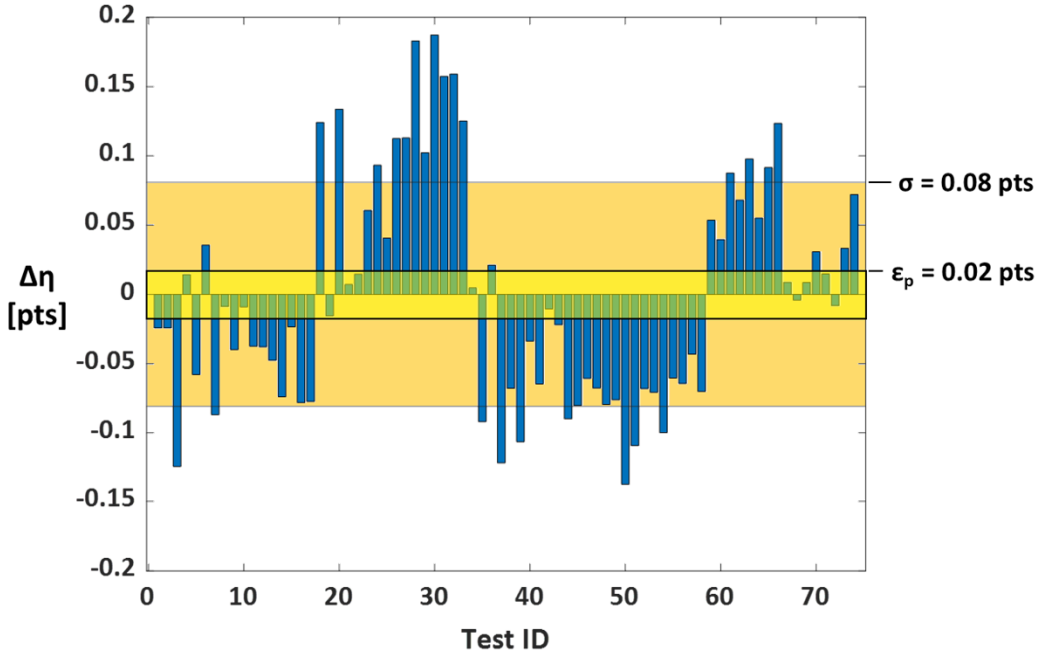
$$W_{actual,\ aero} = \Delta H = [\dot{m}_{MGP} h_{MGP,1} + \dot{m}_c h_{c,1}] - [(\dot{m}_{MGP} + \dot{m}_c) h_2]$$

$$W_{actual,\ torque} = \Delta H = 2\pi NT$$



These figures show the efficiency range as a function of sector size centered at BDC as it approaches the 360° values



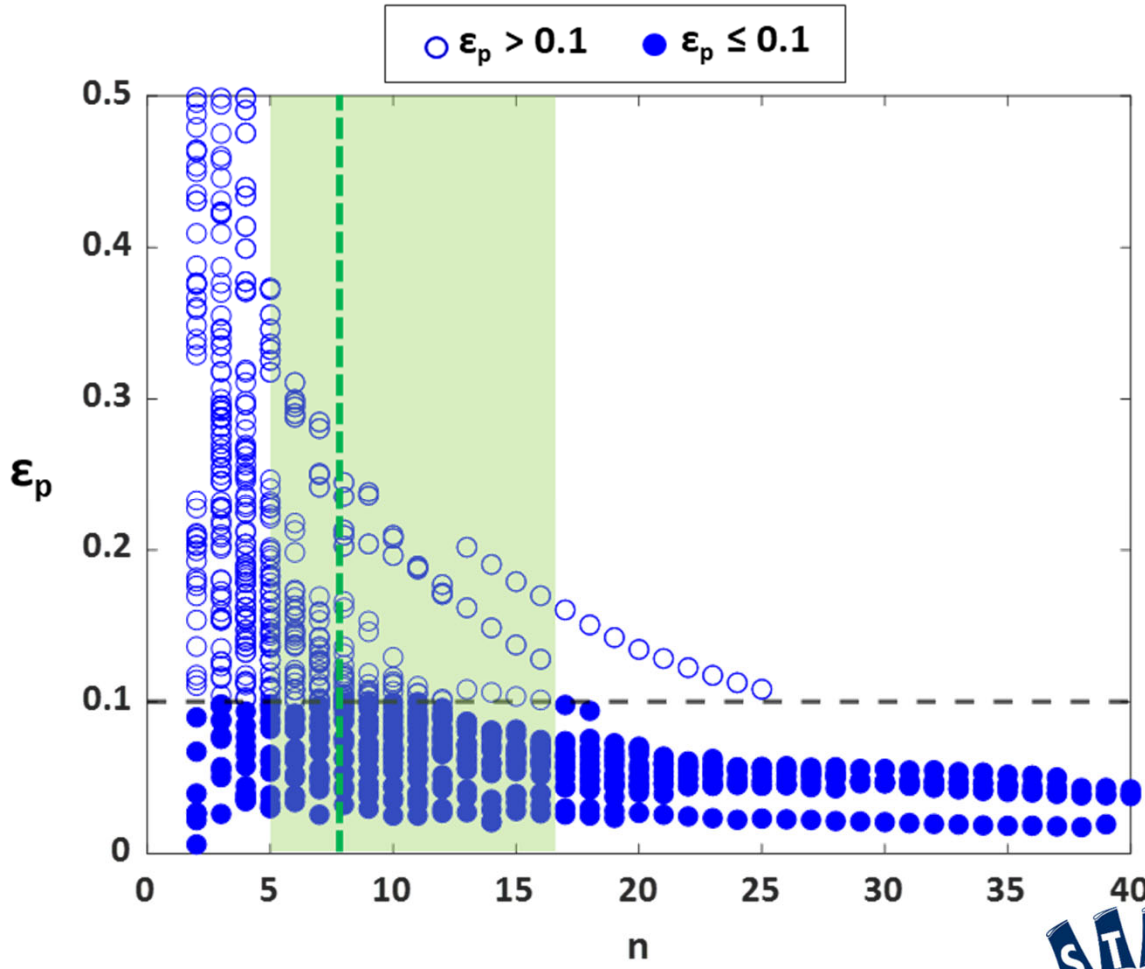


An average of nine tests would be required to obtain a precision uncertainty less than the bias uncertainty, which is 0.1 pts in efficiency

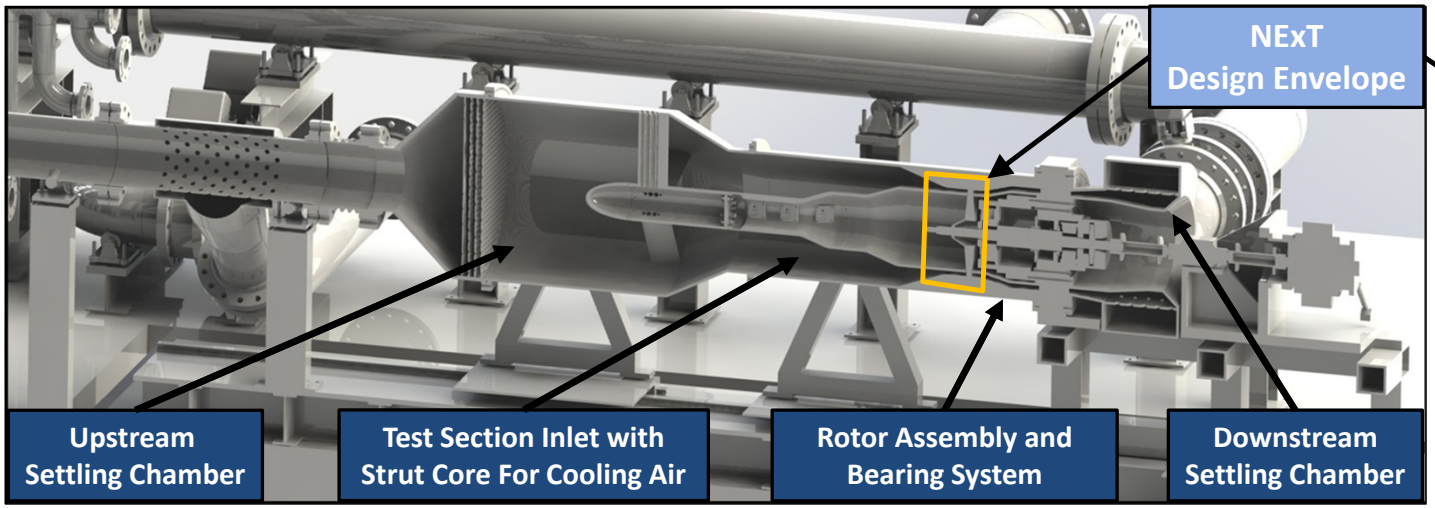
$$t = \frac{\bar{\eta} - \mu}{\sigma / \sqrt{n}}$$

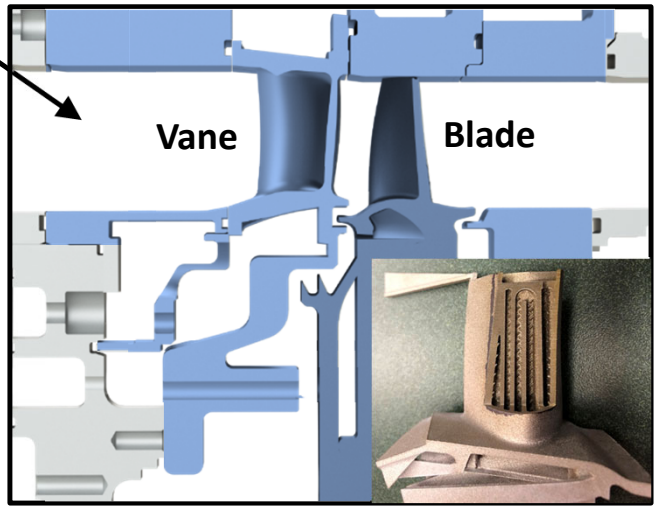
$$\varepsilon_p = \bar{\eta} - \mu = t_{0.95} \frac{\sigma}{\sqrt{n}}$$

ε_p : precision uncertainty
μ : expected mean
σ : stand. dev.
n : sample size



The National Experimental Turbine (NExT) Project allowed START to develop a PSU-proprietary turbine that is "public" and designed through industry partners





NExT

NATIONAL ENERGY TECHNOLOGY LABORATORY

PRATT & WHITNEY
DEPENDABLE ENGINES

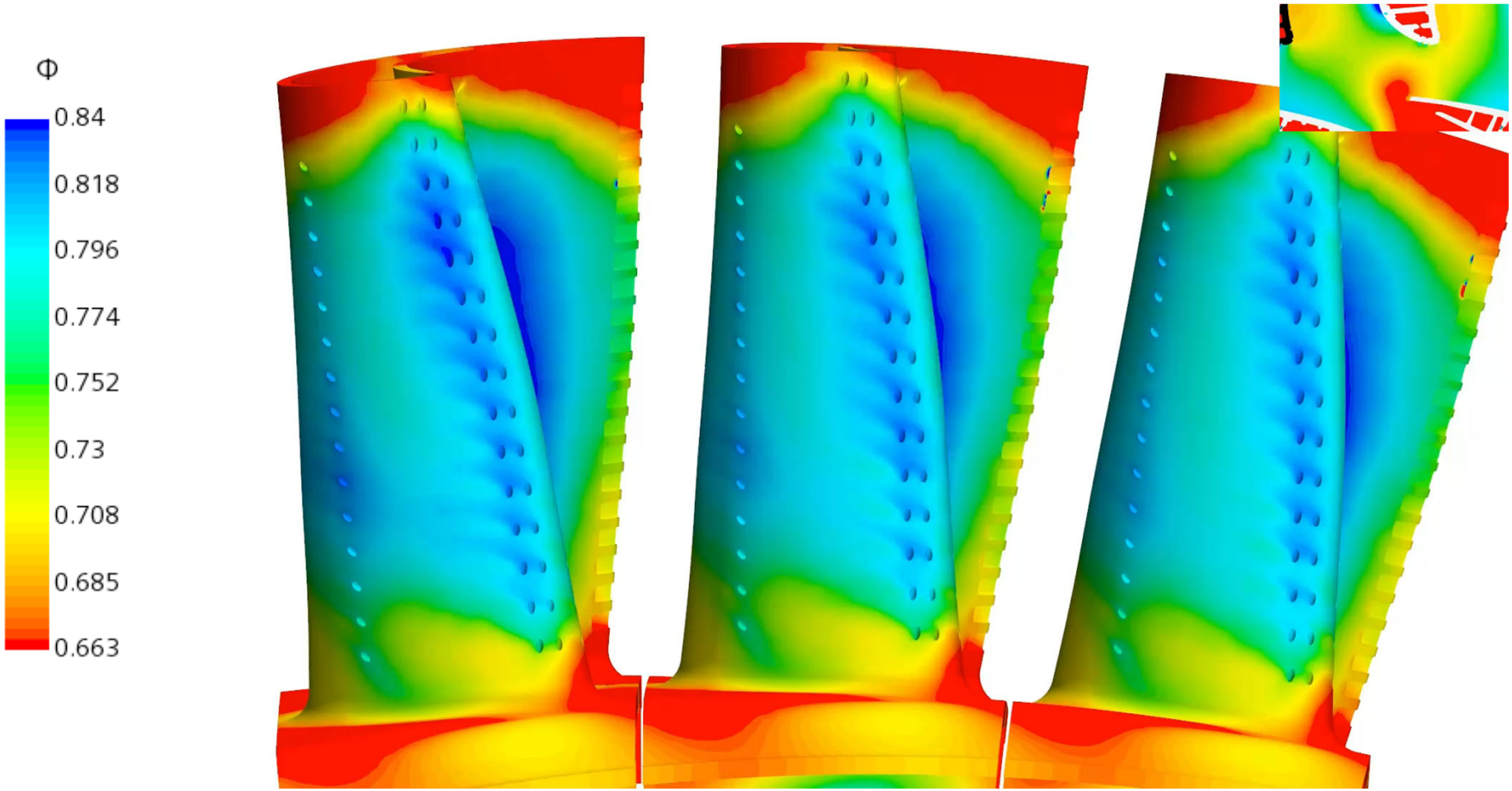
Solar Turbines
A Caterpillar Company

AGILIS
Revolutionary Insight

Honeywell
AEROSPACE

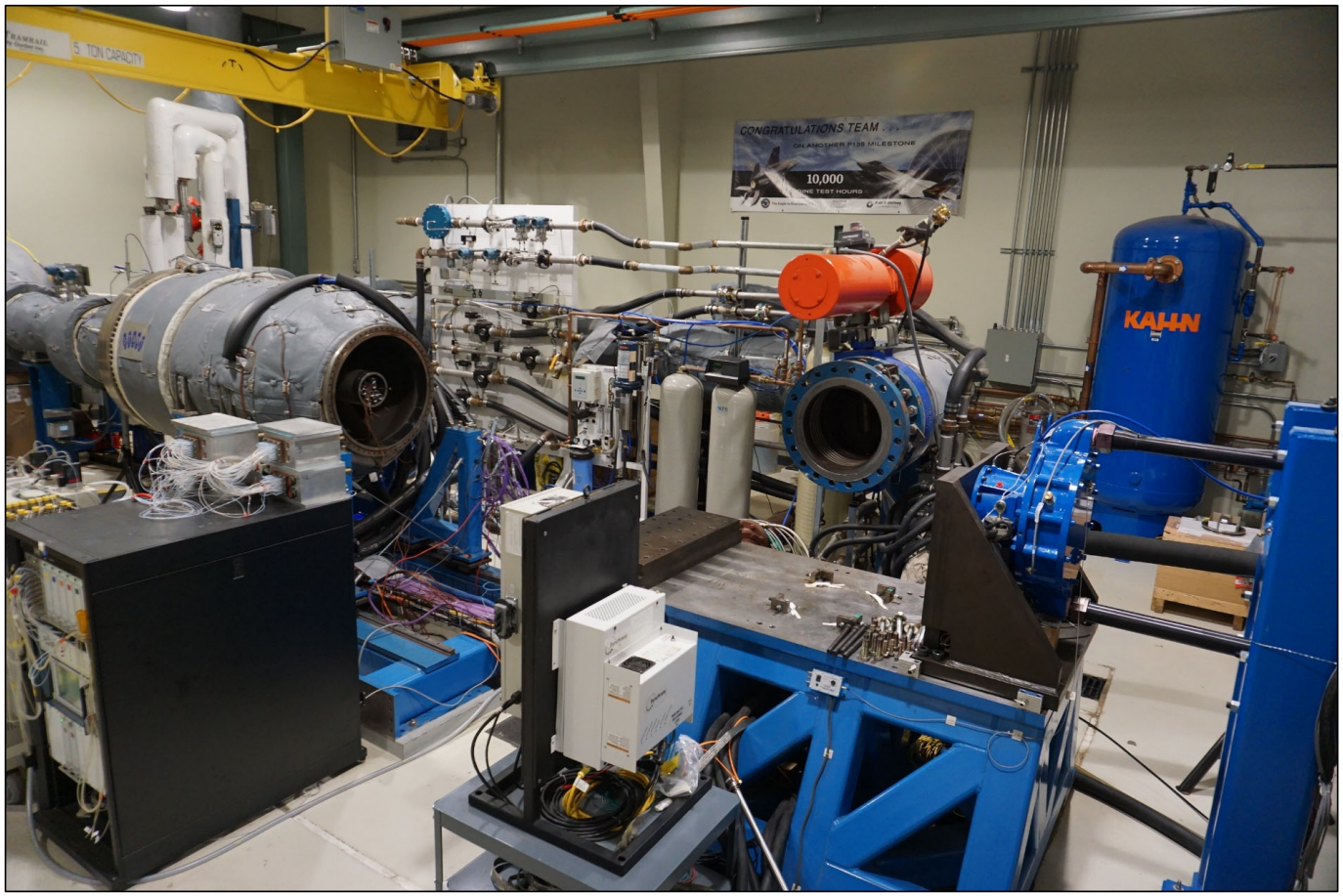
SIEMENS energy

Pre-test CFD predictions identified unsteady effects

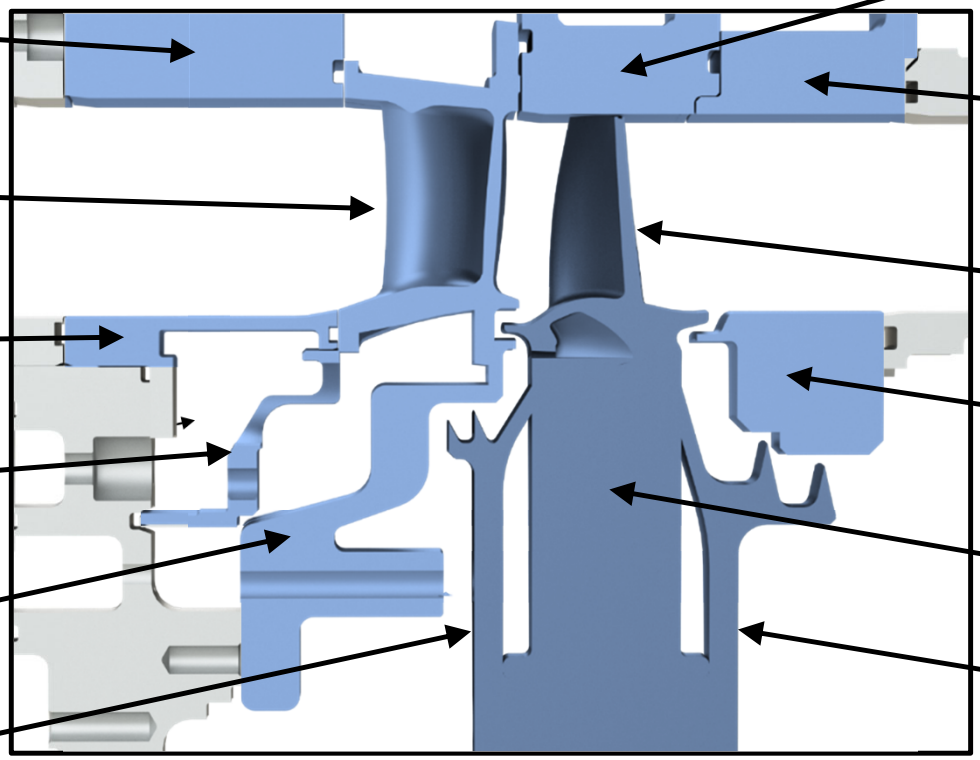


Robert Kunz, Leland Tien 2022

The current status of the START rig is the turbine test section is in many pieces as we build up the new flowpath for NExT

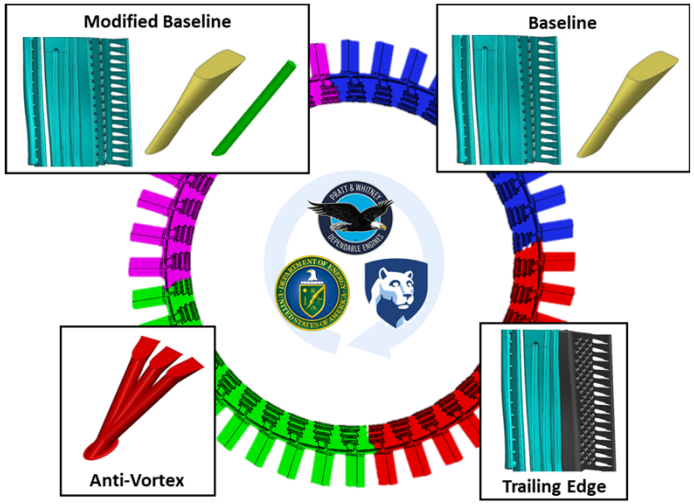


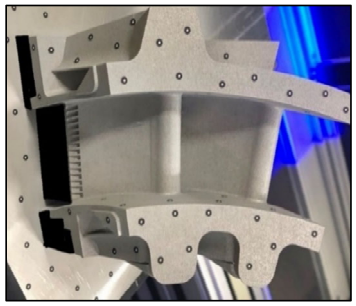
The NExT hardware is currently being assembled and instrumented to prepare for the upcoming baseline test campaign



Manufacturing for blades and vanes shows dramatic reduction in time using AM

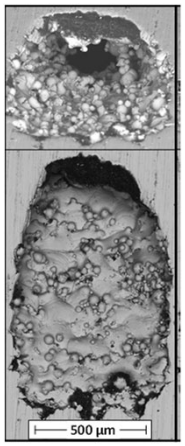
	Type of Manufacturing / Time to Manufacture (weeks)	Time To Manufacture	Expected Delivery
DoE Cooled Blades	Conventional Cast (core yield 25-75%)	3.5 years	Early 2023
NExT Vanes	AM Without Holes	10 months	October 2022
NExT Vanes	AM With EDM Holes	6 Months	June 2022
NExT Blades	AM With EDM Holes	10 months	October 2022
NExT Blades	Cast Using AM Printed Mold (No Tooling)	1 year	Mid 2023



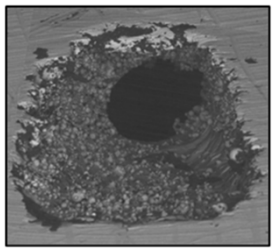


Film-cooling holes and small features continue to be challenging to print at small scales, but AM technology has been advancing over time

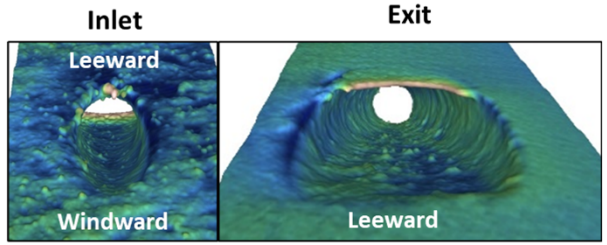
2017

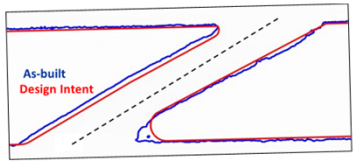


2019

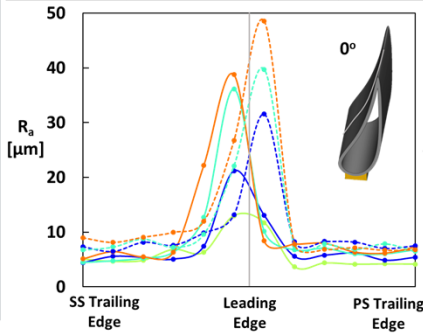


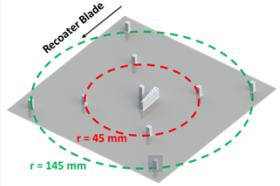
2021



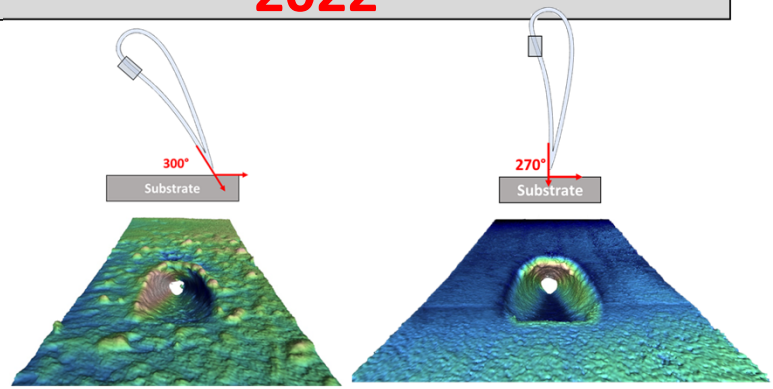


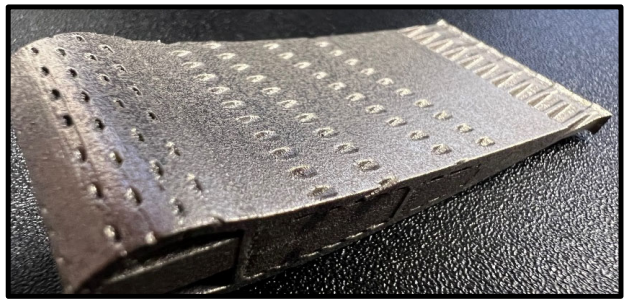
AM Machine	Layer Thickness [µm]	Build Radius [mm] 75	112.5	187.5
EOS M400-1	40			
EOS M400-1	80			
EOS M290-1	40			





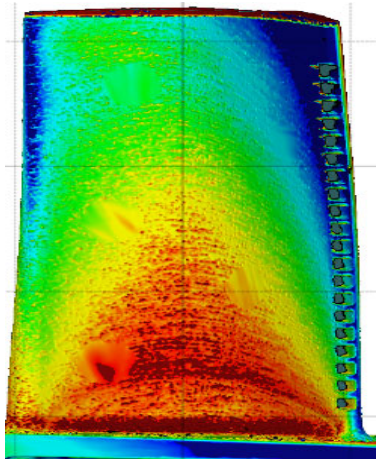
2022



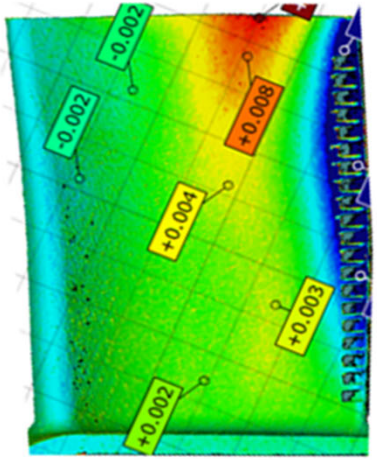


In practice, trial prints of blades and vanes are still a requirement to assess build direction, processing parameters, feature choices, etc

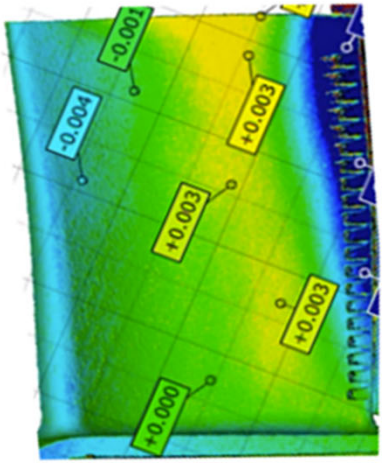
Trial #1

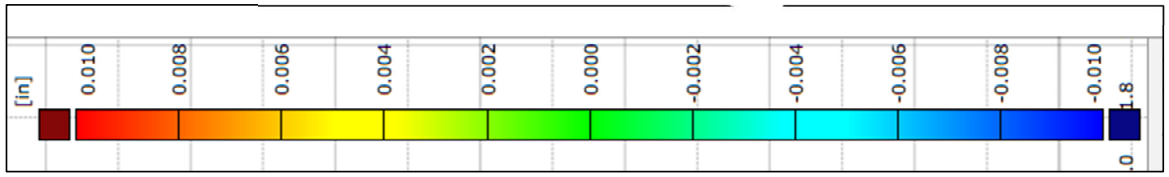


Trial #2

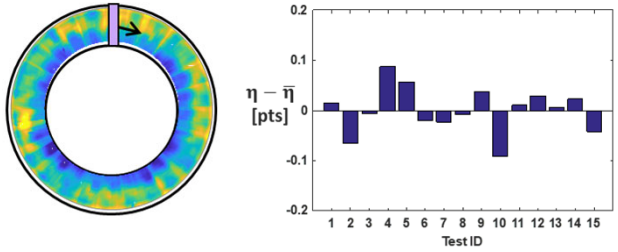


Trial #3

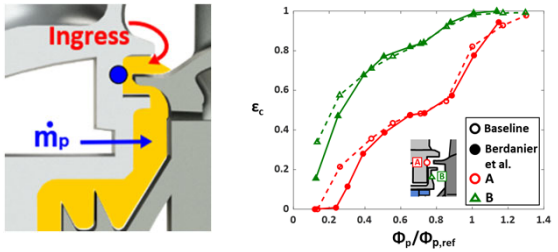




An initial baselining program will characterize NExT design point performance in three specific ways benefitting next-generation turbine analysis goals

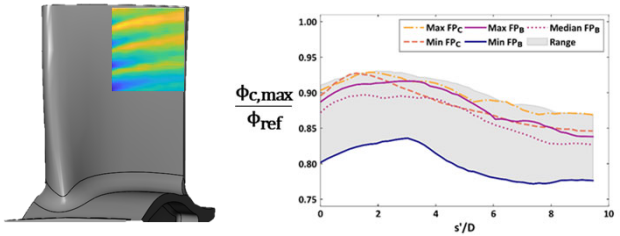


Turbine stage efficiency using aero and torque-based calculations



Quantification of rim sealing effectiveness

Rig Build 1
Oct-Nov 2022



Durability assessments through airfoil IR surface temperature measurements

Rig Build 2
Nov-Dec 2022

FACILITY VARIABLES:

Cooling Flow Rates

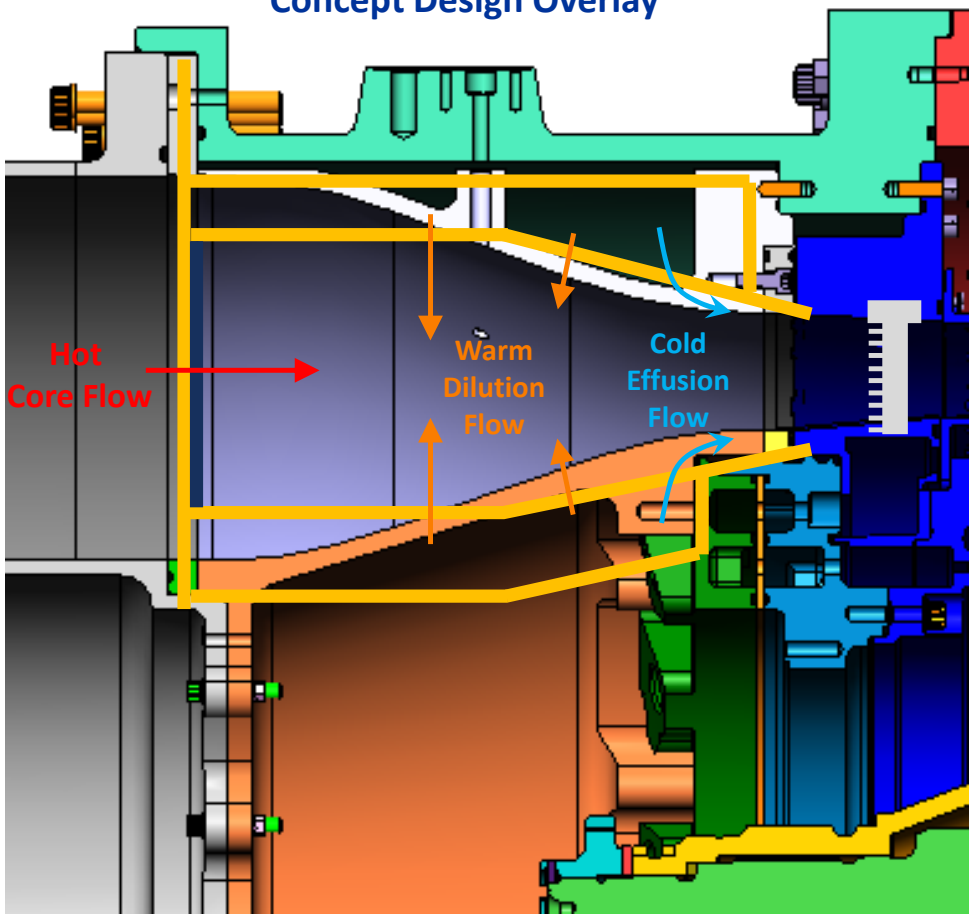
Blade Speed

T_{MGP}
T_{cool}

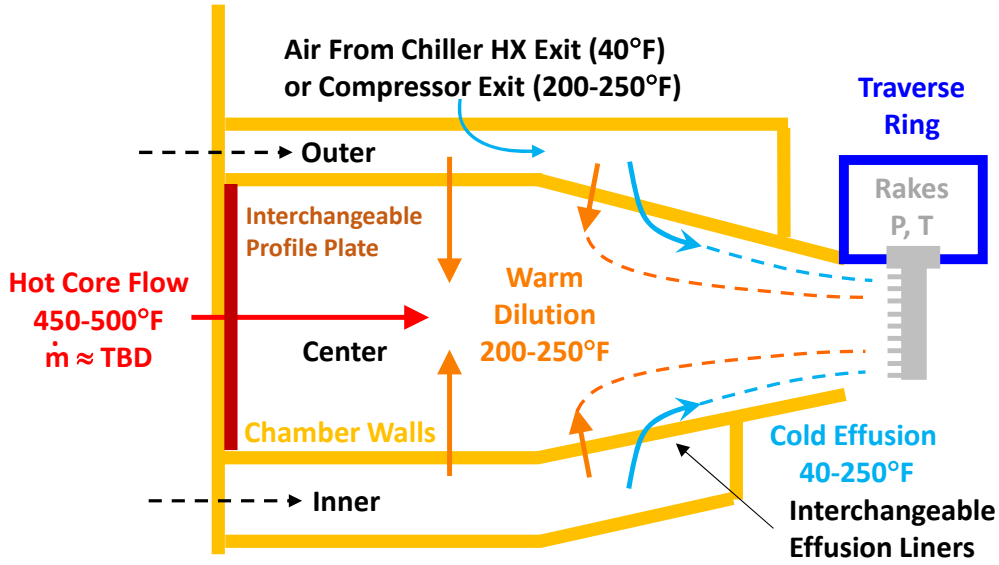
Supply Pressures

START upgrade is being developed to simulate combustor exit profiles

Concept Design Overlay



Concept Design



AGILIS Design Scope:

- Preliminary and Detailed Designs, Manufacturing Drawings
- Chamber Walls, Profile Plate, Traverse Ring, Rakes

PSU START Design Scope:

- 1D flow calculations, CFD Design
- Chamber wall locations, inlet profile plate
- Dilution and effusion hole patterns - size, quantity, locations

In conclusion, we are ready to do the baselining for NExT and are excited to share this data with our community

A huge thanks to DOE-NETL and especially Rich Dennis for supporting these efforts.