

TURBULENCE VISUALIZATION VIA BEAM EMISSION SPECTROSCOPY ON KSTAR

George R. McKee

University of Wisconsin-Madison, Madison, Wisconsin, USA

US-KOREA WORKSHOP
OPPORTUNITIES FOR EXPANDED FUSION SCIENCE AND
TECHNOLOGY COLLABORATIONS WITH THE KSTAR PROJECT

GENERAL ATOMICS
SAN DIEGO, CALIFORNIA, USA
MAY 19-20, 2004



OUTLINE

- Introduction and Motivation
- Benefits to US program
- BES Capabilities and Value to KSTAR Program
- Implementation on KSTAR
- Estimates of Resource Requirements & Time Line



IMPORTANCE OF TURBULENCE VISUALIZATION TO KSTAR

- Turbulence is inherently 2D phenomenon ($k_{\parallel} \ll k_{\perp}$, k_r and so ignorable)
 - Learn more than with 1D, single-point or spatially-averaged measurements
- Develop more comprehensive understanding of turbulence and transport processes
 - Highly nonlinear phenomenon
 - Self-regulation (zonal flow generation & feedback)
- Develop and validate predictive capability for transport in AT plasmas
 - Complex interplay between transport, MHD, auxiliary systems/profile control
 - particle, energy, momentum transport: profiles, shear
 - Advanced scenarios will likely lead to reduced turbulence conditions
- Uniqueness of KSTAR
 - AT plasma capability: significant auxiliary systems, profile control
 - Steady-state operation: excellent SNR for ensemble-averaged properties
 - New ρ^*
- One of 4 topics of high interest for US/Korea Collaboration

Strongly justified on scientific basis



VALUE AND BENEFITS TO THE US FUSION PROGRAM

- Continue US leadership role in vital fusion science areas
- Strengths of US fusion program include:
 - Turbulence simulation and transport modeling
 - Advanced diagnostics (esp. fluctuation) development
 - Advanced Tokamak scenario development and operation
- Physics of Transport and Turbulence in AT operation essential
- Contribute to development of fully predictive transport modeling for ITER and beyond

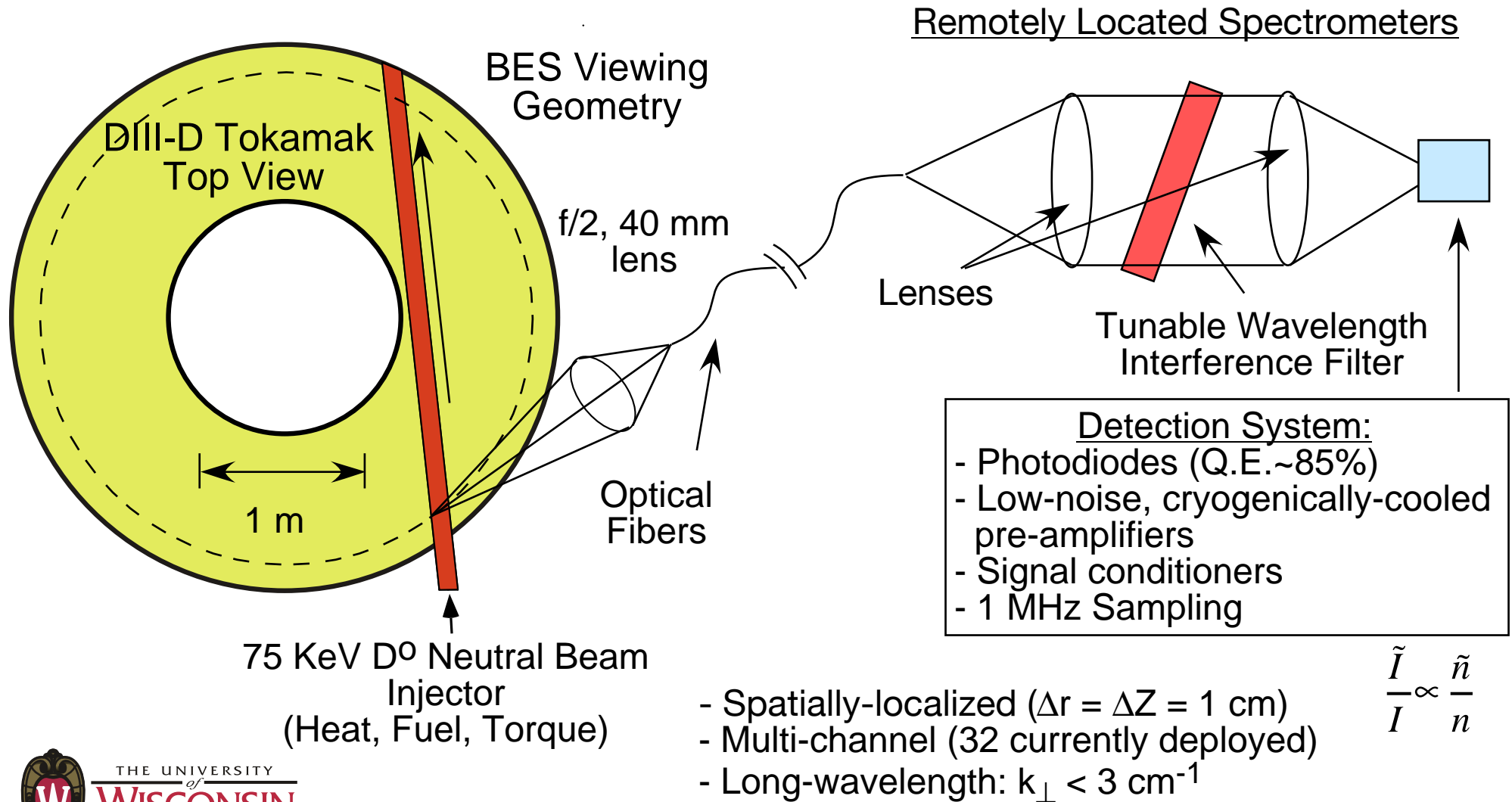
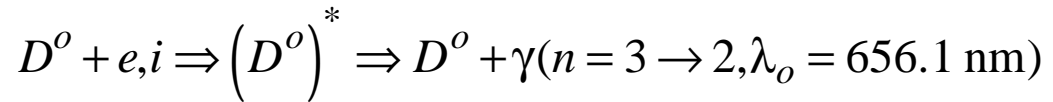
US/Korea Collaboration on KSTAR on Advanced Diagnostics for Turbulence Visualization

- leverages strengths of US program
- exploits scientific and technical capabilities
- provides access to cutting edge resources and facilities at KSTAR
- further US Fusion goal of advancing fusion science, and contributing to ITER/burning plasma experiments



BEAM EMISSION SPECTROSCOPY (BES) DIAGNOSTIC MEASURES LOCAL, LONG-WAVELENGTH ($k_{\perp}\rho_i < 1$) DENSITY FLUCTUATIONS

Collisionally-excited,
Doppler-shifted
beam fluorescence

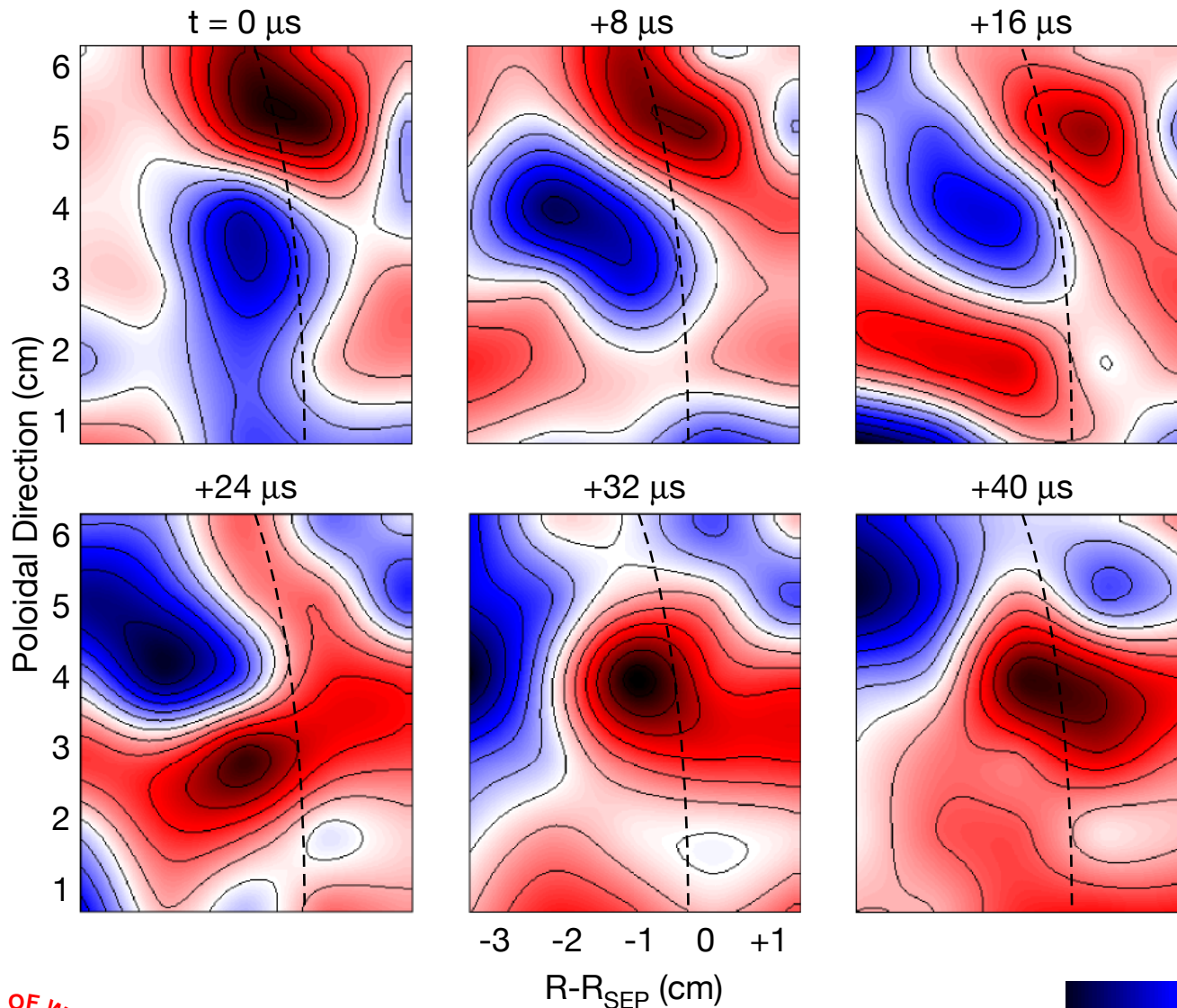


BES MEASUREMENT CAPABILITY

- First-order spectral characteristics of turbulence:
 - \tilde{n}/n
 - $L_{c,r}, L_{c,\theta}$ (correlation lengths)
 - τ_c (decorrelation time)
 - Equilibrium poloidal flow
- Zonal flow (GAMs) via Time-Delay-Estimation analysis
- Nonlinear turbulence quantities
 - growth rates, energy transfer rates
- 2D measurements (images and movies, turbulence visualization)
 - $S(k_r, k_\theta)$
 - Poloidal flow shear (equilibrium and zonal flows)
 - Velocimetry:
 - velocity fluctuations: relation to electrostatic, ExB fluctuations?
 - turbulent particle flux
 - vorticity
 - Quantitative nonlinear studies (2D and multiple fields)
- Variant: Ion temperature fluctuations
- MHD, ELM, SOL/pedestal studies



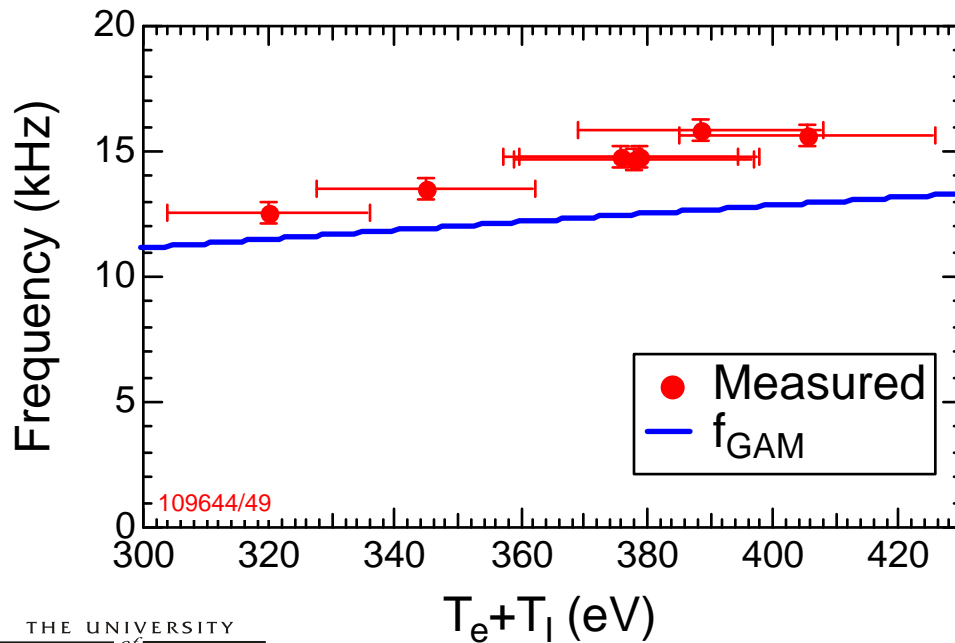
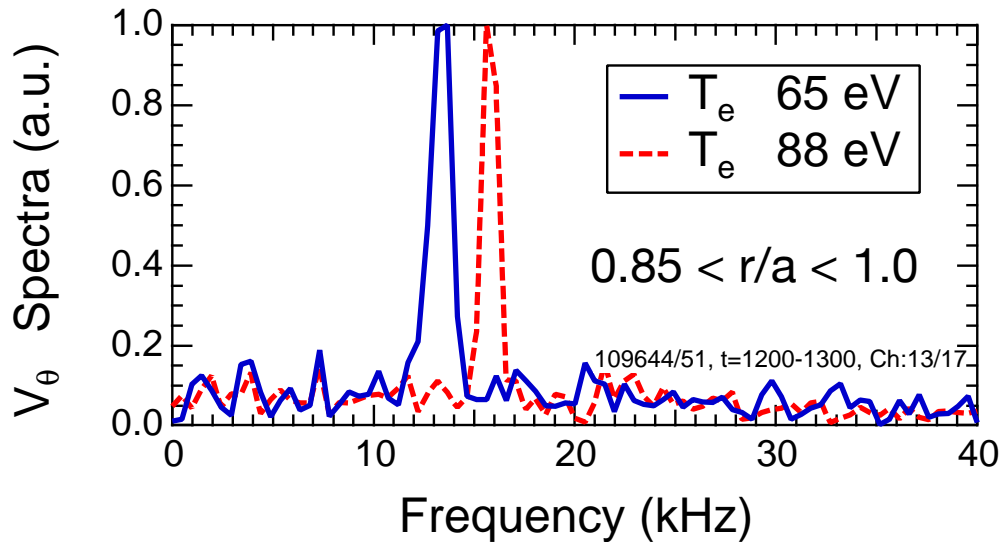
TWO-DIMENSIONAL IMAGES OF DENSITY FLUCTUATIONS ELUCIDATE COMPLEX, NONLINEAR INTERACTIONS OF TURBULENT EDDIES



- 1 MHz sampling
- 5 x 6 cm region near outer midplane ($0.9 < \rho < 1.05$)
- L-mode plasma:

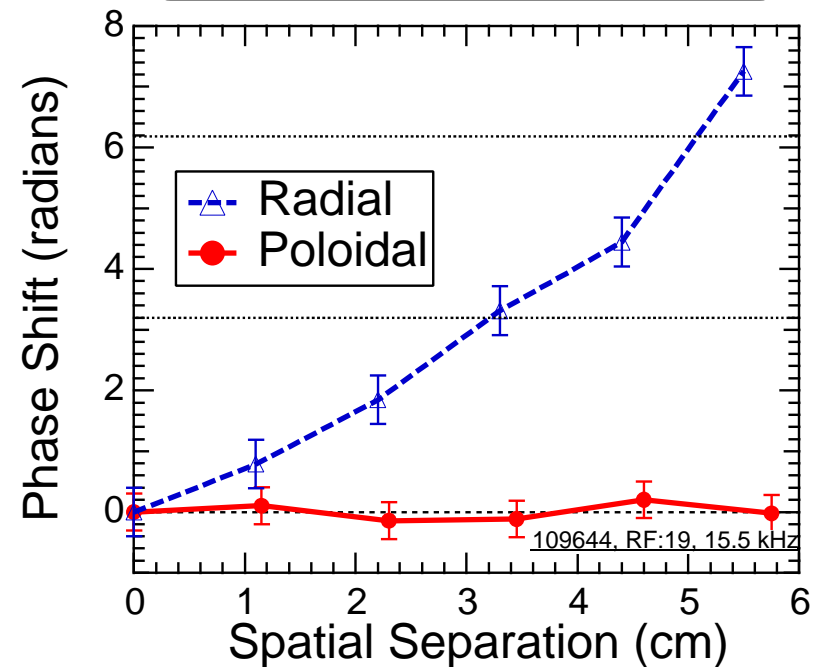
5 MW neutral beams
 Upper Single Null
 $T_e \sim 75$ eV
 $T_i \sim 200$ eV
 $n_e \sim 1.5 \times 10^{19} \text{ m}^{-3}$

GEODESIC ACOUSTIC MODES (ZONAL FLOW) OBSERVED WITH BES ON DIII-D



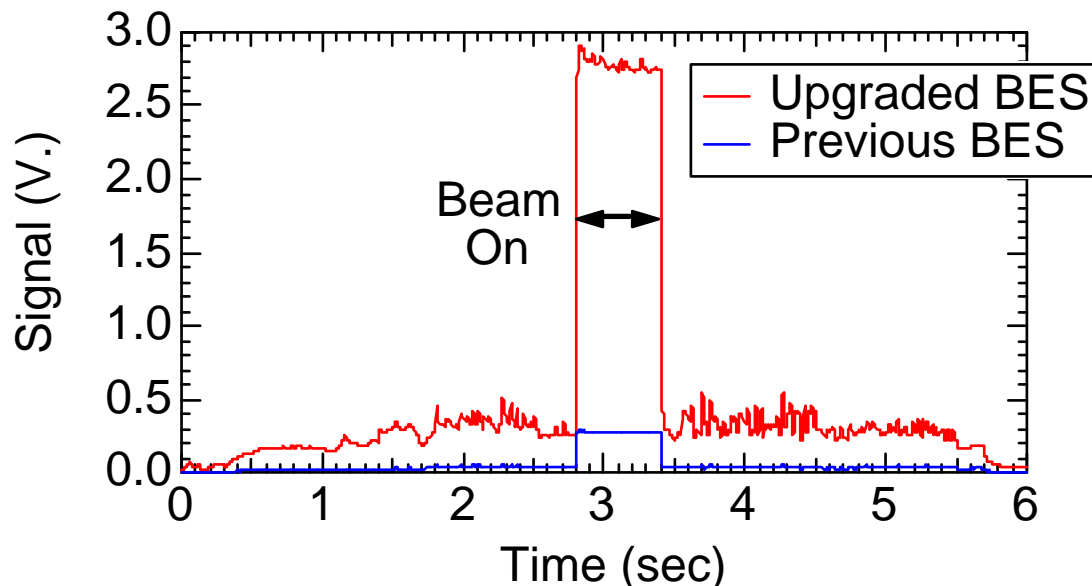
- Coherent poloidal flow oscillation
- Poloidal correlation length large compared to turbulence
- Radial localized (~ 2 cm)
- Frequency scaling matches that of GAM

Radial and poloidal phase shift of v_θ differ

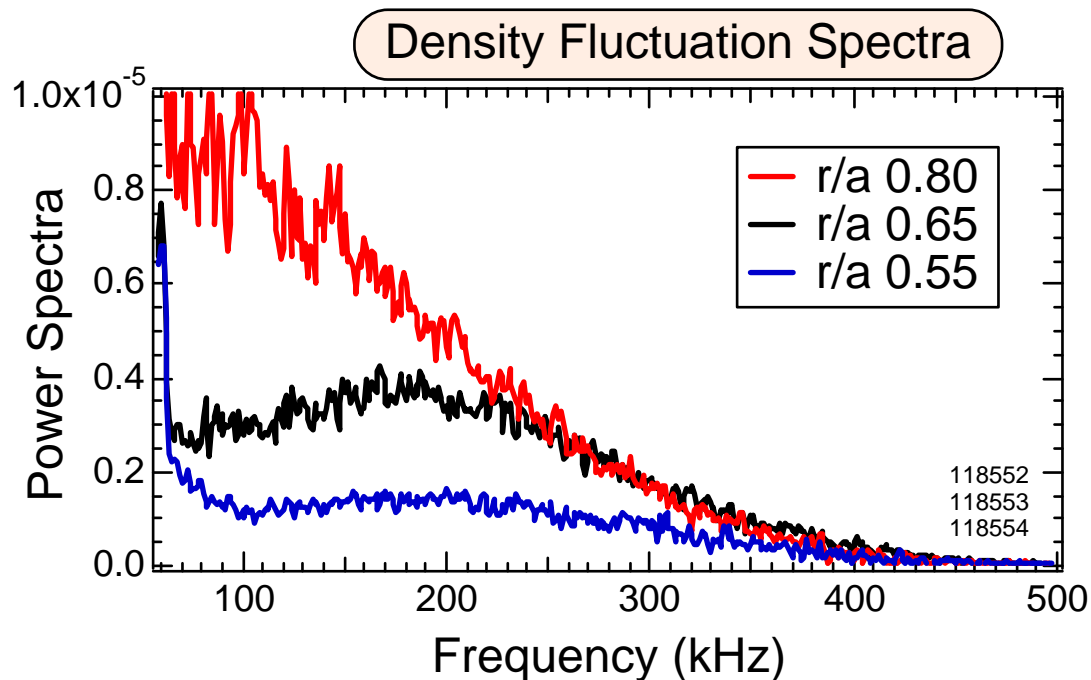


UPGRADED BES ON DIII-D SHOWS EXCELLENT PROMISE FOR STUDIES OF TURBULENCE IN AT/HIGH PERFORMANCE PLASMAS

- Upgraded BES system achieves **order-of-magnitude increase** in signal
- Numerous improvements:
 - Larger imaged area/channel
 - High-transmission filters
 - Larger, low-noise detectors
 - High-Reflectivity mirrors



- Broadband density fluctuations from 50-200 kHz observed with upgraded system **in H-mode**
Not observed with previous BES system in H-mode

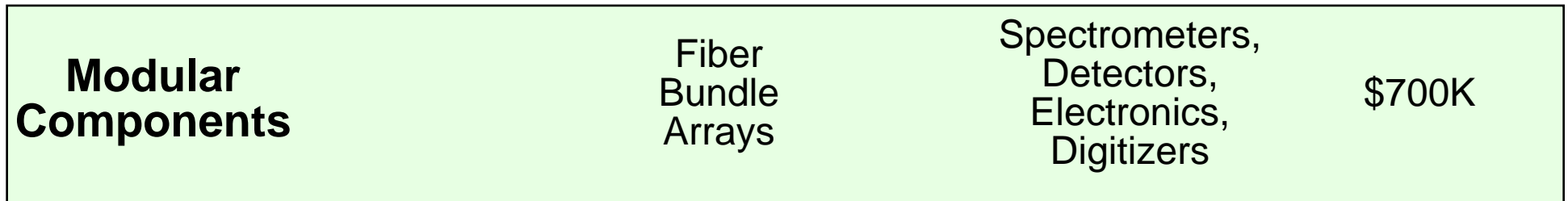
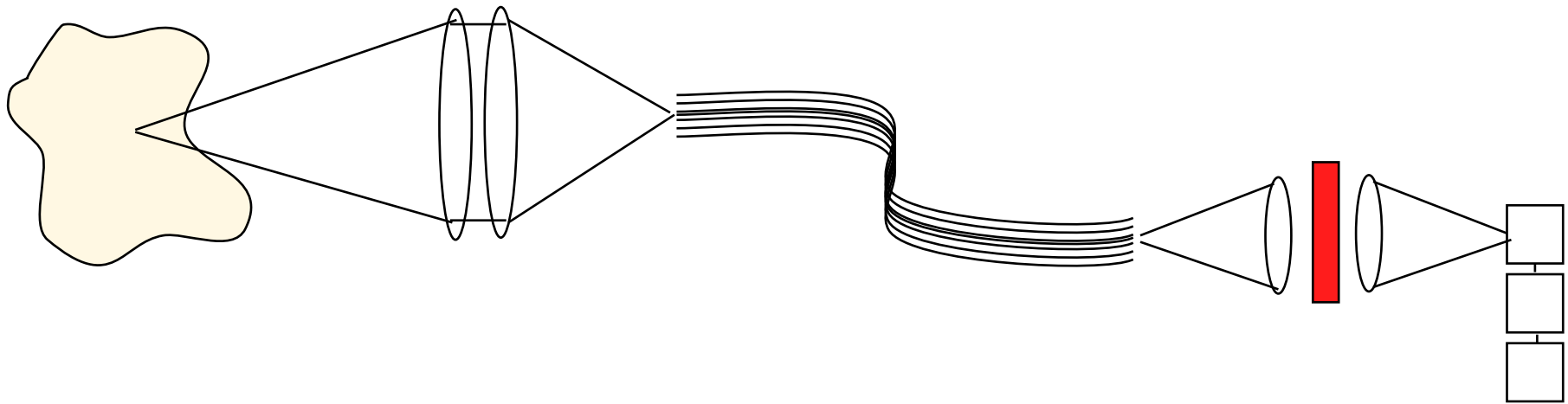


BES SYSTEM IMPLEMENTATION ON KSTAR (RECOMMENDATIONS)

- Employ demonstrated technologies (one approach)
 - Significant similarities to DIII-D BES system (but higher spatial resolution)
 - Upgraded BES shows good promise for diagnosing core plasma region with high SNR, application to high-performance (lower turbulence) modes
- 40-64 spatial channels (32 on DIII-D, marginal for imaging)
 - allow 5x8 to 8x8 imaging
 - Capture full radial and poloidal wavenumber distribution and allow for good statistics for flow and nonlinear analyses
 - More channels welcomed, depending on scientific goals and budgets
- Advanced technologies to consider
 - Optical amplification (mitigate preamplifier noise, eliminate cryogenic needs)
 - Monolithic camera structure (as opposed to discrete detectors)
 - single lens system, filter array, detector and preamplifier array
 - may reduce overall costs at similar performance
 - simply upgrades and modifications
 - enforce greater system uniformity
 - Lyman-alpha (VUV) BES: much higher light flux, more difficult technologies
 - High-intensity diagnostic beam (small aperture, moderate duration)
 - Higher-k capability (masking, spatial resolution optimization)



MODULAR DEPLOYMENT OF SYSTEM COMPONENTS



- Fixed system components deployed initially
- Modular components implemented in a staged, budget-driven fashion



BES SYSTEM COMPONENTS AND ESTIMATED COSTS

64-channel system built with “conventional” technologies

Subsystem	Cost
Machine Optics	\$100K
- lens, mirrors, motorized mounts	
Fiber Optics	\$500K
(64 channel, 11 fibers/channel, 70 meter length)	
Detector Boxes (8 boxes)	\$40K
Interference Filters	\$80K
Spectrometer optics	\$10K
Preamplifiers	\$30K
Conditioning Electronics	\$20K
Digitizers	\$30K
Cryogenic supply lines/control	\$100K
Vacuum systems	\$30K
Total	\$950K



PLAN A: DEVELOP, DEPLOY, OPERATE BES SYSTEM AT KSTAR

Year	2006	2007	2008
Equipment	500	250	240
Personnel	280	290	300

(\$K)

Total: \$2.7M

- Personnel: 1 FTE (physicist), 1 technician, 1 post-doc
- Designing diagnostic system (modeled on upgraded BES at DIII-D)
- Procuring, testing, integrating components
- Integrating and implementing on KSTAR
- Full development and utilization of remote operation capability
 - Being developed at DIII-D for remote collaborators
 - UW program engaged in remote operations testing (BES on DIII-D)
- Participation in scientific program and analysis (~\$300K/year)



PLAN B: CONSULTATION PROGRAM (MORE LIMITED)

Year	2006	2007	2008
Equipment	0	0	0
Personnel	150	160	170

Total: \$480K

- Personnel: 0.5 FTE (physicist), 1 post-doc
- Consulting on design (again, modeled on upgraded BES at DIII-D)
- Procuring, testing, implementing, integrating on KSTAR by KBSI
- Exploit remote operation capability
- Participation in scientific program as requested



ISSUES WITH PRESENT DESIGNS

- Window size: Should be significantly larger than 4"
 - $f/2$, $f=40$ cm objective lens for $\Delta X=1$ cm, ~ 10 1-mm fibers/channel
 - 10" window used on DIII-D
- Magnetic field line alignment (may be OK)
 - sightlines should be nearly aligned with field line for optimal spatial resolution (may be ok in present setup)
 - 17 degree pitch appears significant
 - proper orientation(?)
- Detectors are NOT PMTs (unless “quantum” leap in Quantum Efficiency)
 - Photodiodes: high Q.E., but low signal
 - Low noise, high gain preamps and cryogenics required
 - Avalanche Photodiodes: high Q.E., high gain, but excess noise factor
- Orientation with respect to tangential beam injection
 - looking “towards” or “away from” beam
 - “away from” yield better spatial resolution over wider range
 - spectral line pollution (wall material, carbon lines?)
- 70 meter distance to spectroscopy labs: possible to shorten?
 - fiber attenuation (tens of percent)
 - fiber cost



EDUCATIONAL OPPORTUNITIES

- BES program provides very fertile ground for training new scientists
- Strongly-science-based project aimed at turbulence & transport
- Program requires development of variety of diagnostic skills
 - optics, electronics, cryogenics, vacuum, system integration
 - software development, sophisticated analysis, publications
- U. Wisconsin BES programs on TFTR and DIII-D:
 - 4 graduate students performed theses on BES-related work (+2 current students, several other students have contributed)
 - 4 postdoctoral researchers



TIME LINE AND COSTS

	2006	2007	2008	2009
Design	—————			
Procurement, testing		—————		
Installation, implementation, integration			—————	
Commission, operation			—————	
Budget (\$K)	780	540	540	300

SUMMARY

- Implementation of BES on KSTAR would provide significant scientific capability
 - Turbulence visualization
 - Significantly build on past work and explore turbulence in new regimes
 - Benefit from unique capabilities of KSTAR
 - Steady-state operation
 - Advanced Tokamak capability
 - Play a crucial role in validating turbulence and transport models to develop predictive capability for application to future machines/ITER
- Benefits US program:
 - exploits strengths in turbulence and transport, diagnostics, AT operation
 - maintain leadership in key areas
 - ITER relevant: development of predictive capability
- Can readily implement using existing technologies
 - Could potentially benefit from newer developments/advances

