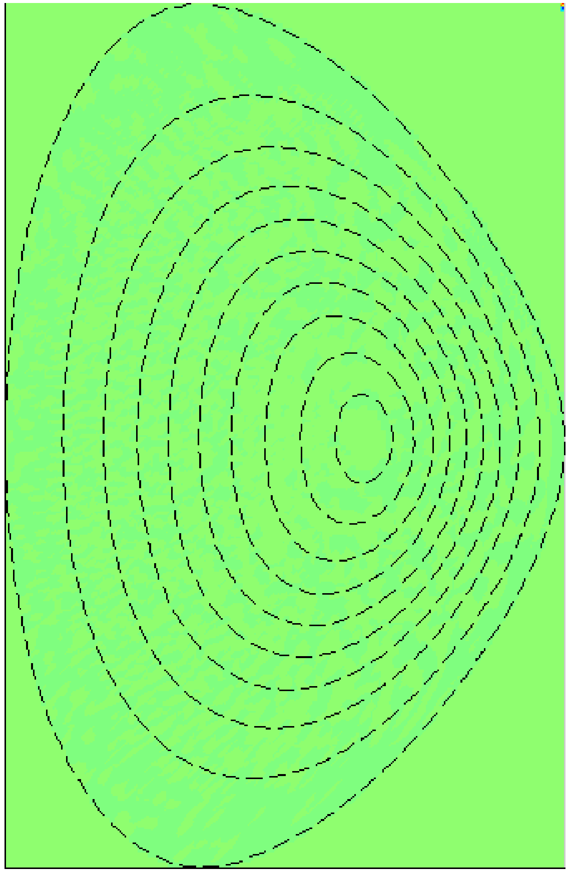
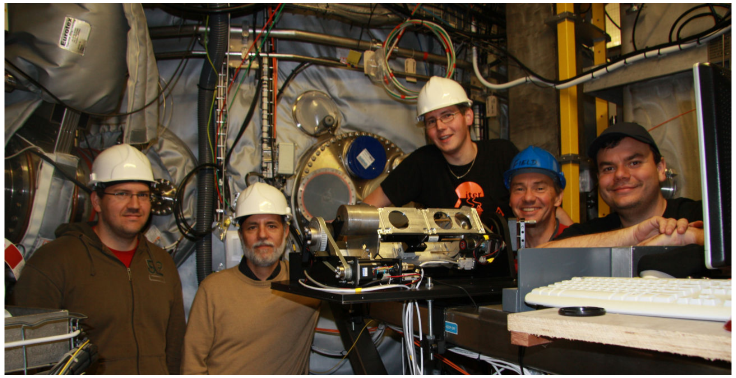
MAST BES imaging system

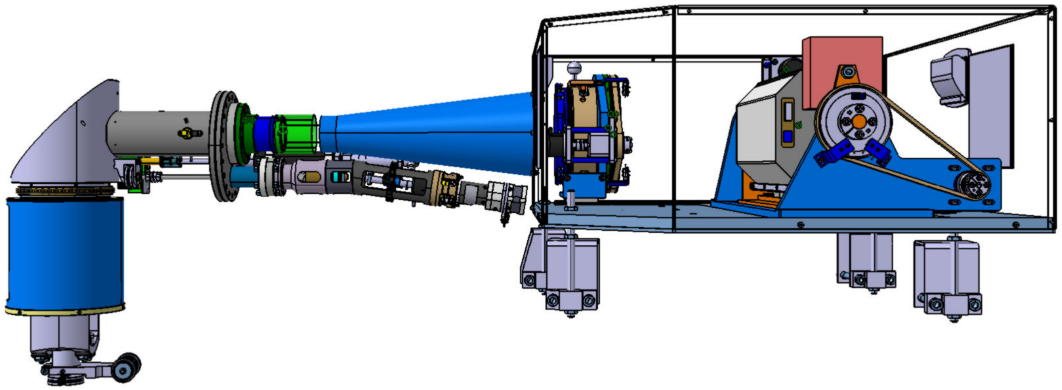
ORB5: Global, non-linear



Anthony Field

PPPL, 1st March 2011



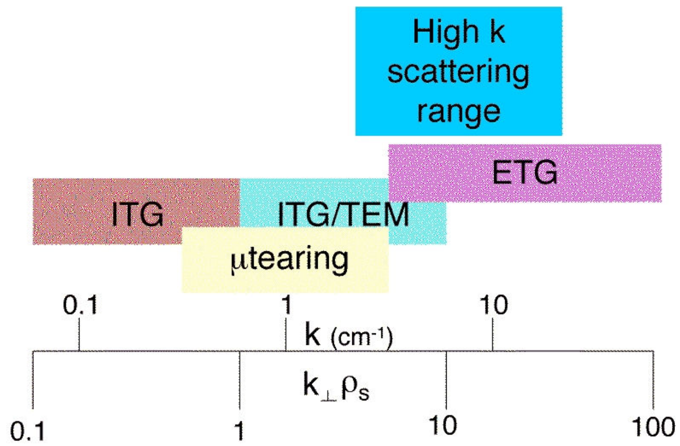


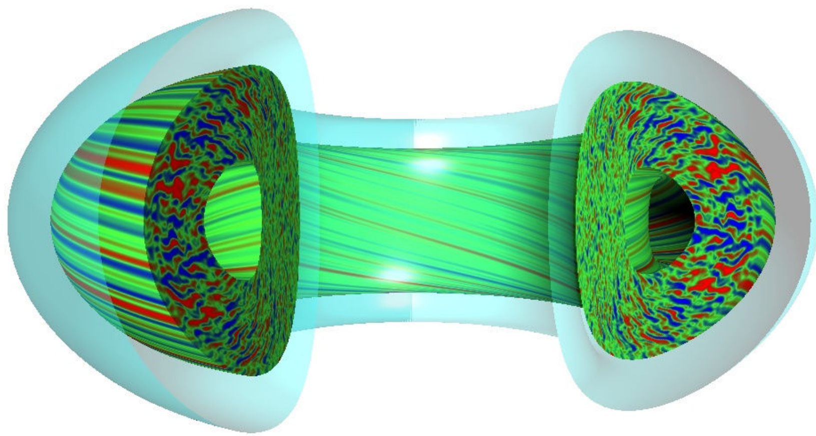
CCFE CULHAM CENTRE FOR FUSION ENERGY

2D BES: Physics goals

Physics goals:

- Is transport due to ITG turbulence largely stabilised by strong flow shear in ST?
- Detect density fluctuations resulting from low-*k*, ion-scale turbulence, $k_\perp \rho_i \leq 1$
- Requires multi-channel 2D radial/poloidal measurements, $\Delta x \leq 2$ cm for $k_\perp \leq 1.6$ cm^{-1}
- Detection of steady and fluctuating poloidal flows (GAMs, zonal flows)
- Detection of coherent fluctuations, e.g. due to fast-ion driven MHD also possible
- Comparison with results from non-linear, gyro-kinetic turbulence simulations

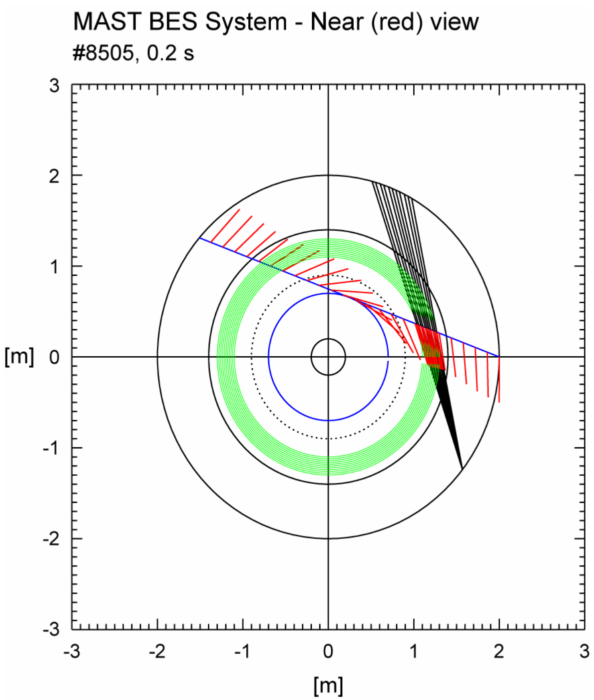


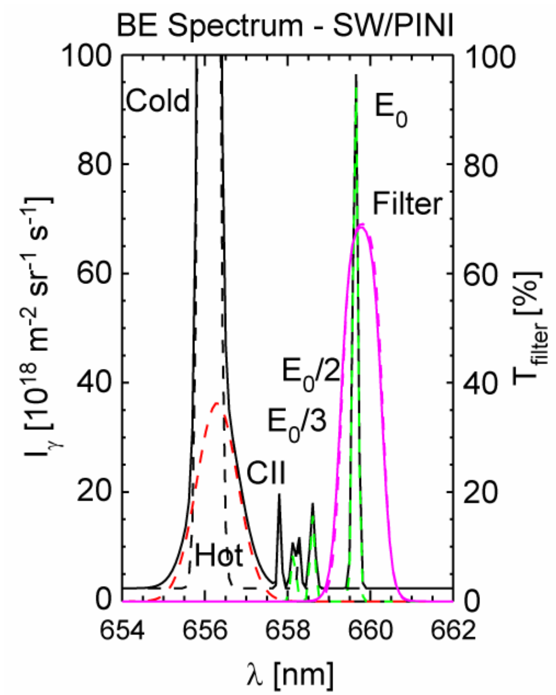


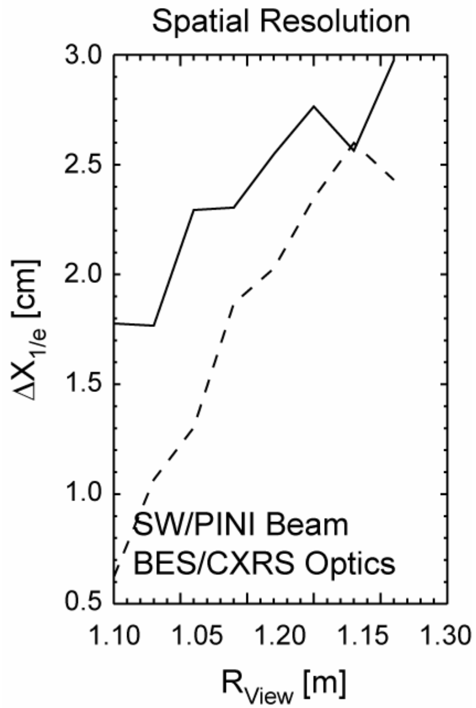
2D BES: Principle

Detection principle:

- View Doppler shifted (2-4 nm) D_α emission from energetic 70keV heating beam
- Intensity fluctuations proportional to local density fluctuations, $\delta n / n \sim 1/3 \cdot \delta I / I$
- Requires high-efficiency collection optics and sensitive, high speed detector
- Simulations show achievable SNR ~ 230 at detected photon flux $N_\gamma \sim 3\times10^{11} s^{-1}$



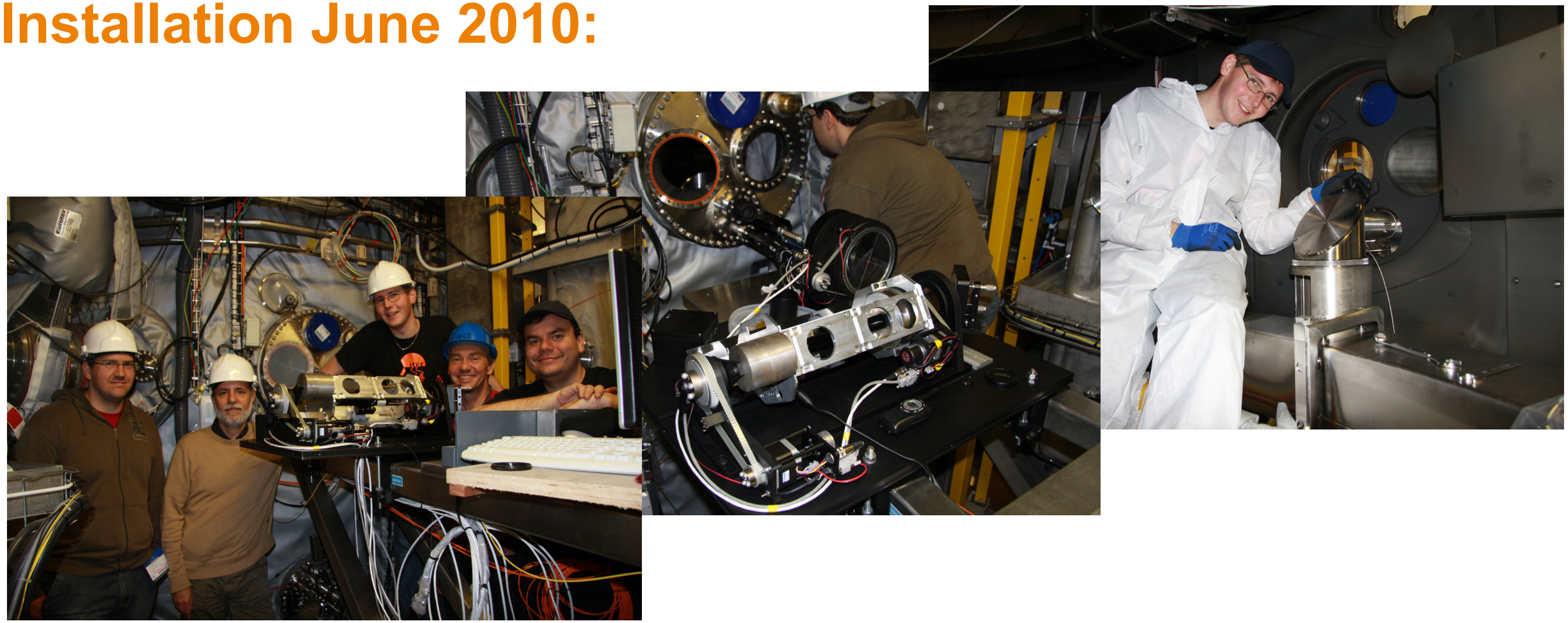




1.3.11 MAST 2D BES system

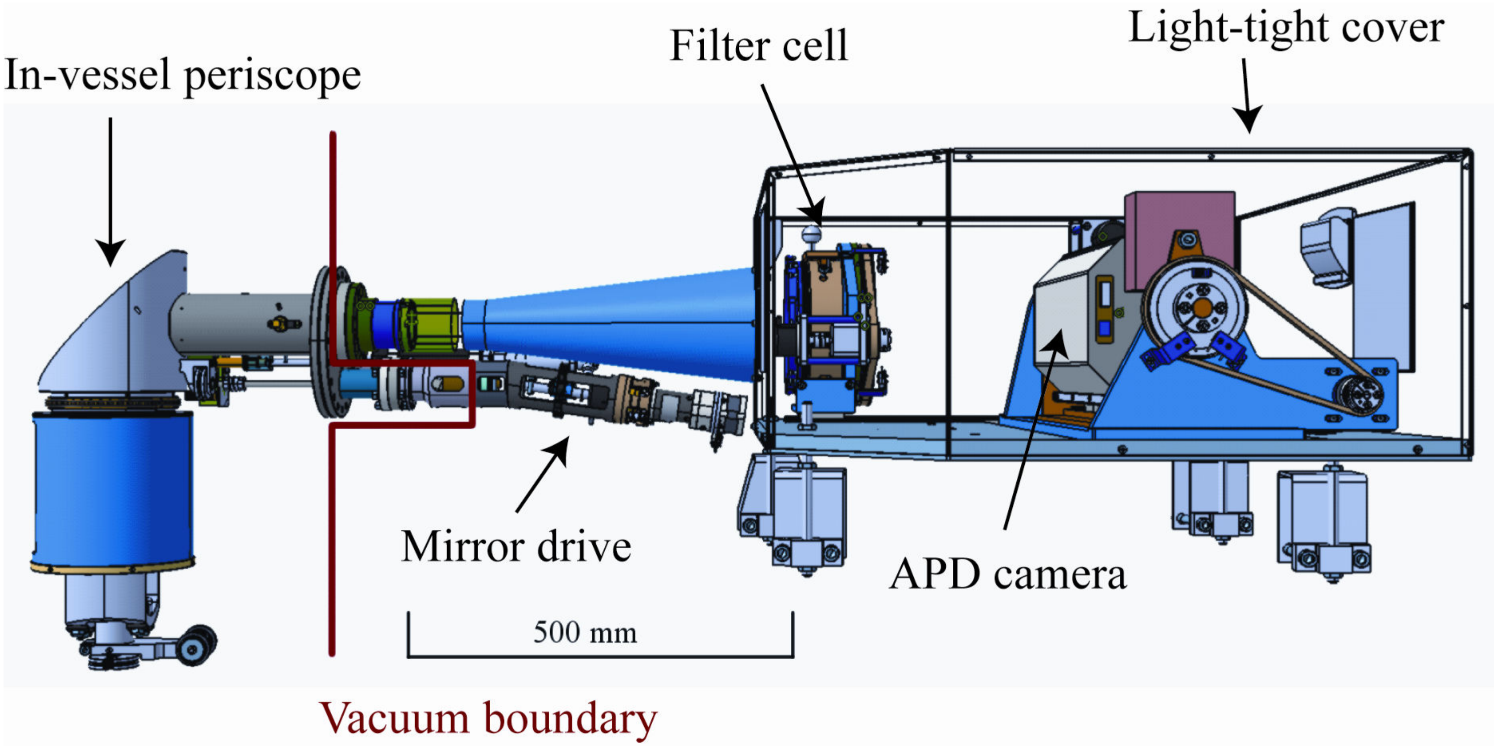
2D BES: Development

Installation June 2010:



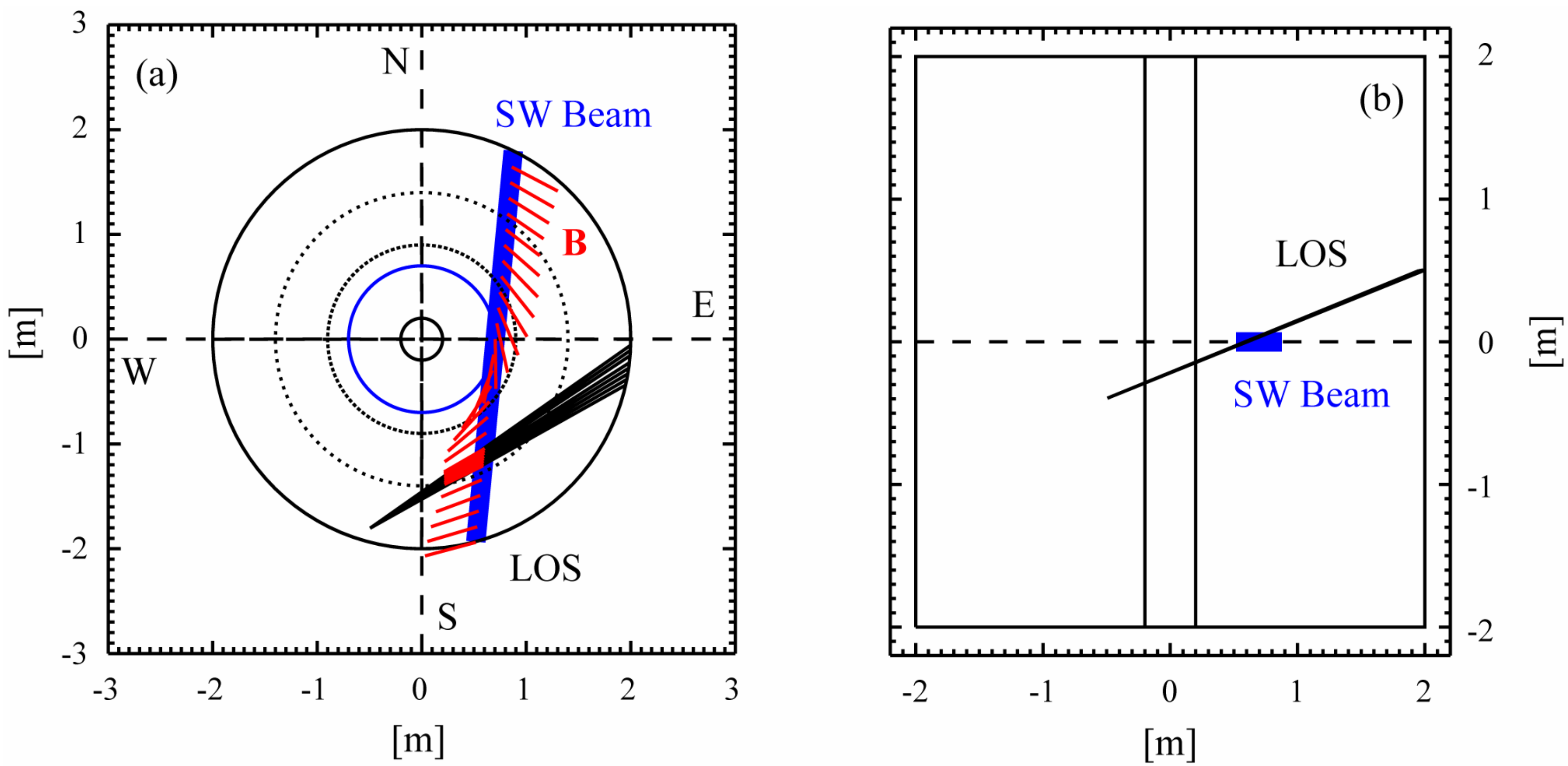
- Developed in collaboration with RMKI of HAS during period 2006-10
- BES hardware manufactured and tested at RMKI
- Custom APD camera designed and manufactured by ADIMTEC Ltd

2D BES: Hardware



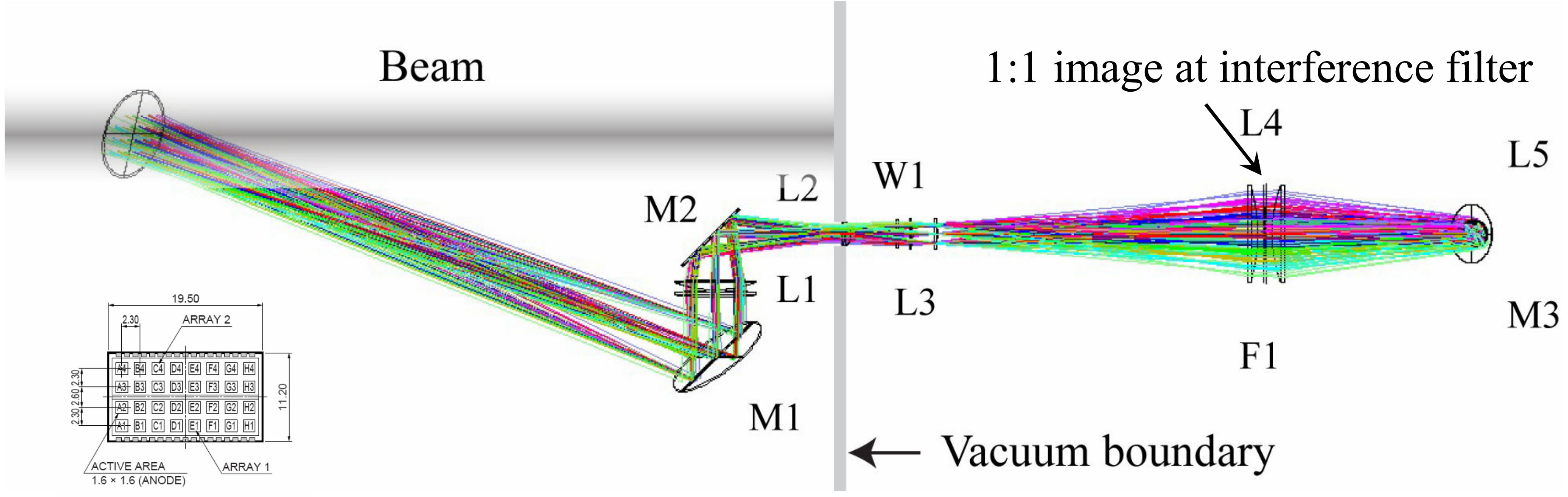
- 2D imaging of density turbulence from D_α beam emission
- APD array (8×4) camera (2 MHz) $\Delta R \sim \Delta z \sim 2$ cm for $k_{r,\theta} \leq 1.6$ cm^{-1}
- High-throughput optics for sensitivity of $\delta n_e/n_e \sim$ few × 0.1%

2D BES: Viewing geometry



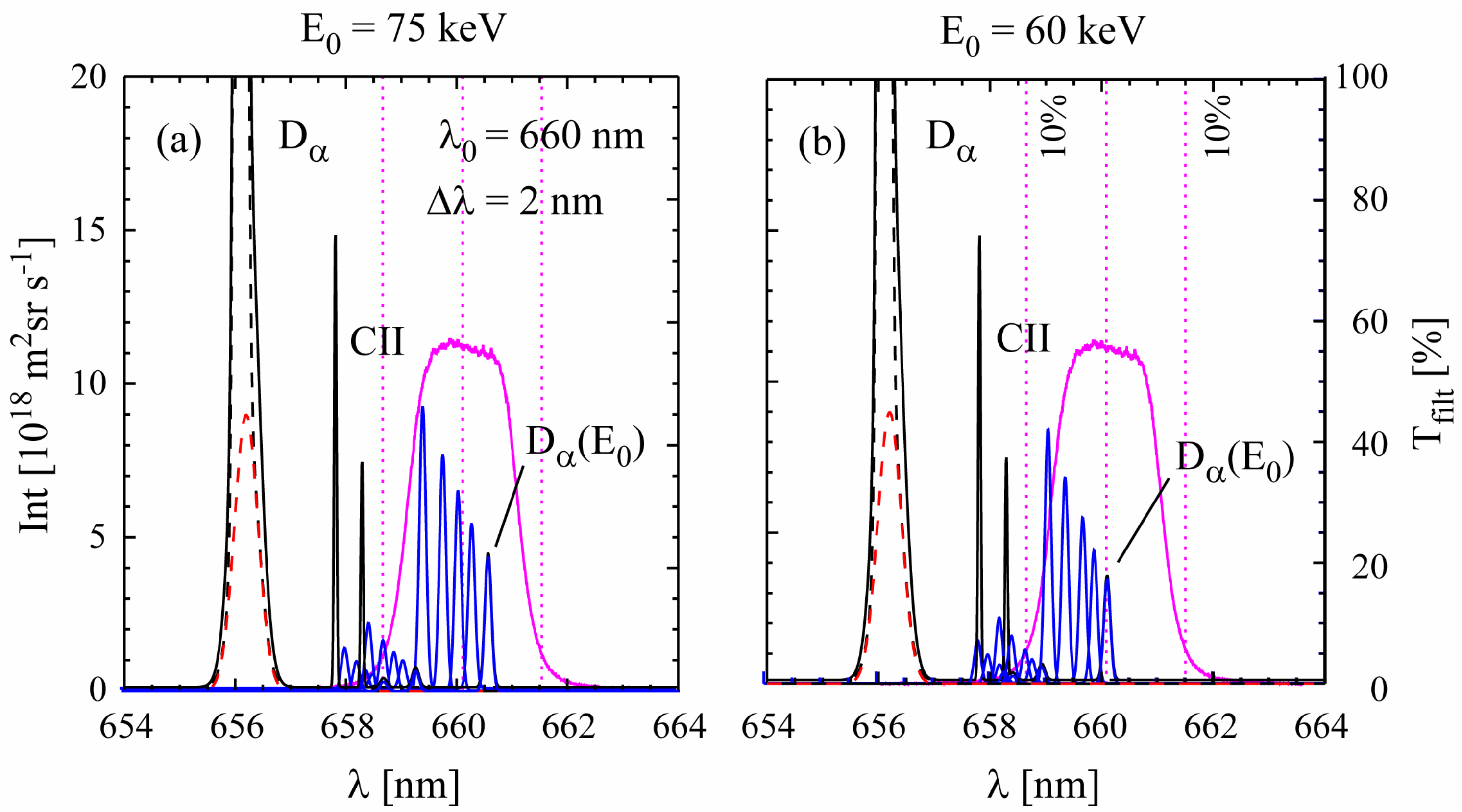
- Detection of small fluctuations requires viewing along B-field at beam ($k_{||} << k_{\perp}$)
- Provides for Doppler red-shift (2-4 nm at 70 keV) D_{α} emission from background
- No existing port at required location of collection optics

2D BES: Optical layout



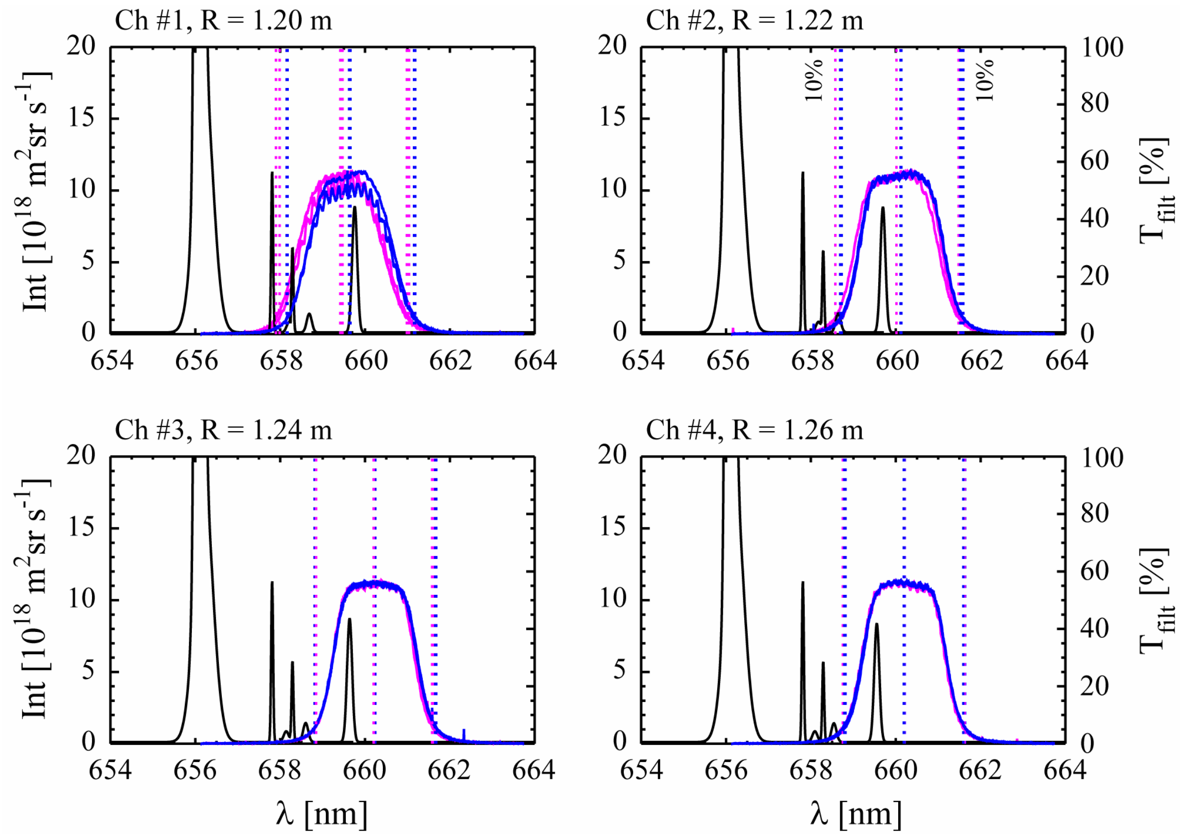
- Direct-coupled optics for high coupling efficiency (F/1.2 at detector)
- Save cost of large diameter collection fibres required to achieve same étendu
- Use of periscopic collection optics allows use of existing small, mid-plane port
- Limits to fixed geometry of 8×4 pixel (2.3 mm pitch) APD array
- Magnification of ×8.7 achieves spatial resolution of 2×2 cm^2 at beam

2D BES: Predicted spectrum



- Single large interference filter (170x90 mm^2) located at 1:1 image of beam (F/10)
- High-transmission (57%), 3-cavity filter (Andover Corp.), 660.2±2.2 nm band-pass
- Some broadening of band-pass at corners of filter area (see next)

2D BES: Filter band-pass



- Filter band-pass blue shifted and broadened at extreme edges
- Background CII lines outside 10% transmission except at corner pixels
- Careful spectroscopic measurements required of background light

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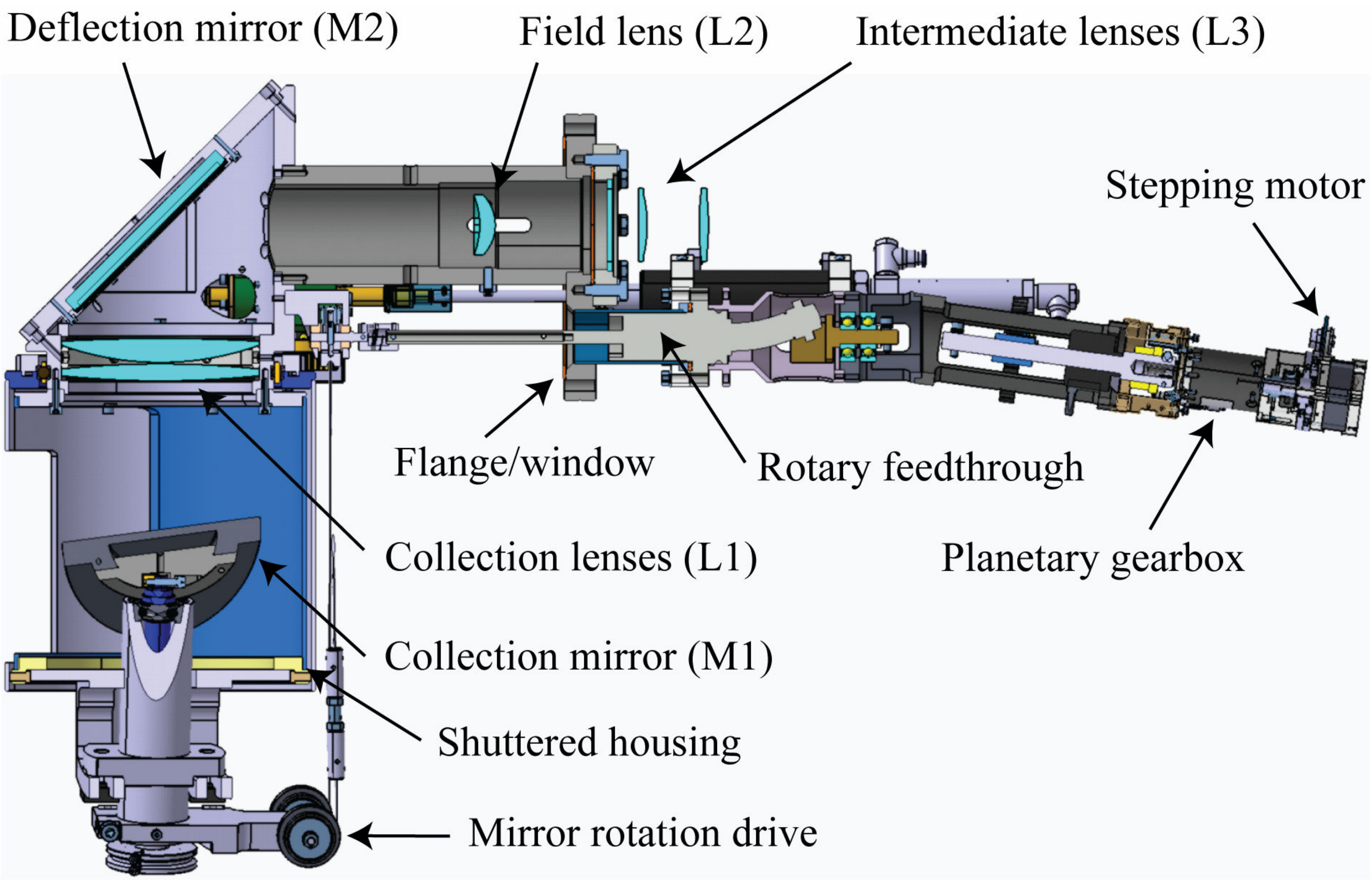
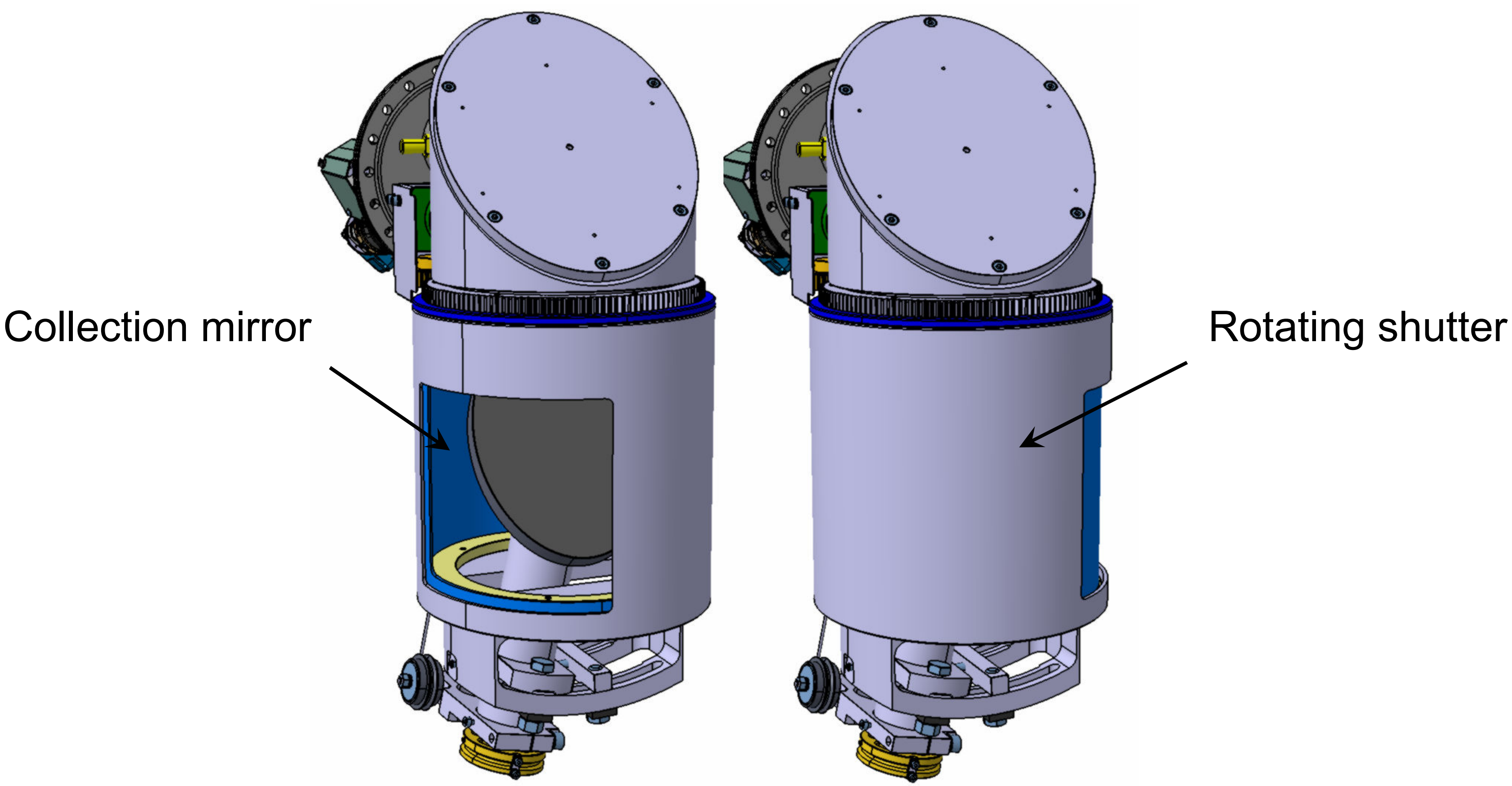
2D BES: In-vessel optics

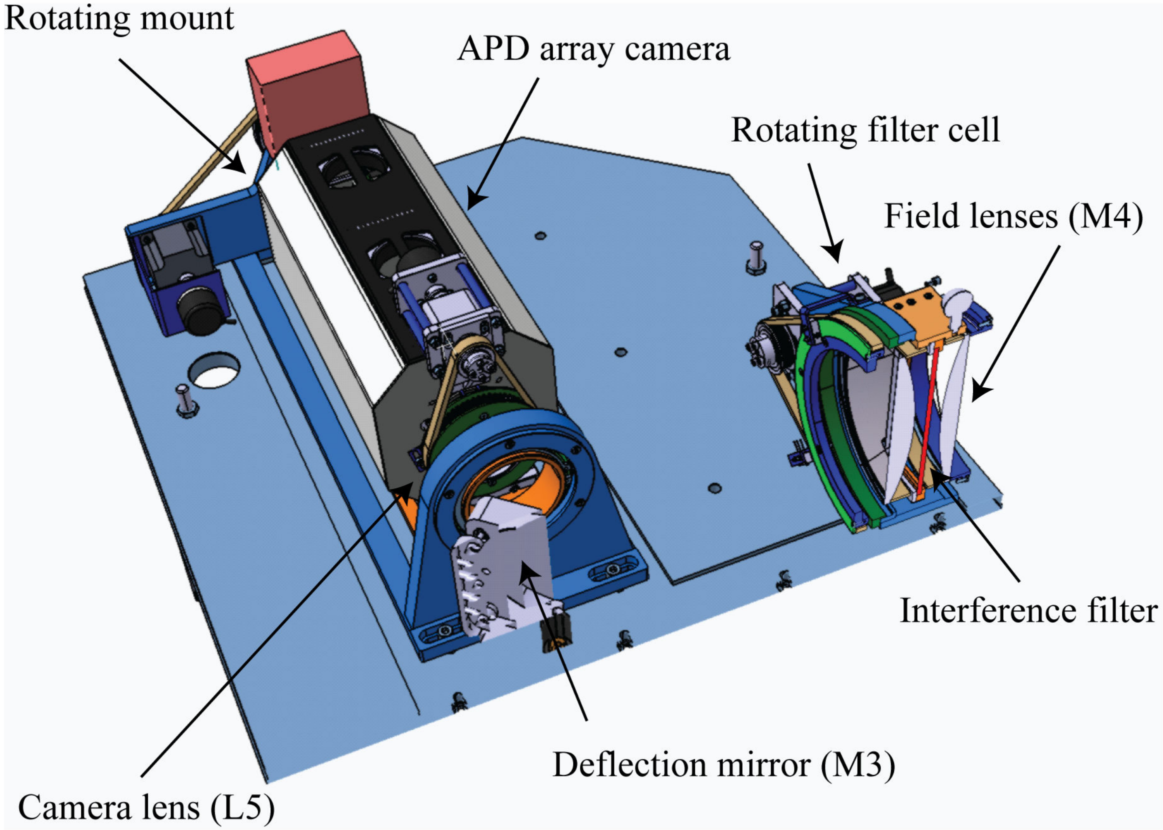


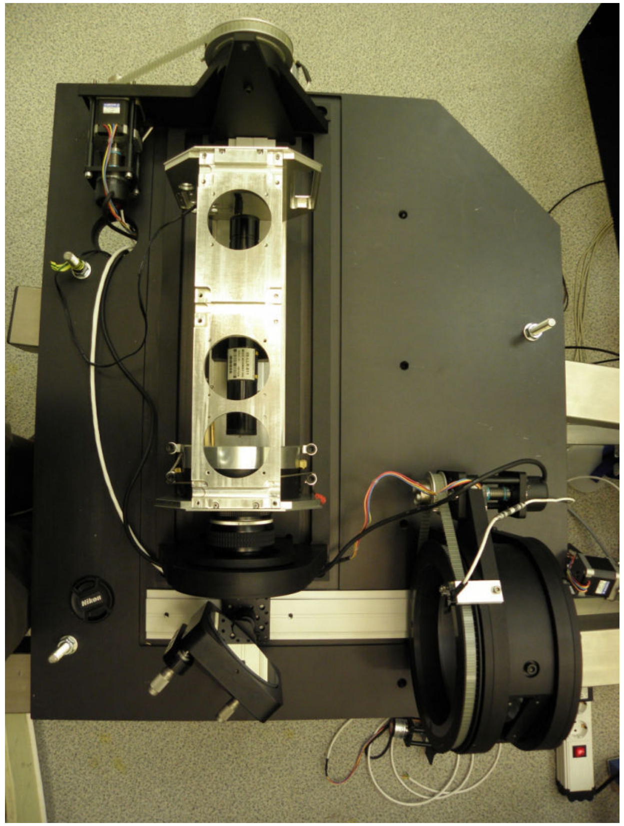
2D BES: In-vessel periscope



- Incorporates collection lenses, protective shutter and two deflection mirrors
- Mirror rotation axis tilted from vertical to track view along beam axis

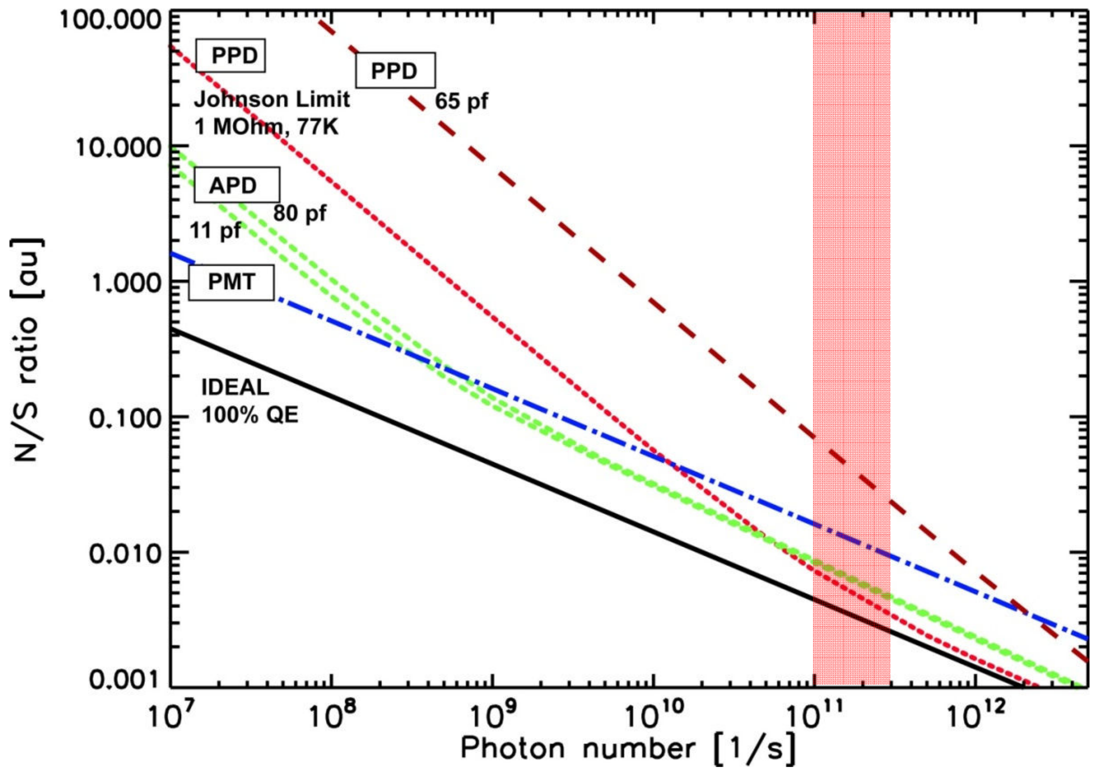
2D BES: Ex-vessel optics





- Rotation of in-vessel collection mirror to move view position rotates image
- Necessitates simultaneous rotation of filter and APD camera
- Focusing at beam achieved by adjustment of camera objective

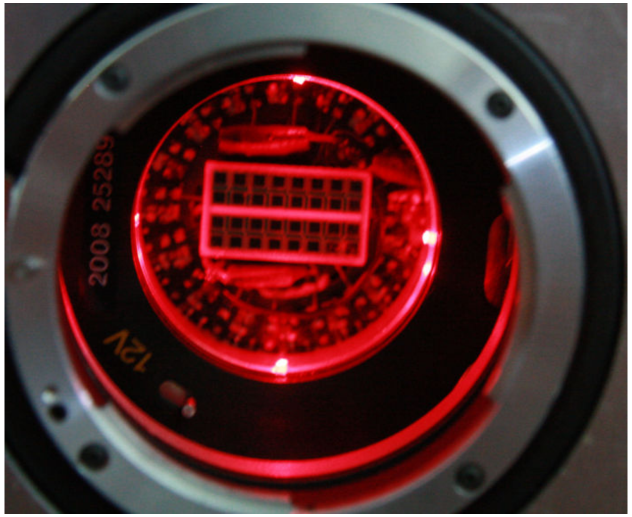
2D BES: Detector choice

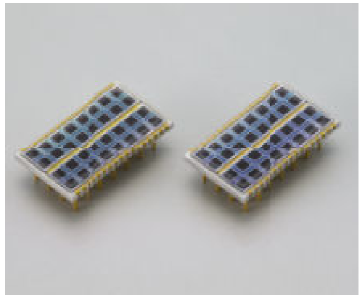


- At expected photon flux ~ 10^{11} s^{-1}, APD is superior to PMT due to high QE ~ 85%
- Photo-diodes require cryogenic operation (77K) to achieve higher SNR than APD
- Predicted SNR in range 100-300 is within factor ~ 2 of ideal detector

2D BES: APD Camera

Calibration light source



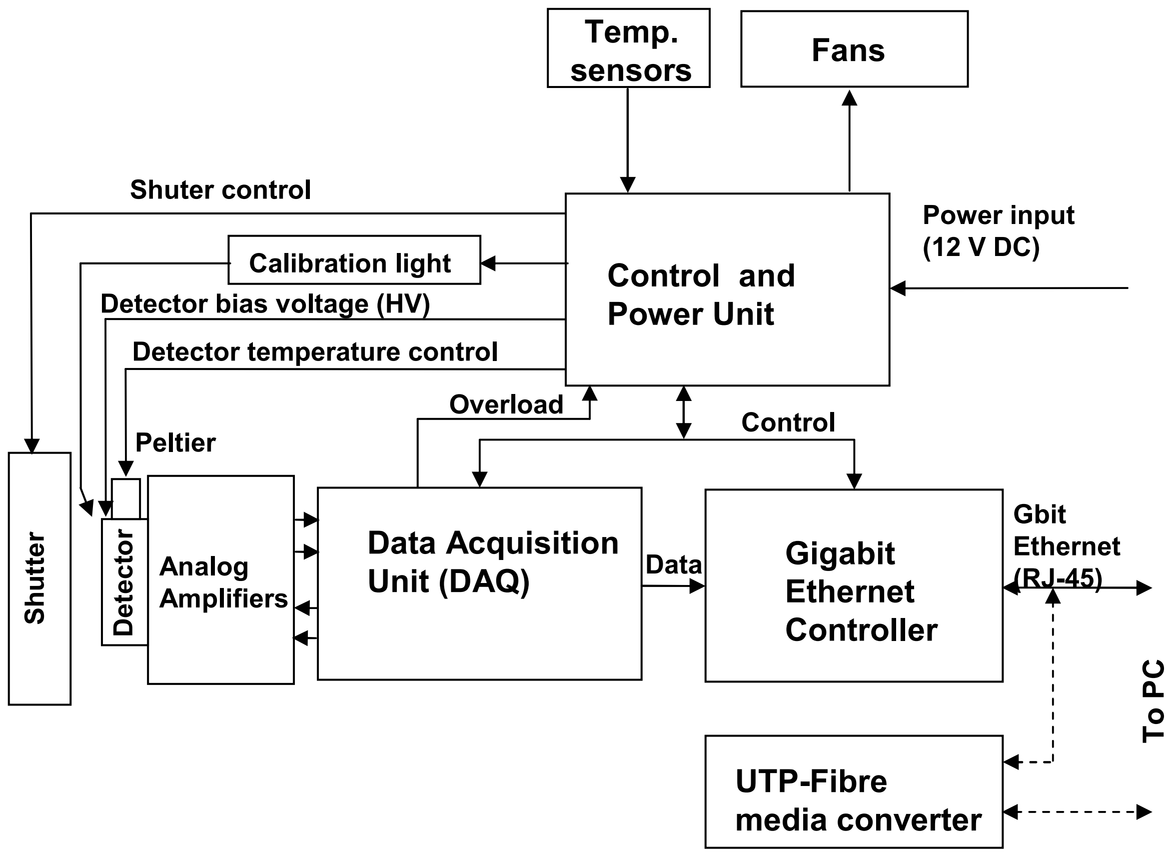


Hamamatsu S-8550

APDCAM Integrated detector system:

- Hamamatsu S-8550, 8×4 pixel sensor, 1.6×1.6 mm^2 size, 2.3×2.3 mm^2 pitch
- Integrates HV PSU control, data acquisition, processing, communication
- Sensor temperature stabilisation, magnetic shutter, calibration source
- Four 8 channel, 14-bit, 50 MHz ADCs, 1 Gbit Ethernet data transfer

2D BES: APD Camera schematic



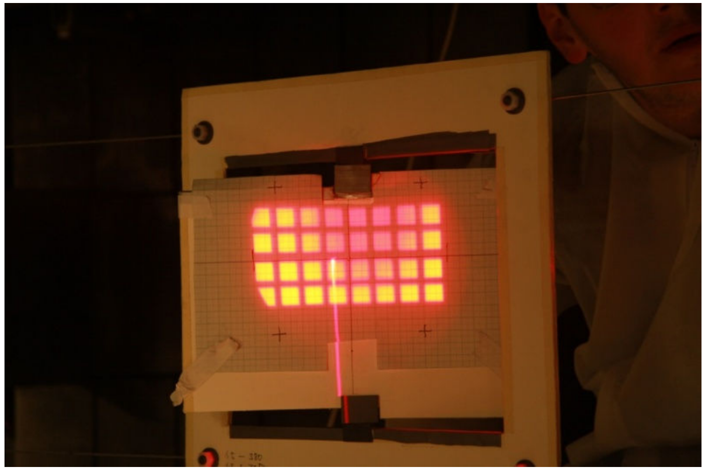
- FPGA controls triggering, clock synchronization, data rate
- Integrated digital filtering for data reduction, 10 kHz – 10 MHz
- Converts ADC output to UDP data stream, transmitted by standard 1Gbit Ethernet

2D BES: In-vessel alignment

Alignment & Calibration:

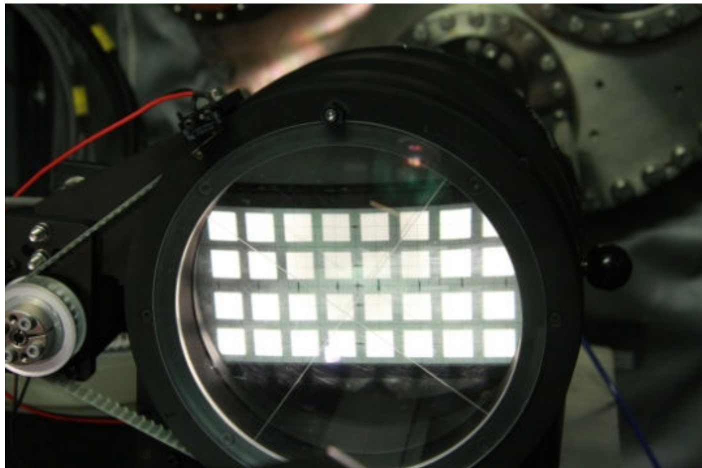
- Alignment performed with detector mimic
- Dummy camera head with illuminated mask
- Stepper motors calibrated at view locations
- Optics focused at beam location
- Calibration integrated into DATAQ software

Detector image at beam



Stepper control unit

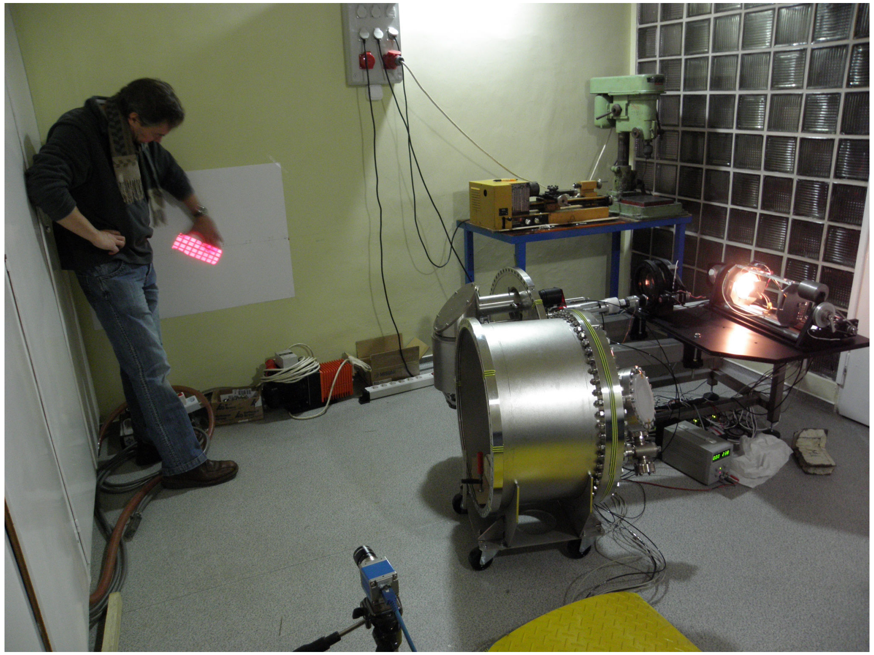
Detector image at filter location



2D BES: Testing at RMKI

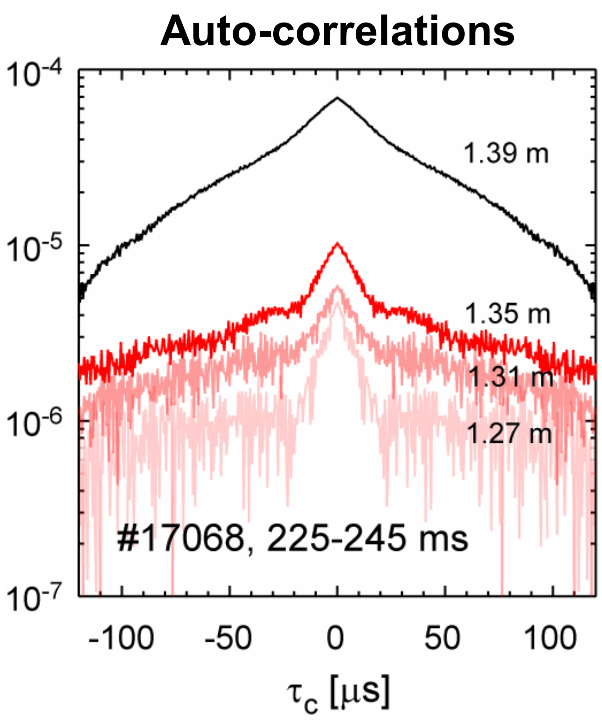
Vacuum testing & bake-out rig

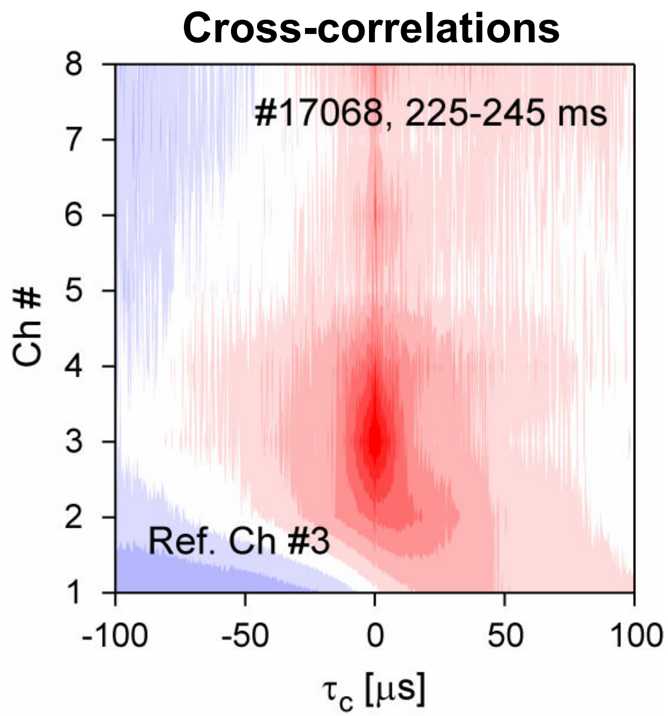
Optical and mechanical testing



- Complete system set up in test vacuum tank at RMKI
- Baked to 150°C for 2 days under UHV vacuum
- Shutter and mirror rotations tested for reliability and reproducability
- Optical system aligned and imaging properties tested in lab

Trial BES results – L-mode





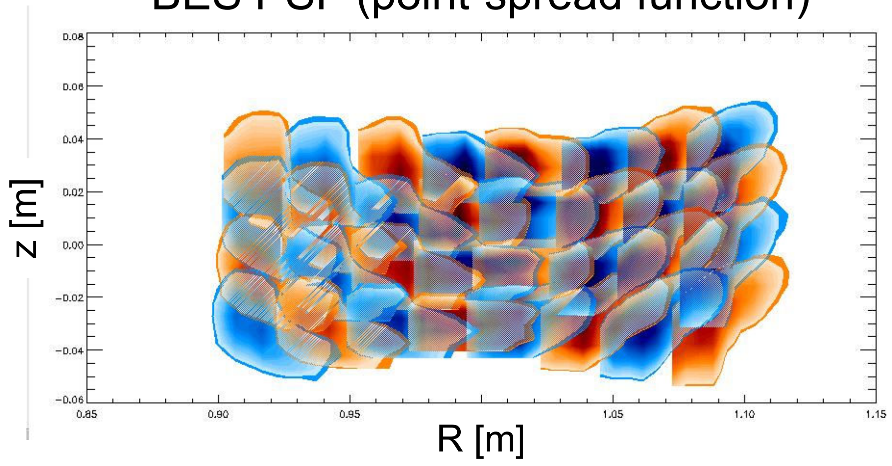
- Amplitude higher at edge (~ 1%) than in core plasma (~ 0.2%)
- Correlation time in core τ_c ~ 10μs and longer at edge τ_c < 100μs
- Cross-correlation of adjacent channels indicates L_c ~ 4 cm

2D BES: Data analysis

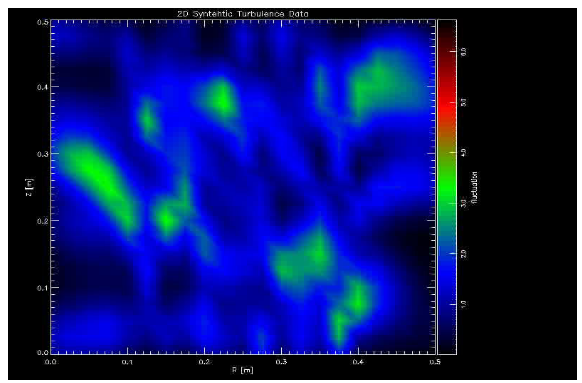
Synthetic BES data:

- Aim to generate synthetic BES data from turbulence simulations
- Compare characteristics of measured and simulated turbulence
- Requires calculated spatial response of BES system (PSF)
- 'Toy' fluctuation data used to determine sensitivity of flow measurements

BES PSF (point-spread function)

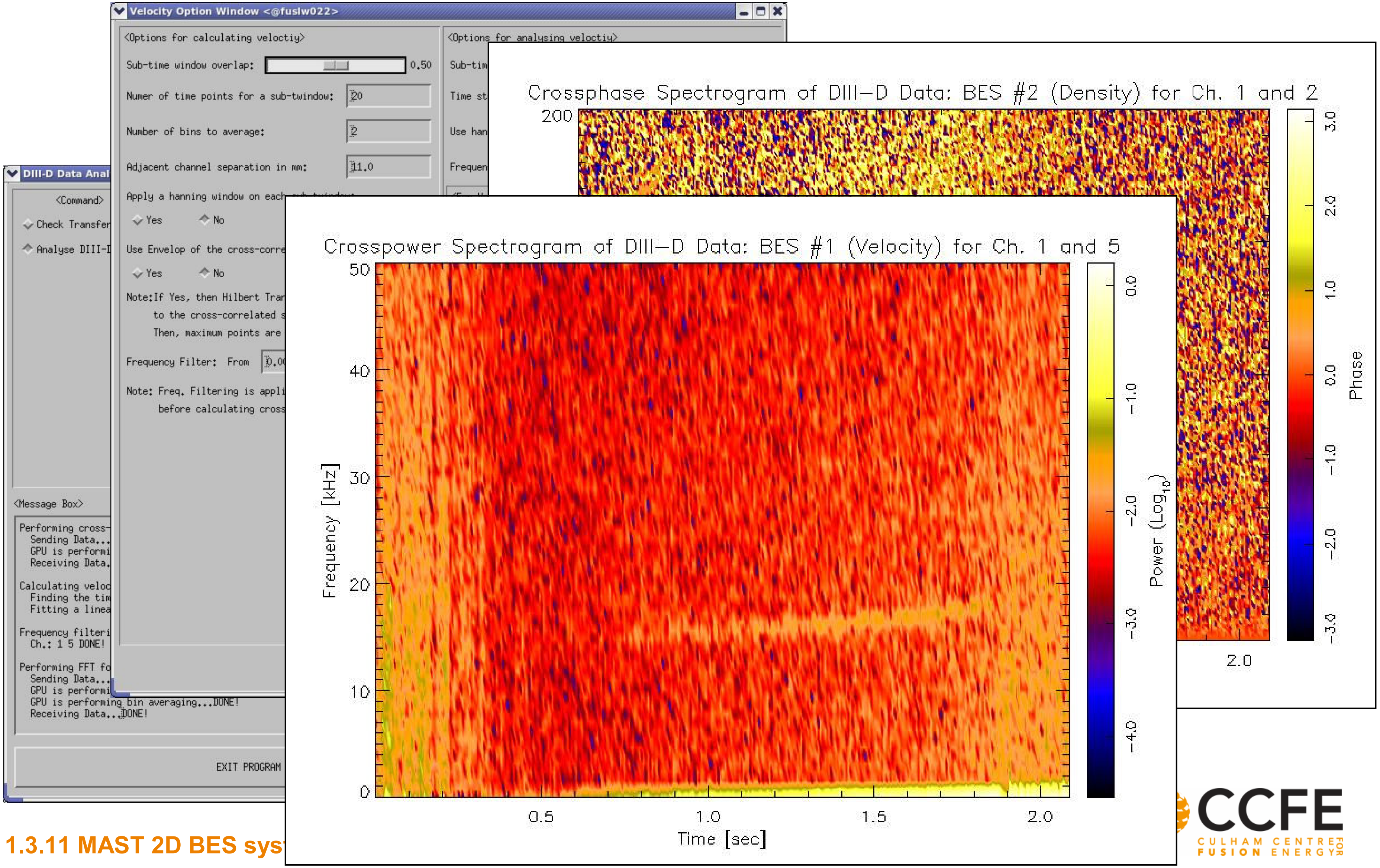


Synthetic 2D turbulence

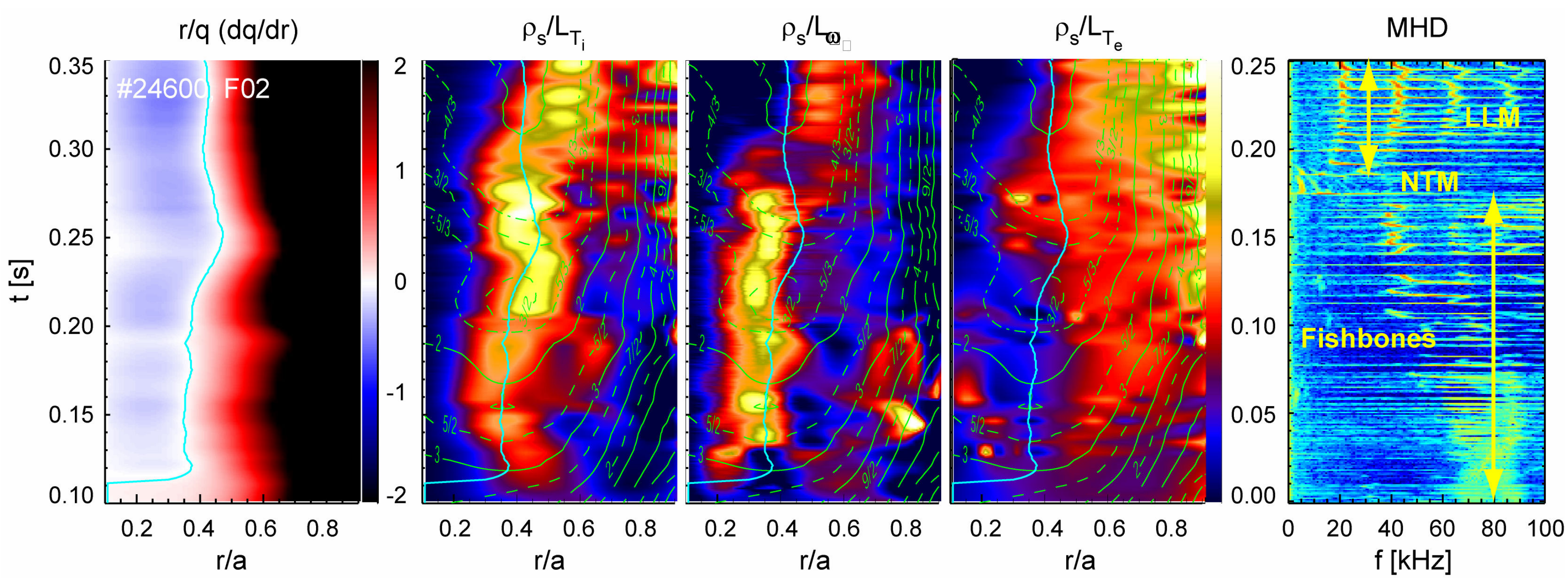


See talk by Young-chul Kim, Oxford University

2D BES: CUDA Widget



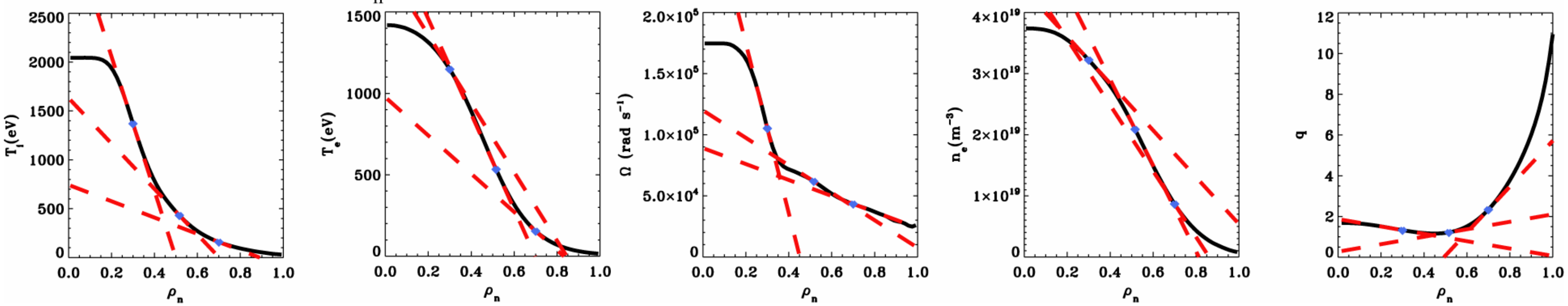
ITB formation



- Role of q-profile and flow shear in ITB formation and evolution studied
- Ion thermal and momentum ITBs form in region of zero/negative shear
- Characterise influence of flow shear and magnetic shear on turbulence

Micro-stability of co-NBI discharge

#22807, F03, 0.25 s, ρ_n = 0.3, 0.52, 0.7

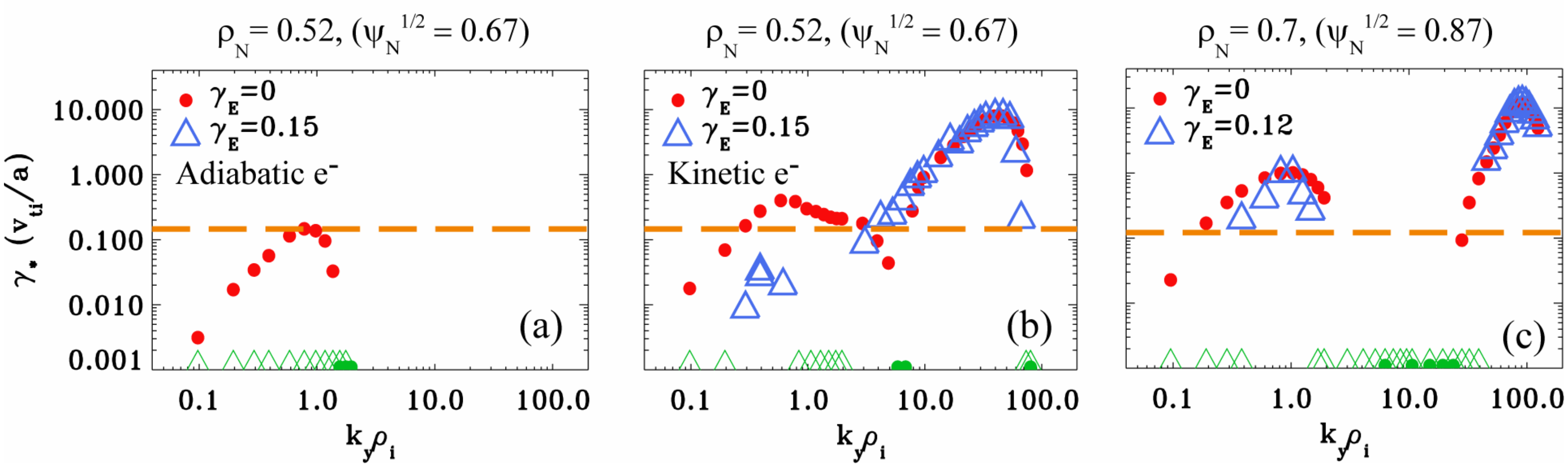


- Linear, GS2 calculations with kinetic electrons and with/without flow shear
- Performed for three surfaces, ρ_n = 0.3 (core), 0.52 (mid-radius), 0.7 (outer)

Inner surface – located in ITB region:

- Linearly stable to all modes at ion and electron scales (both with and without flow shear) due to weak negative magnetic shear
- Including electro-magnetic effects does not affect this result

Micro-stability of co-NBI discharge



Mid-radius (ρ_n = 0.52):

- Adiabatic electrons – ITG modes fully stabilised by flow shear
- Kinetic electrons – appreciable drive for TEM modes, only partially stabilised by flow shear

Outer surface (ρ_n = 0.7):

- Weak flow shear insufficient to stabilise strongly growing ITG modes
- TEM modes stable due to reduced drive at higher collisionality

M8: BES related experiments

- Commissioning of BES system (D/A, analysis, visualisation codes)
- Turbulence characterisation in baseline L-/H-mode plasmas
- Influence of flow shear, e.g. using RMP breaking from ELM coils
- Turbulence suppression at ITB – search for zonal flows
- Identification of GAM oscillations in plasma boundary region
- Comparison with synthetic BES data from numerical simulations
- Dependence on non-dimensional parameters (ν^*, β, q)