ADVANCED DIAGNOSTIC SYSTEMS AS A PATHWAY FOR AN AUSTRALIAN CONTRIBUTION TO KSTAR AND BEYOND

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KSTAR presentation April 2010
Outline

- Spatial heterodyne “Coherence imaging” systems
  - What are they and what do they do?
- Some examples:
  - Doppler measurements in the DIII-D divertor
  - Motional Stark Effect and CXRS imaging on the TEXTOR tokamak (last week)
- Possibilities for coherence imaging or other diagnostics on KSTAR
An alternative approach: a simple polarization interferometer gives contrast and phase at a single optical delay

Simple polarization interferometer:

\[ S = I(1 + \zeta \cos \phi) \]

Waveplate (delay \( \phi = 2\pi LB/\lambda \))

Input

Interferogram

To recover the fringe properties, measurements are required at multiple interferometric delays

Fourier transform

GA presentation July 2009
Spatial heterodyne interferometer

Savart plate introduces lateral displacement that gives an angular phase shear \( \rightarrow \) generates straight parallel fringes imprinted on image.

Demodulate for brightness, contrast, phase \( \rightarrow \) plasma properties
**Motivation: scrape-off-layer (SOL) and divertor flows**

Complex physics requiring sophisticated modeling

SOL/Divertor used to exhaust helium ash, impurities, manage waste heat load.

*Flow patterns are not well understood: multiple sources and sinks*

- B-independent sources: In-out diffusion asymmetry, plasma detachment
- B-dependent sources: Grad B drifts, ExB, grad p
- Divertor sink: retention, recycling, radiative cooling etc

*Experimental validation of modeling is required. Present edge flow measurement diagnostics include:*

- Doppler spectroscopy - small number of chords, poor spatial resolution
- Mach probe - Intrusive and of limited spatial reach or coverage

Current diagnostics status:
Doppler spectroscopy of impurities (e.g. carbon, DIII-D)

Above: R-Z projections of single channel spectrometer view chords.

Poor coverage, spatial inhomogeneity in brightness, Zeeman effect, temperature, flow speed ...  

Above: CIII 465nm triplet time evolution
Difficult to fit and interpret
Courtesy Neil Brooks

See e.g. Carbon flows in attached divertor plasmas, R. C. Isler et al, Physics of Plasmas, 1999
Spatial heterodyne coherence imaging

- The spatial heterodyne coherence imaging system is a “snapshot” imaging polarization interferometer that delivers images of interferometric phase and contrast at one or more optical delays (multiple independent carriers).

- Why measure optical coherence?
  - Interferometers have throughput advantage (for $R>100$)
  - Robust alignment, birefringent optics, simple instrument function
  - **2D imaging with simple interpretation**
    - Tomography ➔ physics studies, synchronous imaging of structures
    - Flux surface constraints
Divertor viewing geometry on DIII-D
CIII 465nm and CII 514nm Doppler coherence imaging

A tangentially viewing vacuum ultraviolet TV system for the DIII-D divertor, D. G. Nilson, et al, RSI, 1999
Demodulated brightness and phase images during divertor detachment (#141110)

First images of counter-propagating parallel sonic flows
Parallel flow projections reverse sign when the toroidal field reverses.
Superficial similarities between UEDGE modeling and tomographically inverted brightness and parallel flow

Experiment #141170, 4562ms

UEDGE Modeling

Scale
-12 km/s (blue)
+30 km/s (red)
Injected beam atoms feel induced electric field in frame of the beam $E = \vec{v} \times \vec{B}$.

- Splitting of $H_\alpha$ and Doppler shift
  - $\pi$ and $\sigma$ components are orthogonally polarized. $\sigma$ is parallel to $(\vec{v} \times \vec{B})$ so orientation gives pitch angle of $\vec{B}$
  - Apply multiple narrowband filters & measure pitch angle. Typically 10-20 spatial channels
  - An interferometric filter allows time resolved imaging of $B_z(r,z)$
TEXTOR imaging Stark effect system

- Spatial encoding (no modulation, single snapshot)
- Analyze polarization of full multiplet: wideband filter, tolerant of contamination and background
- Interferometric approach allows 2-D spatial imaging $B_z(r,z)$
TEXTOR images

- View of the internally illuminated vessel wall
- Plasma background in the 662nm MSE passband
- Beam on. Note appearance of fringes due to *polarized* emission
MSE imaging on TEXTOR (Results – new prism)

Reverse Bt, Ip

Normal Bt, Reverse Ip

Polarization tilt angle

Raw images, 5ms exp

No calibration corrections
Calculated and measured beam Doppler shifts

Above: Measured Doppler phase shift agrees with phase shift calculated for 50keV beam of divergence ~ 1-2 degrees (unaffected by prism coating)

Left: The beam intensity and beam energy exhibit coherent noise (mean phase fluctuation amplitude 0.2 radians → 0.4 keV)
**CXRS imaging on TEXTOR**

Shot number 112431  Time = 0.86 s

Beam off

Beam on

Beam x10 brighter, but internal structure still visible
CXRS imaging on TEXTOR (first results)

- **Raw image**
  - Exposure time 40 ms

- **Brightness**

- **Phase shift**
  - Max $v_\phi \sim 70$ km/s
  - Uncertainty $\sim 2$ km/s

- **Contrast**
  - Max $T_i \sim 1.3$ keV
  - Uncertainty $\sim 50$ eV

- **Max $T_i \sim 1.3$ keV**
- **Uncertainty $\sim 50$ eV**

KSTAR presentation April 2010
Flow and temperature evolution

- Beam on (Co-)
- Beam on (Counter)
- Beam on with DED

Shafranov shift

Structure due to internal back reflections
Possibilities for Australian involvement with KSTAR I

- Wide angle Doppler imaging of SOL and Divertor
  - Simultaneous imaging of multiple carbon species for benchmarking physics modeling of flows and temperatures
  - Stark coherence imaging of $H$ density in divertor
  - Synchronous coherence imaging of ELMS and edge phenomena
Possibilities for Australian involvement with KSTAR II

- Divertor flow tomography
  - Simultaneous imaging of multiple carbon species for benchmarking physics modeling
Possibilities for Australian involvement with KSTAR III

- Fast/synchronous MSE imaging
  - q-profile determination
  - Synchronous imaging: possibility for study of current structures and reconnection during MHD/sawteeth

Projection of MHD activity in the H-1 heliac
Possibilities for Australian involvement with KSTAR IV

- Vertical and/or horizontal CXRS imaging?
  - Simultaneous $v_{\text{Tor}}$ and $v_{\text{Pol}}$ (with vertical view)
  - 2-d imaging to constrain equilibrium reconstruction
Conclusion and next steps

- Australia can make contributions to KSTAR through advanced imaging diagnostic systems.

- Australia also has expertise in other areas of diagnostics (interferometry, polarimetry, scattering etc) and associated advanced signal processing techniques (Blackwell, von Nessi)

- Imaging on KSTAR?
  - High resolution SOL and divertor imaging (Doppler and Zeeman)
    - Multiple views, multiple species, wide-angle
  - Snapshot MSE (synchronous techniques for MHD etc?)
  - Snapshot CXRS – vertical and/or horizontal views
Counter propagating flows are sensitive to edge pressure: plasma detachment during density ramp
Possibilities for Australian involvement with KSTAR V

- Other ANU diagnostic expertise:
  - 2D density interferometry, microwave scattering
  - Other optical spectroscopy – supersonic He beams etc.
  - Probes and magnetics (B. Blackwell)
  - Combining imaging diagnostics and sophisticated data analysis (Bayesian inference) for equilibrium studies (talk by Greg von Nessi) and data mining

- Expertise at other Australian universities and organisations
  - Uni of Sydney (A. Samarian)
  - Australian ITER forum (M. Hole).
**Imaging Motional Stark Effect Polarimetry**

Motional Stark effect polarimetry is a beam emission diagnostic that gives the magnetic field pitch angle at multiple discrete points along the tokamak major axis.

It is based on measuring the polarization orientation of polarized hydrogen atom Stark emission due to induced E-field in local reference frame.

Technical limitations ➔ restricted to a small number of single channel instruments.

Interferometric approach allows 2-D spatial imaging ➔ $B_z(r,z)$