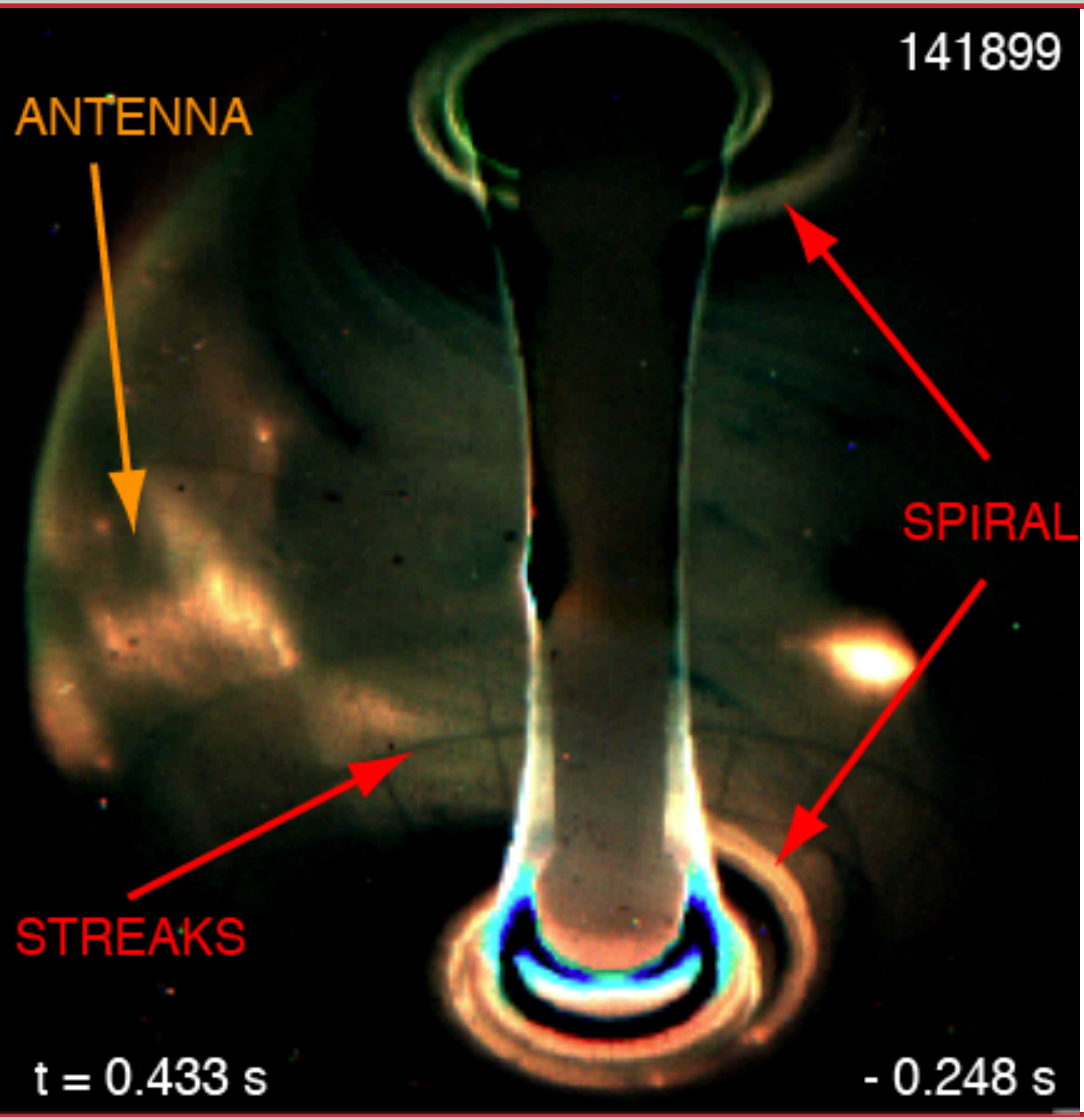
RF interactions with edge produce a bright hot spiral on the divertor



- Edge interactions apparent on camera images
- Bright streaks emanate from antenna region
- Bright spirals form on both upper and lower divertor
- IR cameras show strong divertor heating under spiral
  - Edge loss up to ~ 60% of RF power

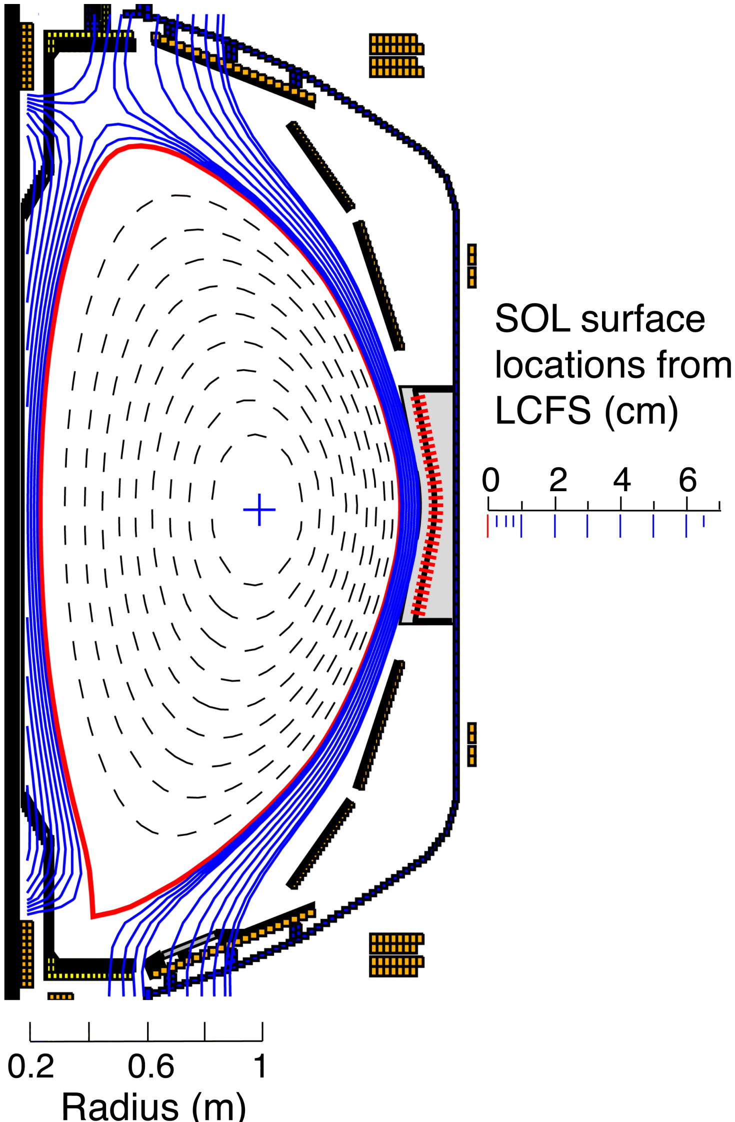
Evidence that RF power couples SOL and flows along field lines to divertor

- Experimental observations
  - IR cameras measure strong heat flux underneath RF spirals
  - Position measured with divertor floor camera (Li I line)
  - RF spiral moves when magnetic pitch changes
    - Movement observed with Langmuir probes and current-sensing tiles

- Numerical modeling: HHFW power flows along field lines
  - Magnetic mapping from SOL midplane to divertor
  - Mapping agrees with IR data and with divertor-floor images
  - Mapping reproduces spiral motion when pitch is changed

- Conclusion: RF spiral originates from across the SOL at the midplane and not solely from the antenna face
  - Consistent with location of onset density for perpendicular fast-wave propagation

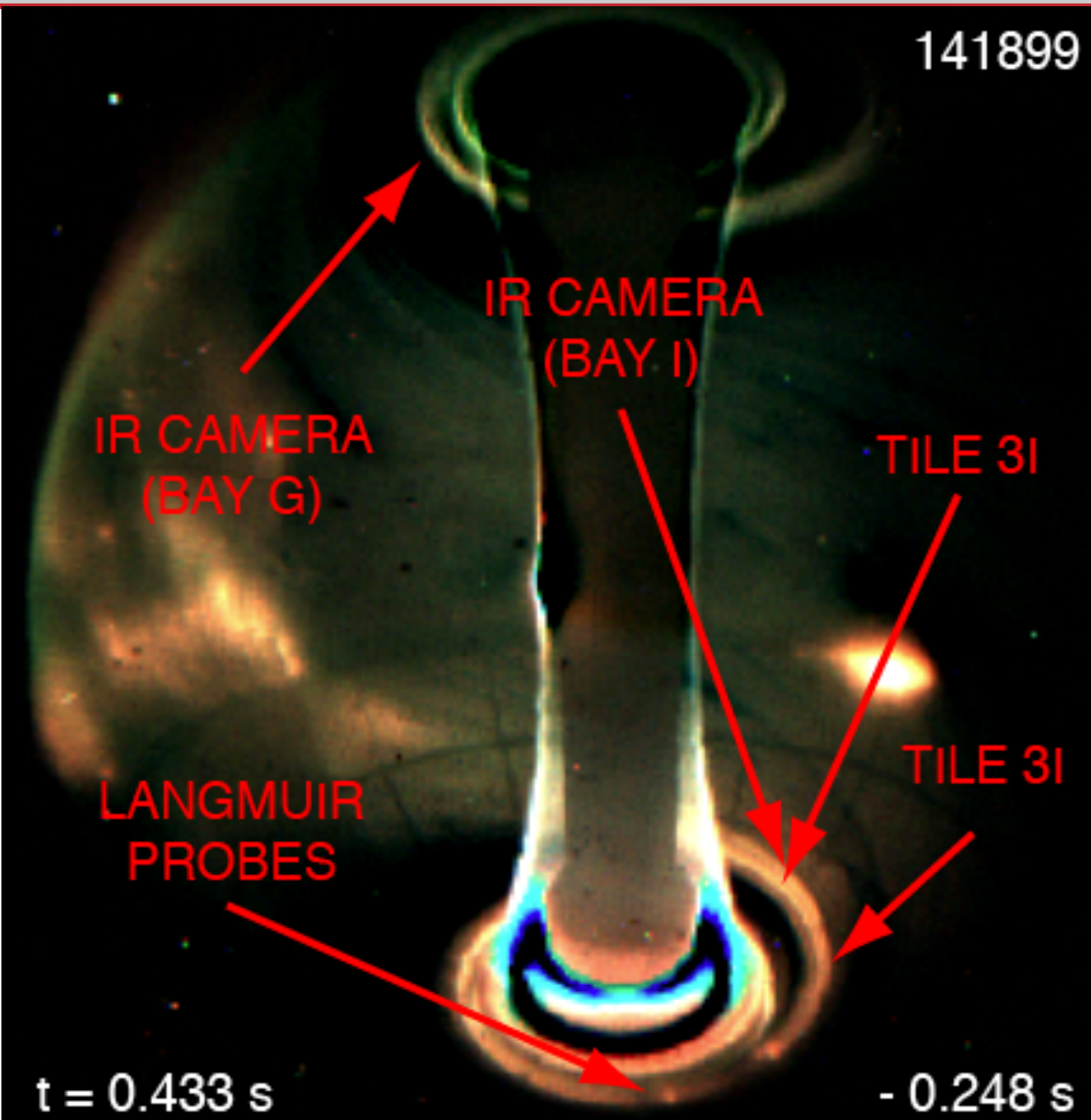
Hot RF spiral suggests fast-wave propagation along field lines in SOL



- Fraction of HHFW power lost is related to location of onset density for perpendicular fast-wave propagation*
  - Moving the onset density too close to antenna seems to induce more losses
- Suspect standing wave patterns are formed in SOL
  - Leads to significant Poynting flux along SOL magnetic field
- Could be other loss mechanisms: such as hot ion flux due to parametric decay instability

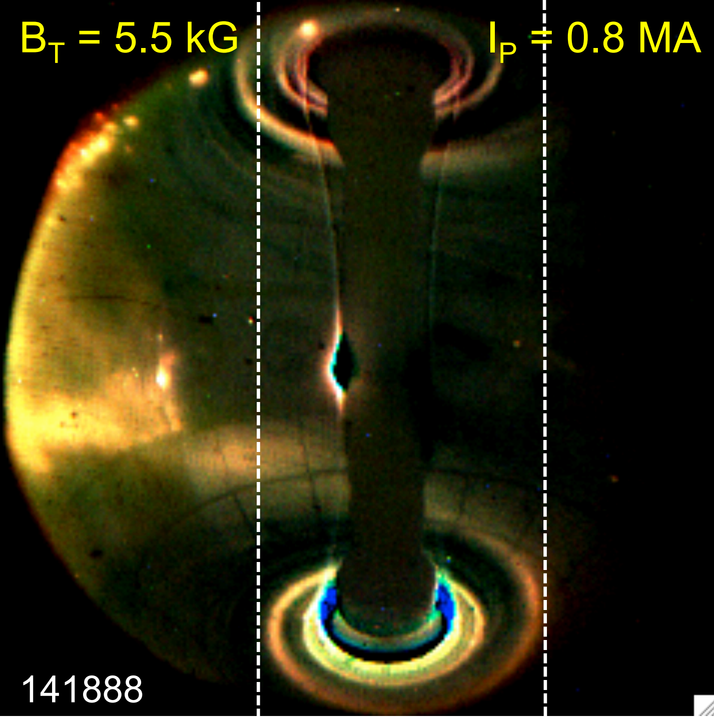
*J.C. Hosea et al., *Physics of Plasmas* **15** (2008) 056104.

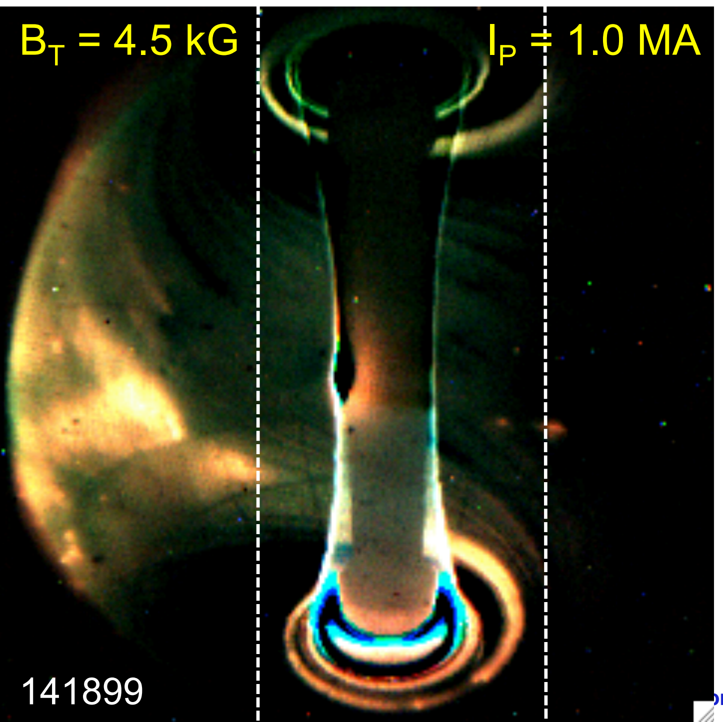
Diagnostics in divertor measure RF spiral properties



- **IR cameras** show strong divertor heating under spiral
- **Divertor optical camera** (Li I line)
- **Langmuir probes** respond strongly to RF when under spiral
- **Current-sensing tiles** detect increase in tile currents when under spiral

Major radius of RF spiral at any toroidal position depends on field pitch

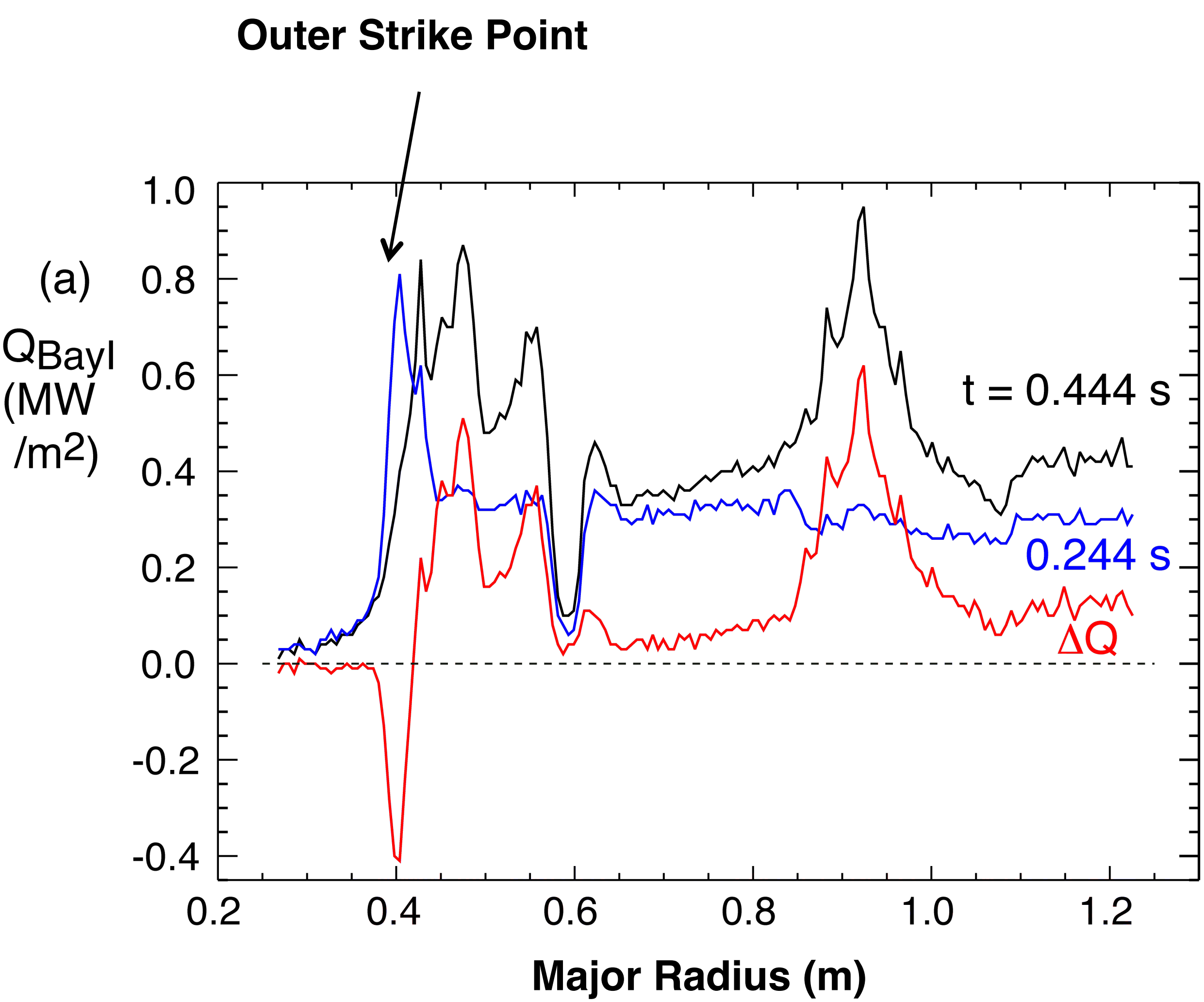




- Radius shifts by ~ 15 cm inward with increased pitch
  - Upper figure: low pitch I_P/B_T = 0.8 MA/ 5.5 kG (31°)
  - Lower figure: high pitch I_P/B_T = 1 MA / 4.5 kG (42°)
- Can sweep RF spiral across diagnostics by changing the field pitch

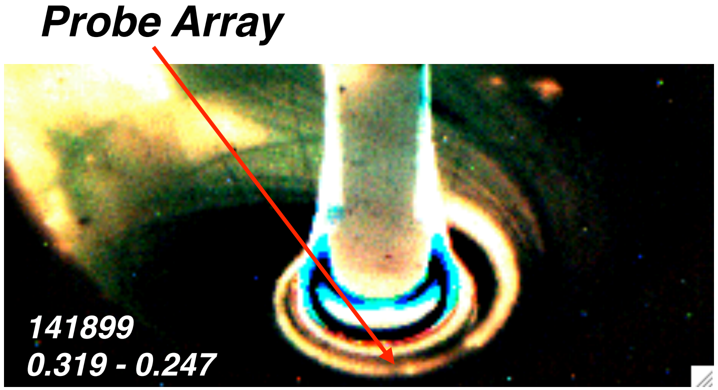
141888 time = 0.312s - bkg 0.247s
141899 time = 0.319s - bkg 0.247s

Divertor IR cameras show strong RF-induced heating

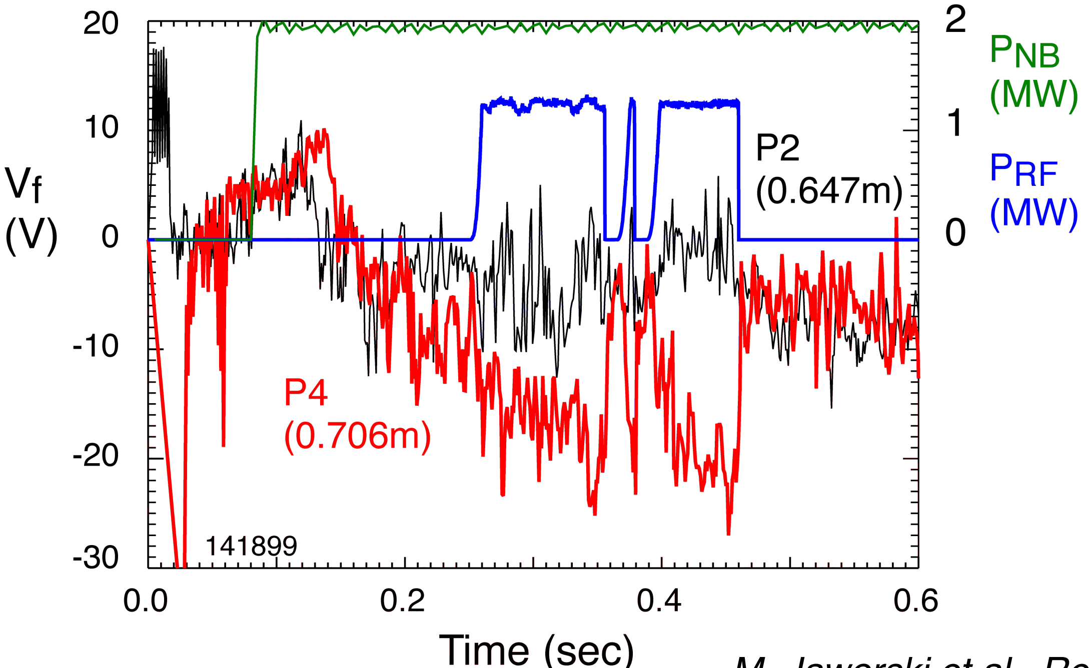


- Strong divertor heating under spiral during RF (t=0.444 s)
- Pre-RF heat profile (t=0.244 s) subtracted
- RF-induced divertor heating (ΔQ) at various radii
  - Including outer divertor region well away from outer strike point
- Negative dip due to outward motion of outer strike points

High field pitch puts spiral over Langmuir probe* 4 but not on other probes a few cm in



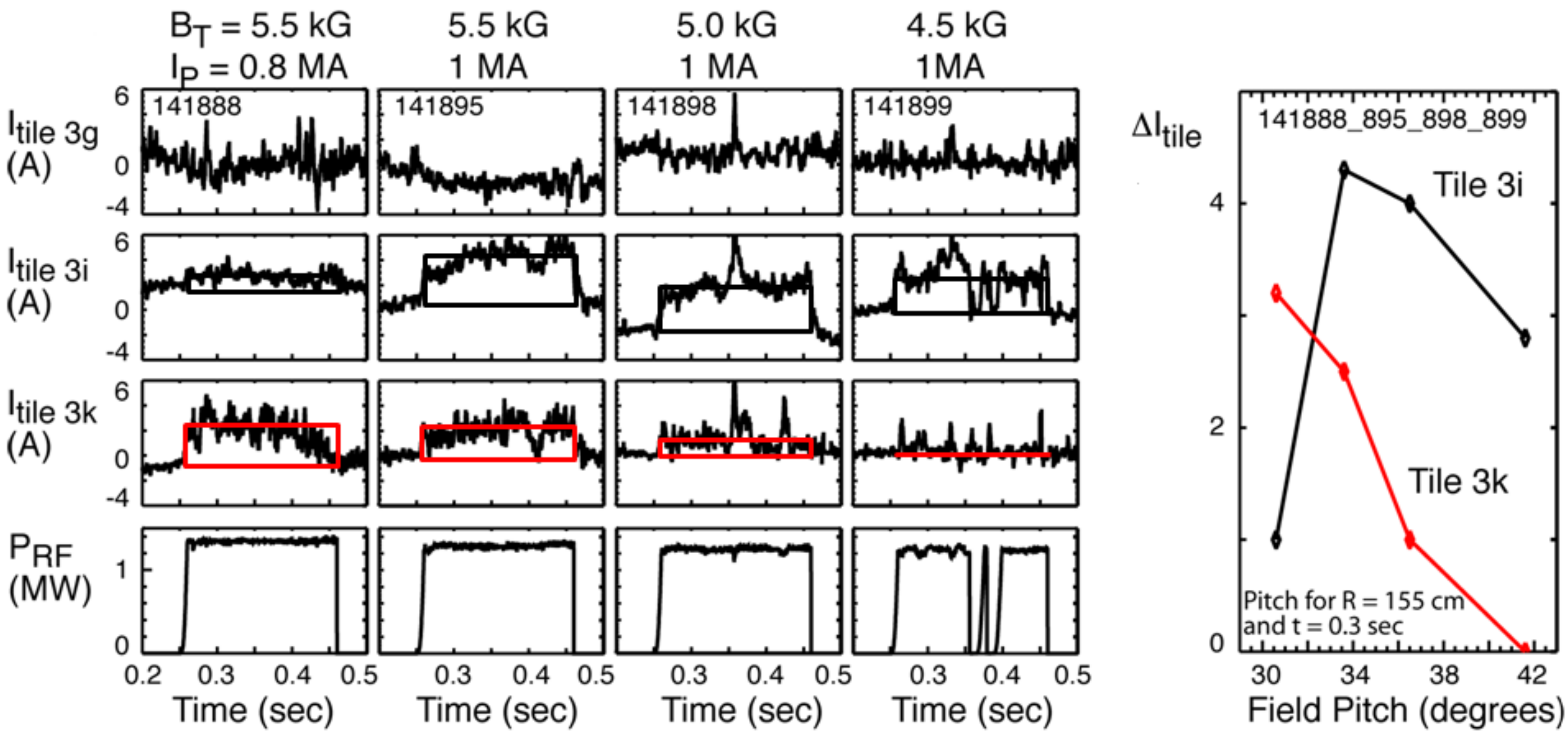
- Probe array embedded in divertor floor at Bay B
- RF-induced effects are localized



- Probe P4 floating potential responds strongly to RF at high pitch
- Probe P2, 6 cm inboard, has a much weaker response

M. Jaworski et al., Review of Scientific Instruments 81 (2010) 10E130.

Current-sensor tiles track movement of RF spiral

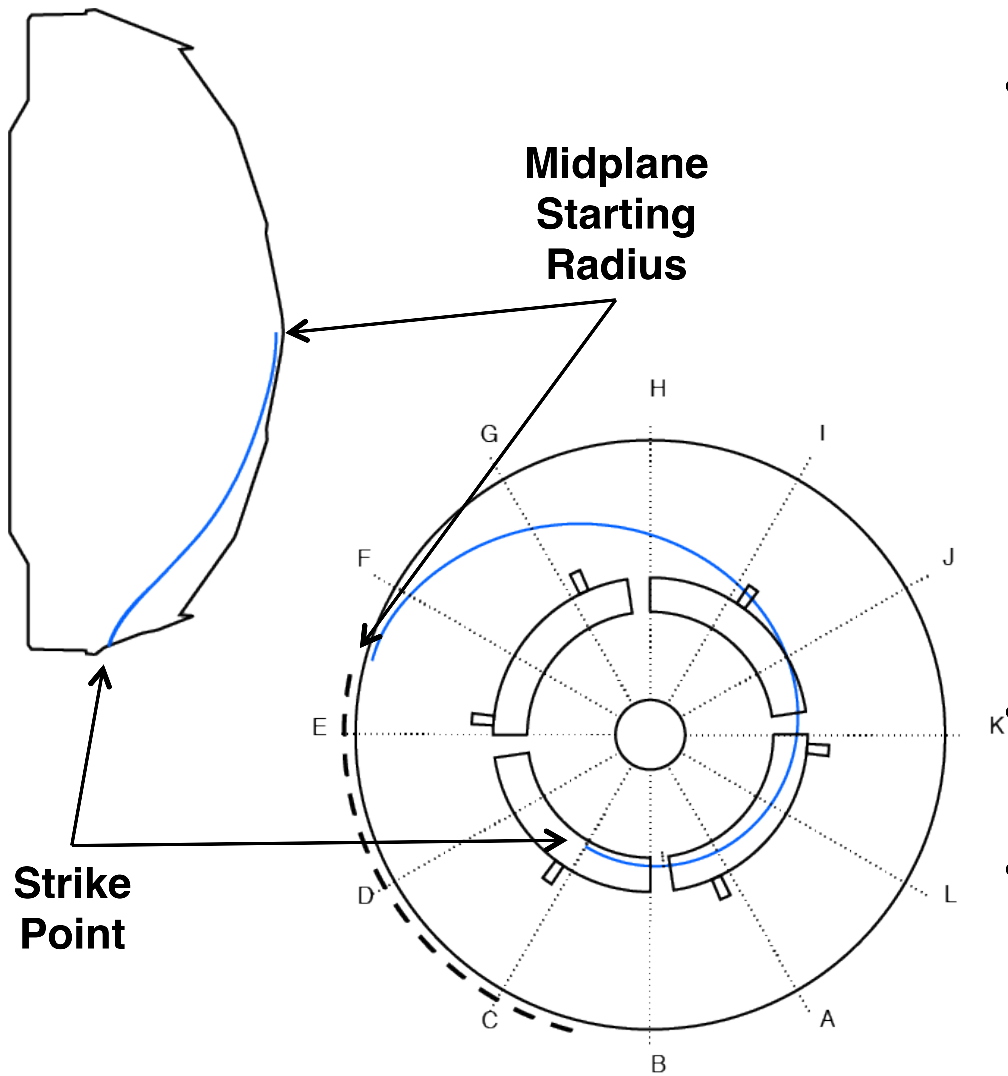


(k_ϕ =-8 m^{-1}/ϕ_{Ant} =-90°, D_2, P_{NB} = 2 MW)

- Certain divertor tiles are instrumented to measure currents
- Bay K tile current decreases as RF spiral moves inward…
- … while Bay I tile current rises

S. Gerhardt et al., Review of Scientific Instruments 82 (2011) 103502.

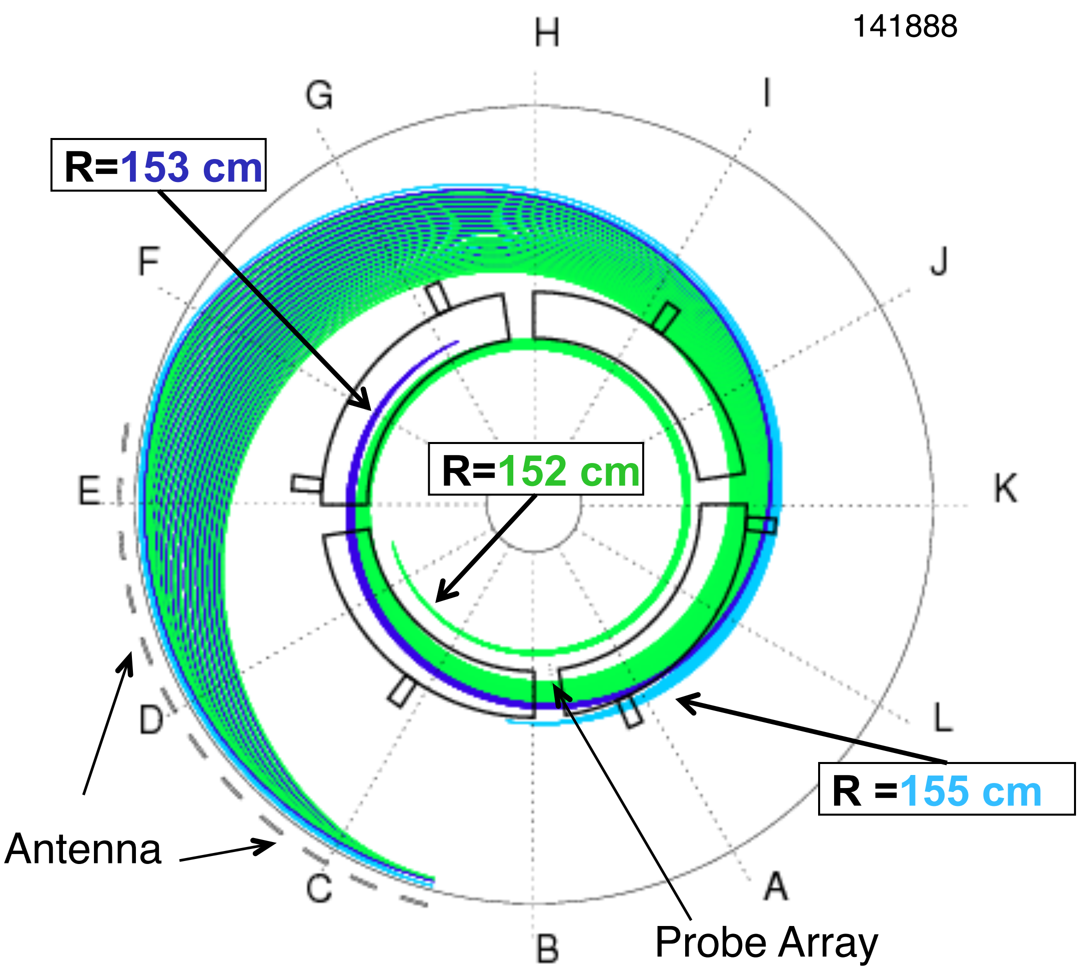
Field-line mapping hypothesized to show path of HHFW power flow



- Follow field lines using SPIRAL code
  - SPIRAL is a full-orbit code
  - Particle trajectories approximate field lines to high accuracy
  - Only using field-line tracing ability of SPIRAL
- Start field lines between antenna and separatrix
- Integrate SOL field lines until they strike divertor

G.J. Kramer et al., 22 IAEA Fusion Energy Conference (Geneva, 2008) CD-ROM file IT/P6-3.

Field-line mapping models flow of RF power along field to divertor



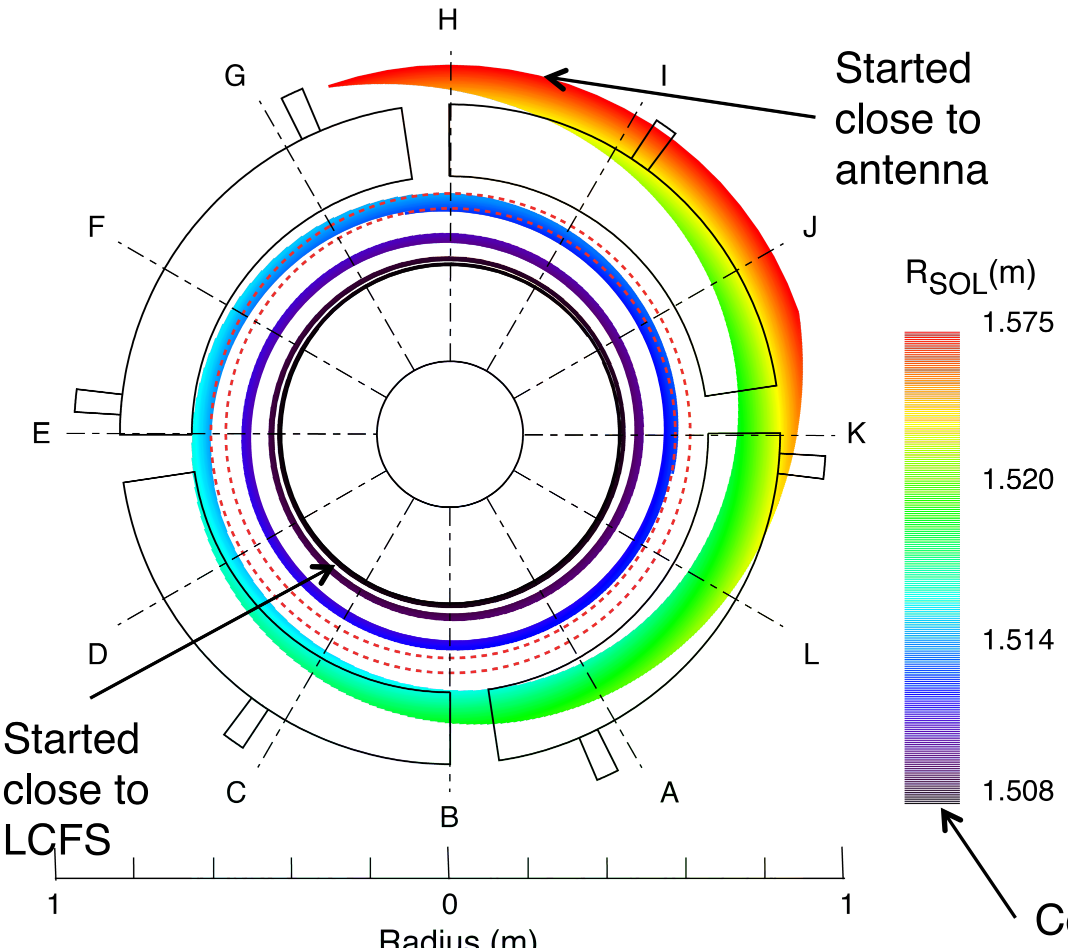
At midplane: R_{ANT} = 157.5 cm
R_{LCFS} = 151 cm

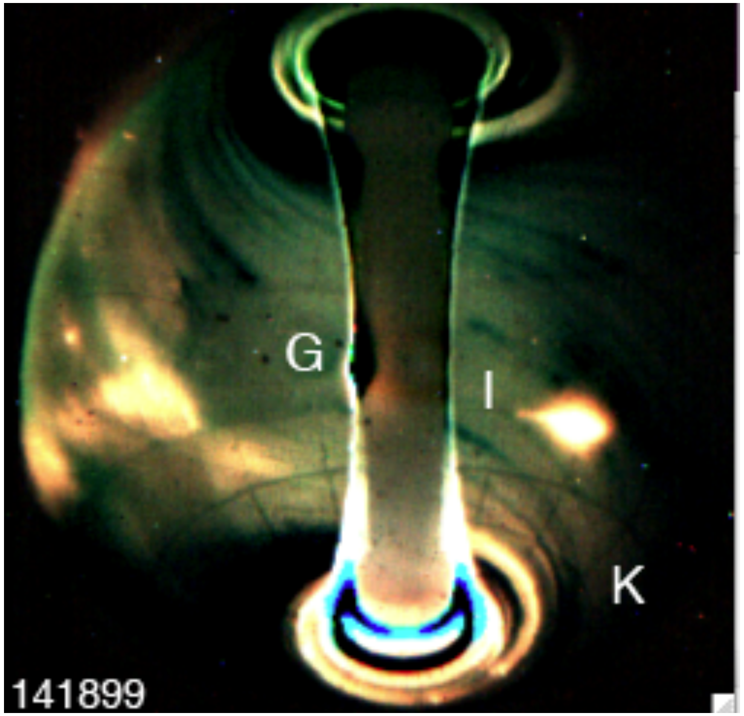
- Analyze a set of field lines
  - Colors indicate different starting radii at midplane
  - Field lines have ninety degree span (same as antenna)
- Field lines spiral and focus radially around the center column
- Field lines started farther from antenna spiral in more
- Field lines to probe come from 153 cm at midplane, well away from the antenna

Strike points on divertor form a spiral that closely matches the observed RF spiral

Strike points on divertor for field lines started at midplane…

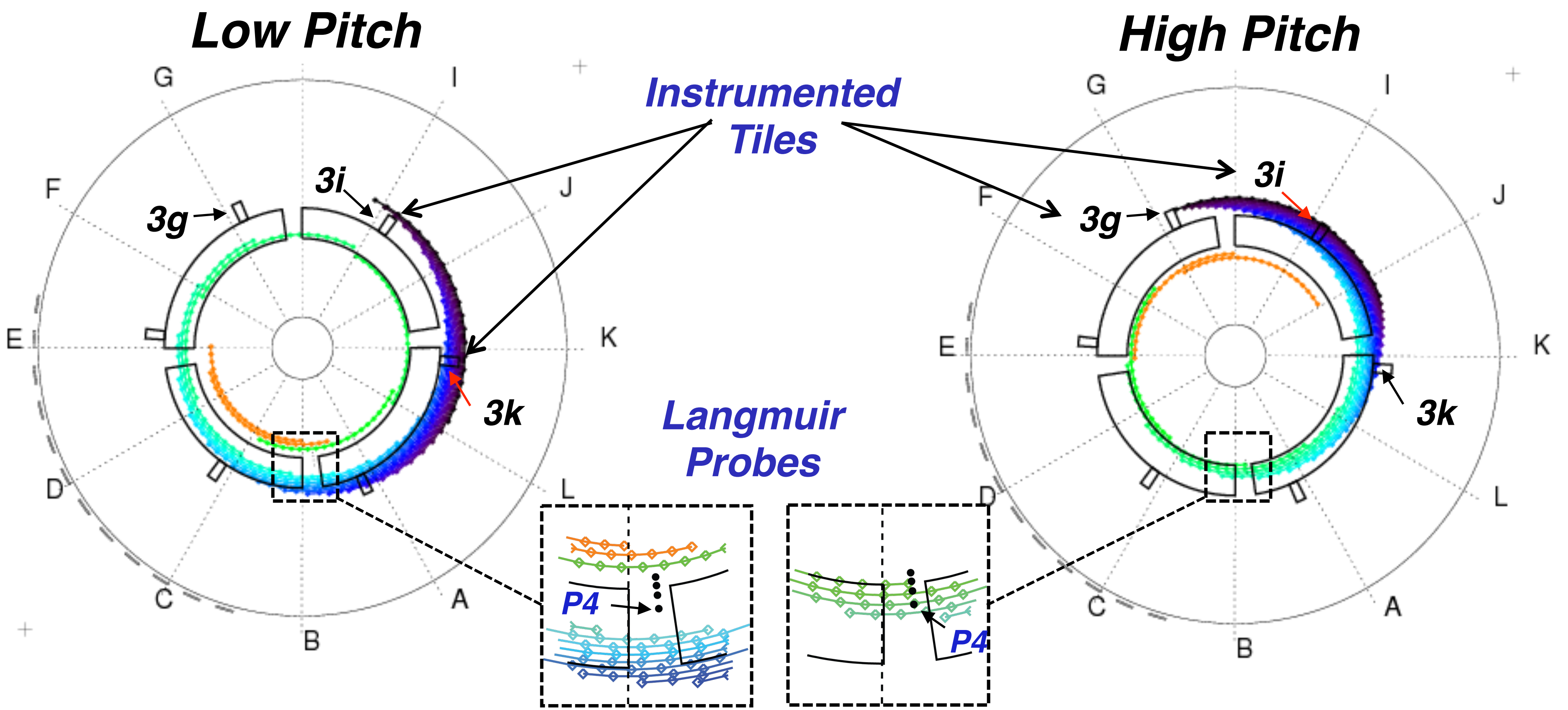
… create spiral pattern close to camera images





Colors indicate starting radius at midplane

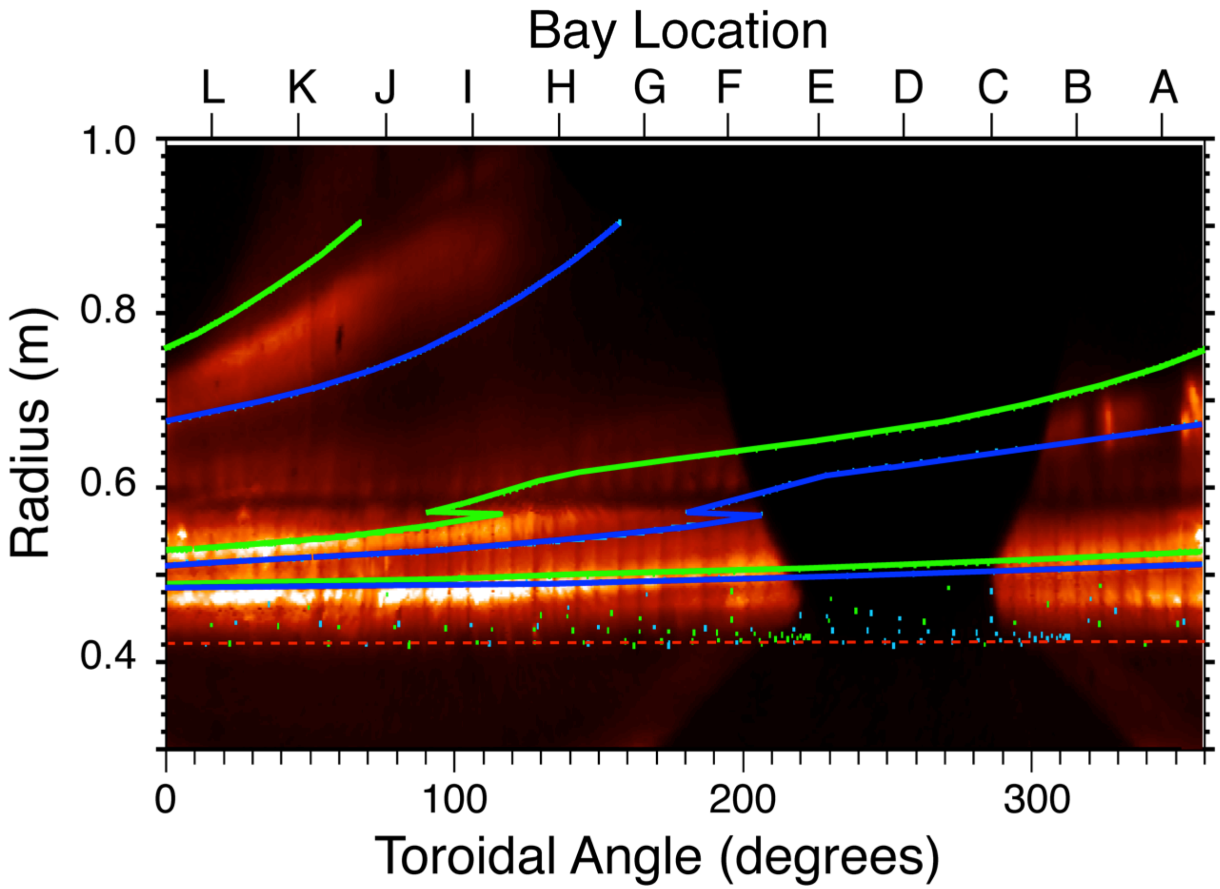
Computed strike points move with pitch and match diagnostic measurements



- Strike points move with pitch and match tile and probe measurements
- As the magnetic pitch increases:
  - Spiral moves over probe 4 location
  - Spiral moves over tile 3i and off of tile 3k

<u>NOTE</u>: Coloring scheme differs from previous slide

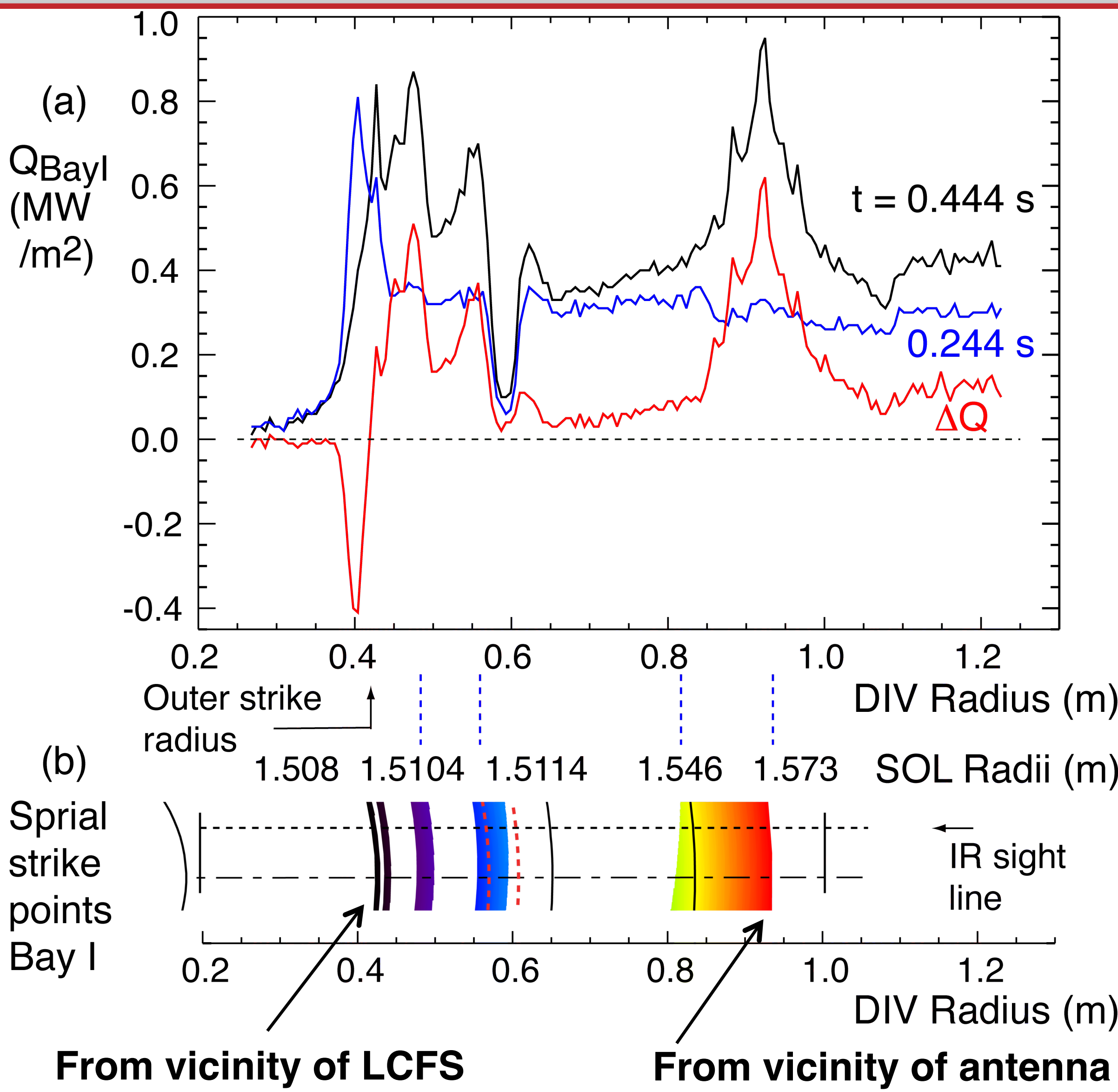
Optical divertor camera agrees with SPIRAL strike points until close to LCFS



- Green strike points come from right edge of antenna
- Blue strike points come from left edge

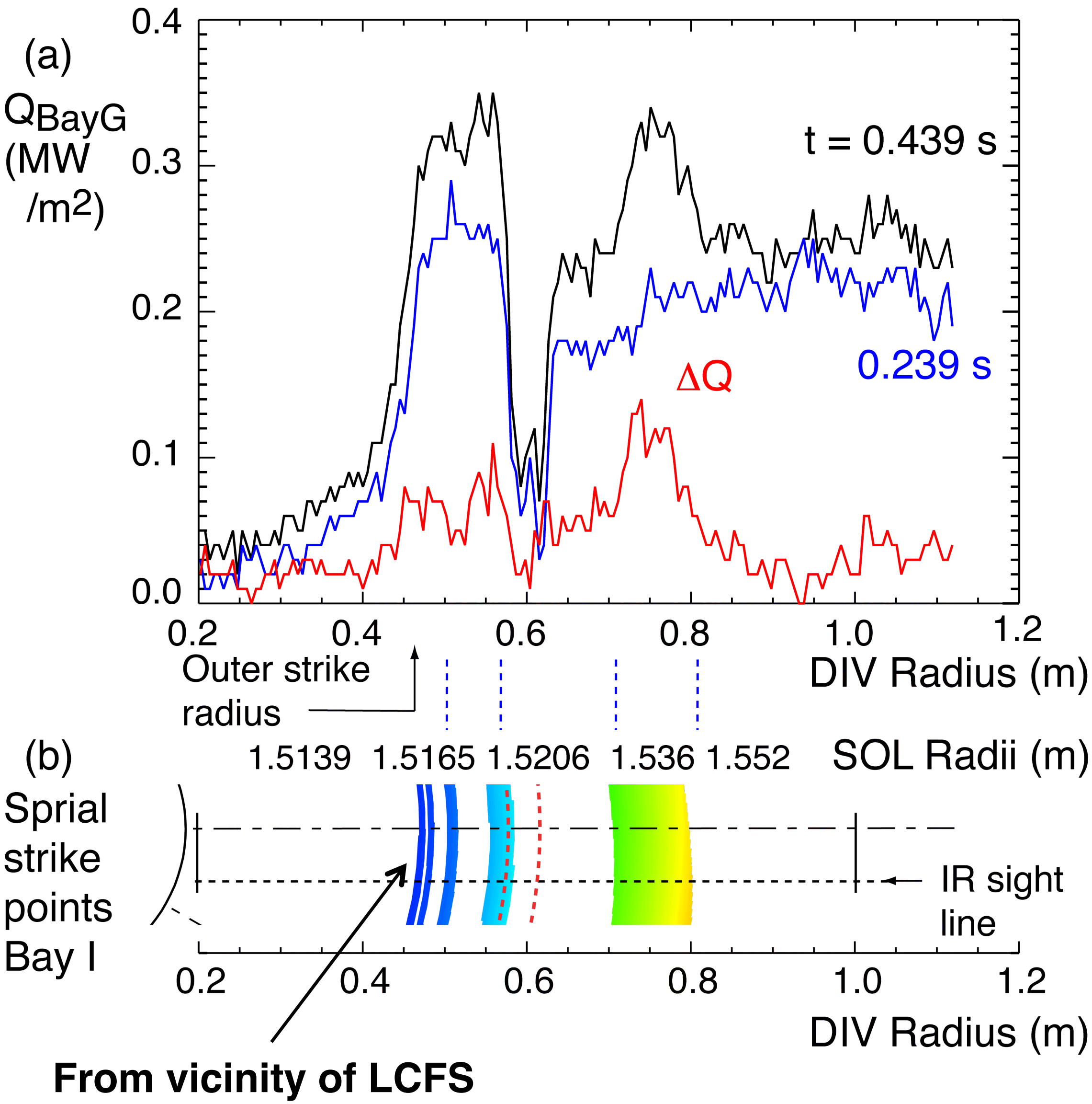
- Optical divertor camera measures Li I emission
  - Li comes from wall (divertor) sputtering
  - Enhanced via RF sheaths or RF-driven particle flux
- Overlayed with SPIRAL strike points
  - Jagged portion due to CHI gap
- Camera data agree with strike points until close to the LCFS
- EFIT02 equilibrium fit

Lower divertor IR camera data agrees with SPIRAL strike points



- RF pulse heats divertor in several locations
- Measured radii of deposited heat coincide with strike-point radii computed by SPIRAL
- Inverting the magnetic map gives an idea of how much HHFW power couples to different SOL field lines
- LRDFIT04 equilibrium fit

Upper divertor IR camera data agrees with SPIRAL strike points



- Upper divertor IR signal weaker than lower divertor
    - Could be up/down asymmetries
    - Could be toroidal position of camera relative to spiral
- Measured radii of deposited heat coincide with strike-point radii computed by SPIRAL
- LRDFIT04 equilibrium fit

Summary

- Strike points computed by SPIRAL agree with experimental data
  - IR cameras measure heat peaks at strike-point locations
  - Strike point positions agree with camera images
  - Strike points move as magnetic pitch changes, rotates spiral
  - Langmuir probe and divertor tiles show strong RF-response when under the RF spiral
- Much of the RF power-deposition spiral comes from the SOL between antenna and separatrix
  - Could be consistent with location of onset density for perpendicular fast wave propagation
- Will invert map to estimate midplane profile of HHFW power coupling to field lines
- Will explore differences in strike-point locations with different magnetic field equilibrium fits