NSTX edge losses are field aligned and likely due to fast-wave propagation in SOL

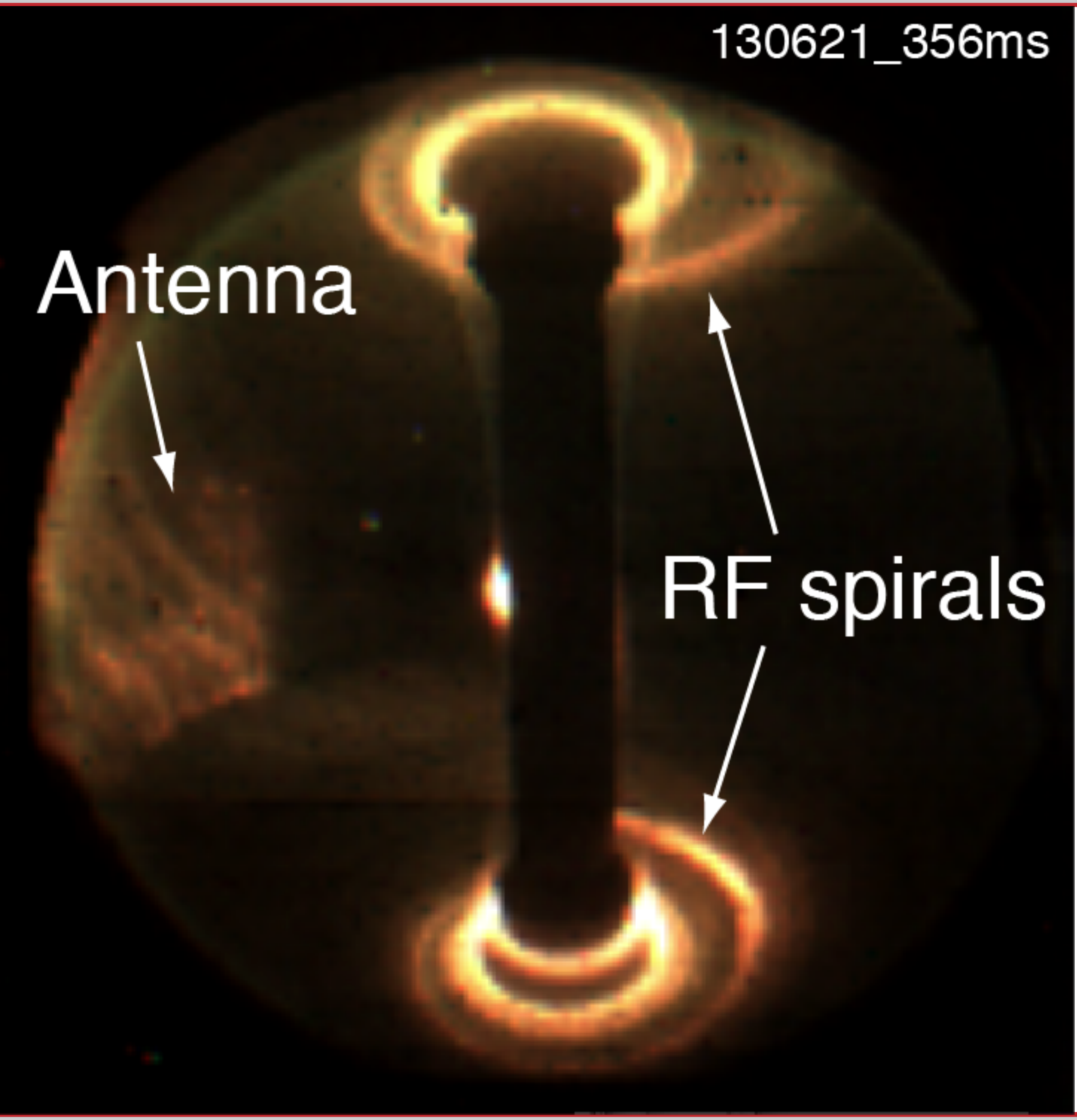
- **HHFW is lost to divertor along SOL field lines**
  - Good agreement between field-line mapping and measurements

- **HHFW power couples to all SOL field lines in front of antenna**
  - … not just field lines connected to antenna components

- **Obtain radial profile of HHFW power coupling to SOL field lines**
  - Profile peaks near both antenna and last closed flux surface (LCFS)
  - Obtained by applying field-line mapping to divertor heat flux

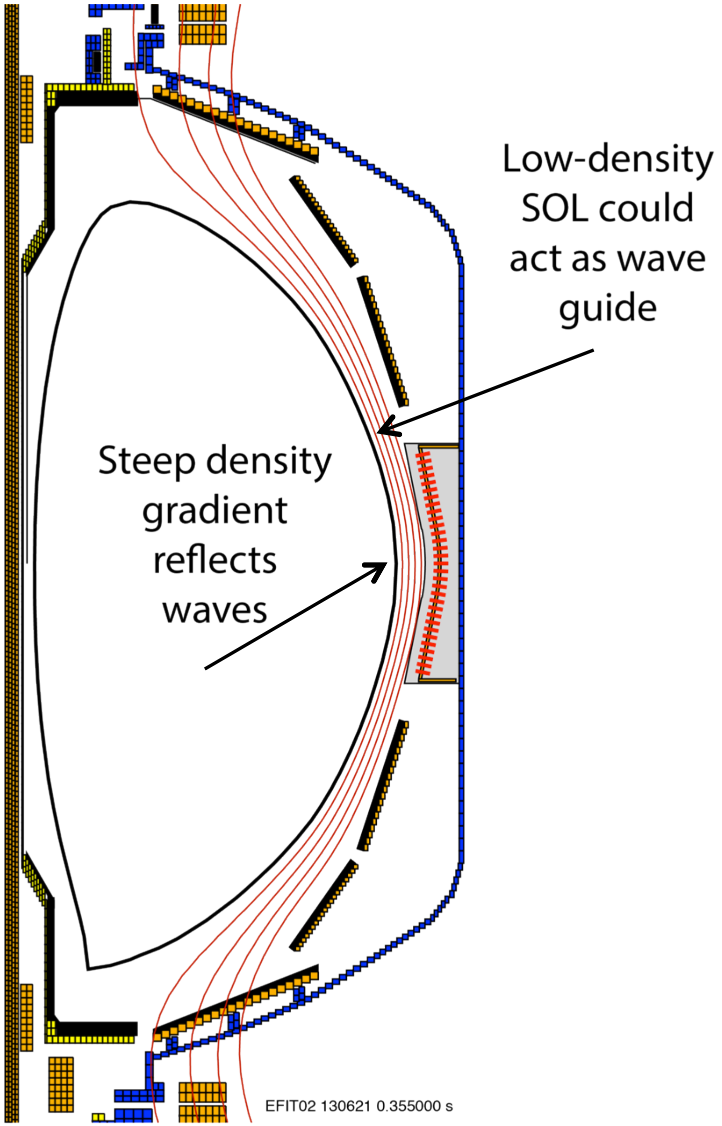
- **Coupling profile suggests fast-wave propagation in SOL**
  - Profile suggests radial standing wave structure
  - Edge losses also correlate onset density for perpendicular fast-wave propagation

RF power lost *directly* to divertor regions through the SOL on NSTX



- Edge interactions apparent from bright streaks in camera images
- Bright spirals form on both upper and lower divertor
  - IR cameras measure large heat flux in spirals
- Edge loss can be up to 60% of coupled RF power

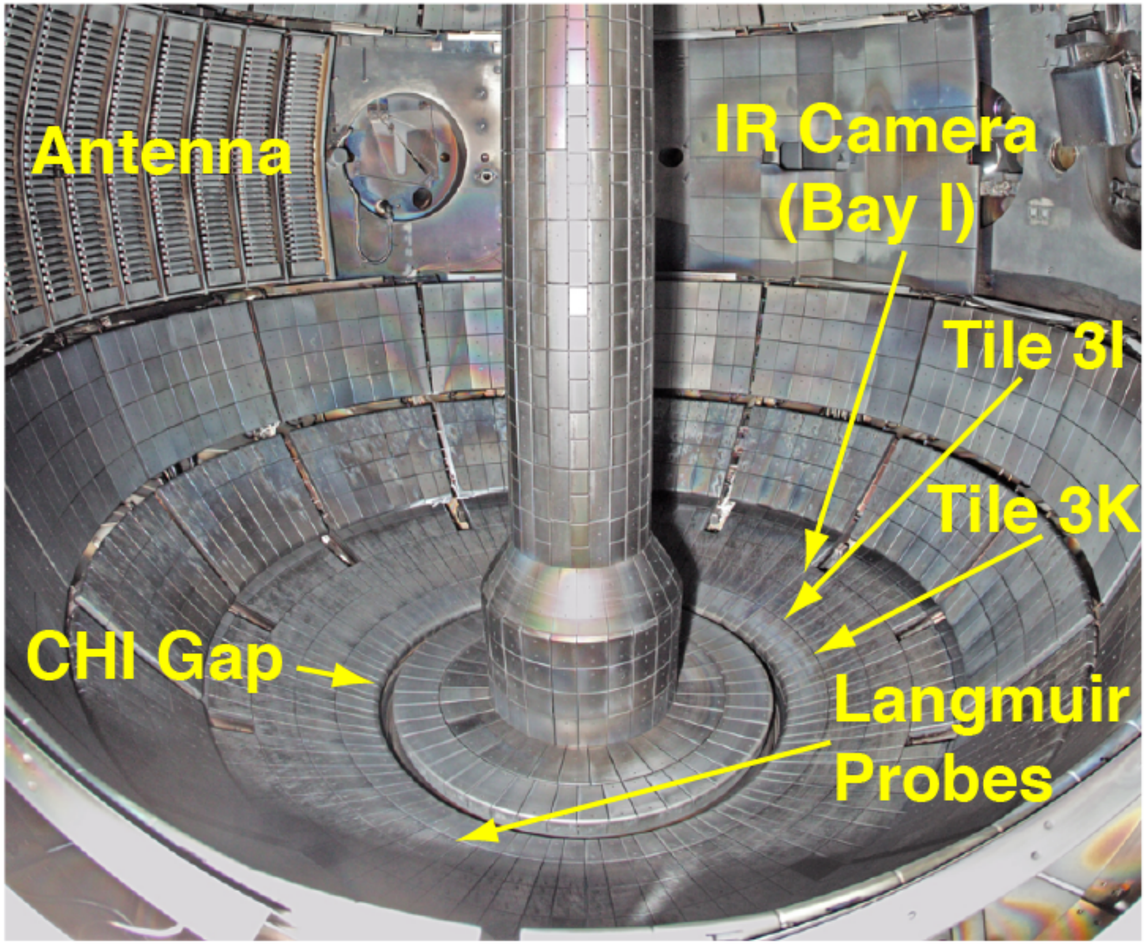
Edge loss possibly caused by fast-wave propagation in SOL



- Edge loss is correlated with onset density for perpendicular fast-wave propagation*
  - Enhanced loss when onset density too close to antenna
- HHFW coupling profile at midplane suggests standing-wave patterns in SOL
- Could be other loss mechanisms
  - e.g., hot ion flux due to parametric decay instability

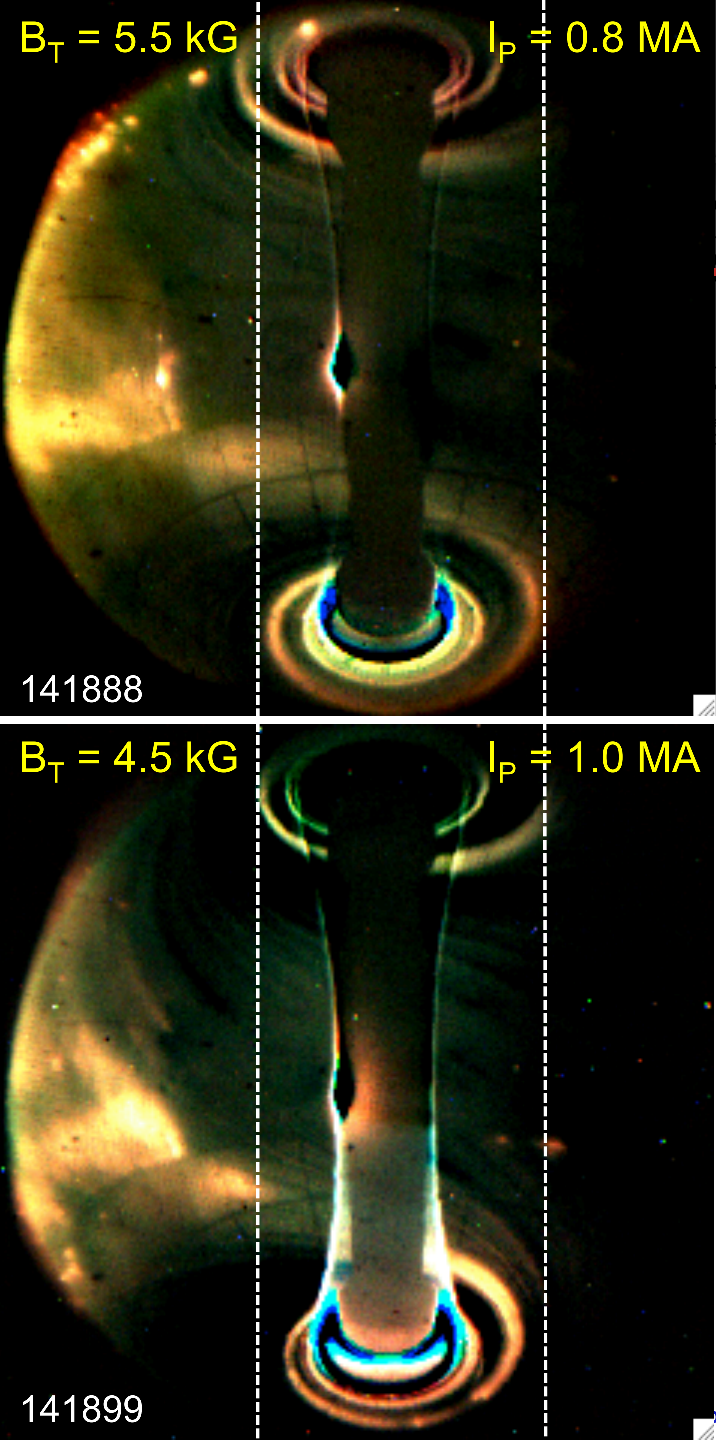
*J.C. Hosea et al., *Physics of Plasmas* **15** (2008) 056104.

Diagnostics in divertor measure RF spiral properties



- **IR cameras** show strong divertor heating under spiral
- **Divertor optical camera** (Li I line) shows strong emission in spiral zone
- **Langmuir probes** respond strongly to RF when under spiral
- **Current-sensing tiles** (Tile 3I and 3k) detect increase in tile currents when under spiral

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

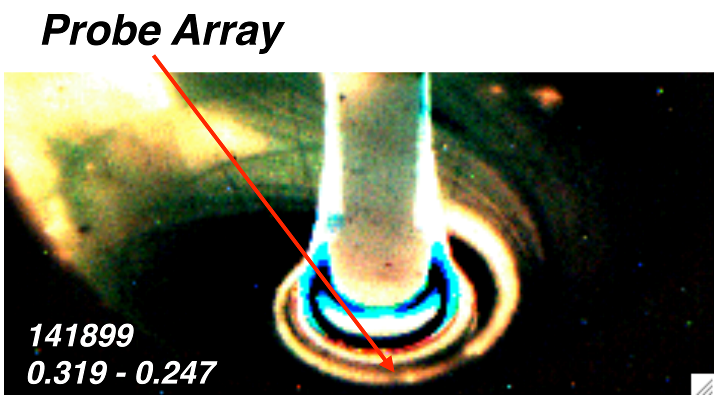


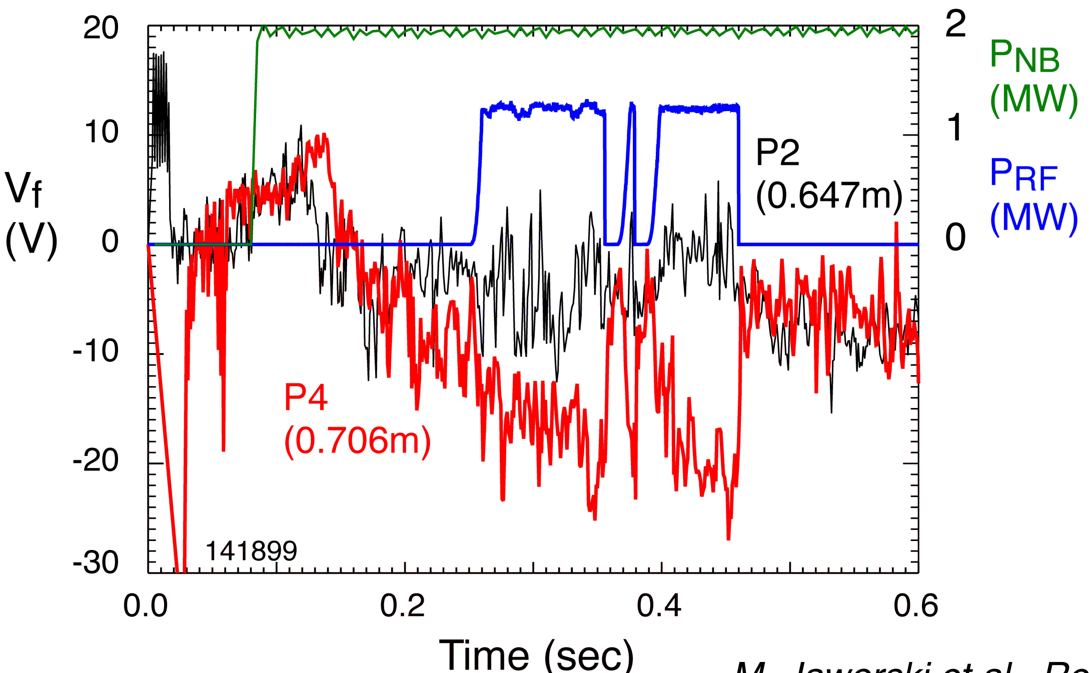
- Radius shifts by ~ 15 cm inward with increased pitch
  - Upper figure: low pitch I_P/B_T = 0.8 MA/ 5.5 kG (31°)
  - Lower figure: high pitch I_P/B_T = 1 MA / 4.5 kG (42°)
- Can sweep RF spiral across diagnostics by changing the field pitch

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

R.J. Perkins et al., Physical Review Letters ***109 (2012) 045001***

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

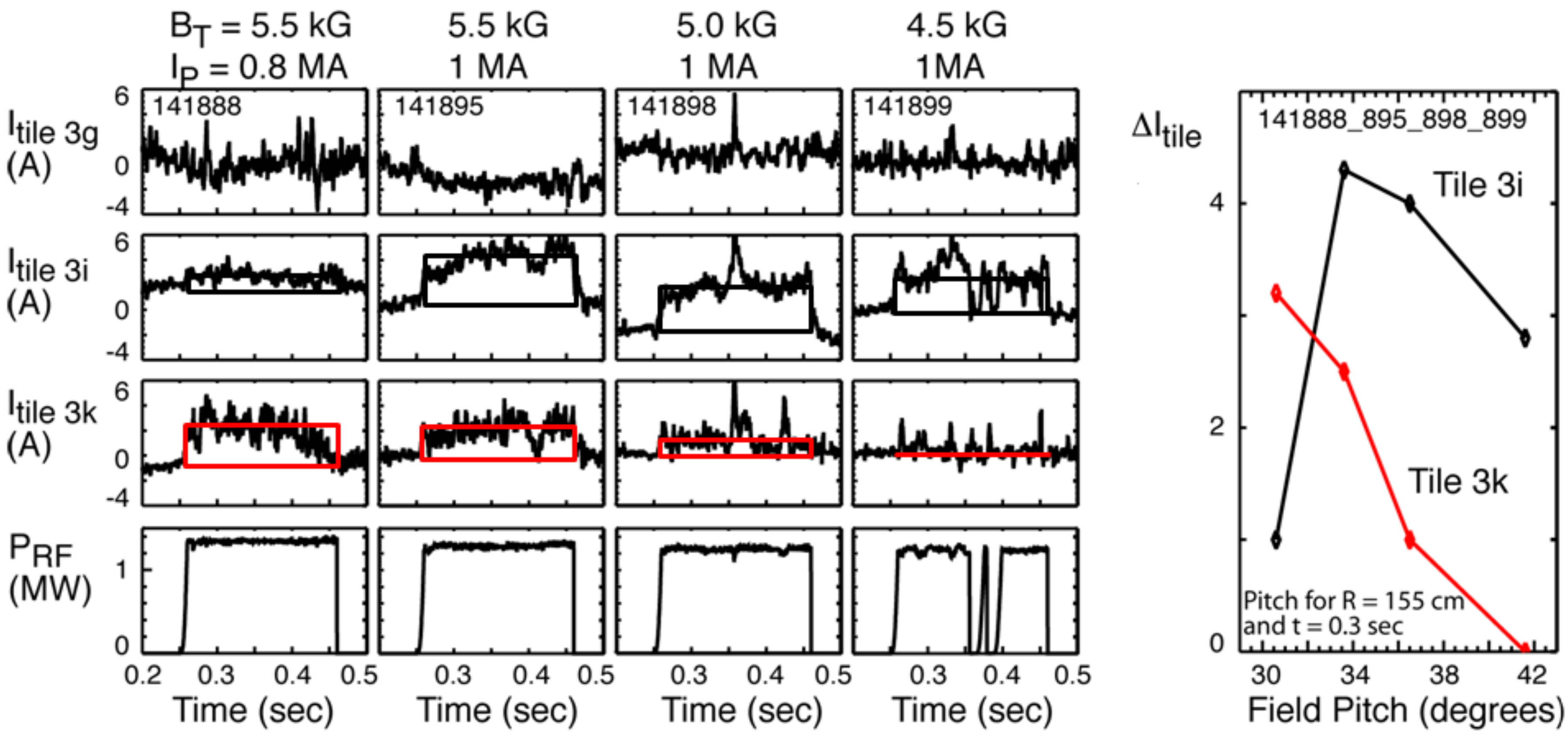




- Probe array embedded in divertor floor at Bay B
- RF-induced effects are localized
- Probe P4 floating potential responds strongly to RF at high pitch
- Probe P2, 6 cm inboard, has a much weaker response

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

Current-sensor tiles track movement of RF spiral

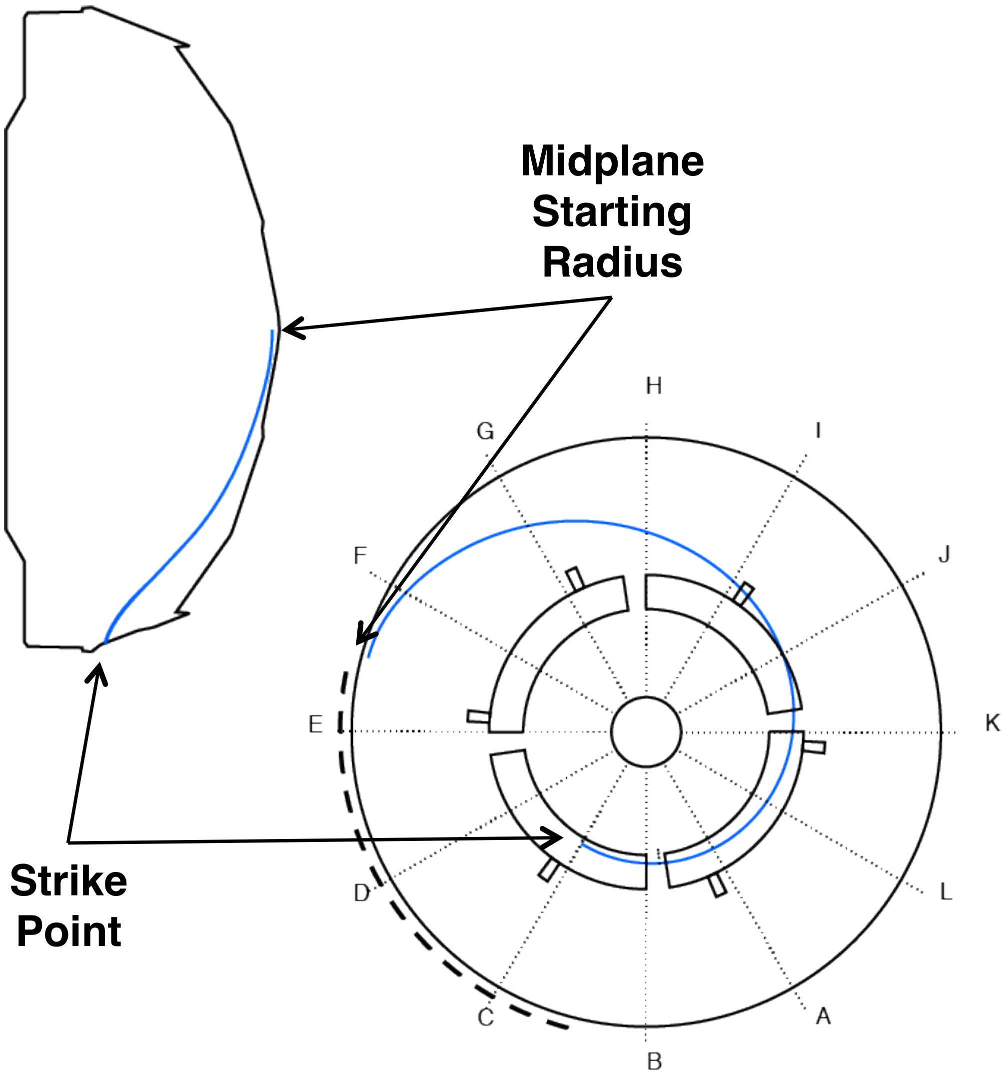


(k_ϕ =-8 m^{-1}/ϕ_{Ant} =-90°, D_2, P_{NB} = 2 MW)

- 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.

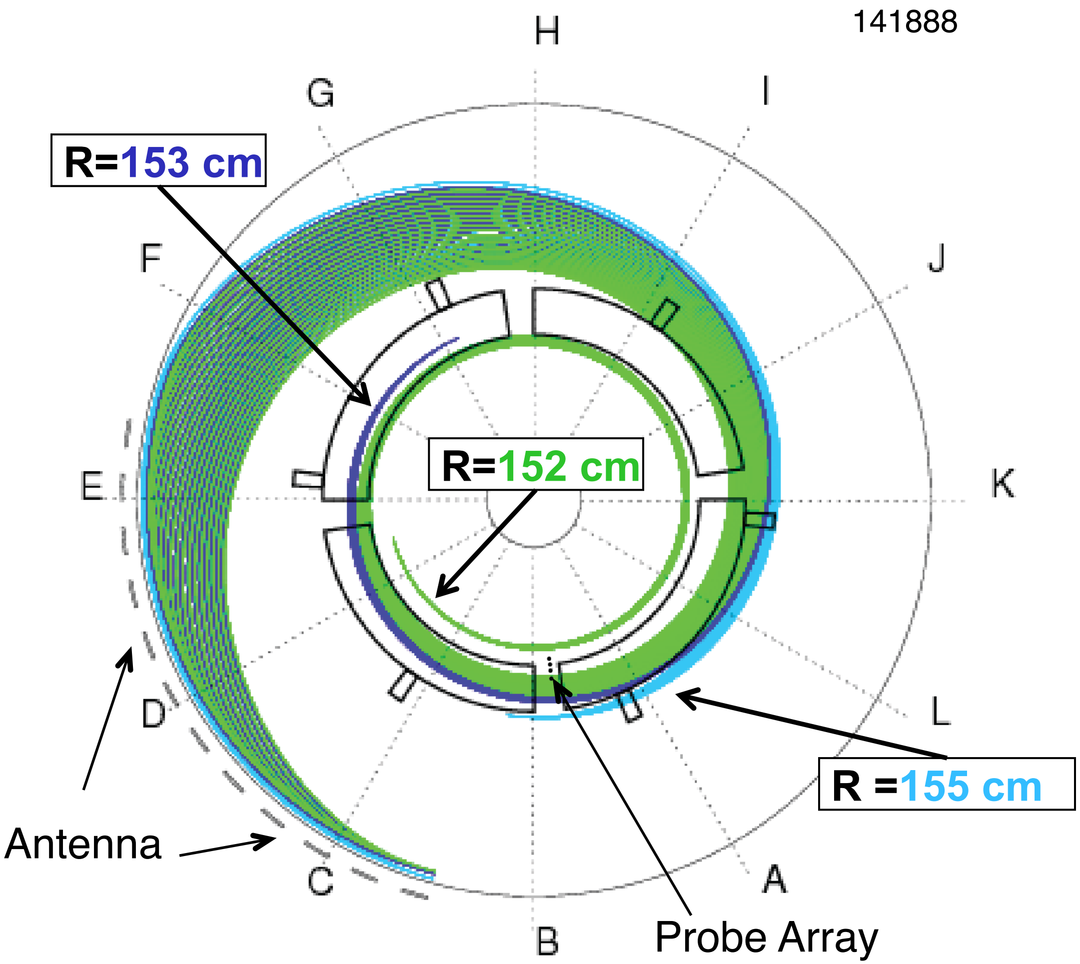
Field-line mapping shows path of lost HHFW power from antenna to divertor



- Follow field lines using SPIRAL code
  - SPIRAL is a full-orbit code
  - Particle orbits closely follow field lines
  - Only using field-line tracing ability of SPIRAL
- Start field lines at midplane between antenna and LCFS
- Track field lines until they strike divertor

G.J. Kramer et al., 22 IAEA Fusion Energy Conference (Geneva, 2008) CD-ROM file IT/P6-3, and G.J. Kramer et al., submitted to Plasma Physics and Controlled Fusion (2012)

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

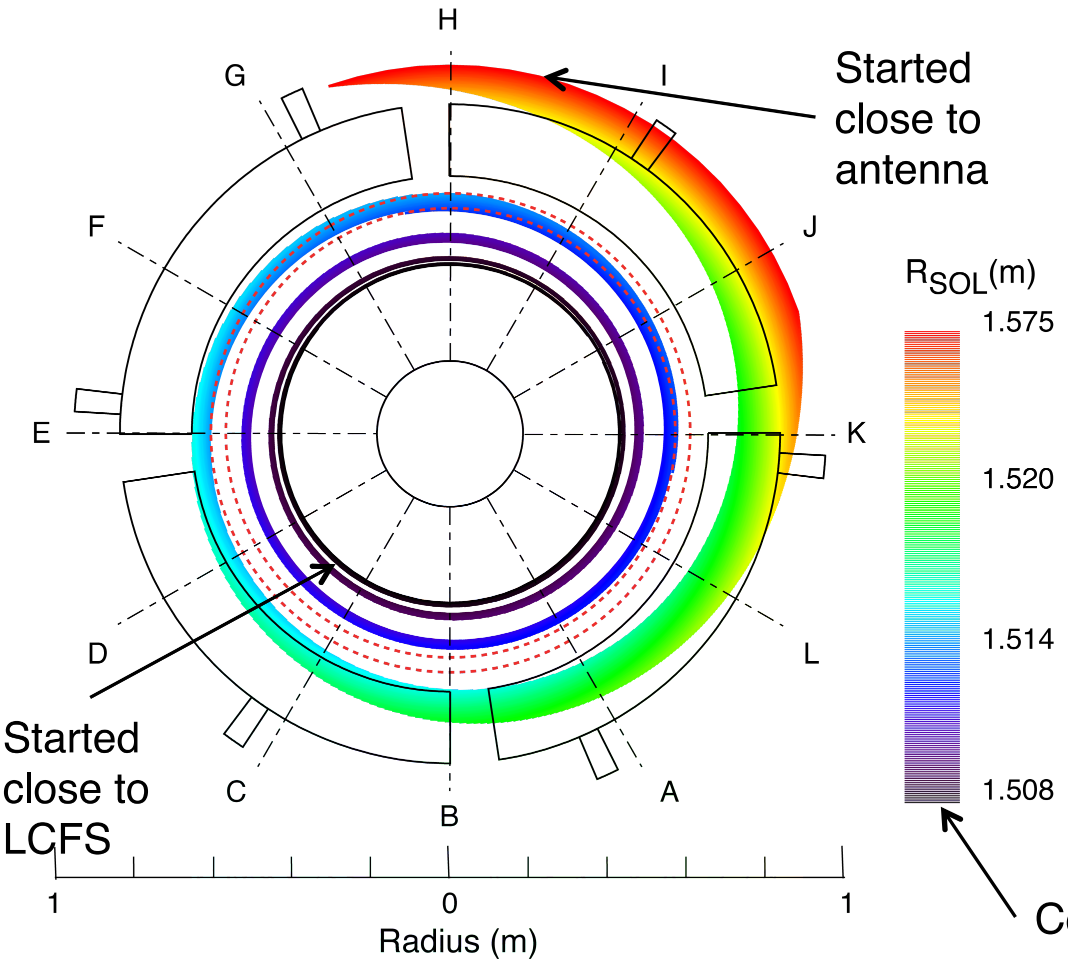


At midplane: R_{ANT} = 157.5 cm
R_{LCFS} = 151 cm

- Three sets of field lines plotted
  - Colors denote different starting radii at midplane
  - Each set has 90° span (same as antenna)
- Field lines spiral and focus radially around the center column
  - Resembles camera images
- Field lines started farther from antenna spiral in more
- Field lines to probe come from 153 cm, well away from the antenna

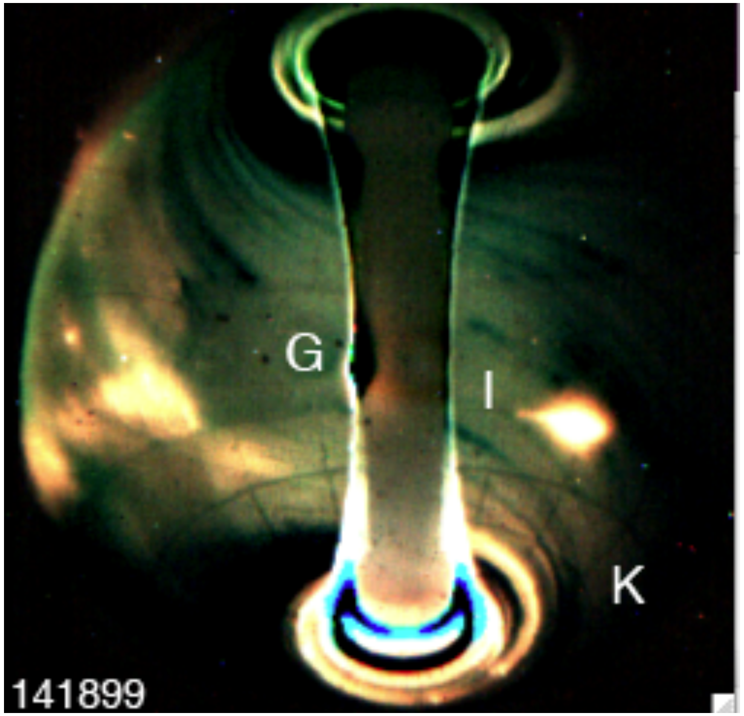
Calculated strike points on divertor form a spiral that closely matches the observed RF spiral

Strike points for field lines started at across entire SOL midplane…

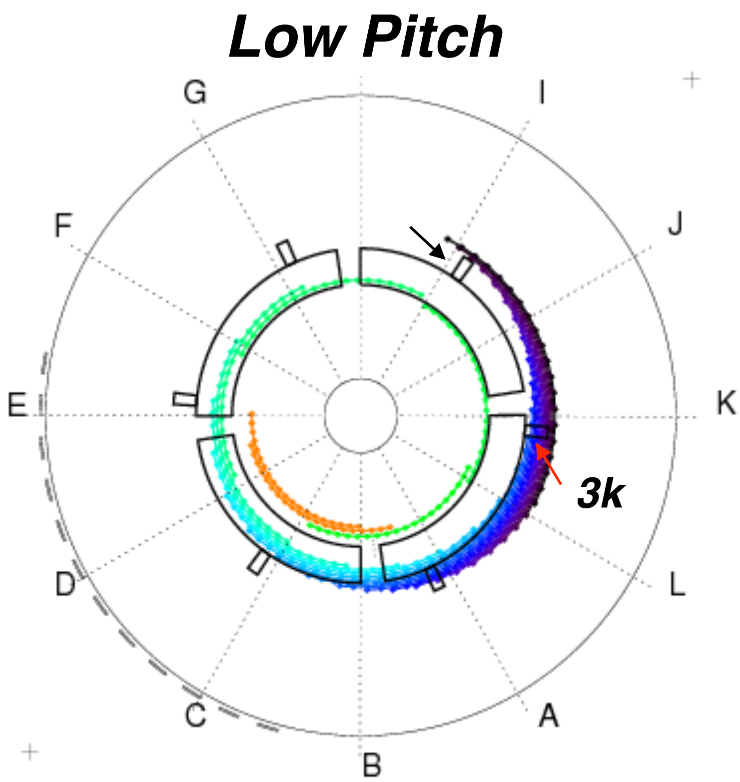


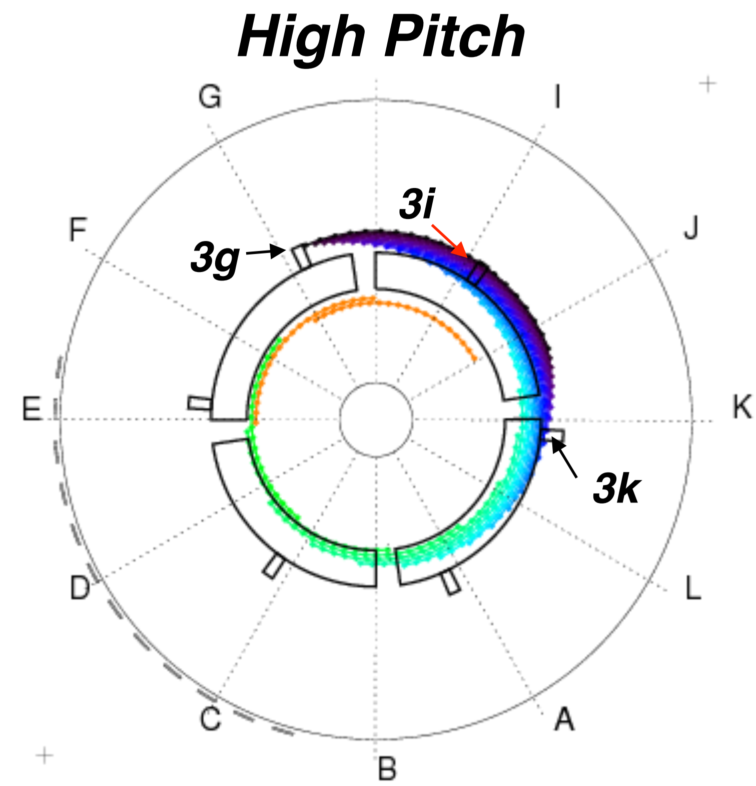
Colors indicate starting radius at midplane

… create spiral pattern close to camera images when all SOL field lines are included.



Computed strike points move with pitch as seen in camera images

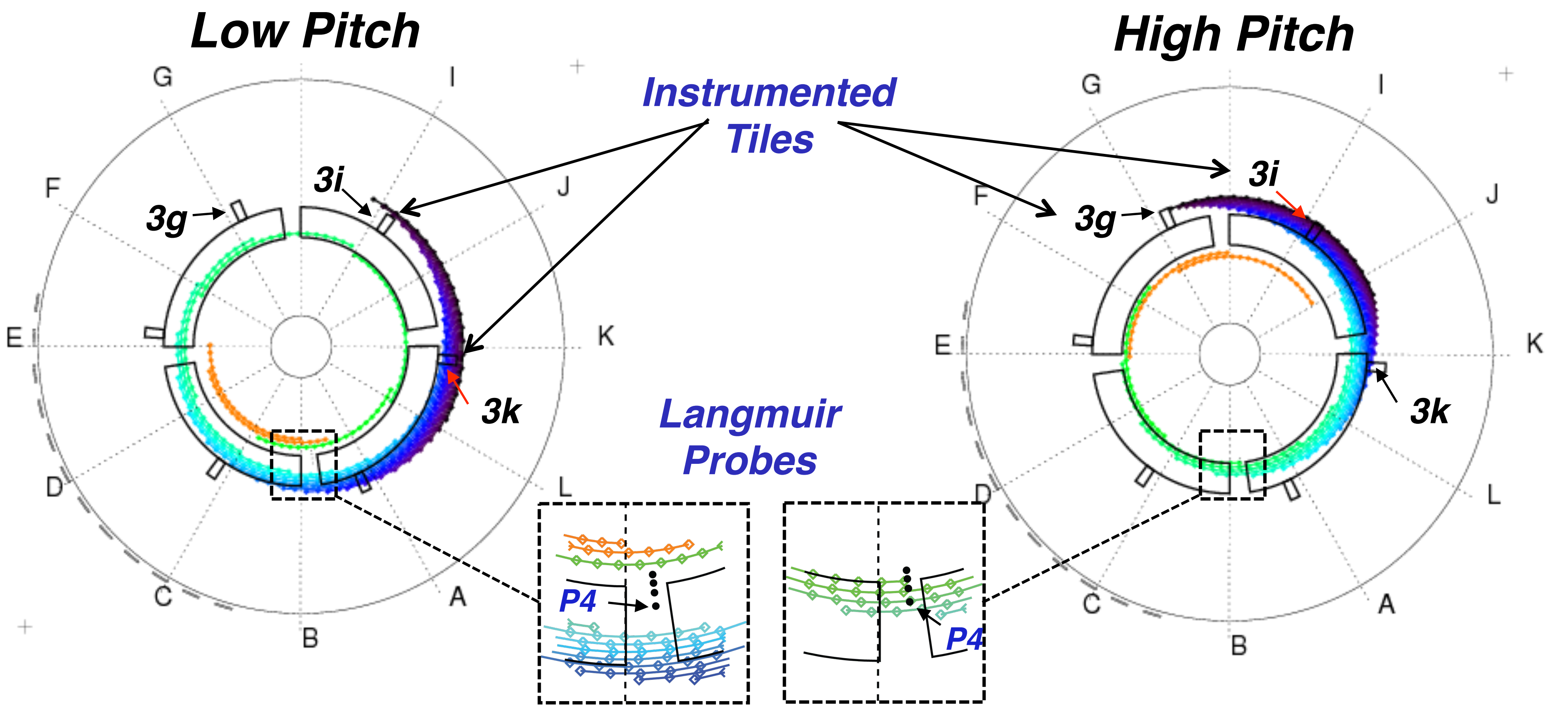




- Strike points move in agreement with camera images
- Strike points reveal that spiral motion is a rotation due to changing field pitch

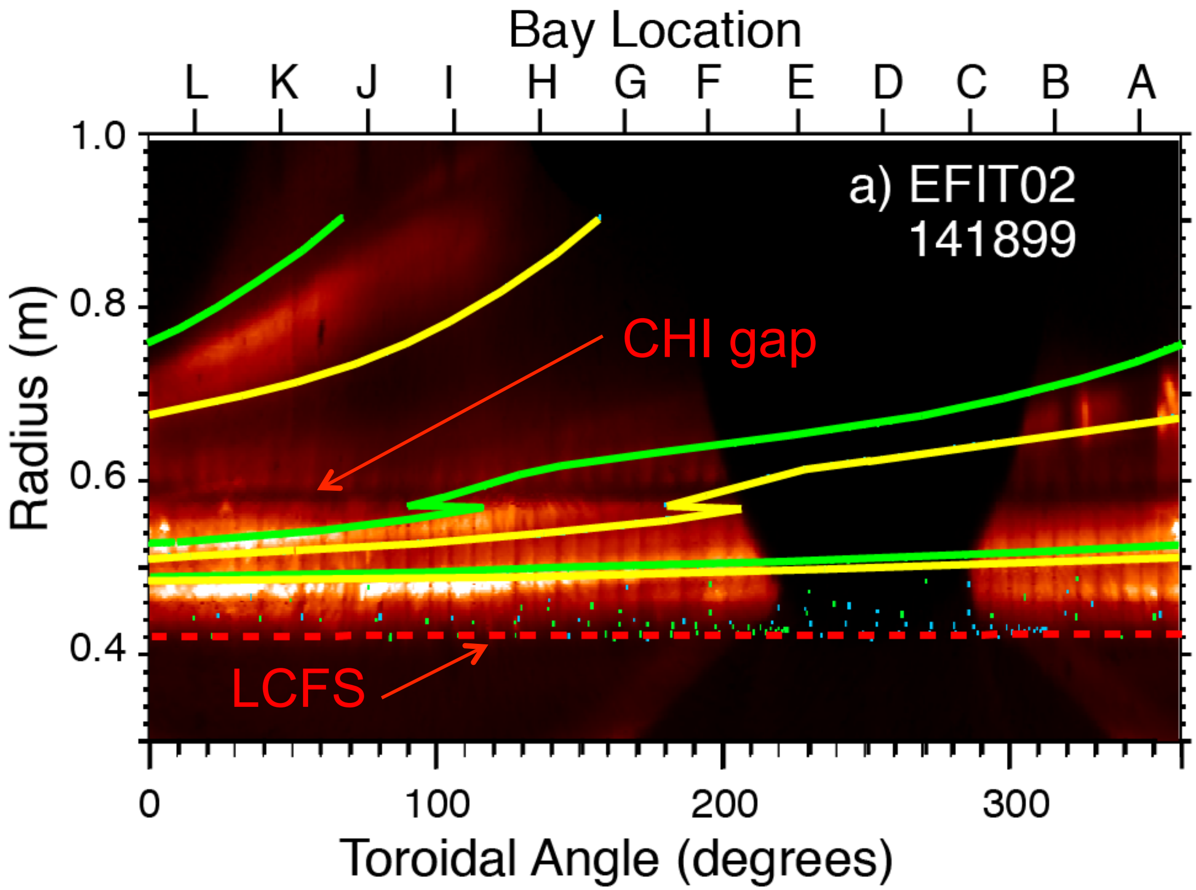
<u>NOTE</u>: Coloring scheme differs from previous slide

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

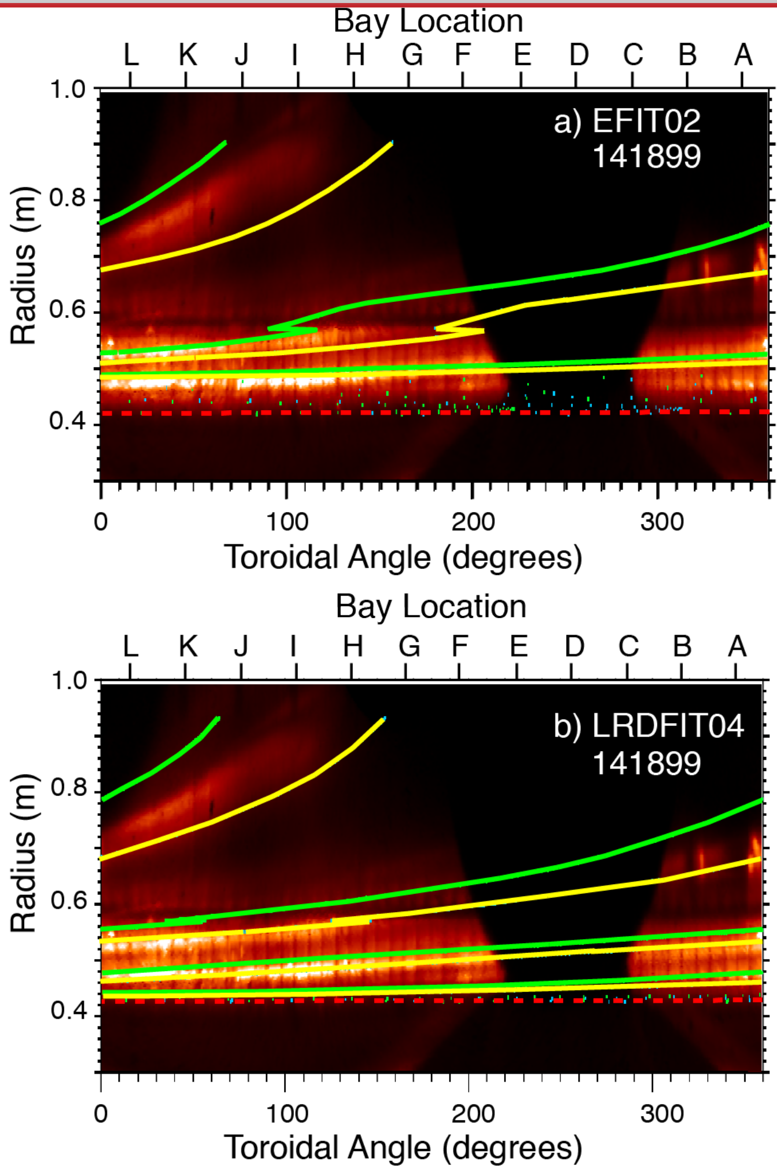
Optical divertor camera agrees with SPIRAL strike points until close to LCFS for EFIT02 Equilibrium



- Camera image of divertor Li I emission
  - Li from sputtering
  - Enhanced via RF-driven sheaths or particle flux
- Camera data agree with strike points until close to the LCFS
  - Jagged portion due to CHI gap
  - EFIT02 equilibrium fit

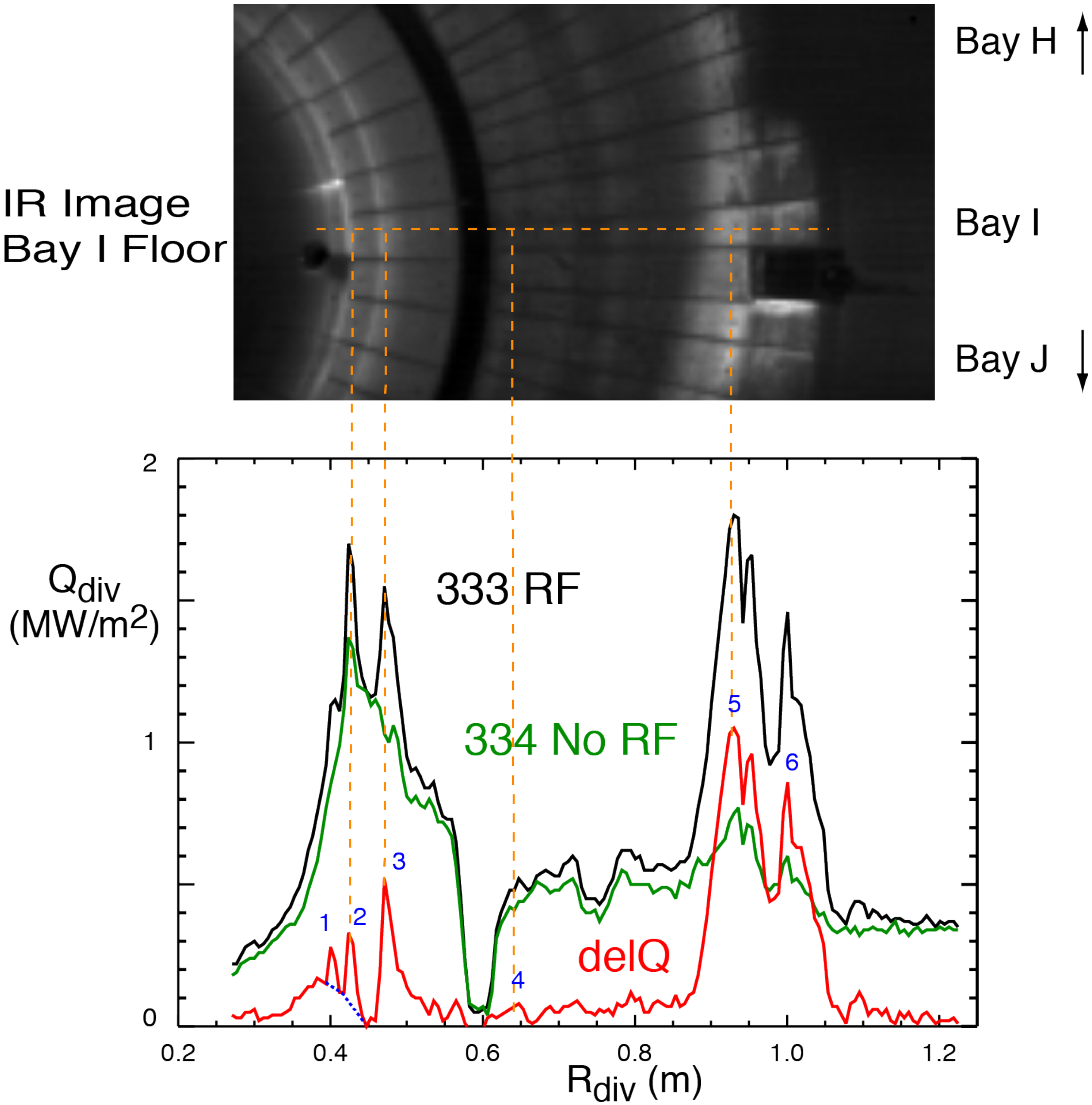
- Green strike points from right antenna edge
- Yellow strike points from left edge
- Black portion due to inversion (hidden by center column)

Field-line mapping agreements is robust even with different equilibrium fits



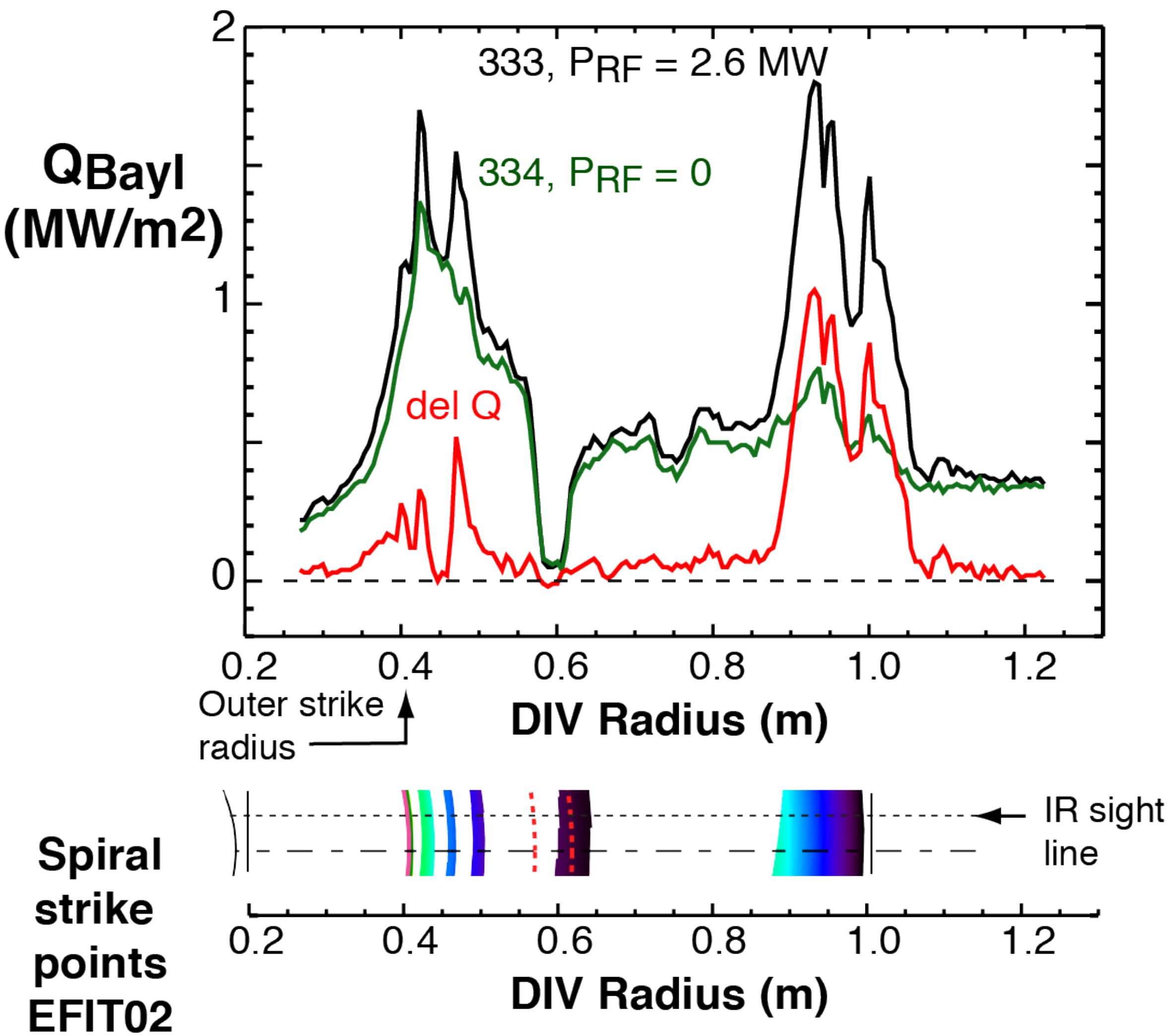
- Top figure: EFIT02
  - Fits RF spiral very well at outer radii and just inside CHI gap
  - Eventually deviates at radii approching the outer vessel strike radius
- Bottom figure: LRDFIT04
  - Does not fit the RF spiral as well as EFIT02 at larger radii
  - Fits better than EFIT02 at smaller radii
- Both equilibrium fits produce strike poitns that generally match spiral
  - Small changes between fits do not alter main conclusions
  - They do put a limit on equilibrium accuracy

Divertor IR cameras measure strong RF-induced divertor heating



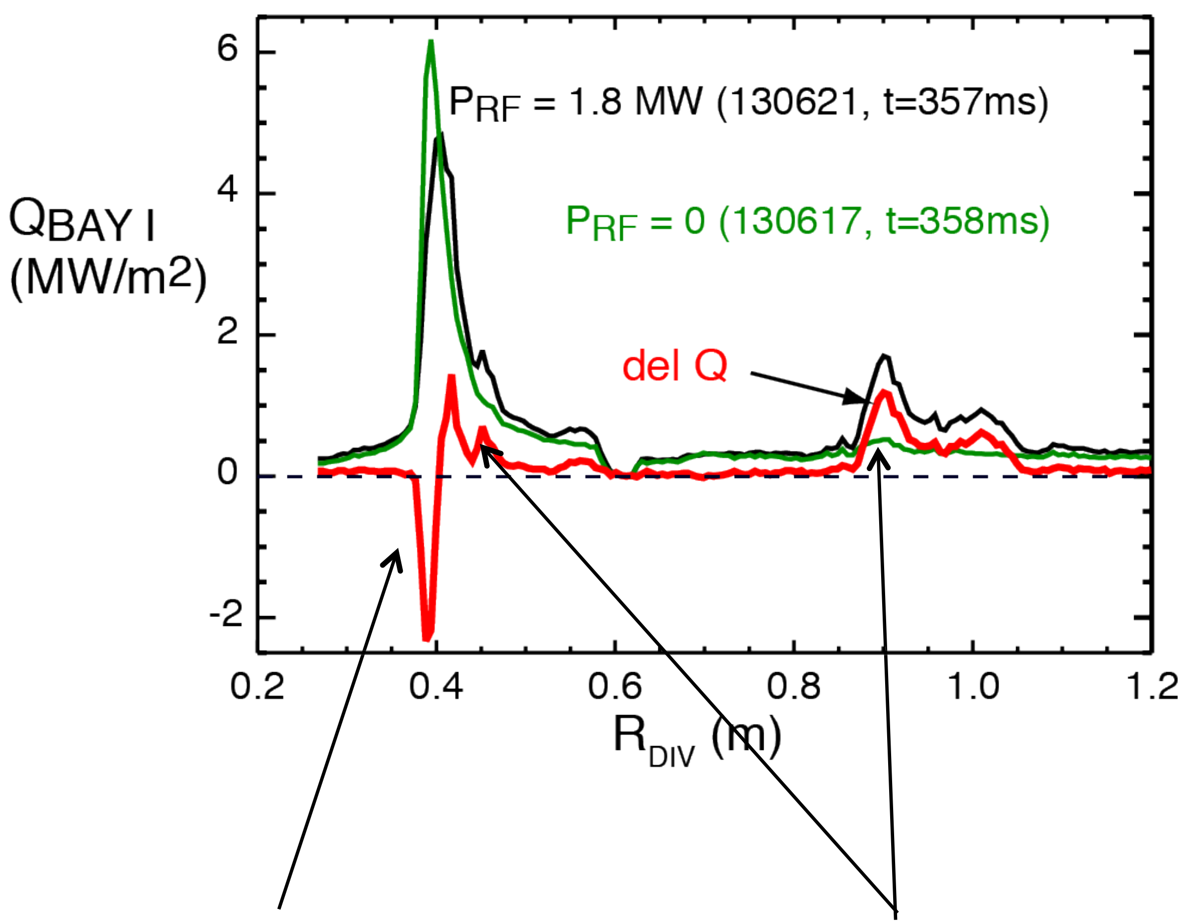
- RF spiral seen in IR image
  - Heat profile taken along near-radial horizontal line
- RF-induced divertor heating (del Q) in red
  - Shot 135333 with 2.6 MW RF (ELMy H-mode)
  - Shot 135334 no RF
  - Difference gives RF heat
- Several RF-induced heat peaks clearly resolved

RF-induced heat peak on lower divertor agree with SPIRAL strike points at Bay I



- Outer RF heat peak coincides with first computed spiral pass
- Second pass of spiral has weak heat deposition
  - However, second pass heating seen on other shots
- Several heat peaks seen at small R_{DIV} near LCFS
  - Computed spiral also makes several passes there
  - Exact positions depend on equilibrium fit (next slide)

ELM-free discharge has negative dip in RF-induced heat flux

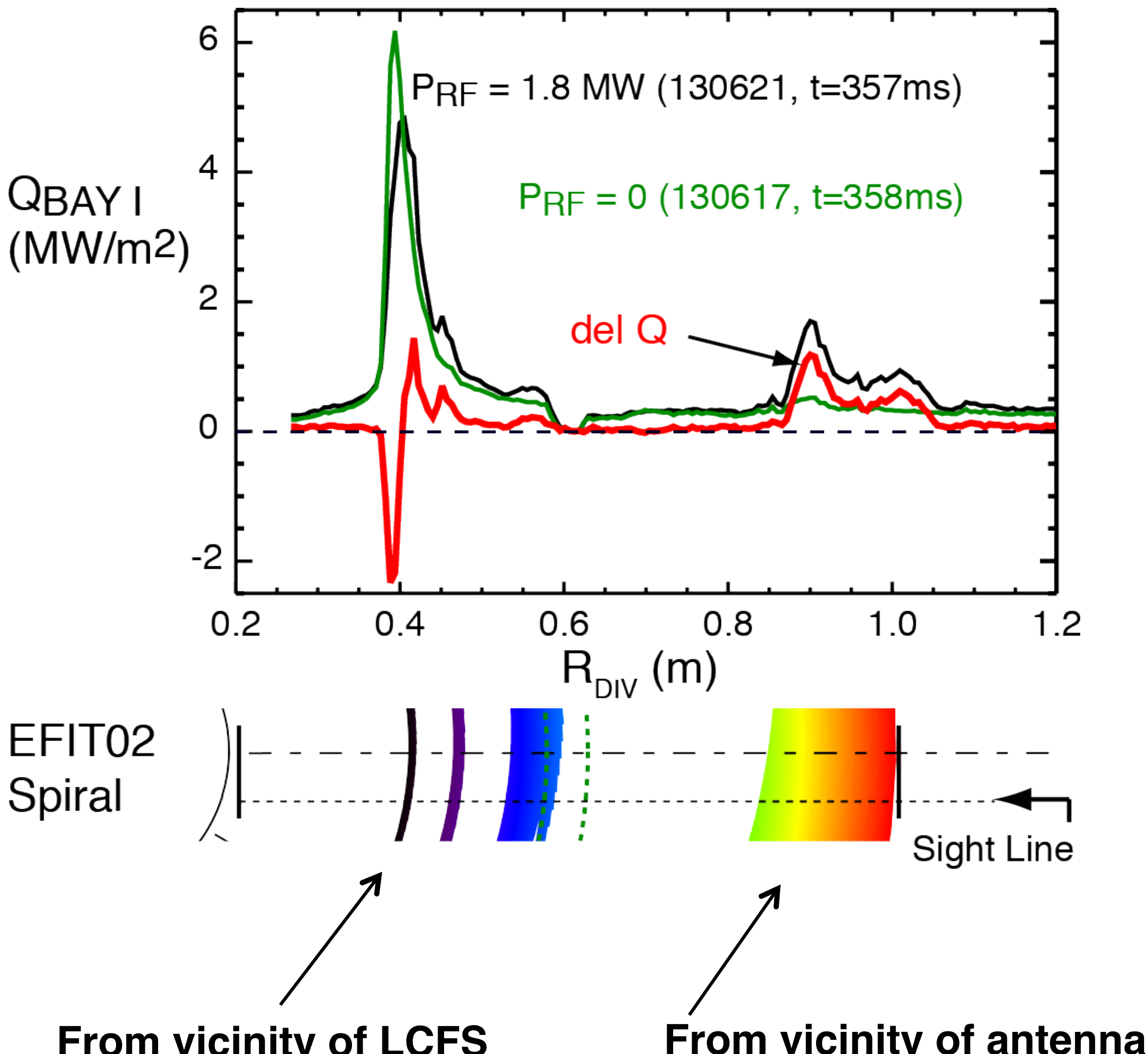


Negative dip in del Q due just outside outer vessel strike radius

Heat peaks caused by *direct* RF heating of divertor along SOL field lines

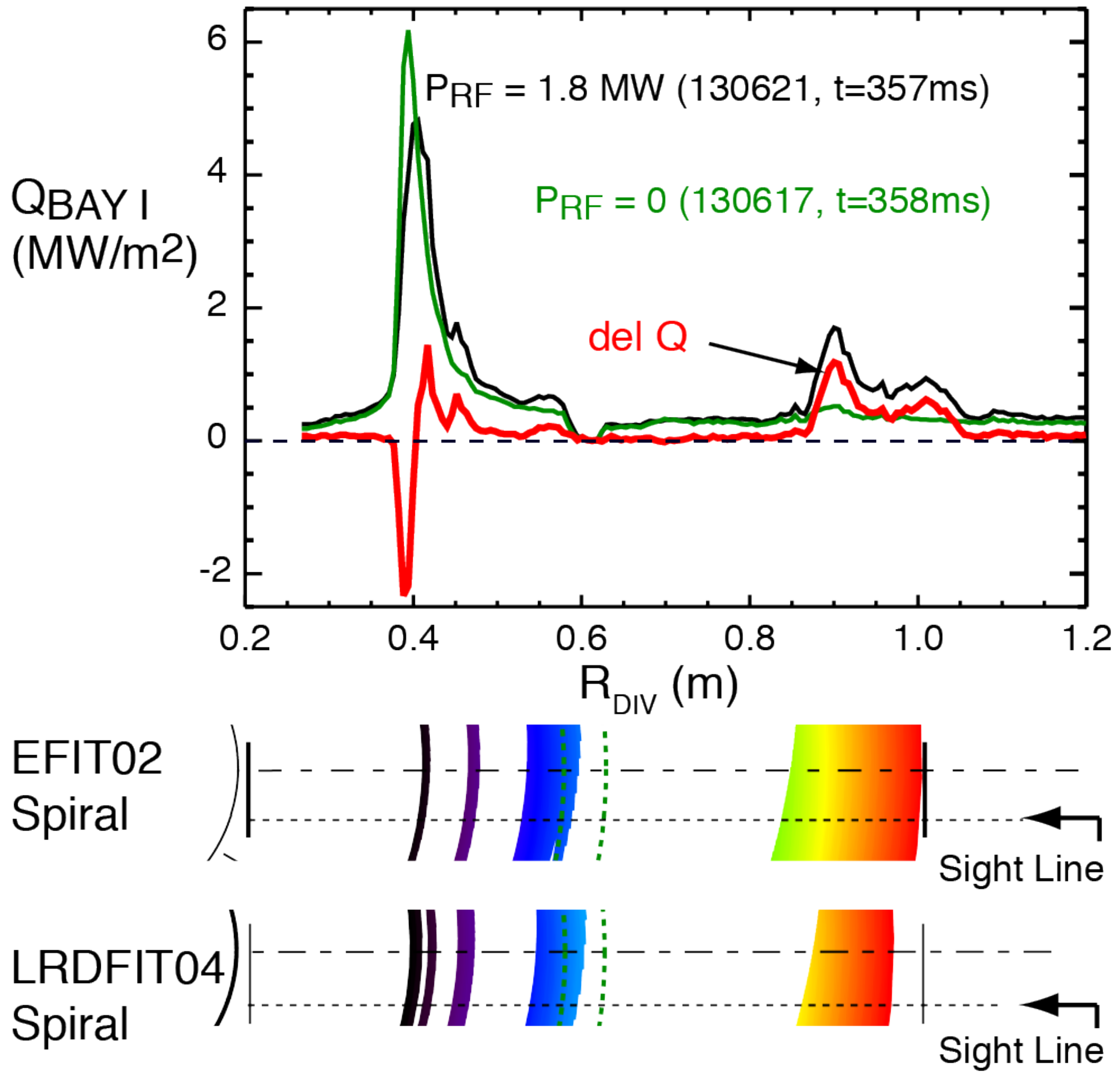
- Negative dip in del Q near outer vessel strike radius
- Due to change in plasma exhaust that prevents resolution of RF heat peaks near outer vessel strike radius
  - ELM-free shot (130621) has lower edge density
    - Less edge loss leads to more core heating & exhaust
  - ELMy shot (135333, prev. slide) has higher edge n_e, stronger edge loss, weak core heating

IR data for ELM-free shot agrees with SPIRAL strike points



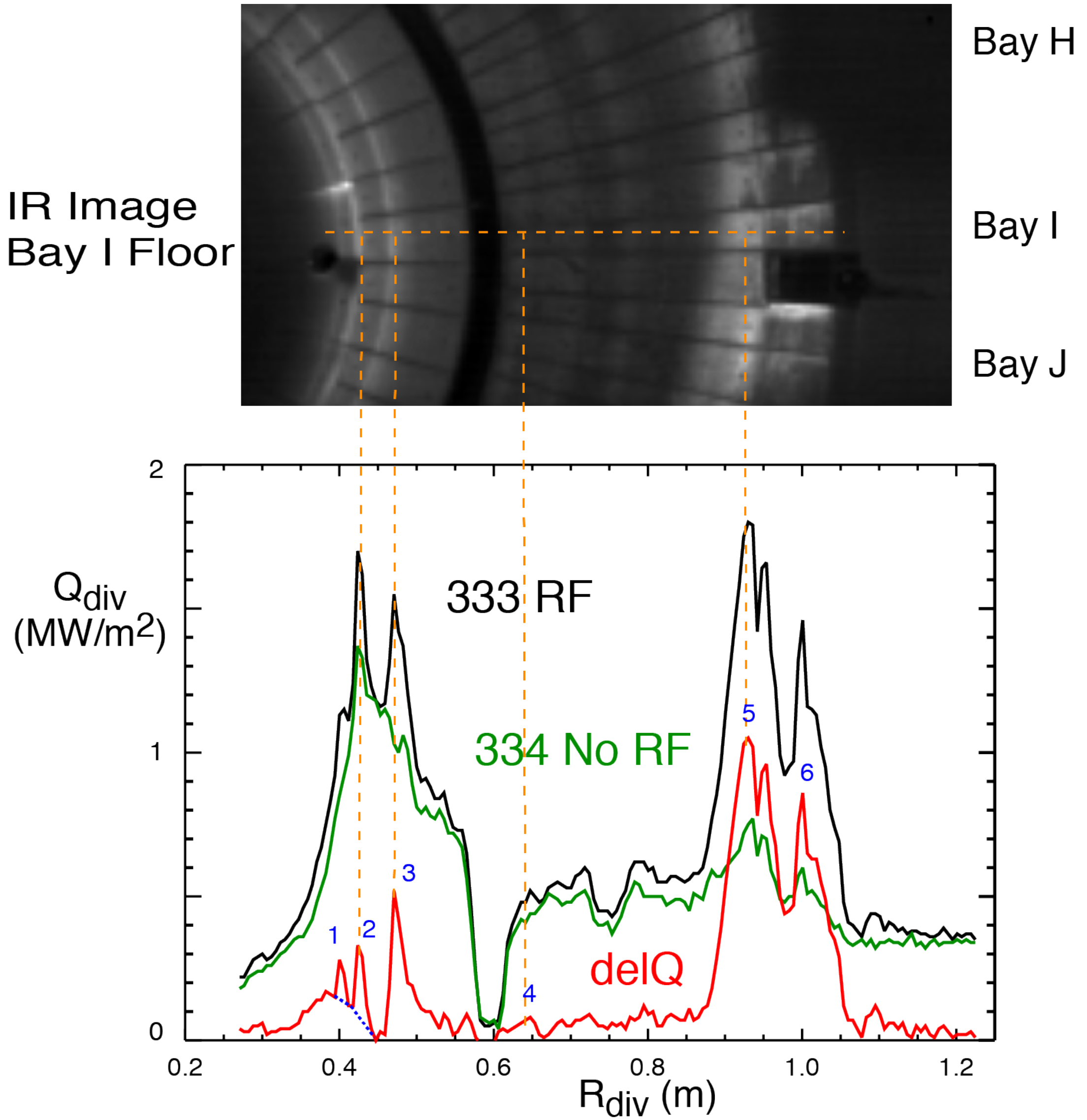
- RF pulse heats divertor in several locations
- Measured radii of deposited heat coincide well with strike-point radii computed by SPIRAL
- Negative dip obscures RF heat peak nearest outer vessel strike radius

Differences in equilbrium fits shift strike points slightly but do not change conclusion



- Strike points shift slightly at Bay I by using LRDFIT04 instead of EFIT02
- However, alignment of heat peaks with calculated strike points is quite good in both cases

Radial profile of HHFW power coupled to SOL field lines and lost to divertor



- Map divertor IR data back to antenna midplane along field lines
- Can only map peaks of heat flux to midplane
  - IR data obtained at Bay I
  - Cannot recreate entire coupling profile (would need data from around the torus)
- Must factor in flux expansion (next slide)

Flux expansion needed to map RF divertor heat flux back to its origin at antenna midplane

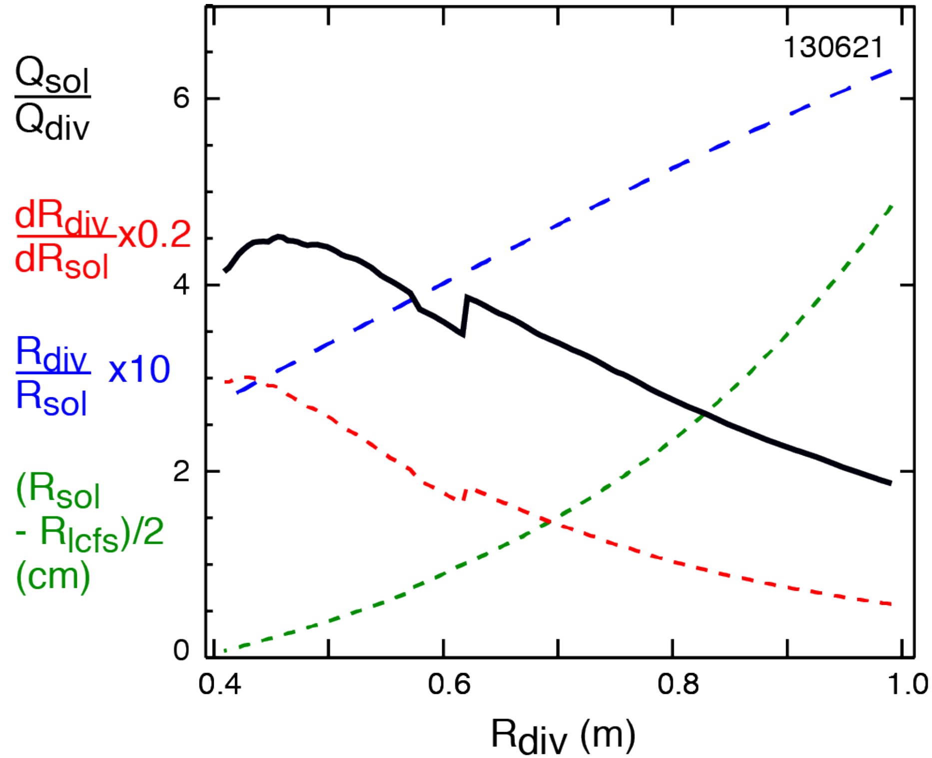
- RF divertor heat flux, Q_{div}, measured with IR cameras
- HHFW power coupled, Q_{SOL}
- Consider differential surface element in divertor and its image at midplane under mapping:

$$Q_{SOL} R_{SOL} d\varphi dR_{SOL} = Q_{div} R_{div} d\varphi dR_{div}$$

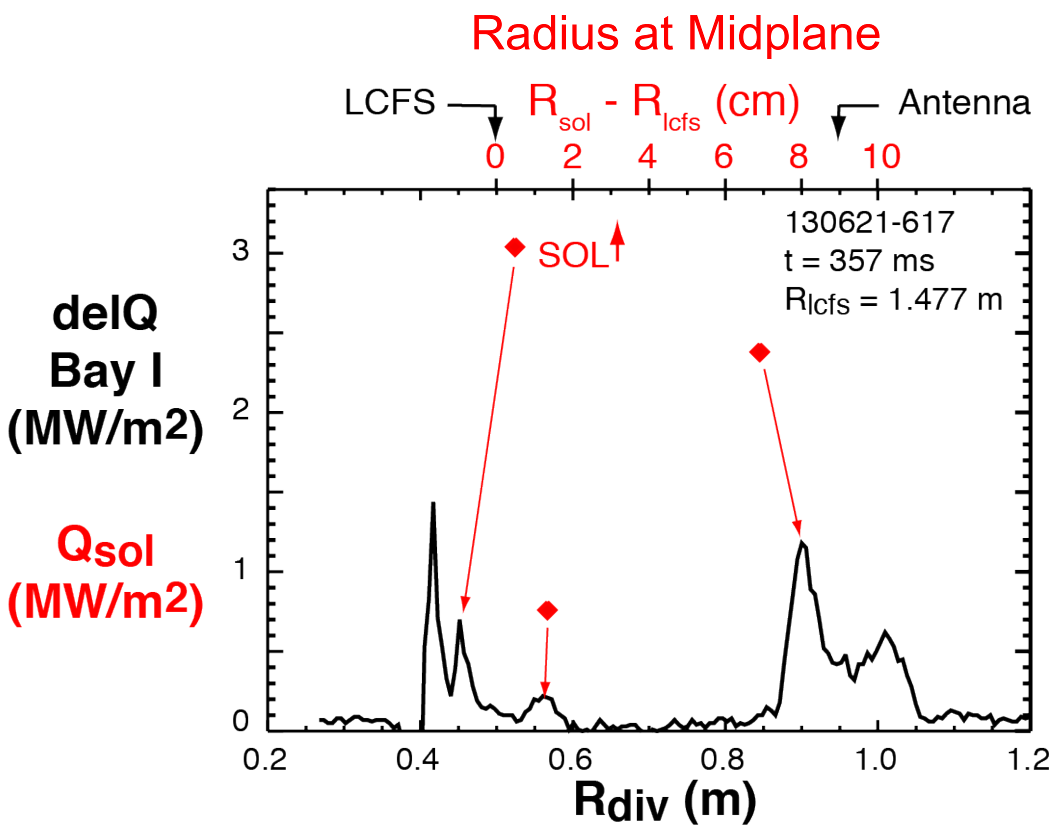
- It follows that

$$Q_{SOL} = Q_{div} \frac{R_{div}}{R_{SOL}} \frac{dR_{div}}{dR_{SOL}}$$

- Use this computed factor Q_{SOL}/Q_{div} to convert Q_{div} to Q_{SOL}

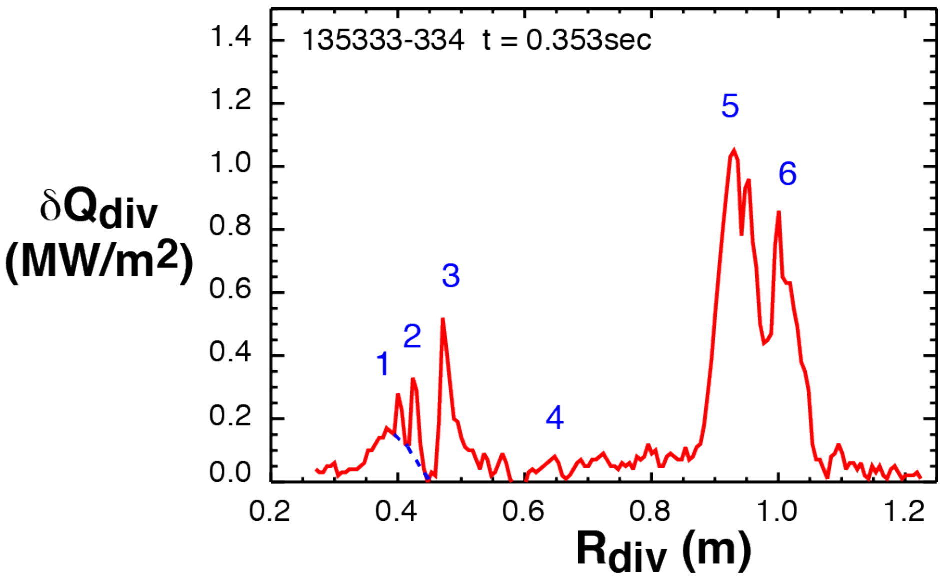


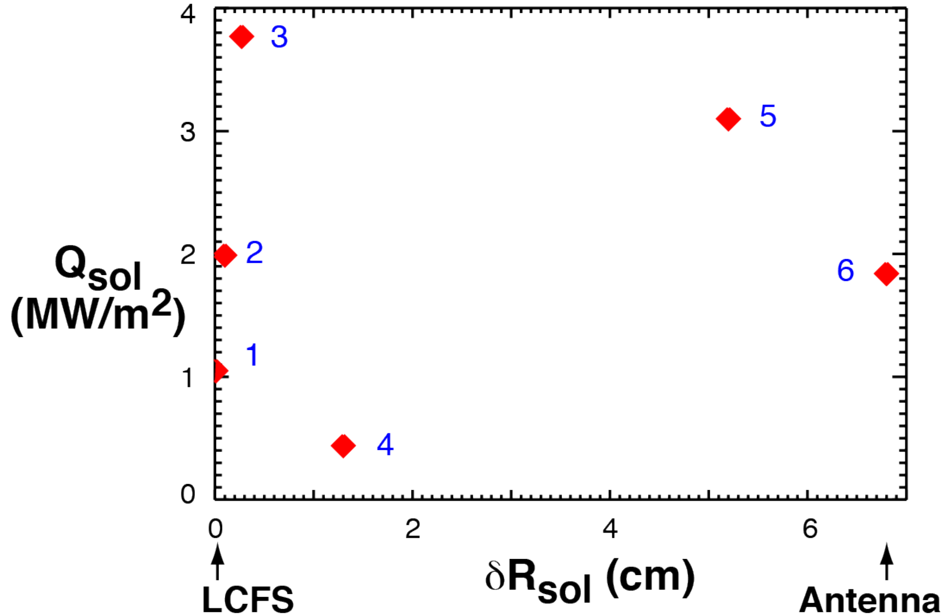
Midplane coupling profile Q_{sol} (MW/m^2) peaks near antenna and LCFS in ELM-free case



- HHFW power couples strongly to field lines close to antenna and LCFS
    - Underlying mechanism cannot be localized to antenna
- Power loss coupled to SOL relatively weak in between
    - Suggests a radial standing wave pattern

Midplane coupling profile for ELMy case (135333) has similar structure – peaks resolved to LCFS





- Midplane profile contains similar structure:
  - Peaking of power coupled close to antenna and LCFS
  - Relatively low coupling in between
- Increased resolution near LCFS shows mid-plane peak ~ 2 mm from LCFS, whereas the outer peak is ~ 1.7 cm from the antenna

Summary

- HHFW power flow in the SOL to the divertor is along field lines in NSTX
  - Good agreement between diagnostic measurements and field-line mapping
- This HHFW power couples to all SOL field lines in SOL in front of the antenna
  - Losses are not isolated to field lines connected to antenna
- The mid-plane HHFW power coupling profile for this SOL power loss is obtained
  - Losses are not isolated to field lines connected to antenna
  - Power couples strongly to field lines near antenna and LCFS
  - Power couples weakly in between for ELMy and ELM-free cases studied
- Results suggestive of fast-wave propagation in SOL
  - Losses occur across width of SOL with profile suggestive of a radial standing wave
  - Direct measurements of RF fields will be needed to confirm this