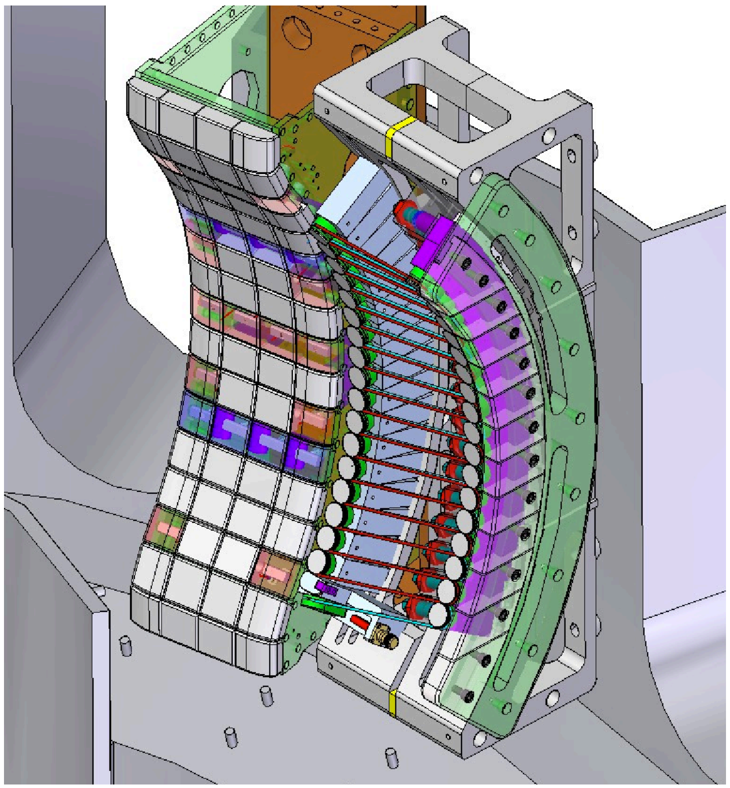
Alcator C-Mod Shoelace Antenna System

for active probing of boundary plasma turbulence



Background
Shoelace Antenna
Excitation of Drift-Alfven Wave

B. LaBombard, T. Golfinopoulos*
R. Parker, W. Burke
and Shoelace Antenna Team

*PhD thesis topic

Alcator C-Mod

PPPL - May 24, 2013

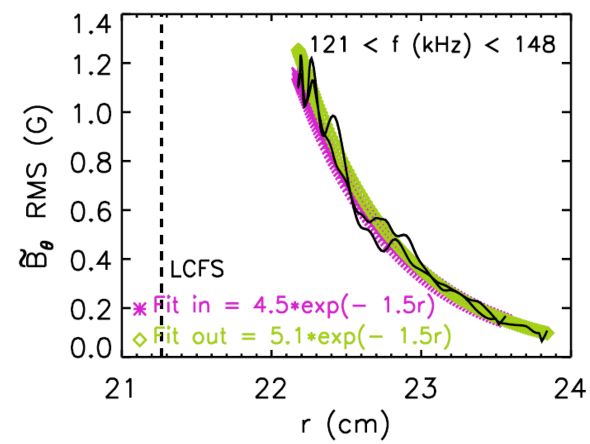
Background: High k_θ Drift-Alfvenic turbulence plays key role in boundary layer transport

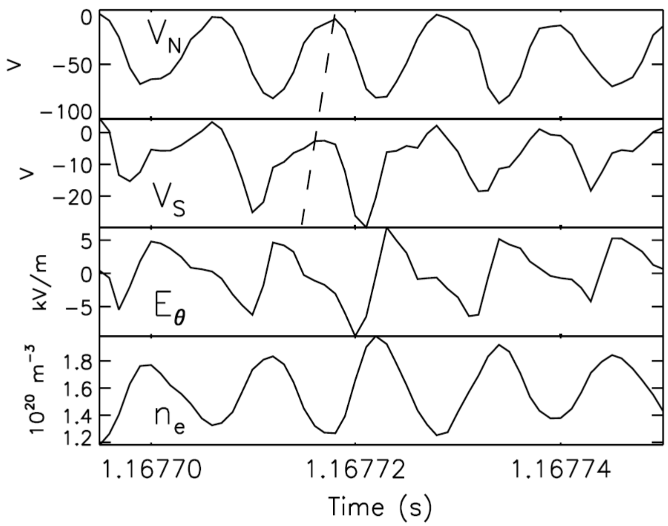
Profiles -
Pressure gradients are 'clamped' to canonical α_{mhd} ~ 1 (L-mode), ~ 7 (H-mode)

Fluctuations -
L-mode: broad-band $\tilde{B}_\theta$ observed

H-mode: QCM with clear $\tilde{B}_\theta$ signature

Data from magnetic probe [Snipes *et al.*, 2001]





Probe data: QCM (and broad-band turbulence) drives significant <n Vr> flux…

QCM is very important for C-Mod because it arrests impurity accumulation in H-modes (EDA).

We desire a 'knob' to turn up broad-band boundary layer EM turbulence and/or QCM phenomena, both to study it and to exploit it:
control pedestal gradients, core impurity levels, SOL heat flux footprints, …

Idea: Build a 'QCM' antenna' to excite boundary layer EM turbulence

Background: High k_θ Drift-Alfvenic turbulence plays key role in boundary layer transport

Profiles -

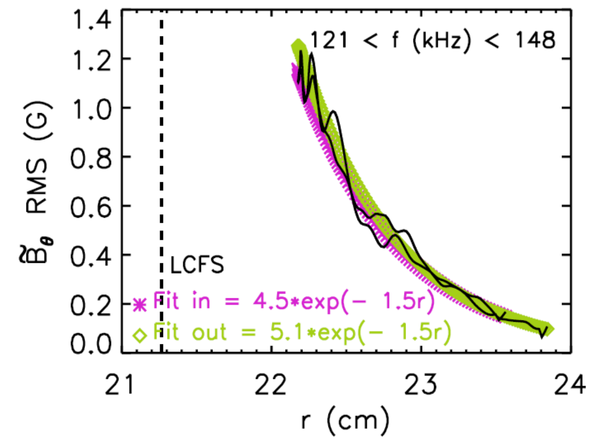
Pressure gradients are 'clamped' to canonical α_{mhd} ~ 1 (L-mode), ~ 7 (H-mode)

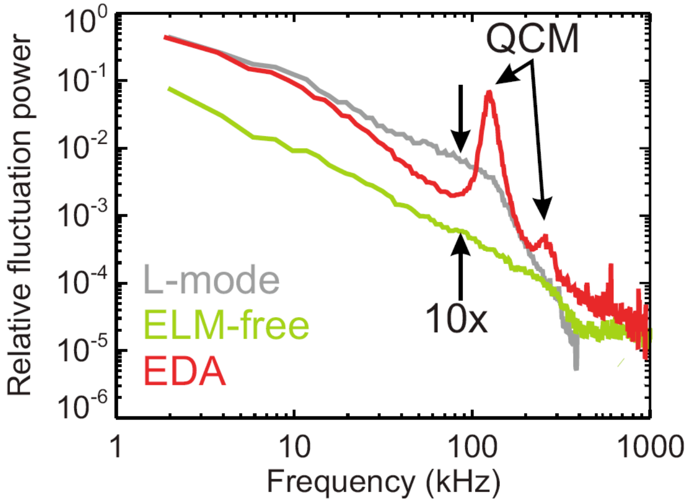
Fluctuations -

L-mode: broad-band $\tilde{B}_\theta$ observed

H-mode: QCM with clear $\tilde{B}_\theta$ signature

Data from magnetic probe [Snipes *et al.*, 2001]





[Cziegler *et al.*, PoP 2010]

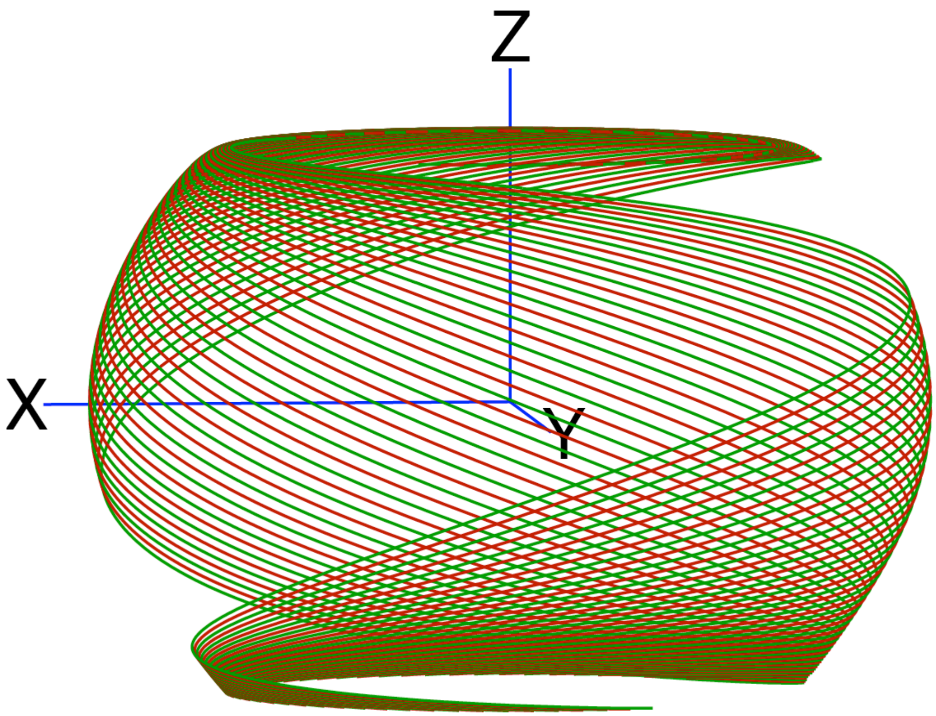
GPI data: Activity at QCM frequencies is a prominent feature in power spectra

QCM is very important for C-Mod because it arrests impurity accumulation in H-modes (EDA).

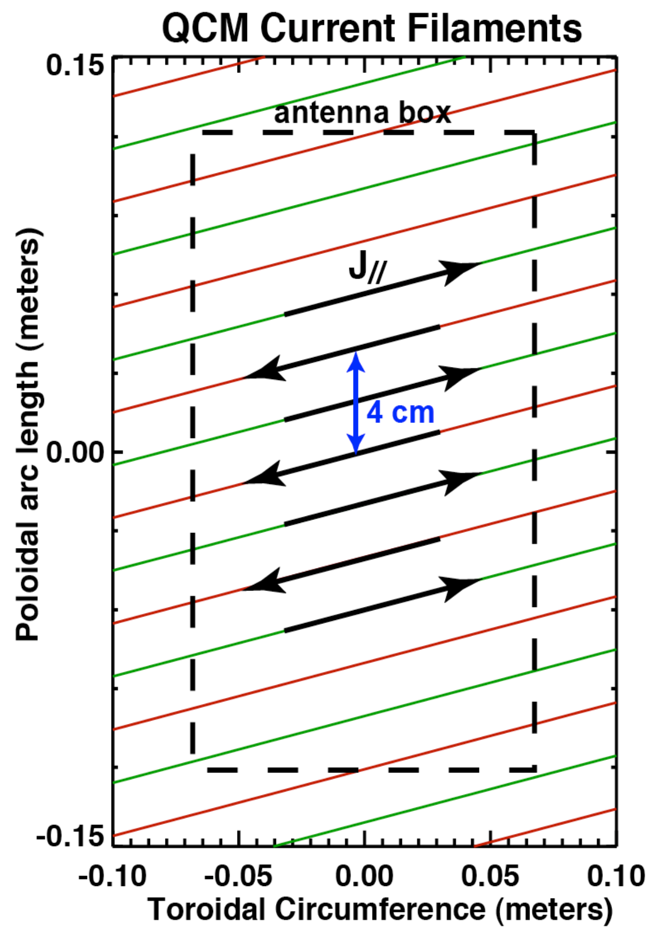
We desire a 'knob' to turn up broad-band boundary layer EM turbulence and/or QCM phenomena, both to study it and to exploit it:
control pedestal gradients, core impurity levels, SOL heat flux footprints, …

Idea: Build a 'QCM' antenna' to excite boundary layer EM turbulence

Idea: Build an antenna to inductively couple with and reinforce $J_{//}$ filament structures at k_θ of QCM -- the most unstable and important k_θ in boundary layer turbulence



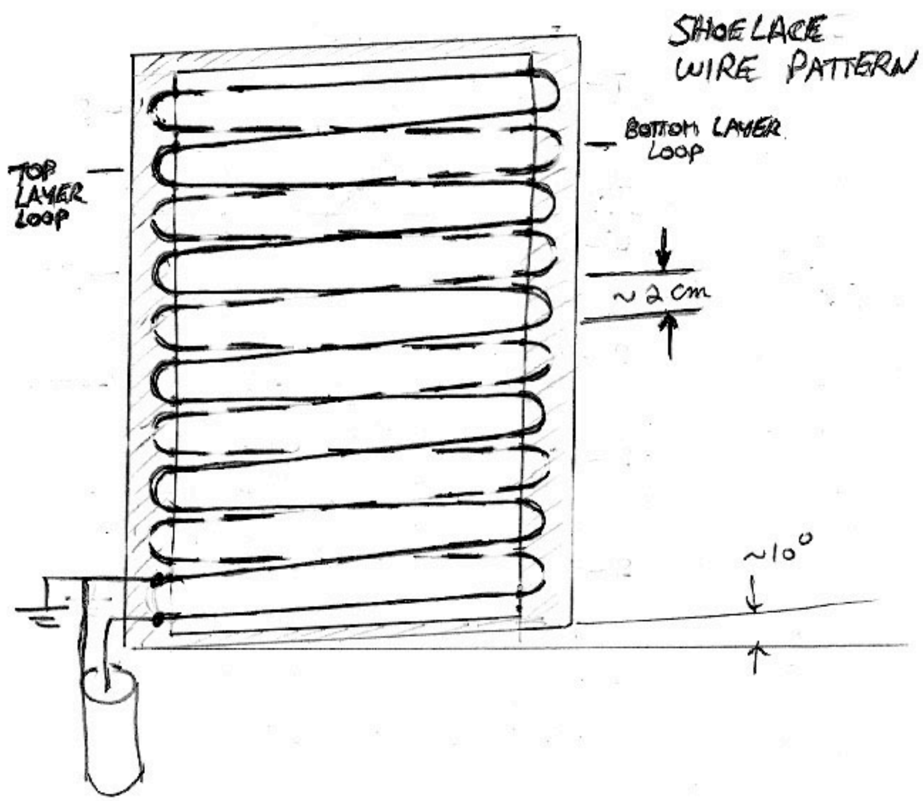
3D view of QCM $J_{//}$ filaments -- based on theory and consistent with measurements ($k_\theta \sim 1.5\ cm^{-1}$, $q_{95} \sim 3$)



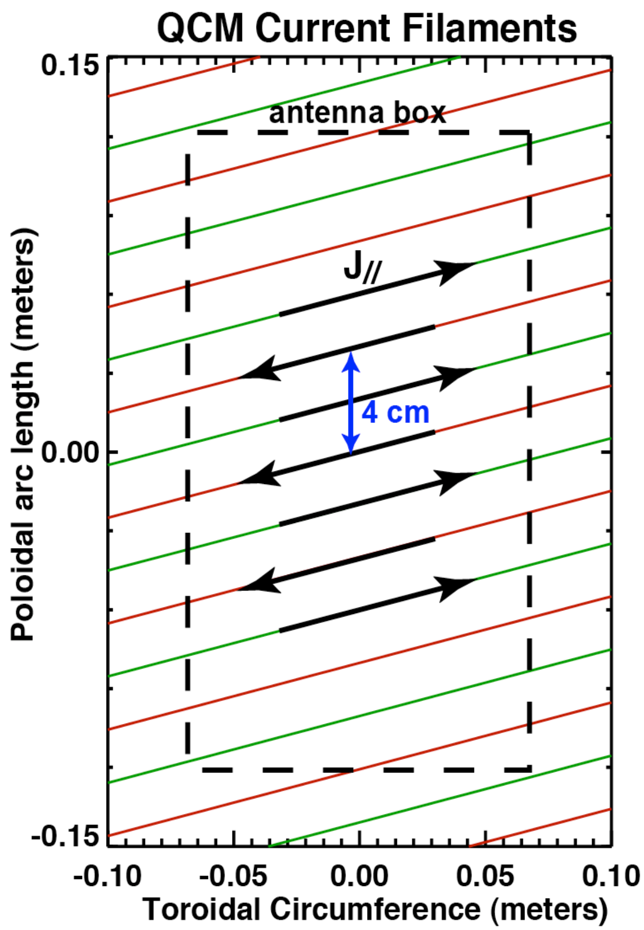
View of $J_{//}$ filaments passing in front of a possible 'antenna box' on outer midplane

Idea: Build an antenna to inductively couple with and reinforce $J_{//}$ filament structures at k_θ of QCM -- the most unstable and important k_θ in boundary layer turbulence

Design current pattern in antenna to mimic the QCM …



… and place it close to the QC mode layer.



View of $J_{//}$ filaments passing in front of a possible 'antenna box' on outer midplane

A simple 'shoelace' antenna made from moly wire can satisfy requirements.

<u>Idea</u>: Build an antenna to inductively couple with and reinforce $J_{//}$ filament structures at k_θ of QCM -- the most unstable and important k_θ in boundary layer turbulence

'Shoelace Antenna'

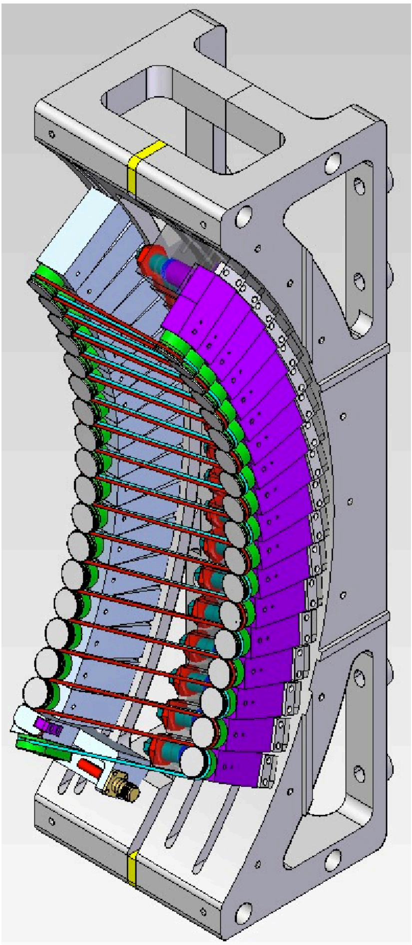
f = 50 – 300 kHz

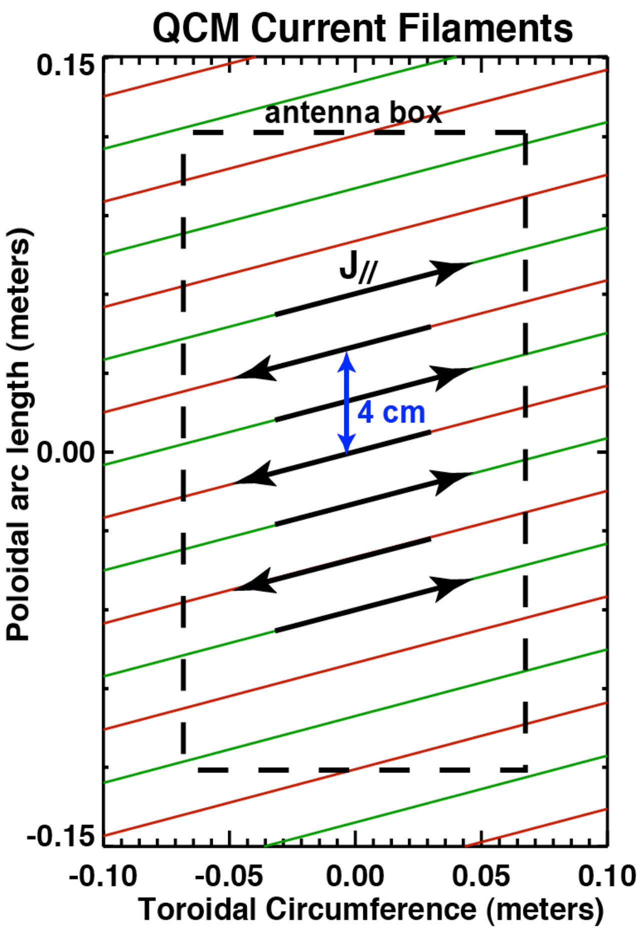
$k_\theta = 1.5\ cm^{-1}$

Field-aligned windings, 14.5 degrees (q_{95} ~ 3)

$B_r \sim B_\theta \sim 1.5$ mT at LCFS (60 amps)

(Note QCM: $B_r \sim B_\theta \sim 0.5$ mT)

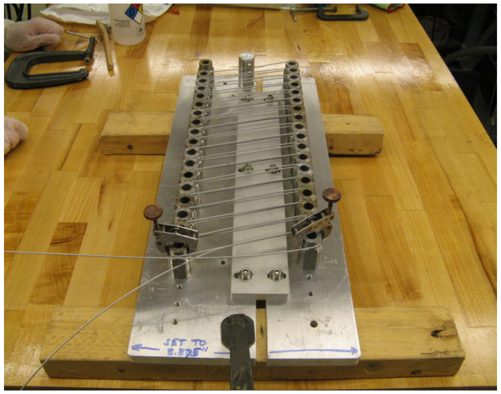




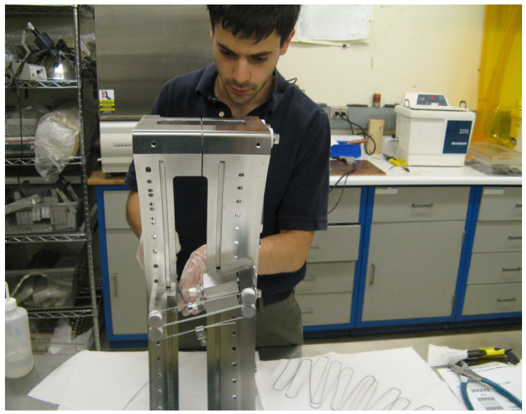
View of $J_{//}$ filaments passing in front of a possible 'antenna box' on outer midplane

A simple 'shoelace' antenna made from moly wire can satisfy requirements.

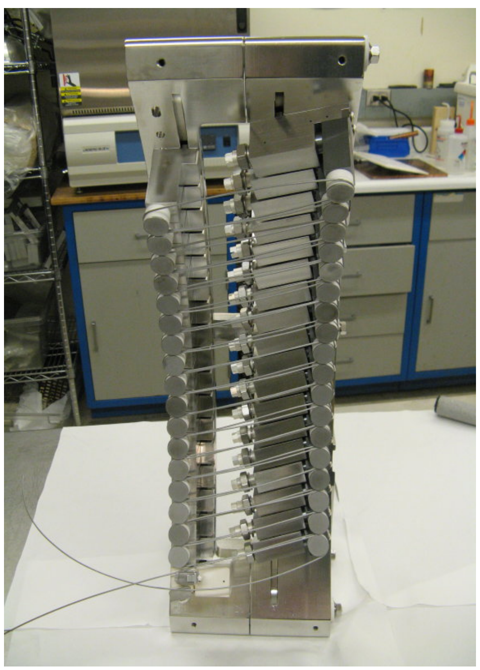
Shoelace antenna winding and installation



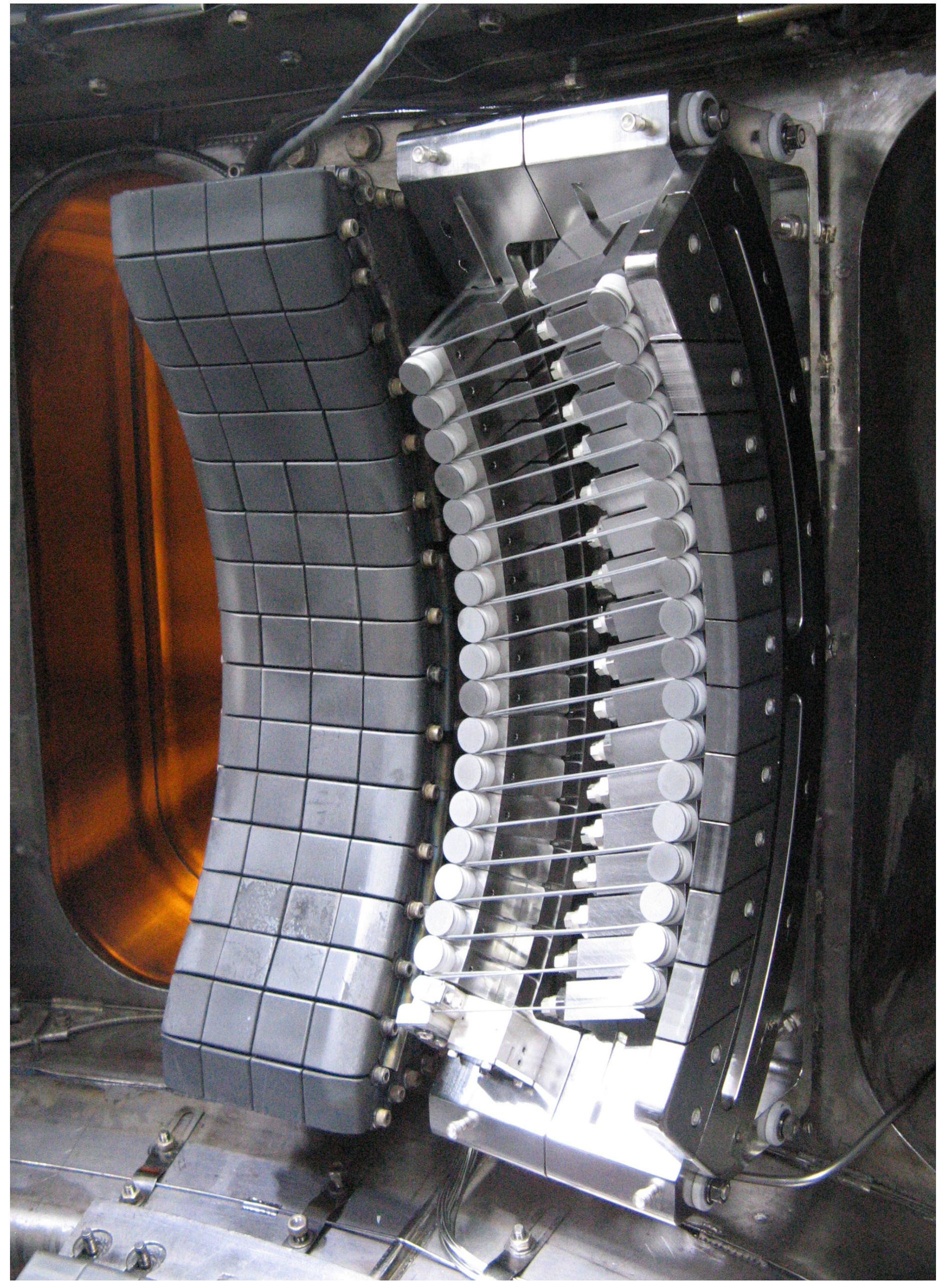
Winding fixture



Test fit-up



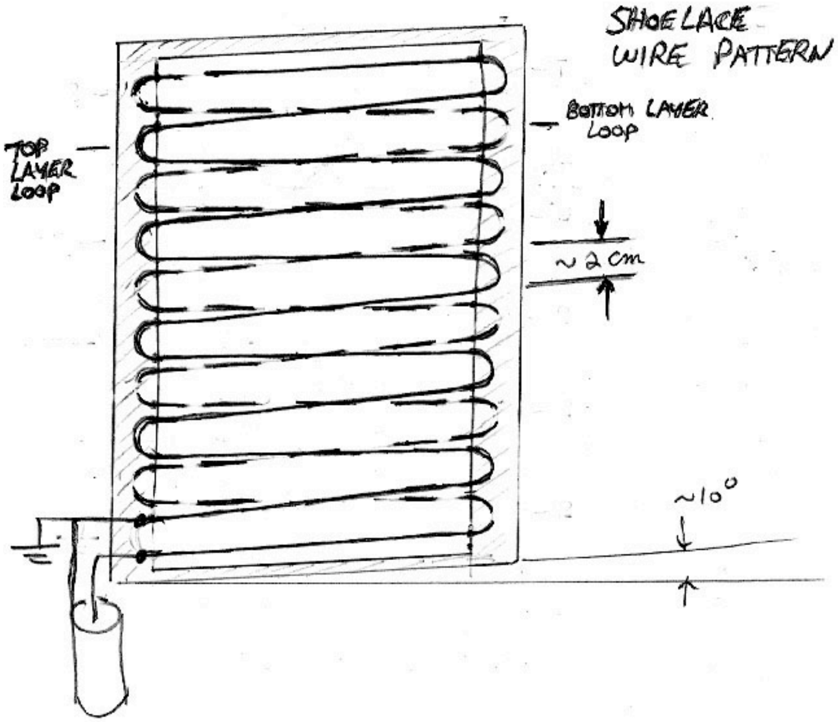
Winding on antenna posts



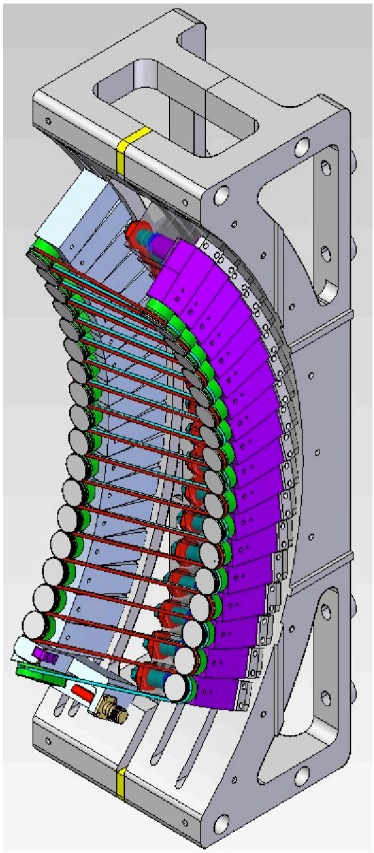
Installed

Rapid deployment, thanks to excellent engineering team

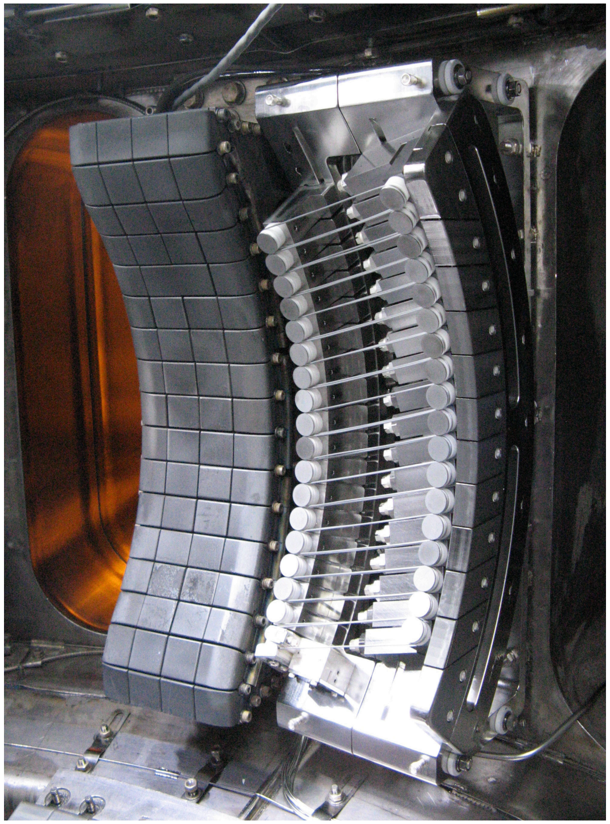
July 10, 2010



April 7, 2011



August 8, 2011

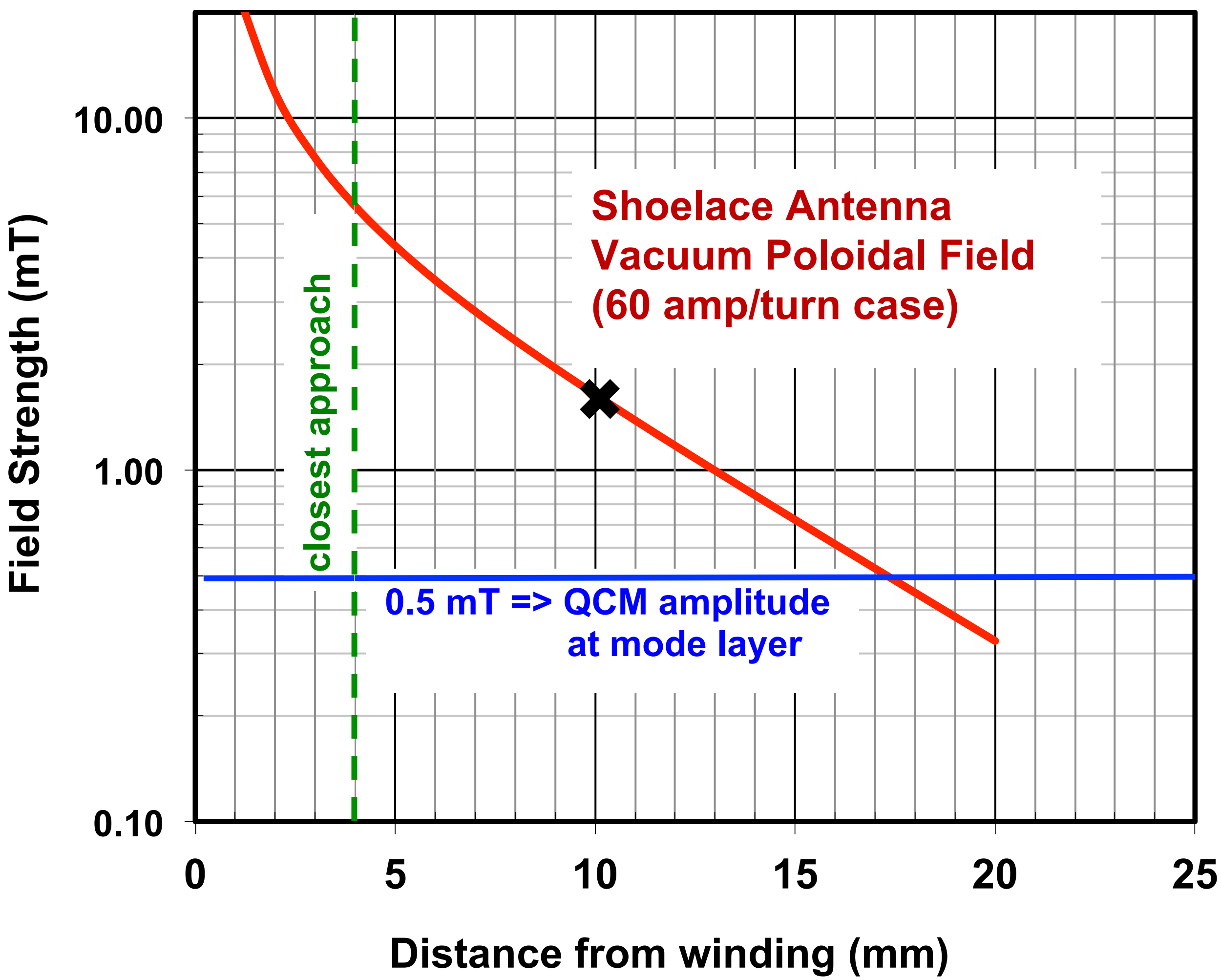


QCM Antenna mechanical design team

Two optimizations are required for shoelace system:

- Windings must be positioned very close to targeted 'mode layer'.
- High antenna current is desired; amps/RF watt must be maximized.

Antenna Poloidal Field

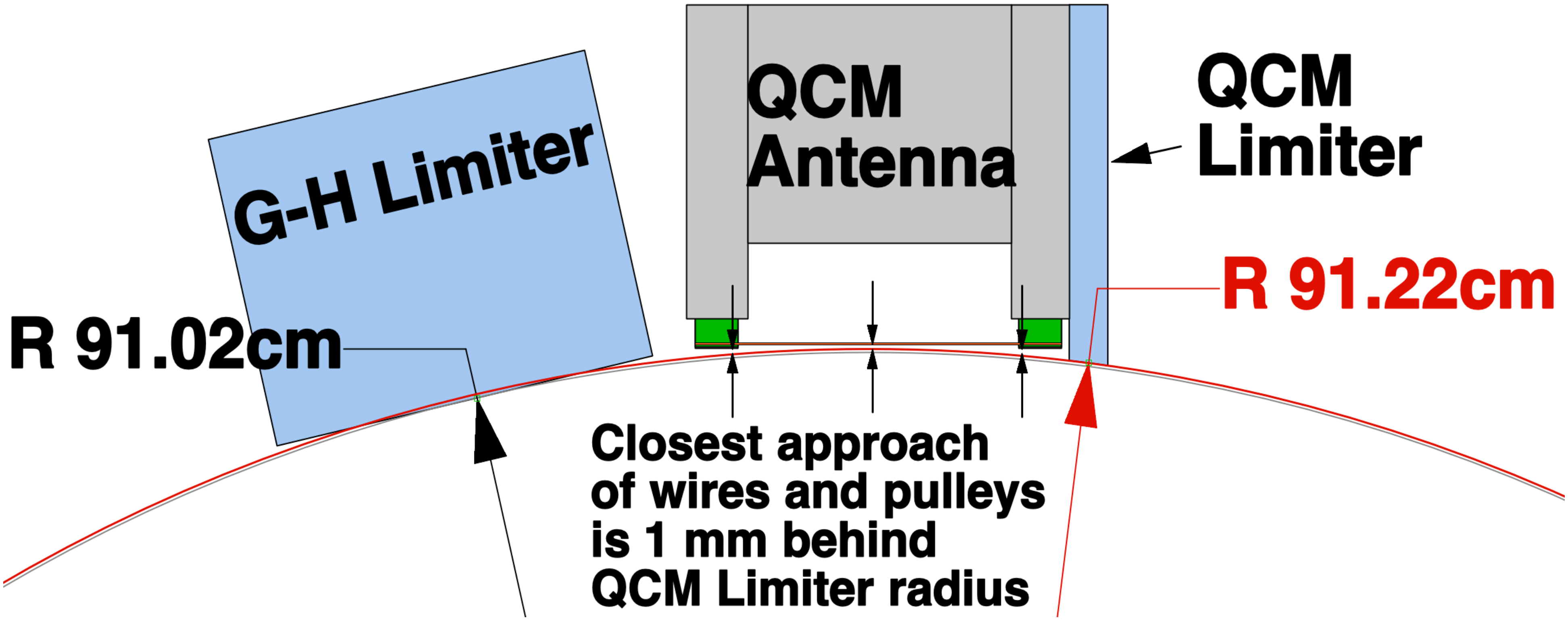


For distance of 10 mm,
$B_r \sim B_\theta \sim 1.5$ mT
(60 amp/turn case)

Note QCM:
$B_r \sim B_\theta \sim 0.5$ mT
at mode layer (LCFS)

Shoelace windings are set 3 mm behind main limiter

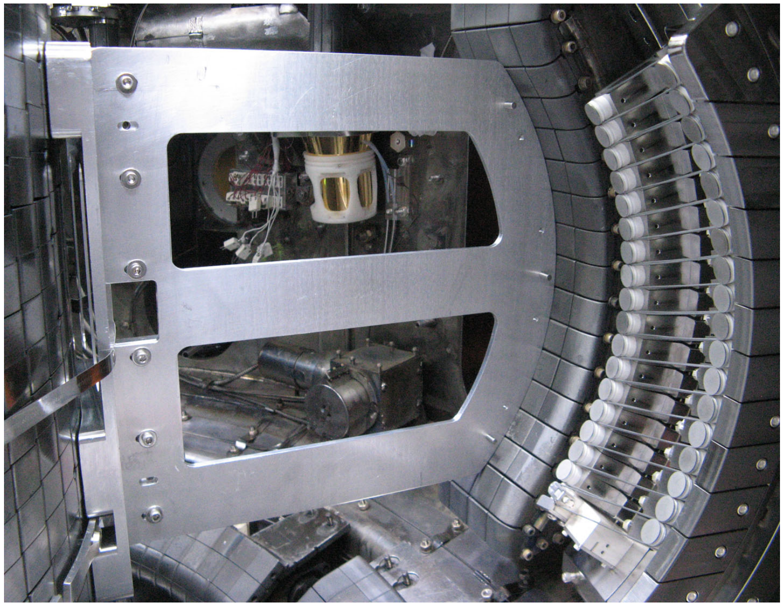
La-Mo wire and Mo ‘posts’ are set 1 mm behind local ‘QCM limiter’



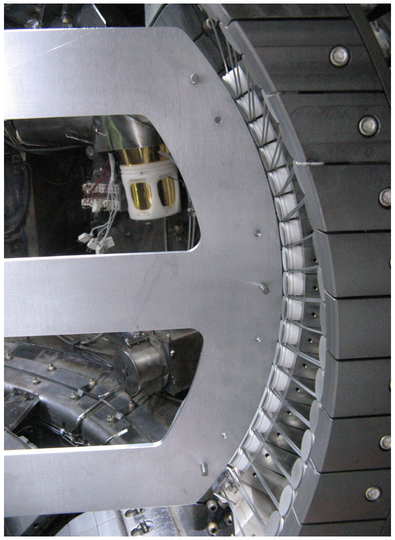
A special alignment fixture is used to position antenna components …

Shoelace windings are set 3 mm behind main limiter

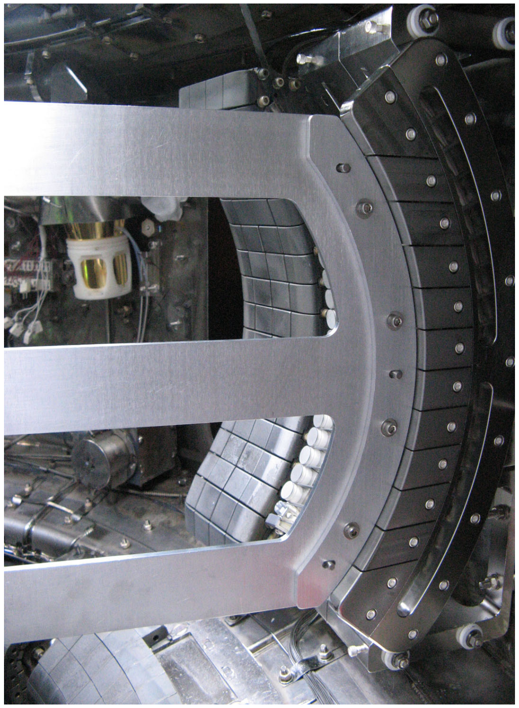
(1) Alignment fixture touches GH limiter



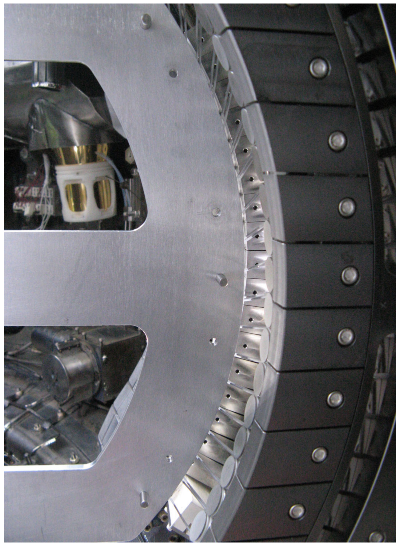
(2) check 'left' pulley clearance

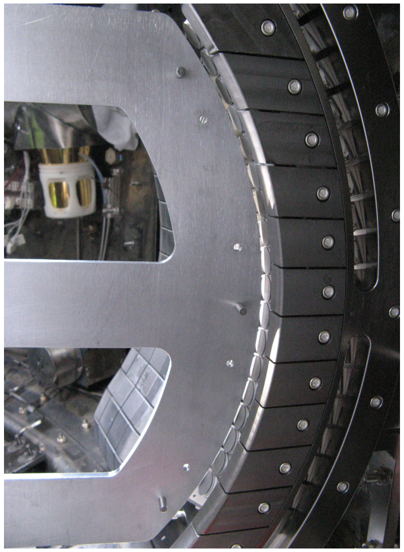


(5) check QCM limiter clearance



(3) check midpoint wire clearance

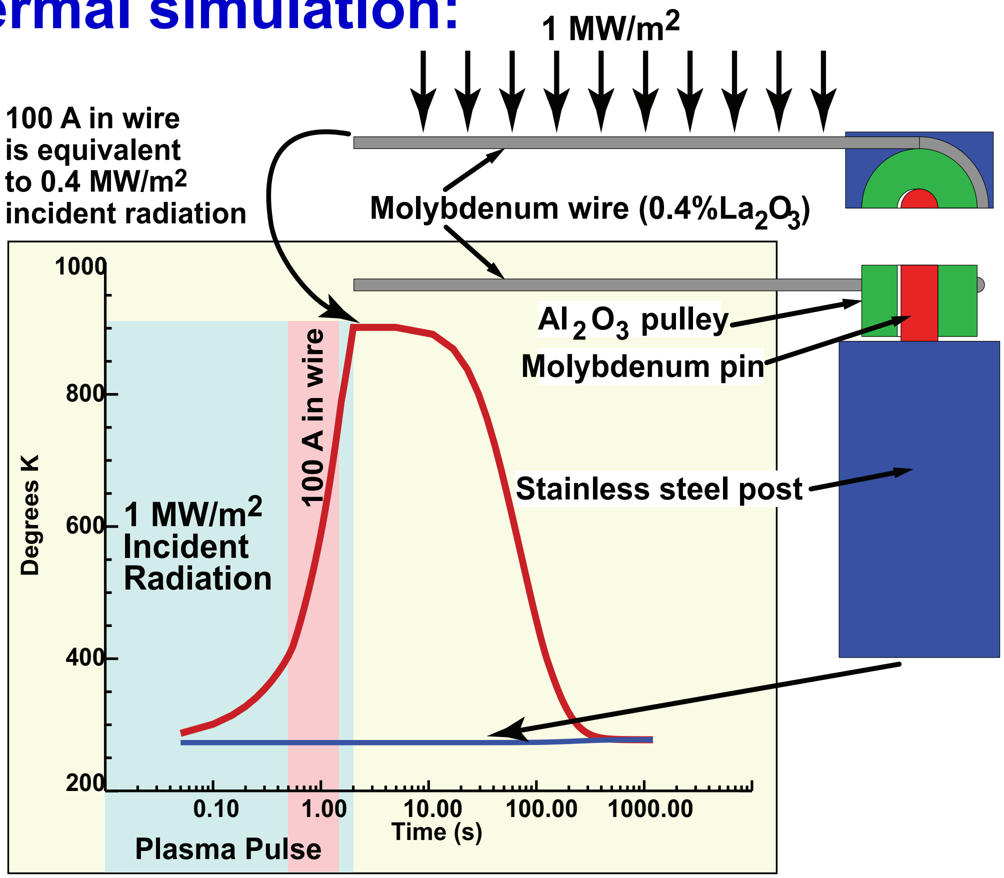




(4) check 'right' pulley clearance

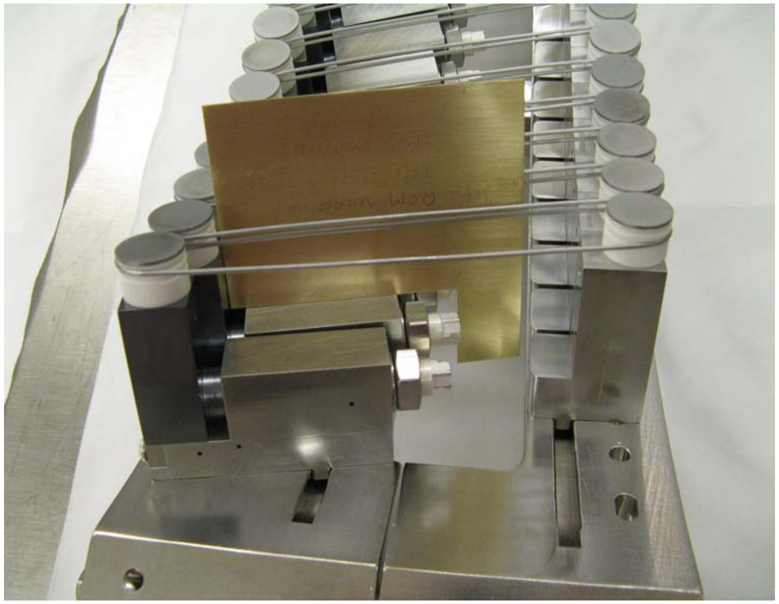
Antenna is designed to take the heat

Results from thermal simulation:

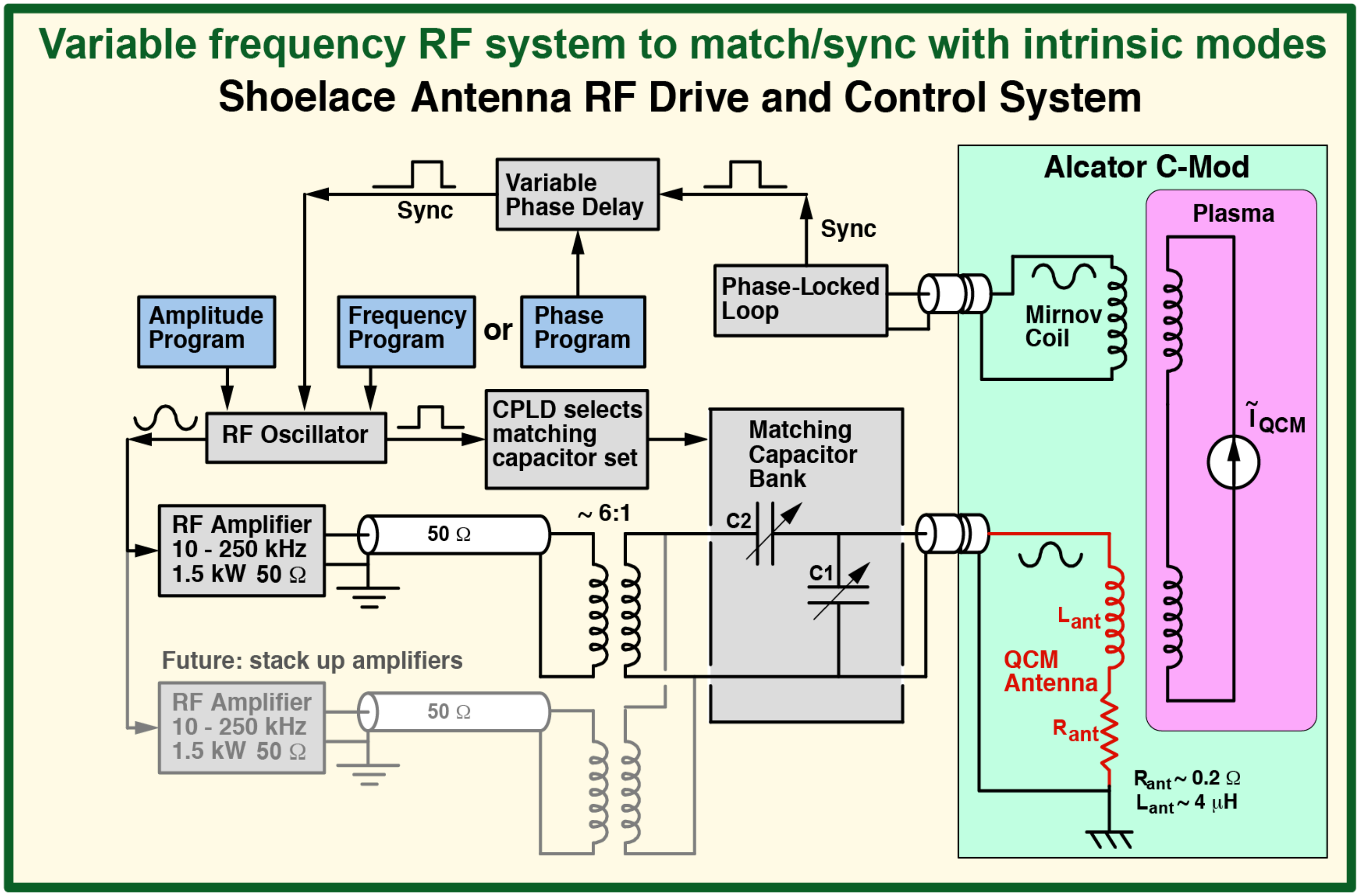


- Wires could reach 600 C at highest thermal load
- La-doped moly wire can operate at 1500 C

- Thermal expansion (~0.3 mm) is accommodated by spring-loaded 'tensioners' (50 pound preload per wire)



RF drive requirements: Maximize antenna current over a wide range of RF frequencies, with phase control



- Capacitor values C1, C2 switched in real time to match antenna impedance

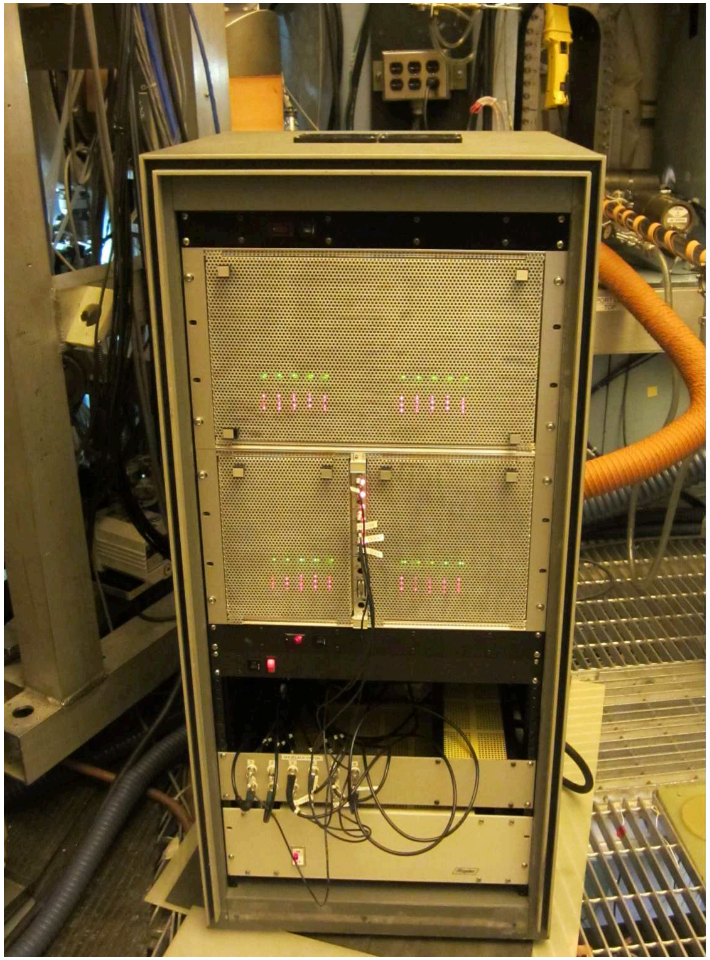
  MOSFET-switched capacitor bank (160 switches) accomplishes this.

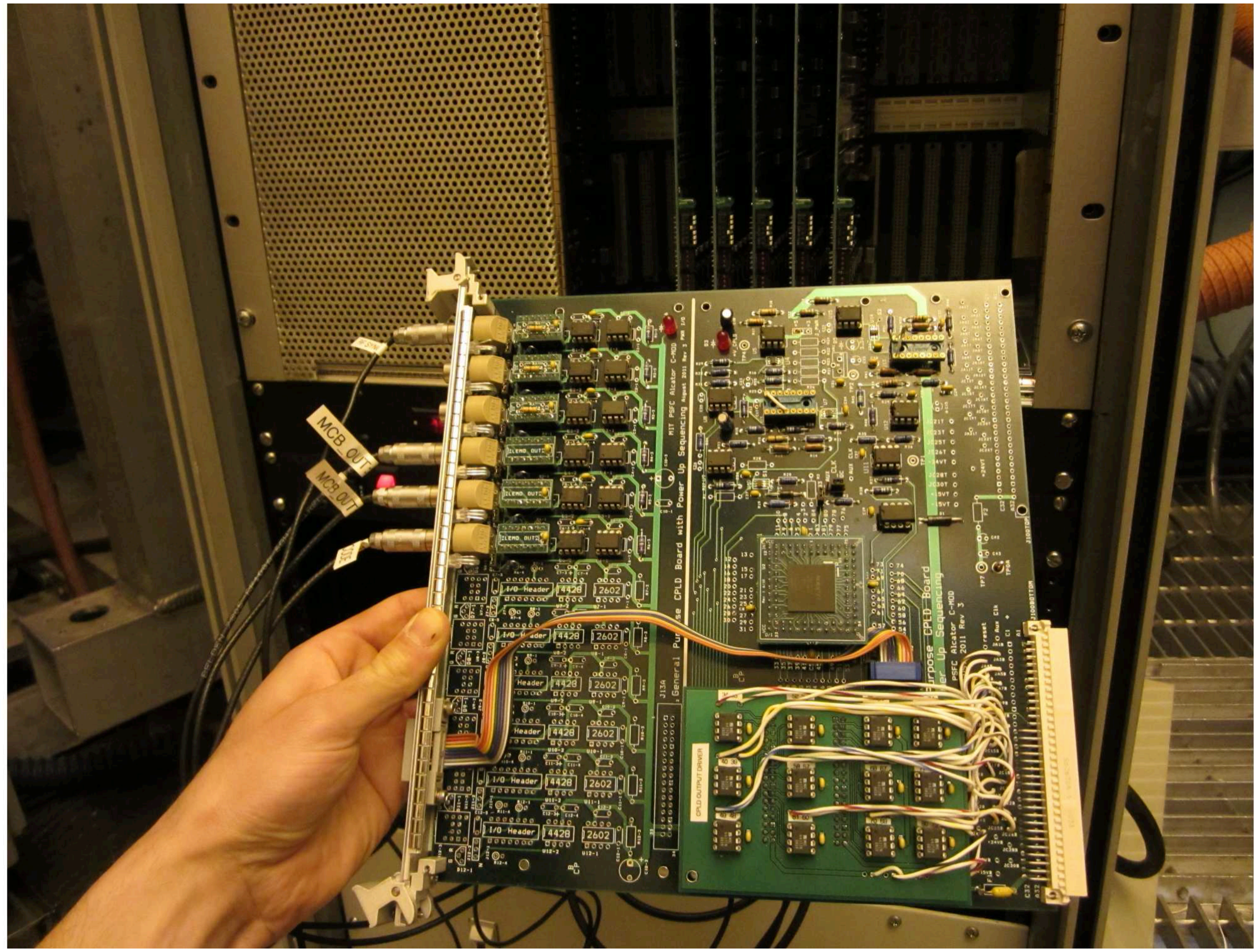
- Simple external controls: RF Amplitude and frequency (or phase)

- Ability to synchronize antenna drive to external pick-up signal

  Custom-designed signal conditioning and phase-lock circuitry

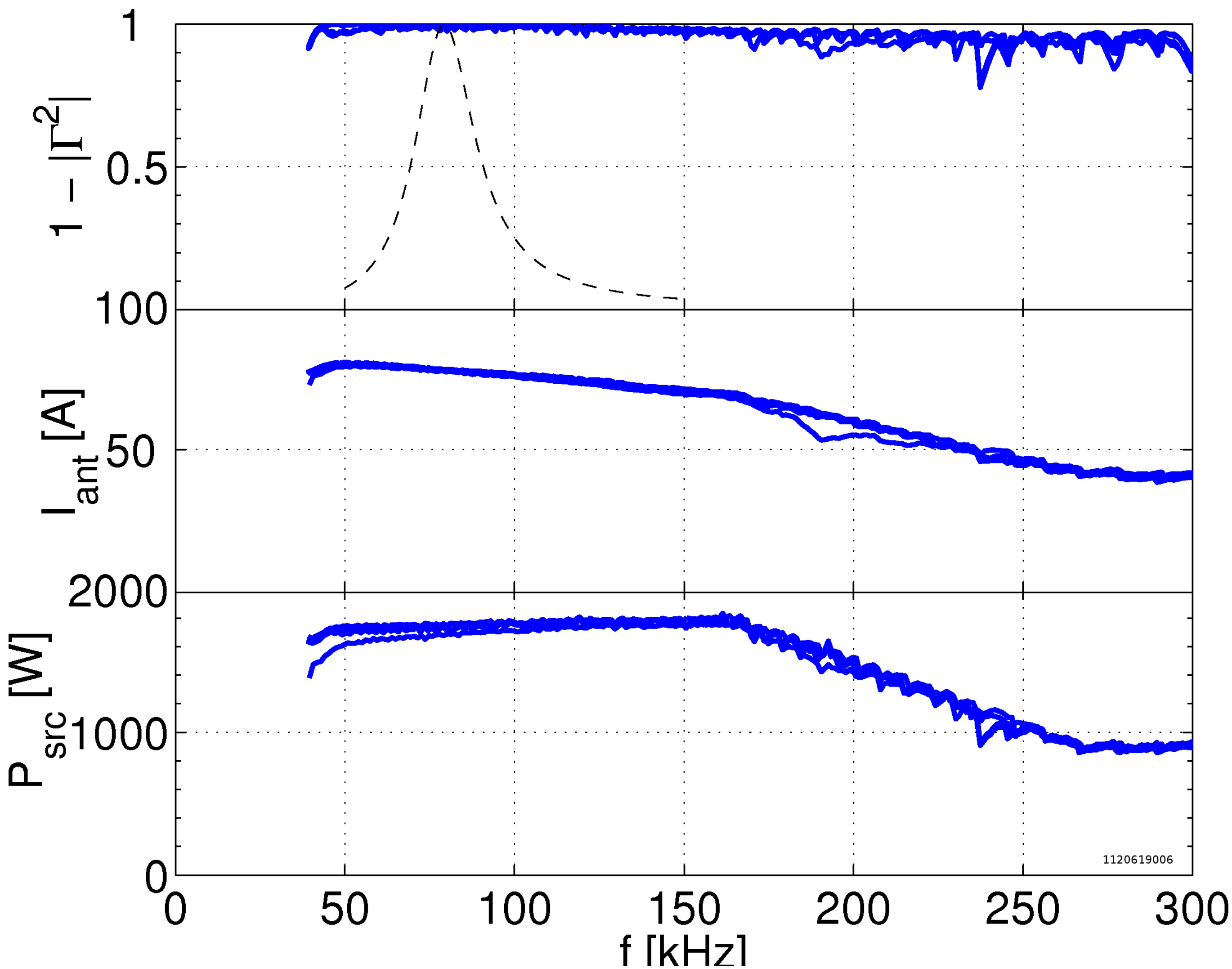
Dynamic Matching System: Hardware





- Electronics housed in RF-shielded card frame with RF and TTL back bus
- 20 capacitor cards, each with 8 MOSFET switches
- Master CPLD measures frequency and switches in capacitors as needed

Dynamic Matching System: Performance



- **Broadband matching demonstrated, 45 kHz < f < 300 kHz**
- **Less than 10% power reflected**
- **Dynamic matching with slew rate > 1MHz/s**

Results: Shoelace Antenna drives an 'Artificial Quasi-Coherent Mode'

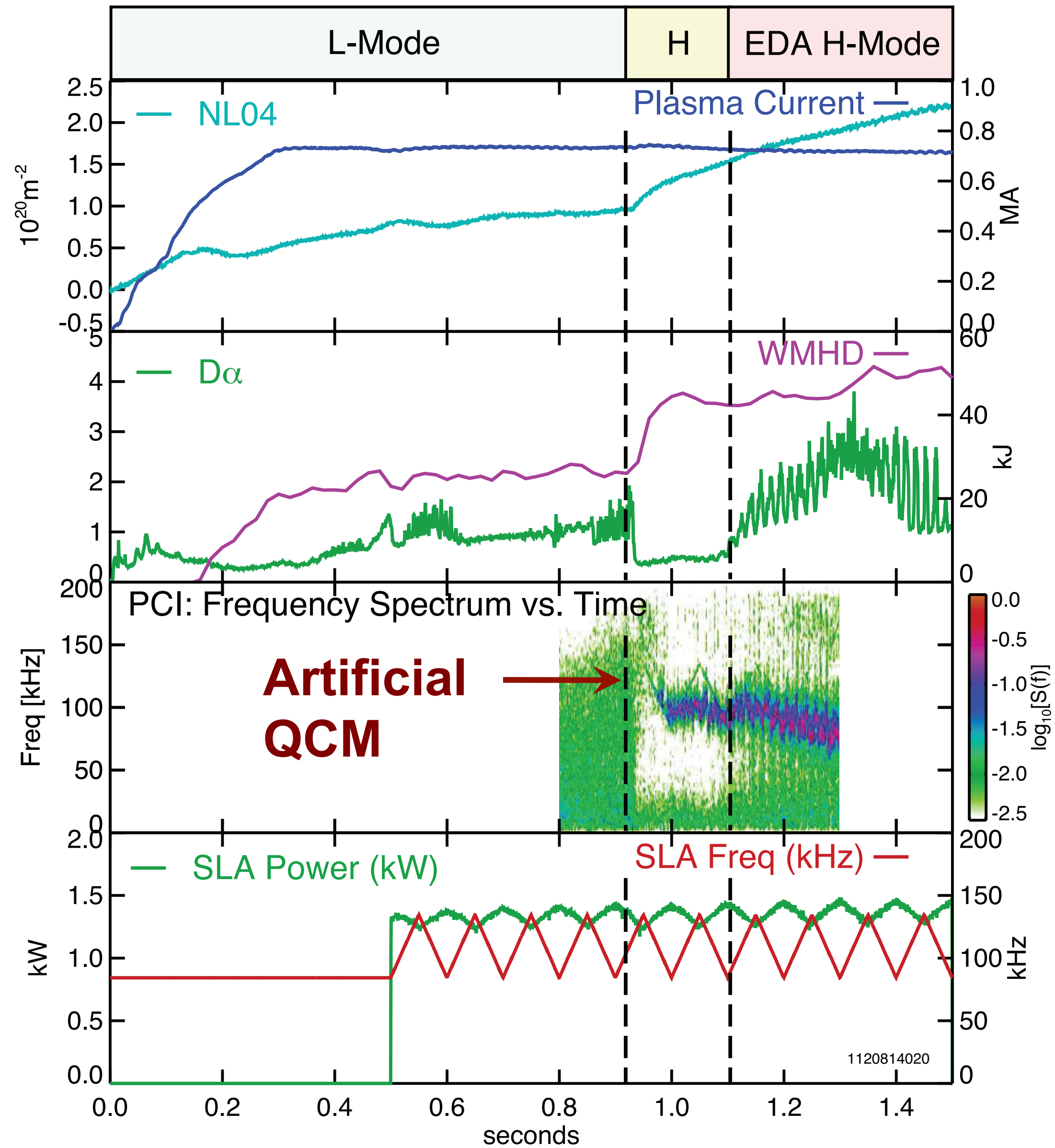
Target discharge:
ohmic EDA H-mode

L-H transition at ~0.92 s

Intrinsic QCM begins at ~0.99 s

Driven mode ('artificial QCM') begins immediately after L-H transition

1.3 kW into SLA; frequency sweep 90-140 kHz

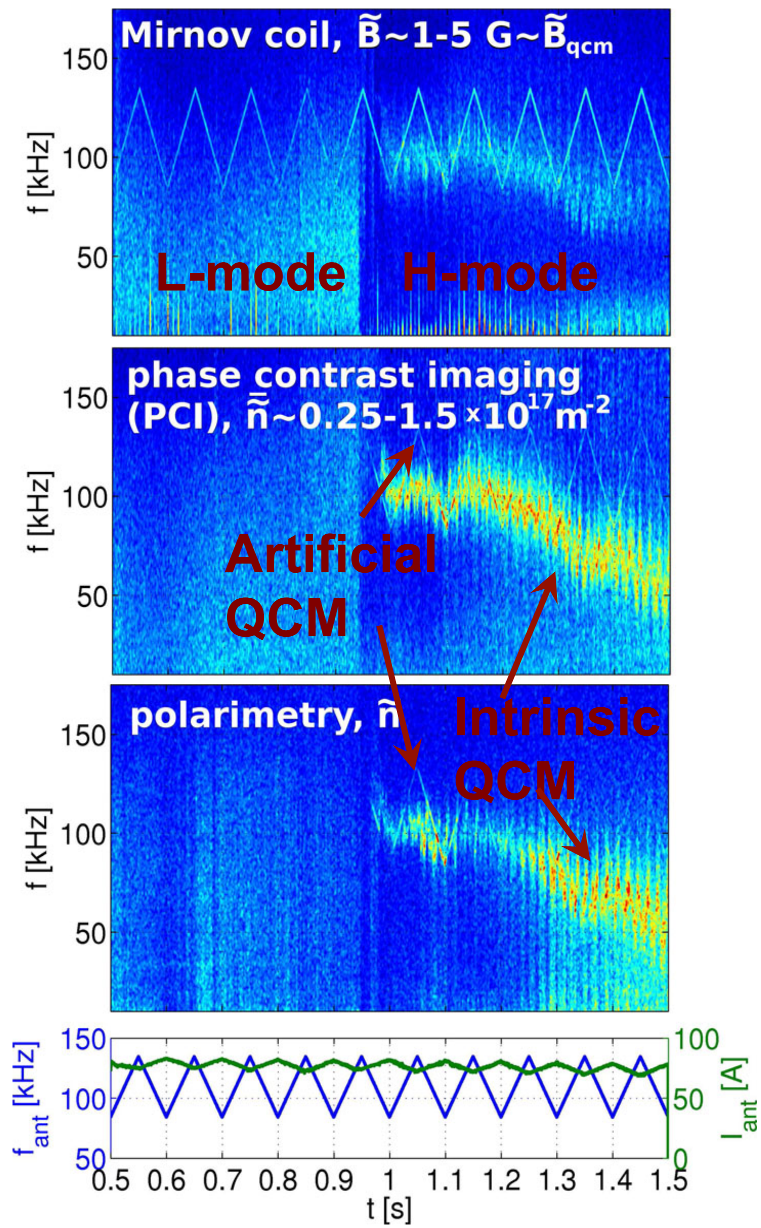


Results: Shoelace Antenna drives an 'Artificial Quasi-Coherent Mode'

Mirnov coils always see field-aligned current perturbation in boundary, ~same magnitude as intrinsic QCM.

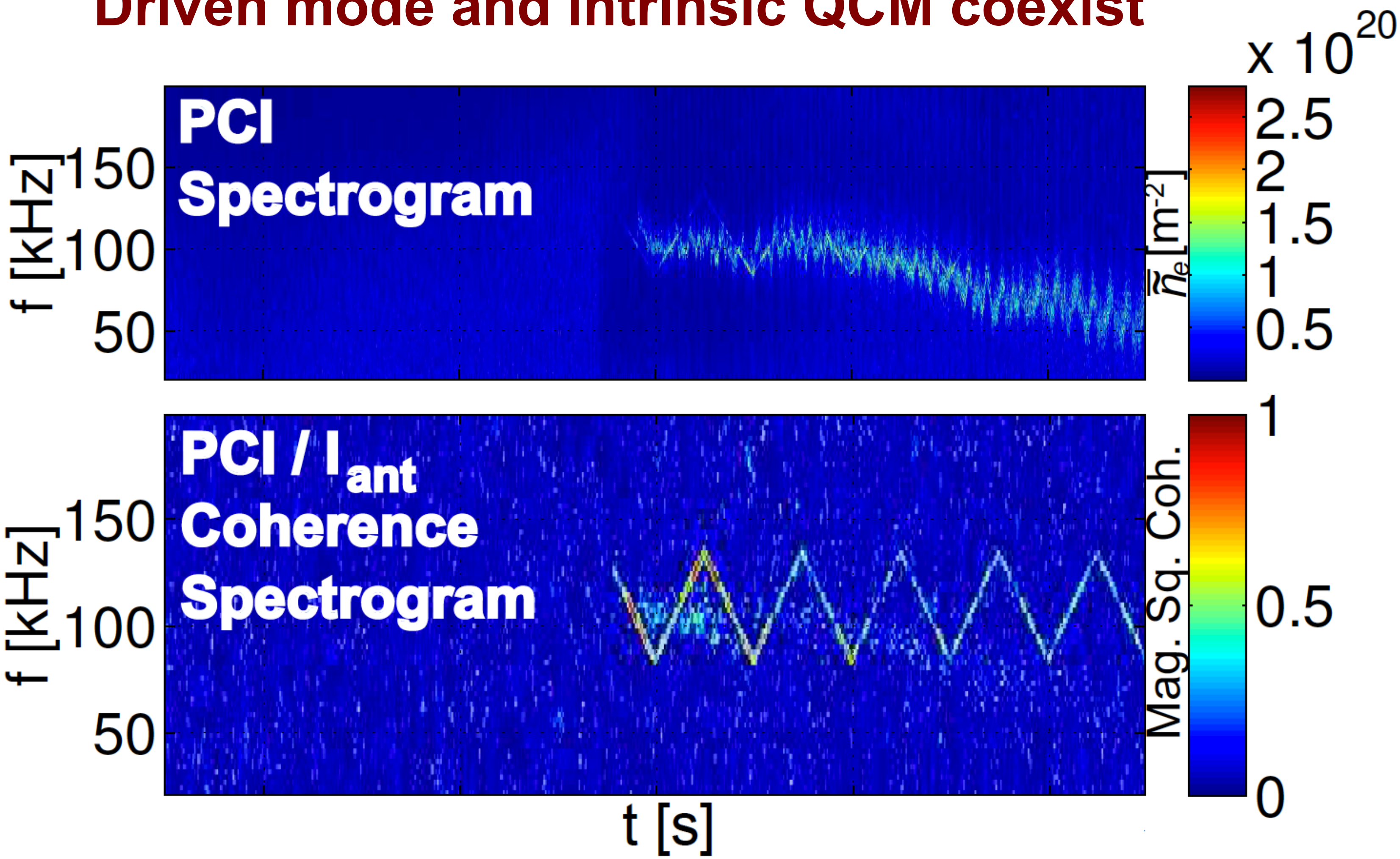
PCI and Polarimeter detect antenna-driven density perturbation, only after L-H transition – *i.e.*, under conditions when intrinsic QCM appears.

~80 amps driven in SLA;
frequency sweep 90-140 kHz



Results: Shoelace Antenna drives an 'Artificial Quasi-Coherent Mode'

Driven mode and intrinsic QCM coexist

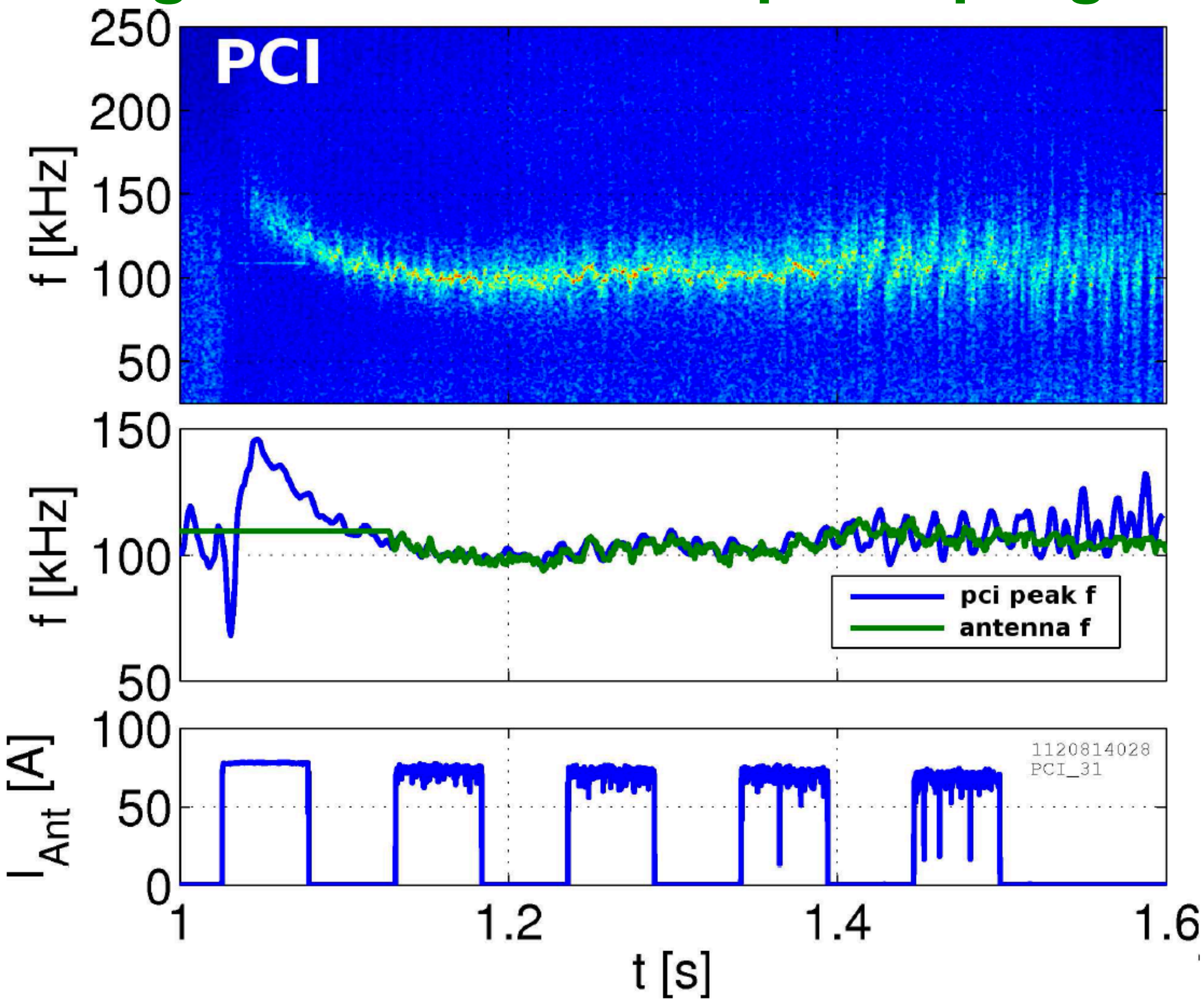


Antenna / PCI (mode) cross-coherence remains strong, despite evolving frequency of intrinsic QCM

Driven and intrinsic QCMs do not appear to strongly interact.

Results: RF phase lock to QCM partially demonstrated

A single PCI channel is 'pick-up signal'



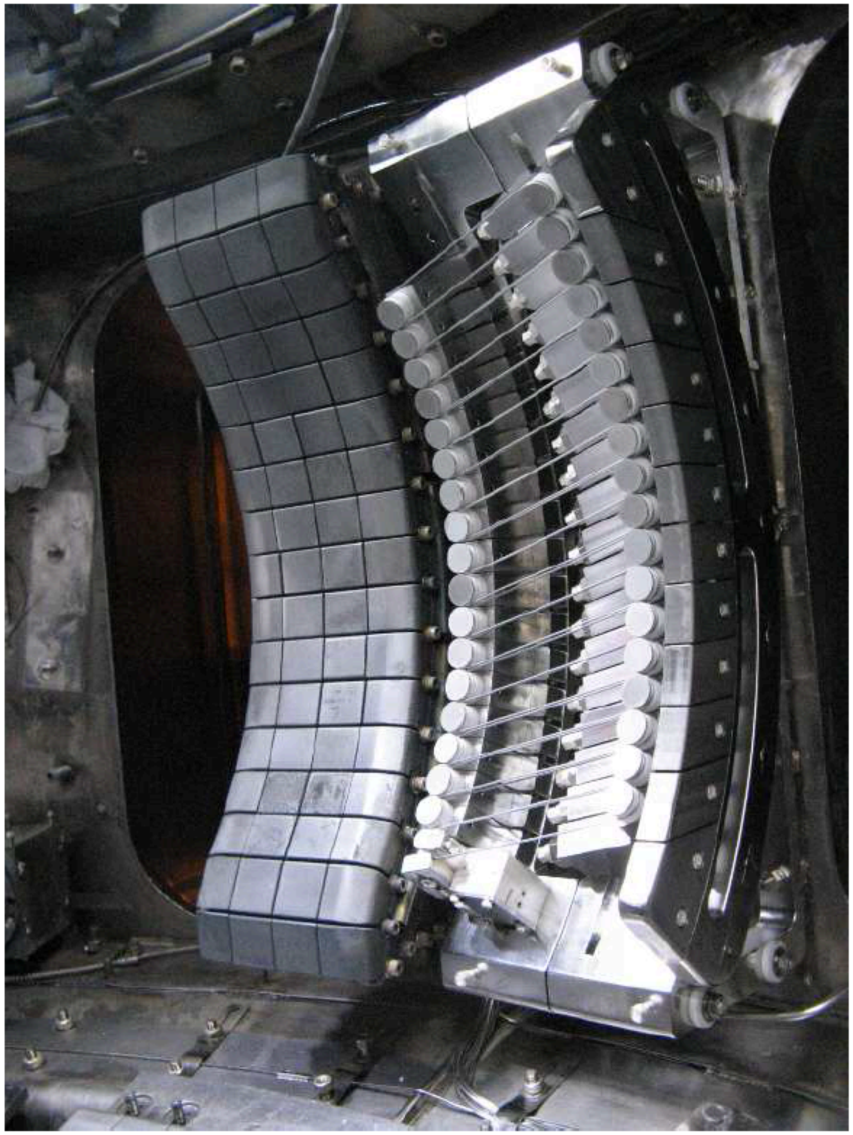
Shoelace Antenna RF is ~phase-locked with QCM

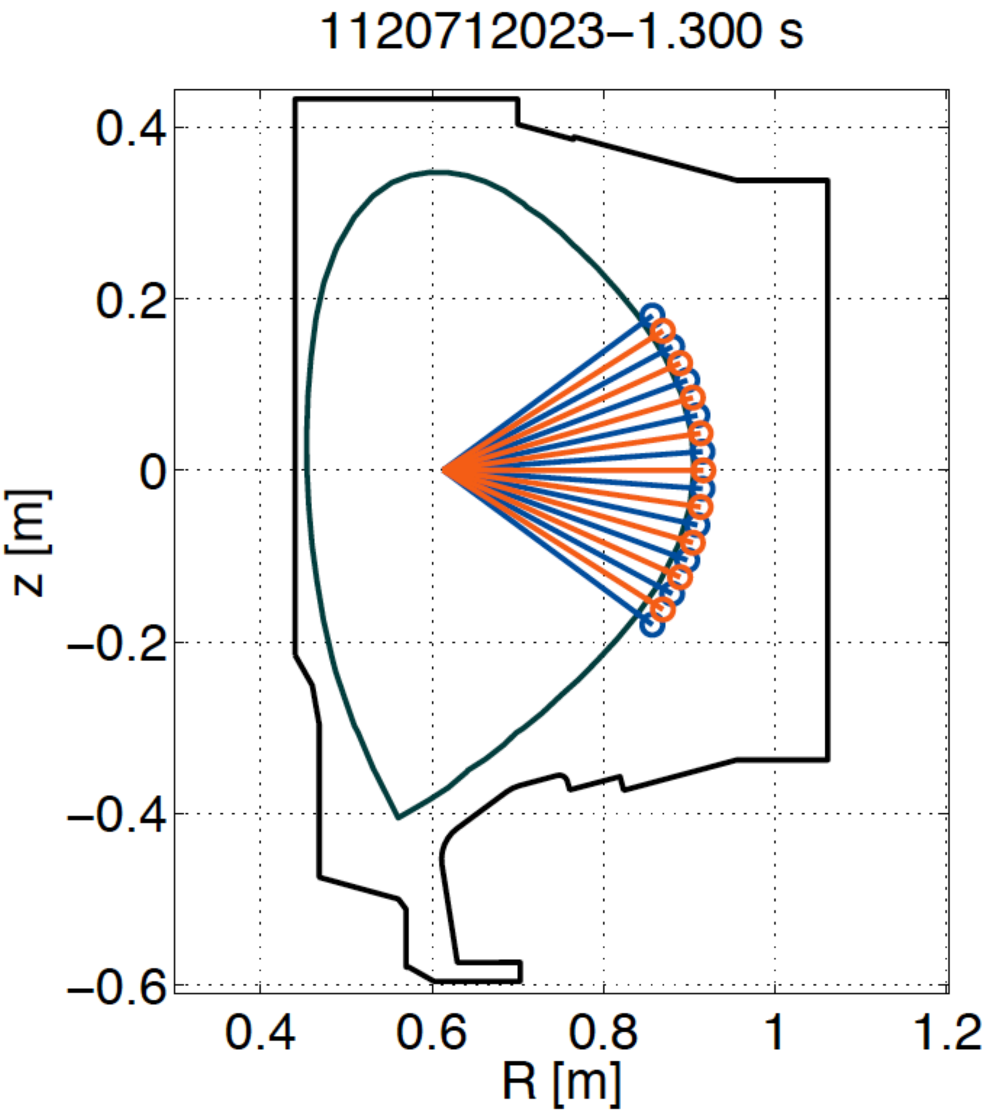
High fidelity phase lock is not quite achieved.

Possible enhancement of intrinsic QCM; may be superposition

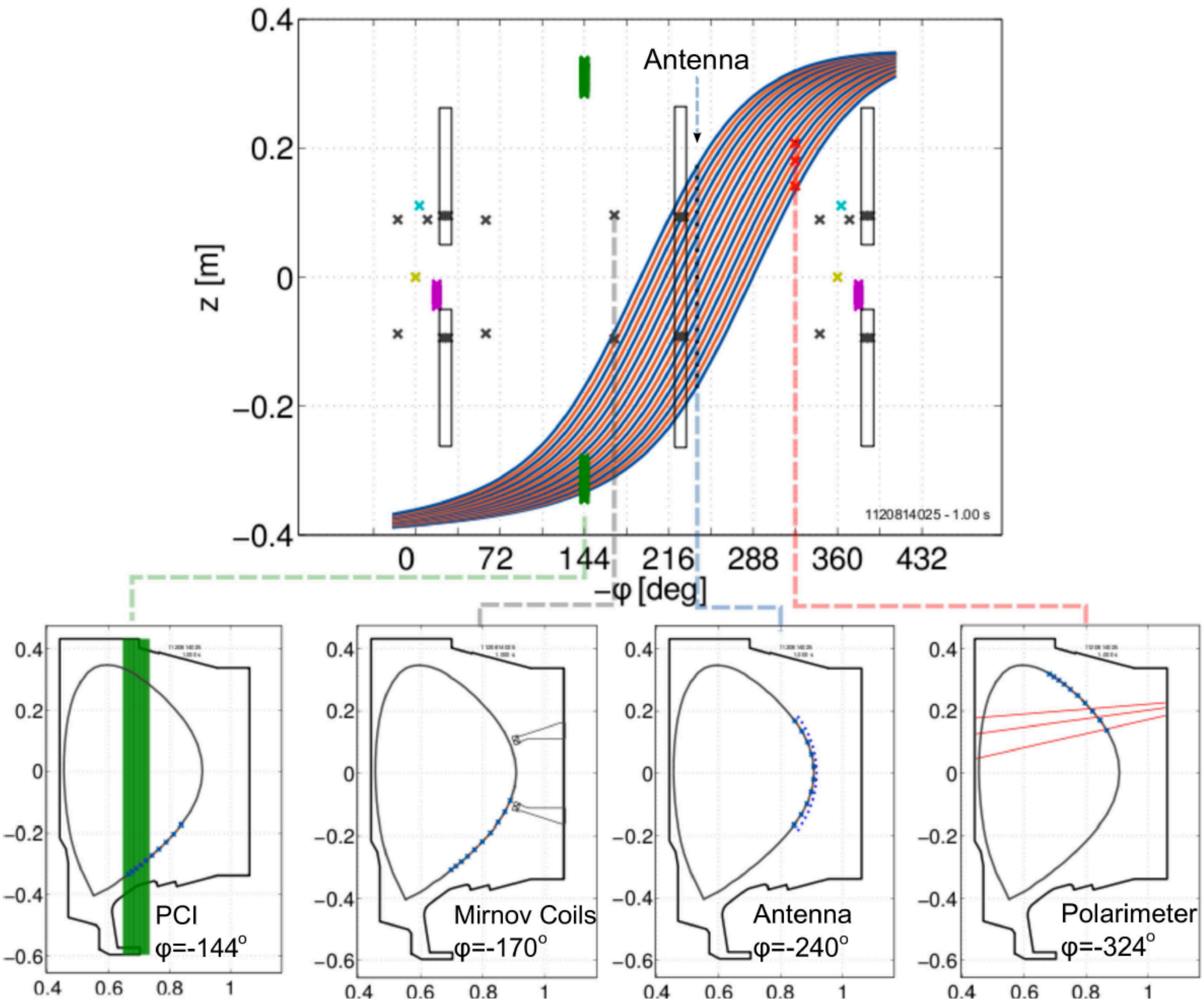
Results: Driven mode is ~field-aligned

Map field lines from front of antenna to diagnostics…

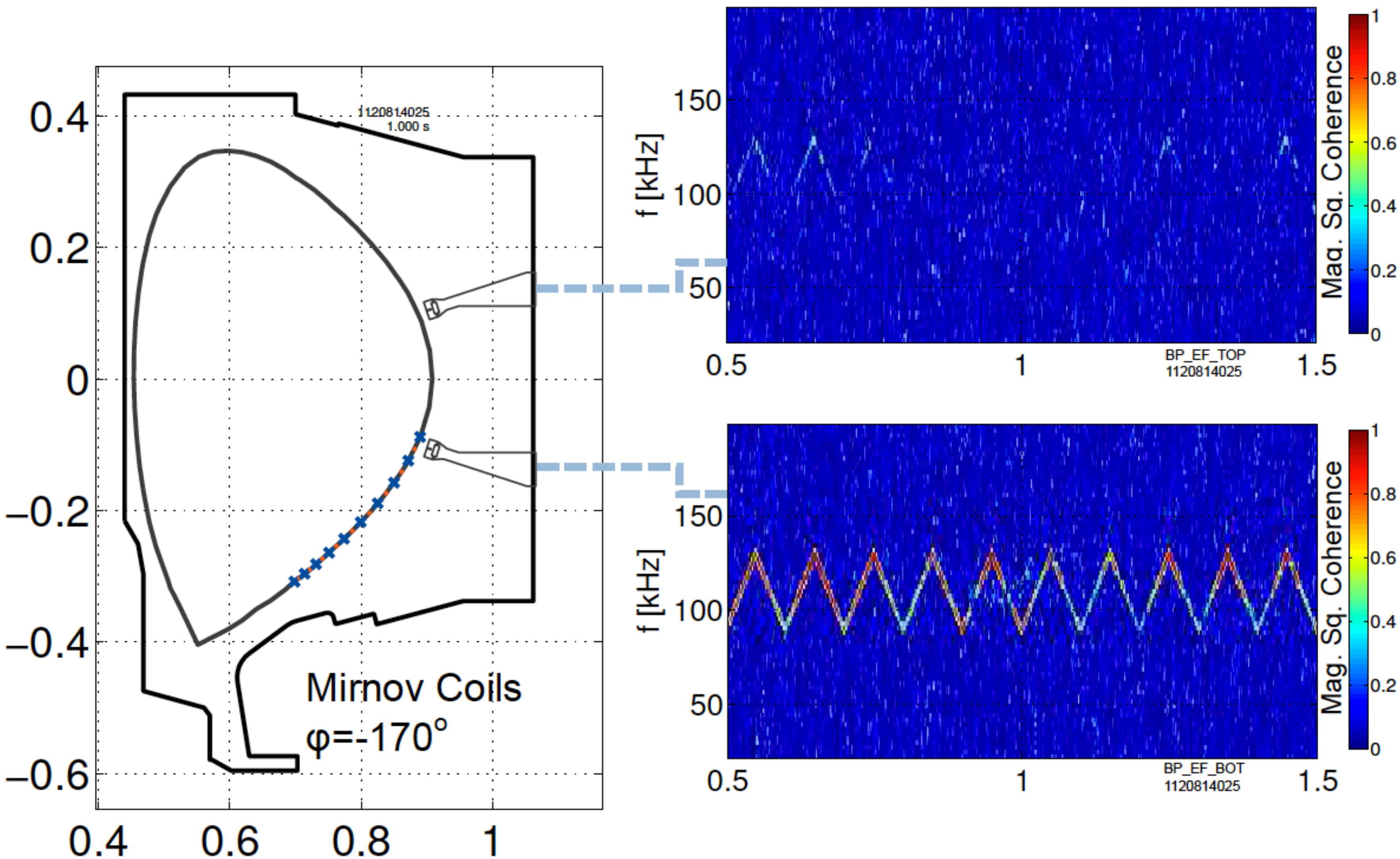




Results: Driven mode is ~field-aligned



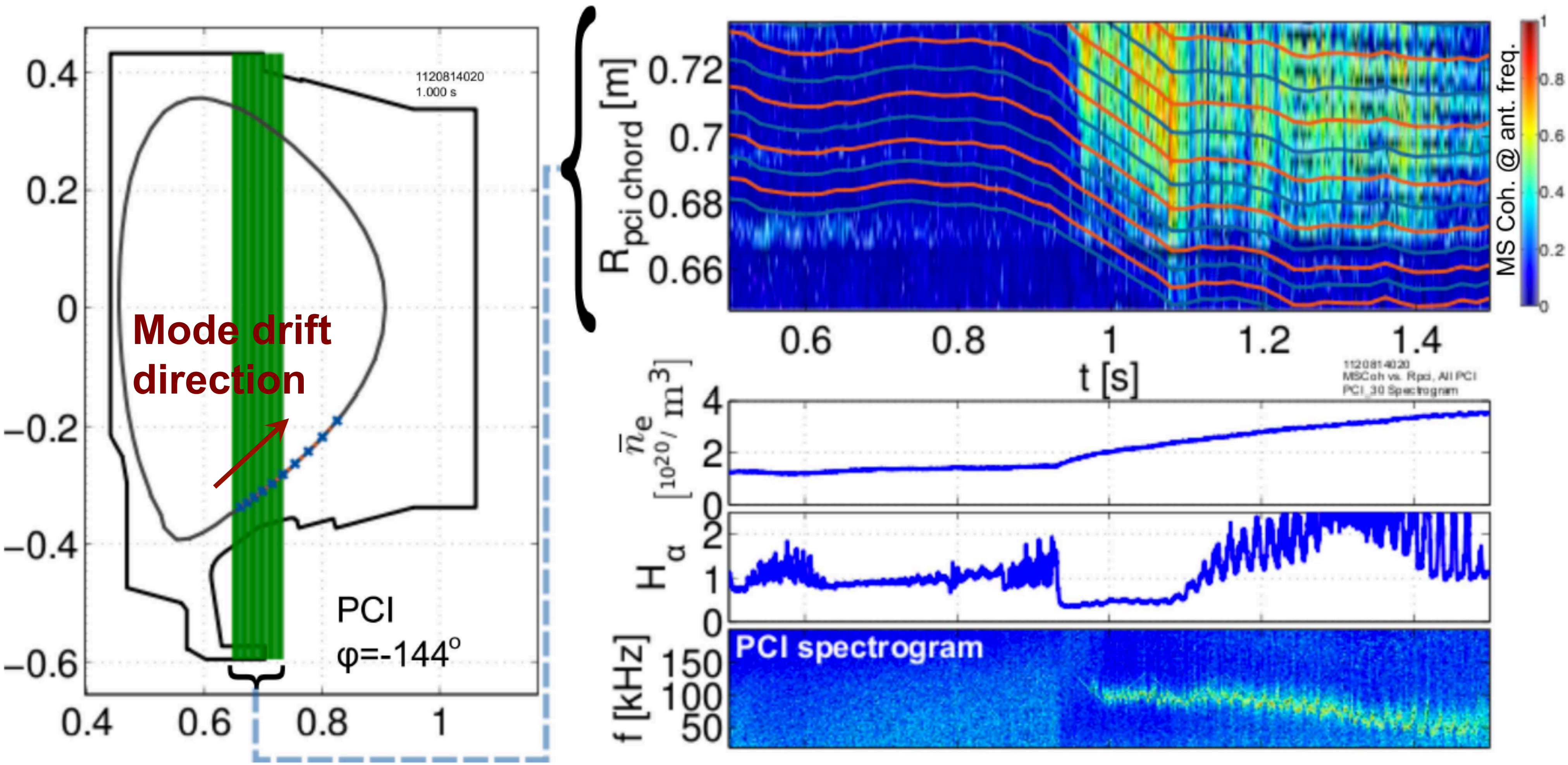
Results: Driven mode is ~field-aligned



Cross-coherence between SLA and Mirnov coils always strong, but only on field lines that map in front of antenna.

Results: Driven mode is ~field-aligned

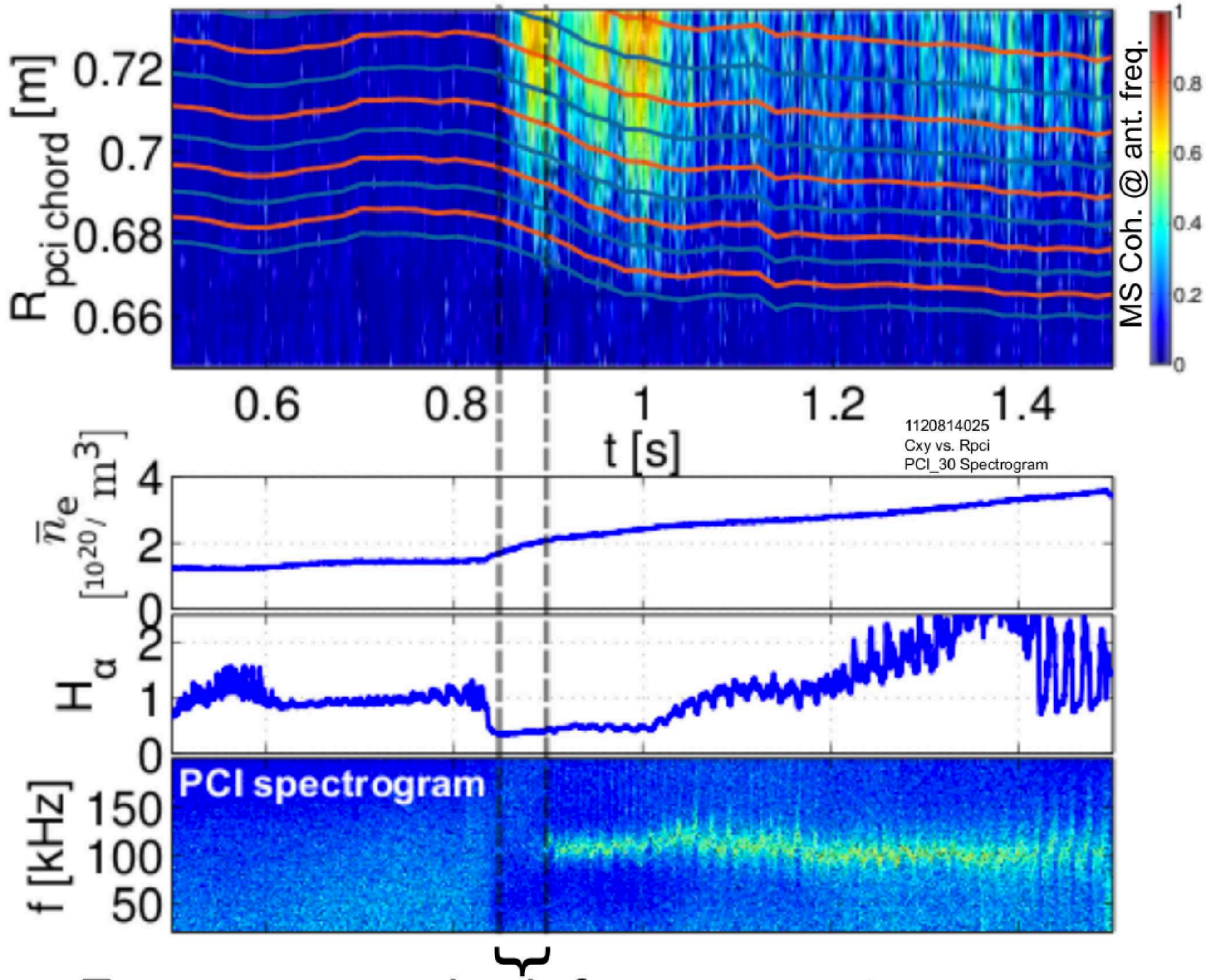
Field-aligned response on PCI tracks rapid change in q95



A drift-mode gets excited, but it does not persist beyond influence of antenna => drift mode is strongly damped.

Q: Doesn't this mean that intrinsic QCM must also be damped?

Results: Linear system analysis tools can be applied (with caution) to interrogate plasma response…



Freq. sweep - look for resonant response

Results: Transfer function analysis suggests resonance

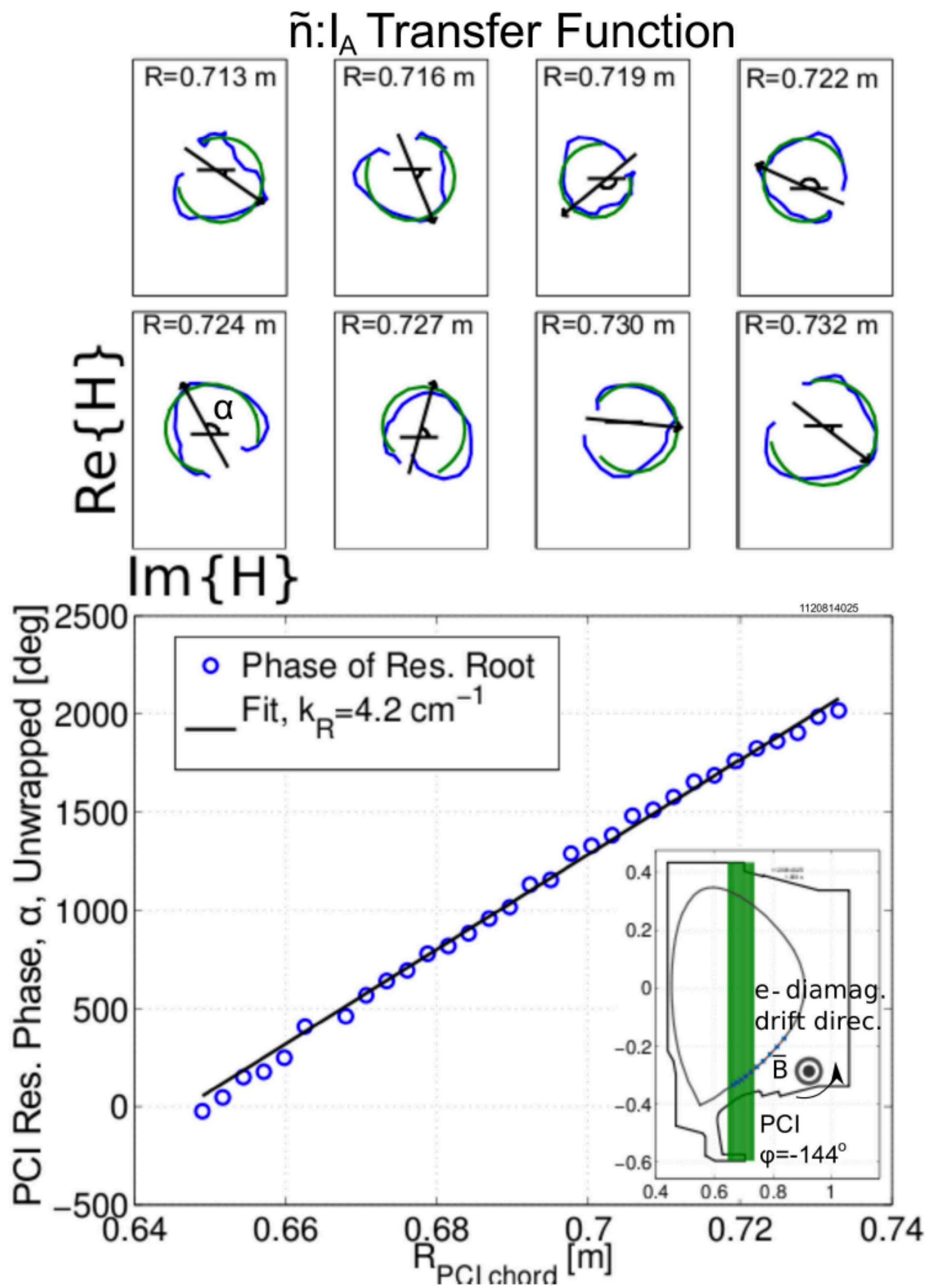
As frequency is swept, Transfer Function sweeps out circular trajectory in complex plane

Suggests resonant pole response

Phase angles provide measure of k_R

=> same as QCM

mode propagates in e^- diamagnetic direction



Very likely that an electron drift-Alfven wave is being excited

Shoelace Antenna: Summary

Shoelace Antenna (SLA) is an 'induction antenna', driving currents along field lines in the boundary layer, with $k_\perp \sim 1.5$ rad/cm

Under conditions that produce a QCM (H-mode), SLA excites a resonant, QCM-like response in density, with similar $k_\perp$ and propagation direction (electron diamagnetic).

It is likely that SLA is exciting a drift-Alfven wave.

Driven mode (drift wave) occurs over a range of frequencies, above and below intrinsic QCM

$\omega_{dw} = k_\perp (V_{dia} + V_{ExB})$ varies strongly across boundary layer; this matching condition is almost always satisfied somewhere.

Driven mode is strongly damped, even at intrinsic QCM frequency; it does not propagate beyond SLA.

Implies that intrinsic QCM is also strongly damped (! ?)

Further implies that intrinsic QCM is being 'pumped' by another mode. Resistive interchange mode is candidate.

Shoelace Antenna: Summary

Next steps:

(if we could) measure antenna-induced particle transport and detailed mode structure with Mirror Langmuir Probe

(if we could) study spatial damping of mode – its propagation beyond the last ‘rung’ of the SLA

Model plasma response with BOUT++
=> slab model including drift wave physics + magnetic shear (for damping), perhaps also interchange drive

PhD thesis (Ted Golfinopoulos)