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Measurement of scrape-off-layer current dynamics during MHD activity and disruptions in HBT-EP

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with the HBT-EP Group:

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COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

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Key results in HBT-EP*

- Direct measurements of toroidal vessel currents reveal asymmetric, oscillating *co-* and *counter-*I_p wall currents during kink modes and disruptions
  - Insulating breaks constrain vessel current to complete its circuit through SOL plasma
  - Currents reach ~4% of I_p during disruptions.

- I_p asymmetry characteristics agree with JET results[1] and ITER modeling[2]
  - Slope of asymmetry $\Delta I_p/\Delta M_{IR,IZ}$ scales like $1/a$

- Wall touching kink mode (WTKM)[3] and Asymmetric toroidal eddy current (ATEC)[4] models can qualitatively explain some HBT-EP measurements, but each model is incomplete as formulated.
  - *Both* ATEC and WTKM concepts are significant for vessel currents
    - Both models also have problems explaining some of the observations
  - Each model can qualitatively explain observed plasma current asymmetries
    - Conditions for ATEC appear more restrictive overall

[1] Gerasimov S.N. *et al.*, *Nucl. Fusion* **54** 073009 (2014)

[2] Roccella R. *et al.,* "Modelling ITER asymmetric VDEs through asymmetries of toroidal eddy currents" IAEA FEC [EX/P6-40] (2016)

[3] Zakharov L.E. *et al.*, *Phys. Plasmas* **19** 055703 (2012)

[4] Roccella R. *et al.*, *Nucl. Fusion* **56** 106010 (2016)

*** Levesque, J.P. *et al.*, *Nucl. Fusion* 57 086035 (2017)**

Outline

- HBT-EP device overview
  - Scrape-off layer current (SOLC) diagnostics and vessel geometry
  - Discharge characteristics
- Measurements during routine kink mode activity
- Measurements during disruptions
- Interpretation in context of WTKM and ATEC models
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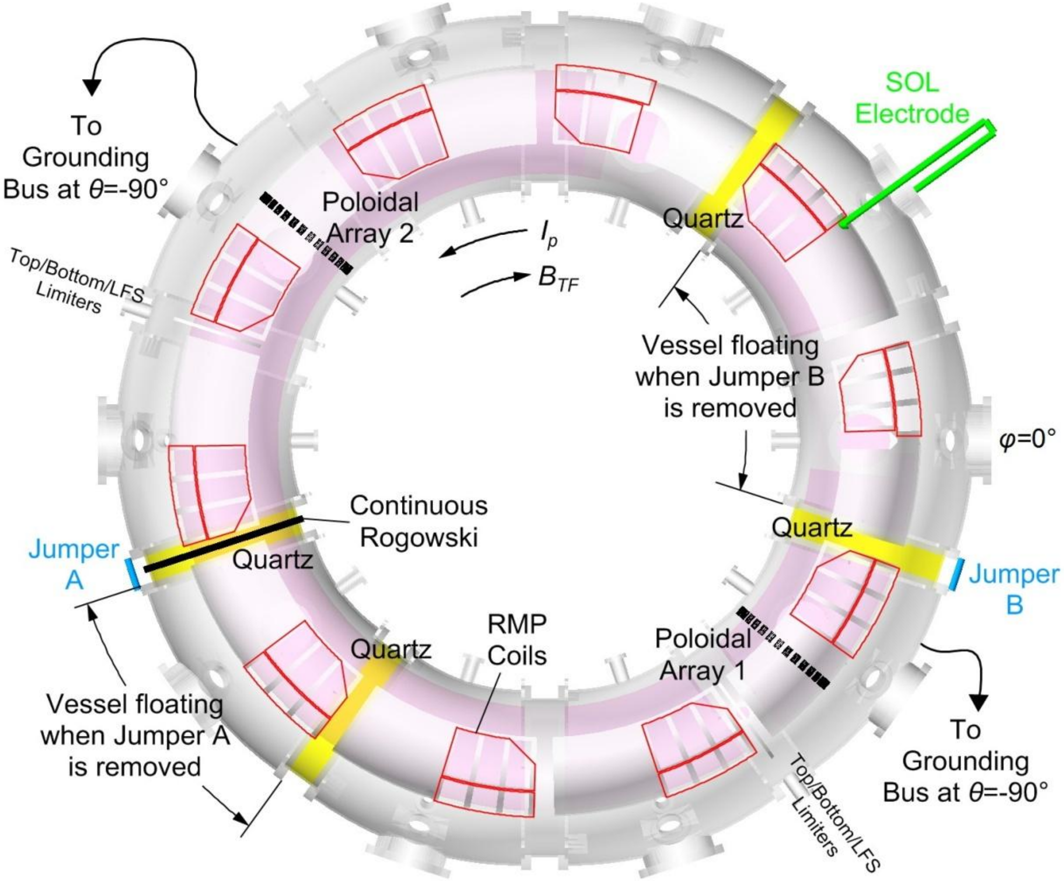
SOL current diagnostics on HBT-EP

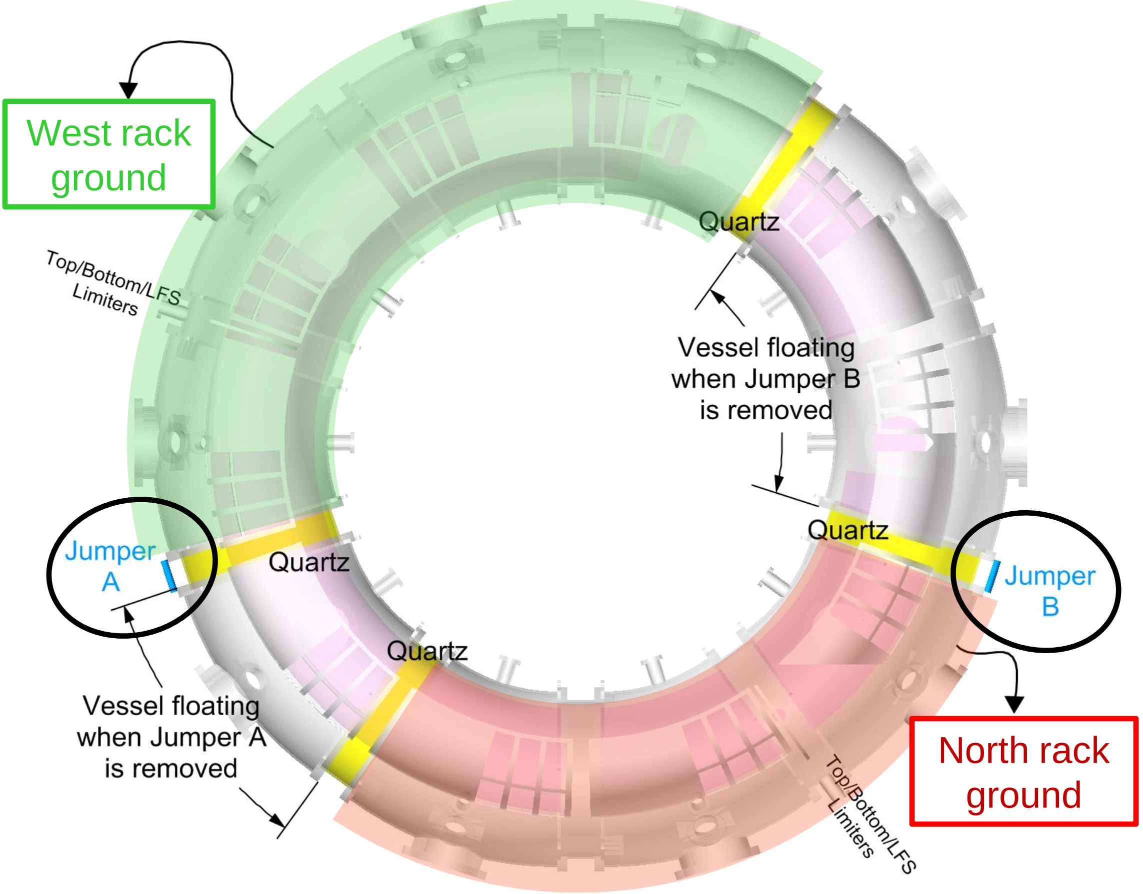


- Isolated chamber sections
- Jumpers between isolated vessel sections
- Poloidal arrays of B_θ sensors
- Grounded electrode in the SOL

Typical discharge parameters

Major Radius:	92 cm
Minor Radius:	15 cm
Plasma Current:	~15 kA
Toroidal Field:	0.33 T
Pulse Length:	5 - 10 ms
Electron Temperature:	≤ 150 eV

SOL current diagnostics on HBT-EP



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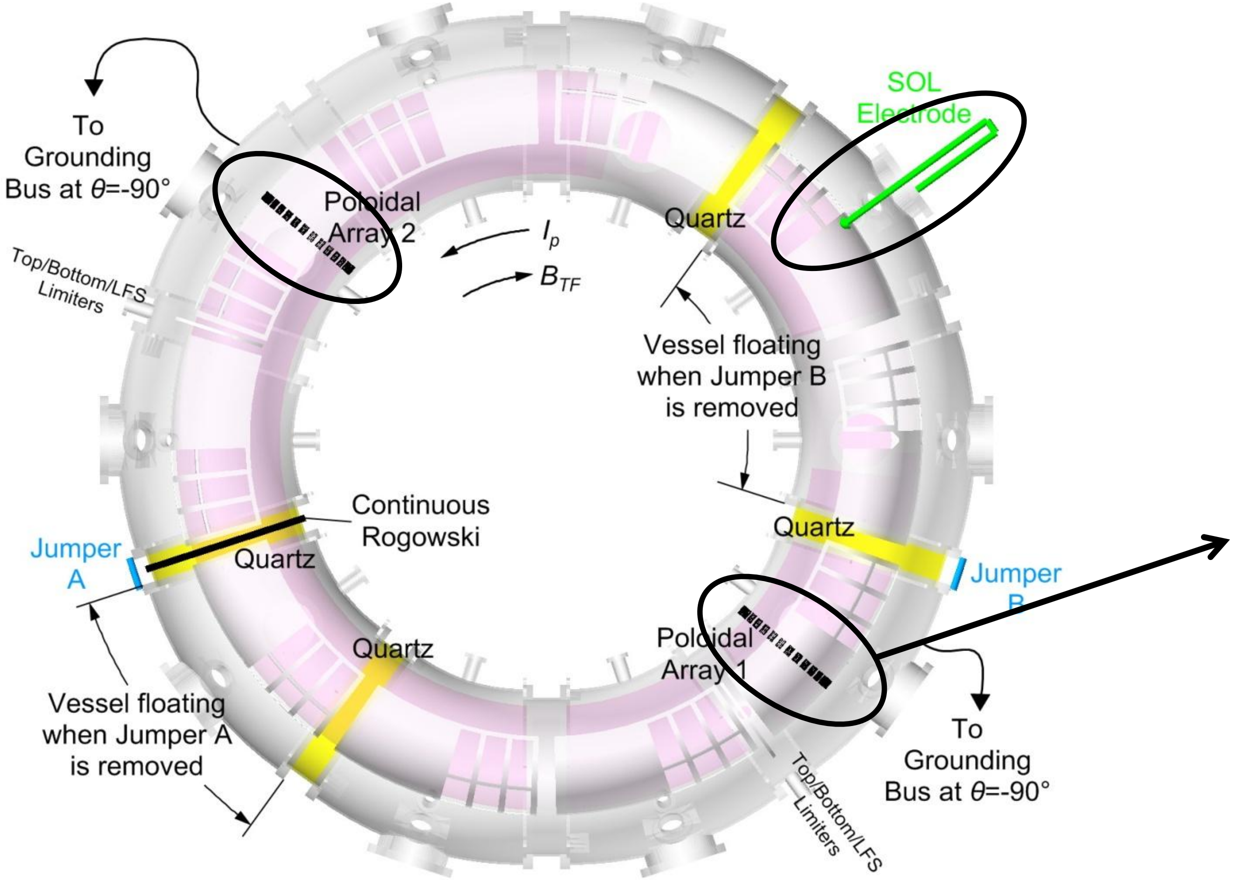

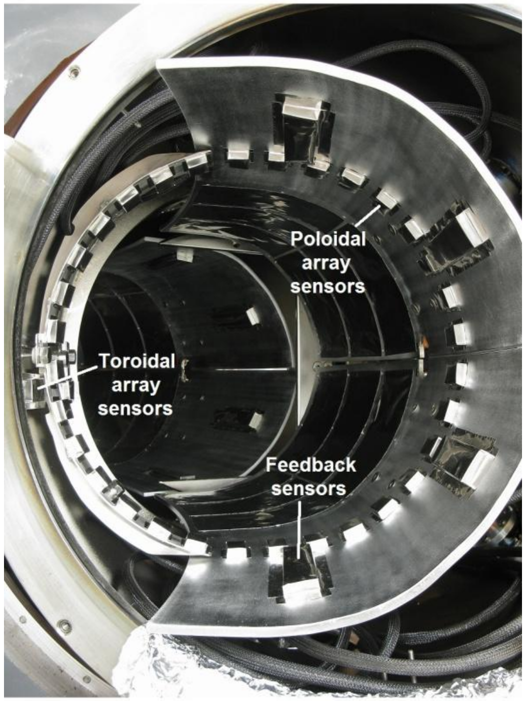

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SOL current diagnostics on HBT-EP

- Poloidal arrays measure *I_p* asymmetry and current moments:

Plasma current at each φ: $I_{\mathrm{p}}^{\mathrm{PAp}} = \oint \vec{B} \cdot \mathrm{d}\vec{l}\,/\mu_0$

Plasma current asymmetry: $\Delta I_{\mathrm{p}} = I_{\mathrm{p}}^{\mathrm{PA2p}} - I_{\mathrm{p}}^{\mathrm{PA1p}}$

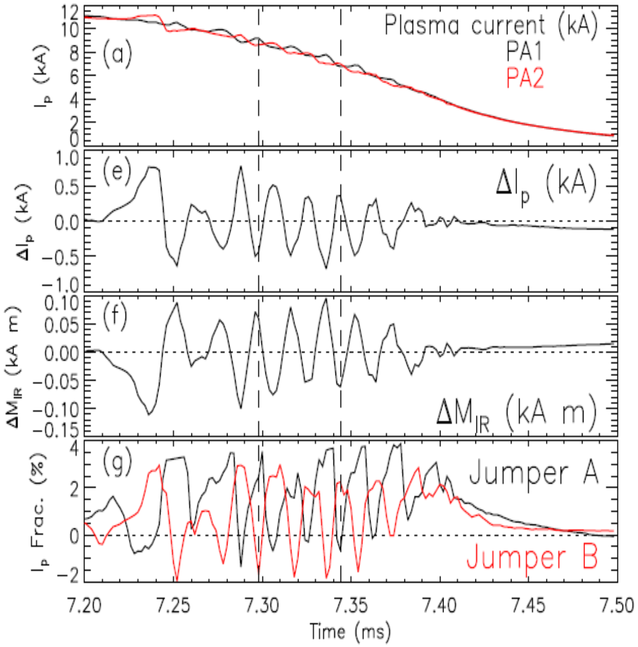
Fractional I_p asymmetry: $f_{\mathrm{PA}}^{\mathrm{asym}} = 2\Delta I_{\mathrm{p}}/(I_{\mathrm{p}}^{\mathrm{PA2p}} + I_{\mathrm{p}}^{\mathrm{PA1p}})$

Vertical current moment: $M_{\mathrm{IZ}} \equiv \int Z j_{\mathrm{plasma}}\, \mathrm{d}R\mathrm{d}Z$

Radial current moment:

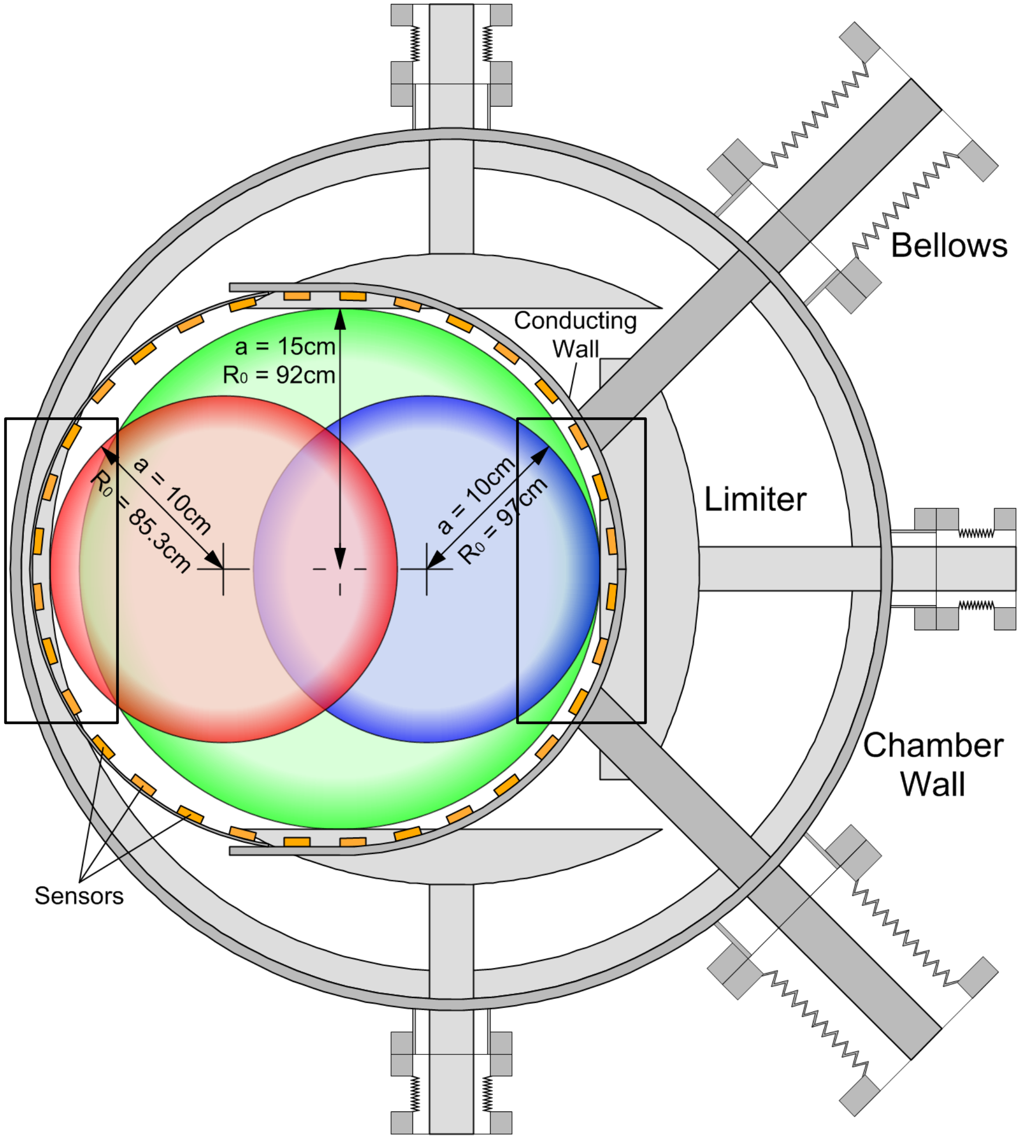
$$M_{\mathrm{IR}} \equiv \int (R - R_{\mathrm{cent}}) j_{\mathrm{plasma}}\, \mathrm{d}R\mathrm{d}Z = \sum B_{\theta i}(R_i - R_{\mathrm{cent}})\mathrm{d}l_i/\mu_0$$

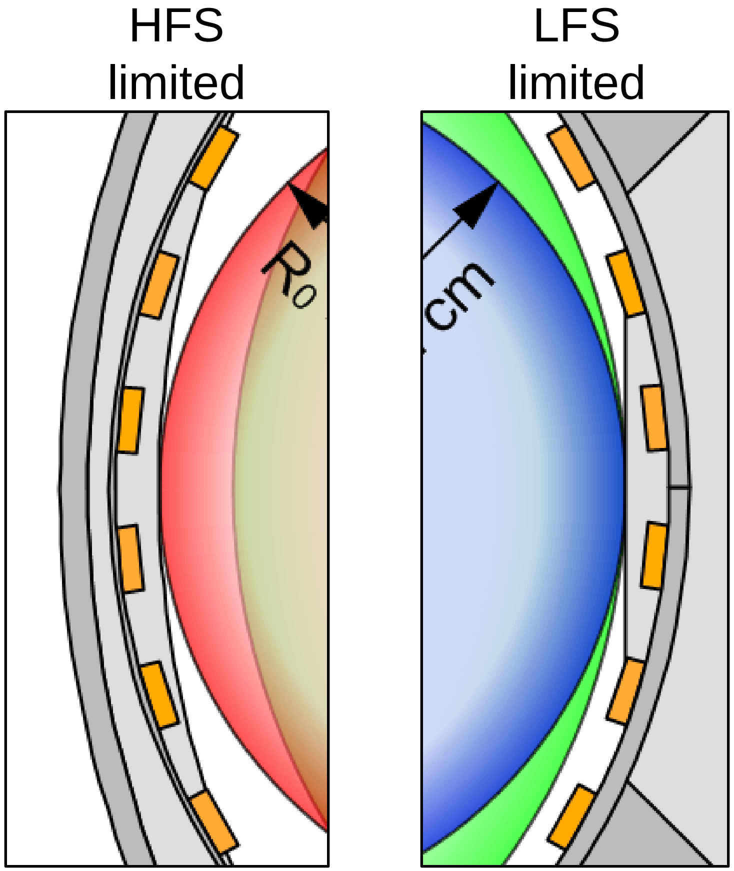
Radial moment asymmetry: $\Delta M_{\mathrm{IR}} = M_{\mathrm{IR}}^{\mathrm{PA2p}} - M_{\mathrm{IR}}^{\mathrm{PA1p}}$



- Jumpers across quartz breaks directly measure toroidal vessel current
  - Positive current defined as co-*I_p*
  - Fractional current is normalized to plasma current: $f_{A,B}^{\mathrm{jumper}} = I_{A,B}^{\mathrm{jumper}}/I_{\mathrm{p}}$

HFS- and LFS-limited plasmas have only ~1cm thick vacuum/SOL region between LCFS and magnetic sensors





- Limiting surfaces are at different toroidal angles than the sensors

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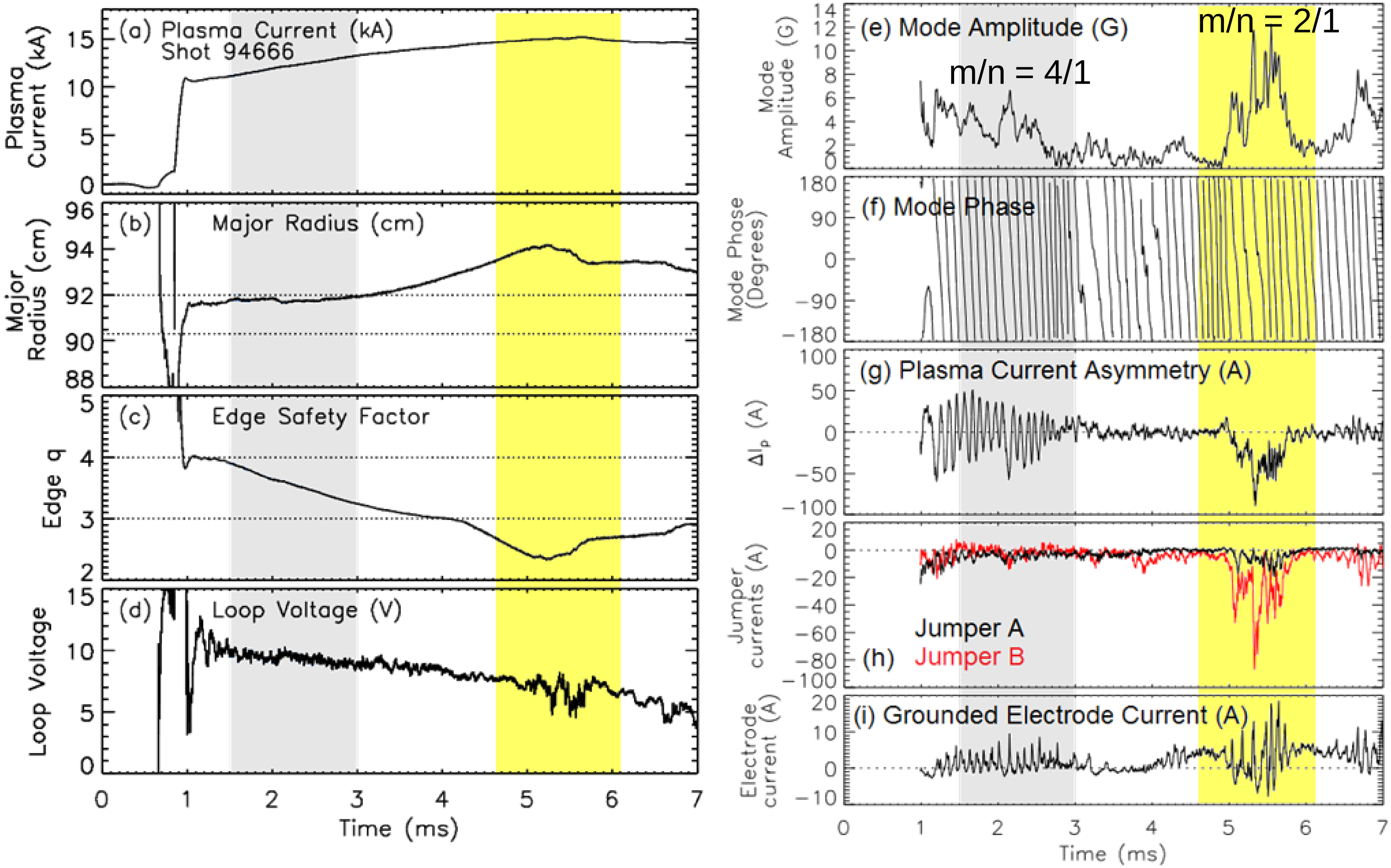
MHD modes during main discharge are accompanied by I_p asymmetries and driven vessel currents that must conduct through the SOL



- An $m/n=4/1$ kink mode initiates after startup, then decays as q_* decreases
- An $m/n=2/1$ mode appears later at lower q_*
- SOL current features are different for each mode and diagnostic

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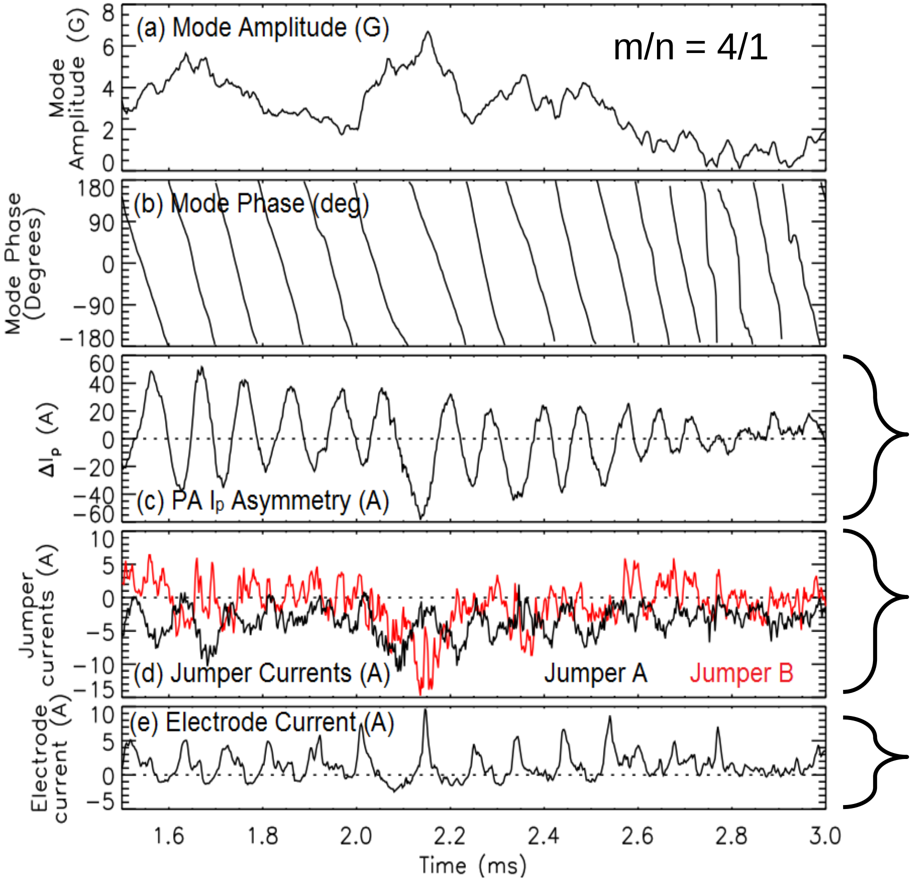
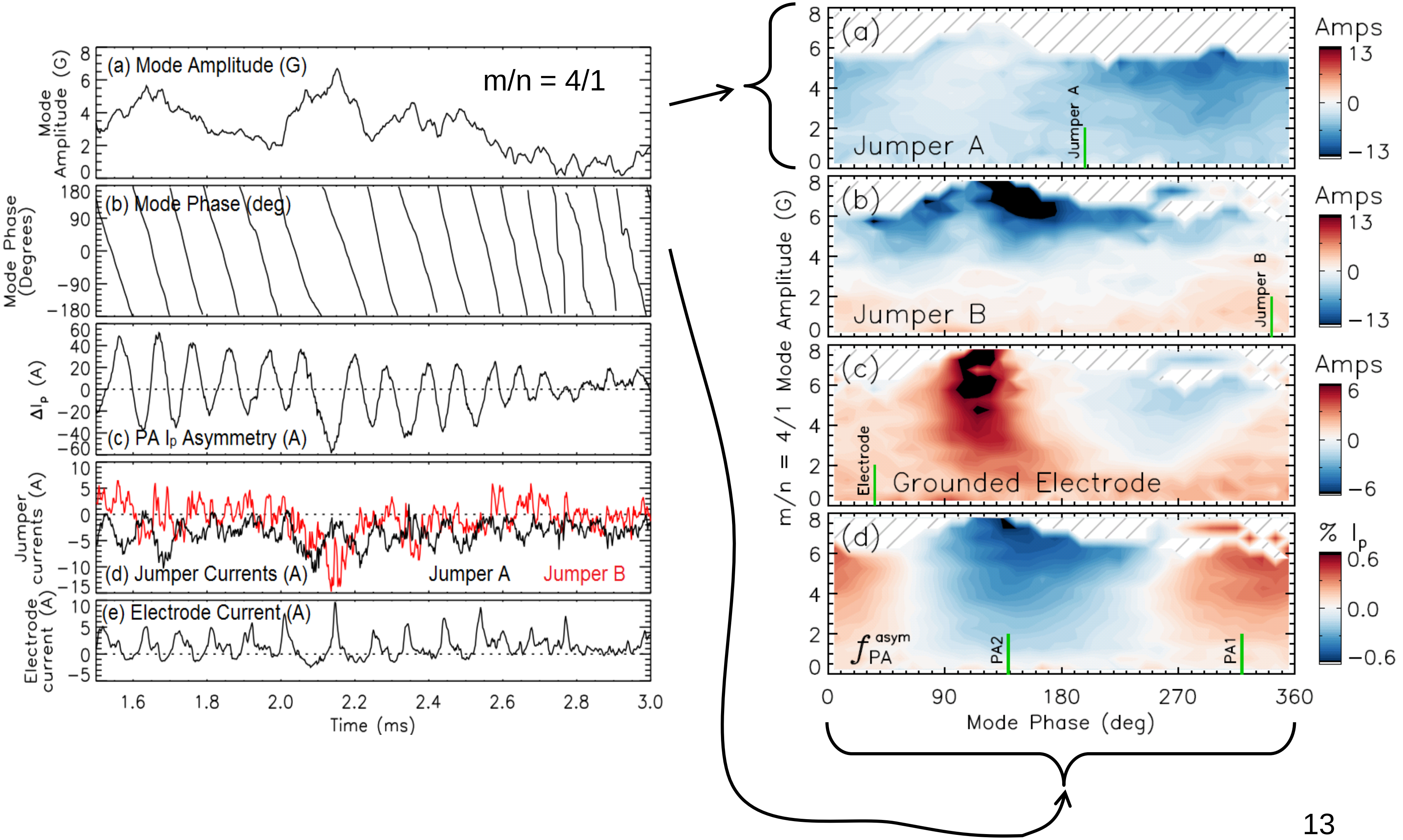


For the initial 4/1 mode:

- SOL currents are modulated by mode amplitude and phase
  - Stronger currents for larger mode amplitudes
- I_p asymmetry of up to 0.5%
- Toroidal Jumper currents are mostly counter-I_p (negative)
- Grounded electrode measures brief current spikes
  - Positive current for collecting electrons

I_p asymmetry and driven vessel current behavior is consistent for early 4/1 modes in each discharge



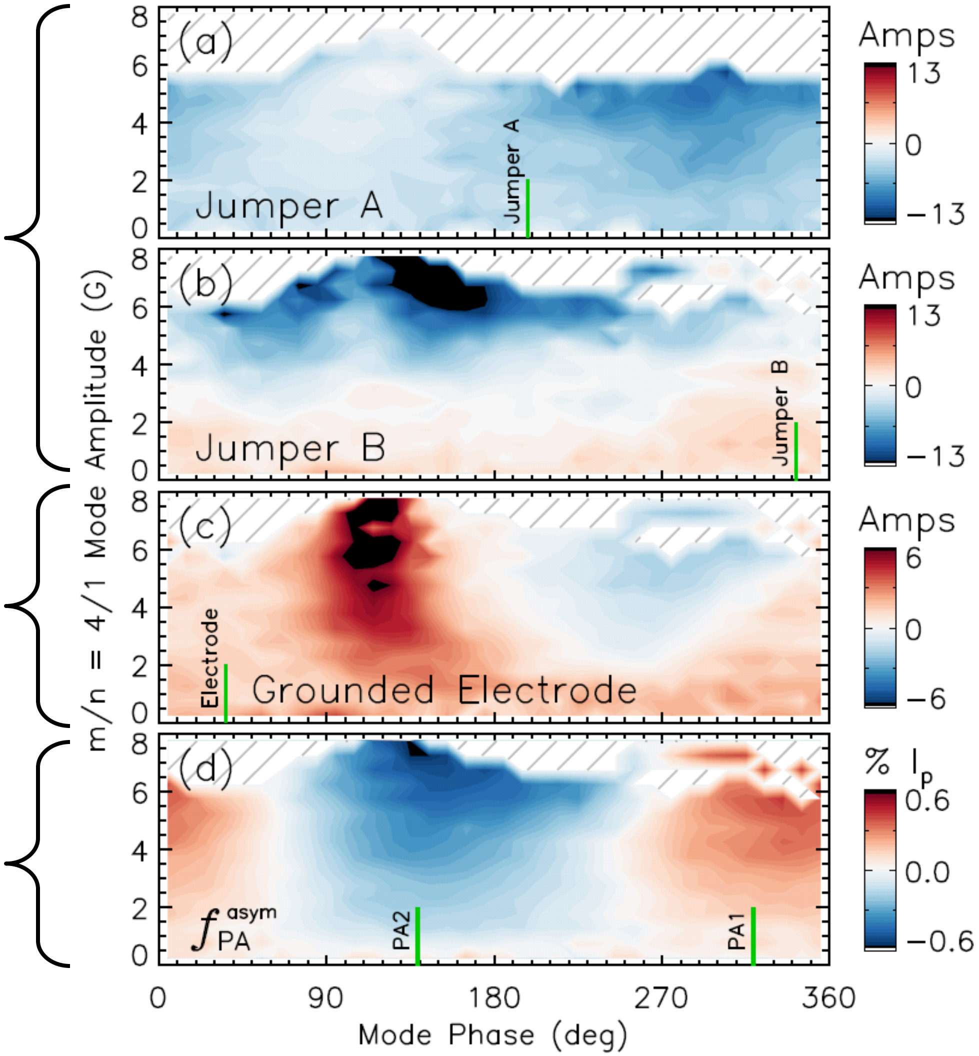
I_p asymmetry and driven vessel current behavior is consistent for early 4/1 modes in each discharge

- Toroidal jumper currents are weak (~0.1% of I_p) and mostly counter-I_p in response to larger modes

- Grounded SOL electrode collects largest electron current when δB_r is maximum at the probe location

- Each poloidal array measures elevated I_p when the nearby jumper current is counter-I_p

24 discharges



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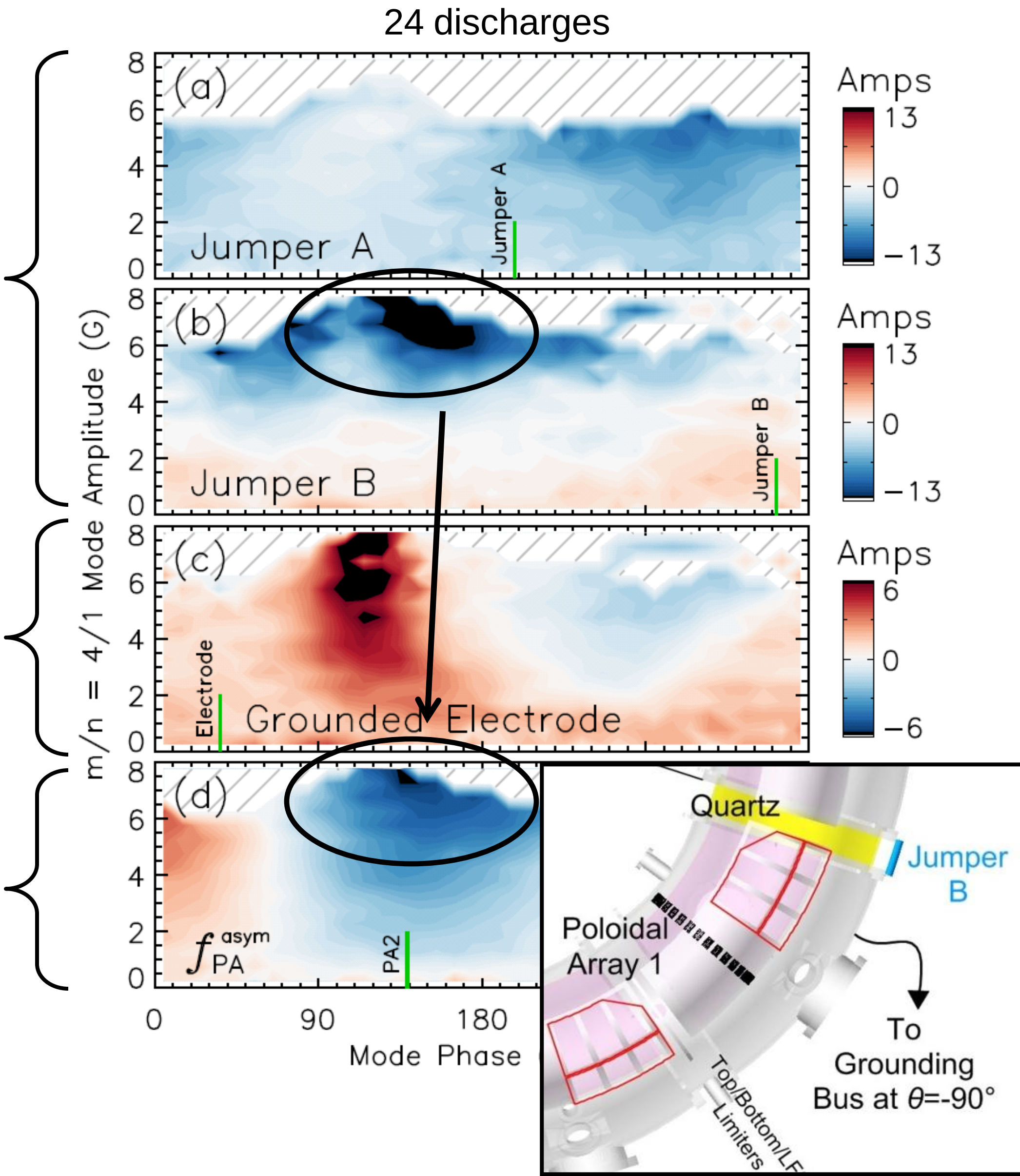
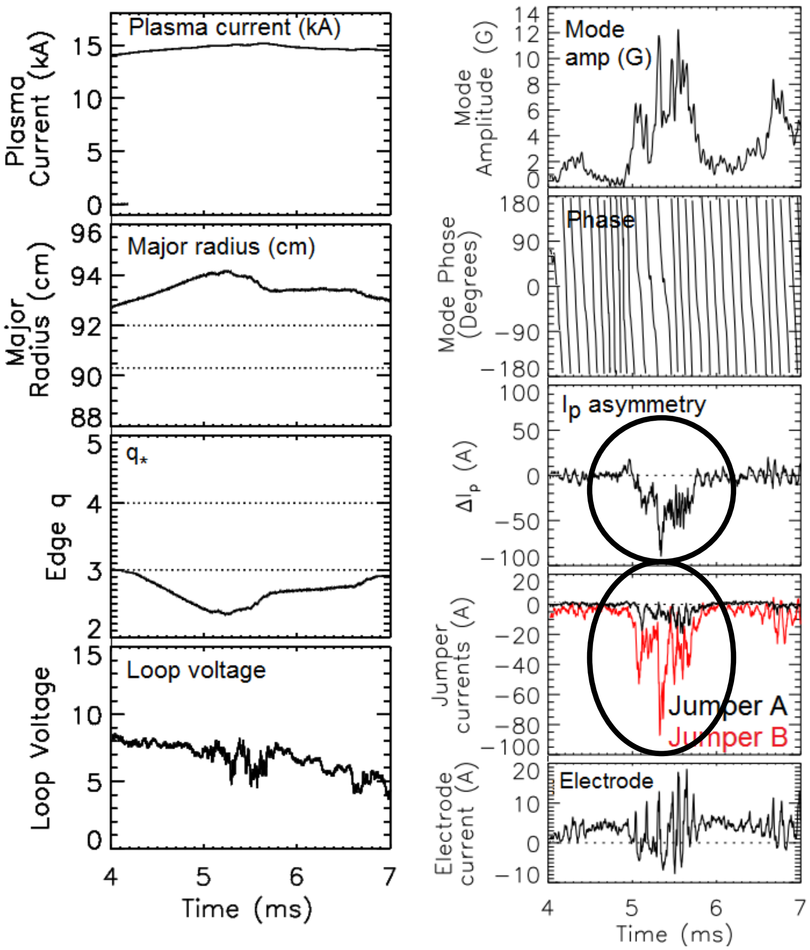


Later *m/n=2/1* modes have different features

- During rotation of a strong transient 2/1 mode, I_p asymmetry *does not* rotate
  - I_p remains elevated on one side of tokamak despite several periods of mode rotation
- Jumper B measures much stronger current than Jumper A throughout rotation



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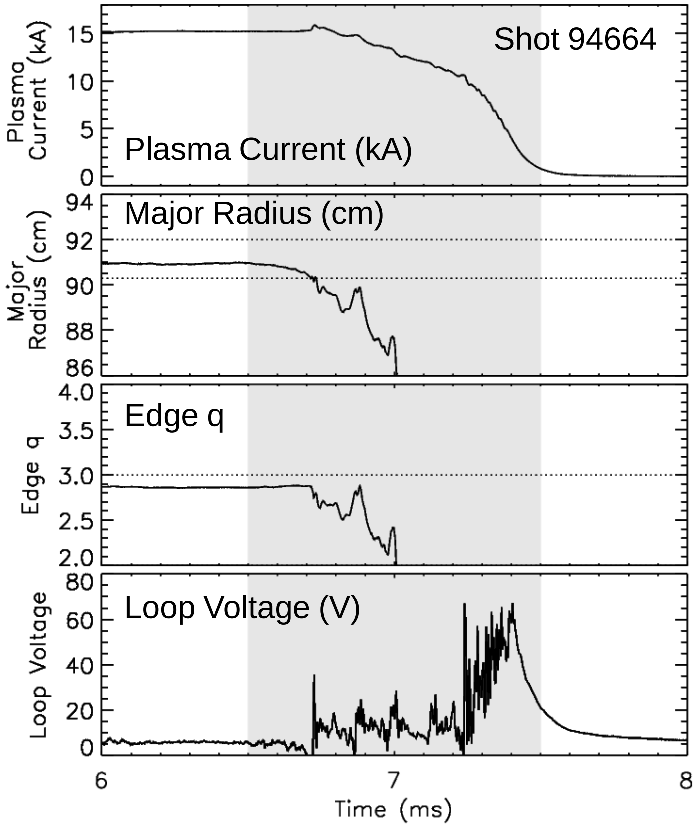
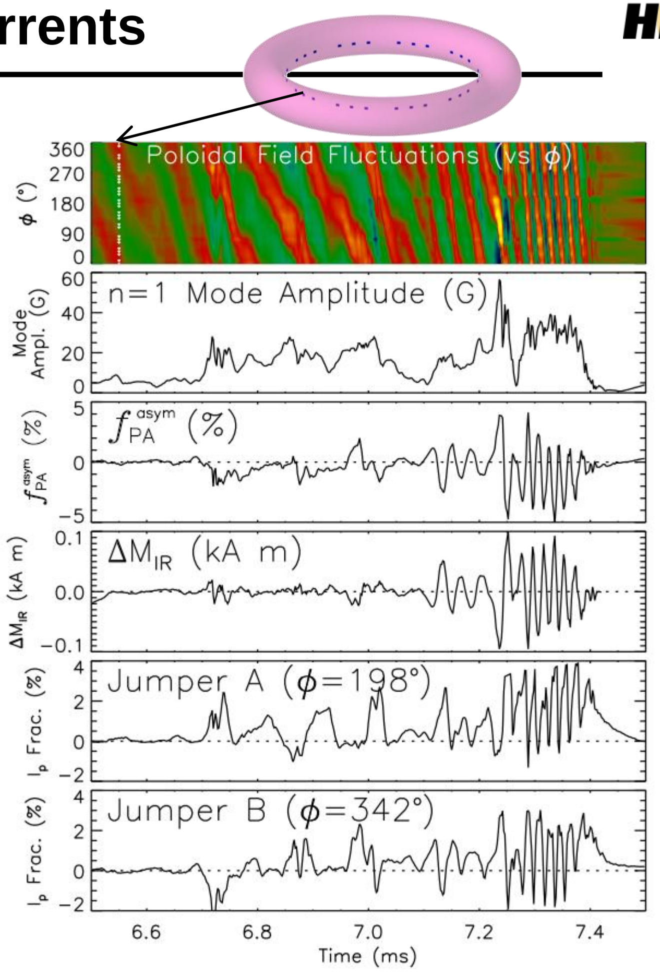
Disruptions yield large asymmetries in plasma current and toroidal vessel currents

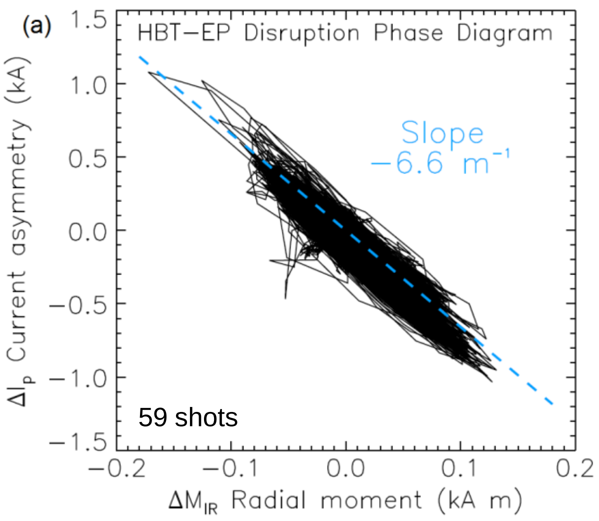




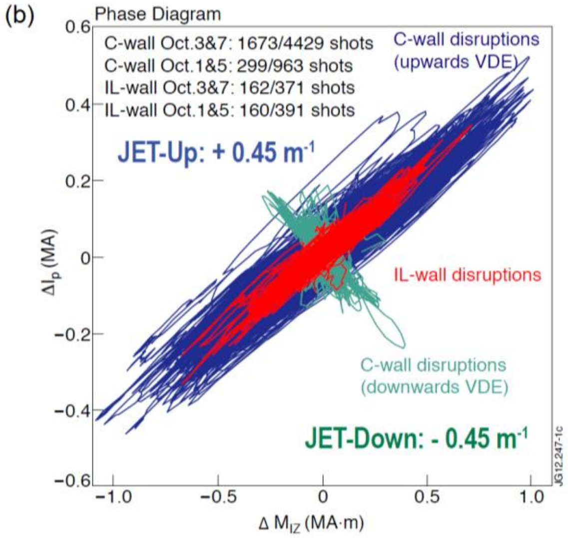
- Asymmetric field $\delta B_\theta/B_\theta$ reaches 20%
- Jumper currents and I_p asymmetry are ~5% of pre-disruption I_p
- Halo current rotation is much faster than in larger tokamaks
  - Generally above 20kHz, rather then below 2kHz

Plasma current asymmetries scale with displacement of current centroid toward the vessel wall

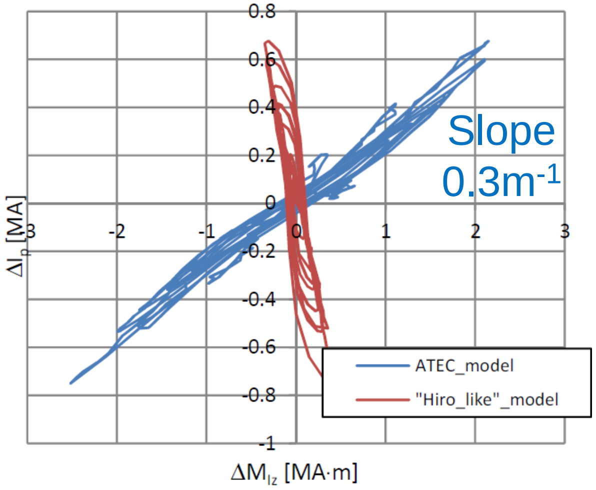
HBT-EP



JET[1]



ITER[2]



- Relation between ΔI_p *and* ΔM_I asymmetries agree with JET measurements and ITER predictions using ATEC model
  - – Opposite pitch is due to which direction gives motion into the wall

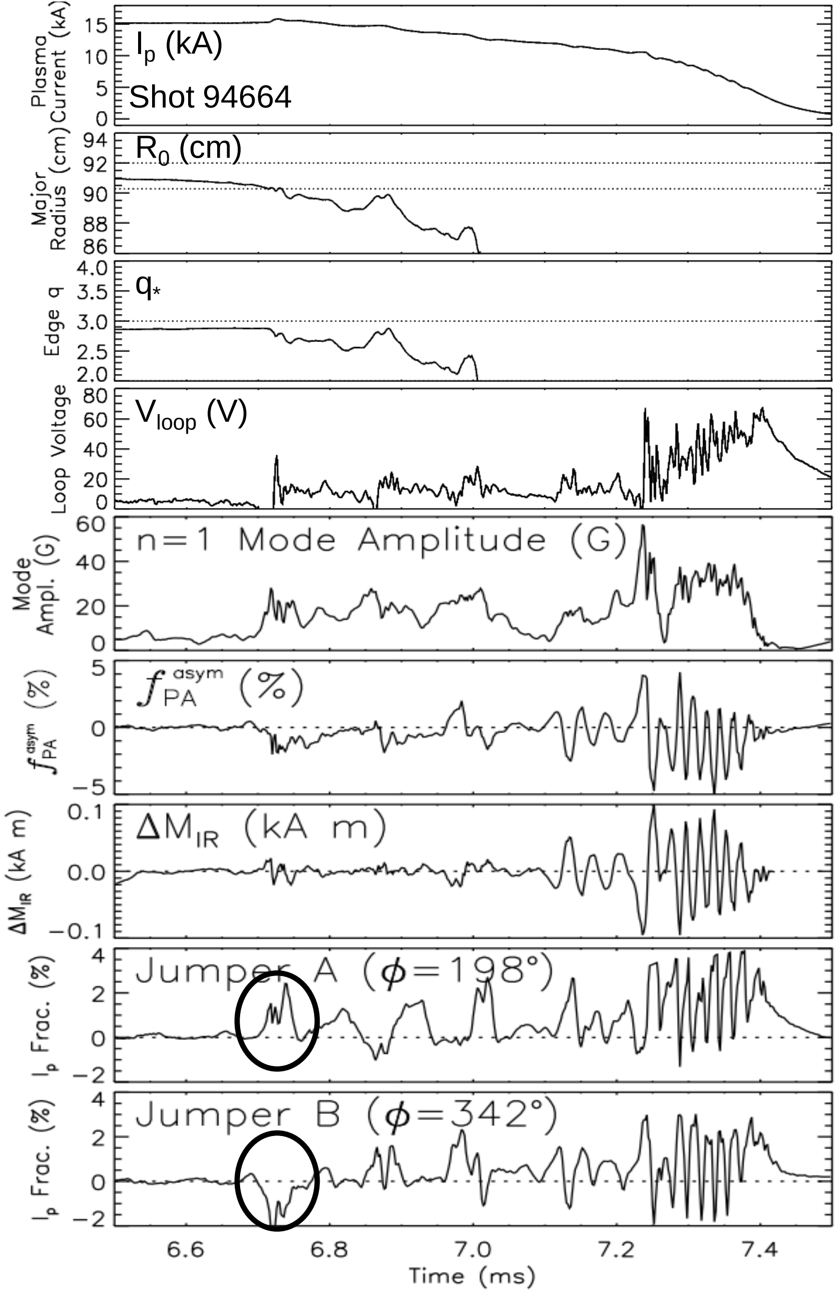
- Slope scales as ~*1/a* characteristic for each tokamak

[1] Gerasimov S.N. *et al.*, *Nucl. Fusion* **54** 073009 (2014)
[2] Roccella R. *et al.,* “Modelling ITER asymmetric VDEs through asymmetries of toroidal eddy currents” IAEA FEC [EX/P6-40] (2016)

Different SOL current characteristics at varying stages of disruptions

1. Current spike
   - Toroidal jumpers usually measure a counter-I_p spike, but occasionally measure co-I_p spikes.
     - Co-Ip spike occurs when plasma is HFS-limited
2. Slow I_p decay
   - Mode rotates at 10-20kHz
   - Rotation is irregular
3. Fast I_p decay
   - Fast halo current rotation at ~50kHz
   - Rotation is smooth
4. Symmetric vessel currents
   - Co-I_p vessel currents conduct across insulating breaks after mode decays

①



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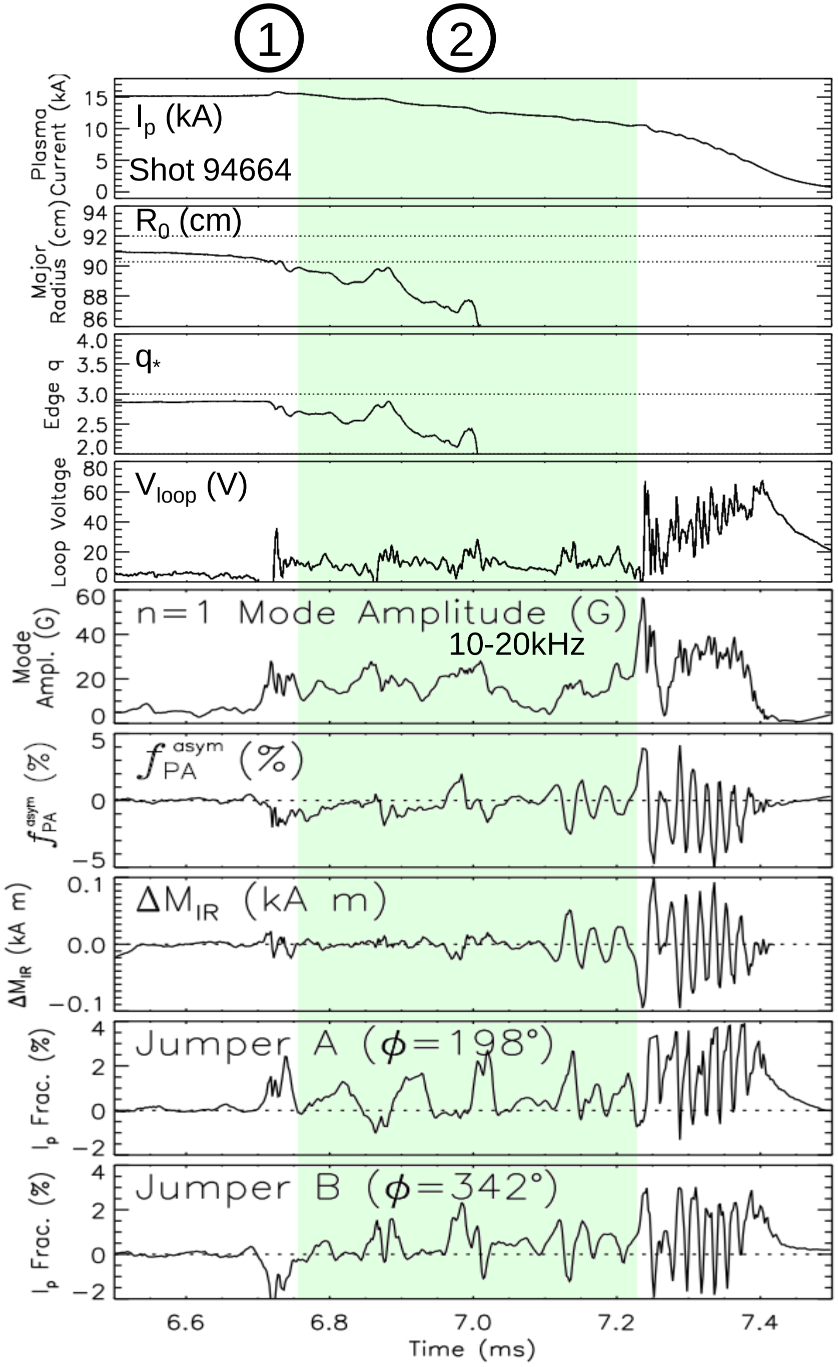

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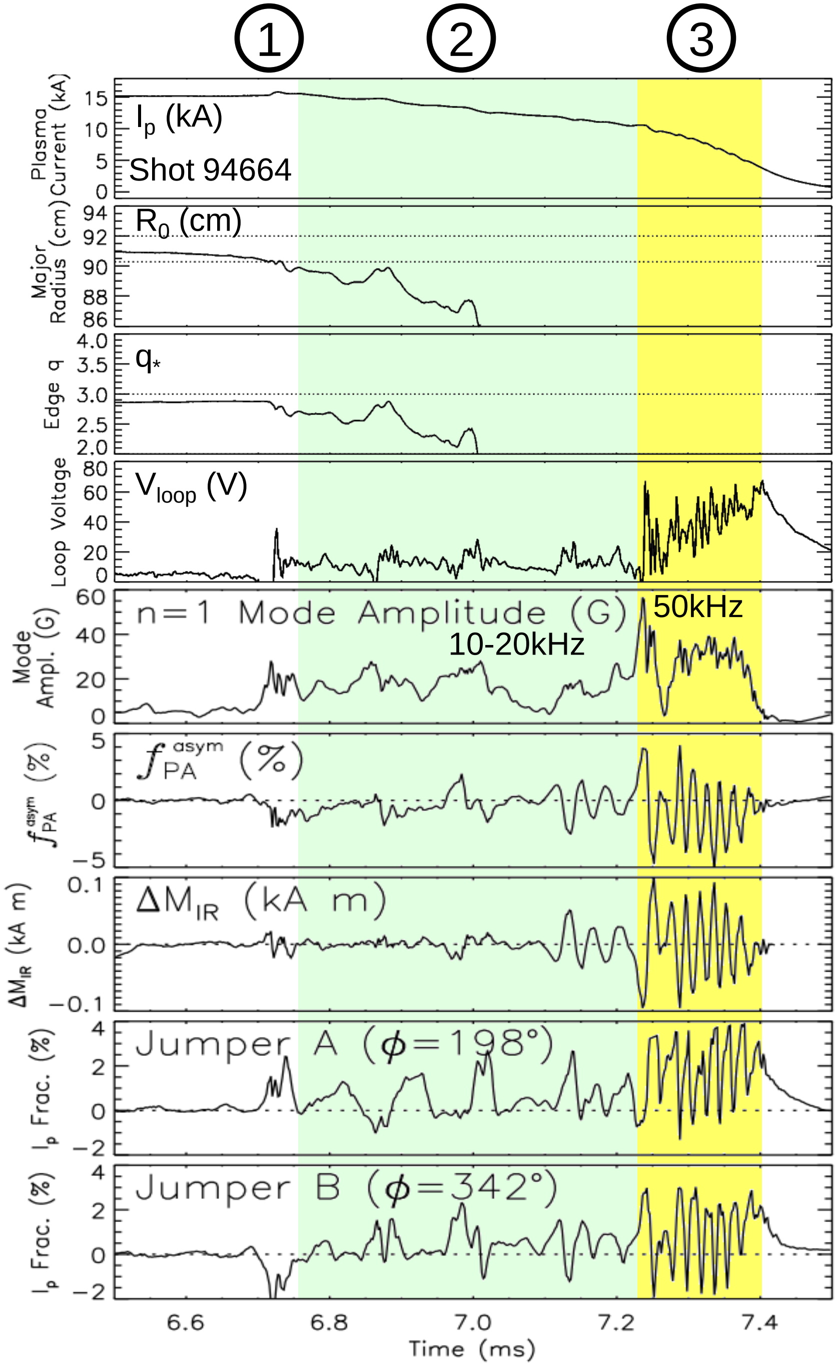

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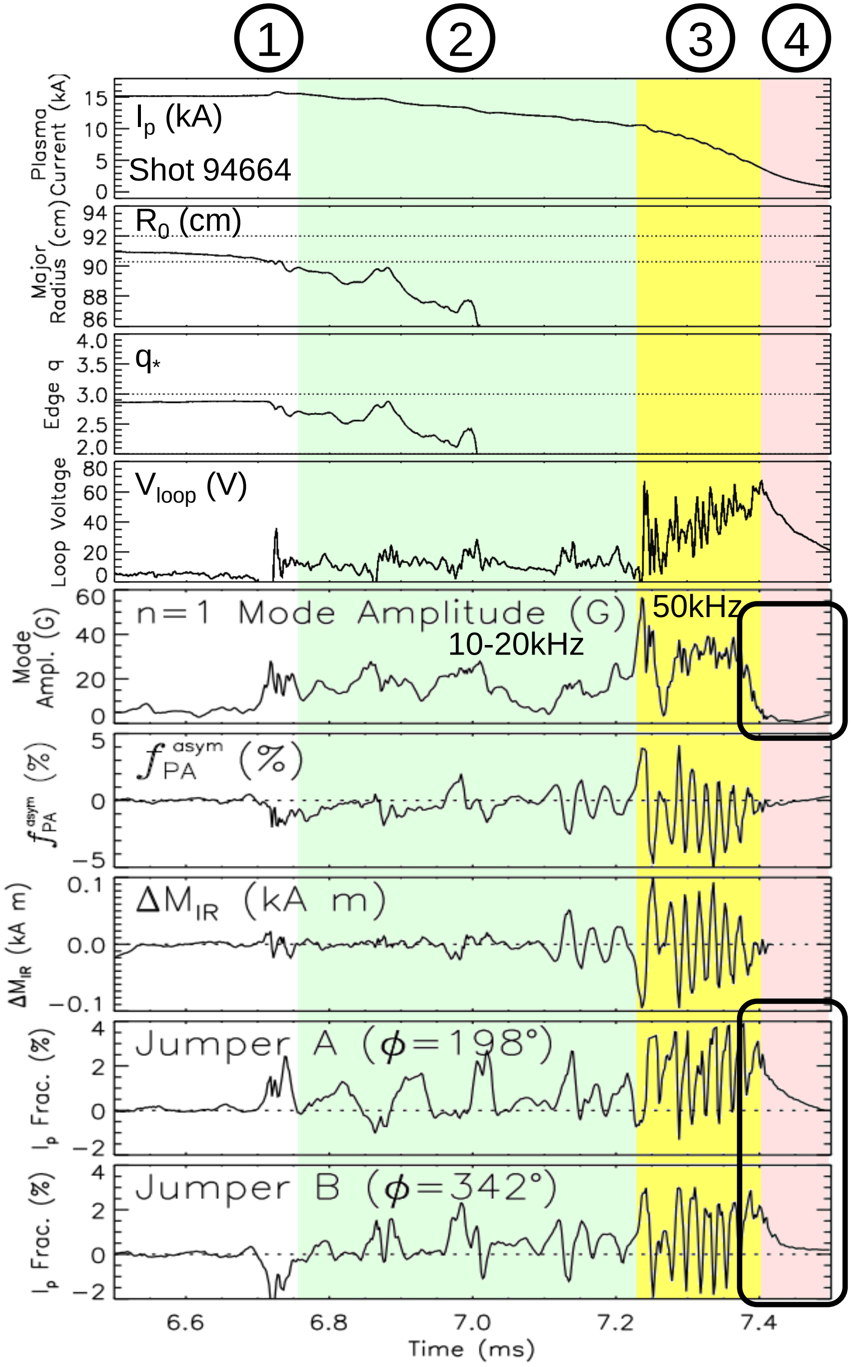
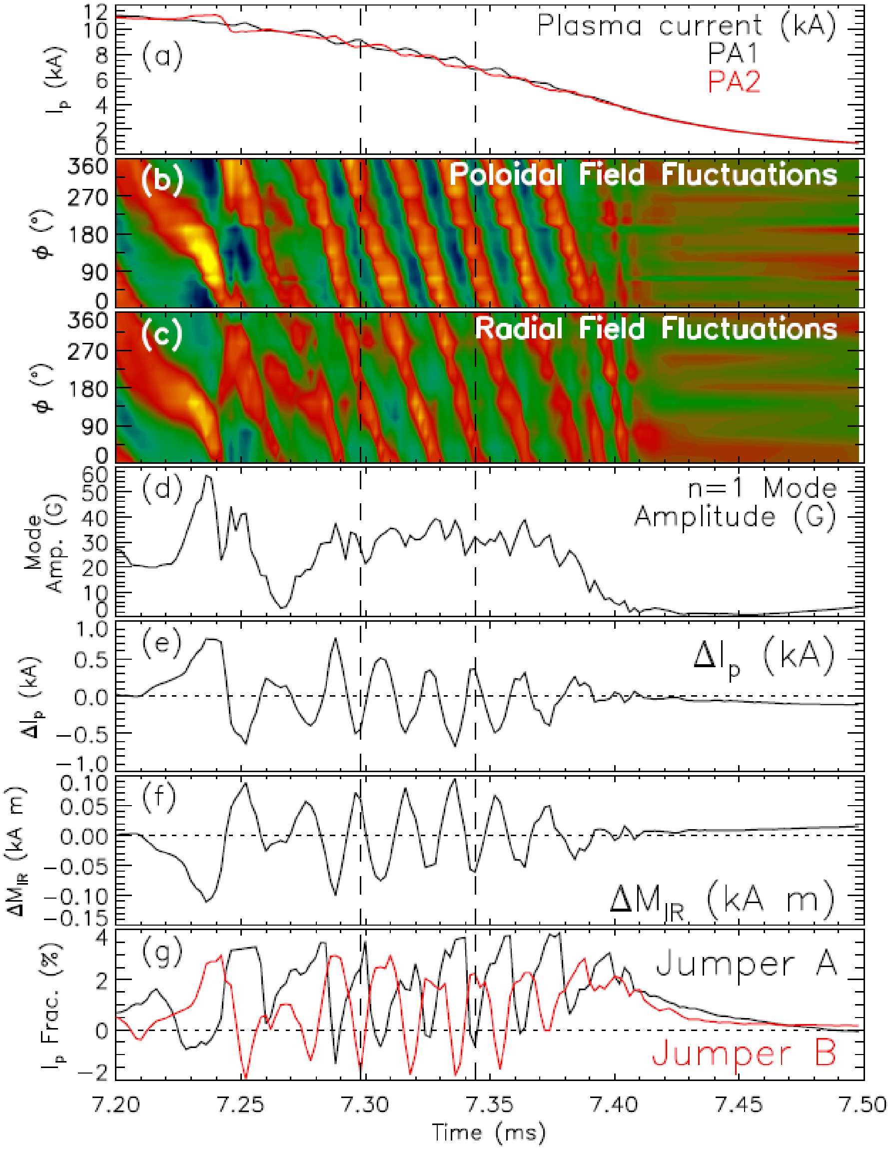
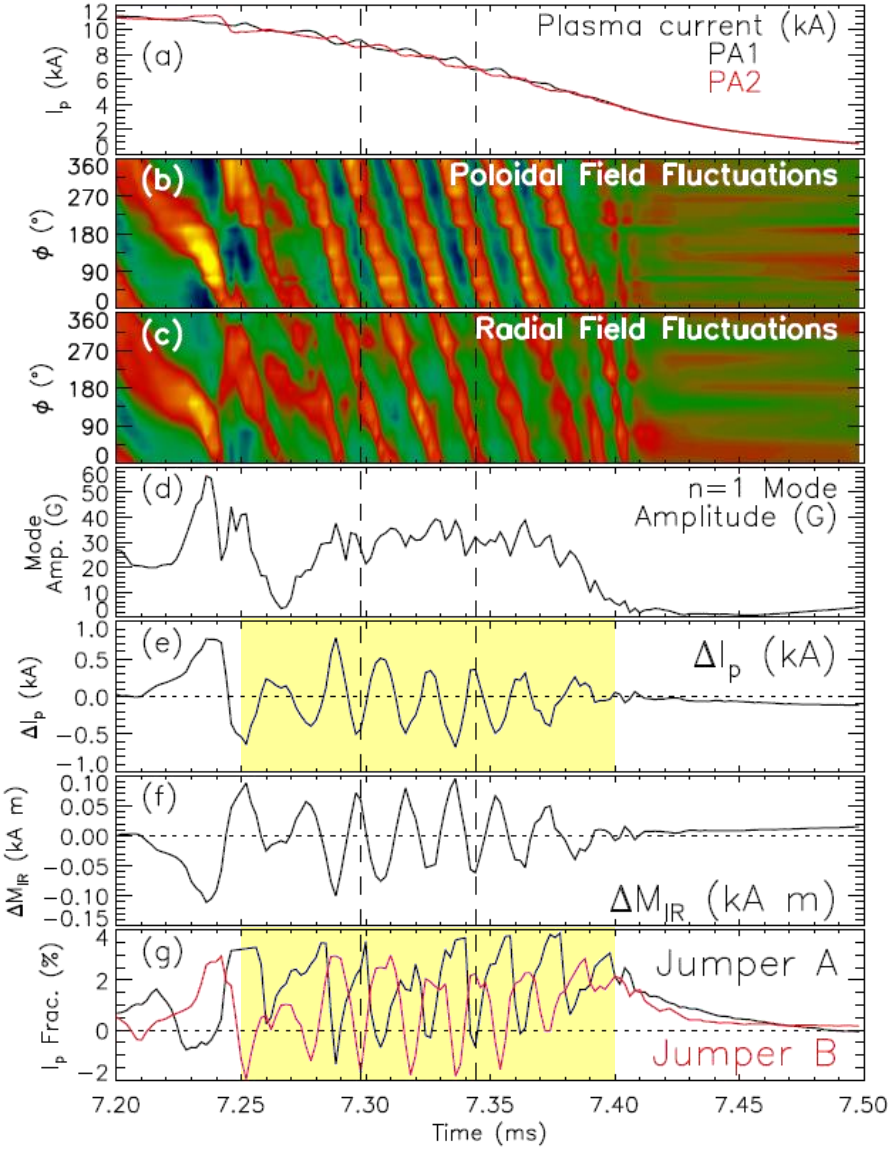


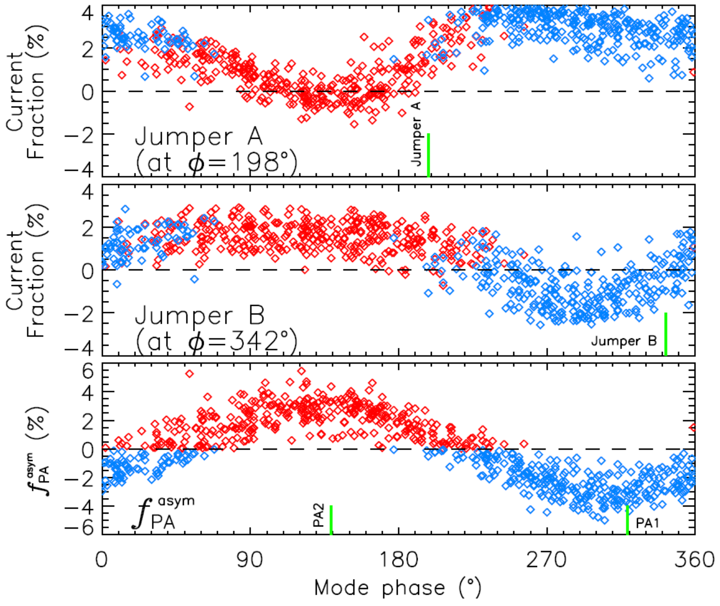
High frequency mode during fast CQ ramp accompanies the largest current asymmetries in HBT-EP



- Coherent mode rotating at ~50kHz

Clear phase relation exists between I_p asymmetry and toroidal vessel currents





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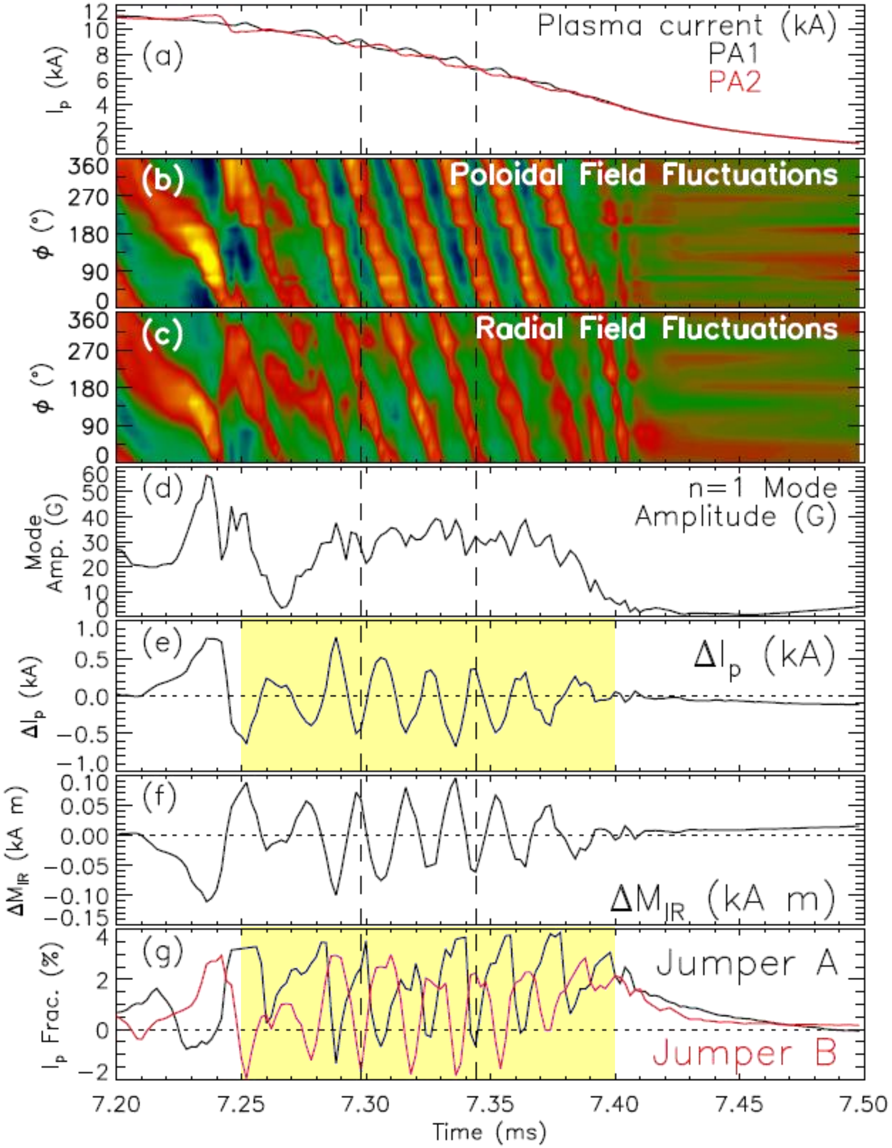
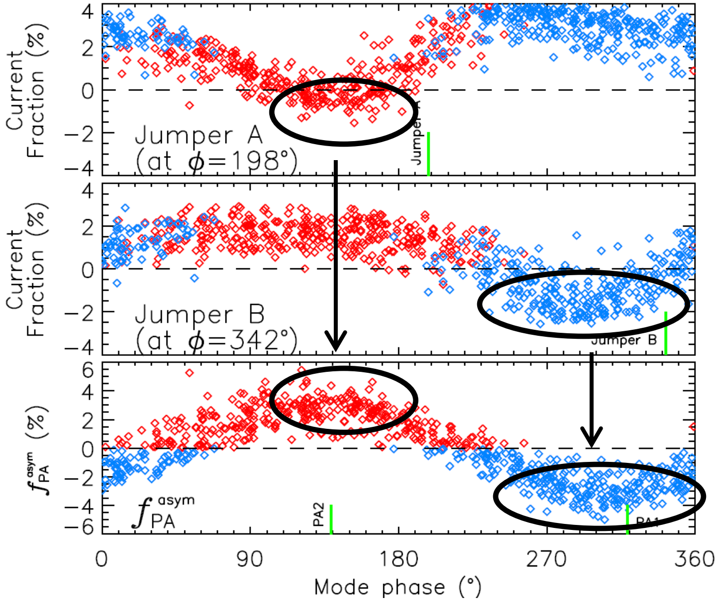
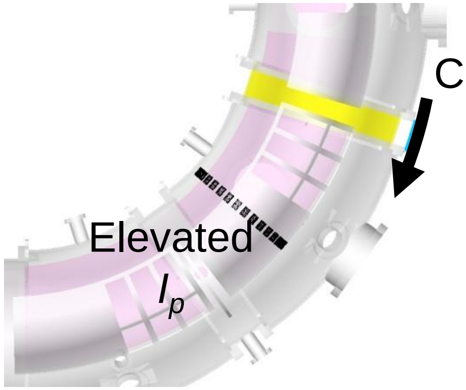


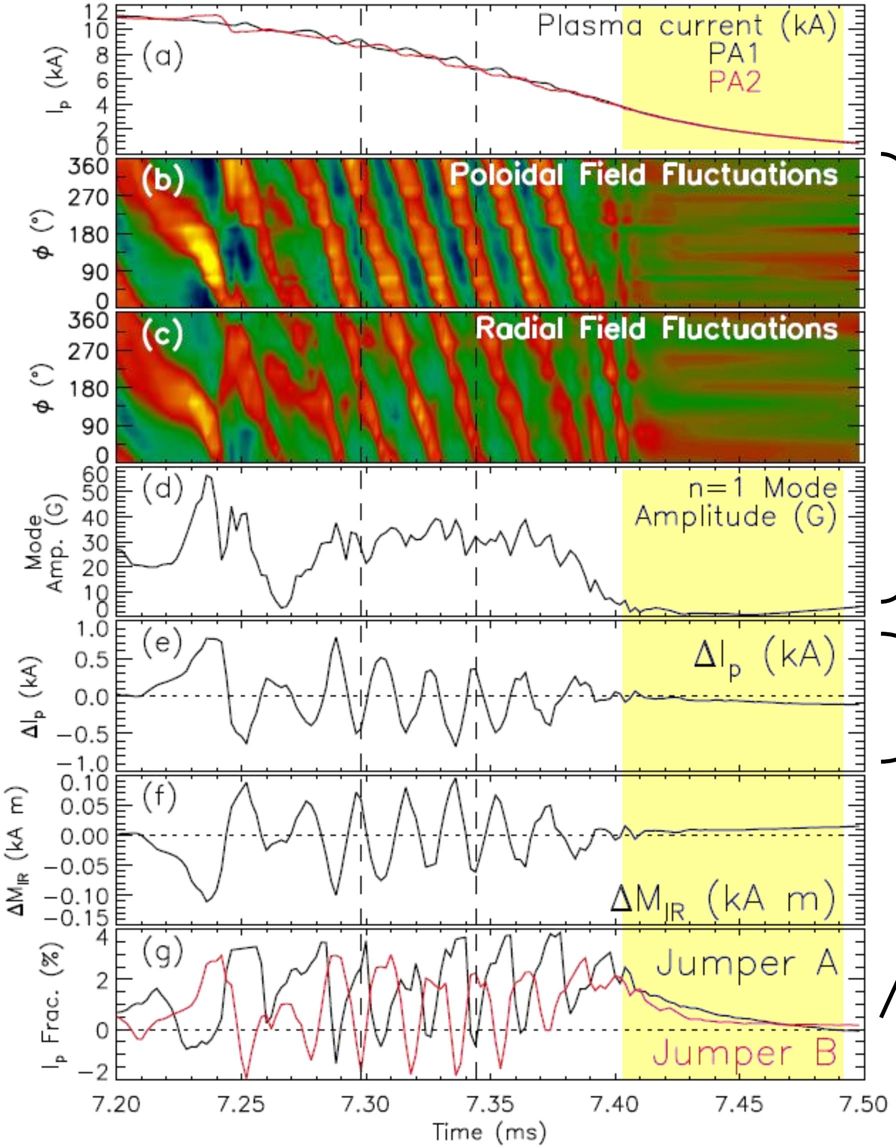


- Local I_p is higher when nearest toroidal jumper has its most negative current



Counter-I_p vessel current

Jumper currents symmetrize in co-I_p direction at end of the current quench



- n=1 mode decays without evidence of locking
- I_p asymmetry vanishes
- Jumper currents remain significant
  - Current must flow across SOL to bridge chamber sections

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How do HBT-EP measurements compare to models of SOL/vessel currents during disruptions?

- WTKM and ATEC models are considered

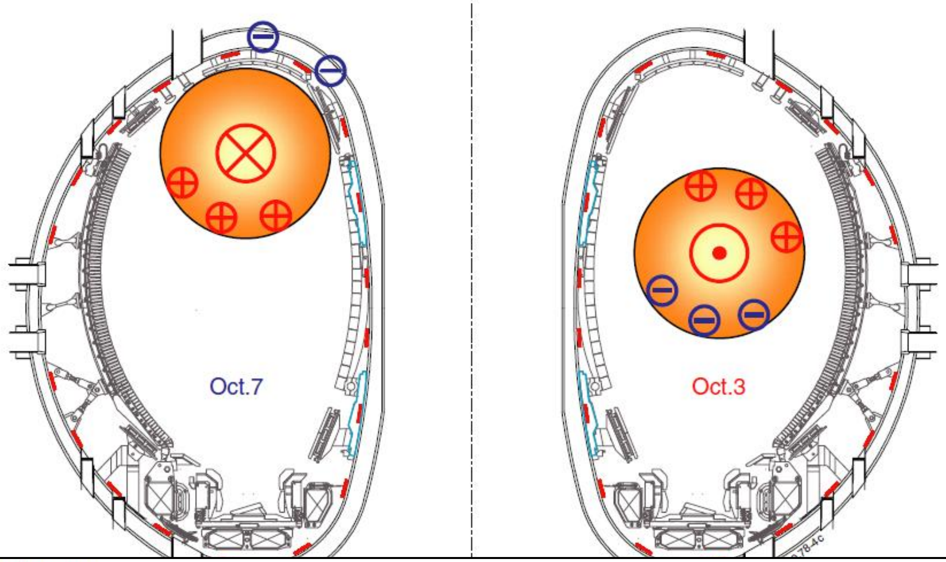
- Models yield contrary predictions for the sign of strong toroidal vessel currents
  - WTKM predicts mostly counter-I_p currents
  - ATEC predicts mostly co-I_p currents

- Disclaimers:
  - This is my personal interpretation of each model
  - Not considering other models

WTKM vs ATEC models for upward VDEs in JET

WTKM

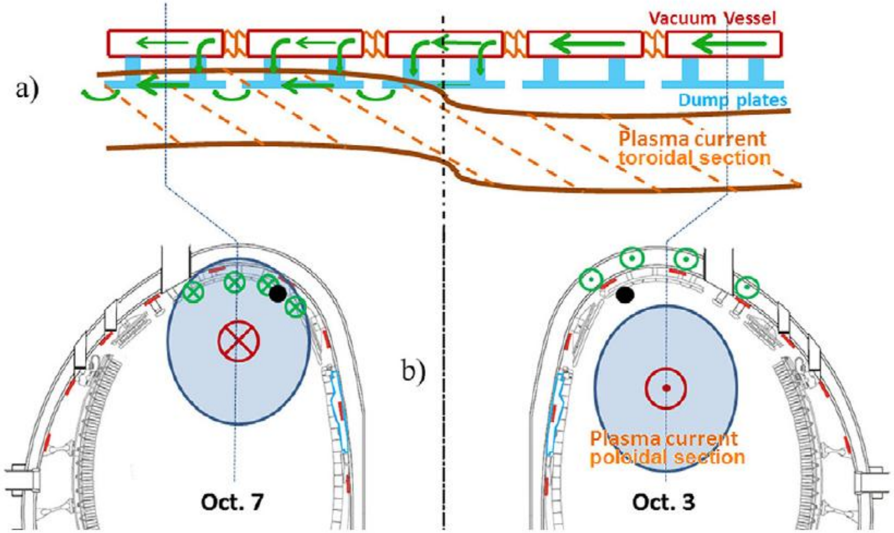
Nucl. Fusion **54** (2014) 073009 S.N. Gerasimov *et al*



- Surface current generated in response to kink will conduct through the vessel upon contact

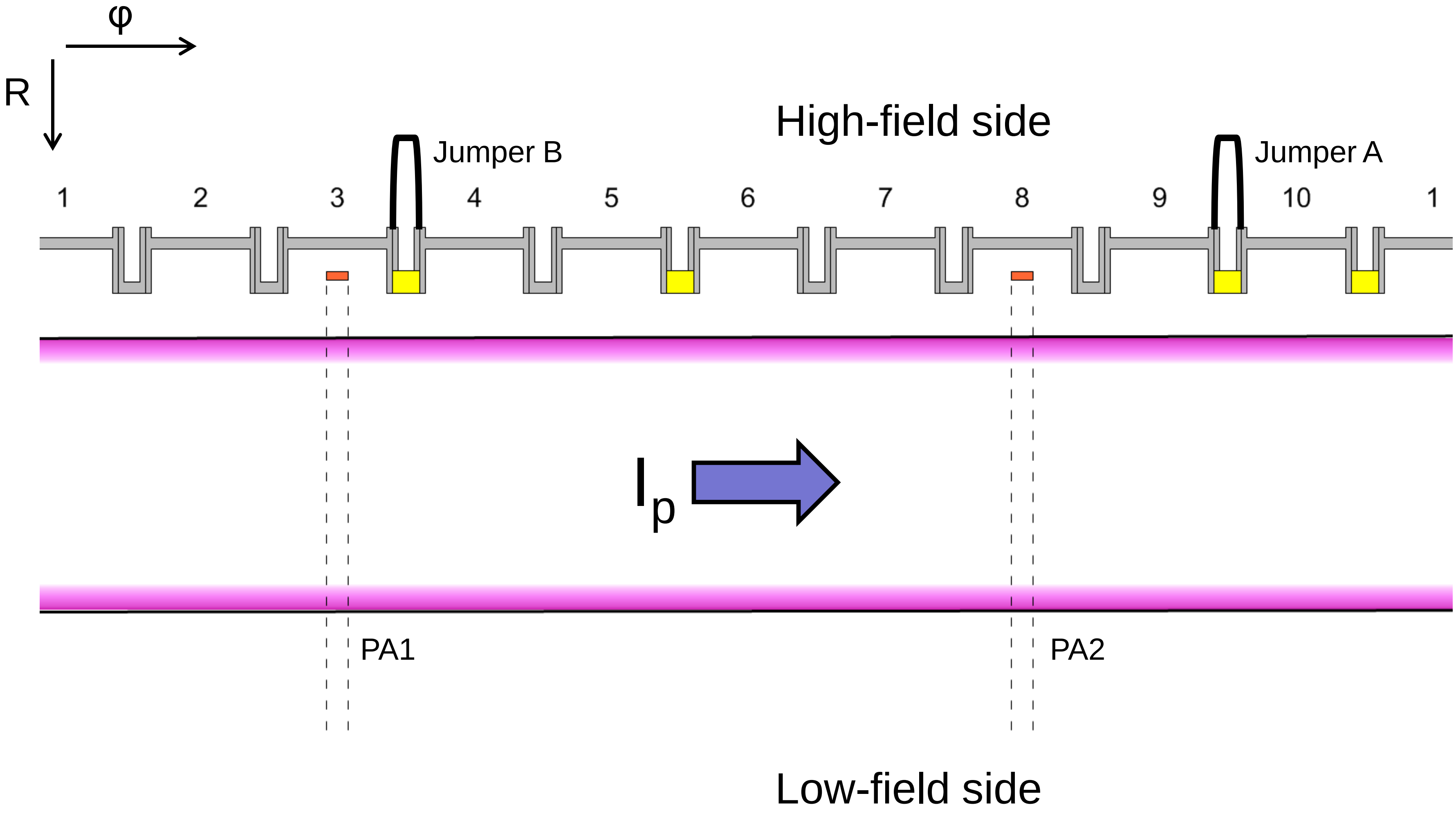
ATEC

Nucl. Fusion **56** (2016) 106010 R. Roccella *et al*



- Vessel eddy current from decaying I_p partially conducts through the plasma upon plasma-wall contact (shorting across tile gaps)

Expected currents in response to disruption kinks in HBT-EP



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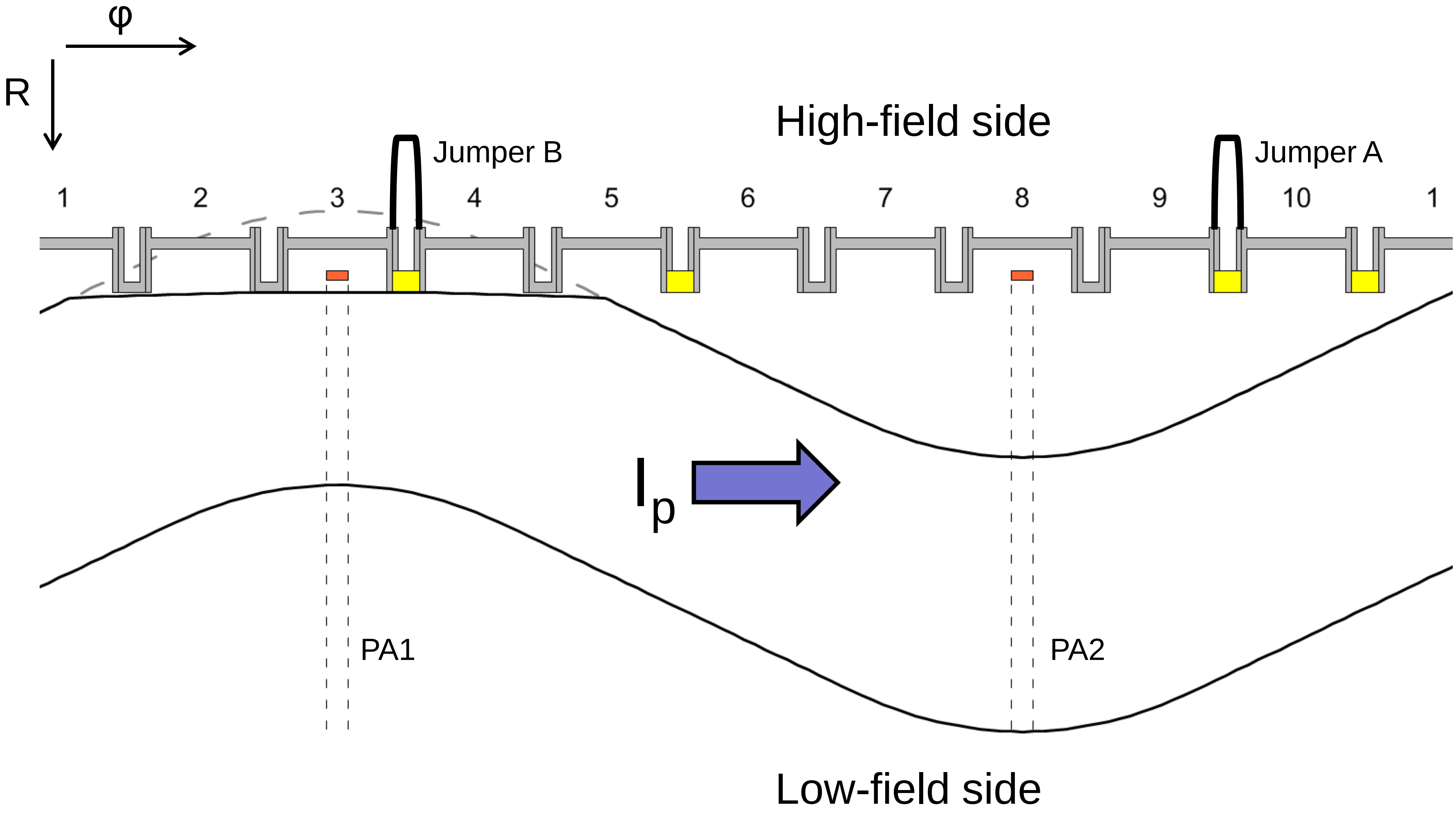

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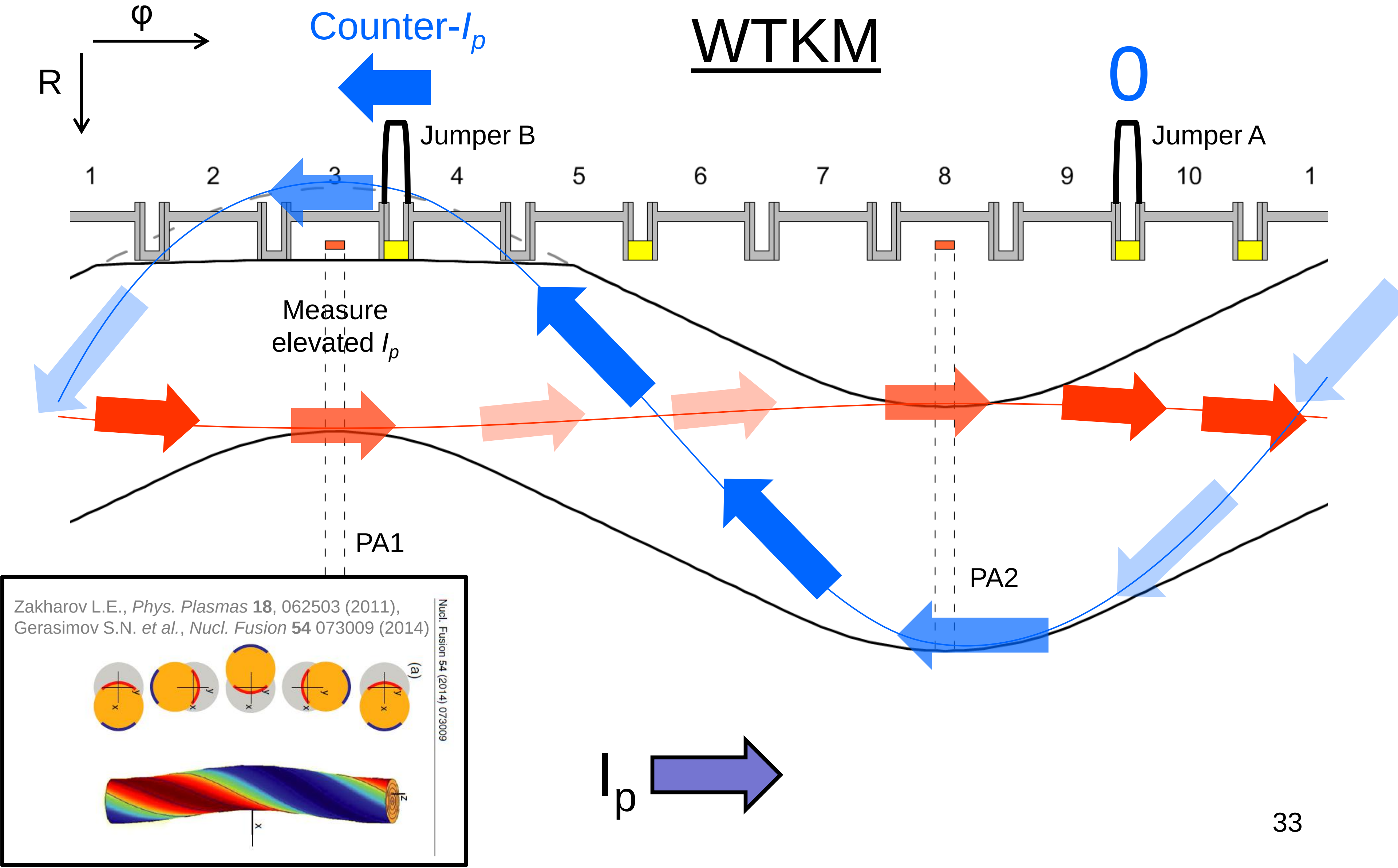

Zakharov L.E., *Phys. Plasmas* **18**, 062503 (2011),
Gerasimov S.N. *et al.*, *Nucl. Fusion* **54** 073009 (2014)

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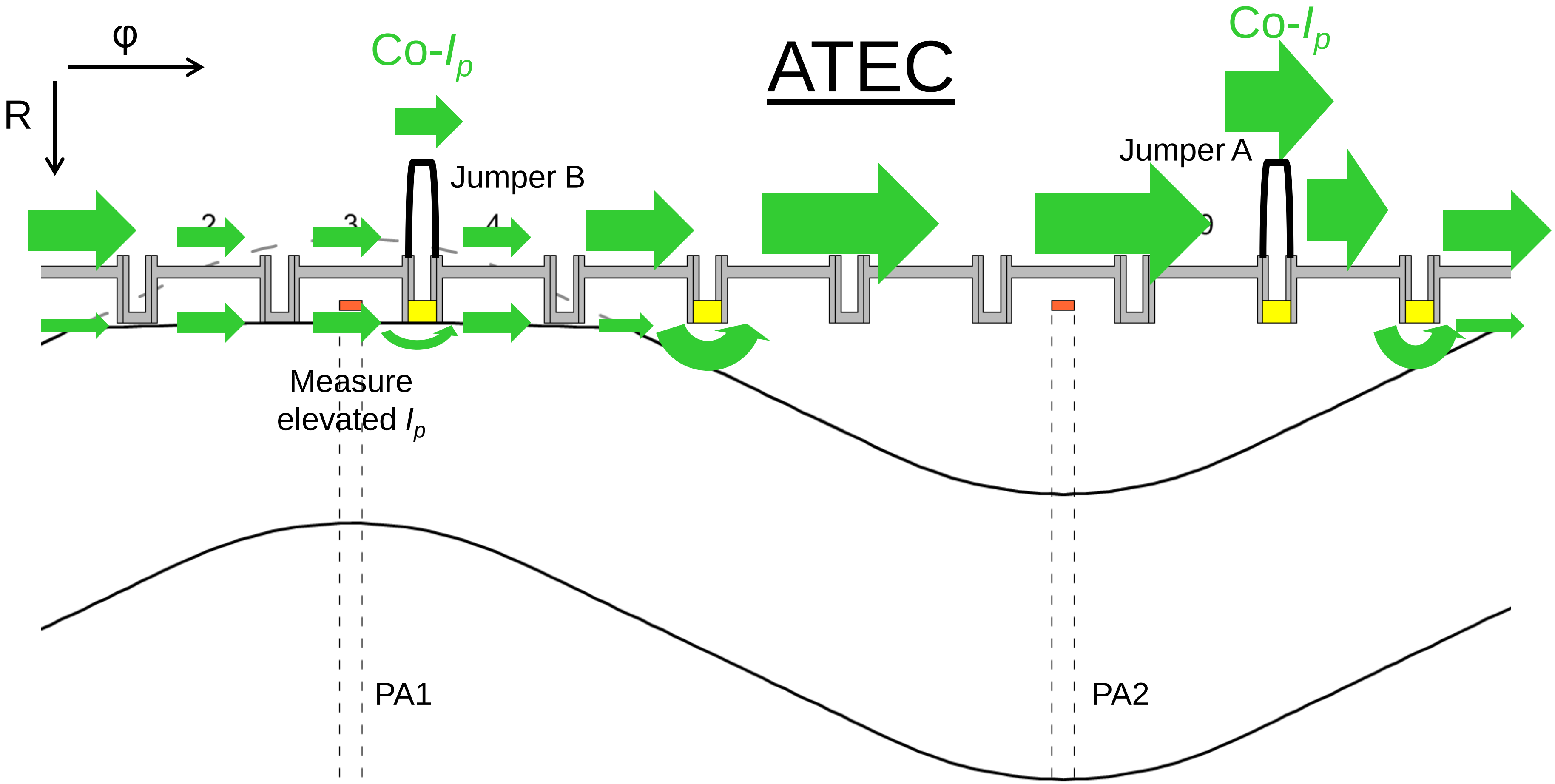
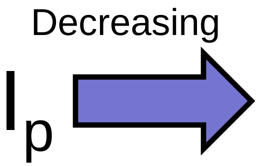


- Using ATEC as formulated for JET, with no plasma motion



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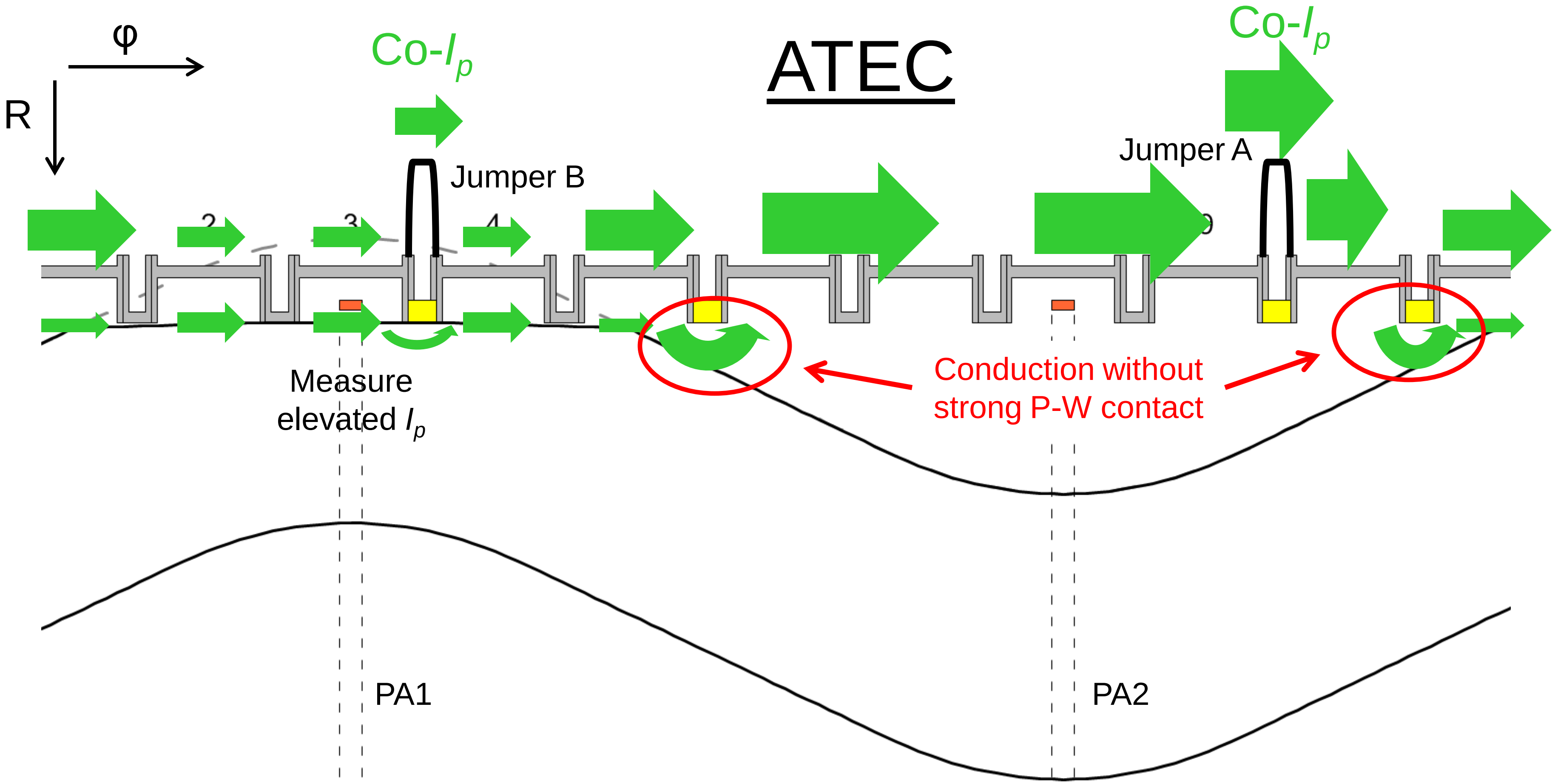
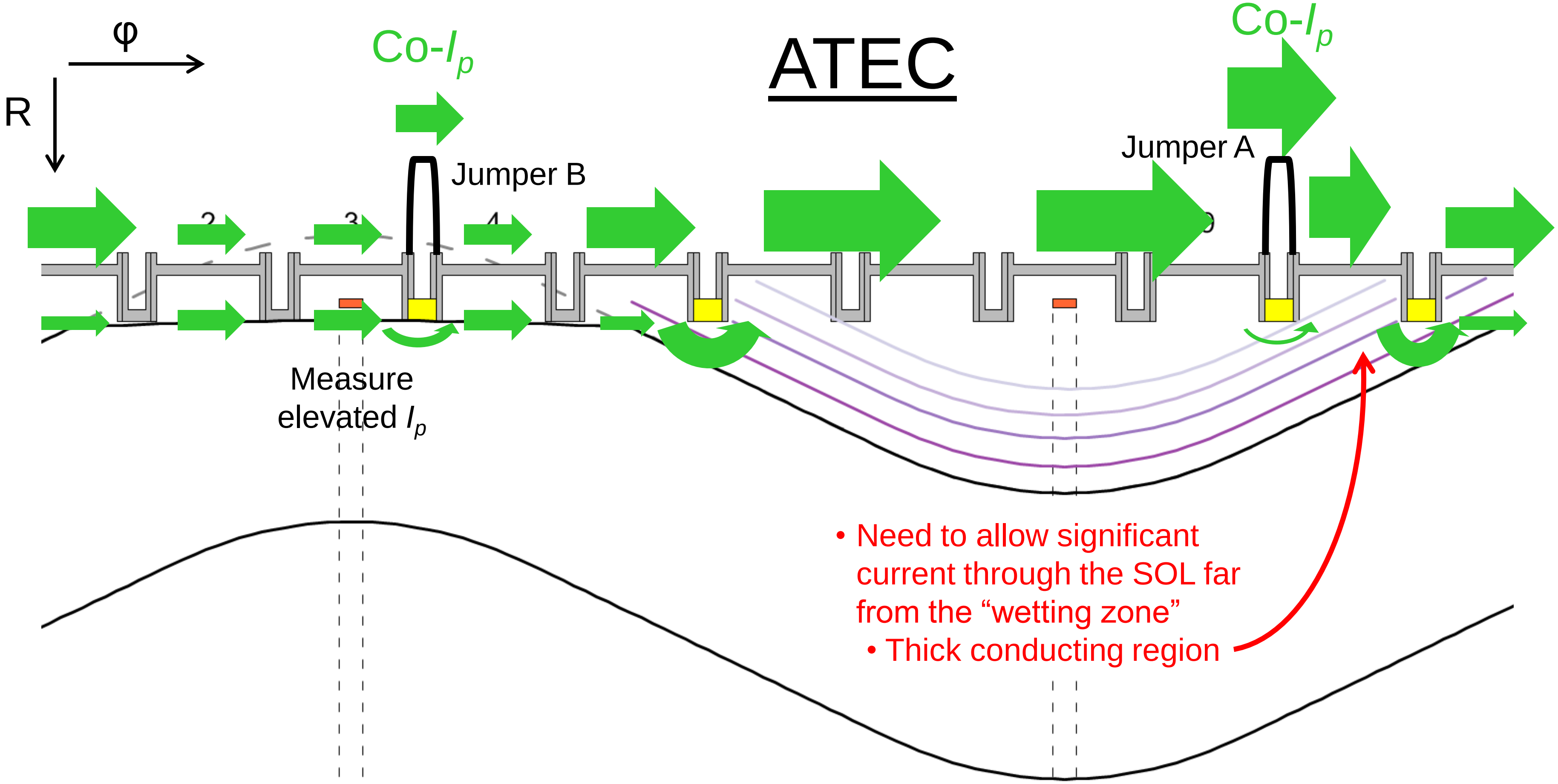


Conduction without strong P-W contact

- Using ATEC as formulated for JET, with no plasma motion

Decreasing I_p

Expected currents in response to disruption kinks in HBT-EP



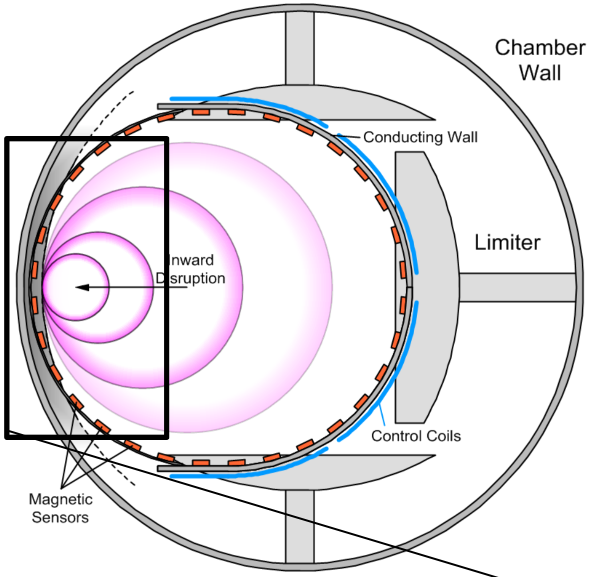
- Need to allow significant current through the SOL far from the "wetting zone"
  - Thick conducting region

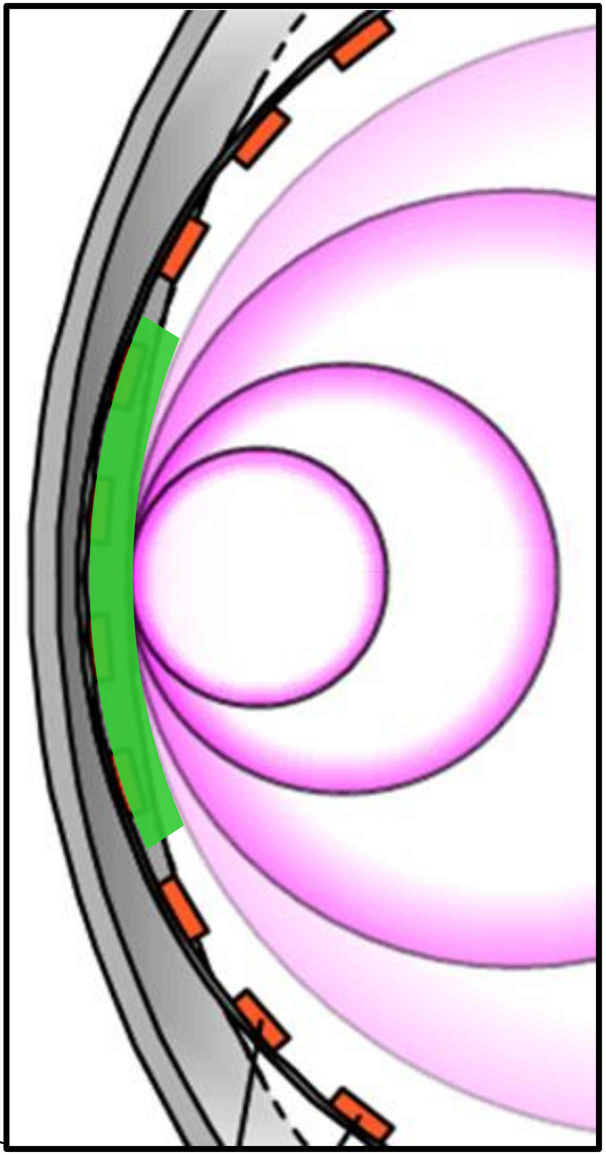
- Using ATEC as formulated for JET, with no plasma motion

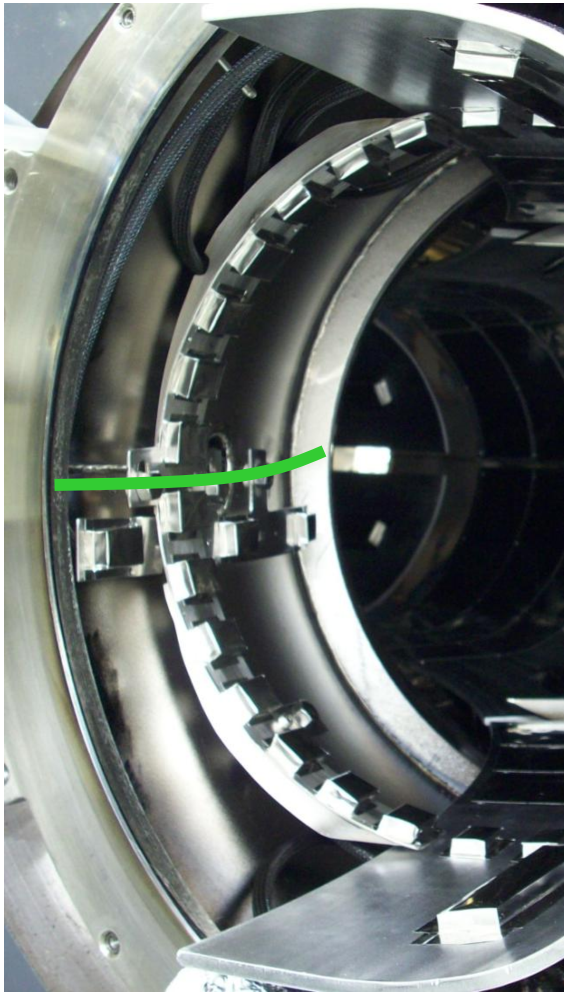
Decreasing I_p ➡

ATEC current responsible for elevated I_p measurement needs to flow in a ~1cm thick SOL region

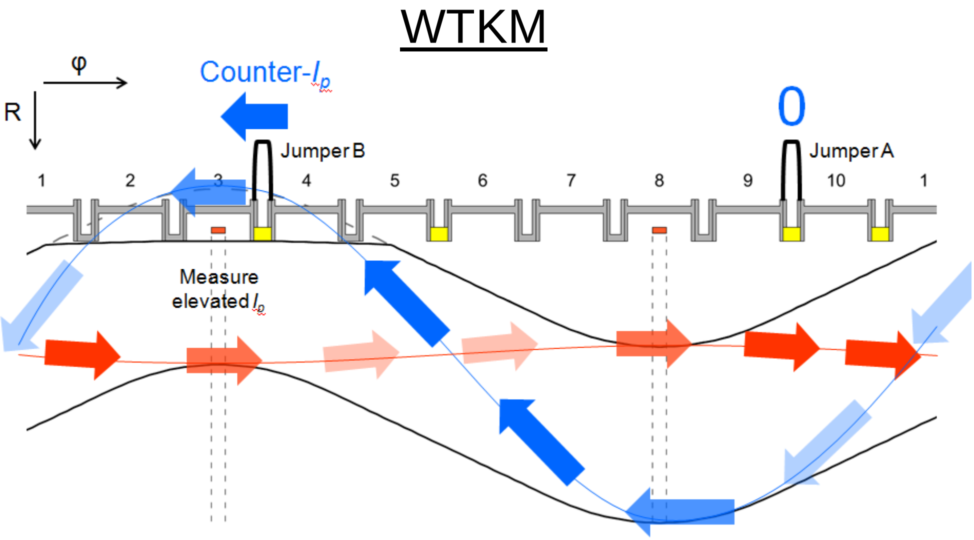
- No bulk conducting materials exist between poloidal array sensors and LCFS
  - Only 64µm thick SS shimstock shielding in front of sensors

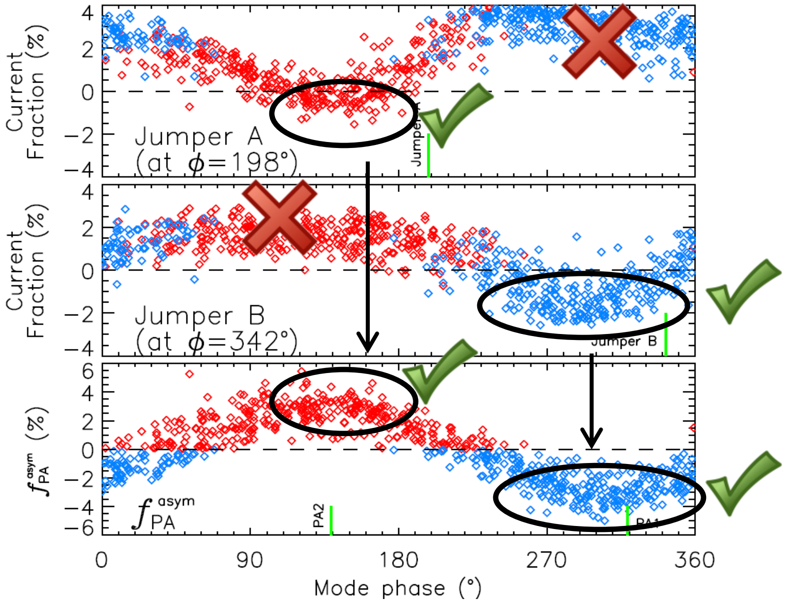






Evaluation of WTKM model





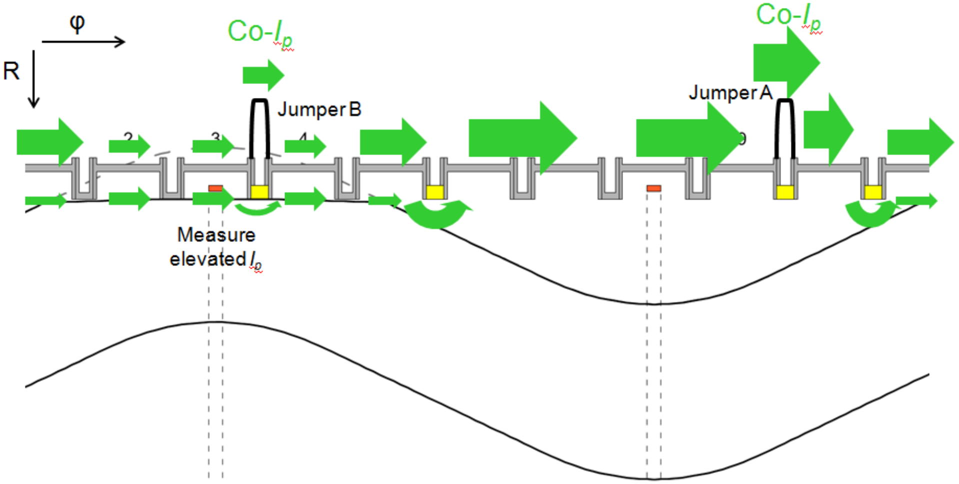
- Local Counter-I_p vessel current agrees with elevated I_p measurement
- *Large* Co-I_p vessel current is not predicted
  - Co-I_p "Evans" current is allowed, but should not be strong
    - Source-limited from plasma dissipation[1]:
  - Co-I_p wall current should not extend to opposite side of vessel
  - Consider allowing very broad contact area and strong co-I_p halo current

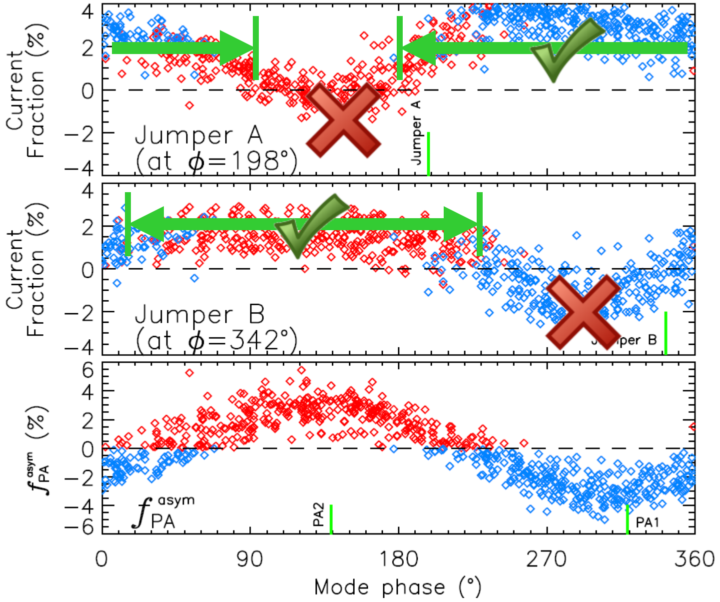
$$I^{\mathrm{Ev}} \leqslant e\frac{\mathrm{d}N_{\mathrm{e}}}{\mathrm{d}t}$$

[1] Gerasimov S.N. *et al.*, *Nucl. Fusion* **55** 113006 (2015)

Evaluation of ATEC model

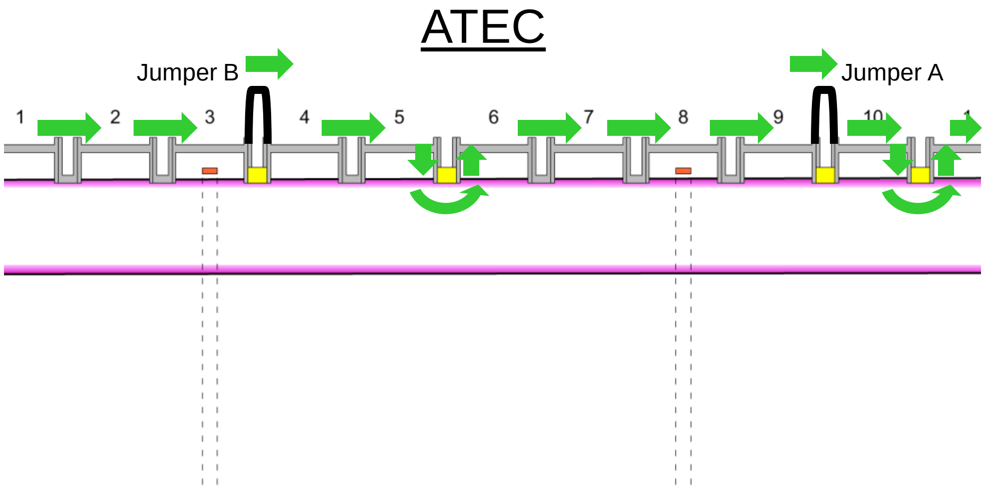
ATEC

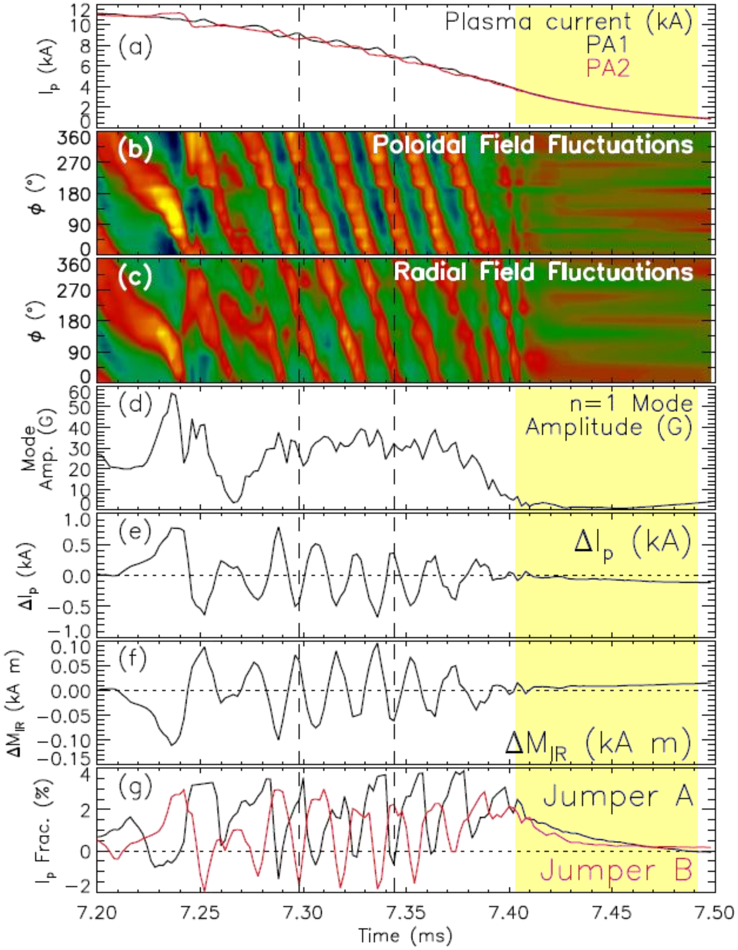




- Measured jumper currents are co-I_p for most of the disruption duration
- ATEC Predicts co-I_p jumper current where I_p is elevated
  - Current in local jumper would be lower than in the other jumper, but both still co-I_p
- Neglecting plasma motion, there should be no counter-I_p jumper current
  - Allowing counter-I_p currents induced by plasma motion could overpower co-I_p current from I_p decay
- Strong co-I_p current must flow in a relatively thin SOL region in front of poloidal array sensors

ATEC concept of toroidal eddy current flowing through SOL could explain symmetric current at end of CQ


ATEC



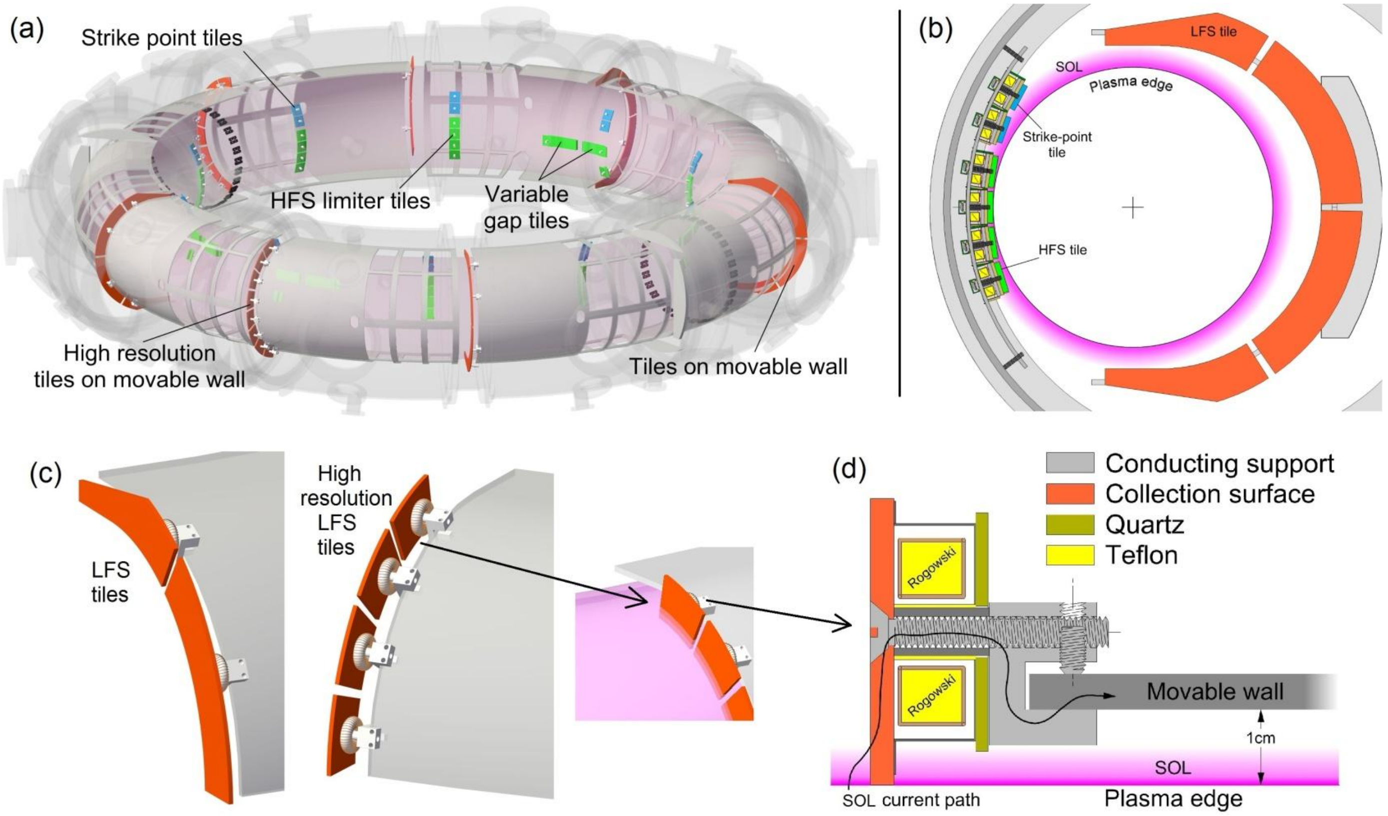
- Current passing through jumpers must conduct to neighboring vessel sections through the SOL

Outline

- HBT-EP device overview
  - Scrape-off layer current (SOLC) diagnostics and vessel geometry
  - Discharge characteristics
- Measurements during routine kink mode activity
- Measurements during disruptions
- Interpretation in context of WTKM and ATEC models
- Upcoming simulation and experiments

Upcoming simulation and experiments

- VALEN/IVB modeling
  - Compare direct source/sink currents versus vessel currents due to rotating kink mode eddy currents
- ATEC calculations for HBT-EP
- Upgraded SOLC diagnostics for further experiments:



Summary

- Direct measurements of toroidal vessel currents reveal asymmetric, oscillating *co-* and *counter-*I_p wall currents during kink modes and disruptions
  - Insulating breaks constrain vessel current to complete its circuit through SOL plasma
  - Currents reach ~4% of I_p during disruptions.

- I_p asymmetry characteristics agree with JET results[1] and ITER modeling[2]
  - Slope of asymmetry $\Delta I_p / \Delta M_{IR,IZ}$ scales like $1/a$

- WTKM[3] and ATEC[4] models can qualitatively explain some HBT-EP measurements, but each model has deficiencies as formulated.
  - *Both* ATEC and WTKM concepts are significant for vessel currents
    - Both models also have problems explaining some of the observations
  - Each model can qualitatively explain observed plasma current asymmetries
    - Conditions for ATEC appear more restrictive overall

- Upcoming experiments will improve validation of disruption current models

[1] Gerasimov S.N. *et al.*, *Nucl. Fusion* **54** 073009 (2014)
[2] Roccella R. *et al.,* "Modelling ITER asymmetric VDEs through asymmetries of toroidal eddy currents" IAEA FEC [EX/P6-40] (2016)
[3] Zakharov L.E. *et al.*, *Phys. Plasmas* **19** 055703 (2012)
[4] Roccella R. *et al.*, *Nucl. Fusion* **56** 106010 (2016)

*** Levesque, J.P. *et al.*, *Nucl. Fusion* 57 086035 (2017)**