Study of Thermo-electrically Driven Scrape-Off-Layer Current (SOLC) in NSTX Tokamak

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ABSTRACT

Study of Thermo-electrically Driven Scrape-Off-Layer Current (SOLC) in NSTX Tokamak,* H. Takahashi, E. Fredrickson, J. Kallman, S. Gerhardt, R. Kaita, D. Mansfield, S. Zweben, *PPPL,* R. Maingi, *ORNL* – SOLC flow in ELMing discharges in NSTX has been found qualitatively similar to that in DIII-D [1], with steady small amplitude during a quiescent period leading to a rapid change to much larger values, abruptly beginning just before ELM onset (as detected by D-alpha signal). Current density (spatially averaged normal to divertor plate) in NSTX is comparable to that in DIII-D during the main ELM event, but is much smaller during the quiescent period. The possible thermo-electric origin of the current in the quiescent period will be investigated using flush-mounted Langmuir probes and halo current sensors to see whether observed SOLC distributions can be quantitatively related to sheath parameters at divertor plates. Effect on SOLC of Lithium coating of plasma facing surfaces will also be examined.

[1] H. Takahashi, et al., Paper TP6.00033, 50th Ann. Mtg. of APS-DPP, Dallas, TX, Nov., ‘08.

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Highlights

Old Subject Re-visited
What Determines ELM Period?

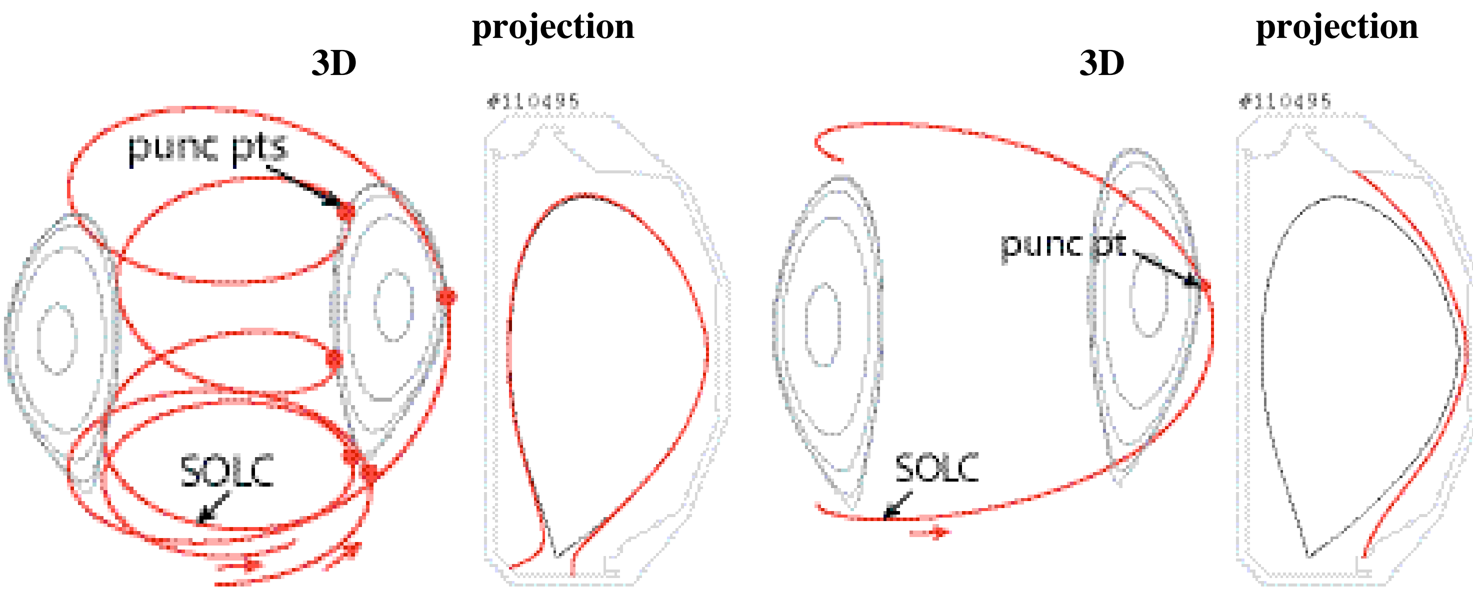
A robustly cyclical mechanism for triggering ELMs may be found in the SOL during its repetitive inundation and pump out following ELM crash.

This work is ongoing effort to examine whether temporal evolution and spatial structure of thermo-electrically-driven Scrape-Off-Layer Current (SOLC) may *harbor the seeds for a cyclical triggering mechanism* through breakdown of sheath at the interface of the SOL plasma with divertor target plates.

BACKGROUND

SOLC Flows along Open Field Lines…

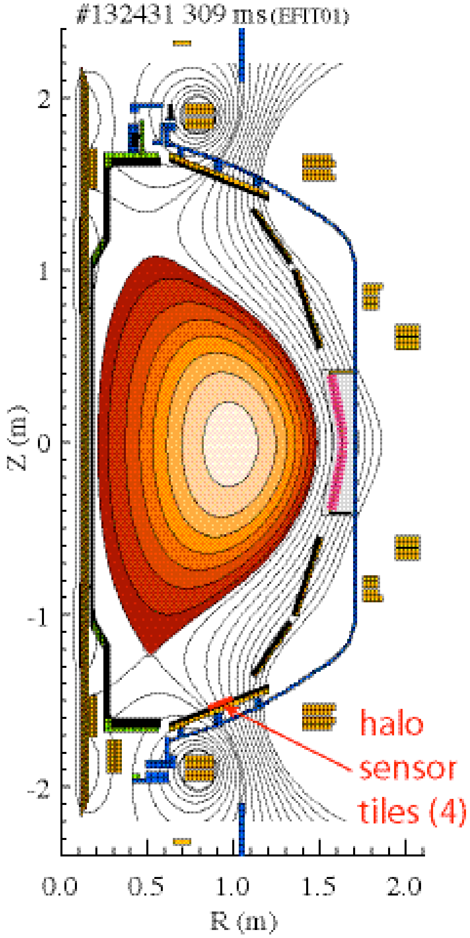
Circumnavigating **SOLC Filament** ***Interrupted*** **SOLC Filament**



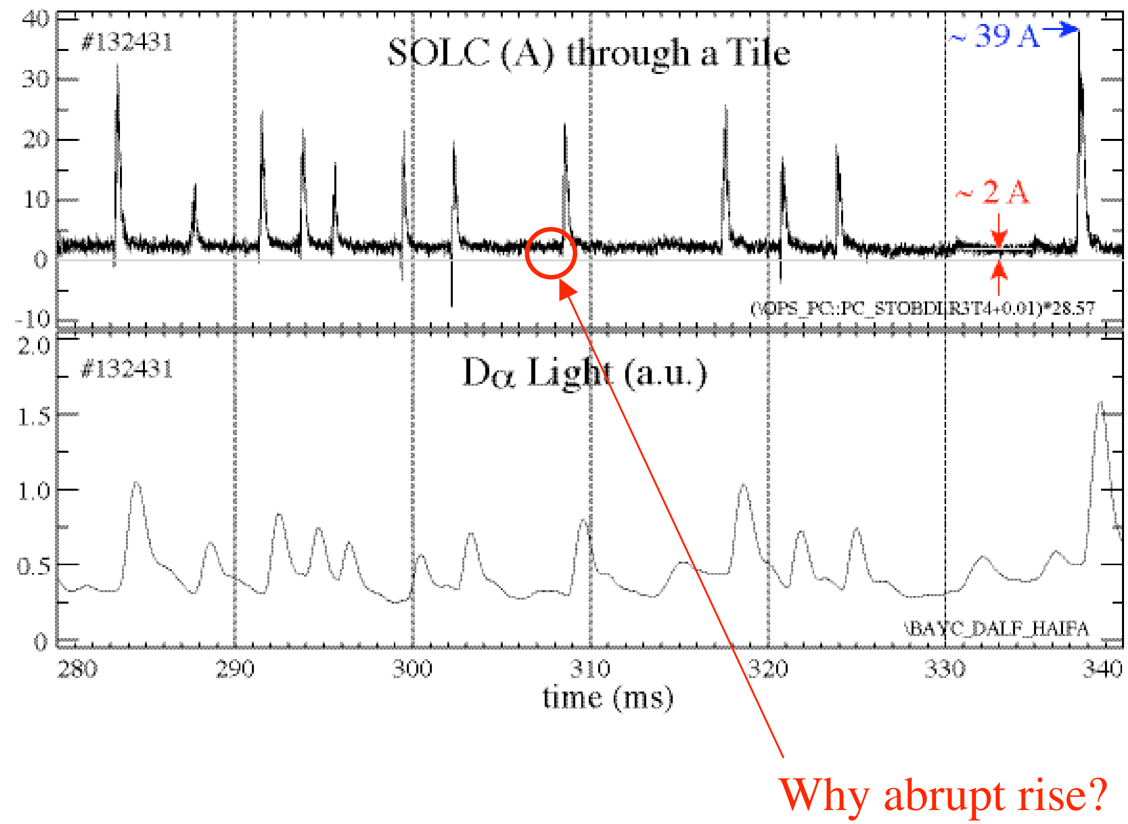
Line-current Representation of SOLC

…and Completes its Circuit through Tokamak Structure.

SOLC Flows Also In-between ELMs in Tokamaks-1



NSTX

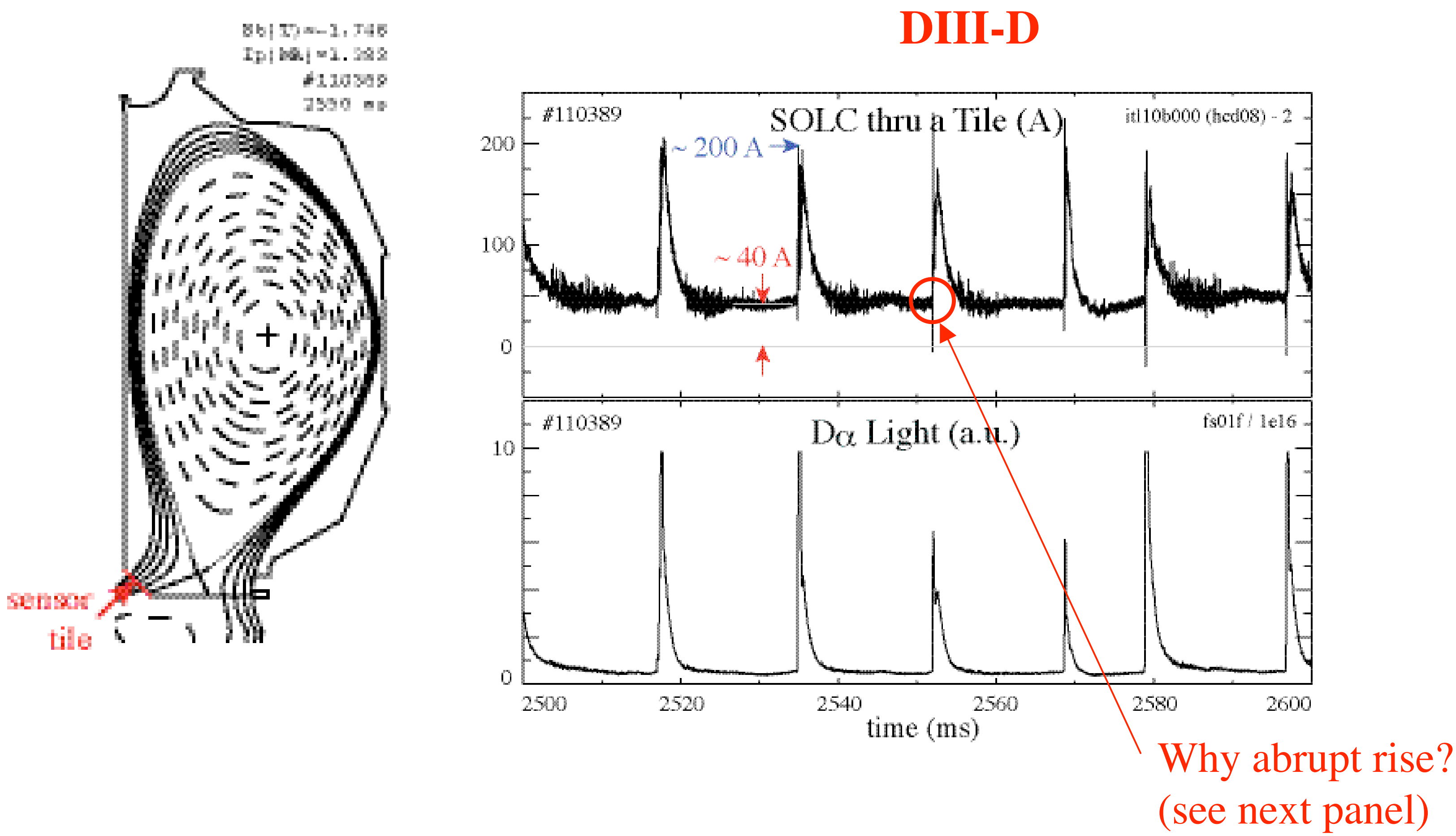


Data taken during pre-lithium period

4 tiles (out of 96 in a ring) have a sensor, each tile 6 cm (3.75 deg) wide toroidally and 12 cm long poloidally

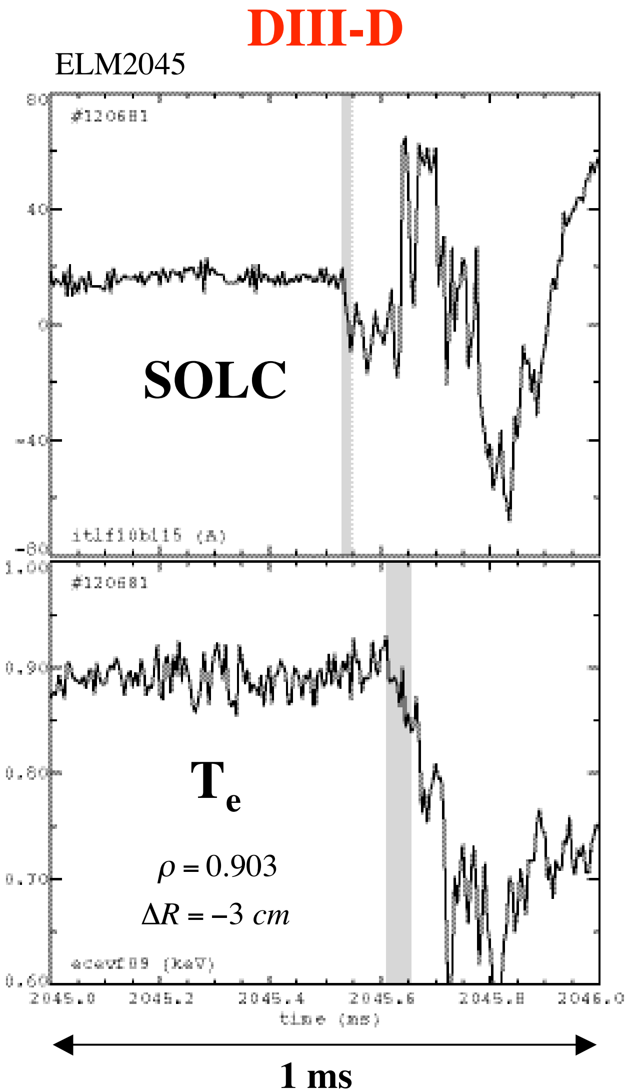
SOLC and D_α signals recorded on separate digitizers (with possible consequent error in relative timing)

SOLC Flows Also In-between ELMs in Tokamaks-2



6 tiles (out of 48 in a ring) have a sensor, each tile 15 cm (7.5deg) wide toroidally and 15 cm long poloidally
SOLC and D_α signals recorded on separate digitizers (with possible consequent error in relative timing)

SOLC May Play a Role in ELM Trigger



SOLC often has a sharply defined onset, rising to values several times noise level in 5-20 μs.

SOLC begins to change* earlier (by 80 - 100 μsec in this ELM) than edge T_e collapse - thought to be due to peeling-ballooning instability - indicating that SOLC, *at least initially,* is not an effect of heat and particle flux to divertor due to ELM collapse.

SOLC-generated field, non-axisymmetric in structure, may play a role in ELM trigger process.

*See Takahashi, et al., EPS '05 for more details.

SOLC and ECE (T_e) signals are recorded on the *same digitizer* to eliminate timing errors.

A gray band in plots indicates time range for an onset, with confidence level in its identification increasing from left to right within the band.

ELM Trigger Model*

1. **Largely axisymmetric thermoelectrically-driven SOLC flows in pre-ELM phase, with its magnitude capped by ion saturation current limit of sheath at plasma-divertor plate interface.**

2. **Momentary localized sheath breakdown allows rapid growth of non-axisymmetric SOLC, producing non-axisymmetric magnetic field (*dynamically* generated error field).**

3. **Error field helps to destabilize MHD modes, leading to thermal collapse at plasma edge (ELM trigger).**

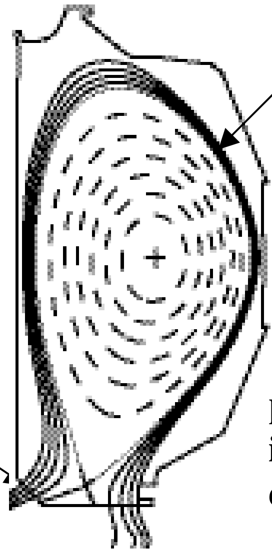
4. **Thermal collapse injects heat and particles into SOL, in a largely axisymmetric pattern, diminishing non-axisymmetric thermoelectric drive, and hence error field (non-linear feedback interaction).**

5. **Density pump-out in SOL brings down ion saturation current, increasing potential impressed across the sheath (priming for next ELM).**

***from Takahashi APS(2005) CP1.00023**

Te Difference Drives Thermo-electric SOLC%

DIII-D



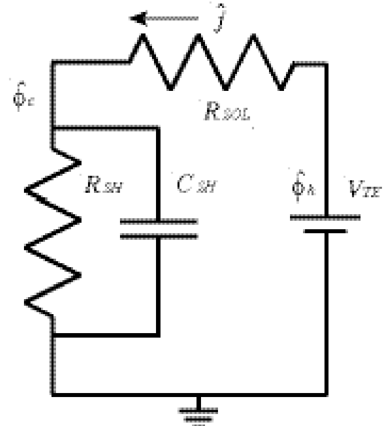
SOL

plate in cold divertor^

plate in hot divertor^

^ hot/cold relationship may reverse with radial location.

Equivalent Circuit



SOL resistance (linear) and ion sheath resistance (non-linear) form a voltage divider

Equations*

$$\hat{j} = -\gamma\,[(\hat{\phi}_h - \hat{\phi}_c) + \varsigma\,(\Theta - 1)] \qquad (1)$$

$$\hat{\phi}_c = \kappa - \ln[1 + \hat{j}\,] \qquad (2)$$

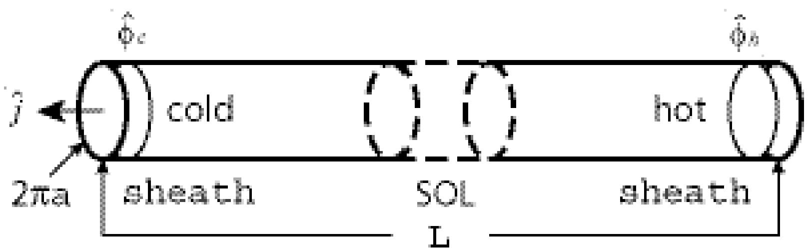
$$\hat{\phi}_h = \hat{\phi}_0 + \Theta\{\kappa - \ln[1 - \sqrt{\Theta}\,\hat{j}\,]\} \qquad (3)$$

$\hat{j}$: current norm by ion sat current at cold-divertor plate

$\hat{\phi}$: potential norm by Te at cold-divertor plate

κ=3.89 ζ=0.703 ϕ_0=0

Flux tube in SOL terminates at divertor plates



Governing equations are a two-parameter system in:

γ **: sheath-to-SOL resistance ratio**

Θ **: hot-to-cold-sheath Te ratio**

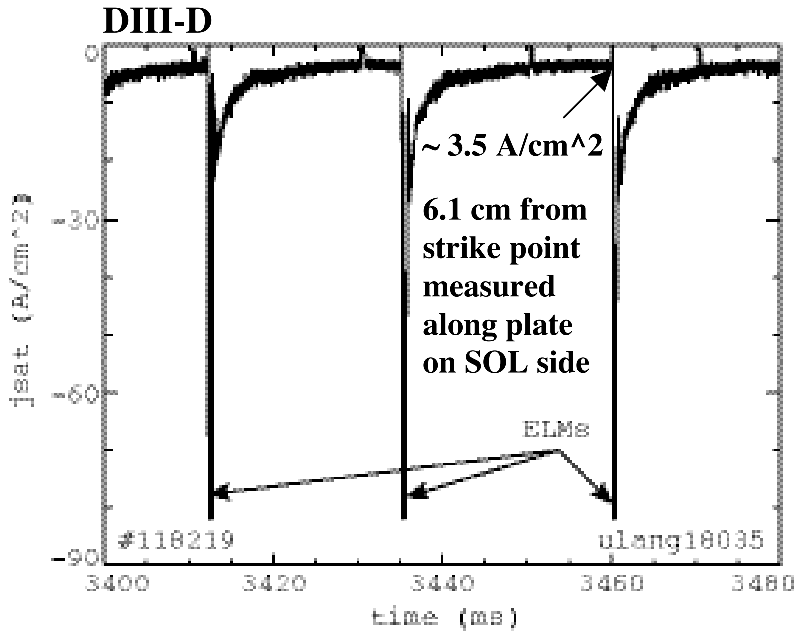
*Harbour, Contrib. Plasma Phys. 28(1988)415
Staebler and Hinton, NF 29(1989)1820

%from Takahashi APS(2005) CP1.00023

Ion Saturation Current Limit Caps SOLC…*

Ion Saturation Current Density
measured by
strongly negatively biased Langmuir probe
(signal inverted and saturated at peaks)

$$j_{sat} \propto n_i \sqrt{T_e}$$



Robust Cyclical Process

Ion saturation current density (j_{SAT}) at sheath in cold divertor ("ion sheath" - collecting net positive charge) rises rapidly, as ion density builds up following an ELM thermal collapse, and then plummets toward what appears to be a limit value before next ELM, as density in SOL pumps out.

Plummeting j_{SAT} becomes, just before an ELM, comparable to the density of SOLC flowing through (unbiased) divertor plates, with an attendant consequence of increased potential impressed across the sheath.

…unless Sheath Breaks down Just before ELM

***from Takahashi APS(2005) CP1.00023**

Cyclicity

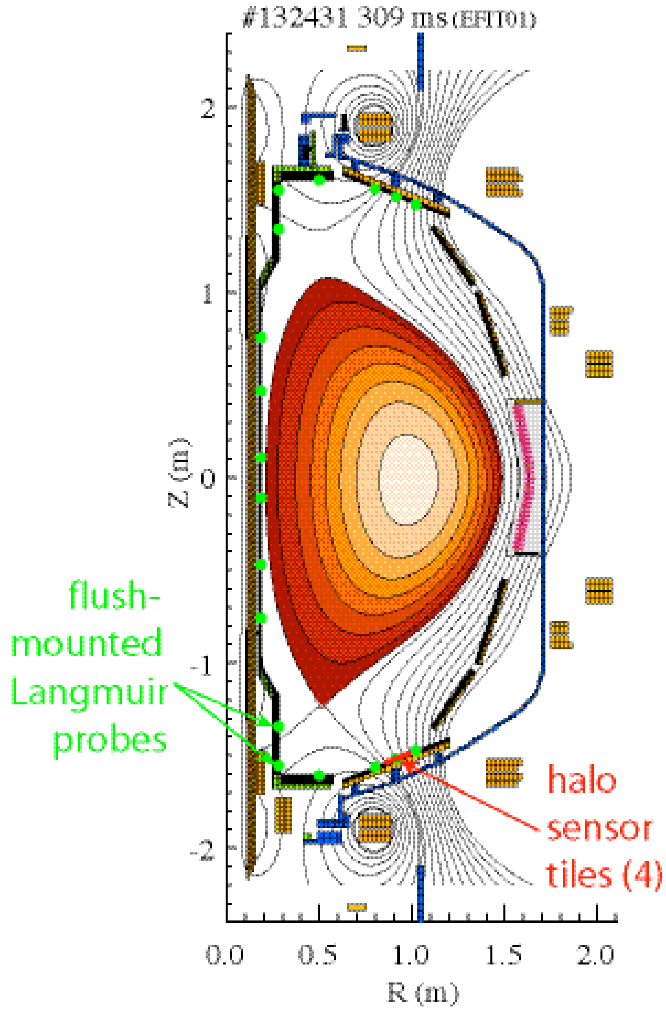
In a leading physical model for the ELM based on peeling-ballooning mode, repeated build-up of steep gradients at plasma edge due to reheating, following thermal collapse, is the mechanism for cyclicity. Gradients exceeding thresholds trigger ELMs.

In the ELM model* considered here based on Scrape-Off-Layer Current (SOLC), plummeting ion saturation current, following inundation of divertors with ions caused by thermal collapse, is the mechanism for cyclicity. Breakdown of sheath at the interface between the SOL plasma and divertor tiles trigger ELMs.

***See Takahashi EPS(2005)4.018 (also Zheng PRL100(2008)115001 considered SOLC and peeling-ballooning mode together in a feedback loop).**

SOLC MEASUREMENT

SOLC Diagnostics in NSTX



Halo Current Diagnostic - a toroidal array of four divertor tiles, equally spaced 90 degrees apart in the outboard bottom divertor and each instrumented with a resistive sensor, measures SOLC flowing through the tiles.

Two poloidal arrays of flush-mounted Langmuir probes, one on inboard and another on outboard divertor plates, are to be used to determine the electron temperature and density at two ends of a flux tube, as well as SOLC driven by thermo-electric potential between the two ends.

Schaffer/Takahashi 2005

Approach to Study of Thermo-electrically Driven SOLC in NSTX

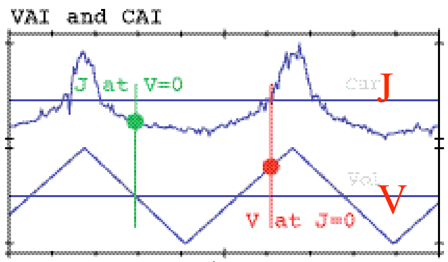
Effect of SOLC on MHD stability, if any, would mainly come from non-axisymmetric field generated by the current, making determination of SOLC's spatial structure a central goal of the study.

The initial plan was to use highly-localized Langmuir probe measurement for radial structure and spatially-integrating halo current sensors for toroidal variations.

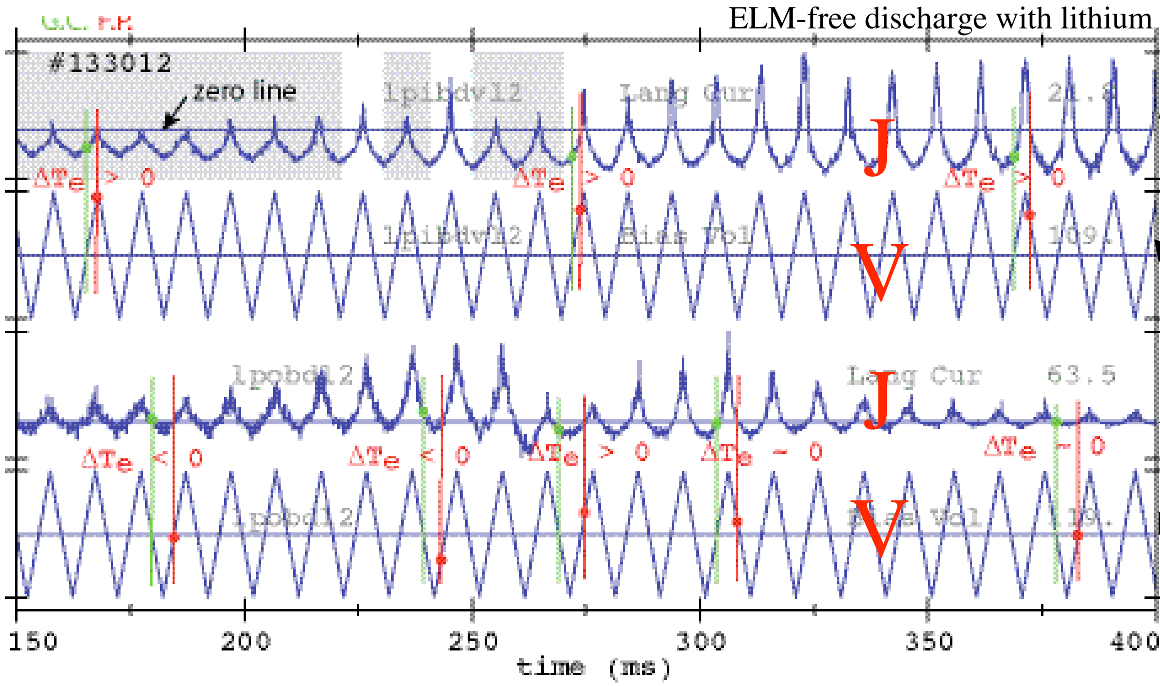
A Langmuir probe could *in principle* determine, not only SOLC flowing in the flux tube connected to it, but also T_e at the sheath of the two ends of the flux tube, helping to confirm a thermo-electric origin of the measured SOLC.

However, difficulties have been encountered in interpreting Langmuir probe data (evidently common experience with tokamak SOL), which have slowed down the progress of the study (see below). This paper reports on its present status.

SOLC Found by Tracking Zero-Crossings of Langmuir Probe Current and Bias Voltage



Tracking Current Axis Intercept (probe current at zero bias voltage) and Voltage Axis Intercept (bias voltage at zero probe current) of Langmuir probe signals yields evolution of ground current (SOLC) and floating potential (ΔTe).



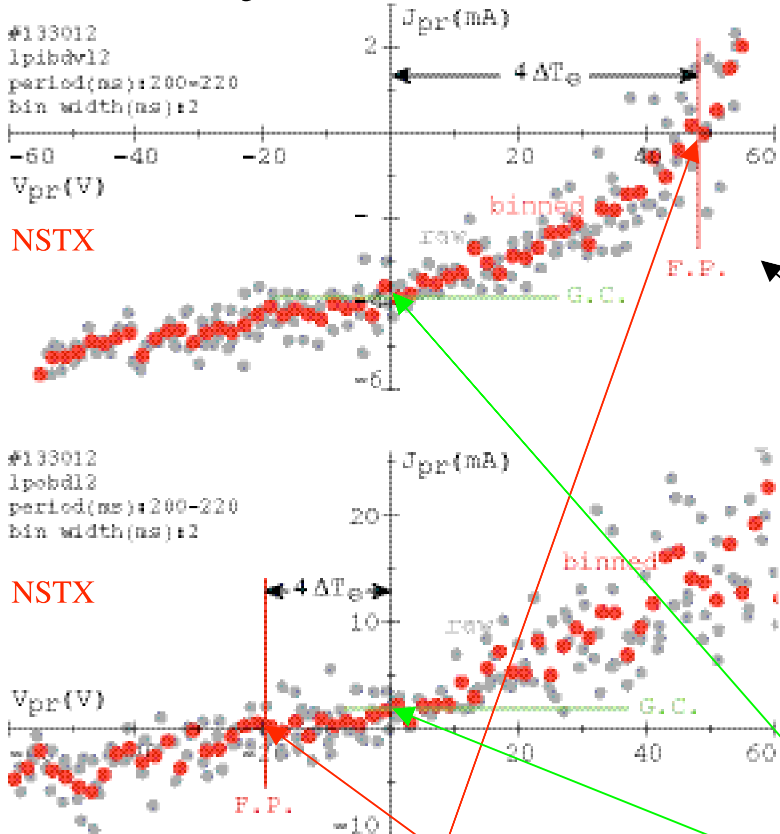
For this inboard probe in far SOL, CAI is persistently negative and large - SOLC is nearly as large as Jsat+, and VAI is persistently positive and large - far end of flux tube is hotter (ΔTe > 0)(see below).

For this outboard probe in near SOL, both CAI and VAI are small, bipolar, and vacillating - SOLC ~ 0 as well as ΔTe small or ~ 0.

Large Bipolar Excursions of Floating Potential

ELM-free discharge with lithium

Langmuir Probe I-V Characteristic



It is a common observation, though not widely discussed, that floating potential takes large bipolar excursions during a tokamak discharge.

Te is higher at far end of flux tube. Ground current is negative (nearly as large as Jsat+ in this example).

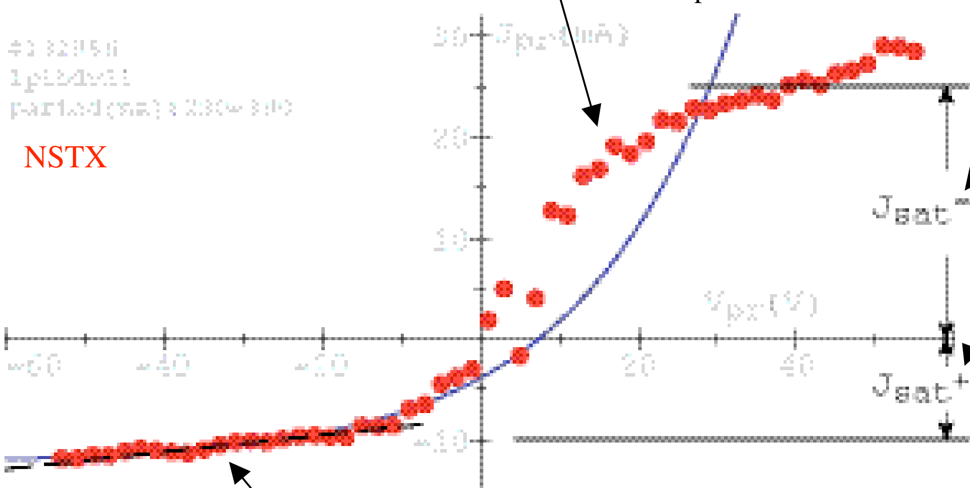
Te is higher at near (probe) end of flux tube. Ground current is positive (small compared to Jsat+ in this example).

Finite floating potential (F.P.) may be evidence for T_e difference at two ends of flux tube driving finite ground current (G.C.) - which is in fact SOLC measured by the Langmuir probe.

Conventional Langmuir Probe Interpretation Encounters Obstacles

(ii) Non-exponential I-V characteristic (thought to be caused by resistance in plasma, including one due to *cross-field transport*.

exp fit to V_{pr} < F.P.



(iii) "Creeping" or soft current saturation at large negative bias voltage (thought to be caused by *Debye sheath thickening*).

These difficulties have historically been observed in many tokamaks.

(i) Too small saturation current ratio (~ 2.5 here),

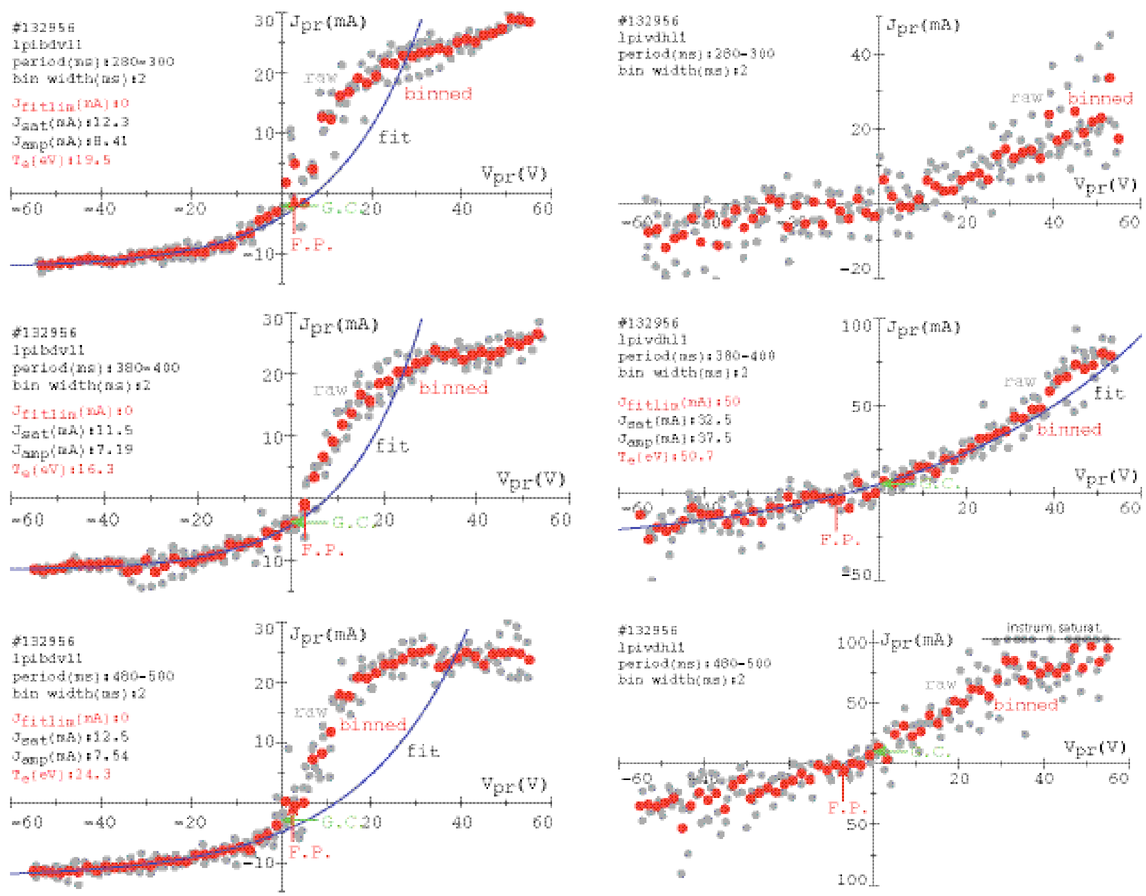
$Jsat^+ / Jsat^- << (mi/me)^{1/2}$,

(thought to come from ion current saturation at *far end of flux tube*).

No Fit Model for Widely Varying Forms

All NSTX
(ELM-free discharge with lithium)

Double-probe-like Characteristic **Exponential-like Characteristic**



Noise would make fitting unreliable or impractical.

Straight line may fit well.

Nearly entire voltage range fitted (no convergence for fit to F.P.).

Well-saturated on both ion and electron sides.

Straight line may be just as acceptable.

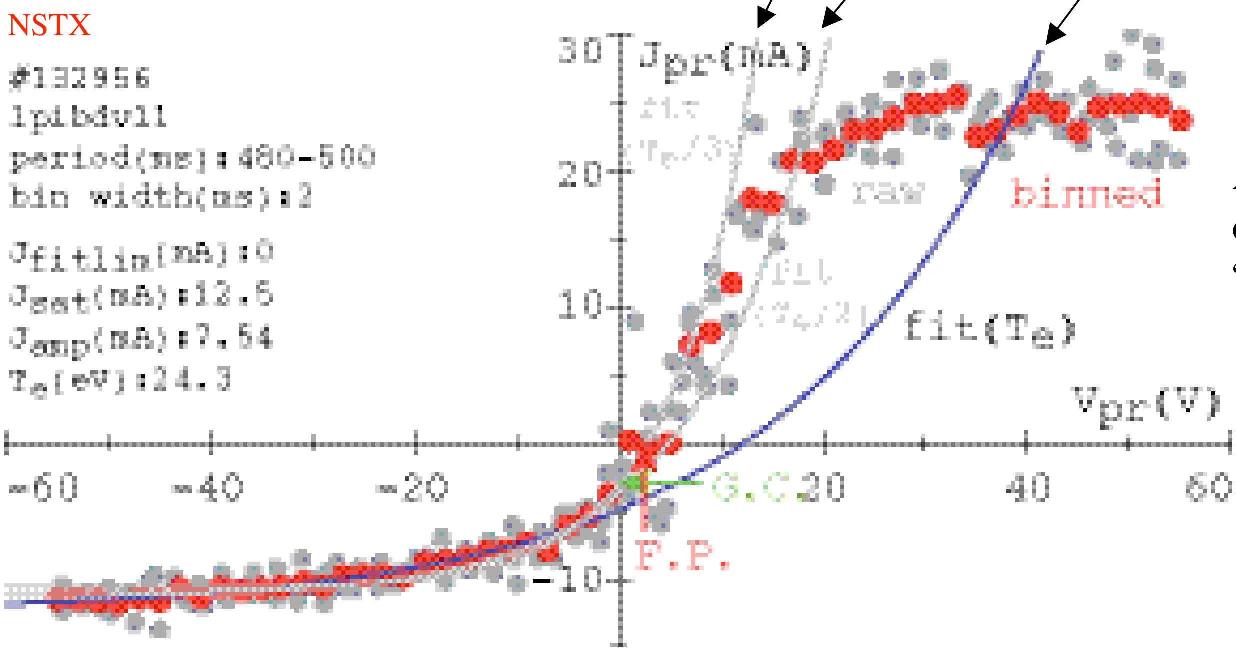
"Accepted" prescription is to fit an exponential curve to data only with V_{pr} < F.P.

Exponential Fit to I-V Characteristic Yields Highly Uncertain T_e

Inclusion of data beyond F.P. would yield a *lower* Te - opposite of the case reported in Tagle PPCF 29(1987)297.

$T_e/3$ $T_e/2$

Exp fit to V_{pr} < F.P. yields $T_e \sim 24$ eV



A case of well-saturated current on both ion and “electron” sides

A *flux-tube model* (often called “double-probe”) appears more promising for these data.

Plan for Extending SOLC Study in NSTX

In the context of a flux tube model, SOLC and driving ΔT_e may be derived from CAI and VAI without data fitting over an entire probe voltage sweep range. But such an analysis will not yield T_e at the sheath edge, and thus potential imposed across the sheath - an important parameter sought in the sheath breakdown model.

The present plan is to devise a method based on a flux tube model for reliably extracting T_e from Langmuir probe data - *a feat that eluded the fusion community for decades**.

(*) Stangeby, P.C. and McCracken, G.M., NF30(1990)1225 (review paper): "It thus appears to be necessary to restrict the use of Langmuir probe data to probe voltage values below Vf" (p. 1236).

Mathews, G.F., PPCF36(1994)1595 (review paper): "…, it can be concluded that Langmuir probes suffer from the first law of diagnostics - the ease of interpretation is inversely proportional to the ease of implementation" (p. 1597); "Hence, if we restrict ourselves to fitting the characteristic below the floating potential we can use the conventional Langmuir theory to extract a value for Te"(p. 1598).

Stangeby, P.C., *Plasma Boundary of Magnetic Fusion Devices,* IOP Publishing, 2000: "The price paid for these experimental advantages is that probe interpretation is notoriously difficult" (p. 84); "Thus, a common practice in tokamaks is to use only the net ion-collecting part of the I-V characteristic to deduce Te" (p. 90).

Recent private communication with Langmuir probe experts in ITER confirms that the above statements on the status of understanding of Langmuir probe behavior still stands valid in the year 2009. Additionally it may be necessary to use at least partially proud probes and avoid detached divertor plasmas.

Effect of Lithium Coating on SOLC

If SOLC plays a role in ELM trigger process through sheath breakdown as postulated in this study, *surface condition changes due to lithium coating affecting breakdown threshold* may be a candidate mechanism for ELM suppression by lithium.

Cursory observations so far suggest that the SOL of discharges with lithium evaporation is "quiet" in that noise level of Langmuir probe current as well as SOLC signals appears to be much lower than that in discharges without lithium.

Quantitative assessment of SOLC in discharges with lithium evaporation, and hence physics investigation of lithium effect, will have to wait till an effective Langmuir probe analysis method is developed.

Quiet SOL is meanwhile advantageous in developing a method of interpreting Langmuir probe signals.

Summary

• The possible thermo-electric origin of SOLC during the quiescent period between ELMs and in ELM-free discharges has been examined as part of continuing effort to investigate roles SOLC may play in ELM trigger process.

• SOLC in ELMing discharges in NSTX measured using the halo current diagnostic is qualitatively similar to that in DIII-D, with steady small amplitude during a quiescent period leading to a rapid change to much larger values, abruptly beginning just *before* the ELM onset.

• Langmuir probe data, needed to correlate sheath parameters to measured SOLC, exhibit in NSTX characteristics observed in many other tokamaks that historically limited reliable interpretation of the data. Effort is underway to develop an effective analysis method based on a *flux tube model* needed to make a further progress in the present SOLC study.