13 回 QUEST研究会_2017.02.09-10

QUESTにおけるトロイダル分割型ダイバータバイアスによる周辺･SOLプラズマ制御の初期実験と今後の計画

Initial Experiment and Future Plan of Toroidally Segmented-Divertor Biasing for Edge-SOL Plasma Control in QUEST

東井和夫[1]、図子秀樹[2]、黒田賢剛[2] 、長谷川真[2]、恩地拓巳[2]、
中村一男[2]、出射浩[2]、花田和明[2]、QUEST実験グループ[2]
[1] 核融合研(名誉教授)、[2] 九大応力研

K. Toi[1], H. Zushi[2], H. Kuroda[2], M. Hasegawa[2], T. Onchi[2],
K. Nakamura[2], H. Idei[2], K. Hanada[2], QUEST Experiment Group[2]
[1] NIFS(Professor emeritus), [2] RIAM, Kyusyu Univ.

科研費 KAKENHI JSPS_#26630476

はじめに

➢ 定常熱負荷制御の課題

ITERではWダイバータ板の健全性保持＝＞定常熱負荷上限: ≤ 10 MW/m^2

＝＞部分的 or 完全非接触ダイバータ（Partially/fully detached divertor ）運転が必須.

（課題）非接触ダイバータ運転条件下での高性能Hモードの,準定常維持は極めて困難

非接触プラズマの低温フロントは不安定で小さな外乱で容易にX点に到達

＝＞Hモード性能の大幅な低下

（対策）低密度で部分的非接触ダイバータ＋ ???

<本研究の目的＞

➢ 過渡的熱負荷制御の課題

ELM (edge localized modes) 等による熱負荷許容値: ≤ 20 MW/m^2.

=> ELM抑制や影響緩和のELM制御 => 3D磁場(RMPs, nRMPs) 制御は進展

DIII-D, JET, AUG, MAST, NSTX, LHD

ELM自身によるSOL電流生成 => RMP生成とダイバータ熱負荷分布に影響

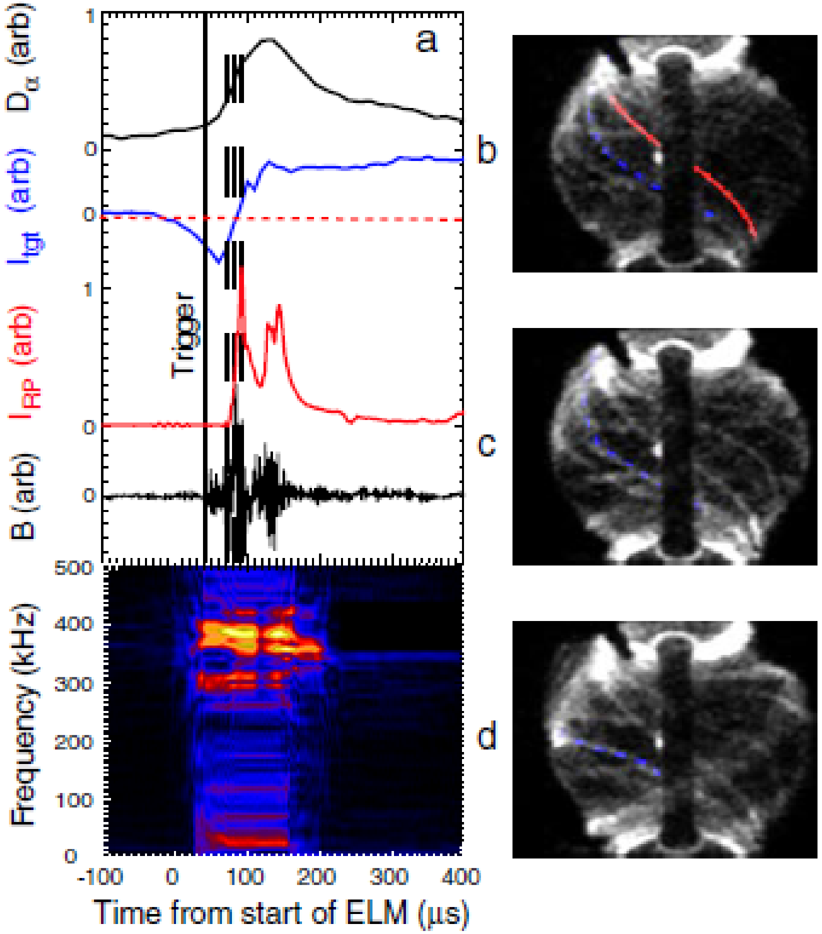
T. Eich et al., PRL 2003, Takahashi et al., PRL 2008, Kirk et al., PRL 2006, J.W. Ahn et al., NF 2014.

（課題）容器内接地RMP コイルはDEMOで使用不可

=> 外部制御したSOL電流によるRMP生成 ＜本研究の目的＞

ELMによるSOL電流の誘起の例(1)

MAST



Kirk et al., PRL 2006

I_{tgt}: SOL current measured by a shunt resister at the target plate

Negative (anti-parallel to I_p) at the onset of an ELM

Positive (parallel to I_p) around the peak and decay phase

Transient SOL currents are carried by ELM-generated filaments

本研究の目的

＜手法＞トロイダル方向に分割したダイバータ板の位相制御電気的バイアス法

(1) SOLプラズマの径方向輸送の増大=> 熱流束減衰長 λ_q の増大

乱流輸送の増大やExBドリフトの増大）

駆動乱流の候補 (collisional drift waves, current convective mode, resistive interchange mode, rippling mode, K-H instabilities …)

主にQUESTでPoP実験

(2) 位相制御したSOL 電流駆動によるRMP生成＝＞ELM制御

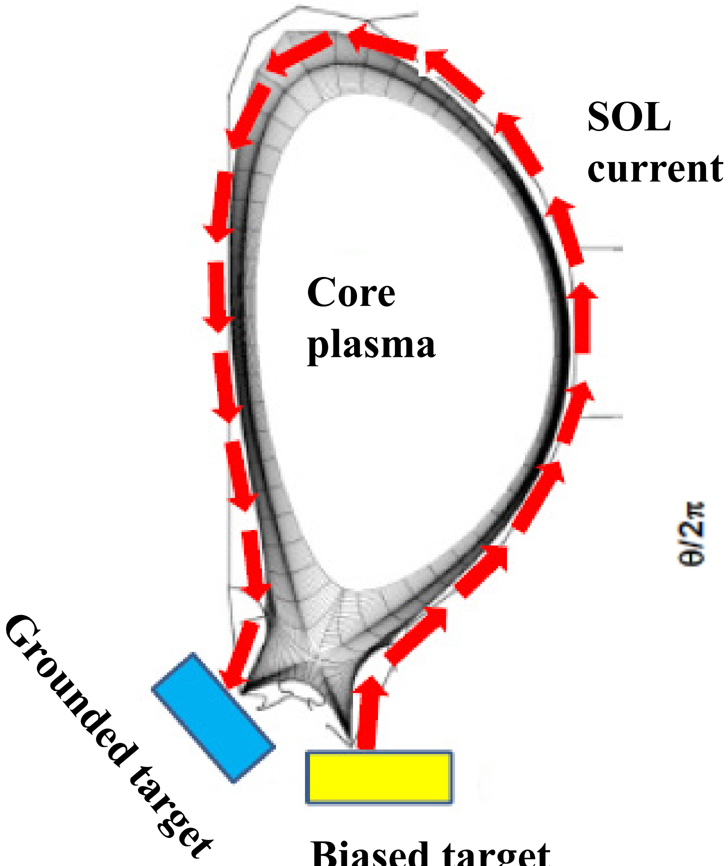
$q_{SOL} \sim q_{95}$なので本質的にRMPとなる

SOL電流はHモードペデスタルに近接

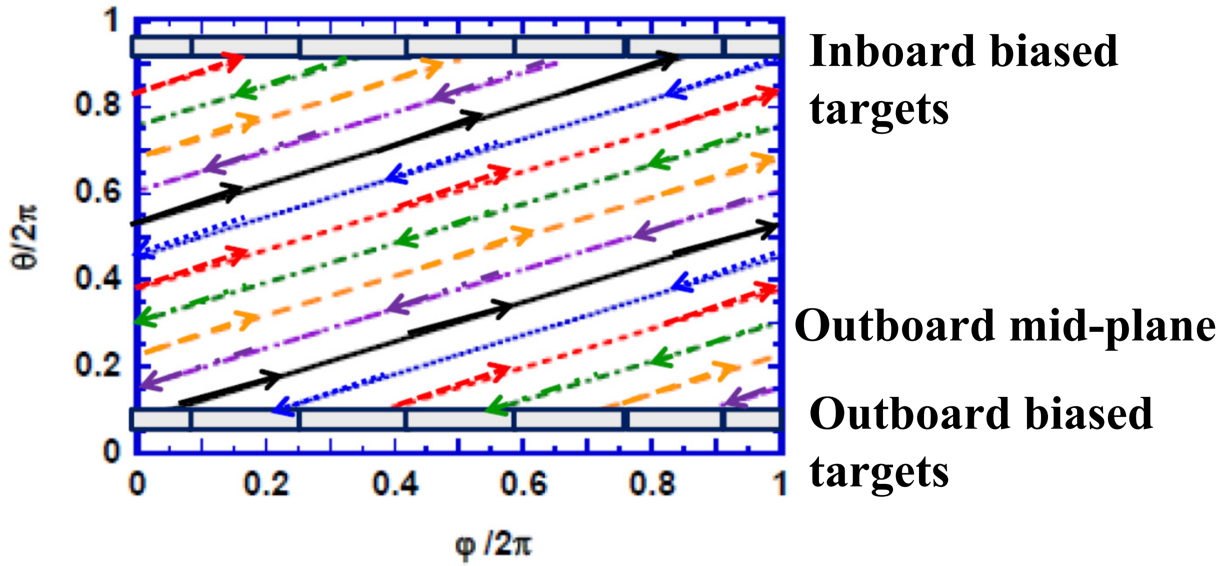
数10kAの電流で b_{mn}/B_t=(2-4)x10^{-4} [ELM制御閾値]を実現可能

ELMy Hモードプラズマでテスト

トロイダル分割型ダイバータバイアス法による SOL電流駆動とRMP生成モデル



Method: Electric biasing of toroidally segmented divertor targets against the vacuum vessel with appropriate phasing



One-side biasing
(Both-side biasing is also possible)

[Example] Inboard-outboard both-side biasing for generation of n=3 RMPs

トロイダル分割型ダイバータバイアス法による駆動SOL電流値の評価

<u>Magnitude of SOL Currents</u>

Ion saturation current: $i_{is} \cong 0.61 Zen_i \sqrt{\frac{T_e+T_i}{m_i}}$

(Assump.)

Electron saturation current: $i_{es} \cong \sqrt{\frac{m_i}{m_e}} i_{is} \sim 68 i_{is}$ => $i_{es} \cong 10 i_{is}$

Biasing voltage: $V_{bias} \geq \alpha \mathcal{R}_{\parallel} I_{SOL} + \kappa T_e$, $\kappa = 4 \sim 5$

[Ohmic drop, 0<α<1]

[Potential drop in sheath]

トロイダル分割型ダイバータバイアス法による駆動SOL電流の経路長の評価

Path Length of SOL Currents

(1) Collisionless SOL : $A_{\parallel}\Gamma_{\parallel} + A_{\perp}\Gamma_{\perp}=0$ (<= "Large area Langmuir probe")

$$A_{\parallel}=dh\ ;\quad A_{\perp}=2(d+h)L_{\parallel f};\quad \Gamma_{\parallel}=\frac{1}{4}nv_{\parallel};\quad \Gamma_{\perp}=-D_{\perp}\nabla n$$

=> $L_{\parallel f}=\frac{d^2hv_{\parallel}}{8(d+h)D_{\perp}}$ where $L_{\parallel ef}$(electrons) >>$L_{\parallel if}$(ion)

(2) Collisional SOL: $L_{\parallel ec}$ for electrons; $L_{\parallel ic}$ for ions

$L_{\parallel ec}=\sqrt{\lambda_{ei}L_{\parallel f}}$, λ_{ei}: mean free path

S.A. Cohen, JNM 1978; P.C. Stangeby, JPD 1985

(3) Connection length in the SOL: $L_c \sim 2\pi R q_{SOL}$

In QUEST

- **Scenario I**: SOL, T_e~10-20 eV, $n_e \sim 5\text{x}10^{16}$ m^{-3}, q≲10, $D_{\perp}=D_B$~2 m^2/s

  $L_c=2\pi Rq \sim 50$ m, $\lambda_{ei}\sim 20$ m

  $L_{//f\_el}$=18 m => $L_{//c\_el}$=19 m < L_c; i_{is}= 0.2 kA/m^2 (I_{is}~ 0.06 A)

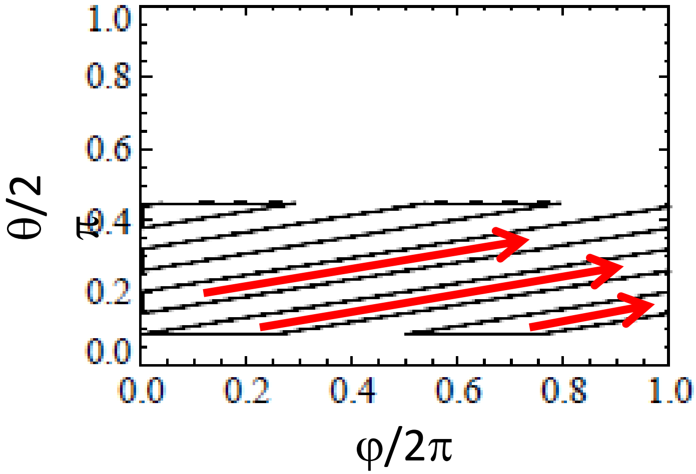
  $I_{SOL}= i_{es}S \sim 10\ i_{is}S \sim 0.6$ A

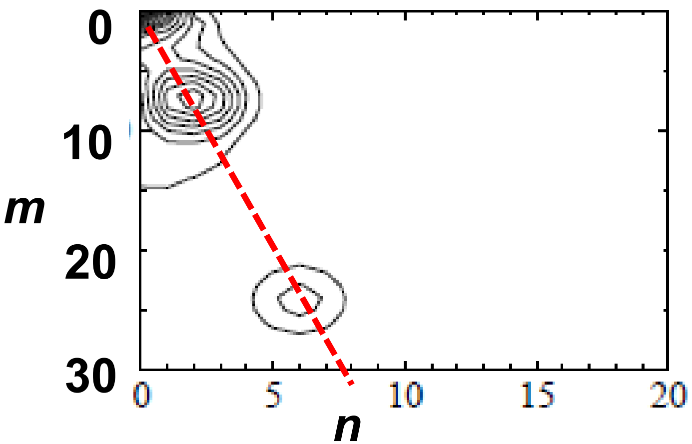
  (Similar to detached diveror like without much ionization process)

- **Scenario II**: Increase in h, Te and decreased ne, q => $L_{//c\_el} > L_c$

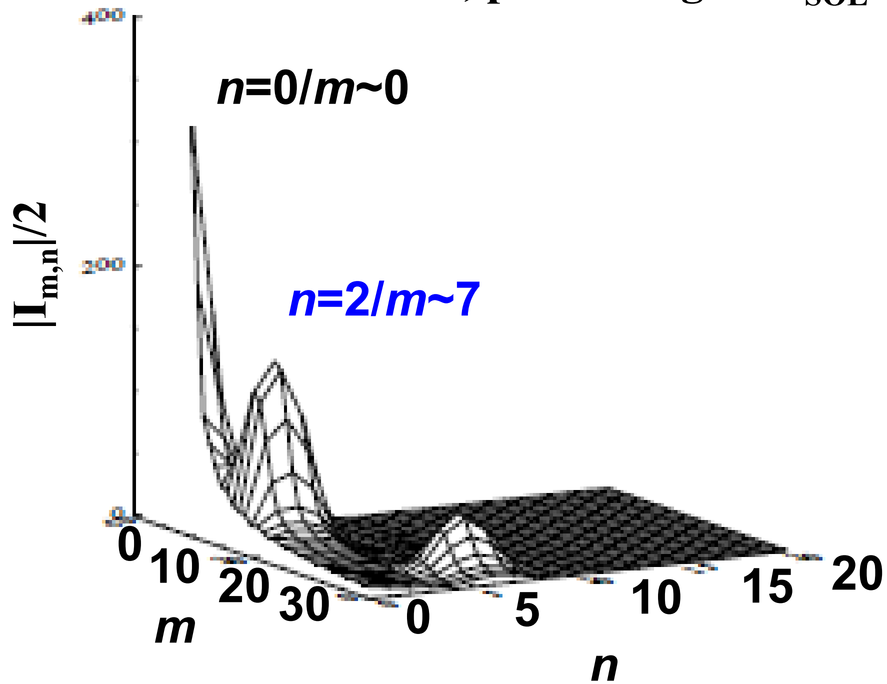
トロイダル分割型ダイバータバイアス法で生成される SOL電流群のフーリエ成分

Example of Single Null Divertor on
$L_{//c\_el} < L_c$
@ Single null divertor
@ Outboard target biasing (PFPF)





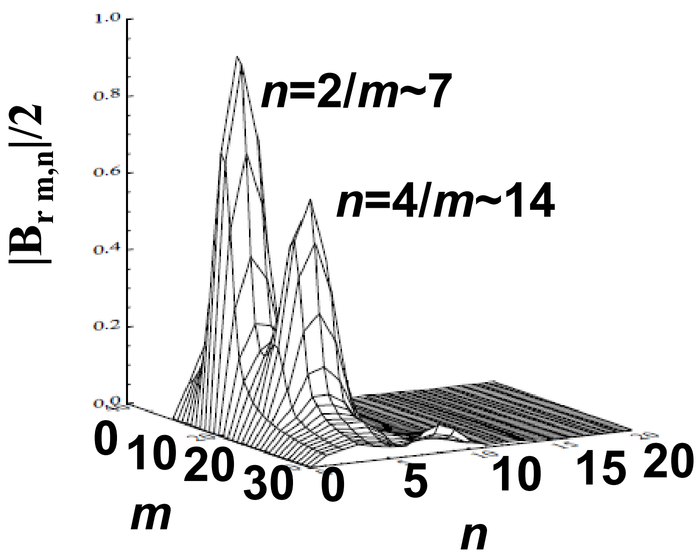
q_{SOL}~3.5
Collisional SOL: $L_{\parallel ec}/L_c$=0.44
Assumption: Return current flows only radially toward the grounded vacuum vessel, preserving divJ_{SOL}=0



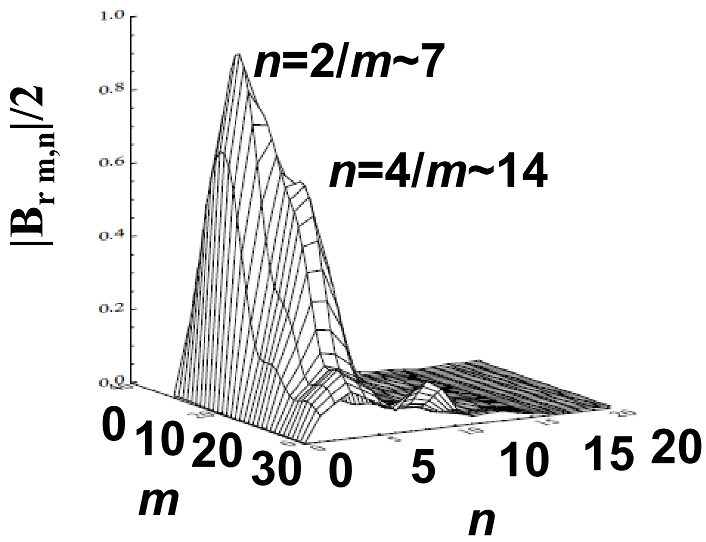
Fourier components are nearly dominated by the components with $m/n \sim q_{95}$, although appreciable m=0 component exists.

トロイダル分割型ダイバータバイアス法による駆動SOL電流群の作る径方向磁場のフーリエ成分

Case A: $L_{\parallel ec}/L_c$=0.44



Case B: $L_{\parallel ec}/L_c$=0.15

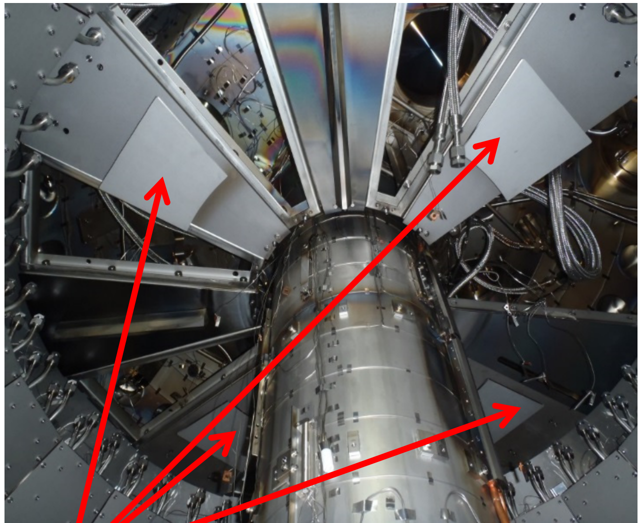


If the collisional path length of the SOL current is in the range of $0.1L_c < L_{//c\_el} < L_c$, n=2 RMP can reach the necessary level for ELM control when the distance between the SOL current layer and pedestal is ~ 0.05<a>.

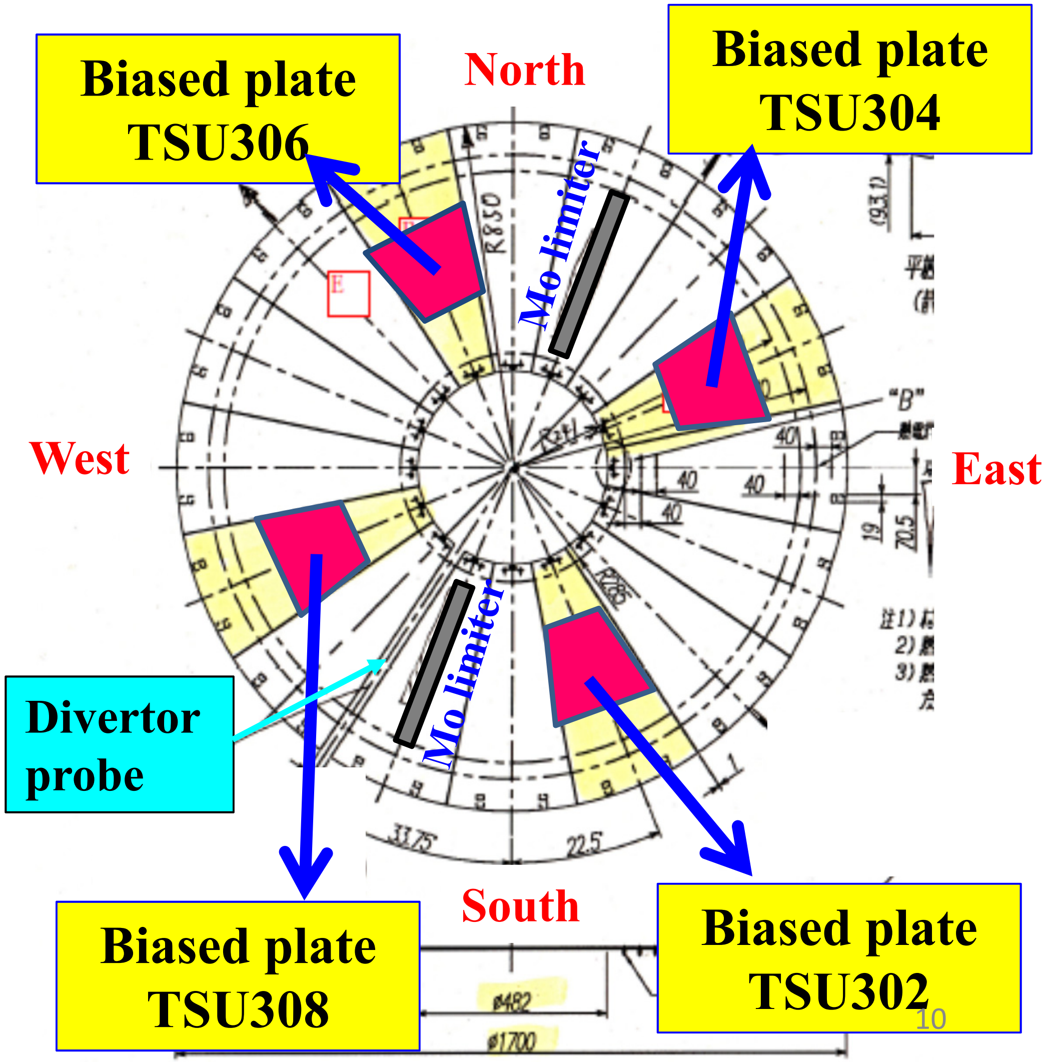
QUESTでのトロイダル分割ダイバータバイアス実験
---- バイアス板の設置----

QUEST(RIAM, Kyusyu Univ., Japan)

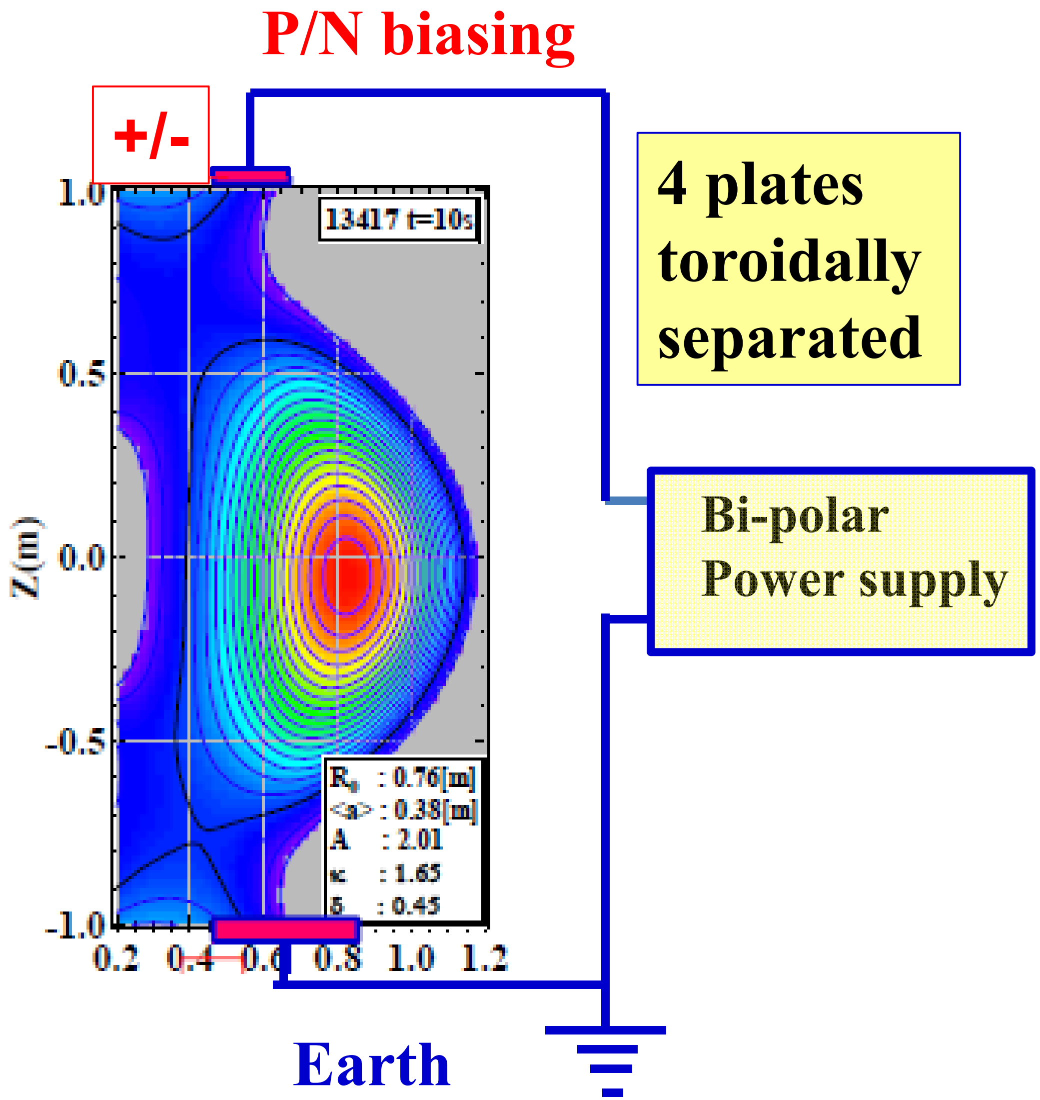
B_t=0.25 T at R=0.64m; R=0.76 -0.80 m
a=0.38 – 0.45m; I_p= 66 kA => 100 kA



Upper divertor targets for phased biasing
(Operation scenarios:
4 plates for n=1 and n=2 RMPs)



電気的バイアス法



Voltage application between divertor plates and vacuum vessel

Bi-polar power supply

-75V ≤V≤ +75V or

-25V ≤V≤ +125 V

|I| ≤ 7A

frequency：DC-250 kHz

SOL current Phasing：

P-P-P-P => n=4のb_r

P-F-P-F => n=2

P-P-F-F => n=1

…….. …..

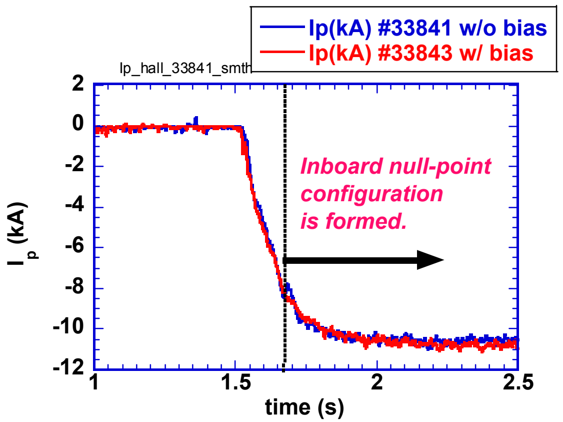
実験条件

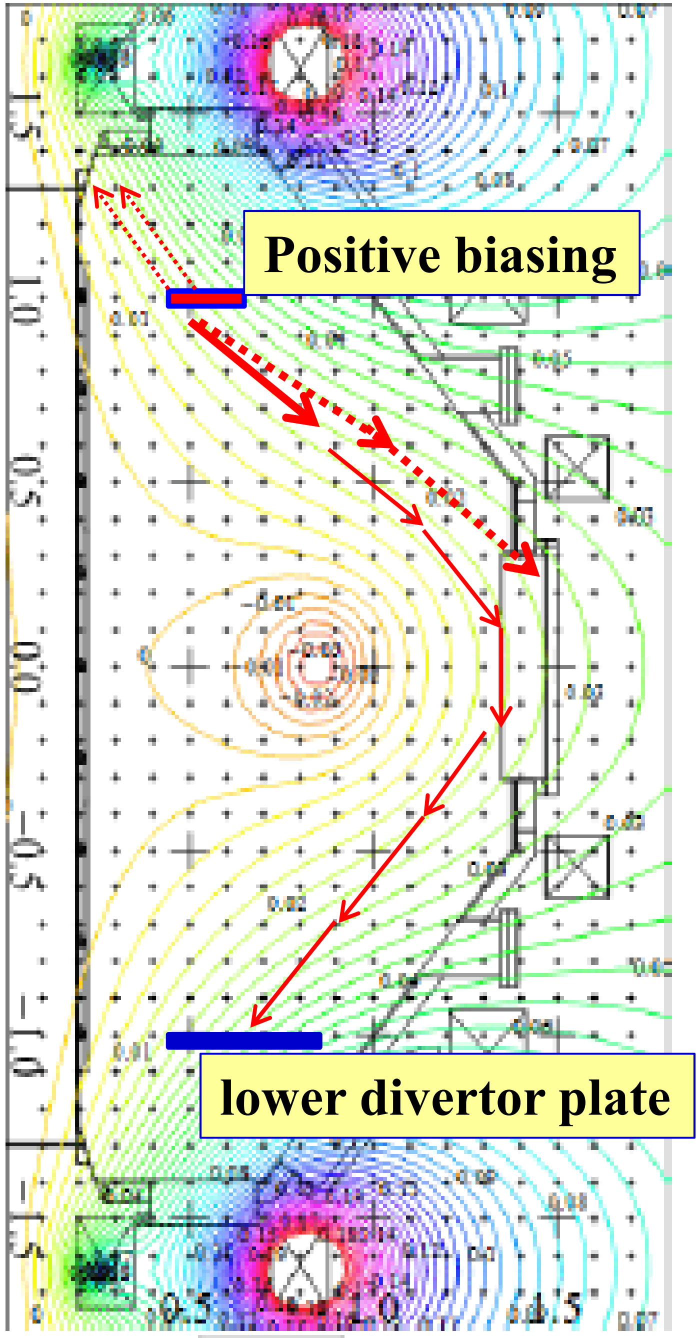
- **SOL plasma parameters (assumed):**
  T_e~10-20 eV, n_e ~ 5x10^{16} m^{-3}, R~0.8 m,
  q≲10, B_t=0.1-0.3 T, Ip~ 10 kA (Inner X confi
  L_c=2πRq ~ 50 m, λ_{ei}~ 20 m

@Further assumptions: d = 0.03m,
h=$L_t$sinθ_{in}~0.2sin(3°)~0.01 m, $D_\perp$=D_B~2 m^2

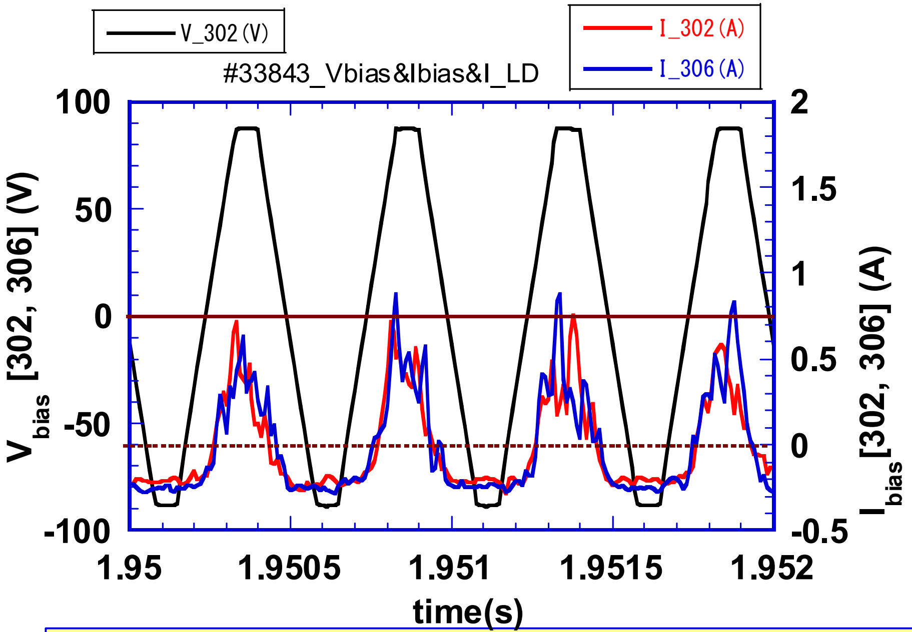
- **Current path length:**
  $L_{//f\_el}$=18 m => $L_{//c\_el}$=19 m < L_c=>
  Flow leakage from the biased flux tube?
- **Driven currents:**
  i_{is}= 0.2 kA/m^2, S=dh~1x10^{-4} m^2 => I_{is}~ 0.06 A

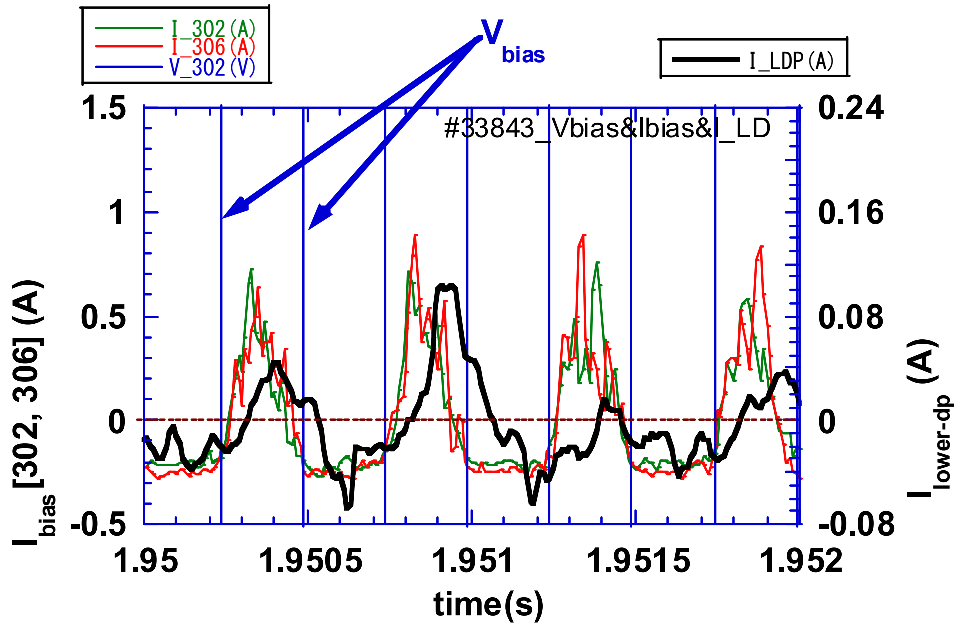
=> Expected current for each biased target
I_{SOL}= i_{es}S ~ 10 i_{is}S ~ 0.6 A





上側バイアス板及び接地電位下側ダイバータ板で観測された電流





Observed current flows out the biased 302 or 306 plate:

Positive biasing phase=> I_{bias}~0.6-0.7 A (from Plate to SOL plasma)

Negative biasing phase => I_{bias}~ -0.2 A (from SOL plasma to Plate)

Observed current flows in the lower plate reaches ~0.1 A (~7 % of the total driven current by biasing target), synchronizing with the biasing voltage waveform.

＝> It seems to be consistent with the situation of $L_{//c\_el} < L_c$.

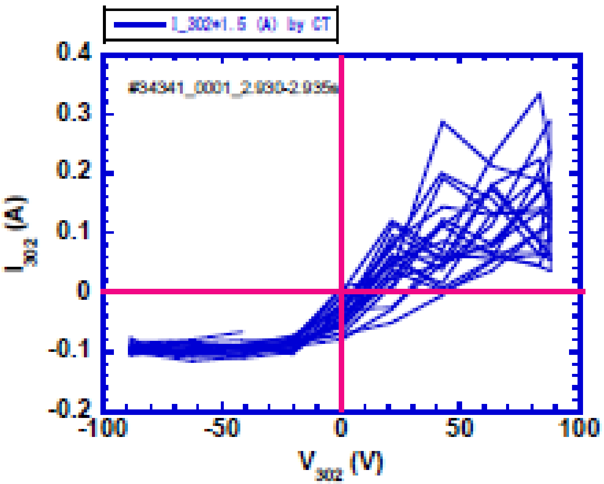
*** Where does the other part of current flow to ?**

*** The current rise time is ~0.1ms to ~0.2 ms for the biasing voltage.**

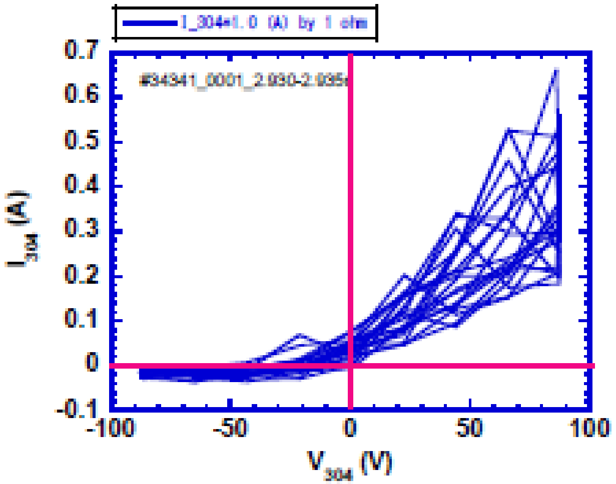
(L and ℜ of the biased flux tube: L~ 60 μH, ℜ~ 0.6 Ω => τ=L/ℜ ~ 0.1 ms)

バイアス板でのV-I特性

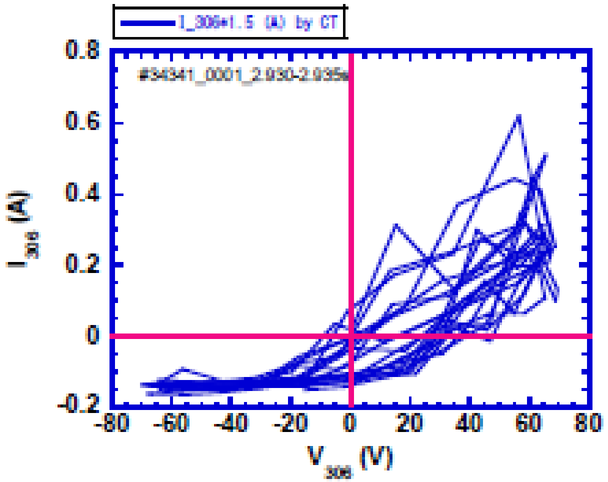
#302 plate



#304 plate



#306 plate

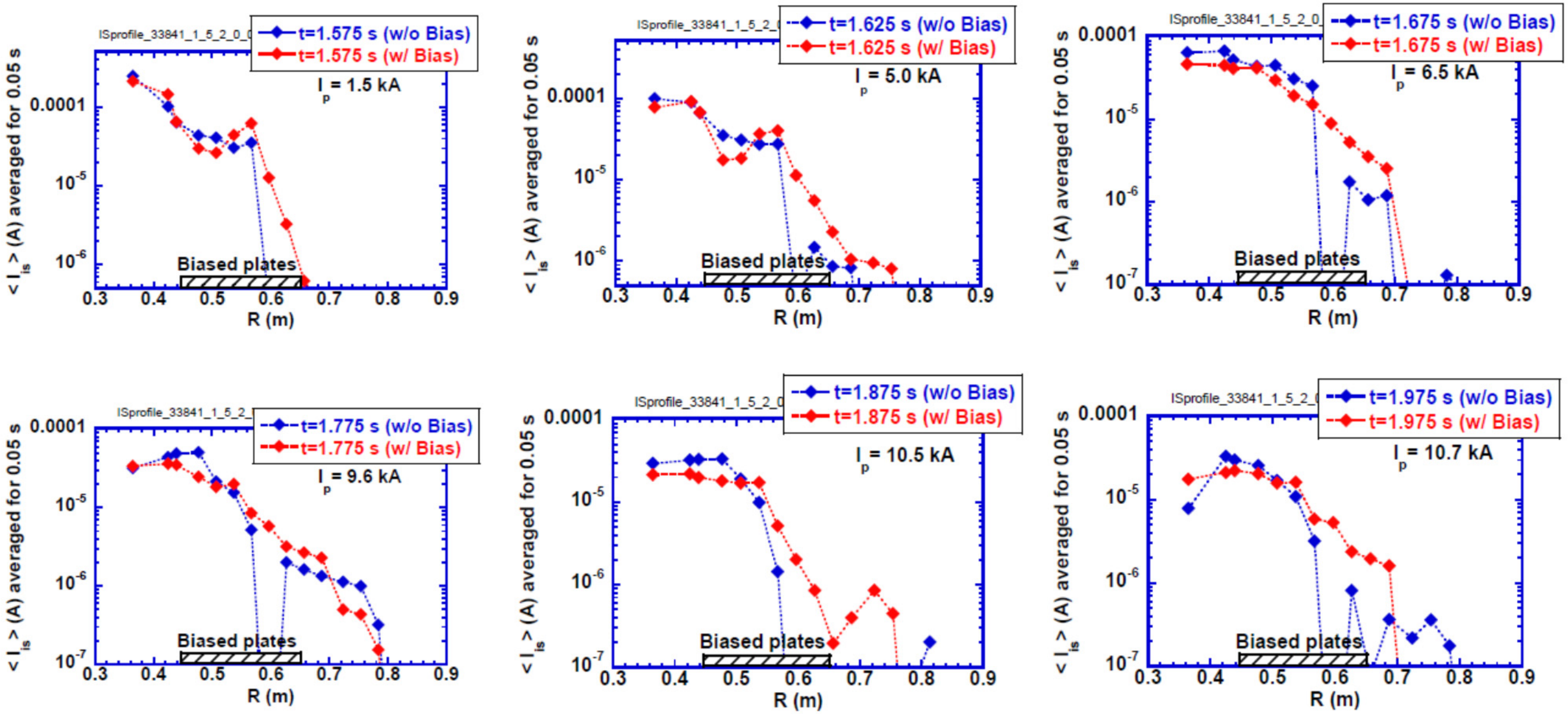


Single probe characteristics are found between the applied voltage and current through the biased plate.
Note that the voltage is monitored at the bi-polar power supply, ~ 10 m away from the biased plate.
Ion saturation current is close to the predicted one using plausible assumption.
Floating potential is positive for the vessel potential. I seems to be dependent on the plate.
No clear saturation is observed in the positive biasing.

トロイダル分割ダイバータバイアスのダイバータ粒子束への影響

Biasing off (#33841)
Biasing on (#33843)

$\langle I_{is} \rangle$: averaged over t-0.025s to t+0.025s



Divertor biasing in the upper divertor plates slightly expands the ion saturation current profiles measured at the upper divertor region.
Mechanisms: *E*×*B* effect or enhanced radial transport
(+ biasing => outward ExB drift)

まとめ

- トロイダル方向に分割されたダイバータ板のバイアス法による(1)SOLの径方向熱輸送の増大によるダイバータ熱流束制御法の開発と(2)SOL電流フィラメント群の能動的駆動によるRMP生成を狙った研究計画と初期実験結果を示した。

- <u>＜初期実験条件＞</u>
  8.2GHz RF生成内側X点配位プラズマ(Ip ~ 10 kA, B_t=0.25 T (R=0.64 m))
  バイアス条件：±75V, 2 kHzの鋸歯状波
- <u>＜実験結果 ＞</u>

\# 駆動SOL電流： $I_{biased\ plate}$ ~ 1A (flow-out) at V_{bias}=+75 V(positive biasing),
~-0.2A (flow-in) at V_{bais}=-75 V(negative biasing)
$I_{lower\ target}$ ~ 0.1 A (flow-in) (slow rise of ~0.1-0.2 ms)
=> Only ~7 % of total currents driven by biasing

\# ダイバータ粒子。熱流速分布への影響：

2プレートのダイバータバイアスにより、ダイバータ粒子束のR方向分布の拡張を示唆する結果を得た!!

今後の計画

2017年度の計画

1. バイアス駆動電流のSOL以外への漏えい防止策を施す
（改造バイアス板を2016年度中に設置予定）

2. バイアス板のプローブ特性とプラズマパラメータ測定
T_e, n_e, $L_{//e}$, SOL電流生成の磁場等

3. ダイバータ粒子束の大きい高密度プラズマでの直流と交流（up to ~100 kHz)バイアスの影響を調べる（粒子束分布とSOL中の揺動計測 (可動LP+MPアレイ設置を計画）

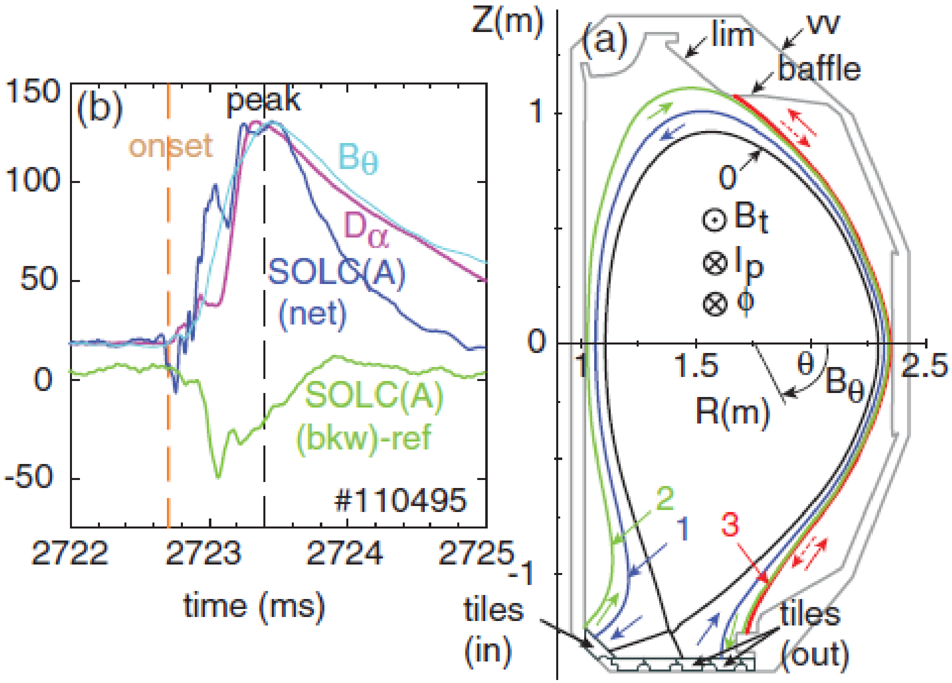
4. SOL電流路中の計測と生成RMP強度分布計測 (可動LP+MPアレイ設置を計画）

5. 上側X点及びダブルX点配位での実験

Backup

ELMによるSOL電流の誘起の例(2)

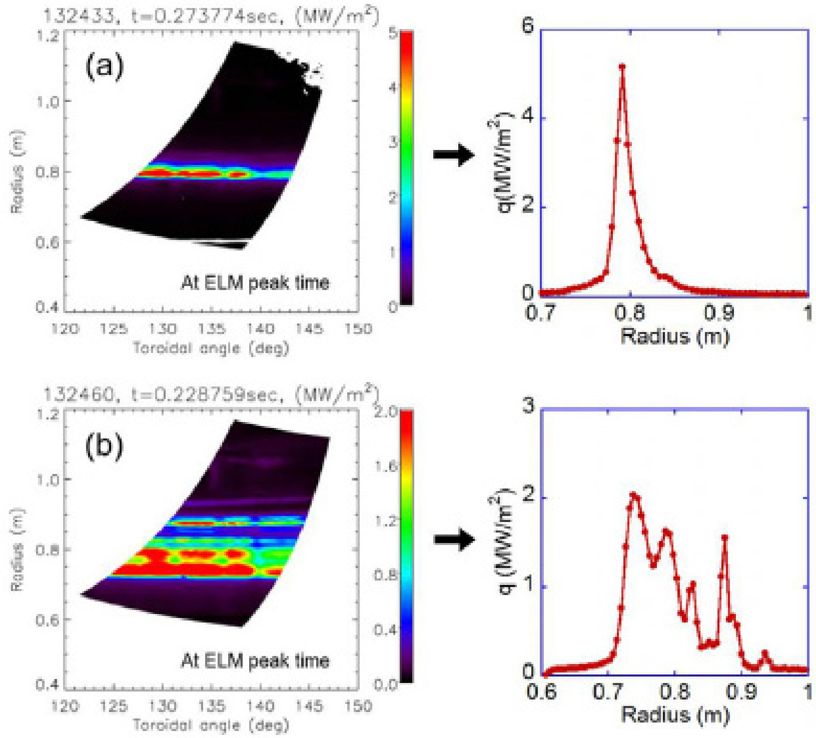
DIII-D



SOL currents (SOLCs) are induced by an ELM, having a short negative spike and decays with a similar waveform to the D_α emission.

Takahashi et al., PRL 2008

NSTX

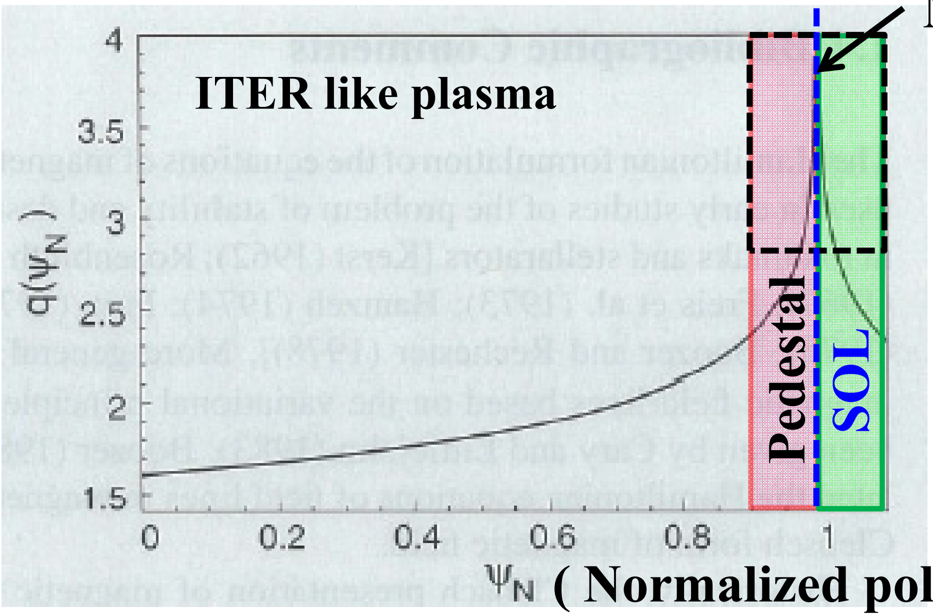


Broadening & splitting of the heat load patterns on the targets were observed during ELMs in NSTX, depending on the number of the filamentary striations.

J.W. Ahn et al., NF 2014

トカマクプラズマの閉じた磁気面領域のq分布とSOL領域での拡張q分布

q-profile in the tokamak SOL



S. Abdullaev, *Magnetic Stochasticity in Magnetically Confined Fusion Plasmas*, 2014, Springer

Effective q value in SOL just outside the separatrix (q_{SOL}) is close to q_{95} just inside the separatrix.

$\Rightarrow$ SOL current can generate magnetic perturbations which nearly resonate with the field in the pedestal region.

QUESTの仮定プラズマパラメータで評価した電流値と電流路長(計算例)

Path Length of SOL Currents

(1) Collisionless SOL : $A_{\parallel}\Gamma_{\parallel} + A_{\perp}\Gamma_{\perp}=0$ (<= "Large area Langmuir probe")

$$A_{\parallel}=dh \;;\quad A_{\perp}=2(d+h)L_{\parallel f};\quad \Gamma_{\parallel}=\frac{1}{4}nv_{\parallel};\quad \Gamma_{\perp}=-D_{\perp}\nabla n$$

=> $L_{\parallel f}=\dfrac{d^2hv_{\parallel}}{8(d+h)D_{\perp}}$ where $L_{\parallel ef}$(electrons) >>$L_{\parallel if}$(ion)

(2) Collisional SOL: $L_{\parallel ec}$ for electrons; $L_{\parallel ic}$ for ions

$$L_{\parallel ec}=\sqrt{\lambda_{ei}L_{\parallel f}}\,,\quad \lambda_{ei}\text{: mean free path}$$

S.A. Cohen, JNM 1978; P.C. Stangeby, JPD 1985

(3) Connection length in the SOL: $L_c \sim 2\pi R q_{SOL}$

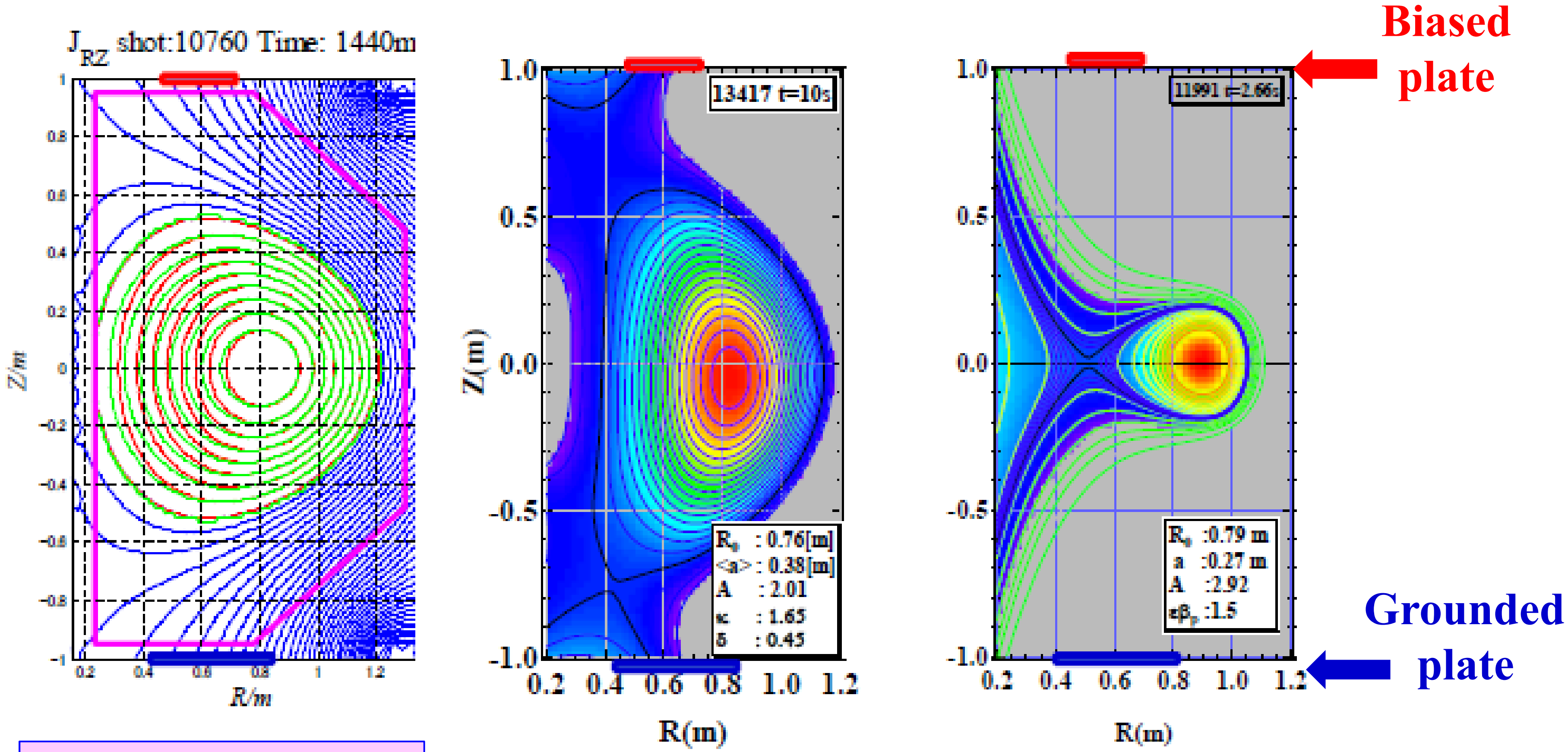
In QUEST

◆ Scenario I: SOL, T_e~10-20 eV, $n_e \sim 5\times10^{16}$ m^{-3}, R~0.8 m, q≲10, B_t=0.1-0.3 T
$L_c=2\pi Rq \sim 50$ m, $\lambda_{ei}\sim 20$ m

Further assumptions: d = 0.03m, h=$L_t \sin\theta_{in}$~0.2sin(3°)~0.01 m, $D_{\perp}=D_B$~2 m^2/s
$L_{//f\_el}$=18 m => $L_{//c\_el}$=19 m < L_c; i_{is}= 0.2 kA/m^2, S=dh~1x10^{-4} m^2 => I_{is}~ 0.06 A
=> Expected I_{SOL} for each biased target $I_{SOL}=i_{es}S \sim 10\, i_{is}S \sim 0.6$ A

◆ Scenario II: Increase in h, Te and decreased ne, q => $L_{//c\_el} > L_c$ might be realized=> $I_{SOL}=i_{is}S \sim 0.06$ A

QUESTでこれまでに実現された平衡配位

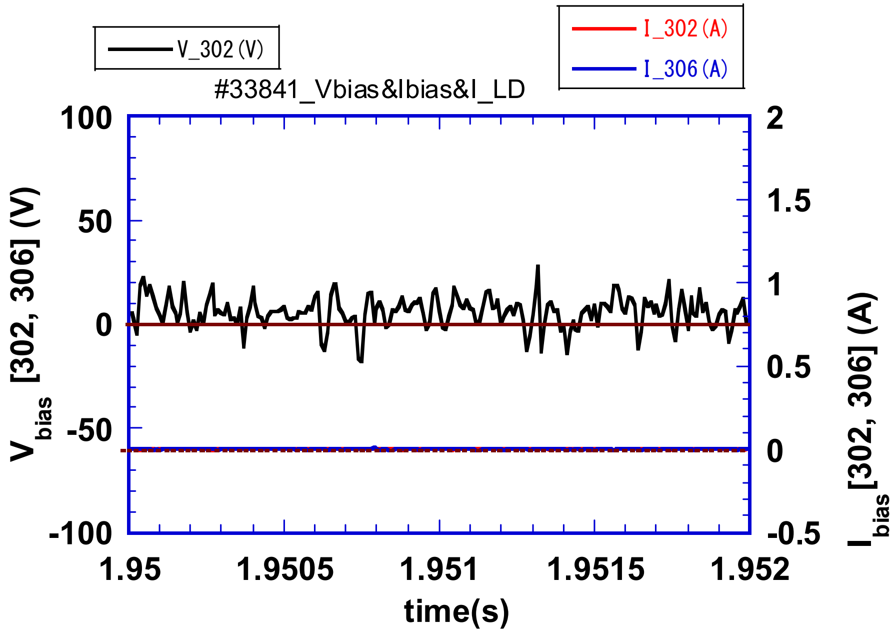


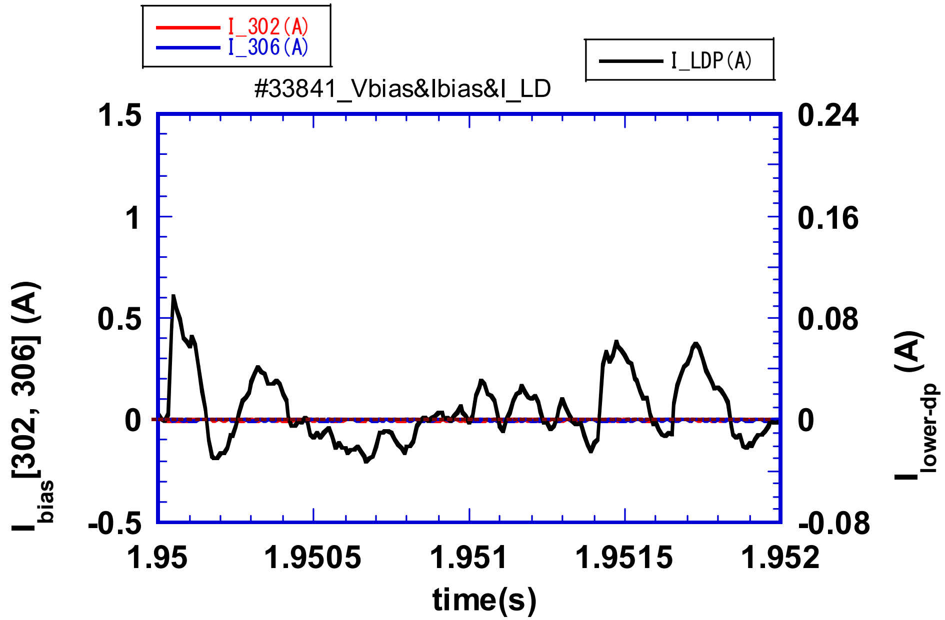
Inner limiter configuration

Lower/upper single-null configuration
&
Double null configuration

Inner X-point configuration

非バイアス時の上下ダイバータ板での電流





Without biasing of 302 & 306 plates:

The currents in the upper plates are random and much smaller than the current driven by biasing.

The current through the lower plate flows randomly.