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# Study on Sawtooth and Transport in part of Japan-TEXTOR Collaboration 1995

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**Abstract**

A collaboration programme "physics of sawtooth and transport" has been performed in the frame work of the Japan-TEXTOR collaboration. The summary of the workshops and collaborations in 1995 is reported.

*† Main contributors to this collaboration programme are: K. Itoh, K. N. Sato and N. Noda (NIFS), S.-I. Itoh, M. Yagi, M. Sakamoto (RIAM, Kyushu Univ.), A. Fukuyama (Okayama U.), H. Soltwisch (Bochum/Julich) H. Koslowski and K. H. Finken (Julich).*

Key words:

TEXTOR tokamak, Anomalous transport, Sawtooth, Current profile, Pellet injection

# Overview of the Research

## 1. Programme of Collaboration

This collaboration aims to address the long range problem, the physics of the magnetic structure and transport. The TEXTOR Group mainly provides the experimental data, and Japanese group contributes the theoretical modelling with a guide for the analysis of experimental data. Thorough the joint work, it is expected to provide a new scientific outcome. This collaboration programme has been initiated last fiscal year, as a part of the collaboration on pellet study. It is extended in this year under the new title.

Considering the characteristic feature of the TEXTOR experiment

(1) Measurement of the current profile,

(2) active experiments by use of pellet injection,

(3) Improved confinements,

and the theoretical activity in Japanese side on

(1) Self-sustained turbulence, transport and catastrophe,

this collaboration would be beneficial for the research of the both parties.

Main contributors to this programme are:

| | |
|---|---|
| *Japan*: | K. Itoh, K. N. Sato, N. Noda (NIFS), S.-I. Itoh, M. Yagi, M. Sakamoto (Kyushu Univ.), A. Fukuyama (Okayama Univ.) |
| *Julich*: | H. Soltwisch, K. H. Finken, H. R. Koslowski |

In this year, we have chosen the following points:

(1) Details and accuracy of the experimental observations, in particular that for the poloidal magnetic field, sawtooth dynamics and pellet injection (Julich)

(2) Progress in transport theory (Japan)

(3) In search of the phenomena which require the new modelling (Both)

The activity of this fiscal year covers:

(1) Prof. Soltwisch (Bochum U.) was invited by NIFS in May. On occasion of this visit, the workshop [Workshop on Sawtooth Physics] was held. (See the discussion record in Appendix.) Intensive discussion was made on the new observation of the magnetic perturbation and models are made.

(2) Prof. S.-I. Itoh and K. Itoh have attended the 22nd EPS meeting on Plasma Physics and Controlled Fusion (Bournemouth), and had discussion with TEXTOR group on the experimental data from improved confinement modes.

(3) Dr. Yagi of Kyushu Univ. visited Germany in October and had a discussion on transport theory and comparison with experimental data. He has made two lectures entitled

1. *Ohmic scaling based on current diffusive ballooning mode*
2. *Self-sustained turbulence due to current diffusion.*

(4) Dr. Koslowski was invited to 7th Toki conference and extended his stay in Nagoya. In this occasion, workshop on the sawtooth physics is held, and the discussion was made.

(5) Transport analysis of the TEXTOR profile has been continued by use of Fukuyama code. The new theory for the current sheet generation, which was found on TEXTOR just after the sawtooth crash, is proposed. Comparison with experimental data is now on-going.

**2. Physics of the Sawtooth Crash**

It was a pronounced progress that the horizontal channel of microwave interferometer (for Faraday rotation angle measurement) started to yield the experimental data. By use of this horizontal channel, the helical deformation amplitude of the magnetic axis was measured just before the sawtooth crash. This observation was the first in the history of plasma research. By this, the experimental test for the question

Whether the deformed magnetic axis touches the q=1 rational surface at the time of crash or not was reported for the first time. This measurement may be as important as

the finding of the sawtooth itself

the confirmation of the fact $q(0)<1$ after the crash.

We see the important progress every about 10 years.

Based on this observation, the following was found:

(1) In the sawtooth crash of the OH plasmas, the helical deformation of the magnetic axis remains of the order of 1cm, and is much smaller than the radius of the $q=1$ rational surface (about 15cm). It is clear that the magnetic axis *does not* reach the $q=1$ rational surface.

(2) In the additional heating plasmas (NBI, ICRF), sudden happening of the deformation of the axis (about a few cm or more) is observed. At this stage, it is not conclusive whether the helical axis reaches the $q=1$ rational surface or not. It will be decisive after the time resolution of the system will be improved in the near future. These observations are very important and will be decisive in judging the validity of various theories.

[I] For instance, in the Kadomtsev model, it is conjectured that the magnetic axis reaches the $q=1$ rational surface, and the region of $q<1$ disappears at the end of the collapse. The observation of $q<1$ after the crash on TEXTOR had large impacts. Recently, Biskamp and others has remedied the model by taking into account the plasma flow after the magnetic axis reaches the $q=1$ surface. As has been pointed by the Bubble theory of Kadomtsev, the outer cold region moves into the central region, so as to form the final state such that $q(0)<1$ holds. This model, together with Kadomtsev model, requires that the excursion of the magnetic axis must be as large as the $q=1$ surface. The resolution by the bubble formation is also proved insufficient by this new observation. On the other hand, Japanese group (with Lichtenberg) has proposed the stochasticity mode for the onset of sawtooth crash. This model also requires that the helical deformation must be as large as some threshold value for the stochastization, which is usually about some fraction of the $q=1$ rational surface. It is necessary in future to test, carefully, whether the experimental value is sufficient for the threshold.

[II] The sudden burst of the axis deformation in the case of additional heating also has strong impact for the picture of the helical instability in plasmas. This phenomena is called as the *Magnetic Trigger problem.* Instabilities are usually analyzed by use of linear theory when the amplitude is small. In such theories, the growth rate has been calculated in terms of the equilibrium plasma parameters (such as the current profile or the pressure profile). This means, the linear growth rate can change in time only with the slow time scale of the transport process. The rapid change such as 100 μs is not allowed in such theories. However, the experimental observations have shown that the growth rate can change within the time scale of 100 μs or less. These observations clearly demonstrates that the picture of the linear instability is insufficient.

Related with this problem, a new theory of the transport catastrophe has been proposed by Japanese group. It will be discussed in relation with TEXTOR experiment in future. In the workshops, wide area of issues were discussed, including

*Theory:*

Stochasticity model

Full reconnection and bubble formation (MHD simulation)

Full reconnection and bubble formation (particle simulation)

*Experiments:*

Faraday rotation experiment on TEXTOR

SX Tomography

Pellet injection (snakes)

Radial electric field.

Details are given in the attached documents.

### 3. Physics of Transport

Steady progress is also seen in the field of plasma transport.

One of the topics of plasma transport is the energy confinement in OH plasmas. In the case of Ohmic heating, the heating power depends on the plasma temperature, and the heating profile is determined by the current profile. In comparison with the additional heating experiments, the OH plasmas less freedom in the heating. The characteristics of the plasma dynamics itself becomes more clear. The OH plasmas are proper subject to study the structural organization in confined plasmas.

We have applied the transport analysis based on the current diffusive ballooning mode (CDBM) turbulence. It is found that the Alcator confinement is explained by the combination of

(1) energy transport by the CDBM turbulence

(2) MHD mechanism that limit the central q-value

(3) collinearity between $Z_{eff}$ and plasma density

leading to the linear dependence of the energy confinement time on the plasma density. Discussion was made on the TEXTOR experiments.

The important point in this new theory is that the plasma turbulence has the nature of the *self-sustaining*. The turbulence in confined plasmas is not the growth of the linearly-unstable mode, but is sustained by the turbulence itself. If the fluctuations exists in plasmas, a mode of interest increase its growth rate so as to enhance the turbulence level. In other words, they are described as a family of sub-critical turbulence. The turbulent state is not directly dependent on the linear stability, but is characterized by the stationary state and bifurcation/transition. The problem of magnetic trigger, which is mentioned above, could be analyzed in this context of the theory.

Japanese group has been developing this theoretical view widely. Through the collaboration with TEXTOR experiments, these theoretical attempts could be deepened.

## 4. Comments and Acknowledgements

Following the last fiscal year, this collaboration programme has been performed in this fiscal year. The activity turns out to be more than was expected. In particular, it was a lucky opportunity that the horizontal channel, which has required long time for preparation, started to yield the data. Improvements in experimental accuracy will be steadily pursued. The pellet injector will be remodelled soon and the comparison with the last one will soon be possible. We would like to continue this collaboration programme next fiscal year. The participation of Dr. D. Biskamp (Max-Plank-Institut fur Plasmaphysik, visiting professor at NIFS) in the discussion is also akcnowledged.

In performing this collaboration, as a part of the Japan-TEXTOR collaboration programme, the activities were partially supported by the Grant-in-Aid for Scientific Research of Ministry of Education Japan and by the collaboration programme of National Institute for Fusion Science. We would like to acknowledge Prof. T. Kuroda, Prof. G. H. Wolf, and those who have supported this work.

# 研究概要

## 1. 課題と実施

本共同研究の課題は、長期的には磁場構造と輸送係数を研究することである。TEXTOR側が実験研究を担当し、日本側が主として理論モデルや理論からの予言等、実験解析への指針を提供し、相互に啓発しあって研究をまとめようというものである。昨年度、ペレット共同研究の一貫としてスタートを切り、共同研究に着手した。今年度は、新たなタイトルの下で、共同研究を続けている。

TEXTOR実験の特徴、すなわち、
（1）電流分布計測に蓄積がある
（2）ペレット実験を積極的に行っている
（3）改善閉じこめモードがみつかっている
事を考え、一方、日本側で
（1）自己維持乱流の描像にたつ輸送理論やカタストロフィー理論
をすすめている事から、この共同研究は、両者に相補うものである。主たる研究参加者は　伊藤公孝、佐藤浩之助、野田信明（NIFS)、伊藤早苗、矢木雅敏、坂本瑞樹（九大）、福山淳（岡山大）、 H. Soltwisch, K. H. Finken, H. R. Koslowski（Julich側）他である。

今年度の研究討論の課題としては
（1）実験（特にポロイダル磁場計測、ペレット入射や鋸歯状振動の観測）の詳細と精度　（ドイツ側の準備）
（2）輸送理論の進展　（日本側の準備）
（3）モデルを必要とする現象　（相互の準備）
が選ばれている。

今年度の実行は以下の通り。

（1）ユーリッヒ（ボッフム大学）Soltwisch教授が、核融合科学研究所に招聘されたのを機会に、ワークショップを開催した。（資料は別添）そこで磁場計測の結果について、討論を行い、モデルの検討をおこなった。その成果は、discussion record にまとめられている。
（2）また、Bournemouth で開催された　２２回　ヨーロッパ会議に伊藤早苗および伊藤公孝が出席した機会には、当地にて、TEXTOR実験グループと研究打ち合わせを行い、TEXTORにおける改善閉じこめ実験のデータを検討した。
（3）矢木雅敏（九州大学、応用力学研究所）が１０月に約３週間派遣され、輸送理論の討論と、実験との比較を進めた。同氏は、
Ohmic scaling based on current diffusive ballooning mode
Self-sustained plasma turbulence due to current diffusion
と題する２件の講演を行った。
（4）ユーリッヒ　Koslowskii 氏が土岐会議に招かれた機会に、滞在を延長し、討論・検討を進めた。
（5）TEXTOR プラズマの輸送解析が、福山コードを用いて進められている。　また、TEXTOR で観測された鋸歯状崩壊後の電流層の理論モデルが議論された。

## 2. 鋸歯状崩壊の物理

TEXTOR の高時間分解 microwave 干渉計がデータを得始めたのは特筆すべき進展であった。この水平方向の channel を用いた Faradey 回転角計測により、崩壊直前の磁気軸の螺旋変形の変位がプラズマ研究史上初めて測られた。その結果

崩壊直前に磁気軸がq=1有理面に達しているか否か

初めてデータが得られたことになり、

Sawotooth そのものの発見

q(0) ‹ 1 が崩壊直後に満たされている事の検証

にならぶ、重要な実験の進展である。およそ１０年に一度づつと言った、質的進展が得られたことになる。

この観測から、次の事が判った。

1. OHプラズマの鋸歯状崩壊では、磁気軸の螺旋変形振幅は１cm 程度に止まり、q=1 の有理面の小半径が r=15-17cm であるのに比べて十分小さく、崩壊中に磁気軸は q=1 有理面に達していないことがはっきりした。

2. NBI やICRFの追加熱を行うと、数センチ・メートル程度の変形が突発する事が認められた。（時間分解を近い将来に改善し、最大螺旋変形振幅を決定する予定である。現在の所、磁気軸が有理面に達しているか否か、まだはっきり結論できない。）

これらの発見は、重要な意義を持ち、様々な理論モデルの当否を決めるものである。

[I] たとえば、しばしば論及されるKadomtsev model では、磁気軸が q=1有理面に達し、q‹1の領域が消失して崩壊が終わるとされている。しかし、実験の様に崩壊後に q(0)‹1 が満たされているだけでなく、磁気軸が有理面に達していなければ、full-reconnectionは起きていない。最近 q(0)‹1の問題を解決するために、Biskampらは、Kadomtsevの言うように磁気軸がq=1有理面に達した後、そこで現象は終結せず、更に変形はすすみ、（Kadomtsev が Bubble Theroy で述べたように）、外部のプラズマがbubbleの様に入り込み、新たにq(0)‹1の領域を形成し、それで崩壊が終結するという描像を示している。この解決法も、本実験観測では除外される。一方、日本側研究グループは、Lichtenbergと Stochasticity model を提案している。そこでは、磁気軸がq=1有理面に達しなくとも、崩壊が起きることが説明された。この理論でも、磁気面破壊が発生する閾値として、磁気軸の螺旋変形がq=1有理面の小半径の数分の一に達する事が挙げられている。この観測値で、磁気面破壊が発生しているか否か、注意深い検討が今後必要である。

[II] また、追加熱で観測される磁気軸変形の突発は、プラズマの螺旋変形不安定性の描像を一変する。この現象を Magnetic Trigger の問題と呼ぶ。不安定性は、振幅が小さいうちは、線形理論で解析されるのが常である。そうした立場から、多数の理論が計算されてきた。成長率が電流分布や圧力分布の関数として求められている。すると、成長率の変化は、平衡分布パラメターが変化する時間で変化するはずであり、100 マイクロ秒やそれ以下では変化できないはずである。しかし、実験では、変形の突発は100マイクロ秒かそれ以下で起きており、線形理論の理解が不十分であることを示している。

これについては、日本側グループの新しい輸送崩壊モデルが近年提唱されており、今後の検証を待つところである。

ワークショップでは、理論・計測・実験にわたる研究方法が議論された。詳細は資料に添付する。

理論

Stochasticity model
full reconnection and bubble formation (MHD simulation)
full reconnection and bubble formation (particle simulation)

実験

TEXTOR Faradey回転計測
SX Tomography
ペレット入射実験
電場計測

等、幅広い領域にまたがるものとなり、広範なインパクトが在ることが判った。今後とも研究を続ける予定である。

## 3. 輸送の物理

輸送に関する物理の研究も昨年同様着実に進歩している。

一つの課題として、従来提唱している電流拡散型バルーニング・モード乱流による輸送モデルが、OHプラズマを説明しうるか否かの問題が在る。OH加熱の場合、加熱分布はプラズマ電流の分布で定まり、また、加熱入力自体がプラズマ温度に依存する事から、追加熱の場合より自由度が少なく、プラズマの自律性が顕著になる。自律的閉じ込め構造の解析として興味深い。解析を進めた結果、

(1) 電流拡散型バルーニング・モードに拠るエネルギー輸送
(2) MHD活動による中心q値を拘束する機構
(3) プラズマ壁相互作用を通じて、不純物濃度とプラズマ密度が相関を持つこと

の三つの機構が組合わさり、エネルギー閉じ込め時間が密度にほぼ比例するという"アルカトール則"が現れることが示される。

このような理論的進展を説明しつつ、TEXTOR実験の結果との比較を論じた。

理論の重要な点は、プラズマ乱流が自己維持される点にある。すなわち、プラズマの乱流は、線形不安定性が発達するのではなく、揺動が発生すると、その揺動が成長率を高め、ますます不安定にする、と言った非線形機構で維持されるものである。言い替えれば、亜臨界乱流として記述されるものである。その結果、乱流状態は、線形成長率の変化に応じて変わる物ではなく、定常的乱流と分岐・遷移によって特徴づけられる事が判る。上に述べた Magnetic Trigger の問題も、このような物理的方法で解決できるものと考えている。

日本側研究グループでは、こうした理論的描像を総合的に展開しているが、TEXTORにおける様々な観測とあわせ、研究を深めることが可能になっている。

## 4. 終わりに

昨年度に引き続き、本課題についてTEXTORとの共同研究を進めることができた。計画時の予想以上に研究のインパクトを得ることができている。特に、長期間準備してきた水平方向Faradey回転角計測がまさに結果を出す時点にあったことは幸運であった。ペレット装置も増強され、前回の結果との比較もいずれ可能になることが予測される。来年度にも本共同研究を継続したい。またBiskamp博士 (Max-Planck-Institut fur Plasmaphysik、核融合科学研究所客員教授)　　　に議論へ参加いただいたことを感謝します。

今年度の共同研究の実施に当たっては、日本-TEXTOR協力の事業の一環であるとともに、科学研究費（国際学術研究）、本研究所共同研究等の援助を受けた。黒田教授 ・Wolf教授他、ご援助いただいた各位に感謝します。

# Appendix: Note of Discussions
# on Physics of Sawtooth and Transport

*Discussion Memo 1*

*Discussion Memo 2*

*Workshop on Sawtooth Physics*

*Record of Research and Discussion (in Japanese)*

*Discussion Record on Sawtooth Physics and Collaborations*

*Discussion Record on Sawtooth Physics*

**Discussion Memo 1 (May 17, 1995)**

[Itoh, Itoh, Soltwisch, Yagi]

*0. Time Schedule for Discussion during May 17-19*

*1. Materials for Discussion*

1.1 Discussion Record of the previous meeting (at Julich)
1.2 Koslowski's manuscript
1.3 Transport simulation on TEXTOR plasma (-1st draft)
1.4 Comment from Waidman on transport theory
1.5 Experimental data from Finken
1.6 New data from horizontal channel.

*2. Revisit of the Discussion Record of Last Meeting*

I. Method of accuracy of measurement
Horizontal Polarimetry Channel: Achieved
*beat freq. of 100kHz; possible if fast AD converter will come.
*time resolution; OK
*high S/N ratio; OK
[details will be discussed on 18-19]

II. Observation on precursors.
Achieved. (see Koslowski paper.)
*phase of the precursor (in density) at crash is random with respect to the device, but has clear phase relation with SX. (i.e., m=1 structure at the collapse even for the density.)

III. Disappearance of Sawtooth
Future study by use of the Horizontal channel will give progress.

IV. Influence of NBI/rotation on period
Change in the frequency of the precursor is newly found.
(see the details in the workshop OHP)

V. Magnetic Structure after the Crash
Status: As it was.

VI. Theory
Paper was finished, and was submitted to PPCF.
Returned with referee's comments.

VII. Fluctuations at Crash
Jadoul's paper will be completed soon.
It will be sent if it is completed.
Theoretical estimates for the predicted characteristics of the fluctuations are welcome. This may provide information to design experiments.

VIII. $I_p$ modulation Experiment
See the draft for the transport simulation.

IX. Others
* Structure of the "Snake" will be investigated by use of the new horizontal channel.

*3. Experimental data from Dr. Finken*

New pellet system is operating.

(1) Time variation in the pellet ablation is discussed in Julich in connection with the magnetic field structure. (A dip is expected at the rational surface.)

(2) Toroidal view of the pellet ablation is reported. The inclination of the $H_\alpha$ brightness with respect to the horizontal plane may indicate the local direction of the magnetic field.

These implications needs careful investigation. The purpose for showing the data is to inform the present status of the pellet system.

*4. Discussion on Comment from Waidman on transport theory*

I. In the attached memo, tentative experimental result is summarized. It says;

1. Under the different $B_t$ condition of OH discharges (others are constant), heat pulse propagation was observed. The $T_e$ and $n_e$ profiles have the same profiles for different $B_t$ values.
2. When $B_t$ increases, the pulse propagation became slower.
3. It suggests that the thermal conductivity, deduced from pulse propagation, scales as $B_t^{-2}$.
4. This implies that thermal conductivity scales with $q(a)^{-2}$.
5. This is in contrast to Itoh and others model of $q^2$ dependence.

II. Arguments are as follows.

(i) On the point 5, this is partly misunderstanding. The theoretical model has predicted the local dependence as

$$\chi \propto B_p^{-2} B_t^0$$

(ii) This form has still difference from Waidman's conjecture 3,4, if the $B_p$ profile as well as the plasma profile is unchanged. [cf: it is often discussed by experimentalist that the q=1 surface, deduced from the inversion radius of the sawtooth, has the dependence like $r_1/a = 1/q(a)$. In the quasi-steady phase of Ohmic discharges of TEXTOR with sawtooth activity, the dependence like $r_1/a = q(a)^{-1/2}$ was observed (IAEA, Kyoto Conf.). This indicates the fact that, by changing the main magnetic field, the current profile varies even for the constant total current.]

(iii) Following possibility is possible:

(a) Profiles in experiments are not equal for different $B_t$ discharges. (If equal, then the energy confinement time is independent of $B_t$. It is experimentally true? The discussion on the q=1 rational surface above also indicates the difference in the profile.) This requires the detailed investigation of the profiles.

The small change of the gradient could easily influence the transport coefficient.

(b) By changing the toroidal field, the current profile is no longer same. For instance, the difference in the shear (which has an important role in the theory) counts for the difference.

(c) Thermal conductivity deduced from the heat pulse propagation has the different $B_t$ dependence form that given by the power balance. (Theory applies to the stationary plasma; it treats the transport associated with power balance.) If this is the case, this will also cast an important basis in identifying the transport characteristics.

Future experimental efforts for the better profile information and theoretical study with simulation are required. The reply will be sent to Dr. Waidman in a separate letter.

**Discussion Memo 2 (May 19, 1995)**

[Fukuyama, Itoh, Itoh, Soltwisch, Tsuji-Iio, Yagi]

**I.** Detailed discussion on the recent observation on TEXTOR is made based on the view graph. Important issues includes following points.

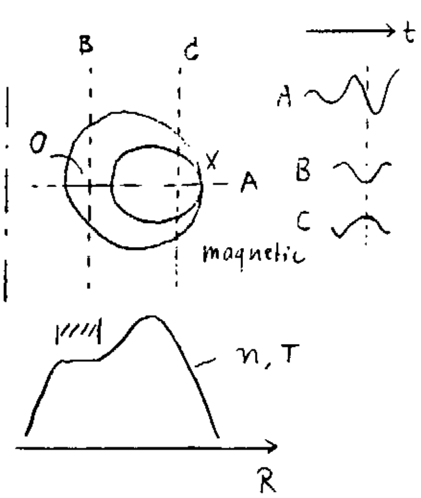
## II. Ohmic Plasmas

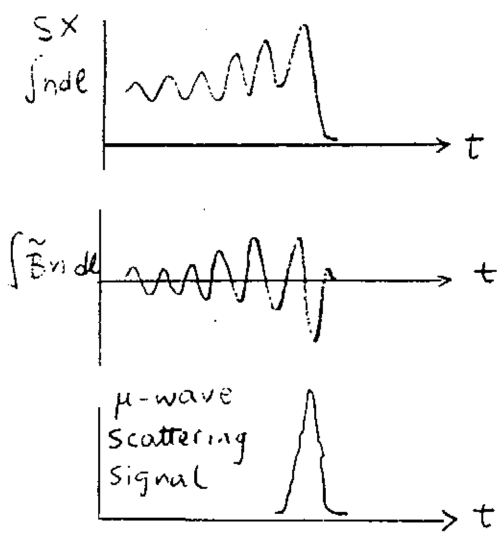
1. Magnetic field variation in precursor/crash is observed.
   1.1 Phase relation between $\tilde{n}$ and $\tilde{B}$
      'flat density and temperature' exists at the poloidal angle where magnetic O-point is expected.
      cf. Radial location of the 'flat-density' (or 'flat temperature') relative to magnetic O-point: needs further study.

2. Axis shift was found O(cm): maybe 5cm? but not more
   2.1 Unambiguous observation that there is no full reconnection
   2.2 Needs further calibration to determine absolute value of $\tilde{B}$

3. Without complete reconnection, sawtooth crash can happen.
   3.1 It is typical in OH
      (more than tens are observed)
   3.2 Large spike should not be missed, if it exists.

4. Future Exp for OH plasmas
   4.1 Increase observations
   4.2 Onset of micro-turbulence will be simultaneously observed by use of micro-wave scattering.
   4.3 Snake will be investigated by the help of pellet.
      Feed the density by the pellet in the region where the magnetic island is expected. The high confinement time, characteristic to the snake is investigated.
      Small size and high velocity will be necessary.
      If the pellet is too big, the refraction causes the difficulty in observation. If too small, the central region is not reached.



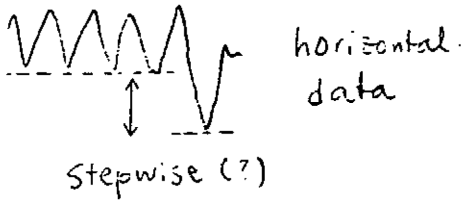



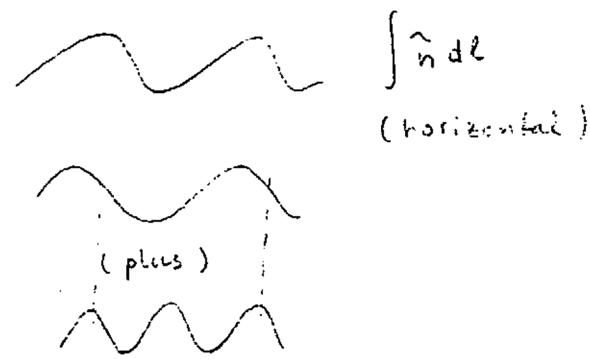
## Q/A and free discussion

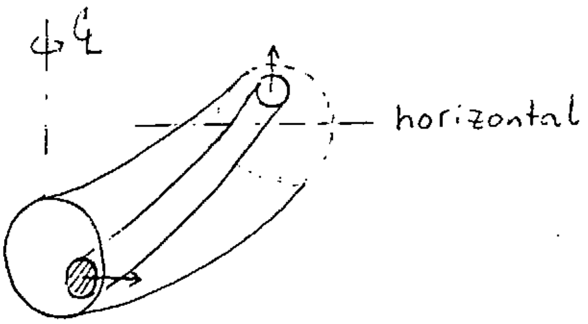
1. Step-wise increment of the magnetic amplitude seems to exist just before the onset of crash. (Important for the stochasticity model)
   Is it possible to find this step by carefully choosing the case where the plasma column moves to upward/downward at the toroidal angle of horizontal channel. This selection will be possible by seeing the SX array and vertical array. (The result of high time-resolution will answer.)

2. Density change in the horizontal channel: oscillation may be decomposed of fundamental and doubled frequencies of the following phase difference.

3. Snake observation would examine the theoretical idea that there is a threshold size for the snake to exists (i.e., to have a long confinement time in the localized region).

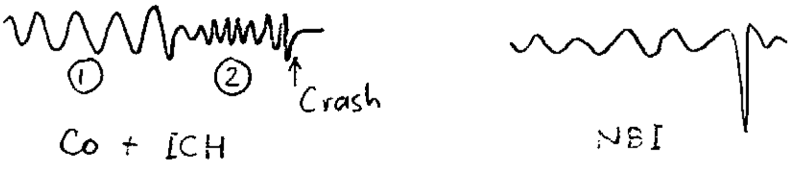


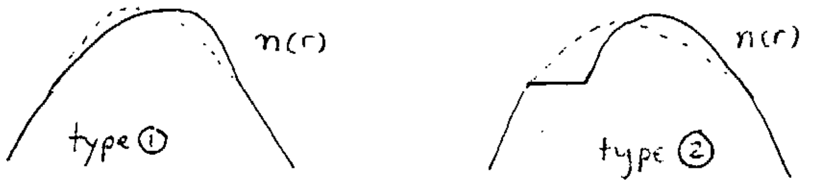
### III Case of Additional Heating

1. Variety is seen:
   1.1 Frequency doubling(?) in CO-NBI + ICH (I-mode)
   1.2 Sharp spike in the case of CO + CNTR-NBI



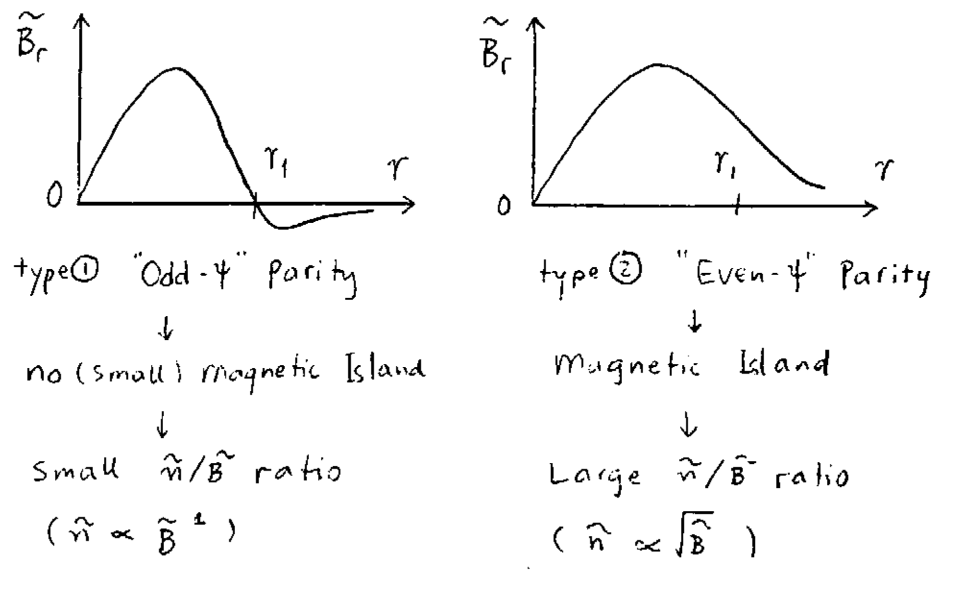

2. Mode characteristics

   2.1 In the first type in (1.1), the ratio $\Gamma \equiv \left(\int \tilde{n}\, d\ell\right)\left(\int n\tilde{B}\, d\ell\right)^{-1}$ is smaller than the case of the second type.
   2.2 In the second type, the ratio Γ is same as that in OH plasma.
   2.3 This indicates that in the first type, magnetic island is not formed.

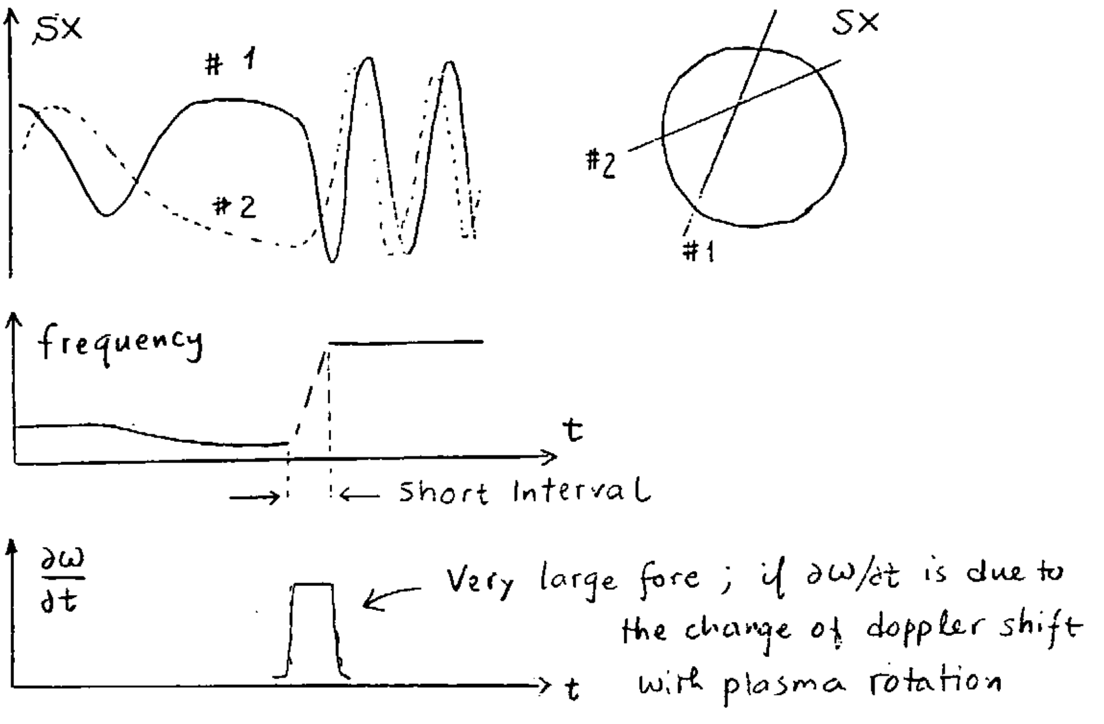



(Let ξ be the shift of the plasma. Density perturbation may be estimated as $\tilde{n} \approx \xi \nabla n_0$. If the magnetic island is formed, then the relation $\xi \propto \sqrt{\tilde{B}}$ holds leading $\tilde{n} \propto \sqrt{\tilde{B}}$.
* On the contrary, if there is no island, then $\xi \propto \tilde{B}$.
* As a result of these difference, the ratio Γ is larger in the case where the magnetic island is formed.)

2.4 One of the possible eigen function of the magnetic perturbation is discussed as follows.
2.5 SX tomography will give better data to identify this.



3. Reversal of the poloidal propagation with the change in frequency is found in the case of CO + CNTR NBI case.
   3.1 Plasma Rotation is not observed yet (future task)
   3.2 Mode-locking seems not occur; this is because the plasma motion at the crash is not uni-directional.
   3.3 The frequency change implies the two eigen modes.
   (If it were the change of plasma motion, then the acceleration should be sudden and very large.)




**IV A Speculation for the Two Modes**

4.1 Mode with island and that without are implied.
   Even-ψ parity mode (tearing) and Odd-ψ parity mode (rippling, ballooning trapped particle) are observed?

4.2 The theories on the kink-tearing mode and fish-bone mode are reminded. (See attached figures.)

4.3 The first type of oscillation (small ratio Γ).
   Is it Odd-ψ parity mode?
   Is it the so called fish-bone mode?
   Is this oscillation resonates with drift of trapped high energy ions?

*Test:*

(1) Loss of energetic ions by the oscillation, if it exists, can be checked by the neutral particle analyzer data.

(2) Resonance with toroidal drift of hot ions can be tested if the plasma motion is observed. Also the dependence of the frequency on the magnetic field and heating power must be studied. (According to the conventional theory, the frequency, in the plasma frame, of the kink-tearing mode is smaller than that of the fish-bone mode. In the TEXTOR observation, the first one has lower frequency than the other. Unless the Doppler shift exists, the interpretation by the fish-bone mode is wrong.)

**Workshop on Sawtooth Physics (May 18, 1995, NIFS)**

This workshop is organized under the Collaboration Program of National Institute for Fusion Science, and is also supported, as a part of the Japan-TEXTOR collaboration, by the Grant-in-Aid for Scientific Research of the Ministry of Education, Science and Culture Japan

**Programme**

1. Welcome and Introduction (K. Itoh)
2. Recent Results of Sawtooth Studies on TEXTOR (H. Soltwisch)
3. Heat Flow during Sawtooth Collapse on WT-3 (K. Hanada)
4. Fast Potential Change in Sawtooth in JIPP T-IIU Tokamak Plasmas (K. Toi)
5. Sawtooth Crash Model Driven by Stochasticity (A. Fukuyama)
6. Gyrokinetic Simulation of the m=1, n=1 Mode in Tokamak (H. Naitou)
7. Summary and Discussion

**Participants/Contributors**

| | |
|---|---|
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# 研究討論報告

九州大学応用力学研究所　矢木雅敏

派遣期間：　　平成７年１０月１日より平成７年１０月２２日まで。
派遣研究所：　ドイツ連邦共和国ユーリッヒ研究機構プラズマ物理研究所。

日本－ＴＥＸＴＯＲ協力に基づいてドイツ連邦共和国ユーリッヒ研究機構プラズマ物理研究所を訪問し、鋸場状波振動解析及びエネルギー輸送の研究に関して議論、検討を行ったのでここに報告する。

## １．研究発表

'Ohmic Scaling Based on Current Duffusive Ballooning Mode'

'Self-sustained Plasma Turbulence due to Current Diffusion'

と題する２つの講演を行った。

最初の講演は我々が提案している電流拡散バルーニングモードによる異常輸送から予測されるオーミックプラズマのエネルギー閉じ込め則について論じたものである。このモデルがLモードと呼ばれるトカマクの閉じこめモードをよく説明できることはすでに指摘されていたが、Alcator則と呼ばれるオーミック閉じ込め則を説明できるかどうか比較、検討したものである。結論として、電流拡散バルーニングモード単独のモデルから説明することは困難であり、MHD効果、プラズマ・壁相互作用とこのモードの共同現象によりAlcator則が説明できる可能性を示した。講演に対する質問としてAlcator則から飽和オーミック閉じこめモード(SOC)と呼ばれるモードを包括的に説明できるかどうかというものがあった。今のモデルではプラズマ・壁相互作用を通じて陰に閉じこめモードが変わるというシナリオであり、プラズマ・壁相互作用が乱流の飽和レベルに対し、定量的にどの程度影響を与えるのかについては今後の検討課題であると答えた。

２番目の講演は電流拡散交換型不安定性に基づく非線形数値シミュレーションによって実際にプラズマ乱流が自己維持されることを示し、我々の理論モデルの妥当性に関し、検討を行ったものである。プラズマ乱流がサブクリティカル乱流であることを講演では強調した。結論として、非線形不安定性のキーになっているのは電流のノーマルカスケードであり、またこれが圧力の構造形成に大きな影響を与えていることを示した。講演に対し、ドリフト波との結合によって乱流の性質が変わり得るのでモデルの改良が必要であろう点、またトロイダル効果が非線形不安定性を加速する可能性があるので検討すべきであるというコメントがあった。今後検討していく予定であると答えた。

## ２．研究討論

### ２．１　ダイナミック現象

#### ２．１．１　ＥＬＭ

De Blank, Suttrop, Zohm氏らとType IやType III ELMに関する実験結果及びそれらの現象論モデルに関する議論を行った。特にDe Blank氏とはType I ELMを理想バルーニングモードによるバースとだと仮定したモデルについて議論した。

#### ２．１．２　Sawtooth（鋸歯状波振動）

Koslowski, Fuchs, Bessenrodt氏らとsawtoothに関する計測を中心に議論を行った。オーミックプラズマに関してはprofile consistencyがかなりの精度で成り立っていることが実験的に示された。またsawtoothが

おっこた時、プラズマの流れを計測する方法、磁気島のｘ点を決定する方法等に関して議論を行った。saw-toothがおこった時、m=1磁気島近傍の磁気面に表皮電流が流れていることを示唆する実験データが示されたがこれを説明するモデル及びMHDモデルの適用限界について議論した。

### ２．１．３　Fishbone、ＴＡＥ

Kass, Weller, Lackner氏らとFishbone, TAEモードに関する議論を行った。ロスメカニズム、分布関数の変化、preditor-prayモデルに基づく現象論的モデルに関して議論した。またモード構造の計測に関しても議論した。

## ２．２　閉じこめ現象

### ２．２．１　新古典理論

Rogister氏とプラズマ周辺領域における新古典輸送理論の適応限界に関して議論した。さらに、FLR効果により修正された新古典輸送係数及び、Hモードにおけるこのモデルの応用について議論を行った。

### ２．２．２　Ｌモード閉じこめ則

Waidmann, Kraemer-Flecken氏らとＬモード則を中心にＬモード輸送全般にわたって議論を行った。特に我々の提案する電流拡散バルーニングモード乱流モデルが実験を説明できるかどうかを議論、検討した。実験結果について土岐会議で発表後に内容をまとめた本論文を執筆中とのことであった。

### ２．２．３　輸送係数

Stroth氏と熱パルス伝搬、局所的輸送係数に関して議論を行った。熱伝搬実験でECEパワーを切ったとき輸送係数自体が非常にはやい時間スケールで減少する一種の転移現象に関して議論を行った。

### ２．２．４　改善閉じこめモード

Messiaen, Ongena, Suttrop, Kallenbach氏らとIモード、detached-Lモード、Completely Detached-H (CDH) モードに関して議論を行った。ネオンパフを行った時のみ、detachedプラズマが得られることが指摘されその理由に関して議論を行った。またradiationが介在したときの閉じこめ特性等に関しても議論した。

## ２．３　非線形現象

### ２．３．１　モデリング

B. Scott氏と乱流モデル,特にドリフト効果、トロイダル効果に関して議論を行った。またcray T3Dコンピューターの性能及びコードのチューンナップに関するテクニック等に関し議論した。

# ３．　考察

### ３．１　LH, ELM, Sawtooth, Fishbone

Type IとType IIIをMHDの立場から説明するモデルがある。すなわち、Type I ELMは理想バルーニングモードによると考え、Type IIIは抵抗性バルーニングモードによるとするものである。一方でSawtoothとFishboneはキンクモードにつながる２つの分枝であるとするモデルがある。これらの間に類似性があるのかどうか検討した。TAE, Fishbone, Type IIIは中立安定の回りの振動と解釈するとPred-itor-preyモデルで説明できる可能性がある。ただしType IIIの振動はFishboneやTAEのバーストに比べてカオティックであるのでリミットサイクルのみならずカオスを含むモデルが必要と考えられる。またロスメカニズムの特定が必要である。

実験データにおいてSawtoothからFishboneへ遷移が観測されているがもしこれらがキンクにつながる分枝と仮定するとモードのパリティーが変わっている可能性がある。実験的(ECE,polarimetry等)にそれが見えるどうか検討した。データ不足のため今後の実験課題ということになった。

さまざまなSawtoothモデルが提案されているが流れのパターンを実験的に計測できればそれぞれのモデルの妥当性が検証できる可能性がある。そのためには新しい計測法を導入し、精度を上げる必要がある。また磁気島のｘ点を確定する必要がある。今後の実験課題ということになった。

3．2　CDHモード

CDHモードにおいてはm=1モードは飽和しており、通常sawthoothは観測されていない。可能性としては不純物による安定化の効果が考えられる。この場合Fishb-oneは観測されるのかどうか疑問をもったが実験データが十分でないため残念ながら今後の実験待ちということになった。

L, H, detached-L, detached-H(CDH)の間での電場構造は変化するのか？radi-ation, impurityの介在によりELM, MHDの性質が変わってくるのかどうか検討した。
定量的評価のためには統計的な実験が必要であり、今後の実験待ちということになった。またVHモード+detachedに関しても今後の課題となった。

4．　今後

今回の討論をもとに日本－ＴＥＸＴＯＲ協力に基づく鋸歯状振動解析及びエネルギー輸送の研究に対し、今後一層の充実、発展をはかっていきたいと考える。手始めとしてKoslowski氏来日により議論を深め、今後の共同研究を実り多いものにしたいと考える。

この場を借りて、本出張を援助、支援してくださった皆様方に感謝いたします。

# Discussion Record on Sawtooth Physics and Collaborations

*Participants*: K. Itoh, S.-I. Itoh, H. R. Koslowski, M. Yagi

On occasion of Dr. Koslowski's visit to Japan, discussion was made on the following topics

*(1) Helical deformation of magnetic axis at crash*
*(2) Sheet current generation*
*(3) Details at crash*

**Topic (1)**

Helical deformation of the magnetic axis before the crash was observed on TEXTOR. In one case, the deformation was quantified (about 1 cm) in EPS conference. (Note that the minor radius of the q=1 rational surface is about 15cm.) In NBI, saturated m=1 oscillation with axis shift of 2cm was observed. In the sawtooth crash of NBI, pulsative motion is not yet be quantified (time resolution is not complete). If one uses the present value of Faraday rotation angle of 2 degree, the helical axis shift will be about 10cm.

The OH sawtooth clearly demonstrates that the complete reconnection does not occur in this case. Also it is suggested that the magnetic stochasticity may not reach the center at the level of the helical shift of 1cm.

The tomographic reconstruction together with this measurement will be surely very interesting.

**Topic (2)**

A model of the toroidal current sheet at the sawtooth crash was proposed. Discussion is made on the theoretical modelling and on how it could be compared to the experimental observation.

At present m=1 component of the toroidal sheet current is modelled. Experiments has shown the m=0 component of the sheet current as well, which is left open now.

The current sheet model allows the estimation of the toroidal shift of the magnetic axis. Since the toroidal shift at the crash was observed and reported (PPCF **37** 667), this toroidal shift must be calculated and compared. (Task for theory group.)

The plasma parameter is reported in the EPS paper, so that the computation of the sheet current is available. If the perturbed magnetic field is calculated by Japanese members, it will be sent to HS and HRK, and the additional Faraday rotation will be evaluated.

Another aspect is the dynamic nature. The temporal decay of this sheet current was observed in experiments. Theoretical evaluation for the decay time is necessary, and is another way of the comparison. (Task for theory.)

As a whole, this problem is recognized as a good path of the collaboration, and the future home work is identified. Both sides are not urged, by the external forces, to complete this report.

**Topic (3)**

Precursor oscillation in micro-wave signal was clearly obtained by accumulating many crash data. (See, e.g., Julich report 3114.) Advancement of the data analysis, particularly for the short period of the crash, is proposed: by subtracting the 'reconstructed precursor oscillation' from each raw data, additional information could be obtained. This variance, of cause, is consist of noise; however, by observing the variance, it may be possible to show the new dynamic mode at the onset of crash.

Rough idea and plausibility is discussed. Based on the present computational method and data base, it seems possible to give an answer by use of the present data base. HRK will consider after coming back to Julich.

# Discussion Record on Sawtooth Physics

On occasion of the Dr. Koslowski's visit as a part of the Japan-TEXTOR collaboration and Dr. Biskamp's stay as a visiting professor, a small workshop was held. The record of the discussion is as follows.

**Participants**: D. Biskamp, K. Itoh, H. R. Koslowski, A. Nagayama, N. Noda, I. Nomura, K. N. Sato

**Contributions**

(1) Measurement of Sawtooth on TEXTOR (Koslowski)
(2) Tomographic Picture of Sawtooth Crash of TFTR (Nagayama)
(3) Snake Formation by Pellet (Sato)
(4) Nonlinear Simulation of Sawtooth Crash (Biskamp)
(5) Trigger Problem and Models (Itoh)

## I Magnetic Axis Motion in the Sawtooth

Result of the horizontal channel (Faraday rotation of FIR laser) of TEXTOR is reported by Koslowski. Within the time resolution (Nyquist frequency = 5kHz), the typical behaviours observed are:

(i) In OH plasmas, the sawtooth precursor grows with a growth rate of about 600 $s^{-1}$, but the final amplitude is small. The helical axis shift amounts to 0.9cm (the minor radius of the q=1 rational surface is 15-17 cm for these discharges). The poloidal angle of the magnetic o-point agrees that of the region of density flattening. The magnetic axis shift may exceed 1cm during the crash, but clearly is below/about 1/10 of the q=1 surface.

These observation suggests that (a) an island is formed, (b) full reconnection does not occur, (c) the stochastic region, if it exists, can probably not reach the plasma center. In other words, the previous models (complete reconnection in simulations, or the stochasticity model) have difficulties in explaining the observations. The mystery of sawtooth crash is clearly identified.

(ii) In NBI (and or ICH) plasmas, large pulsative motions are observed. The rotation angle amounts to 1-2 degree in the peak. (According to KI's memory, this angle was in "arbitrary unit" in the last EPS; we see the progress in the experiment.) These spikes are indicative for a pulsative motion. The pulse width is of the order of 100 μs, and the Nyquist frequency is too low. Efforts are made presently to increase it to 25kHz. Conclusion must be made after this improvement of the system. (The Faraday rotation angle of 1-2 degree, if it is correct, implies that the axis shift amounts to 5-10 cm.) Although there is a possibility that the signal suffers from up-to-now-unrecognized perturbation, one can conclude that "something happen" with additional heating, because these are not seen in the OH plasmas.

The heating power was continuously increased, and the change of 'spike' was measured. Gradual change of the spike height is observed. This is another confirmation that there is not a big shift during the OH crash.

(iii) Progress was made in measuring the "stationary m=1 oscillation" during the NBI heating. The stationary deformation of 2cm was observed.

The future tomographic reconstruction from TEXTOR together with this measurement of the magnetic axis shift will be very much interesting for the understanding of the sawtooth crash.

## II Tomographic Picture of Sawtooth Crash of TFTR

Nagayama gave additional information of the sawtooth crash based on tomographic measurements. SX tomography can deviate from the magnetic signal, because the SX intensity is a complex function of the impurity density as well as electron temperature. Based on the ECE tomography, the demonstration was given that the full temperature collapse occurs without complete magnetic reconnection.

The detailed observation of the ECE contours (deformed by m=1 mode) suggests that there are additional small scale modifications near the outer region of the torus.

The picture of local reconnection (i.e., the magnetic reconnection occurs localized toroidally, at the location where x-point comes to the outside of torus) is proposed.

## III Snake Formation by Pellet

Sato reported on snake formation by pellet injection into the TEXTOR plasma. When the pellet ablation point is approaching to the inversion radius of the sawtoothing plasma, the m=1 snake-like density modulation appears spontaneously. (Temperature measurement suggests that the m=1 deformation does not appear in the temperature profile, so that the snake is the local peak of the density.) The snake has the life time of the order of a few-10 ms, and a second one can also appear. Comparing the minor radius of the second and first snakes, it is conjectured that the q=1 rational surface expands in the interval between these two snakes. This will provide a tool to measure the dynamics of the q=1 surface by pellet injection.

The experiment will be continued in the next year, and more data will be available. A difference is that the future pellets introduce about $1\times 10^{20}$ particles, while the previous ones have $(4\sim 6)\times 10^{19}$ particles. Hence pellets will have a much larger effect on the plasma, which may change their value as a diagnostic tool.

## Theory, Modelling and Simulation

*The physics problem is separated into*

- *(a) Mechanism to keep the plasma stable against m=1 mode until the sawtooth happens.*
- *(b) Mechanism of the trigger*
- *(c) Mechanism of the rapid collapse and the recovery of q(0) < 1 after the collapse.*

*Problems (b) and (c) are discussed.*

## IV Trigger Problem

Itoh introduced the 'trigger problem'.

One of the models to understand the trigger is the onset of magnetic stochasticity associated with m=1 island. In addition, the behaviour of the m=1 deformation at the crash, observed in TEXTOR OH sawtooth, suggests that there is a mechanism, other than the growth of m=1 mode, to cause the sawtooth crash. The above problem (b,c) was addressed based on the picture of the transport catastrophe. According to the theory of self-sustained turbulence, the nonlinear stationary turbulence, which corresponds to the L-mode transport, disappears at a certain threshold pressure gradient. At this threshold gradient, the catastrophe of the transport coefficient occurs, leading to the avalanche of the plasma profile. A critical pressure gradient of the form $|\beta'|\sim s/R^2\kappa$ (s: magnetic shear, $\kappa$: bad magnetic curvature) was proposed.

This mechanism is relevant to the finite-beta plasmas. There may exist the sawtooth at the zero-beta limit, for which a different mechanism is necessary. (Also the application to the giant ELMs was made.) In addition to it, The m=1 mode (or other global mode) is not considered in this model. The combination of the analyses of microscopic and global modes is required.

## V Nonlinear Simulation of Sawtooth Crash

Biskamp reported on recent nonlinear simulations of the sawtooth crash. Hence, the simulations address only problem (c). (Problems (a) and (b) are left outside.)

The basic equation is the current-diffusive MHD equation of a cylindrical plasma with $q(0) < 1$.

The rapid growth of the internal (resistive) kink mode is observed. The hot spot is deformed strongly, and the original magnetic axis reaches the q=1 rational surface (as Kadomtsev model). Since, however, the kinetic energy is large at the time of full reconnection, the plasma flow continues deforming the magnetic surfaces into a horse-shoe like shape. The edges of horse-shoe touch and reconnect again so as to capture helical flux within the new q=1 rational surface.

Depending on the initial choice of the current profile the ratio of $\psi_h$(the helical flux within the q=1 rational surface) before and after the crash, $\psi_h(\text{after})/\psi_h(\text{before})$, can be increased.

Introducing diamagnetic effects into the model, the m=1 kink mode is found to saturate at finite island size, if the density gradient near the q=1 rational surface is sufficiently large.

These simulations confirm that full reconnection, rapid collapse and $q(0)<1$ after the crash are compatible. At the same time, the simulations illuminate that the TEXTOR observations on the OH sawtooth are really mysterious.

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