Expert Group Meeting
「高エネルギー粒子，加熱および定常運転」理論関係報告

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International Workshop on Physics of Internal Transport Barrier,
Edge Pedestal and Steady State Operation in Tokamaks
IPP Garching, Germany, 2001/04/23-27

- 高エネルギー粒子：Zonca, Jaun, Fukuyama
- 加熱：Fukuyama, Prater, Vdovin
- 定常運転：
- コメント

Zonal Flow Excitation by Nonlinear EPM Dynamics

F. Zonca (ENEA, Frascatti)

- **3D Hybrid MHD-Gyrokinetic code による EPM の非線形シミュレーション**
  - Briguglio et al. PoP 2 (1995) 3711; PoP 5 (1998) 3287
  - EPM の非線形発展と粒子輸送
    — EPM の励起がしきい値を越えると
    $\longrightarrow$ 高速粒子の分布が径方向に再分配され
    $\longrightarrow$ モードが飽和する.
    — $n = 8$ EPM: $\beta_{\mathrm{E0}} = 0.75\,\%$, $L_{\mathrm{pE}}/R_0 \simeq 0.075$, $\rho_{\mathrm{LE}}/a = 0.01$
  - EPM による渦構造が径方向に分裂 ($k_\theta = k_\parallel = 0$)
    — 高速イオンの拡散的輸送
- **変調不安定性と EPM 渦の径方向分裂 (analytic)**
  - pump EPM ± zonal flow = sidebands

Alfvén Eigenmode Experiments on JET

A. Jaun (Alfvén Lab)

- **これまでの理解：PENN code**
  - アルヴェン固有モードの安定性はモード変換が支配
  - ダイバータ配位における X 点近傍の安定化効果
- **パラメータ依存性**
  - 反転磁気シア：安定化／不安定化ははっきりしない．
  - β 依存性：β の増加とともに中心部の減衰増大：KTAE?
  - B 依存性：減衰率は B に依存せず．Radiative damping ではない．
  - q_0 依存性：$q_0 > 5$ の場合，$I_r p$ に依存しない低減衰率モード出現
    Drift-kinetic Alfvén eigemodes?
- **ITER に対する検討事項**
  - 実験データと理論モデルとの定量的比較
  - 高 q_0 プラズマにおいて出現する低減衰モードの影響

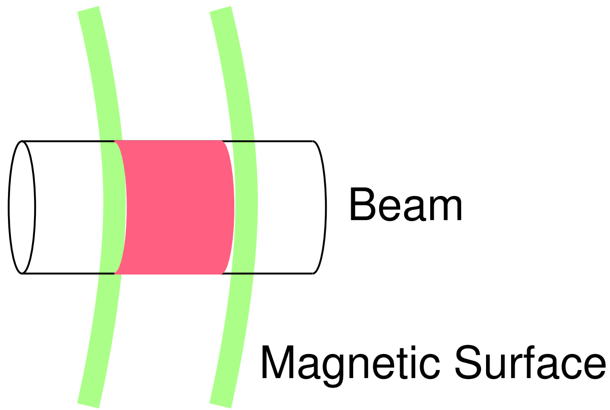
加熱・電流駆動・定常運転

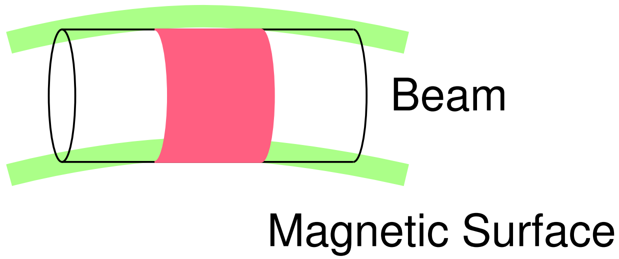
- **EC**:
  - **Fukuyama: Evaluation of Radial Deposition width in ECCD**
  - **Prater: Progress on ECH and ECCD in DIII-D**

  — 電子の β 値とともに電流駆動効率増加（理論と一致）
  — 小半径の大きな領域や異なる入射角での実験が必要
- **IC**
  - **Vdovin: ICRF シナリオ in ITER**

Motivation

- Current profile control by EC waves
  - Localized profile of driven current
  - Position control by injection angle
- Control of MHD instability
  - Suppression of island growth due to tearing instability
  - Localized current profile is required
- Evaluation of the current profile width
  - Doppler broadening, decay length
  - Finite beam size, focusing
  - Defraction
- Limitation of ray tracing
  - Defraction effect cannot be included





Beam Tracing Method

- **Beam size perpendicular to the beam direction: first order in** δ

- **Beam shape : Weber function Hermite polynomial:** H_n)

$$\boldsymbol{E}(\boldsymbol{r}) = \mathrm{Re}\left[\sum_{mn} C_{mn}(\delta^2\boldsymbol{r})\boldsymbol{e}(\delta^2\boldsymbol{r})H_m(\delta\xi_1)H_n(\delta\xi_2)\,\mathrm{e}^{\,\mathrm{i}\,s(\boldsymbol{r})-\phi(\boldsymbol{r})}\right]$$

  - **Amplitude :** C_{mn}, **Polarization :** $\boldsymbol{e}$, **Phase :** $s(\boldsymbol{r}) + \mathrm{i}\,\phi(\boldsymbol{r})$

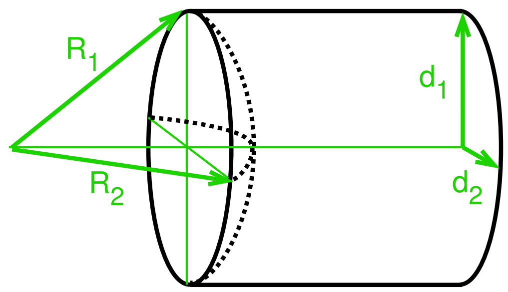
$$s(\boldsymbol{r}) = s_0(\tau) + k^0_\alpha(\tau)[r^\alpha - r^\alpha_0(\tau)] + \frac{1}{2}s_{\alpha\beta}[r^\alpha - r^\alpha_0(\tau)][r^\beta - r^\beta_0(\tau)]$$

$$\phi(\tau) = \frac{1}{2}\phi_{\alpha\beta}[r^\alpha - r^\alpha_0(\tau)][r^\beta - r^\beta_0(\tau)]$$

  - **Position of beam axis :** $\boldsymbol{r}_0$, **Wave number on beam axis:** $\boldsymbol{k}^0$

  - **Curvature radius of equi-phase surface:** $R_\alpha = \dfrac{1}{\lambda s_{\alpha\alpha}}$

  - **Beam radius :** $d_\alpha = \sqrt{\dfrac{2}{\phi_{\alpha\alpha}}}$



- **Gaussian beam : case with** $m = 0$, $n = 0$

Beam Propagation Equation

- **Solvable condition for Maxwell's equation with beam field**

$$\frac{\mathrm{d}r_0^\alpha}{\mathrm{d}\tau} = \frac{\partial K}{\partial k_\alpha}$$

$$\frac{\mathrm{d}k_\alpha^0}{\mathrm{d}\tau} = -\frac{\partial K}{\partial r^\alpha}$$

$$\frac{\mathrm{d}s_{\alpha\beta}}{\mathrm{d}\tau} = -\frac{\partial^2 K}{\partial r^\alpha \partial r^\beta} - \frac{\partial^2 K}{\partial r^\beta \partial k_\gamma} s_{\alpha\gamma} - \frac{\partial^2 K}{\partial r^\alpha \partial k_\gamma} s_{\beta\gamma} - \frac{\partial^2 K}{\partial k^\gamma \partial k^\delta} s_{\alpha\gamma} s_{\beta\delta} + \frac{\partial^2 K}{\partial k^\gamma \partial k^\delta} \phi_{\alpha\gamma}\phi_{\beta\delta}$$

$$\frac{\mathrm{d}\phi_{\alpha\beta}}{\mathrm{d}\tau} = -\left(\frac{\partial^2 K}{\partial r^\alpha \partial k^\gamma} + \frac{\partial^2 K}{\partial k^\gamma \partial k_\delta} s_{\alpha\delta}\right)\phi_{\beta\gamma} - \left(\frac{\partial^2 K}{\partial r^\beta \partial k^\gamma} + \frac{\partial^2 K}{\partial k^\gamma \partial k_\delta} s_{\beta\delta}\right)\phi_{\alpha\gamma}$$

- **By integrating this set of 18 ordinary differential equations, we obtain trace of the beam axis, wave number on the beam axis, curvature of equi-phase surface, and beam size.**

- **Equation for the wave amplitude C_{mn}**

$$\boldsymbol{\nabla} \cdot \left(\boldsymbol{v}_{\mathrm{g}0}|C_{mn}|^2\right) = -2\left(\gamma |C_{mn}|^2\right)$$

Group velocity: $\boldsymbol{v}_{\mathrm{g}0}$, Damping rate: $\gamma \equiv (\boldsymbol{e}^* \cdot \overleftrightarrow{\epsilon}_{\mathrm{A}} \cdot \boldsymbol{e})/(\partial K/\partial\omega)$

Beam Tracing in a Uniform Plasma

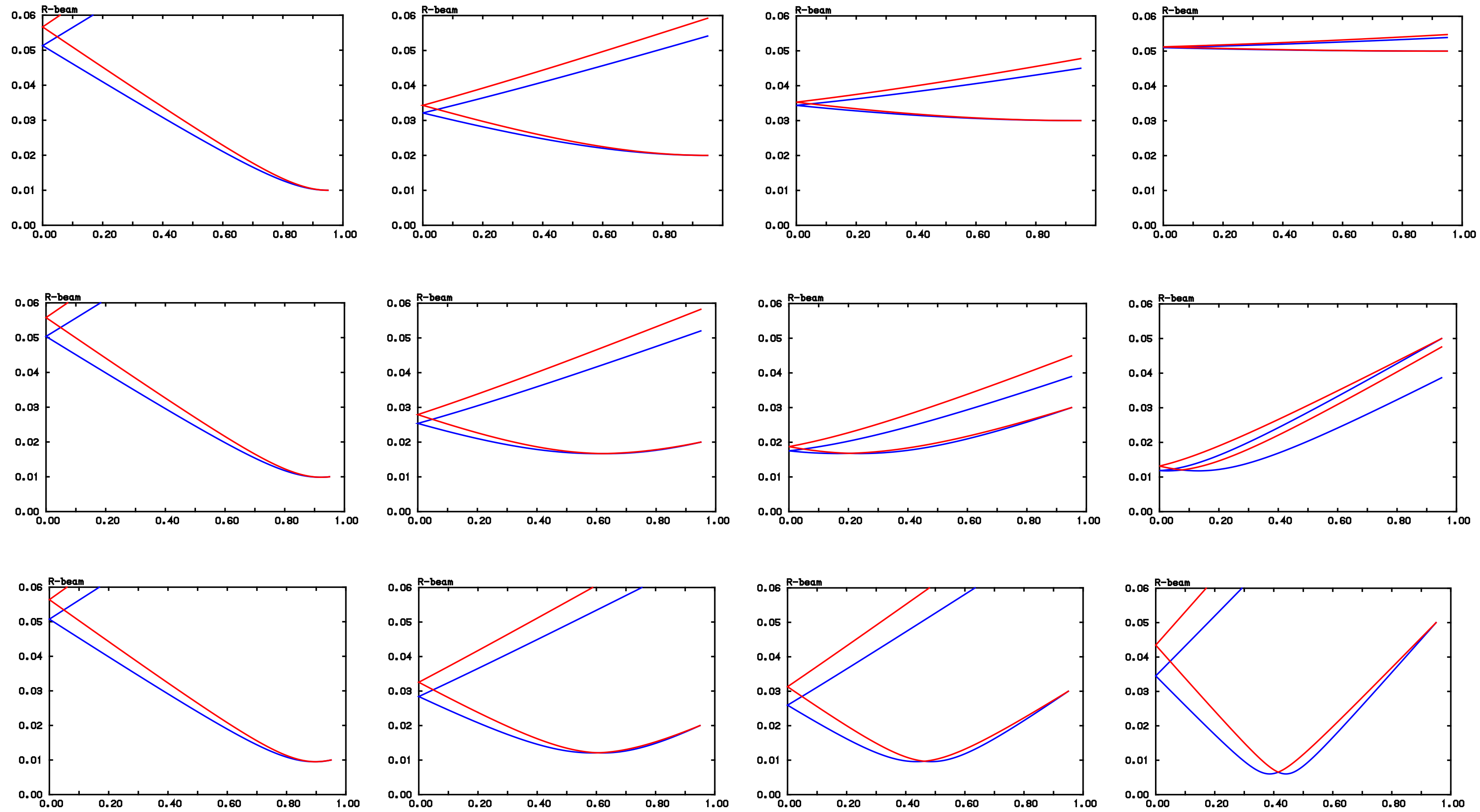
- **160 GHz, Ordinary Mode, Perpendicular Injection**

$R_b = 0.01$ m | $R_b = 0.02$ m | $R_b = 0.03$ m | $R_b = 0.05$ m

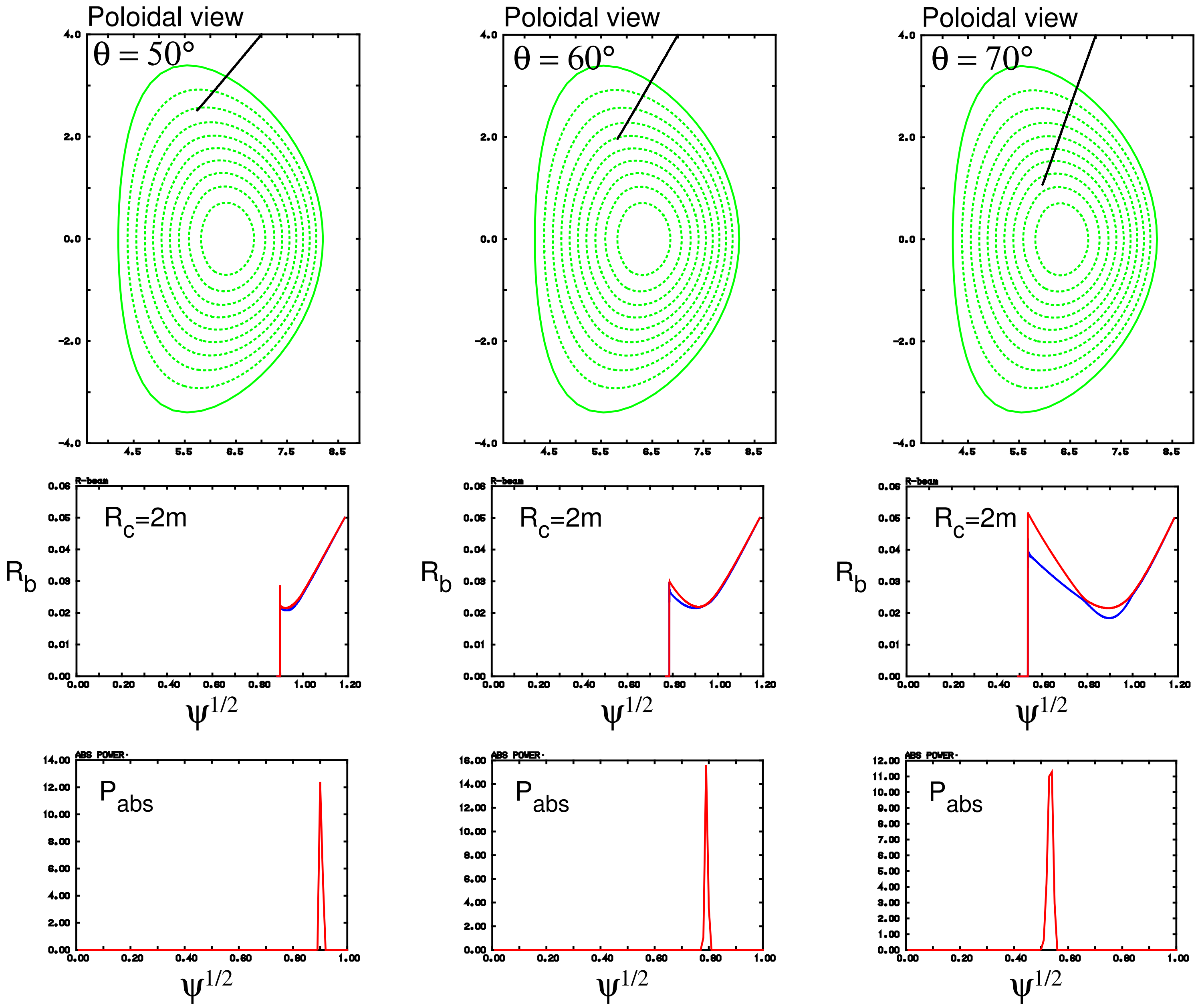
$R_c = \infty$ m

$R_c = 1$ m

$R_c = 0.5$ m



Beam Tracing in ITER-FEAT Plasma



Summary

- **Based on the formulation of beam tracing, the wave propagation code TASK/WR was extended to calculate the spatial evolution of the EC beam size.**

- **We have confirmed the diffraction effect and the initial wave front curvature dependence of the beam size.**

- **In order to focus after 1 m propagation, initial beam radius of 3cm is required for 160 GHz.**

- **In the case of ITER-FEAT, initial beam radius of 5cm is required to focus in the NTM island region.**

- **To dos:**
  - **Magnetic surface average**
  - **Coupling with Fokker-Planck Analysis**

コメント

- IAEA Fusion Energy Conf. 2002 に予定されている論文題目
  - Collective modes and Fast Particle effects on ITER
  - Progress on Steady State scenarios for ITER

- 今後の課題（理論・シミュレーション）
  - 高速粒子
    — アルヴェン固有モードの安定性
    （負磁気シア配位，EPM, ドリフト波との結合）
    — アルヴェン固有モードによる非線形効果（飽和，バースト，再分配）
  - 定常運転
    — ECCD による NTM の安定化
    — 輸送障壁：エッジ温度，内部輸送障壁
    — 粒子輸送：密度限界，不純物輸送，燃料補給