第20回NEXT研究会

Simulation Research on disruptions and runaway electrons

A. Matsuyama, M. Yagi, H. Nuga, N. Aiba, and Y. Ishii
JAEA, Rokkasho, Japan

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Y. Shibata, A. Ito, M. Furukawa,
S. Tokuda, A. Fukuyama

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Outline

1. Introduction
2. Recent Topics of RE (Runaway Electron) simulations in NEXT
   - ✓ *Transport by Magnetic Perturbations*
   - ✓ *Generation and Acceleration*
   - ✓ *Equilibrium with RE beam*
3. Summary and Future Plan

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Introduction:
Disruption Mitigation Study towards ITER

Control Strategy

Prediction → Avoidance → Mitigation

Main Target of Mitigation

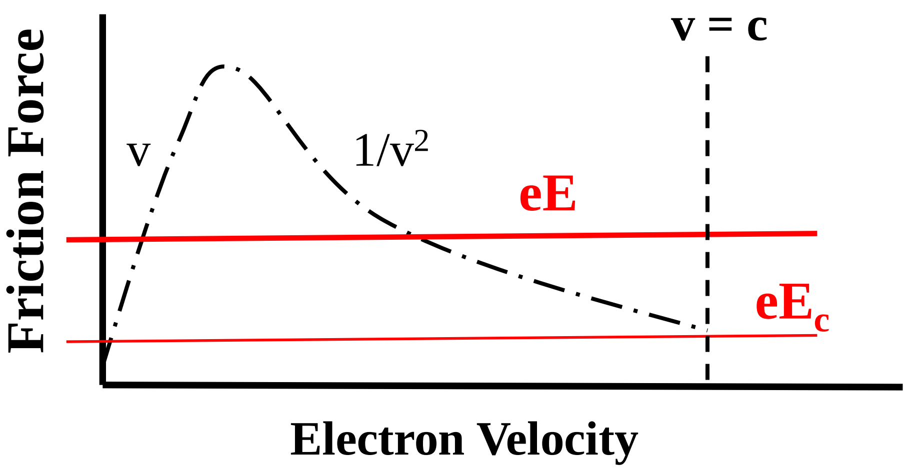
- **Thermal load**
- **Electromagnetic loads: VDEs and Halo current**
- **Runaway electrons**

Why REs are important in ITER?

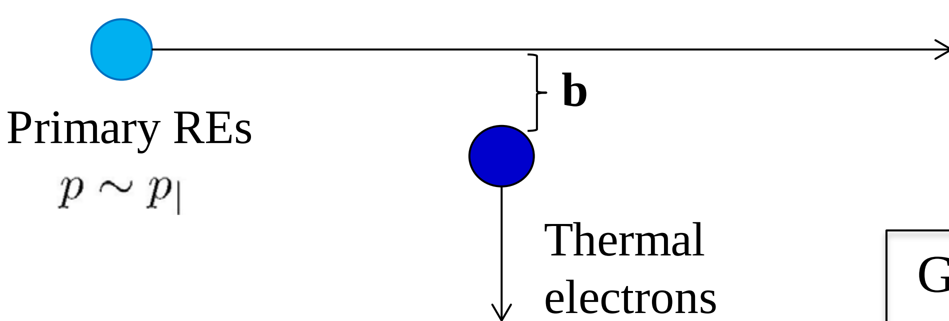
- **High amplification gain ~ $\exp(2.5 \times I_p[\mathrm{MA}])$**
- **Mitigation strategy in ITER**
  - ✓ **Metallic wall environment tends to avoid RE generation in unmitigated disruptions because of slow current quench (CQ) (de Vries, et al., PPCF2012)**
  - ✓ **However, massive gas injection (MGI) for mitigating other targets (thermal loads & halo) yields fast current quench and REs (Comparison bet. JET-C/JET-ILW, Reux, et al., PSI2014)**

Mechanisms of primary & secondary RE generation

(1) Dreicer RE generation (schematic.)



(2) Avalanche amplification (schematic.)



Gain ~ exp(2.5 × I_p[MA])

- Relativistic constraints (Connor & Hastie, NF1975) determine the critical field such that no REs if $E<E_c$.

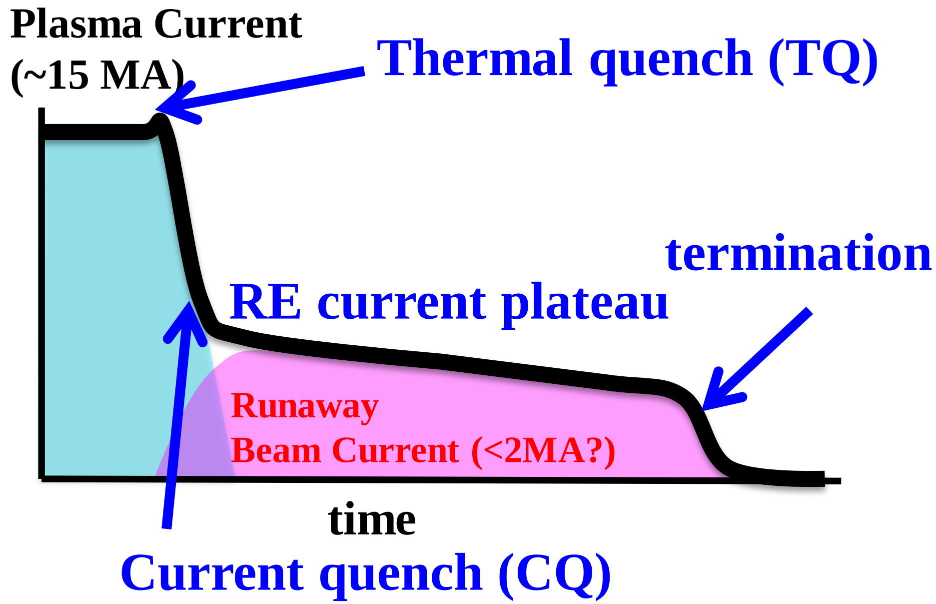
$$E_c = \frac{n_e e^3 \ln \Lambda}{4\pi\epsilon_0^2 m_e c^2}$$

- In experiments, electric field is within the range of **$E_c \sim E << E_D$** during CQ phase of major disruptions. Electron tails can become REs. (kinetic modeling is essential.)
- Once primary REs are generated, close collisions between REs with cold thermals yield secondary REs (**avalanche**).

Gain: 150@2MA ⟵⟶ 1.9×10^{16}@15MA
Seed for I_r = 7.5 MA, $I_{seed} = 4\times10^{-10}$A

Comprehensive Picture of disruption-induced REs and of their mitigation is still missing

<u>Evolution of Plasm Current with RE Generation</u>



<u>Physics Issues</u>

- **Various mechanisms affect RE generation:** MHD instabilities, plasma-wall interactions, microturbulence (e.g. Whistler-wave instability)
- **After beam formation (RE plateau):** electric field & RE dissipation, termination mechanisms (VDEs & external kink), beam-pellet interactions

→ *Development of both integrated and hybrid simulations is underway in NEXT*

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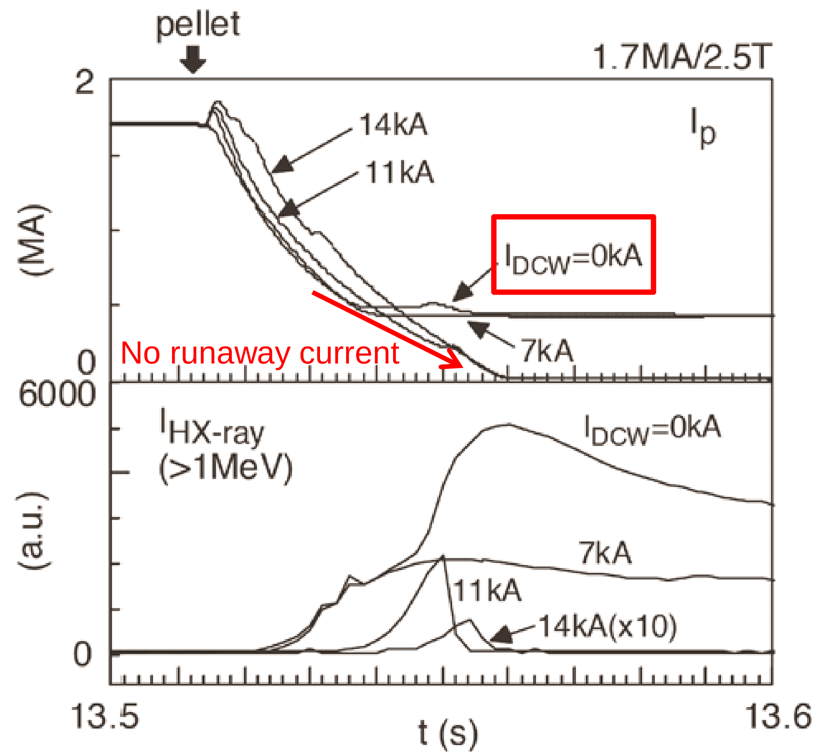
RE suppression with magnetic perturbation in JT-60U

Background

- **Exp.: RE suppression with RMPs are demonstrated in JT-60U (Kawano, IAEA1996) & TEXTOR (Lehnen, PRL2008).**
- **Theory: REs are mitigated if the confinement time is much shorter than avalanche growth time (Helander, PPCF2002).**



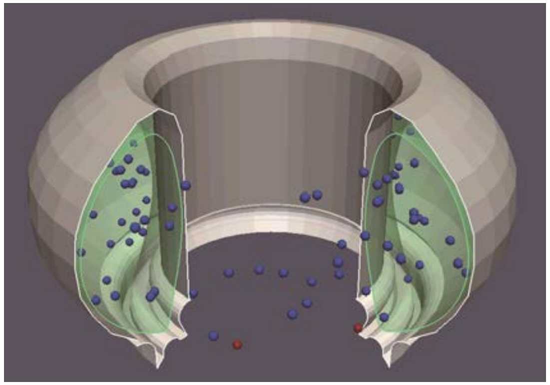
Issue on necessary fluctuation level

- **Transport by microturbulence (Mynick & Strachan, PF1981) with $\delta B/B \sim 10^{-4}$-10^{-5} may be too small for affecting avalanches.**
- **Overlapping of low-order islands ($\delta B/B \sim 10^{-3}$-10^{-2}) can induce large transport with stochastization of core magnetic fields (Tokuda & Yoshino, NF1999).**

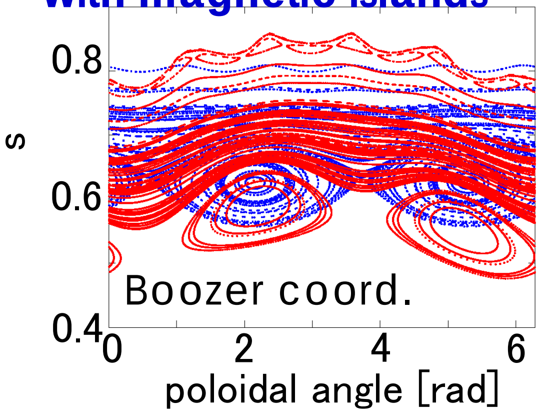
ETC-Rel code: Relativistic Guiding-Center Orbit Code

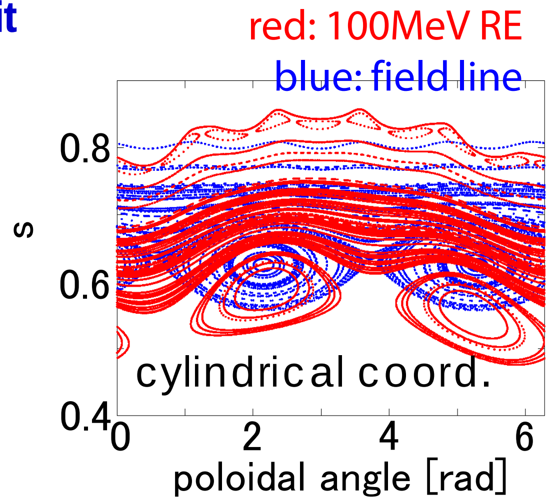
- ETC-Rel code (Tokuda & Yoshino, NF1999; Matsuyama, et al., NF2014) has been developed under NEXT project:
  - ✓ Solving GC drift eqautions by Runge-Kutta (explicit/implicit) schemes
  - ✓ Boozer/Cylindrical coordinates
  - ✓ Parallelization, optimized for Helios
  - ✓ Implementation of Relativistic collision model (Papp, et al., NF2011)

3D visualization of RE drift orbit with ITER 2D wall geometry



Benchmarking of RE drift orbit with magnetic islands

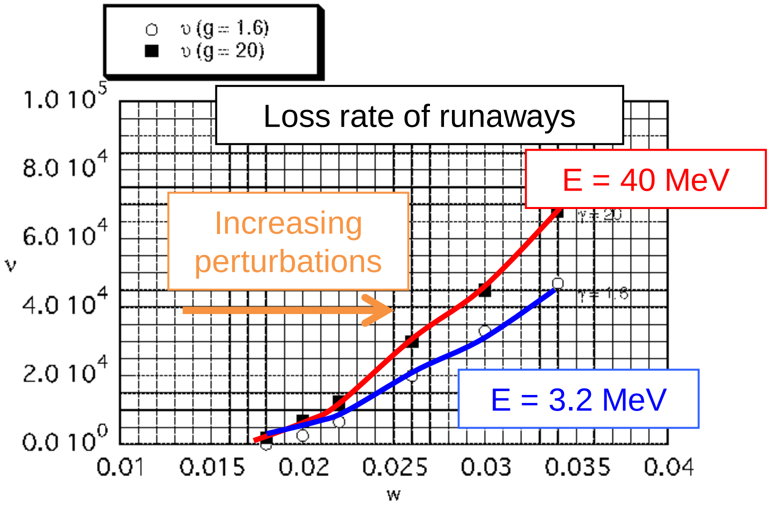


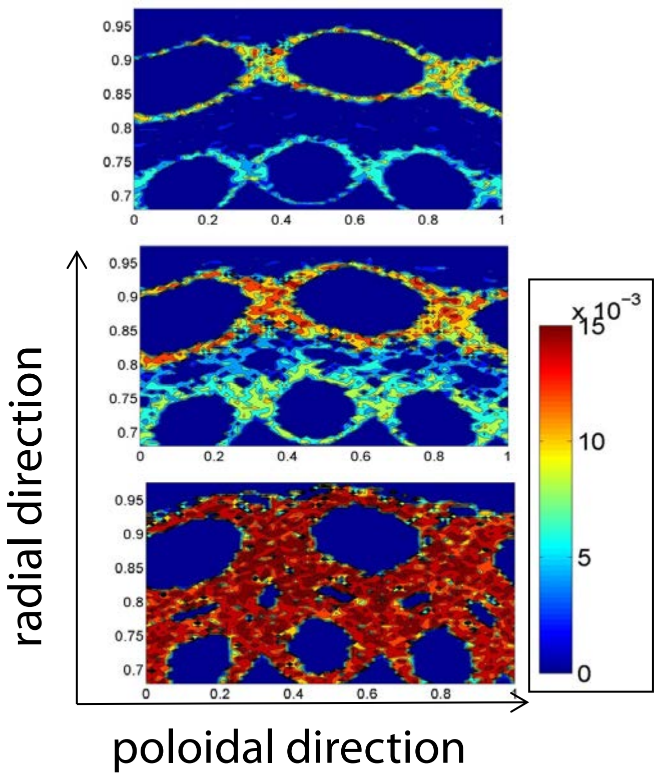


Stochastic transport of REs by macroscopic magnetic perturbations

Background

- **In lowest-order, REs follow magnetic field lines (travelling at v ~ c). Enhanced RE transport connects to islands widths and stochastization of magnetic field lines (Tokuda & Yoshino, NF 1999).**
- **Global chaotic field results in free motion of REs across the plasma minor radius.**
- **The resultant transport level is sufficient to avoid RE avalanches.**

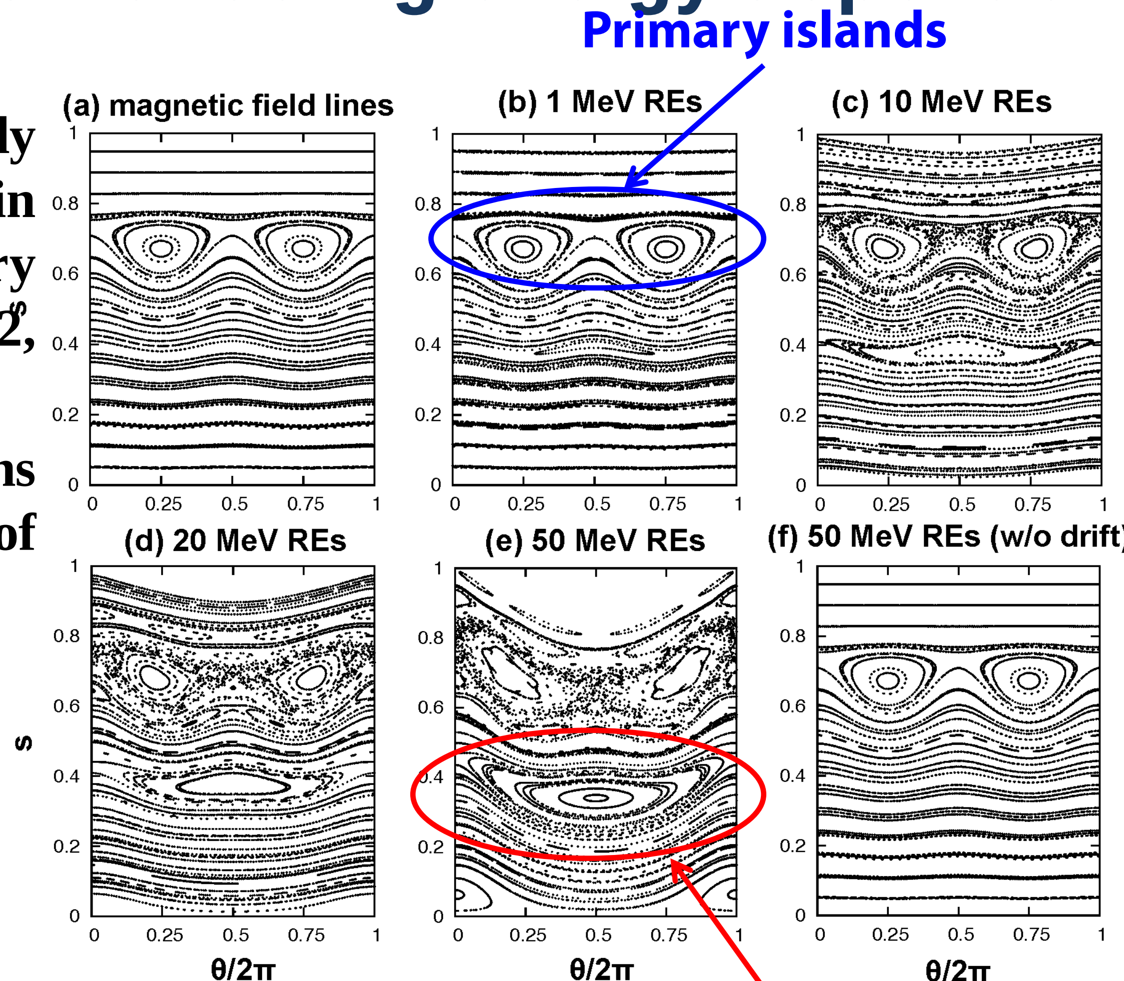




Spatial distribution of Liapunov exponents calculated for 25 MeV REs in JT-60U size

Drift-resonance induced stochastization is studied as mechanism affecting energy dependence

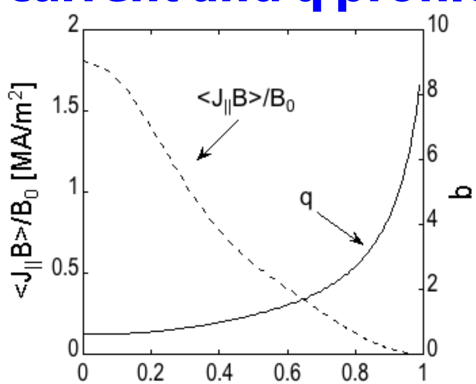
- In the presence of radially global modes, orbit shift in R direction yields secondary islands (m'=m±k) k=1, 2, … (Mynick, PFB 1994)
- Secondary island widths scaled with square-root of RE energy



Secondary islands

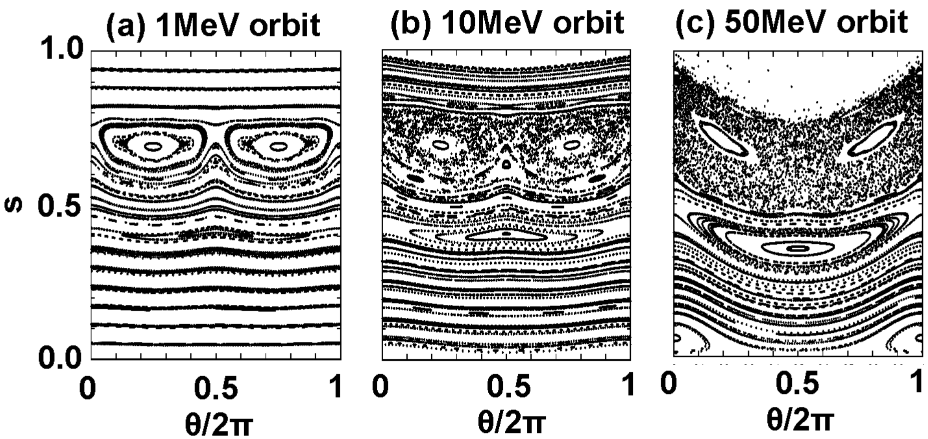
$$\frac{\Delta r}{R_0} = \sqrt{\frac{2q\rho_1 \partial_r b_{mn}}{nRq'}} \quad \rho_1 \sim q\gamma v_{\parallel}/\omega_c$$

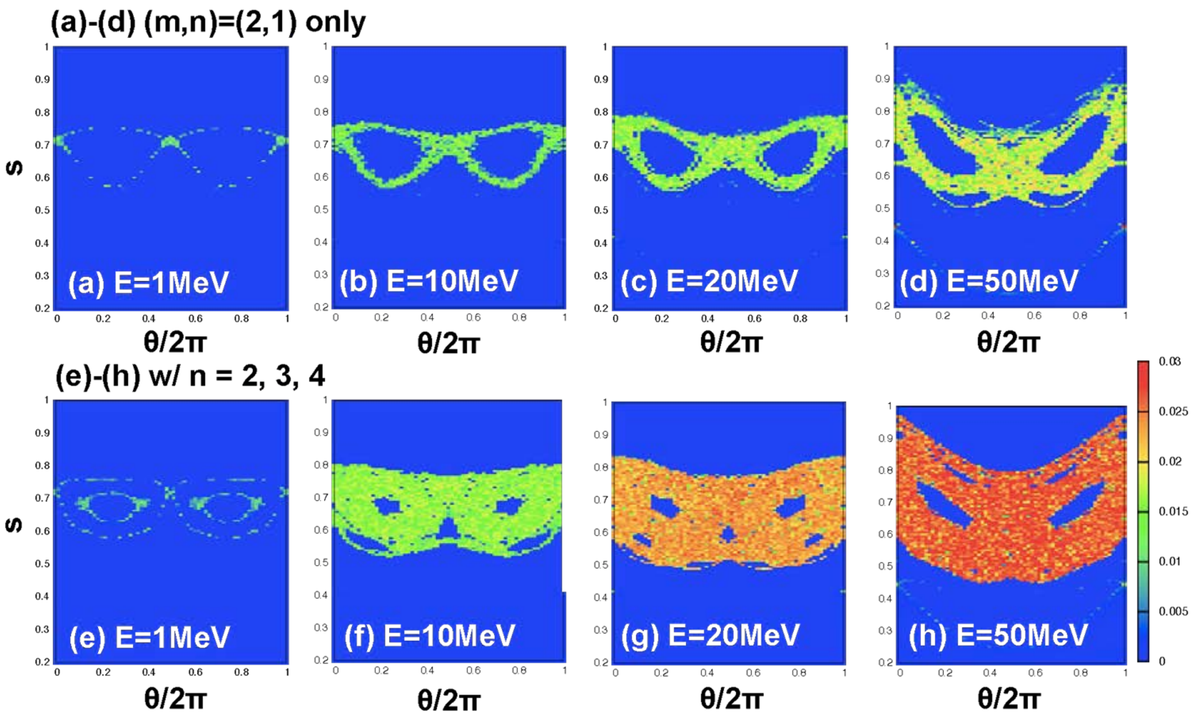
current and q profiles



➢ **JT-60U size: R = 3.4 m, a = 1 m, B = 3 T, κ = 1.5**

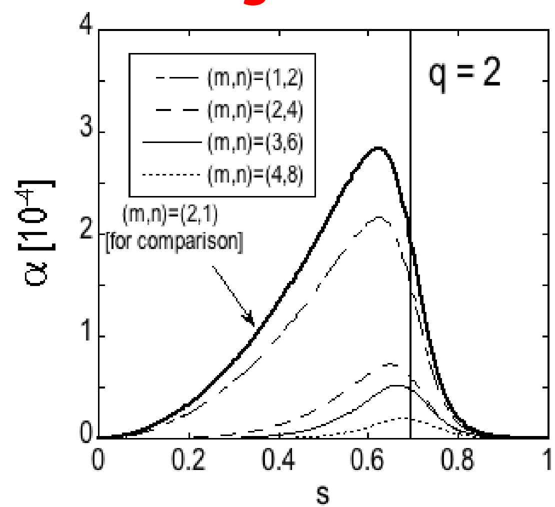
Secondary islands yields energy-dependence of onset of stochastic RE drift orbit





- **Examples for m/n = 2/1 modes**

tearing-like model



$$\delta \mathbf{A} = \alpha(\psi,\theta,\varphi)\mathbf{B}_{eq}$$

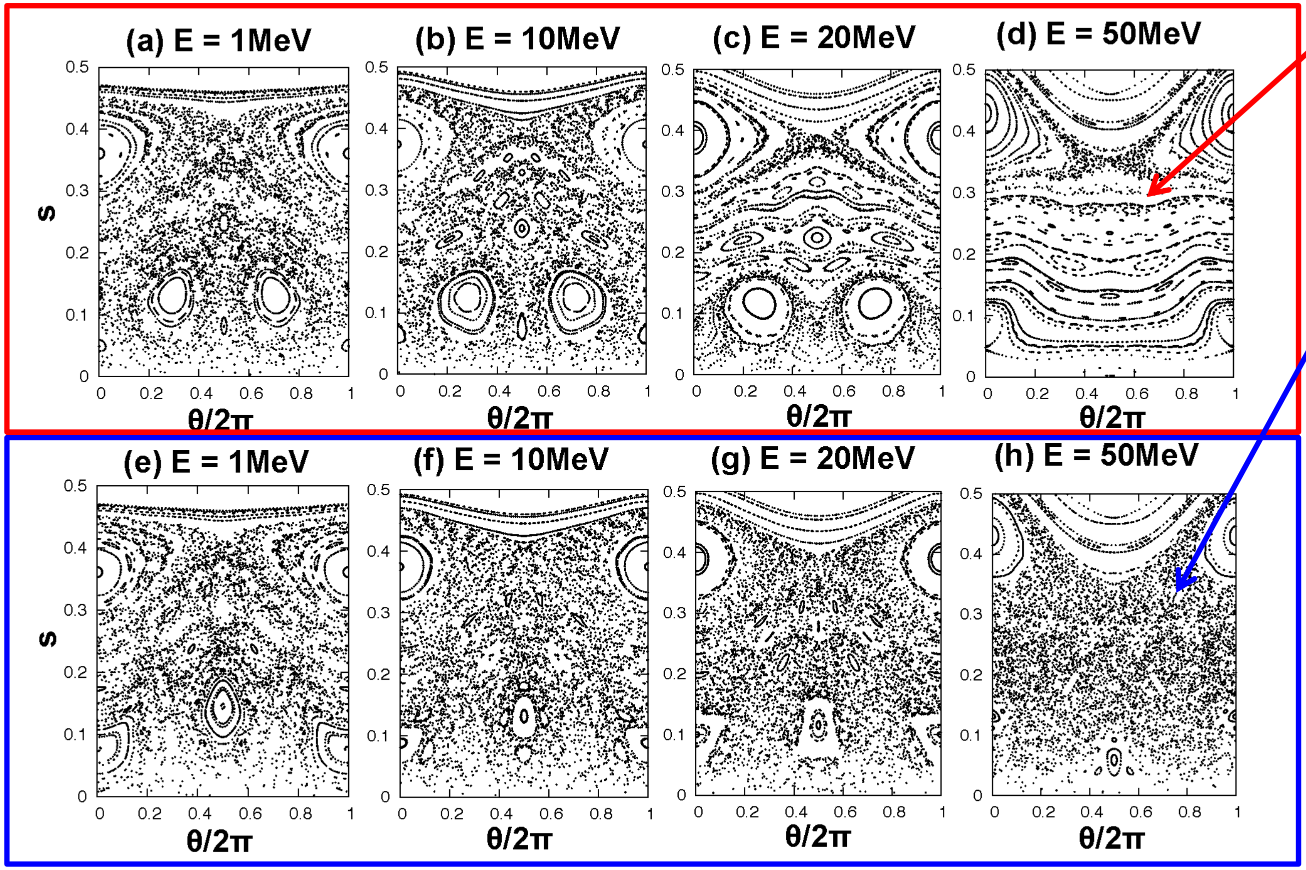
$$\alpha(\psi,\theta,\varphi) = \sum_{m,n} \alpha_{m,n}(\psi)\cos(m\theta - n\varphi + \nu_{m,n})$$

Matsuyama, et al., NF2014

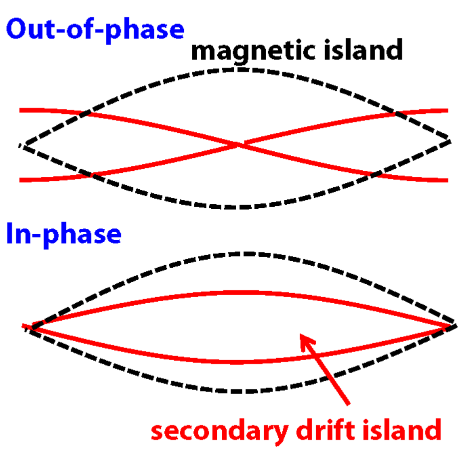
Dependence on phase difference between islands of different helicities

- Examples for m/n = 1/1 and 2/3 modes

Out-of-phase case [suppress (2, 3) mode]



In-phase case [enhance (2, 3) mode]



Phase of secondary drift island is determined by the primary modes.

Matsuyama, et al., NF2014

Future Strategies: Coupling with MHD codes

- ✓ Towards self-consistent analysis, 3-field RMHD code in toroidal geometry (Ishii & Azumi, NF2003) and linear full MHD code (MINERVA, Aiba, et al., CPC2009) will be applied.

Ex. Toroidally localized RE wall load induced by m=4 ideal external kink

(Matsuyama, PSI2014)

$\delta B/B = 1.0\times 10^{-2}$

Ex. Redistribution of RE tracer by Resistive kink

(Matsuyama, IAEA-FEC2014)

RE density profile evolution (19 MeV seed)

Parameters:

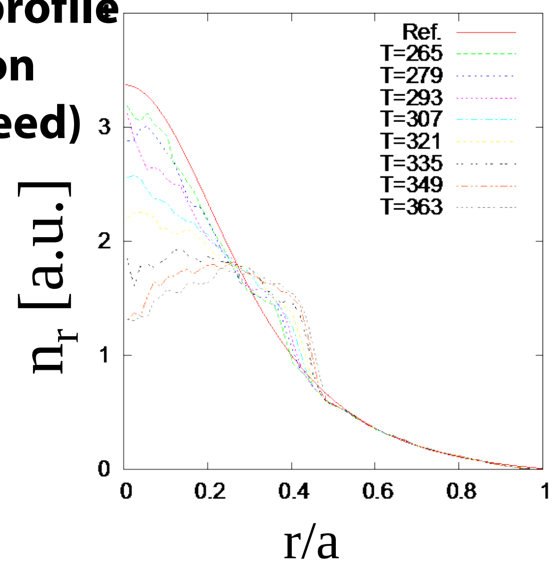
R = 3.4 m

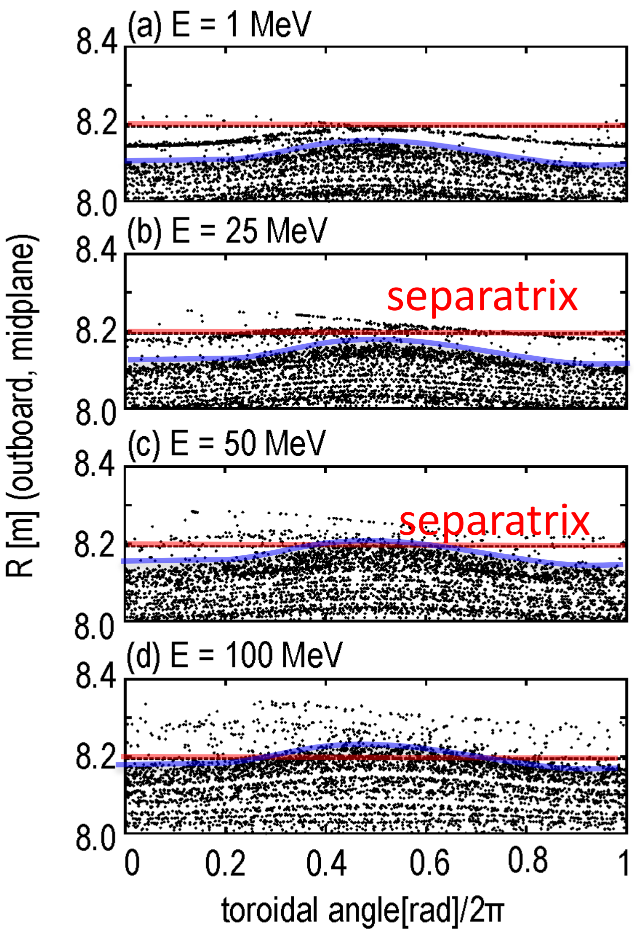
B = 3 T

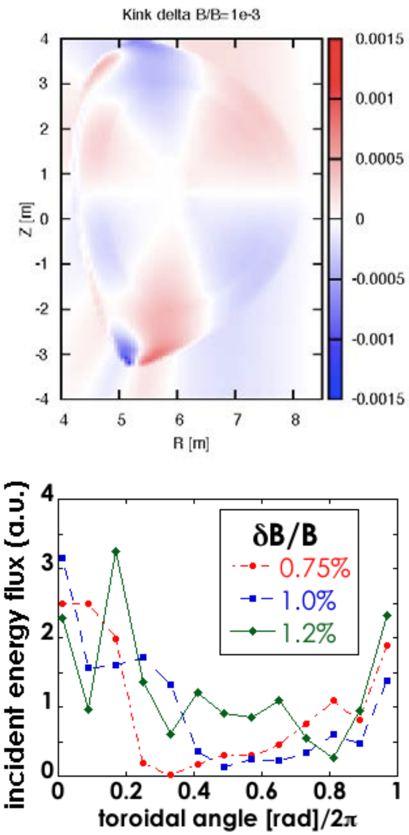
a = 1 m

κ = 1.5

I_p = 1.6 MA







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Monte-Carlo Source Model of RE Generation

- **Runaway generation and amplification are taken into account by analytic model.**

Primary electron generation (Connor & Hastie NF1975)

$$\dot{n}_r^I \simeq \frac{n_e}{\tau}\left(\frac{m_e c^2}{2T_e}\right)^{3/2}\left(\frac{E_D}{E_\parallel}\right)^{3(1+Z_{\rm eff})/16} \exp\left(-\frac{E_D}{4E_\parallel}-\sqrt{\frac{(1+Z_{\rm eff})E_D}{E_\parallel}}\right)$$

Secondary electron generation (Rosenbluth & Putvinski NF1997)

$$\dot{n}_r^{II} \simeq n_r \frac{E_\parallel/E_c - 1}{\tau \ln L}\sqrt{\frac{\pi\varphi}{3(Z_{\rm eff}+5)}}\left(1-\frac{E_c}{E_\parallel}+\frac{4\pi(Z_{\rm eff}+1)^2}{3\varphi(Z_{\rm eff}+5)(E_\parallel^2/E_c^2+4/\varphi^2-1)}\right)^{-1/2}$$

- **Number of test particles loaded per time step Δt**

$$\Delta n_r = \dot{n}_r^I(n_e, T_e, Z_{\rm eff}, E_\parallel)\Delta t + \dot{n}_r^{II}(n_r, n_e, T_e, Z_{\rm eff}, E_\parallel)\Delta t$$

For simplicity, $p_{\parallel}/p \sim 1$, and $v\sim 2v_c$ are assumed. (v_c: critical velocity)

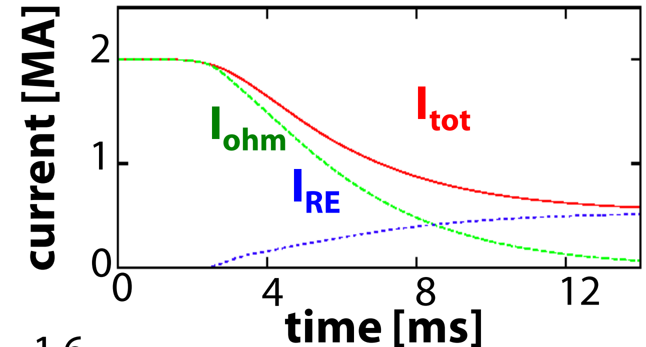
- **Runaway density is introduced with surface-averaging runaway source term.**

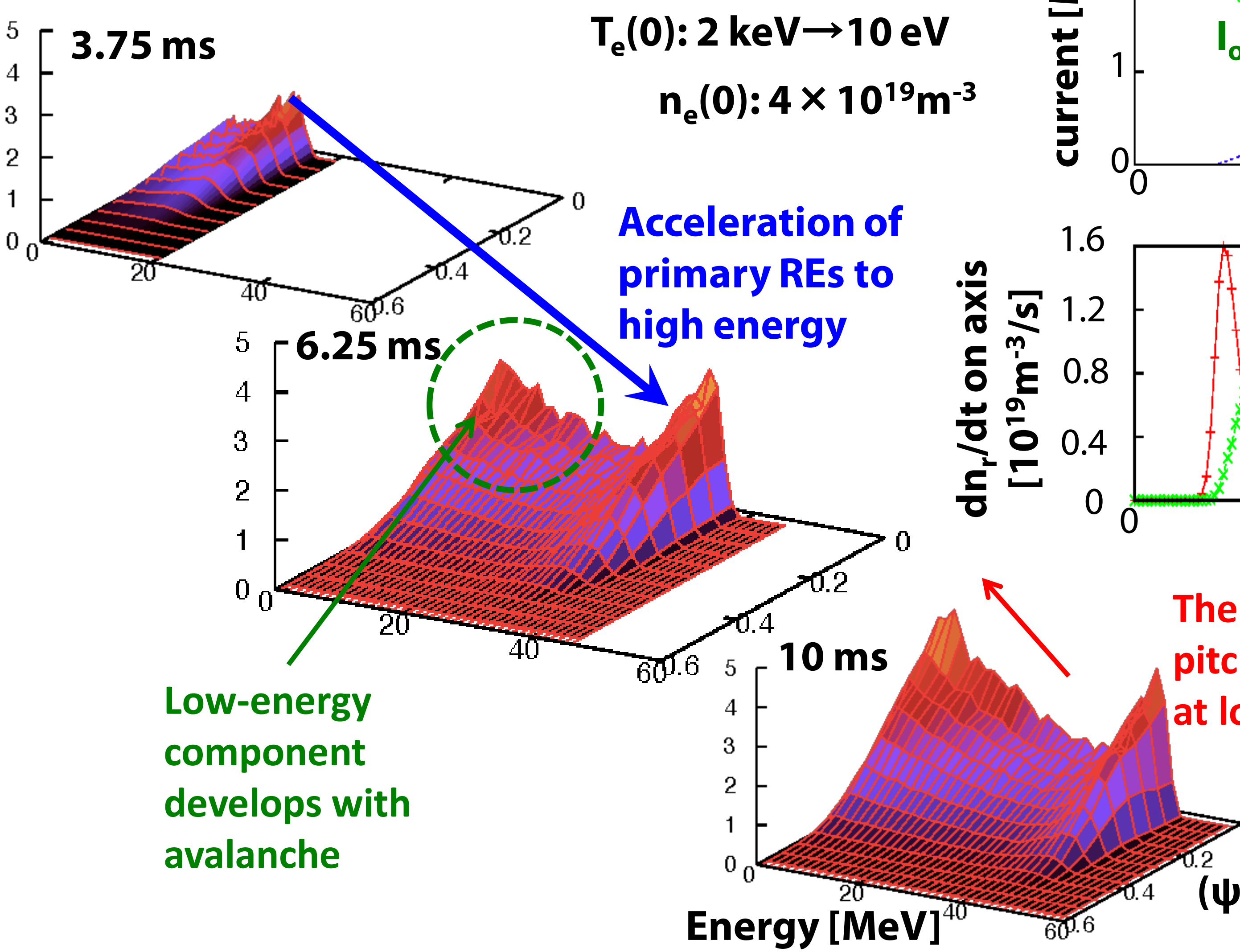
$$n_r(\rho_i) = \frac{1}{\Delta V}\sum_i w_s^i, \quad w_s = N_p/N_s, \quad N_p \equiv \int d\rho\, n_r(\rho)\frac{dV}{d\rho}$$

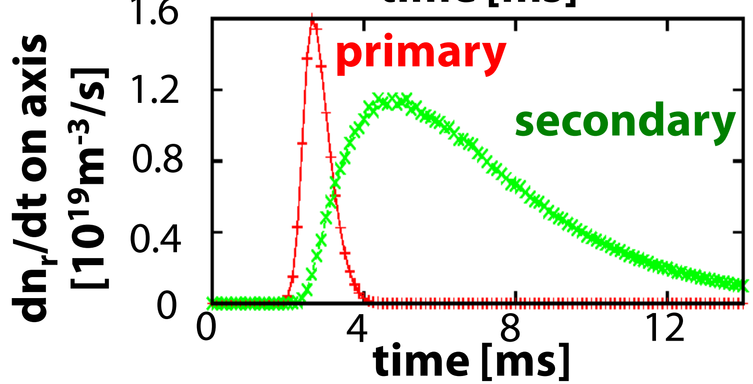
Particle weight for representing local runaway density

Full-f Monte-Carlo code developed for RE generation

✓ ETC-Rel is extended to include RE generation process as full-f Monte-Carlo code, including self-consistent electric field, energy slowing down, pitch-angle scattering, & avalanche (Matsuyama, APS2013)







Energy Spectrum strongly depends on Generation Mechanisms

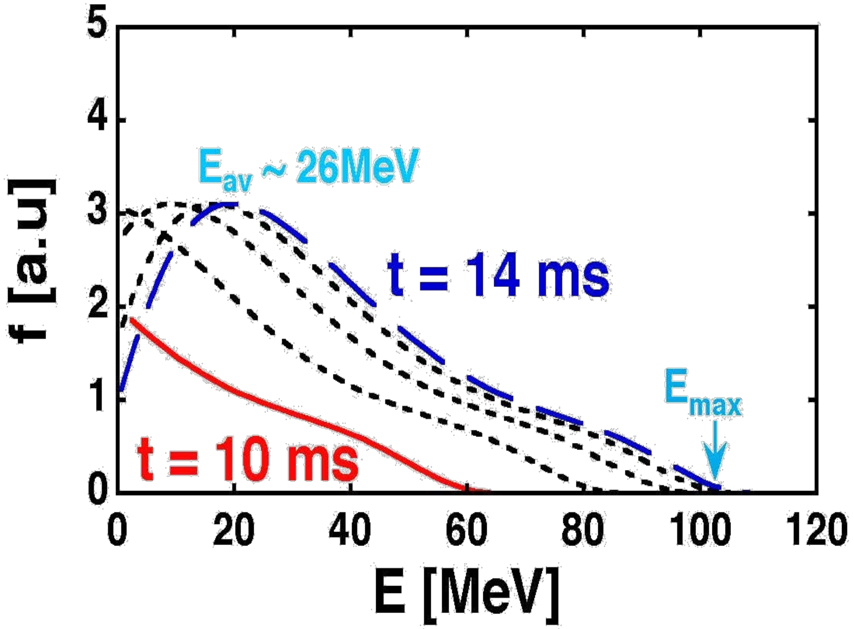
RE energy spectrum is described by …

- 1D current diffusion (Eriksson, Helander, et al. PRL, 2004)→loop voltage
- relativistic F-P equation incl. radiation (Martin-Solis, et al., PoP 1998)

15MA ITER disruption

(from ITER Physics Basis)

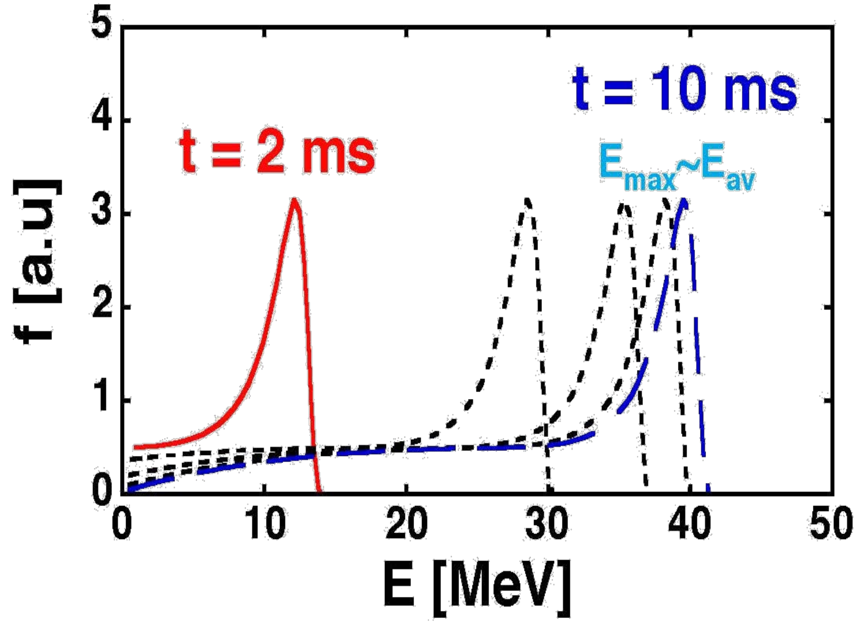
Low-energy component is dominant in ITER due to secondary generation



2MA JT-60U disruption

(from Yoshino, et al., PPCF 1997)

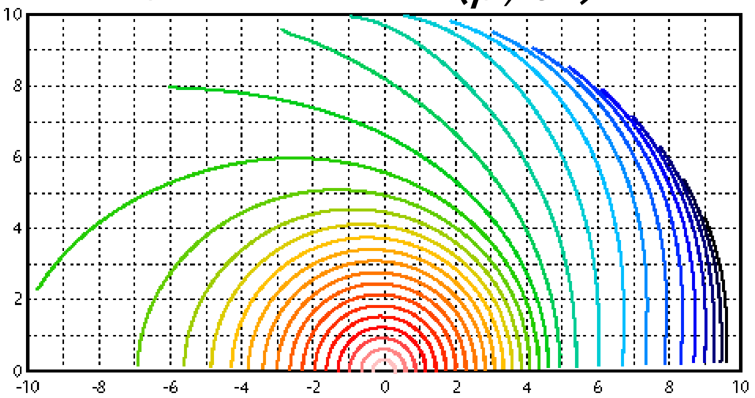
Several MA case: RE current is dominated by Dreicer accelerated electrons



- Numerical simulations explaining observed energy spectrum is still missing …

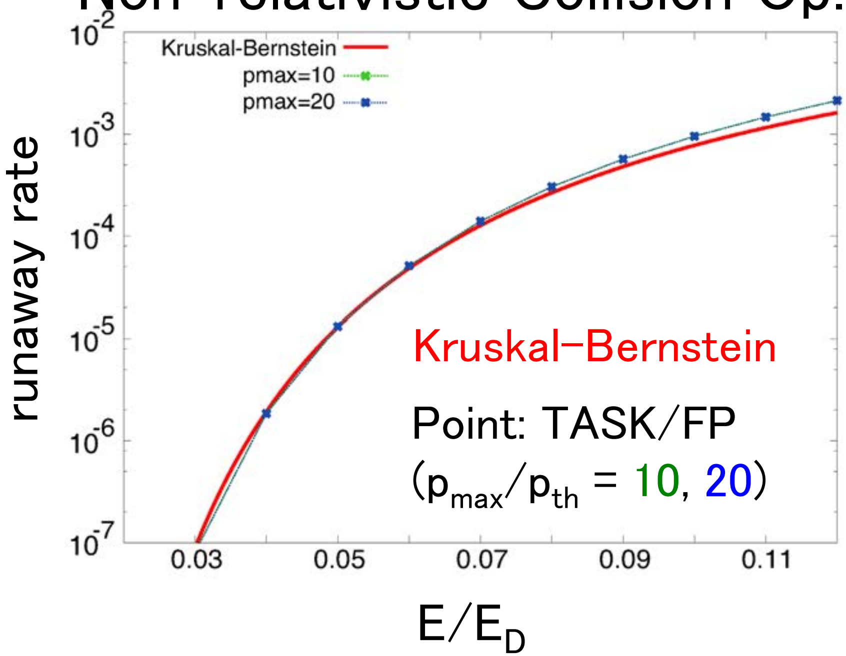
Verification of analytic RE source model by direct numerical simulations (by Nuga-san)

2D contour of f(p, θ)

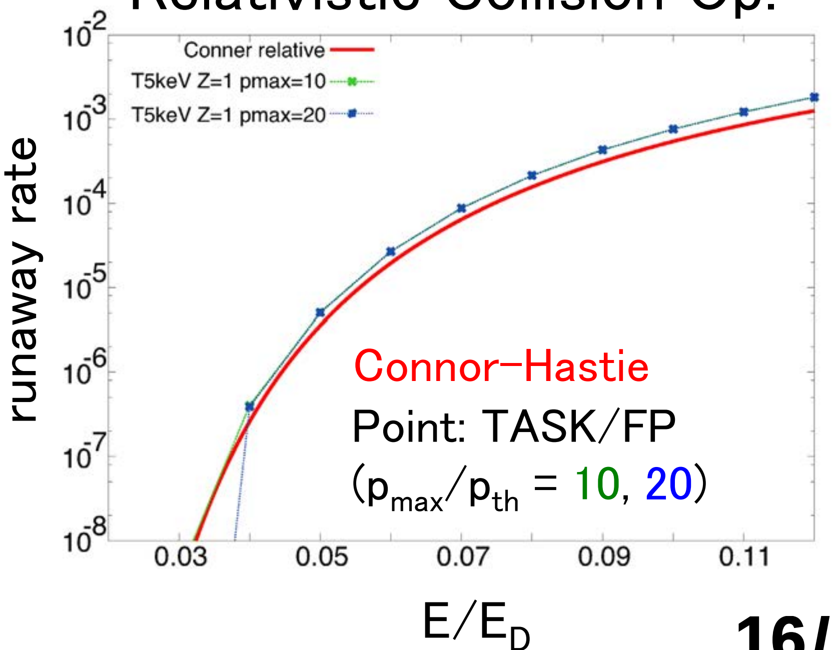


- **2D Fokker-Planck code TASK/FP is applied to evaluated RE generation rate.**
  - RE generation rate is evaluated as the flux across the momentum-space boundary $p = p_{max}$.
  - Successful benchmark against theoretical model for $E_{||}$ = const.

Non-relativistic Collision Op.



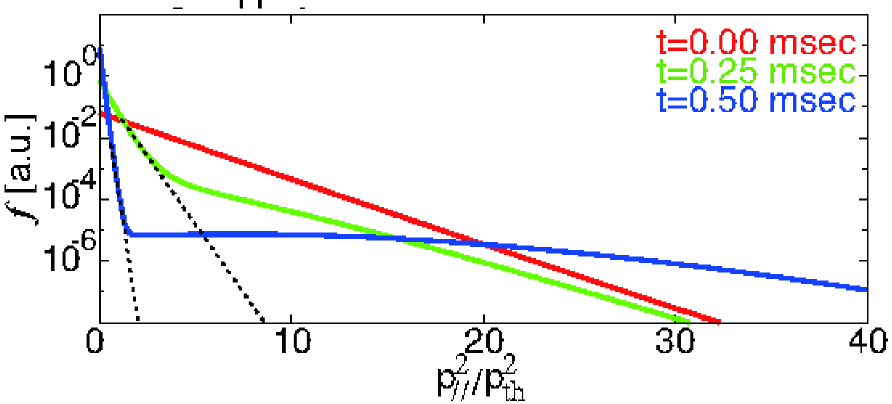
Relativistic Collision Op.



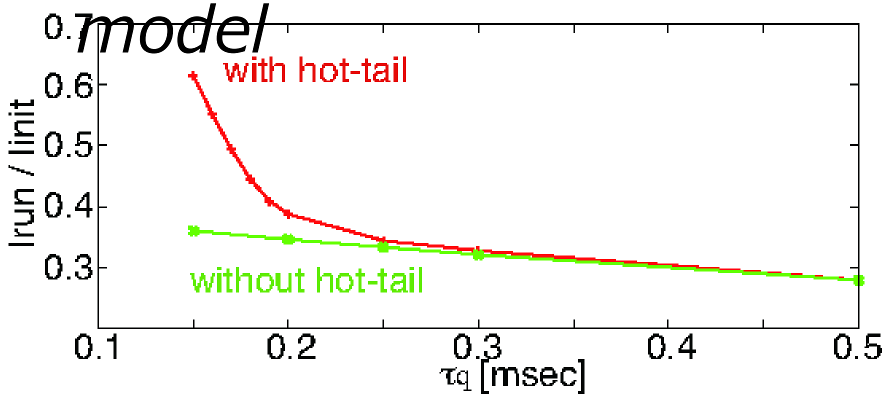
Hot-tail generation becomes significant for faster thermal quench than slowing down of e-tail

- **Full kinetic simulations with transient electric field has been performed by TASK/FP**
  - ***Existing F-P simulation mainly for fixed electric field***
  - **I_r/I_p always less than unity by magnetic flux conservation.**
  - **Hot-tail generation (Smith, PoP2008) becomes significant when thermal quench is much faster than slowing-down of e-tail by e-e collisions (Nuga, accepted in PFR).**

Electron distribution func. in $E_{||}$ direction



Comparison of normalized RE current with analytic model



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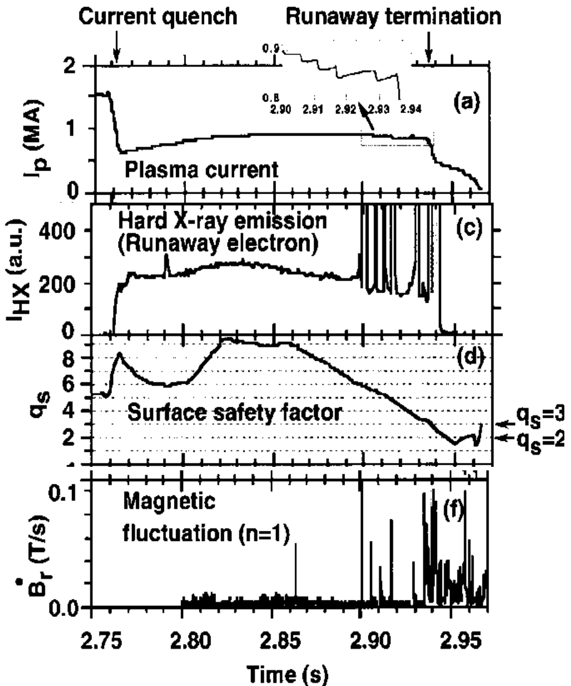
Equilibrium with kinetic RE beams

- **After RE plateau formation, equilibrium is sustained by kinetic RE beams**
  - **$I_r/I_{tot} \sim 1$**
  - **Typically high l_i (peaked current profile)**
  - **RE beam control by external coil systems needs to be developed in ITER (Lehnen, *private commun.*)**



- **MHD equilibrium model including kinetic RE beam needs to be developed.**
  - **will be coupled to ETC-Rel (arbitrary energy spectrum) and transport and eddy-current codes (coupling to external circuit)**

→ Future simulation of beam formation

typical orbit-width and gyroradius

	JT-60U grade	ITER grade
Eav	19 MeV	25 MeV
Emax	42 MeV	107 MeV
(Δ/a)_av	0.06	0.025
(Δ/a)_max	0.13	0.09
(ρ/a)_av	0.009	0.003
(ρ/a)_max	0.017	0.015

Axisymmetric Equilibrium Solver with kinetic RE components has been developed

- **Kinetic component (Belova, et al. PoP 2003)**

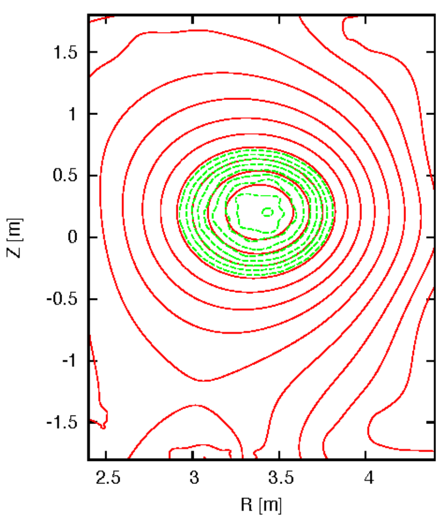
$$\mathbf{j}_r = \frac{1}{\mu_0}\nabla F_r \times \nabla\phi + j_{r\phi} R\nabla\phi = \mathbf{j}_{gc} + \nabla\times\mathbf{M}$$

→ Evaluated from Guiding-center MC code

- **Grad-Shafranov type equations obtained from force-balance (Yoshida, NF1990). Assuming $n_r << n_e, n_i$**

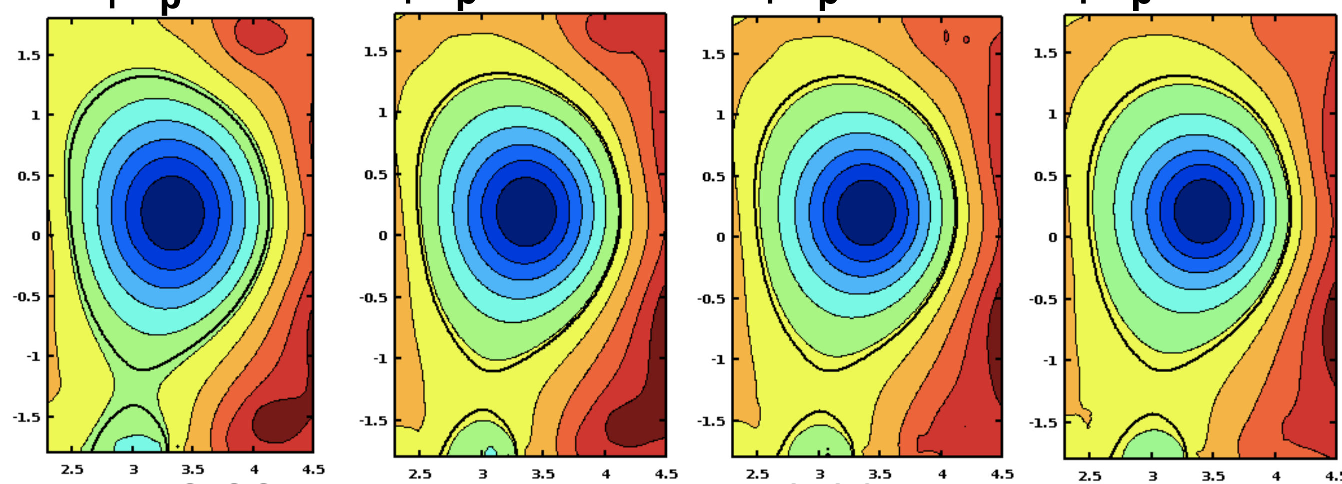
$$\Delta^*\psi = -\mu_0 R^2\frac{dp}{d\psi} - (F_p + F_r)\frac{dF_p}{d\psi} + \mu_0 R j_r$$

✓ **Test for JT-60U diverted tokamaks (I_p = 1MA; R=3.3 m, R_0B_0=12.4Tm)**



RE bith position
$\langle E_{av}\rangle$ ~ 19 MeV

I_r/I_p = 0 | I_r/I_p = 0.25 | I_r/I_p = 0.5 | I_r/I_p = 0.75



R_{ax} ~ 3.33m | 3.36m | 3.39m | 3.41m

Shafranov shift induced by beam inertia

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Summary and Future Plan

- **Disruption and RE mitigation is one of the most important challenges in ITER. Comprehensive picture of disruption-induced REs and their mitigation is still missing.**
- **Here, recent topics of RE simulations in NEXT project have been outlined.**
  - ✓ Simulation of RE redistribution by macroscopic modes with magnetic and drift resonance
  - ✓ Development of full-f Monte-Carlo code and verification of source model by Fokker-Planck code
  - ✓ Study of MHD equilibrium with beam currents including effects of beam inertia
- **Improvements of simulation code and physics models will be continued. Additionally, other disruption loads such as thermal and electromagnetic loads in close collaboration with DEMO design group.**