DE LA RECHERCHE À L'INDUSTRIE

PROGRESSES IN MODELING THE RUNAWAY ELECTRON PHYSICS

(EUROFUSION, ER15-CEA-09)

Y. Peysson[1], *G. Anastassiou*[2], *J.-F. Artaud*[1], *A. Budai*[3], *J. Decker*[4], *O. Embréus*[5], *O.Ficker*[8], *T. Fulöp*[5], *L. Hesslow*[5], *K. Hizanidis*[2], *Y. Kominis*[2], *T. Kurki-Suonio*[6], *P. Lauber*[7], *R.Lohner*[3], *J. Mlynár*[8], *E. Nardon*[1], *G. Papp*[7], *R. Paprok*[8], *G. Pokol*[3], *F. Saint-Laurent*[1], *C. Reux*[1], *K.Sarkimaki*[6], *C. Sommariva*[1], *A. Stahl*[5], *G. Wilkie*[5], *P. Zestanakis*[2]

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5) Chalmers University, Göteborg, Sweden
6) Aalto University, Finland
7) Max-Planck Institute for Plasma Physics, Garching, Germany
8) Institute for Plasma Physic, Prag, Czech Republic

www.cea.fr

https://www2.euro-fusion.org/erwiki

The Runaway Electron (RE) dynamic

- During disruptions runaways sometimes form a beam of MeV electrons which can carry a significant fraction of the initial current. The runaway beam can become unstable and hit the wall, creating great damages → *identified as a serious issue for ITER*

- The electron distribution evolves under the combined influence of several phase-space mechanisms for RE generation (collisions, $E_{||}$ acceleration, diffusion by RF waves, synchrotron reaction force, etc) and RE transport (kinetic instabilities, MHD instabilities, RMPs, turbulence)

- During disruptions, the runaway generation can be dominated by the avalanche process : runaway dynamics is highly non-linear. In addition RE population and $E_{||}$ acceleration must be self-consistently determined

- Small variations in the balance between runaway generation and transport can lead to large differences in the resulting density of runaways and the formation of a RE beam. The influence of a seed may be also critical.

A kinetic description of runaway electron dynamics is necessary

The Work Package for Enabling Research (EUROfusion)

- The Work Package for Enabling Research ***ER15-CEA-09*** « Kinetic modelling of runaway electron dynamics » supported by EUROfusion for studying RE dynamics started in 2014, and **will officially end in December 2017**. *(Invaluable contribution from Pr T. Fülop of Chalmers University)*

- The WPER has gathered the effort of about 8 European universities or research institutes

- The primary aim of the kinetic modeling effort of RE dynamics is to describe the formation of the suprathermal beam, taking into account selfconsistently of transport and non-linear effects, developing synthetic diagnostics and benchmark against experiments *(available tools → kinetic solvers: LUKE, CODE; tokamak simulators: METIS, GO, synthetic diagnostic: R5-X2,…)*

- The ultimate goal is to validate robust techniques for RE mitigations, but also find solutions to limit the formation of a multi-MeV beam once the thermal quench as occured.

https://www2.euro-fusion.org/erwiki for reports and references

European RE teams and collaborations

RE theory

Chalmers University *: O. Embreus, T. Fülöp, A. Stahl, G. Wilkie, L. Hesslow*

RE experiments

JET *: C. Reux*
TCV *: S. Coda, J. Decker*
COMPASS *: J. Mlynar, R. Paprok*
ASDEX-U*: G. Papp*
C-Mod*: A. Tinguely, R. Granetz*

RE modelling

CODE (+ GO) → ***Chalmers University :*** *A. Stahl and* ***IPP Garching*** *: G. Papp*
LUKE (+ METIS) → ***CEA, France:*** *Y. Peysson, J.-F. Artaud*
LUKE (+ ITM) → ***BME, Budapest*** *: A. Budai, G. Pokol and* ***CEA, France:*** *Y. Peysson*

RE transport

IPP Garching *: G. Papp*
Aalto University, Finland: *T. Kurki-Suonio, K.Sarkimaki*

Kinetic instabilities

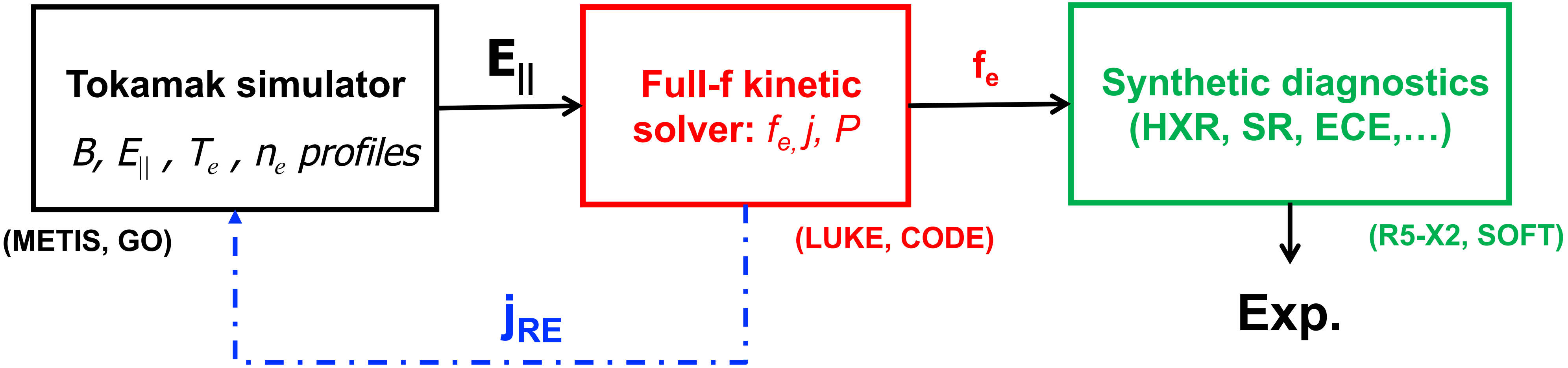
BME, Budapest *: A. Budai, G. Pokol*
NTUA, Greece*: A. Zestanakis, Y. Kominis, G. Anastassiou, K. Hizanidis*

MHD instabilities

IPP Garching *: G. Papp, P. Lauber*
IRFM/Polytechnique *: X. Garbet , R. Sabot, G. Brochard*

Global objectives

- Focusing on the generation and transport mechanisms (avalanches, additional forces that could limit the formation of a runaway beam,…)
- Integrating the various processes self-consistently in tokamak simulations
- Building synthetic diagnostics and performing comparisons with experiments.



Tokamak simulator

$B, E_{||}, T_e, n_e$ *profiles*

(METIS, GO)

$E_{||}$

Full-f kinetic solver: f_e, j, P

(LUKE, CODE)

f_e

Synthetic diagnostics (HXR, SR, ECE,…)

(R5-X2, SOFT)

Exp.

j_{RE}

Global objectives

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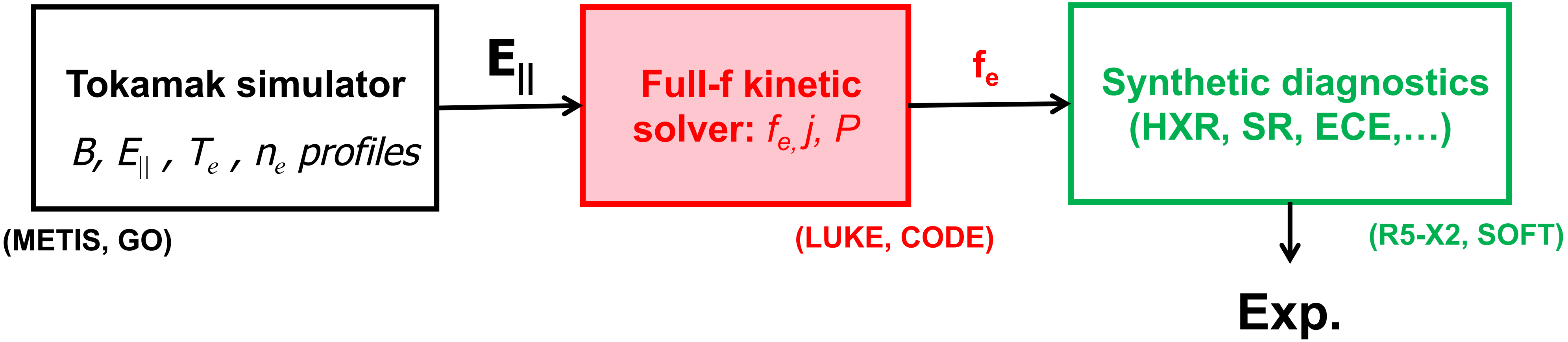

Tokamak simulator

$B, E_{||}, T_e, n_e$ *profiles*

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$\mathbf{E_{||}}$

Full-f kinetic solver: f_e, j, P

(LUKE, CODE)

$\mathbf{f_e}$

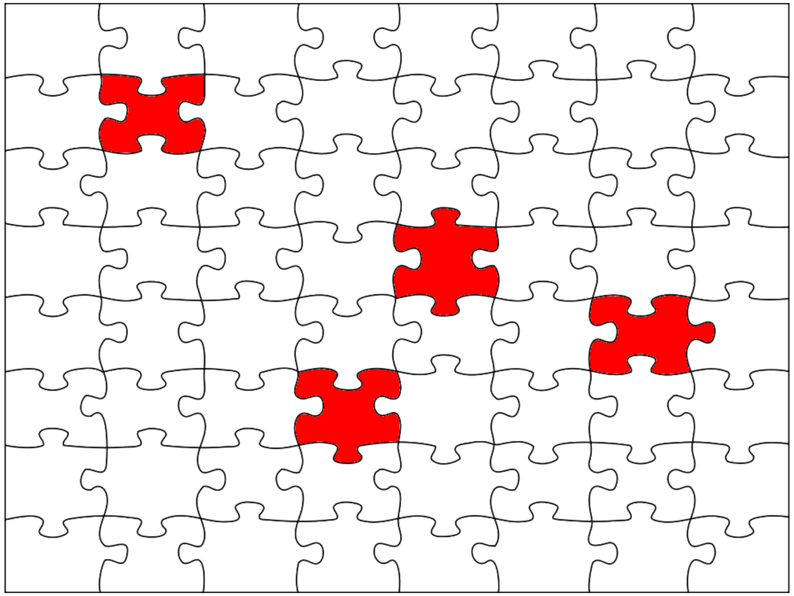
Synthetic diagnostics (HXR, SR, ECE,…)

(R5-X2, SOFT)

Exp.

Momentum space physics of RE generation

Finite difference Fokker-Planck solvers



- Synchrotron radiation reaction force (ALD): CODE, LUKE (with toroidal effects)
- Bremsstrahlung radiation reaction force: CODE
- Knock-on operator for RE avalanches : CODE, LUKE (with toroidal effects)
- Effects of partially screened impurities on the collision operator : CODE
- *Implement the quasilinear model for kinetic instabilities (EXEL waves): LUKE*

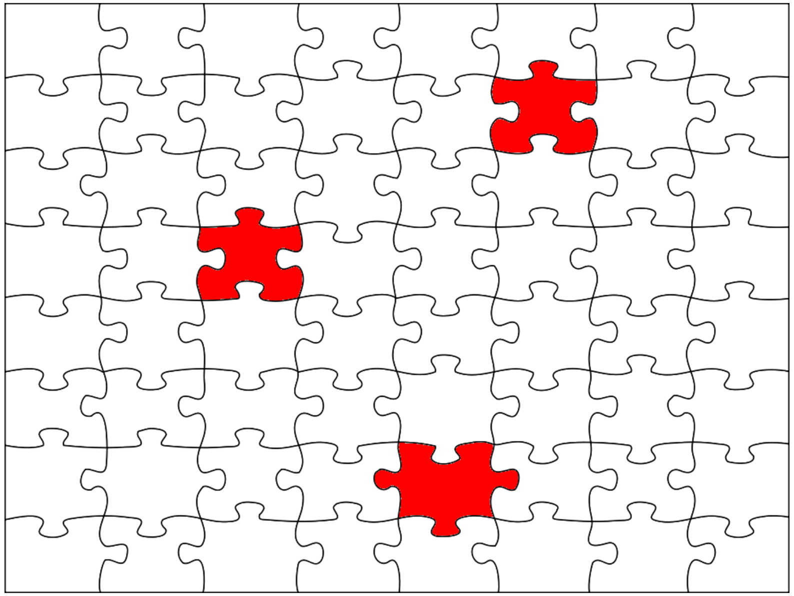
CODE (cylindrical): 2-D momentum space (Chalmers U., Sweden)
LUKE (toroidal): 2-D momentum + 1D configuration spaces (CEA, France)

M. Landreman et al. Comp. Phys. Comm., 2014, 185, 3, pp. 847 - 855

Peysson, Y. and Decker, J., FST, 65 (2014) 22

Configuration space physics of RE

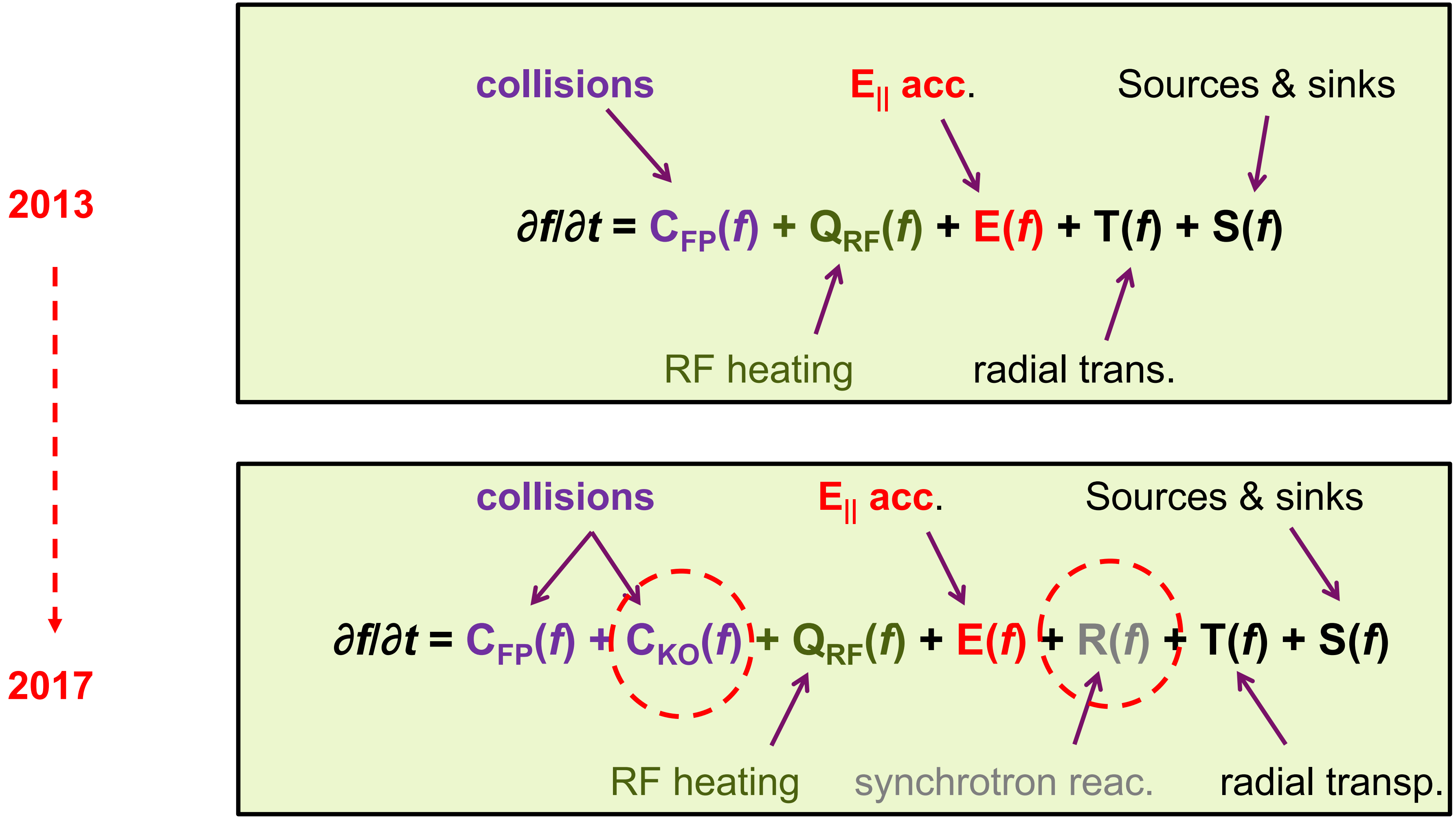
Finite difference Fokker-Planck solvers



- Drift-diffusion RE transport model in magnetic fields that contain both stochastic regions and islands from orbit-following code ASCOT. Applicable for LUKE in the presence of MHD instabilities, magnetic turbulence or RMP

LUKE (toroidal): 2-D momentum + 1D configuration spaces (CEA, France)

LUKE : 3-D relativistic linearized bounce-averaged GC Electron kinetic equation



2013

collisions

$E_{||}$ acc.

Sources & sinks

$$\partial f/\partial t = C_{FP}(f) + Q_{RF}(f) + E(f) + T(f) + S(f)$$

RF heating

radial trans.

2017

collisions

$E_{||}$ acc.

Sources & sinks

$$\partial f/\partial t = C_{FP}(f) + C_{KO}(f) + Q_{RF}(f) + E(f) + R(f) + T(f) + S(f)$$

RF heating

synchrotron reac.

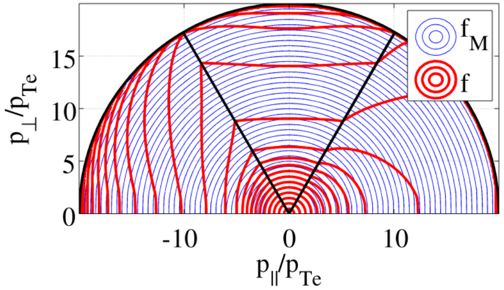
radial transp.

J. Decker and Y. Peysson, EURATOM-CEA report, (2004) EUR-CEA-FC-1736

Peysson, Y. and Decker, J., FST, 65 (2014) 22

LUKE : 3-D relativistic linearized bounce-averaged GC electron kinetic equation

- **Full-f finite difference code with non-uniform grids**
  - Energy scale from eV to hundred MeV
  - Refined description near $\xi_0 = p_{\parallel 0}/p \sim 1$
  - Radial zoom over regions of interest



- **Various geometries** (toroidal, dipole, cylindrical) ; plasma shaping effect. Zero banana width approximation (ZOW)

- Choice of **different time schemes**: from collisional to equilibrium times

- **Standard moments of f_e** : J, P_{RF}, P_C, P_E, Γ_R, …

- **Benchmarked** against neoclassical conductivity, RF heating, primary and secondary runaway rate, etc. Extensively used for LH, EC and EBW physics

- **Numerical structure ready to include self-consistent radial and cross-term dynamics (FOW)**: neoclassical transport, wave-induced transport, Ware pinch, etc

- Self-consistent ripple losses: loss cone and critical energy

LUKE : 3-D relativistic linearized bounce-averaged GC Electron kinetic equation

- **Bounce-averaged Fokker-Planck equation is cast in a conservative form**

$$\frac{\partial f}{\partial t} + \nabla \cdot \mathbf{S}_{\psi,p,\xi_0}(f) = K(f;\psi,p,\xi_0)$$

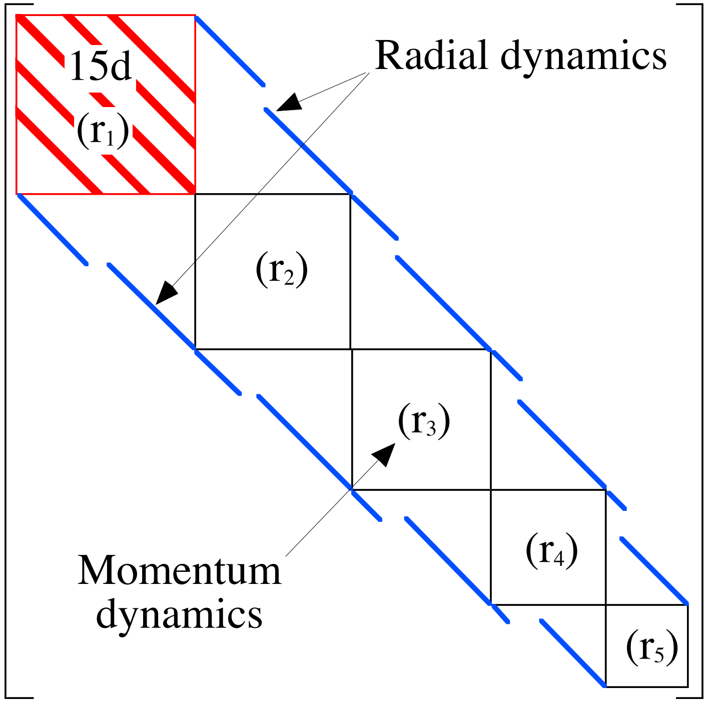
- **Fully relativistic Fokker-Planck** collision operator **including momentum conserving integral term**

$$C(f) = \mathbf{\nabla} \cdot \mathbf{S}^C(f) + I^C(f)$$

- **Universal quasilinear operator** for electron interaction **with all types of RF waves**

- Written in Matlab® and coupled to powerful external matrix inversion packages (MUMPS, …) with some specific modules in C (C3PO ray tracing) or Fortran.

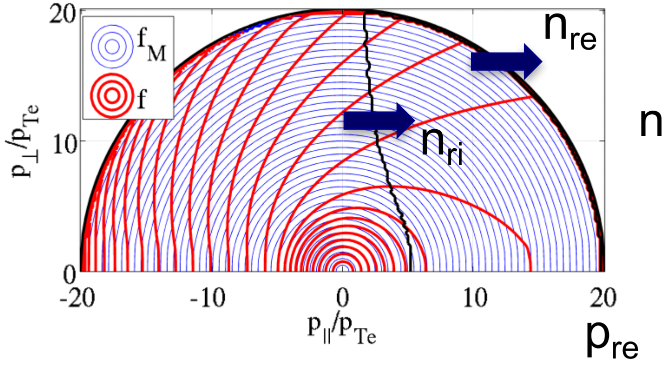
- Distributed (CPU+ GPU) and remote processing for fast calculations



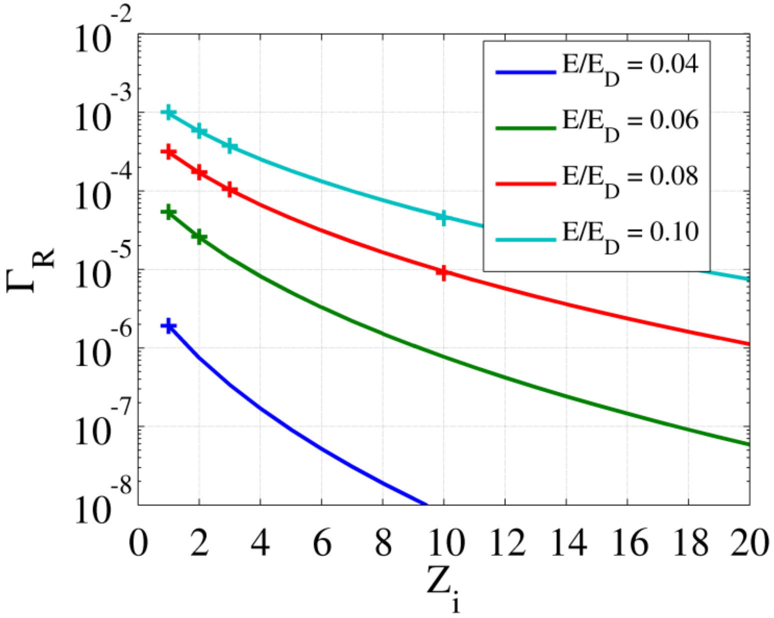
Peysson, Y. and Decker, J., FST, 65 (2014) 22

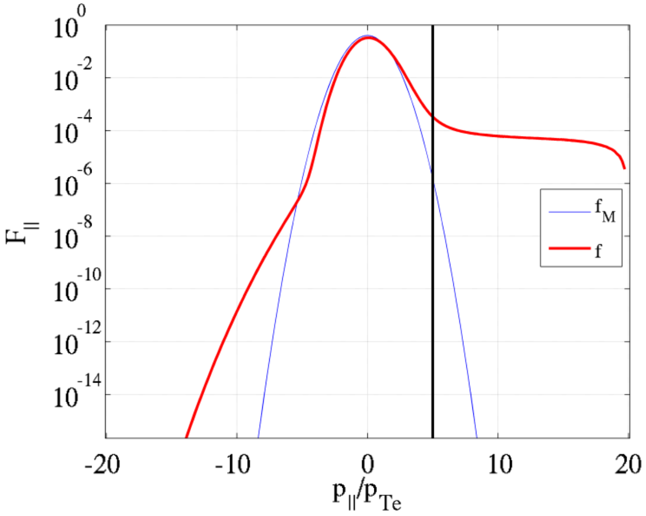
LUKE : primary runaway rate

- **Standard runaway rate calculation (Dreicer mechanism)**
- Non-relativistic limit, cylindrical plasma
- Excellent agreement with Kulsrud theory (+)



$n_r = n_{ri} + n_{re}$





R.M. Kulsrud et al., Phys. Rev. Lett., 1973, 31, 11, pp. 690-693

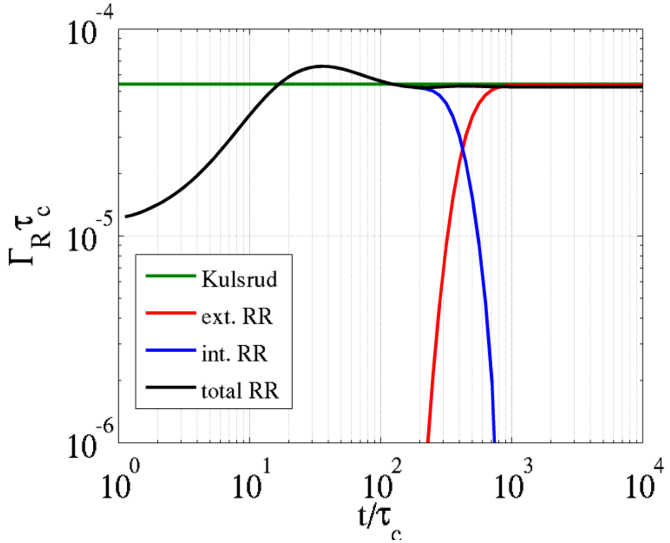
LUKE : time evolution of primary runaway rate

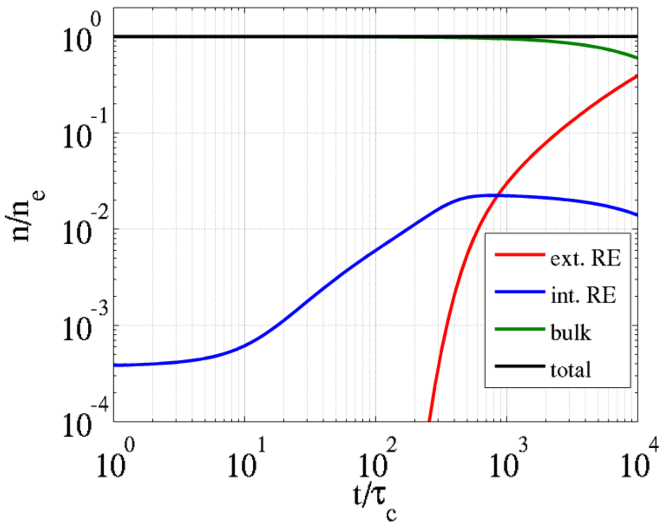
- $E/E_D = 0.06$, $Z_i = 1$, NR limit, cylindrical plasma
- Primary runaway rate :

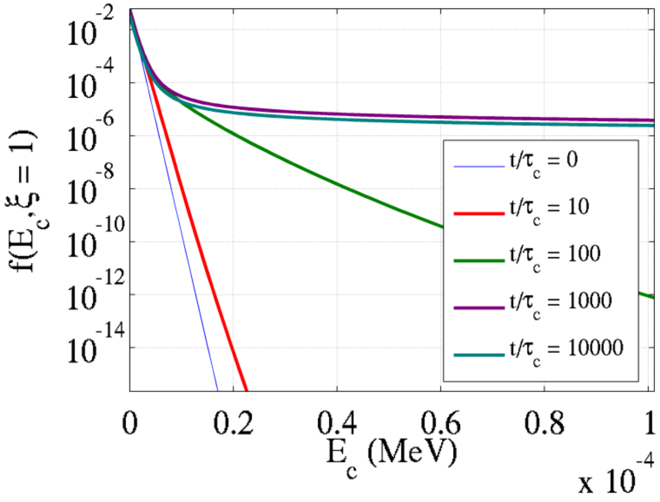
$$\Gamma_r = \frac{1}{n_b}\frac{dn_r}{dt} = \frac{1}{n_b}\frac{dn_{ri}}{dt} + \frac{1}{n_b}\frac{dn_{re}}{dt}$$

- Time asymptotic rate :

$$\Gamma_r = \frac{1}{(1-n_{re})}\frac{dn_{re}}{dt}$$

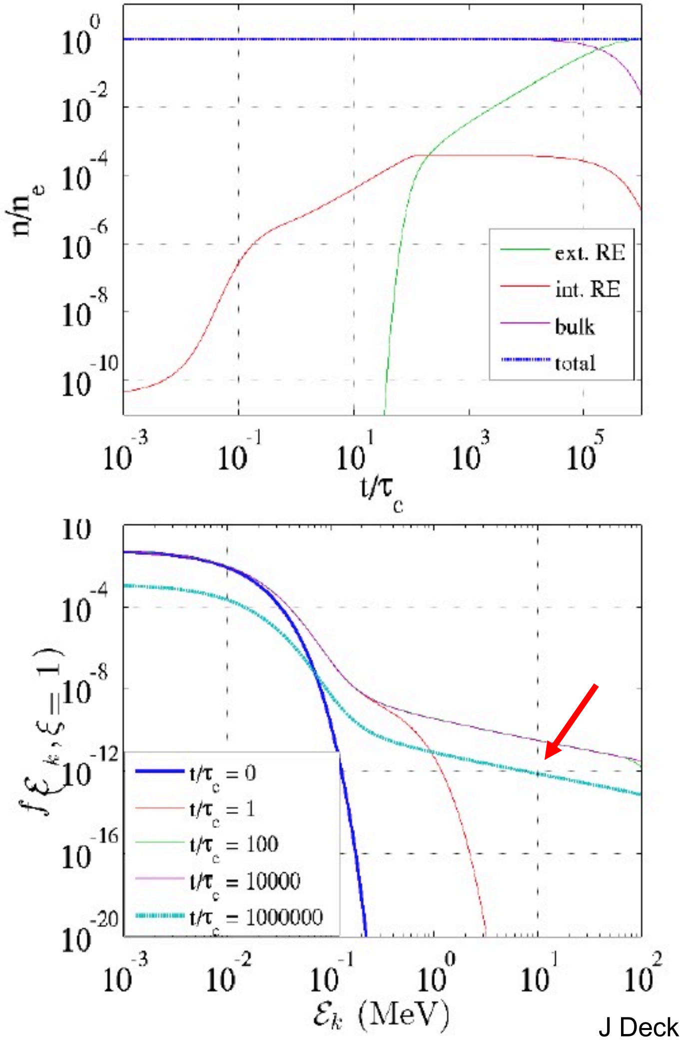






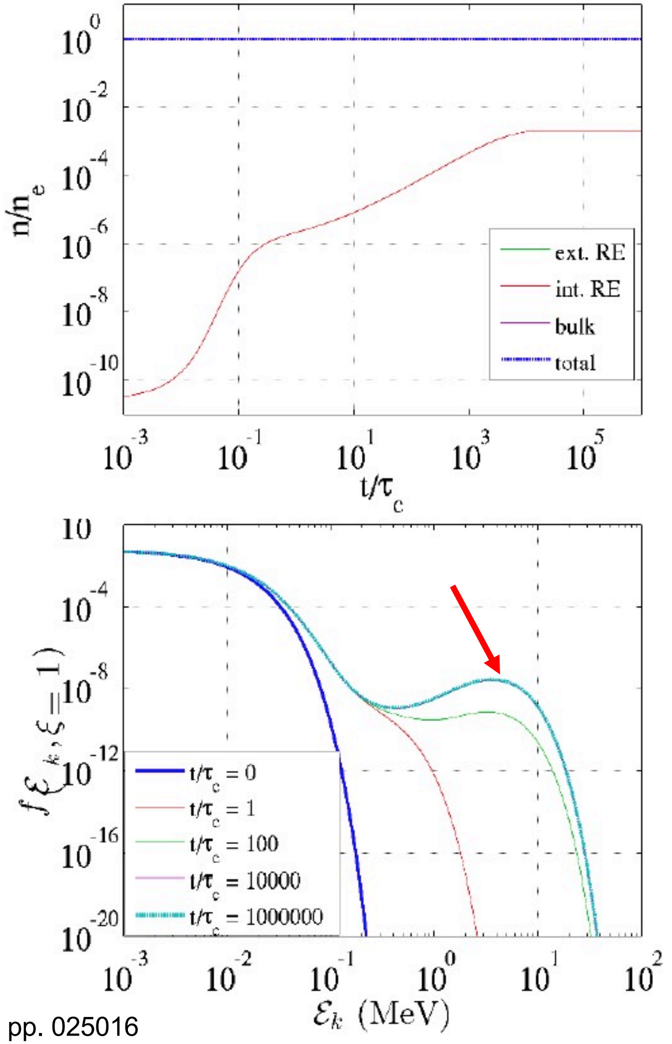
LUKE,CODE : time evolution of primary runaway rate with synchrotron radiation reaction force (ALD)

NO ALD FORCE



$E_{||} = 3$
$\sigma_r = 0.6$
$\beta = 0.1$
$Z_i = 1$

WITH ALD FORCE



ALD

- ○ Upper energy limit of ten MeV
- ○ Steady state regime

J Decker et al., *Plasma Phys. Control. Fusion*, 2016, 58, pp. 025016

LUKE,CODE : beyond Fokker-Planck, knock-on collisions

- Rosenbluth-Putvinski formulation using Moller relativistic electron-electron differential cross section → **Maxwellian electrons are at rest.** Knock-on electrons decsribed by a source term in FP codes

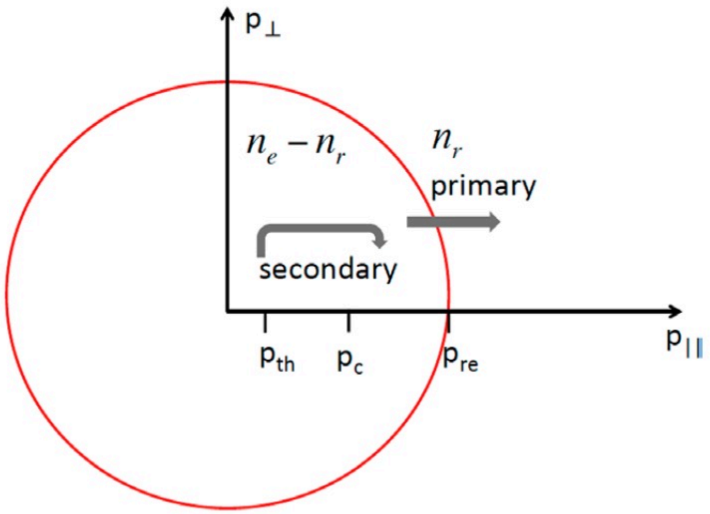
$$\mathbf{S}(p,\psi,\xi,\theta) = n_e n_R c\frac{d\sigma}{d\Omega} = n_e n_R c r_e^2 \frac{1}{p\gamma(\gamma-1)^2}\delta(\xi-\xi^*(p))$$

- The knock-on electrons emerge highly magnetized → **bounce-averaging is essential**

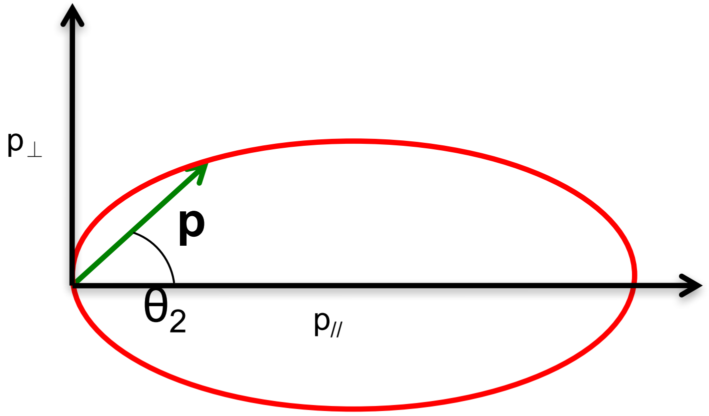
$$\{\bar{\mathbf{S}}\} = \frac{1}{\lambda\tilde{q}}\left[\frac{1}{2}\sum_\sigma\right]_T \int_{\theta_{min}}^{\theta_{max}} \frac{d\theta}{2\pi}\frac{1}{|\hat{\psi}\cdot\hat{r}|}\frac{r}{R_p}\frac{B}{B_p}\frac{\xi_0}{\xi}\bar{\mathbf{S}}(\psi,p,\xi)$$

- Particle conserving form of avalanche process:

$$S = S_+ - \langle S_+\rangle \bar{f}_M \quad \left\{ \begin{array}{l} S_+ = n_e n_r c\dfrac{d\sigma}{d\Omega} \\ n_r + n_e = const \end{array} \right.$$



p_{re} = min(p_c, 1 MeV)

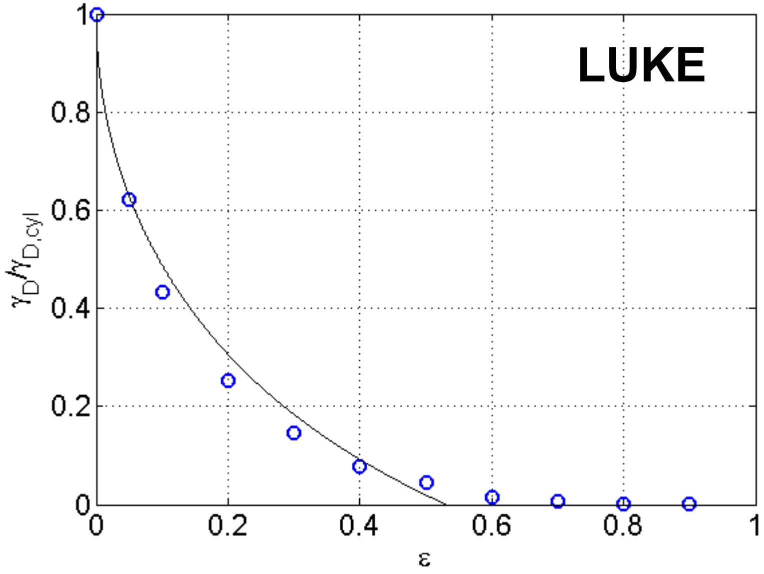


E.Nilsson et al., Plasma Phys. Control. Fusion, 2015, 57, 9, pp. 095006

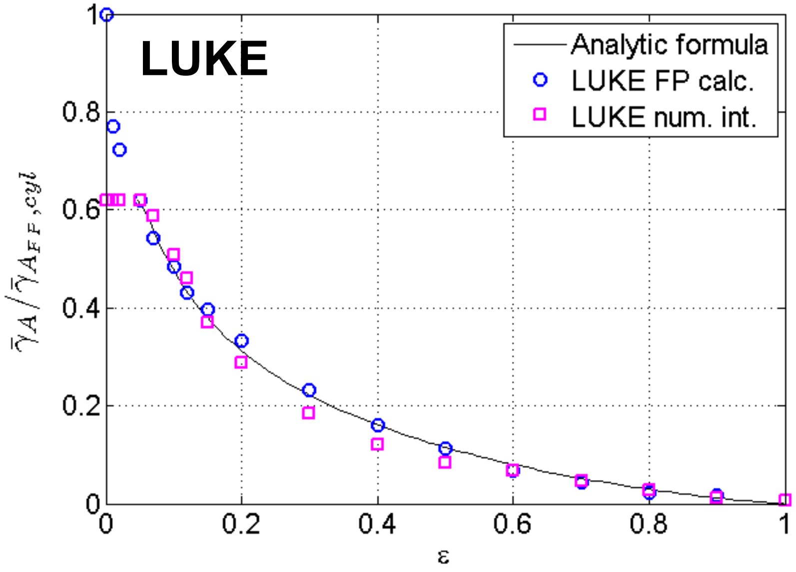
Influence of toroidicity on primary and secondary RE

Growth rate: $$\frac{\partial n_r}{\partial t} = n_e\left(\gamma_D + \gamma_A\right)$$ $$\gamma_A = n_r\,\overline{\gamma}_A$$

Dreicer growth rate, Z_{eff} =1



Avalanche amplification factor



E.Nilsson et al., Plasma Phys. Control. Fusion, 2015, 57, 9, pp. 095006

Runaway rate strongly reduced due to trapped electrons

Agrees with predictions by ARENA code *[Eriksson & Helander, Comp. Phys. Comm.* ***154*** *(2003)]*
and CQL3D code *[Harvey & McCoy, IAEA (1992)] [Decker & Peysson, EUR-CEA-FC-1736, Euratom-CEA, 2004]*

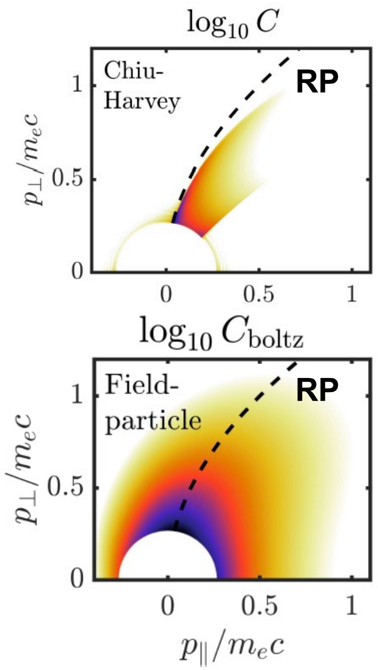
Advanced description of knock-on collisions

- To describe knock-on collisions a (simplified) linearized Boltzmann operator is added (n_r << $C_{\text{knock-on}} = C_{\text{boltz}}\{n_e\delta(\mathbf{p}),\ f_e\}$ (only field-particle term)

Rosenbluth-Putvinski: $f_e(\mathbf{p}) = n_{\text{RE}} \lim_{p_0\to\infty} \frac{1}{p^2}\delta(p-p_0)\delta(\cos\theta-1)$

Chiu-Harvey: $f_e(\mathbf{p}) = F(p)\delta(\cos\theta-1)$ $\quad F(p) = \int_{-1}^{1} f_e(\mathbf{p})\,\mathrm{d}(\cos\theta)$

- Model limitation:
  - Double counting collisions
  - Non-conservation of momentum and energy
  - Chiu-Harvey model ignores pitch-angle distribution
  - Arbitrary cut-off affecting solutions



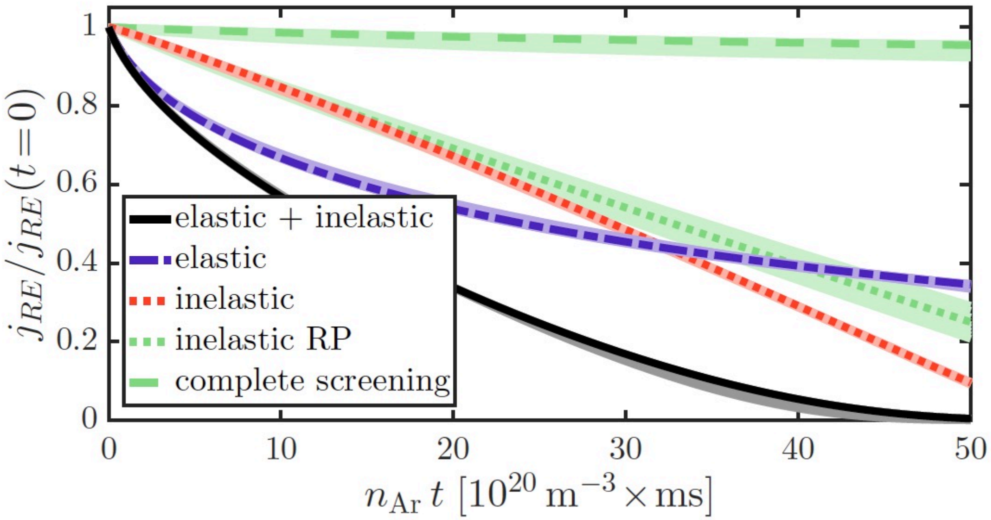
- **New rigorous approach**:
  - Accounting for full f_e(p)
  - Including the test-particle term: *restores conservation laws*
  - Modify lnΛ in Fokker-Planck operator: *avoids double counting*

Reduction of the avalanche generation for $E/E_c \leq 2\text{-}3$

O. Embreus, Chalmers U, REM 2017

CODE: Effects of partially screened impurities on the collision operator

- Weakly ionized impurities with Z >> 1 in very cold plasma (Ar: 18, W: 74)
- Elastic scattering e/i described in Born approximation, v/c >> Zα (α = 1/137)
- Weakly energetic electrons “feels” a screened ion, while very energetic ones interacts with the nucleus → more accurate collision operator
- Inelastic scattering e/e needs also corrections
- **Large effect of reduced screening** (CODE)
  - Enhanced collision frequencies
  - More isotropic distribution function
  - Enhanced effective critical electric field E_c^*
  - Faster runaway current decay



L. Hesslow et al., Phys. Rev. Letter, 2017, 118, pp. 255001

Global objectives

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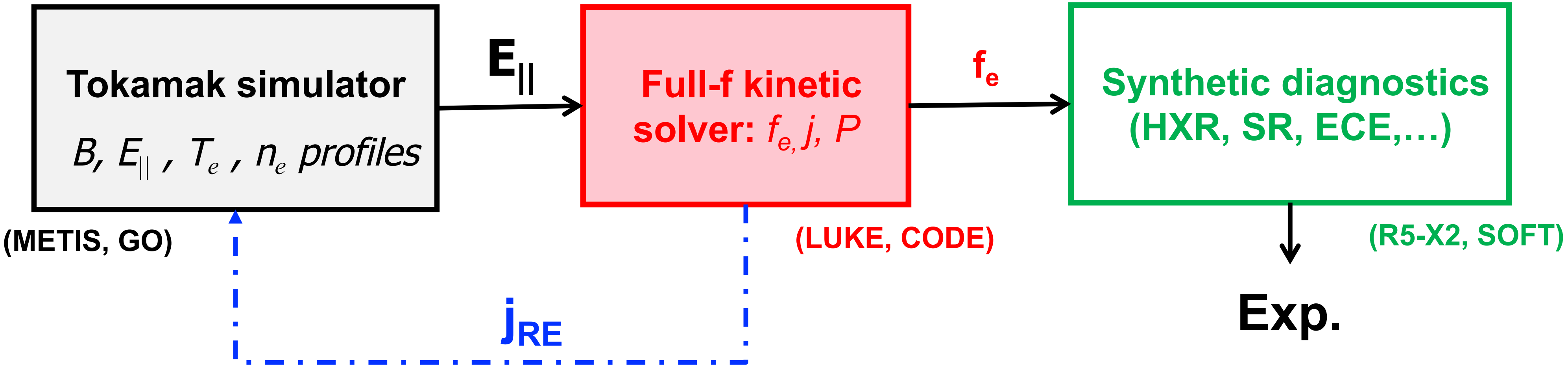


Tokamak simulator

$B, E_{||}, T_e, n_e$ *profiles*

(METIS, GO)

$\mathbf{E_{||}}$

Full-f kinetic solver: f_e, j, P

(LUKE, CODE)

$\mathbf{f_e}$

Synthetic diagnostics (HXR, SR, ECE,…)

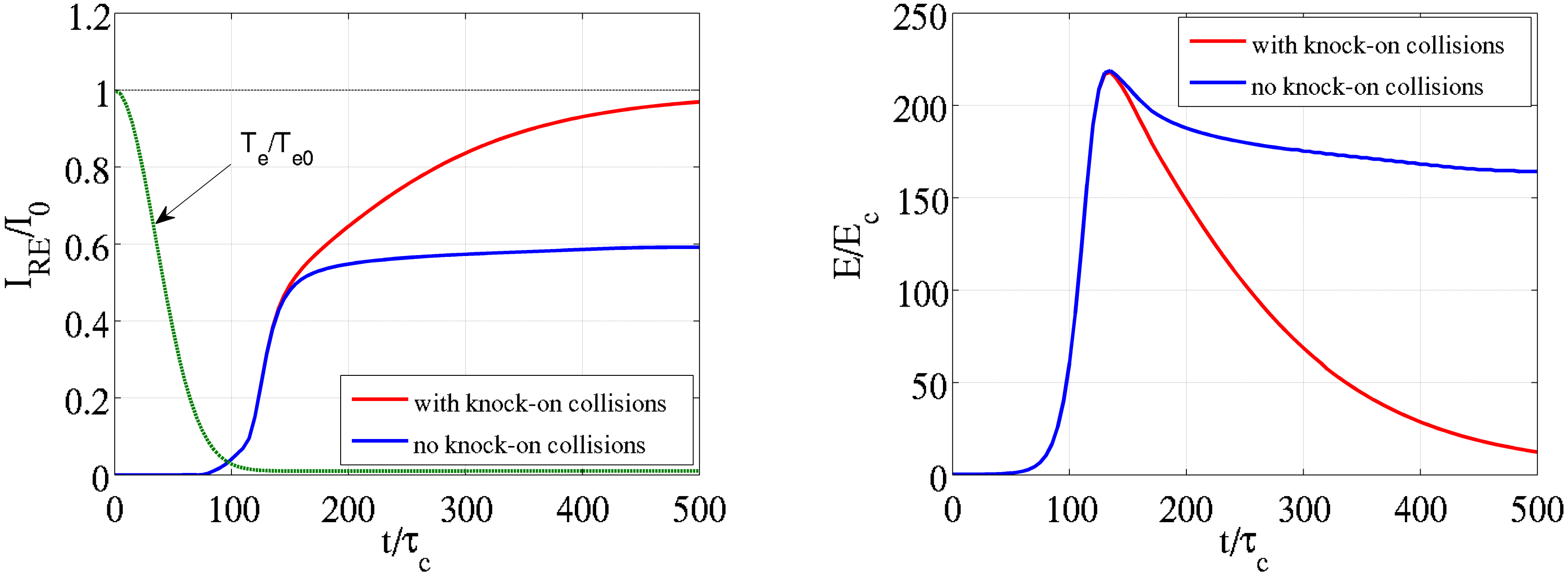
(R5-X2, SOFT)

Exp.

$\mathbf{j_{RE}}$

LUKE, CODE: importance of RE avalanches after thermal quench (hot-tail generation)

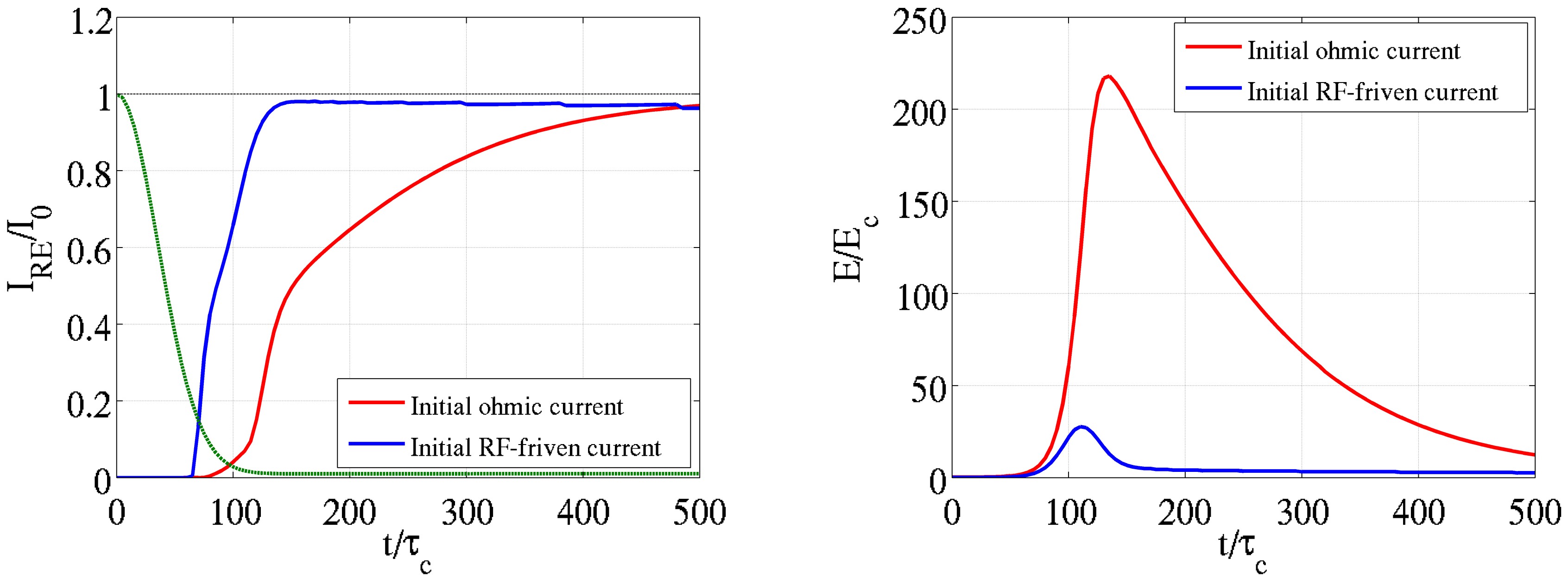
- $Z_i = 1$, cylindrical plasma, **local electric field adjusted to constant $J=J_0$ = 1 MA/m^2**
- **T_e evolution enforced through collisions**: $T_e(t) = T_f + (T_{e0} - T_{ef}) \times \exp[-(t/t_q)^2]$
- T_{e0} = 5.1 keV ; T_{ef} = 51 eV ; $t_q = 50\ \tau_c$ (5 ms)



- Avalanche effect dominates E-field evolution (R-P model not so bad as E/E_C >>1)
- Effect of synchrotron reaction force is negligible (internal RE, not energetic enough)

A. Stahl et al., Nucl. Fusion, 2016, 56, pp. 112009

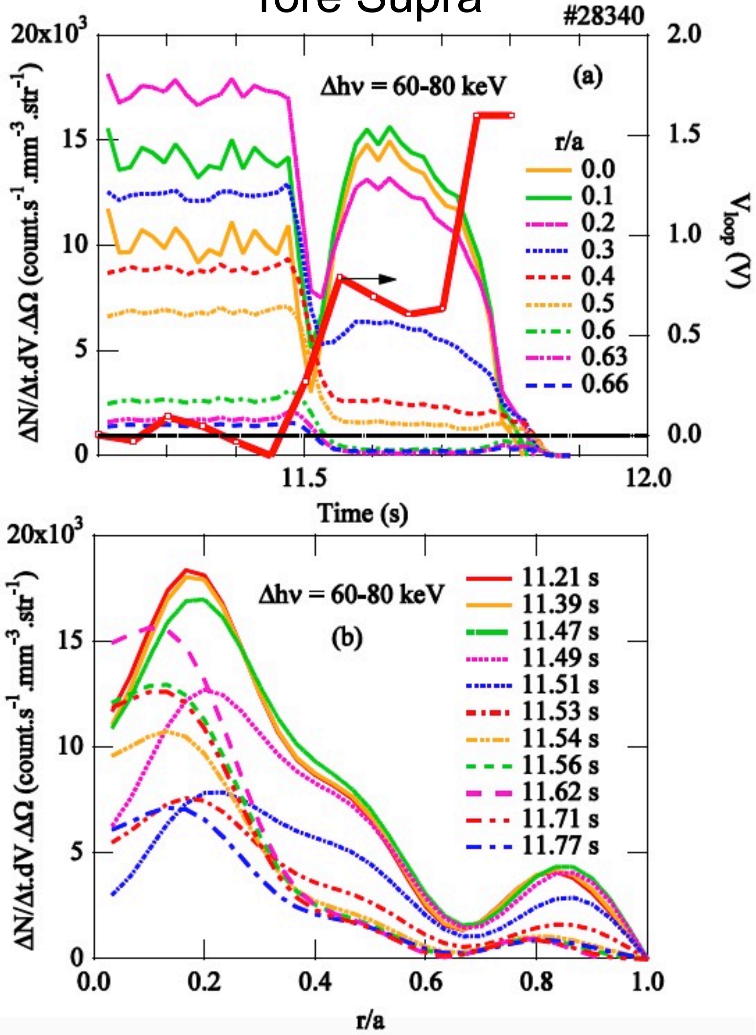
LUKE: Lower Hybrid wave-driven initial distribution



- LHCD, $v_{min} = 3.5$, $v_{max} = 7.0$, P_{LH} adjusted to $J_0 = 1$ MA/m^2, LH power turned off at t = 0
- With LH-driven initial distribution, knock-on collisions play no significant role (but R-P avalanche model likely inaccurate since $E/E_C \sim 1$)
- Importance of seed fast electrons

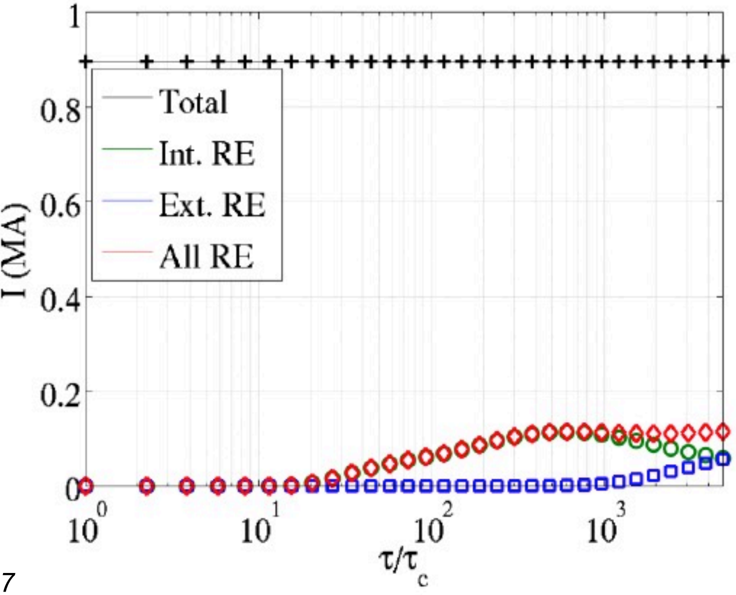
LUKE: Lower Hybrid wave-driven initial distribution

Tore Supra



Y. Peysson and F. Imbeaux, Rev. Sci. Instr., 1999, 70, 10, pp. 3987-4007

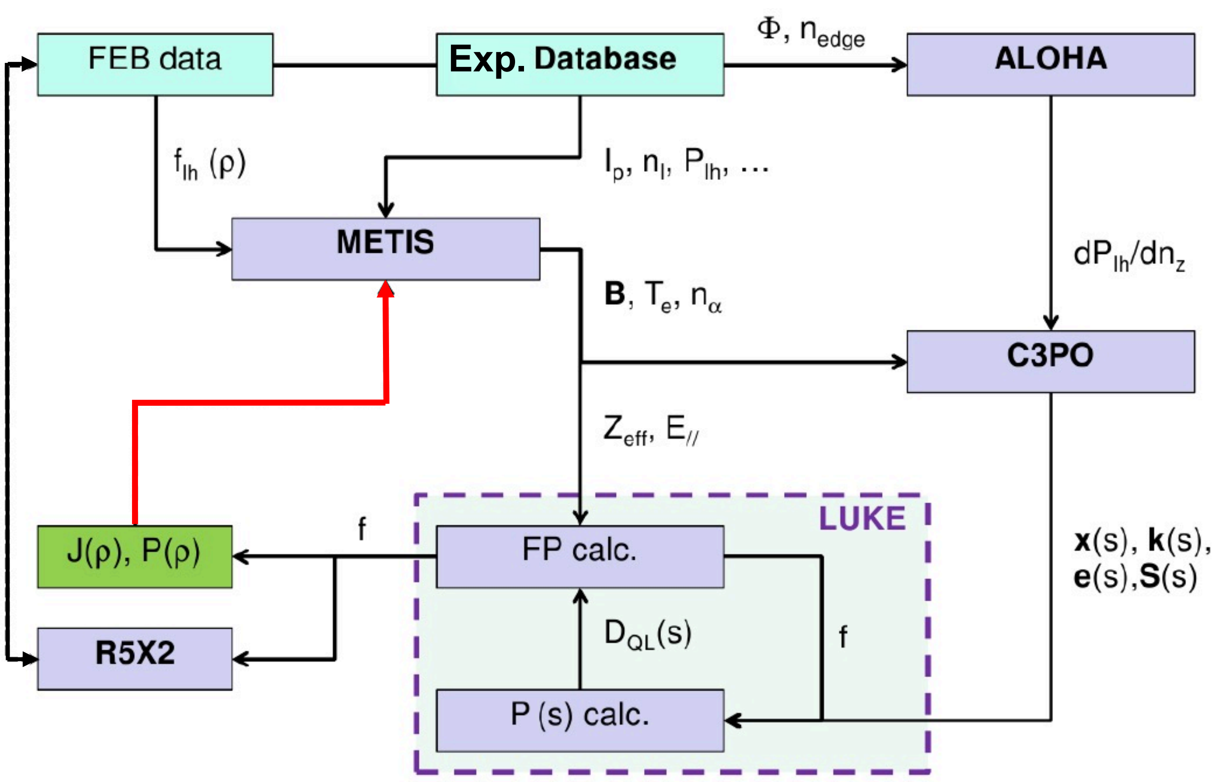
- ○ Sudden drop of LH power from 4.3 MW (steady-state non-inductive discharge) to 1.0 MW then 0 MW at constant I_p = 0.85 MA, B_t = 3.7 T
- ○ Time-space resolved HXR bremsstrahlung



18% of current is carried by RE

Full self-consistent modeling of RE

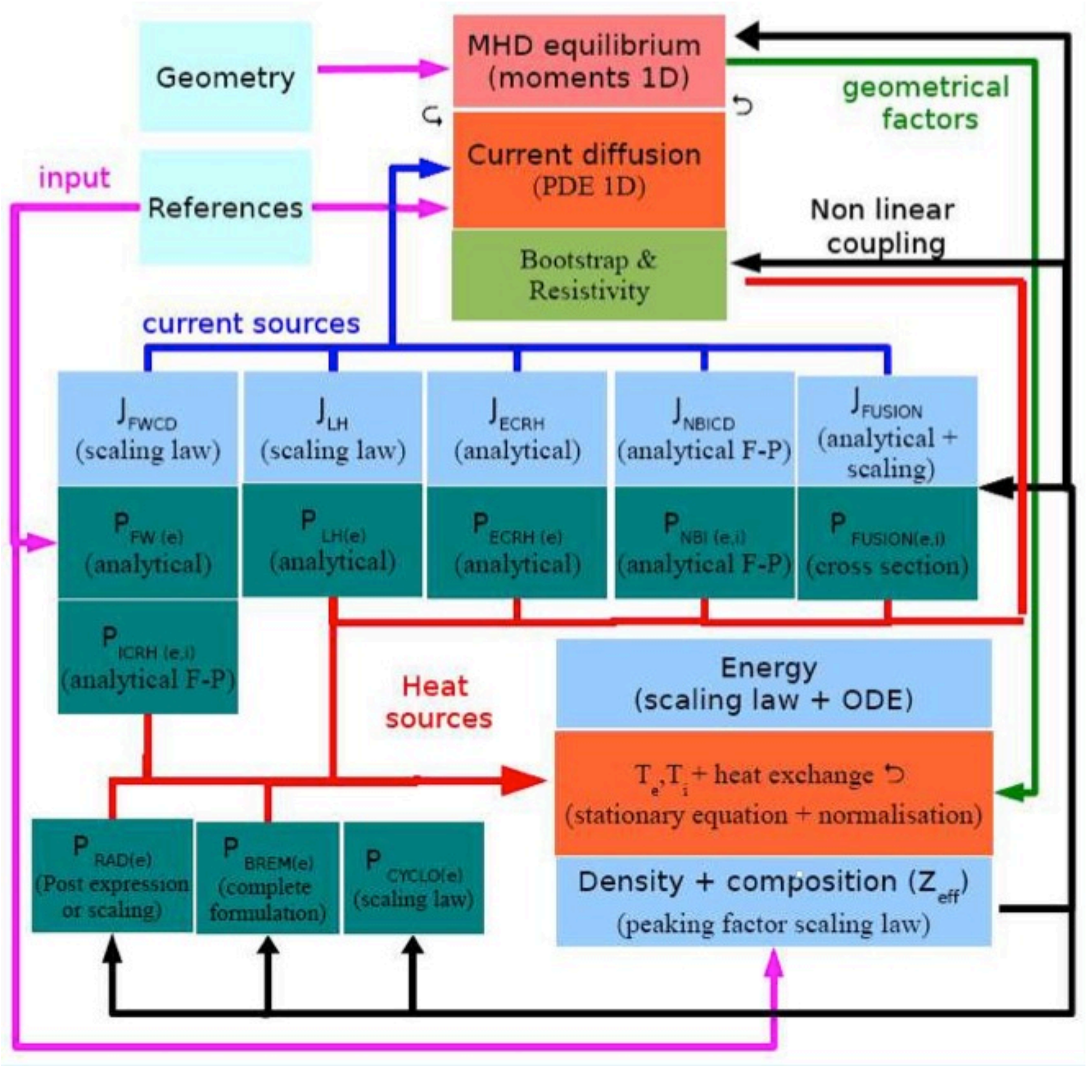
- Cylindrical : GO (1D radial) + CODE (2D momentum space)
- **Toroidal, arbitrary plasma shape : METIS (1D radial) + LUKE (1D radial + 2D momentum space)**
- LUKE in ITM and soon in **IMAS (ITER)**



- **Full coupling loop METIS – LUKE is done**
- Stability of the convergence between j and $E_{||}$ is under investigation.
- Test Tore Supra discharge #28340
- *Effect of RF waves on RE can be studied (EC waves)*

G. Papp et al., Nucl. Fusion, 2013, 53, pp. 123017
Artaud et al., Nucl. Fusion, 2010, 50, 4, pp. 043001

METIS: Minute Embeded Tokamak Integrated Similator



Matlab
Simulink

J. F. Artaud et al, Nucl. Fusion ***50*** *(2010) 043001*

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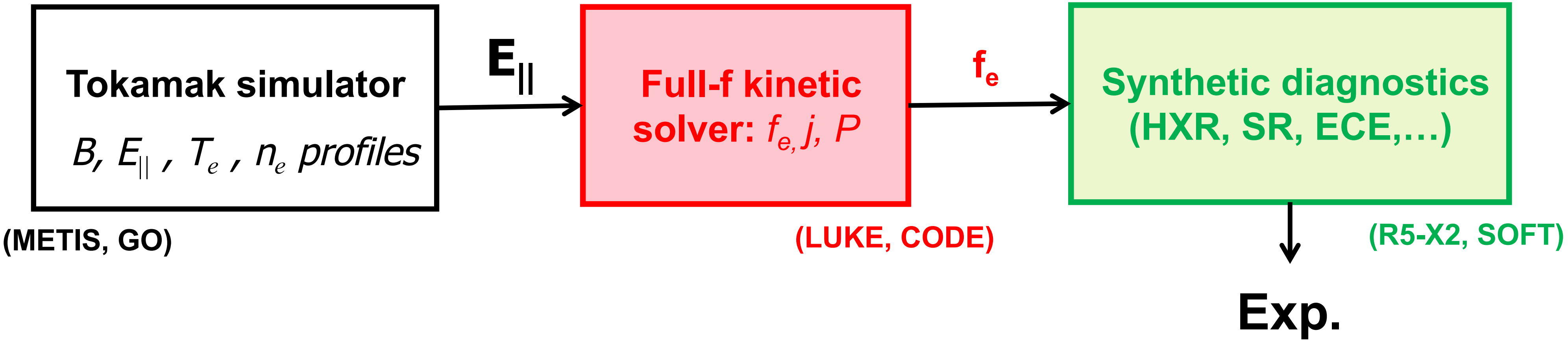


Tokamak simulator

$B, E_{||}, T_e, n_e$ profiles

(METIS, GO)

$\mathbf{E_{||}}$

Full-f kinetic solver: f_e, j, P

(LUKE, CODE)

$\mathbf{f_e}$

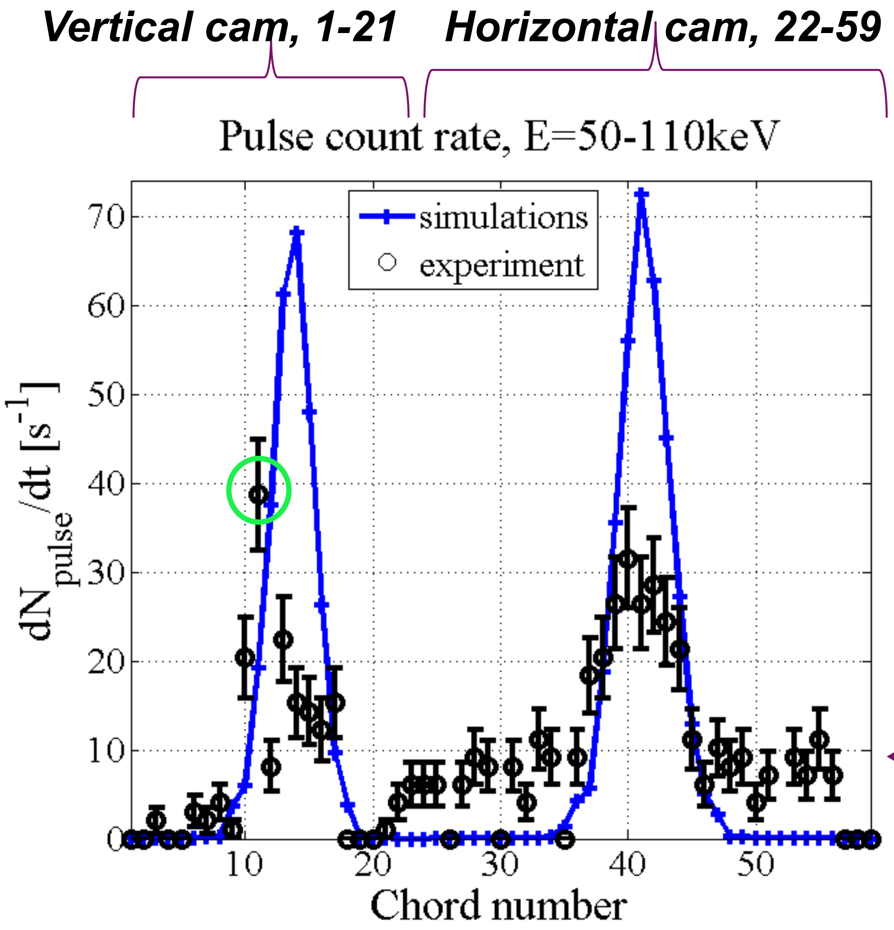
Synthetic diagnostics (HXR, SR, ECE,…)

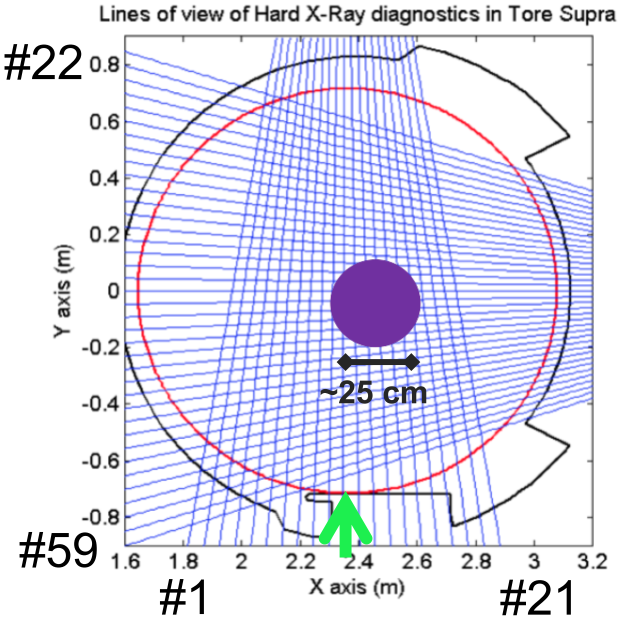
(R5-X2, SOFT)

Exp.

Fast electron bremsstrahlung emission from RE (Tore Supra)

- HXR tomographic system
- **R5X2**: Synthetic diagnostic for bremsstrahlung emission *[Peysson & Decker, Phys. of Plasmas **15** (2008)]*





RE discharge: Emission profile reproduced at the end of the current flattop (METIS+LUKE (open loop) + R5-X2)

X-rays backscattered by the tokamak inner wall

*[Peysson et al., Nucl. Fusion **33** (1993)]*

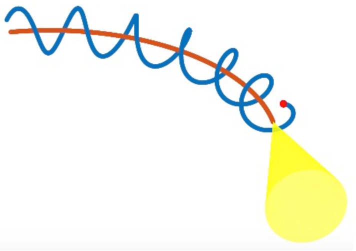
E. Nilsson, PhD thesis, Ecole Polytechnique, France, 2015

Synchrotron radiation emission from RE (C-Mod)

- New synthetic diagnostic **SOFT**
- Angular and spectral distribution of synchrotron radiation:

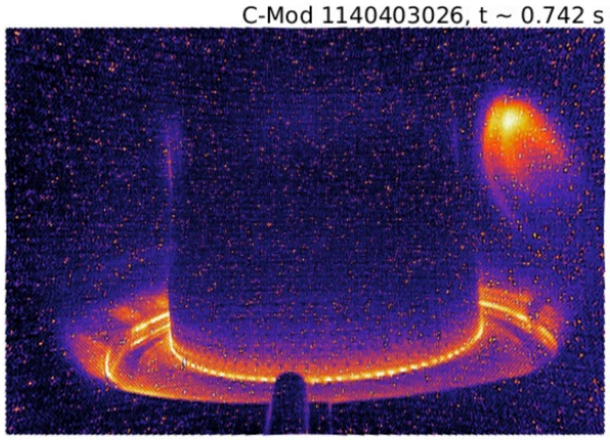
$$\frac{d^2P}{d\omega d\Omega} = \frac{3e^2\beta^2\gamma^6\omega_B}{32\pi^3\epsilon_0 c}\left(\frac{\omega}{\omega_c}\right)^2\left(\frac{1-\beta\cos\psi}{\beta\cos\psi}\right)^2\times\left[K^2_{2/3}(\xi)+\frac{(\beta/2)\cos\psi\sin^2\psi}{1-\beta\cos\psi}K^2_{1/3}(\xi)\right]$$

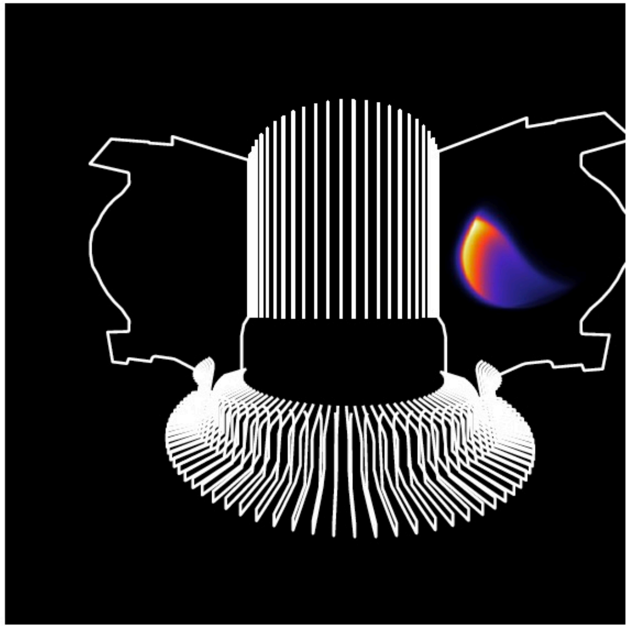
- Gyro-angle averaging



- Alcator C-Mod, 3-8 T

$E_{RE} \approx 30$ MeV





Mathias Hoppe, Chalmers U., REM 2017

Conclusions

- Within the Work Package for Enabling Research framework, significant improvements have been achieved in four years for realistic post-disruptive RE kinetic modeling. Progresses have been essentially devoted to momentum space physics (with and without toroidal corrections). A synthetic diagnostic has been developed for synchrotron radiation (SOFT).

- Full 1-D effects taking into account of toroidal curvature and plasma shaping is the next challenge of RE kinetic modeling: transport in mixed stochastic/coherent structures (link with MHD and orbit-following codes), as well as interaction between RE and MHD instabilities. Validation of the modeling tools against experiments must be also performed at large scale with the developped tools.

- The LUKE Fokker-Planck solver coupled to METIS simulator is a powerful tool for purpose. *Contributions from non-CEA collaborators within CEA license are welcome (use and developments)*

- Even if the Enabling Research framework will stop by end of 2017 (except if a new call from EUROfusion is launched very soon!), the activity on RE physics modeling will continue through active bilateral collaborations. A another success of the WPENR !