Benchmark cases and 1st Energetic Particle ITPA group meeting in Lausanne

N. N. Gorelenkov

Princeton Plasma Physics Laboratory, Princeton

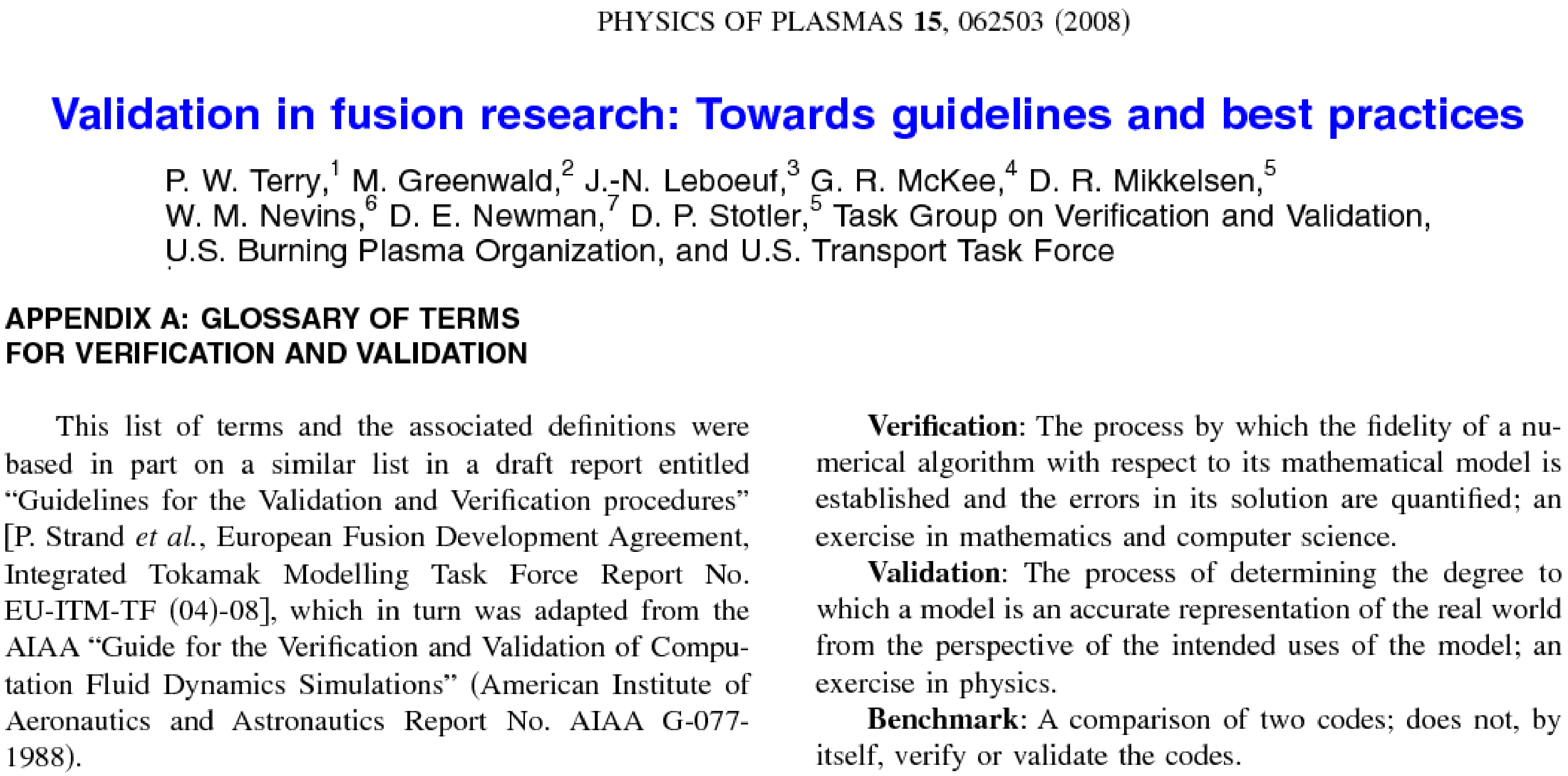
▷ 1st ITPA Energetic Particle meeting, Lausanne, chairman S. Günter:

- ~27 talks, 2.5 days:
  - ○ half on benchmark cases/discussions,
  - ○ ripples in ITER,
  - ○ nonlinear simulations (Briguglio, Todo),
  - ○ EP transport experiments (Van Zeeland, Fredrickson),
  - ○ EFDA EP programme (Borba)
  - ○ other topics

PEPSC meeting, Dallas, TX, November 16, 2008

On definitions

Recent V&V efforts coordinated by TTF



PHYSICS OF PLASMAS **15**, 062503 (2008)

Validation in fusion research: Towards guidelines and best practices

P. W. Terry,[1] M. Greenwald,[2] J.-N. Leboeuf,[3] G. R. McKee,[4] D. R. Mikkelsen,[5]
W. M. Nevins,[6] D. E. Newman,[7] D. P. Stotler,[5] Task Group on Verification and Validation,
U.S. Burning Plasma Organization, and U.S. Transport Task Force

APPENDIX A: GLOSSARY OF TERMS FOR VERIFICATION AND VALIDATION

This list of terms and the associated definitions were based in part on a similar list in a draft report entitled "Guidelines for the Validation and Verification procedures" [P. Strand *et al.*, European Fusion Development Agreement, Integrated Tokamak Modelling Task Force Report No. EU-ITM-TF (04)-08], which in turn was adapted from the AIAA "Guide for the Verification and Validation of Computation Fluid Dynamics Simulations" (American Institute of Aeronautics and Astronautics Report No. AIAA G-077-1988).

Verification: The process by which the fidelity of a numerical algorithm with respect to its mathematical model is established and the errors in its solution are quantified; an exercise in mathematics and computer science.

Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model; an exercise in physics.

Benchmark: A comparison of two codes; does not, by itself, verify or validate the codes.

ITPA Tasks

1. **Destabilisation of Alfvén waves and Energetic Particle Modes (EPMs)**
    - measurements of damping rates of Alfvén waves (together with reliable mode identification: eigenfunction, frequency etc) and comparison with theory
    - investigation of the drive of different kinds of Alfvén waves (TAEs, BAEs, RSAEs,...) and EPMs depending on the fast ion distribution function (energy and pitch angle)
    - measurements of the influence of fast particle driven instabilities on the fast ion distribution function, expulsion of fast ions, comparison between experiments and state of the art non-linear theory/codes
    - definition of benchmark test cases for fast particle stability codes
    - development of relevant diagnostics, recommendations for ITER diagnostics
    - prediction of the role of fast particle driven modes in ITER conventional and steady state scenarios, including the power load on the first wall caused by the fast particle losses; recommendations for operation
2. **Effect of non-axisymmetric magnetic fields**
    - comparison between theoretical predictions and measurements of fast ion losses caused by magnetic field ripple and error fields in present day devices
    - prediction of the power loads to the first ITER wall caused by error fields, ferritic inserts, test blanket modules and perturbation fields (ELM mitigation coils)
3. **Interaction of fast ions with background MHD**
    - investigation of the interaction of background MHD and fast particle confinement in present day devices, comparison with theory

- prediction of the influence of NTMs and possible synergistic effects with field ripple/error fields on fast particle confinement in ITER
- influence of fast ions on sawtooth stability (leading role of MHD-TG in the development of control tools for ITER)

4. **Runaway electrons (leading role of MHD-TG)**
    - study of generation of runaway electrons by disruptions in present day devices, comparison with theory
    - development of mitigation/control tools for ITER, in particular perturbation fields Heating and current drive (support for IOS-TG only)
    - investigation of localisation of NBI heating and current drive
    - prediction of the role of NBI current drive on current profile control in ITER
    - momentum input
    - particle current drive

Benchmarks cases from ITPA summary

- Ripple loss/effects benchmarks
- Well diagnosed JET discharges with measured **linear** damping rates for low n (1 and/or 2) and intermediate n (~5) shall be used (D. Testa, A. Fasoli)
  - Codes (persons involved): LIGKA (Ph. Lauber, S. Günter), NOVA-K (N. Gorelenkov), CASTOR-K (D. Borba), TAEFL (D. Spong), LEMan (N. Mellet, A. Fasoli), and TASK/WM(A. Fukuyama, Y. Todo).
- **Non-linear** benchmarks: interaction between the excited waves and the fast particle distribution function. The group again decided for a benchmark case to be chosen (N. Gorelenkov).
  - Codes involved: MEGA (Y. Todo), HAGIS (S. Pinches), HMGC (S. Briguglio), TAEFL (D. Spong), M3D (R. Nazikian), NIMROD (J. Carlsson).

Simple benchmarks case of n=1 linear TAE

n=1, R0=3m, a=1m, circular, zero beta tokamak equilibrium,
q=1.1+psi where psi is a normalized poloidal flux varying from 0 at axis to 1
Plasma density profile is constant.

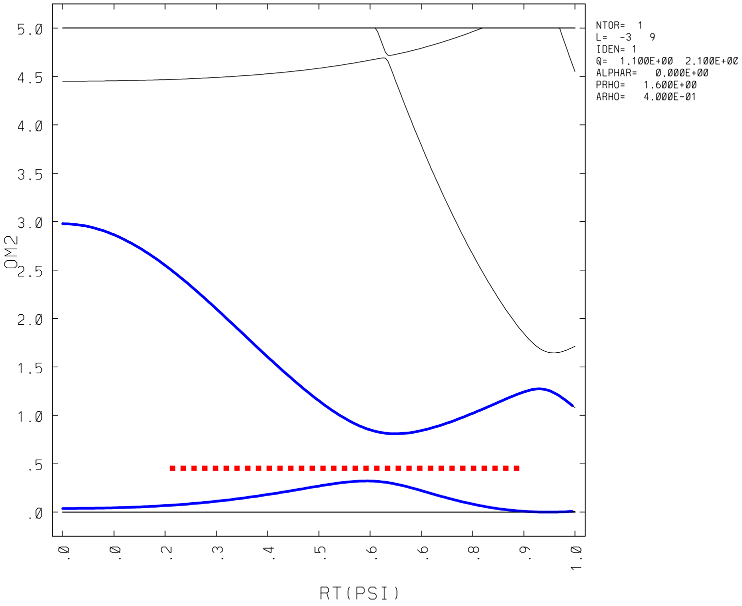
Energetic ion parameters: v_h/v_A =1.7 rho_h/a =0.085
EP beta profile ~ exp(-psi/0.37)

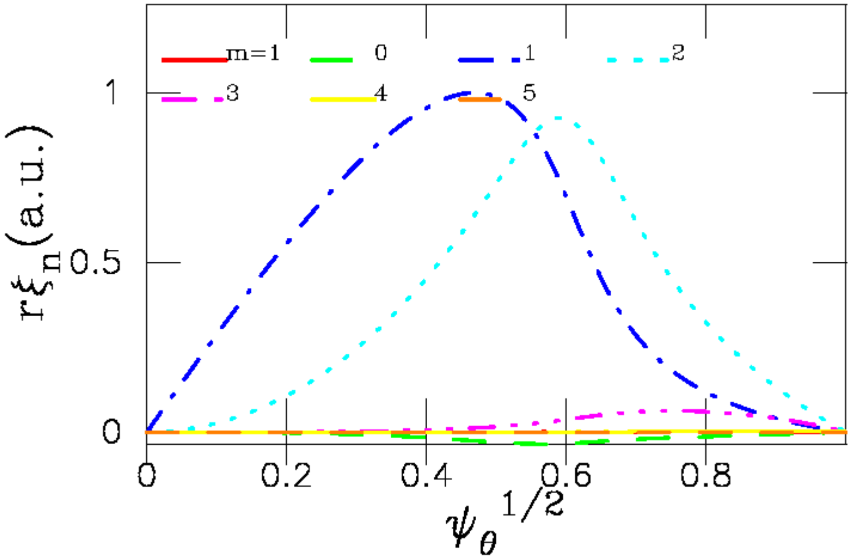
Distribution function is taken either Maxwellian or slowing down. In the latter case we have f=1/(v**3+v_crit**3) * exp(-psi/0.37) where velocities are normalized to the injection velocity v_h and v_crit=0.58

These parameters can correspond to deuterium plasma and EP mass and charge:
m_i = m_f = 2, z_i = z_f = 1

E_{f0} = 173keV B0 = 1T, $n_e = 4.142 \times 10^{13} cm^{-3}$, Te = 3.14 keV (used for v_crit value).

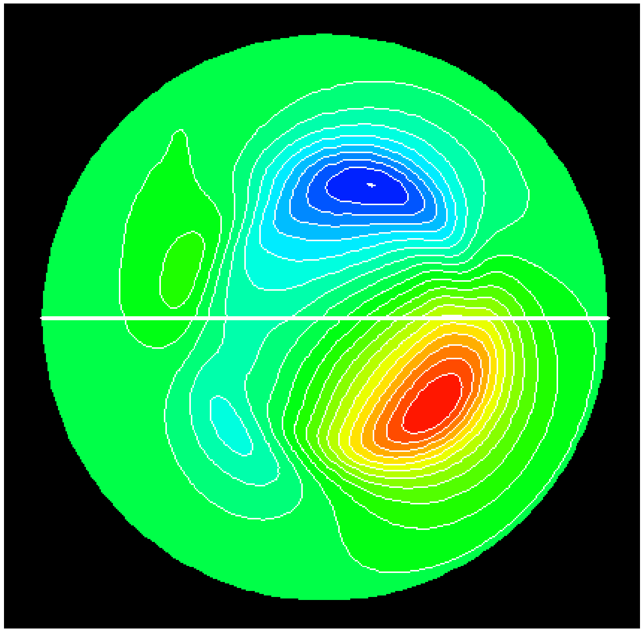
n=1 TAE gap and structure

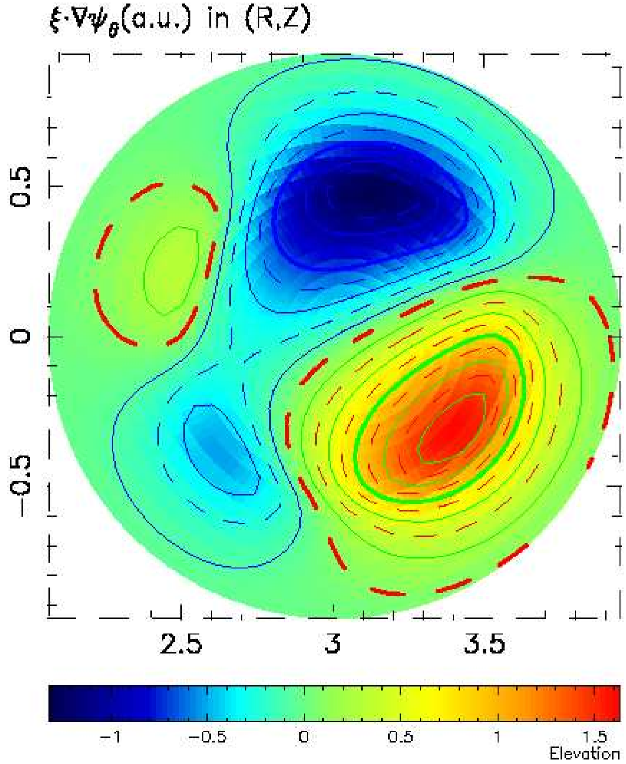




- Choice was to have just two dominant harmonics

Mode structure compares well with one from M3D





Computing the growth rate from fast ions

In comparison we will use theoretical growth rates

$$\frac{\gamma}{\omega} \simeq -\frac{v_A^2 m_f^2 \pi^2}{2\omega R^2 B^2 E_{f0}} \int d^3v \left[-\frac{E_{fo}\partial}{\partial E} - \frac{\omega_*}{\omega} \right] f_f \left(\frac{v_\perp^2}{2} + v_\parallel^2 \right)^2 \delta\left(\omega - \left(k_\parallel \pm \frac{1}{qR} \right) v_\parallel \right), \quad (1)$$

Assumptions are: passing particles contribution, no FLR effects.

Maxwellian distribution function

Distribution function

$$f_M = \frac{n_f}{\left(\sqrt{\pi} v_T\right)^3} e^{-v^2/v_T^2}, \quad (2)$$

where $v_T = \sqrt{2T/m}$, m is mass, and n_f is the fast ion density.

$$\frac{\gamma}{\omega} \simeq \sum_{\pm} \frac{-\sqrt{\pi}\beta_f}{2^2 R^2} \frac{v_A^2}{\omega^2} \chi_l \left(\frac{1}{2} + \chi_l^2 + \chi_l^4 \right) \left(1 - \frac{\omega_*}{\omega} \right) e^{-\chi_l^2},$$

where $\chi_l = (v_A/v_0)/|1 + l v_A/qR\omega|$, $l = \pm 1$. Two signs of l correspond to $v_\parallel = v_A$ and $v_\parallel = v_A/3$.

Slowing down distribution function

Isotropic s-d EP distribution in the form

$$f_b \simeq \frac{3\beta(r)B^2}{2^5\pi^2E_{b0}}\left(1-\frac{3}{5}\bar{v}_{cr}^2\right)^{-1}H(v_0-v)\left[\frac{H(v-v_{cr})}{v^3}+\frac{H(v_{cr}-v)}{v_{cr}^3}\right], \tag{3}$$

where H is the step function, v_{cr} is the critical velocity below which the drag on thermal ions becomes dominant, and $\bar{v}_{cr} = v_{cr}/v_0$.

We find from general growth rate expression:

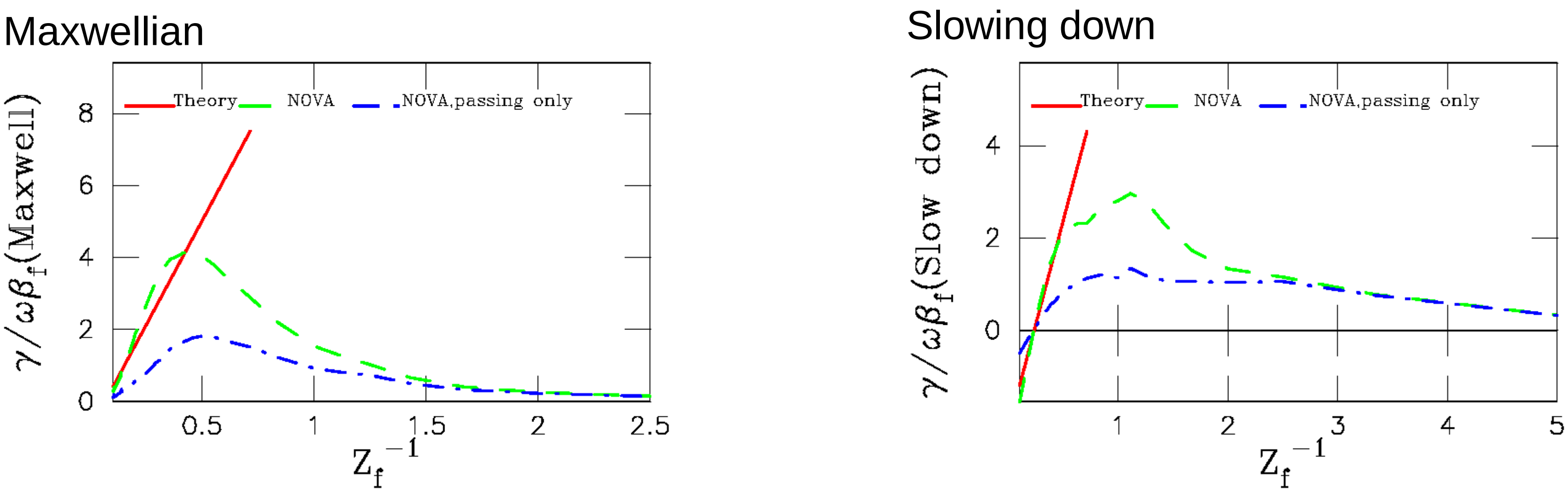
$$\frac{\gamma}{\omega} \simeq \Sigma_{\pm} \frac{-3\pi\beta}{2^5R^2}\frac{v_A^2}{\omega^2}\left\{\frac{3}{2}\chi_l^2\left(2+\frac{\chi_{lcr}^2}{3}+\frac{\chi_l\chi_{lcr}}{3}+\frac{\chi_l^2}{3}+\frac{1}{\chi_l\chi_{lcr}}\right)(\chi_{lcr}-\chi_l)+\frac{\chi_l}{2}\left(\chi_l^4+2\chi_l^2+1\right)\right. \tag{4}$$

$$- \frac{\omega_*}{\omega}\chi_l^4(\chi_{lcr}-\chi_l)\left(1+\frac{2}{\chi_l\chi_{lcr}}+\frac{1}{3\chi_l\chi_{lcr}^3}+\frac{1}{3\chi_l^3\chi_{lcr}}+\frac{1}{3\chi_l^2\chi_{lcr}^2}\right) \tag{5}$$

$$\left. - \frac{\omega_*}{\omega}\frac{\chi_l^7}{2\bar{v}_{cr}^3}\left[\frac{1}{3\chi_{lcr}^6}+\frac{1}{\chi_{lcr}^4}+\frac{1}{\chi_{lcr}^2}-\frac{7}{3}\right]\right\}, \tag{6}$$

where it is assumed that $v_{cr} < v_0$ and $\chi_{lcr} = \min\left[(v_A/v_{cr})/|1+lv_A/qR\omega|, 1\right]$.

Theory agrees well with NOVA-K growth rate



- Fast ion FOW are tested by changing ion charge.
- Many publications exist, but most use some approximations: *Fulop, PPCF'96.*
- $n = 2$ mode results are shown.
- Benchmark with M3D is in progress.

Comments on EP distribution function models

PPPL

- For the purpose of comparisons we can use isotropic distribution functions:
  - even then it should be treated equally in different codes.
  - NOVA-K: $f = f(v)\, f(\langle\psi\rangle)\, f(\lambda)$, $\lambda = \mu B_0/\mathscr{E}$, ψ is time average over particle orbit.
- For the codes like M3D/GKM i would suggest to have a map in $\left\{v, P_\varphi, \lambda\right\}$.
  - Then quantities like $\langle\psi\rangle$, $\omega_{b,t}$, ω_{pr} are known.
  - Such mapping is done for trapped ions in NOVA-KN.