Modeling of the Effects of TAEs and TAE Avalanches on Neutral Beam Ion Orbits in NSTX

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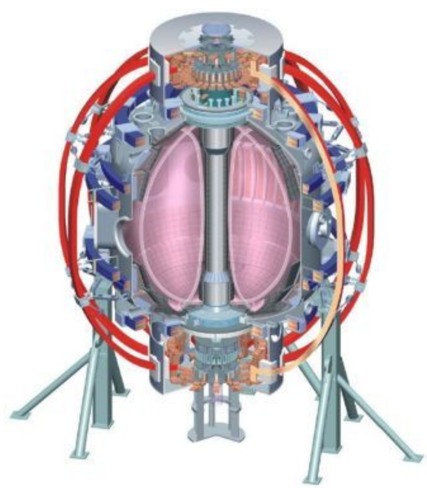

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Outline

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Motivation

- Beam particle loss due to TAE avalanches observed in experiments
  - NSTX shot 141711 and 141719 show sudden drop in neutron production right after a TAE burst
  - Quite different signatures on scintillator detector – Why?
- Difficulties on dealing with wave-particle resonance analytically
  - Analytical criteria may fail to predict the exact resonance in a realistic configuration
  - Hard to evaluate the effect of the resonance on the particles analytically.
  - Stochastic effects need to be considered

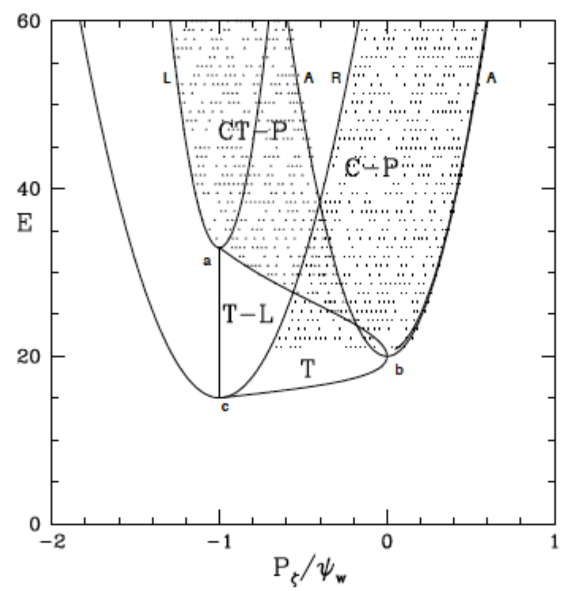
Introduction – Phase Space Description

- Particle's motion totally determined by three quantities
  - Energy -- E
  - Magnetic Moment -- μ
  - Toroidal Canonical Momentum – $P_\zeta = v_\parallel \frac{g}{B} - \psi_p$
- $\omega \ll \Omega_i$, magnetic moment still conserved.
- Different particle behaviors are separated by P-E plane curves.

T : Trapped
P : Passing

C: Co-moving
CT: Counter-moving

L: Loss



Introduction -- Equilibrium

- In equilibrium, particle's energy, magnetic moment, and toroidal canonical momentum are conserved quantities. A particle will stay at its initial position in the phase space. We can categorize particles based on their initial phase space position.
- An equilibrium could be linearly unstable to several TAEs, this is considered the main cause of the onset of a TAE avalanche.
- Equilibrium is chosen to be fixed in our work, thus the effects of evolution of perturbations and beam ion distribution on the equilibrium are neglected.
- Equilibrium is obtained via solving Grad-Shafranov Equation. See EFIT section for details.

Introduction – TAEs

- In a torus, B depends on cosθ. This couples different m modes and creates “gaps” in Alfven continuum.
- Magnetic shear plays a role like “defects” and make it possible to have a discrete eigenmode inside the gap. Since there is no continuum damping, this kind of mode can be easily excited.
- For a given n number, a lot of m’s are coupled together. But modes with different n number are still uncoupled in an axisymmetric system.
- Several n’s are observed simultaneously in experiments within an avalanche. But they are dealt separately in our work.

Introduction – Destruction of Good KAM Surface

- In Hamiltonian mechanics, for an integrable system, its phase space consists of a set of nested surfaces – KAM surfaces. The system will stay on the surface on which it initially resides. In our case, without perturbation, particle will stay on constant E, μ, and P_ζ surface.
- A perturbed Hamiltonian can change this picture significantly near a resonance. The surface which is resonant to the perturbation will be deformed into a chain of islands. The islands have a certain "width", in principle, outside the islands there are "good" KAM surfaces. But if two resonant surfaces are so close to each other such that the sum of their islands widths is greater than the distance between them, "overlap" occurs and "good" KAM surfaces disappear. This is usually considered as the criterion of stochasticity.

Methods -- EFIT

- EFIT is a Grad-Shafranov Solver
- Current and pressure profiles are obtained through various diagnostics.
- Cylindrical coordinates are used. Components of magnetic field, poloidal and toroidal flux are given on every grid points as an output.
- In our work, the equilibrium right before the onset of TAE avalanche is used as a static background.

Methods – NOVA-K

- NOVA-K is an non-variational kinetic-MHD solver
- Energetic particles can be included into the MHD equations via an anisotropic pressure which is given by kinetic theory.
- NOVA-K can calculate linear mode structure of ideal TAEs for a given equilibrium.
- The mode amplitude is determined by fitting the density fluctuation level with result given by reflectometry diagnostics.

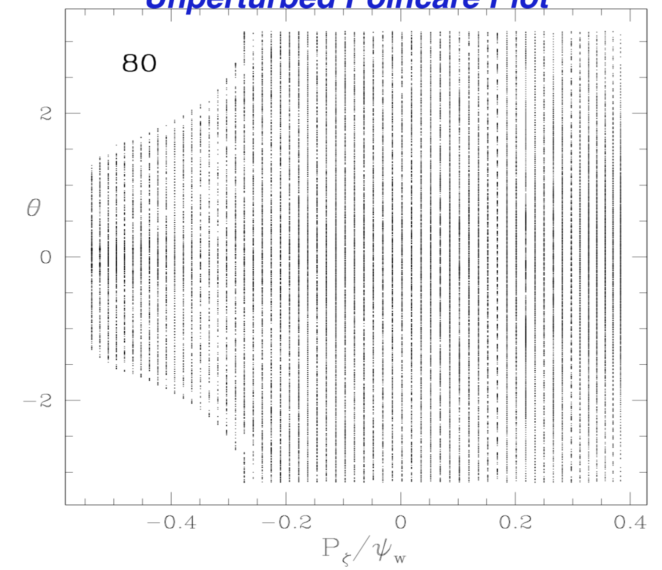
Methods -- ORBIT

- ORBIT is a single particle guiding-center motion solver based on Hamiltonian formalism.
- Boozer Coordinates are used, and the evolution of particle's guiding-center position (ζ,θ,ψ) and "parallel gyro radius"($\rho_{\|} \equiv \frac{v_{\|}}{B}$) is obtained by integrating the equations of motion numerically.
- Perturbations are set to have the form of $\delta\vec{B} = \nabla\times\left(\alpha\vec{B}\right)$, where only the component on $\nabla\psi$ direction is considered important.
- Multiple particles can be treated independently, and various information can be obtained, e.g. kinetic Poincare plots, and resonance positions in phase space.

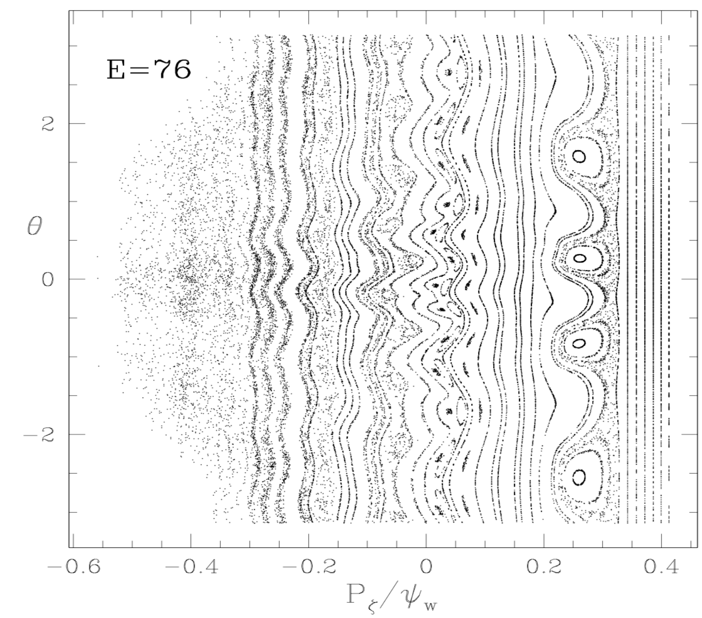
Methods – ORBIT (cont.)

- Kinetic Poincare plots are widely used to investigate the effect of perturbation on particle orbits. One can get a self-consistent plot only if particles are launched along a line in phase space on which $nE - \omega P_\zeta = const$, where n is the toroidal mode number and ω the corresponding mode frequency.

Unperturbed Poincare Plot

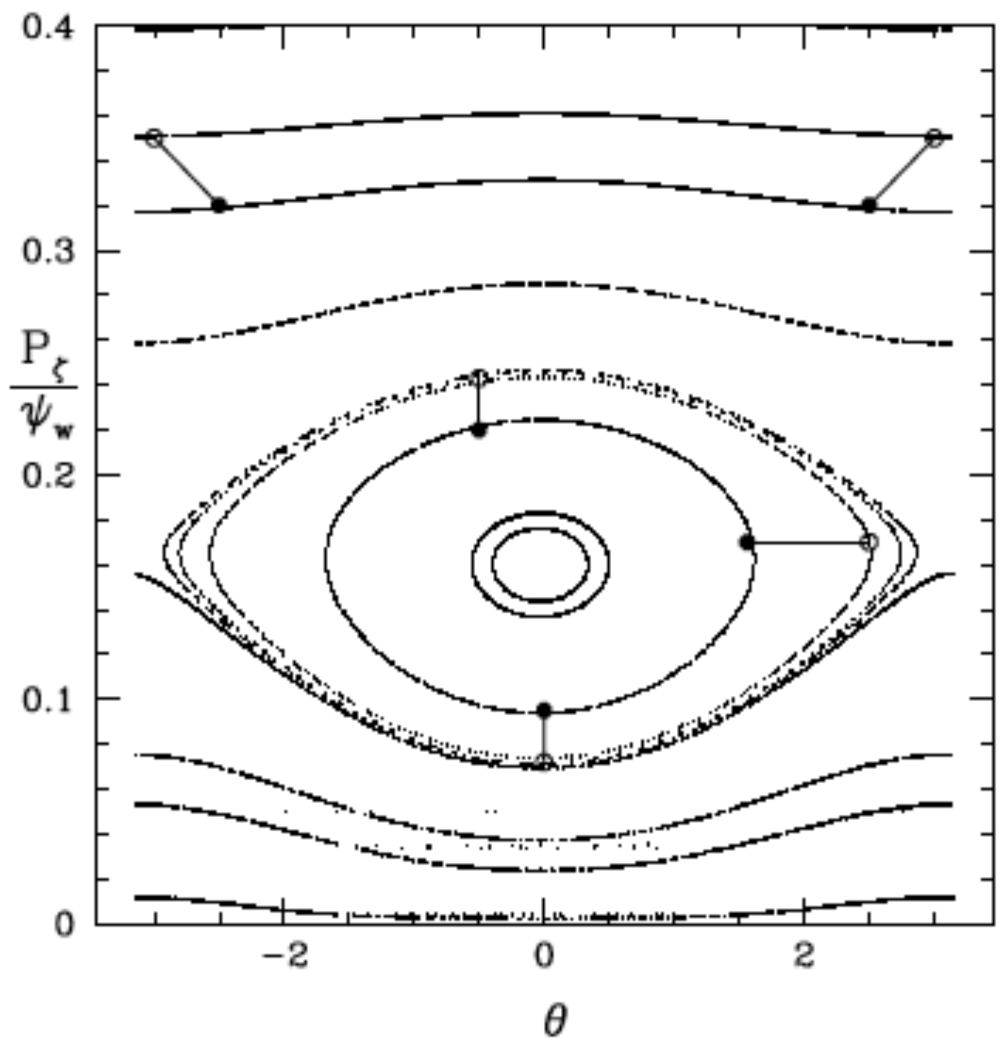


Perturbed Poincare Plot



Methods – ORBIT (cont.)

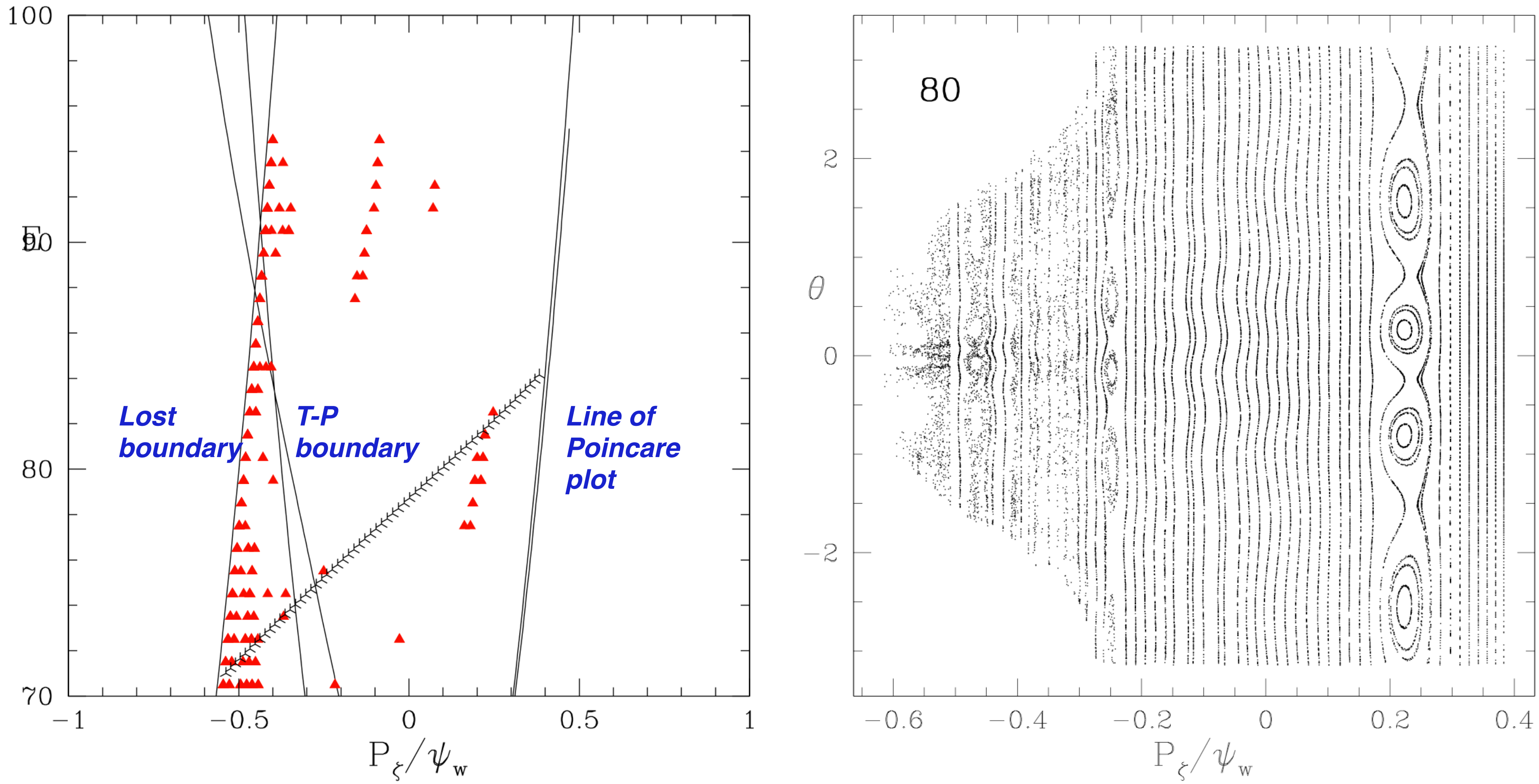
- Resonance positions in phase space can be determined by launching a pair of test particles and tracing the phase vector rotation. Particles on adjacent good KAM surfaces will keep their phase vector angle change less than π, while the phase vector angle between particles located in resonant islands can change 2π.



Results -- Amplitudes

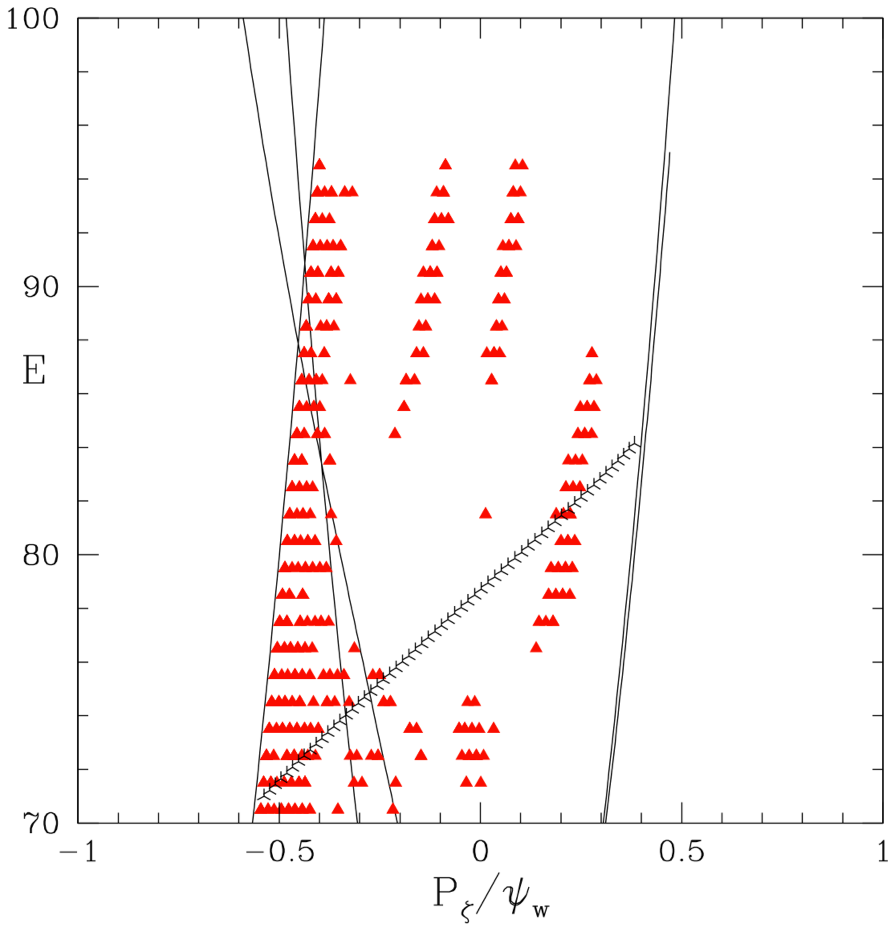
- As the mode amplitudes are varied, how does the size of the apparent stochastic region change?

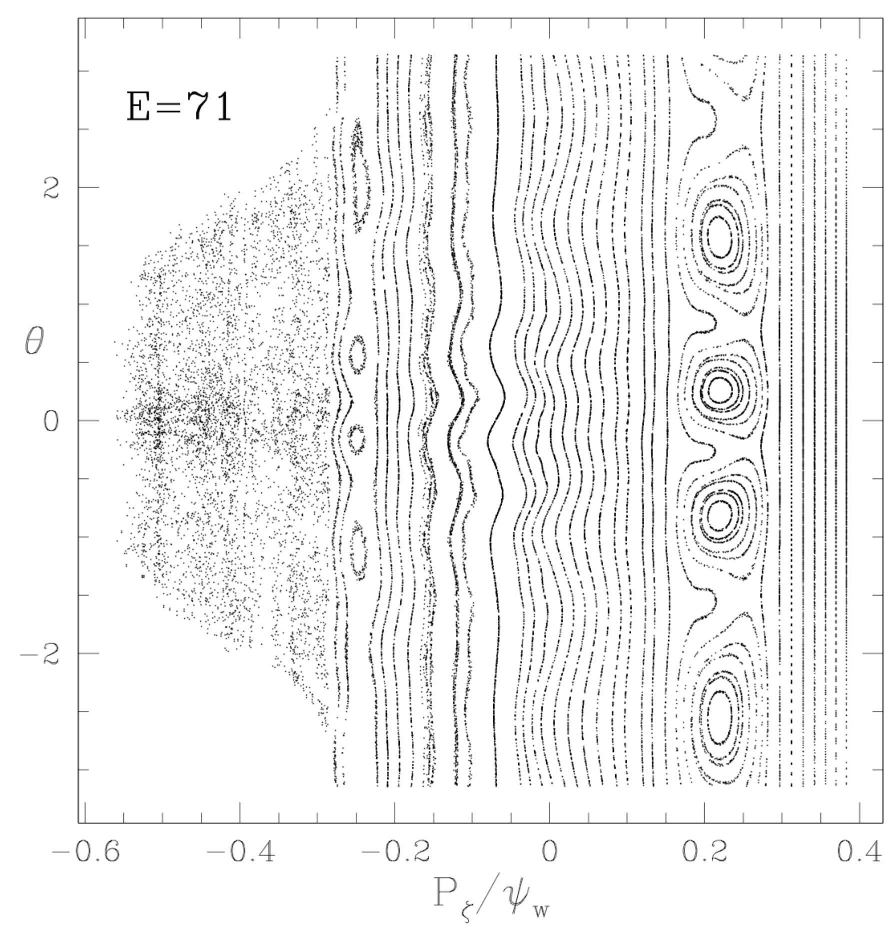
Amplitude ~ 0.2



Results – Amplitude (cont.)

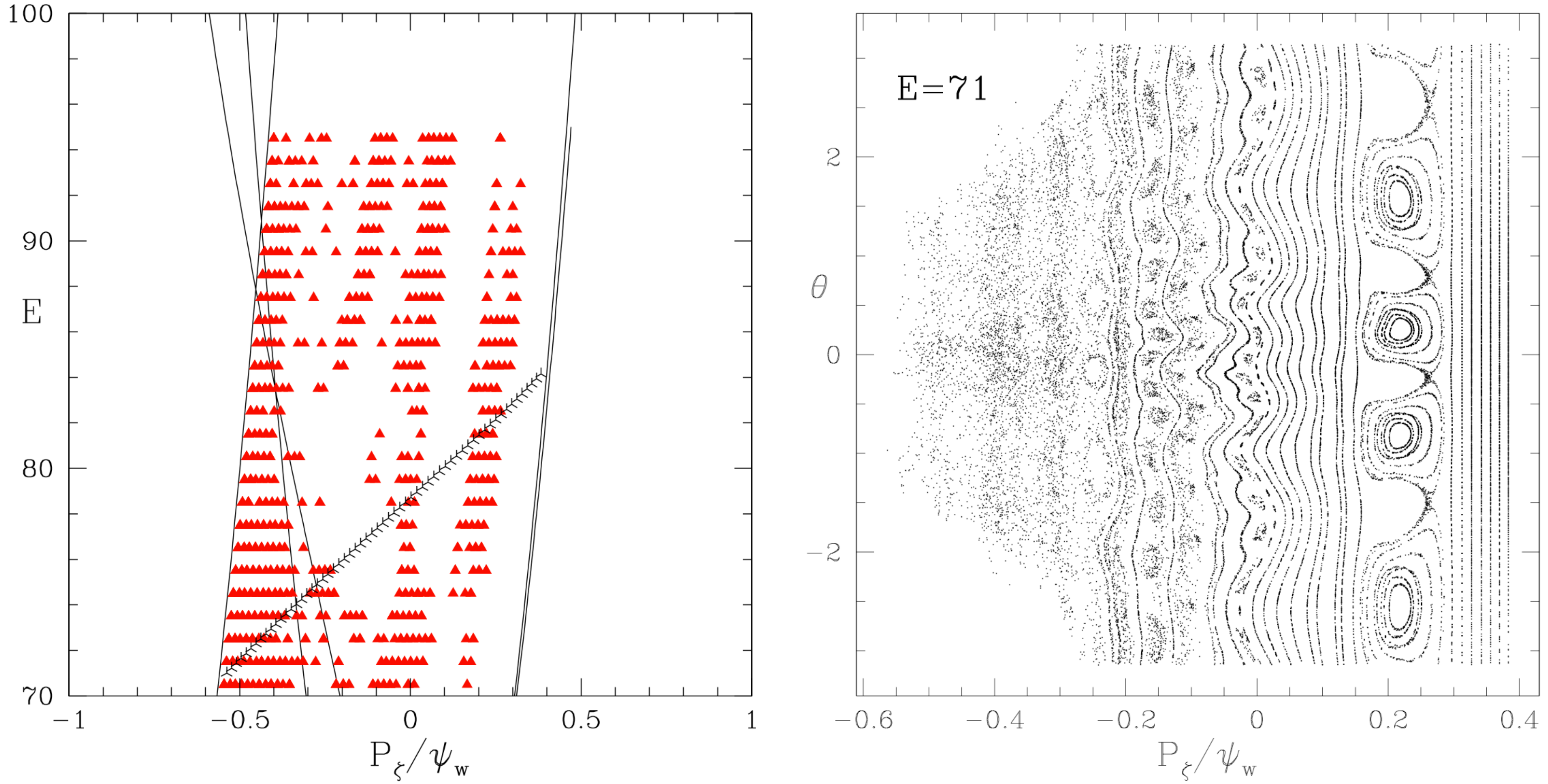
Amplitude ~ 0.5





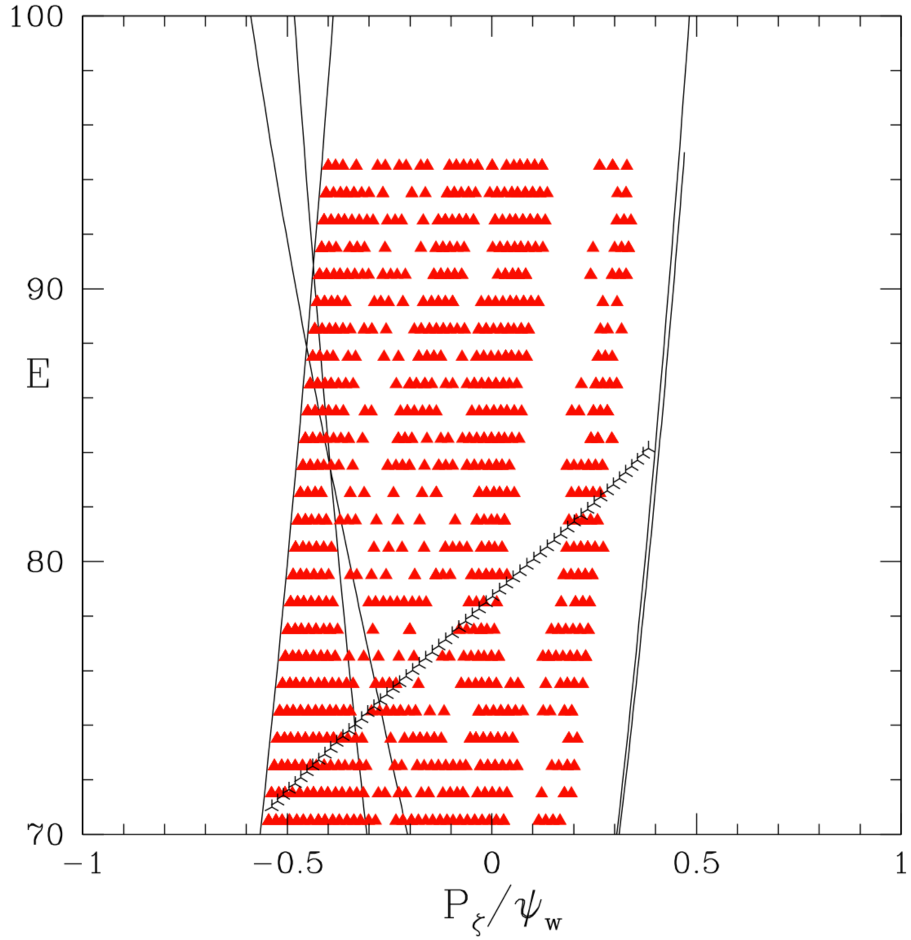
Results – Amplitude (cont.)

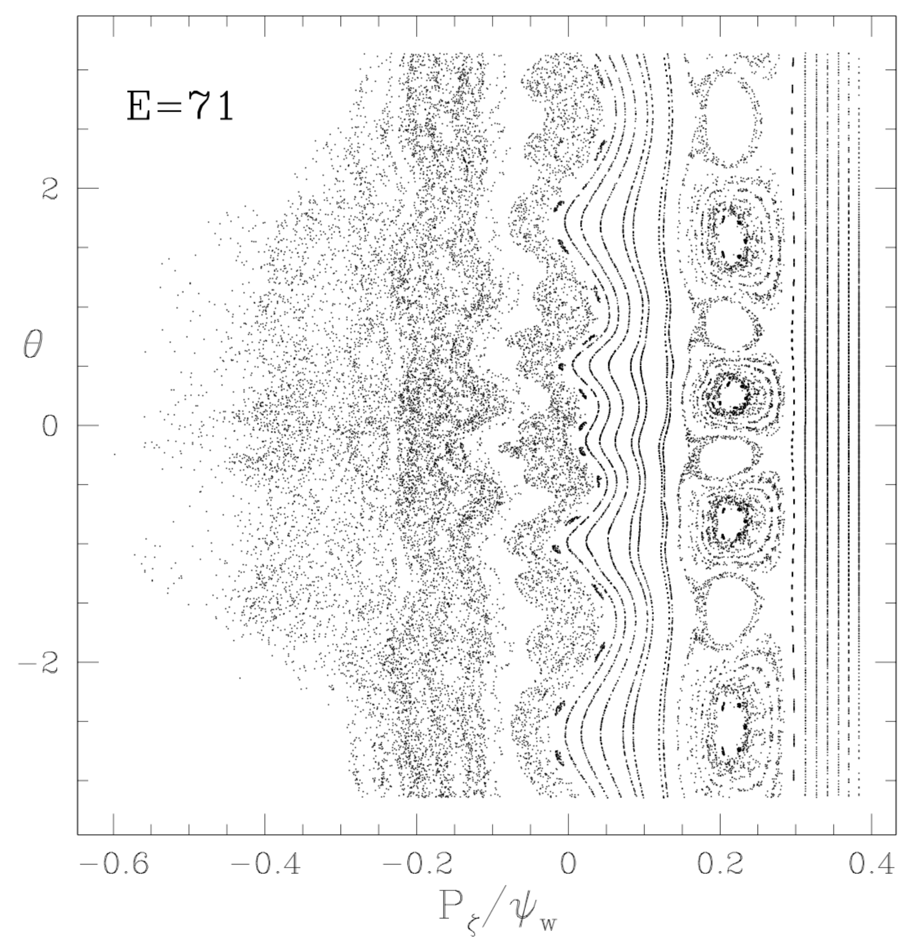
Amplitude ~ 1.0



Results – Amplitude (cont.)

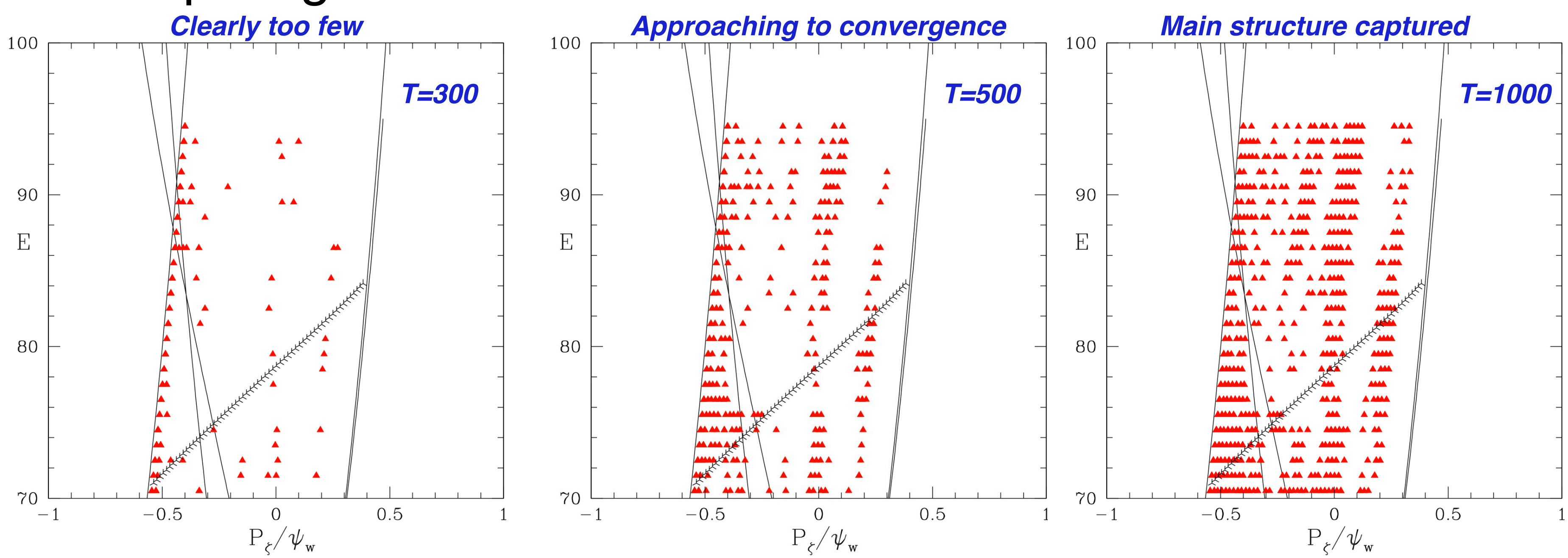
Amplitude ~ 1.5





Results – Stochastic Domain Vs. Number of Transits

- Plots below show the resonance spots calculated for different numbers of toroidal transits. It's clear that most of them appear after a certain time. Longer run may not be necessary since most of the resonant characteristics are captured. Choosing the time wisely may save a lot of computing effort.

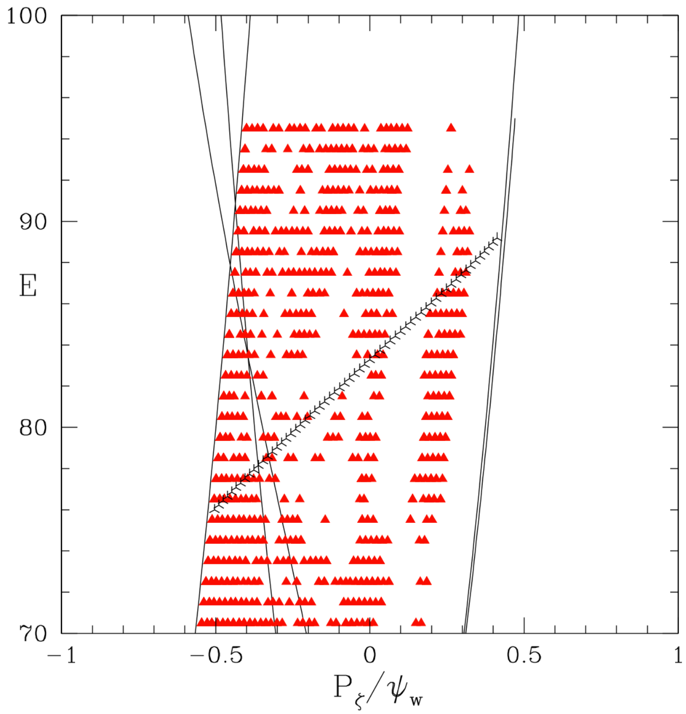


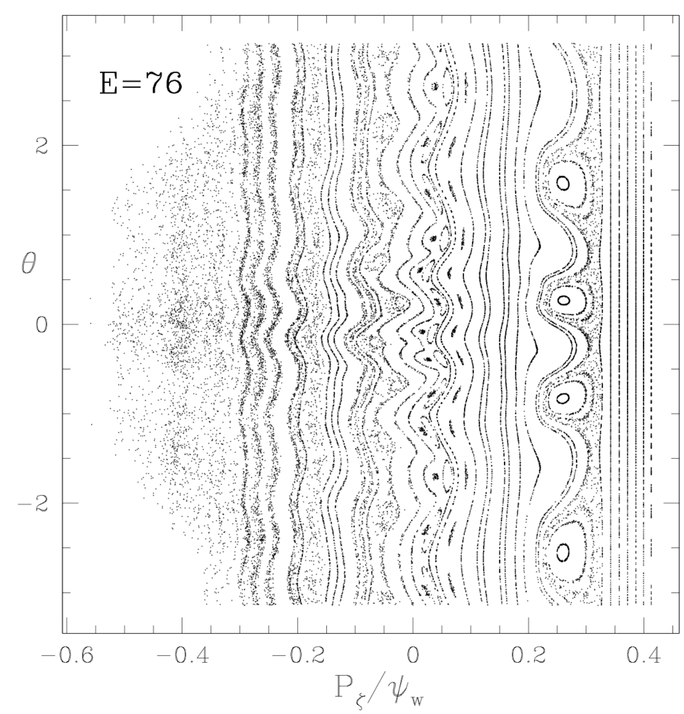
Amplitude ~ 1.5

Results – Test Pair Spacing

- The space between the test pair of particles may affect the result significantly. Choosing the space too small will make the result very sensitive to tiny structures which may be irrelevant to the problems we are interested in. On the other hand, a large space may result in losing information that is important.

Good Choice : ΔP_ζ=2e-3



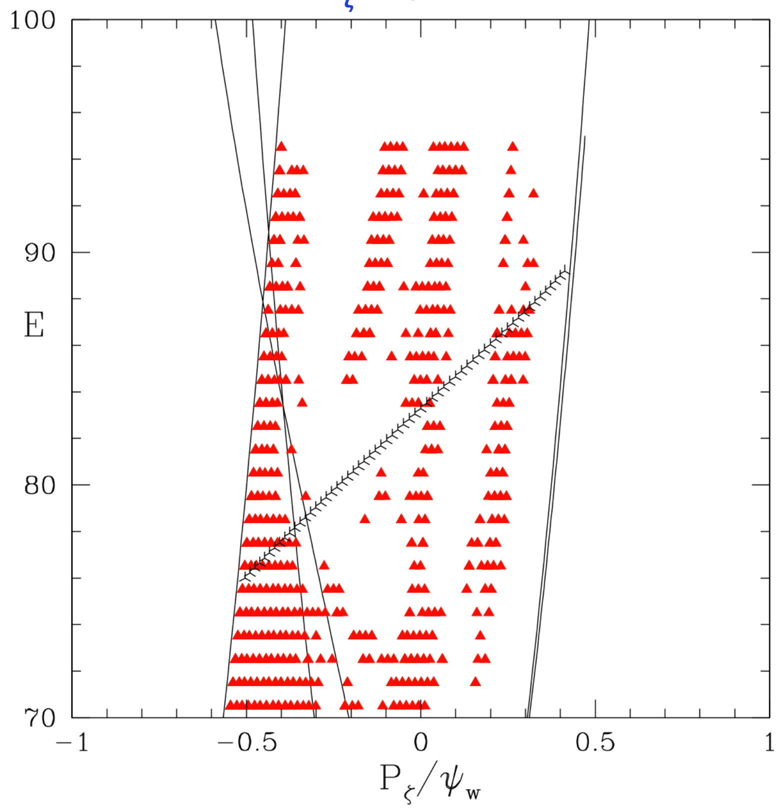


Results – Test Pair Spacing

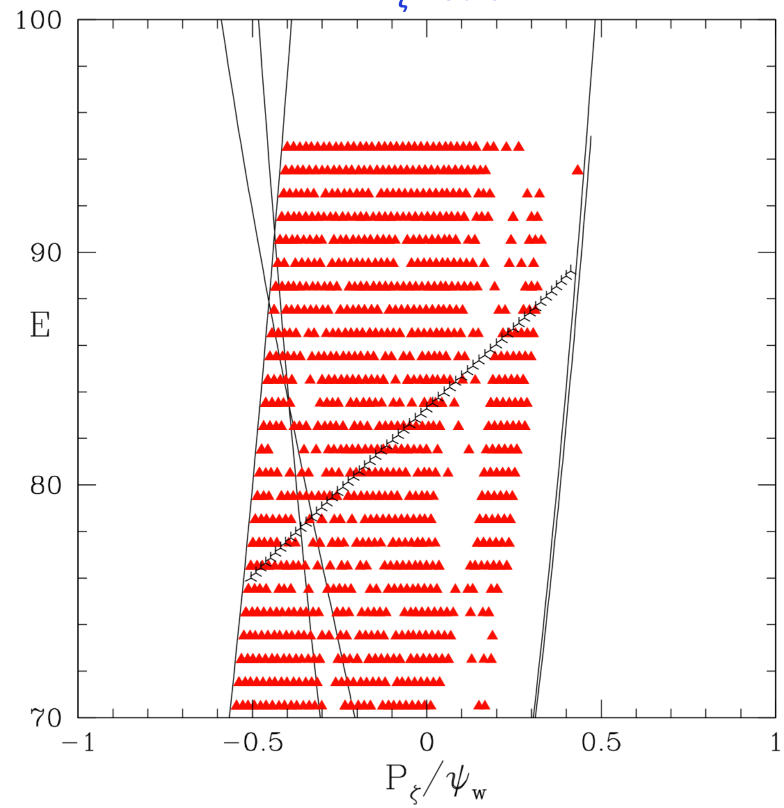
Space too big, missing islands between -0.4 ~ 0

Space too small, capturing tiny structures, red spot every where

ΔP_ζ = 1e-2



ΔP_ζ = 5e-5



Discussion

- More comprehensive view of resonance in phase space
- Faster than Poincare plot.
- Combining with initial particle deposition data, can predict the lost particle distribution qualitatively.
- Mode amplitude fixed.

Future Work

- Mode amplitude and frequency evolution
- Non-linear effects
- Other kinds of modes
- Means to determine the best parameters (number of transits, test pair spacing)