Modelling interaction of Runaway electrons with Whistler waves using KORC-AORSA model

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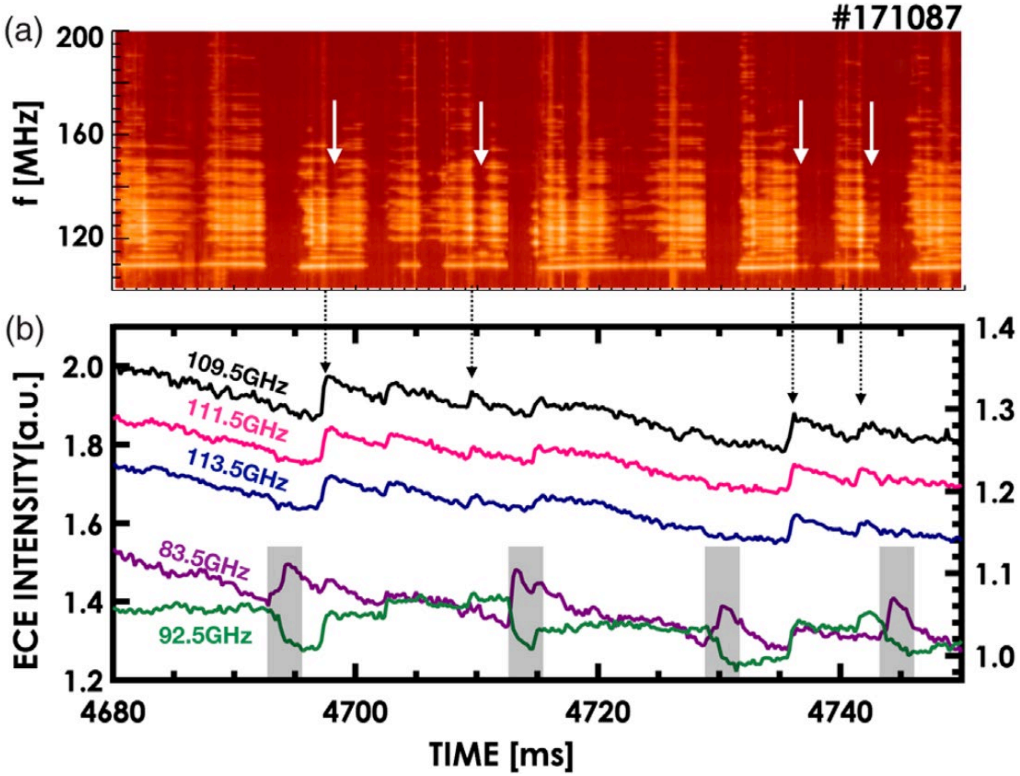
Interactions between runaway electrons and whistlers may lead to pitch angle scattering of runaways

2017 Frontier science experiments on DIII-D – to make connection between space and fusion plasmas.

  - subsequent experiments were performed in 2018/2019/2022.
  - Possibility to intentionally launch whistlers to dissipate RE beams in fusion devices

- Model whistler-REs interactions and study the underlying physical phenomena



D. Spong et al., "*First Direct Observation of Runaway-Electron-Driven Whistler Waves in Tokamak*", PRL, (2018)

Outline

- Resonant interactions between Whistlers and REs
- Previous modelling efforts
- AORSA+KORC model
- Simulation results
  - Evolution of RE distributions
  - Identifying resonant REs
- Summary

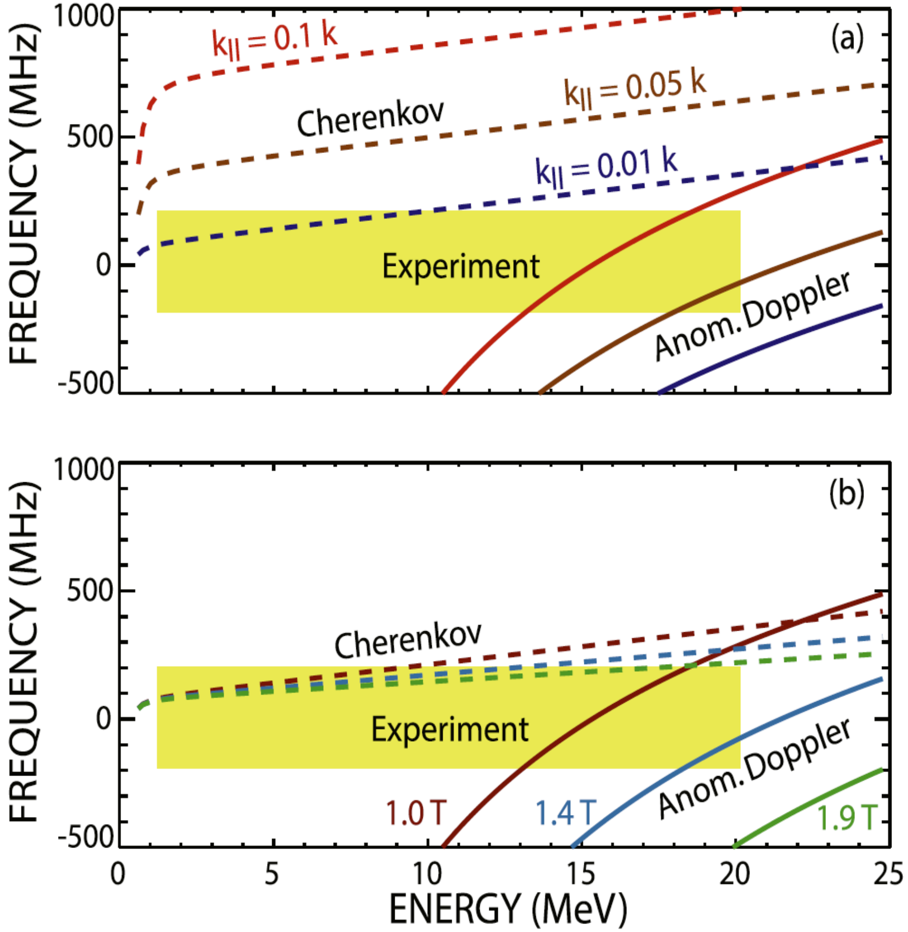
Possible resonant pathway is anomalous Doppler resonance and Cherenkov resonance

- Various pathways for interaction between REs and Whistler waves exist.
- In previous studies, resonance condition is given by[W. Heidbrink, 2019] :

~100 MHz Few GHz 10 MHz Few GHz

$$\omega - k_{\|}v_{\|} - k_{\perp}v_{d} - l\Omega_{ce}/\gamma = 0 \qquad \text{---(1)}$$

$l = -1$ for anomalous Doppler res
$l = 1$ for normal Doppler res
$l = 0$ for Cherenkov res



W. Heidbrink et al., PPCF, 61,014007 (2019)

Modelling efforts have been based on quasi-linear diffusion analysis

- T. Fülöp et al, (2006) studied REs driven magnetosonic whistler instabilities
  - quasi-linear analysis showed pitch angle scattering of REs due to whistlers
- Aleynikov and Breizman [2015] performed stability analysis of RE driven Whistler instabilities using a ray tracing code- COIN.
- C. Liu et al. [2018] studied the effects of kinetic whistler wave instabilities on the runaway electron avalanche
  - quasilinear diffusion model with GHz range whistler frequencies
  - Studied the role of kinetic instabilities leading to anisotropic RE distribution producing non-thermal ECE
- Z. Guo et al., [2018] used quasi-linear diffusion analysis to study role of externally injected whistlers on REs

We model interactions between tokamak whistler waves and REs by coupling AORSA fields with KORC

AORSA

Whistler Wave fields calculated from warm plasma full wave solver

KORC

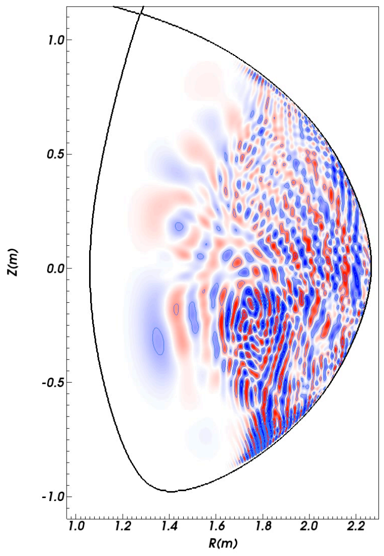
Full orbit tracer particle code evolves RE trajectories the presence of wave fields from AORSA

Whistler waves - Runaway electrons interactions

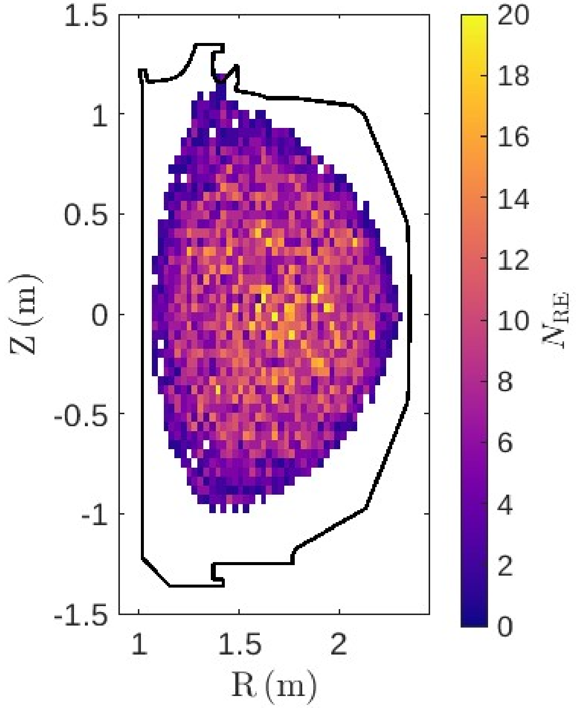
Ref. [1] D. A. Spong et al, PRL (2019); [2] W. Heidbrink et al., PPCF, 61,014007 (2019).
[3] M. T. Beidler et al., Phys. Plasmas, 27,112507 (2020).

Identifying underlying physical phenomena for pitch angle scattering of REs due to whistlers is not straightforward

AORSA



KORC

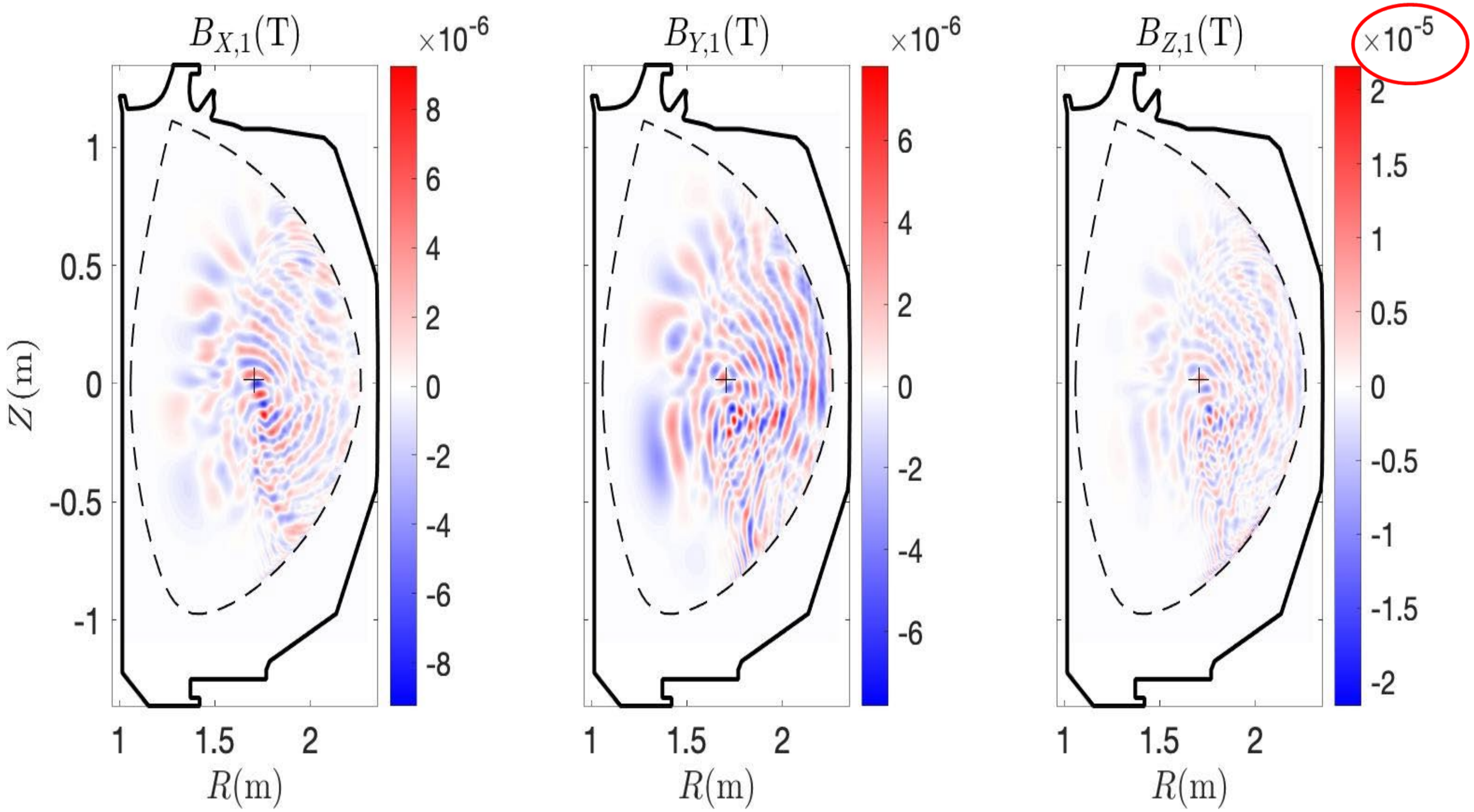


#REs=10240

$$\omega - k_{||}\mathrm{v}_{||} - k_{\perp}\mathrm{v}_{d} - l\,\Omega_{ce}/\gamma = 0$$

- Resonance condition not simple anymore: several poloidal modes coupled
- AORSA+KORC model simulates the complex resonant interactions between Whistler waves and runaway electrons
- **We used statistical analysis as a tool to identify the nature of these interactions**

Whistler wave eigenmodes from AORSA with 200MHz frequency along with EFIT equilibrium from DIII-D experiments are used to evolve RE trajectories in KORC

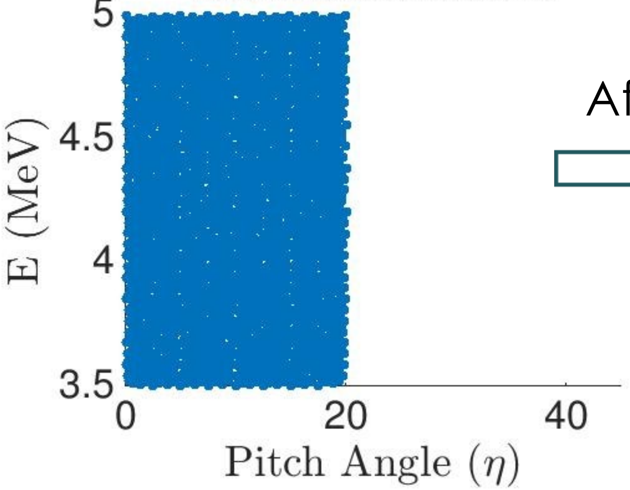


Whistler wave amplitude

Challenge-Whistler wave amplitudes not measured in experiments

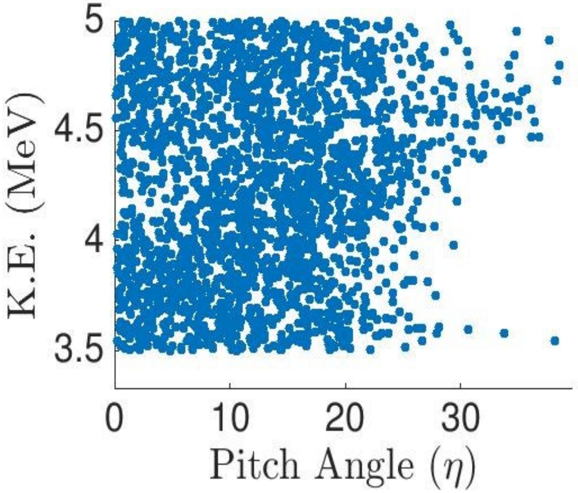
Variation in phase-space (E-η) distribution of REs is substantial with scaled whistler fields

Initial distribution

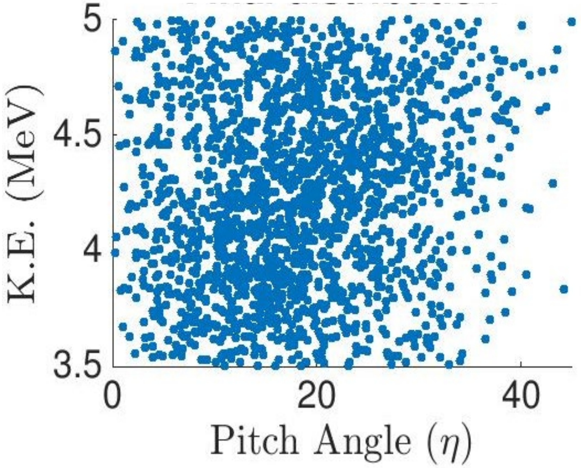


After 0.8 ms

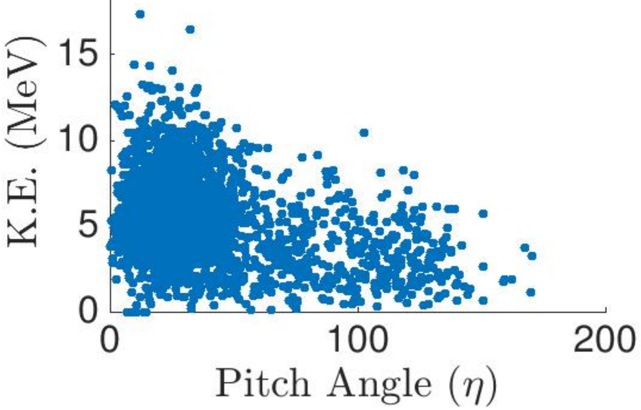
$\delta B_{max}/B \approx 10^{-5}$
$\delta E_{max}/cB \approx 10^{-6}$



$\delta B_{max}/B \approx 10^{-4}$
$\delta E_{max}/cB \approx 10^{-5}$



$\delta B_{max}/B \approx 10^{-3}$
$\delta E_{max}/cB \approx 10^{-4}$



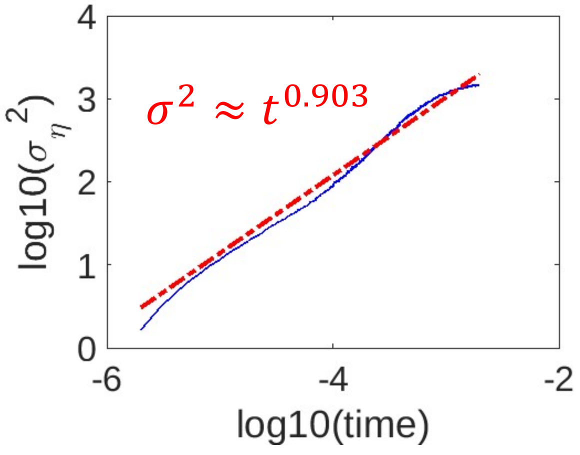
Pitch angle scattering of REs to large angles and gain in KE becomes evident

To study nature of RE transport, moments of total pitch angle displacements after 2ms and their scaling with time is calculated

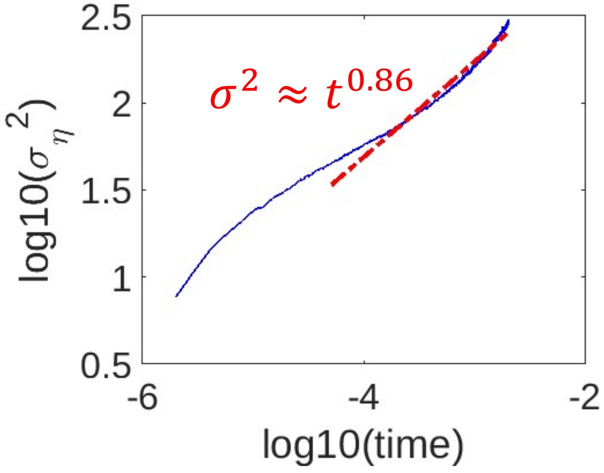
$\sigma_\eta^2 =< [\delta\eta_i - < \delta\eta_i >]^\wedge 2 >$
Here, $\delta\eta_i = \eta_i - \eta_0$

We identified the scaling of $\sigma_\eta^2 \sim t^\alpha$

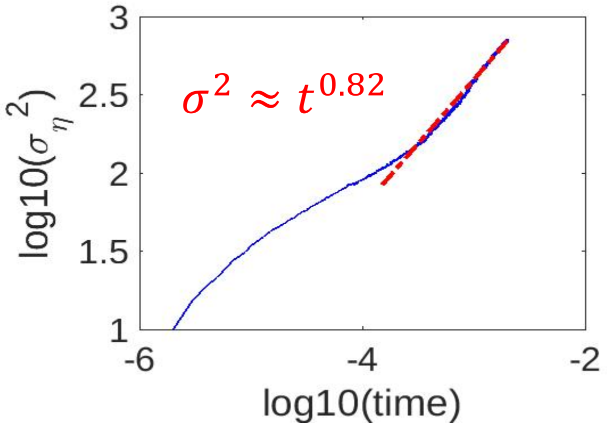
- If $\alpha > 1$: Super-diffusion
- If $\alpha = 1$: Diffusion
- If $\alpha < 1$: Sub-diffusion



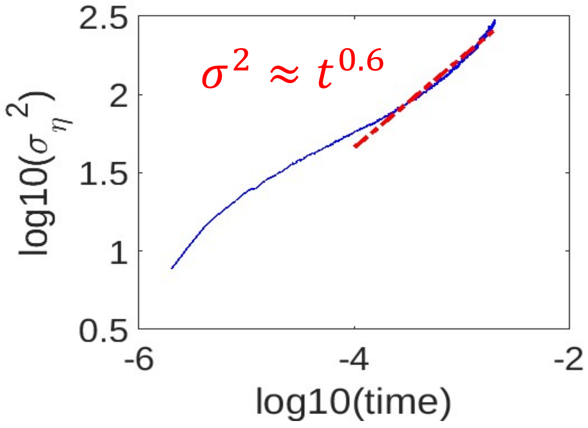
$E_{\_\text{initial}}$ 1-5MeV



$E_{\_\text{initial}}$ 5-10MeV



$E_{\_\text{initial}}$=10-15MeV



$E_{\_\text{initial}}$=15-20MeV

Ref: D. del-Castillo-Negrete et al., POP, 11, 3854 (2004)

To study nature of RE transport, moments of total pitch angle displacements after 2ms and their scaling with time is calculated

$\sigma_\eta^2 =< [\delta\eta_i - < \delta\eta_i >]^\wedge 2 >$

Here, $\delta\eta_i = \eta_i - \eta_0$

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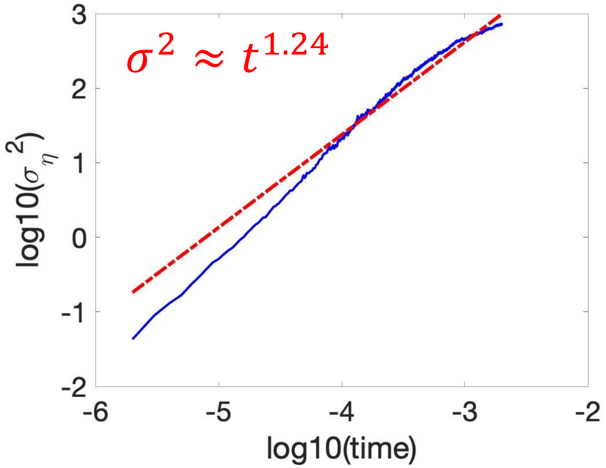
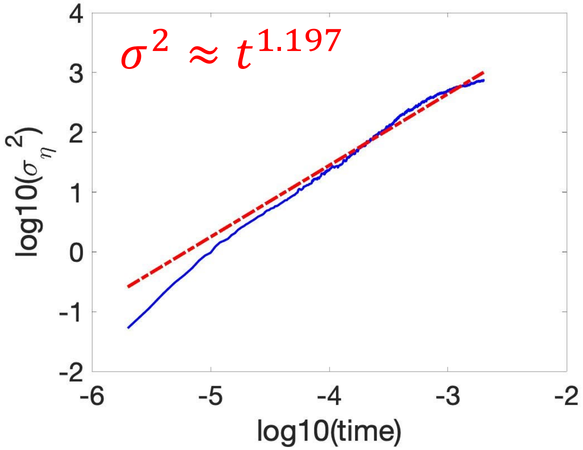
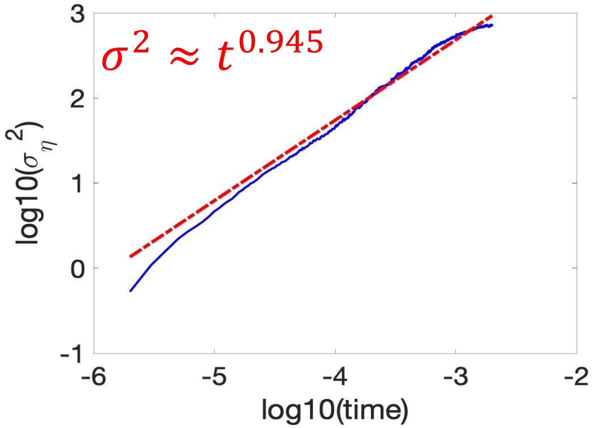


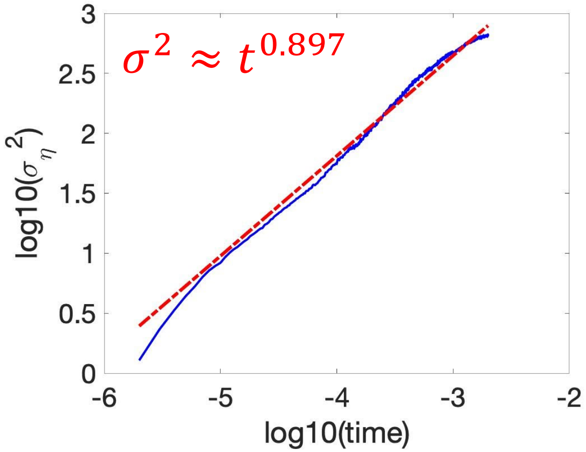
$E_{\_initial}$=1-2MeV



$E_{\_initial}$=2-3MeV



$E_{\_initial}$=3-4MeV



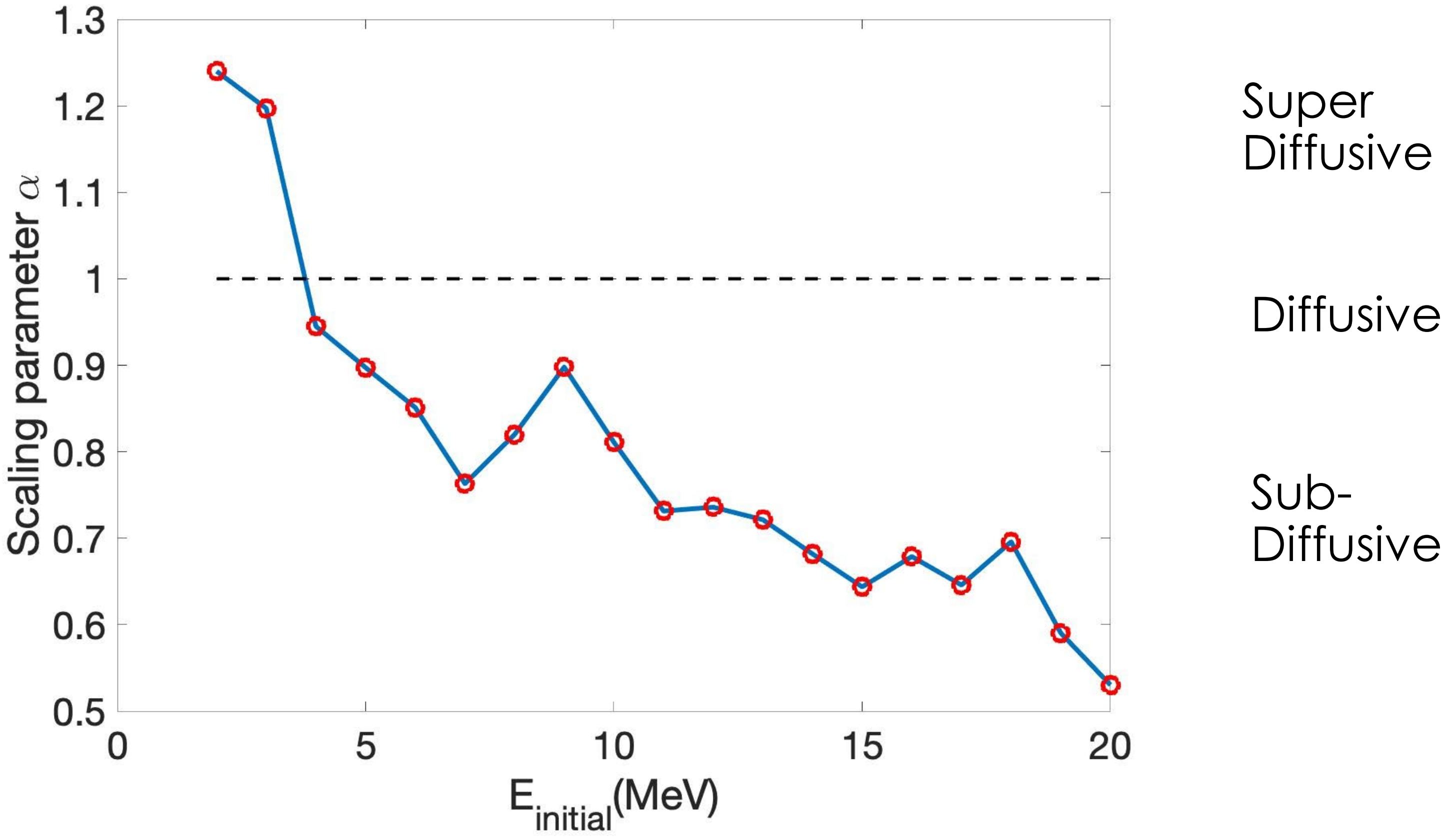
$E_{\_initial}$=4-5MeV

Net Pitch angle diffusion is a function of initial energies

$\sigma_\eta^2 =< [\delta\eta_i - < \delta\eta_i >]\hat{}2 >$
Here, $\delta\eta_i = \eta_i - \eta_0$

We identified the scaling of $\sigma_\eta^2 \sim t^\alpha$

- If $\alpha > 1$: Super-diffusion
- If $\alpha = 1$: Diffusion
- If $\alpha < 1$: Sub-diffusion

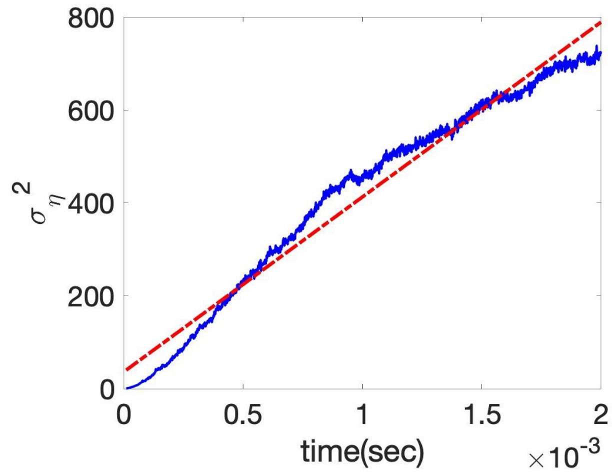


We calculated the diffusivity of net pitch angle displacements for narrow ranges of energies from the slope of variance-time curve

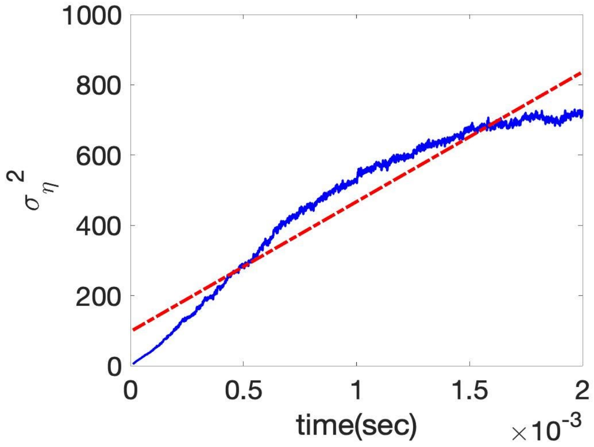
Assuming the pitch angle scattering to be a diffusive phenomena ($\alpha = 1$), we aim to identify the parameter "D" known as diffusivity given by the equation:

$$\sigma_\eta^2 = D * t ;$$

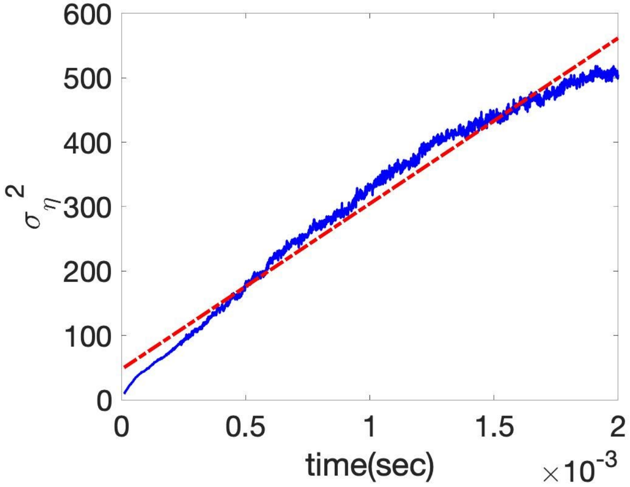
For different ranges of REs energy.



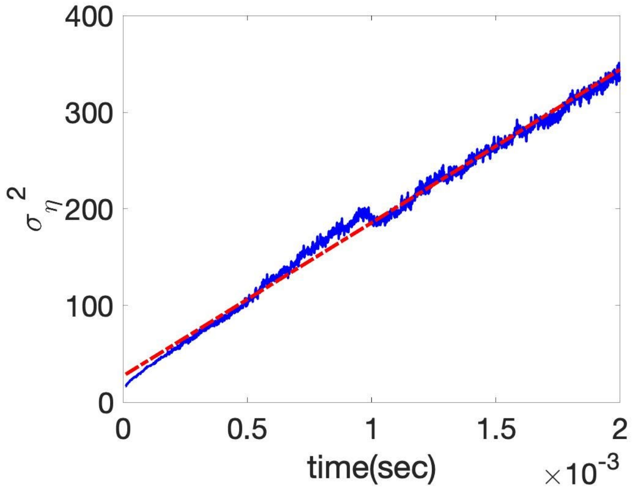
E_initial=1-2MeV



E_initial=3-4MeV



E_initial=7-8MeV



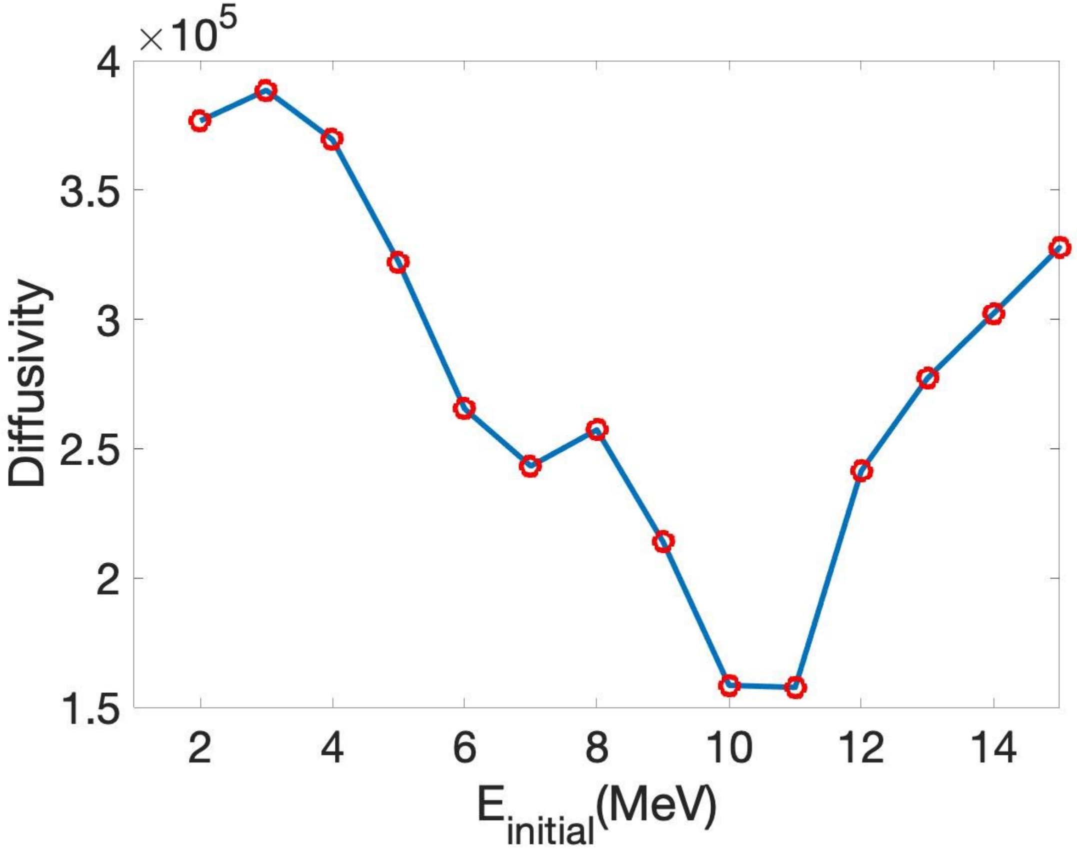
E_initial=9-10MeV

Diffusivity coefficient is also a function of initial energies of REs

Assuming the pitch angle scattering to be a diffusive phenomena ($\alpha = 1$), we aim to identify the parameter "D" known as diffusivity given by the equation:

$$\sigma_\eta^2 = D * t \;;$$

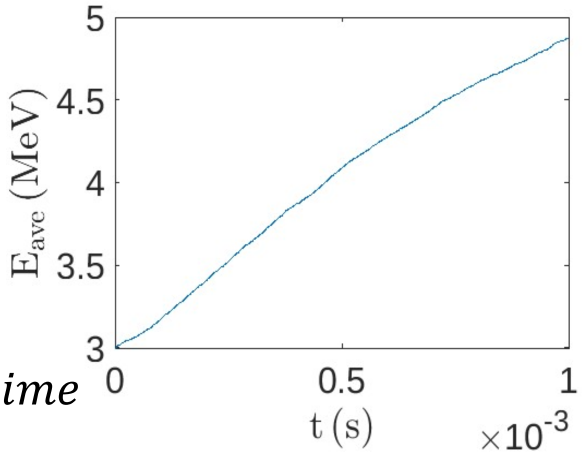
For different ranges of REs energy.



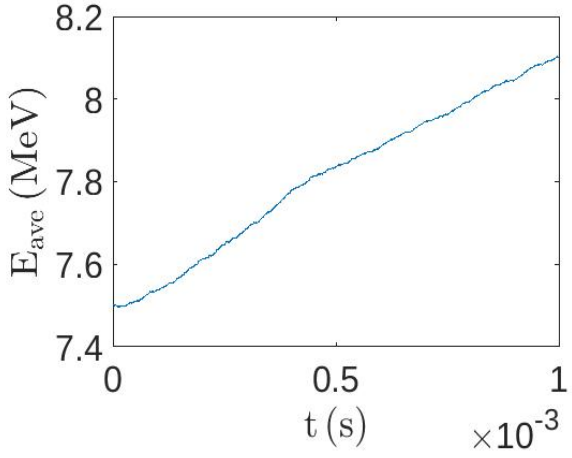
Evolution of ensemble averaged RE energy with time indicates a dependence of energy gain on initial energy of REs

$$E_{avg} = \frac{\sum E_i}{N_{active}}$$

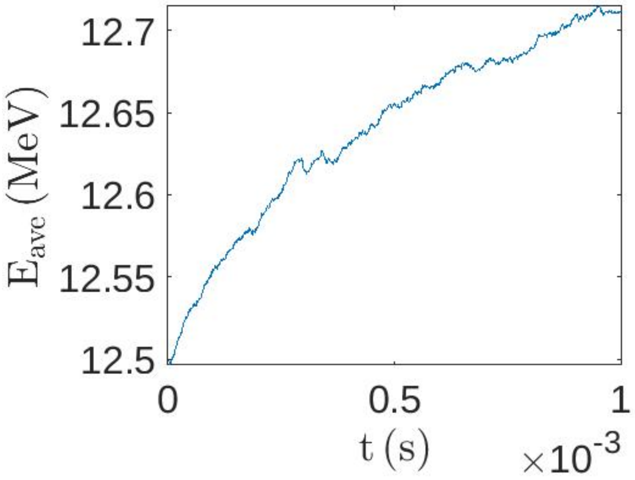
$where\ i{\sim}10240\ \#particles\ at\ every\ time$



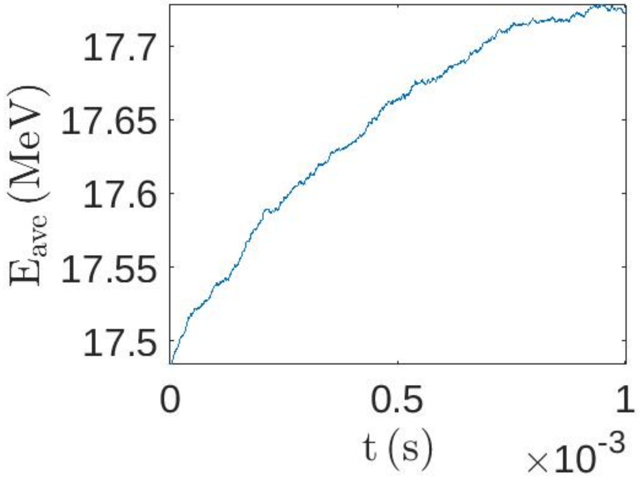
$E_{\_initial}$=1-5MeV



$E_{\_initial}$=5-10MeV



$E_{\_initial}$=10-15 MeV



$E_{\_initial}$=15-20 MeV

Does pitch angle scattering and energy gained by REs also depend instantaneous energy of REs?

- We will now perform statistical analysis of the **kicks** to REs pitch angle and kinetic energy at for instantaneous energy of REs

- Variance in pitch angle kicks:

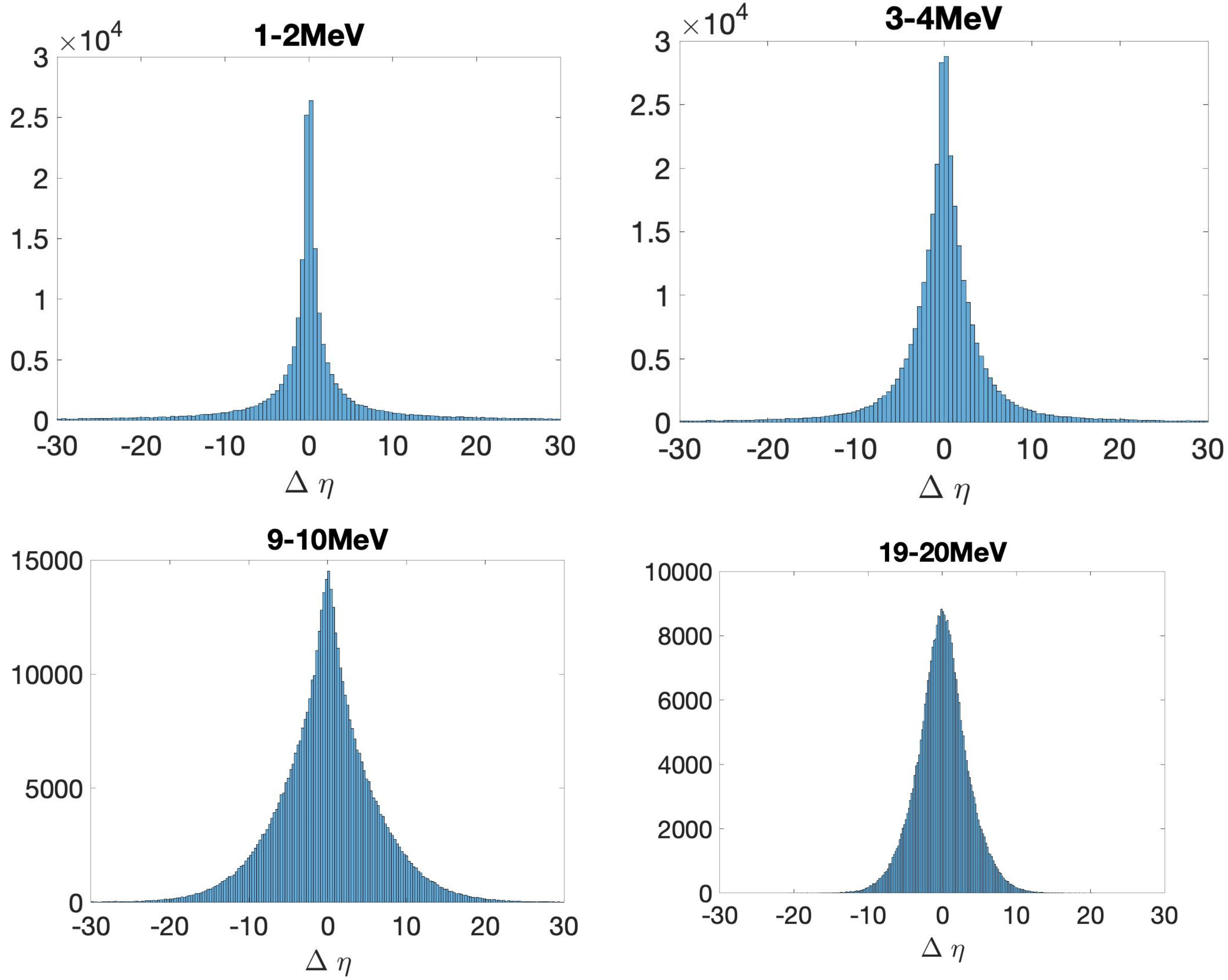
$$\sigma_{\eta}^2 =< [\Delta\eta_i -< \Delta\eta_i >]\hat{}2 >$$

Here, $\Delta\eta_i = \eta_i - \eta_{i-1}$

- Variance in kinetic energy kicks:

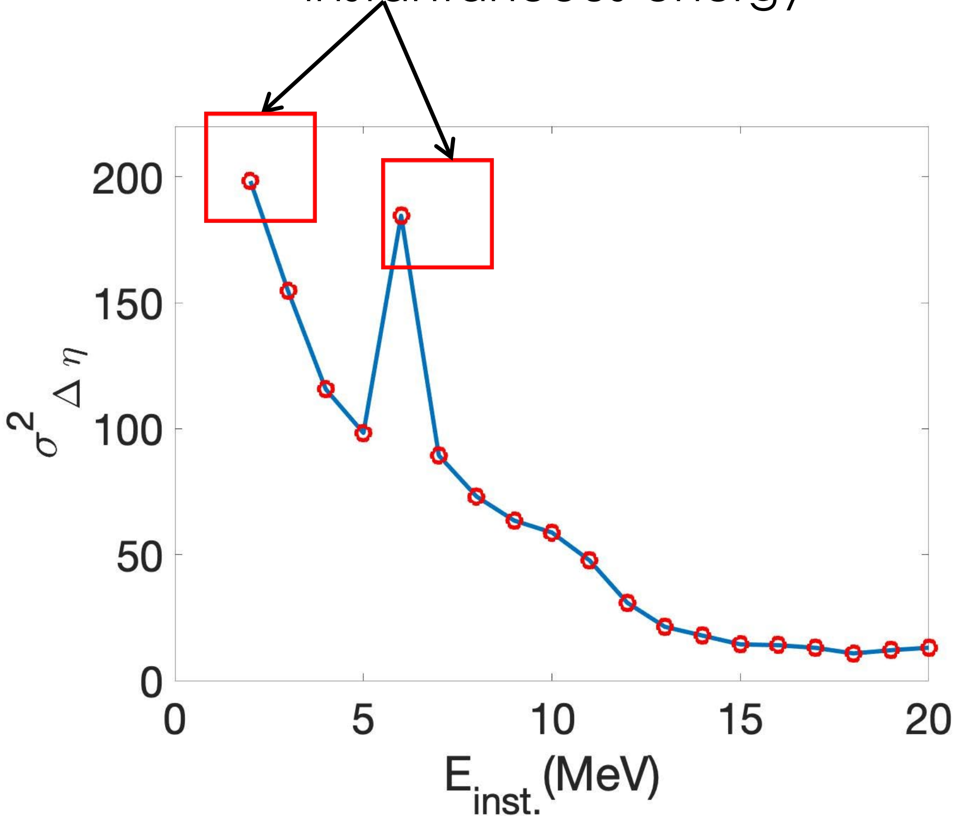
$$\sigma_{KE}^2 =< [\Delta KE_i -< \Delta KE_i >]\hat{}2 >$$

Here, $\Delta KE_i = KE_i - KE_{i-1}$

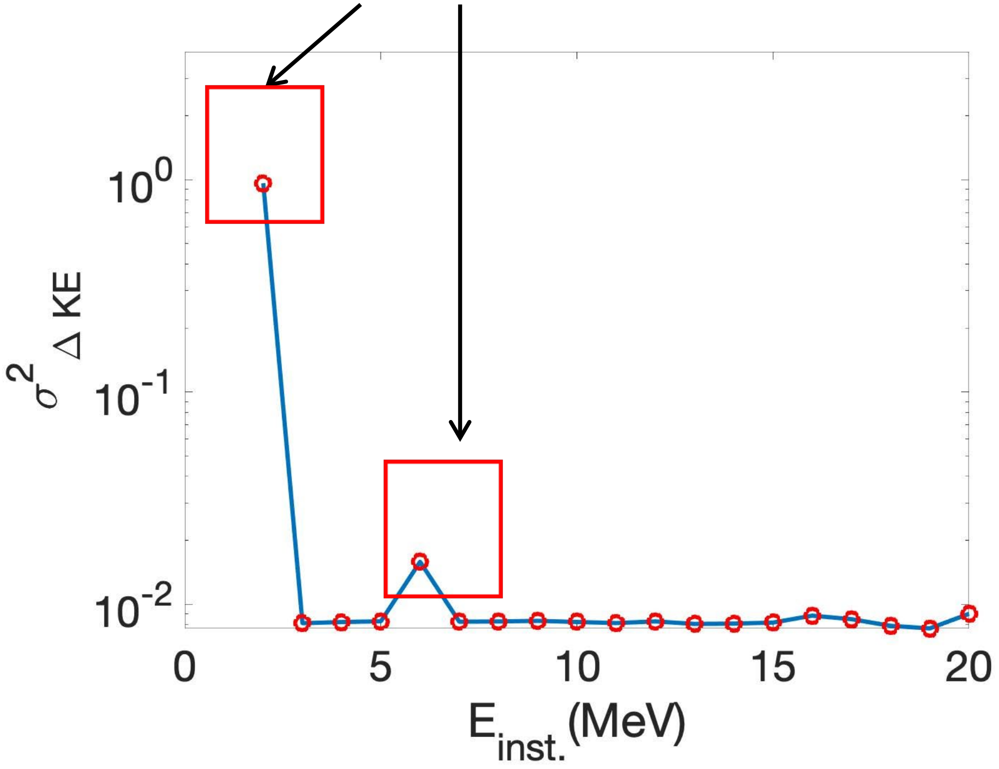


Variation of instantaneous pitch angle displacement indicate resonant interactions between Whistlers and REs at 2MeV and 6 MeV energies

Peak in the variance of pitch angle kicks w.r.t instantaneous energy



Peak in the variance of kinetic energy gain w.r.t instantaneous energy



Summary

- KORC+AORSA model provides a unique capability to predict and model these interactions for a range of frequencies of interest (100s of MHz in the DIII-D experiments).
- Via statistical analysis, RE displacements are observed to be a function of instantaneous energies of REs.
- Peaks in variance of instantaneous pitch angle displacements with energies indicate possible resonances between REs and whistlers between 1-2 MeV and 5-6 MeV energies for whistler frequency of 200MHz.

Future work: Calculate the resonant energies for different whistler frequencies

- Further analysis to explore effectiveness of synchrotron radiation as a possible mechanism to dissipate RE energy during disruptions in tokamaks.