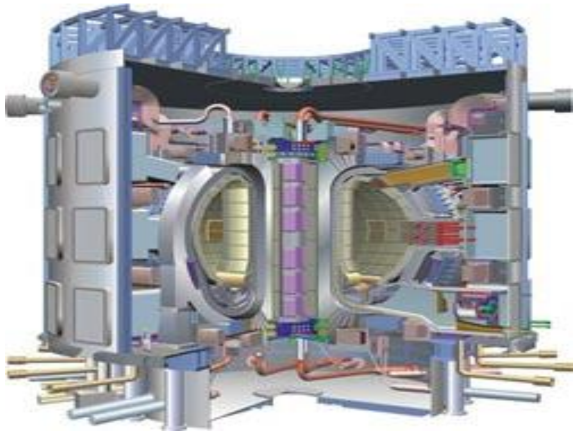

An ITPA joint experiment to study threshold conditions for runaway electron generation and suppression

R. Granetz, A. DuBois, B. Esposito, J. Kim, R. Koslowski, M. Lehnen,
J. Martin-Solis ,C. Paz-Soldan, T.-N. Rhee, P. de Vries, J. Wesley, and L. Zeng

IAEA FEC 2014
St. Petersburg, Russia
2014/10/16

Critical *E*-field for runaway electrons

High electric fields, such as those that occur during disruptions, can accelerate electrons to relativistic energies.

In tokamak plasmas, several energy loss mechanisms exist that can oppose this acceleration.

- one of these is Coulomb collisional drag

Considering ONLY Coulomb collisional drag, and using a fully relativistic derivation, there is a minimum *E*-field required to generate *and* sustain any runaways:

$$E_{\text{crit}} = \frac{n_e e^3 \ln \Lambda}{4\pi\varepsilon_0^2 m_e c^2}$$

J.W. Connor and R.J. Hastie, Nucl.Fusion 15 (1975) 415

This E_{crit} criterion applies to *both* primary (Dreicer) and secondary (avalanche) mechanisms.

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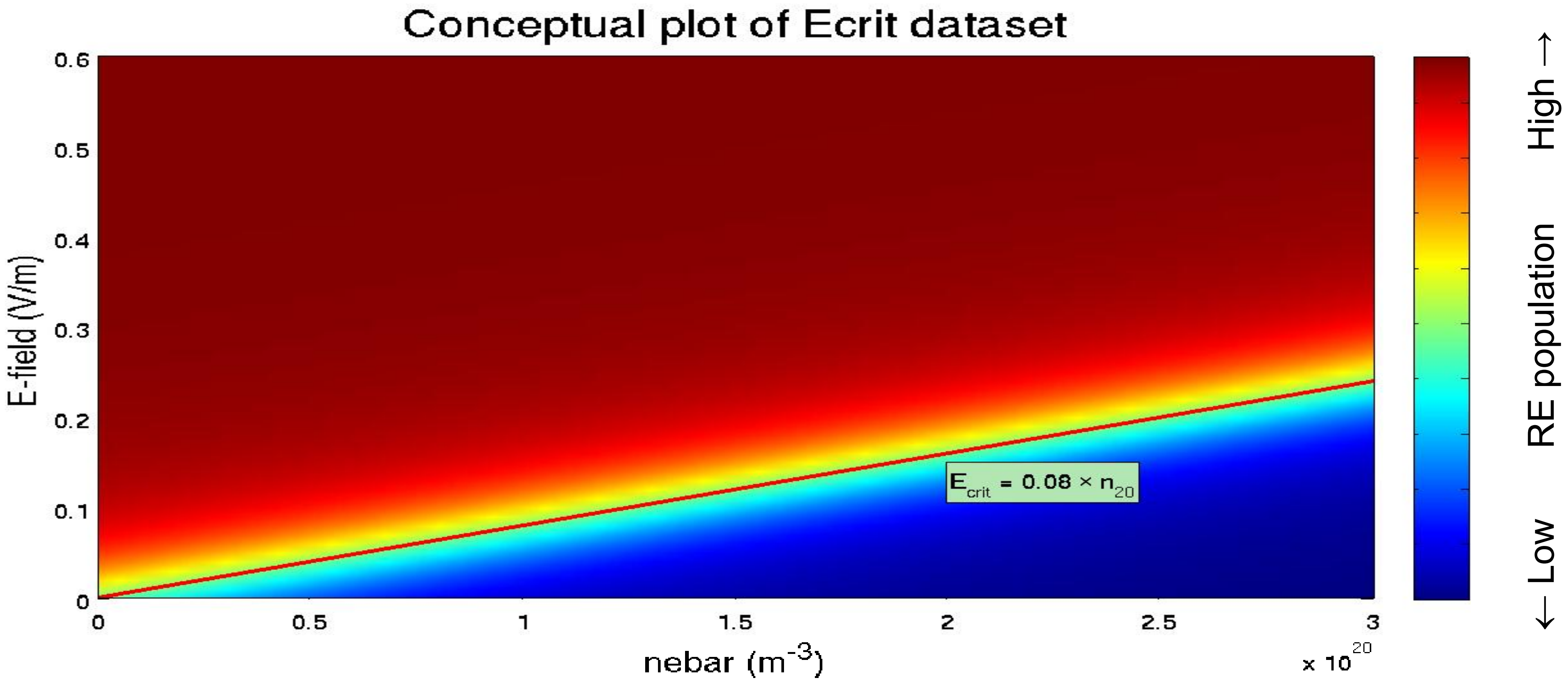
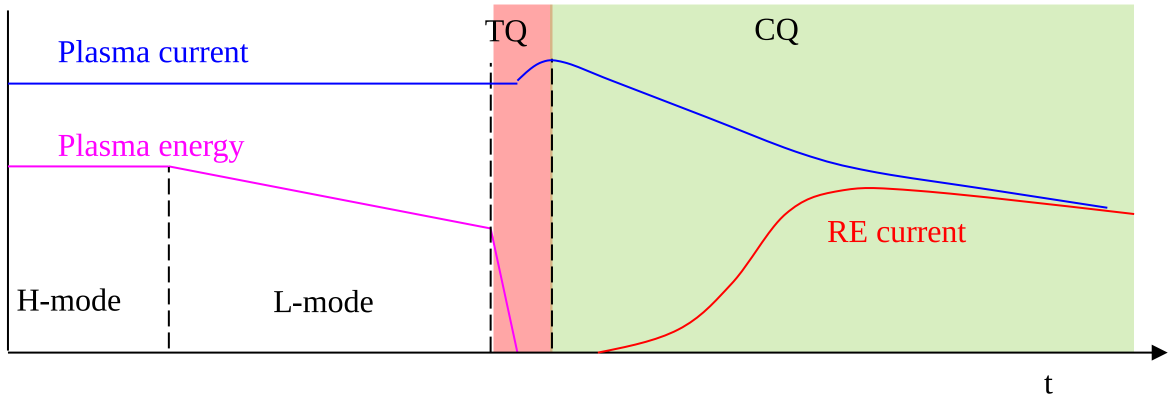
$$E_{\mathrm{crit}} = \frac{n_e e^3 \ln\Lambda}{4\pi\varepsilon_0^2 m_e c^2} = 0.08\, n_{20} \quad (\text{for } \ln\Lambda = 15)$$

This E_{crit} criterion applies to *both* primary (Dreicer) and secondary (avalanche) mechanisms.

Parameter space: runaway population vs E-field and density



Disruption runaways in ITER



$$V_{Loop} = -L_{plasma}\frac{dI_p}{dt}$$
$$= 5\,\mu\mathrm{H} \times (15\,\mathrm{MA}/50\,\mathrm{ms})$$
$$= 1500\ \mathrm{volts}$$
$$E_{//} = V_{Loop}/2\pi R = 38\ \mathrm{V/m}$$

Modeling of ITER 15 MA disruptions leads to predictions of up to 10 MA of current carried by runaways, with 10-20 MeV energies

- Potentially very damaging to blanket and divertor modules

Runaways need to be mitigated, collisionally or otherwise

- ***Collisional-only*** mitigation requires extremely high n_e :
  $E_{crit} = 0.08 n_e \quad \Rightarrow \quad n_e \geq 38/0.08 = 4-5 \times 10^{22}\ \mathrm{m}^{-3}$ (Rosenbluth density)
- Serious implications for tritium-handling plant, cryopumps, etc.
- Experiments in ASDEX-U and DIII-D have been unable to surpass 25% of the Rosenbluth density

Motivation for ITPA joint experiment

Do we really have to get to the Rosenbluth density to quench runaway electrons in ITER?

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- If yes, is it true for tokamaks in general?

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- If yes, is it true for tokamaks in general?

$\Downarrow$

Measure threshold E-field in well-controlled and well-diagnosed conditions on a number of tokamaks, and compare with E_{crit}

Constraints for ITPA joint experiment

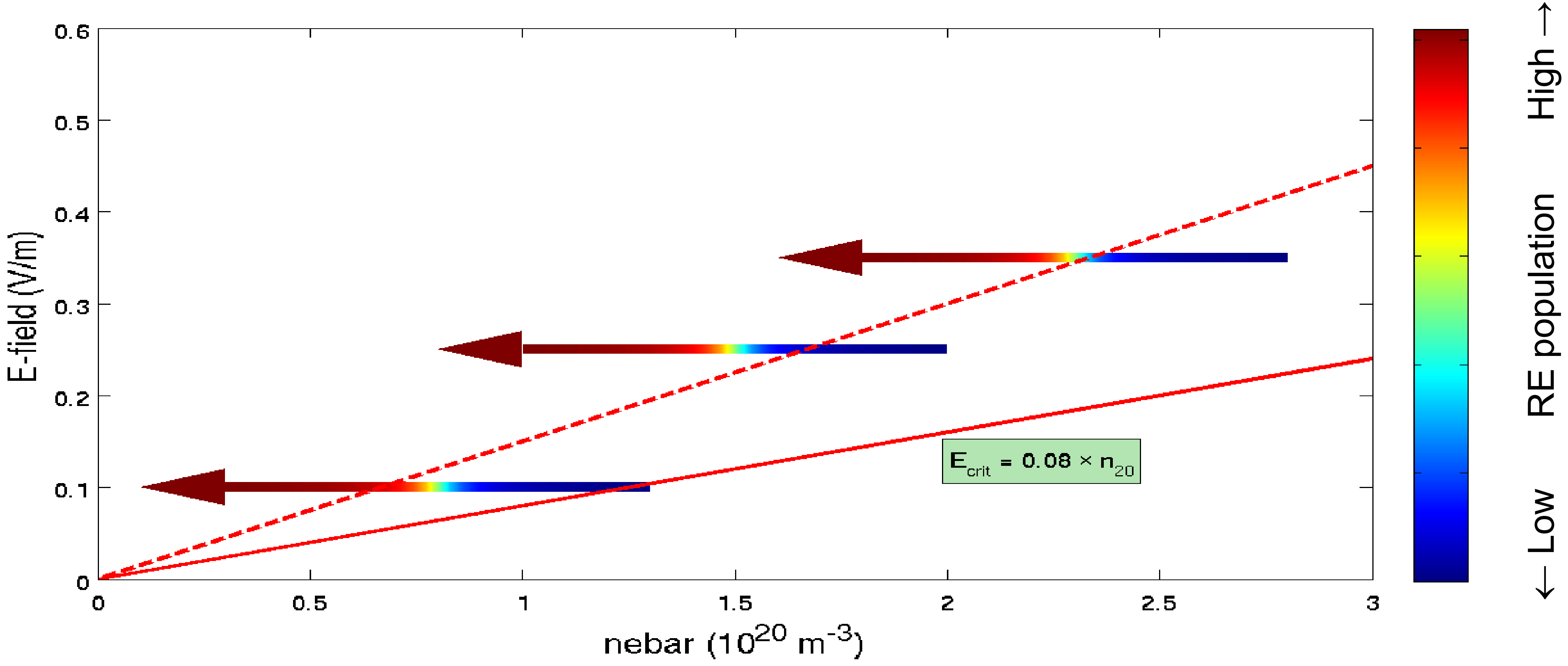
- Make measurements during quiescent flattop, rather than during disruptions, because results should be more reproducible, and the loop voltage, electron density, Z_{eff}, T_e, etc. can be accurately measured.
- To minimize confusing factors, exclude discharges with LHCD or ECCD, because they can distort the electron velocity distribution
- Several different diagnostics are used for detecting runaways:
  - hard x-ray (HXR), γ-ray detectors
  - detection forward-peaked emission (IR, visible)

Participants in MDC-16 so far:

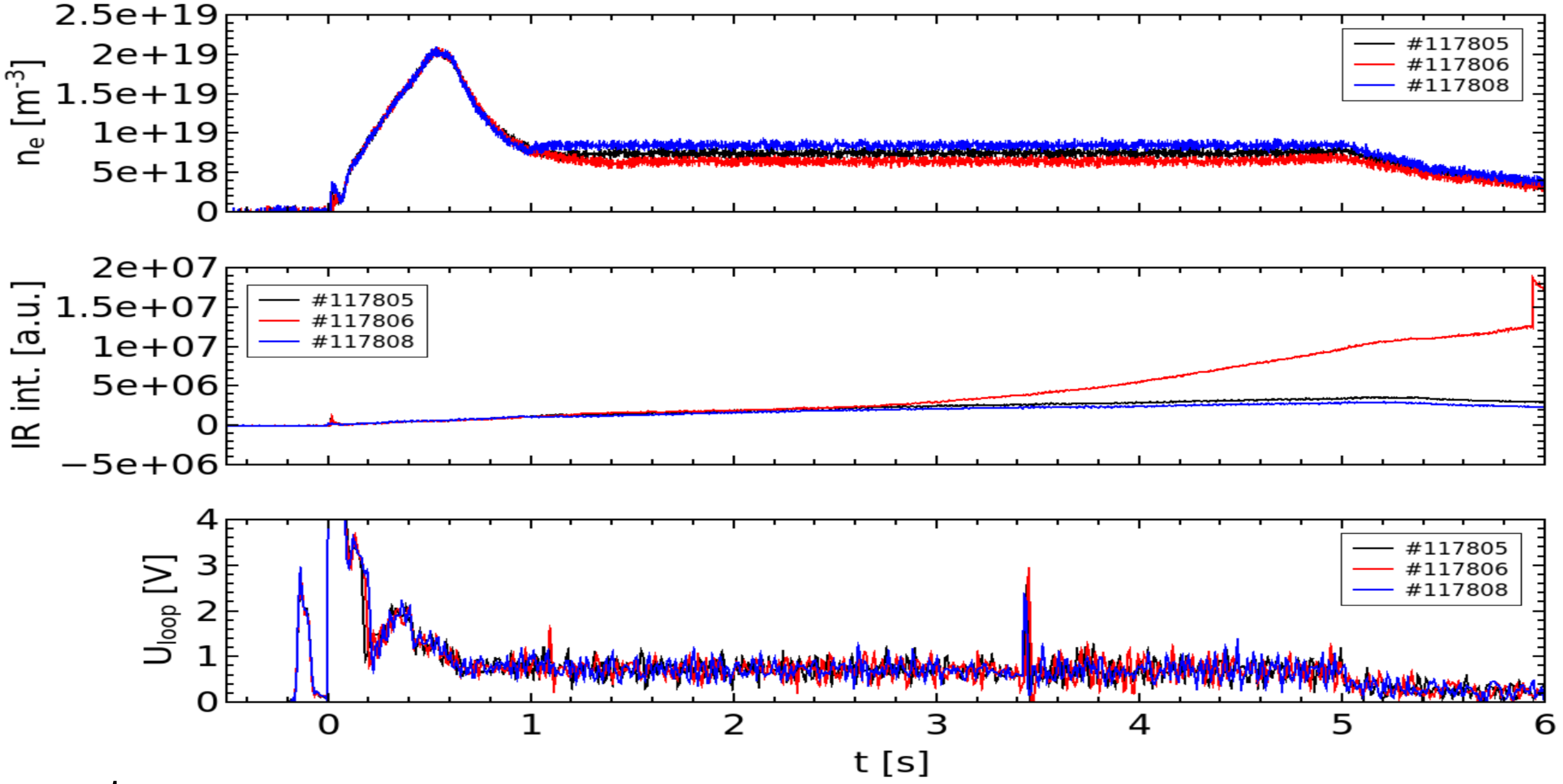
- FTU (dedicated experiments)
  - J. Martin-Solis, B. Esposito
- TEXTOR (dedicated experiments)
  - R. Koslowski, M. Lehnen
- Alcator C-Mod (data mining and dedicated experiments)
  - R. Granetz
- DIII-D (data mining and dedicated experiments)
  - J. Wesley, C. Paz-Soldan
- KSTAR (data mining)
  - T. Rhee, J.H. Kim
- JET (data mining; *not during flattop*)
  - P. deVries
- MST (dedicated experiments; RFP run in tokamak mode; low T_e)
  - A. DuBois, B. Chapman

Several possible ways to measure threshold *E*-field:

(1) Determine RE onset by decreasing n_e



TEXTOR dedicated experiment

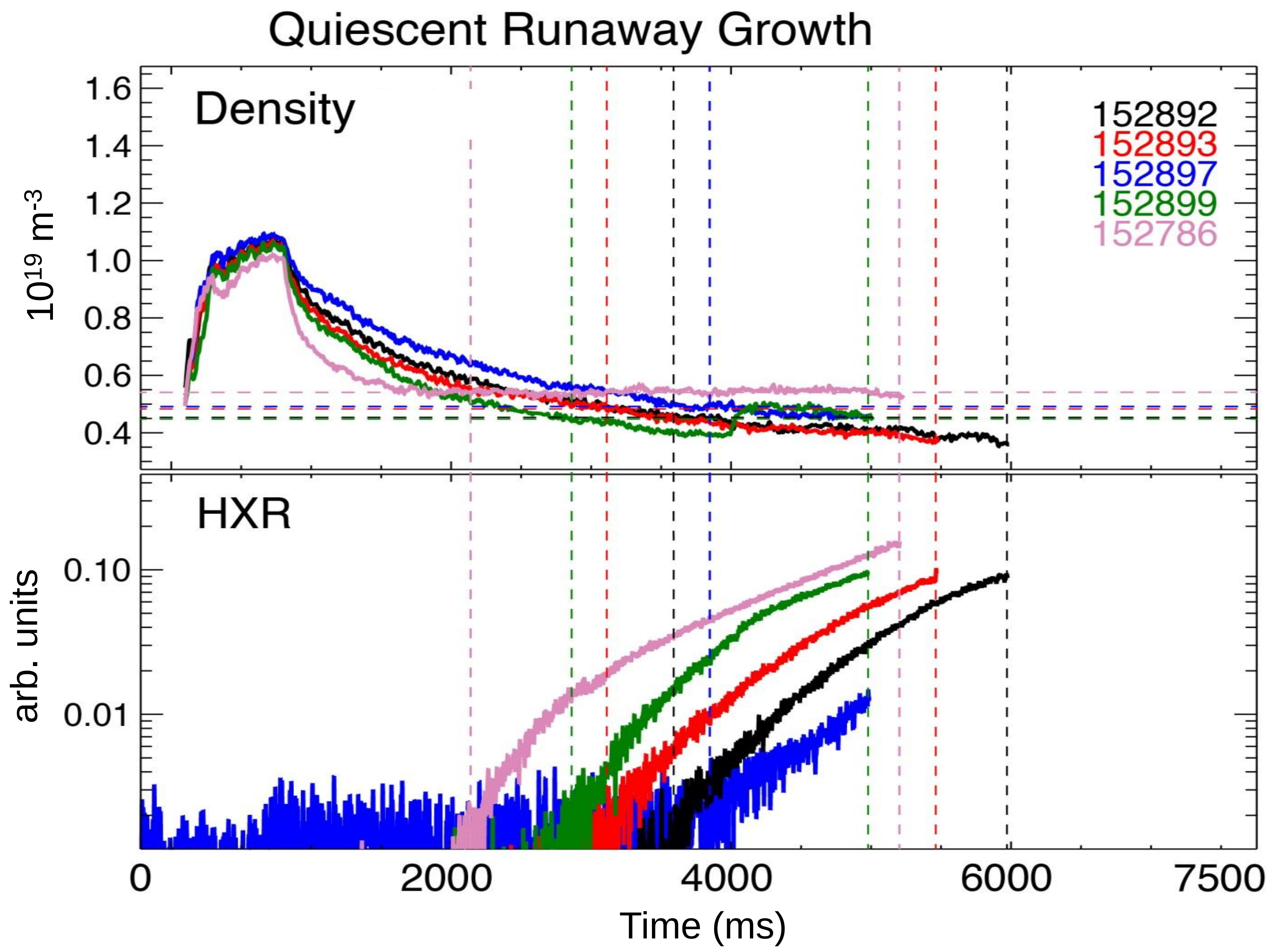


RE onset:

$E = 0.066$ V/m

$n_e = 0.07 \times 10^{20}$ m^{-3}

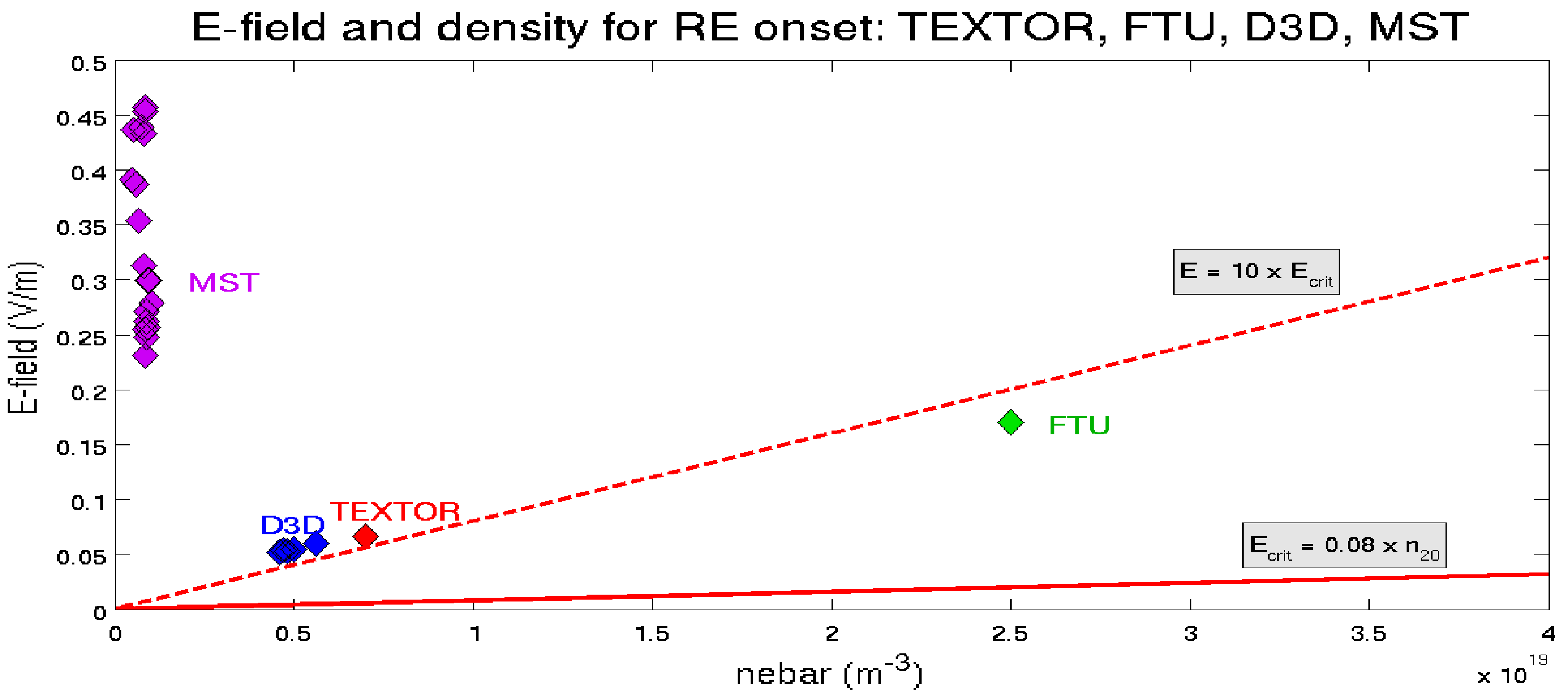
DIII-D dedicated experiments



Shot	E (V/m)	n_e (10^{20} m^{-3})
152892	0.052	0.046
152893	0.055	0.050
152897	0.053	0.048
152899	0.054	0.047
152786	0.060	0.056

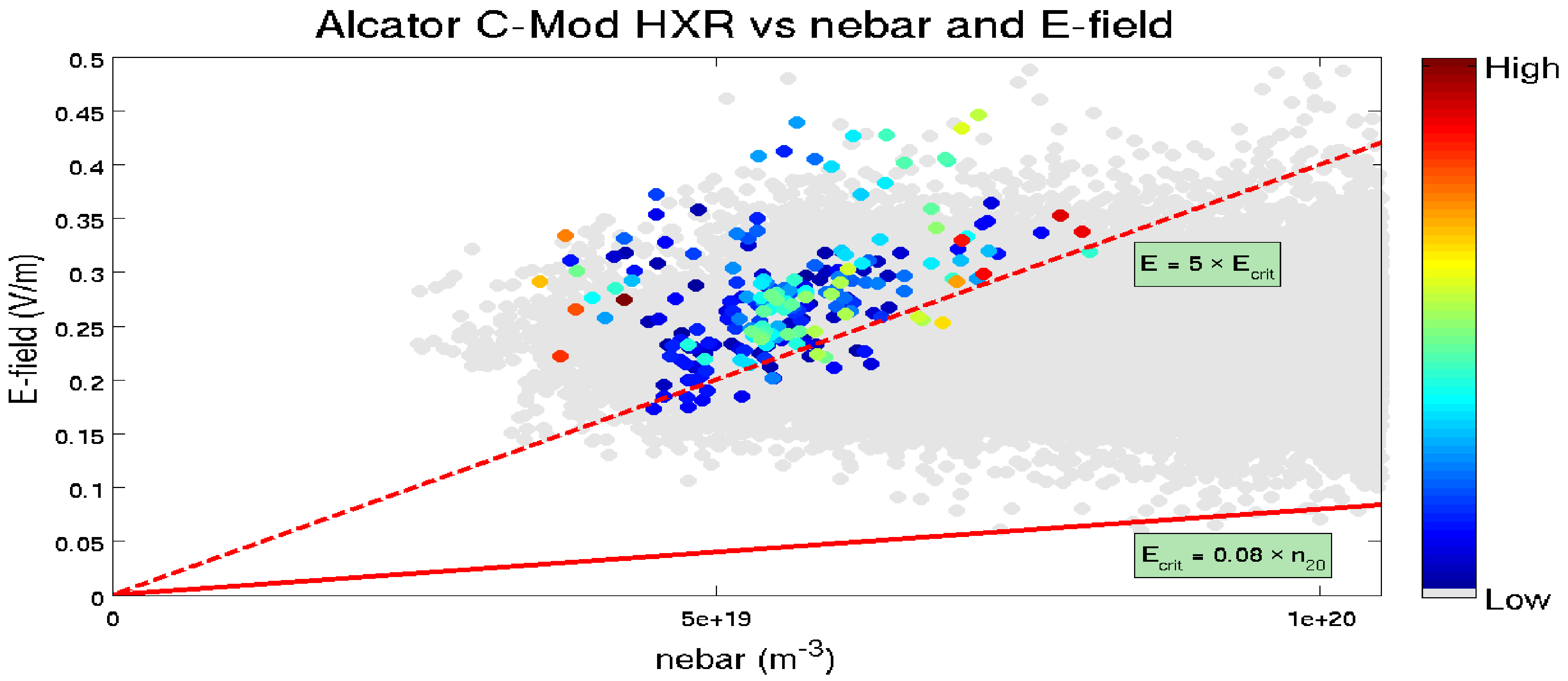
Note: intrinsic error fields must be carefully reduced to prevent locked modes at these low densities

E-field and density for RE onset

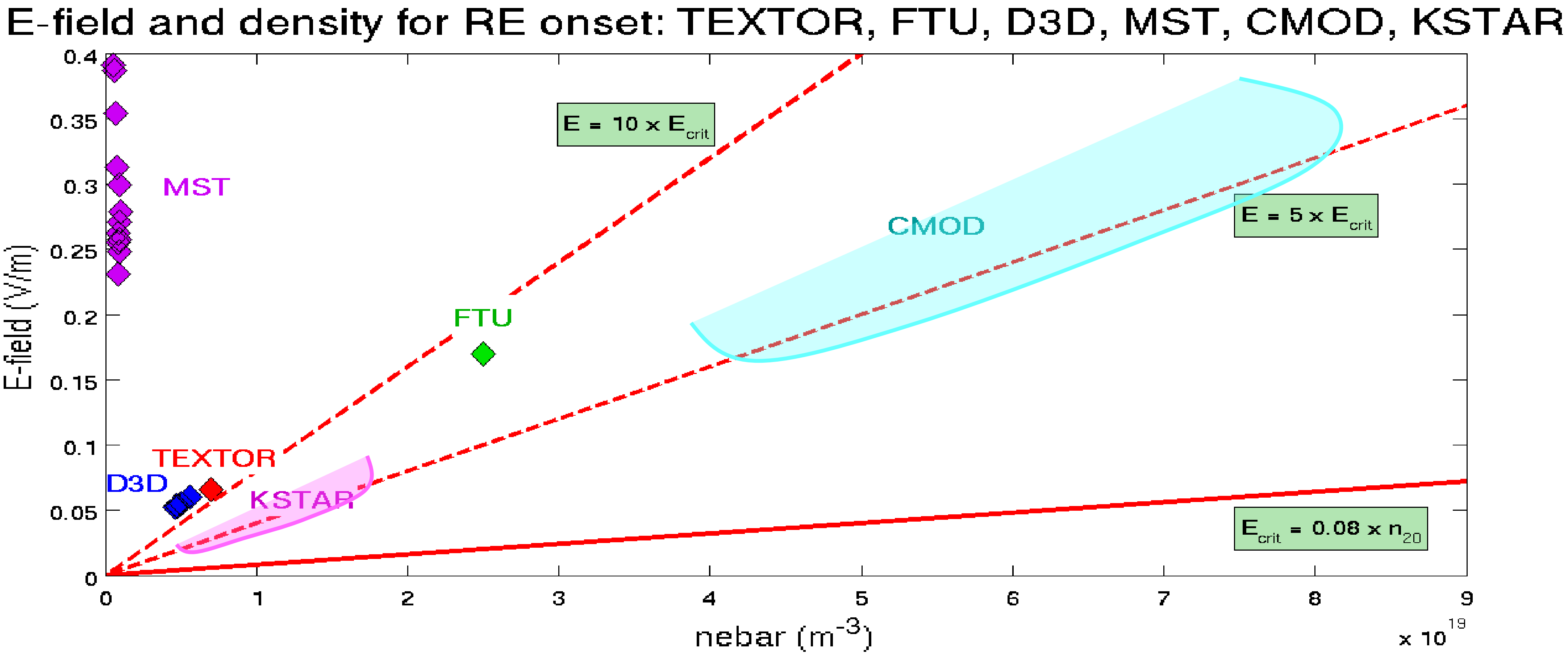


Several possible ways to measure threshold *E*-field:

(2) Assemble dataset of (*E*, *n*, RE) from previously existing data; Determine threshold boundary



Thresholds for RE onset on multiple machines



Caveats of using ‘onset’ method to determine threshold E-field

1) RE detectors (usually HXR) have finite sensitivity, i.e. a minimum detectable level of REs

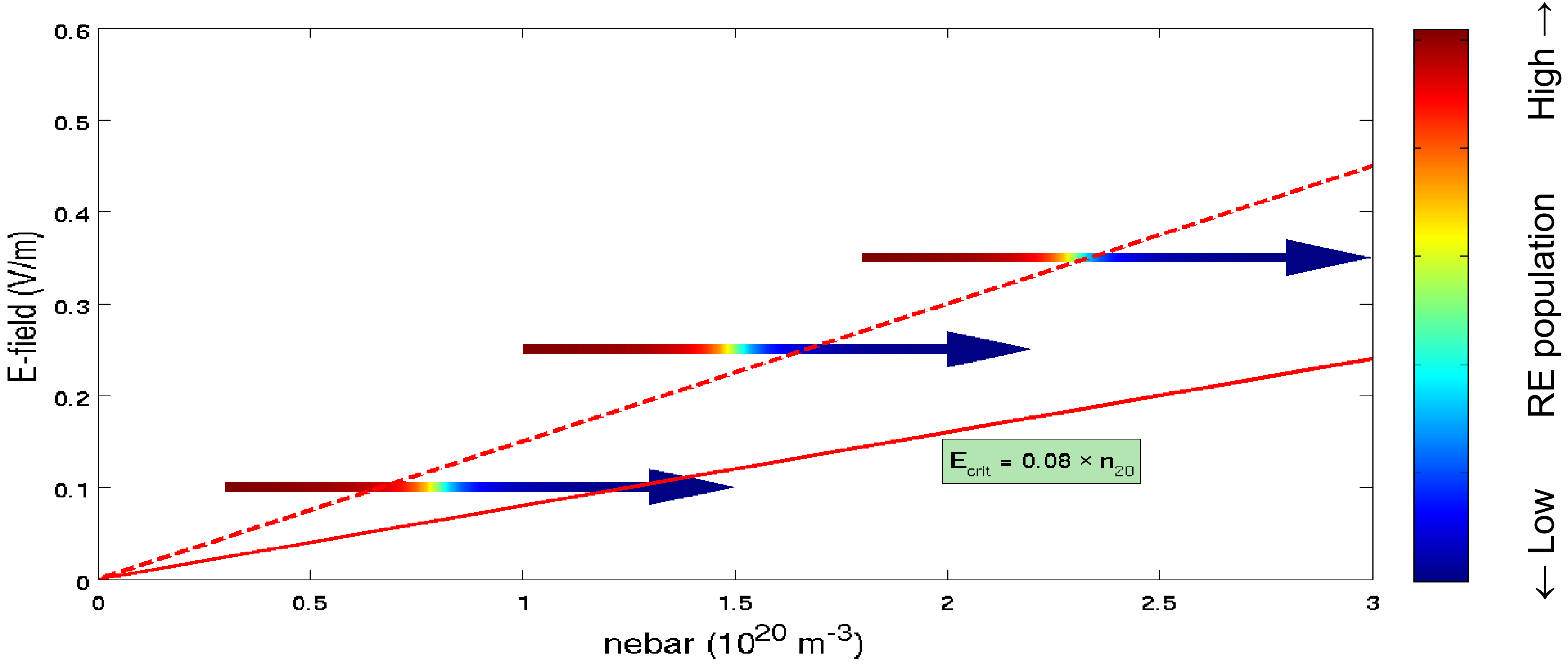
2) In a Maxwellian of a few keV and ~10^{20} electrons, with V_{loop} ~ 1 volt, the initial number of runaways is well below detectable limits

Therefore, in order to be detected, i.e. the observed “onset”, the RE population must grow to a measurable size, which takes finite time, comparable to the duration of these discharges.

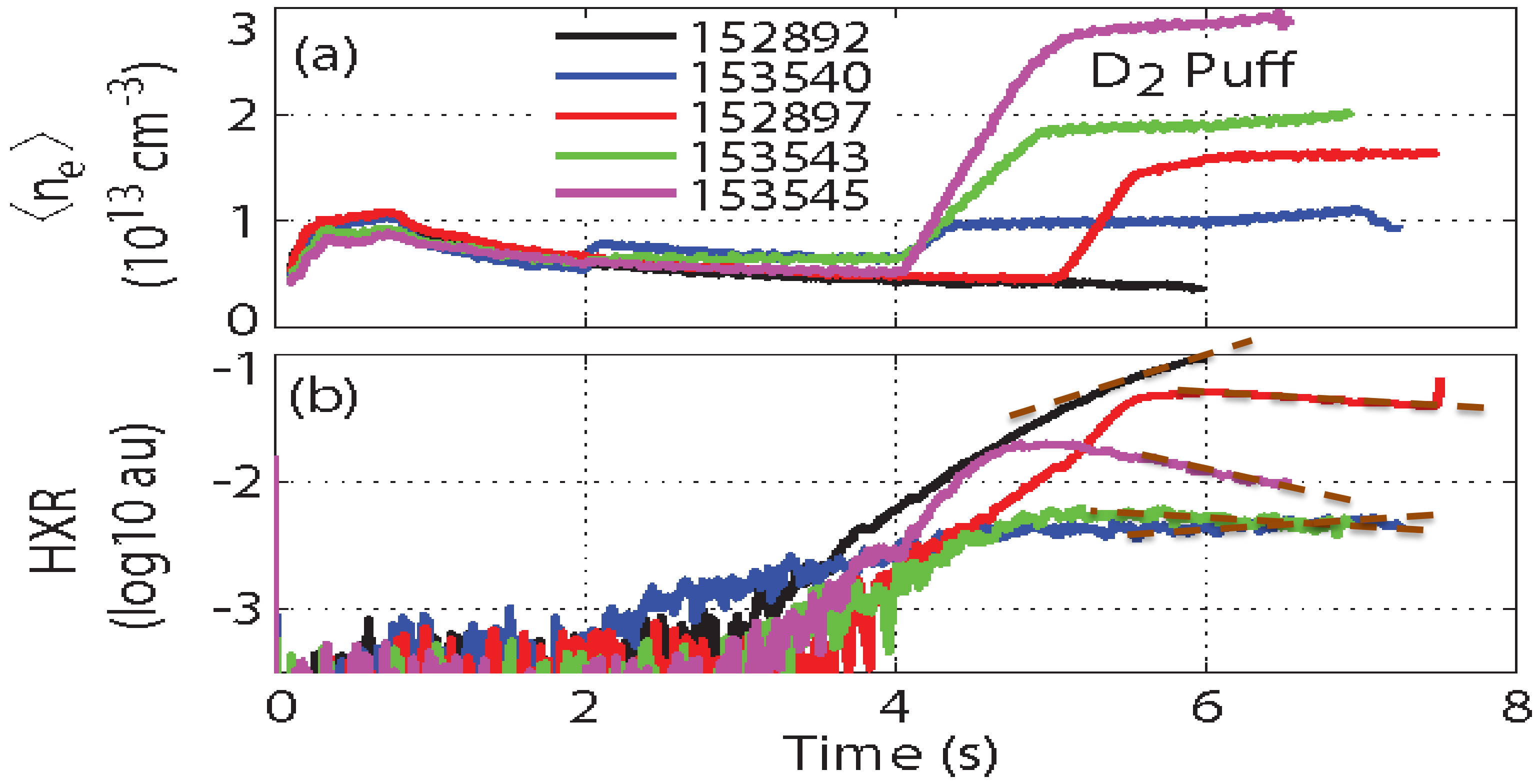
Hence, E and n_e at the time of onset detection may not be the same as E and n_e at the RE threshold

Several possible ways to measure threshold *E*-field:

(3) Start in low-density regime with RE's and *increase* n_e to find threshold for RE suppression

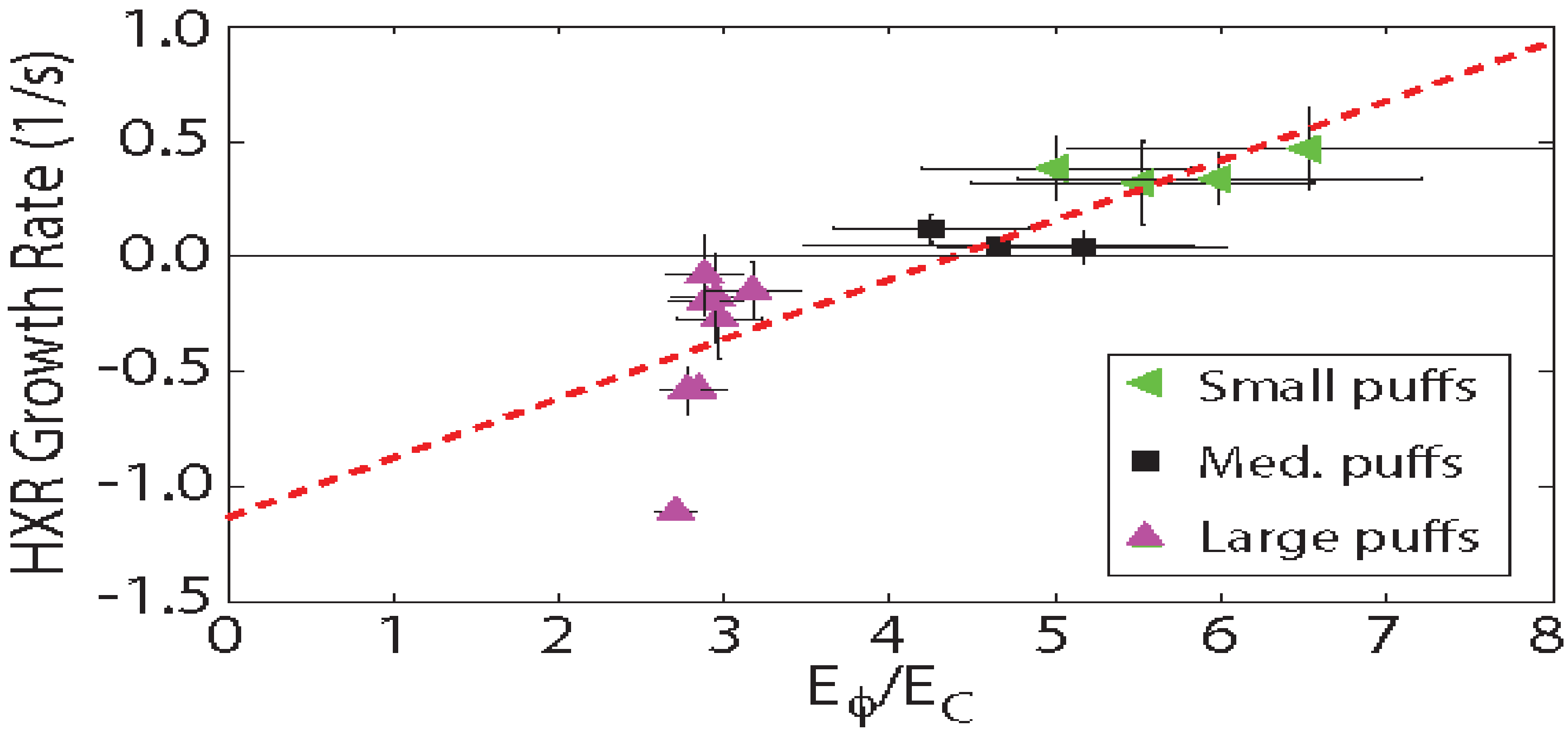


Measuring RE growth & decay rates on DIII-D



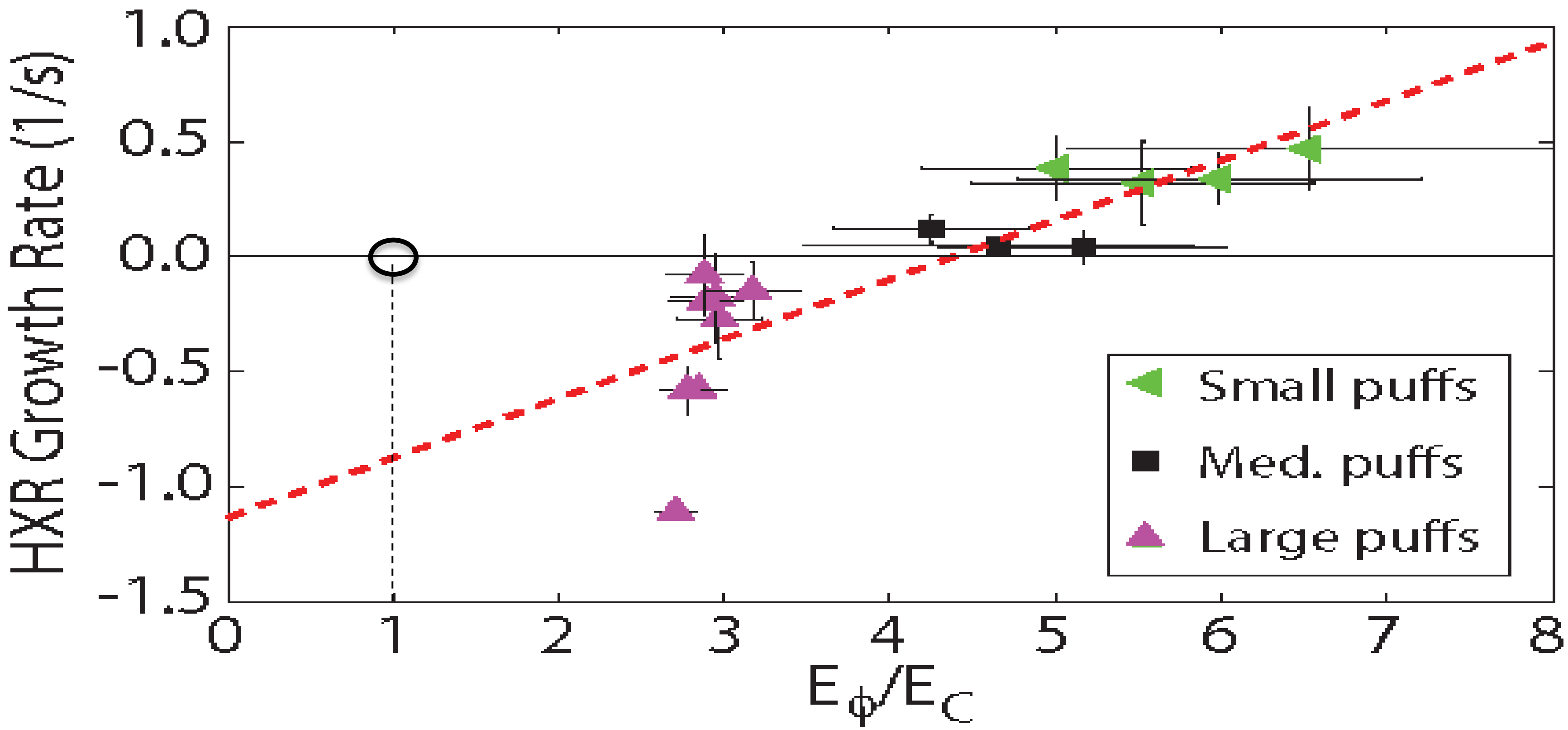
- First, get RE’s by reducing density
- Then change density to new value and hold constant to reach new steady-state
- Determine growth or decay rate

Measuring RE growth & decay rates on DIII-D



- Transition from growth to decay occurs at E/E_{crit} ~ 3 – 5

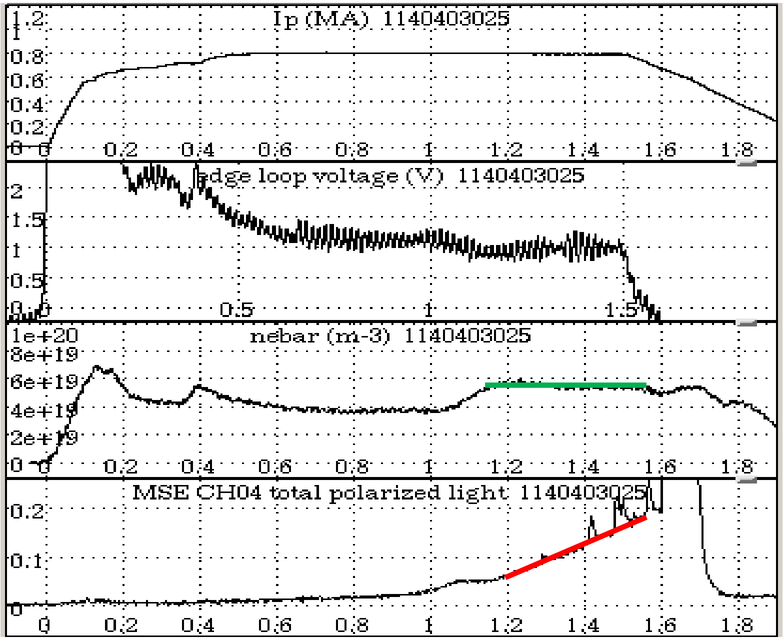
Measuring RE growth & decay rates on DIII-D



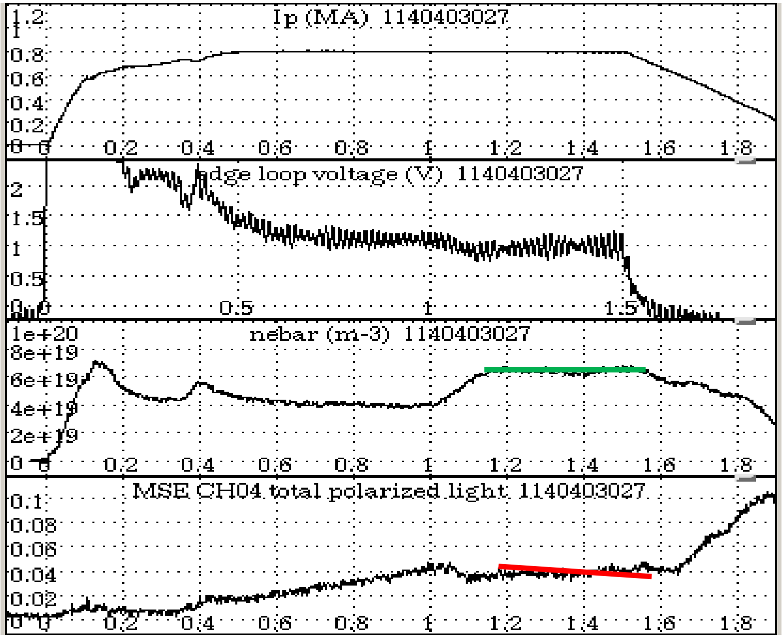
- Transition from growth to decay occurs at E/E_{crit} ~ 3 – 5
- Theory says this should occur at $E/E_{crit} = 1$

Measuring RE growth & decay rates on C-Mod

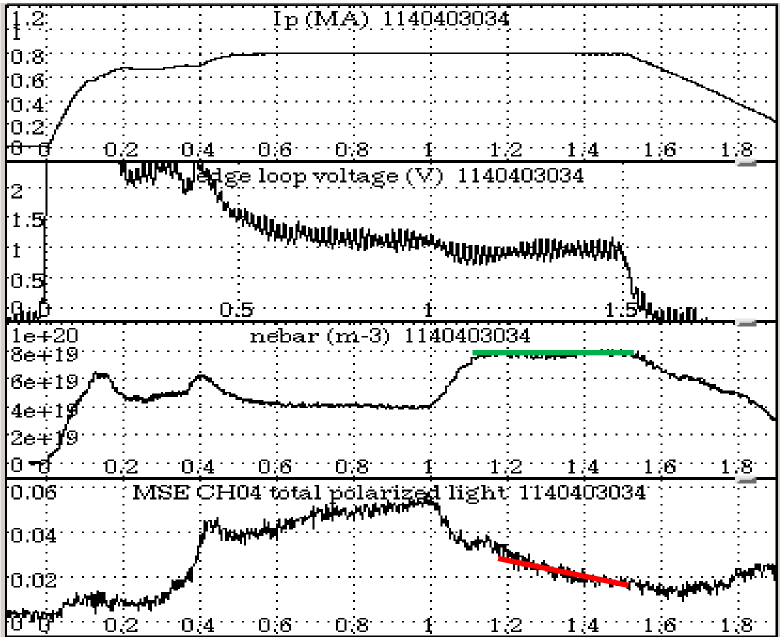
increasing RE’s



nearly steady RE’s



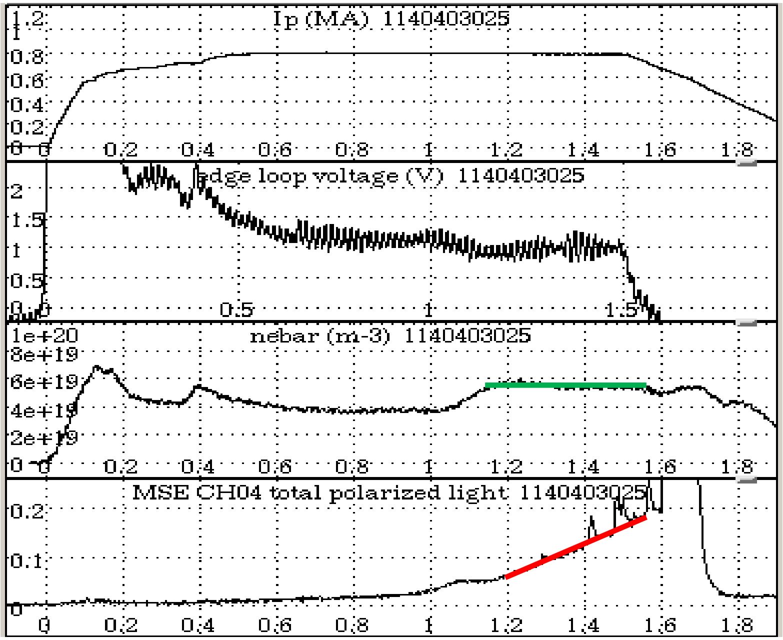
decreasing RE’s



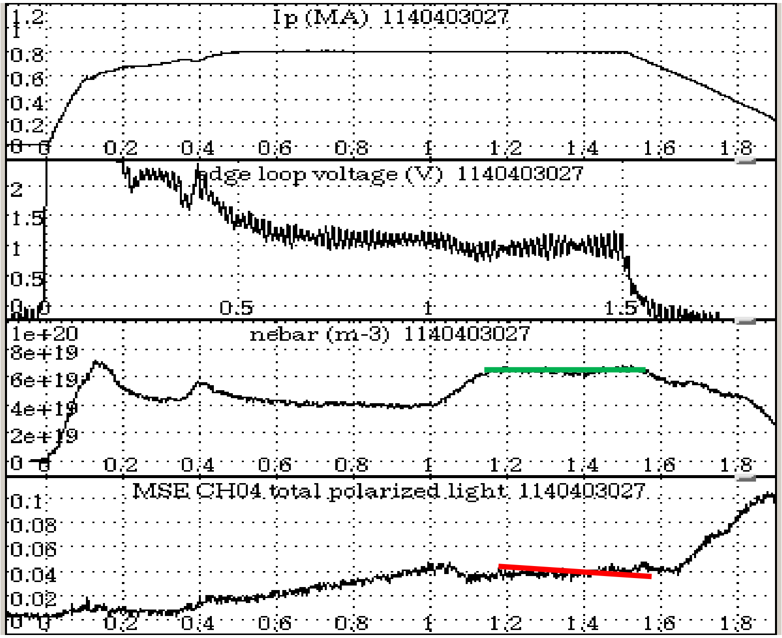
- First, get RE’s by reducing density
- Then change density to new value and hold constant to reach new steady-state
- Determine n_e, $E_{//}$, and dn_{RE}/dt for each case

Measuring RE growth & decay rates on C-Mod

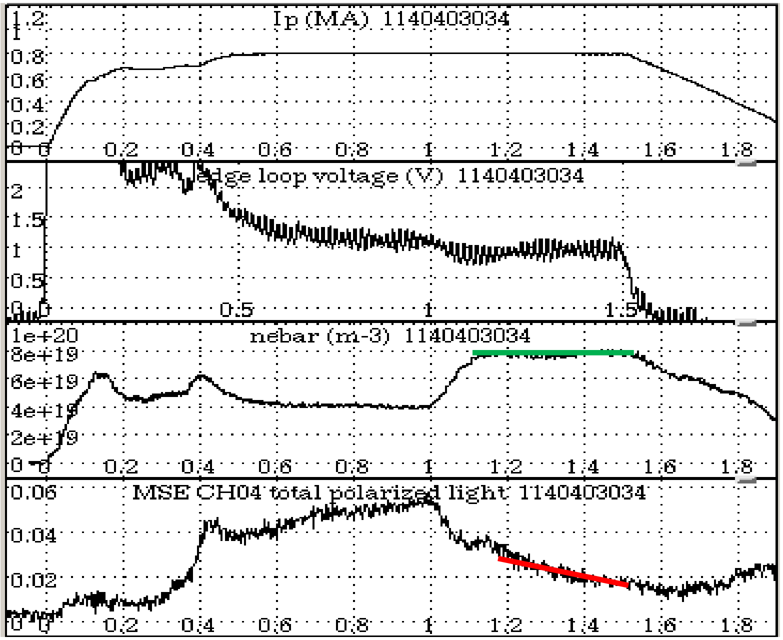
increasing RE's



nearly steady RE's

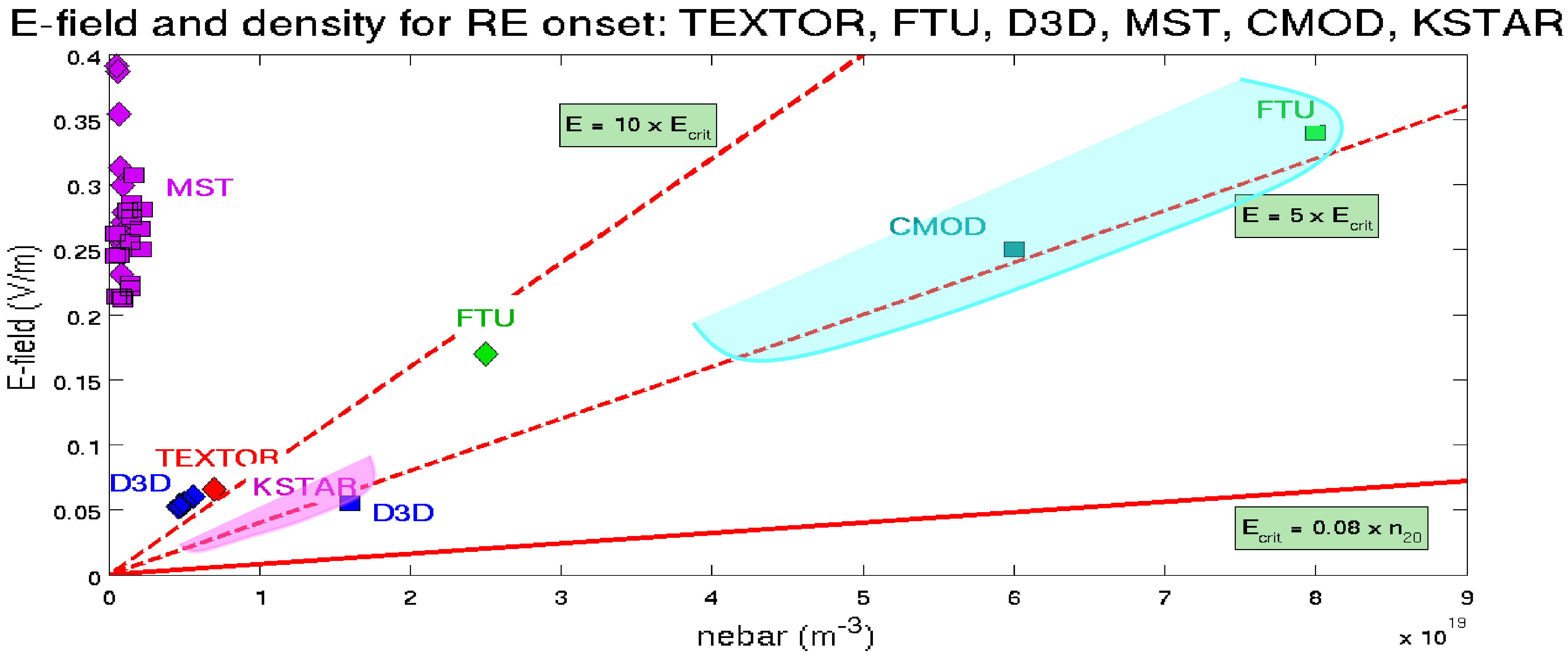


decreasing RE's



- First, get RE's by reducing density
- Then change density to new value and hold constant to reach new steady-state
- Determine n_e, $E_{//}$, and dn_{RE}/dt for each case
- Center case has $n_e = 0.6\times10^{20}$ m^{-3}, $E_{//} = 0.25$ V/m

Thresholds for RE onset (◆) and suppresion (■) on multiple machines



Summary: results

A study of runaway electrons under well-controlled, well-diagnosed conditions in a number of tokamaks finds that the threshold density for both onset and decay of RE signals is at least 4 – 5 times less than expected from collisional damping only.

This implies that there are other significant RE population loss mechanisms in addition to collisional damping, *even in steady-state quiescent plasmas*.

Possible RE loss mechanisms in addition to Coulomb collisional drag include:

- synchrotron emission losses from Larmor motion
- drift orbit losses
- stochastic losses due to B (which are probably much larger during disruptions)
- scattering in velocity space due to RE instabilities

Implications for ITER RE mitigation

During disruptions on ITER, the ***E*-field *is about two orders of magnitude higher***, and ***T_e* *is about two orders of magnitude less*** than in the quiescent plasmas of this ITPA joint study.

Do the results of this study apply to ITER disruptions?

Thresholds for RE onset on multiple machines