XP1032: Error Field Threshold scalings

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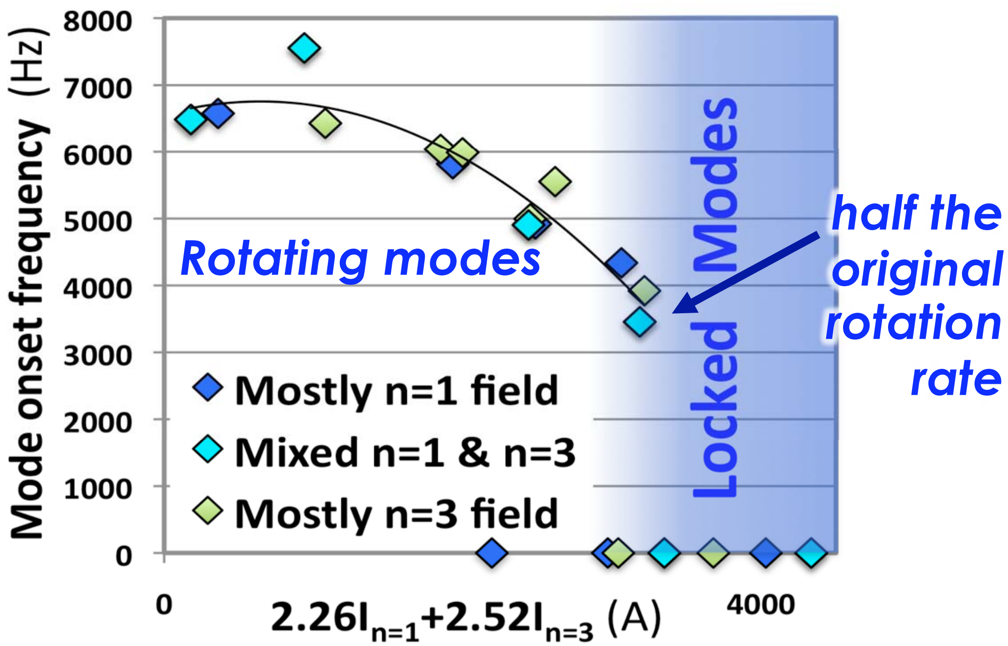
GENERAL ATOMICS

In H modes, Error Fields Destabilize Rotating Modes

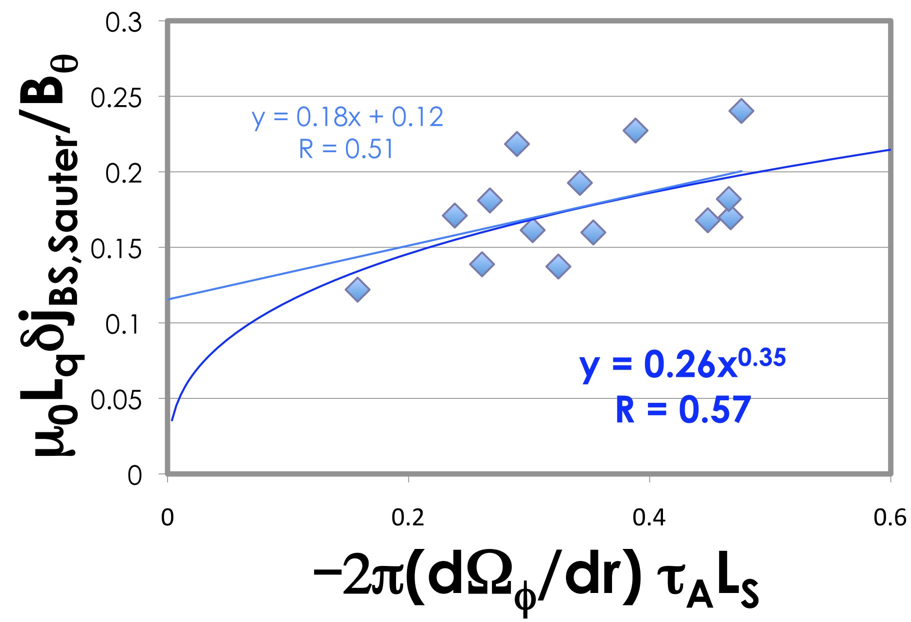
- **Error field brakes plasma:**
  - If close to 2/1 NTM beta limit, the 2/1 NTM can is destabilised by the reduction in rotation shear
  - Further from NTM limit rotation braking reaches bifurcation point for 'penetration' – bifurcation to large locked mode

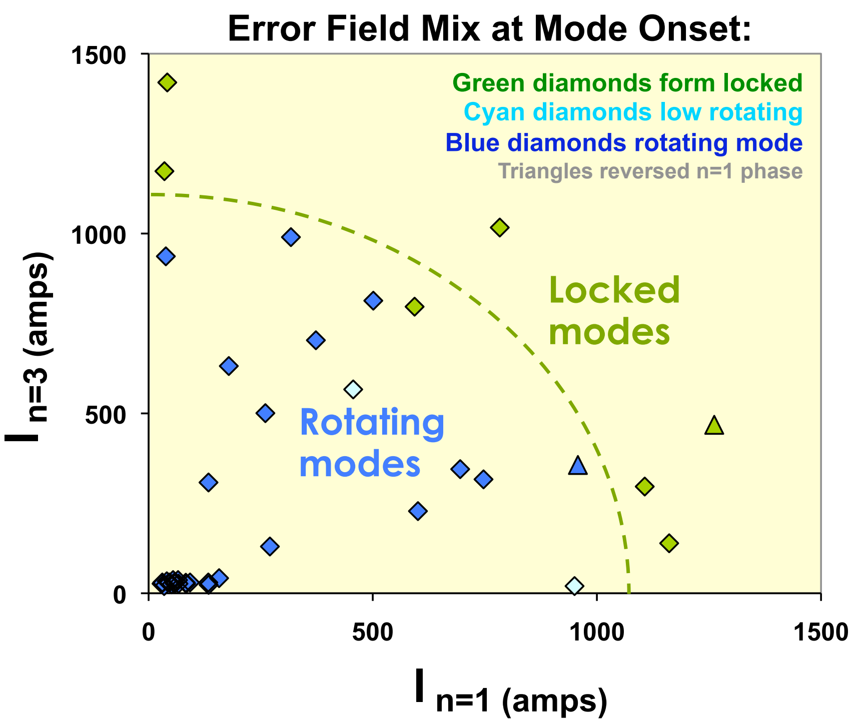


- **Key point is mode forms when substantial braking**
  - ***Criteria is about overcoming plasma rotation***
  - A lot like Ohmic criterion
- ***Look for similar threshold scaling at given β_N and profiles***

Error Field Braking Changes NTM stability:
Action through n=1 or n=3 fields

- **Rotating mode accessed at lower bootstrap drive with less rotation shear →**

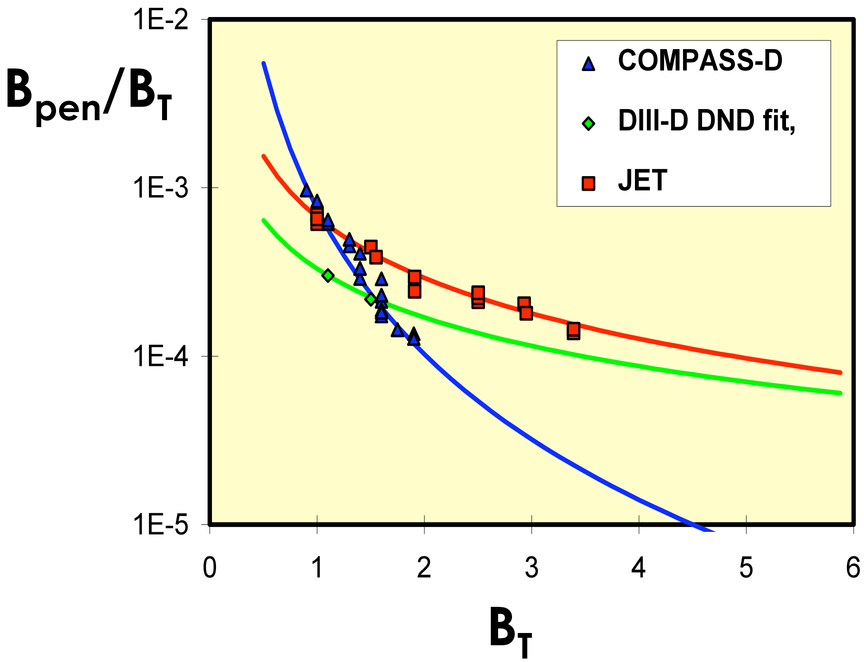




- **But can get two types of mode**
  - **Locked** or **rotating**
  - ***What is practical limit given these apparently different processes?***

Goal XP 1032: Obtain Scaling of Error Field Threshold in H-modes to Predict Future Devices

- **Error field threshold dictated by a torque balance**
  - When electromagnetic torque overcomes inertia & viscosity
  - Shielding response bifurcates to resonant widespread tearing



- **Scalings obtained for Ohmic regimes, but H mode may differ:**
  - Proximity to NTM: weak Δ' stability?
  - Underlying rotation may scale differently cf Ohmic

➔ **Experiments to measure principal scalings with B_T and density**
  - Infer machine size scaling from dimensional invariance:

$$B_{pen}/B_T \propto n^{\alpha_n} R^{\alpha_R} B^{\alpha_B} q^{\alpha_q}$$

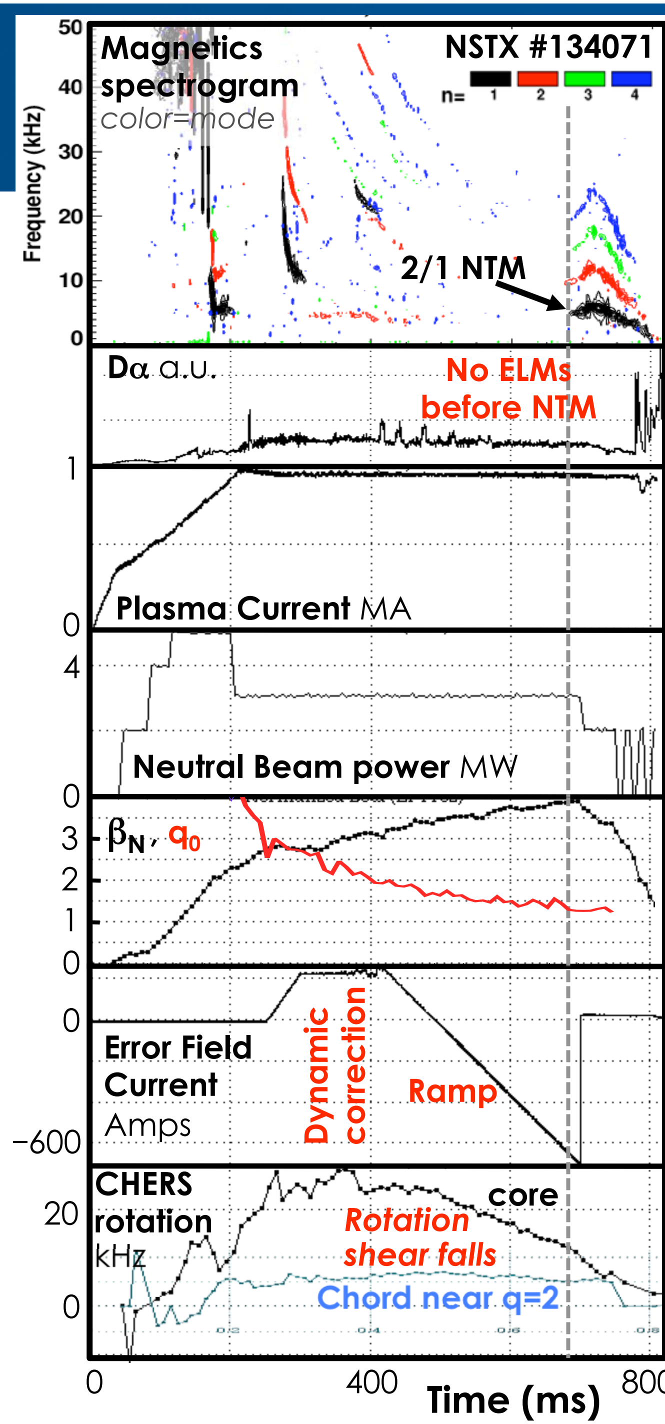
Experiments to Extrapolate EF Thresholds to Next Step Devices like ST-CTF or ITER

- **Ramp up error field to measure mode thresholds**
- **Scan in ne and Bt**
  - Infer machine size scaling from Connor-Taylor constraint
- **Hard part:**
  - Maintain constant shape, betan, li, density and q profile at time of mode onset

- ***Goal: Understand how the torque balance based error field threshold extrapolates to future devices.***

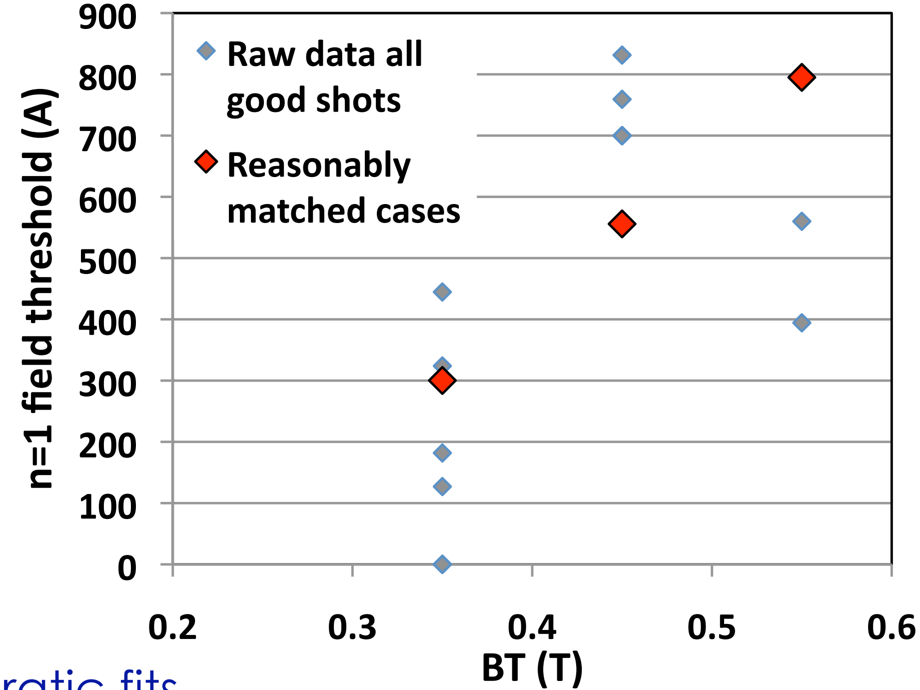
Experiment

- **Built on 2009 shot (shown)**
  - **β_N feedback added to give constant β_N with time**
    - **Worked well at 3 different Bt values**
    - **Avoided need to repeated retune discharges to reach target**
  - Lithium to control ELMs & conditions
    - Avoid as tearing trigger
    - Required more this year: 150mg/shot
- **n=1 field ramps to trigger mode**
  - ✓ Scan 3 B_T at constant q_{95}
  - ✓ Adjust field ramp and gas to compensate for density & q_0 variation



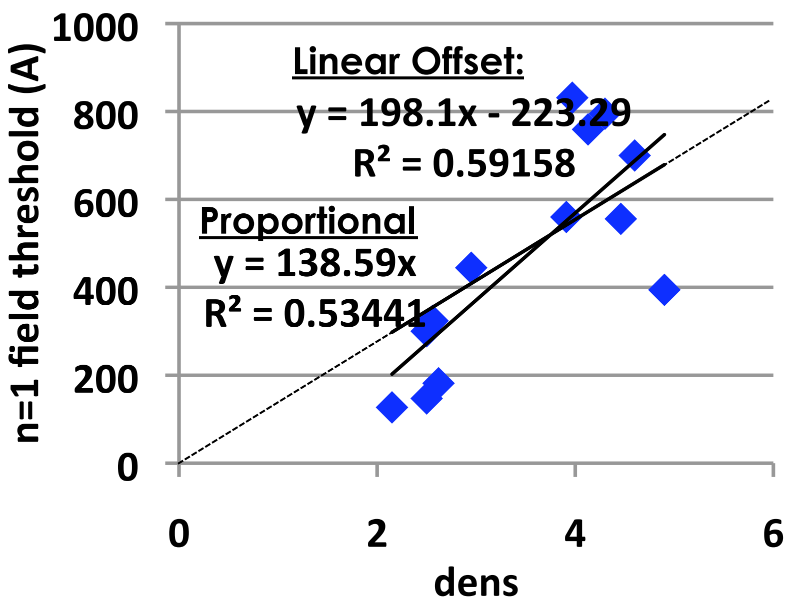
Raw data suggests a dependence with Bt

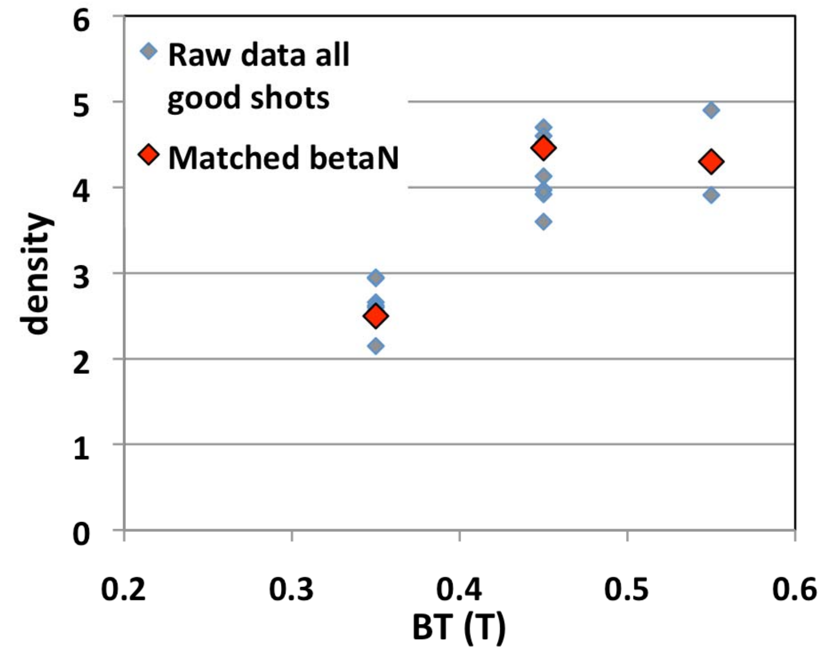
- **Full B_T range explored – lowest, highest & middle**
  - 0.35T/0.7MA to 0.55T/1.1MA
- **Wide variation in thresholds**
  - β_N, density, q profile play a role in changing threshold & varied somewhat across points taken
  - Requires careful analysis to strip out – ***data taken to enable this***
- **Some reasonably matched shots show preliminary trend**
  - Well fitted by offset linear or quadratic fits
  - But possible underlying density dependence…



Underlying density variation plays a strong role

- **Lower field shots are lower in density**
- **Threshold correlate with density**
  - Consistent with linear or steeper scaling:

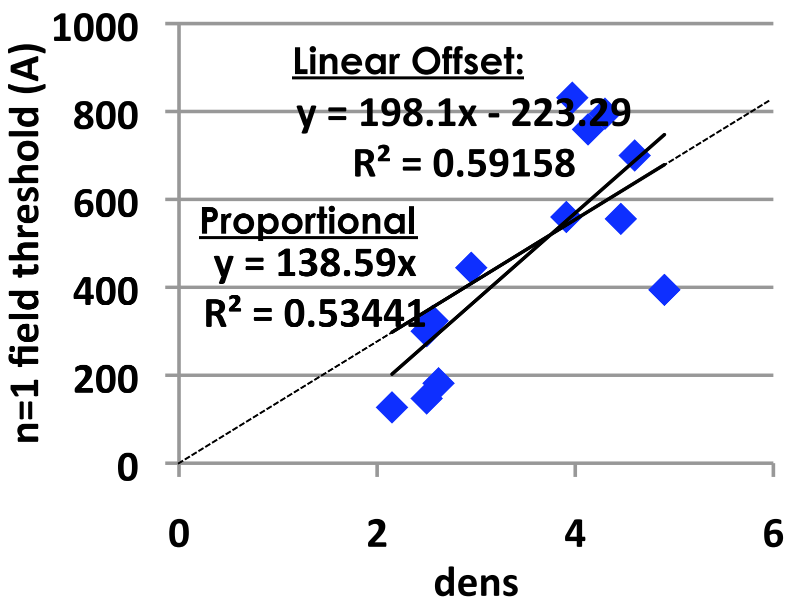


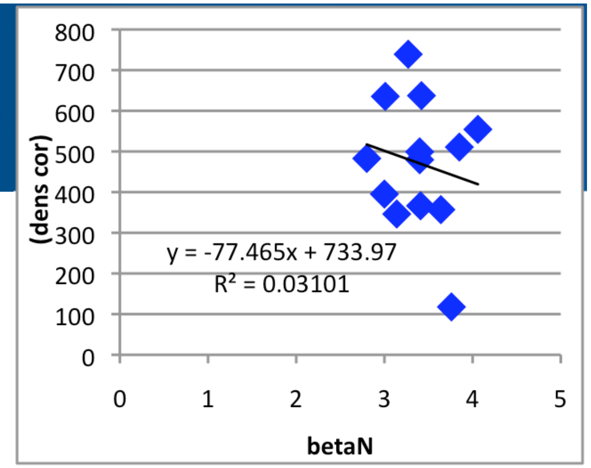


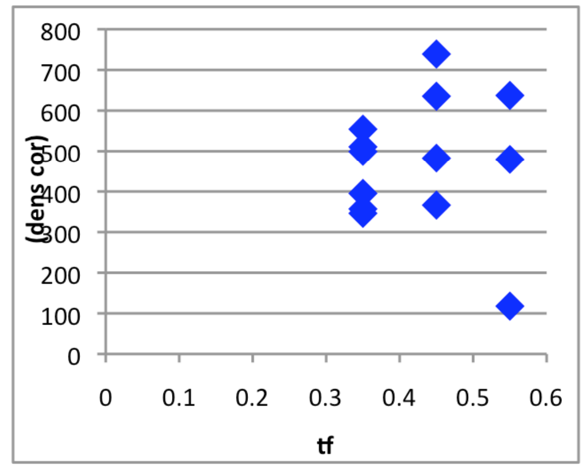
Need to see if we can pull out trends with fitting & phenomonelogy…

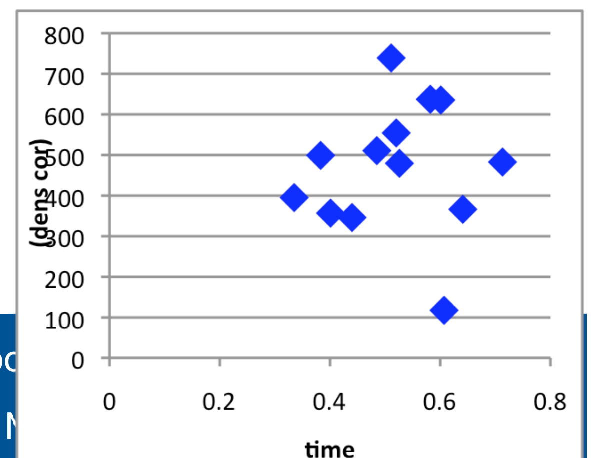
After density dependence extracted, residual dependencies seem small

- **Use offset linear density fit to correct out density variation**
  - No obvious trend in other variables now! ➔
  - Can we do better based on phenomenology?...







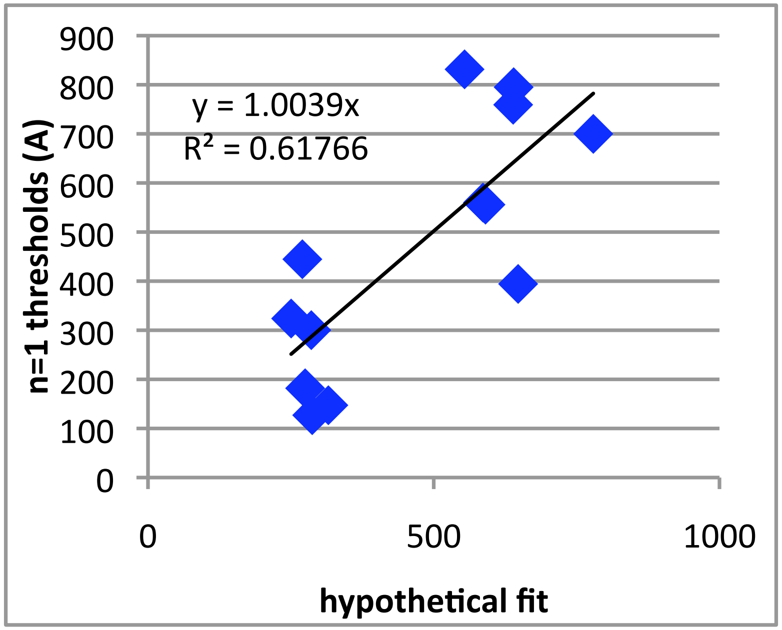


Make a fit based on intuition

- **Hypothesize power law form constructed:**
  - Positive density dependence seems clear
  - Shot phenomenology shows less or no error field needed if higher β_N – suggests negative β_N exponent
  - Arbitrary TF coefficient
- **Start from this and vary coefficents by hand to minimise residual**
  - ***Actually get a better fit than regression fitting!***
- **Form found:**

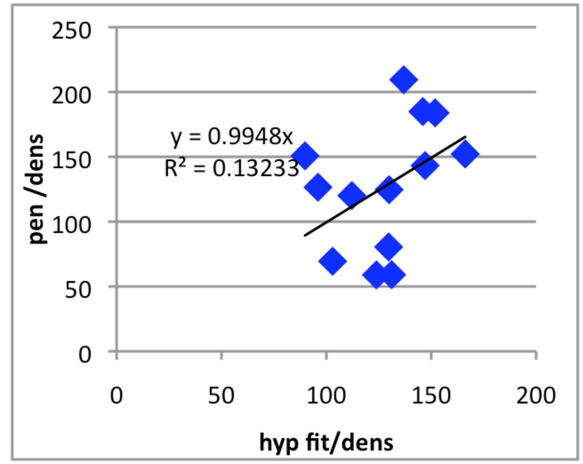
$$I_{pen} \sim n_e \ \beta_N^{-1.25} B_T^{0.6}$$

  - Can we constrain more than one variable?

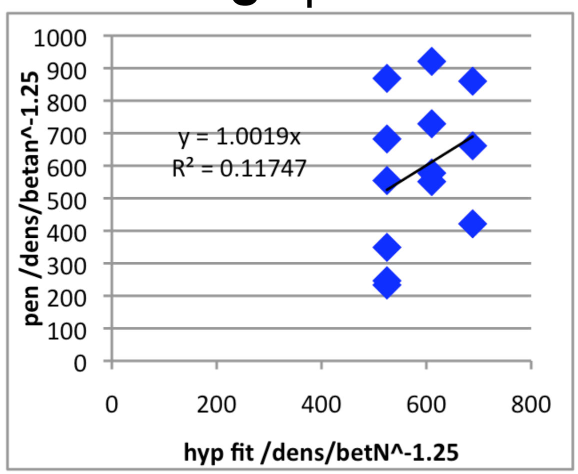


Is there a residual dependence in the fit?

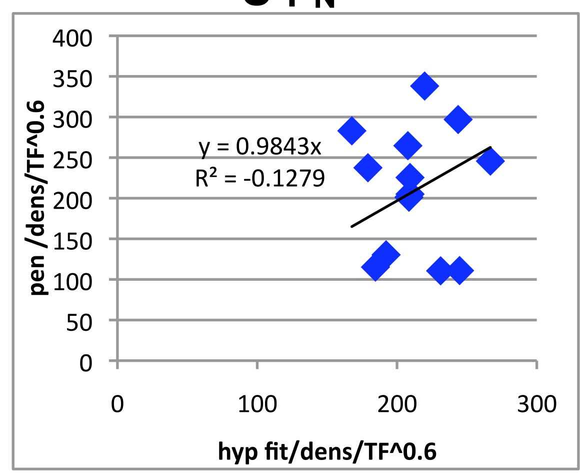
- **Stripping out density dependence ➔ leaves weak correlation**
  - Further analysis shows might be B_T or β_N,
  - but neither is well constrained & there may be no further trend!
  - **Possible further hidden variables?**
    - **Keep looking!**
    - **q profile, MHD?**



Remaining B_T variation:



Remaining β_N variation:



Conclusions

- **Wide scan of error field thresholds made in H-modes**
  - Bt is main unknown parameter for extrapolation
  - Other parameters varied to strip out their natural variation
- **Principal dependence observed was with density!**
  - Other dependencies are too weak to see or below scatter
  - Lack of strong negative trend with BT at least encouraging for future devices
- **H mode error field threshold scalings seem to go linearly or steeper with density → good for future devices**

- ***Bit more work to do look at phenomenology and consider further hidden variables – suggestions welcome…***

Fin

Shot Plan – logic here – see XP for detail

1. **Establish reference 0.9MA 0.44T and tune if needed – 3 shots**
2. **Change density (ideally: puff gas after 300ms to avoid big profile effect) +30-40%**
   - If needed tune heat switch on time
   - Tune EF ramp rate/time to get mode at same betan and time
3. **Tune shot to get mode at same time and beta**
4. **Further density step up +60% cf 1**
5. **TF & Ip scan (fixed q95) to 0.3T and 0.6T, with tuning as above.**

Reserve: Governing Physics – á la old Ohmic theory… Penetration is about overcoming the plasma rotation

- **Modes form when resonant surface is braked by resonant response to EF to half it's natural frequency**
  - Tiny static island induced by EF
  - Viscous forces try to keep bulk plasma rotating slipping past the island - *this opposes island growth*
  - Torque exerted through island and viscosity to brakes plasma
    - *N=3 NTV effects assist this process?*
  - If rotation slows enough, island can grow, increasing torque and bifurcating to a locked mode state
  - Threshold scales as $B_{pen} \sim B_T \omega_0 \tau_A (\tau_{rec} / \tau_v)^{1/2}$
    - *ω_0 often taken to be electron diamagnetic rotation*
- **Criteria could also be regarded/generalised as condition for when we approach rapid rotation change**
- **Critical elements are:** what determines ω_0; whether plasma response changes; and how readily plasma rotation is overcome

But data suggests underlying density dependence

- **Linear**