Disruption Science Issues and Opportunities for a Burning Plasma Science Experiment

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Disruption Isssues and Science in a BPX*

- Foreseeable BPX's are tokamaks

- Tokamaks have disruptions

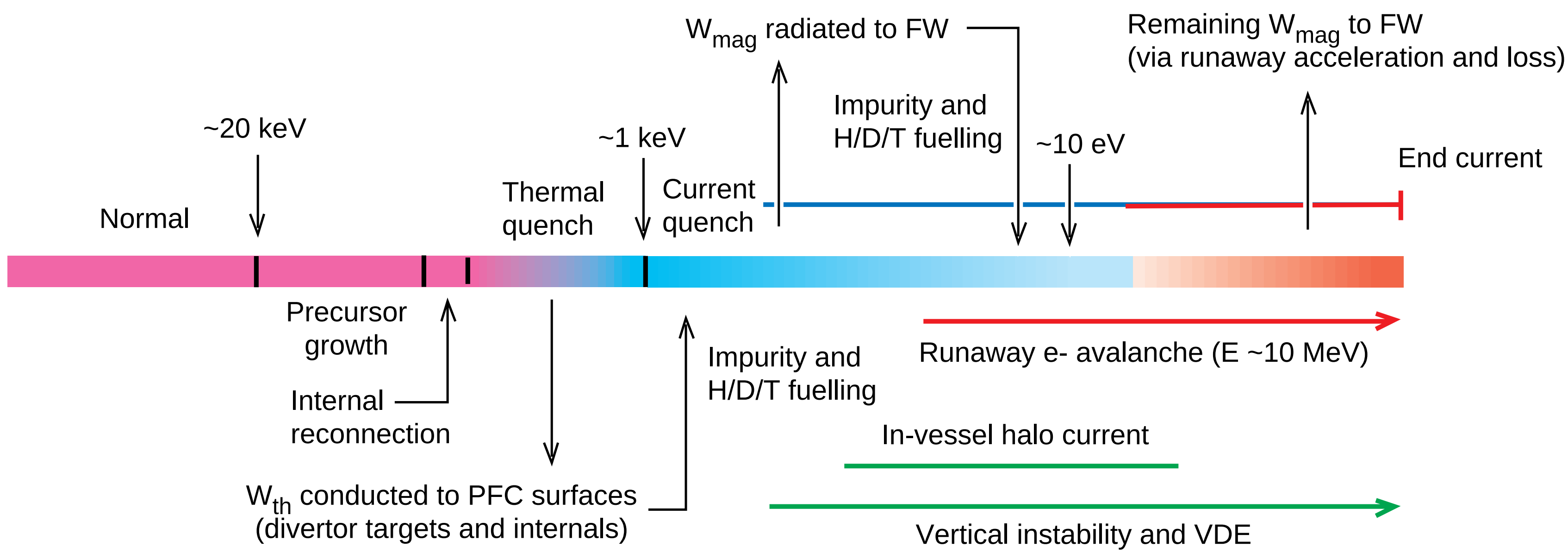
- Disruptions will occur in BP-science regime tokamaks

- BP disruptions will have features (and science bases) that are qualitatively and quantitatively distinct from features of disruptions in present tokamaks

- There is both a critical need and an opportunity to address these BP-unique features in a BPX device and program

*generic Burning Plasma Experiment

Disruption Effects and Consequences



- **Disruption mechanism is onset of rapidly-growing ideal MHD instability (2:1+1:1 modes); many causes; details/dynamics ‘rich’, still debated (MHD)**

- **Impact on BP attainment and unique BP science aspects lie in aftereffects**

- **Avoidance and/or mitigation desirable: addressed at end of presentation**

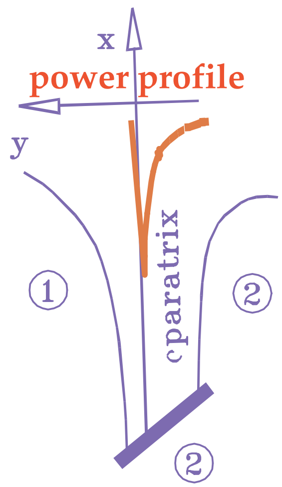
Disruptions in Burning Plasma Experiments

- A BPX requires a larger scale device than the largest present tokamaks
- This increase in 'scale' (higher B or larger R or both) results in an increase in the plasma specific energy — W_{th}/A_{FW}
- The thermal-quench consequences of disruptions in a BPX are qualitatively different for the corresponding consequences in present tokamaks. All burning plasma-capable tokamaks have W_{th}/A_{FW} for disruptions large enough to cause macroscopic vaporization and erosion of the quench-affected PFC surfaces — the limiter or divertor target(s)
- Key parameter is W_{th} per wetted area: present tokamaks have energies ≤ 1 MJ/m^2; BPX's will have energies of 10-100 MJ/m^2
- Surface response at ≥ 1 MJ/m^2 is vaporization and ionization; ensuing 'plasma shield' stops further energy deposit, but reradiates incident energy to nearby surfaces. Net erosion is ~few μm per disruption
- BPX target lifetimes are ~100 disruptions (or less: melt layer loss, etc.)

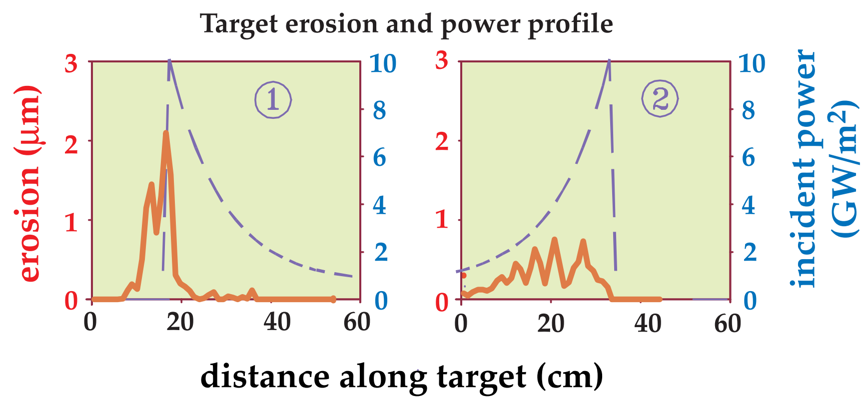
Disruption Plasma–Surface Interaction Issues

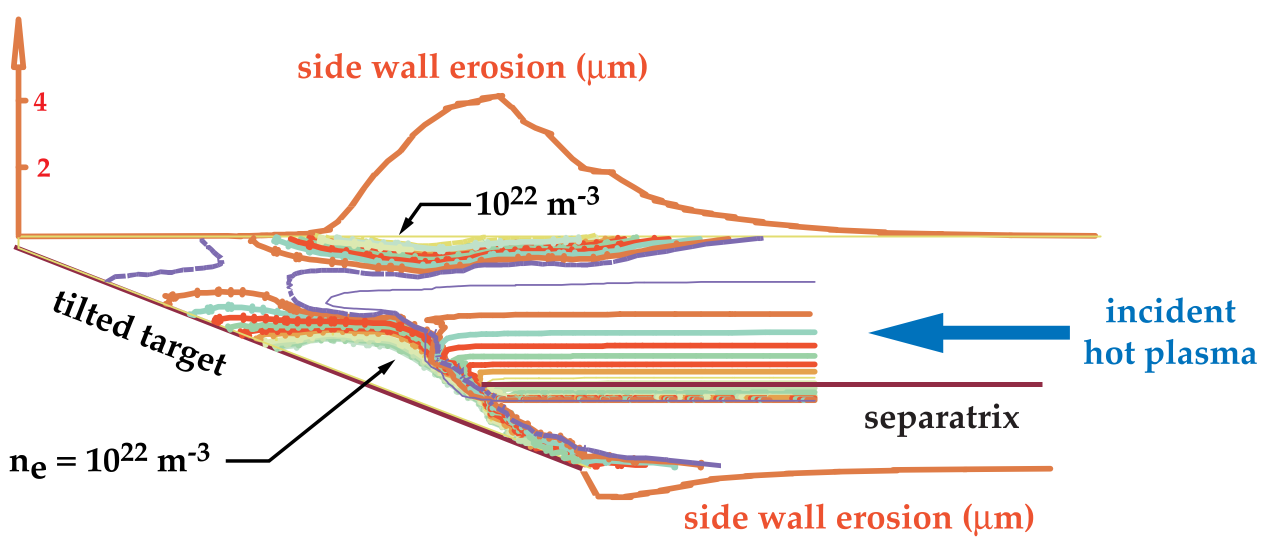
- Critical issues/science for BP regime: 3-D dynamics of plasma shield, radiative redistribution (optical transparency of ablated plasma) and target material surface response (melting, vaporization, cluster spallation, redeposition and resolidification)
- Present status: simulation with specialized 2-D and 3-D models (next VG)
- Model validation from plasma gun experiments (1-D); no data available or possible from present tokamaks ($W_{th}/A < 1$ MJ/m^2)
- Provisional conclusions:
  - — Target lifetime is acceptable (~100 disruptions) if melt loss effects are limited; worst-case progressive failure lifetimes are much shorter
  - — Massive (kg) quantities of material are involved/potentially transported: concerns are wall deconditioning, contamination, target damage (local)

2-D Simulation of Disruption Effect (ITER-FDR, Würz, Koening *et al*)



outboard divertor





Wall Deconditioning: a Critical BP Operation Issue?

- Significant after-disruption deconditioning of first walls owing to surface material modification effects of disruption is seen in present tokamaks
- The higher magnitude of specific energy in BPX disruptions makes it likely that deconditioning effects will be quantitatively more serious
- After-disruption wall reconditioning measures will be mandatory: the question/challenge lies in how other design constraints (steady-state TF field with SC magnets, limited pulse rate and number with resistive TF magnets, limits on wall coating, e.g., B or Li owing to T inventory) will impact the timely recovery of 'full-performance' wall conditions.
- If multiple reconditioning pulses are required after each disruption, and if disruption occurrence frequency on a per pulse basis is ~10% (see below), then loss of usable pulses becomes a serious BPX operation and 'science campaign' implementation issue

Electromagnetic Effects

- Electromagnetic effects of disruption in BPXs will not be qualitatively different for those seen in present experiments. But the magnitude of the forces and loadings will be higher

- The rapid current quench that follows disruption results in induced toroidal currents in toroidally-continuous plasma-facing structures (e.g., vacuum vessels), induced ‘eddy currents’ in isolated plasma-facing surfaces (e.g., first wall tiles) and, owing to loss of vertical equilibrium control after thermal quench, poloidal ‘halo currents’ in plasma-facing surfaces that have poloidal electrical continuity.

- Equivalent magnetic pressures are $\sim B_{pol}^2/2\mu_0$, or ~10 atm. Accommodation of the resulting global and local loadings is a matter of engineering design: solutions are possible, but space (radial build) is required and practical design solutions can adversely impact design complexity and maintenance

Runaway Electron Conversion

- **Potential for conversion of the pre-disruption plasma current to post-disruption runaway electron current via 'knock-on electron avalanche' is unique to the BP regime (exponential RAe growth if $E >> E_{crit}$)**

- **Avalanche multiplication (gain) increases rapidly with plasma current:**
  — for 'low-current' (2-5 MA), multiplication is 'small' (10^2-10^5),
  — for higher-current high-field BPXs, multiplication is moderate (10^7),
  — for highest-current 'reactor-like' SC devices (e.g., ITER), multiplication is extremely large ($\geq 10^{16}$)

- **For moderate (~10^7) gain, a substantial (~0.1 A) 'seed' population of initial runaways is required for after-disruption runaway current to reach dangerous levels (~1 MA); for reactor-like multiplication, even minute seed currents can lead to near-total thermal-to-runaway current conversion and ~10 MA runaway currents**

- **Prompt runaway losses from MHD fluctuation may offset some degree of avalanche gain, so estimates of possible after-disruption runaway levels in both resistive and SC BPXs are uncertain. *If* MA runaway currents develop, then serious local damage to at-risk PFCs is possible in one disruption**

Fast Plasma Power and Current Shutdown

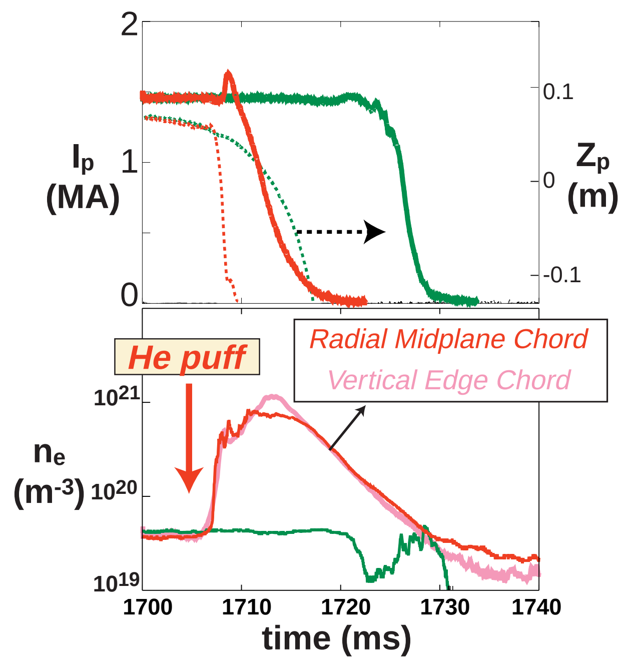
- The time required to effect a controlled and disruption-free shutdown of a BP is 5–100 s. Lower end of range applies to the most compact resistive magnet BPX candidates; upper end applies to large SC candidates
- These times are longer than the 'thermal tolerance' times of the at-risk plasma facing surfaces, hence 'fast' burn and current shutdown is desirable, and may even be mandated by regulatory authorities
- Triggering disruption is one certain means, but desire is for a shutdown which is more benign than an actual disruption. If this is possible, then preemptive application becomes a 'disruption mitigation' method
- Candidates: massive gas injection (next VG), liquid jet injection and massive pellet injection. Potential that BPXs have for runaway conversion argues for injecting low-Z materials: H/D or He or possibly Li
- Ability of gas and pellet injection to mitigate disruption and vertical displacement event (halo current) effects in present experiments is well documented. But how such mitigation/shutdown means extrapolate to BP regime remains an open research question, but recent DIII-D tests are encouraging

Energy can be dissipated via radiation of “impurities” introduced into the plasma on the time-scale of the disruption. Radiative mitigation > 90% has been achieved on current tokamaks.

	No puff	He puff
Gas injection	-----	10^{23} in ~10 ms
Peak I_{halo} (MA)	0.30	0.13
TPF	~2	1.2
Vessel movement (mm)	1.5 mm	< 0.9 mm
W_{floor} (MJ)	0.73	< 0.05
W_{rad} (MJ)	1.38	1.95

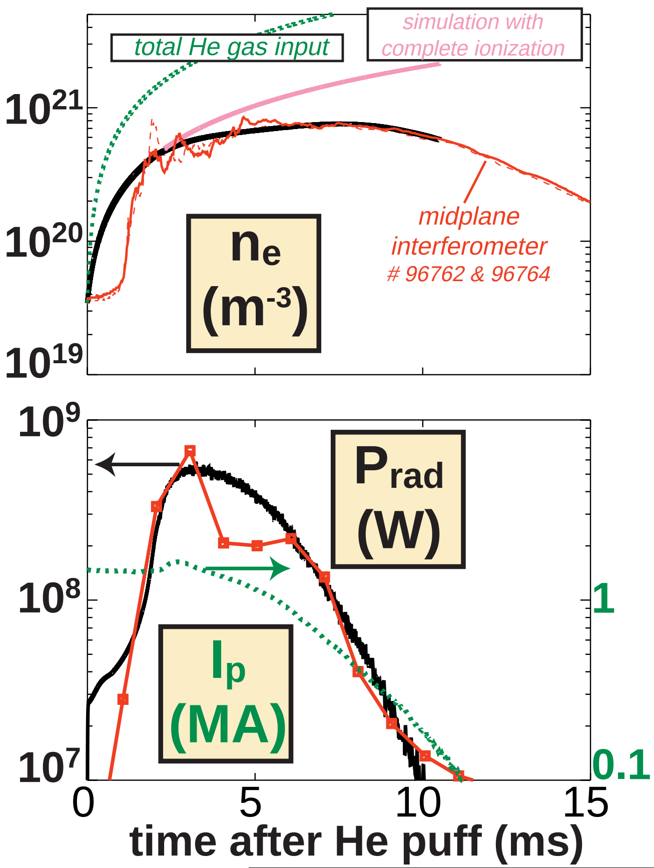
Reduced halo current (Peak I_{halo}, TPF, Vessel movement)

Radiation mitigation of divertor heat flux (W_{floor}, W_{rad})



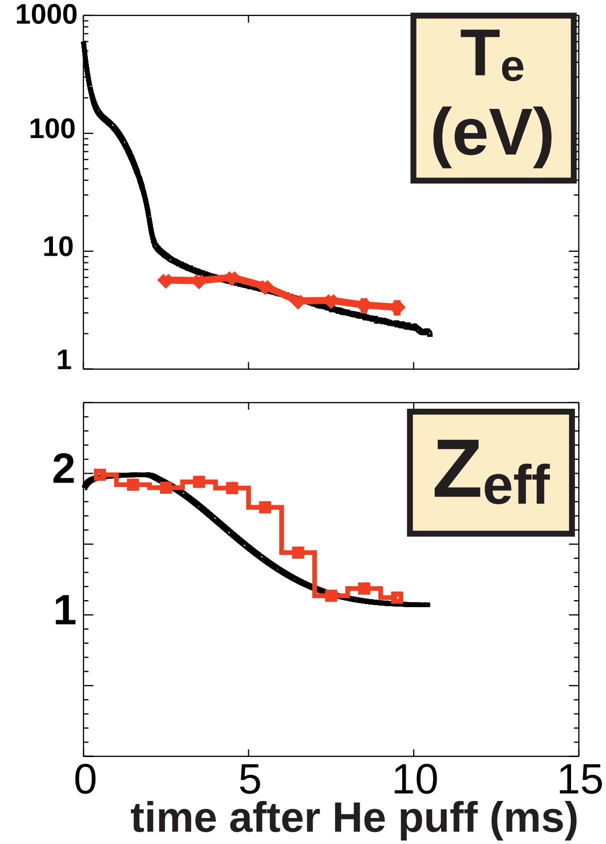
Example of DIII-D disruption mitigation with high-pressure(~ 70 atmospheres) He gas injection

Current radiation mitigation results are well understood in terms of injected species' radiation efficiency, penetration efficiency and the ionization & energy balance of the resulting plasma.



Model

Experiment



Example of DIII-D disruption mitigation modeling with high-pressure(~ 70 atmospheres) He gas injection

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Efficient penetration of a large impurity density has been achieved using high-pressure gas jets.

- ***Basic principle:***

  Higher pressure gas penetrates through lower pressure plasma

  – **Density of jet cloud can exceed cloud density around pellet.**

- **Preliminary results from DIII-D confirm this hypothesis.**

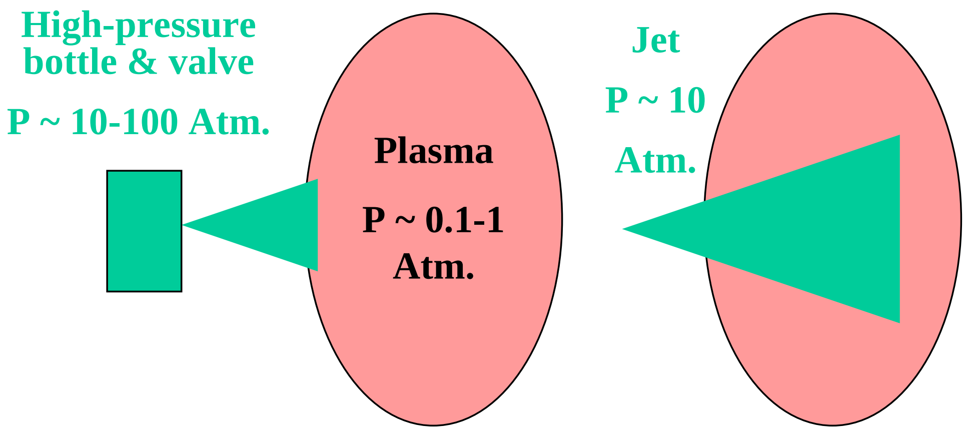
  – **Different gases penetrate equally well consistent with thermal time-of-flight for gas to center of plasma.**

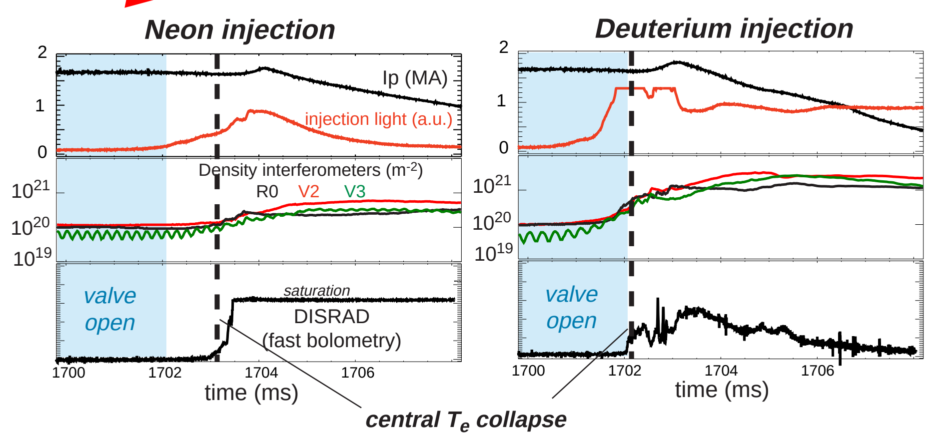
- **Advantages of method**

  – Simple technology.

  – Very large N_{inject}.

  – Jet pressures > burning plasma pressure (~1 Atm.) available.





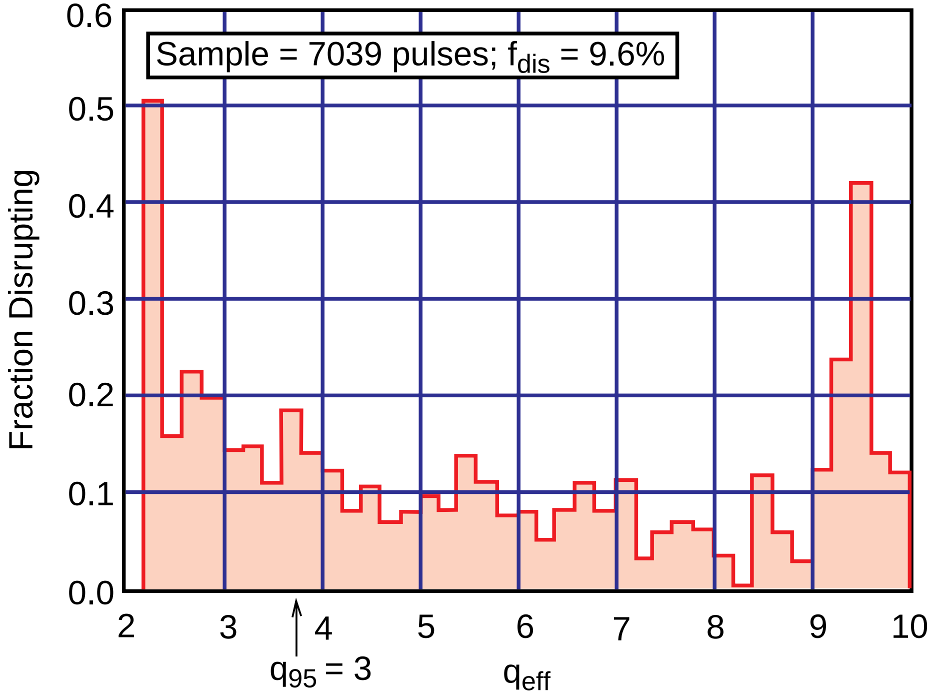
Disruption Frequency

- Frequency of disruption in present tokamaks on a per pulse basis can be ≤ 1% in well-documented and carefully-controlled discharges. This low frequency can be obtained even with ‘challenging’ high-performance discharges that lie close to a number of disruption-triggering MHD stability and plasma operation limits.

- Precise control of the various machine systems involved is essential, but once such ‘control’ (including proper wall conditioning) is obtained, discharges can be repeated with high reliability, and there appears to be little evidence for any secular tendency of such ‘well-set-up’ plasmas to disrupt as the duration of the full-performance phase is extended

- More frequent disruption occurs during exploratory campaigns necessary to establish such operation. Per-pulse frequency of disruption in present tokamaks conducting wide-ranging plasma development and science exploration campaigns is ~10%, and ‘new-regime’ and ‘performance optimization’ campaigns can produce frequencies of 30% and higher. ITER estimate is/was 10% overall, with periods of 30% frequency expected during initial hardware and BP operations procedure ‘development’ periods

Disruption Frequency in JT-60U (current flattop, no other selection)



- ~10% per pulse disruption likelihood is typical for present tokamaks with mature hardware, plasma control systems and wall conditioning procedures
- Most (essentially all) disruptions have an identifiable cause (MHD, power balance, hardware fault, control fault, operator error, ...). Occurence is ***not*** random (next VG)
- Frequency of unexpected/unexplained disruption in 'well-set-up' pulses is ≤ ~1%
- Incremental likelihood of disruption after 'steady-state' is reached is ≤ 1% per pulse

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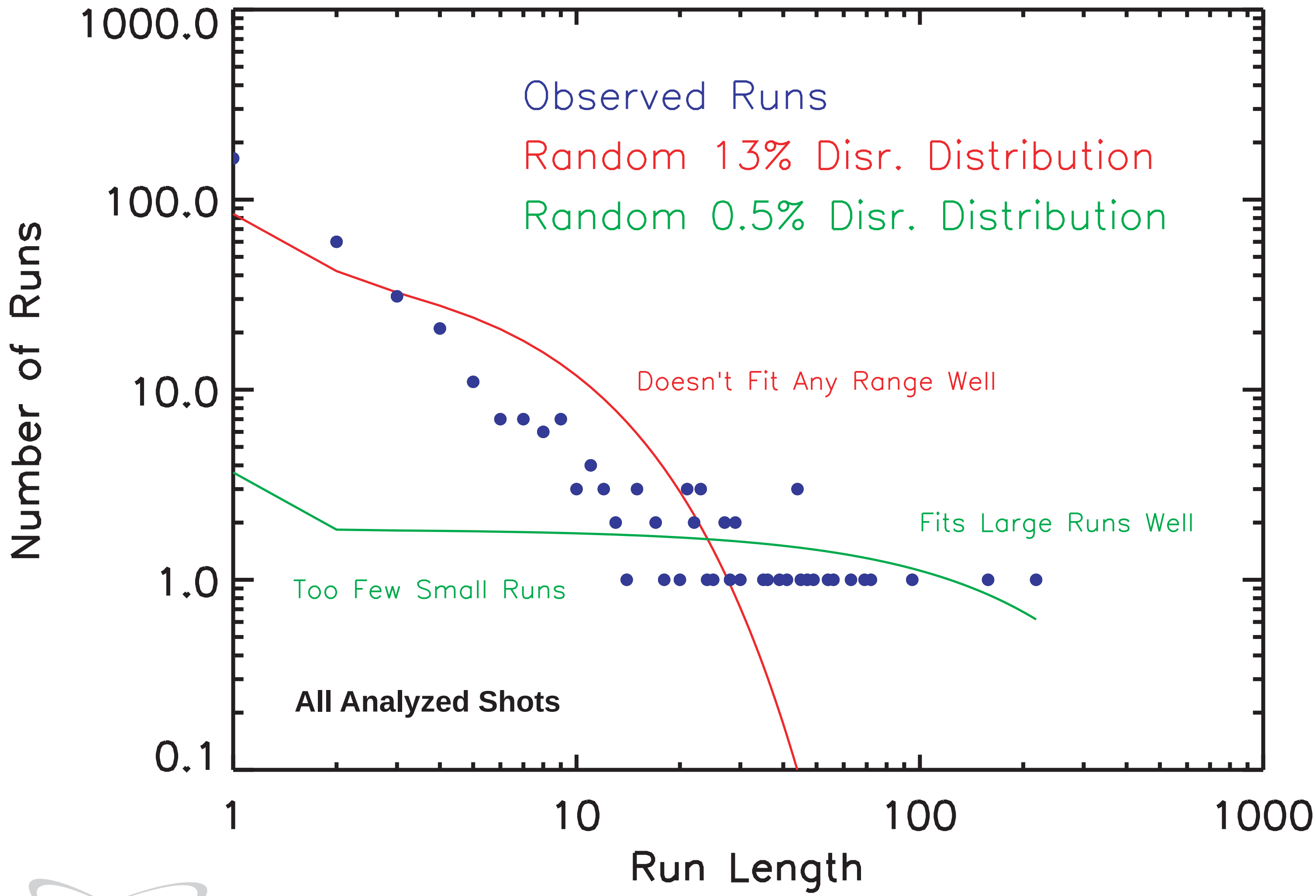
Observed Runs Distribution Is Not Random



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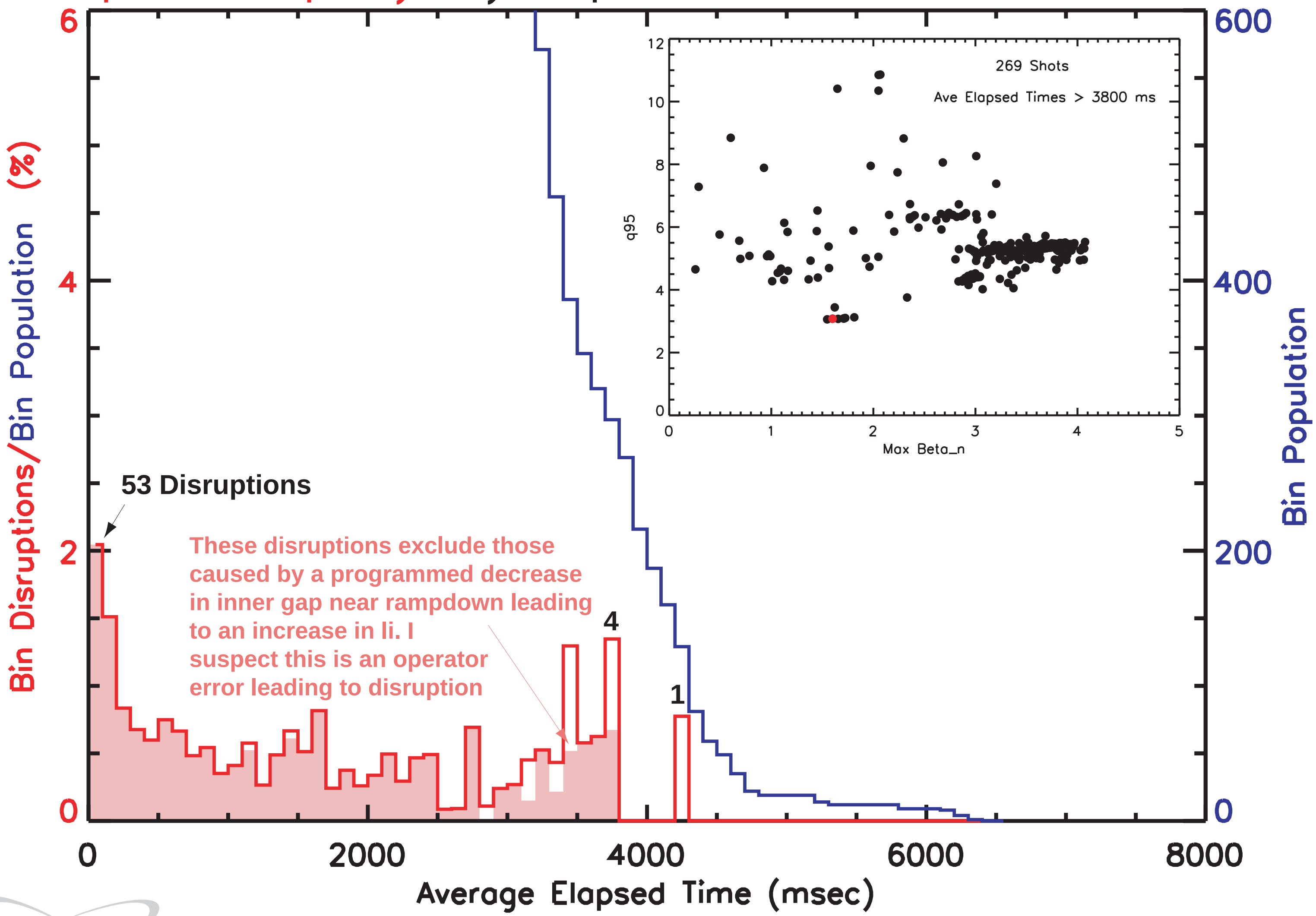
Elapsed Disruptivity May Drop To Zero As The Plasma Relaxes



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BP Disruption Science VG-17

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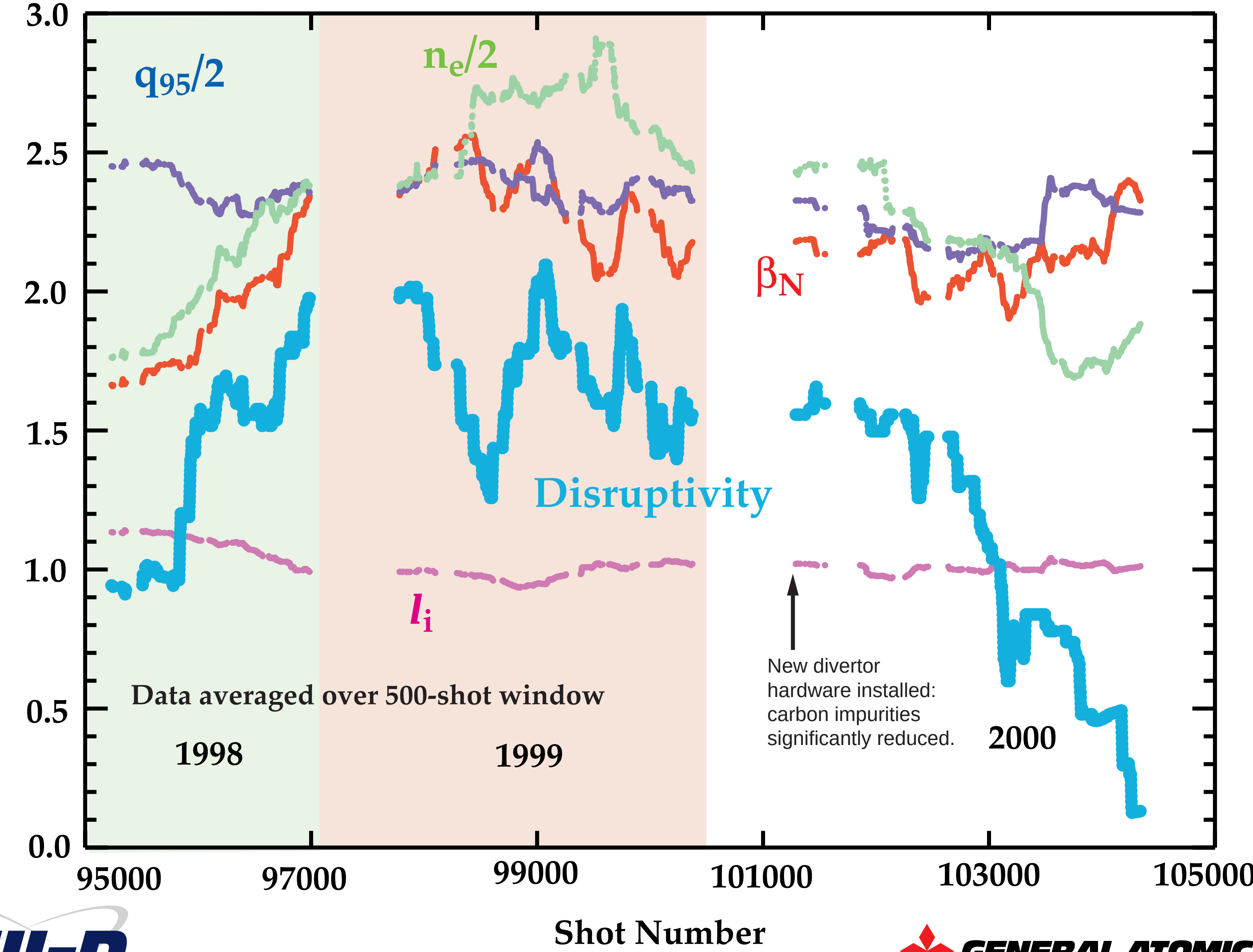
Average disruptivity does not correlate with β_N, l_i, q_{95} or n_e



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BP Disruption Science VG-18

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Disruption Avoidance

- The impact of ‘unnecessary’ disruptions on science data acquisition is well known in present experiments and can be expected to be equally (or more) important in future BPXs
- Explicit cost of one disruption in ITER FDR was estimated to be $ 1M, plus lost time and continuity in the acquisition of scientific data. There is a strong incentive to provide future BP operators and experimenters with as robust of an ***a priori*** predictive means of disruption avoidance as possible
- Various means, both direct (MHD stability) and indirect (neural networks, etc.) have been proposed and to some extent tested in present tokamaks, many times with substantial success, at least within a finite regime of operation. For a BPX, provision of a benign fast shutdown means that allows reliable plasma termination without adverse consequences (or with lesser consequences than a ‘natural’ disruption) will also be needed
- It is arguable that development of a reliable ‘vertically integrated’ disruption prediction and mitigation means constitutes an important (and necessary) ‘mission element’ for a BP science experiment and program

Summary

- ‘Disruption science’ and ‘BP-relevant’ disruption avoidance and/or mitigation means are essential elements of a BP fusion science program
- BP disruptions will have features (and science bases) that are qualitatively and quantitatively distinct from the corresponding aspects of disruptions in present tokamaks:
  - — massive divertor target evaporation, plasma shielding and in-divertor energy reradiation
  - — potential for more wall deconditioning and material transport
  - — potential for avalanche-driven runaway electron conversion
- The thermal-quench/high-specific-energy consequences of disruption in a BPX will be applicable to a broad range of toroidal confinement systems
- A BPX will provide a first-of-kind and unique ‘laboratory’ for fusion to address these burning plasma energy and ‘off-normal-event’ challenges
- Pursuit of ‘disruption science and avoidance/mitigation’ studies in the present MFE program is essential to have methods and understanding in place in time to support a BPX. Inadequate attention to such matters in a BPX design and program will compromise the overall science mission capability