NSTX-U PAC-31 questions – day 1

1a. What are the research priorities for the 5 year renewal period
  - That leverage new NSTX-U capabilities in advancing the 4 stated mission elements?
  - That address critical path issues to a FNSF?

1b. Use slide 50 in your talk to briefly describe the process for collaborations during the upgrade. Describe the status of the conversations with the collaborating facilities.

2. Based on density and power control consistent w/ existing database, what is projected pulse length for 1 MA? 2 MA?
3. Based on density and power control consistent with the existing database, what is the maximum current for fully non-inductive, 5 sec operation in NSTX-U?

Summary of response to question 1a:
5 research thrusts / high-level goals for 5 year plan

Note: as requested, these thrusts are ordered/prioritized assuming general FNSF needs - (not necessarily) ST-specific

- Demonstrate 100% non-inductive current at performance that extrapolates to ≥ $1 MW/m^2$ neutron wall loading in FNSF
- Access reduced ν^* combined with ability to vary q & rotation profile to dramatically extend ST plasma understanding
- Develop and utilize high flux expansion divertor magnetic configuration for heat flux mitigation
- Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation w/ small/no solenoid
- Assess high-Z PFCs + flowing liquid lithium to develop high-duty-factor integrated PFC/PMI solution for FNSF, beyond

Demonstrate 100% non-inductive current at performance that extrapolates to ≥ $1 MW/m^2$ neutron wall loading in FNSF

- Importance: Critical issue for using tokamak as steady-state neutron source (for both low and conventional A), Demo
  - Especially important for ST w/o solenoid, also informs ITER-AT
- Leverages:
  - New more tangential NBI for increased non-inductive current drive
  - Utilizes new higher B_T from new CS to increase plasma T, pulse-length
  - Lithium coatings, then cryo-pump for long-pulse density control
  - rt-MSE (funded thru collaboration), control collaboration w/ Lehigh, GA
  - Existing/new fast-ion diag. (FIDAs/ssNPA) for NBI redistribution
- Projected performance levels
  - – A ~ 1.7-1.8 , κ ~ 2.75-3, I_P ~ 1MA, $B_T \geq 0.75T$, $I_P/aB_T \geq 2.5\text{-}3.5$
  - – $\beta_N \geq 4.5$, $\beta_T \geq 10\text{-}15\%$, $n_e / n_G = 0.7\text{-}1$, $H_{98} \geq 1$
  - – Demonstrate this for few $\tau_E \rightarrow$ 1-2 τ_{CR} initially
  - – Extend to longer pulse with long-pulse divertor (including cryo), β and RWM control, J(r) control, disruption avoidance techniques

Access reduced ν* combined with ability to vary q & rotation profile to dramatically extend ST plasma understanding

- Importance: Understanding and optimizing confinement (core and edge) and stability (RWM/NTV) through ν* and *q* + rotation will be important for FNSF (low or conventional A)
  - Scaling of $B_T\tau_E$ with ν* important for compact low-A FNSF
- Leverage:
  - Projected 3-5x lower collisionality from higher temperature from:
    - 2x higher TF and I_P from new center-stack, structural enhancements
    - 2x higher heating power from 2nd NBI
  - Upgraded high-k_θ diagnostic, increased BES resolution, polarimetry
  - Existing 2nd SPA for EFC/RWM coil spectral flexibility
  - Off-axis NBI current-drive and momentum deposition to modify q, Ω
  - NCC coils for improved rotation control (up to n=6), ELM control, and increased stable operating β
- Unique high β + low ν* plasmas to validate range of models, provide knowledge-base for FNSF, ITER, Pilot/Demo

Develop and utilize high flux expansion divertor magnetic configuration for heat flux mitigation

- Importance: heat-flux mitigation in divertor critical issue for using tokamak as steady-state neutron source, Demo
  - Projected peak heat fluxes at low-A and high-A above long-pulse material limits for conventional divertor
- Leverages:
  - High (unmitigated) peak heat flux accessible in NSTX-U (30-45MW/m^2) from increased NBI (+ HHFW) power, narrower SOL at 2MA
  - New up/down symmetric divertor PF coils implemented in new CS
  - Snowflake x-point control being developed in PCS (w/ LLNL and GA)
  - Cryo-pumping for ability to systematically vary core and SOL density
- Scientific approach:
  - Measure and model peak heat flux reduction vs. flux expansion, core density, impurity content/radiation, and access to partial detachment
  - Contribute to improving predictive capability for detachment, and detachment control - remain critical issues for ITER, next-steps

Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation w/ small/no solenoid

- Importance: Low-A FNSF requires substantial/full non-inductive start-up/ramp-up current

- Leverages:
  - More tangential 2nd NBI couple to/ramp-up low-I_P target plasma
  - Higher field and pulse-length of new CS for stability, profile equilibration
  - Upgraded CHI + higher TF (1T) to increase start-up current to ~0.4MA
  - Existing HHFW heating and current drive for NBI ramp-up target
  - ECH: 1MW 28GHz for heating start-up plasma for HHFW/NBI ramp-up
  - Metallic divertor (to reduce impurity radiation during CHI)
  - Plasma guns to provide/test retractable helicity injection start-up

- Develop predictive capability
  - 2D and 3D models of plasma start-up and ramp-up – TSC, TRANSP, NIMROD, possibly M3D-C1

Assess high-Z PFCs + flowing liquid lithium to develop high-duty-factor integrated PFC/PMI solution for FNSF, beyond

- Importance: high-Z (namely W) is leading candidate for PFC in FNSF, and there are major concerns about sputtering/erosion that motivate replenished/flowing liquid lithium/metals
- Leverages:
  - NSTX Li coating experience that shows little lithium going into core plasma, reduced recycling, improved confinement & ELM stability
  - CDX-U tray results on heat-flux handling ability of liquid metals
  - LTX high-Z wall experiments with and without lithium (solid & liquid)
  - NSTX LLD experience of Li on porous Mo to protecting underlying PFC
  - MAPP tests on LTX for NSTX-U + lab-based R&D on surface chemistry
  - Lab-based R&D on flowing liquid metal concepts, emphasizing reliability
  - High heat flux (energy to divertor) accessible in NSTX-U with 2nd NBI
- Approach: progressively test Mo (or W) tiles in divertor → FW
- Implement flowing Li when technically ready
  - Proceed in way compatible with other goals described previously

Q1b “Collaborations: Held team-wide discussion on FY12-13 opportunities and expectations in Sep-Dec 2011” (started Mar/Apr 2011)

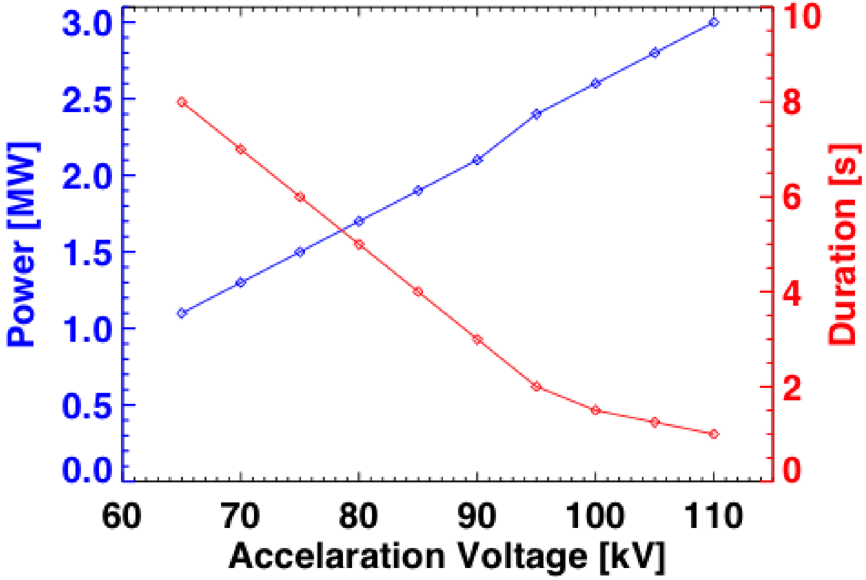
- Collaboration should aim to support NSTX-Upgrade mission
  - Also support toroidal physics generally, ICCs, and non-fusion applications
- For all researchers, use Upgrade outage as opportunity to:
  - Extend and improve your ongoing and future research on NSTX
  - Learn about other facilities – bring back knowledge, best practices
  - Try or learn something new – new physics, diagnostics, analysis, …
- Aim to form small teams from NSTX (PPPL + non-PPPL)
  - Coordinate research plans, analysis, travel, and participation
- Expectations for researchers:
  - Select 1 primary and 1 secondary/backup collaboration project
  - Aim for 1st author papers, invited talks – PRL/NF/PoP, APS/IAEA
  - Present your results periodically to NSTX, PPPL research seminars
- Facilities: MAST, DIII-D, C-Mod, LHD, EAST, KSTAR, JET, more to come
- Funding: PPPL covers salaries of PPPL NSTX researchers by default
- Challenge: no additional NSTX funding dedicated to collaboration
- Working closely with PPPL off-site research department

Summary of Answers to questions #2 and #3

- Q: Maximum pulse length at 1MA, 0.75T, 1st year parameters?
  - A1: Full 5 seconds at 1025-1300 kA, four 80 kV sources, $q_{min}>1$, w/o challenging I^2t on any coil.
  - A2: Can achieve 8-10 seconds at ~1 MA using six 65 kV or interleaved modulated 80 kV beams, $q_{min}>1$, approaching OH and TF I^2t limits.
- Q: Maximum pulse length at 2 MA, 1T?
  - 2 MA operation requires 1T, is likely limited by q-evolution rather than solenoid flux or heating.
    - Current redistribution time with six 80 kV beams is 0.6-0.8 at $f_{GW}=0.7$.
  - A: For year 2 operation with 1-2 sec TF flat-top, can use the full TF w/o encountering OH I^2t limit or q_{min} problems.
    - Allow physics studies of PMI, BP, MS, EPs, transport and turbulence.
    - Will fit in PFC temperature limit w/ SFD and some divertor radiation.
- Q: Maximum current that can be sustained non-inductively for 5 seconds (80 kV Beams)?
  - A1: 635-800 kA with four beams, 0.75 T
  - A2: 750-1225 kA with six beams, 1.00 T

Background Information On Simulations (Much Covered in ASC Talk)

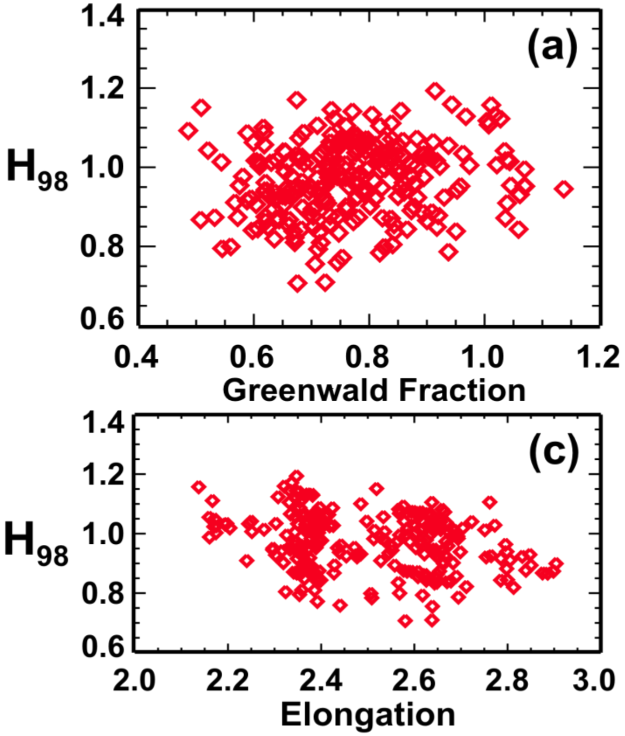
- Typically assess a scenario using two profile and two confinement assumptions.
  - Good for bracketing the expected operating points.
- Central NBCD tends to drive down q_{min} for f_{GW}<~0.7.
  - The exact low-density boundary for $q_{min}=1$ depends on the configuration.
- NSTX discharges become strongly susceptible to core m/n = 1/1+2/1 modes as q_{min} approaches 1.
  - ***Define "maximum sustainable current" as that which leads to q_{min}~1.1-1.2.***
  - Typically more limiting than the solenoid flux or I^2t limits.



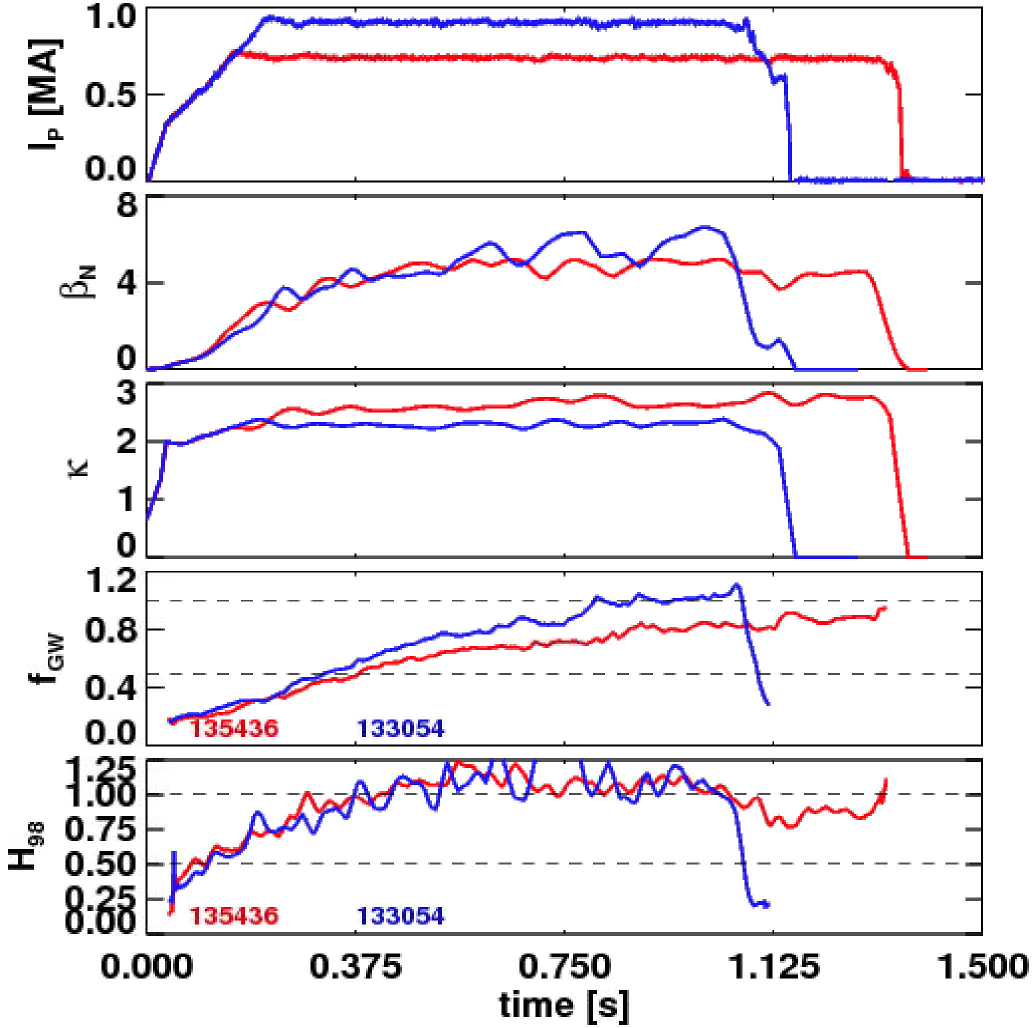
- Heating duration is a strong function of the beam voltage.
  - Limits are due to heating on the primary energy ion dump.
    - Upgraded ion dumps could result in extension of pulse lengths.
  - 5 seconds generally required 80 kV sources, with 1.7 MW/source

Discharges Have Shown Good Confinement and High Density and Elongation.

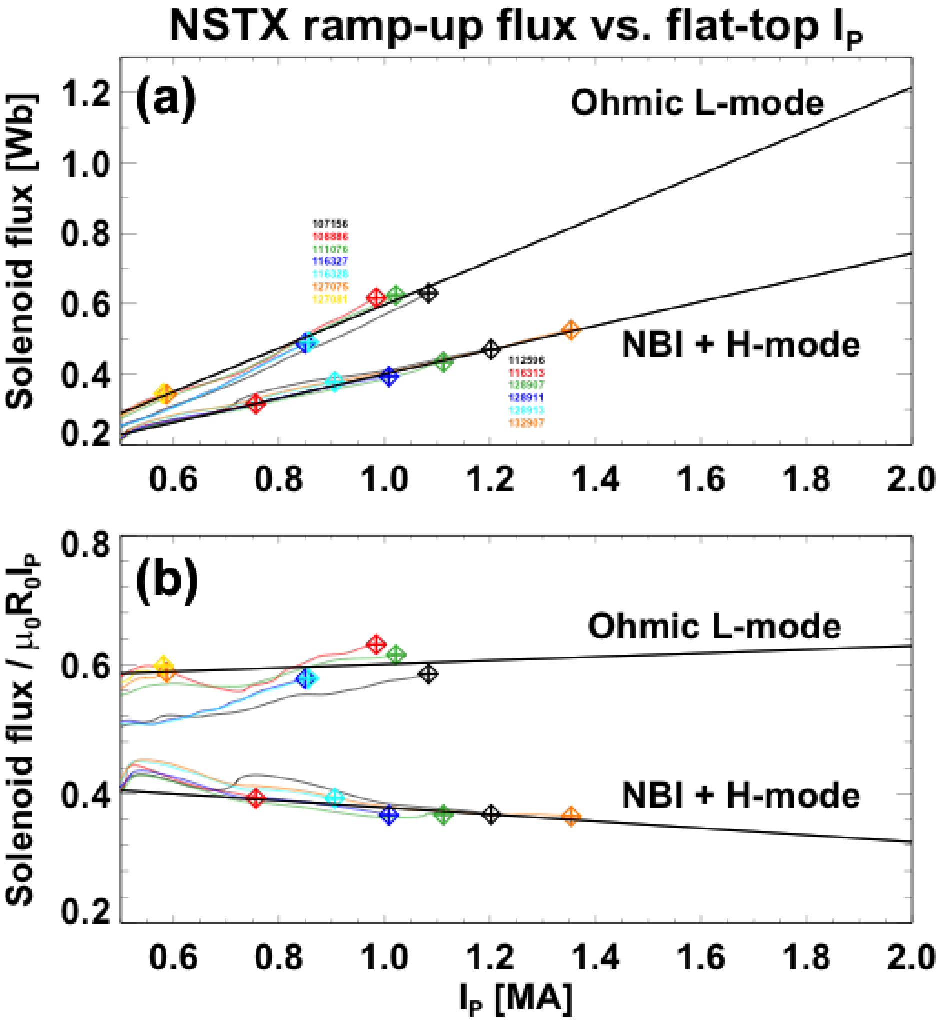
- Upgrade simulations generally call for H_{98}=1 at $0.65<f_{GW}<1.0$.
- Database analysis shows this regime is accessible with Upgrade-relevant shaping.



Time Traces of Discharges with Good Confinement at High Density



Flux Consumption Assumptions for the Upgrade Based on Extrapolation of NSTX Results

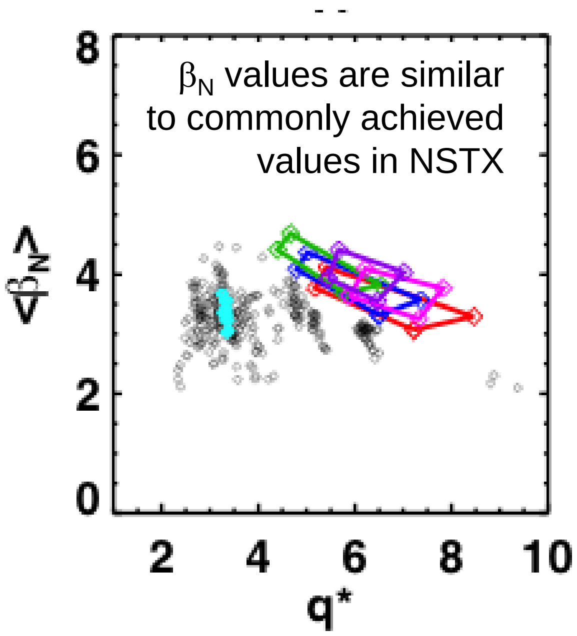


- Upgrade OH capacity is substantially improved
  - Factor 3.5 increase in I^2t limit.
  - Vs capability increased from 0.75 Wb to 2.1 Wb.
  - Very few high-performance scenarios limited by flux consumption.
    - Extrapolate ramp-up flux for 2MA as ~0.8 Wb.
    - Must keep surface voltage under (2.1-0.8)/5 = 0.25 V
    - 2MA scenarios project to 0.2-0.3 V.
- Similar increase in TF capability.
  - Factor of 20 increase in I^2t.
  - Maximum field increase by factor of ~2.
  - Results in quite long TF Flat-top durations compared to NSTX.
    - ~6.5 s at 1 T, ~11.5 s at 0.75 T

Question: Non-Inductive Sustainment Level for 5 seconds? Answer: 750-1225 kA for 1T, 635-800 kA for 0.75 T

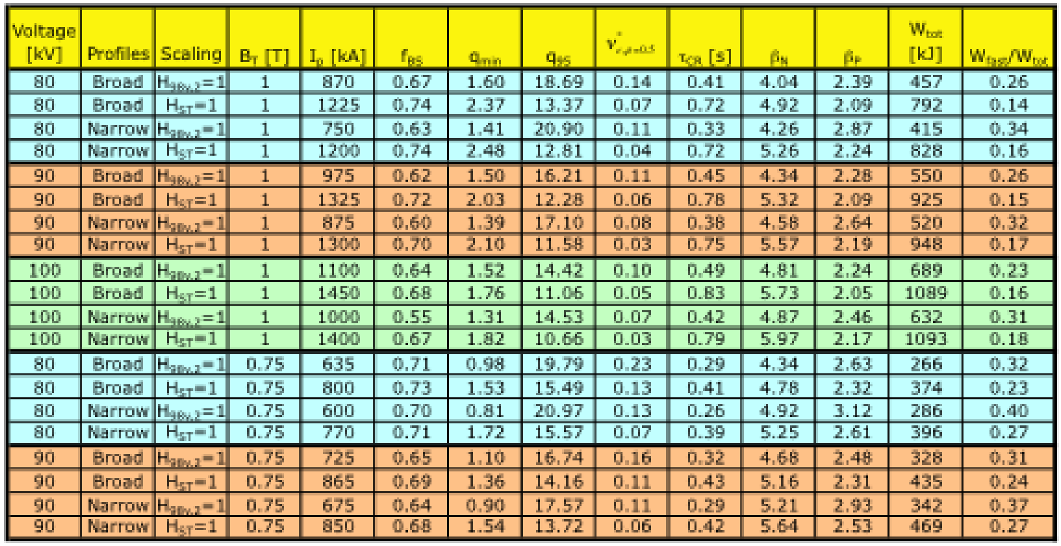
Summary of Fully Non-Inductive Scenarios at 0.75 & 1 T

Voltage [kV]	# of Sources	Heating Duration	B_T [T]	Non-Inductive Current Range	Current Time [s]
80	4	5	0.75	635-800	0.25-0.4
90	4	3	0.75	675-865	0.3-0.43
80	6	5	1.0	750-1225	0.35-0.7
90	6	3	1.0	875-1325	0.4-0.8



β_N values are similar to commonly achieved values in NSTX

All the details for the 100% non-inductive scenarios

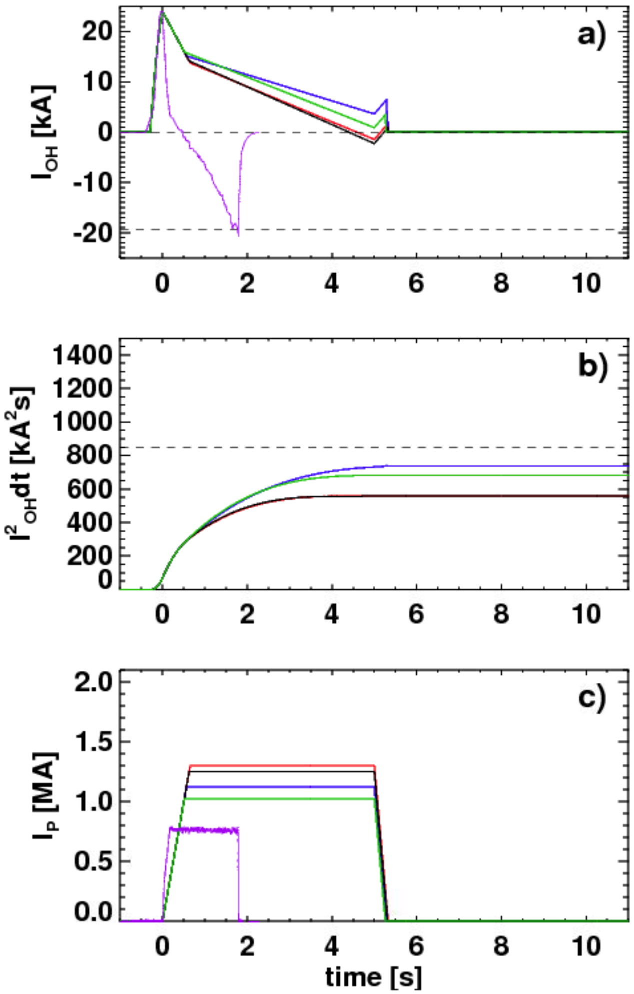


Voltage [kV]	Profiles	Scaling	B_T [T]	I_p [kA]	f_{BS}	q_{min}	q_{95}	$v^*_{e,\rho=0.5}$	τ_{CR} [s]	β_N	β_P	W_{tot} [kJ]	W_{fast}/W_{tot}
80	Broad	$H_{98y,2}=1$	1	870	0.67	1.60	18.69	0.14	0.41	4.04	2.39	457	0.26
80	Broad	$H_{ST}=1$	1	1225	0.74	2.37	13.37	0.07	0.72	4.92	2.09	792	0.14
80	Narrow	$H_{98y,2}=1$	1	750	0.63	1.41	20.90	0.11	0.33	4.26	2.87	415	0.34
80	Narrow	$H_{ST}=1$	1	1200	0.74	2.48	12.81	0.04	0.72	5.26	2.24	828	0.16
90	Broad	$H_{98y,2}=1$	1	975	0.62	1.50	16.21	0.11	0.45	4.34	2.28	550	0.26
90	Broad	$H_{ST}=1$	1	1325	0.72	2.03	12.28	0.06	0.78	5.32	2.09	925	0.15
90	Narrow	$H_{98y,2}=1$	1	875	0.60	1.39	17.10	0.08	0.38	4.58	2.64	520	0.32
90	Narrow	$H_{ST}=1$	1	1300	0.70	2.10	11.58	0.03	0.75	5.57	2.19	948	0.17
100	Broad	$H_{98y,2}=1$	1	1100	0.64	1.52	14.42	0.10	0.49	4.81	2.24	689	0.23
100	Broad	$H_{ST}=1$	1	1450	0.68	1.76	11.06	0.05	0.83	5.73	2.05	1089	0.16
100	Narrow	$H_{98y,2}=1$	1	1000	0.55	1.31	14.53	0.07	0.42	4.87	2.46	632	0.31
100	Narrow	$H_{ST}=1$	1	1400	0.67	1.82	10.66	0.03	0.79	5.97	2.17	1093	0.18
80	Broad	$H_{98y,2}=1$	0.75	635	0.71	0.98	19.79	0.23	0.29	4.34	2.63	266	0.32
80	Broad	$H_{ST}=1$	0.75	800	0.73	1.53	15.49	0.13	0.41	4.78	2.32	374	0.23
80	Narrow	$H_{98y,2}=1$	0.75	600	0.70	0.81	20.97	0.13	0.26	4.92	3.12	286	0.40
80	Narrow	$H_{ST}=1$	0.75	770	0.71	1.72	15.57	0.07	0.39	5.25	2.61	396	0.27
90	Broad	$H_{98y,2}=1$	0.75	725	0.65	1.10	16.74	0.16	0.32	4.68	2.48	328	0.31
90	Broad	$H_{ST}=1$	0.75	865	0.69	1.36	14.16	0.11	0.43	5.16	2.31	435	0.24
90	Narrow	$H_{98y,2}=1$	0.75	675	0.64	0.90	17.57	0.11	0.29	5.21	2.93	342	0.37
90	Narrow	$H_{ST}=1$	0.75	850	0.68	1.54	13.72	0.06	0.42	5.64	2.53	469	0.27

Question: Pulse Duration at 1 MA?

Answer #1: At 0.75 T, the Maximum Sustainable Current is in the Vicinity of 1000-1300 kA for 5 Seconds.

1100-1300 kA Scenarios Don't Challenge OH Coil Limits

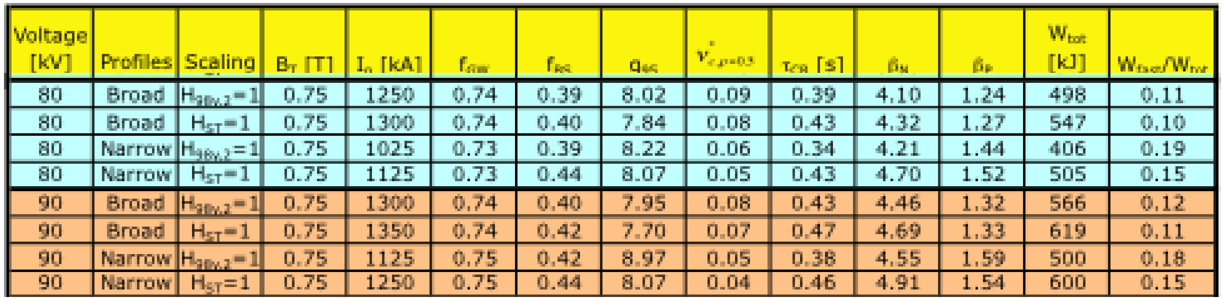


Summary of 0.75 T scenarios with q_{min}~1.15

Sustainable current exceeds 1 MA at 0.75 T, even for most pessimistic confinement assumptions

Voltage	# of Sources	Heating Duration	B_T [T]	Range of Sustainable Currents	Current Time [s]
80	4	5	0.75	1025-1300	0.35-0.45
90	4	3	0.75	1125-1350	0.4-0.5

Table With Complete Details on 0.75 T Scenarios with q_{min}~1.15

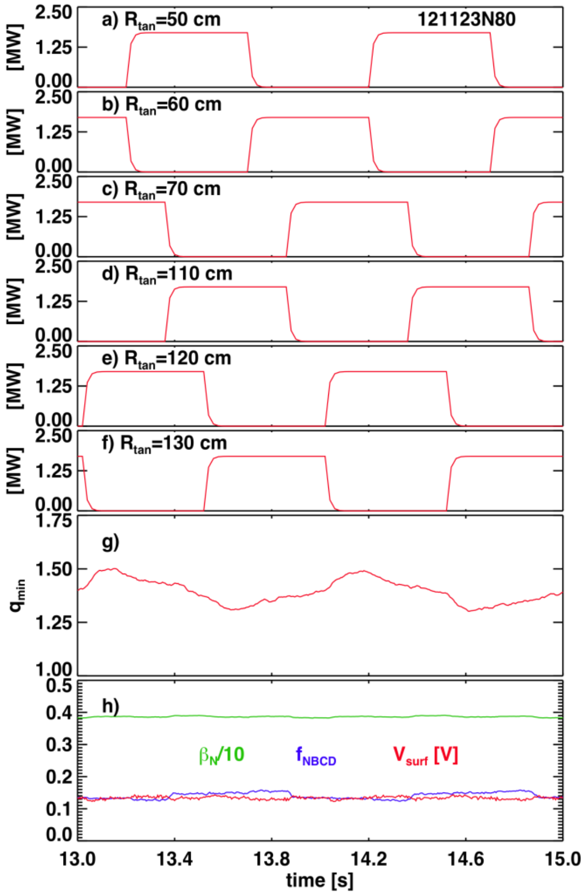


Voltage [kV]	Profiles	Scaling	B_T [T]	I_P [kA]	f_{GW}	f_{BS}	q_{95}	$\nu^*_{e,\rho=0.5}$	τ_{CR} [s]	β_N	β_P	W_{tot} [kJ]	W_{fast}/W_{tot}
80	Broad	$H_{98y,2}$=1	0.75	1250	0.74	0.39	8.02	0.09	0.39	4.10	1.24	498	0.11
80	Broad	H_{ST}=1	0.75	1300	0.74	0.40	7.84	0.08	0.43	4.32	1.27	547	0.10
80	Narrow	$H_{98y,2}$=1	0.75	1025	0.73	0.39	8.22	0.06	0.34	4.21	1.44	406	0.19
80	Narrow	H_{ST}=1	0.75	1125	0.73	0.44	8.07	0.05	0.43	4.70	1.52	505	0.15
90	Broad	$H_{98y,2}$=1	0.75	1300	0.74	0.40	7.95	0.08	0.43	4.46	1.32	566	0.12
90	Broad	H_{ST}=1	0.75	1350	0.74	0.42	7.70	0.07	0.47	4.69	1.33	619	0.11
90	Narrow	$H_{98y,2}$=1	0.75	1125	0.75	0.42	8.97	0.05	0.38	4.55	1.59	500	0.18
90	Narrow	H_{ST}=1	0.75	1250	0.75	0.44	8.07	0.04	0.46	4.91	1.54	600	0.15

Question: Pulse Duration at 1 MA?

Answer #2: Heating and magnetic system capable of 8-10 s ~1 MA pulses!

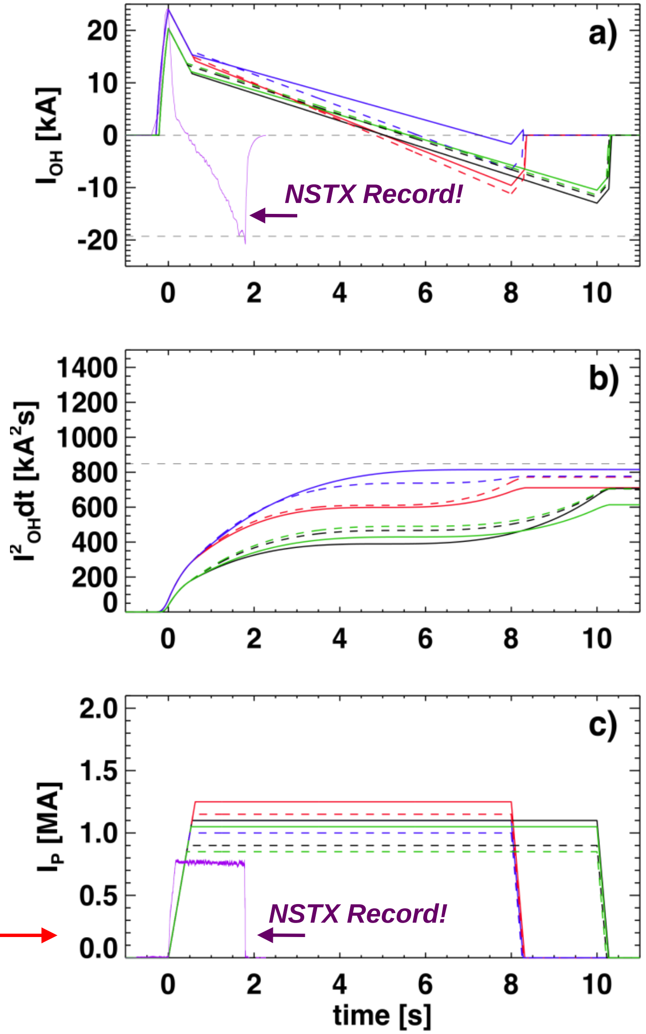
- B_T=0.75 T scenarios with 5.1 or 6.6 MW input power
  - Interleaved 80 kV case can sustain q_{min}> 1with 850-1050 kA for 10 sec.
  - 65 kV case can sustain q_{min}>1 with I_P=1000-1250 kA for 8 sec.



Example Beam Modulation Pattern Designed to Minimize q_{min} Variation

Results in 5.1 MW for 10 s!

Solenoid Current & Heating, and Plasma Current Waveforms



Question: Pulse Duration at 2 MA?

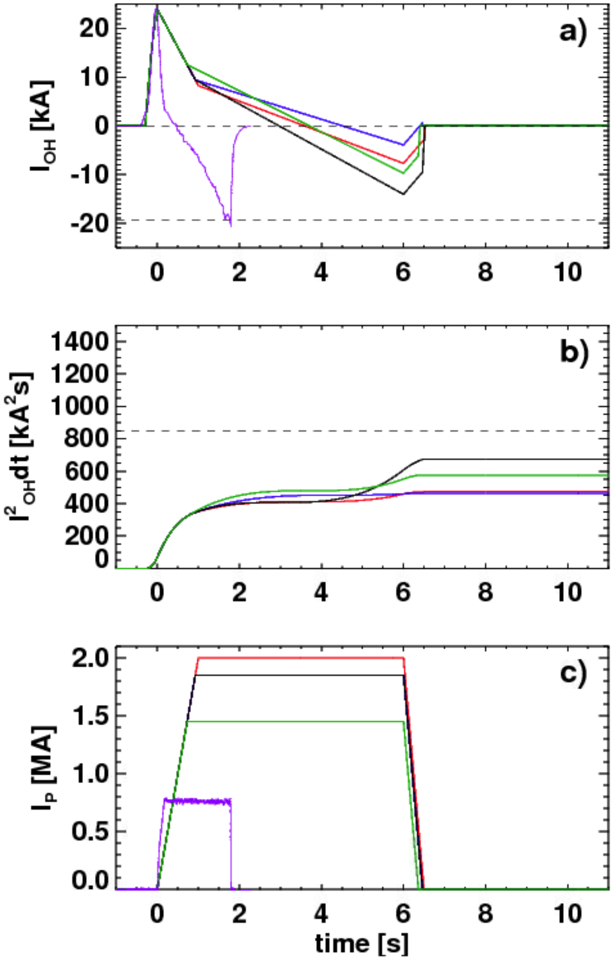
Answer 1: The “maximum sustainable current” is typically a somewhat less than 2 MA.

Summary of 1.0 T scenarios with q_{min}~1.15

Only most optimistic projections at high f_{gw} result in relaxed q_{min}>1 at 2 MA

Voltage [kV]	# of Sources	Heating Duration [s]	B_T [T]	f_{GW}	Range of Sustainable Currents [kA]	Current Time [s]
80	6	5	1.0	0.7	1250-1800	0.44-0.8
80	6	5	1.0	1.0	1500-2000	0.4-0.6
90	6	3	1.0	0.7	1350-1900	0.5-0.85

10.2 MW, 1500-2000 kA Scenarios at f_{GW}=1 Don’t Challenge OH Coil Limits



Question: Pulse Duration at 2 MA?

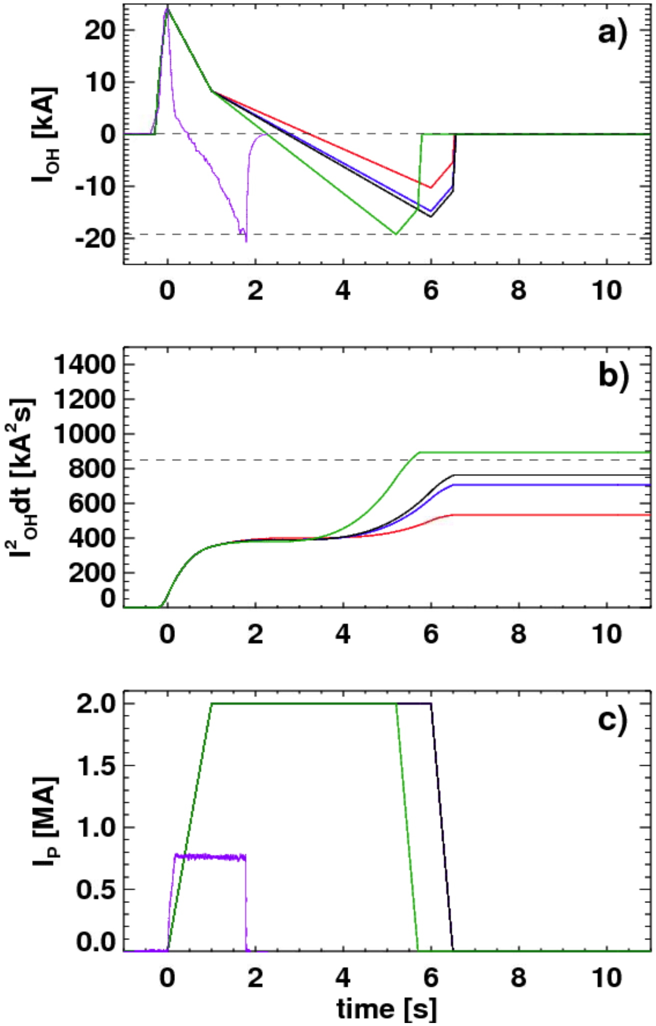
Answer 2: Long Current Redistribution Times Will Allow Long Pulse

Summary of 10.2 MW, 1.0 T , 2 MA, 5 sec. scenarios

Scaling	Relaxed q_{min}	Current Time [s]
ITER	0.46-0.54	0.65
ST	0.78-0.85	0.75-0.8

- NSTX discharges evolving to $q_{min}<1$ typically last ~4 τ_{CR}.
- By similar logic, expect 2-3 seconds at 2 MA.
    - Sufficient for all confinement, stability, and boundary physics studies.

2000 kA Scenarios at f_{GW}=0.7 Only Challenge OH Coil For Unfavorable Confinement and Profiles



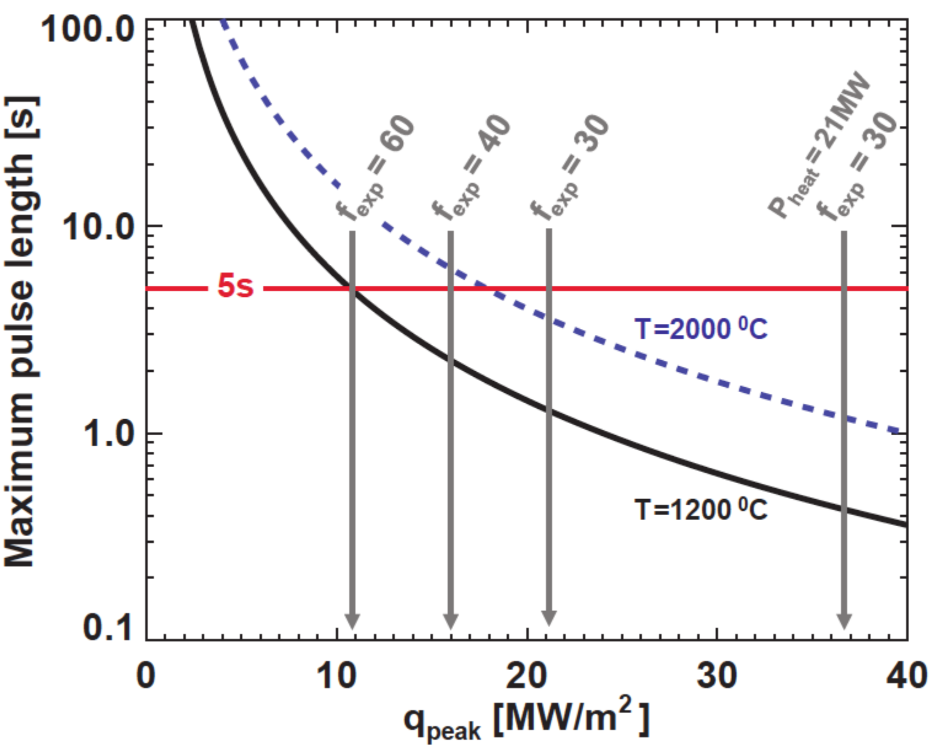
Divertor Temperature Can Be A Pulse Length Limiting Factor

- For f_{exp}=30 and f_{div}=0.5, and no radiation:
  - Limited to ~1.5 second for a 1200 C divertor.
  - Approximately matches the expected pulse length for year 2, 1 T, 2MA operation.
- Relief could come from impurity radiation.
  - Snowflake divertor utilized to achieve large f_{exp} promotes detachment.
  - Research plan will develop radiative divertor control if SFD does not naturally develop them.
  - Higher density for q_{min}>1 purposes helps promote divertor radiation solutions.

$$Q_{out}^{peak} = \frac{P_{heat}^{SOL}(1 - f_{rad}) f_{div} \sin(\theta_{plate})}{2\pi R_{strike} f_{exp} \lambda_q}$$

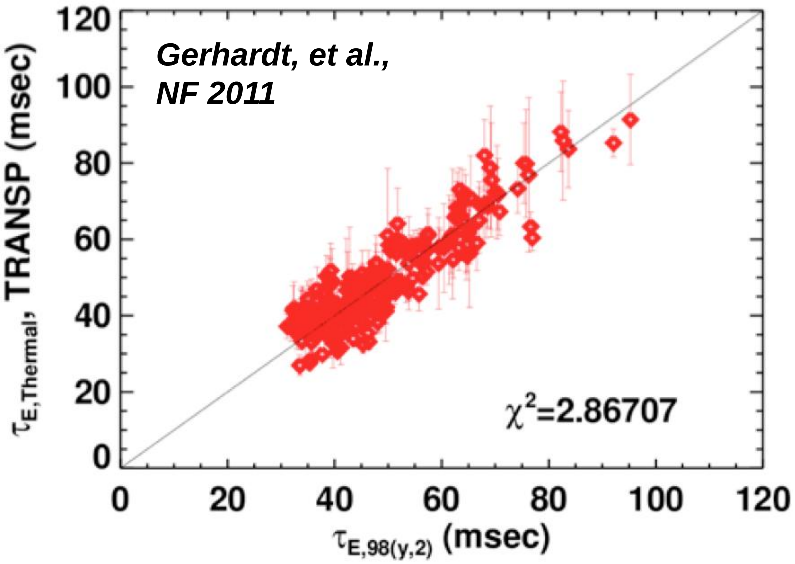
Pulse Length as a Function of Peak Heat Flux.
Menard, et al., submitted to Nuclear Fusion

P_{heat} = 12MW, I_P = 2MA, f_{div} = 0.5, R_{div} = 0.5, λ_q^{mid} = 3mm



NSTX Context For Confinement and Flux Consumption Assumptions in Upgrade

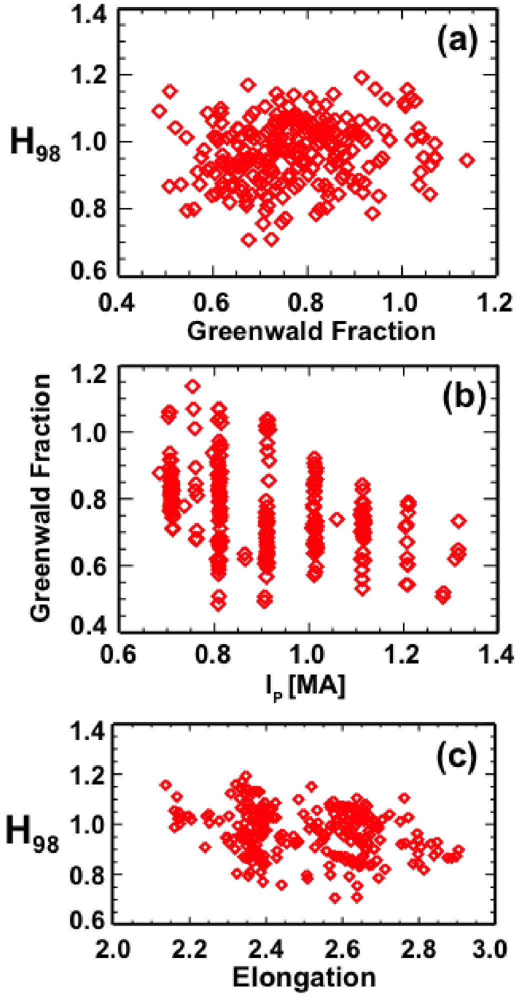
Confinement Quality in Recent Lithiated Discharges Agrees Strikingly Well with ITER-98y,2



Gerhardt, et al., NF 2011

See comparison to "ST-Scaling" in talk by Y. Ren.

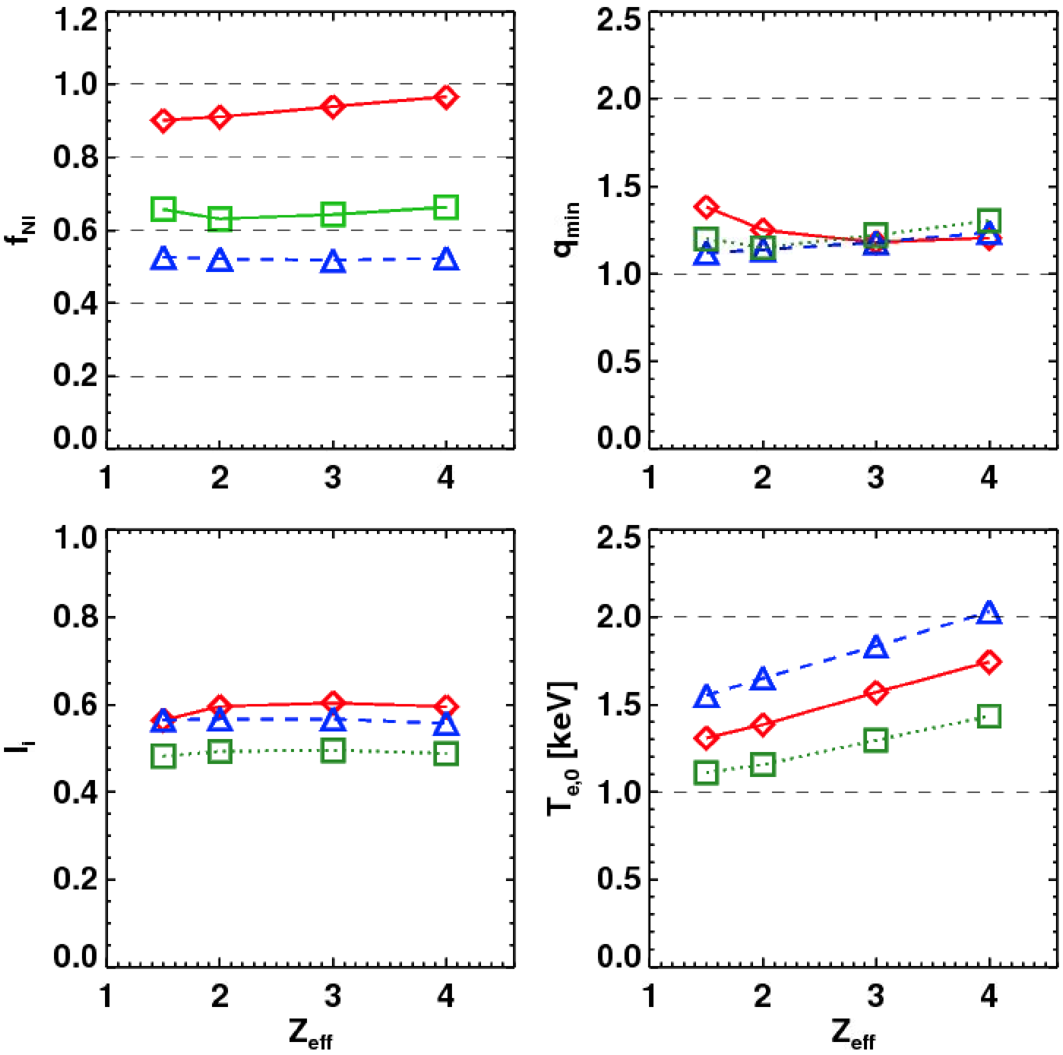
Relationship Between Confinement, Density, and Elongation



Menard, et al., Submitted to Nuclear Fusion

Scenario Goals Can be Met over a Range of Z_{eff}, Provided Confinement is Maintained

- Li H-modes, even w/ small ELMs and controlled density, tend to have Z_{eff}~2-4.
  - Best confinement at the higher Li evaporation rates.
- Increasing Z_{eff} with fixed T_e reduces non-inductive fraction.
- Increased Z_{eff}, with fixed H_{98}, results in very little change.
  - H_{98}~1 confinement (or better) observed in lithiated H-modes over a range of Z_{eff}
- The electron confinement is a critical variable in determining the scenario performance.



1.0 MA, 1.0 T, P_{inj}=12.6, near non-inductive

1.6 MA, 1.0 T, P_{inj}=10.2 MW, partial inductive

1.2 MA, 0.55 T, P_{inj}=8.4 MW, high β_T

All: f_{GW}=0.7, H_{98}=1