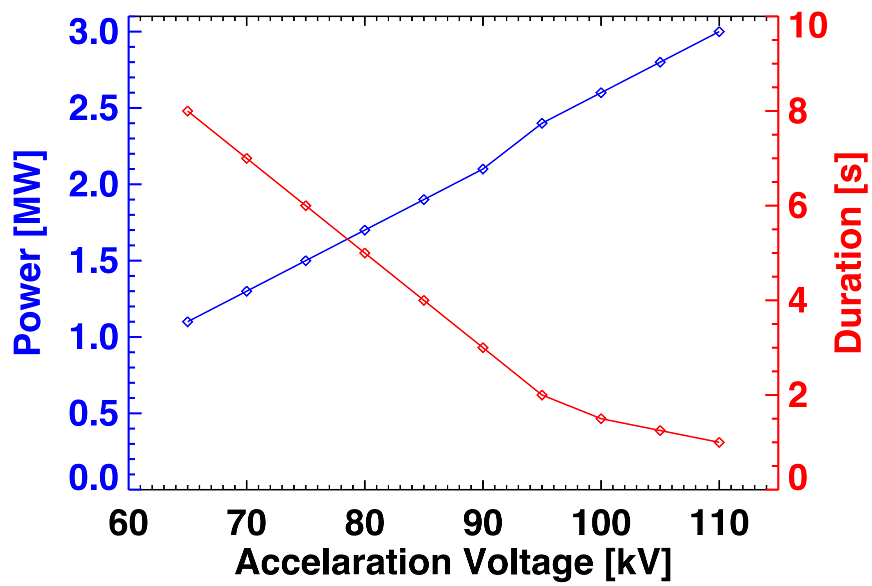
Summary of Answers

- 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)

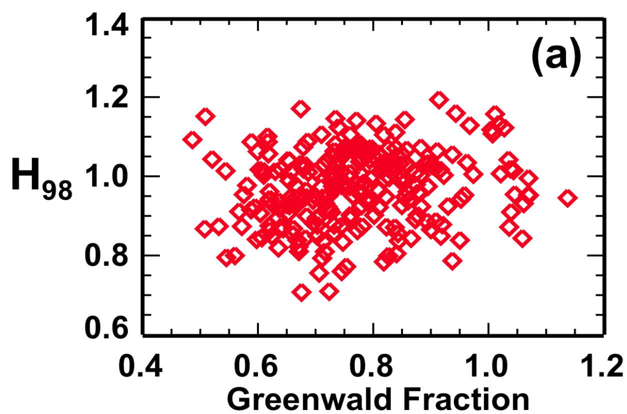
- Typically assess a scenario using two profile and two confinement assumptions.
  - Good for bracketing the expected operating points.
- Central NBCD tends to drive down q_{min} for f_{GW}<~0.7.
  - The exact low-density boundary for q_{min}=1 depends on the configuration.
- NSTX discharges become strongly 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.

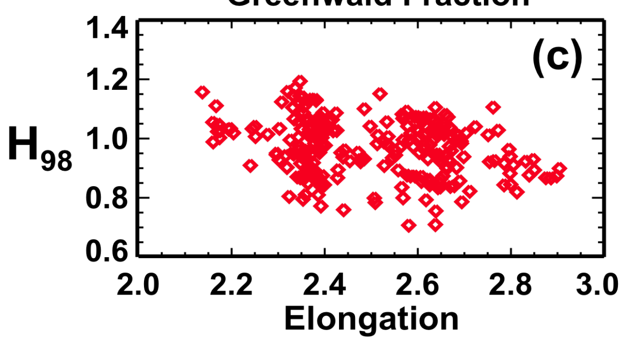


- Heating duration is a strong function of the beam voltage.
  - Limits are due to heating on the primary energy ion dump.
    - Upgraded ion dumps could result in extension of pulse lengths.
  - 5 seconds generally required 80 kV sources, with 1.7 MW/source

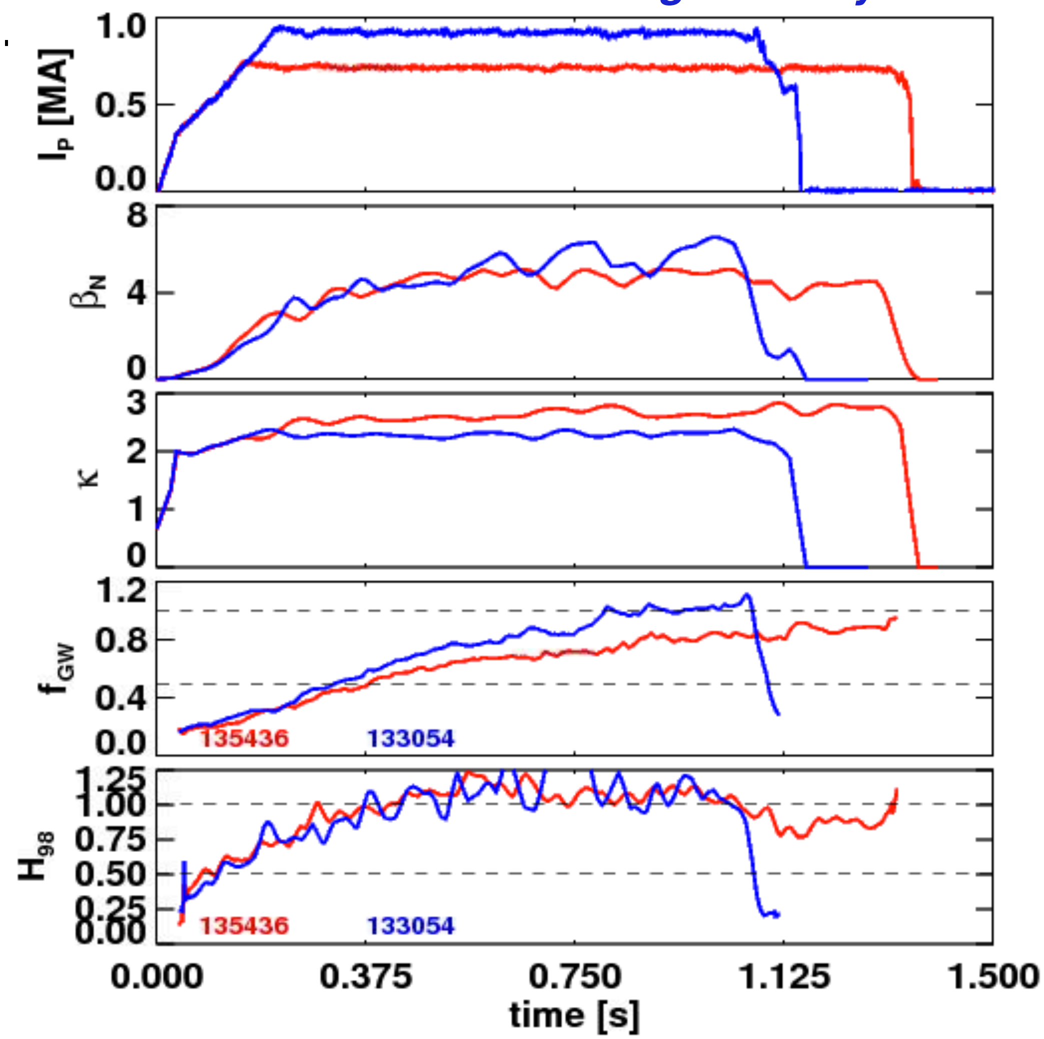
Discharges Have Shown Good Confinement and High Density and Elongation.

- 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.

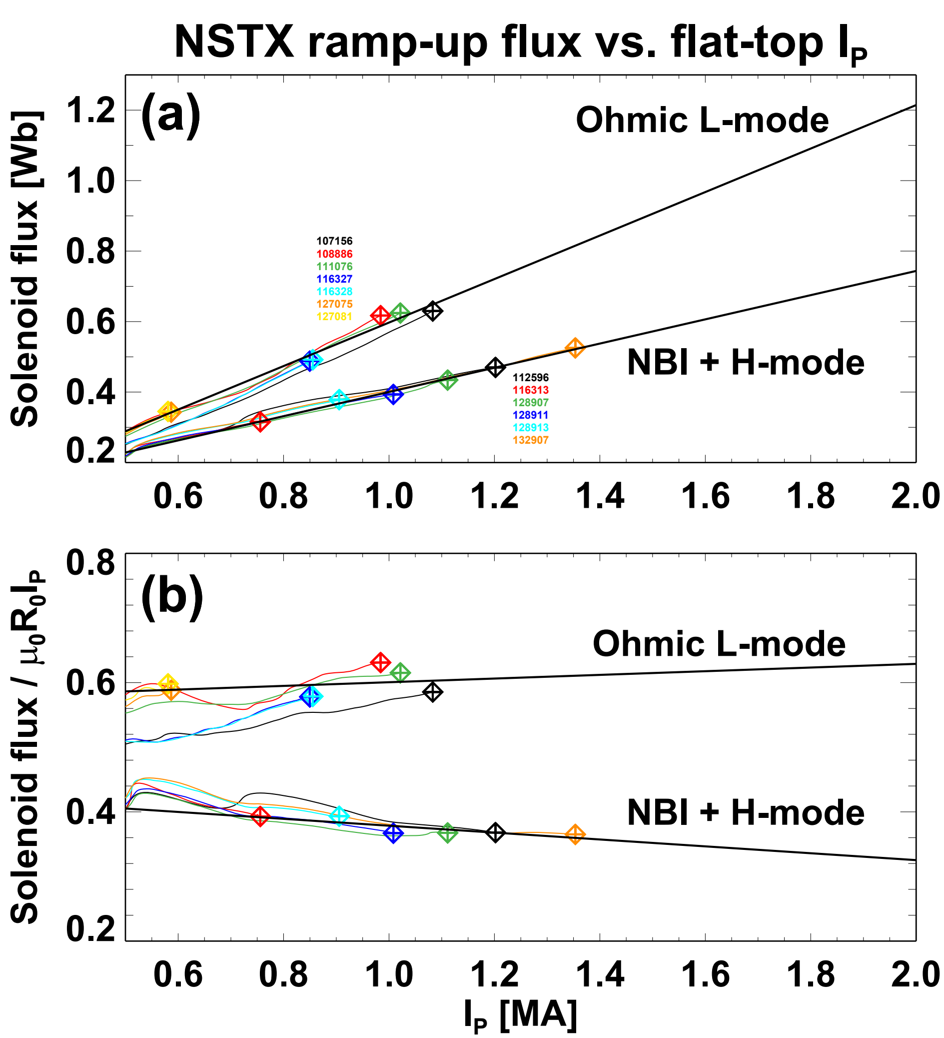




Time Traces of Discharges with Good Confinement at High Density



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

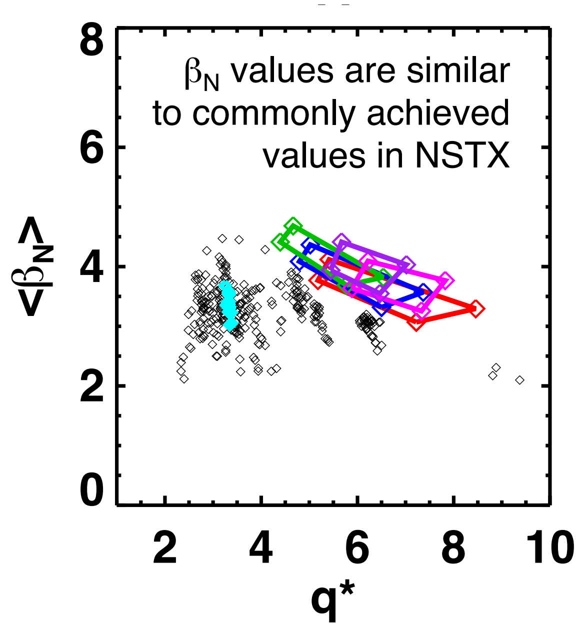


- Upgrade OH capacity is substantially improved
  - Factor 3.5 increase in I^2t limit.
  - Vs capability increased from 0.75 Wb to 2.1 Wb.
  - Very few high-performance scenarios limited by flux consumption.
    - Extrapolate ramp-up flux for 2MA as ~0.8 Wb.
    - Must keep surface voltage under (2.1-0.8)/5 = 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



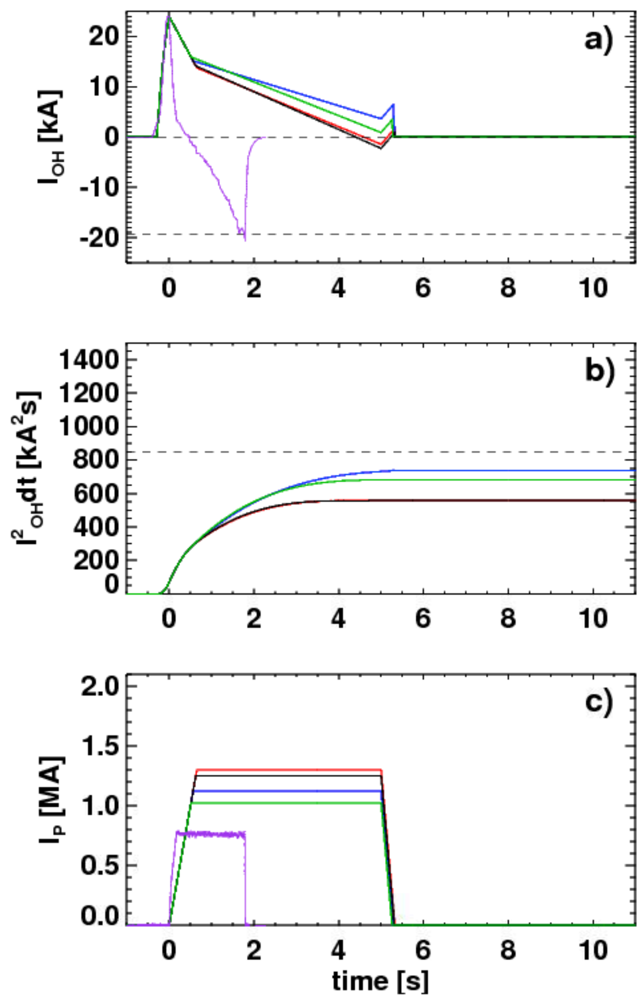
All the details for the 100% non-inductive scenarios

Voltage [kV]	Profiles	Scaling	B_T [T]	I_p [kA]	f_{BS}	q_{min}	q_{95}	$\nu^*_{e,\rho=0.5}$	τ_{CR} [s]	β_N	β_P	W_{tot} [kJ]	W_{fast}/W_{tot}
80	Broad	$H_{98y,2}=1$	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

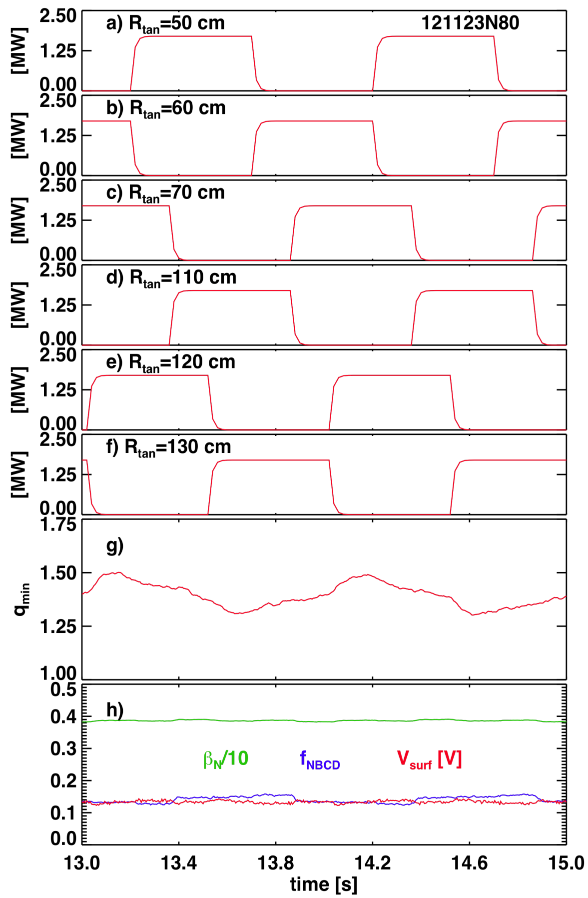
Table With Complete Details on 0.75 T Scenarios with q_{min}~1.15

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!

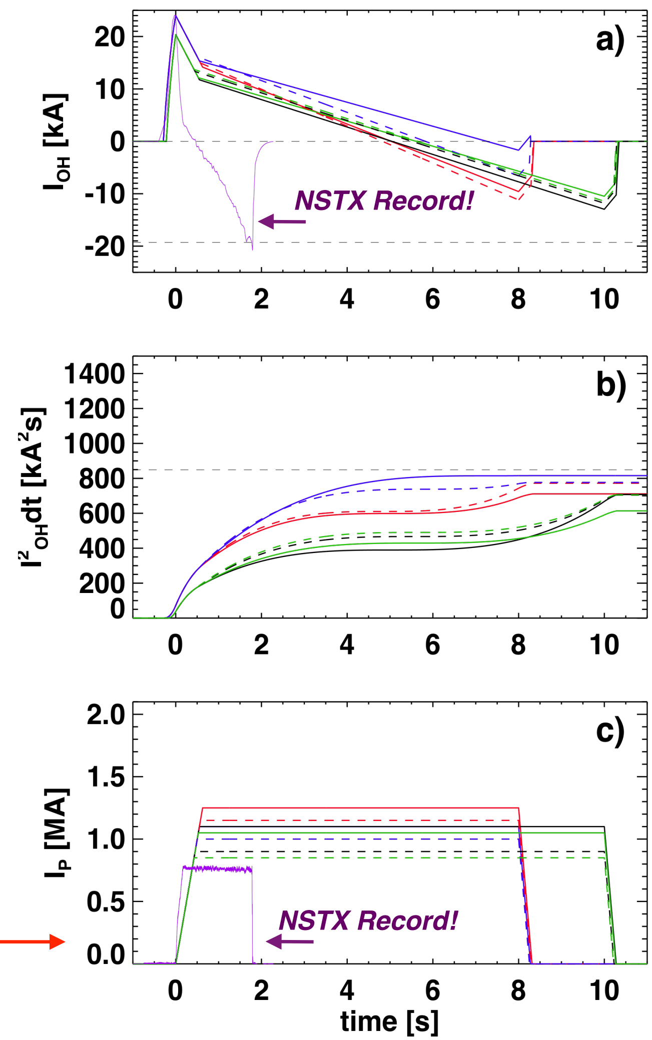
- B_T=0.75 T scenarios with 5.1 or 6.6 MW input power
  - Interleaved 80 kV case can sustain q_{min}> 1with 850-1050 kA for 10 sec.
  - 65 kV case can sustain q_{min}>1 with I_P=1000-1250 kA for 8 sec.



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?

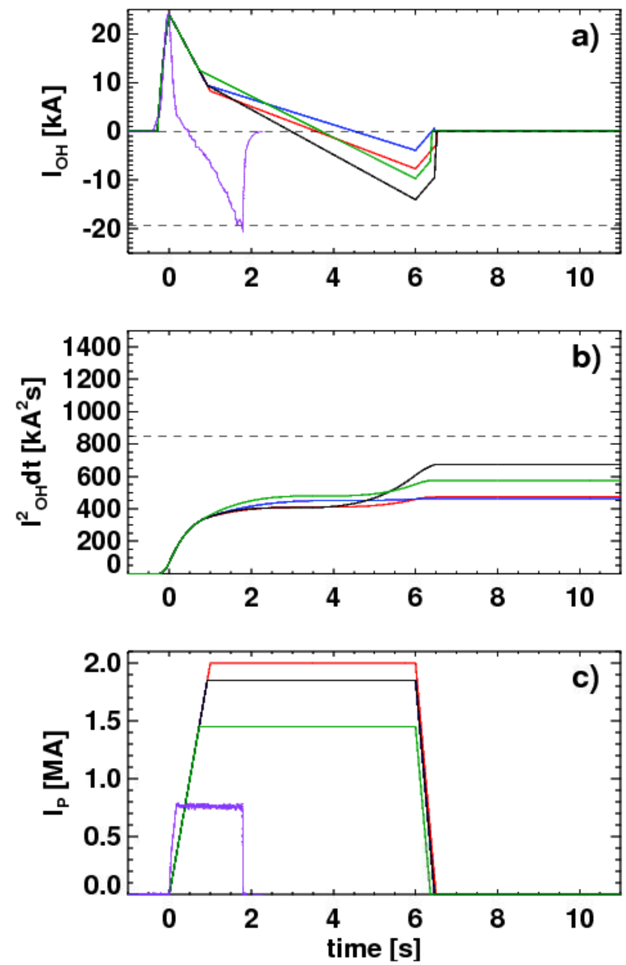
Answer 1: The "maximum sustainable current" is typically a somewhat less than 2 MA.

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?

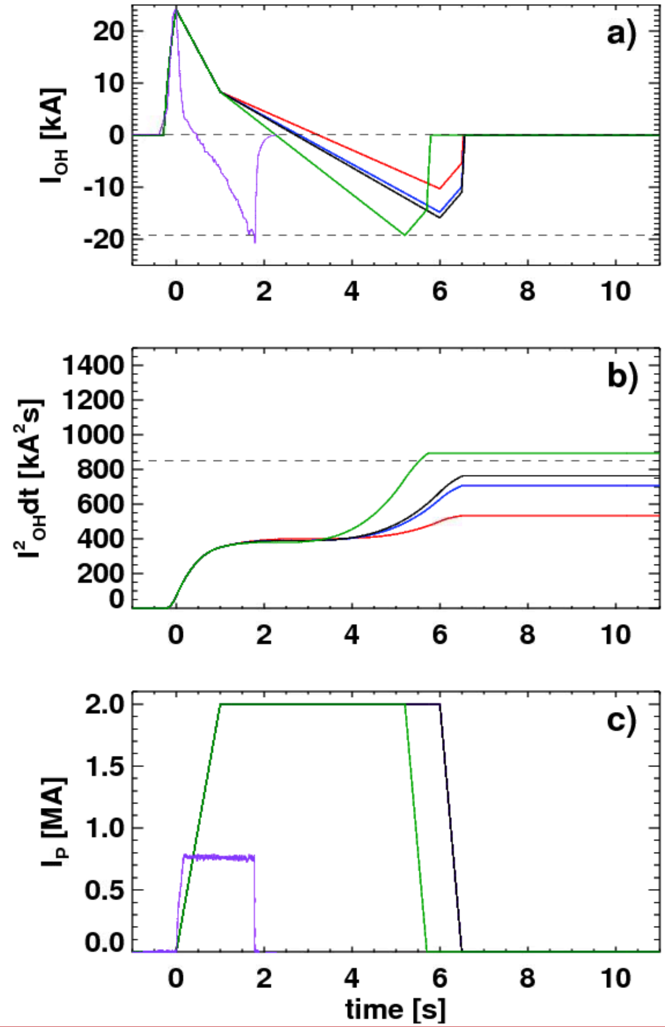
Answer 2: Long Current Redistribution Times Will Allow Long Pulse

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

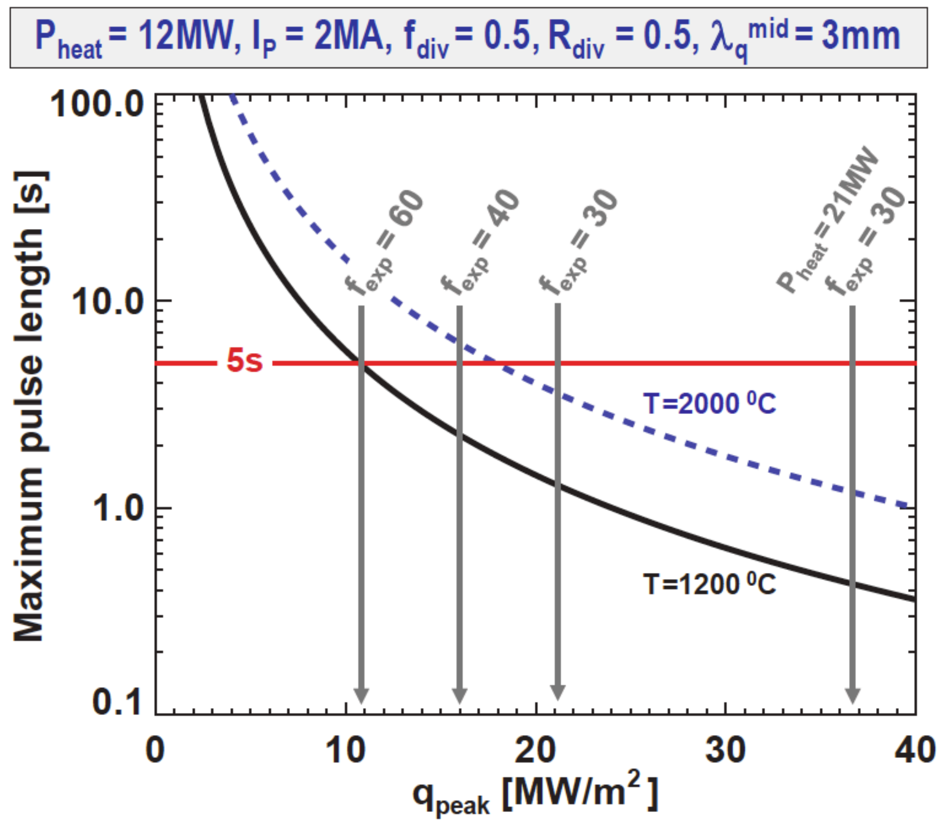


Divertor Temperature Can Be A Pulse Length Limiting Factor

- 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.

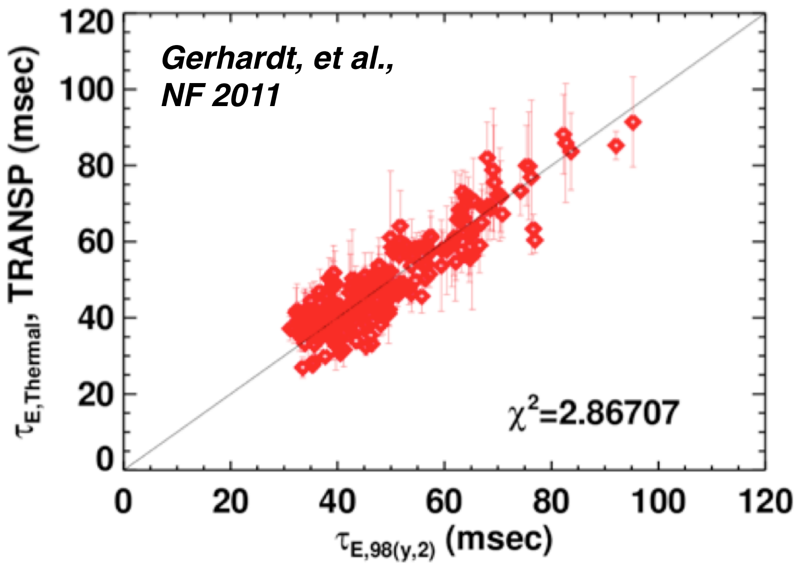
$$Q_{out}^{peak} = \frac{P_{heat}^{SOL}(1-f_{rad})f_{div}\sin(\theta_{plate})}{2\pi R_{strike} f_{exp} \lambda_q}$$

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



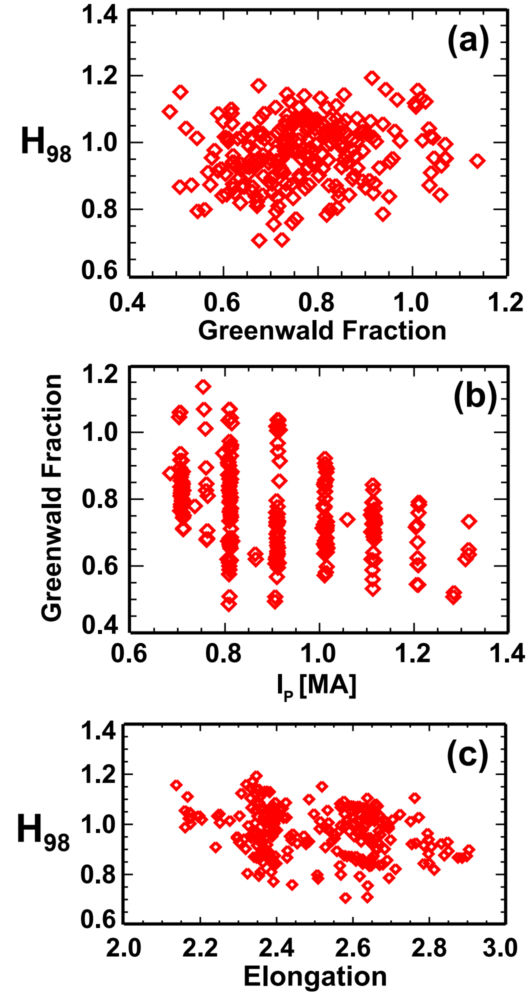
NSTX Context For Confinement and Flux Consumption Assumptions in Upgrade

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



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