Princeton Plasma Physics Laboratory

NSTX Experimental Proposal

Title: **Optimization of ELM pace-making with 3D fields**

OP-XP-943	Revision:	Effective Date: *(Approval date unless otherwise stipulated)* Expiration Date: *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

Responsible Author: J.M. Canik	Date: 5/8/09
ATI – ET Group Leader: D. Gates	Date5/8/09
RLM - Run Coordinator: R. Raman	Date5/8/09

Responsible Division: Experimental Research Operations

Chit Review Board (designated by Run Coordinator)

MINOR MODIFICATIONS (Approved by Experimental Research Operations)

NSTX EXPERIMENTAL PROPOSAL

TITLE: Optimization of ELM pace-making with 3D fields No. **OP-XP-943**
AUTHORS: J.M. Canik, A.C. Sontag DATE: **5/8/09**

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1. Overview of planned experiment

The goal of the experiment is to optimize fuelling and the use of 3D fields to trigger ELMs for discharge control during lithium-enhanced ELM free H-modes. The plasma shape, the waveform of the n=3 field application, and the particle fuelling will be optimized with a goal of producing a discharge with stationary density and radiated power, with small triggered ELMs.

2. Theoretical/ empirical justification

Previous experiments in NSTX have shown that the application of 3D magnetic fields can destabilize ELMs in discharges in which lithium conditioning has been used to induce ELM-free plasmas. The restoration of ELMs to these plasmas had a positive impact on discharge evolution, decreasing the rate at which the density and radiated power increased during the shot. However, the size of the triggered ELMs was very large, with a single ELM ejecting as much as 20% of the total stored energy. While these experiments demonstrated that 3D fields can be used for ELM pace-making to control impurity buildup, further optimization of the technique is required both to reduce the ELM size, and to achieve stationary conditions during Li-enhanced plasmas. This will be achieved partly by optimizing the plasma shape: during limited elongation scans performed in previous experiments, ELM size and frequency was increased significantly in $\kappa=2.4$ compared to 2.0. Additionally, the waveform of the n=3 field will be optimized; previous experiments showed that large ELMs occurred after a pulse failed to trigger an ELM, and that impurity expulsion was more effective at the highest triggering frequency, showing the desirability of achieving high frequency, high reliability triggering. Finally, the fuelling will be adjusted to that the plasma is primarily fuelled using the shoulder valve, which has a faster response so that fuelling after breakdown can be better controlled.

3. Experimental run plan

1. Produce reference discharge (2 shots)

- Reload 132592: Ip=1.0 MA, Bt=0.45 T, $\kappa=2.2$, $\delta=0.8$, drsep~ -1 cm, PNBI = 3 MW, LITER at ~50 mg/min, 600 mg/shot
- Change drsep to ~0 and κ to 2.5, LITER to 40 mg/min, ~300 mg/shot (1 shot)
- If necessary increase LITER for ELM-free conditions (1)

2. Waveform optimization: maximize frequency of ELMs, minimize duty cycle of n=3 (13 shots)

- Start with SPA waveform from 130670, but lower frequency to reduce braking: 1.2 kA, 11 ms pulses, 20 Hz repetition (1 shot)
- Increase amplitude as much as possible to try to trigger ELMs faster (3)

  - SPA current scan at fixed pulse width: 1.5, 2.0, 2.5 kA
- Control shot: remove SPA pulses to check that LITER rate is sufficient for ELM suppression (1)
- At highest current, decrease pulse length as much as possible with reliable triggering (2)
- Increase frequency as much as possible, until excessive braking leads to termination of discharge (3)
- Add short (~2 ms) SPA current reversal to end of each pulse, test if this allows further increase of pulse frequency (2)
- Control shot: remove SPA pulses to check that LITER rate is sufficient for ELM suppression (1)

3. Shape optimization: minimize ELM size, maximize frequency (12 shots)

- Reduce κ to 2.1
- Start with best SPA waveform from series 2) (1 shot)
- Reduce pulse frequency until triggering is reliable (2)
- Control shot: remove SPA pulses to check that LITER rate is sufficient for ELM suppression (1)
- Raise κ to 2.7, in increments of 0.2. At each, perform the following:
  - Start with low-frequency SPA waveform from κ=2.1 (1 shot)
  - Increase frequency as much as possible, maintaining reliable triggering (2)
- Control shot: remove SPA pulses to check that LITER rate is sufficient for ELM suppression (1)

4. Fueling optimization: minimize dn/dt (10 shots)

- Start with fueling from reference discharge, and change CS in increments of 100 torr
- Replace CS with shoulder
  - Shoulder pressure at ~ half CS
  - Shoulder puff at 100-130 ms (~10-30 ms later than CS)

5**. Vacuum shots with SPA pulses (~5 shots)**

- Restore best SPA waveforms from day, run vacuum discharges to measure structure as field penetrates

4. Required machine, NBI, RF, CHI and diagnostic capabilities

This XP requires a fully operational NBI system. We desire LITER operating at an evaporation rate of 40 mg/min with a 10 minute shot cycle.

5. Planned analysis

EFIT/LRFDIT; pedestal profile analysis to use in kinetic BFIT; stability calculations with PEST and ELITE; spectral analysis using vacuum approximation and IPEC

6. Planned publication of results

The results of this experiment will be presented during an invited talk at the APS 09 meeting if the nomination is accepted, and will be published in the corresponding Physics of Plasmas issue.

PHYSICS OPERATIONS REQUEST

TITLE: **Characterization of magnetically triggered ELMs in lithium conditioned discharges** No. **OP-XP-943**
AUTHORS: **J.M. Canik, A.C. Sontag** DATE: **5/8/09**

(use additional sheets and attach waveform diagrams if necessary)

Describe briefly the most important plasma conditions required for the experiment:

Reliable ELM-free operation with lithium conditioning is required.

Previous shot(s) which can be repeated: 130669,130652

Previous shot(s) which can be modified:

Machine conditions *(specify ranges as appropriate, strike out inapplicable cases)*

I_{TF} (kA): 53 Flattop start/stop (s): 0/1

I_{P} (MA): 1.0 Flattop start/stop (s): .15/1

Configuration: **Limiter / [✓ DN] / LSN / USN**

Equilibrium Control: **Outer gap / Isoflux** (rtEFIT)

Outer gap (m): **0.1** Inner gap (m): **0.05** Z position (m):

Elongation κ: 2.5 Upper/lower triangularity δ: 0.7

Gas Species: **D** Injector(s):

NBI Species: **D** Voltage (kV) **A: 90** **B: 60** **C:** 90 Duration (s): 1

ICRF Power (MW): Phase between straps (°): Duration (s):

CHI: **[✓ Off] / On** Bank capacitance (mF):

LITERs: Off / [✓ On] Total deposition rate (mg/min): **40**

EFC coils: Off/[✓ On] Configuration: **[✓ Odd] / Even / Other** *(attach detailed sheet*

DIAGNOSTIC CHECKLIST

TITLE: **Characterization of magnetically triggered ELMs in lithium conditioned discharges** No. **OP-XP-943**

AUTHORS: **J.M. Canik, A.C. Sontag** DATE:5/8/09

Note special diagnostic requirements in Sec. 4

Diagnostic	**Need**	**Want**
Bolometer – tangential array	√	
Bolometer – divertor		√
CHERS – toroidal	√	
CHERS – poloidal		√
Divertor fast camera		√
Dust detector		
EBW radiometers		
Edge deposition monitors		
Edge neutral density diag.		√
Edge pressure gauges		√
Edge rotation diagnostic		√
Fast ion D_alpha - FIDA		
Fast lost ion probes - IFLIP		
Fast lost ion probes - SFLIP		
Filterscopes	√	
FIReTIP		√
Gas puff imaging		√
Hα camera - 1D	√	
High-k scattering		
Infrared cameras	√	
Interferometer - 1 mm		
Langmuir probes – divertor	√	
Langmuir probes – BEaP		
Langmuir probes – RF ant.		
Magnetics – Diamagnetism	√	
Magnetics – Flux loops	√	
Magnetics – Locked modes	√	
Magnetics – Pickup coils	√	
Magnetics – Rogowski coils	√	
Magnetics – Halo currents	√	
Magnetics – RWM sensors	√	
Mirnov coils – high f.		√
Mirnov coils – poloidal array		√
Mirnov coils – toroidal array		√
Mirnov coils – 3-axis proto.		

Note special diagnostic requirements in Sec. 4

Diagnostic	**Need**	**Want**
MSE		√
NPA – E||B scanning		
NPA – solid state		
Neutron measurements		√
Plasma TV		√
Reciprocating probe		
Reflectometer – 65GHz		√
Reflectometer – correlation		√
Reflectometer – FM/CW		
Reflectometer – fixed f		
Reflectometer – SOL		√
RF edge probes		
Spectrometer – SPRED		√
Spectrometer – VIPS		√
SWIFT – 2D flow		
Thomson scattering	√	
Ultrasoft X-ray arrays	√	
Ultrasoft X-rays – bicolor		√
Ultrasoft X-rays – TG spectr.		√
Visible bremsstrahlung det.		√
X-ray crystal spectrom. - H		
X-ray crystal spectrom. - V		
X-ray fast pinhole camera		
X-ray spectrometer - XEUS		

ADDITION TO XP-943

TITLE: Optimization of ELM pace-making with 3D fields No. **OP-XP-943**
AUTHORS: J.M. Canik, A.C. Sontag DATE: **6/8/09**

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1. Overview of planned experiment

The goal of this Addendum is to apply the optimized n=3 perturbation waveform to an ELMy discharge, to test the ability of this pacing method to reduce ELM size in naturally ELMing plasmas. This experiment has similar goals to XP 945 (ELM pacing via vertical jogs), and ideally should be run on the same day for a clean comparison of the pacing techniques.

2. Theoretical/ empirical justification

In the previous runs of XP 943, the application of n=3 perturbation pulses has been optimized towards the goal of triggering small ELMs during lithium-enhanced ELM-free H-modes to fully arrest the secular increase of the density and radiated power. These experiments have led to improvements in the triggering waveform, such that the reliability has been improved to 100% in many cases, and the ELM frequency has been increase to over 60 Hz. In this Addendum, the improved n=3 waveform will be used to attempt ELM pacing during ELMy discharges. The goal of this is to test this method can increase the frequency of natural ELMs, and decrease the size of each ELM from its natural value. If successful, this experiment may support the use of 3D magnetic perturbations for ELM pacing as an option for mitigating ELMs in ITER, where the baseline scenario is a Type-I ELMy H-mode.

3. Experimental run plan

1. Produce target discharge (3 shots)

The reference discharge for this is 133914. The shot should have regular large ELMs, at a frequency of ~30 Hz. In order to make a good comparison to the vertical jog pacing technique, the reference plasma should be as close to that used in XP 945 as possible. No lithium evaporation will be used. This will run on a 15 minute shot cycle, with 9 minutes of HeGDC.

2. Establish triggering with bursts of n=3 field (5 shots)

Although a reliable recipe for ELM triggering with n=3 pulse trains has been developed for lithium-enhanced ELM-free H-modes, this may need to be adapted somewhat given the likelihood that the triggering characteristics are different during ELMy discharges. The strategy for the present experiment will be to start with the best triggering waveform from the with-lithium runs of XP 943, and de-optimize this as necessary to establish reliable triggering.

Begin with high amplitude, short duration n=3 pulses (3 kA, 4 ms, 60 Hz), with fast current reversals after each pulse to compensate eddy currents (e.g. waveform of 133825). If this results is reliable triggering, go on to part 2; otherwise increase the duration of the pulses until triggering is reliable. At each duration, reduce the frequency to keep the duty cycle of the n=3 field at ~25%.

Case	Pulse duration (ms)	Pulse frequency (Hz)	Comment
1	4	60	If this works, test cutting duration by 1ms
2	6	40	“
3	8	33	“
4	20	10	If no luck so far, find ELM onset time with very long pulses
5	~ELM onset time from step 4		

3. Pulse frequency scan (4 shots)

The goal of the frequency scan will be to test the reduction of ELM size expected as the frequency is increased. The execution of this scan depends on the results of part 2 above:

Case 1) 60 Hz triggering from part 2 above was successful. In this case, n=3 pulses will be applied using frequencies of: 30, 40, 50, and 77 Hz

Case 2) The duration had to be increased to get reliable triggering, and so lower frequency than 60 Hz was used. In this case, the frequency scan will be altered to the following:

Frequency 1: n=3 pulses at ~the natural ELM frequency (~30 Hz)

Frequency 2: Halfway between frequency 1 and the frequency where good triggering was seen in part 2

Frequencies 3 and up: Increase triggering frequency from that used in part 2. Use increments of 10 Hz, and continue increasing until excessive braking ruins the plasma

4. Combined vertical jogs and n=3 pulses (4 shots)

Time permitting, a combined pacing using both vertical jogs and n=3 pulses will be used to try to achieve very high frequency ELMs. The plan is essentially to combine the best ELM pacing recipes from the n=3 pulses and vertical jog techniques in order to double the ELM frequency achievable using a single method. This will be highly dependent on the results of XP 945 (vertical jogs), and so this section of the shot list is contingent on the successful development of a recipe for ELM pacing using that technique. That said, 60 Hz triggering with each method has been achieved, so the parameters of these discharges will be used to make a tentative shot list. These are:

Vertical jogs: Kicks are produced by adding square wave pulse trains to the Zpos and drsep requests in isoflux. The parameters are: peak-to-peak requests in Zpos and drsep of -16 and -2 cm respectively, pulse width of 8 ms, frequency 60 Hz

n=3 pulses: 3kA SPA current, 4ms pulse width, 60 Hz

If the combined pacing is unsuccessful, the frequency of each method will be reduced to 40 Hz

If the combined pacing is successful, the timing of the two will be staggered so a single discharge will have a period in which each of the methods are used independently, and a period of overlap where the two techniques are combined.

Case	f_{kick}	$f_{n=3}$	t_{start} kicks (s)	t_{stop} kicks (s)	t_{start} n=3 (s)	t_{stop} n=3 (s)	Comment
1	60	60	0.40833	end of shot	0.4	end of shot	
2	40	40	0.4125	“	0.4	“	If 120 Hz unsuccessful, try 80
3	60	60	0558333	end of shot	0.4	0.7	

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(use additional sheets and attach waveform diagrams if necessary)

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Machine conditions *(specify ranges as appropriate, strike out inapplicable cases)*

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Gas Species: **D** Injector(s):

NBI Species: **D** Voltage (kV) **A: 90** **B: 90** **C:** 90 Duration (s): 1

ICRF Power (MW): Phase between straps (°): Duration (s):

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Bolometer – divertor		√
CHERS – toroidal	√	
CHERS – poloidal		√
Divertor fast camera		√
Dust detector		
EBW radiometers		
Edge deposition monitors		
Edge neutral density diag.		√
Edge pressure gauges		√
Edge rotation diagnostic		√
Fast ion D_alpha - FIDA		
Fast lost ion probes - IFLIP		
Fast lost ion probes - SFLIP		
Filterscopes	√	
FIReTIP		√
Gas puff imaging		√
Hα camera - 1D	√	
High-k scattering		
Infrared cameras	√	
Interferometer - 1 mm		
Langmuir probes – divertor		√
Langmuir probes – BEaP		
Langmuir probes – RF ant.		
Magnetics – Diamagnetism	√	
Magnetics – Flux loops	√	
Magnetics – Locked modes	√	
Magnetics – Pickup coils	√	
Magnetics – Rogowski coils	√	
Magnetics – Halo currents	√	
Magnetics – RWM sensors	√	
Mirnov coils – high f.		√
Mirnov coils – poloidal array		√
Mirnov coils – toroidal array		√
Mirnov coils – 3-axis proto.		

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Diagnostic	**Need**	**Want**
MSE		√
NPA – E||B scanning		
NPA – solid state		
Neutron measurements		√
Plasma TV		√
Reciprocating probe		
Reflectometer – 65GHz		√
Reflectometer – correlation		√
Reflectometer – FM/CW		
Reflectometer – fixed f		
Reflectometer – SOL		√
RF edge probes		
Spectrometer – SPRED		√
Spectrometer – VIPS		√
SWIFT – 2D flow		
Thomson scattering	√	
Ultrasoft X-ray arrays	√	
Ultrasoft X-rays – bicolor		√
Ultrasoft X-rays – TG spectr.		√
Visible bremsstrahlung det.		√
X-ray crystal spectrom. - H		
X-ray crystal spectrom. - V		
X-ray fast pinhole camera		
X-ray spectrometer - XEUS		