Princeton Plasma Physics Laboratory

NSTX-U Experimental Proposal

Title: **Beam ion confinement of 2nd NBI line**		
OP-XP-1522	Revision:	Effective Date: *(Approval date unless otherwise stipulated)* Expiration Date: *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

Responsible Author: D. Liu, W. W. Heidbrink et al.	Date
SG, TSG or TF Leader (assigned by RC):	Date
Run Coordinator (RC):	Date
Responsible Division: Experimental Research Operations	

RESTRICTIONS or MINOR MODIFICATIONS

(Approved by Experimental Research Operations)

NSTX- EXPERIMENTAL PROPOSAL

TITLE: **Beam ion confinement of 2nd NBI line** No. **OP-XP-1522**

AUTHORS: **D. Liu, W. W. Heidbrink et al.** DATE:

1. Overview of planned experiment

Good confinement of beam ions is essential for plasma heating and neutral beam current drive. The primary focus of this XP is to use neutron, FIDA and ssNPA measurements to characterize the confinement of beam ions that are produced by the existing Neutral Beam Injection (NBI) line #1 and newly installed more tangential NBI line #2, and verify the TRANSP/NUBEAM modeling of beam-ion distribution function in quiescent L mode plasmas (in which fast ions are expected to behave classically). We will cycle through all six neutral beam sources with many different injection patterns to infer beam ion confinement time and investigate its dependence on beam source, injection energy, plasma current and toroidal magnetic field. The three main beam modulation patterns are listed below.

(1) Short beam blips (20ms pulses) to check neutron response such as rise rate and decay time

(2) Isolated beam blips in quiescent plasmas to verify TRANSP/NUBEAM modeling

(3) Continued injection of each NB source with notches to check fast ion slowing-down distribution

The XP is divided into two parts based on the beam injection energy: the first part with beam injection energy of 65kV except source 1A operated at 90kV for MSE diagnostic and the second part with beam injection energy of 90kV. It time permits, a two-point scan of plasma current will be performed to check the dependence of beam-ion confinement on plasma current. Some of the data from “FIDA/ssNPA/sFLIP checkout” XMP (B_T=0.5T) will be combined with the dataset from this XP (B_T=0.65T) to check the dependence of beam-ion confinement on toroidal magnetic field. In addition, the sFLIP diagnostic will be used to monitor prompt losses in all conditions.

2. Theoretical/ empirical justification

The second NBI line is a major upgrade component to the NSTX device with the purpose of improving neutral beam current drive efficiency and providing more flexibility in the modification of current and pressure profiles. The performance of second NBI line will strongly impact NSTX-U operation and research. In order to be able to assess and predict the effects of the 2nd NBI line, it is necessary to characterize the confinement and distribution function of beam ions produced by this new and more tangential NBI line, and compare them with the existing 1st neutral beam line and classical predictions. Similar experiments have been performed on other machines after the major upgrade of their NBI systems. It has been shown that the measured beam ion confinement from on-axis and off-axis NBI generally agrees with classical theory in quiescent plasmas in conventional tokamaks. It is worthy to confirm this trend on NSTX-U and provide confidence in utilizing the 2nd neutral beam line for other experiments since NSTX-U is significantly different from conventional tokamaks especially in terms of fast ion physics study.

3. Experimental run plan

Many different neutral beam injection patterns and source mix will be used in this XP. The run plan is divided into two parts based on the beam injection energy. Part A requires neutral beam source 1A (R_{tan}=70cm) operated at 90kV and all the other sources at 65kV. Part B needs all neutral beam sources with E_{inj}=90kV. All the discharges in Part A and Part B will be similar to the "template" discharge shown in Figure 1. The detailed plasma conditions and neutral beam timing are given below.

Baseline conditions: B_t~0.65T, I_p~1MA, density 3-4x10^{13} cm^{-3}, deuterium gas, L mode, reference discharge will be chosen from "FIDA/SSNPA/sFLIP checkout" XMP. Optimize the settings in the ramp-up to avoid early low-frequency MHD. Neutral beam source 1A with injection energy of 90kV will be used to pre-heat the plasma and slow down the evolution of the q profile. The target q_{min} is 2-2.5 around 0.2s. The current flat-top is expected to be around 0.8s, and it is assumed the flat-top starts at 0.2s and ends at 1.0s in this XP.

Neutral beam timing: employ source 1A@90kV during current ramp-up (60-200ms) and near the end (950-1000ms) of flat-top to get MSE and CHERS measurements, see Figure 1. There are various beam modulation patterns during the current flat-top, which is named as "NB modulation phase" in Figure 1. A detailed description of neutral beam source mix and modulation patterns during the "NB modulation phase" is given in Tables 1 and 2.

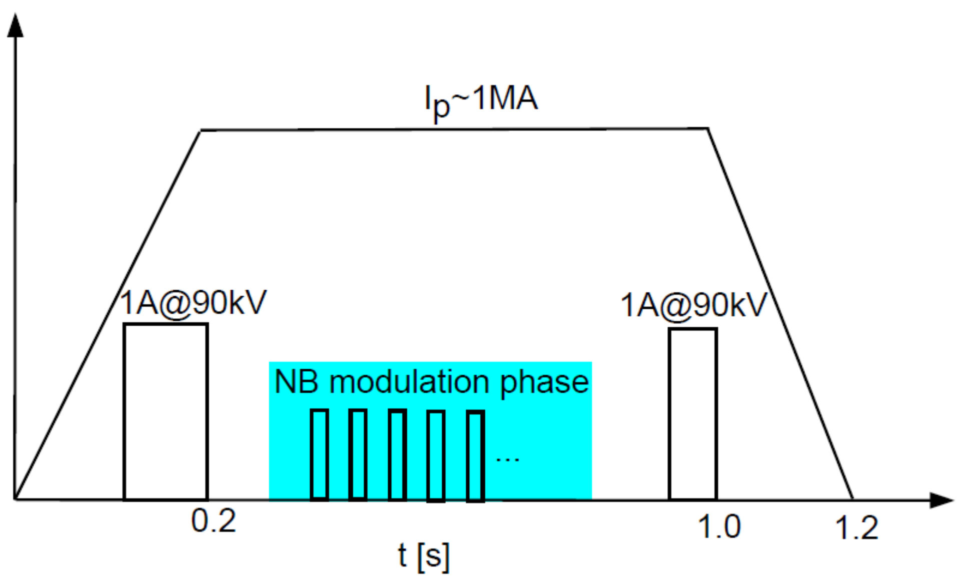


Figure 1: Template discharge. NB source 1A@90kV is employed in the ramp-up phase and the end of flat-top to get MSE and CHERS measurements. During the "NB modulation phase" (blue shaded region), there are various neutral beam mix and modulation patterns.

Part A [14 +1 optional +2 development shots]:source 1A@90kV, all the other sources@65kV

(1) Target plasma: quiescent L mode with n_e=3-4x10^{13} cm^{-3} at t=200 ms [1+2 development shots]
- Start with modulation pattern I with neutral beam sources 1B and 2B@65kV
- It is essential to make the plasma go into a quiescent L mode scenario in this XP. Two techniques can be used: (a) adjust inner gap to achieve a center-stack limited configuration, (b) lower beam energy to 65kV except the neutral beam source 1A. Should the plasma go into H mode, consider the following options: (a) bias the plasma upward, (b) change elongation, (c) delay NB injection or change NB period, (d) use high-field side fueling, and/or (e) adjust plasma density.
- Once the density n_e is between 3-4x10^{13} cm^{-3} at t=0.2s, keeps the gas fueling the same for all the discharges in this XP.
- Optimize the settings in the ramp-up to avoid/minimize early low frequency (f<50 kHz typically) MHD, e.g. modifying the current (or q-profile) evolution by adjusting beam timing, plasma current, and/or plasma density
- It is expected that the target quiescent L mode plasma will be achieved within three shots.

(2) Short beam blips to check neutron build-up and decay rates [2 shots]
- one shot with modulation pattern II and neutral beam source 1C@65kV and 2A@65kV
- one shot with modulation pattern III and neutral beam source 1A@90kV and 2C@65kV

(3) Isolated beam blips in quiescent plasmas [3 shots]
- one shot with modulation pattern IV and neutral beam source 1A@90kV and 2C@65kV
- one shot with modulation pattern V and neutral beam source 1B@90kV and 2B@65kV
- one shot with modulation pattern VI and neutral beam source 1C@90kV and 2A@65kV

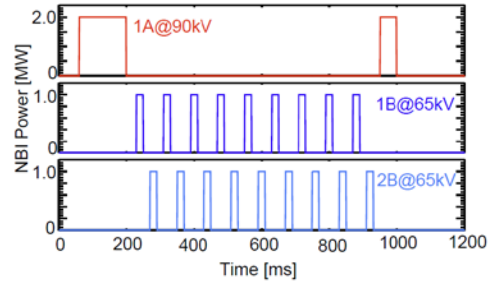
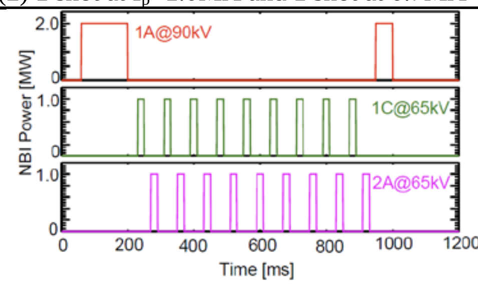
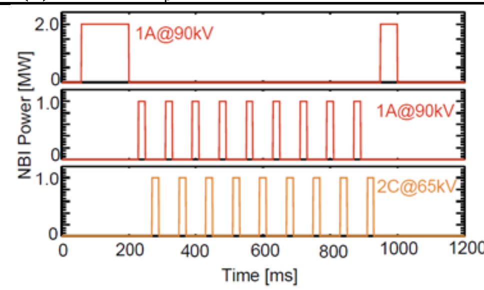
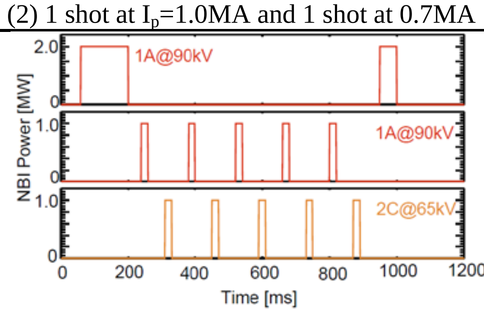
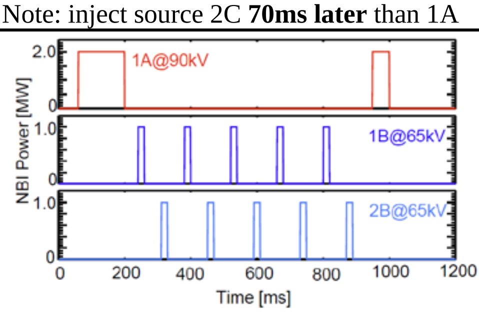
(4) Relatively long neutral beam pulses to get stationary slowing-down distribution [5+1 optional shots]
- one shot with modulation pattern VII and neutral beam source 1B@65kV and 2A@65kV
- one shot with modulation pattern VIII and neutral beam source 1B@65kV and 2C@65kV
- one shot with modulation pattern IX and neutral beam source 1B@65kV and 2B@65kV
- one shot with modulation pattern X and neutral beam source 2B@65kV and 1B@65kV
- one shot with modulation pattern XI and neutral beam source 2B@65kV and 1C@65kV
- one optional shot with modulation pattern XII and neutral beam source 2B@65kV and 1A@90kV

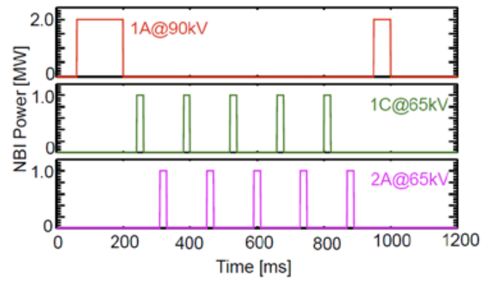
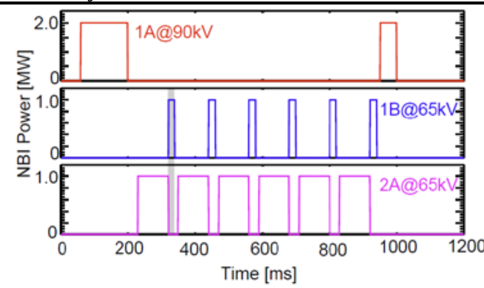
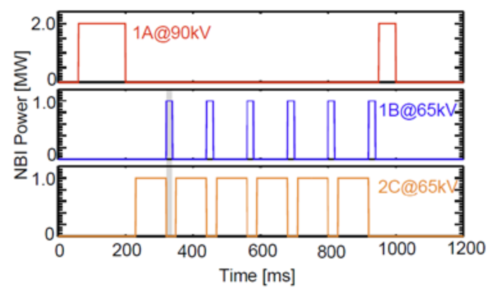
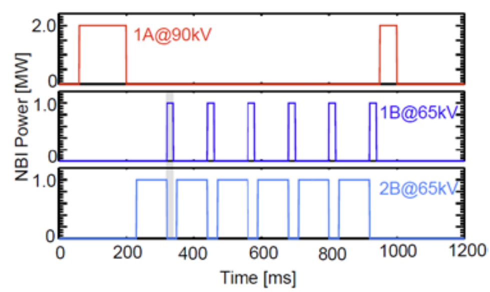
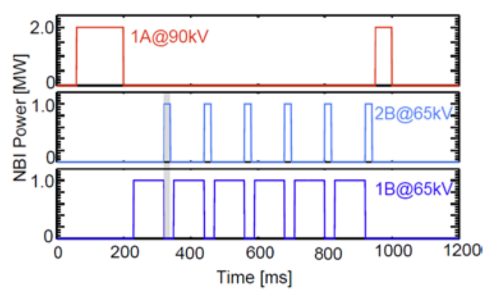
(5) Short beam blips at I_p=0.7MA to check neutron build-up and decay rates [3 shots]
- one shot with modulation pattern I and neutral beam source 1B@65kV and 2B@65kV
- one shot with modulation pattern II and neutral beam source 1C@65kV and 2A@65kV
- one shot with modulation pattern III and neutral beam source 1A@90kV and 2C@65kV

Part B [15 shots]: all neutral beam sources operated at 90kV

Repeat steps 1-5 in Part A, but change beam injection energy to 90kV for all neutral beam sources. In addition, the optional shot in step (4) is changed to priority 1 in part B. For completeness, a detailed description of neutral beam source mix and modulation patterns for Part B is given in Table 2.

Table 1: neutral beam modulation patterns and source mix for Part A

Pattern #	Priority	NB Source	E_{inj} [keV]	Start Time [ms]	# of pulses	On time [ms]	Off time [ms]	NBI modulation pattern and notes
I	1	1B	65	230	9	20	60	
		2B	65	270	9	20	60	Note: (1) inject source 2B **40ms later** than 1B (2) 1 shot at I_p=1.0MA and 1 shot at 0.7MA
II	1	1C	65	230	9	20	60	
		2A	65	270	9	20	60	Note: (1) inject source 2A **40ms later** than 1C (2) 1 shot at I_p=1.0MA and 1 shot at 0.7MA
III	1	1A	**90**	230	9	20	60	
		2C	65	270	9	20	60	Note: (1) inject source 2C **40ms later** than 1A (2) 1 shot at I_p=1.0MA and 1 shot at 0.7MA
IV	1	1A	**90**	**240**	5	20	120	
		2C	65	**310**	5	20	120	Note: inject source 2C **70ms later** than 1A
V	1	1B	65	**240**	5	20	120	
		2B	65	**310**	5	20	120	Note: inject source 2B **70ms later** than 1B

VI	1	1C	65	**240**	5	20	120	 Note: inject source 2A **70ms later** than 1C
		2A	65	**310**	5	20	120	
VII	1	1B	65	**320**	6	20	100	 Note: inject source 1B **right after** than 2A
		2A	65	**230**	6	90	30	
VIII	1	1B	65	**320**	6	20	100	 Note: inject source 1B **right after** than 2C
		2C	65	**230**	6	90	30	
IX	1	1B	65	**320**	6	20	100	 Note: inject source 1B **right after** than 2B
		2B	65	**230**	6	90	30	
X	1	2B	65	**320**	6	20	100	 Note: inject source 1B **right after** than 2B
		1B	65	**230**	6	90	30	

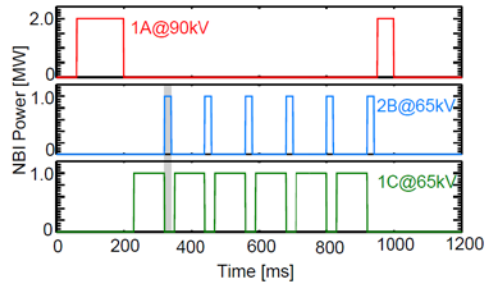
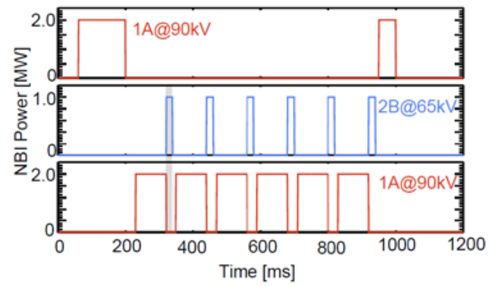
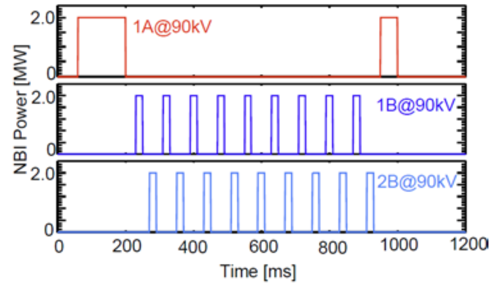
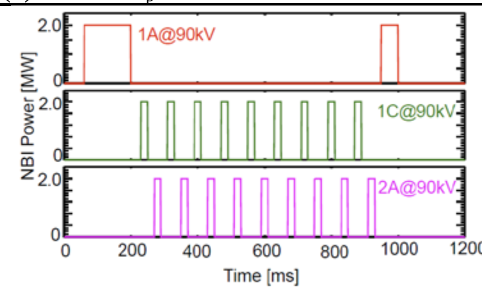
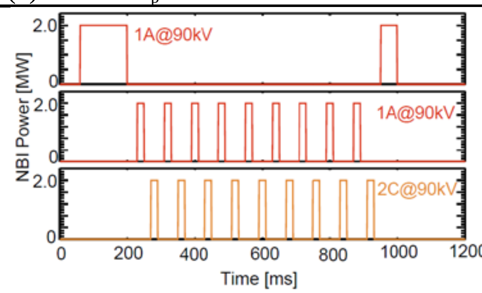
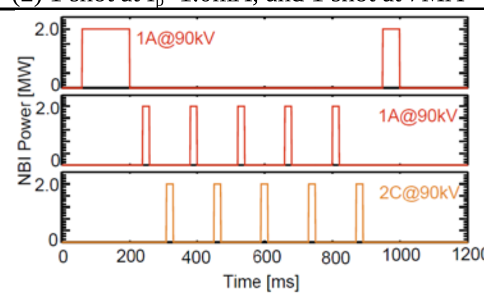
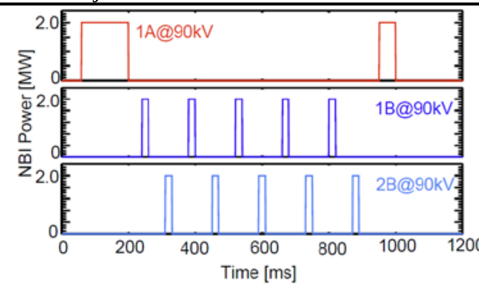
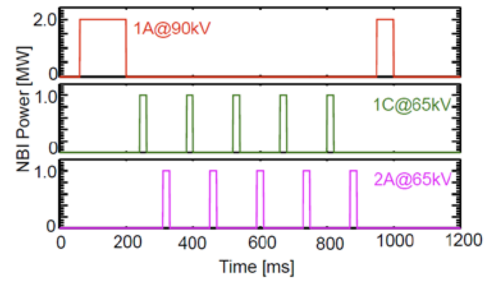
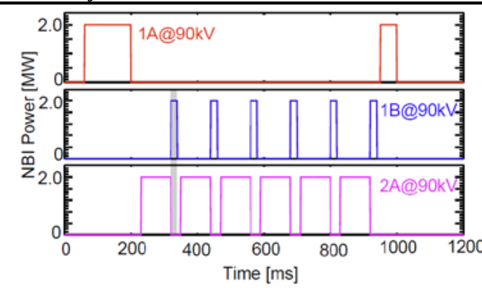
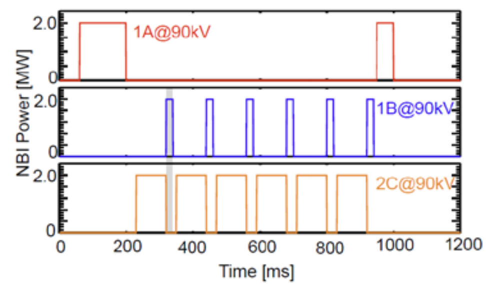
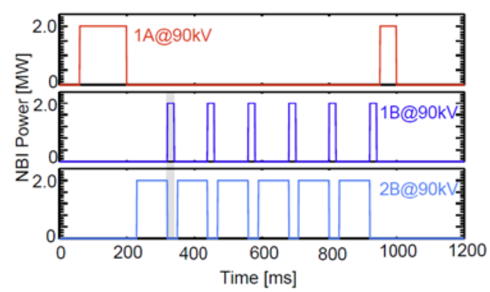
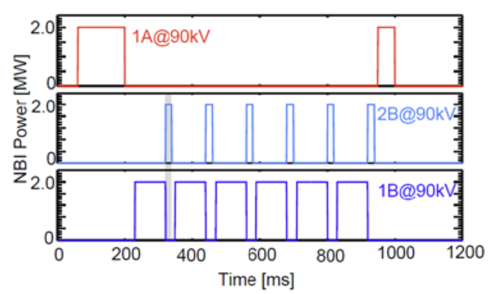
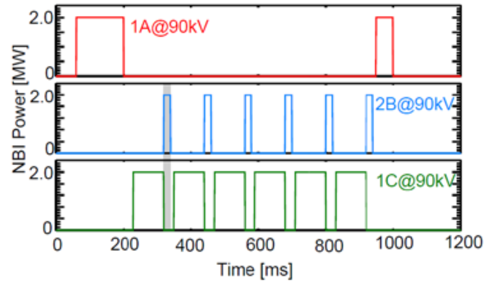
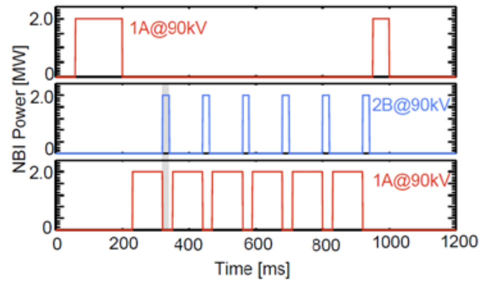
XI	1	2B	65	**320**	6	20	100	 Note: inject source 1C **right after** than 2B
		1C	65	**230**	6	90	30	
XII [optional]	2	2B	65	**320**	6	20	100	 Note: inject source 1A **right after** than 2B
		1A	**90**	**230**	6	90	30	

Table 2: neutral beam modulation patterns and source mix for Part B

Pattern #	Priority	NB Source	E_{inj} [keV]	Start Time [ms]	# of pulses	On time [ms]	Off time [ms]	NBI modulation pattern and notes
I	1	1B	90	230	9	20	60	
		2B	90	270	9	20	60	Note: (1) inject source 2B **40ms later** than 1B (2) 1 shot at I_p=1.0MA and 1 shot at 0.7MA
II	1	1C	90	230	9	20	60	
		2A	90	270	9	20	60	Note: (1) inject source 2A **40ms later** than 1C (2) 1 shot at I_p=1.0MA and 1 shot at 0.7MA
III	1	1A	90	230	9	20	60	
		2C	90	270	9	20	60	Note: (1) inject source 2C **40ms later** than 1A (2) 1 shot at I_p=1.0mA, and 1 shot at 7MA
IV	1	1A	90	**240**	5	20	120	
		2C	90	**310**	5	20	120	Note: inject source 2C **70ms later** than 1A
V	1	1B	90	**240**	5	20	120	
		2B	90	**310**	5	20	120	Note: inject source 2B **70ms later** than 1B

VI	1	1C	90	**240**	5	20	120	 Note: inject source 2A **70ms later** than 1C
		2A	90	**310**	5	20	120	
VII	1	1B	90	**320**	6	20	100	 Note: inject source 1B **right after** than 2A
		2A	90	**230**	6	90	30	
VIII	1	1B	90	**320**	6	20	100	 Note: inject source 1B **right after** than 2C
		2C	90	**230**	6	90	30	
IX	1	1B	90	**320**	6	20	100	 Note: inject source 1B **right after** than 2B
		2B	90	**230**	6	90	30	
X	1	2B	90	**320**	6	20	100	 Note: inject source 2B **right after** than 1B
		1B	90	**230**	6	90	30	

XI	1	2B	90	**320**	6	20	100	 Note: inject source 2B **right after** than 1C
		1C	90	**230**	6	90	30	
XII	1	2B	90	**320**	6	20	100	 Note: inject source 2B **right after** than 1A
		1A	90	**230**	6	90	30	

In case not all neutral beam sources are available, this XP requires at least three NB sources 1A, 1C, and 2A with injection energy of 65kV and 90kV. The run plan for Part A and Part B will be changed accordingly.

Backup plan part A [6 +2 development shots]:source 1A@90kV,1C and 2A @65kV

(1) Short beam blips to check neutron build-up and decay rates [1 shot]

- one shot with modulation pattern I in Table 3 and neutral beam source 1C@65kV and 2A@65kV

(2) Isolated beam blips in quiescent plasmas [1 shot]

- one shot with modulation pattern II in Table 3 and neutral beam source 1C@65kV and 2A@65kV

(3) Relatively long neutral beam pulses to get stationary slowing-down distribution [2 shots]

- one shot with modulation pattern III in Table 3 and neutral beam source 1C@65kV and 2A@65kV
- one shot with modulation pattern IV Table 3 and neutral beam source 2A@65kV and 1C@65kV

(4) Short beam blips at I_p=0.7MA to check neutron build-up and decay rates [1 shot]

- one shot with modulation pattern I in Table 3 and neutral beam source 1C@65kV and 2A@65kV

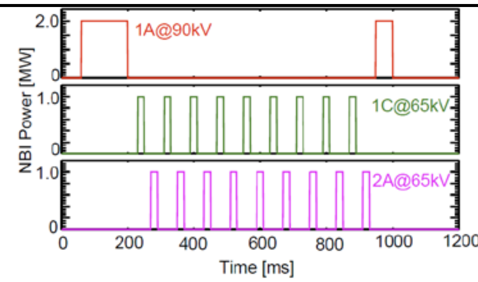
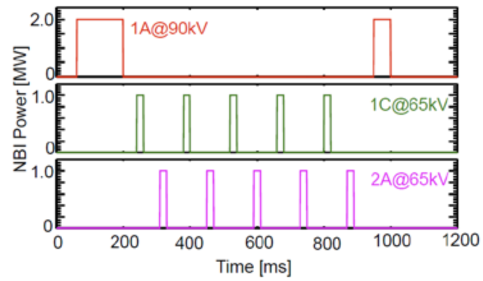
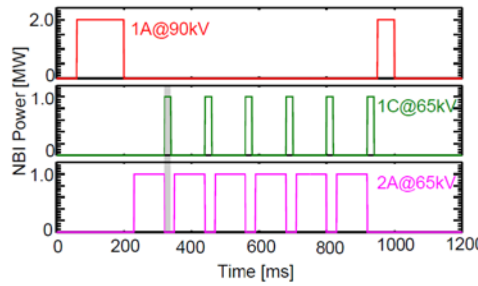
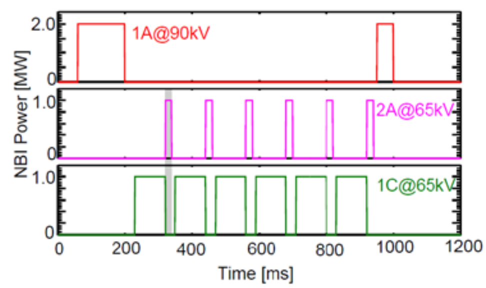
(5) Isolated beam blips at I_p=0.7MA in quiescent plasmas [1 shot]

- one shot with modulation pattern II in Table 3 and neutral beam source 1C@65kV and 2A@65kV

Backup plan part B [6 shots]: 1A, 1C and 2A @90kV

Repeat steps 1-5 in backup plan part A, but change beam injection energy to 90kV.

Table 3: neutral beam modulation patterns and source mix for backup plan part A

Pattern #	Priority	NB Source	E_{inj} [keV]	Start Time [ms]	# of pulses	On time [ms]	Off time [ms]	NBI modulation pattern and notes
I	1	1C	65	230	9	20	60	
		2A	65	270	9	20	60	Note: (1) inject source 2A **40ms later** than 1C (2) 1 shot at I_p=1.0MA and 1 shot at 0.7MA
II	1	1C	65	**240**	5	20	120	
		2A	65	**310**	5	20	120	Note: (1) inject source 2A **70ms later** than 1C (2) 1 shot at I_p=1.0MA and 1 shot at 0.7MA
III	1	1C	65	**320**	6	20	100	
		2A	65	**230**	6	90	30	Note: inject source 1C **right after** than 2A
IV	1	2A	65	**320**	6	20	100	
		1C	65	**230**	6	90	30	Note: inject source 2A **right after** than 1C

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

The XP requires reproducible L mode plasmas with minimal MHDs and flat-top >0.8s at B_t=0.65T, I_p=1MA. Need all six beams operational at 65kV/90kV except source 1A always at 90kV. In case not all neutral beam sources are available, the mimimum requirement is three beams: source 1A@90kV, and sources 1C (or 1B) and 2A (or 2B) with injection energy of both 65kV and 90kV. Require Mirnov coils, plasma profile diagnostics (MPTS, CHERS, MSE) and fast ion diagnostics (FIDA, SSNPA, sFLIP, neutron). The machine needs to be relatively clean to avoid impurity contamination on FIDA spectra. Prefer running this XP at least a week later than the "FIDA/SSNPA/sFLIP checkout" XMP and at least a week earlier than M. Podesta's XP1523 "Assessment of NBCD and pressure profile modifications by 2nd NBI line" XP. Neither RF nor CHI is needed.

5. Planned analysis

EFIT and LRDFIT for equilibrium reconstruction. TRANSP for time-dependent modeling of neutron rate and fast-ion distribution. FIDAsim for synthetic FIDA and SSNPA diagnostic.

6. Planned publication of results

It is expected the results from this XP will be shown at the APS 2015 meeting and a Nuclear Fusion paper in early 2016. The results will also contribute JRT-15 and R15-2 reports.

7. Estimated Neutron Production

Based on the number of shots, plasma current levels, and expected durations, estimate the maximum neutron production of this experiment. See calculator in Appendix #2 for this calculation.

# of Shots used in Estimate:_36_____ Estimated Total Neutron Production:_1.22E+16___

PHYSICS OPERATIONS REQUEST

TITLE: No. **OP-XP-**
AUTHORS: DATE:

Brief description of the most important operational plasma conditions required and any special hardware requirement:
Need all six beams operational at 65kV/90kV except source 1A always at 90kV. In case not all neutral beam sources are available, the mimimum requirement is three beams: source 1A@90kV, and sources 1C (or 1B) and 2A (or 2B) with injection energy of both 65kV and 90kV. Require profile diagnostics and all fast ion diagnostics. Need reliable and reproducible quiescent L-mode plasmas and flat-top durations of >0.8s.

Previous shot(s) which can be repeated:

Previous shot(s) which can be modified:

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

B_T Range (T): **0.65** Flattop Duration (s): **>1.2**

I_P Range (MA): **0.7-1.0** Flattop Duration (s): **>0.8**

Configuration: **Limiter**

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

Outer gap (m): **0.10~0.13** Inner gap (m): **0.0** Z position (m): **0**

Elongation: **~2.3** Triangularity (U/L): **~0.6** OSP radius (m):

Gas Species: $\mathbf{D^+}$ Injector(s): **tbd**

NBI Species: $\mathbf{D^0}$ Heating Duration (s): **beam blips**

Voltage (kV) 50 cm (1C): **90/65** 60 cm (1B): **90/65** 70 cm (1A): **90**

Voltage (kV) 110 cm (2C): **90/65** 120 cm (2B): **90/65** 130 cm (2A): **90/65**

ICRF Power (MW): **N/A** Phase between straps (°): Duration (s):

CHI: **Off** Bank capacitance (mF):

LITERs: Off Total deposition rate (mg/min) or dose per discharge (mg): **0**

EFC coils: On for error field correction

DIAGNOSTIC CHECKLIST [1]

TITLE: No. **OP-XP-**

AUTHORS: DATE:

Note special diagnostic requirements in Sec. 4

Diagnostic	**Need**	**Want**
Beam Emission Spectroscopy	**X**	
Bolometer – midplane array		**X**
CHERS – poloidal		**X**
CHERS – toroidal	**X**	
Divertor Bolometer (LADA)		
Divertor visible cameras		
Dust detector		
Edge deposition monitors [2]		
Edge neutral density diag.		**X**
Edge MIGs [2]		
Penning Gauges [2]		
Edge rotation diagnostic		**X**
Fast cameras – divertor [2]		
Fast ion D_alpha - poloidal	**X**	
Fast ion D_alpha - toroidal	**X**	
Fast lost ion probes - IFLIP	**X**	
Fast lost ion probes - SFLIP	**X**	
Filterscopes [2]		**X**
FIReTIP		**X**
Gas puff imaging – divertor		
Gas puff imaging – midplane		
Hα cameras - 1D [2]	**X**	
Infrared cameras [2]		**X**
Langmuir probes – divertor		
Langmuir probes – RF		
Langmuir probes – RF ant.		
Magnetics – Diamagnetism		**X**
Magnetics – Halo currents		
Magnetics – RWM sensors	**X**	

Note special diagnostic requirements in Sec. 4

Diagnostic	**Need**	**Want**
MAPP		
Mirnov coils – high f.	**X**	
Mirnov coils – toroidal array	**X**	
MSE-CIF	**X**	
MSE-LIF		
Neutron detectors [2]	**X**	
Plasma TV		**X**
Reflectometer – 65GHz		
Reflectometer – correlation		
Reflectometer – FM/CW		
Reflectometer – fixed f		**X**
Reflectometer – SOL		
SSNPA [2]	**X**	
RF edge probes		
Spectrometer – divertor		
Spectrometer – MonaLisa		**X**
Spectrometer – VIPS		**X**
Spectrometer – LOWEUS		**X**
Spectrometer – XEUS		**X**
TAE Antenna		
Thomson scattering	**X**	
USXR – pol. Arrays		**X**
USXR – multi-energy	**X**	
USXR – TG spectr.		**X**
Visible Brems. det. [2]		**X**

Notes:

[1] Check marks in this table do not guarantee diagnostic availability. Check with diagnostic physicists or research operations management to ensure diagnostic coverage.

[2] In some cases, a given line represents multiple diagnostics. For instance, there are multiple SSNPAs, multiple IR cameras, multiple neutron detectors, and multiple Langmuir probe arrays.

Appendix #1: Allowed Neutral Beam Power vs. Pulse Duration

Heating of the primary energy ion dump limits the beam duration to that given in the following table[1]:

Acceleration Voltage [kV]	MW per Source	MW per Beamline	Pulse Length [s]
65	1.1	3.2	8
70	1.3	3.8	7
75	1.5	4.5	6
80	1.7	5.1	5
85	1.9	5.8	4
90	2.1	6.4	3
95	2.4	7.1	2
100	2.6	7.7	1.5
105	2.8	8.4	1.25
110	3.0	9.0	1

Table A1: Beam power and pulse length as a function of acceleration voltage

Appendix #2: Table for neutron rate estimations:

Change only the blue cells					
I_p Range [kA]	Center of I_p Range [kA]	Number of Discharges	Typical Discharge Time [s]	Assumed Neutron Rate [N/s]	Fluence at this I_p [N]
$0<I_p?400$	200	0	0	0.00E+00	0.00E+00
$400<I_p?600$	500	0	0	1.00E+14	0.00E+00
$600<I_p?800$	700	6	1.2	2.00E+14	1.44E+15
$800<I_p?1000$	900	30	1.2	3.00E+14	1.08E+16
$1000<I_p?1200$	1100	0	0	4.00E+14	0.00E+00
$1200<I_p?1400$	1300	0	0	5.00E+14	0.00E+00
$1400<I_p?1600$	1500	0	0	8.00E+14	0.00E+00
$1600<I_p?1800$	1700	0	0	1.30E+15	0.00E+00
$1800<I_p?2000$	1900	0	0	2.00E+15	0.00E+00
Total # of Discharges		36		Total Fluence	1.22E+16

Table A2: Neutron Emission Rate Calculator. Double click to open in excel for automatic calculation. Change only the blue cells.

[1] J.E. Menard, et al., Nuclear Fusion **52**, 2012 (83015)