**PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76CH03073**

PPPL-3561
UC-70

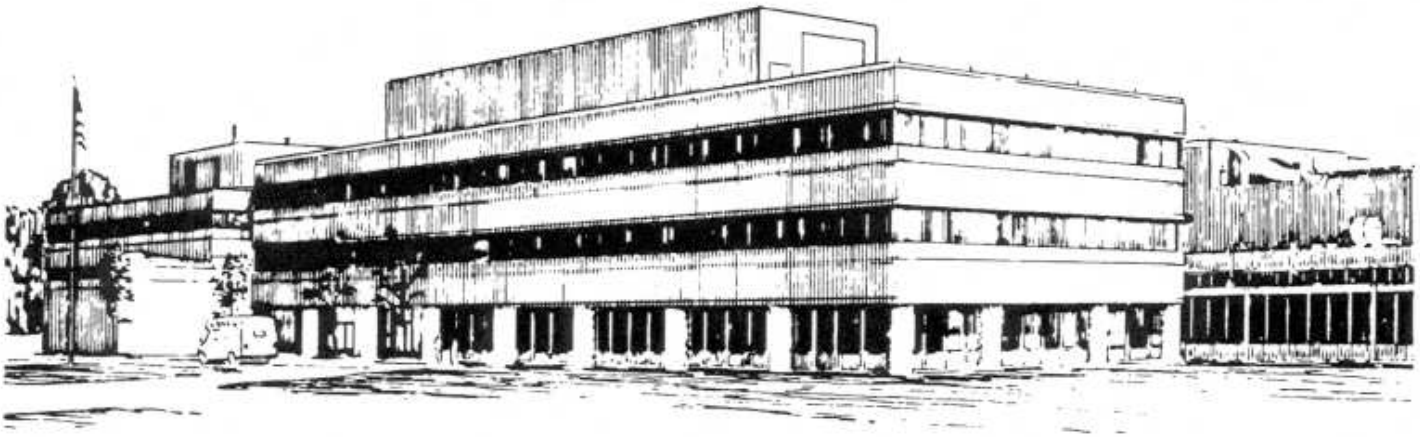
PPPL-3561

Initial Results from Coaxial Helicity Injection Experiments in NSTX

R. Raman, T.R. Jarboe, D. Mueller, M.J. Schaffer, R. Maqueda,
B.A. Nelson, S. Sabbagh, M. Bell, R. Ewig, E. Fredrickson, D. Gates,
J. Hosea, H. Ji, R. Kaita, S.M. Kaye, H. Kugel, R. Maingi,
J. Menard, M. Ono, D. Orvis, F. Paoletti, S. Paul, M. Peng,
C.H. Skinner, J.B. Wilgen, S. Zweben, and the NSTX Research Team

May 2001

PPPL
PRINCETON PLASMA
PHYSICS LABORATORY



**PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY, PRINCETON, NEW JERSEY**

PPPL Reports Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Availability

This report is posted on the U.S. Department of Energy's Princeton Plasma Physics Laboratory Publications and Reports web site in Calendar Year 2001. The home page for PPPL Reports and Publications is: http://www.pppl.gov/pub_report/

DOE and DOE Contractors can obtain copies of this report from:

U.S. Department of Energy
Office of Scientific and Technical Information
DOE Technical Information Services (DTIS)
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401

Fax: (865) 576-5728

Email: reports@adonis.osti.gov

This report is available to the general public from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Telephone: 1-800-553-6847 or
(703) 605-6000

Fax: (703) 321-8547

Internet: http://www.ntis.gov/ordering.htm

Initial results from Coaxial Helicity Injection experiments in NSTX*

R. Raman[1], T.R. Jarboe[1], D. Mueller[2], M.J. Schaffer[3], R. Maqueda[4], B.A.Nelson[1], S. Sabbagh[5], M. Bell[2], R. Ewig[1], E. Fredrickson[2], D. Gates[2], J. Hosea[2], H. Ji[2], R. Kaita[2], S.M. Kaye[2], H. Kugel[2], R. Maingi[6], J. Menard[2], M. Ono[2], D. Orvis[1], F. Paoletti[5], S. Paul[2], M. Peng[6], C.H. Skinner[2], J.B Wilgen[6], S. Zweben[2] and the NSTX Research Team

[1] *University of Washington, Seattle, WA*

[2] *Princeton Plasma Physics Laboratory, Princeton, NJ*

[3] *General Atomics, San Diego, CA*

[4] *Los Alamos National Laboratory, Los Alamos, NM*

[5] *Columbia University, New York, NY*

[6] *Oak Ridge National Laboratory, Oak Ridge, TN*

Abstract

Coaxial Helicity Injection (CHI) has been investigated on the National Spherical Torus Experiment (NSTX). Initial experiments produced 130kA of toroidal current without the use of the central solenoid. The corresponding injector current was 20kA. Discharges with pulse lengths up to 130ms have been produced.

I. Introduction

The Spherical Torus (ST) is a magnetic confinement concept that has the potential advantages of high beta, high bootstrap current fraction and increased stability. These favorable properties of the ST arise from its very small aspect ratio ($A \leq 1.5$). Experimental results from the Small Tight Aspect Ratio Tokamak (START) demonstrated some of the favorable high beta properties with good confinement [1,2]. This motivated the construction of two large STs, NSTX in the USA [3,4] and the Mega Ampere Spherical Torus (MAST) in the UK [5]. To minimize the aspect ratio, elimination of the central solenoid is a consideration for future ST designs. This requires the demonstration of plasma creation and sustainment by non-inductive current drive methods. Coaxial Helicity Injection (CHI) is a promising candidate for generating target plasma for non inductive current drive methods and for driving edge current (inside the last closed flux surface) during the sustained phase.

The first experiments on helicity injection current drive in a ST were conducted on the Current Drive Experiment-Upgrade (CDX-U) at the Princeton Plasma Physics Laboratory (PPPL) [6]. CHI was initially used for the generation of spheromak plasmas [7,8,9]. The possibility of using CHI in a ST was first proposed in the late 1980's [10]. The idea gained support as a result of experiments conducted on the Proto-Helicity Injected Torus, and the Helicity Injected Torus-I (HIT-I) at the University of Washington [11]. These experiments used a thick conducting copper wall for equilibrium control of the CHI produced plasma configuration. These were followed by two other experiments, the Himeji Institute of Technology Spherical Torus (HIST) in Japan and the SPHEX

device (operated in a ST mode) in the UK [12,13]. These devices also employed passive wall stabilization for equilibrium control and confirmed that CHI could be used in the presence of an external toroidal. Later HIT was rebuilt as the HIT-II experiment, which extended CHI to a true ST device by employing 28 poloidal field coils for equilibrium control instead of from image currents induced on copper walls [14]. HIT-II produced substantial plasma currents (200 kA) using transformer action or using CHI [15]. An important goal for the NSTX program is to conduct proof-of-principle experiments to validate this concept on a device that has a volume about 30 times that of HIT.

The CHI method drives current initially on open field lines creating a current density profile that is hollow. Taylor relaxation [16] predicts a flattening of this current profile through a process of magnetic reconnection leading to current being driven throughout the volume, including closed field lines. Current penetration to the interior is eventually needed for usefully coupling CHI to other current drive methods and to provide CHI produced sustainment current during the long pulse non-inductive phase.

For an ST, the primary goal of a CHI system is to generate a suitable target plasma that can be ramped up in current to a high bootstrap current fraction regime using non inductive current drive methods and without the use of the Ohmic coil. On NSTX, this requires the CHI system to produce target plasmas with a temperature of about 200eV. This temperature is needed for coupling to High Harmonic Fast Wave (HHFW) current drive. A secondary goal is to extend the pulse duration of 1MA Ohmic discharges by producing target plasma for Ohmic discharges.

This paper is organized as follows. Section II describes the CHI components on NSTX. In section III we describe the experimental results obtained thus far; the final section is a brief summary of the results.

II. Experiment description

The nominal NSTX machine parameters are major/minor radius of 0.85/0.65m, elongation ≤ 2.2, a plasma volume of 14m^3 and a machine volume of 30m^3 [3]. As on the HIT device, the stainless steel vacuum vessel of NSTX is fitted with toroidal ceramic breaks at the top and bottom so that the central column and the inner divertor plates (the inner vessel components) are insulated from the outer wall and the outer divertor plates. Four pairs of Poloidal Field (PF) coils placed symmetrically above and below the midplane outside the vacuum vessel are available for equilibrium control. The lower divertor region has an additional coil positioned below the inner divertor plate. This and the lowest PF coil allows one to set up the vacuum CHI injector flux in a manner that it connects the lower inner and outer divertor plates. The coils allow for the generation of up to 500mWb of injector flux. The corresponding maximum toroidal flux (TF) for a nominal 0.3T discharge is 1.5Wb.

CHI is implemented on NSTX by driving current along field lines that connect the inner and outer lower divertor plates. A 25kA, 1kV DC power supply is connected across the inner and outer vessel components, as shown in Figure 1, to drive the injector current. The standard operating condition for CHI in NSTX uses the inner vessel and inner

divertor plates as the cathode. The outer vessel is the anode. A dedicated gas injection system in the lower divertor region injects gas from four ports in the lower inner divertor plates toroidally separated from each other by 90 degrees. For the initial CHI experiments, a fixed volume plenum was filled to a known pressure and quickly emptied into the divertor region by opening a fast valve. To increase the speed of the gas delivery system, a total of four plenums and corresponding four fast valves are used, one for each of the four gas injection ports located in the cathode region. The initial fast puff transiently produces a high gas pressure in the lower divertor region. This facilitates gas breakdown when voltage is applied to the lower divertor plates. An 18 GHz, 10kW Electron Cyclotron Heating Pre Ionization system (ECH-PI) is used to produce a vertical EC resonance layer near the center stack (at a radius of 40cm). The EC resonance layer intersects the inboard injector flux footprints, facilitating gas breakdown at the lower fill pressures.

The operational procedure involves first energizing the TF coils and the CHI injector coils to produce the desired flux conditions in the injector region. A voltage is now applied to the inner and outer divertor plates and a pre-programmed amount of gas is injected from the inner lower divertor plate ports. ECH-PI is turned on for a pre programmed time duration. These conditions cause the gas in the lower divertor region to ionize and result in current flowing along magnetic field lines connecting the lower divertor plates. The applied toroidal field causes the current in the plasma to develop a strong toroidal component, the beginning of the desired toroidal plasma current. If the injector current exceeds a threshold value, the resulting ΔB_{tor}^{2}, ($\mathbf{J}_{pol}$ X $\mathbf{B}_{tor}$), stress across

the current layer exceeds the field line tension of the injector flux causing the helicity and plasma in the lower divertor region to move into the main torus chamber. Once extended into the vessel, currents need to be driven in the PF coils for equilibrium position control.

III. Experimental results

That this method works on a large ST is shown in Figure 2. First, Figure 2a shows a CHI discharge evolution as recorded by a fast framing camera [17]. These fish eye view images of the entire NSTX vessel show that at t=16ms, the discharge originates in the lower divertor region. As the injector current (shown in Figure 2b) increases, the fluxes connecting the lower divertor plates are extended into the confinement chamber (at t = 18ms). At even higher injector currents, the discharge nearly fills the entire chamber (at t = 20ms). In this discharge a peak toroidal current (Figure 2b) of 20kA is obtained for an injector current of about 7kA resulting in a current multiplication of about 3. The injector current is the current supplied by the 1kV CHI power supply that flows through the plasma load. The toroidal current is that measured by the NSTX plasma current measurement system.

Figure 3, shows the applied injector voltage, divertor coil current, injector current and CHI produced toroidal current, for a high current discharge. The divertor coil current is a measure of the poloidal flux (the injector flux) that connects the lower divertor plates (see Figure 1). For the case where the divertor coil currents are in the same direction and linearly proportional to each other the injector flux is nearly linearly proportional to the current being driven in the CHI divertor coil. The applied voltage determines the amount

of injector current that can be driven for this combination of injector flux and divertor gas pressure.

This discharge has two phases. For times less than 50ms (phase 1), the applied voltage and the divertor coil currents are constant. This results in an injector current of 20kA and a toroidal current of 50kA (a current multiplication factor of ~2). To increase the current multiplication factor, the divertor coil current is ramped down during phase 2 (t > 50ms). This results in reduced injector flux and consequently the injector impedance increases. To compensate, the injector voltage is increased as shown in Figure 3. The programmed voltage ramp maintains a constant injector current. Since the injector flux is decreasing with time, while the toroidal flux is constant, for reasons described in the next paragraph one expects the current multiplication factor to increase. Indeed, the toroidal current increased during the course of the discharge, resulting in a maximum of about 130kA at t = 100ms, a current multiplication factor of 6.5. The discharge for its entire duration was maintained in equilibrium using pre-programmed coil currents only.

Energy conservation and helicity balance require that the ratio λ_{ST} of the obtained toroidal current to the toroidal flux of the discharge in the ST $(\lambda_{ST} = \mu_o I_{toroidal}/\Psi_{toroidal})$ be less than the ratio of the injector current to the poloidal flux $(\lambda_{inj} = \mu_o I_{inj}/\Psi_{inj})$ where Ψ_{inj} is measured between the toroidal breaks between the inner and outer electrodes using the poloidal flux loop signals. Here the term ST refers to the device and not to the type of plasma present in the machine. During steady state current drive, the efficiency for current drive is given as, $\varepsilon = \lambda_{ST}/\lambda_{inj}$ [16,18,11]. Here the efficiency is defined as injector flux utilization

efficiency. The maximum current multiplication is predicted to be the ratio of the ST flux over the injector flux. From the above, $(I_{toroidal}/I_{inj}) = (\lambda_{ST} / \lambda_{inj}) (\Psi_{toroidal} / \Psi_{inj})$, so current multiplication depends on the λ ratio, too. Uniform λ cannot be assumed. However, λ_{ST} is not expected to exceed λ_{inj}. For the shot shown in Figure 3, Figure 4 shows the ratio of the toroidal flux, calculated assuming that the plasma fills the entire region between the electrodes, to injector poloidal flux multiplied by the injector current and compared to the measured toroidal current. This analysis shows that within uncertainties the amplification factor is nearly as large as possible (at t = 110ms). The measured current approaches 80% of the theoretical maximum current showing that CHI is effective at driving toroidal current on large devices. The ratio is low during the early part of the discharge as only a small portion of the maximum possible toroidal flux (1.5Wb) links the injector flux. While the CHI has successfully driven toroidal current in NSTX, it is not yet known whether this current is flowing on closed field lines. Although a definite conclusion will probably have to await the implementation of diagnostics for the direct measurement of the spatial profile of the toroidal current, there is some indirect evidence for the reconnection process occurring during the CHI.

Figure 3 shows an increase in voltage fluctuations during phase 2 of the discharge. The fluctuations have a coherent mode at ~9kHz. Analysis of the Mirnov coil signals shows a similar global mode during phase 2. A toroidal Mirnov coil array on the center column shows the magnetic signature of the discharge to be toroidally symmetric with a coherent n=0 mode, similar to that seen in the HIST experiment [12]. There is no toroidal Mirnov array on the NSTX outer vessel to discern the toroidal mode number near the outer shell.

On the HIT experiments, an n=1 coherent mode activity, located on the outer shell probes only, is seen during high current discharges [11,14]; n = 0 activity is also seen by the outer Mirnov coils in some discharges. On NSTX, coherent fluctuations were also seen by a fast photodetector that sampled a chord passing through the center of the plasma. This mode activity seen by both magnetic and optical diagnostics is an encouraging result. On HIT experiments, an n=1 mode seen on the outer vessel Mirnov coils is deemed necessary for the generation of closed flux surfaces. An outer vessel Mirnov array is being installed on NSTX.

To examine the effect of injector impedance at lower pressure, a scan was conducted in which the injector current was measured as the vessel pressure was reduced from 16 to 4mTorr with the same flux and applied voltage. It was found that there is little change in injector current as the pressure is reduced. Experiments were also successful in generating discharges at a vessel pressure of 1mTorr. Since pressures of about 4mTorr are compatible with high recycling divertor operation, these results indicate that on NSTX, from a density standpoint, it should be possible to couple CHI discharges to Ohmic discharges. Compared to similar measurements on HIT-II, these results indicate a more favorable density scaling of the injector impedance that very likely result from the longer field line length on NSTX.

IV. Summary and Discussion

In summary, initial CHI experiments on NSTX have successfully generated 130kA of toroidal current using about 20kA of injector current. Stable discharges lasting for 0.13

seconds have been produced using pre-programmed coil currents and at vessel neutral densities compatible with high recycling divertor operation. Experiments to date have shown that CHI engineering systems can be successfully applied to a large ST for the production of substantial toroidal currents as predicted by previous work on smaller experiments. However, there is insufficient evidence at this time to confirm the generation of closed flux surfaces in these discharges. Future experiments aimed at studying closed flux generation will involve producing CHI discharges at higher toroidal currents that will be diagnosed using multi point Thomson scattering temperature and density profiles. The region of closed flux will be reconstructed using an equilibrium fitting code adapted to allow current flow on open field lines and the private flux region.

References

[1] Sykes, A., et al., Phys. Rev. Lett. **84** (2000) 495.
[2] Gates, D., et al., Phys. Plasmas **5** (1998) 1775.
[3] Ono, M., et al., Nucl. Fusion **40**, 3Y (2000) 557.
[4] Kaye, S., et al., Fusion Technol. **36** (1999) 16.
[5] Darke, A.C., Fusion Engineering **2** (1995) 1456.
[6] Ono, M., et al., Phys. Rev. Lett. **44**, (1980) 393.
[7] Turner, W.C., et al., J. Appl. Phys. **52** (1981) 175.
[8] Jarboe, T.R., et al., "Production of field-reversed configurations with a magnetized coaxial plasma gun", Proc. Int. Symp. on phys. of open ended fusion systems (Tsukuba 1980).
[9] Armstrong, W.T., et al., Plas. Phys. Contrl. Nucl. Fusion Res. 1980 (IAEA, Vienna) Vol I, p481.
[10] Jarboe, T.R., Fusion Tech. **15**, (1989) 7.
[11] Nelson, B.A., et al., Phys. Plasmas **2** (1995) 2337.
[12] Nagata, M., et al., 17th IAEA Fusion Energy Conference, Yokohama, IAEA-CN 69/EXP4/10 (1998).
[13] Browning, P.K., et al., Phys. Rev. Lett. **68** (1992) 1722.
[14] Jarboe, T. R., et al., Phys. Plasmas **5**, (1998) 1807.
[15] Jarboe, T.R., et al, 17th IAEA Fusion Energy Conference, Yokohama, IAEA-CN 69/PDP/02 (1998).
[16] Taylor, J.B., Rev. Mod. Phys. **28**, (1986) 243.
[17] Maqueda, R.J. and Wurden, G.A., Nucl. Fusion **39** (1999) 629.
[18] Barnes, C.W., et al., Phys. Fluids **29** (1986) 3415.

E-mail address of R. Raman: raman@aa.washington.edu

Acknowledgements

We would like to thank the NSTX Engineering and Operations group for their extensive effort in the installation and commissioning of the CHI hardware on NSTX and for machine operations. Pioneering work on smaller experiments that motivated this large scale experiment on NSTX were first conducted by Thomas R. Jarboe at the University of Washington and by Masa Ono at the Princeton Plasma Physics Laboratory. This work is supported by U.S. D O E contract numbers. DE-AC02-76CH03073, DE-AC05-00R22725, DE-AC03-99ER54463, DE-FG02-99ER54524, DE-FG03-99ER54519, W-7405-ENG-36

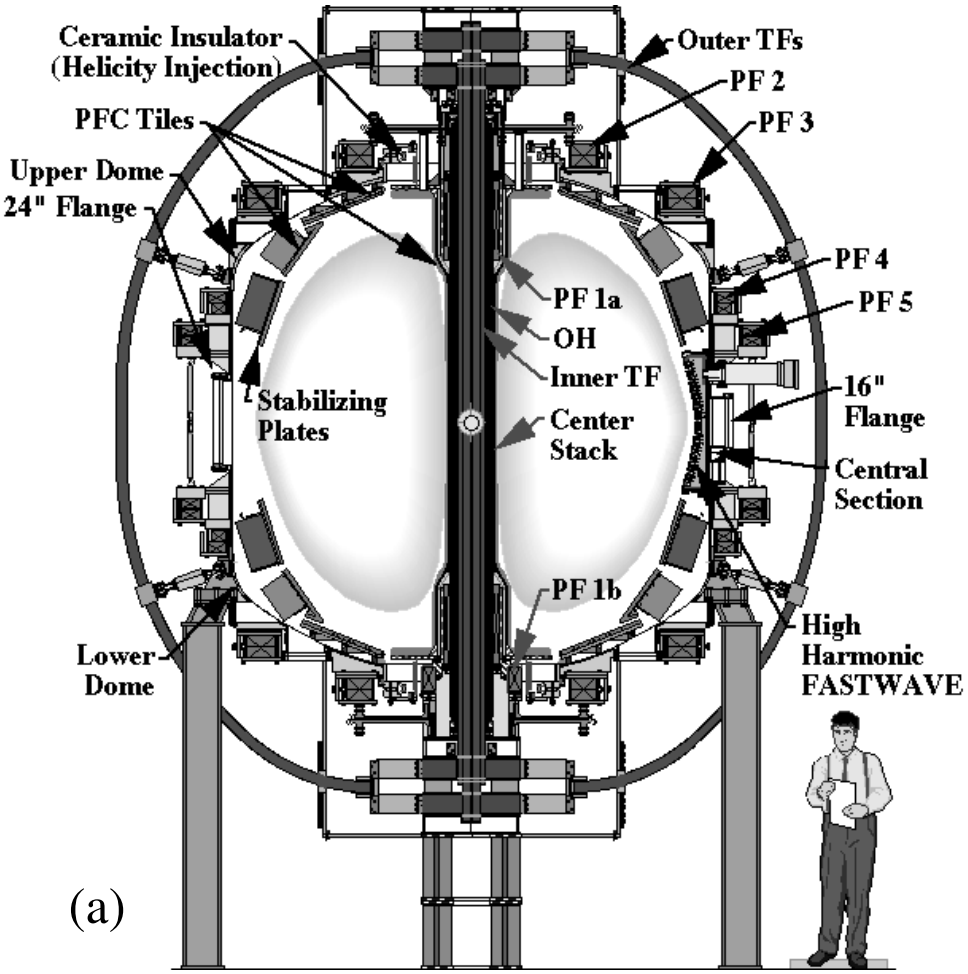
Figure captions:

Figure 1: (a) NSTX machine layout. The PF1B coil is a CHI specific coil used to produce the injector flux. (b) Exploded view of the NSTX lower divertor region showing the CHI components and sketch of representative injector flux connecting the lower divertor plates.

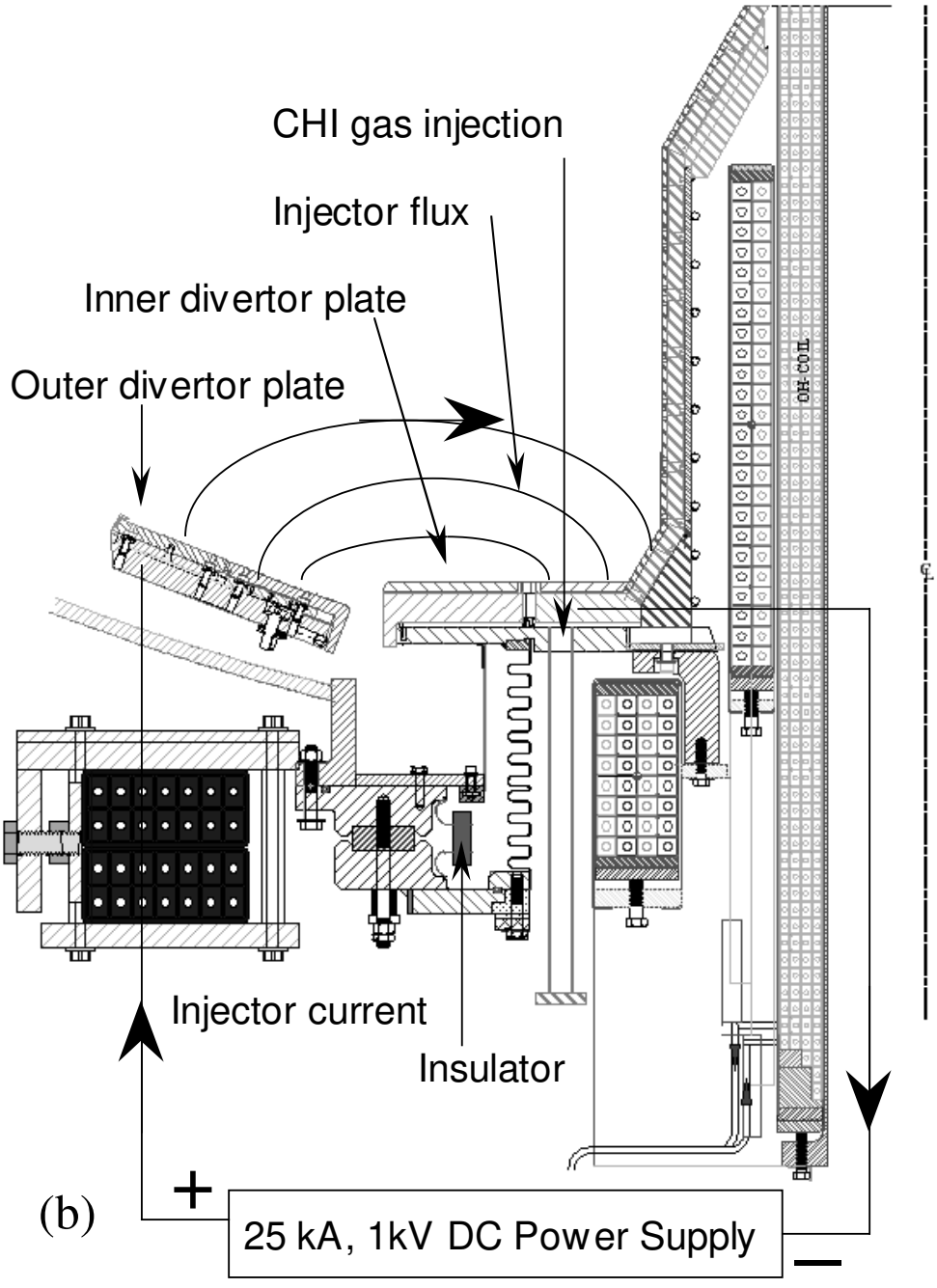
Figure 2: (a) The fast camera fish-eye-view images show that the CHI produced plasma starts in the lower divertor region at 16ms, elongates to fill half the vessel at 18ms and then nearly fills the vessel at t = 20ms (SN 101044). (b) CHI injector current and CHI produced toroidal current. Arrows indicate image times.

Figure 3: High current CHI discharge on NSTX using pre-programmed coil currents for equilibrium control.

Figure 4: Measured and calculated $(I_{toroidal} = (\Psi_{toroidal}/\Psi_{inj}) * I_{inj})$ toroidal currents shows that the measured current approaches 80% of the maximum possible current.

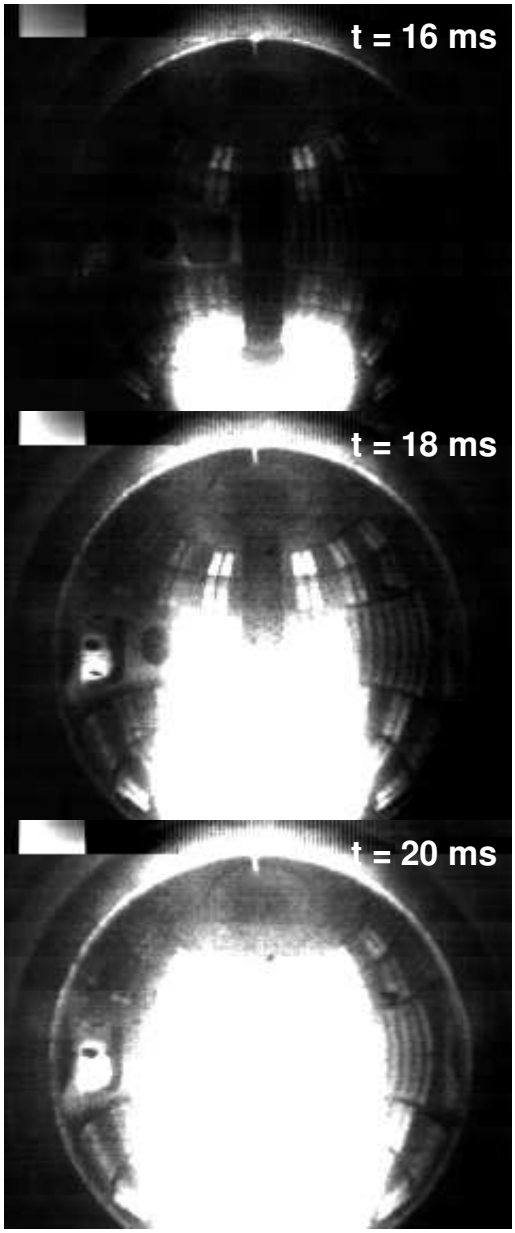

Ceramic Insulator
(Helicity Injection)
PFC Tiles
Upper Dome
24" Flange
Outer TFs
PF 2
PF 3
PF 4
PF 5
PF 1a
OH
Inner TF
Center
Stack
Stabilizing
Plates
16"
Flange
Central
Section
PF 1b
High
Harmonic
FASTWAVE
Lower
Dome

(a)

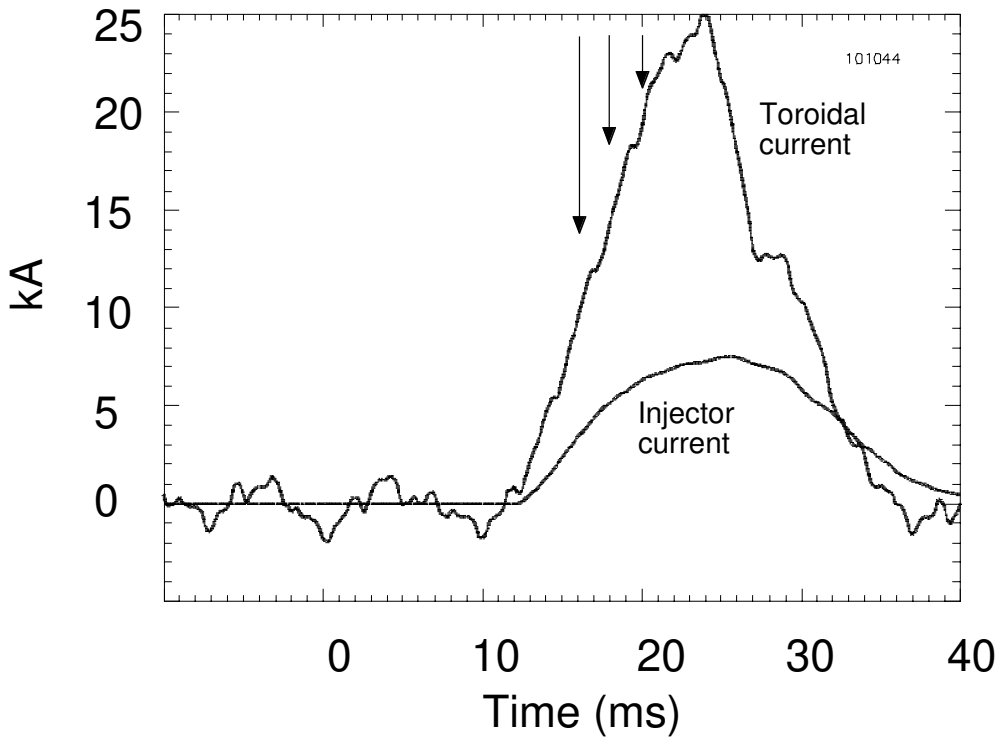

CHI gas injection
Injector flux
Inner divertor plate
Outer divertor plate
Injector current
Insulator
+
25 kA, 1kV DC Power Supply
–

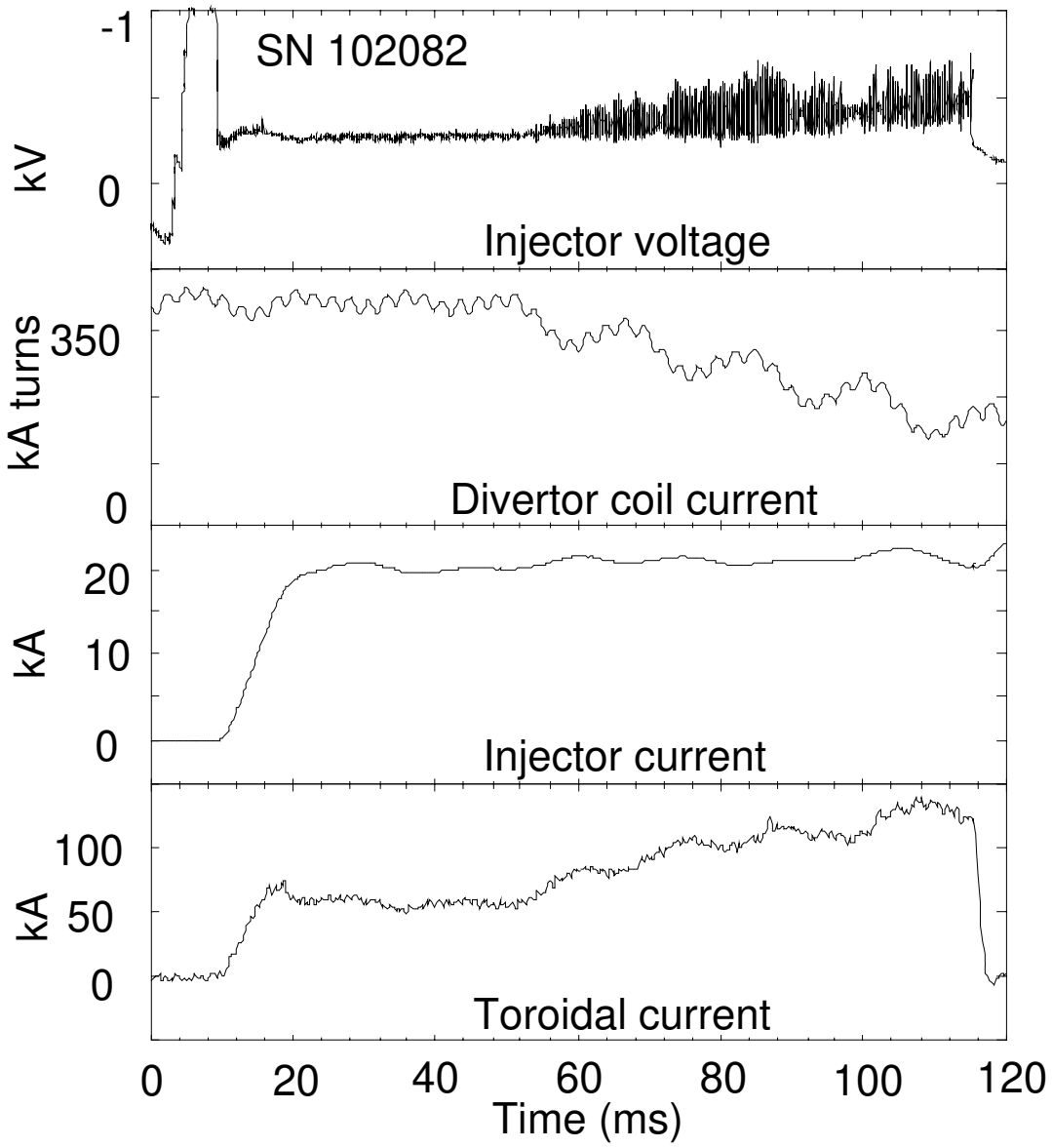
(b)

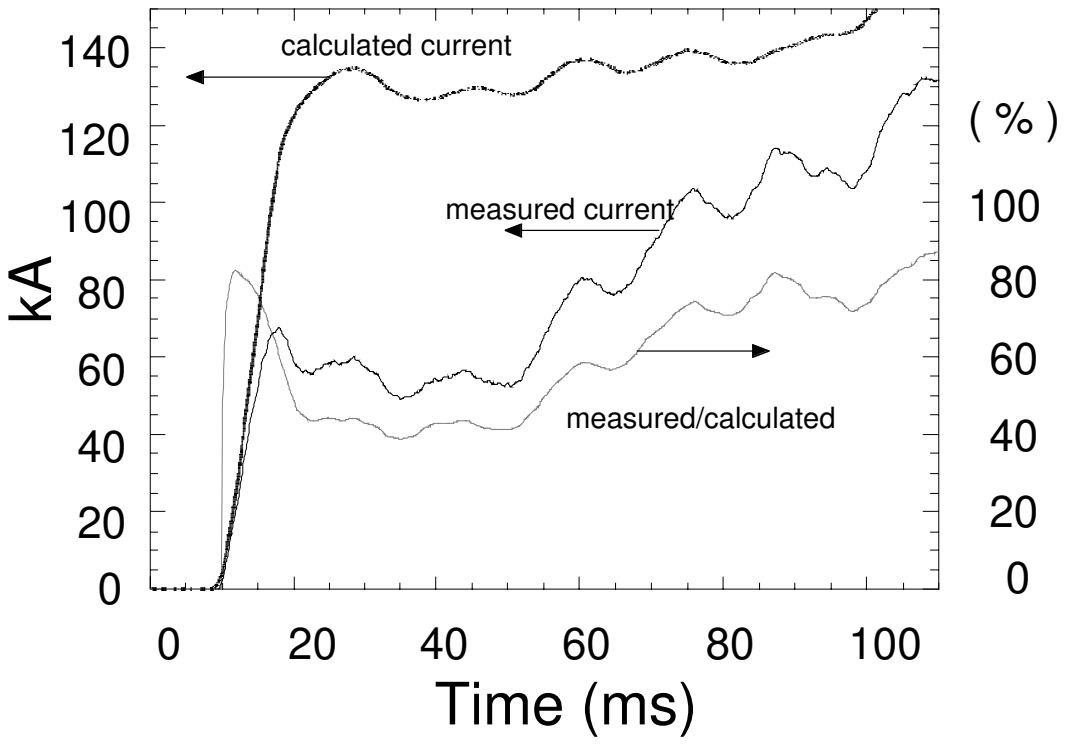
(a)



(b)


25
20
15
10
5
0
kA
101044
Toroidal
current
Injector
current
0
10
20
30
40
Time (ms)


SN 102082
-1
kV
0
Injector voltage
kA turns
350
0
Divertor coil current
20
kA
10
0
Injector current
100
kA
50
0
Toroidal current
0
20
40
60
80
100
120
Time (ms)


calculated current
measured current
measured/calculated
kA
(%)
Time (ms)
0
20
40
60
80
100
120
140

External Distribution

Plasma Research Laboratory, Australian National University, Australia
Professor I.R. Jones, Flinders University, Australia
Professor João Canalle, Instituto de Fisica DEQ/IF - UERJ, Brazil
Mr. Gerson O. Ludwig, Instituto Nacional de Pesquisas, Brazil
Dr. P.H. Sakanaka, Instituto Fisica, Brazil
The Librarian, Culham Laboratory, England
Library, R61, Rutherford Appleton Laboratory, England
Mrs. S.A. Hutchinson, JET Library, England
Professor M.N. Bussac, Ecole Polytechnique, France
Librarian, Max-Planck-Institut für Plasmaphysik, Germany
Jolan Moldvai, Reports Library, MTA KFKI-ATKI, Hungary
Dr. P. Kaw, Institute for Plasma Research, India
Ms. P.J. Pathak, Librarian, Insitute for Plasma Research, India
Ms. Clelia De Palo, Associazione EURATOM-ENEA, Italy
Dr. G. Grosso, Instituto di Fisica del Plasma, Italy
Librarian, Naka Fusion Research Establishment, JAERI, Japan
Library, Plasma Physics Laboratory, Kyoto University, Japan
Research Information Center, National Institute for Fusion Science, Japan
Dr. O. Mitarai, Kyushu Tokai University, Japan
Library, Academia Sinica, Institute of Plasma Physics, People's Republic of China
Shih-Tung Tsai, Institute of Physics, Chinese Academy of Sciences, People's Republic of China
Dr. S. Mirnov, TRINITI, Troitsk, Russian Federation, Russia
Dr. V.S. Strelkov, Kurchatov Institute, Russian Federation, Russia
Professor Peter Lukac, Katedra Fyziky Plazmy MFF UK, Mlynska dolina F-2, Komenskeho Univerzita, SK-842 15 Bratislava, Slovakia
Dr. G.S. Lee, Korea Basic Science Institute, South Korea
Mr. Dennis Bruggink, Fusion Library, University of Wisconsin, USA
Institute for Plasma Research, University of Maryland, USA
Librarian, Fusion Energy Division, Oak Ridge National Laboratory, USA
Librarian, Institute of Fusion Studies, University of Texas, USA
Librarian, Magnetic Fusion Program, Lawrence Livermore National Laboratory, USA
Library, General Atomics, USA
Plasma Physics Group, Fusion Energy Research Program, University of California at San Diego, USA
Plasma Physics Library, Columbia University, USA
Alkesh Punjabi, Center for Fusion Research and Training, Hampton University, USA
Dr. W.M. Stacey, Fusion Research Center, Georgia Institute of Technology, USA
Dr. John Willis, U.S. Department of Energy, Office of Fusion Energy Sciences, USA
Mr. Paul H. Wright, Indianapolis, Indiana, USA

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov