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ORIGINAL RESEARCH

Simplifying the ST and AT Concepts

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Abstract As stated in a IEA Burning Plasma Workshop Review (Donné et al. in Fusion Sci Technol 49:79, 2006) "…there is not much flexibility in the fueling of ITER". High-performance tokamak and ST plasmas greatly benefit from plasma rotation and rotation shear to increase energy confinement time and sustain high beta, made possible due to toroidal momentum injection from neutral beams. Advanced ST and AT scenarios rely on optimized density and pressure profiles that must be maintained for efficient device performance. In addition these discharges require the capability for off-axis current drive. Controlled variable-depth deep fueling that also injects toroidal momentum, in combination with the capability for off-axis current drive, would allow the AT/ST concepts to operate at close to projected performance levels. Advanced fuelling based on compact toroid injection and Electron Bernstein Wave off-axis current drive in conjunction with solenoid-free plasma start-up are proposed as methods to improve FNSF device performance and simplify the ST/AT Demo.

Keywords ST · AT · CT · Compact toroid · CHI · Momentum · Fueling · Simplifying fusion · Current drive · EBW · Steady state · Tokamak · Spherical torus

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Introduction

Both spherical tokamak (ST) and advanced tokamak (AT) scenarios rely on high-beta operation with a high level of bootstrap current drive. This will require capability for pressure and current profile control. A flexible deep fueling system could provide pressure profile control through control of the density profile. To maintain high-beta stability limits, capability for off-axis current drive is needed. Electron Bernstein Wave (EBW) current drive is well suited for this purpose, as conventional electron cyclotron heating (ECH) current drive efficiency rapidly decreases at large radius. Maintaining stability limits also requires a source for toroidal momentum input to induce and maintain plasma rotation and rotation shear. In the remainder of this document both ST and AT are used to refer to the same type of plasmas. The need for an improved fueling system is recognized in a recent review article [1].

Advanced Fueling

Steady-state AT and ST scenarios rely on optimized density and pressure profiles to maximize the bootstrap current fraction. Under this mode of operation, the fuelling system must deposit small amounts of fuel where it is needed, and as often as needed, so as to compensate for fuel losses, but not to adversely alter the optimum density and pressure profiles. Compact toroid (CT) fuelling, which involves the deep injection of small CT plasmas at the required frequency, has the potential to meet these needs, while simultaneously providing a source of substantial toroidal momentum input. This provides rotation capability, in alpha heated reactor discharges, needed for reducing transport and increasing plasma stability limits. A CT fuelling system has a simpler fuel cycle, without the need for tritium cryogenics, and should increase the tritium burn fraction and reduce tritium inventory in the fuel cycle.

Introduction

A CT is a self-contained plasmoid with embedded magnetic fields. The structure is very robust and it can be accelerated to the high velocities needed for fusion reactor fuelling. The CT injection concept was first proposed by Perkins et al. [2] and Parks [3]. CT acceleration was first demonstrated on the RACE facility at the Lawrence Livermore National Laboratory, where accelerated CT velocities of up to 2000 km/s were achieved at high acceleration efficiencies [4]. Further experiments on the ITER scale MARAUDER device at a US Air Force laboratory demonstrated acceleration of mg sized CTs to velocities of over 300 km/s [5]. These are the parameters required for a reactor CT fueller. The accelerator design was further improved by the Canadian Fusion Fuels Technology Project (CFFTP) in collaboration with the University of Saskatchewan, Lawrence Livermore National Laboratory and the University of California-Davis, for the purpose of injecting these plasmoids into high temperature tokamak plasma [6]. This resulted in the first successful tokamak injection experiments being conducted on the TdeV tokamak [7]. Subsequent experiments on the STOR-M and JFT-2M tokamaks showed that CT injection can also be used to trigger advanced confinement modes [8, 9].

Figure 1 is a qualitative representation of the CT Fuelling concept, meant to show the relative size of the CT and ST plasma. An accelerated CT traveling with a velocity v, would have a directed kinetic energy density $0.5\rho v^2$ where ρ is the plasma mass density. To first order, if this kinetic energy density exceeds the target magnetic energy density $B^2/2\mu_0$, then the CT would have sufficient energy to push aside the target magnetic field, *B*, and penetrate the target plasma.

Because of the increasing magnetic field at smaller major radii due to the toroidal field gradient as a function of radius, and increased drag as the traveling CT expands, the CT would stop at a location where the target magnetic energy density equals the CT kinetic energy density. At this location, the fuel from the CT would be deposited in the region where fusion reactions take place.

Compact Toroid Fuelling

A spheromak compact toroid is generally formed and accelerated in a magnetized Marshall gun, although fully inductive formation and acceleration is also possible. From a pulsed power technology aspect, the Marshall gun approach is easier, and as described later impurities are not expected to be an issue. Figure 2 shows the main components of a CT fuelling system. A CT injector consists of four regions. These are the formation, compression, acceleration and transport regions and are described in References [10–14].

Benefits of CT Fueling

The primary strengths of the CT fueller are its capability for real time density profile control, tritium tailoring and momentum injection. Figure 3 shows a conceptual layout for a reactor-class device [10, 14].

Variable Depth Fuelling and Profile Control

The injector would typically operate at about 20 Hz or higher. By controlling the mass and the radial location of fuel deposition at each of these fuel pulses [10, 14] the density profile could be maintained at the required levels without introducing strong perturbations to the required

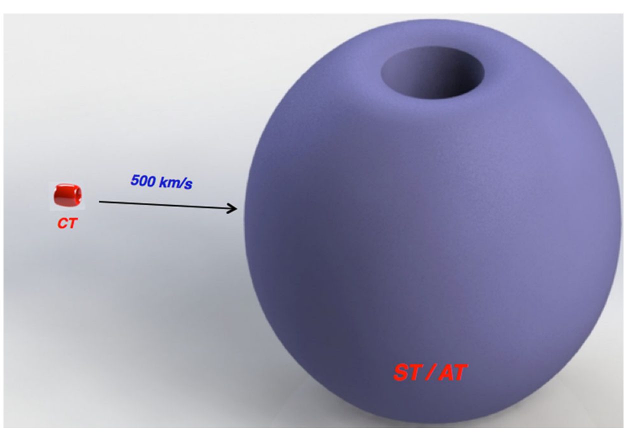

Fig. 1 Pictorial representation of CT fueling

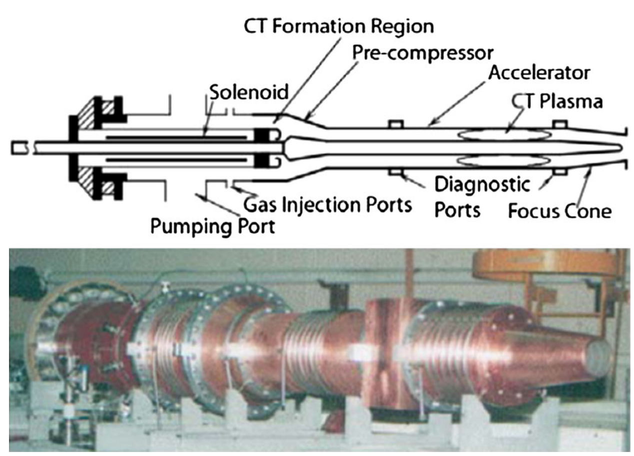

Fig. 2 *Top* shown are the different regions of a CT injector. *Bottom* the CT injector in storage at PPPL. The device is 3 m long and powered by two capacitor bank power supplies (not shown)

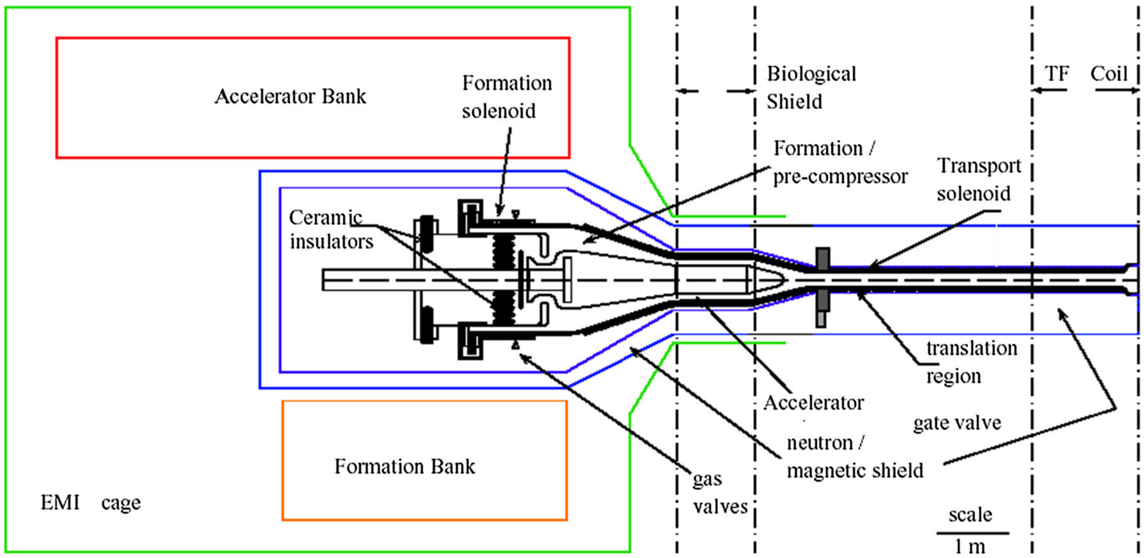

Fig. 3 Components of a reactor-class CT fueller [Refs. 10, 14]

density and pressure profiles. This is because each CT pulse would introduce a total particle inventory per pulse (mass contained in the CT/total fuel mass in the target plasma) of less than 1 %.

Tritium Wall Inventory Reduction and Reduced Wall Recycling to Improve Plasma Performance

Without deep fuelling, the fuel must diffuse from the edge into the plasma. With deep fueling, edge recycling will decrease. This should lead to improved plasma performance, as the edge pedestals can be maintained at higher electron temperature and reduced density.

A future 1 GW fusion reactor will burn on the order of about a kg of tritium/day. With shallow edge fuelling only a small amount of the injected tritium would be burnt, typically about 5 %. This means that the gas control system must process on the order of 20 kg tritium/day. Most of it simply being re-circulated to and from the reactor because of the very low fuel burn-up fraction [13]. With deep core fueling relatively more of the injected fuel would be burnt and fuel burn-up fraction would be on the order of 10 % [15]. Thus a core fuelling system such as CT injection would have the immediate impact of reducing the size of the tritium gas handling system requirements [13]. There will therefore be less tritium inventory at any given time. This by itself represents a significant improvement factor in the cost and maintenance of tritium systems in a reactor.

It is useful to note that the injector uses gas and not cryogenic pellets, so there is no need for a cryogenic system. In addition, the injector would typically inject a 50–50 ratio of D/T. Thus the exhaust gases from the reactor vacuum vessel could be directly cycled back into the injector after the D/T is separated from the He ash and other impurities [13]. A separate high concentration tritium or deuterium stream would be used to adjust the correct D/T mix in the formation chamber.

Momentum Injection

High-performance tokamak plasmas greatly benefit from plasma rotation and rotation shear to increase energy confinement and sustain high beta. This has been possible due to the injection of substantial momentum from tangentially injected neutral beam injection (NBI) systems that also contribute to important core fueling in such plasmas. In larger devices such as ITER or DEMO, higher beam injection energies are required to penetrate to the plasma core, and this reduces the momentum input per unit power. As a result, ITER is projected to have low toroidal rotation relative to present devices. CT fueling has the potential to fill this very serious gap in momentum injection, and in addition provide a source of deep controlled fueling for density profile control in burning reactor grade plasmas.

In reactors that do not need NBI for plasma heating during steady state operation, because alphas are isotropic, it is desirable to have a system for toroidal momentum injection to induce and maintain plasma rotation at the preferred levels. A CT with mass m and velocity v, has a momentum equal to mv. For a ST-FNSF, a 5 MW CT system injecting 2 mg deuterium CTs at 20 Hz will impart the same momentum as a 69 MW, 500 keV NBI system, while supplying 14 times more core fueling.

A reactor CT injector [10, 14] would typically inject 2.2 mg toroids of DT plasma or pure tritium plasmas at a fuelling rate of about 20 Hz. This represents a fuelling rate of 20.2 Pa m^3/s for a equimolar combination of deuterium–tritium or 16.1 Pa m^3/s for a pure tritium plasma. This fuelling rate is based on the assumption that significantly higher burn-up fractions could be achieved as a result of deeper fuelling with CTs [15]. These would be injected at a nominal velocity of 300 km/s, but have capability to vary the velocity (200–500 km/s) in order to vary the fuel deposition location. The injector would be positioned with some tangency with respect to the radial direction to be able to inject toroidal momentum. Two to three injectors with different tangency radius could be used to control the rotation shear.

These three aspects clearly show the tremendous advantage a CT fueller offers to future AT/ST tokamak operation.

Impurities

Impurities are not expected to be an issue for a reactor CT fueller for the following reasons. CTs produced by the magnetized Marshall gun method have the potential for generating two types of impurities. These are typical gaseous impurities such as carbon and oxygen and metallic impurities. Impurities such as carbon and oxygen would be present in present-day single pulse injectors for the simple reason that the injectors are typically operated once every 10 min. This time is sufficiently longer than the time needed for a monolayer to form on the surface of the electrodes. However, in high frequency injectors, the carbon and surface layers are ablated after several injector pulses, so there is no other possible source for such impurities.

However, during multi pulse operation, electrode material would erode due to sputtering and these could be a source of metallic impurities. Electrode erosion can be reduced by careful attention to the electrode formation processes. During the construction of the compact toroid fueller device [6] for CT injection, this was done and state-of-the-art technologies were used for coating all plasma facing surfaces with a very dense layer of tungsten. After these CTs were injected into a high-temperature tokamak plasma there was no evidence for metallic contamination of the tokamak discharge [7]. Even on the RACE experiment [4], tungsten could not be observed spectroscopically in accelerated CTs. The reason for the lack of tungsten entrainment in accelerated CTs is because of the fact that a low temperature tungsten ion does not travel very far during the time scale of injector operation. A 10 eV tungsten ion has a velocity of 2 km/s, which is much less than the CT velocity. During the 10 μs it takes to form the CT, the heavy tungsten ion travels just 2 cm. During this time the expanding CT plasma field lines typically move at a velocity of about 100 km/s. Therefore it is difficult for the released ion to be trapped in the CT plasmoid. If the ion is released as bulk eroded neutral material, it should not couple at all to the CT. In the accelerator the CT residence time at any location is on the order of 1 μs, which means that it is even more difficult for released tungsten ions to couple to the CT in the accelerator section.

Even if the ion were to be trapped in the CT, it is not confined by the CT magnetic fields. A parameter of importance in magnetically confined plasmas is $\omega\tau$, where ω is the gyro rotation frequency and τ is the collision time. Physically, this is the number of gyro rotations per collision and so is a measure of the extent to which the magnetic field is effective in slowing down cross-field transport. Usually, $\omega\tau \gg 1$ implies good magnetic confinement. For a 10 eV tungsten ion in 1–5 T fields $\omega\tau \ll 1$. Even if entrained in the CT, the magnetic confinement is poor and tungsten ions would not be confined by the CT.

These physics arguments support the experimentally observed result that tungsten does not appear to be entrained in accelerated CTs. Thus we do not expect metallic contamination of the CT to be an issue for reactor applications [14].

Required Development Work

The TdeV results show that CTs can be sufficiently clean for the purpose of tokamak fueling. As shown in Ref. [7], during the fueling of a 1.4 T single null divertor discharge the tokamak plasma was not adversely perturbed. While some fuel was deposited deep inside the separatrix, there was no localized fuelling and a large fraction of the fuel was deposited near the edge. This is an inherent difficulty with small tokamaks because the CT axial dimensions are comparable to the tokamak minor radius. As Fig. 4 indicates, these issues can be avoided by selecting a larger cross-section target plasma. A TdeV CT injector sized CT can penetrate toroidal fields of about 1 T.

TdeV CT injection experiments were conducted at 1.4 T. Since the CT axial length was about the same as the TdeV minor radius, localized fuelling was not possible in past experiments. NSTX-U is a 0.4–1 T machine with a minor cross-section much larger than the CT plasmoid length. NSTX-U experiments would allow for a localized fuelling demonstration. The steep toroidal field gradient in NSTX-U makes it an excellent test bed for establishing the penetration scaling laws. Figure 5 shows the proposed layout of a CT injector for such a momentum injection test on the NSTX-U device. The needed experimental results are:

Localized Fuelling

It is necessary to show that by altering the CT injector parameters, that the CT could be used to deposit fuel at an arbitrary location within the tokamak. NSTX-U has a large cross-section plasma at a nominal toroidal field of 0.4–1 T. Thus there is adequate overcapacity in the present injector design to demonstrate this capability in NSTX-U.

Momentum Injection

As shown in Fig. 5, a tangential CT installation is possible in NSTX-U to demonstrate the momentum injection capability of the CT.

Repetition Rate Operation

CT injection from a 10–20 Hz injector into a large tokamak plasma at higher values of the toroidal field is required. The present off-the-shelf hardware capability for high current switches and capacitor banks is such that a 20 Hz system can be built without the need for further research and development in pulsed power technology.

NSTX-U is a particularly good choice for the near-term experiments as neutral gas has considerable difficulty penetrating the torus. Besides having a large plasma cross-section and low toroidal field, NSTX-U is a spherical tokamak. As a consequence NSTX-U has a very large toroidal field gradient. The toroidal field on the inboard side is an order of magnitude higher than on the outboard side. Since the CT penetration criterion depends on the toroidal field, it means that on NSTX-U the CT stopping location is more precisely defined. This makes NSTX-U or any large spherical tokamak an ideal candidate in which to study the CT penetration scaling laws.

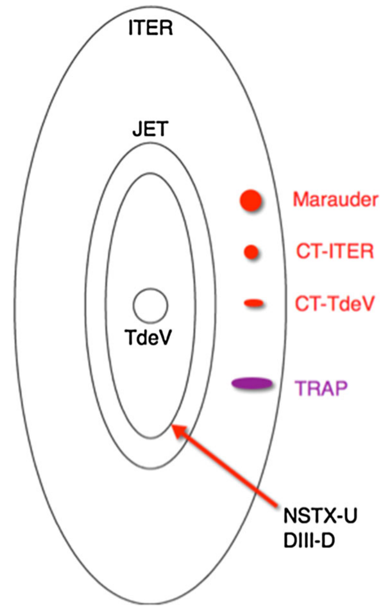

Fig. 4 Qualitative representation of the poloidal cross-section of different tokamak and CT plasmas

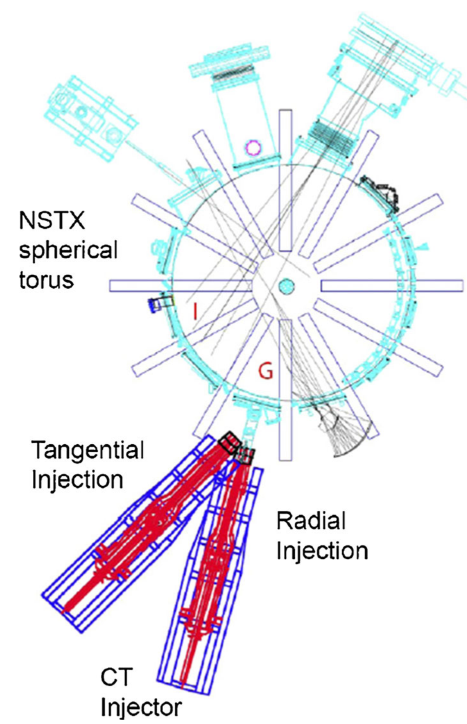

Fig. 5 Layout of the CT injector on NSTX-U for variable angle CT injection to study momentum injection and density profile control

EBW Current Drive

In addition to maintaining the optimized density profiles, and a small amount of core current drive needed to control q(0) and q_{min}, the only other need is for a small amount of off-axis current drive. This is because most ST/AT scenarios have a large fraction of bootstrap current, and therefore require capability for off-axis current profile control. The efficiency of conventional, Fisch-Boozer Electron Cyclotron Current Drive (ECCD) rapidly decreases at large radius due to trapping of electrons in banana orbits [16]. However, in overdense plasmas, such as STs and other high beta fusion devices, electron trapping allows Ohkawa Electron Bernstein Wave Current Drive (EBWCD) [16, 17] that can drive current efficiently, even well off the magnetic axis.

Simulations for NSTX and NSTX-U high beta scenarios show that EBWCD can provide up to 40 kA/MW of current drive for sustained operation in high electron density (n_e) plasmas [18, 19]. GENRAY-ADJ [20] numerical simulations were run for two $I_p = 1.2$ MA, B_T (0) = 1 T, 100 % non-inductive NSTX-U NBI-heated H-mode cases, one with broad electron density and temperature profiles and the other with narrow profiles [21]. The location of the antenna was scanned in poloidal angle from the midplane to 70° above the midplane and the antenna was oriented to launch $n_{//}= 0.7$ to maximize O-mode to X-mode to EBW (O-X-B) double mode conversion near the plasma edge. For cases where the antenna was within 40 degrees of the midplane the EBW-driven current density profile was narrow, with peak CD densities of 0.8 MA/m^2/MW near r/a = 0.2 (Fig. 6). When the antenna was greater than 40° above the midplane the location of the peak current density shifted further off-axis to r/a = 0.3–0.6 and the CD density fell to 0.05–0.1 MA/m^2/MW (Fig. 7). The EBWCD efficiency reached 40 kA/MW when the CD was located near the axis and fell to 10–15 kA/MW when current was driven out at r/a = 0.6–0.7 (Fig. 7a). The CD efficiency was similar for the broad and narrow profile cases but for a given antenna poloidal location the EBW-driven current density peaked further off axis for the case with narrower n_e and T_e profiles (Fig. 7b).

A Synthetic Aperture Microwave Imaging diagnostic (SAMI) [22] will be installed on NSTX-U in 2015. The SAMI diagnostic will measure the B-X-O mode conversion efficiency and determine under what conditions the B-X-O conversion efficiency is a maximum, and also how stable the angular mode conversion window is with respect to fluctuations in the edge. These EBW mode conversion measurements, together with ray tracing and Fokker–Planck simulations, will provide valuable data for the design of an EBW heating and CD system for NSTX-U.

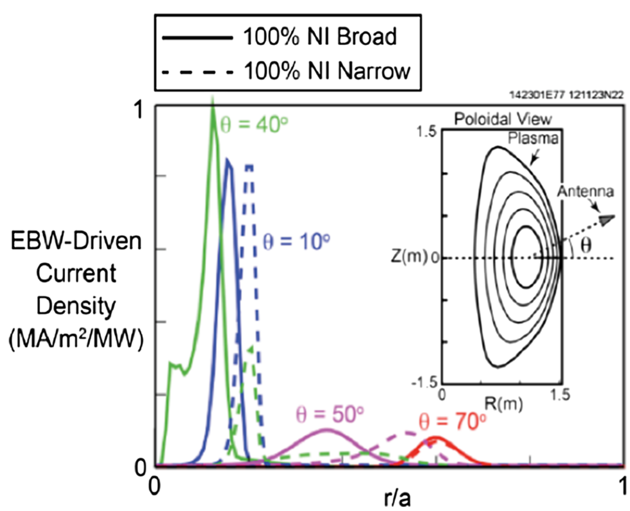

Fig. 6 EBW driven current density versus normalized minor radius (r/a) for two $B_T(0) = 1$T, $I_p = 1.2$ MA NSTX-U 100 % NI H-mode plasmas for the antenna oriented to launch nII = 0.7. The central electron density is about 12–13 × 10^{19} m^{-3} and the central T_e is about 2 keV

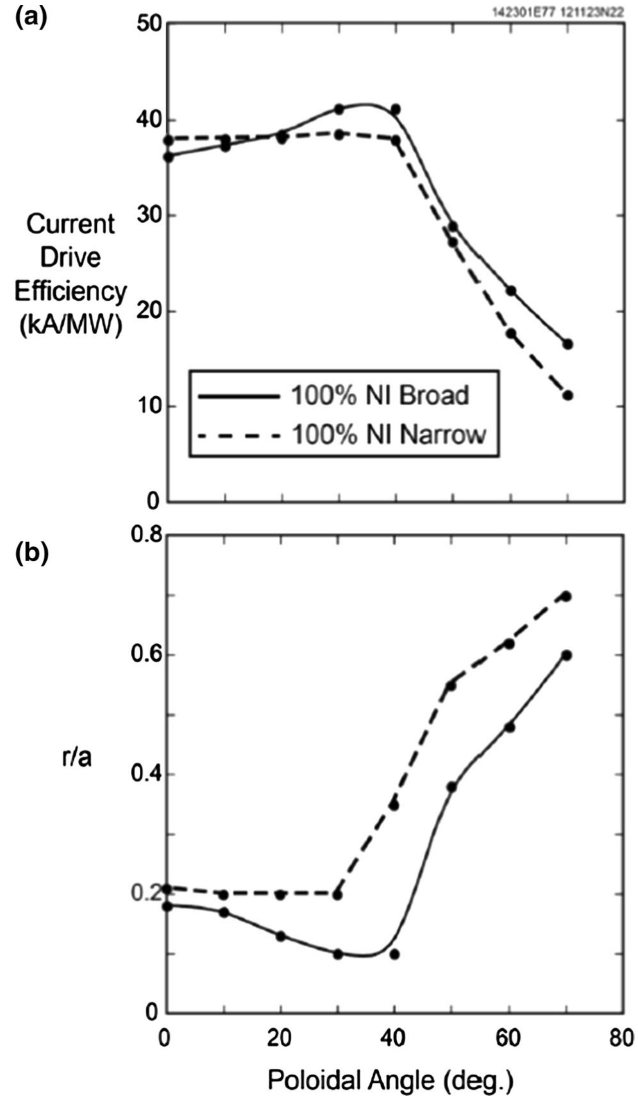

Fig. 7 EBW driven current density versus normalized minor radius for the case shown in Fig. 6

Required Development for EBW Installation on a Reactor

The primary technology development needed to support the implementations of EBWCD is the development of high-power, long-pulse gyrotrons. Good progress is being made in this area over a wide frequency range, from 14 to 300 GHz [23]. ST and AT based reactors will need frequencies in the range of 60 to over 160 GHz, which depends on the maximum toroidal field in AT based devices. Gyrotrons in this frequency range will need to operate continuously. Because of the small wall footprint, the design of the antenna itself is well suited for reactor applications. Neutron streaming back to the sources can be avoided by introducing bends in the waveguide.

Solenoid-Free Plasma Startup (SFPS)

Methods for initiating the plasma discharge without reliance on the solenoid would remove an expensive component and provide greater flexibility in device aspect ratio optimization, which can lead to improvements in overall device performance. During the next five-years of NSTX-U operations, SFPS capability will develop an understanding of the current start-up requirements for FNSF applications. Coaxial helicity injection (CHI) [24] is the most developed system on NSTX. EBW start-up [25] and local helicity injection [26] will also be developed on NSTX-U. Design studies for a FNSF have identified new configuration features that simplify the CHI system design, but require experimental validation on STs.

By the end of the 5 years, we hope to demonstrate full solenoid-less plasma start-up and current ramp-up to the steady-state current sustainment levels, initially using CHI. After EBW start-up and local helicity injection start-up systems are technically ready, these too would be used to study and develop solenoid-free start-up scenarios.

Conclusions

Steady-state ST and AT scenarios rely on optimized pressure and current profiles to maximize stable plasma beta with bootstrap current fraction. Under this mode of operation, the fuelling system must deposit small amounts of fuel where it is needed, and as often as needed, so as to compensate for fuel losses, and to maintain the required pressure profile. Conventional fuelling methods have not demonstrated successful fuelling of AT-type discharges and may be incapable of deep fuelling long pulse ELM-free discharges in ITER. The capability to deposit fuel at any desired radial location within the plasma would provide burn control capability through control of the density profile. An advanced fuelling system should also be capable of fuelling well past internal transport barriers. CT fuelling has the potential to meet these needs, while simultaneously providing a source of toroidal momentum input and reducing tritium inventory in the walls. Experimental and theoretical work indicates that deep fuelling of magnetized fusion reactors can be achieved by CT injection. The capability of a CT based system for precision density profile control and its potential for momentum injection needs to be developed on present STs. In addition to maintaining the optimized pressure profiles, a small amount of off-axis current drive is needed for current profile control to optimize plasma beta. EBWCD drive has the potential to meet these needs for these high-performance ST and AT type discharges. Simulations for NSTX-like high beta geometry show that EBWCD power can provide up to 40 kA/MW of current drive for sustained operation.

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