Self-organized Bootstrap Current in ET at Zero Loop Voltage

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Abstract

The most important innovation needed in tokamaks is to achieve non-inductive current profiles with zero loop voltage [1]. We are adding two low velocity (<10 kV) neutral beams on ET in summer 2004 for fuelling, toroidal momentum input and diagnostic purposes. Simulations with TSC [2] indicate that steady state can be achieved at beta normal of 2 in about 3 seconds of time evolution. This result is surprising but it can be understood based on self consistent ideas. Namely, the ET current density is so low and the normalized ohmic beta is so high that a self organized bootstrap current can develop. The resulting current profiles are stable to ballooning modes. Since we do not need to raise beta above the presently achieved ohmic values, we expect that the existing superior confinement (tau(0) = 1 sec) will allow a noninductive steady state to be reached below 100 KW of NB heating. The beams need to be balanced in order to prevent large uncontrolled toroidal rotation that would deteriorate the machine's performance. Detailed predictions will be presented based on the TSC code.

Neutral Beam on ET

Tangential injection of the neutral in ET vacuum chamber

Counter injection neutral on ET
Time Evolution

TSC Predicted Bootstrap current Evolution in ET

- Ip=50 kA
- Bootstrap current (100%)
- Lovv voltage (1 V F.S.)
- NB power (100 kW F.S.)
- Density (5e12/cm³ F.S.)
- Te, Ti (500 eV F.S.)

Time ==> 8 sec
Ohmic Plasma Profiles
Bootstrap Current Driven Profiles

TSC/MHD Derived Plasma Profiles

- $q[5 \text{ max}]$
- $T_e[1 \text{ keV max}]$
- $\chi E[2 \text{ m/sec}^2]$
- $N_e[5\times10^12/\text{cm}^3]$
- $V_{\text{loop}}[1 \text{ Volt}]$
Stability Analysis (DCON)
Time evolution of Bootstrap Current Profile with Ballooning
Neutral principle

The basic design involves an RF plasma source on the left, biased to the injection energy, and a plasma neutralized section, biased at the tokamak chamber potential. A tenuous plasma in the right hand chamber is generated by a filament in order to electrically neutralize the extracted fast ions. In this context the incoming fast ions are first charge neutralized by the electrons and then they are charge exchange on the ambient neutrals.

The electrons in each chamber are “private” by virtue of a negatively biased separator grid. While the ions can enter the neutralizer chamber from the plasma source, the electrons cannot leave the neutralizer chamber due to the negatively biased separator grid.
Infrared Photo of NB Injector

Neutral Beam Test (IR photo 5/12/04)

--- ET

Beam Loss

RF Plasma Source

Pierre
Neutral beam efficiency

The final design of the co-injection and counter-injection beams of ET was based on the following absorption formula for H beam:

\[ \Delta l = \frac{1}{n_e^{\text{plasma}} \left( \sigma_{\text{CX}} + \sigma_i + \frac{\langle \sigma_e v_e \rangle}{v_b} \right)} \]

The charge exchange cross section at 10keV is \( \sigma_{\text{CX}} \approx 10^{-19} \text{m}^2 \), the ionization by ion cross section at 10keV is \( \sigma_i \approx 8 \times 10^{-21} \text{m}^2 \) and the ionization by electron cross section at 10keV is \( \sigma_e \approx 7 \times 10^{-21} \text{m}^2 \). Finally \( n_e^{\text{plasma}} \) is the electron target plasma density. The attenuation \( \Delta l \) for a 10keV beam is:

- 4 m at a density of 2.5x10^{18} \text{m}^{-3}
- 1 m at a density of 10^{19} \text{m}^{-3}

One neutral beam is already running on the machine.

Doppler spectroscopy of NB results at 50A for different bias voltages which gives the correspondence between beam energy and extraction voltage.
RF hardware

We plan to operate eight low field side antennas at an input power of 1MW. The injection efficiency of each antenna is around 50%, due to various dielectric losses. Eight push-pull RF oscillators will be capable of injecting 1MW each in the antennas system for more than 5s.

Antennas are coupled to the plasma through a Faraday shield. A ground plane prevents radiation to leak in the tokamak bay (Figure 16). The 2d harmonic frequency for ET is 6.5MHz at a major radius of 5m. Each antenna is individually tunable using high power capacitors filled with dielectric water. The capacitance varies from 1nF to 5nF and makes possible a wide variety of antenna designs.
RF capabilities

Second harmonic hydrogen majority heating

IBW mode conversion CD from high field side RF launch at 2nd Harmonic

Fast wave current drive

Antenna distribution around ET's plasma
Conclusion

• Large bootstrap fraction is predicted for ET at 100 kW power input

• The NB and ICRF hardware is in place to test CD and bootstrap efficiency

• The high performance is the consequence of plasma size and low magnetic field

• TSC simulation of ohmic plasmas show 1 second confinement

• Control of long pulse dynamics is in hand except for the density

• NB injection will be used for fueling and plasma diagnosis

• Current drive is not required, except for possible stabilization