Current ramp-up modelling for STEP

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The STEP (Spherical Tokamak for Energy Production) program is currently developing a spherical tokamak reactor for producing net electricity. The spherical tokamak (ST) concept benefits from a higher beta and elongation than conventional tokamaks but it also has the disadvantage of limited space for a central solenoid. A critical requirement for a ST reactor is therefore to be able to reach the flat top plasma current with only very limited use of a central solenoid to drive current. Since a non-inductive ramp to large plasma current has not been demonstrated on a ST, the STEP design process relies solely on modelling to demonstrate the feasibility of a non-inductive ramp. In this work, integrated predictive non-inductive current ramp-up simulations are performed with the JETTO-ESCO code using a near zero or zero loop voltage boundary condition for a ST with R=2.5m and B=2.4T to explore the possibility of a non-inductive ramp with limited flux swing from a central solenoid.

Plasma breakdown and burn-through have occurred before the start of the simulations followed by an inductive phase with purely Ohmic heating and simplified assumptions on the density and temperature. The plasma consists of a 50/50 DT mix with Carbon included as an interpretative impurity with $Z_{eff} = 1.8$. In this phase the density is kept fixed, and the electron temperature is set with a parabolic profile. In this work, focus is on the non-inductive phase which starts at 1MA. The modelling performed predicts T_e, T_i, n_e and q profiles using simple source and transport models, self consistently with an evolving fixed boundary shape (Figure 1). The density and temperature profiles are evolved with NCLASS for neoclassical transport and for turbulent transport the Bohm-gyroBohm transport model is used with coefficients set as for JET with dominant ion transport [1]. Radiation is assumed at 50% auxiliary power and a continuous pellet model is used to fuel the plasma keeping a specified Greenwald density fraction. Electron cyclotron (EC) heating will be a main HCD system for STEP and is used to ramp up the current to the flat top operating current. Note that a non-

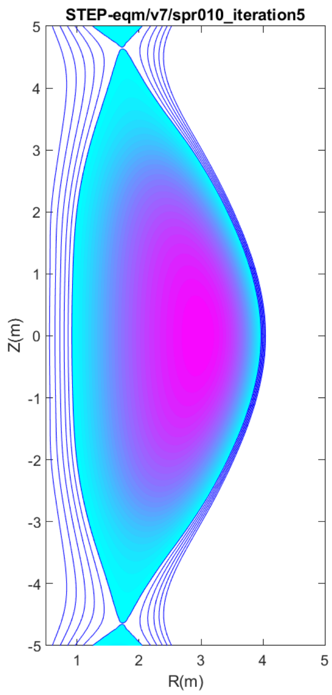

Figure 1. Plasma boundary during the non-inductive current ramp up. Elongation 2.8 and triangularity 0.5

inductive ramp behaves very differently to a more standard inductive current ramp [2]. The current drive system can be used to tailor the current rather than current diffusing from the edge. The timescale of the ramp is still set by the resistive timescale which is on the order of 1000s. The current drive profile needs careful optimisation to avoid strong shear reversal from the development of a "current hole" in the plasma centre. Strong shear reversal is avoided because of the possibility of the associated performance limiting instabilities [3], and the related risk of triggering a very strong (instability driving) internal transport barrier. In these simulations, the deposition profile is gradually broadened out from the centre and, to avoid the problem of a current hole from the back EMF, additional central current drive is applied using feedback control to constrain q_0. The current density profile is given by a simple scaling $j_{ECCD} \propto \frac{T_e}{n_e}(1 - f_t)P_{EC}$ where f_t is the trapped particle fraction. The ECCD code GRAY [4] is used at individual times during the ramp to validate the resulting current drive efficiency.

The power required to ramp up the current non-inductively to the flat top operating current depends strongly on current drive efficiency and transport assumptions. Due to the presence of significant auxiliary heating early in the ramp, the maximum elongation of the plasma needs to be reached early in a manner that remains MHD stable to allow the plasma to be diverted to comply with exhaust constraints. To maximize the current drive efficiency the

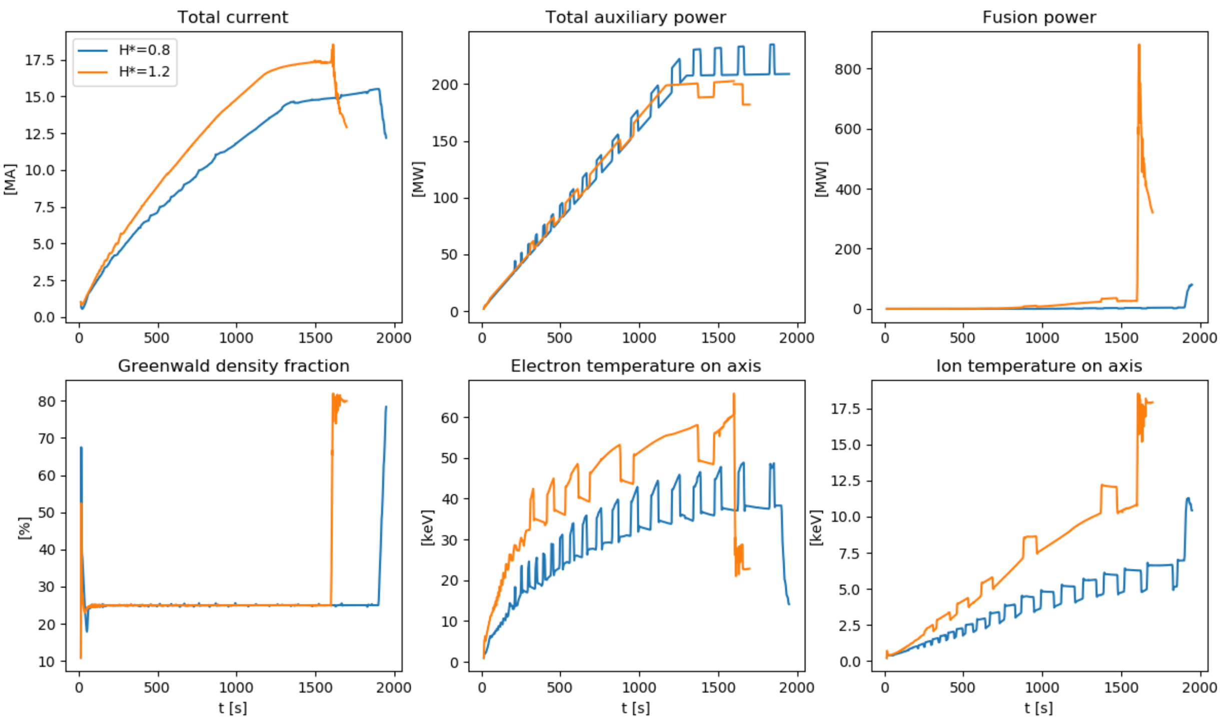

Figure 2. Summary of two fully non-inductive current ramps at different confinement, H98Z (radiation corrected) illustrating the importance of high enough confinement. The jagged time series are a result from the feedback control on q_0.

current is ramped at low density. Access to more favourable conditions for fusion requires a subsequent transition to a high density, high bootstrap current regime at the flat top current. Figure 2 illustrate the resulting current ramp from the end of the inductive phase to the flat top current setting the confinement scaling to $H98_{z,2}$=0.8 and 1.2 (not radiation corrected). Here about 200MW of auxiliary power is used to ramp the current at $< n >/n_G = 0.25$ with a current drive efficiency 90kA/MW for most of the ramp. The electron temperature on axis reaches up to 60 keV at the end of the ramp with $T_e/T_i \sim 6$. At the flat top current, a rapid transition to $< n >/n_G = 0.8$ with subsequent reduction in T_e and increase in T_i allows the plasma to reach a fusion power transiently approaching the flat top value of 1 GW for the higher confinement case. Note that this rapid density increase results in a rapid reduction of current drive efficiency and the increase in bootstrap current is insufficient to sustain the flat-top current, I_P. The simple scaling used for the current drive efficiency is potentially insufficient to capture this large range of densities. Note that the very high T_e/T_i regime resulting from the fact that the EC system mainly heats the electrons has historically been less explored. In STEP reference flat top plasmas the turbulent transport expected to be dominated by MTMs [5] while during the current ramp up other modes including ITGs could be important. How stiff the transport is and how to get out of the low ion temperature regime needs to be explored. Initial simulations with Qualikiz Neural Network -hyper (10D)[6], shown in Figure 3 demonstrate that

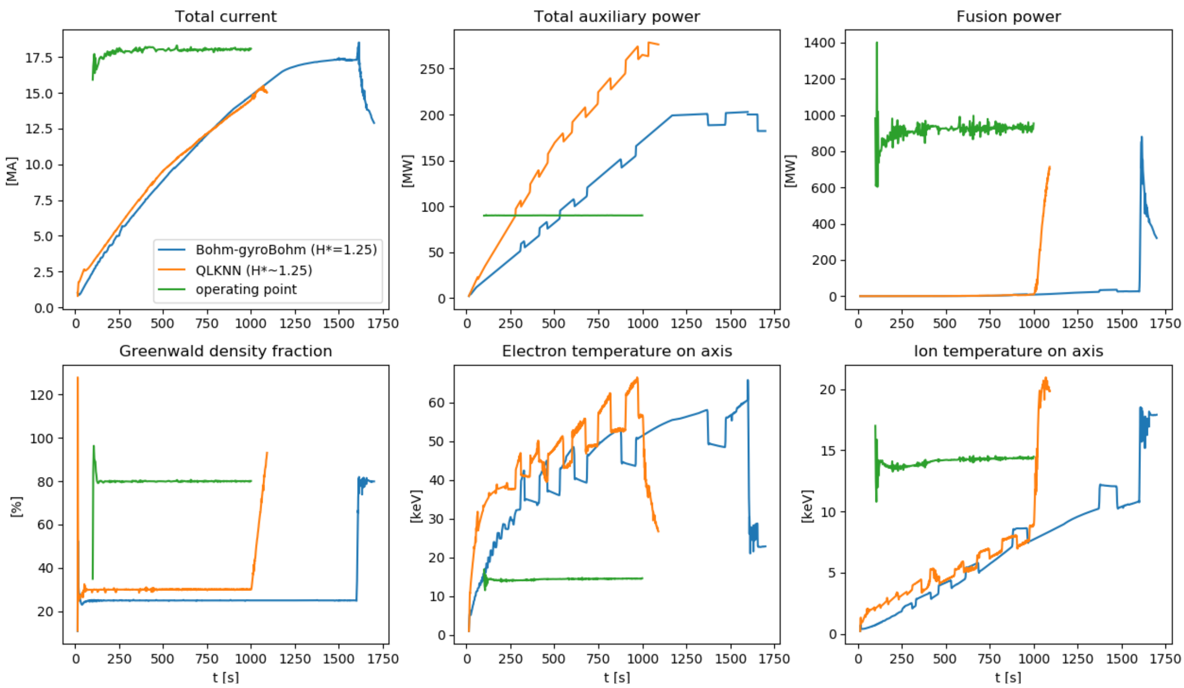

Figure 3 Current ramp with two transport models, BgB and QLKNN. The flat top operating point is included in green.

the electron-ion coupling is increased enough to heat the ions allowing the fusion power to increase towards the flat top operating point.

The impact of the amount of magnetic flux consumption allowed is tested in the simulations shown in Figure 4. A comparison is made between a current ramp with a small non-zero loop voltage, zero loop voltage (used in the simulations in Figures 2 and 3) and zero central solenoid. Here the total loop voltage is the sum of contributions from the central solenoid, the PF coils, and the plasma inductance. Based on these simulations the preliminary conclusion is drawn that a viable current ramp is possible using zero central solenoid and the addition of a few Vs of flux will not help much for the strongly heated non-inductive ramp. Here the difference in total current is on the order of a few percent only.

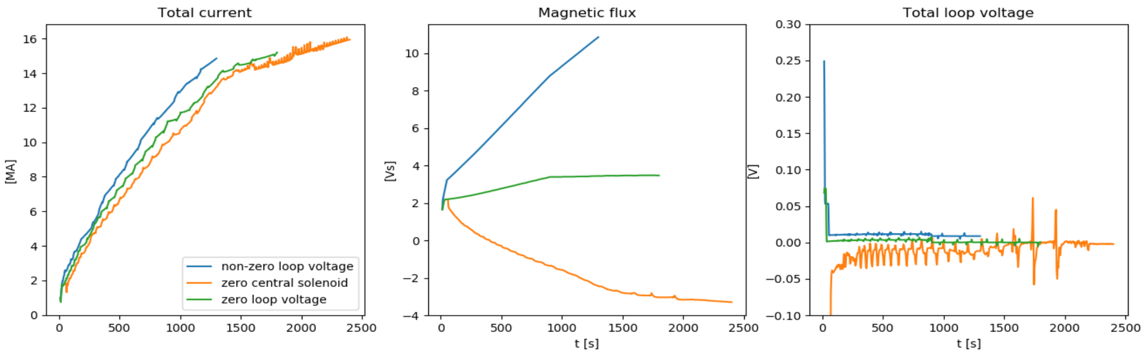

Figure 4 Current ramp using different boundary conditions for input loop voltage

Based on these exploratory simulations on one ST reactor concept, a non-inductive ramp appears feasible with ECCD being a good solution during the early ramp up, with a possible transition to EBW at later phase if this heating systems is selected for flat top operation. Initial simulations using the GRAY code scanning over launcher angles and frequency to optimize current drive efficiency for each radial location in the plasma is shown in Figure 5 at 400s. At this point the current drive efficiency was assumed as 90 kA/MW in the ramp up simulations which is substantially lower than the optimized values. A higher current drive efficiency than previously assumed may be possible though self-consistent runs are needed using GRAY for ECCD calculation to strengthen that possibility.

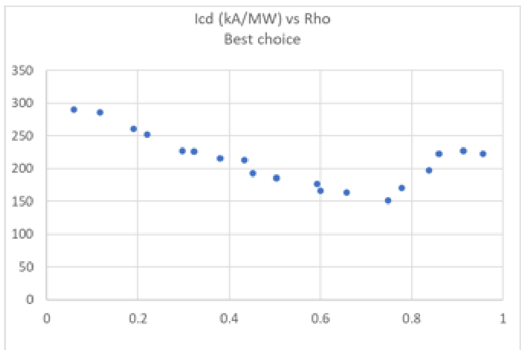

Figure 5 Optimized current drive efficiency for each radial position based on a scan in frequency and launching angles for possible launching positions

[1] M Erba PPCF 39 (1997) 261-276
[2] S C Jardin Nucl.Fusion 40 (2000) 1101
[3] T C Hender PPCF 44 (2002)
[4] D Farina Fusion Science and Technology (2007)52:2
[5] D Kennedy poster at this conference
[6] K van de Plassche PoP 27 (2020) 022310