

Solenoidless Startup Research Thrusts for Tokamaks

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1 Issues

The current tokamak path to commercial magnetic fusion [1] entails a variety of machine types which can be characterized between two extremes defined by 1) large scale superconducting moderate aspect ratio devices (e.g. ITER) and 2) a normal conducting low aspect ratio device (e.g. ST-CTF). Below we explore what would be necessary to generate plasma current without the use of a solenoid PF coil component in the context of the mainline tokamak program.

Solenoidless in Context of DEMO: Here we discuss utilization of tokamak heating and current drive systems to produce solenoidless plasma startup. Other means including CHI and other helicity injection schemes, are very promising but typically require complex new hardware not presently envisioned for a fusion demonstration facility (DEMO). We discuss solenoidless startup in the context of systems typically envisioned for a DEMO facility and available or planned for major tokamaks in operation today.

Solenoidless Ramifications: Lack of a central solenoid, which is the primary flux generation component of a typical tokamak, imposes severe limitations for inductive startup. Tokamaks containing a poloidal field coil system that completely encompass the plasma provide a means of approximately decoupling flux generation from plasma shape control. This can be done in hardware with separate coil systems as is done in DIII-D and JT-60U, or in software via sophisticated control of shared-use coils, as is done in EAST, KSTAR and ITER. Once the solenoid is removed the plasma current (through flux) and plasma shape are integrally linked. This linkage severely limits the inductive current capability of the device using the remaining coils. In addition, the magnetic energy input typically produced by an Ohmic Heating (OH) coil system must be provided by auxiliary current drive sources. This puts enormous pressure on systems like RF and neutral-beams, which must effectively over-drive the plasma current to overcome the back-emf produced during a rampup. This is even more challenging during rampup since current drive phenomena is less effective than during flattop operation where most present current drive experiments are performed. The fundamental equilibrium control problems are also more challenging due to the intrinsic coupling of flux and shape control. On the positive side of the equation is the fact that, without an OH coil current swing limitation, a virtually arbitrary amount of time is available to achieve the required current flat top. For a superconducting device this would mean we just need sufficient current overdrive in the auxiliary systems to compensate for the resistive losses in the plasma. This is probably not viable for a device with resistive coils, whose sustained current will consume substantial steady state power. In any case, experimental validation of a scenario to achieve full plasma current without the use of a solenoid has not been achieved to any degree in present major devices. Such a demonstration is of great

potential value, since substantial auxiliary current drive capability during the current ramp up could greatly reduce central solenoid size required and thereby machine costs.

Existing Experiments: Solenoidless operation is an ongoing research topic in the area of spherical tokamak experiments. Most techniques use unique helicity injection schemes or internal coil startup and are not considered in this paper. JT-60U has performed the best series of experiments using solenoidless operation in a major tokamak using conventional auxiliary current drive means [2]. They report producing 100kA of current using only outer PF coils and strong ECH pre-ionization. Figure 1 shows the primary results of this experiment. In addition, plasma current could be produced with substantial vertical field (~800G) with the assist of ECH. Nominally, this technique is only capable of producing 10% of the current achievable using the ohmic solenoid system and the remaining 90% would require auxiliary current drive.

2 Technical Requirements

Solenoidless operation requires an integrated program to drive to full plasma parameters (I_p , β_n) using only outside PF coils and conventional current drive methods (ECCD, neutral-beam ...). Research challenges which must be overcome to achieve solenoidless operation include:

- Sufficient control of initial plasma formation under passively unstable conditions
- Maximization of current drive from auxiliary systems under low current, transient conditions
- Maximization of current overdrive within plasma beta limits
- Current drive systems consistent with startup requirements and capable of operation in a reactor neutron environment.

3 Research Thrusts

Any research thrust for solenoidless startup of tokamaks should include a combined modeling and experimental program. The electromagnetic (EM) scenario development is quite amiable to theoretical modeling and can provide the maximum flux generation trajectories within the stability limits of existing tokamaks. An effort should be made to enhance control systems in existing machines for early detection and control of highly shaped plasmas. Unique control sensors, actuators and control methods should be explored to maximize the control performance as well as the flux capability of the shaping coil system during the plasma startup phase. Current drive capabilities of existing systems during transient, low plasma current operation are not as well understood as the electromagnetic aspects of the problem and will require substantial experimental development. Existing machines should quantify the current drive capability of different auxiliary systems at low plasma currents and under varying plasma parameters. The ultimate goal is to achieve the maximum overdrive current (and thereby maximum rampup rate) within constraints imposed by current drive efficiency as well as MHD and Beta limits. This should be done at static low-level currents and under transient conditions. Results of these studies should be incorporated into a full scenario and tested on existing machines.

4 References

- [1] Greenwald Report, "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan for Magnetic Fusion Energy", Report to FESAC, October, 2007.
- [2] Ushigome, M., et.al., "Development of completely solenoidless tokamak operation in JT-60U", Nucl. Fusion **46**, (2006), 207.

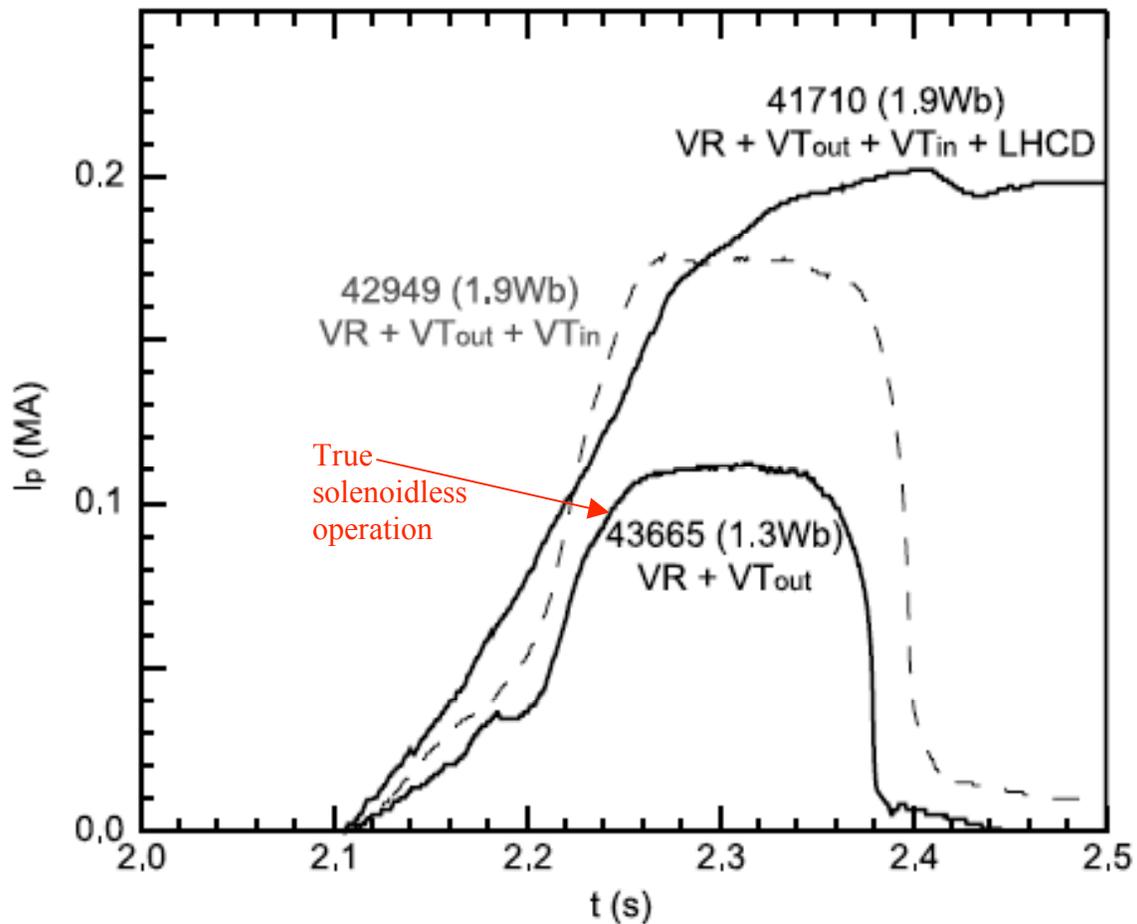


Figure 1 . JT-60U Solenoidless I_p start-up. Shot 43665 uses outside PF coils only and ~1MW ECH to achieve 100kA and is truly a solenoidless startup. Other discharges used a partial solenoid for startup. 41710 used LHCD to achieve further I_p rampup. [2]