A Proposed Experiment to Study Relaxation Formation of a Spherical Tokamak with a Plasma Center Column

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Abstract

A spherical tokamak (ST) with a plasma center column (PCC) can be formed via driven magnetic relaxation of a screw pinch plasma. An ST-PCC could in principle eliminate many problems associated with a material center column, a key weakness of the ST reactor concept. This work summarizes the design space for an ST-PCC in terms of flux amplification, aspect ratio, and elongation, based on the zero-\(\beta\) Taylor-relaxed analysis of Tang & Boozer [Phys. Plasmas 13, 042514 (2006)]. The paper will discuss (1) equilibrium and stability properties of the ST-PCC, (2) issues for an engineering design, and (3) key differences between the proposed ST-PCC and the ongoing Proto-Sphera effort in Italy.

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I. INTRODUCTION

The spherical tokamak (ST) is a promising magnetic confinement configuration, offering higher maximum plasma \( \beta \) than conventional tokamaks. However, the low aspect ratio requirement results in severe space-constraint for the material center column, which in a conventional ST reactor must house the inboard toroidal field (TF) coils, the Ohmic solenoid, and shielding against fusion neutrons. The small center post probably eliminates the possibility of an inboard tritium-breeding blanket, and it results in very high Ohmic dissipation of the center column TF current. An ST with a current-carrying plasma center column (PCC) could in principle overcome many of the weaknesses of a material center column. The PCC used in combination with coaxial helicity injection (CHI) could serve four purposes: (1) ST formation via driven relaxation of a screw pinch plasma, (2) carry the inboard TF coil current, (3) help sustain the ST in steady-state in combination with rf and neutral beams, and (4) eliminate the need for neutron shielding since there is no material center column to suffer radiation damage. For a reactor, power dissipation still remains an issue for a plasma center column, but the other advantages conferred are all very compelling.

An ST-PCC can be formed via driven magnetic relaxation of a screw pinch plasma. The relaxation formation scheme, to be described in more detail in Sec. II, is largely inspired from spheromak research and in particular a recent spheromak formation experiment that showed how a current-driven kink instability of a plasma column leads to relaxation and poloidal flux amplification. This approach also takes advantage of the substantial body of work on CHI for ST startup and sustainment. Using Taylor-relaxed plasmas as a base-line example, a recent theoretical and numerical study by Tang & Boozer clarified the design space of an ST-PCC in terms of flux amplification, aspect ratio, elongation, and vacuum bias flux. The proposed ST-PCC is based on the initial study by Tang & Boozer.

This paper is organized as follows. Section II will describe the conceptual basis for forming an ST-PCC via driven magnetic relaxation of a screw pinch plasma. Section III will summarize the design space for an ST-PCC and discuss the equilibrium and stability properties. Section IV will discuss the primary engineering issues for designing a concept exploration (CE) class ST-PCC experiment, and Sec. V will discuss key differences between the proposed ST-PCC and the Italian Proto-Sphera project, the first and only other effort in the world exploring the plasma center column concept for an ST. Section VI...
provides a summary.

II. ST-PCC FORMATION VIA DRIVEN MAGNETIC RELAXATION

A large body of work exists with regards to the formation of compact toroid plasmas, such as spheromaks via driven relaxation. By driving current on open bias field lines, a \( \lambda \) (ratio of plasma source current to flux) gradient is established, which drives instabilities and causes the plasma to relax, \( i.e. \) flatten the spatial profile of normalized current density \( (j_{||}/B) \). Thus, by driving current on edge open field lines, relaxation will “transport” the edge current into the closed-flux core region, in effect resulting in current drive. In the simplest case, a plasma column is driven kink unstable and undergoes global relaxation, resulting in the formation of a spheromak. The tendency of plasmas to relax due to nonlinear processes is what makes forming spheromaks easy and indeed almost unavoidable. Driven relaxation formation of spheromaks inspires and provides the foundation and a large body of empirical results for establishing the ST-PCC concept, which will rely on the same concept of driving a plasma column unstable and allowing it to relax. However, in the case of the proposed ST-PCC, an additional CHI system will provide a new degree of freedom for driving current-driven instabilities needed for global relaxation, and to actively modify the \( q \) profile of the relaxing PCC to “coax” it into the ST state. After ST-PCC formation, the PCC current and flux would be adjusted to provide the ST equilibrium toroidal field.

A subtle difference between the flux-core spheromak and ST-PCC is the ratio between the center column flux \( \chi_c \) that intercepts the electrodes and the closed poloidal flux \( \chi_p \) in the axisymmetric \( n = 0 \) magnetic field after relaxation. For a conventional gun-driven spheromak experiment, \( \chi_c/\chi_p \) is small so that the toroidal field from the plasma current passing through the center column is small compared with the magnetic field generated by the toroidal plasma current flowing inside the separatrix. By increasing \( \chi_c/\chi_p \), one has the freedom to manipulate the toroidal field in comparison with the poloidal field, and thus the \( q \) profile, in the relaxed plasma inside the separatrix. The chamber geometry (elongation) has a strong effect on \( q \) and provides perhaps the most effective “knob” for manipulating the \( q \) profile. As will be described below, there is a parameter regime where an ST \( q \) profile can be obtained with a PCC alone, even in the limit of complete Taylor relaxation, \( i.e., \) a spatially uniform \( \lambda \) profile. The proposed ST-PCC formation scheme will be based on this
unusual relaxation solution branch.

Controlled decay of spheromaks has resulted in several-hundred eV electrons, implying the existence of nested closed magnetic flux surfaces. This fact provides promise that a CE-class experiment will be able to obtain $T_e \approx 100$–$200$ eV ST-PCC plasmas with good particle confinement. This target plasma can then be sustained in follow-on research using other non-inductive current drive and heating schemes, such as rf and neutral beam injection.

The sustainment phase of an ST-PCC requires consideration of additional physics issues. First, the relaxed plasma after the initial formation stage typically has low $\beta$ and a rather flat $j_{\parallel}/B$ profile, both of which reduce the energy drive for MHD instabilities. The sustainment aims to ramp up the plasma pressure towards a conventional high-$\beta$ equilibrium. The effect of a PCC (instead of a material center column) on the stability of external MHD modes must be understood. Second, an electrostatic bias must be present throughout the discharge to maintain the toroidal magnetic field in an ST-PCC plasma. How the externally imposed electric field affects transport properties via $E \times B$ flow must also be understood in order to assess the attractiveness of the concept.

### III. ST-PCC DESIGN SPACE

A recent theoretical and numerical study by Tang & Boozer based on zero-$\beta$ magnetically relaxed (spatially uniform $\lambda$) equilibria has clarified the design space for an ST-PCC. Although a real ST-PCC will have finite $\beta$ and non-uniform $\lambda$ profiles, a study based on Taylor-relaxed plasmas was used as a base-line example to provide insight into the equilibrium properties of a driven relaxation experiment in a simply-connected chamber. (Of course, finite $\beta$ equilibrium and stability studies and nonlinear MHD simulations must be performed to justify and support the design of a real experiment.) The zero-$\beta$ study showed that two essential factors influence the ST-PCC design space: (1) flux amplification is directly related to the aspect ratio (ratio of major to minor radius) and (2) plasma elongation $\varepsilon$ (ratio of chamber height to radius) has a large affect and vacuum bias flux $\chi_0$ a smaller subtle effect on the $q$ profile.

Tang & Boozer numerically solved the force-free equation $\nabla \times B = \lambda B$ for a finite length cylinder and $\chi_0$ on the boundary. They showed that relaxed ST-PCC equilibria exist in a
particular parameter regime described below. They investigated the relationship between aspect ratio and flux amplification and found that the aspect ratio scales approximately inversely proportional to the flux amplification factor, independent of $\varepsilon$ (see Fig. 3 of Ref. 10). An ST-relevant aspect ratio of 1.5–2 is achieved with a flux amplification factor of 1–2.5, which is routinely achieved in laboratory helicity injection experiments. A smaller aspect ratio down to 1.25 would require a flux amplification factor of 9, which may be achievable but probably not a good choice for a conservative ST-PCC experimental design. They also investigated the $q$ profile as a function of $\varepsilon$ and showed that $q_{\text{edge}}$ scales approximately linearly with $\varepsilon$ from $\varepsilon \approx 0.5$–3 (see Fig. 4 of Ref. 10). To achieve $q > 1$ throughout the interior of the separatrix, an $\varepsilon = 2$–3 is required (see Fig. 6 of Ref. 10).

Thus, high $\varepsilon$ and high flux amplification are desirable for forming an ST-PCC equilibrium in order to achieve $q > 1$ and low aspect ratio, respectively, as required for an ST. ST-PCC stability, however, constrains both $\varepsilon$ and flux amplification. These constraints can be understood through the properties of the force-free (Chandrasekhar-Kendall\textsuperscript{20}) eigenmode solutions of the discharge chamber, which entirely determines the stability for a relaxed plasma. For $\varepsilon \lesssim 1.67$, the stability of the lowest energy axisymmetric relaxed state $\lambda_1^{(n=0)}$ is guaranteed because it is the overall lowest energy state of the system. For $\varepsilon \gtrsim 1.67$, the lowest energy helical eigenmode $\lambda_1^{(n=1)}$ becomes a lower energy state than $\lambda_1^{(n=0)}$.\textsuperscript{21,22} This means that if one forms an axisymmetric relaxed state for $\varepsilon > 1.67$ at $\lambda > \lambda_1^{(n=1)}$, the plasma will be unstable. Thus, for $\varepsilon \approx 2$–3 as required for $q > 1$, the ST-PCC $\lambda$ must be less than $\lambda_1^{(n=1)}$ for stability. The latter limits flux amplification which scales as $[(\lambda_1^{(n=0)})^2 - \lambda^2]^{-1}$.\textsuperscript{10} It should be noted that the vacuum bias flux can be adjusted to optimize the flux amplification at a given $\lambda$.\textsuperscript{10}

Table II summarizes the design space for an ST-PCC. For a much more detailed discussion of relaxed ST-PCC equilibria and stability, the reader is referred to Ref. 10. Further studies are necessary to characterize the equilibrium and assess the stability of finite-$\beta$ driven ST-PCC’s, and for designing an optimized experiment.

IV. ENGINEERING DESIGN ISSUES

An experiment to form an ST-PCC via driven relaxation of a screw pinch plasma would benefit from having two sets of biased electrodes with a cylindrical boundary. A primary
consideration is to have the versatility to drive a $\lambda_{\text{PCC}}$ that is different from the relaxed $\lambda_{\text{ST}}$. This provides freedom to drive relaxation by exciting either a center column kink or an open flux kink on the CHI bias flux. A further benefit of a separate CHI system is the natural formation of a single null plasma where edge current can be tuned independently of the center column current. This would become especially important for ST-PCC sustainment. Figure 1 shows a conceptual drawing for a CE ST-PCC experiment, including all the important sub-systems. Below, each sub-system will be discussed separately along with their primary issues.

*Vacuum chamber and boundary:* Shape and geometry ($\varepsilon \approx 2$–3) are chosen to optimize coupling between PCC and ST during driven relaxation formation, as well as equilibrium and stability of the formed ST-PCC. Wall thickness must allow bias flux penetration while acting as a flux-conserver for the plasma. The boundary requires electrical breaks that will allow the application of bias voltages for driving PCC and CHI current. Toroidal gaps in the boundary on either end of the geometric axis of the device define the electrical breaks for the PCC cathode and anode. The gaps also allow voltage to be applied between the cathode and the outer boundary, as well as between the anode and the outer boundary. Together with the CHI flux, this injects magnetic helicity into the system. The shape of the flux conserving boundary would be chosen to optimize equilibrium and stability properties of the ST-PCC, and to facilitate engineering design of the couplings between PF, TF, and PCC power systems.

*Screw pinch PCC:* The PCC would be created between electrodes located at either end of the geometric axis of the device. Via current ramp-up, the PCC would undergo driven relaxation in concert with the CHI system to form an ST and subsequently carry equilibrium TF coil current. The power system for this plasma source would be a high voltage capacitor bank to create the PCC and to sustain the PCC current below pinch instability thresholds for generating steady TF after relaxation formation. A CE experiment would likely need to last only several milliseconds, which is enough time for a plasma of a few tens of eV to globally relax and settle into the ST-PCC equilibrium. An arc discharge between tungsten sprayed copper electrodes would be used, similar to spheromak and other helicity injection experiments. The current (several hundred kA) and power (tens of MW) would be comparable to SSPX. In a CE experiment, the power dissipation of the center column is probably not an issue. However, this is a key issue when considering how an ST-PCC would
scale to a reactor. Even if the PCC could be maintained at an elevated temperature of a few hundred eV, the power dissipation in the PCC for a 1 GW reactor would probably be on the order of 100 MW. This issue needs careful consideration and study for the reactor viability of the ST-PCC concept.

**TF coils:** A key engineering issue is coupling the outboard TF coil windings to the PCC, which closes the TF coil circuit. In conventional tokamaks and ST’s, the TF coil is a single solenoidal winding with \( n \) turns. With a PCC, the TF coil system would actually be \( n \) turns each connected in parallel, with the PCC being shared by every parallel turn. For a CE experiment, the power source for the TF coils would be the same PCC capacitor bank.

**CHI system:** The CHI system applies voltage across the inner and outer boundaries, which is linked by a bias magnetic flux. The CHI bias flux would be created by a combination of the CHI and PCC bias flux coils. The CHI current is expected to be on the order of several tens of kA driven at a few hundred Volts.

**PCC and CHI bias flux coils:** PF coil sets are needed to provide the poloidal fluxes needed to form and sustain an ST-PCC: (1) axial flux for the PCC and (2) bias flux linking the inner and outer boundaries for CHI. The two fluxes would need independent timing and control and thus would require independent power sources. A CE experiment would likely require several to several tens of mWb for each system.

**Diagnostics:** The primary diagnostics needed for a CE experiment are arrays of magnetic probes to characterize ST-PCC formation and equilibria, as well as voltage and current diagnostics to characterize the PCC and CHI sources. Magnetic (Mirnov) coils would be placed at different toroidal locations on the vacuum chamber wall to monitor toroidal mode activity. Fast camera imaging of global plasma light emission would provide information on plasma evolution and guide the placement of quantitative probe diagnostics. Simple electrostatic probes, such as Langmuir probes to measure \( n_e \) and \( T_e \) and Mach probes to measure ion flow, would also be used. In later stages of a CE experimental program, when higher temperatures in the hundreds of eV range are expected, advanced diagnostics would be proposed and implemented, e.g., Thomson scattering to measure \( T_e \) and interferometry to measure \( n_e \).
V. COMPARISON WITH PROTO-SPHERA

The Italian Proto-Sphera project\textsuperscript{11,12} is under construction and is the first project to study the ST-PCC concept. However, there are several key differences between the present proposed ST-PCC and Proto-Sphera. It would be of interest to explore the relative merits of the two approaches with complementary experimental programs.

Proto-Sphera will use an emissive electrode system to form the PCC. This system is potentially capable of high power handling, relevant for eventual use on proof-of-principle and proof-of-performance class experiments. In contrast, the proposed ST-PCC would use a much simpler arc discharge system at short pulse length to test the relaxation formation scheme.

The proposed ST-PCC formation scheme and target equilibrium are fundamentally different from those of Proto-Sphera, which proposes to use induction via a quick swing of the poloidal field coil current followed by compression of the plasma to raise the $q$ profile.\textsuperscript{11} The Proto-Sphera equilibrium was originally motivated by higher order Chandrasekhar-Kendall modes, and the reference Proto-Sphera equilibrium removes two higher order lobes while retaining a high $\epsilon$ center lobe and PCC.\textsuperscript{24} In contrast, the proposed ST-PCC is based on relaxed states similar to a flux-core spheromak, and would be formed via driven relaxation (likely kink instability) of the PCC and possibly CHI flux.

The final key difference is the initial sustainment method after formation. Proto-Sphera will use helicity injection via the PCC itself, while the proposed ST-PCC uses an independent CHI system which would also play an integral role in the formation phase.

VI. SUMMARY

A plasma center column would eliminate several key weaknesses of the ST reactor concept, although PCC power dissipation in a reactor scale experiment could remain a concern requiring further study. An ST-PCC can be formed via driven magnetic relaxation of a screw pinch plasma. The idea of driving a plasma column kink unstable and allowing the ensuing global relaxation to provide the final desired ST-PCC equilibrium is inspired from spheromak research and helicity injection via magnetized coaxial guns. An initial theoretical and numerical study by Tang & Boozer\textsuperscript{10} has clarified the design space for zero-\(\beta\)
Taylor-relaxed ST-PCC’s. They showed that for high elongation of 2–3 and modest flux amplification factors of 1–2.5, stable relaxed ST-PCC equilibria with $q > 1$ and aspect ratios of 1.5–2 exist. These results are promising and motivate further studies of finite-$\beta$ ST-PCC equilibrium and stability leading to an optimized experimental design. A representative ST-PCC experiment would feature two sets of biased electrodes. One set would form the PCC and drive it unstable for relaxation. The other set would be a CHI system, which would provide additional freedoms in relaxation formation and raising the $q$ profile after the initial relaxation. A concept exploration ST-PCC experiment would be comparable to SSPX in both its hardware and plasma parameters, although the initial research emphasis would be on the relaxation formation scheme.

An ST-PCC concept exploration experiment is needed for detailed studies of the basic plasma physics issues for relaxation formation and non-inductive sustainment, as well as many of the engineering issues which will ultimately determine the reactor potential of the ST-PCC concept.

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TABLE I: Summary of ST-PCC design space, showing some competing factors between equilibrium and stability. A reference design would have $\varepsilon \approx 2–3$ and a modest flux amplification factor of 1–2.5.
FIG. 1: Conceptual drawing of proposed ST-PCC experiment, identifying key components: flux-conserving boundary, screw pinch (SP) and TF circuit and power supply, SP magnets for SP axial flux, CHI magnet for CHI vacuum bias flux, CHI power supply, toroidal insulating gaps, and SP cathode/anode inside the toroidal gaps.