Initiative Proposal

An Integrated Program to Develop Scalable Solenoid-Free Startup Scenarios for Spherical and Advanced Tokamaks

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Executive Summary

Future burning plasma devices must operate in fundamentally different manners than present research devices in order to realize an energy production goal. This includes compatibility with a harsh nuclear environment; pulse lengths of order one year; fully superconducting magnet systems; and the need for robust auxiliary heating and current drive systems compatible with these performance metrics. These differences serve to minimize the role of a central solenoid in tokamaks. Its utility is relegated primarily to plasma initiation and ramp-up, an interval that is expected to be less than 0.001% of a plasma pulse. Solenoid-free startup techniques such as helicity injection and RF offer the potential to simplify the cost and complexity of reactor-class devices by reducing the technical requirements of the solenoid—if not eliminating its presence entirely. Volume that otherwise would be occupied by a solenoid may be allocated to other desirable features, such as additional tritium breeding capacity, siting of high-field-side actuators, or increased TF structural reinforcement for higher B_T and/or smaller plant size. These methods may also afford attractive features from an operational standpoint, such as creating low internal inductance targets. Finally, the need for robust non-solenoidal startup methods has long been recognized as a particular need for the viability of the spherical tokamak as a fusion development device.

At this stage in fusion energy science and technology development, it is premature to presume a final choice of what features will be included in a reactor design. Visions for tokamak reactor concepts span inclusion of a full solenoid, no solenoid, or a special-purpose solenoid (*e.g.* for current ramp-down), depending on its intended application(s), cost, engineering feasibility, etc. More broadly, reactor designs are informed by, and highly dependent on, the suite of available validated techniques underlying the facility design elements.

The intent of this initiative is to provide scientifically and technically validated means of initiating, growing, and possibly sustaining tokamak current without the use of a central solenoid electromagnet. In that respect, it represents an expansion of available tools for future reactor designers. An educated decision of the merits of these design elements will benefit greatly from a well-developed knowledgebase. The spirit of this initiative is to provide these techniques to the community and inform more comprehensive reactor designs.

This initiative combines two proposals from the Madison APS-DPP-CPP workshop [1,2]. It encompasses and expands upon presently funded research activities to establish a sound physics and technology basis for reactor-relevant, non-solenoidal tokamak startup methods. Research on domestic and international experimental facilities in university, national lab, and private contexts will contribute to achieving the initiative's strategic goals. The initiative can be pursued at modest cost (of order $5M/yr).

In the near term, domestic research will leverage an upgraded PEGASUS ST (PEGASUS-III) as a dedicated platform to execute integrated, comparative studies of leading startup techniques (local and coaxial helicity injection, RF methods) and validate appropriate predictive models. Complementary international work on QUEST and ST-40 will explore helicity injection-RF synergies and significantly extend the B_T scaling of CHI, respectively. In the longer term, the results of these activities will be combined to design, construct, and test a robust 1 MA startup system on NSTX-U. Early planning discussions with the NSTX-U group have agreed this should be an element in its second 5-year operational period (~2025).

Collectively, the successful initiative will provide information to inform the design and capabilities of the central column in next-step burning tokamaks.

Goals of Initiative

The goal of this initiative is to develop and verify the scientific and technological basis for reliable solenoid-free startup techniques for spherical and advanced tokamaks that are scalable to next-step, nuclear scale burning plasma devices. This broadly entails:

1. The experimental evaluation, comparison, and integration of relevant non-solenoidal startup concepts to develop a scalable approach that is suitable for future large facility applications; and
2. Establishing validated models to evaluate the feasibility of non-solenoidal startup methods when extrapolated towards fusion conditions.

To accomplish these goals the initiative will employ both a strong domestic component leveraging a dedicated, modest-scale facility and a collaborative international research component. In a ~6–10 year timespan, these activities will identify a unified solenoid-free startup method that is suitable for subsequent deployment and test on larger-scale facilities with high confidence of success for MA-class startup. This initiative will also develop strong partnerships amongst universities, national labs, and private corporations.

Research and development activities under this initiative will address outstanding scientific issues, including: helicity conservation and current drive efficiency; the role of magnetic instabilities in generating toroidal plasma currents; the scaling of plasma confinement and heating in systems with low- to moderate scales of magnetic turbulence; the compatibility and synergy of radiofrequency (RF) heating and current drive with systems driven by helicity injection; the integration and application of electron cyclotron (ECH) and electron Bernstein wave (EBW) heating and current drive to establish toroidal plasmas; determining the conditions for high-efficiency coupling of solenoid-free startup plasmas to subsequent sustainment methods, including neutral beam current drive; the generation and evolution of impurities in the startup process; supporting technology of strong current sources in the edge plasma region; and the optimization of RF launchers and plasma coupling.

The successful initiative will develop the physics understanding and supporting technology needed for high-confidence extrapolation of MA-class solenoid-free startup to NSTX-U and beyond. It will retire a long-standing risk for the feasibility of nuclear-grade STs, which have limited room for inboard nuclear shielding and space for an Ohmic solenoid (if permissible at all). It will also contribute to the aspect ratio optimization of the compact pilot plant endorsed by the recent NAS study [3].

This knowledge base will be developed with a new, dedicated domestic facility—the PEGASUS-III experiment—that is equipped with multiple startup techniques and appropriate diagnostic capabilities to demonstrate non-solenoidal startup to the $I_p = 0.3$ MA level at $B_T \sim 0.6$ T and the handoff of such plasmas to non-inductive sustainment methods. This facility will support the comparative evaluation and integration of existing and newly developed startup techniques.

A second thrust of the initiative aims to leverage two collaborations with international partner facilities whose capabilities complement or extend those available domestically. The first will continue transient coaxial helicity injection (T-CHI) studies on the Japanese QUEST device to develop T-CHI technology and explore RF-helicity injection synergies using ECH. Second, design and implementation of a T-CHI system will be pursued on the privately funded, high-B_T ST-40 ST in the United Kingdom.

The results of the domestic and international research thrusts will facilitate the selection, design, and proposal of an integrated MA-class startup approach (*e.g.*, helicity injection and RF heating/CD) targeted for NSTX-U.

Description of the Initiative

This initiative is comprised of a multi-pronged activity with focused domestic research and collaborative international components. It describes existing programs' scope and a broader vision for enhancements that are required to fully address the solenoid-free startup challenge.

The US domestic component centers on a major upgrade of the $A \sim 1$ PEGASUS spherical tokamak [4] (PEGASUS-III, for PEGASUS Phase III) and a new physics mission to demonstrate high-current, solenoid-free startup and sustainment in a cost-effective, modest-scale facility. The international collaboration component aims to continue present CHI research in Japan and to additionally apply the technique to the high-B_T, privately held ST-40 device in the United Kingdom. International studies on both devices will leverage their RF capabilities to examine synergies of RF with plasmas produced by helicity injection.

PEGASUS-III will become the US center for non-solenoidal startup development. The upgraded facility will integrate multiple startup and sustainment methods in a single device, permitting comparative studies for the first time on the same experiment. These presently include: local helicity injection (LHI) [5]; coaxial helicity injection [6,7]; poloidal field induction; and EBW RF heating and possibly current drive. Diagnostic upgrades will enable the development and validation of physical models underlying the startup techniques. Under this initiative, these capabilities would be expanded to include high-power EBW current drive, ECH and ECCD, and neutral beam current drive. This activity involves teams from the University of Wisconsin-Madison, the University of Washington, Oak Ridge National Laboratory, and Princeton Plasma Physics Laboratory.

The international collaboration component aims to continue present CHI research in Japan and proposes to apply the technique to the high-B_T, privately-held ST-40 device in the United Kingdom. US-Japan CHI research on the QUEST ST [8] will continue the development of a new reactor relevant biased CHI electrode configuration. Scoping reactor design studies using QUEST-like electrodes in an ST-FNSF configuration show that needed in-vessel CHI hardware could be protected from neutron irradiation for the life of the reactor [9,10]. Current experimental plans on QUEST aim to progressively demonstrate the generation of a closed flux plasma current generated by T-CHI, their subsequent plasma heating using ECH, and eventual sustainment of the CHI generated closed flux current using ECH and EBW.

A US team will conduct scoping studies to establish T-CHI capabilities on ST-40. In the near term, they will assess closed flux current startup potential, examine the feasibility of installing an insulated electrode as part of the ST-40 divertor plate, and perform TSC simulations to identify possible improvements to their proposed divertor coils. These will be followed by a detailed engineering feasibility study for CHI electrode installation. In conjunction with results from present studies on ST-40 that aim to develop ECH/EBW startup capability, these US-led studies will determine if an RF-based system by itself is adequate for solenoid-free current startup in the device. If not, they will identify the initial current startup magnitude that would be desirable from a CHI-based system. Such T-CHI plasmas would also be sustained using ECH/EBW.

<u>*Resources and Activities*</u>—This initiative leverages the construction and operation of the PEGASUS-III facility as the US development platform for addressing the solenoid-free startup challenge. This testbed will be used to develop and test models of non-solenoidal plasma startup, growth, and sustainment; develop supporting startup technology, such as helicity injector sources, power systems, and plasma control; and provide experimental data for model validation purposes. This knowledge base will inform the design of an optimized concept for MA-class startup in the future.

A unique capability provided by a dedicated facility is the ability to compare, contrast, and possibly integrate leading startup methods in the same device. The present PEGASUS-III program will equip the facility with LHI, CHI, PF induction, and EBW heating and current drive capabilities in the near term. Additional capabilities and activities are required to fully evaluate the range of relevant startup methods, non-inductive sustainment methods, and assess issues that may arise in larger facilities. These include: expanded RF capabilities, such as higher EBW auxiliary heating power and new ECH / ECCD RF sources; deploying a low-cost NBI system for heating and non-inductive current drive; enhanced power systems and pulse length; and evaluating the effects of close-fitting walls/plates. Other ideas/concepts may be considered as opportunities arise.

The PEGASUS-III program requires only modest resources to provide cost-effective study of the solenoid-free startup problem. Exclusive operational focus will be available to solenoid-free startup and sustainment.[1] Present project funding is O($3M/yr) amongst the host institution and all collaborators. This funding supports personnel, students, experimental operations, solenoid-free startup hardware (LHI/CHI/RF sources, power supplies, diagnostics), travel costs, and publication costs.

Expansion of this existing program under the proposed initiative would require a yearly budget of O($5M/yr). The elements added by this expansion are described below. Future costs required to deploy a MA-class proof-of-principle startup system on NSTX-U, its operation, and supporting personnel are quite uncertain and will depend on the ultimate concept that emerges. Generally, it is expected to require anywhere from $2–10M to deploy.

Activities in the international component focus on furthering T-CHI development on QUEST and initiating T-CHI activities on ST-40. Engineering and hardware costs, operational support, and some dedicated physics diagnostics are supported by the host facilities. US collaborators' personnel-related costs would be the primary cost driver and are estimated at the 2 FTE level [2].

DOE Facility Utilization and New Needs—This initiative utilizes existing DOE-funded programs. The PEGASUS-III facility is a significant expansion of the PEGASUS Toroidal Experiment, which is scheduled for shutdown in 2019. DOE funding was recently awarded to construct PEGASUS-III, as well as new awards to PEGASUS-III collaborators. A major goal of the proposed initiative is to construct, deploy, and operate a MA-class solenoid-free startup system on the NSTX-U national user facility.

PEGASUS-III is a new facility that is presently in the design/fabrication stage. No additional facilities are required to implement this initiative. The PEGASUS-III upgrade is planned in 2020. In the near term, present DOE support will provide an initial slate of LHI, CHI, PF induction, and EBW RF heating/current drive as startup/sustainment methods, a new diagnostic neutral beam, and upgraded diagnostics for physics studies.

Additional resources made available under this initiative will substantially broaden and strengthen this overall program. A multi-MW-level ECH/ECCD RF system, plus an increase in the available EBW power will allow development and comparative evaluation of purely RF-driven startup and sustainment scenarios. The addition of O(1) MW of readily available neutral beams with modest power supply requirements is needed to test handoff of the startup plasma to subsequent sustainment via neutral beam current drive. Expansion of the magnet power supplies for PEGASUS-III will support operation at higher I_p and pulse length if required. These enhanced capabilities will require an increase in supporting scientific and engineering staff.

It is useful to note that while the major US tokamaks (DIII-D and NSTX-U) are focused on developing neutral beam current drive, a system based on RF current drive is probably much more suitable for a reactor system. PEGASUS-III and ST-40 will use ECH/EBW to sustain currents non-inductively. It would therefore be a valuable complement to the US domestic effort in support of an SHPD design.

Enhanced Research Needs—Presently-funded domestic activities are focused on the design, construction, and operation of PEGASUS-III. Additional support from the theory and computation community is highly

[1] Explicitly, PEGASUS-III will not have a central solenoid electromagnet; Ohmic drive will not be an option by design. All plasmas in the device will require reliable solenoid-free startup as a precondition for operation.

desirable, both in the form of advanced modeling (*e.g.* NIMROD, TSC) and personnel to integrate into the overall team.

Advances arising from fusion technology research may benefit this initiative. This may include additive manufacturing and materials developments for advanced helicity injectors that require tolerance to high heat fluxes, be formed in advanced shapes, and minimize impurity production in the immediate vicinity of high-performance tokamak plasmas.

Industry and International Collaboration Needs—This initiative affords opportunities for enhanced industrial participation. Areas of potential interest include power systems and supporting technology, custom diagnostics, and RF sources. Presently funded international activities encompassed in this initiative will engage private industry through new T-CHI studies on ST-40. The PEGASUS-III facility and research program is intended to be sufficiently flexible to integrate relevant findings from our international colleagues as is warranted.

Programmatic Benefit

Solenoid-free plasma initiation and handoff to non-inductive current drive sustainment is a longstanding issue directly relevant to the viability of nuclear-grade STs [11–13] that has been consistently recognized in the scientific literature and strategic/community planning documents. Due to the low-A geometry of STs, this issue is more pronounced with respect to conventional tokamaks. Accordingly, most strategic planning activities related to this topic have been centered in the context of the ST community, with relevant portions summarized herein. However, benefits from successfully developing the physics and technology basis of non-solenoidal startup techniques are not limited to the ST. Reducing the technical requirements of the central solenoid, or eliminating its need entirely, serves to benefit tokamaks in general.

Fundamentally, conflicting constraints amongst the available centerstack space in low aspect ratio tokamaks, a desire to attain a compact plant size, and the need for inboard nuclear shielding in burning plasma devices precludes their use of an Ohmic solenoid. This initially led to solenoid-free centerstack assemblies in ST reactor concepts using disposable, unshielded copper TF magnets [13–15]. More recent ST reactor design studies considering the application of modern high-temperature superconductors and tritium self-sufficiency needs [16,17] show that solenoid-free startup remains a highly desirable capability (allowing for the possibility of a small "starter" solenoid that cannot ramp to the steady-state plasma current), and may be required to fully explore optimization of A for next-step, burning tokamaks.

Developing solutions to solenoid-free startup for STs was identified as a Tier 1 critical issue for the ST in the ITER era in the FESAC Toroidal Alternates Panel report [18], identified the low I_p generated by solenoid-free startup as a gap, and proposed a MA-class solenoid-free startup demonstration as a means to demonstrably close it. This assessment was reinforced by the ReNeW community workshops as a "Key Issue," and articulated the importance of not only attaining high startup current, but also four additional thrusts [19]: (1) demonstrating handoff of MA-class solenoid-free startup targets to non-inductive sustainment via RF and/or neutral beam heating and current drive; (2) developing validated, predictive physics-based models to assess the relative merits between various non-solenoidal startup techniques; (3) developing EBW RF plasma startup; and (4) performing comparative studies of multiple solenoid-free startup methods in a single experimental facility. Finally, the recent NAS study [3] highlights the critical role of the NSTX-U user facility in "assessing whether high-performance STs can be sustained without a transformer, a critical research component since the compact nature of an ST-based Pilot Plant, for instance, will preclude a substantial OH transformer."

The proposed initiative will employ the dedicated PEGASUS-III ST to directly confront these challenges and facilitate the desired MA-class demonstration of non-solenoidal startup and handoff to noninductive current drive in NSTX-U as an explicit goal. It will be the first facility in the world to compare, contrast, and potentially combine relevant startup methods (LHI, CHI, PF induction, EBW/EC RF) to demonstrate plasma initiation and ramp-up to the facility's full I_p rating (0.3 MA) at a 0.6 T B_T exceeding that of NSTX and overlapping the operating regime of NSTX-U and MAST-U. PEGASUS-III will be equipped with suitable diagnostics to measure quantities needed to validate physical models of these startup techniques and support high-confidence extrapolation of their performance to NSTX-U and beyond. Under this initiative, enhancements to PEGASUS-III to provide NBI heating/current drive and additional RF sources and power will address the non-inductive handoff gap as well.

Success in the initiative will bring non-solenoidal startup to the technical level of a routine operational tool. This would allow serious consideration of solenoid-free ST burning plasma devices—and possibly solenoid-free ATs as well. This may enable certain configurations (*e.g.* at lowest A, as discussed above [16,17]), afford cost savings, and possibly provide means to access desirable plasma properties in superconducting devices with reduced control capabilities.

In present-day research tokamaks, including ITER, the Ohmic solenoid is primarily useful for plasma initiation and ramp-up. This phase is a sizable fraction of the device's pulse length. In stark contrast, this phase is a vanishingly small percentage of operating time in power-plant-scale nuclear tokamaks where pulse lengths approach one year. For example, a 0.1 MA/s $\dot{I_p}$ to 20 MA in a recent EU-DEMO startup study allocates ~200 s of ramp-up time [20]. This corresponds to an Ohmic utilization duty cycle less than 0.001% in a year-long pulse. Reducing the technical requirements of or eliminating the need for a costly superconducting Ohmic solenoid system may enable a smaller-size, lower-capital cost fusion core. This arises not only by reducing the cost of the device's magnet system, but also reducing the electromechanical stresses associated with the Ohmic solenoid and leveraging space savings for additional breeding blanket volume or other useful actuators (HFS pellet injection, HFS RF launchers, etc.).

Helicity-driven startup methods may possibly afford beneficial target plasma characteristics and overcome control limitations in superconducting devices that limit the available inductive ramp rates for control of internal inductance. CHI and LHI both produce targets with very low ℓ_i due to the nature of the imposed edge current drive during the startup process [21,22], and do not require the formation of a poloidal field null by the tokamak equilibrium field system. Validated physical models (an output of this initiative) are needed to accurately extrapolate this effect and consider its feasibility in next-step facilities.

US Leadership and Global Context

The proposed initiative presents a significant opportunity to maintain and enhance US leadership in solenoid-free startup research.

A variety of techniques that are envisioned to be compatible with future reactors have been developed and tested on a wide range of facilities worldwide. They broadly fall into three categories: helicity injection methods (LHI, sustained CHI, T-CHI), which rely upon driving currents along open field lines at the plasma boundary with dedicated electrodes/sources; pure RF startup using electron cyclotron, lower hybrid, or EBW waves; and the merging, compression, and reconnection of two seed plasmas using external poloidal field coils ("double null-merging" / DNM). However, a unified study of multiple startup methods on the same facility has not been pursued to date.

For context regarding the present state of solenoid-free startup demonstrations, Table 1 aggregates solenoid-free I_p performance and accompanying plasma properties from multiple machines using startup techniques that are plausibly extensible to nuclear devices.[2] It quotes measured I_p values (net toroidal currents) at the end of the solenoid-free startup phase of the discharge evolution, as well as the extent to which such plasmas have been transitioned to subsequent current drive schemes. Note the representative results summarized in

[2] The merging-compression technique employed on START and MAST produced I_p ~ 0.4 MA plasmas [27,57], but is excluded due to its technical requirement of internal coils that are incompatible with the nuclear environment [58].

Method	Facility	I_p [MA]	t_{pulse} [ms]	n_e [10^{19} m^{-3}]	T_e [eV]	Sustainment Phase(s)	References
LHI	PEGASUS	0.225	10–30	~1	~125	Ohmic	[5,23]
	VEST	0.004	4	—	—	N/A	[24]
	CDX	≤ 0.001	60	$\bar{n}_{e0}\sim 2$	~25	N/A	[25,26]
	CCT	0.006	20	$\bar{n}_{e0}\sim 0.5$	30–50	N/A	[26]
S-CHI	NSTX	0.400	350	—	—	N/A	[27–30]
	HIST	0.150	5	$\bar{n}_e\sim 2$–7	20–30	N/A	[27,31]
	HIT-II	0.350	5	$\bar{n}_e\sim 5$	~40	N/A	[32]
T-CHI	HIT-II	0.100	1	~2	~15	Ohmic	[7]
	NSTX	0.200	5–20	~1	10–30	Ohmic, Ohmic + NBI heating	[27,33]
	HIST	0.100	0.3	~10	10–15	N/A	[34,35]
	QUEST	0.045	15	—	—	N/A	[8]
ECH+PF induction	DIII-D	0.170	50	~2	1000	RF, RF + NBI	[36]
	JT60-U	0.100	250	—	—	RF	[37]
ECH	QUEST	0.070	1,500	0.01	< 100	RF	[35]
	DIII-D	0.033	50	0.5–1	~100	RF	[38]
	KSTAR	0.015	1,800	~0.05	~250	RF	[39]
ECH + LHCD	T-7	0.020	175	$\bar{n}_{e0}\sim 0.1$	75	RF	[40]
EBW	MAST	0.073	450	0.1	100–200	RF	[41]
	LATE	0.015	80	$\bar{n}_e\sim 0.05$	30	RF	[35,42]
LH	PLT	0.100	2,500	$\bar{n}_e\sim 0.1$	350	RF	[43]
	TST-2	0.025	70	$\bar{n}_e\sim 0.05$	10	RF	[35,44]
	GLOBUS-M	0.021	140	$\bar{n}_e\sim 0.2$	15–20	RF	[45]
DNM	UTST	0.080	1	1–3	~5	N/A	[46]

Table 1. Solenoid-free startup performance at end of startup phase as function of startup technique.

Table 1 are not exhaustive, and do not by themselves imply any relative merit or desirability between the startup techniques. Results from this initiative are intended to credibly inform such decisions in the future.

The US is presently a leader on helicity injection startup, having demonstrated $I_p \geq 0.2$ MA, handoff of HI-produced plasmas to subsequent Ohmic current drive, and attaining H-mode [23,33], as well as advancing modeling [47–50] and supporting technology development. A successful initiative as proposed will serve to maintain this leadership position in the near-term and position the US to demonstrate MA-class solenoid-free startup on the NSTX-U national user facility.

In addition to experimental leadership, the US is also a leader in the development of theoretical models and understanding of non-solenoidal startup. For example, computational studies with the 3D resistive MHD NIMROD code have elucidated the role of 3D magnetic reconnection activity and current dynamics in LHI [47] that have been observed in experiment [22]. NIMROD has also been used to simulate flux amplification, closure, and the role of plasmoid-mediated reconnection in T-CHI [50–52]. Continued theoretical study and experimental validation can provide insights to optimize the startup process in present facilities and extrapolate confidently towards next-step devices.

This initiative will provide a world-class solenoid-free startup research capability with relevance to leadership-class ST operating parameters. Specifically, the dedicated solenoid-free PEGASUS-III ST will have B_T overlapping the range of the MA-class NSTX-U and MAST-U STs. In addition to developing startup techniques, it is worth noting these methods provide access to unique ST physics regimes which have already been demonstrated with world-leading parameters and features: $\beta_T \sim 1$, a minimum $|B|$ magnetic topology with high omnigeneity, high κ, low ℓ_i, and high β_N [22,53].

The international component of this initiative aims to leverage capabilities of foreign facilities in parallel. Research on QUEST in Japan is pursuing a biased CHI electrode system in a device with an all-metal wall and high-power ECH capabilities. The high B_T of the ST-40 ST in the United Kingdom (3 T) offers a means to test CHI B_T scalings to levels comparable to conventional tokamaks and ST-FNSF concepts. New research awards are supporting the design and proposed test of reactor-like CHI configurations that do not require an electrical break in the ST-40 vacuum vessel [9].

As noted above, RF current drive systems are highly relevant to reactor systems. ECH/EBW research on PEGASUS-III and ST-40 complements existing US efforts in this regard and supports a broadened physics and technology basis for next-step facility designs.

Timeline of the Initiative

<u>*Science and Technology Readiness*</u>—This initiative is a continuation and potential expansion of present research activities. It is technically and scientifically sound to commence immediately. Success metrics to justify closing the initiative have been clearly defined above.

The domestic component of this initiative (PEGASUS-III) is approved by the DOE and funded through portions of FY21. LHI research will continue on PEGASUS until its planned shutdown in 2019. CHI and RF studies on PEGASUS-III require its B_T upgrade in the near-term (FY20–21). The on-going T-CHI studies on QUEST and CHI design studies for ST-40 are currently funded by the DOE at the 0.6 FTE level to provide technical, design and operational assistance to these programs. Major hardware costs for implementing new systems on these devices is/will be provided by the respective host facilities.

Activities planned for/anticipated in the near-term (1–2 year), medium-term (2–5 year), and longer-term (5+ year) timescales are as follows.

Domestic activities in the near term begin with PEGASUS-III construction and commissioning in 2020. Initial high-I_p, high-B_T LHI experiments and CHI installation and commissioning will be conducted. In the medium term, full-power CHI experiments will take place. Initial EBW experiments will be conducted, as well as experiments exploring HI-RF synergies. Technology to support long-pulse (0.1 s) LHI injectors and demonstrate long-pulse LHI startup scenarios can be pursued. Implementing enhancements to RF capabilities (ECH, ECCD) and deploying NBI are feasible in this time frame, which would support both pure RF startup studies and high-I_p handoff of HI-produced plasmas to non-inductive current drive schemes. As needed, the effects of close-fitting walls or passive stabilizers may be evaluated.

Near-term international activities on QUEST will test T-CHI electrode designs and T-CHI-EC RF synergies to inform experiments at higher current and designs for PEGASUS-III, ST-40, and NSTX-U. Physics simulations with TSC and engineering design activities will be conducted for a T-CHI system on ST-40. In the medium term, the ST-40 T-CHI system can be installed and support high-B_T T-CHI scaling studies and study synergisms with ECH/EBW startup and current sustainment. Details for this period would be contingent on an assessment of ST-40's present ECH/EBW systems' capability to provide pure RF startup.

The long-term goals of this initiative are to define, propose, fabricate, deploy, and test an integrated solenoid-free startup program on NSTX-U, with PEGASUS-III to play a test facility/support role as needed. Early planning discussions with the NSTX-U group have agreed this should be an element in its second 5-year operational period (~2025). This time frame is also appropriate to pursue optimization of non-inductive handoff and sustainment scenarios in PEGASUS-III, in close coordination with the NSTX-U team.

<u>*Community Preparedness*</u>—No additional preparatory community activities are needed to successfully complete this proposed initiative. No siting options or regulatory changes are required. Timely completion of the full initiative described above would significantly benefit from expanded scientific/technical personnel.

Equipment / Facility Design Details

The PEGASUS-III facility (Fig. 1) is a major upgrade of the PEGASUS ST that is under design and fabrication at the University of Wisconsin-Madison. It is a solenoid-free, low aspect ratio ST that will serve as a dedicated US platform for comparative non-solenoidal tokamak startup studies. Its design is briefly summarized here; more detail can be found in recent community presentations [54–56].

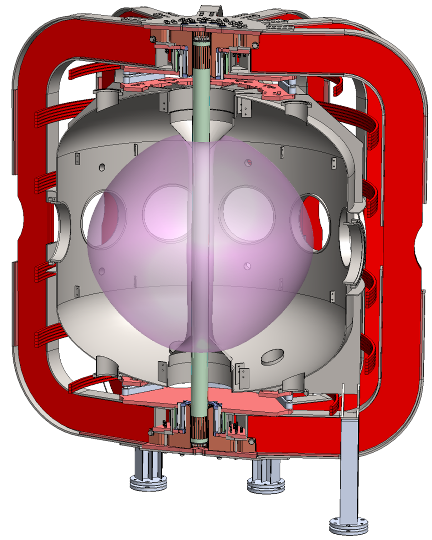

Figure 1. Schematic drawing of PEGASUS-III.

Key engineering parameters for PEGASUS-III are listed in comparison to present PEGASUS values in Table 2. The centerstack will be replaced with a slightly larger, solenoid-free assembly and a new 24-turn TF electromagnet. In conjunction with stronger, less resistive C-shaped TF return legs, the B_T of PEGASUS-III will be increased 4× to 0.6 T, and is being designed to support 0.9 T if required. The PEGASUS vacuum vessel and poloidal field system is largely retained, supporting $I_p = 0.3$ MA plasmas (limited by present power supplies). The new polar region will feature a new torque frame and additional integrated divertor coils for divertor strike point control and CHI studies. Approximately 300 MVA of programmable power systems for the facility will be reconfigured and expanded to support the higher B_T, quadrupled pulse length, expanded poloidal field system, helicity injectors, RF sources, and diagnostic neutral beam.

Parameter	PEGASUS	PEGASUS-III
I_{TF} [MA]	0.288	1.15
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm^2]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50–100
ΔT_{bundle}	< 10℃	< 20℃
R_0 [cm]	45	45
A	1.15–1.3	1.18–1.35

Table 2. PEGASUS-III parameters.

PEGASUS-III will initially be equipped with multiple solenoid-free startup methods: LHI, T-CHI, S-CHI, PF induction, as well as an EBW heating and current drive system. A new diagnostic neutral beam will be commissioned to provide a variety of local kinetic measurements and support model verification studies.

Detailed design and fabrication activities for PEGASUS-III are underway, with major components for the centerstack, TF outer legs, and power system upgrades presently in the procurement process. Shutdown of PEGASUS will take place late in 2019, followed by the PEGASUS-III conversion in early 2020.

As noted above, additional resources are required in the medium term to realize the full scope of the proposed initiative. This would include commissioning NBI heating and current drive; implementing additional RF sources for EBW current drive and commissioning an ECH/ECCD capability; expanding the diagnostic suite; and implementing a plasma control system as the pulse length is extended to support sustainment studies.

Cost Range

Implementing the full domestic mission scope identified above is estimated to be of order $5M/yr. This estimate is derived from extrapolating the cost basis for the present PEGASUS/PEGASUS-III programs with simple estimates of the additional capital equipment and supporting scientific/technical staff to execute the expanded research goals described above. This cost basis explicitly includes all aspects of the program, including personnel, design, construction, and operational costs for equipment and the facility.

Internationally, US collaborators' personnel related costs are the primary cost driver and estimated at the 2 FTE level. Hardware upgrades at the international facilities is provided by the host facilities.

Cross-Cutting Connections

The proposed initiative makes connections to several of the identified APS-DPP-CPP cross-cutting areas.

Workforce Development—The PEGASUS-III team at UW-Madison has a strong demonstrated track record of involving/training students and retaining them to become members of the US fusion community. The team presently supports 9 PhD students. Historically, the MEDUSA and PEGASUS teams have graduated 13 PhD students, 15 MS students, and worked with more than 100 undergraduates.

Investments in a world-class, on-campus university facility that fulfills a dedicated leadership role in the domestic fusion research program helps attract and retain students, staff, and faculty that are critical to the long-term health of the US fusion workforce.

Theory and Computation—Activities supported by this initiative represent an opportunity for enhanced collaboration with the theory and computation community. Topics include development and verification of predictive models for LHI, CHI, and RF physics; developing projections to next-step devices; and the joint experiment-theory participation in validation activities aimed at testing these predictive models. Studies of 3-D MHD NIMROD stability analysis [52] and reconnection [51] in support of high-current helicity injection startup should be continued.

Enabling Technology—The development of a reliable, MA-class solenoid-free startup system is widely recognized as a prerequisite for lower-A nuclear ST designs, and will very likely benefit any AT concept. Such a system may benefit from advances in high heat flux materials, additive manufacturing techniques, power supply innovations, and improved RF sources. The proposed EBW and RF activities in this initiative may cross-cut with high-power RF engineering in other elements of the FES research portfolio.

Advocates of This Initiative

The authors of this initiative represent support from members of the University of Wisconsin-Madison, the University of Washington, Oak Ridge National Laboratory, and the Princeton Plasma Physics Laboratory.

Additional advocates are:

D.J. Battaglia (PPPL), N.W. Eidietis (GA), J.E. Menard (PPPL), O. Schmitz (UW-Madison), and C.R. Sovinec (UW-Madison)

Revision History

- Version 3, 27 September 2019 – Revised joint initiative for Knoxville APS-DPP-CPP workshop.
- Version 2, 29 July 2019 – Updated list of advocates following Madison APS-DPP-CPP workshop.
- Version 1, 30 June 2019 – Initial public initiative release.

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