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# Design of the Flowing LIquid Torus (FLIT)

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## ABSTRACT

The design of the Flowing LIquid Torus (FLIT) at Princeton Plasma Physics Laboratory (PPPL) is presented. FLIT will focus on the development of a liquid metal (LM) diagnostics and divertor system (without a plasma source) suitable for implementation in present-day fusion systems, such as NSTX-U. FLIT is intended to provide proof-of-concept for fast-flowing LM divertor designs for heat fluxes $> 10$ MW/m$^2$. The toroidal test article (ID $\approx$ 0.56 m, OD $\approx$ 1.9 m, $h \approx$ 0.61 m) consists of 12 rectangular coils that can generate a centerline magnetic field of 1 T magnetic for greater than 10 s. Initially, 30 gallons Galinstan (Ga-In-Sn eutectic) will be recirculated within the test article using six jxB pumps to achieve flow velocities of up to 10 m/s across the fully annular radial test section. FLIT is designed to be a flexible machine that will allow experimental testing of various LM injection techniques, the study of flow instabilities, and electromagnetic control concepts to prove the feasibility of the LM divertors within fusion reactors.

## 1. Introduction

Plasma facing components (PFCs) within a tokamak need to withstand a combination of high heat, particle, and neutron fluxes. At the divertor, where anticipated heat fluxes can reach $> 10$ MW/m$^2$, the challenge becomes even more difficult. Although extensive work is underway, it is currently unclear whether solid divertors made from high-Z metals are suitable for a long pulse D-T fusion reactor. Traditional solid divertors suffer from erosion, dust formation, peaked thermal stresses, heat removal issues, confinement degradation, impurity accumulation in the core plasma, and tritium inventory control. Additionally, new research suggests that high-Z impurities may lead to plasma performance degradation [1]. LM PFCs (LM-PFCs) provide an alternative solution that can mitigate these issues and improve plasma performance [2,3].

Tin, lithium, tin-lithium eutectics, and gallium are the main LMs that have been studied experimentally and via simulations. Much of the research is focused on “slow” flow LM solutions as opposed to the “fast” alternatives which are the focus of this paper. The distinction between these two regimes is that “fast” flow removes nearly all of the heat impinging upon a LM-PFC while “slow” flow is mainly for PFCs’ erosion protection and requires a heat removal system similar to the solid alternatives. In general, “fast” flow concepts require flow velocities ranging from ~1–20 m/s and flow thicknesses of roughly 1–20 mm [16,21,29]. Balancing the heat flow into the divertor and thermal capacity of the LM flow is the main requirement that sets the “fast” flow speed for the divertor. Alternatively, “slow” flow LM-PFCs utilize creeping flows held to surfaces by electromagnetic and surface tension forces.

A fast-flowing LM divertor has multiple advantages compared to solid and slow flow systems. Previous studies have shown that hydrogen isotopes are likely to be trapped in liquid lithium surfaces. It is also possible that adequate helium trapping can be achieved in flowing lithium, thus removing the active pumping requirement [2]. This simplifies the divertor design. In addition, because the divertor material takes all the particle and heat flux, it needs to be designed only for neutron fluxes. This permits the use of neutron-tolerant, low thermal conductivity, steels as guide walls or substrates – an innovation which would greatly reduce the need for materials development for fusion. Demonstration of a fast flowing LM wall system could provide a key enabling technology for this approach. Faster flow also reduces the exposure time of the LM to the plasma, leading to lower LM temperatures, which may allow the achievement of low recycling surface (for lithium) and reduced evaporation and impurity diffusion into the plasma. The absence of a piping requirement for heat removal furthermore helps with simplifying the engineering of the divertor. Possibly the most important benefit is the flexibility of the fusion reactor design. As the size of the reactor reduces for a given power level, the reactor generally becomes more cost-effective, but the problem with the divertor heat flux increases. Thus, reactor designs currently optimize the plasma not only for optimal fusion energy gain but also for heat flux requirements to the divertor. Generally, high radiative fraction and less aggressive core plasma parameters are chosen to alleviate this issue. Advanced divertors such as X-divertor, snowflake divertor are also considered but these increase the cost and take up space. If the heat flux were not a concern, compact economical reactors would be much easier

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to achieve. Fast flow development gives us this possibility.

In this paper, we present the design of a fast flowing LM divertor experiment, FLIT, at Princeton Plasma Physics Laboratory (PPPL). Because of the many issues related to MHD fluid flow and LM engineering, it is important to first test and optimize the fast flow concept without the extra cost and complication of tokamak plasma. With the knowledge achieved from this experiment, the developed system can then be applied to a real tokamak or FLIT can be upgraded with a plasma source. The issues related to plasma-LM interactions, such as Kelvin-Helmholtz instabilities and the pressure disturbance, can then be studied.

The FLIT project would test, in a fusion-relevant toroidal magnetic field, the first annular fast-flowing LM divertor target, suitable for deployment in a tokamak. The aim of this experiment is to prove the feasibility of the concept of a fast-flowing divertor under realistic MHD conditions, to develop the engineering for a fast flow system such as jxB pumps, nozzles, and to optimize the LM divertor concept for reactors. In the following, we present a literature review, a conceptual overview of FLIT, and details of the FLIT design before discussing the applicability of the results of FLIT for fusion reactors with fast flow.

## 2. Literature review

The current state of fast-flowing, free-surface LM technology is roughly at technical readiness level (TRL) 2. A few flowing LM concepts were tested in a preliminary fashion but no fast flow system has yet been implemented on a tokamak. Most LM studies have focused on stationary or creeping flow, mainly relying on surface tension effects within a capillary-pore system (CPS). Results from these studies are generally positive for LM surface interaction with the plasma. T-11 M showed that CPS system is stable under high heat loads and plasma conditions were not degraded [4]. NSTX studied a liquid divertor with thin layer of lithium and FTU is currently studying various LM limiter options [5]. LTX showed that the liquid lithium wall produces very high edge temperatures and is beneficial for fusion reactor design [6].

Compared to slow-flow systems, fast-flow systems have received much less attention. LM studies at UCLA with MTOR looked at fluid instabilities under magnetic field conditions with up to ~0.5 T [7]. One option considered was the high-speed droplets formed from a jet at the divertor. Experimental studies at LMX experimentally demonstrated that hydraulic jump location and heat transport within a liquid metal can be adjusted using electromagnetic controls [8–10].

Free surface LM studies in tokamak conditions include those of the Russian TM-3 tokamak in the 1980s, which showed that under fast Bt ramp (1 T in 10 s of ms), LM flow stopped and there was splashing. The high temporal Bt variation induces strong MHD drag and leads to stopping of the flow. This will not be the case for realistic LM operation in a superconducting tokamak/stellarator in which the magnetic field is constant or varying orders of magnitude slower [11]. CDX-U utilized a large-area ~6 mm thick stationary (no flow) free-surface LM limiter tray and improved performance with a lithium limiter [12]. FLiLi, a plate with flowing thin film lithium, demonstrated the engineering concept for flowing lithium in tokamak conditions at EAST [13]. ISTOK looked at the effect of gallium droplets as they pass through plasma, showing that the droplets drift and their shape changes as they move through the magnetic field [14]. Conditions for the ejection of droplets from a LM surface under magnetic fields was studied analytically by Jaworski et al. [15]. Their analysis shows that the particles will eject when the total out-of-plane jxB force is larger than the surface tension.

## 3. FLIT concept

The annular flow in the poloidal direction that is envisioned for a fusion reactor divertor has no side walls or Hartmann layer, which changes the magnetic drag effects. The toroidal magnetic field in a tokamak decays radially (~1/R), and this gradient leads to magnetic drag and changes the surface wave properties. It is not feasible to experimentally test all the issues faced in an annular flow in a tokamak using a simple, rectilinear duct configuration. Thus, a fast-flowing torus setup is necessary.

FLIT will serve as a flexible proof-of-concept experiment of a fast flowing LM divertor. It will aim to answer pertinent questions that have long occupied the fusion community about (1) the feasibility of a annular fast-flowing LM divertor under MHD conditions that can handle high heat fluxes; (2) the engineering required for a fast-flow system (jxB pumps, nozzles –jets/open surface, etc.); and (3) the optimal configuration of the LM divertor concept for reactors (length, curvature etc.).

FLIT is designed to study fast-moving, free-surface, axisymmetric LM flows in similar conditions to a tokamak. This aim translates into the following design criteria:

(1) The system should be able to handle ~10 MW/m$^2$ level heat flux, which approximates the conditions at ITER and high-power fusion reactors.
(2) The system should show the flow of LM in a realistic torus configuration with fusion-relevant magnetics fields, where magnetic gradient effects can be studied.
(3) The system should prove a stable fast flow through the expected ITER heat flux region, which is in the order of 10 s of cm.
(4) FLIT is designed with flexibility to achieve almost all of the relevant non-dimensional parameters (Reynolds, Weber, Interaction parameter, etc.) for NSTX-U and ITER, thus allowing us to compare numerical/theoretical predictions with experimental ones in relevant parameters.

Additionally, in order to keep the costs to a reasonable level, our engineering constraints are the following:

(1) The system should use as much of the preexisting hardware (especially power supplies) that is currently available at PPPL.
(2) The system should minimize the expensive liquid metal inventory.
(3) The system should have easy access for needed adjustments and added diagnostics.

In what follows, we provide an overview of the FLIT design and our decision-making process based on the governing principles outlined above.

(A) First, the cost-saving requirement forces the design to use Galinstan instead of lithium in order to avoid the safety-related overhead. Galinstan is a eutectic alloy mainly consisting of gallium, indium, and tin. It is non-toxic and liquid at room temperature, which makes it easy to work with compared to alternative liquid metals.
(B) Second, ~10 MW/m$^2$ level heat flux leads to a specific liquid flow rate.
(C) The properties of Galinstan and the aim of reducing its volume and cost led us to select a steady state flow velocity in the range 1–10 m/s and LM height of ~5 mm.
(D) In order to prove that the flow can be stabilized for the length of the divertor of a realistic reactor, we chose the flow path to be approximately 30 cm.
(E) In order to give LM flow sufficient time to start and stabilize during an experimental “shot,” FLIT can generate peak magnetic fields for ~10 s.
(F) NSTX-U will operate at 1 T magnetic field at the core. To study and prove the concept for a possible upgrade to NSTX-U with a LM divertor, we chose to design FLIT to 1 T at the core (same as NSTX-U).
(G) Drag calculations and the available power supplies set the number of jxB pumps to 6.
(H) For cost purposes, we confined ourselves to designing a system that will share the power supplies with LTX.

(I) The flow path requirement, jxB pump spacing needs, and human access to the machine set the size of the FLIT coil window to be 75 cm radial × 105 cm vertical.
(J) The size of coils, specifications of the available power supplies at PPPL, 1 T magnetic field, and the $I^2t$ (dissipative power in the toroidal field) heating limits set the coil design.

## 4. FLIT design details

### 4.1. Coil design

The coilset for FLIT is designed around a 0.8″ square conductor with a 0.25″ diameter circular coolant channel. The coils are made of copper insulated with polyester treated glass insulation, fiberglass is used as coil fillers. The inner legs of the coils are shaped as wedges such that the 12 coils fit together in the center and support the structure (see Figs. 3 and 4). The copper mass is sufficient to allow a 10-second pulse at full field (nominally 1 T at the coil center), powered by the largest (20 kA, 500 V) Robicon supply (that is used for LTX at PPPL). The coil mass is chosen so that the $I^2t$ heating of the coil and the $I^2t$ output capability of the Robicon are matched. With these criteria and the reduction of ripples, we chose to use 12 toroidal field coils. The coils will be cooled between pulses, and the design allows for conversion to a silicon oil coolant at a later stage, which would make it feasible to use FLIT for lithium experiments in the future.

A conceptual design of the test divertor and coilset is shown in Fig. 1. A view of the jxB pumping system is shown in Fig. 2.

The design currently includes a total of six jxB pumps, which initial calculations indicate will provide flow rates of up to 10 m/s in the divertor target area. The toroidal reservoir and jxB pump geometry are shown in Fig. 3.

We calculate the detailed heat transfer, electromagnetic and gravitational forces, and the internal stress on FLIT coils and insulators using Ansys. The analysis led to modification of the coils, making the coils rounder at the edges. The higher field side of the 12 coils are designed in wedges so that they can be fitted together, as shown in Fig. 3 on the core section. Examples of stress analyses for the final design for the final design are shown in Fig. 4. The right figure shows the stress on the outside of the coil while the internal stresses on the high-field side, where the stresses are highest, are shown in the *X*-*Y* plane cross-section figure on the right. In the cross-section, the wedge shape on the high-field side is visible with the high stress concentration near the holes, which are the water flow paths that allow the cooling of the coil. All of the mechanical and thermal analyses show that the engineering safety requirements for the system are met.

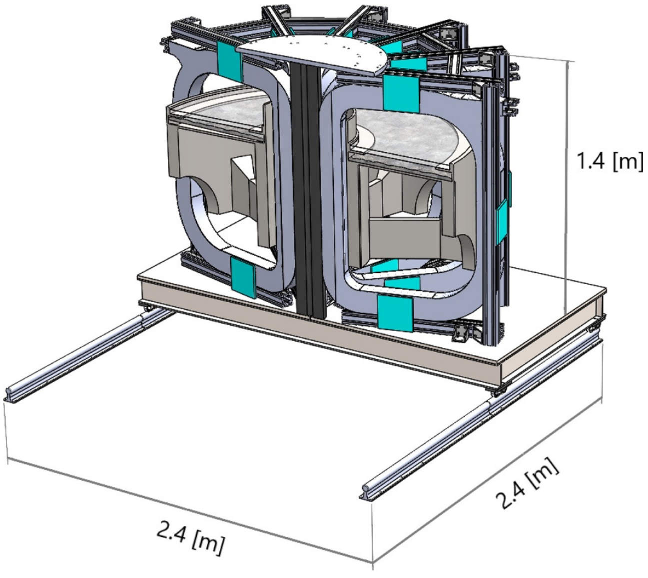

**Fig. 1.** Cut-away of FLIT, showing the initial coilset design, argon chamber, and the preliminary design for the initial test flowing-LM divertor. Bus bars for the JxB pumps are not shown.

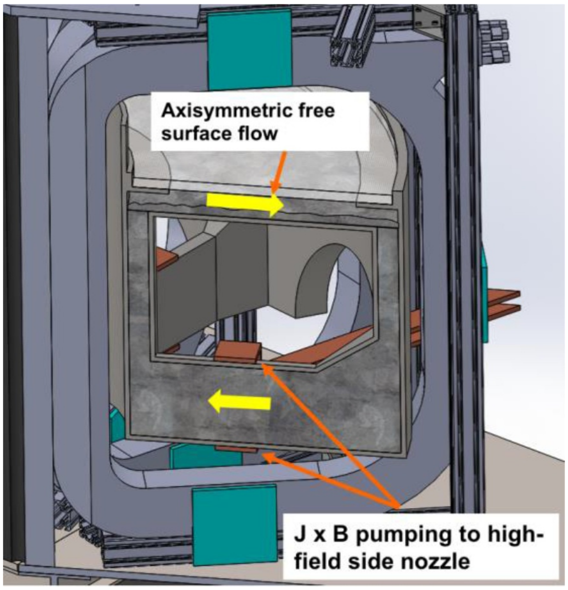

**Fig. 2.** Cross section view of one of the six JxB pumps in FLIT. The pump returns the LM from the low-field-side reservoir to the high-field side and injects the LM along the divertor surface in axisymmetric fashion.

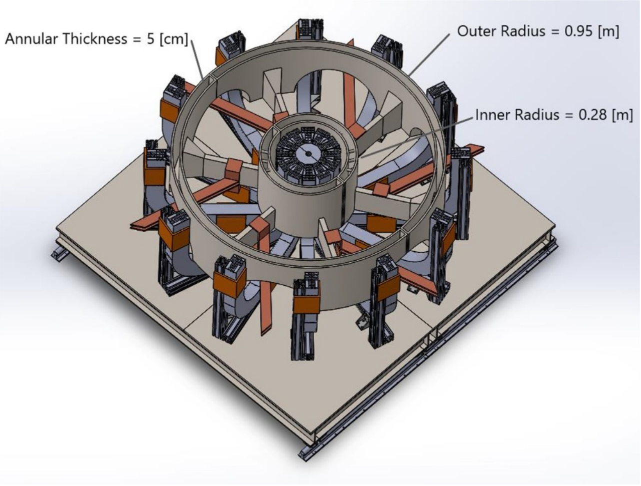

**Fig. 3.** Horizontal cut through FLIT, showing the toroidal LM reservoir, the six JxB return pumps (and the connecting busbars) and the 12 coils.

### 4.2. Nozzle and divertor design

FLIT was designed with physics studies in mind that require flexible operations. The nozzle and divertor setup of FLIT is shown in Fig. 5. The divertor in a fusion reactor can have different angles and curvatures. Thus, the FLIT divertor is designed to have a variable surface. The horizontal surface can integrate an angled insert on top. Initial tests will be carried out in horizontal flow. Then, the angle of the flow will be varied by mounting different panels on top (e.g. acrylic panels). The setup is flexible to also allow curved surfaces for more realistic divertor configurations. In addition, the FLIT nozzle is adjustable, allowing different flow heights and different diffusers, and even different jets of LM droplets.

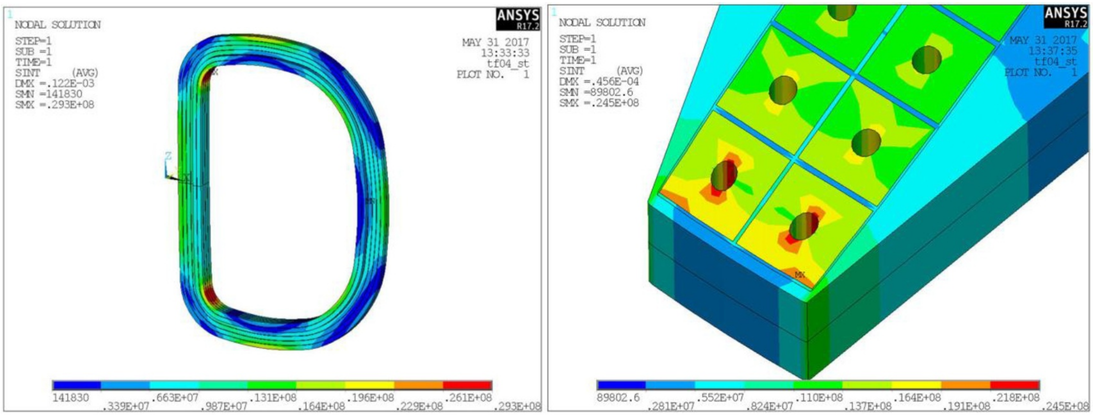

**Fig. 4.** Stress Analysis of the FLIT Coils. On the left, the general overview of the stress on the coil is shown. On the right, the stress on the wedge area is shown (zoomed).

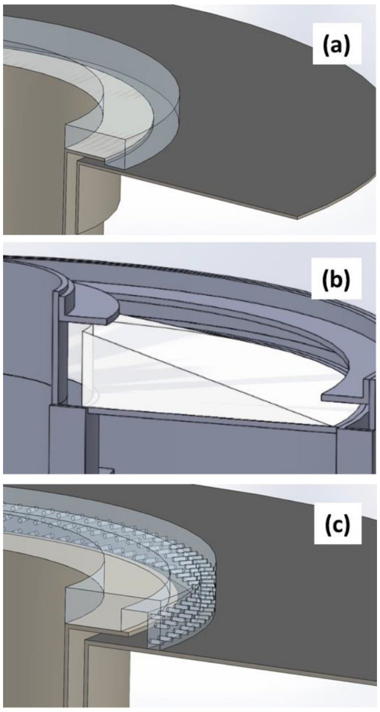

**Fig. 5.** Alternative nozzle and flow types that will be tested on FLIT. (a) Horizontal flow, (b) Angled flow, (c) Droplet nozzles.

### 4.3. Flow depth

The depth of the flowing Galinstan in FLIT will range from mms to a few cms. Wetting of the surface is needed for LM height of 5 mm and below [16,17].

### 4.4. Heat transfer requirements

The motivation for a fast flow system is to remove the heat from the plasma directly with the bulk flow of the liquid. FLIT will not have a plasma and high level heat source. We will initially include a low-power resistive heater to study low-level heat transport. High heating power will be looked into in a future upgrade. However, the aim is to prove that this level of flow provides the necessary heat-taking capability.

During steady-state reactor operation, the power generated inside the tokamak ($Q$) must be equal to the power removed from the system. The energy balance of the system can be written as follows:

$$Q = q\ A = \dot{m}\ c_p\ \Delta T \tag{1}$$

where '$q$' is the heat-flux, '$A$' is the area of the LM exposed to the heat-flux, '$\dot{m}$' is the mass flow rate, and $\Delta T$ is the temperature rise of the LM. The highest heat removal rate can be achieved if we assume perfect thermal mixing (highly turbulent and eddy currents); this would be the optimistic scenario. Then, all the heat coming to the surface is instantly distributed across the LM thickness and taken out at the edge of the flow. For a total power generation of 173 MW (the case for ITER with $P_\alpha + P_{\mathrm{aux}}$ – no radiation), $q$ is ~20 MW/m$^2$. For a simple estimate in a lower single null, we will assume equal loading on the inner and outer divertor, with a radially constant profile. If we allow lithium temperature change of $\Delta T = 200$ (°C), (200 to 400 (°C)), in order to avoid evaporation (this is a conservative estimate, since there is ample evidence that small amounts of lithium evaporation do not adversely affect the plasma, and can form an evaporated -vapor shielding- layer that can reduce the heat to the surface), we obtain

$$Q_{in} = Q_{out}\ = \dot{m}c_p\Delta T = (2\pi r\ h\ V\ \rho)c_p\Delta T. \tag{2}$$

Solving it, we obtain a velocity requirement of 2.6 m/s for a 0.5 cm thick flow and 1.3 m/s for 1 cm thick flow. This is the most optimistic scenario. A worst-case scenario with no turbulent mixing is looked at next.

For the conservative design, we use a simple heat flux model as shown in Fig. 6. Here we assume only conductive heat flux to find the change in the temperature of the LM for a given fusion $q$. This is a conservative design because advective heat transport is ignored. Thus, assuming the thin layer of flowing LM as a solid metal plate moving at a constant velocity, for a plate of finite thickness ($d$), the temperature as a function of time ($t$) and position ($z$) can be calculated as

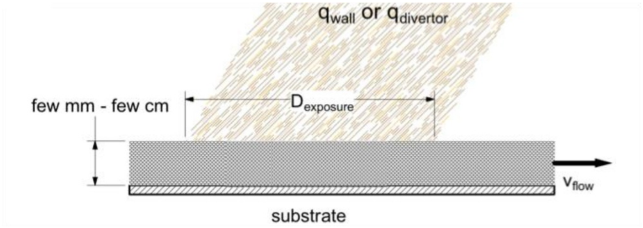

**Fig. 6.** Drawing showing LM surface exposed to constant heat flux.

$$T(z,\, t) - T_\infty = \frac{q}{\rho\ c_p\ d}\left[t + \frac{d^2}{\alpha}\left(\frac{3(d-z)^2 - d^2}{6d^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2} exp\left(-\frac{n^2\pi^2\alpha t}{d^2}\right) cos\left(\frac{n\ \pi(d-z)}{d}\right)\right)\right] \tag{2a}$$

where α is the thermal diffusivity of the lithium. In this equation, ‘*t*’ is the time it takes for the top of the fluid to move across the heat flux region [18,19]. Using Eq. (2), the critical amount of time ($t_{\mathrm{crit}}$) for flowing lithium to reach a particular increase in temperature can be approximated [18] as

$$t_{crit} = \left(\frac{T\ k}{2\ q}\right)^2 \frac{\pi}{\alpha}. \tag{3}$$

For a system like NSTX-U, where the expected power flux is 10 MW/m$^2$, $t_{crit}$ for a liquid-lithium divertor becomes

$$t_{crit} = \left(\frac{(200\ [K] * 85\left[\frac{W}{m-K}\right]}{2 * 10E6\ [W/m^2]}\right)^2 \frac{\pi}{45{*}10^{-6}\ [m^2/s]} \approx\ 0.05\ [s]. \tag{4}$$

Since the radial length of the divertor in NSTX-U is ~0.2 (m), the required flow velocity is

$$v = \frac{L}{t_{crit}} \approx \frac{0.2\ [m]}{0.05\ [s]} = 4\ [m/s] \tag{5}$$

Thus, NSTX-U's worst-case scenario requires ~4 m/s velocity. Similar calculations for ITER give the required velocity to be ~10 m/s.

### 4.5. jxB pump

The main aim of the jxB pumps is to overcome the pressure drop in the LM flow. Along the flow path of the Galinstan, there are two sources of pressure drop: hydraulic losses and MHD drag. Hydraulic pressure drop calculations were performed using standard engineering calculations based on Idelchick [20] and Ansys Fluent. To reduce the MHD pressure losses, we designed the test article to be made of steel lined with an electrical insulator such as Teflon or epoxy. Drag was calculated using Ansys simulations, as shown in Fig. 7. As shown in Fig. 3, FLIT will use multiple jxB pumps to circulate Galinstan around the system. jxB pumps need high current, low voltage power supplies. Commercially available power supplies of this nature, with the required power and the 1 Telsa magnetic field, set the jxB pump design. After discussions with vendors, we elected to use 26 kA@4.38 Vdc power supplies. Optimization of the dimensions of the current jxB pump duct gives: the internal height of pump duct (parallel to magnetic field) at 0.5 in; internal width of pump duct (parallel to electric current) at 8.0 in; length of electrode in flow direction at 4.0 in; and channel wall thickness at 0.125 in. FLIT will require ~ 10.2 atm pressure from 6 independent jxB pumps and power supplies in order to circulate 85 liters/s (~10 m/s) at 1 T. This assumes an argon covergas pressure of 2 atm. Pump efficiency is expected to be approximately 18–19%. The temperature rise of the Galinstan flowing through the jxB pumps will be minimal at ~ 0.2 °C. The jxB pump is connected with six busbars to the power supplies, as shown in Fig. 3. In order to minimize the electromagnetic forces on the system, we use a ‘pancake’ setup where the ingoing and outgoing feeds are pressed against each other separated by a nonconducting layer. Thus, the net current is zero, reducing any perturbation.

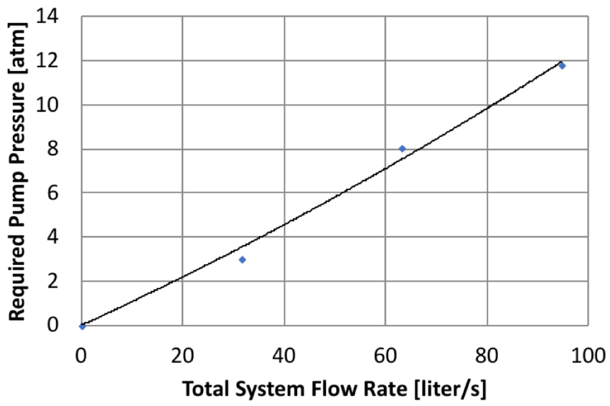

**Fig. 7.** The required jxB pump pressure to achieve different flow rates at maximum toroidal field strength.

### 4.6. Galinstan inventory

It is desirable to keep the Galinstan inventory to a minimum. From a practical point, the Galinstan that will be used within FLIT is an expensive material, and the aim is to purchase as little Galinstan as possible. The system will require ~10 gal of Galinstan for all parts, not including the reservoir, based on the parameters defined above. This volume accounts for the volume of the pump duct, annular divertor region, and a minimum of tubing to connect the two, but does not include the effects of splashing and thermal expansion due to pump heating. The size and design of the reservoir is determined by the jxB pump inlet pressure requirements and the settling of the Galinstan after the “waterfall” to avoid running the pump dry. The test article will be filled with argon to avoid air flowing into the chamber and oxidization of Galinstan. Based on these pressure calculations and insights from running LMX, the reservoir is set to 12 inches in height and 5.25 inches in width, which is roughly an additional 16 gallons. This brings the total system volume to approximately 27 gallons.

### 4.7. Test-article design

The test article recirculates the Galinstan from the “waterfall” through the reservoir and the jxB pump to the high field side and back to the nozzle. The article is composed of two parts to allow placement between the coils with a crane. Based on the jxB pressure calculations, it is designed to have a stainless steel wall that will be electrically insulated on the inside. Internal bracing within the test article will reinforce panels on the high field side to keep the bending and stresses to a minimum.

### 4.8. Free-flow instabilities

The main scientific study of FLIT will be the understanding and control of free-flow instabilities. Although we cannot predict all of the instabilities, FLIT design strived to minimize them. As for the other instabilities, FLIT is able to capture their effects.

#### 4.8.a. Hydraulic instabilities

As a thin layer of fast flowing liquid flows in an open channel, there is a tendency for a phenomenon called “hydraulic jump” to occur. When the Froude number, Fr, the ratio of the inertial forces to gravitational forces (see Table 1), is above 1, called “supercritical,” the fluid tends to move to a “subcritical” condition (Fr $<$ 1) with increased height and reduced velocity. This would substantially degrade the heat-taking capability of the LM and may lead to evaporation [21]. Based on hydraulic jump studies [22–25], FLIT will use a smooth surface and “water fall” style outlet that will reduce back-pressure in the system, thus reducing the possibility of hydraulic jump. Hydraulic jump under MHD conditions was studied at LMX [25] and our projection based on these results suggests that, at the high velocities, FLIT should not have a jump in the flow.

**Table 1**

Characteristic non-dimensional numbers for liquid-metal systems.

| | Equation | Meaning |
|---|---|---|
| Reynolds# | $\frac{\rho\ v\ D_h}{\mu}$ | Inertial forces/Viscous forces |
| Magnetic Reynolds# | $\mu_0\sigma v D_h$ | Induced field/Applied field |
| Hartmann# | $B\ D_h\sqrt{\frac{\sigma}{\mu}}$ | (EM forces/Viscous forces)^0.5 |
| Weber# | $\frac{\rho\ D_h\ v^2}{\gamma}$ | Inertial forces/Surface tension |
| Froude# | $\frac{v}{\sqrt{g\ D_h}}$ | Inertial forces/Gravitational forces |
| Interaction parameter | $\frac{\sigma B^2 D_h}{\rho v}$ | EM forces/Inertial forces |

### *4.8.b. MHD instabilities*

Annular flow has no side wall or Hartmann layer, which should help in reducing the magnetic drag effects. With this in mind, FLIT is designed to minimize the toroidal asymmetry. The nozzle and flow surface are fully symmetric with a single joint that connects two half parts. After joining the two parts, the surface will be polished to obtain a single fully smooth axisymmetric flow path. The toroidal magnetic field in a tokamak decays radially (~1/R), and this gradient leads to magnetic drag and changes the surface wave properties. However, annular flow also allows magnetic propulsion of the LM, which would be beneficial for fast-flow systems but has not yet been studied experimentally. When a poloidal current is applied, pressure gradient due to variation in the jxB force is achieved. The LM is pushed outwards from the higher pressure on the high field side towards the lower pressure on the low field side [26]. FLIT will allow study of magnetic propulsion.

The poloidal magnetic field is typically very small compared to the toroidal magnetic field. For example, in 2 T standard lower-single-null DIII-D [27] discharge, #163303, it is 4% of Bt at the strike point, and it is the perpendicular component to the flow surface, which is a small component, that has a dragging effect. This effect will be analyzed initially by adding permanent magnets under the flow path. In the later phase, poloidal field coils and “copper plasma”, a copper carrying a current in the same location as the core plasma will be added, allowing more realistic study of these effects.

## 5. Applicability of FLIT results to future LM tokamaks (and Stellarators) and comparison of non-dimensional parameters

There is substantial interest in studying different LMs as divertor options. Lithium flow attracts attention due to its positive impact on plasma performance [6,28]. However, due to safety regulations at PPPL, it is faster and less expensive to develop the technology for a fast-flowing system using Galinstan instead of lithium. Although FLIT will use Galinstan, it is designed to give insight into various flowing LM options.

It is important to quantify FLIT operating conditions and compare them to potential future designs. We designed FLIT with the conditions at NSTX-U and ITER in mind. The general way to project the results from one machine to another is to try to reproduce non-dimensional parameter regimes. Not every non-dimensional parameter can be achieved in a different machine, but the important ones should be attempted to be reproduced. The non-dimensional numbers of most relevance in LM research are listed in Table 1.

FLIT is designed as a flexible testing environment to achieve as many of these parameters as possible. Properties such as fluid height ($D_h$), magnetic field strength ($B$), and velocity ($v$) can be varied during FLIT operation. Other parameters such as electrical conductivity ($\sigma$), viscosity ($\mu$), density (ρ), and surface tension (γ) cannot be modified since they are intrinsic properties of the fluid.

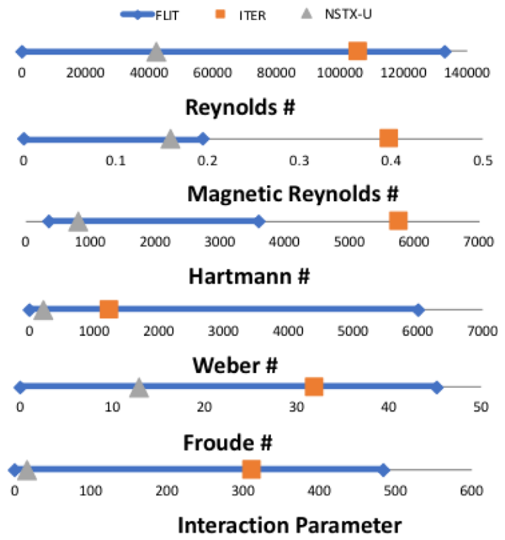

**Fig. 8.** Range of possible parameters that can be achieved at FLIT and comparison to ITER and NSTX-U conditions.

As can be seen from Fig. 8, FLIT, as a flexible machine, will achieve almost all of the important parameters of interest. We will vary the magnetic field, fluid velocity, and height to achieve the non-dimensional numbers of interest and closely approximate anticipated lithium flows. It is important to emphasize that lithium is a factor of ~13x less dense than Galinstan; this will be an advantage for future pump designs for flowing lithium systems. To first order, the force needed to flow the liquid scales with density. This will reduce the pump requirement for the lithium system and make it easier to run at higher velocities after a potential FLIT upgrade. The electrical conductivity of the two fluids is similar, making the effectiveness of running current through the fluids similar for the jxB pump. Lithium is twice as thermally conductive as Galinstan, which reduces the flow speed requirement for a given heat flux. Our design took this into account when setting the flow speed requirements for FLIT.

## 6. Conclusions

The ultimate goal is the design of a flowing LM plasma-facing component (PFC) system for a power-producing reactor; the model validation from this project is a key step toward such a design. The project would result in a first-of-its-kind LM PFC development facility, which can be modified to test LM PFCs in magnetic field configurations relevant to stellarators as well as tokamaks. FLIT will cover the relevant non-dimensional parameters of interest, allow for comparison of benchmarking of numerical simulations, and form the engineering basis for building a fast-flowing LM system for fusion reactors. While there are no plans to produce a real tokamak discharge in FLIT, we intend to eventually investigate poloidal coils and so-called “copper plasmas” – a pulsed coilset, wound in place, within the toroidal chamber, and used to produce magnetic field configurations similar to those found at the edge of tokamaks. FLIT would also be upgraded with localized heating to achieve 10 MW/m2, possibly through the use of electron guns to study heat transport at realistic values. This would allow testing of more realistic magnetic field configurations. The engineering and physics insights gathered from FLIT will be of the utmost importance for any flowing system in a tokamak or stellarator.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nme.2019.01.005.

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