Thermo-magnetic Systems for Space, Nuclear and Industrial Applications

Engineering MHD and software development

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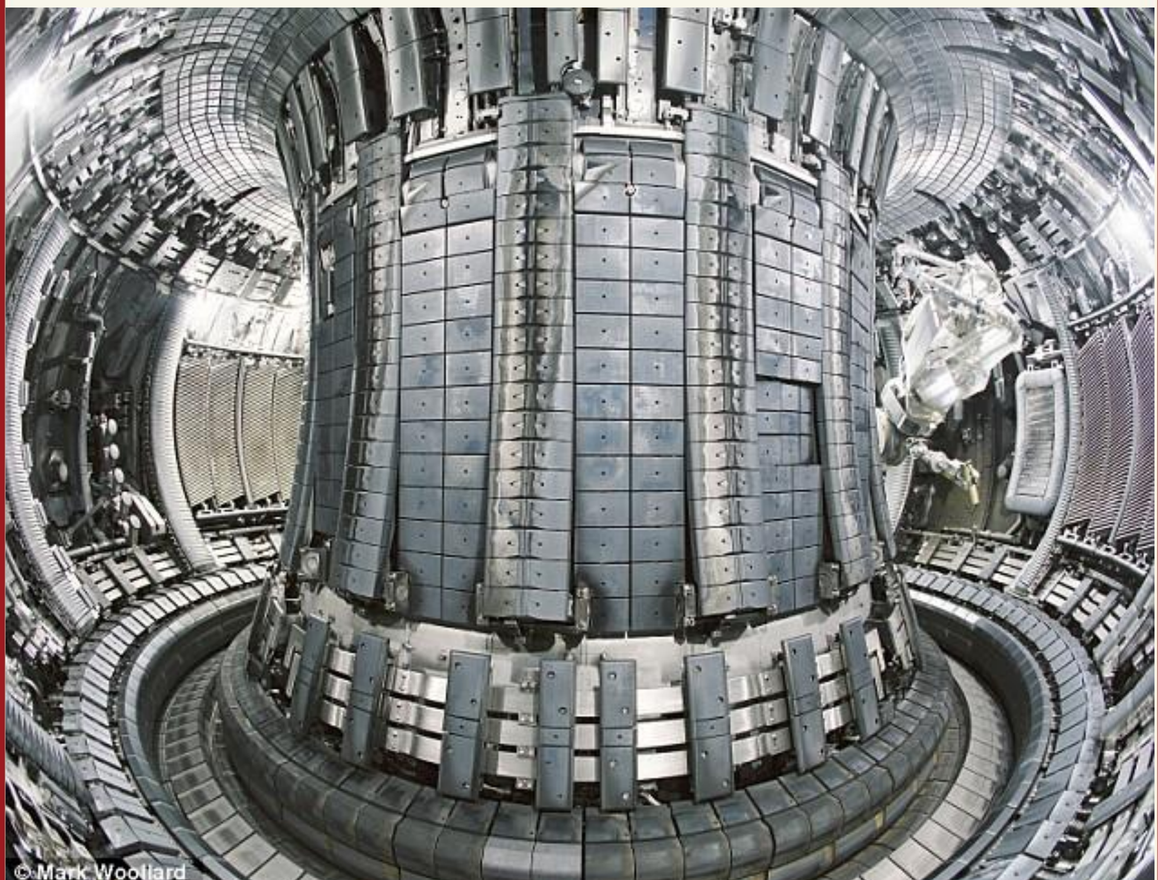
Liquid alloy systems have a high degree of thermal conductivity far superior to ordinary non-metallic liquids and inherent high densities and electrical conductivities. This results in the use of these materials for specific heat conducting and/or dissipation applications. Typical applications for liquid metals include heat transfer systems, and thermal cooling and heating designs. Uniquely, they can be used to conduct heat and/or electricity between non-metallic and metallic surfaces. The motion of liquid metals in strong magnetic fields generally induces electric currents, which, while interacting with the magnetic field, produce electromagnetic forces. Thermo-magnetic systems, such as electromagnetic pumps or electromagnetic flow meters, exploit the fact that liquid metals are conducting fluids capable of carrying currents source of electromagnetic fields useful for pumping and diagnostics.

Liquid metal-cooled reactors are both moderated and cooled by a liquid metal solution. These reactors are typically very compact and they can be used in regular electric power production, for naval and space propulsion systems or in fission surface power systems for planetary exploration. Liquid metals in fusion reactors can be used in heat exchange, tritium breeder systems and in first wall protection, using a flowing liquid metal surface as a plasma facing component. Many high power particle accelerator facilities will need to employ liquid metal targets and beam dumps for spallation and for heat removal where the severe constraints arising from a megawatt beam deposited on targets and absorbers will require complex procedures to dilute the beam and liquid metals constitute an excellent working fluid due to its intrinsic characteristics. In the metal industry, thermo-magnetic systems are used to transport the molten metal in between processes.

The coupling between the electromagnetics and thermo-fluid mechanical phenomena observed in liquid metal thermo-magnetic systems, and the determination of its geometry and electrical configuration, gives rise to complex engineering magnetohydrodynamics and numerical problems were techniques for global optimization has to be used, MHD instabilities understood -or quantified- and multiphysics models analyzed. The environment of operation adds even further complexity, i.e. vacuum, high temperature gradients and radiation, whilst the presence of external factors, such as the presence of time and space varying magnetic fields, can lead to the need of developing active flow control systems.

Dr. Carlos O. Maidana

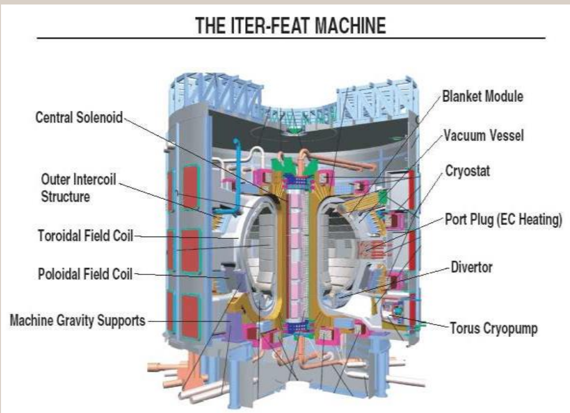


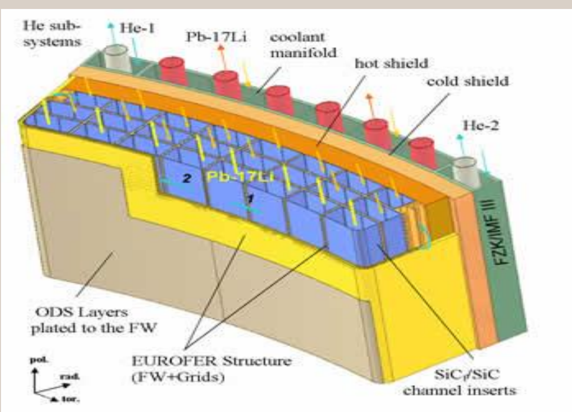
Liquid Metal Technology for Nuclear Fusion Devices

Research and development in nuclear fusion devices is increasing worldwide and experimental facilities and prototypes face new engineering magnetohydrodynamics challenges and needs. Among the latter are the use of liquid metals thermomagnetic systems such as electromagnetic pumps and the use of liquid metals as plasma facing material. Certain engineering MHD problems and solutions are shared by different fields but there are aspects specific to nuclear fusion devices that we aim to solve by developing mathematical, computational and experimental methods and tools useful in the design and multi-physics analysis of engineering components and in the understanding of the MHD phenomena in place.

Liquid Metal Technology for Nuclear Fusion Devices

While fusion power is still in early stages of development, substantial sums have been and continue to be invested in research. In the EU almost €10 billion was spent on fusion research up to the end of the 1990s, and the new ITER reactor alone is budgeted at €10 billion. It is estimated that up to the point of possible implementation of electricity generation by nuclear fusion, R&D will need further promotion totaling around €60–80 billion over a period of 50 years or so (of which €20–30 billion within the EU). Nuclear fusion research receives €750 million (excluding ITER funding) from the European Union, compared with €810 million for sustainable energy research, putting research into fusion power well ahead of that of any single rivaling technology.





Despite many differences between possible designs of power plant, there are several systems that are common to most. A fusion power plant, like a fission power plant, is customarily divided into the nuclear island and the balance of plant. The balance of plant converts heat into electricity via steam turbines; it is a conventional design area and in principle similar to any other power station that relies on heat generation, whether fusion, fission or fossil fuel based.

The nuclear island has a plasma chamber with an associated vacuum system, surrounded by plasma-facing components (first wall and divertor) maintaining the vacuum boundary and absorbing the thermal radiation coming from the plasma, itself surrounded by a "blanket" where the neutrons are absorbed to breed tritium and heat a working fluid that transfers the power to the balance of plant. If magnetic confinement is used, a magnet system is needed, and usually systems for heating and refueling the plasma and for driving current. In inertial confinement, a driver (laser or accelerator) and a focusing system are needed, as well as a mean for forming and positioning the pellets.

The plasma-facing material is any material used to construct the plasma-facing components, those components exposed to the plasma within which nuclear fusion occurs, and particularly the material used for the lining or first wall of the reactor vessel. The plasma facing components in energy producing fusion devices will experience 5-15 MW/m^2 surface heat flux under normal operation (steady-state) and off-normal energy deposition up to 1 MJ/m^2 within 0.1 to 1.0 ms.

Liquid Metal Technology for Nuclear Fusion Devices

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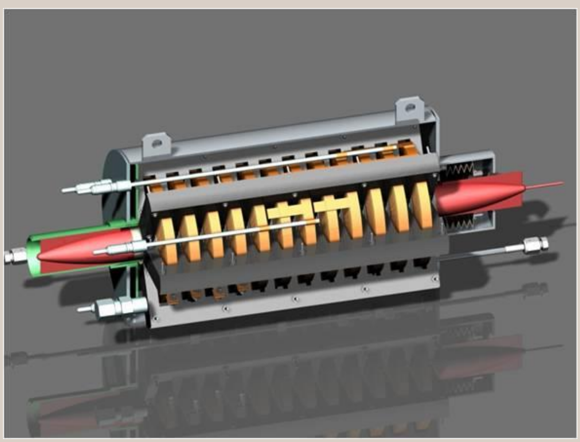
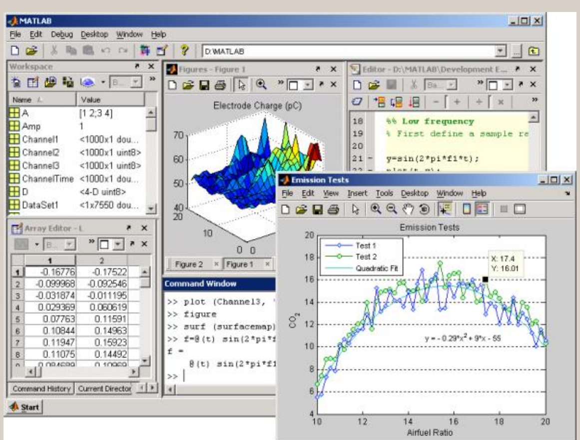
Refractory solid surfaces represent one type of plasma facing component option. Another option is to use a flowing liquid metal surface as a plasma facing component, an approach which will require the production and control of thin, fast flowing, renewable films of liquid metals such as lithium, gallium, or tin for particle control at diverters.





For the latter it is important to develop

1. Techniques for the production, control, and removal of flowing (velocity 0.01 to 10 m/s) liquid metal films (0.5-5 mm thick) over a temperature controlled substrate;
2. Techniques for active control of liquid metal flow and stabilization in the presence of plasma instabilities; and
3. Computational tools that model the flow and magnetohydrodynamic response of flowing liquid metals.

We aim to develop computational tools that model the flow and magnetohydrodynamic response of flowing liquid metals. We aim to investigate the effect of the time-varying electromagnetic field on an incompressible turbulent flow via direct numerical simulation and by using multi-physics analysis tools. We will upgrade CFD solvers for direct numerical simulation which solves the incompressible Navier-Stokes equations, on a staggered grid with second-order finite differencing in space and Adams–Bashforth stepping in time, to be able to compute a conducting fluid coupled with a magnetic field in arbitrary orthogonal coordinates and we can develop as well a low dimensional model of the flow for implementation of closed-loop flow control systems.

Liquid Metal Technology for Nuclear Fission Reactors

Liquid metal-cooled reactors are both moderated and cooled by a liquid metal solution. These reactors are typically very compact and can be used for regular electric power generation in isolated places, for fission surface power units for planetary exploration, for naval propulsion and as part of space nuclear propulsion systems. Certain models of liquid metal reactors are also being considered as part of the Generation-IV nuclear reactor program. The liquid metal thermo-magnetic systems used in this type of reactors are MHD devices which design, optimization and fabrication represents a challenge due to the coupling of the thermo-fluids and the electromagnetics phenomena, the environment of operation, the materials needed and the computational complexity involved. This challenge we aim to solve.

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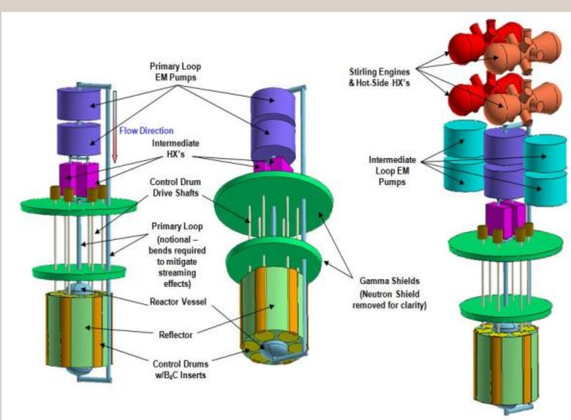
Liquid Metal Technology for Nuclear Fission Reactors

A liquid metal cooled nuclear reactor is a type of nuclear reactor, usually a fast neutron reactor, where the primary coolant is a liquid metal. While pressurized water could theoretically be used for a fast reactor, it tends to slow down neutrons and absorb them. This limits the amount of water that can be allowed to flow through the reactor core, and since fast reactors have a high power density most designs use molten metals instead. The boiling point of water is also much lower than most metals demanding that the cooling system be kept at high pressure to effectively cool the core. Another benefit of using liquid metals for cooling and heat transport is its inherent heat absorption capability.

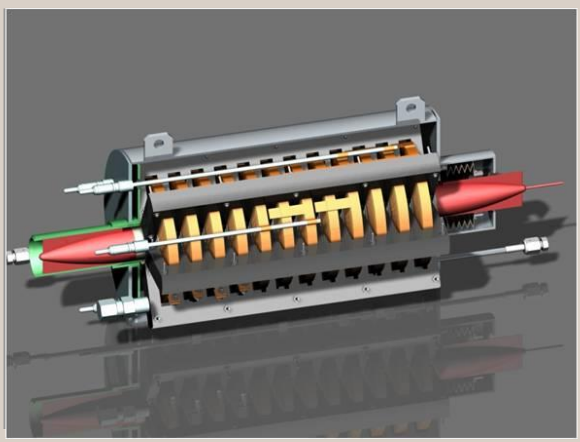


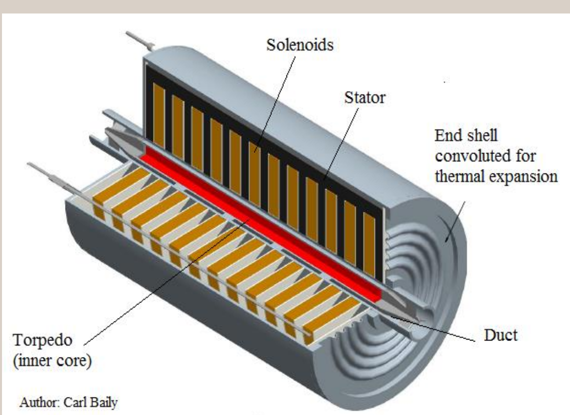
Liquid metals also have the property of being very corrosive and bearing, seal, and cavitation damage problems associated with impeller pumps in liquid-metal systems make them not an option and electromagnetic pumps are used instead. In all electromagnetic pumps, a body forced is produced on a conducting fluid by the interaction of an electric current and magnetic field in the fluid. This body force results in a pressure rise in the fluid as it passes from the inlet to the outlet of the pump.

In space reactors as well as in other types of semi-transportable small modular reactors, weight, reliability and efficiency are of fundamental importance. Furthermore, for the former liquid metals as working fluid are the only option due to the working environment characteristics that outer space provides. For space power systems, the induction electromagnetic pump, because it lacks electrodes, is inherently more reliable than the conduction electromagnetic pump. The annular linear induction pump, furthermore, has several advantages over its flat counterpart because it has greater structural integrity, is more adaptable to normal piping systems, and allows greater design freedom in the coil configuration. The annular design also has a basically greater output capability since the path followed by the induced currents has a lower resistance than the path followed in a corresponding flat pump.

Annular Linear Induction Pumps

The coupling between the electromagnetics and thermo-fluid mechanical phenomena observed in liquid metal thermo-magnetic systems for nuclear, space and industrial applications gives rise to complex engineering magnetohydrodynamics and numerical problems. It is known that electromagnetic pumps have a number of advantages over mechanical pumps: absence of moving parts, low noise and vibration level, simplicity of flow rate regulation, easy maintenance and so on. However, while developing a large-scale induction pump, in particular annular linear induction pumps (ALIPs), we are faced with a significant problem of magnetohydrodynamic instability arising in the device. The manifestation of the instability does not allow linear induction pump development in a certain range of flow rate or the development of high efficiencies under certain flow rates and dropping pressure conditions.





Linear induction pumps use a traveling magnetic field wave created by 3-phase currents, and the induced currents and their associated magnetic fields that generate a Lorentz force. The complex flow behavior in this type of devices includes a time-varying Lorentz force and pressure pulsation due to the time-varying electromagnetic fields and the induced convective currents that originates from the liquid metal flow, leading to instability problems along the device geometry. The determination of the geometry and of the electrical configuration of a thermo-magnetic device gives rise to an inverse magnetohydrodynamic field problem. When the requirements of the design are defined, this problem can be solved by an optimization technique. The objective function which has to be maximized in the optimization problem is derived from the main design requirement. Usually for a magnetohydrodynamic device, this is the efficiency. Other design requirements can be taken into account as constraints. For a non-linear system, such as for linear induction pumps, the main objective functions are low weight and high efficiency and so more than one maximum can exist. In this case a technique for the global optimization has to be used.

Before any optimization method can be used, design approaches should be identified and understood while mathematical and computational models developed. This leads to the study of magnetohydrodynamics instabilities, usually with negative effects on the efficiency and working fluid behavior, as well as to the study of its individual components, its fabrication methods, assembly and system integration procedures.

Annular Linear Induction Pumps

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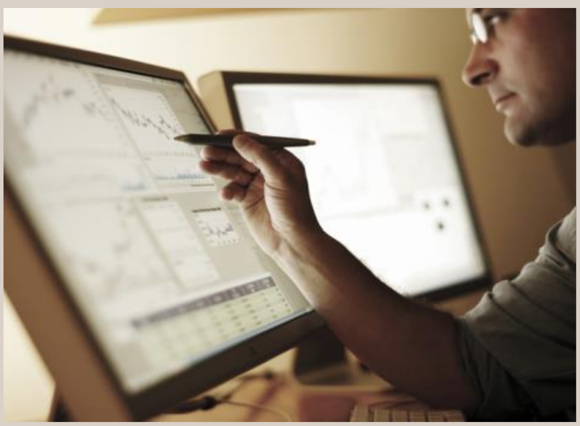
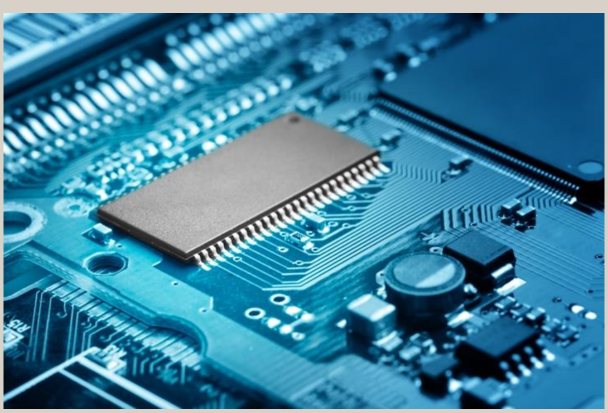
The design process and technology evaluation of thermo-magnetic systems, with emphasis in annular linear induction pumps, can be divided in four stages. The first stage is a basic study of the main electrical, mechanical and thermal parameters. The second stage is the development of a fully integrated model using theoretical, experimental and computational tools for the design and characterization of an ALIP system and its components. The third stage is the development of programming methods and procedures for the design and construction of optimized annular linear induction pumps. At the end of the third stage a test, or proof of concept, device can be built for benchmarking and performance evaluation. The fourth stage involves further study of the magnetohydrodynamic instabilities and the development of control systems for active flow control and machine protection.

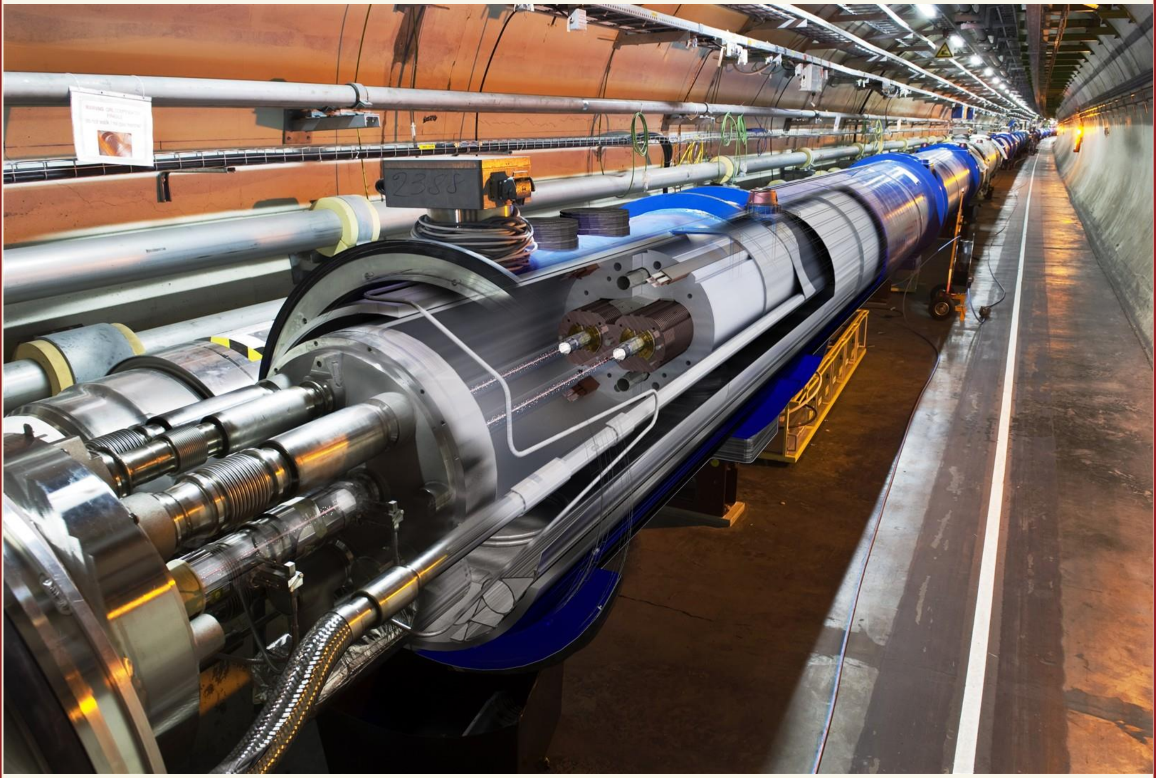




Closed-loop active flow control is the capability to estimate, efficiently alter and maintain a flow rate. Closed-loop flow control is by its nature a multidisciplinary problem involving experimental and computational fluid dynamics, low dimensional modeling, control law design, and sensors and actuators development.

A key to successful implementation of closed-loop flow control is the development of a simple flow model that can capture the essential dynamics of the flow. It is well known that fluid flow is governed by the Navier-Stokes equations, a set of highly non-linear partial differential equations. However, due to the infinite dimensionality, these equations are not very useful for feedback control purposes. To add more complications, a MHD flow is governed not only by the Navier-Stokes equations but also by the Maxwell equations of electromagnetism couple to the former. Therefore, a low dimensional model of the flow is essential for successfully implementing the closed-loop flow control.

We aim to design liquid metal thermo-magnetic systems with emphasis in annular linear induction pumps for fission reactors as well as computational tools for analysis and CAE design of electromagnetic pumps of the ALIP type including measurement and control systems for active flow control, diagnostics, operation and machine protection of the electrical and mechanical systems.

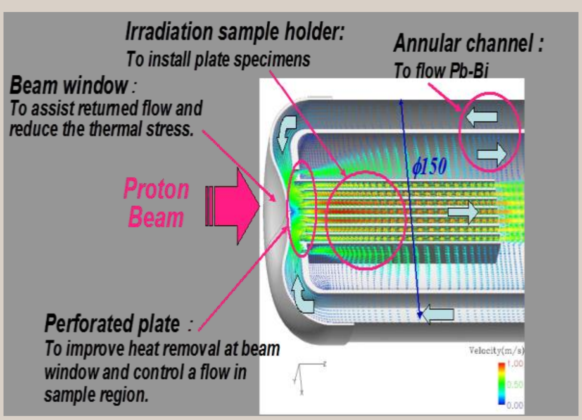


Liquid Metal Technology for High Energy Particle Accelerator Targets and Dumps

Liquid metal targets in particle accelerators are used for spallation purposes. Liquid metal dumps are used as a machine protection mechanism to stop a beam while absorbing and diluting the power stored in the particle beam. Liquid metal insertion devices are used in cooling rings to make the momentum distribution of particles more homogeneous, minimizing the lateral components. Liquid metal channels are used for thermal control of solid targets, accelerator components and experimental stations dealing with high density beams or radiation that could generate a high temperature gradient. We aim to design liquid metal thermomagnetic systems, to study the physical processes in place and the engineering needed on targets, dumps and thermal control and machine protection subsystems.

Liquid Metal Technology for High Energy Particle Accelerators Targets and Dumps

A particle accelerator is a machine that accelerates particles to extremely high energies. These particles are elementary particles or heavy ions. Beams of high-energy particles are useful for both fundamental and applied research in the sciences, and also in many technical and industrial fields unrelated to fundamental research. It has been estimated that there are approximately 26,000 accelerators worldwide. Of these, only about 1% are research machines with energies above 1 GeV, while about 44% are for radiotherapy, 41% for ion implantation, 9% for industrial processing and research, and 4% for biomedical and other low-energy research.



The largest particle accelerators with the highest particle energies, such as the Large Hadron Collider (LHC) at CERN, are used for experimental particle physics for the most basic inquiries into the dynamics and structure of matter, space, and time. These typically entail particle energies of many hundreds of GeV up to several TeV. Besides being of fundamental interest, high energy electrons may be coaxed into emitting extremely bright and coherent beams of high energy photons via synchrotron radiation, which have numerous uses in the study of atomic structure, chemistry, condensed matter physics, biology, and technology. Examples include the ESRF, which has recently been used to extract detailed 3-dimensional images of insects trapped in amber. Thus there is a great demand for electron accelerators of moderate (GeV) energy and high intensity.

For the highest power densities, it is widely expected that many facilities will need to employ liquid metal targets and beam dumps for spallation and for heat removal (passive machine protection). A common problem encountered when using liquids is shock wave generation due to heat deposition resulting from a powerful pulsed beam. The severe constraints arising from a megawatt beam deposited on targets and absorbers will require complex procedures to dilute the beam. Liquid metals, due to their heat capacity and density, are excellent materials to heat removal and spallation.

We aim to design electromagnetic pumps that are required to transport these liquid metals and the heat generated by beam deposition as well as to study the physical processes in place and the engineering needed on targets, dumps and related thermal control and machine protection subsystems.

Thailand mailing address
88/27 Moo 2 Mahidol Rd.
T. Padad, A. Muang
50200 Chiang Mai
Thailand

Tel: +66 8 30033910

France mailing address
34, avenue des Frères Montgolfier
Swiss Post Box: 102197
FR - 69680 Chassieu
France

Tel: +33 (0)970-445546

United States mailing address
2885 Sanford Ave SW #25601
Grandville, MI 49418
United States of America

Tel: +1-208-904-0401
Fax: +1-208-545-5800

Switzerland mailing address
Quai du Montblanc 33
Swiss Post Box: 102197
CH - 1201 Geneva
Switzerland

Tel: +41 (0)22 575 4488
Fax: +41-22-580-2227

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D-U-N-S # 079109504 • US SBC # 000412360 • EU PIC # 952466766 • Swiss Registry CH-660.3.046.012-0
info@maidana-research.ch • www.maidana-research.com