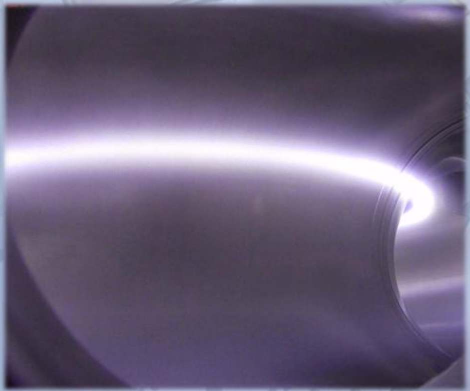
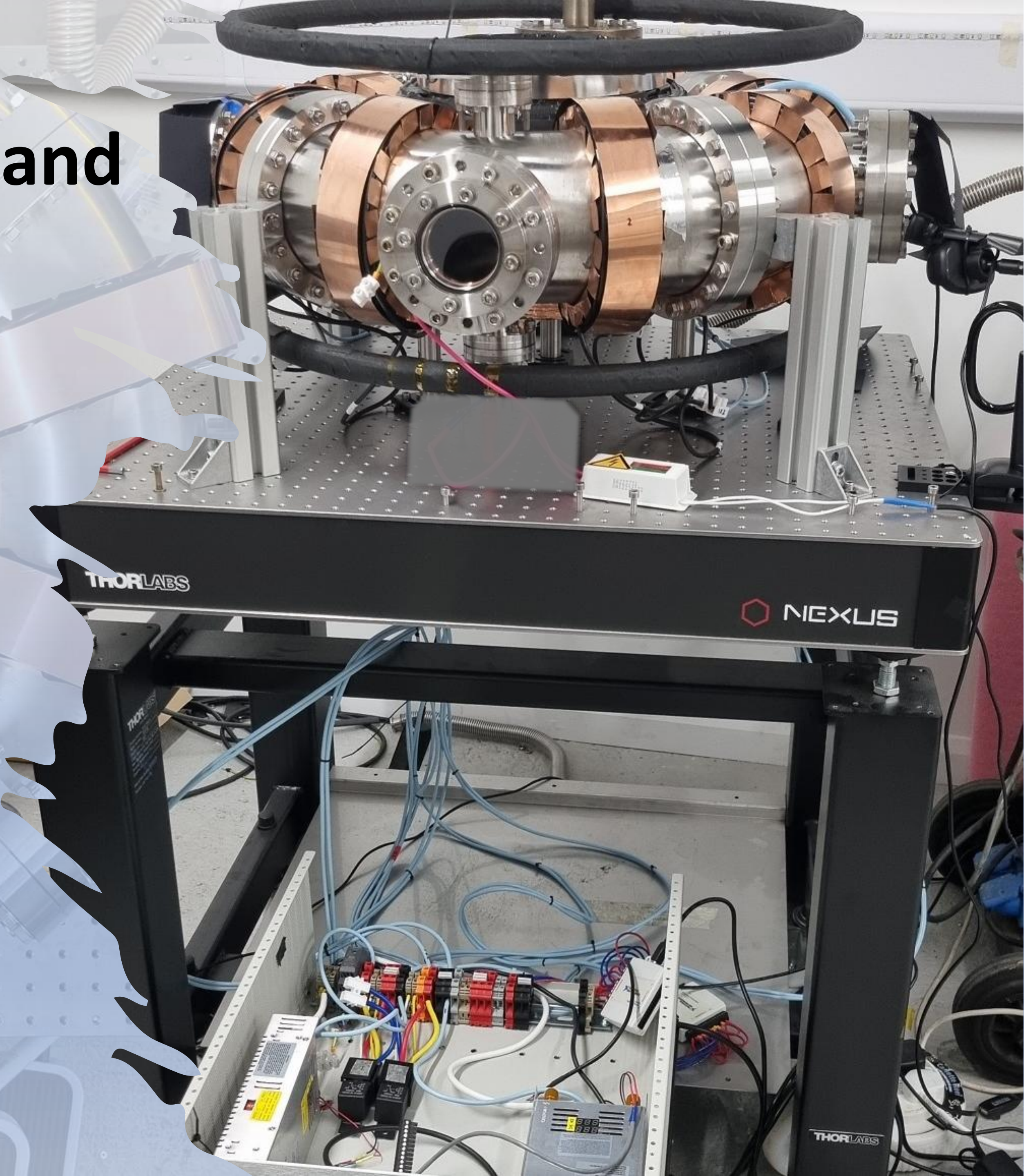
The Minimak. Design, Build and Operation.

Dr Paul Apte

Rideo Systems Ltd





BACKGROUND

Paul Apte

Has over 35 years of laser system experience. He has worked for British Telecom research (Martlesham Heath) and the Rutherford Appleton laboratory (Vulcan Laser facility)

As a founding engineer with the first STFC spin out company Exitech Ltd, he was involved in many high-profile Industrial projects including the development Deep UV Lithography and laser micromachining systems. His current interests include Digital Holography and medical device processing.

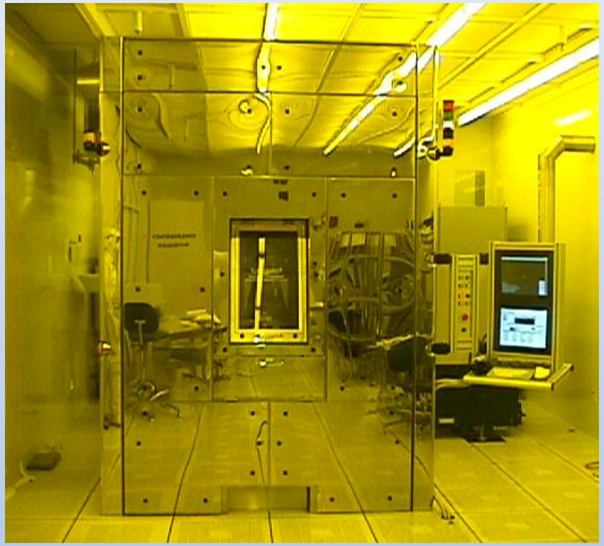
He holds a BSc in Electronics and Physics and PhD in Applied Physics from Loughborough University.

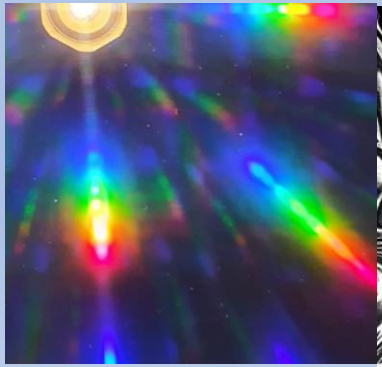
BACKGROUND - MACHINE BUILDING

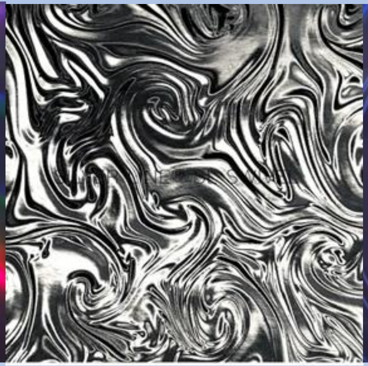
Laser Microvia drilling

Solar cell scribing

DUV Lithography



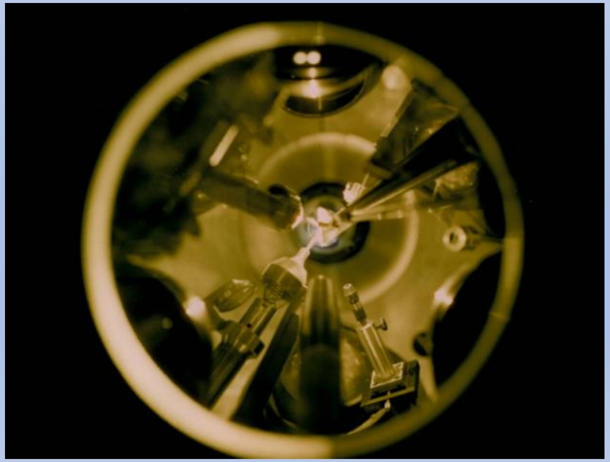


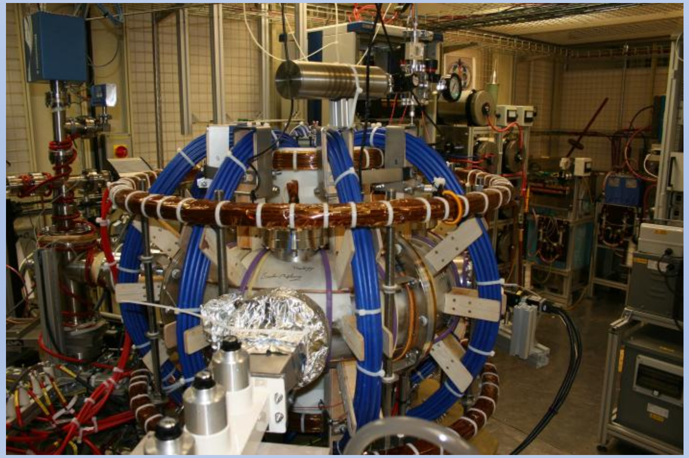


Digital Holography

BACKGROUND - FUSION RESEARCH

RAL VULCAN LASER TARGET AREA 1986





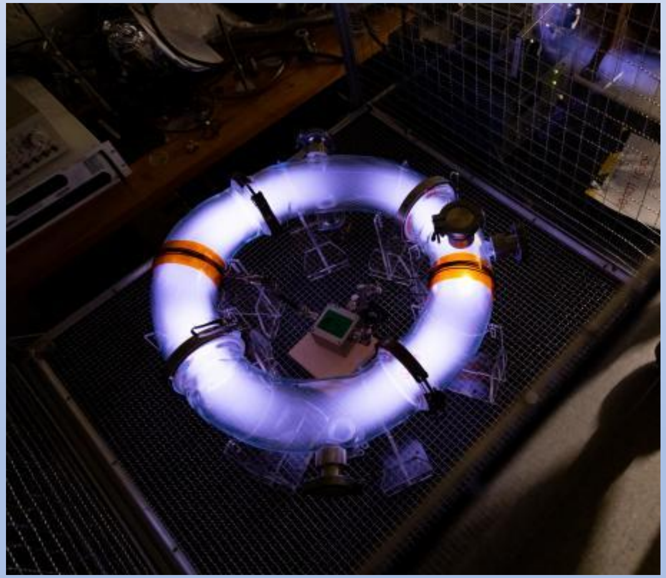
Courtesy Tokamak Energy

TOKAMAK ENERGY ST 25 Cu AND HTS 2014

INTRODUCTION - PURPOSE WHY?

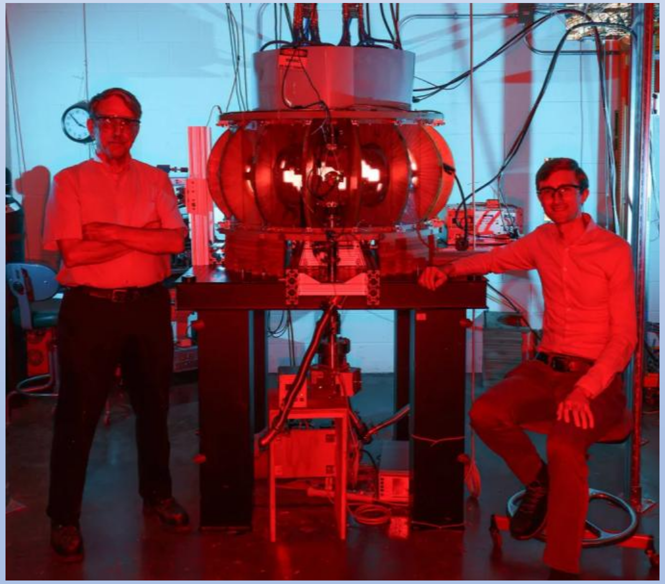
Demonstration for STEM students and public exhibitions
Bridge the gap between a plasma discharge tube and a Tokamak device.
Fun to play and experiment with !

MIT Altator-1 April 2024



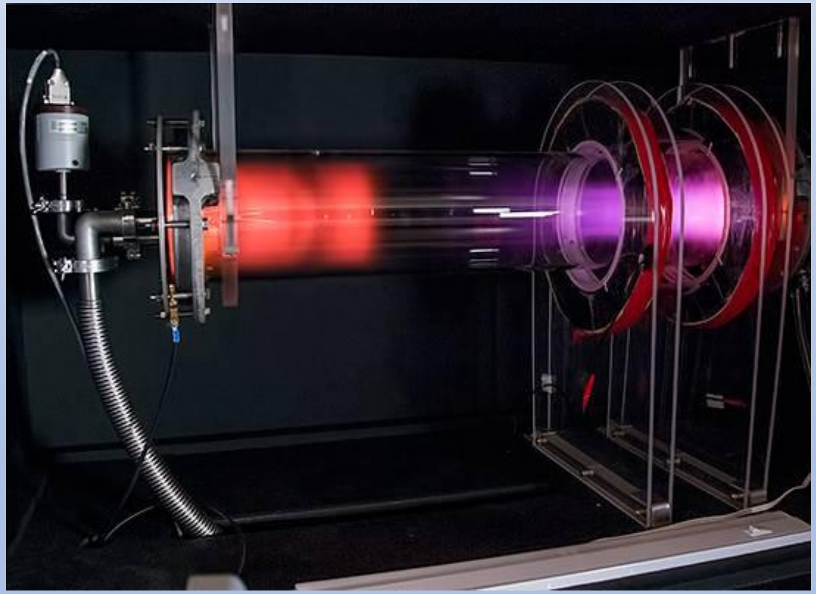
Courtesy MIT

Princeton MUSE 2024



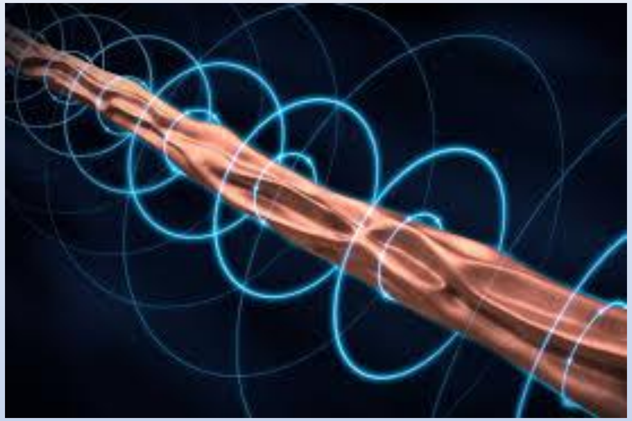
Courtesy PPPL

Princeton RGDX 2014

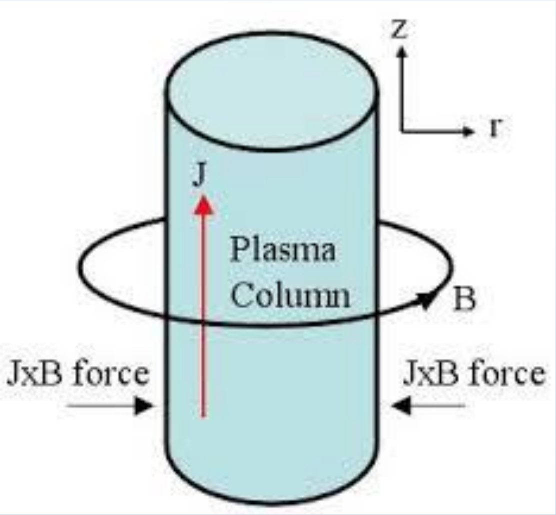


Courtesy PPPL

INTRODUCTION – Z PINCH



Z PINCH EFFECT



LORENZ FORCE

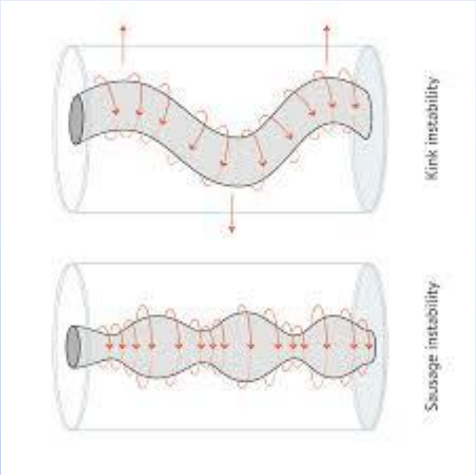
1000 uF HV CAP BANKS

5kV
5000 uF =
100kA for 500 us
into 0.05 Ohms

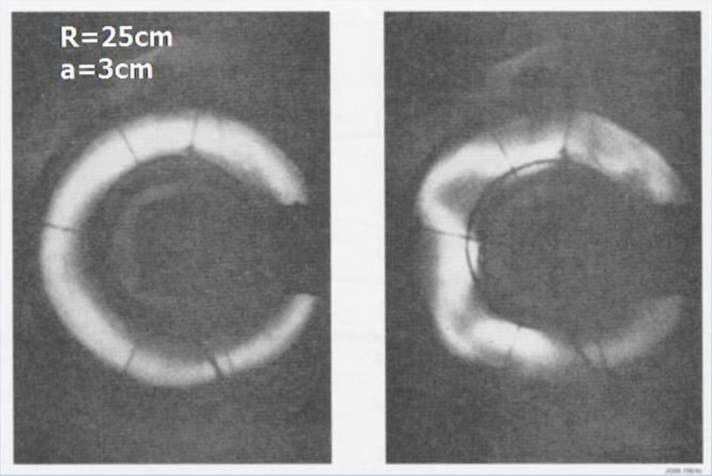
The Bennet relation describing the relation between plasma pressure vs magnetic pressure in a Z pinch (Lorenz force) Calculated that to reach 100Kev (100 million deg, DT Fusion temp) with 10^15 cm^3 density in a cylinder of 1 cm^2 cross section would need only **100 kA of current**.

Hence great excitement to build pinches and create controlled nuclear Fusion

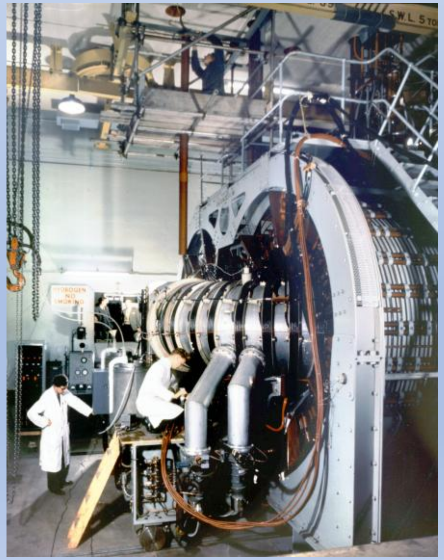
INTRODUCTION – Z PINCH INSTABILITY



KINK INSTABILITY



PLASMA INSTABILITY

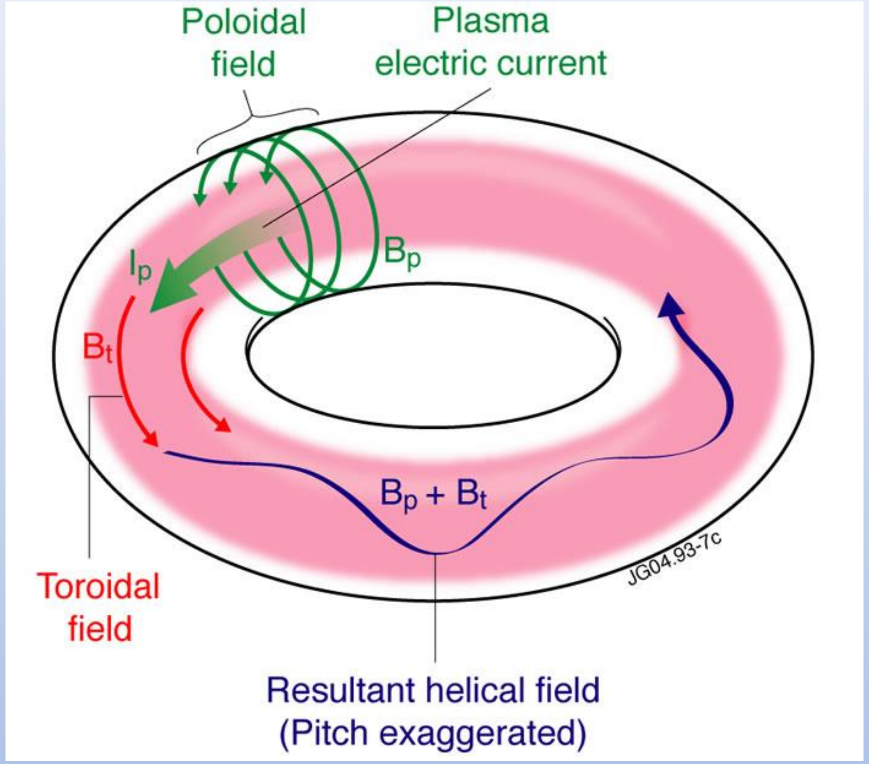


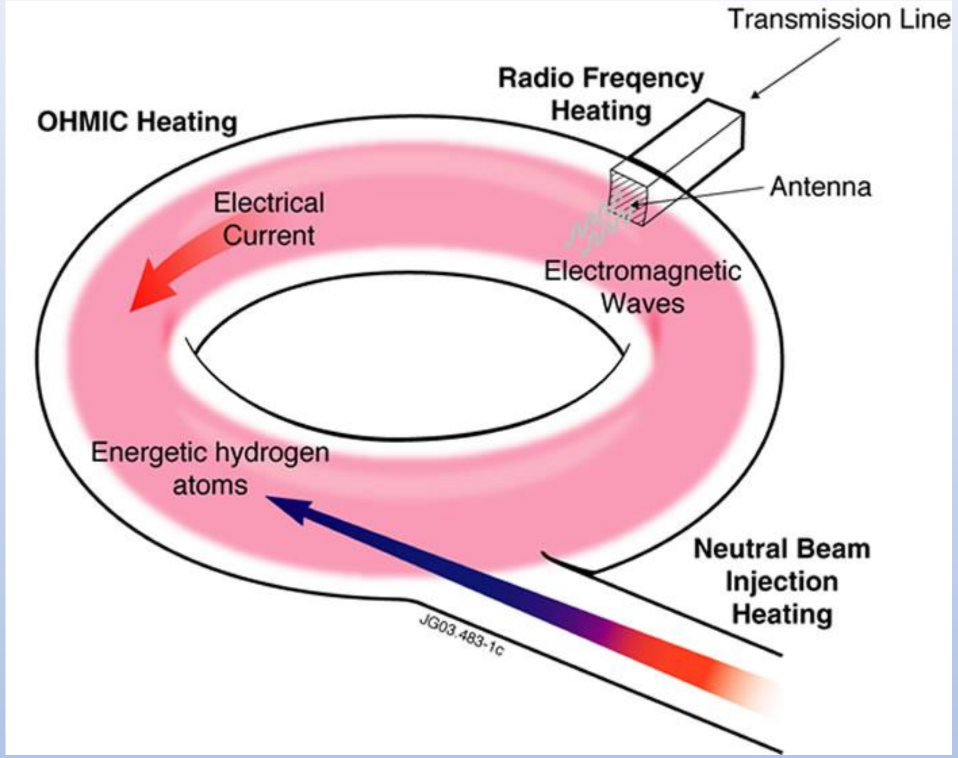
ZETA MACHINE 1950's

HOWEVER, IT DIDN'T WORK !

Kink Instability > lack of confinement > Radiative losses by electrons and ions> drift.
Lead to the development of machines like Zeta- Stabilised pinches
Hence alternative "stabilised" concepts such as the TOKAMAK
The large devices regularly achieve > 1MA Toroidal plasma currents

INTRODUCTION - THE TOKAMAK



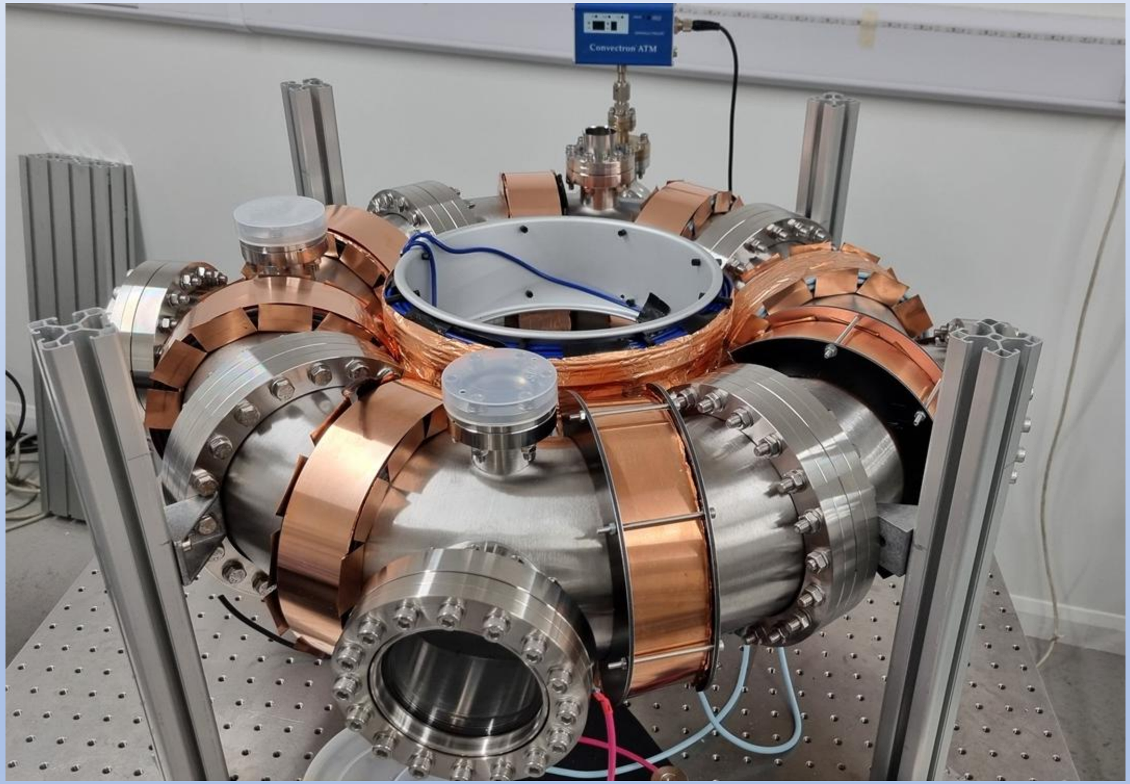


Toroidal and Poloidal magnetic fields compress and contain the plasma within a circular vacuum chamber

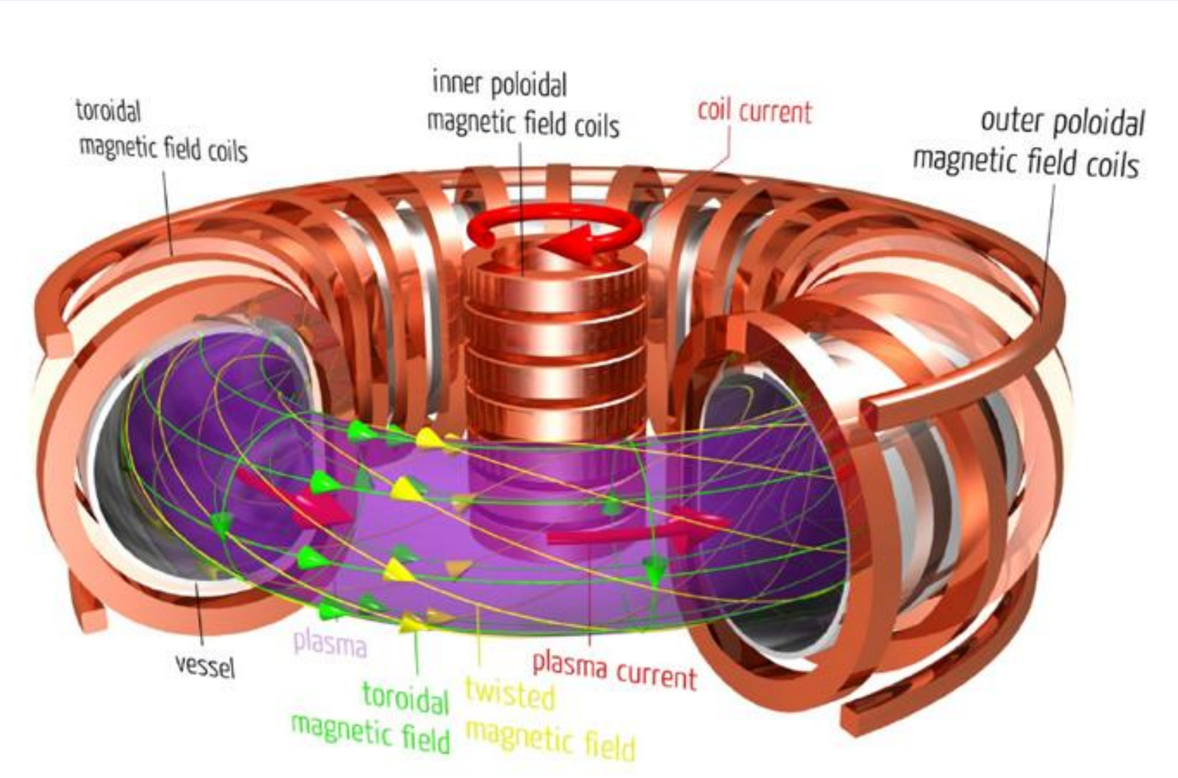
Microwaves and particle beams used to heat the plasma to fusion temperatures

INTRODUCTION - THE TOKAMAK

MINIMAK ARCHITECTURE



TOKAMAK ARCHITECURE



INTRODUCTION - CONCEPT

According to Physlink.com there are at least 1640 University departments in the world. Of these over 600 are in the USA and 200 in Europe, at least 500 are in the developing world.

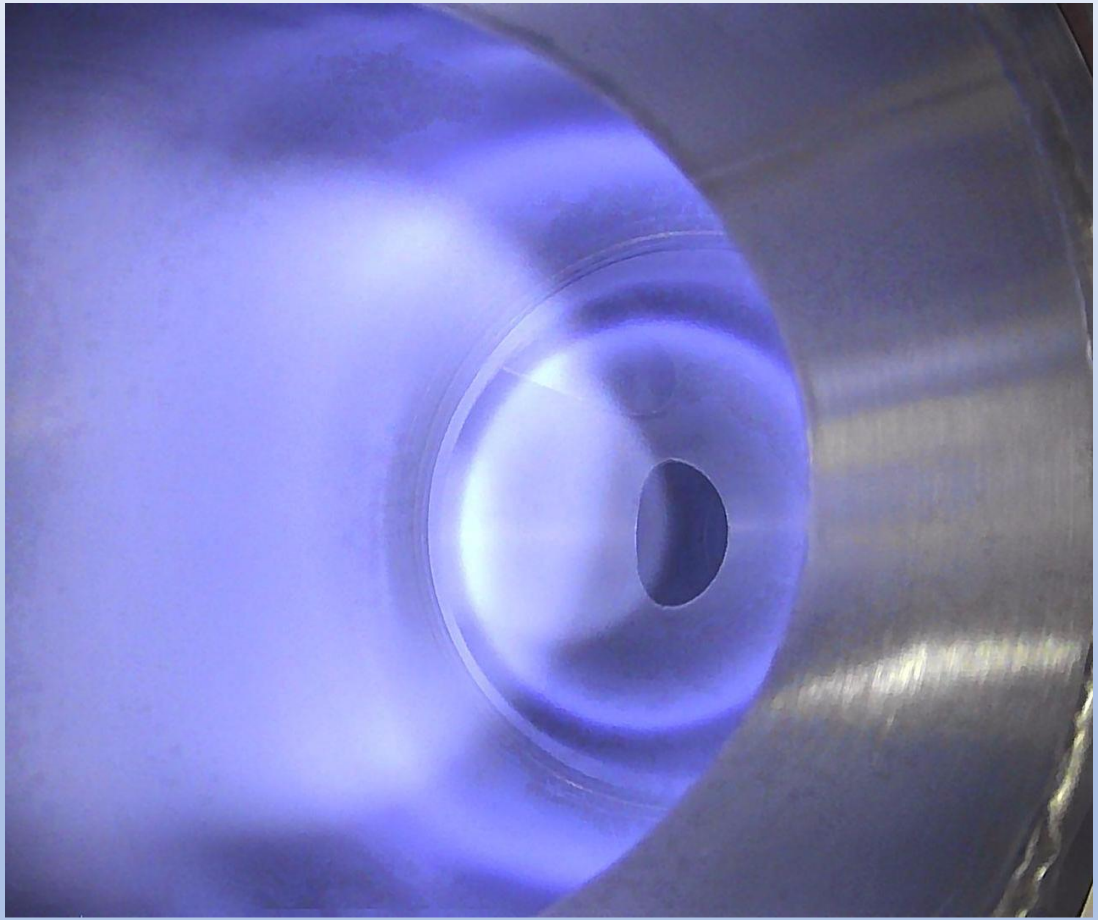
Build a Tokamak like demonstration device showing plasma physics in action, suitable for public demonstrations.

Ideal for undergraduate and graduate teaching.

Post graduate research and Instrumentation development

Cost effective and accessible to developing world universities and institutes.

Modular, Upgradeable performance



INTRODUCTION – TEACHING,TRAINING AND RESEARCH

Vacuum systems and Gas Handling

Magnet technology

Power supplies & HV

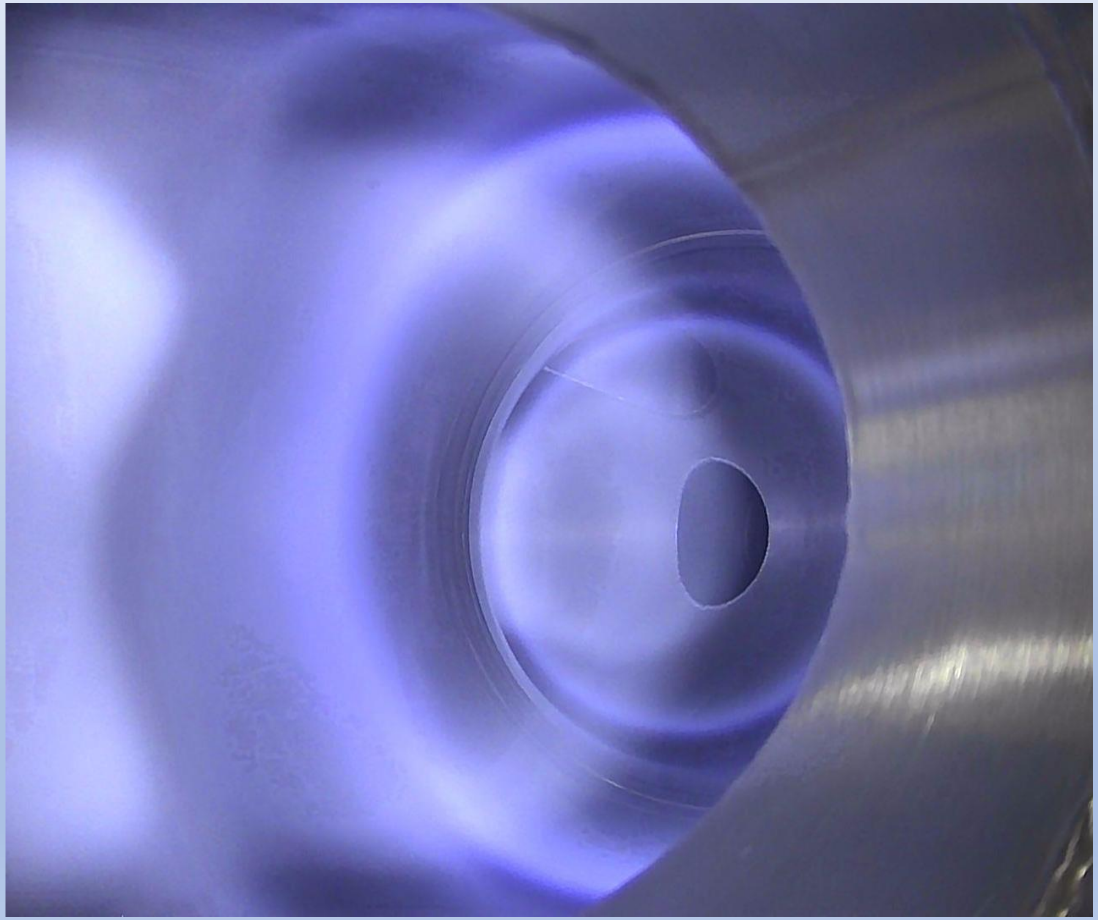
Data Acquisition ,Control systems and software

Plasma & Tokamak Physics

Simulation, Digital twinning, AI control

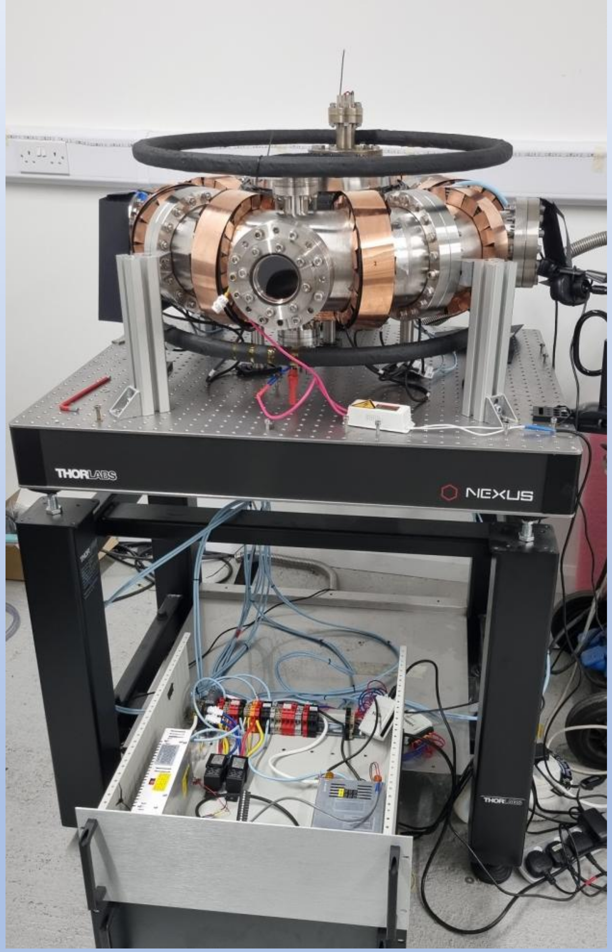
Materials science and Engineering

Safety regulations and compliance



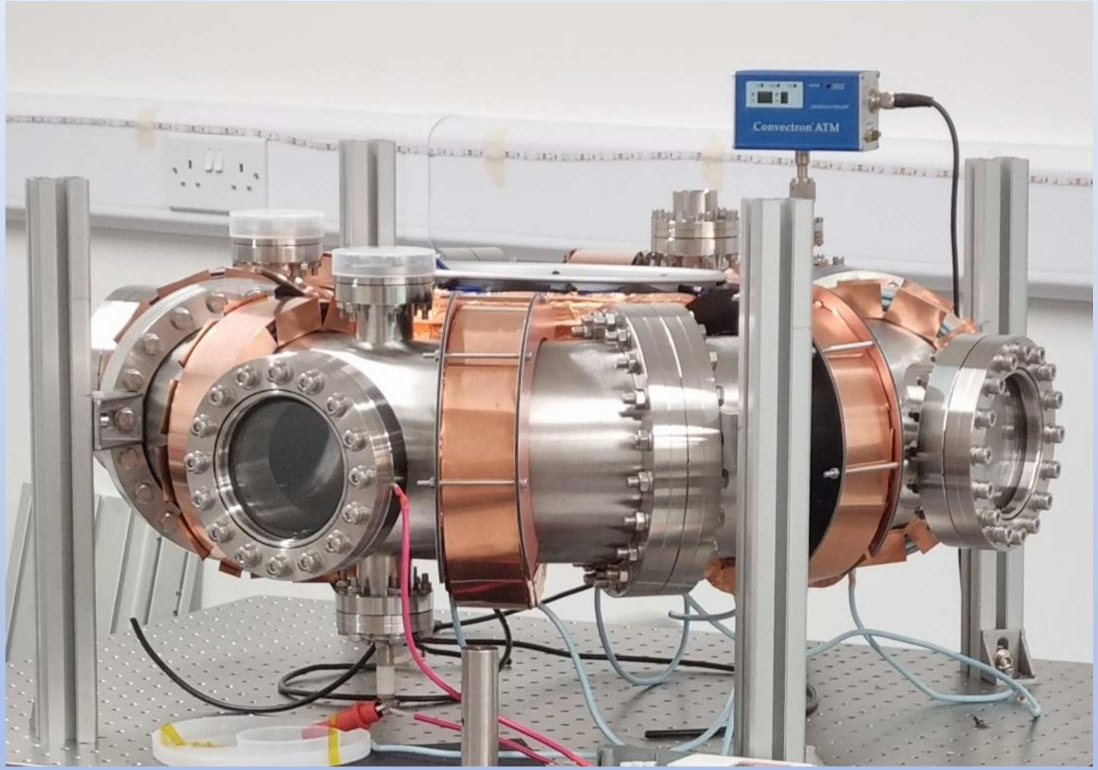
IMPLEMENTATION - SPECIFICATION

- **Simple Magnetized Torus Compact demonstration device, continuous operation. Low temperature plasmas**
- **Self contained within a 90 x 90 cm envelope**
- **Major Radius 23 cm Minor Radius 7.5 cm**
- **8 TF Coils each with independent power supplies**
- **Toroidal field of 0.025 Tesla CW. Up to 0.1T pulsed.**
- **4 Poloidal field coils , each with independent control**
- **Solenoid with variable configurations**



IMPLEMENTATION - SPECIFICATION

- **Low voltage solenoid with DC drive**
- **HV Glow discharge plasma**
- **Vacuum pressure monitoring and control**
- **Camera with vision-based tracking of plasma position and shape**
- **Spectrometer and plasma diagnostics**
- **Modular, Upgradeable performance to suit undergraduate and post graduate teaching. Demonstration of E x B, J x B, Cross field and Plasma Instability effects**



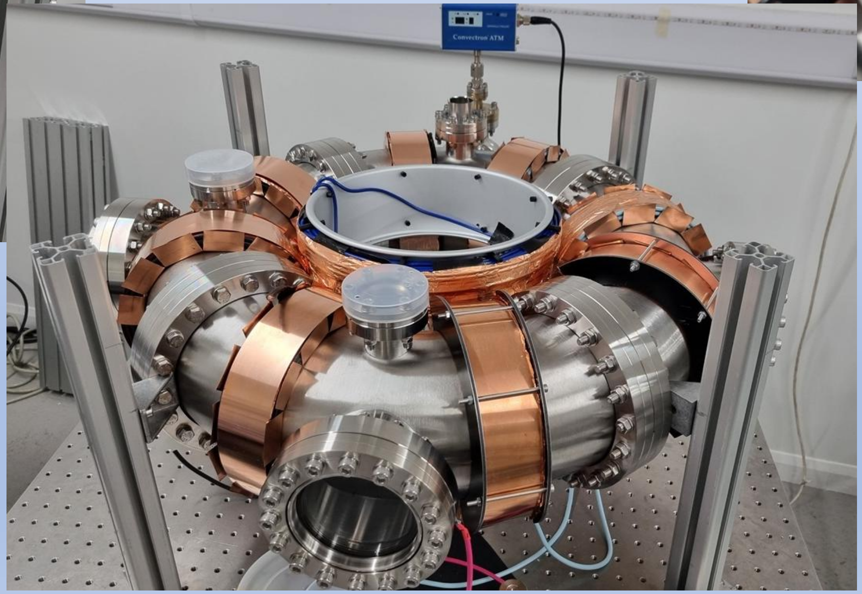
ASSEMBLY –VACUUM CHAMBER

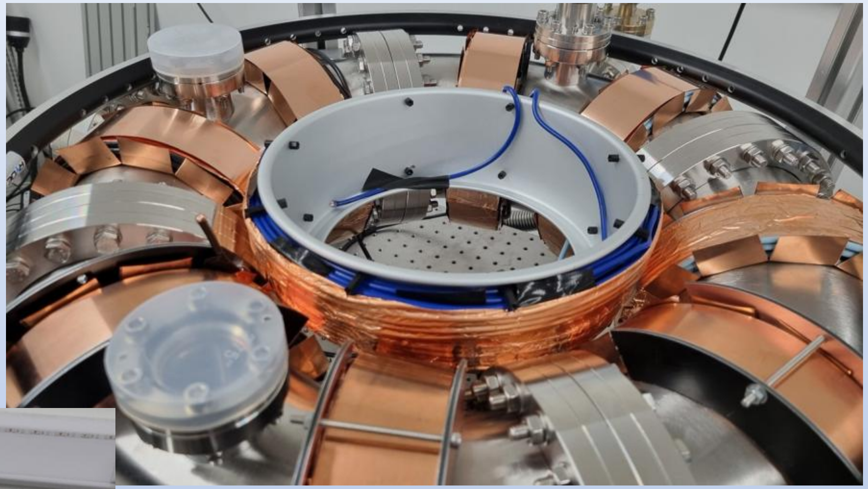
TIG Welded

(Tungsten Inert Gas)

ConFlat seals. Vacuum pressure tested to 10^{-9} mbar (UHV)

ASSEMBLY– MAGNET WINDING

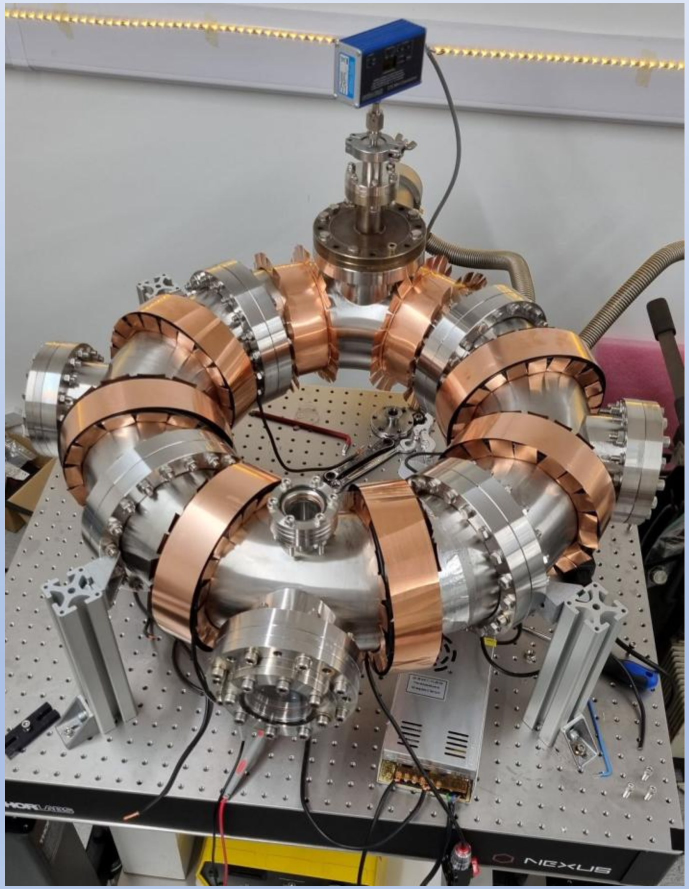




The 8 Toroidal field (TF) Coils are wound directly onto Copper formers mounted directly on the vacuum chamber

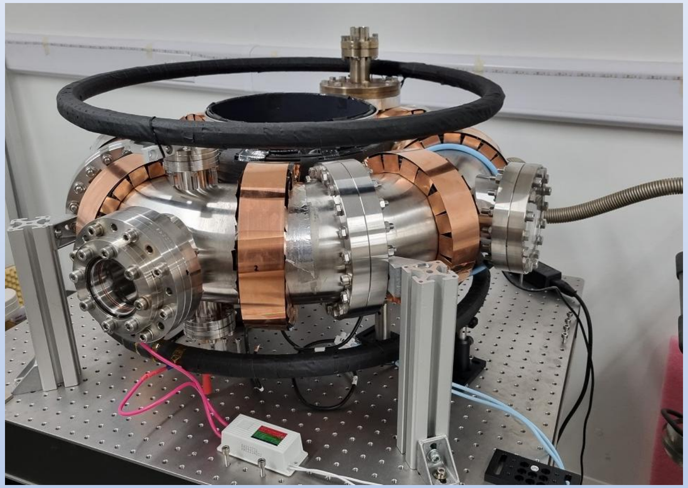
The top and bottom Poloidal Coils (PF) are wound onto metal formers mounted above and below the vacuum chamber together with two larger satellite PF coils

ASSEMBLY– VACUUM SYSTEM



Power supply testing of TF coils

Rotary vane
Vacuum pump



Glow discharge testing with a Nitrogen plasma

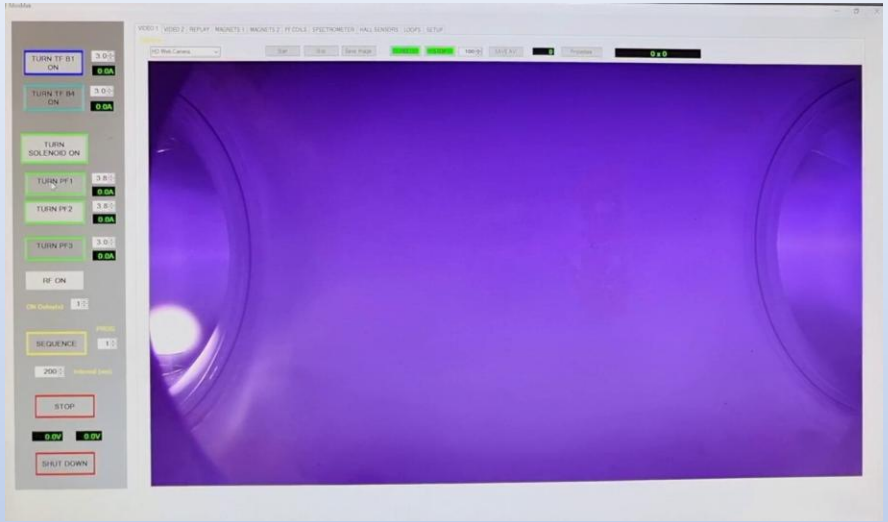
Vacuum pressure gauge

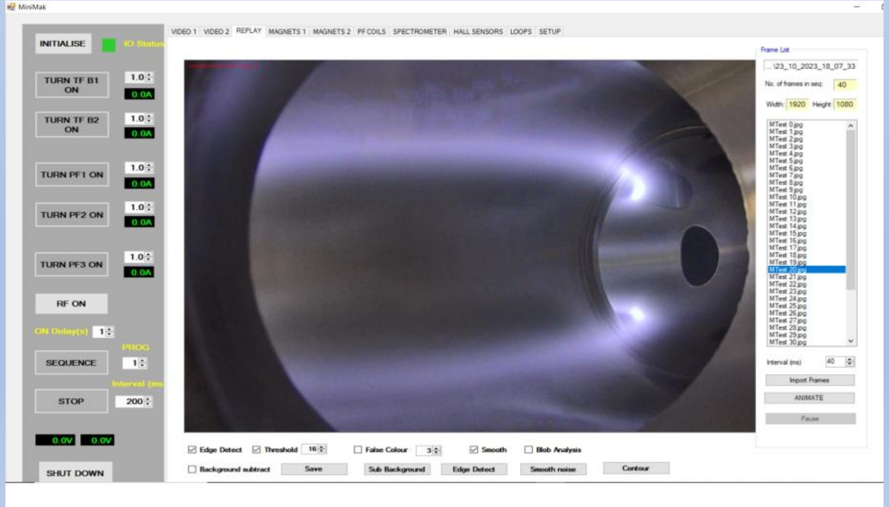
BUILD – CONTROL SYSTEM & DIAGNOSTICS

- **Independent low voltage variable power supplies for continuous coil drive up to 40A per coil**
- **Pulsed glow discharge power supplies 4kV**
- **DC Solenoid drive**
- **PLC based safety monitor**
- **Video & Webcam interface**
- **Wide band spectrometer**
- **PC based and networked digital I/O and DAQ**

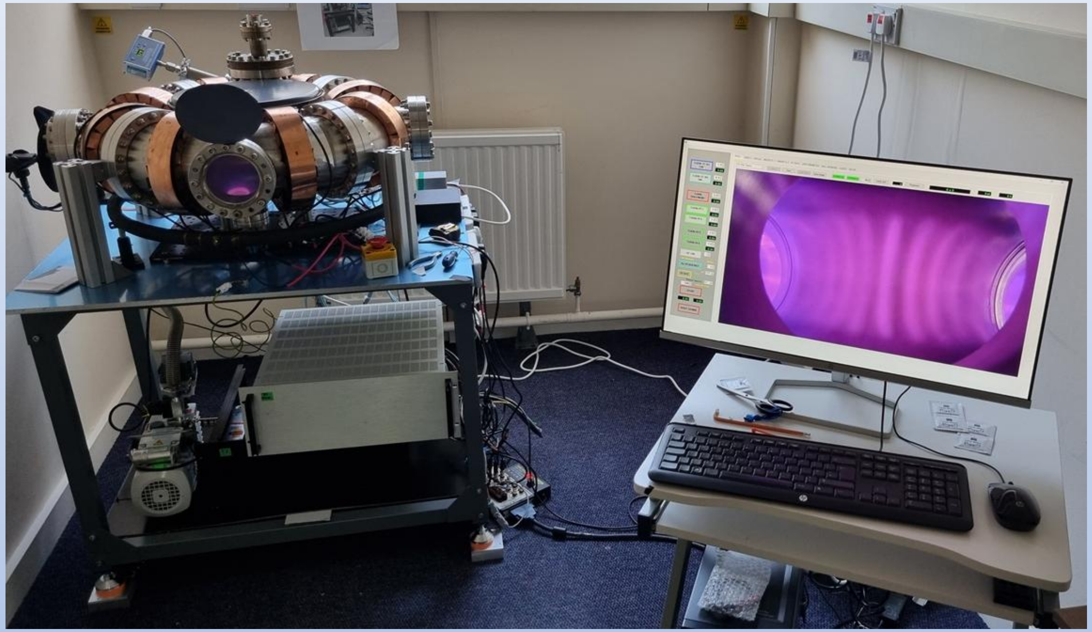
BUILD – SOFTWARE INTERFACE

- **User interface coded in .NET**
- **Option for LabView with networked real time control**
- **Real time video image processing**
- **High speed Data acquisition, Spectral analysis**
- **PLC control of interlock and safety systems**
- **Arduino and RasPI controller support**
- **Python and Matlab integration**

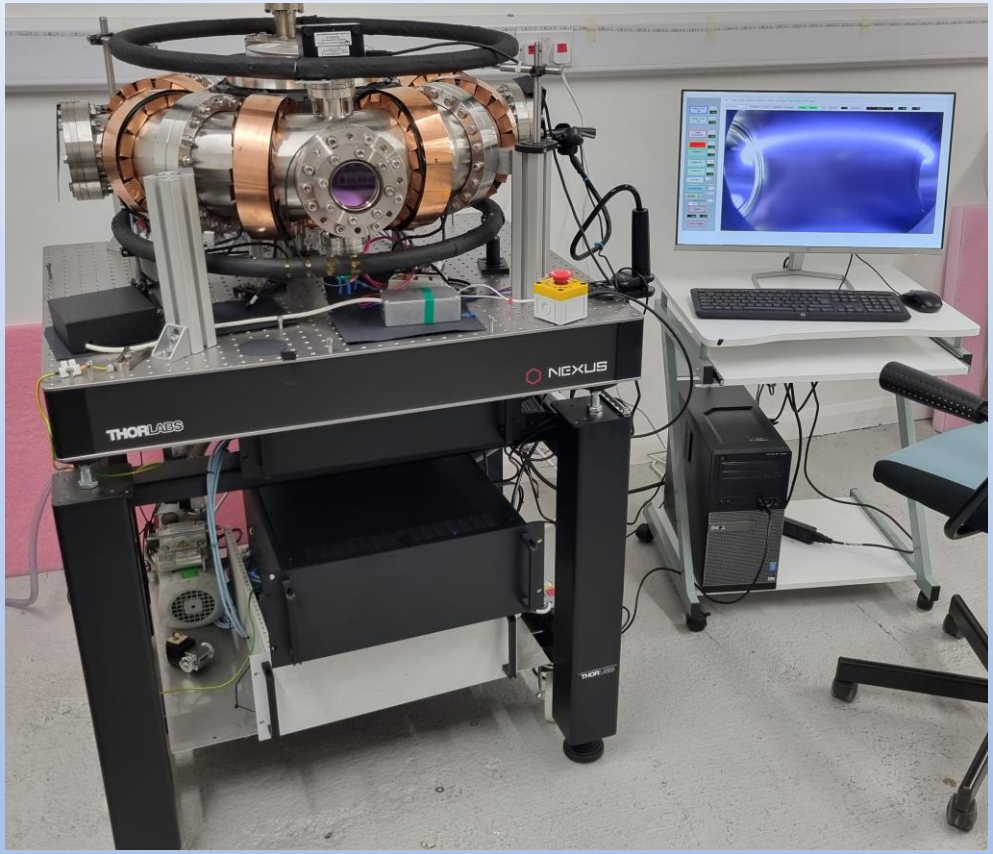




BUILD – COMPLETE SYSTEM

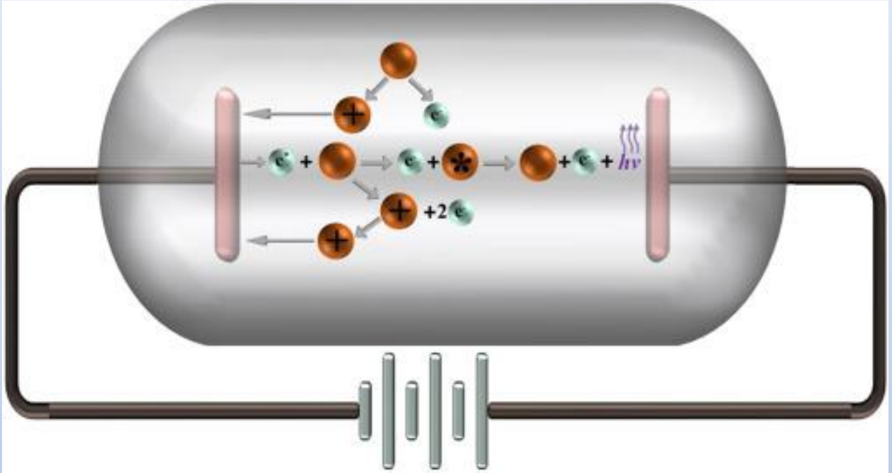


The complete Minimak system running at the Culham Innovation Centre, ready for demonstrations.



Final Test at our laser lab clean room facility on Milton Park

PLASMAS IN ELECTRIC FIELDS - GLOW DISCHARGE



Courtesy Science Direct

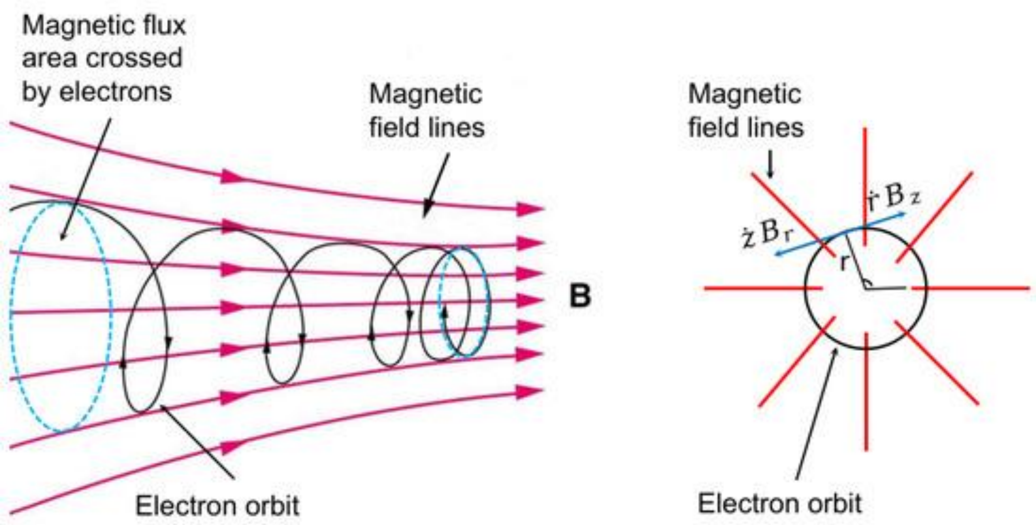
ANODE ELECTRODE

CHAMBER CATHODE

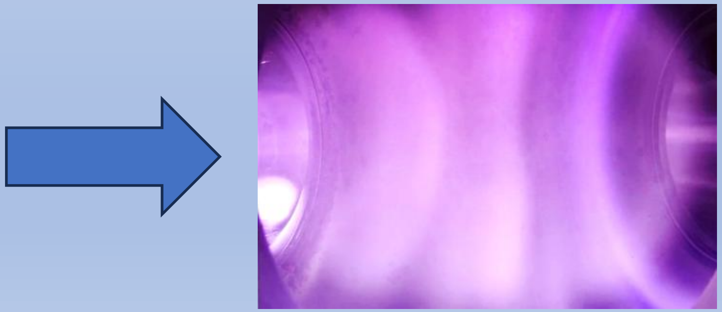
A non-thermal plasma formed by passing a direct current (DC) voltage between two electrodes in a low-pressure gas, creating a luminous glow. This ionization process produces photons, ions, and excited molecules, which cause the gas to emit a characteristic light.

The <u>low temperature r</u>ecombination of ions and electrons produces visible photons.

PLASMAS IN MAGNETIC FIELDS



CHAMBER GLOW



PLASMA STRIATIONS

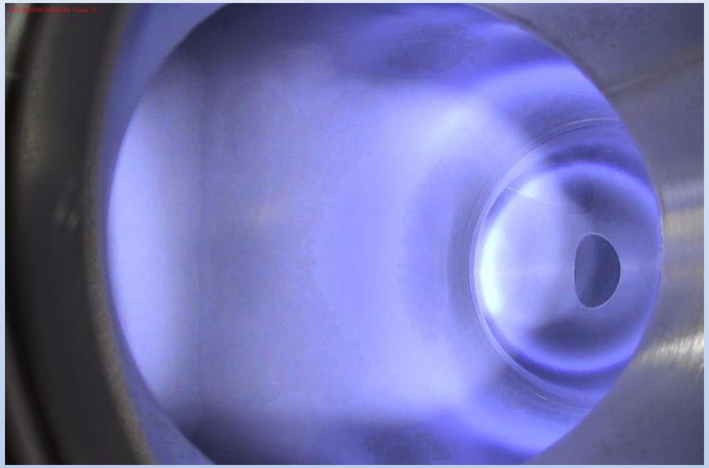
Effect of a magnetic field on the glow discharge
Applying an external magnetic field has a profound effect on the behaviour of charged particles within the glow discharge, leading to a much brighter bremsstrahlung glow.

Bremsstrahlung mechanism: Bremsstrahlung, German for "braking radiation”

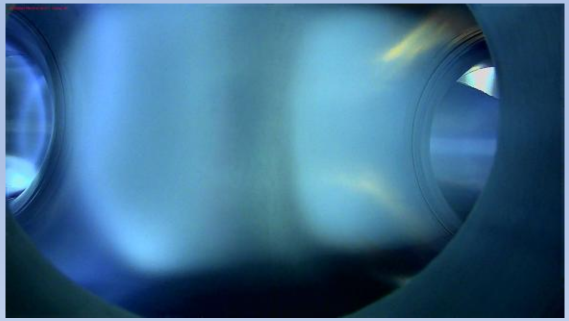
Enhanced confinement, Intensified light emission, Plasma structure

DEMONSTRATION PLASMA

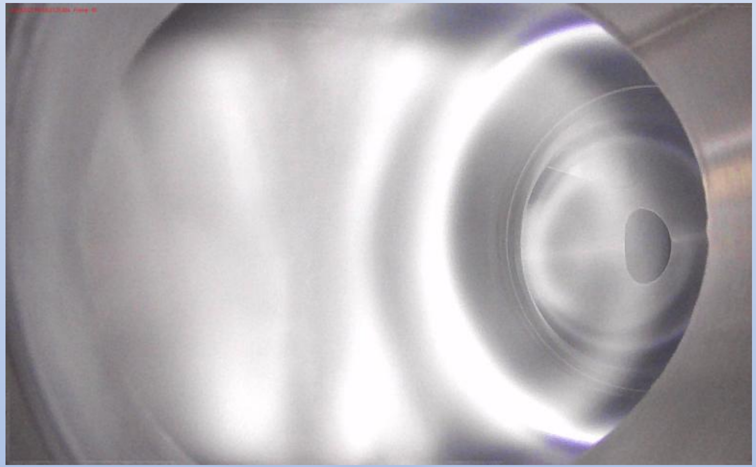
Glow discharge demonstration in a Toroidal magnetic field



PF 1&2 5mT

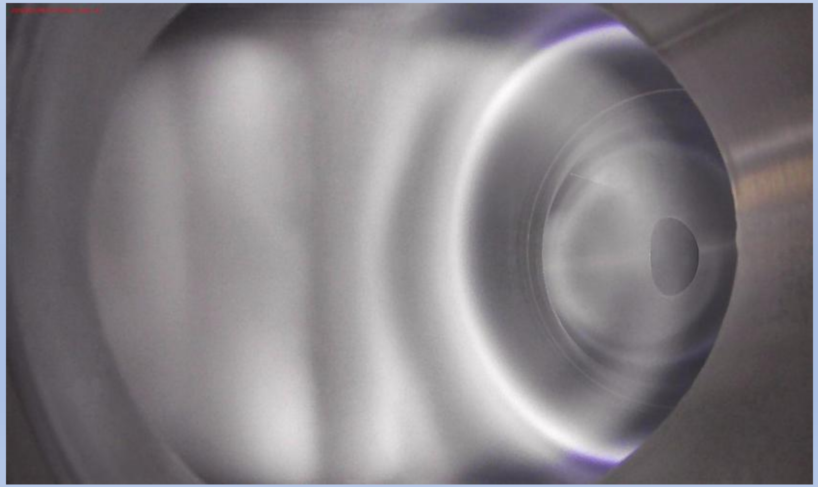


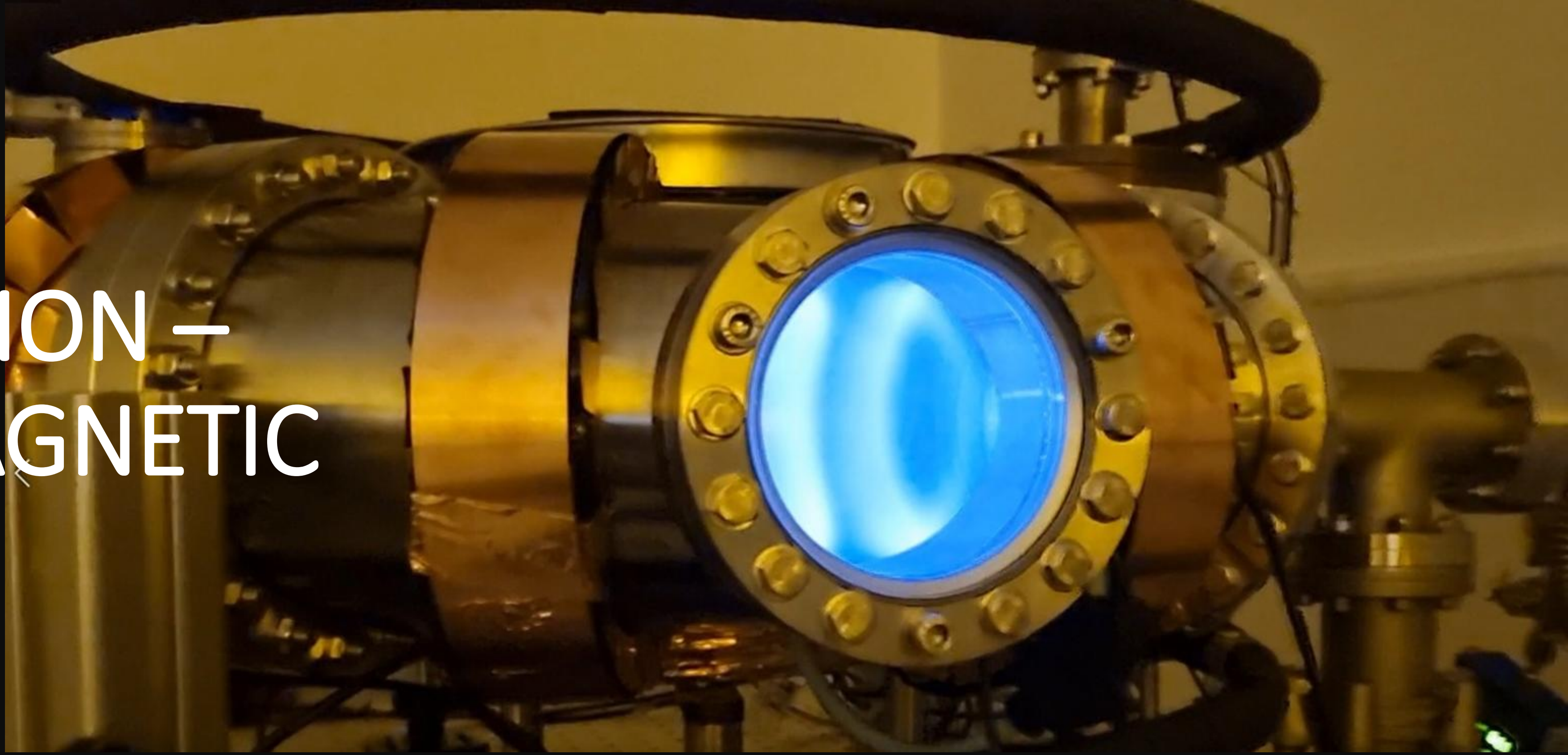
Plasma Striations in a Cross field



TF 5-8 20 mT

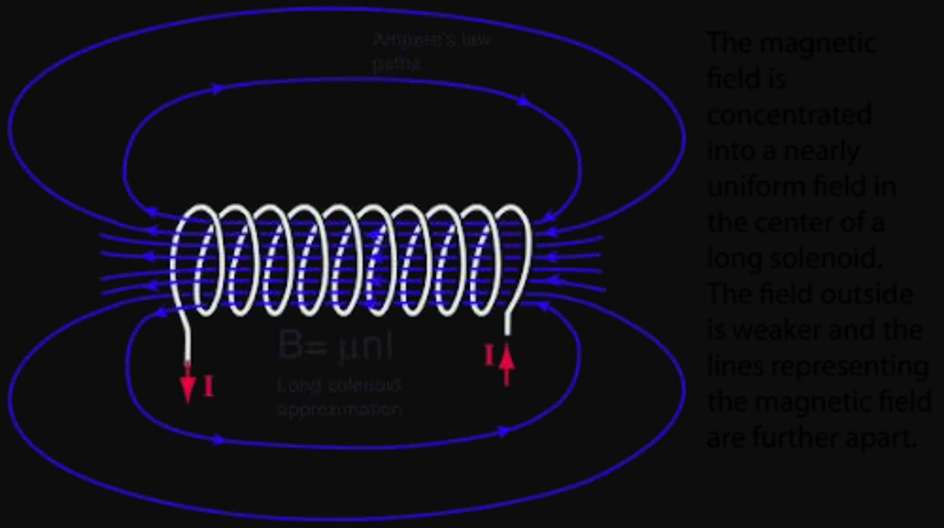
TF 5-8 15mT





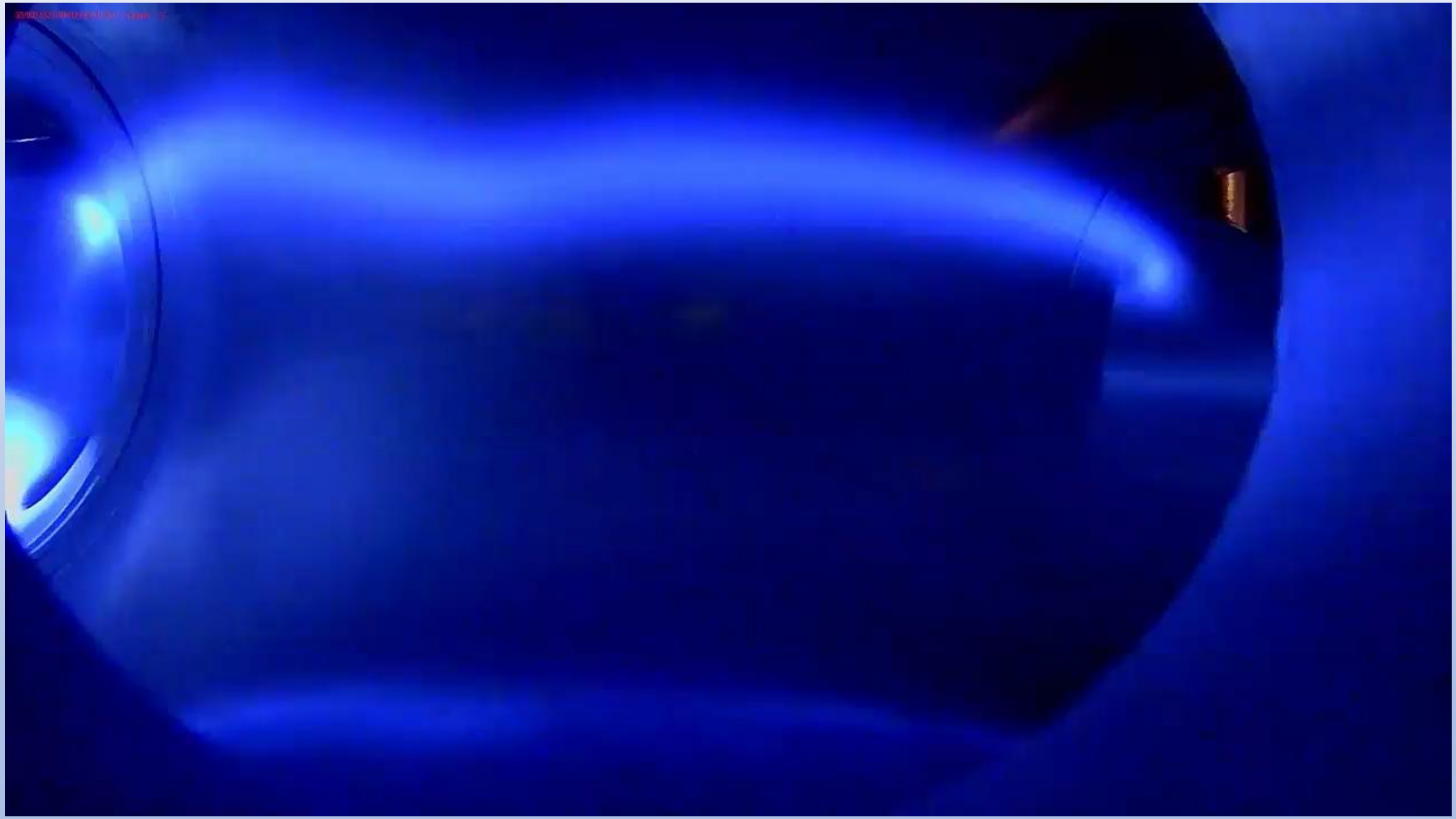
DEMONSTRATION – SOLENOID MAGNETIC FIELD

Modulating Plasma intensity and structure by varying the current in the Toroidal field coils.



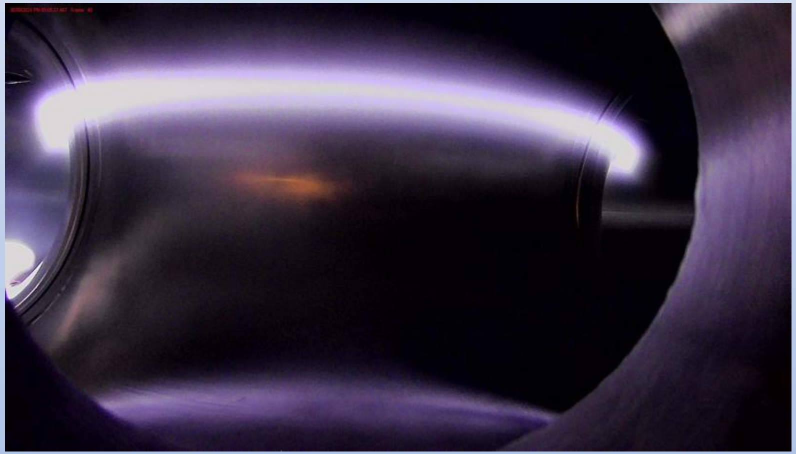
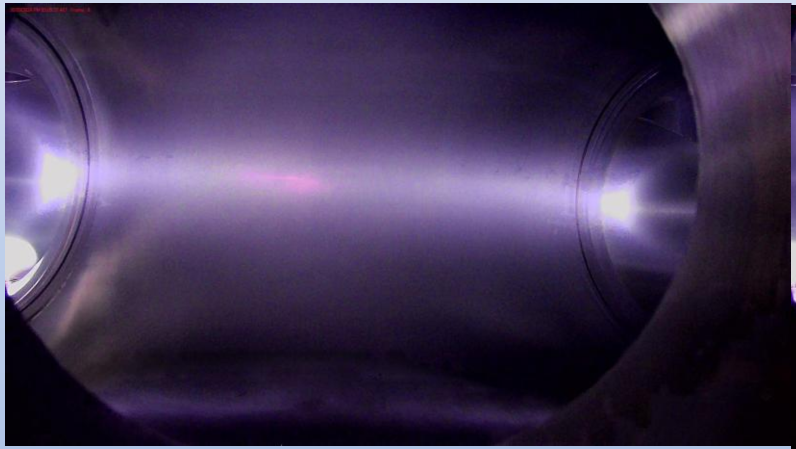
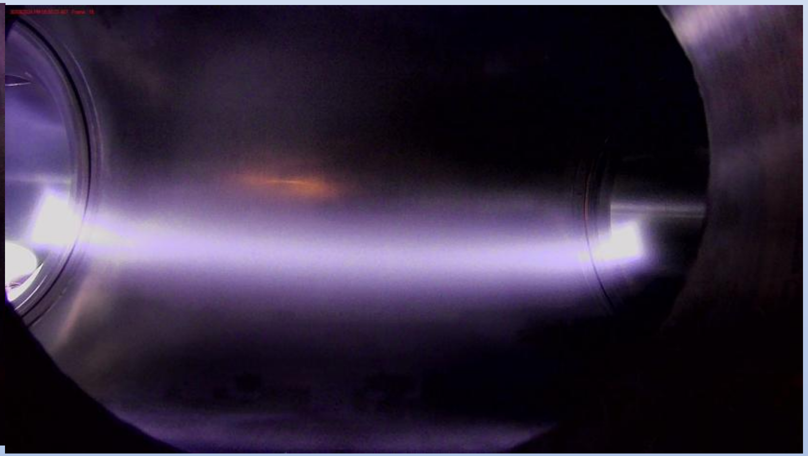
OPERATION – PLASMA VIDEO

- Dipole plasma position control
- Varying Poloidal Field
- Low level of Toroidal field

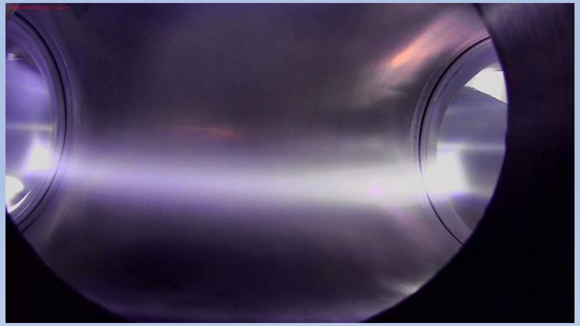
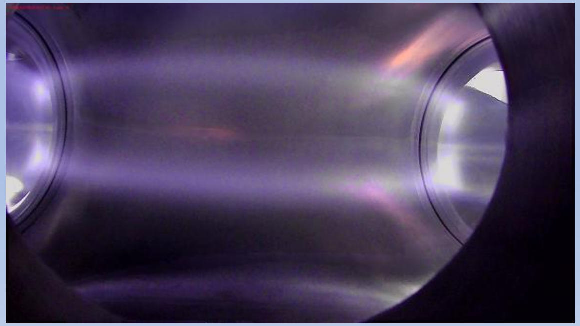
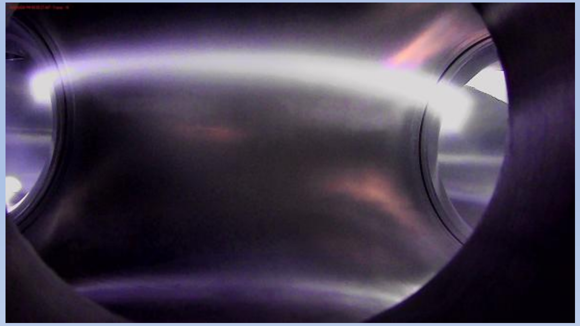


DEMONSTRATION PLASMA – DIPOLE MAGNETIC FIELD

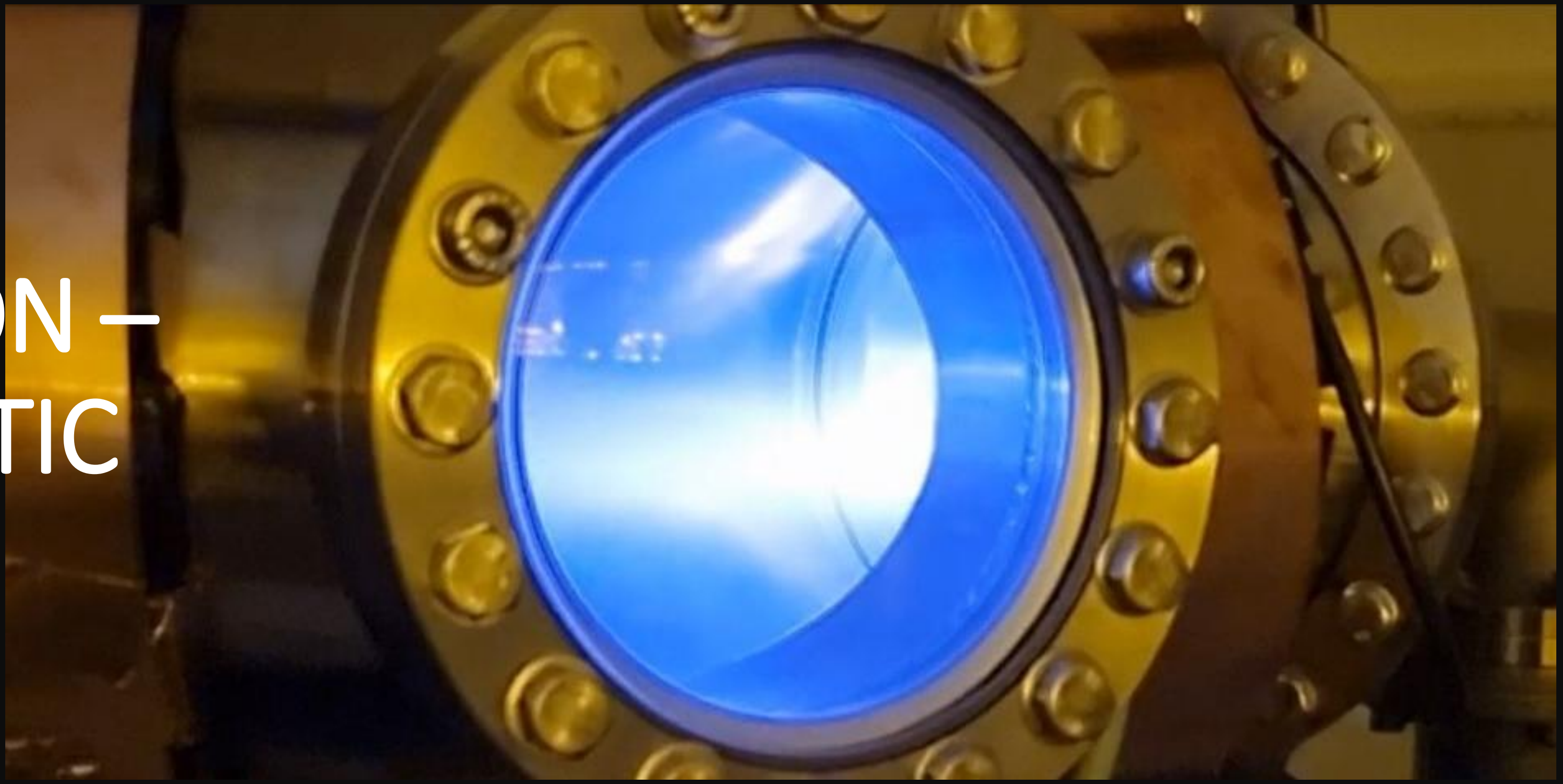
Plasma position control by varying current in Poloidal field coils

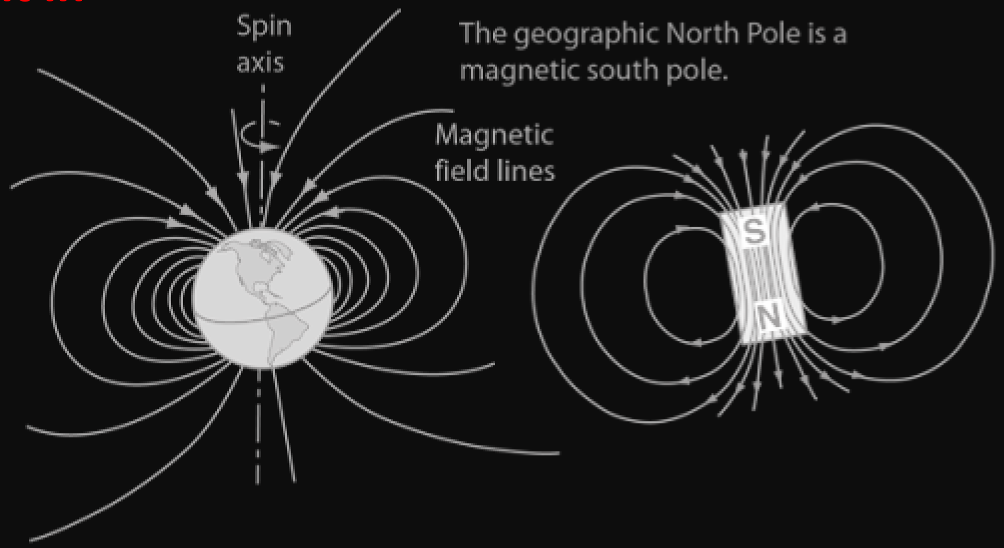
PF 1&2 5mT variable

DEMONSTRATION – DIPOLE MAGNETIC FIELD



Plasma position control by varying current in Poloidal field coils



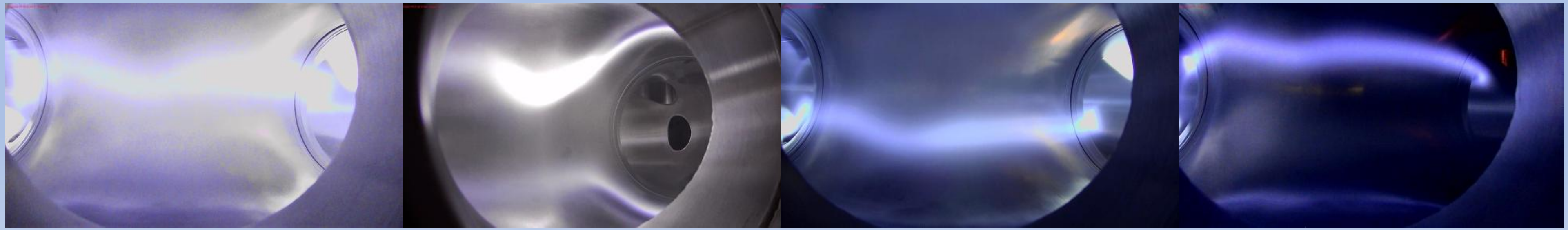
DEMONSTRATION PLASMA

Effect of Poloidal and Toroidal magnetic fields on a Glow discharge Plasma

Plasma Striations

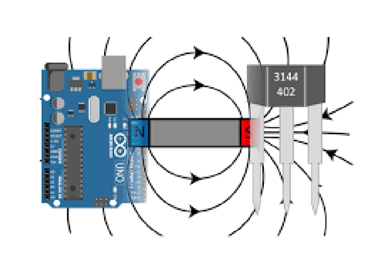
PF & TF 15mT

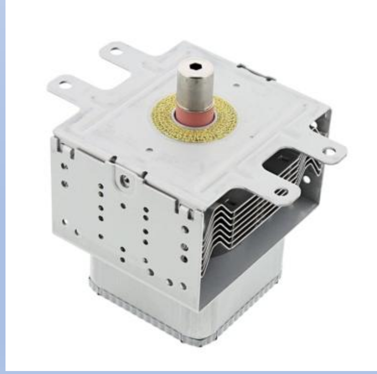
TF 20 mT



FUTURE UPGRADES

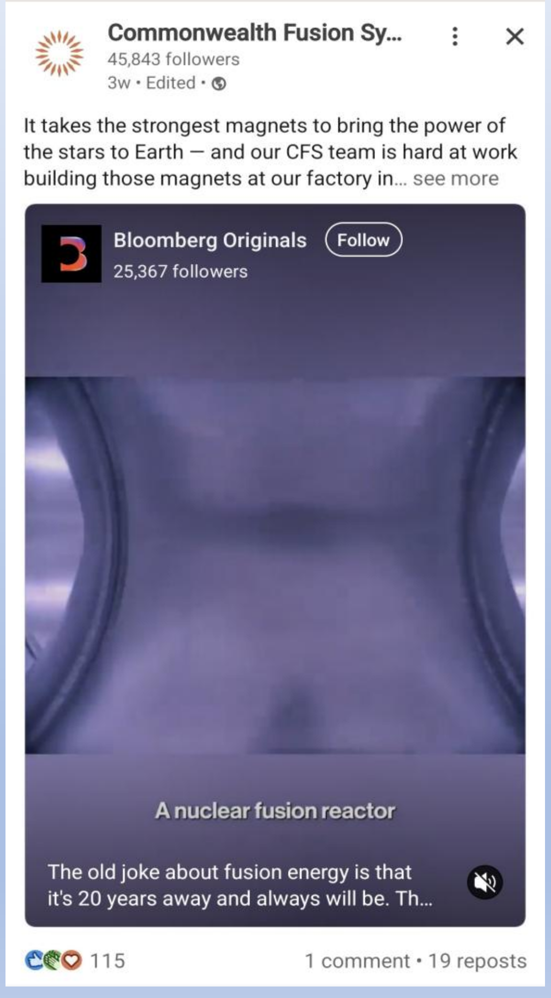
- **2.45Ghz Microwave**
- **Pulsed supercapacitor power supplies.**
- **Turbopump, gauges and gas handling**
- **High speed Video**
- **Rogowski coil**
- **Hall effect magnetometer**
- **Wide band and HR Spectrometers**
- **Langmuir probe**
- **Superconducting (HTS) Solenoid coil**





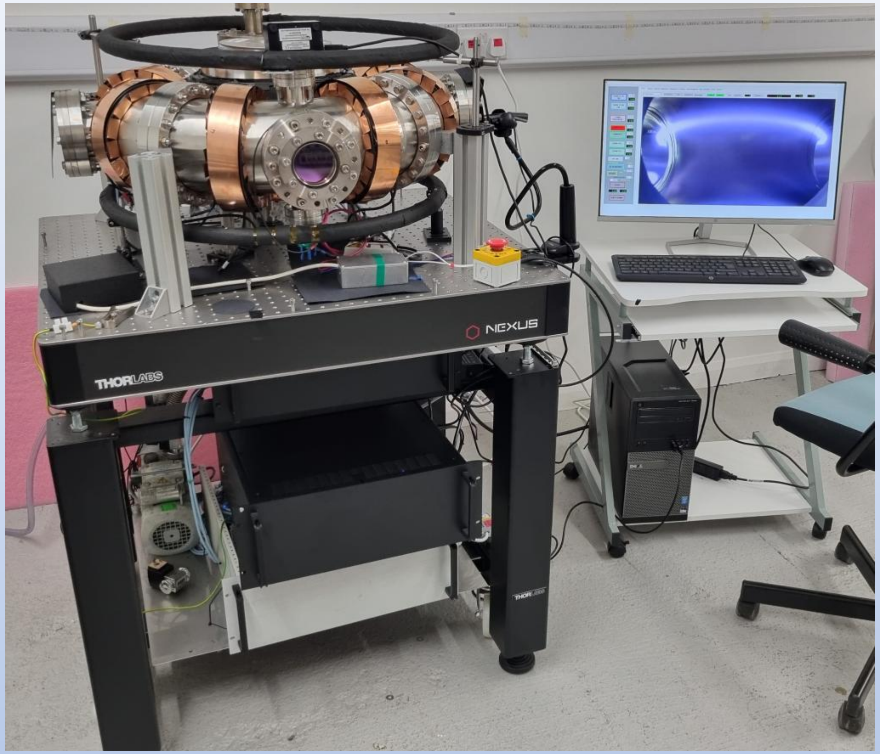
MICROWAVE EXCITED PLASMA (ECRH)

Microwave driven plasma discharge in the Tokamak Energy ST25 Cu



Courtesy Tokamak Energy

QUESTIONS - ?



For more Information

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Oxford educational fusion systems

https://www.oxedfusionsystems.co.uk/home