



Plasma and Fusion Research at Queen's University

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Presented at the Annual CNS Conference

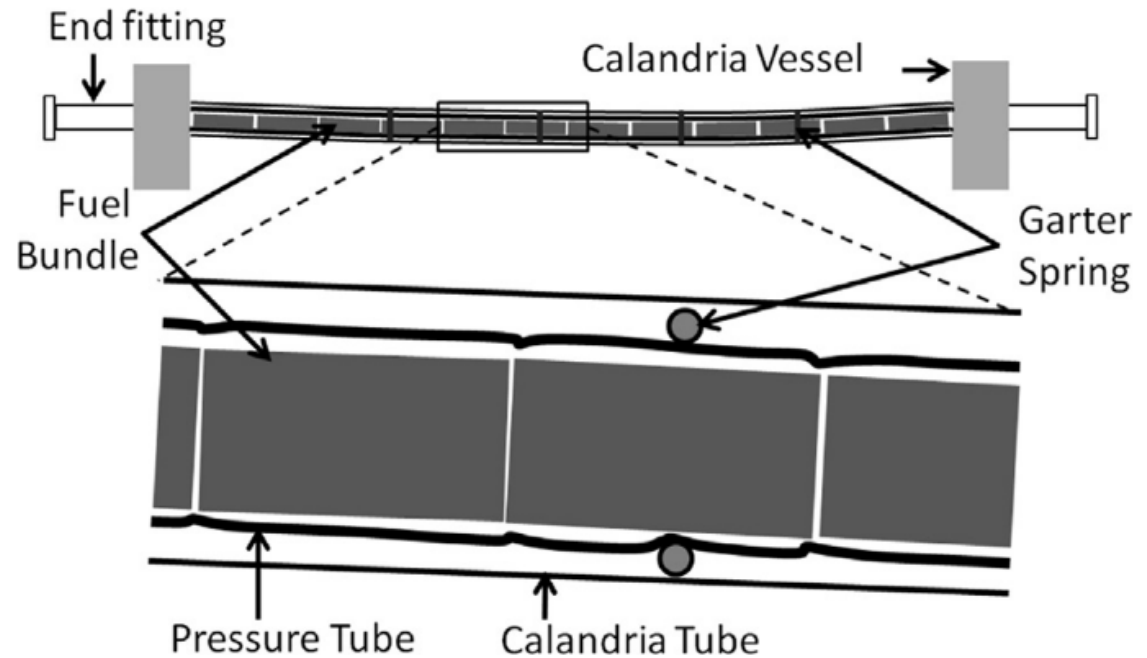
24 June 2019

Applied Magnetism

- Plasma and Fusion research at Queen's University is a part of a program of research in Applied Magnetism:
 - Non-Destructive Evaluation (with RMC)
 - Inductive Propulsion (with Bombardier Transportation Inc)
 - Plasma Physics and Fusion (with ...)

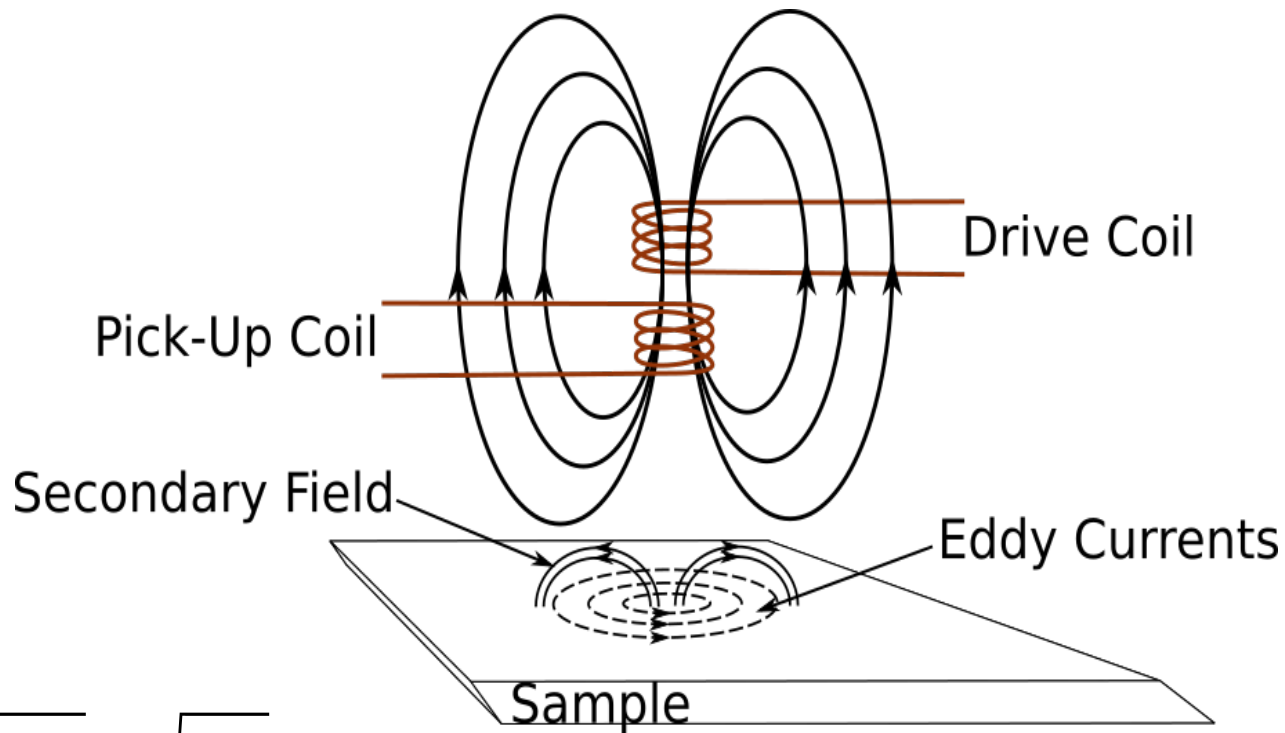
Non-Destructive Evaluation: Candu[®] Reactor Fuel Channel

- Approaching 400 horizontally- orientated fuel channels [1]
- Heat, irradiation, weight results in sag
- Contact between pressure (PT) and calandria tube (CT) could result in cracking of PT
- Inspected using eddy current (EC) probe

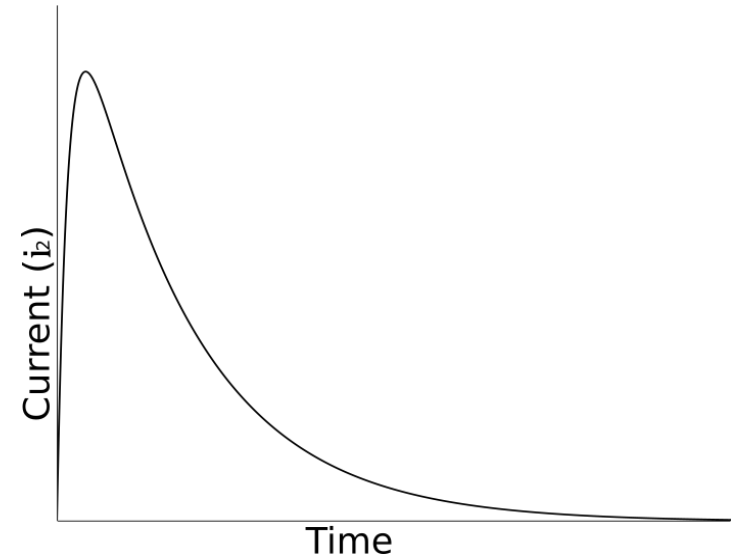
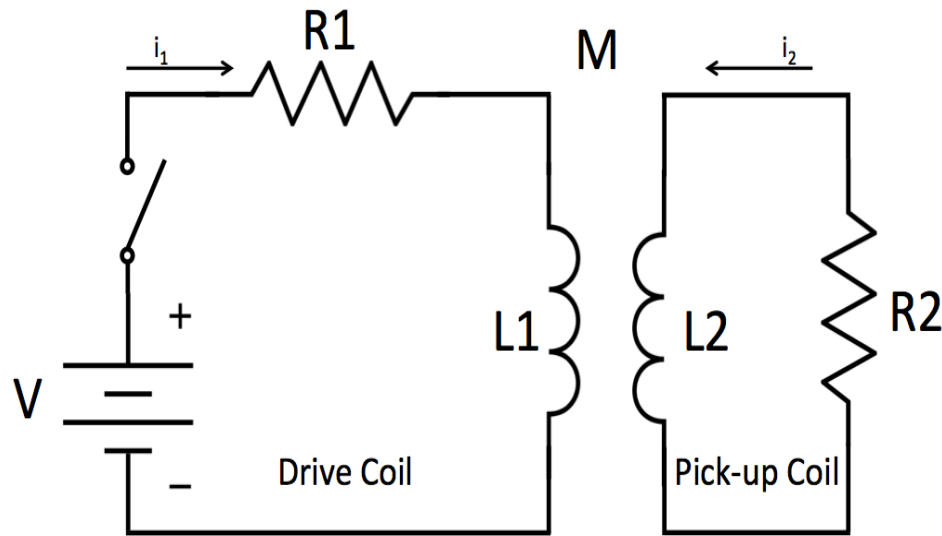


Configuration of a CANDU fuel channel [2].

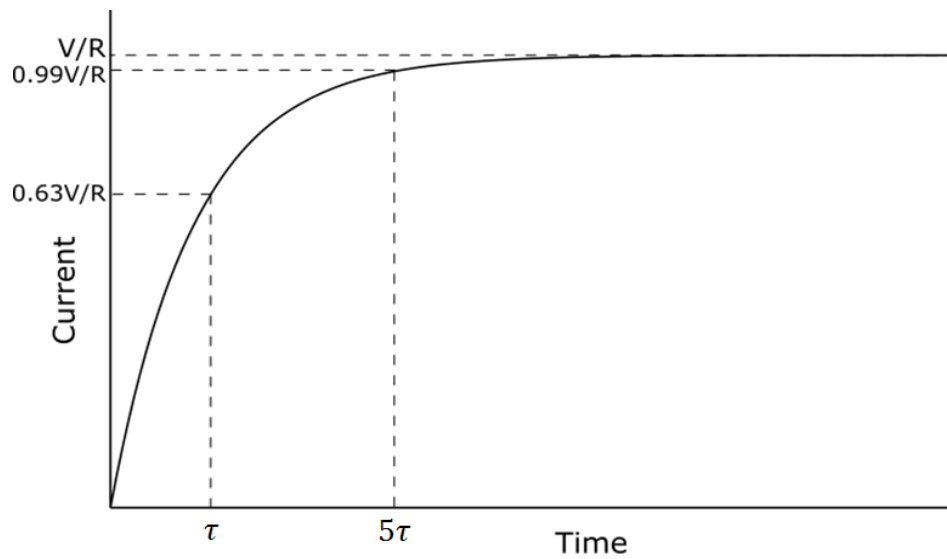
Eddy Current Probe



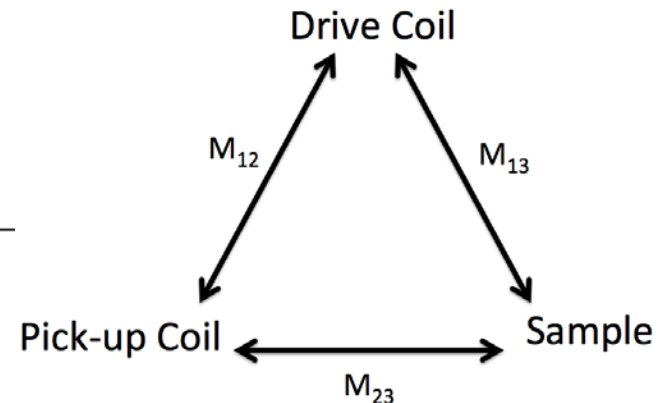
$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} = \sqrt{\frac{T}{\pi\mu\sigma}}$$



Analytical representation of a pick-up coil response when excited by a step function.

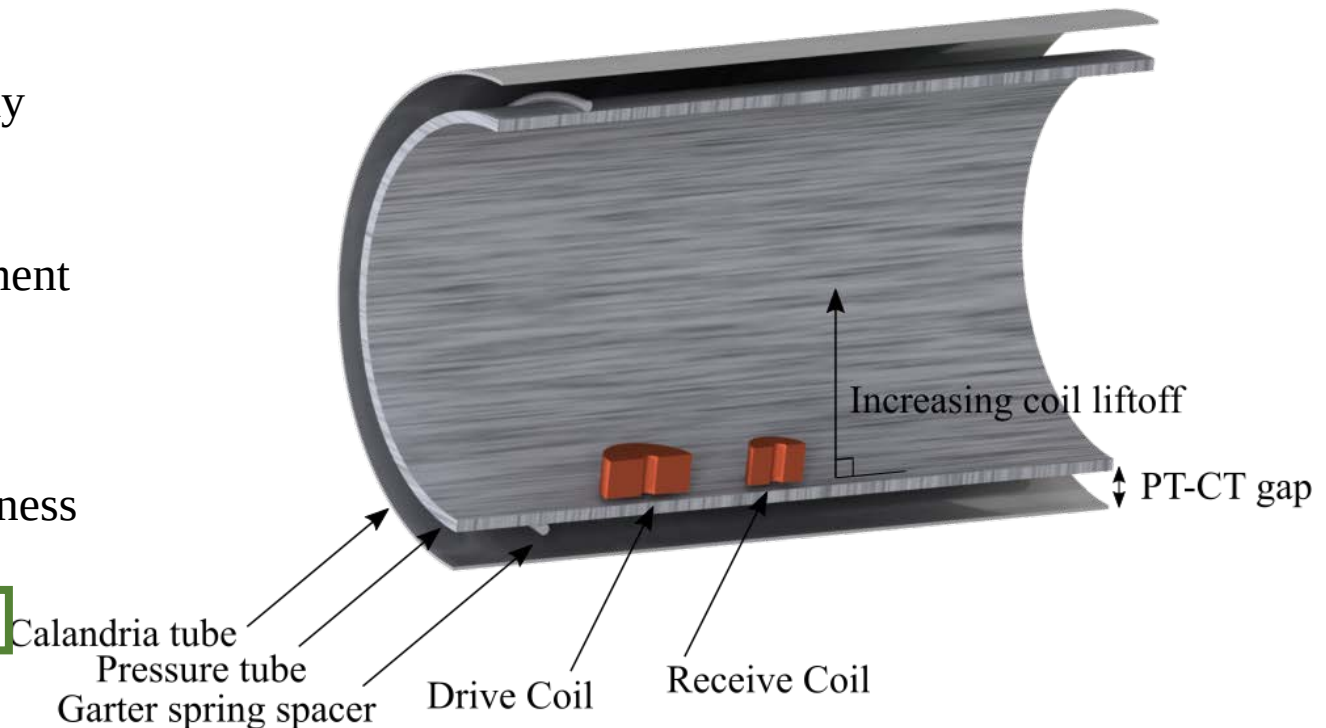


Analytical representation of the drive coil response when excited by a step function.



Gap Probe Sensitive to Resistivity

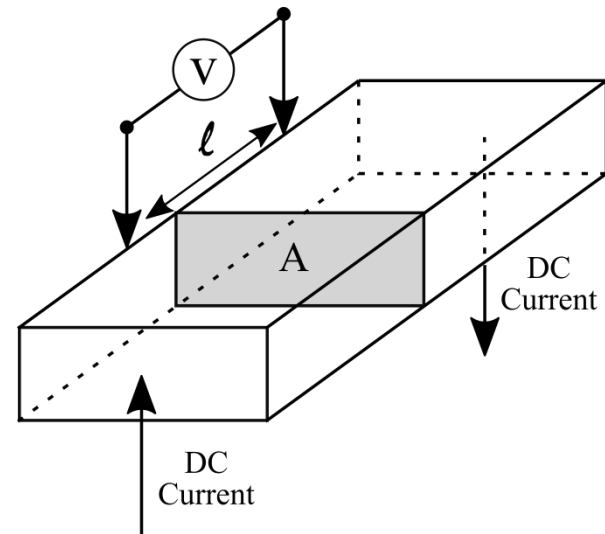
- Inspected using eddy current (EC) probe
- EC based measurement affected by:
 - Probe Lift-off
 - PT Wall Thickness
 - PT Diameter
 - PT Resistivity
 - CT Resistivity
- Algorithm assumes constant resistivity for each channel [4], [5]



Half- section of fuel channel with coils similar to those found on Gap probe [3].

Electrical Resistivity

- Measure of how strong a material opposes the flow of electricity
- Appears in skin depth eqn, and electromagnetic BVPs like analytical PT-CT gap models [6], [7]
- A function of the mean free path of electron; scattering sites reduce path-length



Four Point resistivity measurement setup using rectangular cross section.

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}} = \sqrt{\frac{T}{\pi\mu\sigma}}$$

$$\rho = \frac{VA}{IL_{probe}}$$

Resistivity and Microstructure Coupled

- Resistivity and microstructure coupled
- Resistivity can be affected by:
 - Temperature [8]
 - Heat Treatment [9]
 - Irradiation [10][11]
 - Hydrogen ingress/solute [12]
 - Dislocation density [9]

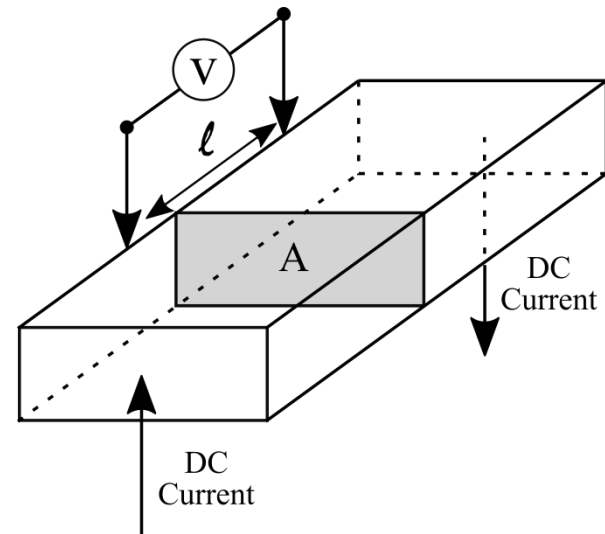
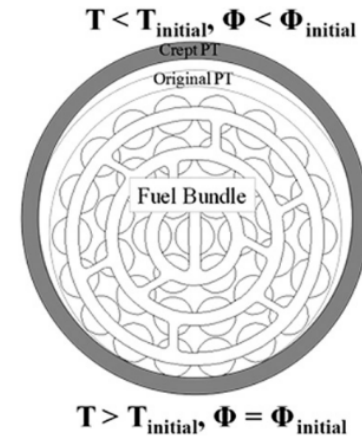


Figure 4. Four Point resistivity measurement setup using rectangular cross section

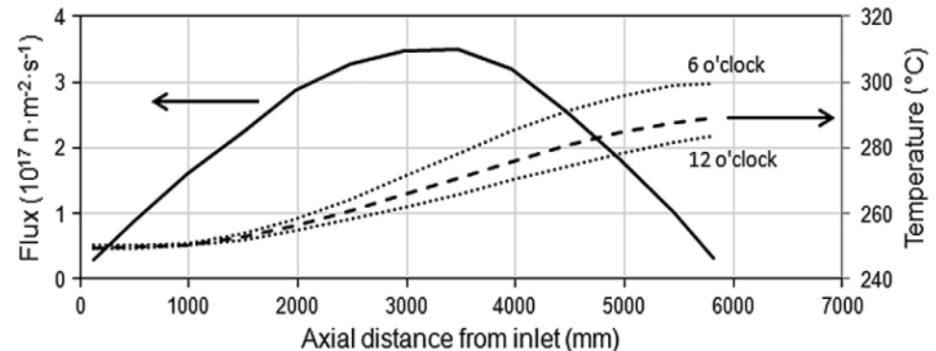
$$\rho = \frac{VA}{IL_{probe}}$$

Non-Uniform Heat Treatment in-channel

- Time and Temperature can lead to:
 - Phase Transformation (TTT plots)
 - Creep
 - Annealing/reordering of dislocations
- Conditions of fuel channel under operation similar to heat treatment
 - Axial and circumferential temperature gradient
 - 250°C - 310°C axial grad.
 - 290°C - 310°C circum. grad.



Schematic diagram illustrating the effects of flow by-pass on the temperature of the pressure tube as a function of clock position [1].



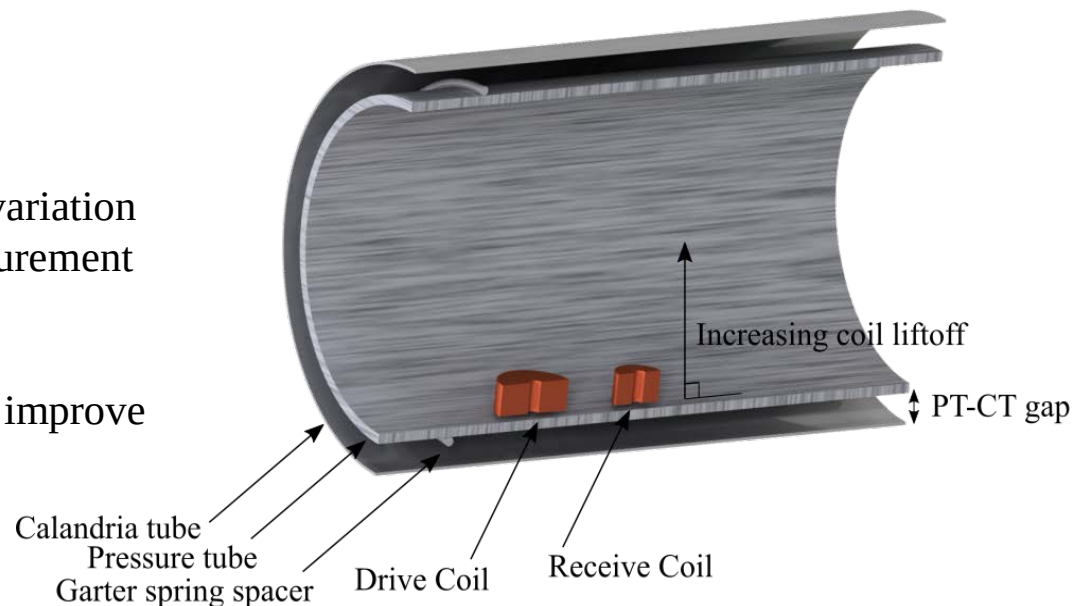
Flux and coolant temperature profiles for typical fuel channel 13].

Relevance to R&D

- Impacts two areas of R&D Interest:
- **Plant Life Extension**
 - Axial and circum. resistivity variation present could affect gap measurement accuracy
 - Improved gap accuracy could improve assurance of PT integrity

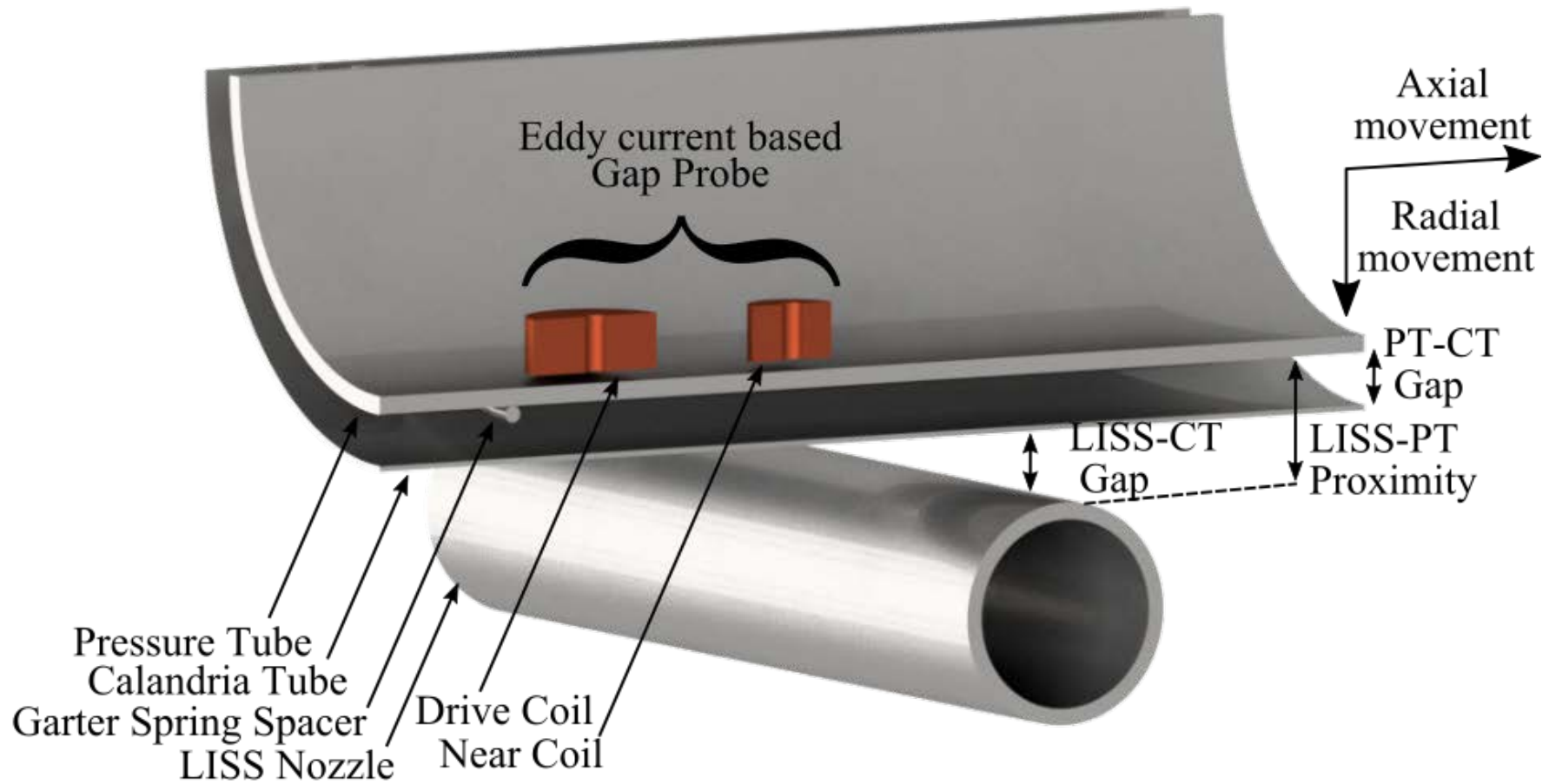
- **Enhanced Functionality**

- Resistivity associated with microstructural condition of channel
- Additional information could be extracted from fuel channel using gap probe

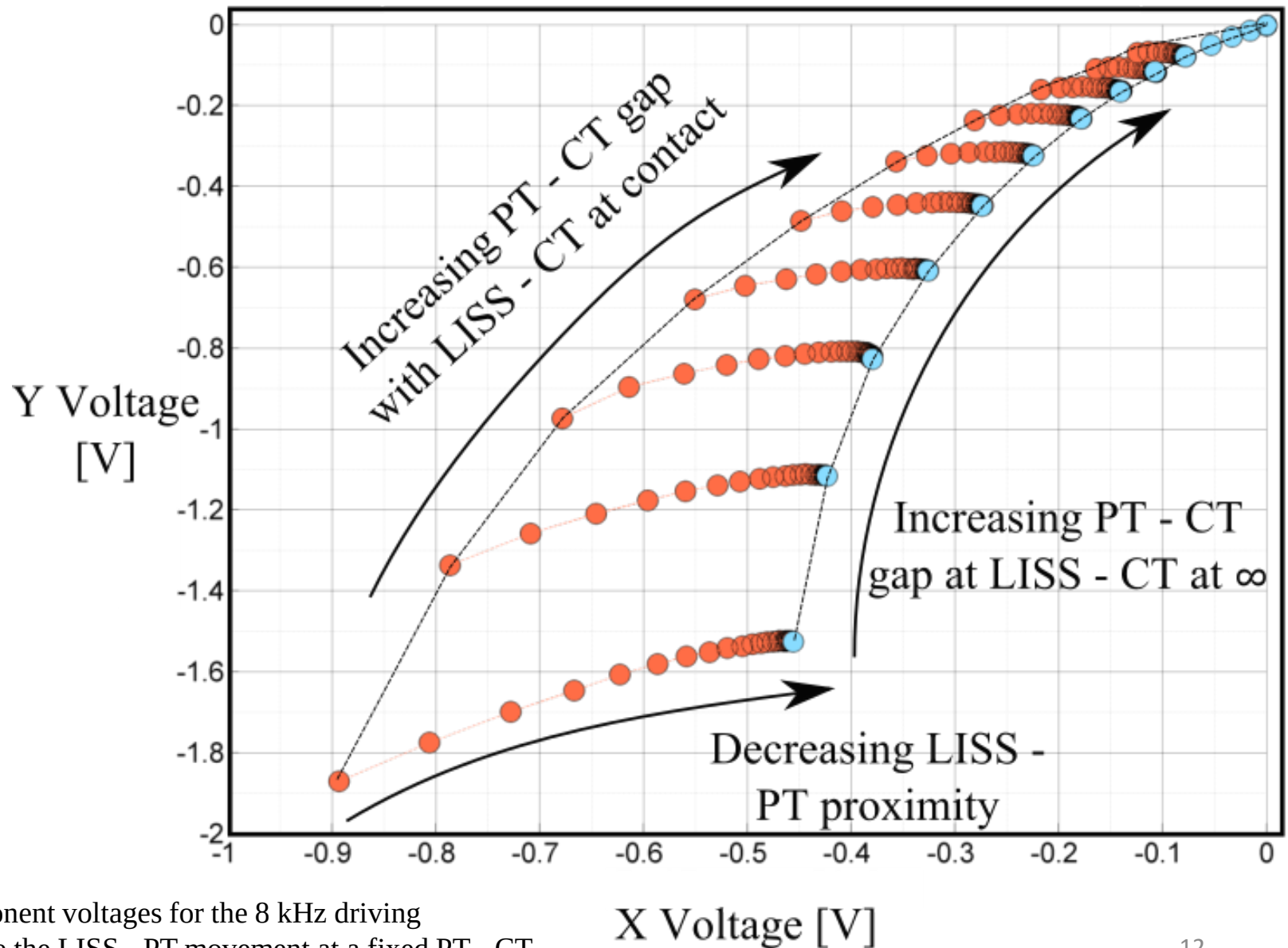


Half- section of fuel channel with coils similar to those found on Gap probe [3].

LISS Nozzle Proximity

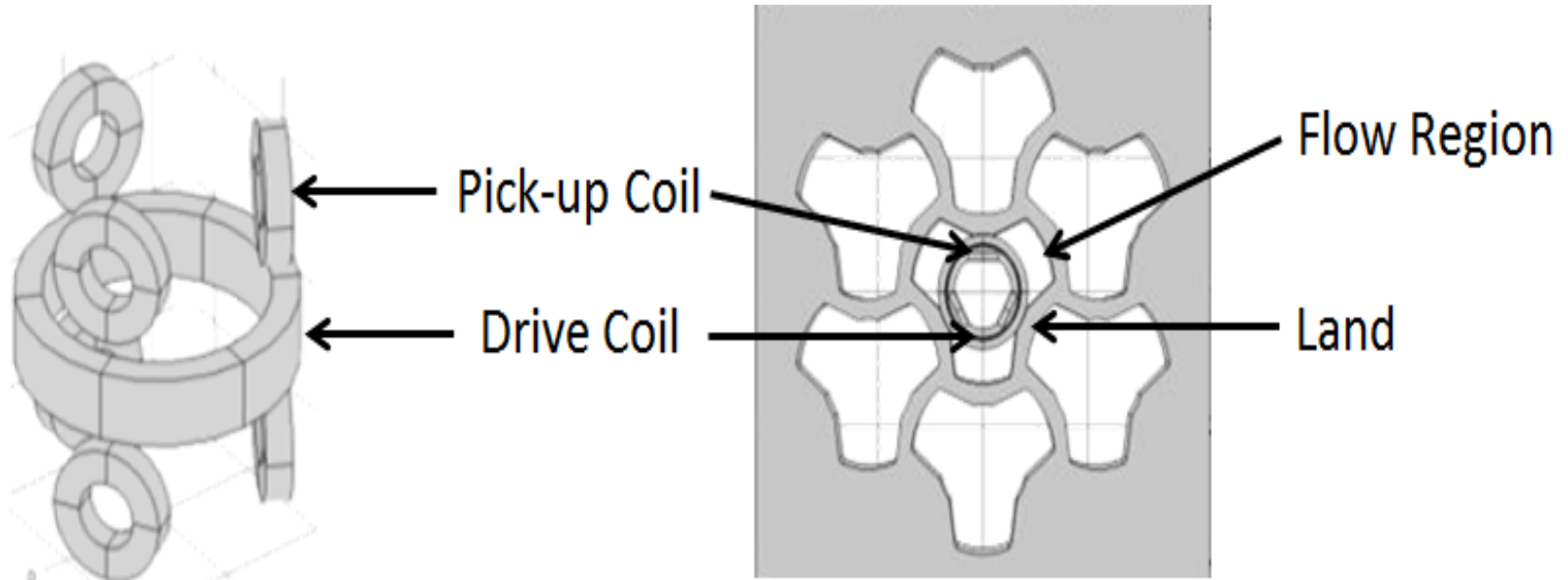


Peak voltage reponses for LISS - PT proximity at 8 kHz



X and Y component voltages for the 8 kHz driving frequency. Note the LISS - PT movement at a fixed PT - CT gap (strips of points) is in the X direction.

Steam Generator Broach Support Plate Inspection

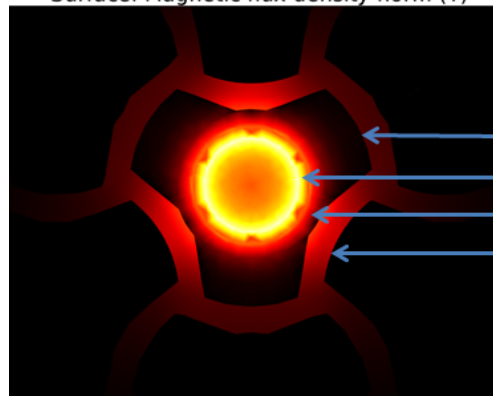


Unflawed Broach Support Plate

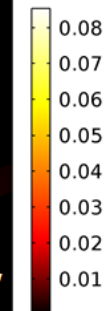
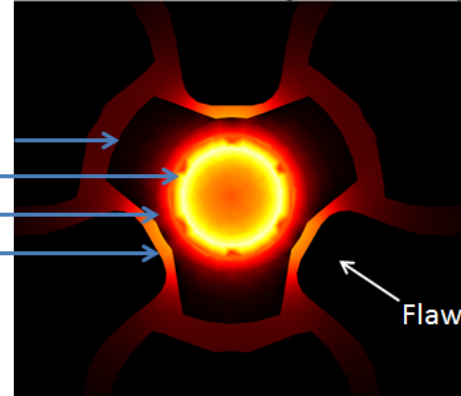
Flawed Broach Support Plate

Time=0.01 s
Surface: Magnetic flux density norm (T)

Time=0.01 s Surface: Magnetic flux density norm (T)



Flow Region
Drive Coil
SG Tube
Land



Comsol
modelling
and
experimental
validation

Post Graduate Positions in Non-Destructive Testing at Queen's University and Royal Military College of Canada



Canadian CF-18

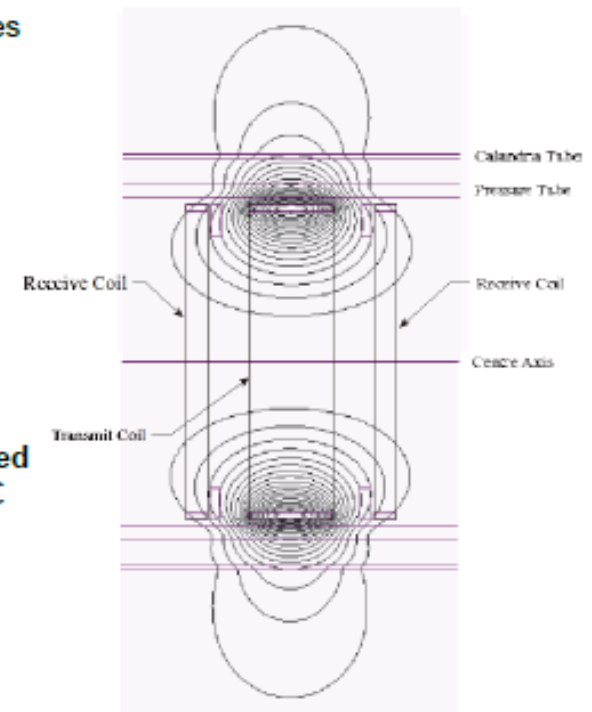
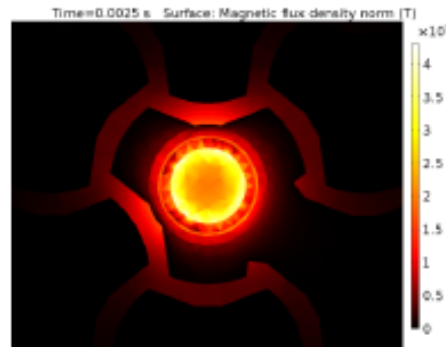
Non-destructive testing is a tool used to evaluate material component integrity. It uses Electromagnetics, Magnetic Properties of Materials, Waves in Solids... and involves Computer based data acquisition and analysis, as well as Computer Modelling.

It is used in:

- Aerospace Industry
- Nuclear Industry
- Gas and Oil Industry
- Petro-Chemical Industry

Research in Non-destructive Testing at RMC is done in the areas of:

- Eddy Current Testing
 - Pulsed Eddy Current (PEC)
 - Ultrasonic Testing
 - Probability-of-Detection
 - Neutron Radiography
- Finite element model of flux density induced in steam generator broach support by PEC



Graduate student positions are open in the area of eddy current inspection of tubular structures using finite element modeling, analytical models and laboratory investigations. Preferred skill set includes LabView, MatLab and COMSOL software. The successful candidate will have a Bachelors degree in Engineering Physics or Physics. For more information contact:

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Modelled magnetic field lines from eddy current coil in a reactor pressure tube

Post Doctoral Position in Magnetic Non-Destructive Evaluation at Royal Military College of Canada

Project: Development of magnetic and electromagnetic technology for nondestructive evaluation of steel.

Location: Royal Military College of Canada, Kingston, with bi-monthly visits to Pure Technologies, Mississauga.

Start: January 1, 2019. **End** December 31 2019.



Description: Multiple pipeline inspection technologies are used in the oil & gas industry, but these require direct access to either the inside or outside of the pipe. Metal Magnetic Memory (MMM) testing technology, based on magnetoelasticity (Villari) effect, is a robust and rapidly expanding method that uses magnetization by the earth's magnetic field for detection of anomalies in magnetic fields at the surface or in vicinity of a ferromagnetic component as a result of local changes in its stress state. In contrast to other magnetic inspection methods, which require application of an external magnetic field (and magnetization device), MMM is a passive technique. MMM can be used to determine pipe location from above ground and has potential to assess pipe line stress state by detection of magnetic anomalies. The goal of the current project is to design and validate the application of cost-effective non-contact MMM inspection techniques to detect stress anomalies in pipelines, which could lead to monitoring and improving service life and performance of infrastructures such as water/wastewater and gas/oil pipelines. The work will be done in collaboration with Pure Technologies, Mississauga.

Pure Technologies is a world leader in the development and application of innovative technologies for critical infrastructure. In January 2018, Pure Technologies was acquired by Xylem, a leading global water technology company committed to developing innovative technology solutions to the world's water challenges. Pure Technologies expertise and patented technology-driven solutions are used around the world to help utility operators reduce the



Pure Technologies employee utilizing the Spectrum XLI tool. Spectrum XLI is the most reliable way to collect above-ground survey data.

Inductive Propulsion



2-D Quasi-Static Solution of a Coil in Relative Motion to a Conducting Plate

Majd Abdelqader¹, Jordan Morelli¹, Ryszard Palka², and Konrad Woronowicz³

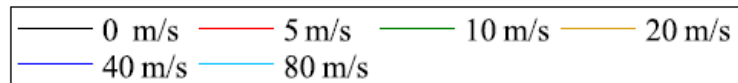
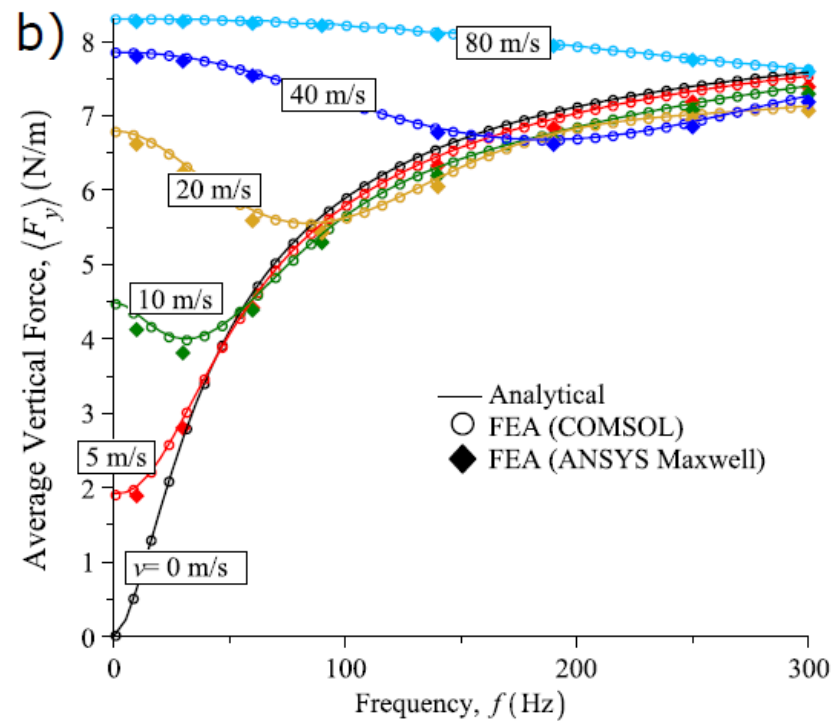
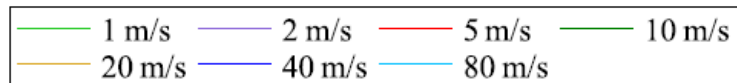
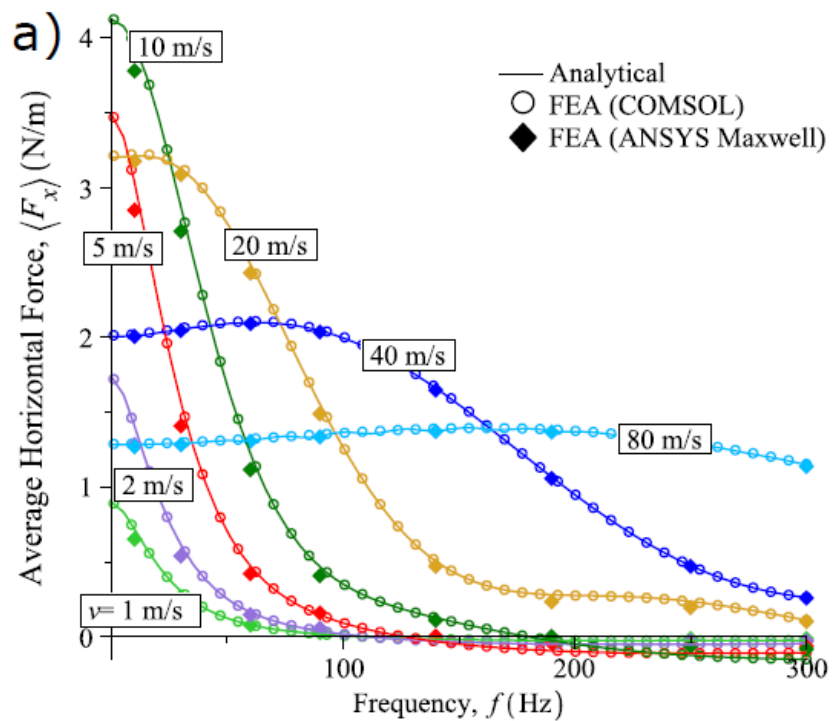
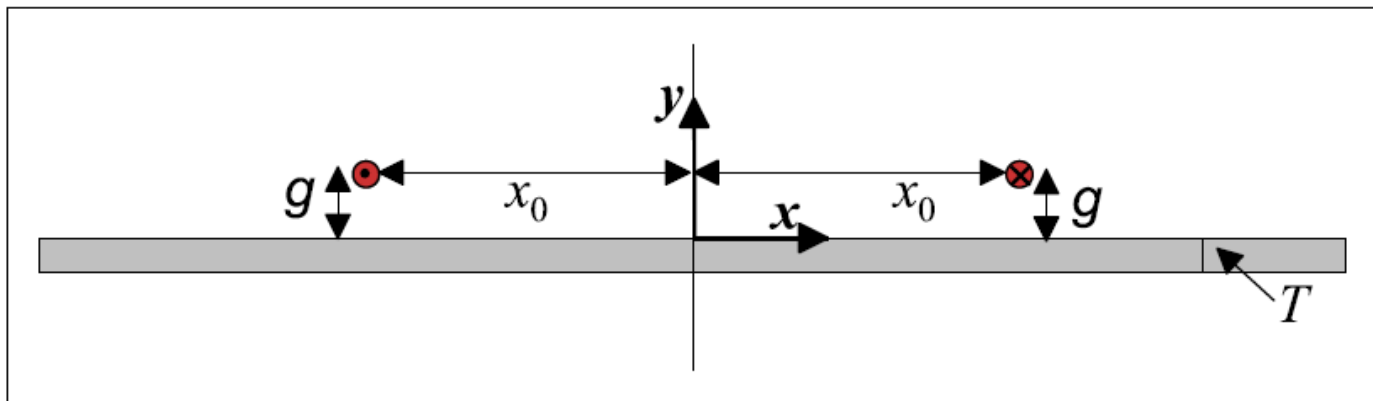
¹Queen's University, Kingston, Ontario, Canada

²West Pomeranian University of Technology, Szczecin, Poland

³Bombardier Transportation Inc., Kingston, Ontario, Canada







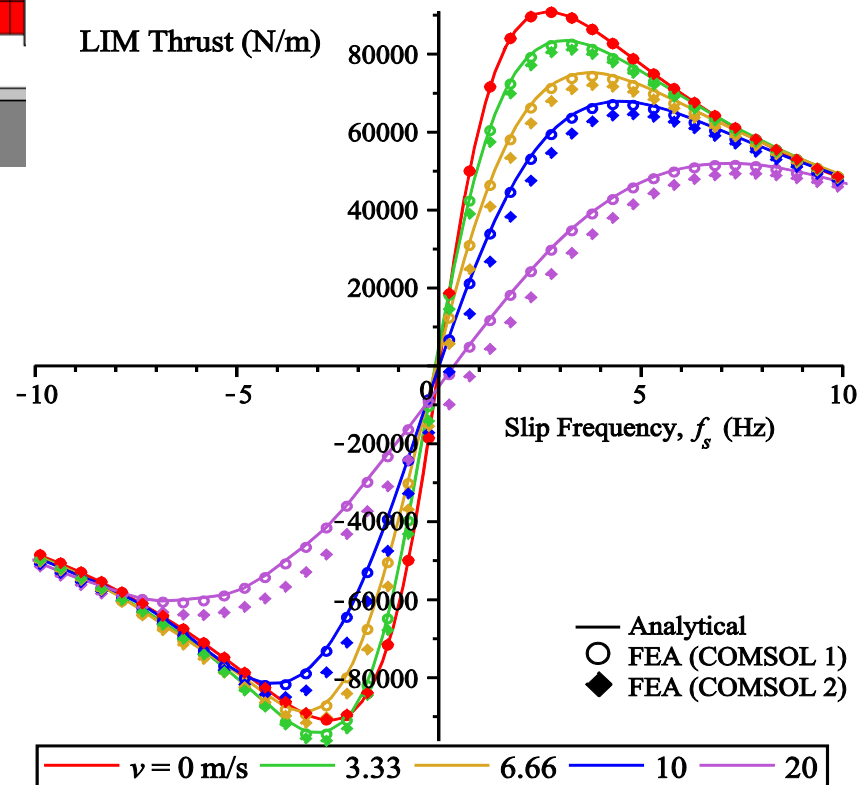
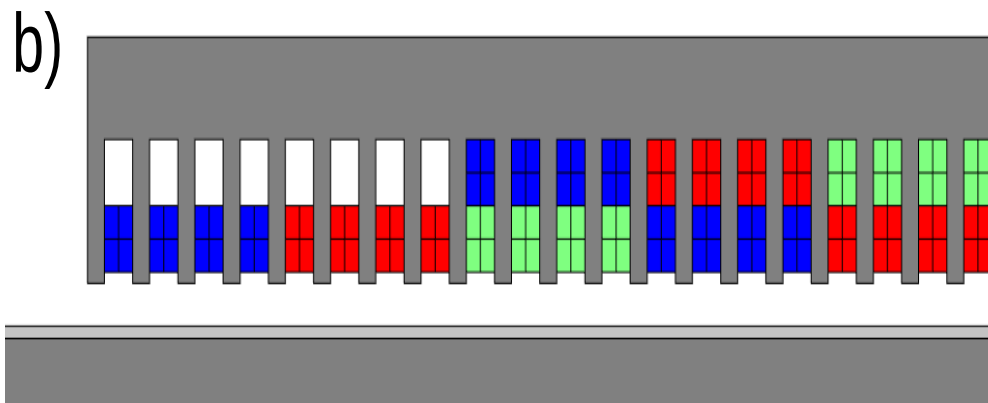
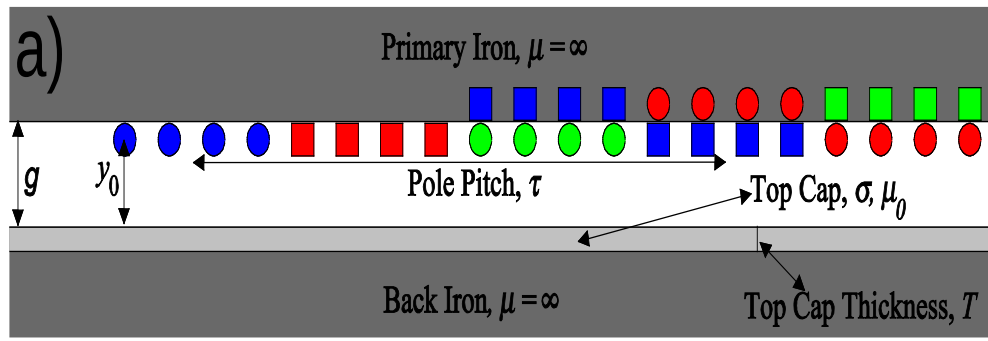
2-D Quasi-Static Fourier Series Solution for a Linear Induction Motor

Konrad Woronowicz¹, Majd Abdelqader², Ryszard Palka³, and Jordan Morelli²

¹ Bombardier Transportation Inc., Kingston, Ontario, Canada

² Queen's University, Kingston, Ontario, Canada

³ West Pomeranian University of Technology, Szczecin, Poland



Advanced Rail work:

- Bombardier Transportation - LIM
- Hyperloop propulsion
- Hydrail

Plasma Physics and Fusion:

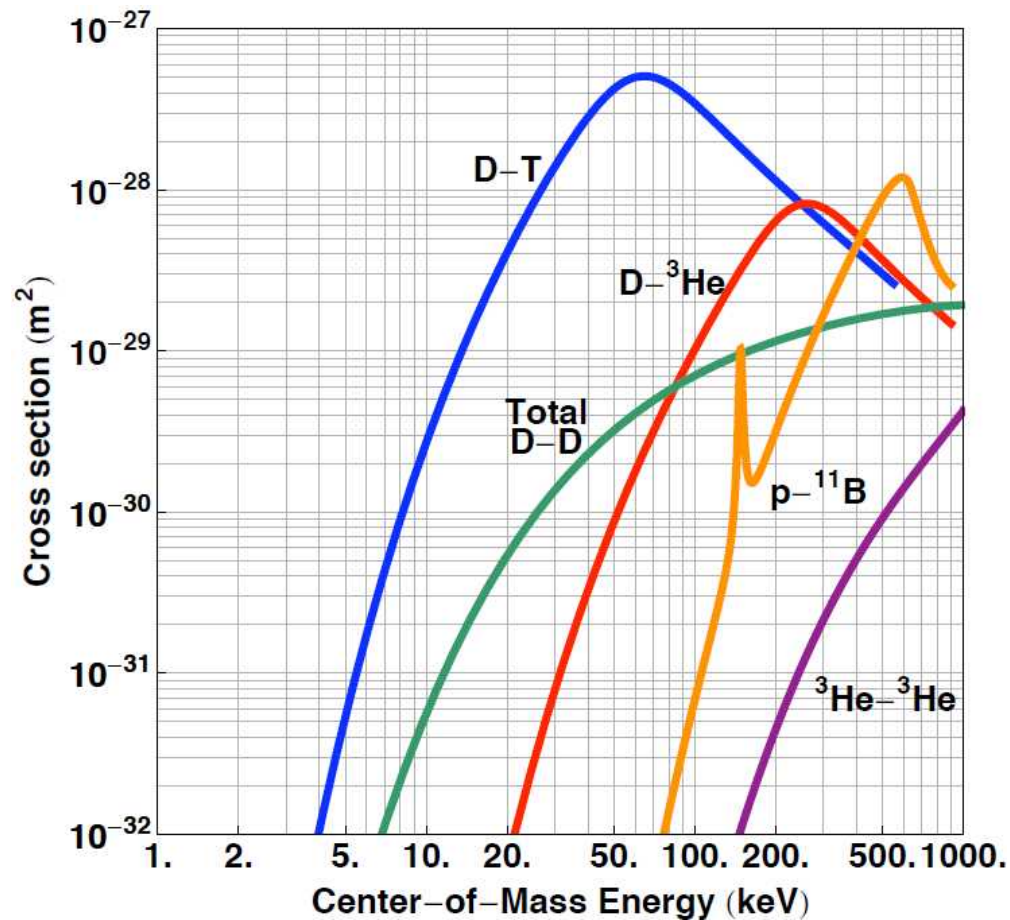
Fusion Reactions:

- Choose a reaction with high energy yield and is easy to fuse.
- Easy energy capture, radioactivity involved might also be important.
- At first glance, we note DT has a very high energy yield.
- Next step is to understand how likely a reaction is to occur.

<u>name</u>	<u>fusion reactions</u>	<u>yield MeV</u>
DT:	$D + T \rightarrow {}^4_2\text{He} (3.54) + {}^1_0\text{n} (14.05)$	17.59
DDn:	$D + D \rightarrow {}^3_2\text{He} (.82) + {}^1_0\text{n} (2.45)$	3.27
DDp:	$D + D \rightarrow T (1.01) + p (3.02)$	4.03
TT:	$T + T \rightarrow {}^1_0\text{n} + {}^1_0\text{n} + {}^4_2\text{He}$	11.3
D- ${}^3\text{He}$:	$D + {}^3_2\text{He} \rightarrow {}^4_2\text{He} (3.66) + p (14.6)$	18.3
p- ${}^6\text{Li}$:	$p + {}^6_3\text{Li} \rightarrow {}^4_2\text{He} + {}^3_2\text{He}$	4.02
p- ${}^{11}\text{B}$:	$p + {}^{11}_5\text{B} \rightarrow 3({}^4_2\text{He})$	8.68

Energy yields and cross sections for selected reactions (Dolan, 1982)

Fusion Reaction Cross-Section versus Temperature



Ignition:

- Desirable to find the point where He heating balances losses.

$$P_{\text{loss}} = P_{\alpha}$$

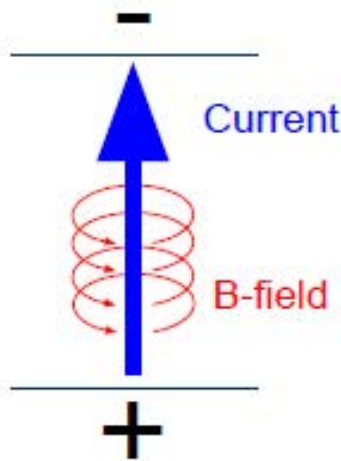
- This reduces to the “triple product” (aka **Lawson criterion**):

$$nT\tau_E > 3 \times 10^{21} \text{ m}^{-3} \cdot \text{keV} \cdot \text{s}$$

- τ_E is the confinement time and reflects the rate of energy loss.
- Desirable to design our reactor to meet this condition.

Magnetic Confinement: Z-Pinch

- One of the first attempts at fusion in the 1940s.
- A strong current in z-direction creates magnetic field.
 $\mathbf{v} \times \mathbf{B}$ force confines and compresses current.
- Unfortunately, it's unstable - sausage, kink instabilities.
- Also need really strong currents that will destroy electrodes.

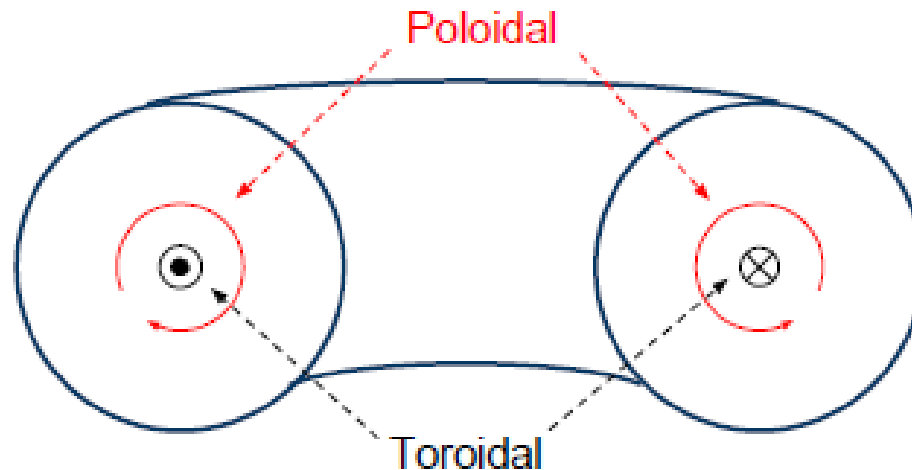


([https://en.wikipedia.org/wiki/Pinch_\(plasma_physics\)\)](https://en.wikipedia.org/wiki/Pinch_(plasma_physics)))

(Left) Z-pinch confinement. (Right) Crushed can from pinch machine.

Magnetic Confinement: Tokamaks

- Bend the Z-pinch into a donut shape (toroid), and induce current to flow around in a circle.
- Current creates a poloidal field that mixes charge. Need it otherwise charge separation due to gradient drift.
- To safeguard against instabilities, need to stiffen magnetic field with external toroidal field.
- The net magnetic field of these component fields is helical.



Magnetized Target Fusion

- ‘New’ approach to fusion where a self-confined plasma is rapidly compressed.
- Magnetized plasma reduces thermal conductivity and enhances energy deposition (ie alpha particle heating).
- A mix of MCF and ICF, requiring less demanding fusion conditions.



Shiva Star at the [Air Force Research Laboratory](#) at Kirtland Air Force Base:

- ▶ $10\mu\text{s}$ confinement
- ▶ $n = 10^{-26}\text{m}^{-3}$
- ▶ $T = 10\text{keV}$
- ▶ 10^5atm pressure

Compact Toroids

- Early pinch experiments led to discovery of self-confining plasmas.
- This is due to conservation of magnetic helicity, K
 - (interconnectedness and twistedness of magnetic flux tubes).
- Taylor (1974) showed that, to conserve K , plasmas can relax to a minimum energy state satisfying:

$$\nabla \times \mathbf{B} = \lambda \mathbf{B}$$

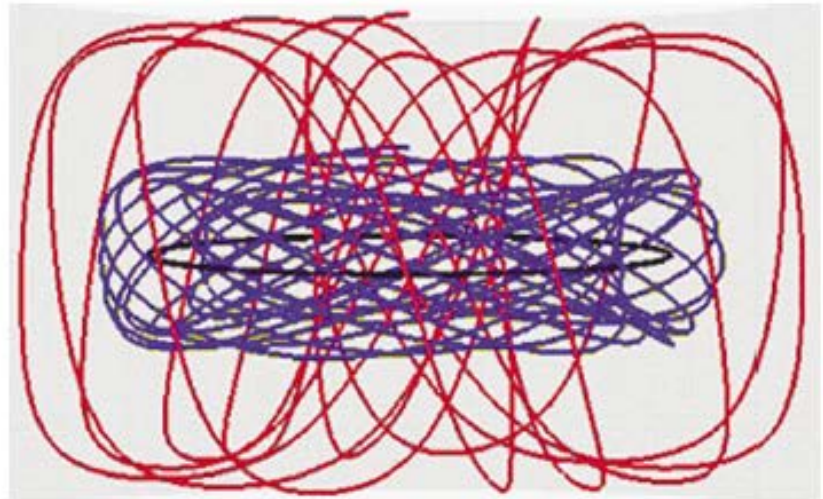
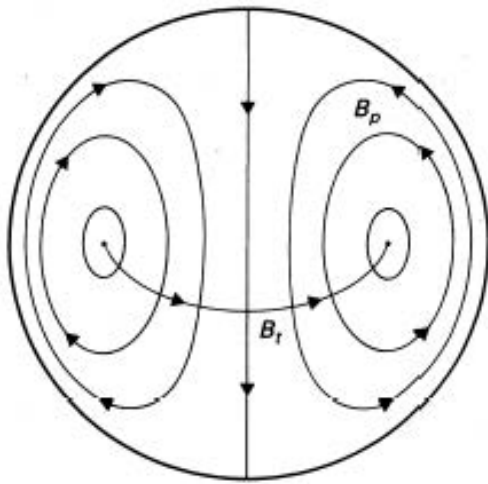
- In doing so, can form a plasma with a self-confining magnetic field:

$$\mathbf{J} = \frac{\lambda \mathbf{B}}{\mu_0}$$

- These are known as compact toroids. The current ($\mathbf{J}$) and magnetic field ($\mathbf{B}$) follow a helical path.

Compact Toroids

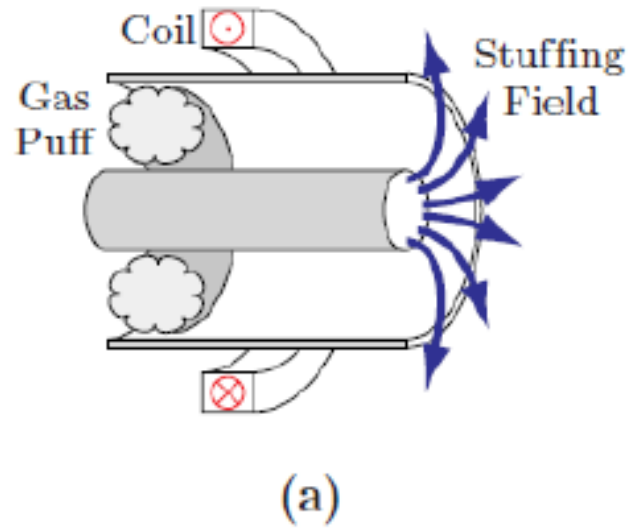
- Two main types of compact toroids are the **spheromak** and **field reversed configuration** (FRC).
- A spheromak has mainly poloidal fields at its edges, and mainly toroidal fields near its centre.
- FRC has no toroidal field.



Spheromak magnetic structure (Taylor, 1986; Jarboe, 2005).

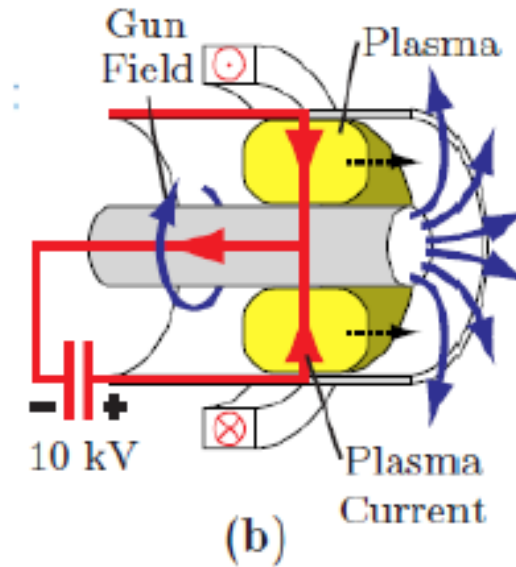
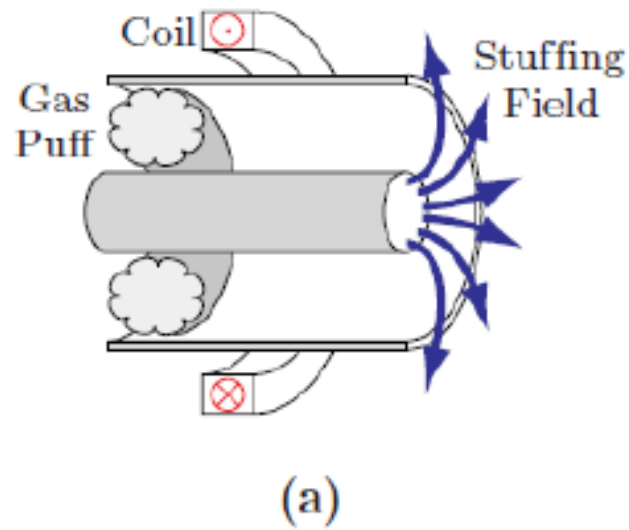
Spheromak Formation (Kornack, 1998)

Generate stuffing field, puff gas into injector vacuum.



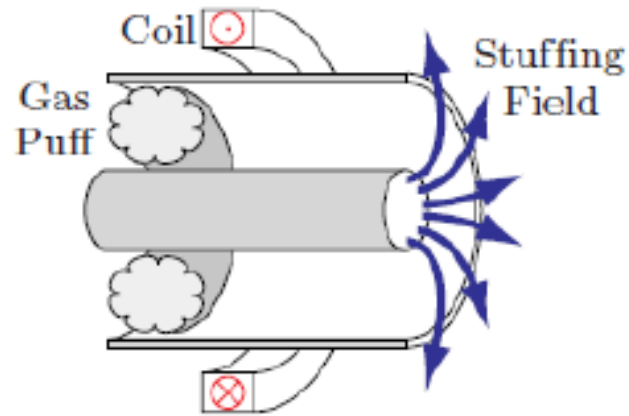
Spheromak Formation (Kornack, 1998)

Voltage applied, plasma formed, current creates gun field.

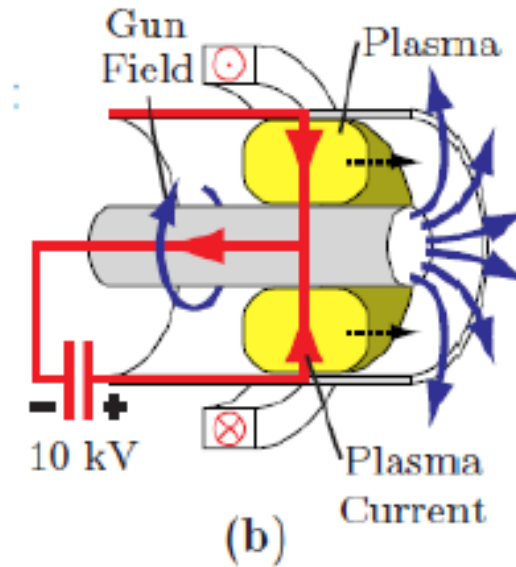


Spheromak Formation (Kornack, 1998)

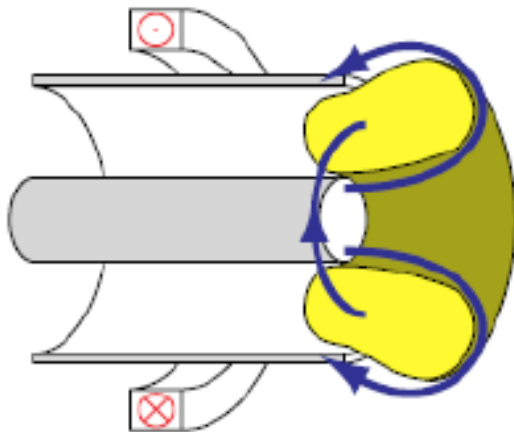
Gun field pushes plasma out, stretching stuffing field.



(a)



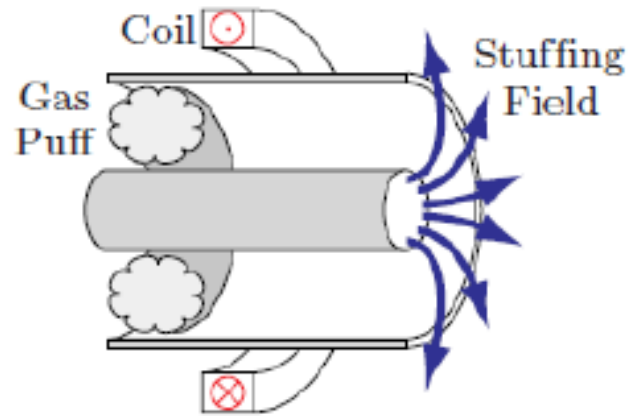
(b)



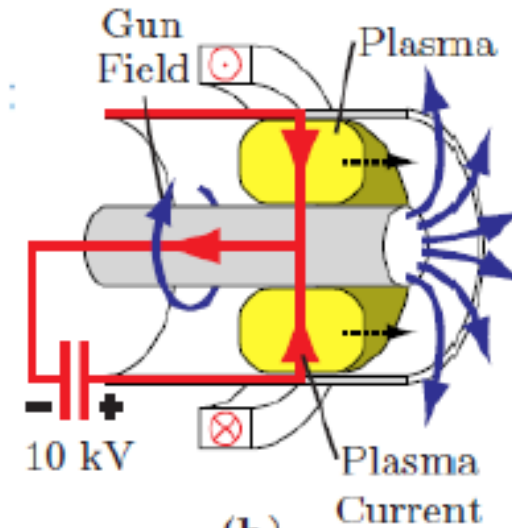
(c)

Spheromak Formation (Kornack, 1998)

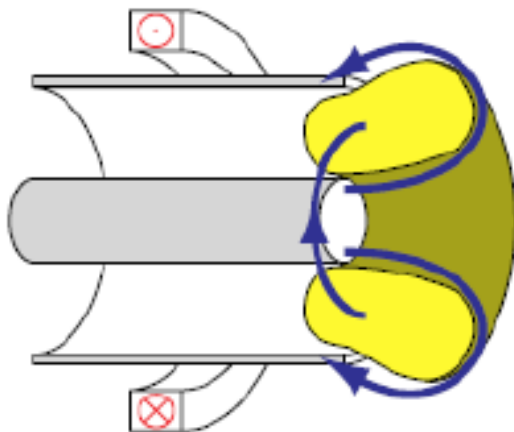
Stuffing field reconnects, and spheromak formed.



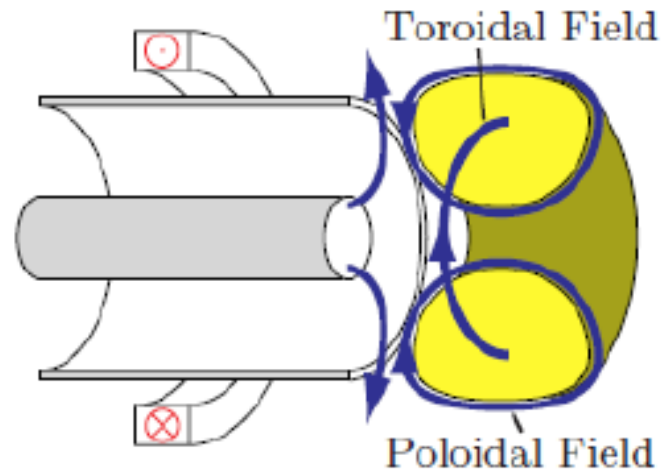
(a)



(b)



(c)

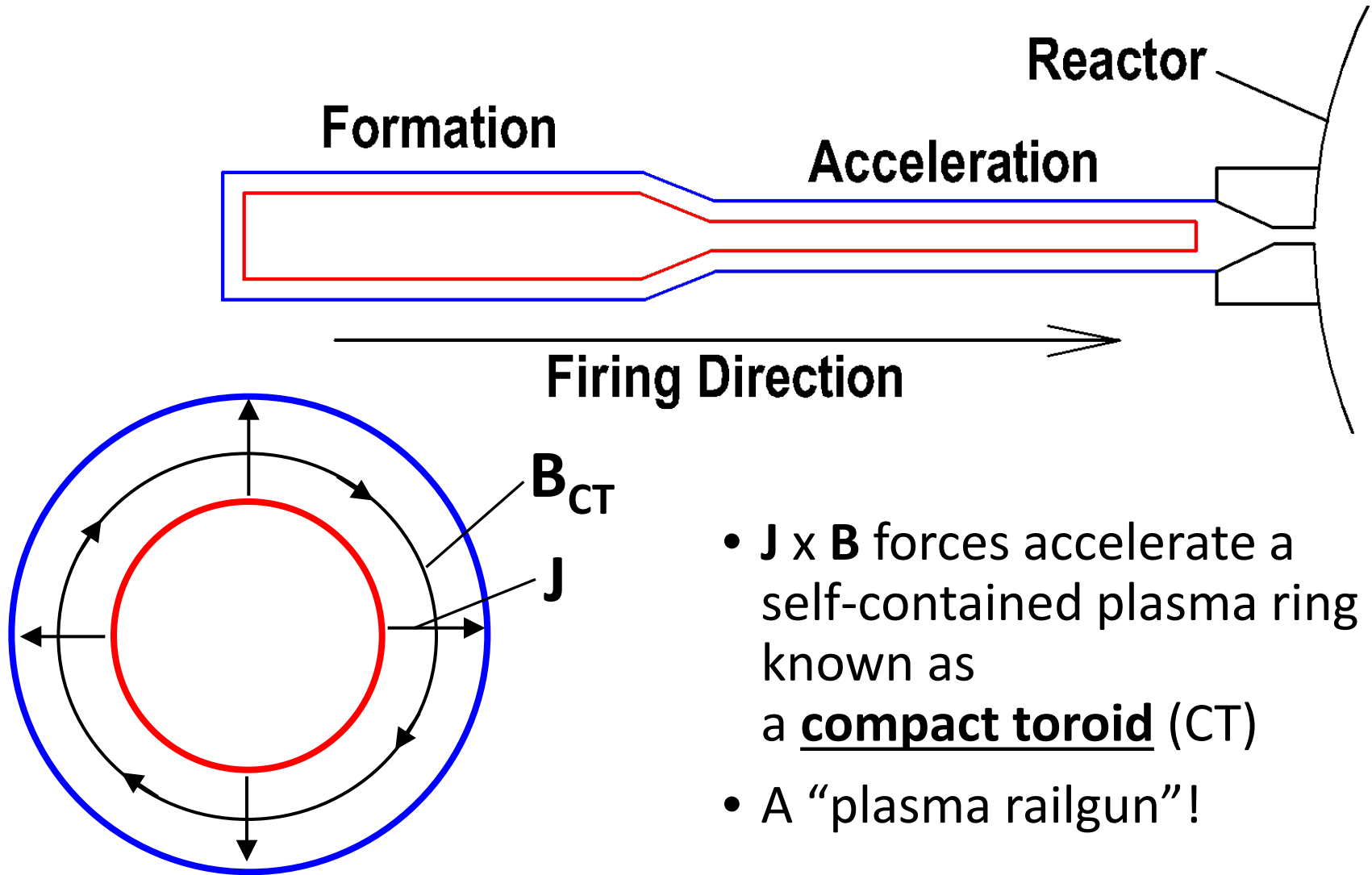


(d)

Spheromak Acceleration

- Accelerator bank fires after formation, to accelerate spheromak down tube.
- Electrode geometry compresses spheromak to higher density, temperature, and magnetic field.

Plasma Ring Acceleration



- $J \times B$ forces accelerate a self-contained plasma ring known as a **compact toroid** (CT)
- A “plasma railgun”!

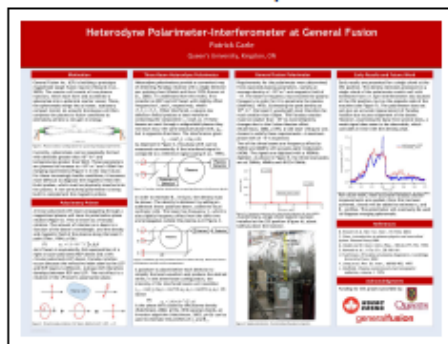
Patrick Carle's work with GF

Introduction

Contributions

- ▶ Polarimeter for an accelerated spheromak.
- ▶ Among fastest plasma polarimeters in the world.
- ▶ Use phase retarding reflectors in place of waveplates.
- ▶ Contributions have been published [2].

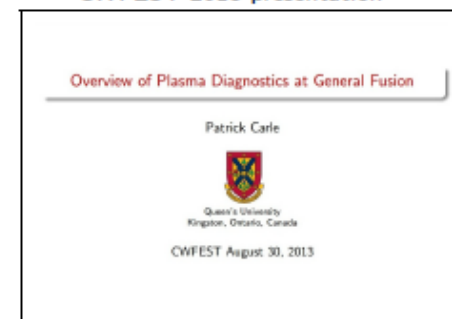
APS DPP 2011 poster



RSI 2013 article



CWFEST 2013 presentation



FRC Amplification via Translation – Collisional Merging

- FAT-CM device at Nihon University

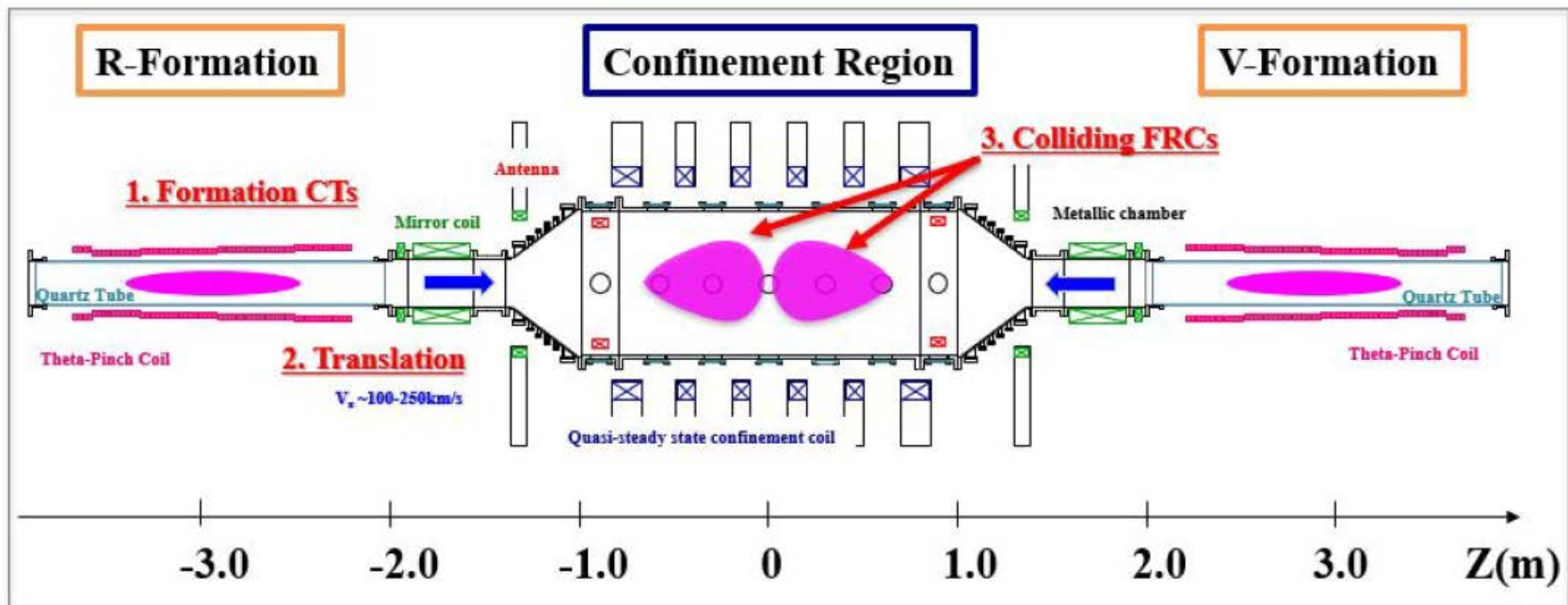


Figure 1: Schematic picture of FAT-CM device

Biasing Experiments

- Limiter Biasing improves stability:

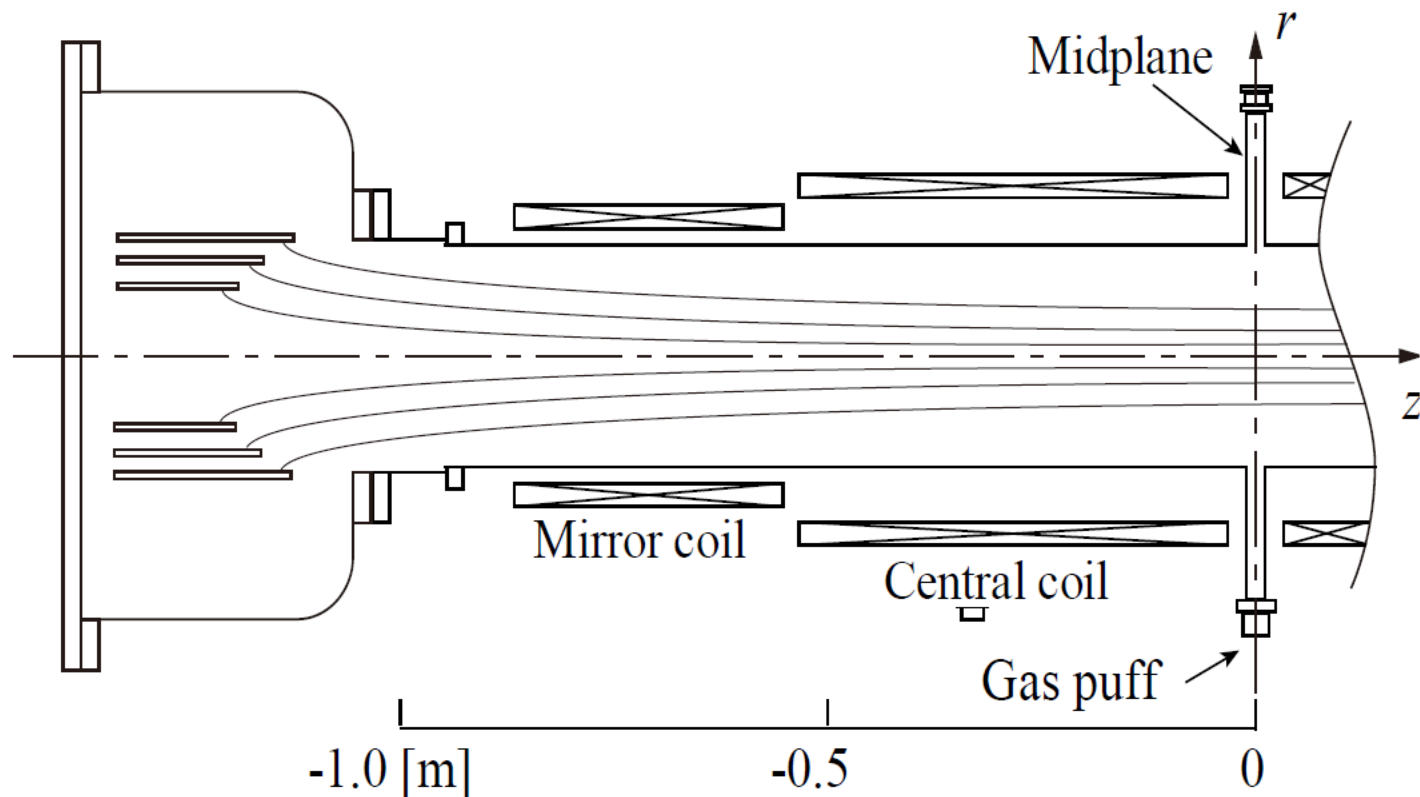


Figure 3. Conceptual view of coaxial biasing electrodes

Geoff Olynyk's work:

IOP Publishing and International Atomic Energy Agency

Nuclear Fusion

Nucl. Fusion 48 (2008) 095001 (9pp)

doi:10.1088/0029-5515/48/095001

Development of a compact toroid fuelling system for ITER

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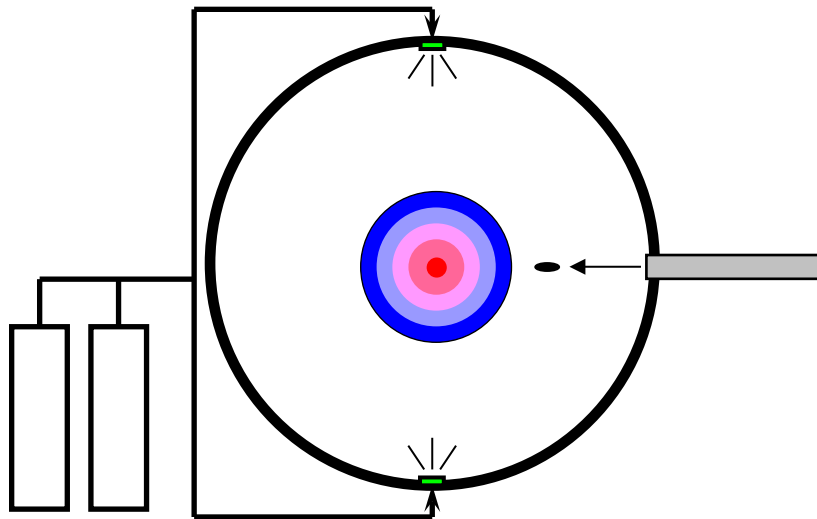
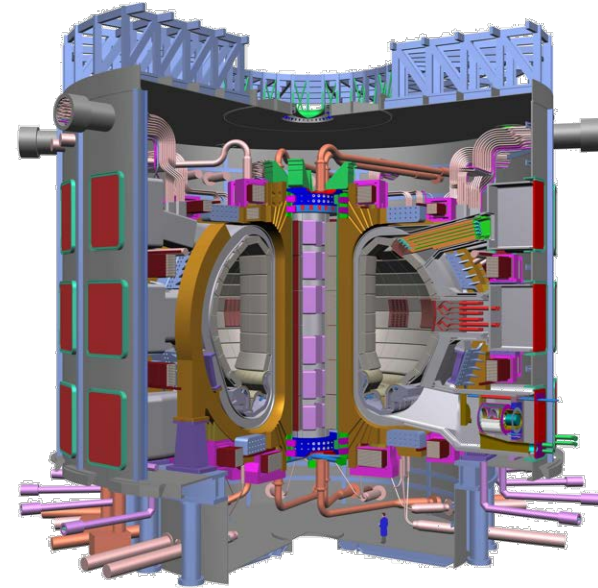
Abstract

A review of literature relevant to compact toroid (CT) injection is presented. A design is then developed for a repetitive-fire CT injection fuelling system for the ITER (2001) tokamak. Advantages of central over edge fuelling include plasma density control and higher deposition rates, implying lower tritium usage. The reference design offers $50 \text{ Pa m}^3 \text{ s}^{-1}$ of 90%T/10%D fuelling. 1.29 mg CTs are injected at a rate of 50 Hz (in order to synchronize with the European power grid) and a speed of 300 km s^{-1} . A new six-degree-of-freedom model of CT trajectory in the tokamak is developed and applied to the proposed injector design. The fueller is intended to work in parallel with the $400 \text{ Pa m}^3 \text{ s}^{-1}$ edge gas puffing system and to replace the centrifuge pellet-injection system in the ITER (2001) reference design. Each injected CT adds only 0.68% to the plasma inventory, implying that the injection process will be non-disruptive. Power consumption will be approximately 15 MWe. The strengths of the design compared with the current pellet-injection system are highlighted.

PACS numbers: 25.60.Pj, 52.25.Dg, 52.50.Dg, 52.55.Pa, 52.59.Dk, 52.65.Kj

ITER & Central Fuelling

- ITER (2001) – the first experimental fusion reactor planned to reach $Q > 0$ for sustained periods.

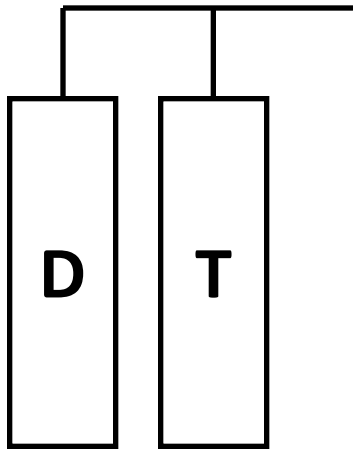


- Long operation necessitates fuelling
- Central fuelling most effective

Status-Quo ITER Fuelling Systems

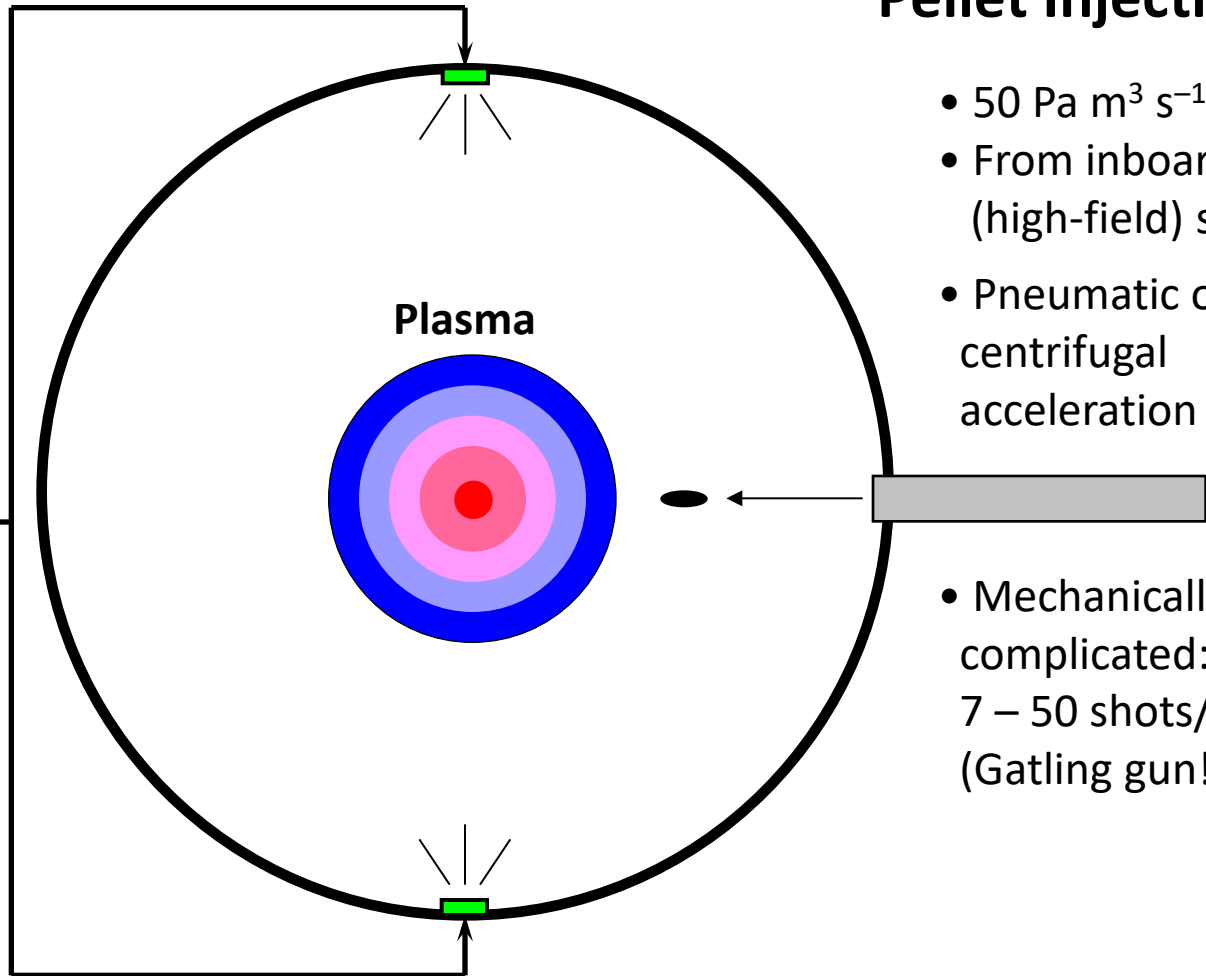
Gas Puffing

- $400 \text{ Pa m}^3 \text{ s}^{-1}$
- Two poloidal locations (top and bottom)
- Six toroidal locations

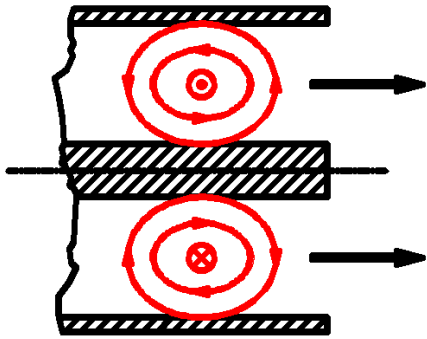


Pellet Injection

- $50 \text{ Pa m}^3 \text{ s}^{-1}$
- From inboard (high-field) side
- Pneumatic or centrifugal acceleration
- Mechanically complicated: 7 – 50 shots/s (Gatling gun!)

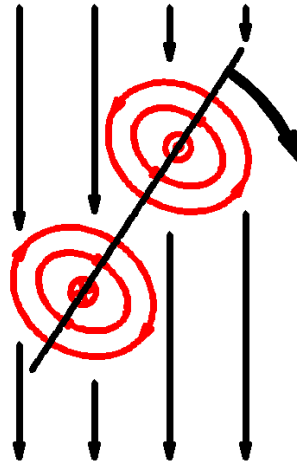


Compact Toroid Dynamics



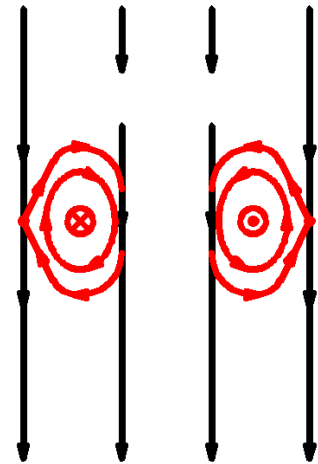
1

Firing



2

Tilting

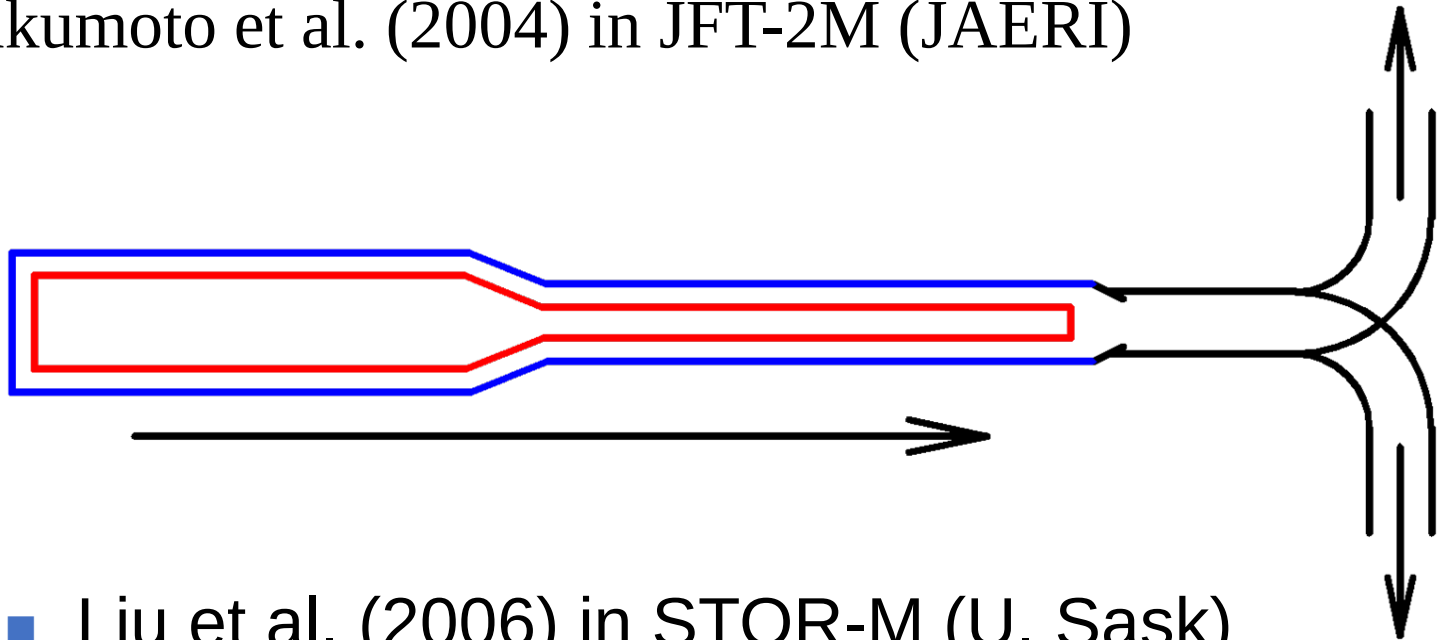


3

Reconnection

Vertical Injection

- Fukumoto et al. (2004) in JFT-2M (JAERI)



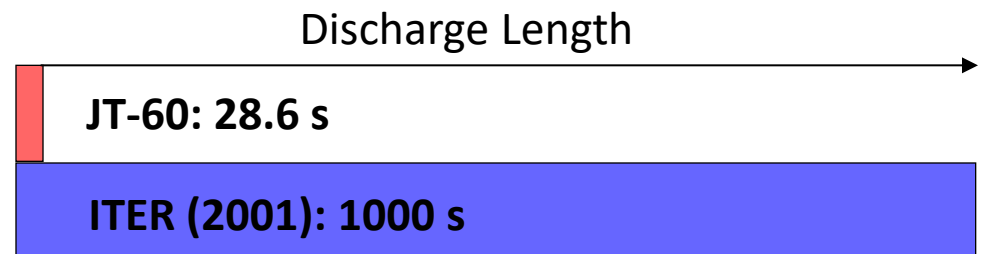
- Liu et al. (2006) in STOR-M (U. Sask)

Objective

- To **design** a repetitive-fire compact toroid injector which can deliver $50 \text{ Pa m}^3 \text{ s}^{-1}$ of deuterium / tritium fuel to the plasma core.
 - $64.4 \text{ } \mu\text{g/s}$
- To **evaluate** the proposed fueller's design and expected performance in the context of competing designs.

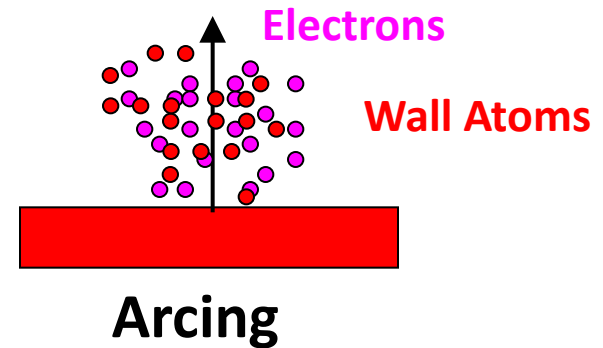
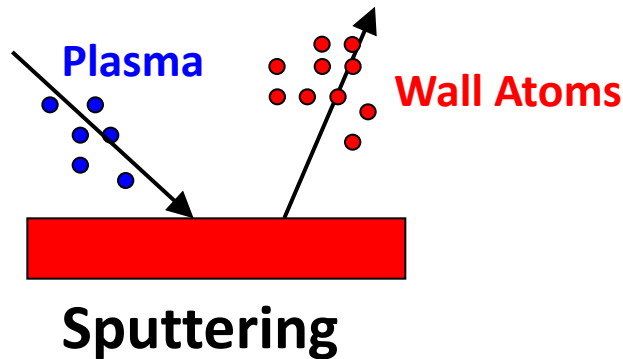
Design Considerations

- Physical layout
 - Must fit into ITER (2001) design
 - Attempt to achieve central deposition of fuel
- Power consumption
 - ITER Hybrid #1 operation mode – 700 MWt
- Neutral & metallic leakage into plasma
- Longevity
 - Repeatability
 - Maintenance



Wall Material Requirements

Want to avoid



- Stainless steel sputters too easily – probably ruled out
- Tungsten – highest sputtering threshold of any material
- Thoriated tungsten – used in fluorescent lights
- Lanthanum-oxide-doped tungsten – planned for ITER wall already, low electron work function

CT Dynamics Investigation

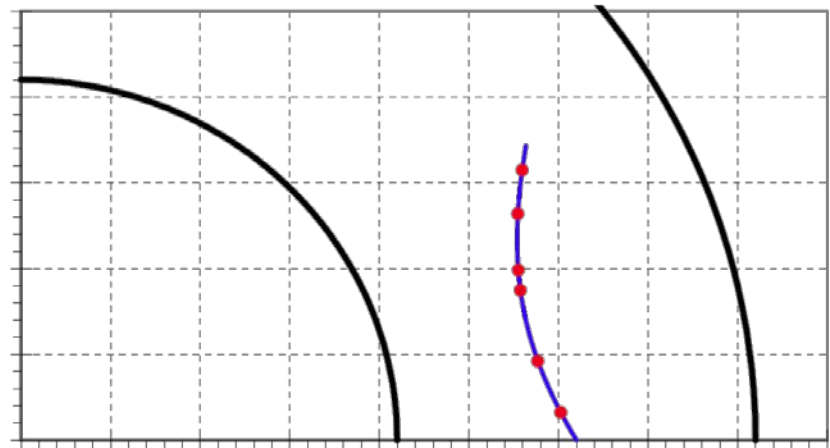
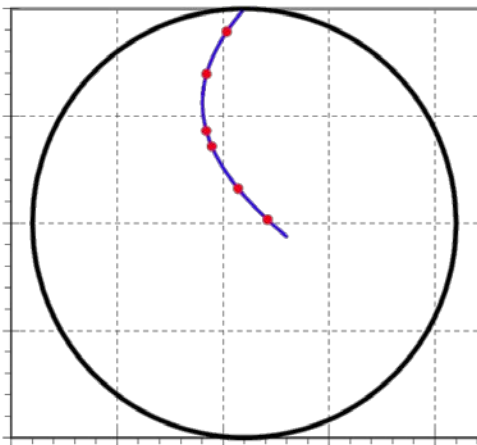
- Coordinates $R, \varphi, Z, \alpha, \beta, \gamma$

$$\begin{aligned} \mathcal{L} = & \frac{1}{2} m_{CT} \left(\dot{R}^2 + R^2 \dot{\phi}^2 + \dot{Z}^2 \right) + \frac{1}{5} m_{CT} r_{CT}^2 \left(\dot{\alpha}^2 + \dot{\beta}^2 + \dot{\gamma}^2 \right) \\ & - \frac{B_0^2 R_0^2}{2\mu_0 R^2} \frac{4}{3} \pi r_{CT}^3 - \frac{k B_{CT}}{\mu_0} \frac{4}{3} \pi r_{CT}^3 \frac{B_0 R_0}{R} \times \\ & (\cos \alpha \sin \beta \cos \gamma \sin \phi + \sin \alpha \sin \gamma \sin \phi + \sin \alpha \cos \gamma \cos \phi - \cos \alpha \sin \beta \sin \gamma \cos \phi) \end{aligned}$$

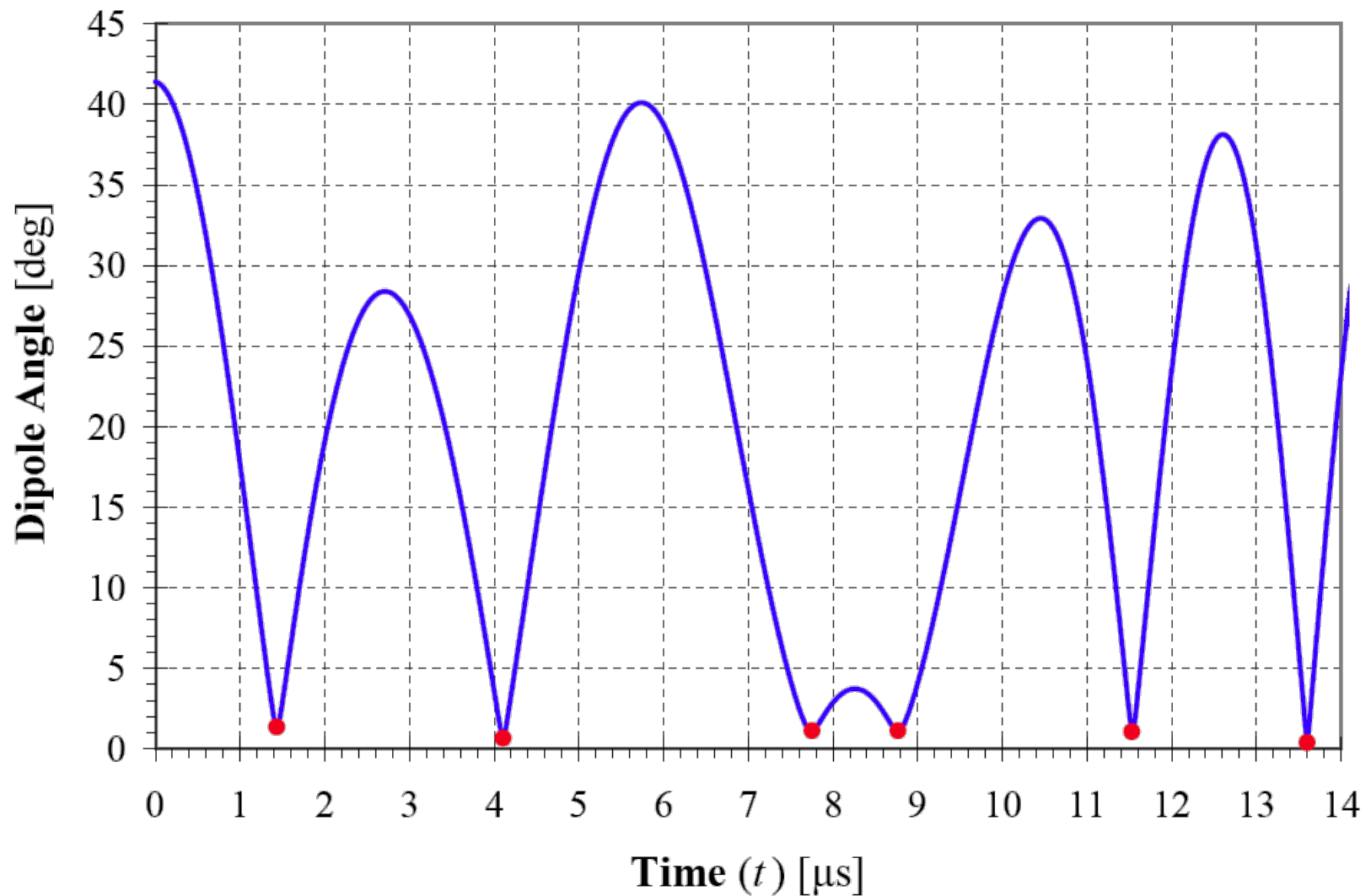
$$\mathcal{F} = \pi \rho r_{CT}^2 I V_A \times \left(\dot{R}^2 + R^2 \dot{\phi}^2 + \dot{Z}^2 \right)$$

CT Dynamics Investigation

- Lagrangian formulation of CT dynamics developed as an extension of the model of Bozhokin (1990) and Xiao et al. (1998)
- Models CT as conducting sphere in plasma
- Used to determine optimal parameters.
Results: $V_0 = 300 \text{ km s}^{-1}$, $\theta_T = 60^\circ$, $\theta_P = 30^\circ$



CT Dynamics Investigation



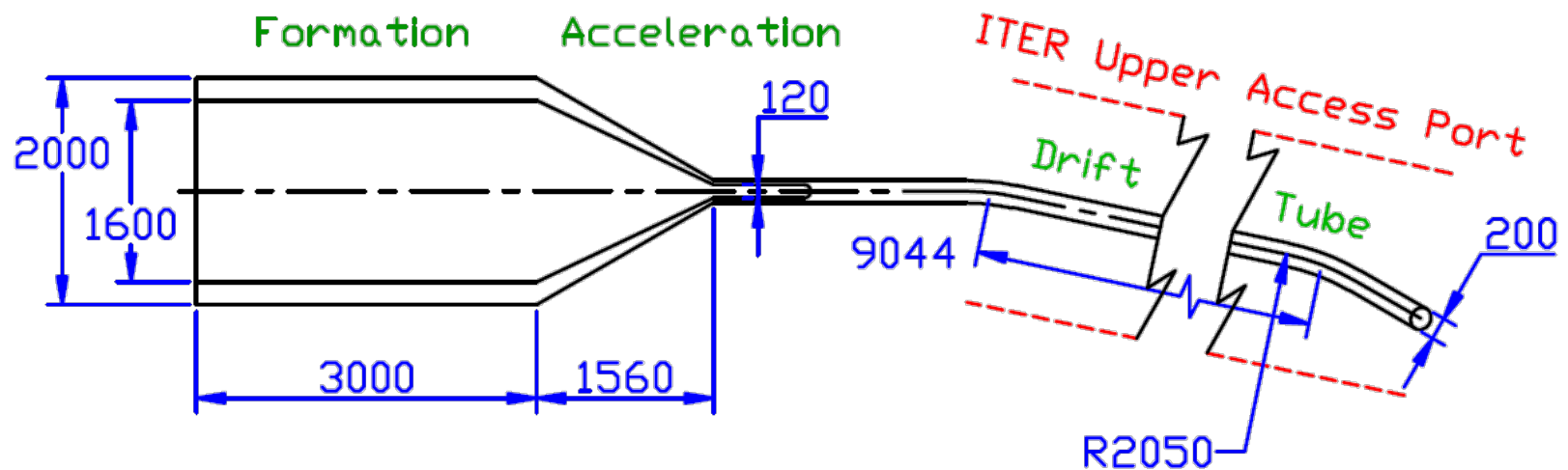
Choice of Parameters

- Parameters **chosen based on past experiments**: gun diameter, voltage, length
- Parameters **assumed equal to those from previous work**: CT magnetic field, tungsten entrainment in CT
- Parameters **chosen to fit the ITER fueller**: injection velocity, injection angle, CT dimensions and density

Parameter	Value
CT Radius	0.1 m
CT <i>B</i> -field	0.4 T
CT velocity	300 km s ⁻¹
Toroidal angle	60°
Gun voltage	3.5 kV
CT mass	1.29 mg
Firing rate	50 Hz
Efficiency	20 – 30 %

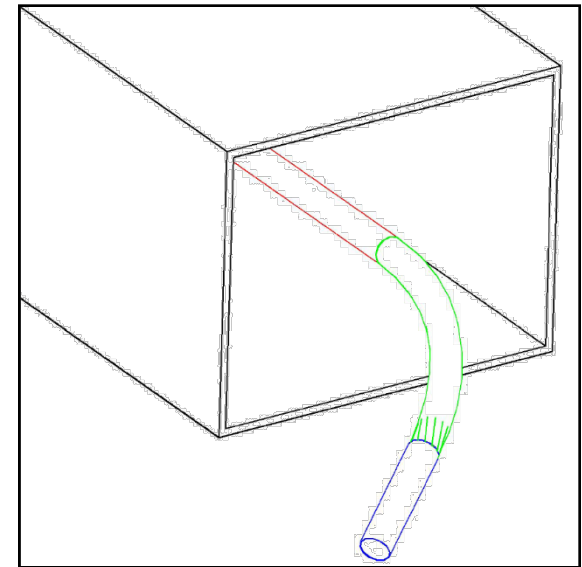
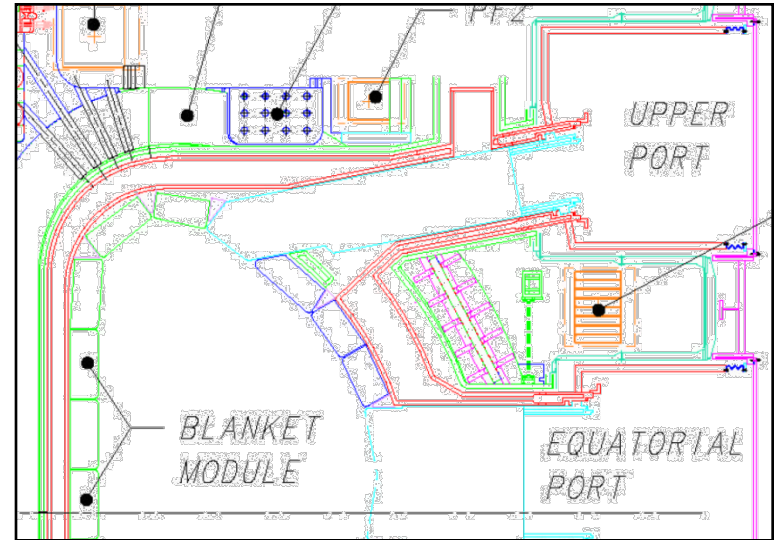
Design Overview

- Large (2 m) formation region connected to 200 mm drift tube; gun fires at 300 km s^{-1} .
- Tube bends at end to inject 60° in toroidal direction from top of tokamak, 30° poloidally inwards.



Design Elements

- Physical layout in ITER building:
vertical injection using upper port as access
- Gun fabricated of **copper with tungsten armour**
- Shielding of electronic components provided by **conical acceleration region**



Design Elements

- 240 fast gas puffing valves, actuated for 680 μs per shot allows 1.29 mg gas through
- Fuel (90% T / 10% D) supplied via stainless steel T₂ and DT lines from ITER “ring manifold” – always in gas phase
- Assuming comparable formation and acceleration efficiencies to previous work, power consumption should be $\sim 14.5 \text{ MW}$

Olynyk's Conclusions & Future Work

- Possible to deliver $50 \text{ Pa m}^3 \text{ s}^{-1}$ of central D_2/T_2 fuelling at a power consumption of approximately 15 MW.
- Each injection (50 per second) adds 0.67% to tokamak particle inventory
- Simpler fuel handling than pellet injection.
- Desirable to refine CT trajectory model and verify using experimental results (on the scale of US DOE MARAUDER project)

Banks' and Segal's work:

- Comsol Release 5.0 in 2014 was not backward compatible with Release 3.3 from 2006. Models needed to be recreated.

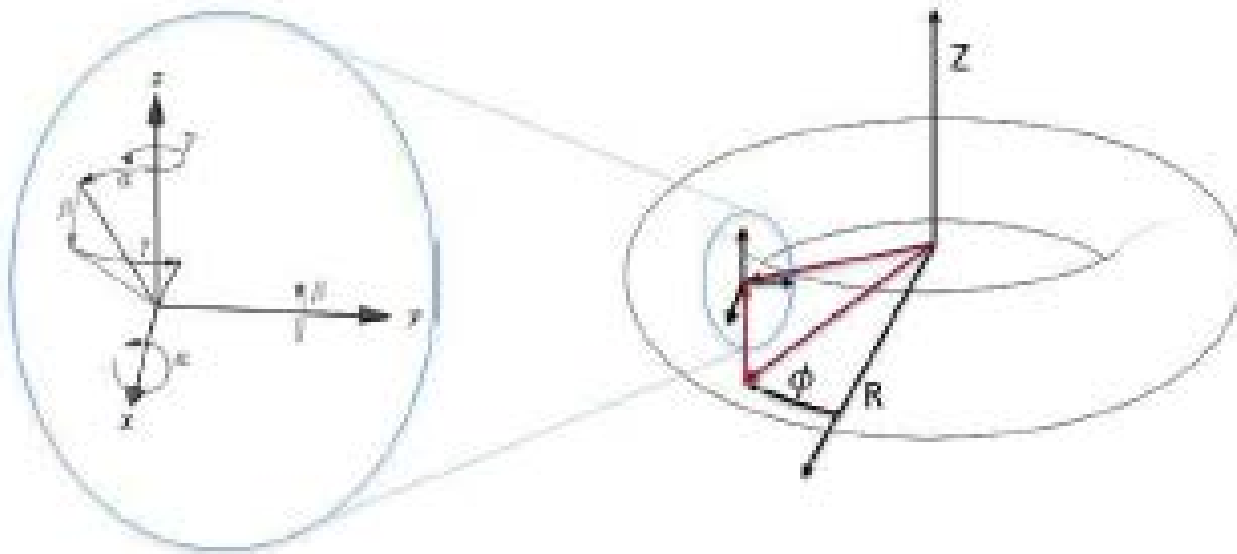


Figure 4: rotation angles for the CT dipole moment (α, β, γ) about degenerate body axes (x, y, z). Degenerate body axes correspond to Global tokamak axes (X, Y, Z).

Modeling

- The equations of motion for the CT in the tokamak magnetic field are derived from the 6 DOF Lagrangian [7] :

$$\begin{aligned}
 \mathcal{L} = & \underbrace{\frac{1}{2} m_{\text{CT}} (\dot{R}^2 + R^2 \dot{\phi}^2 + \dot{Z}^2)}_{\text{linear kinetic}} + \underbrace{\frac{1}{5} m_{\text{CT}} r_{\text{CT}}^2 (\dot{\alpha}^2 + \dot{\beta}^2 + \dot{\gamma}^2)}_{\text{rotational kinetic}} \\
 & - \underbrace{\frac{B_0^2 R_0^2}{2\mu_0 R^2} \frac{4}{3} \pi r_{\text{CT}}^3}_{\text{magnetic field exclusion}} - \underbrace{\frac{k B_{\text{CT}}}{\mu_0} \frac{4}{3} \pi r_{\text{CT}}^3 \frac{B_0 R_0}{R}}_{\text{dipole/tokamak interaction}} \\
 & \times \underbrace{(\cos \alpha \sin \beta \cos \gamma \sin \phi + \sin \alpha \sin \gamma \sin \phi)}_{\text{dipole/tokamak field interaction (cont'd)}} \\
 & + \underbrace{\sin \alpha \cos \gamma \cos \phi - \cos \alpha \sin \beta \sin \gamma \cos \phi)}_{\text{dipole/tokamak field interaction (cont'd)}},
 \end{aligned}$$

Modeling

Brief side note on Lagrangian Mechanics

- The Lagrangian can is defined by

$$L = T - V$$

Where T is the kinetic energy and V is the potential energy

- Given a Lagrangian for a physical system, the evolution of that system is describe by the equation

$$\frac{d}{dt} \left(\frac{\partial \mathcal{L}}{\partial \dot{q}_j} \right) - \frac{\partial \mathcal{L}}{\partial q_j} + \frac{\partial \mathcal{F}}{\partial \dot{q}_j} = 0$$

Where the index j is taken over all the degrees of freedom [9]

Modeling

- Euler-Lagrange equations contain another term for the non-conservative force (Rayleigh dissipation), $\mathcal{F}$, caused by magneto hydrodynamic wave drag

$$\frac{d}{dt} \left(\frac{\partial \mathcal{L}}{\partial \dot{q}_j} \right) - \frac{\partial \mathcal{L}}{\partial q_j} + \frac{\partial \mathcal{F}}{\partial \dot{q}_j} = 0$$

$$\mathcal{F} = \pi \rho r_{\text{CT}}^2 I V_A \times (\dot{R}^2 + R^2 \dot{\phi}^2 + \dot{Z}^2)$$

$$I = \frac{V_s}{V_A} \left[\frac{2}{9} \left(1 + \ln \frac{V_A}{V_s} \right) - 0.37 \right]$$

I is a dimensionless drag coefficient derived by Newcomb

Modeling

- Constants solved for using the most recent parameters for the ITER final design

- Other important equations:

$$V_A = B_0 / \sqrt{\mu_0 n_0 \bar{m}} \quad V_s = \sqrt{\gamma Z k_B \left(\frac{T_e}{\bar{m}} \right)}$$

- Can then procedurally calculate the E-L equations of motion

Parameter	Description	Value
m_{CT}	Mass of the compact toroid	$1.29e - 3 [kg]$
r_{CT}	Radius of the (spherical) compact toroid	$0.1 [m]$
a	Minor radius of the ITER tokamak	$2 [m]$
B_0	Average toroidal magnetic field intensity inside the tokamak	$5.3 [T]$
R_0	Major radius of the tokamak	$6.2 [m]$
V_A	The Alfven velocity	$7.5792e + 06 [m/s]$
V_s	The ion sound velocity	$9.5863e + 05 [m/s]$
I	Dimensionless parameter [5]	0.0394
n_0	ITER plasma density	$9.3e19 [m^{-3}]$
$\bar{m}$	Average ion mass ($\bar{m} \cong 2.5m_H$) [4]	$4.1843e - 27 [kg]$
γ	Adiabatic index (equation 6 only)	1
Z	Number of protons (equation 6 only)	1
T_e	Average electron temperature in the ITER tokamak	$9.6 [KeV]$

Vertical Injection

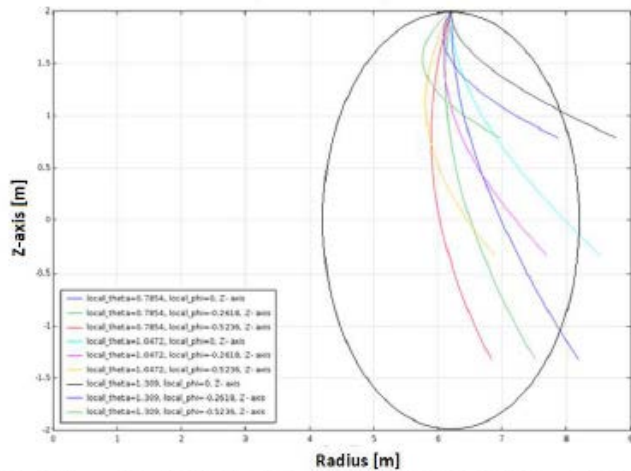


Figure 5: Radius versus Z axis plot of Vertical injection through all permutations of local $\theta = [45, 60, 75]$ degrees and local $\phi = [0, 15, 30]$ degrees, over a time periods of 20 μ s with an injection velocity of 300 km s⁻¹. The circular cross section of the tokamak has been made elliptical by the axis choice of the plot.

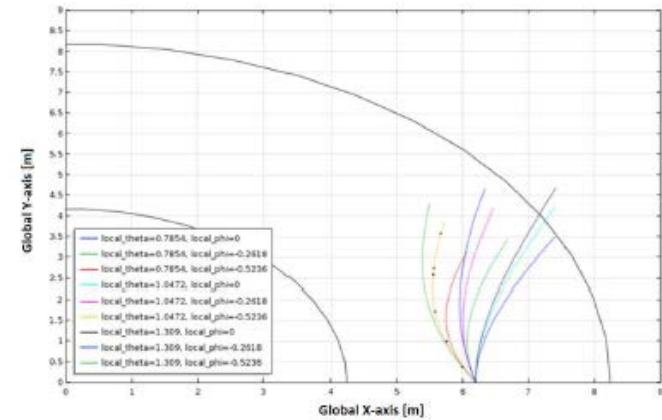


Figure 6: Global X versus Y plot of Vertical injection through all permutations of local $\theta = [45, 60, 75]$ degrees and local $\phi = [0, 15, 30]$ degrees, over a time periods of 20 μ s with an injection velocity of 300 km s⁻¹. The dots along the yellow trajectory indicate possible reconnection opportunities.

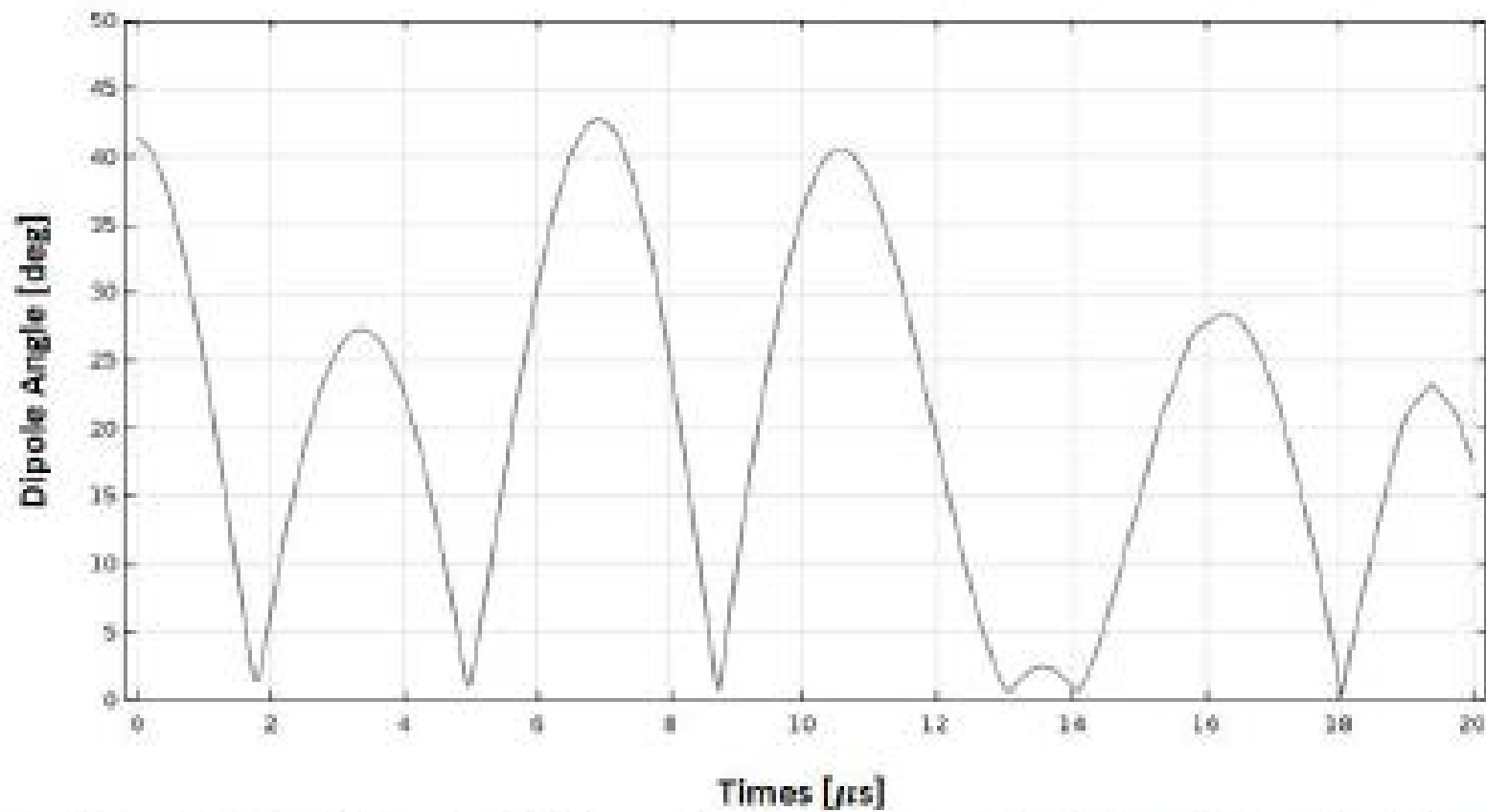


Figure 7: The calculated angle between the CT dipole angle and the tokamak magnetic field lines as a function of time. Minima indicate possible reconnection events

Time [μs]	Dipole Angle [deg]
1.79	1.3361
4.98	1.0079
8.73	0.7647
13.1	0.5986
14.05	0.6693
18.04	0.3971

Horizontal Injection

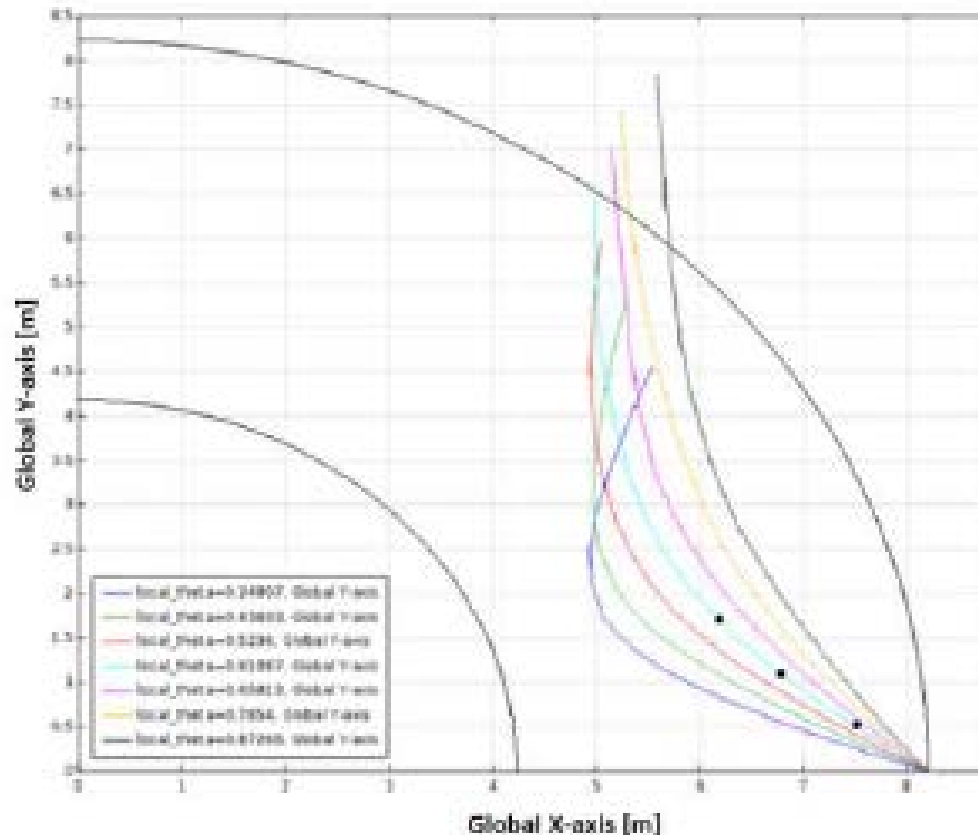
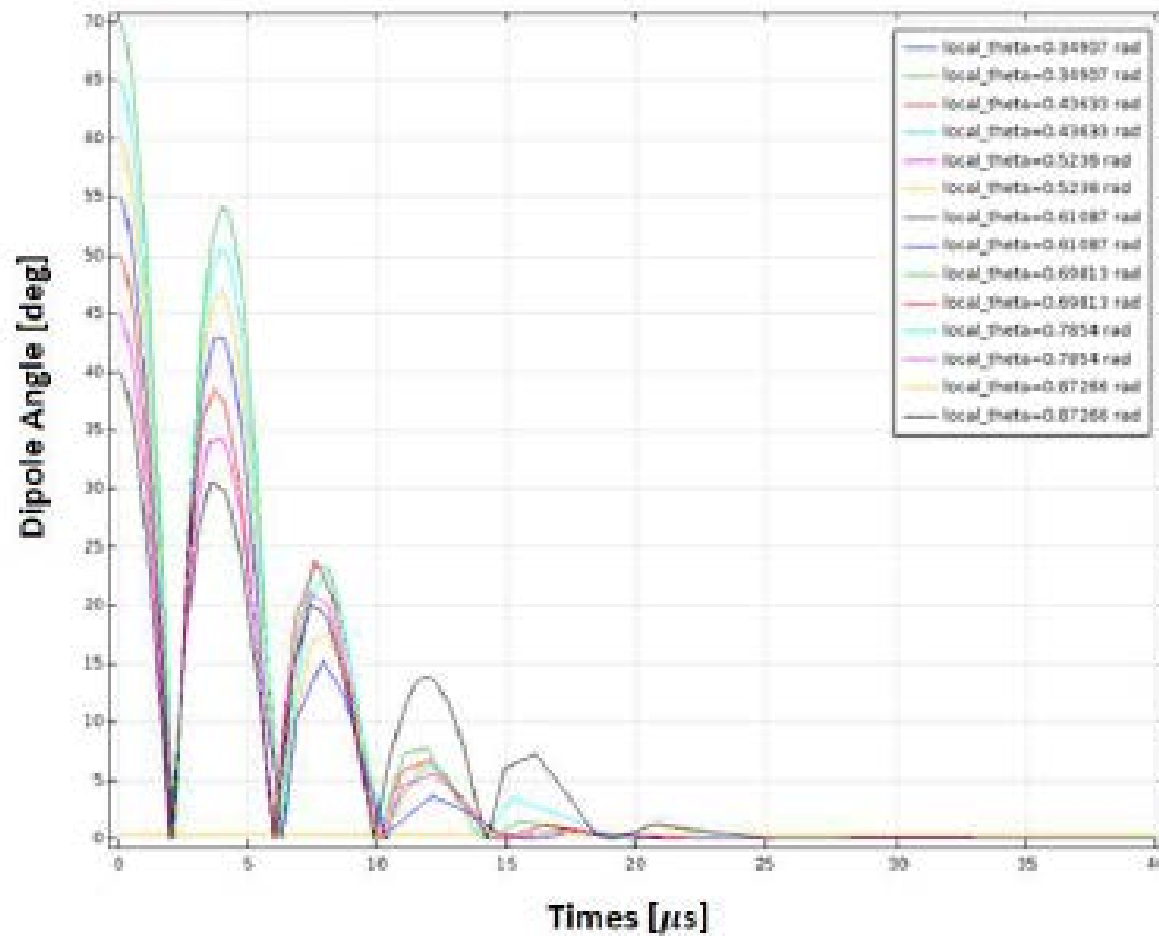


Figure 8: Plot of horizontal injections in the global X-Y plane where the injection angle $\text{local } \theta$ was varied over the range (20, 50) degrees. Each trajectory is a $40 \mu\text{s}$ path with an injection velocity of 300 km s^{-1} .



Time [μ s]	Dipole Angle [deg]
2.055	0.0383
6.31	0.0071
10.33	0.0140

Figure 9: Plot of the Dipole angles of each trajectory in Figure 8 where the injection angle local θ was varied over the range (20, 5, 50) degrees.

- Convergence of the solutions was approximately 6s on an Intel® Xeon® CPU E5-2650 v3, 2.3 GHz processor with 4 GB of RAM.
- Previously required approximately 30s in 2007 when Olynky ran simulations.

Fusion Research Opportunities:

- ? Collaborate with General Fusion to model their injector for possible installation on a large tokamak such as JET.
- ? Comsol vs VAC code.
- ? Collaborate with Nihon University and TAE Inc.



Advance Fuels – Aneutronic Fusion



Graduate Student Opportunities:

- Position for a fully funded Ph.D. student
 - Must be a Canadian citizen or Permanent Resident
 - \$25,450.00 per year guaranteed for up to four years.
- Position for a fully funded M.A.Sc./M.Sc.
 - Must be a Canadian citizen or Permanent Resident
- Post Doctoral research position in NDE

Areas of research:

- Fusion work
- Advanced Rail work
- NDE work

Acknowledgements

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Questions

