Surface plasma Arc by Radiofrequency - Control Study (SPARCS)

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1 Project Objective

This paper is to summarize the work carried out between April 2012 and April 2013 for development of an experimental device to simulate interactions of off-normal detrimental events in a tokamak and ICRF antenna. The work was mainly focused on development of a pulsed plasma source using theta pinch and coaxial plasma gun. This device, once completed, will have a possible application as a test stand for high voltage breakdown of an ICRF antenna in extreme events in a tokamak such as edge-localized modes or disruption.

Currently, DEVeX does not produce plasma with high temperature enough to requirement for an ELM simulator. However, theta pinch is a good way to produce high temperature ions. [1] The unique characteristic of plasma heating by a theta pinch is advantageous for an ELM simulator due to its effective ion heating. The objective of the proposed work, therefore, is to build a test facility using the existing theta pinch facility in addition to a coaxial plasma gun. It is expected to produce a similar pulsed-plasma heat load to the extreme events in tokamaks and to be applied for studying interactions of hot plasma and ICRF antennas.

2 Divertor Erosion and Vapor-Shielding Experiment (DEVeX)

Divertor Erosion and Vapor-Shielding Experiment (DEVeX) was developed to produce energetic plasma flow to initially study vapor shielding phenomenon. The key components are the the θ pinch device and the target chamber. The theta-pinch device is used to generate hot and dense plasmas and the target chamber is housed with several diagnostics and diagnostic ports for optical access. Fig. 1 shows the schematic of the experimental setup and . A single-turn, four-segmented theta coil is used to generate and tocompress the plasma and it is conically tapered to 1 ° to expel the plasma preferentially into the target region, although in reality the plasma goes both directions. The theta coil has an inner diameter 0.1 m, an outer diameter of

Table 1: Summary of plasma parameters for DEVeX-Upgrade and ITER ELM

Parameters	**DEVeX-Upgrade**	**ITER ELM**[2]
n_e (/m^3)	$\sim 10^{21}$	$10^{21} - 10^{22}$
T_e (keV)	≥ 0.1	~ 1
Flow velocity (m/s)	5×10^4	$\geq 1 \times 10^5$
τ_p(ms)	≤ 0.1	0.1 - 1
Plasma Energy (MJ/m^2)	~ 0.1	1-3
Heat Flux GW/m^2	$0.1 - 1$	≤ 10

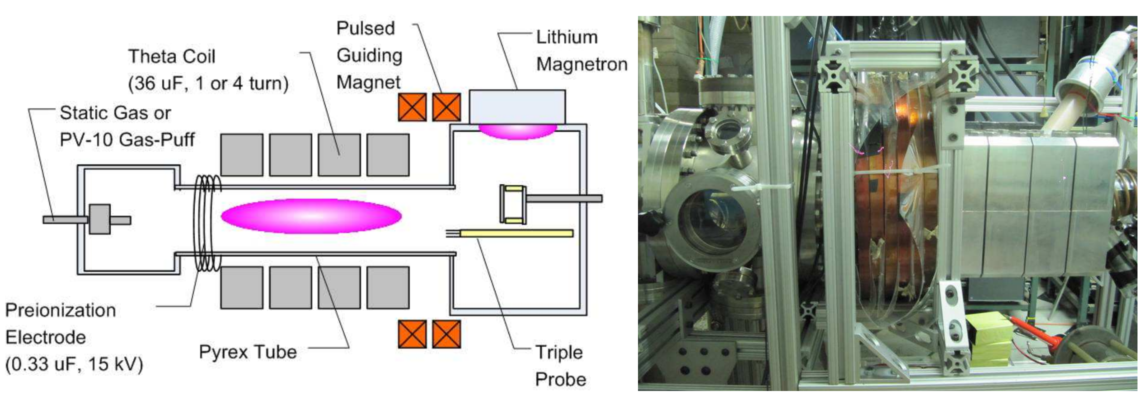
0.254 m, and a length of 0.36 m. Using the formula in [3], the inductance of the theta coil is estimated to be approximately 40 nH for one-turn and 500 nH for four-turns.

In order to produce high current through the theta coil, 18 capacitors in parallel with total 36 μF are connected to a single turn theta coil through 15 Heliax cables. The theta coil surrounds a 10 cm diameter quartz tube, in which plasma is generated and compressed. A main railgap switch is used to discharge the main capacitors and is controlled by a high-voltage trigger and handles more than 300 kA peak current. The capacitors can hold up to 60 kV, however, for all the experiments presented here the charging voltage of the capacitor is xed at 20 kV or less, resulting maximum 7 kJ of electric energy stored up in the capacitors.

3 Gas-Puff Driven Theta Pinch Experiment

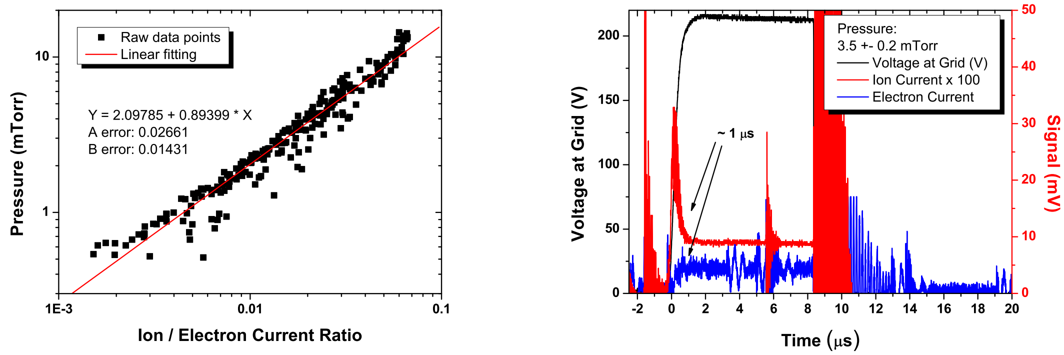
While the plasma is heated in the theta pinch by implosion process and adiabatic heating, plasma energy is lost during translation process due to 1) decrease in the magnetic field outside the coil, resulting in a large amount of energy loss in the radial direction and 2) numerous collisions of energetic particles with the neutral gas before they reach the target. The collision further reduces plasma diffusion, thereby plasma flow velocity, and enhances diffusion across the magnetic field. Since the operation pressure is around 5 to 10 mTorr for the static-filled gas experiment, mean free path is only a few centimeters and the energetic particles will lose their energies mainly via charge-exchange process. However, use of gas puff may mitigate energy loss through collisions because one can control flow of gas and trigger the pulse device at such a time that gas in the plasma generation region is high while the transport region is sub-mTorr. Veeco PV-10 piezoelectric valve is used to control gas flow into the chamber.

In order to achieve the objective, a reliable way to measure the fast-changing gas pressure is indispensable. A hot filament ion gauge is considered one of the best ways to measure the time-varying pressure. However, commercially available fast ionization gauges are usually very expensive; therefore, a small size ionization gauge (355 Micro ion gauge, Brooks Granville-Phillips) is tested for fast response pressure measurement. In order for the ion gauge to be applicable for the fast-response measurements, the gauge needs to have 1) a linear response up to the pressure of interest 2) an open structure to minimize the perturbation of gas flow, and 3) fast rise time with a good signal to noise ratio [4]. As for 1), volume of the gauge should be much smaller than mean free path of the gas to ensure that number of electrons resulting from the ionization process is smaller than electrons emitted from a filament, thereby the collected ions at the collector come from the ionization process by electrons from filament. For 3), an amplifier circuits are added very close to the pressure gauge to minimize Miller effect and expand the measurement range down to 10^{-6} or even lower [5]. However, the amplifier circuit has an inherent limitation in bandwidth so that a fast-response measurement is still troublesome. For 355 Micro ion gauge, its size is smaller than other pressure gauges,



(a) (b)

Figure 1: (a) the schematic of the DEVeX experimental setup (b) the picture of DEVeX chamber



(a) (b)

Figure 2: (a) Pressure calibration with Baratron gauge [6] (b) Bandwidth test result with a square voltage pulse at the collector.[6]

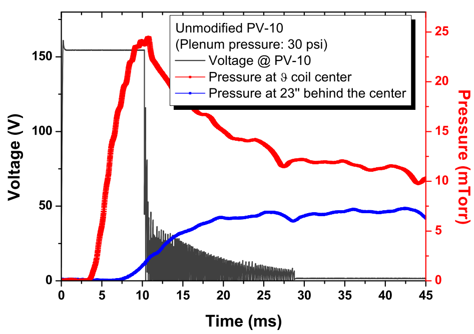


Figure 3: Pressure measurement using the fast ionization gauge in DEVeX at two different locations. The red lines are pressure at the center of the theta coil and the blue lines are 23 inch away from the center of the coil.

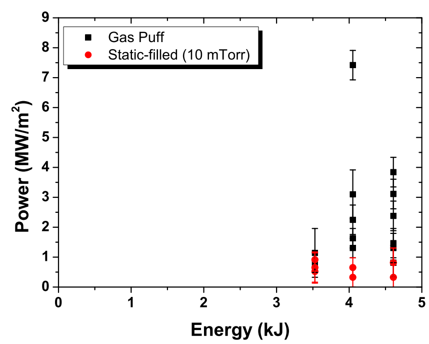


Figure 4: Plasma heat flux on the target for static-filled and gas-puff cases.

ensuring linear measurement up to 50 mTorr. Moreover, since we are interested in at lowest 10^{-4} Torr, the complexity of amplifier circuit can be avoided.

In Fig 2(a), the ratio of ion and electron current follows a linear response up to 10 mTorr or higher. The sensitivity factor of the calibration is estimated 8.0, which is close to an ideal sensitivity factor of the Bayard-Alpert ionization gauge for hydrogen. The calibration curve is obtained to convert the ion and electron current ratio to pressure. Fig 2(b) shows the response time of the ion gauge with 10 μs 180 V square voltage pulse applied to the collector at 3 mTorr. The rise time of the ion current is approximately 1 μs, resulting in approximately 350 kHz bandwidth.

Fig 3 shows measured gas pressure at two different locations in the chamber at 30 psi in the PV-10 valve. The gas arrives at the center of the coil at 4 to 5 ms, while the gas is not detected at the target region until 7 or 8 ms after the triggering. While the maximum achievable speed at supersonic flow for hydrogen is 3 km/s, the gas flow speed is very slow, just a few hundred m/s, possibly due to shock formation in the gas flow. The slow flow velocity is actually more desirable for this experiment because it gives larger time window for fueling purpose.

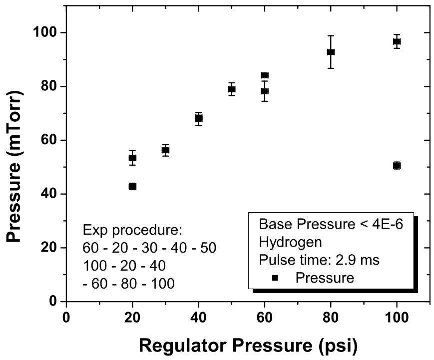


Figure 5: Relation of the regulator pressure and the chamber pressure for Series 9

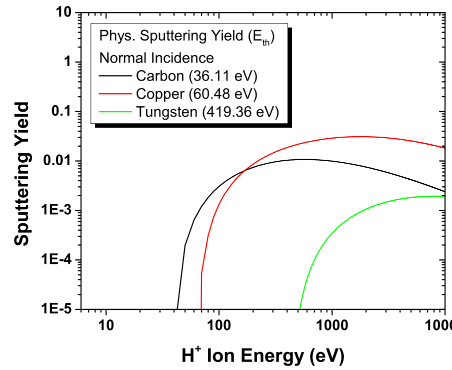


Figure 6: Physical sputtering yield of several electrode materials with an impact of a hydrogen ion as a function of energy

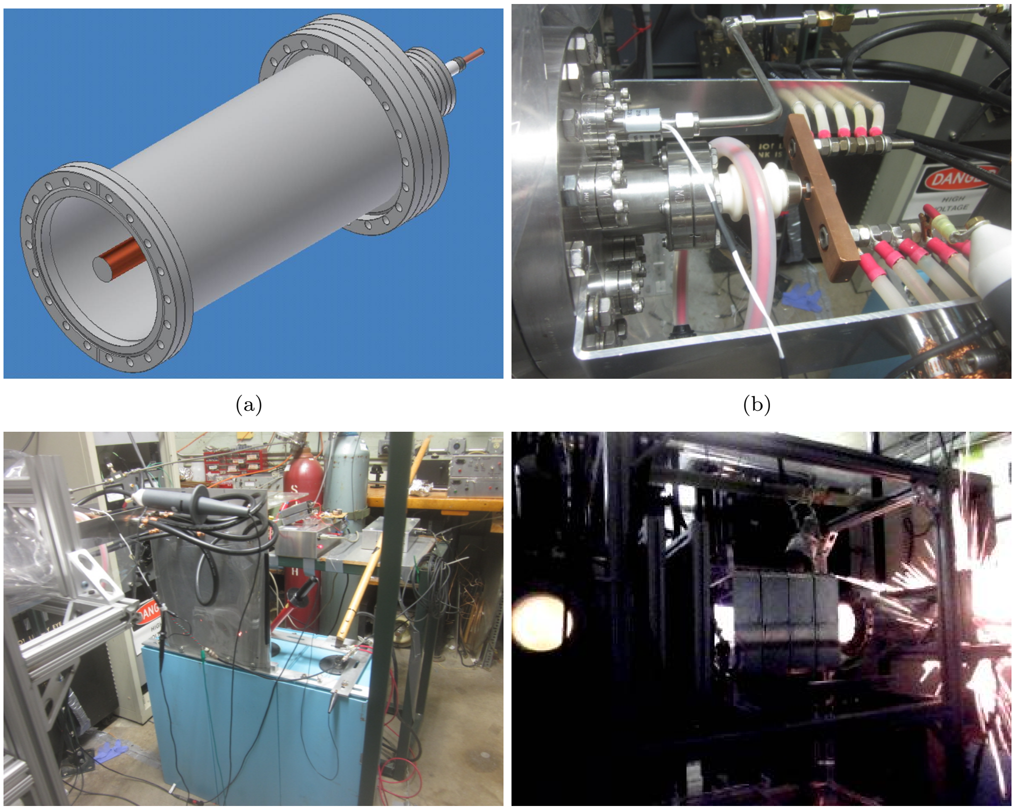
A thin foil target (56 mm × 56 mm × 0.003 Molybdenum), K-type thermocouple, Labjack DAQ device and LJTick-InAmp are used to measure the temperature increase. Fig 4 shows energy delivered on the target with four-turn theta coil and external solenoid low density preionization electrode powered by 0.33 μF at 15 kV. Maximum 7.4 ± 0.5 MW/m^2, avg. 2.4 ± 1.4 MW/m^2 achieved with gas-puff while the steady-state case at 10 mTorr produces 0.92 ± 0.35 MW/m^2. Gas-puff-driven theta pinch shows more than a factor of two larger energy flow to the target than the static-filled case.

Since PV-10 valve has very slow opening and closing time and the gas flux is low, a better gas puff valve is required. A series 9 Parker valve is purchased and tested. It has a response time less than 3 ms and higher gas flux is provided by the valve. Fig 5 shows increase in pressure with various regulator pressures. Pulse on-time is fixed at 2.9 ms during the operation. Fig 5 shows that approximately 100 mTorr of the chamber pressure was achieved at 100 psi regulator pressure and 2.9 ms pulse on-time and the pressure can be further increased with increasing pulse on-time.

4 Coaxial Plasma Gun Experiment

Plasma heating by implosion and adiabatic compression is effective only when a sufficient amount of preionized plasma exists in the chamber at a pre-implosion stage.[7, 8, 9, 10] Not only that, plasma drift velocity by axial diffusion is too low to simulate the extreme events in tokamaks. While several preionization methods such as inductive coupled plasma generation with a capacitor bank or an RF power supply were tried and showed increase in plasma energy, the degree of ionization was too low to observe a significant pinch effect. Moreover, axial diffusion in a theta pinch is too a slow process to be comparable with the drift velocity in off-normal events in tokamaks. A plasma gun, or a plasma accelerator is one of the best methods to produce preionized plasma and accelerate it at the same time.[11] Therefore, a coaxial type plasma gun is manufactured and added to the device.

There are a few limitation factors on arc plasma gun. The most serious and important one is ablation [12], mainly caused by surface heating and arcing. This is detrimental for two reasons: [13, 14] 1) it creates drag force on the accelerating plasma described as $\dot{m}v$ force and 2) it may form a new plasma region called plasma restrike which steals current from the main plasma. Therefore, the electrodes, especially the cathode on which ions bombard, need to be made of a material with high thermal conductivity and high melting temperature. Physical sputtering yield for several materials at a normal incidence is shown in Fig. **??** While tungsten provides the least sputtering yield in a full range of energy up to 10 keV, it is not used due to difficulty in machining. In case of carbon, possible chemical reactions of hydrogen and carbon causes



(a) (b)

(c) (d)

Figure 7: (a) a 3-D drawing of the coaxial plasma gun and the chamber (b) installation of the cathode to the chamber and coaxial transmission lines (c) a capacitor bank composed of three 500 μF capacitors and a transmission plate for the connection of coaxial cables (d) generation of plasma using the pulsed coaxial plasma gun at 500 mTorr static pressure

additional chemical sputtering. Therefore, oxygen-free copper has been chosen as the first candidate for the cathode. Design parameters $r_i = 1$ cm, $r_o = 5$ cm, and length = 0.4 m minimizes modification of the existing device.

An oxygen-free copper rod is connected through a medium voltage feed-through to a capacitor bank. The capacitor bank is assembled together and charging/discharging units including high voltage relays, a spark gap switch and a spark gap igniter are assembled to operate. The inductance of the transmission line is reduced by using 10 RG-217 coaxial cables. The capacitor bank is discharged through a spark-gap switch. High voltage insulation was tested up to 7 kV and no failure of insulation was observed. However, a lower voltage feed-through (rated at 12 kV) had an insulation failure at 7 kV, 500 μF capacitor bank shot. Therefore, a new voltage feed-through rated at 20 kV and 150 A was purchased and installed.

DC breakdown voltage is measured using a DC power supply and plotted in Fig 8. When pressure is above 100 mTorr, breakdown voltage doesn't change significantly and stays approximately 400 V. However, as pressure decreases below 100 mTorr, breakdown voltage starts to increase dramatically. Below 50 mTorr, plasma after the breakdown shows a different regime such that plasma is no more localized at the plasma gun but is diffused throughout the chamber. No breakdown was observed up to 1.5 kV when pressure decreases approximately below 30 mTorr.

Initial Experiments on plasma generation with the pulsed coaxial plasma gun are carried out. Capacitor voltage is fixed at 5 kV and the chamber pressure varies from 200 mTorr to 500 mTorr. 100 mTorr shot is

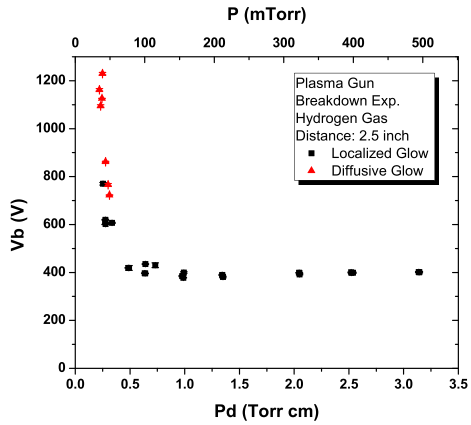


Figure 8: Breakdown voltage measurement at various pressures

erroneous with a huge jitter so that it is not included in the analysis. Pulse duration is 100 - 200 μs, voltage at the cathode is $\leq$ 4 kV, and the current exceeds a maximum value (= 12 kA) that can be measured by the rogowski coil used.

The remaining steps will be 1) higher voltage capacitor shot, 2) the plasma gun operation with gas puff system, 3) gas parameter measurement such as gas flow velocity and pressure at various locations in the chamber using a fast ionization gauge, 4) plasma parameter measurement using a triple Langmuir probe and time of flight technique, and 5) combined operation of the plasma gun with the theta pinch device.

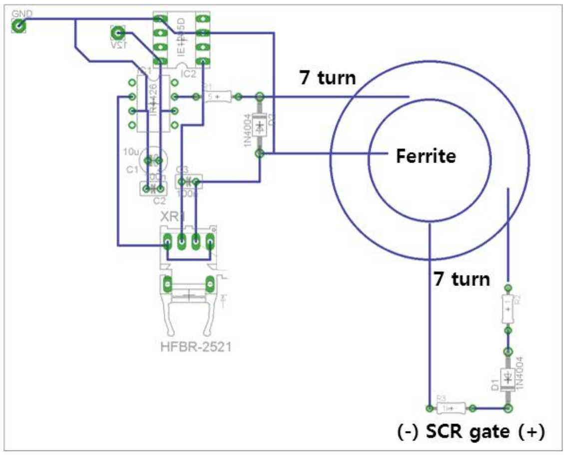
5 Installation of Guiding magnets

The important parameter to find is plasma diffusion characteristic time, since it is one of the factors that determine plasma transport from the theta pinch. Using the theory of Bohm diffusion, plasma diffusion time for 100 eV is approximately 30 μs at B = 0.1 T and 80 μs at B = 0.2 T. Since this approach assumes plasma size is very small compared to the size of the tube, actually diffusion time can be a factor of 2 - 4 lower than those calculated from Bohm diffusion. Not only that, plasma diffusion in the radial direction allows plasma to decrease its temperature due to adiabatic expansion. If there is no additional field, magnetic field produced at the theta coil decays dramatically and plasma is radially diffused by ambipolar diffusion. Therefore, these constraints invoke necessity of strong guiding magnetic field. The guiding magnetic field should be strong and straight in z-direction so that the field suppresses the radial expansion of plasma while it is transported to the target region.

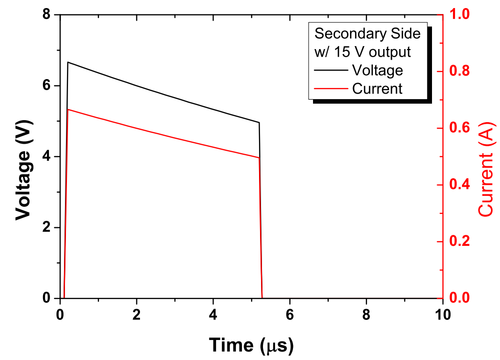
While the guiding magnet is required to produce high magnetic field, steady-state operation of magnet is not desirable for heat dissipation issue; therefore, a semiconductor switch is used to control the current pulse in the magnet. A SCR switch is chosen since the guiding magnets need to generate magnetic field only in one direction. In order to operate the SCR switch, a switch driver is required. There is another problem caused by high-side operation, where the negative side of the switch is connected to the load, not to the ground so that the reference voltage of the switch changes from zero to high voltage when the pulse is on. Therefore, an adequate voltage isolation is required.

50RIA60 SCR switch is selected for its capability to handle maximum 1.5 kA non-repetitive surge current at maximum at 600 V maximum off-state voltge. It requires minimum 0.1 A peak positive gate current and 2.5 V gate voltage to trigger. IR4426 is selected as a SCR driver for its maximum 20 V and 6 A output capability and controllability with CMOS logic signal. The isolation is double-folded: 1) isolation of signal generator from the main circuit using an optical fiber and 2) isolation of the main circuit from the SCR switch using an isolation transformer.

Fig 9(a) shows the scr driver circuit for 50RIA60 SCR switch. IR4426, DC-DC voltage converter, and



(a)



(b)

Figure 9: (a) SCR driver circuit in PCB layout (b) SCR output simulation at the secondary side with PSPICE assuming 10 Ohm resistive load

an optical fiber receiver are integrated to produce a voltage pulse. It is connected to the SCR switch via an isolation transformer with inductance at each side around 100 μH. The circuit simulation using PSPICE at Fig 9(b) shows that it produces enough voltage and current to trigger the SCR.

The position of the magnets need to be determined by computer simulation. The MAXWELL 2D is used to calculate and estimate magnetic flux lines in the chamber. Fig 10(a) shows change of magnetic flux with the guiding magnets. The guiding magnet's size and magnetic field is based on the currently available magnets in the lab. Fig 10(b) shows a current waveform when 4 mF capacitor is discharged at 100 V. Current stops when it becomes zero and $\tau_{1/2}$ is around 35 ms, which gives 16 Hz. The maximum 87 A and 0.17 T is obtained at 300 V discharge, as shown in Fig 10(c). Currently, two sets of guiding magnets are installed. The one closer to the theta coil produces a maximum of 0.4 T with a 8 mF capacitor bank and 40 ms pulse duration and the other set produces a maximum of 0.16 T with a 4 mF capacitor bank and 15 ms pulse duration.

6 Summary and Projected Work

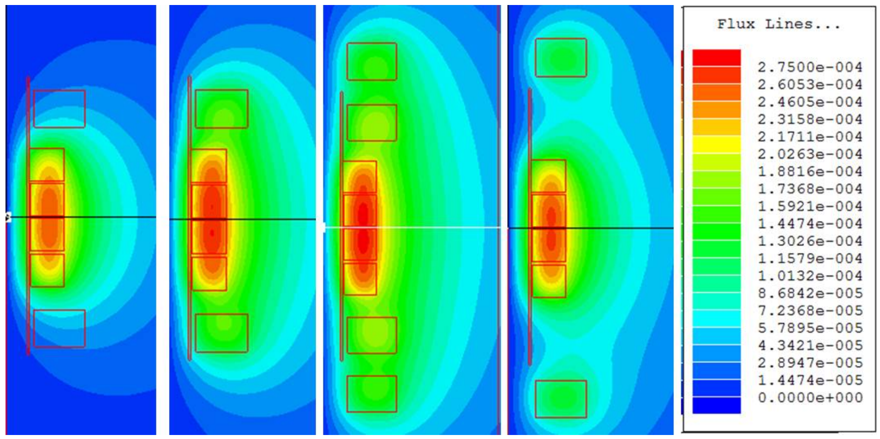
Efforts have been undertaken at University of Illinois to develop a test stand using a theta pinch device and a coaxial plasma gun for high voltage breakdown study in a similar condition to off-normal events in tokamak.

Gas-puff-driven theta pinch shows more than a factor of two larger energy flow to the target than the static-filled case. A new gas puff valve was purchased and it injects gas in much faster time response.

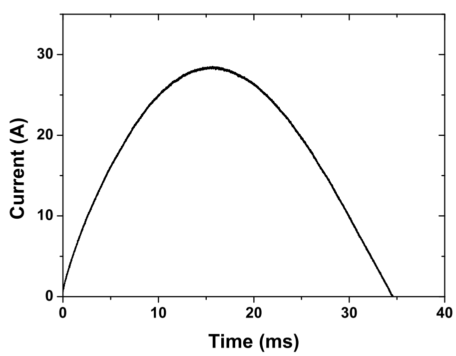
A coaxial plasma gun has been manufactured and breakdown voltage is measured with DC power supply. The data shows that static discharge is obtained at pressure greater than 100 mTorr with approximately 400 V. Pulse discharge is carried out at 5 kV, 500 μF capacitor with static-filled gas and shows that pulse duration is 100 - 200 μs, voltage at the cathode is $\leq$ 4 kV, and current greater than 12 kA is obtained.

A guiding magnet system has been manufactured. SCR triggering systems are manufactured and successfully trigger SCRs and guiding magnets. Maxwell simulations have been carried out to estimate magnetic field distribution in the chamber. Two sets of magnets are tested and installed to the chamber.

The remaining work is to operate the coaxial plasma gun with the gas puff valve, a combined operation of the coaxial plasma gun and the gas puff valve with the theta pinch device, and plasma and gas flow diagnostics.



(a)



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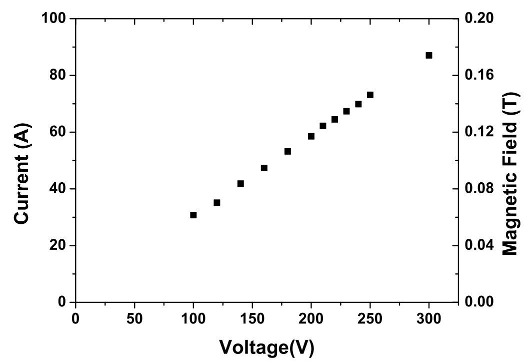

(c)

Figure 10: (a) Plot of magnetic flux in various conditions (from left to right) only 200 kA current at the theta coil, 200 kA current as well as one guiding magnet on each sides with 5 cm gap, 200 kA current at the theta coil as well as two guiding magnets on each side with 5 cm gap from each other, 200 kA current as well as one guiding magnet on each side with 10 cm gap (b) temporal evolution of current in the magnet with 4 mF capacitor discharged at 100 V (c) the relation of charging voltage, current, and magnetic field in the center with 4 mF capacitor

References

[1] K. Miyamoto, *Plasma Physics for Nuclear Fusion*, pp. 441–443. MIT Press, revised ed., 1976.

[2] T. K. Gray, *Ph. D. dissertation.* University of Illinois at Urbana-Champaign, 2009.

[3] F. W. Grover, *Inductance Calculation: Working Formulars and Tables*, p. 94. Dover, 1962.

[4] W. R. Gentry and C. F. Giese, "Ten-microsecond pulsed molecular beam source and a fast ionization detector," *Review of Scientific Instruments*, vol. 49, no. 5, pp. 595–600, 1978.

[5] G. Scoles, ed., *Free jet sources, atomic and molecular beam methods*, vol. 1, pp. 72–74. Oxford University Press, 1988.

[6] S. Jung, L. A. Kesler, H. H. Yun, D. Curreli, D. Andruczyk, and D. N. Ruzic, "A gas-puff-driven theta pinch for plasma-surface interaction studies," Presented at the 54th American Physical Society Meeting, Providence, Rhode Island, USA, 2012.

[7] T. Green, A. Newton, and S. Segre, "Radial implosion of a partially ionized plasma in a theta pinch," *Nuclear Fusion*, vol. 6, no. 3, p. 223, 1966.

[8] M. Kaufmann, "The low-density limit of the theta pinch," Tech. Rep. LA-5019-MS, Los Alamos Scientific Laboratory Report, Los Alamos, New Mexico, August 1972.

[9] S. Jung, V. Surla, T. Gray, D. Andruczyk, and D. Ruzic, "Characterization of a theta-pinch plasma using triple probe diagnostic," *Journal of Nuclear Materials*, vol. 415, no. 1, Supplement, pp. S993 – S995, 2011.

[10] S. Jung, D. Andruczyk, and D. Ruzic, "Laboratory investigation of vapor shielding for lithium-coated molybdenum in devex," *Plasma Science, IEEE Transactions on*, vol. 40, pp. 730 –734, march 2012.

[11] J. Marshall, "Performance of a hydromagnetic plasma gun," *Physics of Fluids*, vol. 3, no. 1, pp. 134–135, 1960.

[12] I. R. R. Shinton, *Ph. D. dissertation.* Massey University, 2005.

[13] P. Ray, "Rail gun performance and plasma characteristics due to wall ablation," *Magnetics, IEEE Transactions on*, vol. 22, pp. 1699 – 1705, nov 1986.

[14] J. V. Parker, "Why plasma armature railguns don't work," Tech. Rep. LA-UR-88-789, Los Alamos Scientific Laboratory Report, Los Alamos, New Mexico, April 1988.