SSX introduction

Here are some introductory ideas for a first time SSXer. These concepts are posed in the form of questions and cover basic E&M ideas, plasma physics, pulsed power, etc. Work together, see me, look stuff up in books or online. Record your calculations in your lab book.

1. Basic E&M: (see Purcell or Griffiths for starters)

B of a wire: What's the B field 1 cm away from a wire carrying 1 A of current (express the answer in gauss and tesla)? This result is worth memorizing.

B of a loop: What's the B field in the center of a 0.4 m loop of wire carrying 30 kA of current? This is a good model for the currents and fields in SSX spheromaks. This is a good one to memorize too (a factor of π bigger than the previous one).

Flux: We can make a uniform field of $B = 2\ T$ in our $2.5''$ diameter inner electrode. How much flux is that (in Webers or mWb)? We call this the "stuffing flux". The inner electrode contains a material called Permandur which supports this high field (iron can only go up to 1 T).

Faraday's law: If the flux in the center electrode is ramped up from 0 to the maximum value found above in 10 μs, how much voltage is that? This is the typical energy a particle can acquire during reconnection.

Skin depth: If the current flowing in a wire is steady (DC), then it flows uniformly over the cross-section. If the current is pulsed (say in a 10 μs pulse), then the current flows in a "skin layer" so the rod looks like a tube as far as the current flow is concerned. What's the ratio of resistances for a 1" diameter copper rod for DC current vs. current at 100 kHz (ie a 10 μs pulse)? The point here is that in our pulsed experiment, R's and L's change because rods and bars turn into tubes and sheets at high frequencies (short times).

Soak time: This is a tricky one but very important. Consider a metal tube of radius r, wall thickness δ, length ℓ and electrical conductivity $\sigma = 1/\rho$. Now consider turning on a uniform magnetic field outside the tube. If the tube were made of a superconductor ($\sigma = \infty$), then eddy currents would flow the short way around the tube (forever) and the magnetic field would never get inside. If the tube were made of an insulator ($\sigma = 0$), then the magnetic field would penetrate (at the speed of light) as if the tube weren't there. If the conductivity is finite, the magnetic field diffuses (or "soaks") through the metal in a characteristic time. The time is the ratio of inductance to resistance $\tau = L/R$. The goal is to calculate this. Consider a sheet of current flowing the short way around the tube. The current makes a magnetic field inside like a solenoid and the flux is given by $\Phi = BA = LI$. The current encounters a resistance depending on the wall thickness δ and the distance around the tube. Once you have a formula for the soak time, calculate it for our new copper flux conserver ($\delta = 0.25\ in, r = 0.25\ m$) and for our stainless steel probe stalks ($\delta = 0.001\ in, d = 0.25\ in, \rho_{ss} \cong 30\ \rho_{Cu}$).

Inductor voltage: For short pulses (high frequencies), inductors behave like open circuits and capacitors behave like short circuits. Whats happens immediately after a switch is thrown connecting a 500 μF capacitor charged to 10 kV to a resistor 1 $m\Omega$ and inductor 100 nHy in series (this is the approximate circuit for the SSX plasma guns). We'll do an analysis of LRC circuits later.

2. Pulsed power: (look online)

Stored electrical energy: How much energy is stored in a 500 μF capacitor charged to 10 kV? How much charge is stored? How much gasoline would you need to burn to get this much energy? How many hydrogen atoms would you need to ionize to get this much charge? (These are the peak specs for each SSX bank).

Stored magnetic energy: We typically have a mean magnetic field of 0.1 T filling our 0.4 m diameter, 0.6 m long flux conserver. How much magnetic energy is that? We usually achieve this with 5 kV on each bank. What's our energy efficiency W_{mag}/W_{elect} (from bank to plasma)? Note that a magnetic energy density W/vol is also a magnetic pressure $F/area$. Its useful to memorize that 0.5 T corresponds to about 1 atm of pressure.

Stored thermal energy: We typically get a plasma density of $5 \times 10^{14}\ cm^{-3}$ and temperature of 20 eV filling our 0.4 m diameter, 0.6 m long flux conserver. How much thermal energy is that? What's the ratio of thermal to magnetic energy $\beta \equiv W_{th}/W_{mag}$? One of the goals of our research is to get β as close to unity as we can (and still have a stable plasma). Here's the scaled formula from the SSX scaling handout:

$$\beta \equiv \frac{W_{kin}}{W_{mag}} = 0.03\frac{n_{14}T_{10}}{B_{0.1T}^2}$$

Hot water: The dump resistors consist of about 1 liter of copper sulfate solution (mostly water). Suppose all the energy in one bank (500 μF at 10 kV) is dumped into the water. How hot will the water get? The point here is that our plasma is hot but doesn't contain much thermal energy in the grand scheme of things.

3. High vacuum: (look online)

Particle inventory: How many protons are there filling our 0.4 m diameter, 0.6 m long flux conserver at a density of 5×10^{14} cm^{-3}? How much mass is that? How many protons are there in one cc of hydrogen at standard temperature and pressure (STP)?

Vacuum: How many molecules are left in the chamber if we pump to 10^{-8} $torr$ (this is our ultimate base pressure)? If the remaining molecules are water (they are) and we collect them into a single drop, what's the diameter of the drop? Compare this to the amount of water/oil in a fingerprint or a glob of spit. This is why we wear latex gloves and don't spit when working inside the chamber.

Glow discharge conditioning GDC: Estimate the number of copper atoms exposed to the plasma by assuming they're on a 1 $\mathring{A}$ grid inside our our 0.4 m diameter, 0.6 m long flux conserver. If each copper atom can serve as a cite for a hydrogen molecule, what is the ratio of the proton inventory in a monolayer inside the flux conserver to the particle inventory found above? This is why we do GDC with helium ions (0.1 $A, 300$ V at 50 microns or so for a few hours) so we can get down to bare copper metal. At a rate of 0.1 A, how long before the number of He ions deposited equals the number of hydrogen (or water) molecules adsorbed? We usually run GDC much longer than this since each He doesn't always knock off a hydrogen and since the hydrogens often re-adsorb. I'd like to understand the GDC process better this summer.

4. Electrical engineering: (look online)

Magnetic force: The "wires" connecting the capacitors to the gun cables are actually aluminum plates a foot wide, a meter long and separated by about an inch. When we pulse the guns about 100 kA flows in them (in opposite directions). What's the force on the plates? What direction is the force? This is why we use heavy plates secured with aircraft bolts instead of wires.

Where is ground?: When we pulse the plasma guns, about 100 kA flows from the capacitor to the center electrode through the plasma back to the outer electrode (and the stainless steel vacuum chamber) and eventually back to the other side of the capacitor. The chamber is $1/8''$ thick, 2 feet in diameter and 2 feet long. The resistivity of stainless steel is about 40 times that of copper. What's the voltage difference from one side of the chamber to the other when 100 kA is flowing? This is the reason we're very careful about what we call "ground".

Inductances: A good rule of thumb is that the inductance of a wire or cable is about $\mu_0 \ell$ where $\mu_0 = 1.26 \times 10^{-6}\ Hy/m$. The formulae are a little different depending on whether its coax or simple wire or a plate. What's the inductance of a 1 meter piece of RG-8 coax cable (I'll get you some)? How about our collector plates (1 meter long, 1 foot wide, 1 inch separation)? How about our plasma gun (2.5 inch ID, 6.5 inch OD)? You get the minimum inductance (and maximum current) with the out-going and return leads as close as possible. Close proximity isn't good for arcing (see below).

Arcing: If two flat pieces of metal have a potential difference of 10 kV between them, how close can they come before the air breaks down between them? This dictates the gap between high voltage components.

Contact resistance: If you don't tighten a bolt in the high current path to the guns, its easy to get a contact resistance as high as 10 $m\Omega$. If the discharge current is 100 kA, how much power is dissipated in the contact? If current flows for 100 μs how much energy is deposited in the contact? This is the reason for good, firm contacts with the high voltage banks.

5. Plasma physics: (NRL formulary, online)

Larmor radii: Calculate the ion and electron Larmor radii for typical SSX parameters ($B = 0.1\ T, T_e \sim T_i \sim 20\ eV$). These set the spatial scale for our experiments (note that SSX is much larger than either $\rho_{i,e}$). Here are some scaled formulae from the SSX scaling handout:

$$\rho_i = 0.32\ cm \frac{T_{10}^{1/2}}{B_{0.1T}}$$

$$\rho_e = 0.075\ mm \frac{T_{10}^{1/2}}{B_{0.1T}}$$

Larmor frequencies: Calculate the ion and electron Larmor frequencies for typical SSX parameters ($B = 0.1\ T$). These set the time scale for our experiments (note that we typically record data at 10 MHz). Here are some scaled formulae from the SSX scaling handout:

$$f_{ci} = 1.52\ MHz\ B_{0.1T}$$

$$f_{ce} = 2.8\ GHz\ B_{0.1T}$$

Alfvén speed: Perturbations happen in magnetofluids such that

$$\frac{1}{2}\rho v^2 + \frac{B^2}{2\mu_0} = const$$

How fast do perturbations in a magnetofluid propagate? This is called the Alfvén speed... its the speed limit in SSX. What's the Alfvén speed in SSX for typical parameters? Here's the scaled formula from the SSX scaling handout:

$$v_A = 22 \frac{cm}{\mu s} \frac{B_{0.1T}}{n_{14}^{1/2}} \text{ where } 22 \ \frac{cm}{\mu s} = 220 \ \frac{km}{s}$$

Sound speed: Perturbations happen in compressible fluids such that

$$\frac{1}{2}\rho v^2 + \frac{1}{2} nkT = const$$

How fast do perturbations in a compressible fluid propagate? This is called the sound speed. How long does it take a H_2 gas pulse to get from the gas valves to the end of the gun (about 0.2 m)? This sets the delay for our gas valves. Note that this is much slower than characteristic times for our plasma.

Magnetic decay time: Our spheromaks are just big plasma loops carrying current. Estimate the resistance and inductance of an SSX plasma loop to calculate the L/R magnetic decay time. You'll need to look up the formula for the Spitzer resistivity of our plasma. This sets the overall time scale for the experiment. Here are the scaled formulae from the SSX scaling handout:

$$\eta = 5.15 \times 10^{-5} \frac{Z \ ln\lambda}{T_e^{3/2}} \Omega \ m$$

where $ln\lambda$ is about 10 for SSX, Z is about unity, and T_e is expressed in eV. Plugging in the values for SSX at 10 eV we get a scaled resistivity and resistive time:

$$\eta_{10}^{SSX} = 1.6 \times 10^{-5} \ T_{10}^{-3/2} \ \Omega \ m$$

$$\tau_{res} \equiv \frac{\mu_0 \ell^2}{\eta} = 770 \ \mu s \ \ell_{0.1m}^2 T_{10}^{3/2}$$

Plasma gun: Consider two parallel conducting wires 2 inches apart. Suppose there's a "sliding short" that straddles the two wires. It has the same mass as 10^{19} protons. Now suppose 100 kA flows up one wire, through the sliding short, and back down the other wire. How much force does the sliding short feel? What's the direction? What's its acceleration? If this force is applied for 10 μs, what's the final velocity of the sliding short? This is the same physics as our plasma guns except that the two wires are replaced by an inner and outer electrode and the sliding short is our plasma.

LRC calculation: We'll build some LRC circuits and analyze them using:

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{q}{C} = V$$

Magnetic probe calculation: We'll build some magnetic probes and use them with the LRC circuit above.