[SQUEAKING]

[RUSTLING]

[CLICKING]

JACK HARE: Let's talk a little bit about plasma diagnostics. So this very word, diagnostic, is pretty interesting. Gnostic here is coming from knowledge, and dia is a word sort of meaning through. So these are objects that we gain knowledge through. And we're trying to gain knowledge about our plasma. This is the whole purpose of this class.

We're trying to gain knowledge about the plasma indirectly. We can't directly look at a plasma and measure its density, or its temperature, or its velocity, or any of the other quantities we're interested in. Instead, we're inferring it from some sort of physical effect the plasma has on something else.

And we're used to this kind of measurement with more basic diagnostics. If we think about something like a thermometer, and it's filled with mercury, what's the physical principle that allows us to measure temperature using a thermometer, a liquid metal thermometer? Yeah.

Yeah. So the thermal expansion of this metal, which moves it up and down here, and we can calibrate this, and then we can measure temperature. So this is an example of something that we are relatively familiar with. Thermal expansion of metal, it's something we can see with our eyes. We can pick up a thermometer. We can touch it.

This is rarely the case with something like a plasma. Our intuition usually fails us. And so we have to fall back on mathematics, or we have to build our intuition for plasma in the same way that we built our intuition for things like thermometers as we were growing up. For example, here we were talking about the expansion of metal. But in a plasma, we may be looking at something as obscure as the polarization of a beam of light telling us something about magnetic fields, something that immediately it isn't obvious that these things are linked at all.

We're going to be assuming very good plasma physics knowledge in this class. So the prerequisite for this class is for students who have taken 22.611. So that's a class that uses Francis Chen's *Introduction to Plasma Physics* textbook. And we'll be drawing extensively from that without redoing any derivations.

This is a very hard class to take at the same time as 22.611. I recommend you don't try, but I know that some of you are going to. And that's fine. But just as a warning, it's going to be very, very difficult.

If you are a little bit shaky in your plasma physics, I suggest revising your electromagnetism, your waves in plasmas, and things like Landau damping, especially later on when we get on to Thomson scattering. Any questions on any of that?

So why do we bother with diagnostics in the first place? Well, there's no point in making a plasma that you can't actually measure. So we could have a huge tokamak, or a giant laser, or a big pulse power machine, and we could make the world's greatest plasma. But if we don't know anything about it, it's completely pointless.

And so plasma experiments really goes hand in hand with plasma diagnostics. And these diagnostics are extremely important in the history of fusion and in the history of plasma physics. So one example that I told the students about in fusion energy last semester that they'll probably remember is the zeta pinch.

So this was a toroidal Z-pinch type device that was built in the UK in the '50s. And the Brits got very excited, because when they cranked up the current on their toroidal pinch, they started measuring bursts of neutrons. And they said, aha! We see neutrons. Therefore, we're getting fusion.

Now, there was a problem with this, because when they looked at it in more detail, they realized that the neutron burst they were getting was not isotropic, so it couldn't be thermonuclear in origin, and also, the temperature of their plasma was far too low. So they didn't have sufficient diagnostics to realize that these neutrons were not coming from a thermonuclear fusion process, but were, in fact, coming from MHD instabilities within the plasma.

This was extremely embarrassing, but the upshot of it was that this team developed a technique called Thomson scattering, which uses a focused laser beam to measure the temperature of a plasma. And they developed it just in time for the Russians to announce their new device, which they called a tokamak, which they claimed had temperatures over a kiloelectron volt, which was about 10 times higher than any other device that anyone had been trying to do fusion with at the time.

This, again, caused a huge furor because lots of groups from around the world didn't believe it. They said, how have the Russians managed to get such an incredible result from their machine? And so the team from the UK who had worked on ZETA and then worked on Thomson scattering flew over to Moscow with their ruby laser and made the first Thomson scattering measurements on a tokamak, confirming that it had temperatures of a kiloelectron volt.

And the rest is kind of history. Immediately everywhere around the world, people started converting their other machines into tokamaks. The Princeton Model C stellarator, they cut off all the long loopy bits and just shoved two halves together, and it became the Princeton Model C tokamak instead. And this happened overnight. And we're still living in a post-Thomson scattering, post-tokamak world, because all of our major devices now are tokamaks.

Another good example is the National Ignition Facility. The National Ignition Facility was carefully designed using the best simulations available-- these incredible radiation hydrodynamics multigroup, everything you can think of all the best physics in the world. And they were very confident that when they turned on the National Ignition Facility they were going to get ignition. They were so confident they put it in the name of the experiment.

And so back in 2009 or so, they started running the first experiments. And they said, we don't really need any diagnostics, because it's going to work. It's obvious. We know exactly what's happening. We'll just have, basically, some neutron counters so that we can go ding, we got to ignition, and tick the box, and move on.

This didn't happen. When they turned on NIF, the signal was barely measurable. There was almost no neutrons at all coming out of it, and they had no idea why. And the reason they had no idea why is because they didn't have any diagnostics to tell them what was actually happening. They only had diagnostics to tell them whether they were successful or not. And the answer was they weren't.

So no one knew what was going on, but a decade later, they now have very good diagnostics at NIF. And it's no coincidence that, of course, we now have ignition as well, because they understand a great deal about the physics going on inside this experiment. So you really need to have good diagnostics to do good plasma physics and to build good fusion reactors as well.

Who needs to know about diagnostics? Well, obviously, experimenters, we kind of-- I imagine many of the people in this room are doing experimental plasma physics. And that's why they're here. They want to understand the plasmas that their machines are producing. They want to probe the mysteries of the universe and get unlimited clean renewable energy and all that sort of stuff.

But they also want to understand the uncertainty involved in their measurements. When someone says to you, the temperature on this tokamak is 1 kiloelectron volt, what does that mean? Where is it 1 kiloelectron volt? What's the error bars on that? Does that true for the entire discharge? There's huge limitations in the diagnostics we have. And we need to understand those limitations.

If you're doing computational work, if you're doing large simulations, you might be interested in diagnostics, because they serve as a primary way of validating your code. Your code is only really worthwhile if it makes predictions that agree with reality. And so you may want to understand how diagnosticians are making these measurements so that they can understand whether your code is right or not.

And you may also be motivated to make useful outputs from a computer simulation. You may get a very large amount of data that's very hard to distill down. One way to distill that down is to think about the diagnostics that experimentalists use and reduce your data set so it looks a bit more like those diagnostics. That gives you an easier way of comparing your data with reality.

If you're a theorist, I think you should still know about diagnostics. I think you should be very skeptical about your experimental colleagues. I don't think you should believe them when they say the temperature is 1 kiloelectron volt. You should ask where, and when, and how sure are you? Because these people are trying to tell you something, and you're going to go out and tell all your colleagues that your theory has been proved. And if they were wrong, you're going to be very, very embarrassed.

You might also be motivated to design theories which have testable predictions. So a lot of theoretical work is phrased in a language which is very different from the way that experimentalists speak. And that means that when experimentalists read your papers, they don't understand what's going on. And they also don't know how exactly they can test your predictions.

If you know how diagnosticians think, you can write papers which are clearer for them. They can go test your theory, prove it right, and then you can go collect your Nobel Prize. So it's pretty important to know how diagnostics work there.

All right, I've been talking for a bit. So I'll pause and see if there's any questions so far. So what sort of things-- there we are. What can we measure? Before we get onto what can we measure, what would we like to measure? What would a theorist like to ask us for? So what can we measure? What do we want?

Well, if it's not too much to ask, we'd like to know the position and velocity of every single particle in the plasma at every point in space and time. So this would be the Klimontovich type distribution here. We'd have sort of f of x as a vector. v is a vector-- time.

And this would simply look like the sum of a series of delta functions, which are the position of particle i, the velocity of particle i, and both of those should be functions of time as well. And our full distribution function is just a sum over all of these particles. So this is three dimensional, three velocity vectors plus time.

Now, of course, the theorists might tell you they want that, but they don't really. No one wants that. It's absolutely impossible to work with. This is a mess. So what theorists really want is they want some sort of moments of this. They would like to have a simplified version of this. At best, they'd like to have a distribution function, which is smooth. This one is very, very spiky and hard to work with.

But they may also be willing to get away with letting you give them some thermodynamic variables, some variables where we've taken moments over this. So if we look at some of the moments that we can take here, we would have things like the density. And this is an integral over the velocity part of your distribution function, d3v.

That's the density. Or you might want to know things like the average velocity of your particles. And you can keep going with this by multiplying your distribution function by larger and larger powers of v. And you start getting tensors and all sorts of exciting things like that. So I'm just going to put et cetera before we get carried away and forget ourselves.

You might also want to know things like magnetic fields. These are pretty important in plasmas because plasmas move in response to magnetic fields. These magnetic fields are caused by currents, fundamentally, electric currents, and those electric currents can be external. So they could be provided by a large set of magnets that surround your plasma.

Or they could be internal. They could be provided by the plasma motion itself-- probably getting a little bit low there. Let's go up. They're clearly very, very important.

Now, in reality, even if we can measure density and velocity and magnetic fields, we're not really going to be able to get them at every point in space and time. We're quite limited. So diagnostic limitations, we're going to end up things which are sparse in space.

I'm just going to use vector x for space and time. So we don't have it all the time. This may be because our diagnostic only measures at a single point as a function of time, or it may be a picture which measures spatial variation at a single time, or it may be some combination of those here.

Our diagnostic is often going to be what we call line integrated. This is especially true for diagnostics which use light. Light famously mostly traveling in straight lines means that you don't get to choose where the light comes from that you're measuring. It's going to be along some cord. So we could say what we're measuring is not the density, but the density along a cord dl here, which is the path of our ray of light through the plasma.

So that means as opposed to knowing n as a specific point, you know the integral of n over some points. If you happen to know some symmetry about your plasma, then maybe you can work out what n is locally. But otherwise, you're kind of stuck with this measurement instead.

Almost certainly your measurement is going to be filtered in some way. And I'm using the word filtered here very broadly. This means that your instrument is in some way an imperfect measurement of the world. And so there is some sort of response function that you have to convolve or deconvolve from your instrument or convolve your synthetic data with in order to understand what it does.

This could be things like a frequency response, if you're measuring voltages. This could be things like a resolution if you're taking images with a camera, that sort of thing. So almost everything has some sort of response function.

And it's also probably going to depend on physics that we just don't understand very well, so depend on poorly understood physics. A great example of this is spectroscopy, so atomic data. Anyone who's ever done spectroscopy will know that there's a lot of electrons. There's lots of places they can be. They can interact in lots of ways. And so it's very hard to actually make predictions for the spectrum of even something as simple as helium.

And so if we're trying to understand spectroscopy, we need to use this atomic data, but we should be cautious of the atomic data, which is mostly provided by theorists as well. So we should be cautious anyway. But we should be cautious of the atomic data because it forms part of our interpretation.

So we may not just have errors due to some of these other things. We may have errors due to how we interpret this. So we should always be on the lookout for like, hmm, that looks weird. I wonder why that's going on and see if we can check whether this is a model dependent effect or whether it's to do with our diagnostic instead.

So in this lecture course, we are focusing on the principles. Professor Hutchinson put this in the title of his book after teaching this course for many years. And he explains what he means by principles in the introduction. And I think it's very, very wise.

He says that we're not going to focus on the practical implementations of diagnostics. Those things change over time. There's always a new camera that works in a new way that's better. But what doesn't change is what a plasma is, the equations that govern it, and some of the techniques that we can use.

Now, there's always new techniques that people are coming up with. This is a very, very lively field. There's a conference every year, High Temperature Plasma Diagnostics, which is well worth going to where people present new diagnostics, new interpretations, new ways of measurement. And it's very, very dynamic. There are lots of different ways to try and measure a plasma.

There are some techniques which are very successful, but have only been implemented in one or two institutions, just simply because of the cost. There's some techniques that are very successful and have only been implemented because of institutional inertia, because of the specialized knowledge to be used.

So it's always worth reading up some papers you'll never find-- you'll never know. You'll probably find that the Russians did it back in the '70s. This is true with almost every diagnostic you can think of. And they published it in some obscure journal. So it's worth looking out to see whether someone's already tried to do what you're trying to do before.

So any questions on this sort of introduction? Then we can have an interactive part of the class. Yes.

AUDIENCE: [INAUDIBLE]

JACK HARE: Yeah. Imagine you've got a plasma, which is glowing. So it's emitting light. And I have a camera. And I'm looking at this plasma. And the plasma is not uniform. Maybe the core of it is very hot, like a tokamak. And the edge is very cold.

But that means along the line of sight between the plasma and your camera over there, you are adding up the emission from each little blob of plasma along your line of sight. So you're adding up emission from some hot bits of plasma, some cold bits of plasma. So if you look at the spectrum of that, you're going to see lines that correspond to a cold plasma and a hot plasma simultaneously. That doesn't make any sense. So you need to know that that's happening.

It gets worse than that, of course. Different bits of plasma can be absorbing as well. And so you may have attenuation of some of those lines as it goes through. This becomes radiation transport, and it's like a whole mess. So that's one simple example there that just as you look through a plasma, you're going to get very different properties, all contributing to your final measurement.

This isn't the case of something that's very local, like a Langmuir probe, or a B-dot probe, or Thomson scattering. But it's very much the case for, I would say, about half the diagnostics we're going to talk about in this course. They're going to suffer from light integration. And the reason is plasma is electromagnetic. Light is electromagnetic.

So we use light to probe plasmas, and light has this problem of line integration. So it almost always comes up, no matter what you try and do. Other questions? How's it going, Columbia? Good. Thumbs up.

So what I like to do-- I found when I taught this class before there's a huge array of people who take it, which is super exciting. And they all work on very different things. And this is my opportunity to find out some of the stuff you work on as we play pin your plasma to the board. So as you can all see, we have a temperature scale on the side here that goes from 0.1 eV-- and yeah, you can still get plasma there-- up to 10 keV and above, whatever.

And then we've got densities here. If you thought that was logarithmic, they go from 10 to 16 particles per cubic meter to 10 to the 32 particles per cubic meter here. So 16 orders of magnitude. And yet we're all sitting in the same room trying to learn the same stuff. That's one of the reasons why this topic is very fascinating, and also quite hard to teach at times.

I've also tried to get the third dimension to you guys. We're going to be using color. And we're looking at the magnetic field here. So I've got a magnetic field going from 0.01, which I think most of us agree is basically 0, all the way up to 100 tesla or so, which I know some places where you get 100 tesla in plasma physics. I don't know whether anyone working here works on those.

But the idea is you're either going to volunteer, or I'm going to start pointing. And you're going to come up, if you're here in the room, or you're going to tell me if you're over there in Columbia, where your plasma falls on this board. So we'll just draw little circles.

So say you've got a plasma that is 100 tesla and it lives up in this corner here. You would just draw a little blob, being like, that's my plasma. You'd put a number in, and by the side of it, you'd maybe write something about your plasma. Maybe it's a magnetized ICF implosion on NIF. And you'd maybe dot down a couple of diagnostics that you work on.

If you don't work on any diagnostics at the moment, that's fine. Maybe just mention a diagnostic you know is used. And you don't have to be exhaustive. If you mention the tokamak, you don't have to list every diagnostic on the tokamak, just the one that you work on. And let someone else have a go at mentioning some of the other ones.

So I'm going to erase that now, because I think that's slightly optimistic, even for a magnetized ICF shot. And I'm now going to turn around and see someone with their hand up as the first willing volunteer. Good. As you're walking up, what's your name and your department?

AUDIENCE: I've worked with Nathan Howard and Pablo Rodriguez Fernandez.

JACK HARE: Can the folks at Columbia hear him OK if I stand nearby or is it very quiet? Oh, dear. You should have this then.

AUDIENCE: OK. Let's pull you up.

AUDIENCE: Hello, everybody. I'm Vince. I work with Nathan Howard and Pablo Rodriguez Fernandez on modeling turbulent transport in the Spark reactor. I don't remember off the top of my head the particle density. I think it's in this range. Just a circle you said? Or like--

JACK HARE: Yeah, where's my little [INAUDIBLE]?

I have 10 to the 20 [INAUDIBLE].

AUDIENCE: 10 to the 20. OK.

JACK HARE: 10 to the 20. Yeah, cool. Cool. But put a little number on it like one, and then just write on the side what's your diagnostic [INAUDIBLE]. Yeah, I should not have made it so high.

AUDIENCE: Let's see. I don't work with any diagnostics at the moment. I work with heat flux data that's generated via simulation code, like TGLF and gyrokinetic [INAUDIBLE].

JACK HARE: Anyone else know [INAUDIBLE]?

AUDIENCE: I don't-- I don't know off the top of my head.

JACK HARE: Well, let's go for that, like a Langmuir probe.

AUDIENCE: Is that how you spell it?

JACK HARE: All right, next volunteer. Let's have one from Columbia, please. Hey, Nigel.

AUDIENCE: Hello. I work with plasmas that are 10 to the 19 density, 100 eV with a magnetic field of 0.1 on that order of magnitude.

JACK HARE: So what was that? 10 to 19, and 100 eV.

AUDIENCE: Yes.

JACK HARE: So kind of about here?

AUDIENCE: Yeah.

JACK HARE: And so what's this plasma?

AUDIENCE: That's the HBT plasma. That's the tokamak that we have at Columbia. And I work with Langmuir probe arrays, Mirnov coils, and tangential extreme electromag-- extreme ultraviolet light. So TUV.

JACK HARE: And Mirnov, which I'm just going to write as B-dot.

AUDIENCE: Yeah, B-dots.

JACK HARE: They're sort of B-dots. Great! A volunteer from in the room. Come on up. I don't know if I can have both of these working at the same time. I think there are spares. There you go.

AUDIENCE: Hi. My name is Amelia. I do some work with DIII-D on a Lyman-alpha diagnostic, and that's roughly here-ish in operating space.

JACK HARE: Is it that low?

AUDIENCE: I think it's like a little higher. It's like four to five often. It's good enough for me.

JACK HARE: OK.

AUDIENCE: And then Lyman-alpha, the spectral line of hydrogen, as we mentioned.

JACK HARE: Great. Thank you. We've got a volunteer from Columbia.

AUDIENCE: Do I need raise my hand? Or can I just--

JACK HARE: Oh, yeah. Please, start. Please go for it.

AUDIENCE: Hi. I'm Jacob. I'm at Columbia. I just got done working with some DIII-D plasmas as well.

JACK HARE: Nice.

AUDIENCE: Roughly the same area, I'd say. And I was working with bolometers.

JACK HARE: Bolometers-- cool! What do bolometers measure?

AUDIENCE: Bolometers were measuring radiation fluxes, mostly heat loads, and it's fast bolometers. So they're AXUVs.

JACK HARE: Awesome. Thank you. Anyone in the room? Come on. One of the NIF people. Come on. We need to push up into this corner. Ok.

AUDIENCE: [INAUDIBLE]

Hi, I'm Chris. So I'm NSC HGDP [INAUDIBLE] confinement fusion. And our temperatures are over here, 3 to 10 keV, I'm going to say. And then I work in units of rho r, so 300 to 600.

JACK HARE: [INAUDIBLE]

AUDIENCE: And that's where I don't know if they operate in magnetic fields. But I'm going to say Skyler does. 10, 100 tesla.

JACK HARE: Yeah, no. I know it is. You don't start with that. Have you been doing the [INAUDIBLE]? Go for it. Yeah, yeah, yeah.

AUDIENCE: I'm going to go with--

JACK HARE: [INAUDIBLE] the yellow one. There we go.

AUDIENCE: NIF extreme, and then what are we up to? Four? So for mine, I'll put neutron spectrometry-- neutron. What about you guys?

AUDIENCE: Prolon cardiography.

JACK HARE: Thomson scattering. Good, good. go on, then.

We've got four there. Where's the mic? Cool. All right, do we have anyone else from Columbia willing to volunteer?

AUDIENCE: Yeah.

AUDIENCE: I also do-- I hope you can hear me. I also do DIII-D experiments, particularly runaway electron experiments. And we use a gamma ray imager and also some hard X-ray detectors. So they're scintillators, which register heart X-ray instagram HXR.

JACK HARE: Cool. I'm going to put that on as gamma rays and hard X-rays. That's good stuff. Anyone in the room? Yeah, go for it.

AUDIENCE: I'm Stan. I'm in NSCI. I also work on Spark. And I do soft X-ray.

JACK HARE: What you are working on?

AUDIENCE: So the ones I'm working on are diamond based, because specifically for Spark, traditional silicone diode would die from the neutrons. So we're using a diamond-based detector instead. And they're in very early stage development. Although, our collaborators in Rome have had some promising results so far.

JACK HARE: Awesome. Yeah.

AUDIENCE: Hi. I'm Nikola. I'm working on arc stuff right now, but I wanted to mention what I was working for my master's back in Serbia. I was working with pseudospark discharges, which were like ionized gases more than actual plasmas. They were somewhere in like this region-ish here. What number is it?

JACK HARE: 5.

AUDIENCE: 5. And what I was doing with those was vacuum ultraviolet spectroscopy. And those were like not magnetized.

JACK HARE: All right, thank you. Anyone from Columbia?

AUDIENCE: I can say one. So CNT is no longer operational. But I'm working on upgrading it. And the operational density was of the order of 10 to the 16th. And magnetic field 0.06 tesla. I think temperature, order of an eV. I'm not too sure.

JACK HARE: OK. So kind of like here?

AUDIENCE: Yeah, probably low, yeah.

JACK HARE: And you said 0.06. I'm going to call that 0.1. We'll round up.

AUDIENCE: Yeah, sounds good. Sounds good.

JACK HARE: Cool. So this is CNT plus plus, or whatever the new name will be.

AUDIENCE: Exactly, exactly.

JACK HARE: Cool. And what are you going to be diagnosing it with?

AUDIENCE: So they had an electron beam that also was paired with a fluorescent rod to map the magnetic field surfaces.

JACK HARE: Nice. Yeah, I saw them doing that technique on W7-X as well. It's really cool.

AUDIENCE: Nice.

JACK HARE: All right.

AUDIENCE: Hi. I'm Lainey. So I actually work in the aerospace department. And I work with non-equilibrium plasmas. So I actually am in-- we go from-- we work from low pressure to atmospheric pressure in this general area. But in a nonthermal plasma, our electrons are closer to the 10 eV, anywhere from 1 to 10 eV. And our gas temperature is much lower, so kind of in that region right there.

And then we typically use OES, Optical Emission Spectroscopy, or FTIR, Fourier Transform Infrared Resonance.

JACK HARE: Thank you. Yeah, so I remember doing this class 2 years ago, and there were some folks from [INAUDIBLE] as well, who came and talked about those plasmas, which is why this scale now goes down to what I consider to be quite a low density. But there we go. And that's why it's kind of fun that we can go all the way up, much higher densities as well. Any more volunteers in the room or from Columbia? Lansing, come on up.

AUDIENCE: Hello, everybody. I'm Lansing. I work with Jack. My project is magnetic reconnection on Z. It's in collaboration with Sandia National Labs. So on the Z machine, the largest pulsed power machine, I think we're achieving densities around 10 to the 24 to 10 to the 25 electrons per cubic meter in the reconnection layer.

And I believe our temperature is-- for the bulk of the plasma, I think are 10's of eV, but for plasmoids can get up to a little bit above 100 eV. So maybe somewhere like in this region-ish. And then I believe the magnetic fields we're achieving are 10's of tesla, typically.

So the work I've been focusing on-- I'll give this a number, number eight. Lately, the diagnostics that I've been working on, it's all been synthetic, so just modeling. But it's preparation for an upcoming shot. It's on shadowgraphy, so using a probing laser beam to try to indirectly constrain the electron density. Thank you.

JACK HARE: All right. Anyone else? Yeah, come on up.

AUDIENCE: So I work with inertial electrostatic confinement fusion, which is a bit different from this. I would assume way up here somewhere, maybe in here. And the range is 40 to 100 keV, but the pressure is incredibly low, very low.

JACK HARE: And try and keep the microphone up.

AUDIENCE: Oh, sorry. So I guess very similar to NIF, we're only using neutron detectors, kind of like Hc3. We're looking to upgrade that soon.

JACK HARE: Right, thank you. Anyone from Columbia?

AUDIENCE: Hey, I'm Daniel. I'm also working on Spark, specifically on equilibrium dynamics. And for that, most of what I'm looking at are flux loops, so finding where the plasma boundary actually is inside the vacuum vessel.

JACK HARE: Nice. Good stuff. Thank you. Anyone in the room? Yeah. Come on up.

AUDIENCE: Hi. I'm Jacob. Similar to Amelia, I'm doing ASDEX Upgrade in pedestal. So I'll put that in her same bubble. And I work on correlation ECE to look at temperature fluctuations.

JACK HARE: What's ECE?

AUDIENCE: Electron Cyclotron Emission.

JACK HARE: We like our acronyms, but we should spell them out at least once. Cool. Anyone else? Yeah. Come on up.

AUDIENCE: Hi. I'm Leo. I'm working on Spark. I'm looking at the SOL in the virtual areas. So depending on how detached it is, somewhere right here. And Langmuir--

JACK HARE: All Langmuir? Cool.

AUDIENCE: Well, I mean synthetics. Probably doesn't exist yet.

[LAUGHTER]

JACK HARE: Good. At least they're planning to have some diagnostics. Nice. All right, anyone else? Yeah. Come on up.

AUDIENCE: So I work with plasma, but it was actually simulation for accelerators. So the magnetic field for some simulation for plasma wakefield accelerator. It went up for some cases, because we were trying to scale up to 15 TeV scaled up to a few thousand tesla. So it's a simulation, so I would put it--

JACK HARE: Another color? There you go. That's yours.

[LAUGHTER]

AUDIENCE: But the diagnostic is all from simulation. So it's like a particle histogram and photon energy.

JACK HARE: [INAUDIBLE]

AUDIENCE: Well, it depends on what collision you want to do. You could make them really ultra tight, and that would put them somewhere like here. For the temperature, I'm not so sure. But the ultimate goal is to scale it up to 15 TeV.

JACK HARE: [INAUDIBLE]

AUDIENCE: It would be good if we had a log scale.

JACK HARE: All right, thank you. Good stuff. Anyone else from Columbia? I know there's-- I think there's like nine of you, and there's 30 of us. So I've been trying to balance it a little bit. So I may have got through you all now. Hey, I see your hand.

AUDIENCE: Hey, yeah. So I've done work on C2W, which sits kind of in between numbers 2 and 3 blobs, so 10 to the 19. And yeah, just under 1 keV. And then the magnetic field is just under 1 tesla.

JACK HARE: 1 Tesla, so I can put it in like this. So what are you using on C2W?

AUDIENCE: Yeah. So a lot of them have been mentioned, but I don't think interferometry has been mentioned, or a bias bolometer, so like energy analyzers.

JACK HARE: Cool. I'll put both of those in, bias bolometer. Nice. All right, anyone else? Anyone from Columbia?

All right, it looks like we're all good. So I feel like the purpose of this exercise is just to get a feel for some of the different things that we might end up talking about. I've got a few other things on here to add. So we've already had Spark and NIF. There's a very cool technique for doing fusion using pulse power. It is dear to my heart, which is magnetized liner inertial fusion.

This is an interesting one because it works using magnetic field compression. So we start out with fields of about 10 tesla or so. And we start out at densities of about 10 to the 26, which is about here, and temperatures of about 300 eV. But then as we compress, we obviously get to much higher densities, much higher temperatures, and we're also compressing the magnetic field.

So in fact, the number I've got written on here means I'm allowed to use the green chalk as well. And we're going to go up to 10 to 29 in density and 8 keV here. So this is magLIF. And there's lots of cool diagnostics that they use on magLIF. But one of the ones which I think is rather neat is that they have some neutron spectrometers that they can actually use to measure the magnetic fields because they fill this with deuterium.

And you get deuterium reactions that make tritium. And then when the tritium reacts, it's already moved some distance along the magnetic field. And so you actually get an anisotropic neutron spectrum from these secondary ET reactions. So you're able to use neutron spectroscopy to get the B-field out, which is not something that you would necessarily expect to be able to do.

Another one I've got on here is a Hall thruster. Does anyone work on Hall thrusters here? This is a type of plasma thruster for satellites. These are working with relatively low magnetic fields. I got 0.01 tesla written here. 10 to the 18 kind of densities. And they're also working at about 30 eV, so somewhere here, so Hall thruster.

I don't a huge amount about the diagnostics used on these. But the sorts of diagnostics people would probably use are things like Langmuir probes, again, because these are relatively low temperature, low density plasmas. So you can get away with sticking stuff inside.

Just down the road from here, in fact, not very far from here at all-- I'm not sure I can point directly at it right now-- is a machine called [INAUDIBLE], which is a helicon plasma. That's used for plasma material interactions. That's got magnetic fields of about 0.1 tesla, densities around about 10 to 17, and relatively low temperatures, about 5 eV. It also sits around about here. So this is a helicon, which is a sort of RF-driven plasma. And again, the diagnostics that tend to be used in that are things like Langmuir probes.

And then the work that I do, both before I came here and now the machine we're building is using pulsed power. So this is similar to the stuff that Lansing was talking about on Z. And what we were talking about with magLIF, but on a more modest scale, because we're only a university. And so we tend to be in a regime where we're dealing with fields of up to about a 10 tesla or so.

We've got densities of around-- I haven't done this in CC. So it's 10 to the 23 or so, and temperatures up to about 100 eV. So quite similar to magLIF and the Mars shot. And we use diagnostics, some of which have already been mentioned, so interferometry, Faraday rotation imaging, which is this technique for measuring magnetic fields using the polarization of light, and my favorite diagnostic, which is why we spend so long talking about it, Thomson scattering.

But that's kind of where I'm coming from, just so you know what my background is. That obviously feeds into my biases about what exactly I spend more or less time teaching. But I will try and cover as much as I can this parameter space and some of the diagnostics that you've mentioned.

But the thing about teaching a class like this that I always find is whenever I teach on some specific diagnostic, there'll be someone in the class who's doing their PhD on it, and they know much more about it than me. And I know much, much less about it. And that's great. This is what makes this class enjoyable.

So please, if I say something that's wrong, or if you think you've got something to add, or "These days, we do it like that. That was 20 years ago," just shout out, and please add to the conversation, because I know I'm not the expert on this stuff. Most of the time, I'm using a textbook to try and learn about it myself.

There are often not very many good review papers either. So if you a good review paper for a diagnostic, I've never found a good one for an electron cyclotron emission diagnostics, for example, then let me know, and I can read that, and then I can regurgitate it to the rest of the class and look very intelligent. So that would help me a great deal.

But I'll pause here. If anyone has any questions, and then we'll probably just leave it for today. I know it's a little bit early, but I think we can all do with a little bit of a break in our first week of the semester. So any questions? Yes.

Yes. I mean, I rushed through this a little bit. So the subtlety is that they were using-- they weren't looking-- they're not looking at the DD neutrons. Those are isotropic. So they fill it with deuterium gas only. There's no tritium in there. And they look at the DD neutrons. That's isotropic on magLIF. It wasn't on ZETA. So on magLIF, it is thermal.

What's cool is that DD reaction can produce a tritium ion. That tritium ion is energetic, but these magnetic fields are huge. So it is magnetized. So in fact, the tritium moves preferentially in one direction or in two directions along the field lines. So when it collides with the deuterium and produces a distinctive neutron at 14 MeV, those neutrons are now coming out anisotropically. And the strength of that anisotropy can be used to measure the magnetic field, because it tells you how confined the tritiums are in a certain direction, which is pretty neat.

So it's not a problem for magLIF, because the neutrons are isotropic. And in a real magLIF, if you wanted to do magLIF as a power plant, then you just do [INAUDIBLE] fusion, and you wouldn't see this anisotropy at all because all the fusion would happen. Any other questions? All right, thank you very much. And I'll see you on Tuesday.