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PROFESSOR: So today we are going to be talking about proton radiography and proton imaging.

So we're starting a series of three lectures in which we're looking at how to use particles as opposed to the plasma previously. You remember we used electromagnetic radiation and we looked at the emission from the plasma, but now we're actively pushing particles through the plasma and seeing what happens.

So imagine-- and we'll talk about exactly how you do this later on-- but you have some source of protons, a beam of protons, with some spread. Maybe it's emitting into 4 pi steradians, maybe it's a tightly focused beam. It doesn't really matter. And you have some plasma here.

And maybe within that plasma, you have some magnetic fields. So you have magnetic field lines that maybe look toroidal from the point of view of the protons here. So they're looping like this. Then as our protons go through here, they're going to feel a force, which is equal to that charge-- I'll just write a z-- when you cross B.

But they've got velocity in this direction. For example here, the magnetic field is pointing into the page, and so the particles are going to feel the force upwards. And these particles here are going to feel a force downwards like this. And if we put some sort of detector some distance away, we should see that our source, which maybe was initially uniform, so we had a uniform number of protons per centimeter squared, millimeter squared, now that's uniform intensity is going to be changed.

So for example, if we draw a little line drawing of intensity over the initial intensity in the absence of this plasma, our intensity profile would just be 1. There's nothing to change the intensity. But in this case here we can see that this magnetic field configuration has created a void. It's pushed the protons outwards, effectively defocus them. So we see that we're going to have relatively few protons in the middle. We're going to have a pile up of protons at the edge. And then far away from the plasma, we're just going to have our standard fluence of 1 because there'll be some particles that just go around the edge here. And here in this little drawing, it's going to be nice and symmetric.

So what this would look like if we looked front on potentially is a bright ring where we have lots of protons and a void in the center. That's the magnetic fields. We could also have a plasma that has electric fields as well. And although we think electric fields are quite small due to bi-shielding, on short timescales in HED plasmas where these are often used, the electric fields can be relatively large because the plasma does not have to be quasi neutral, so we could have some sort of electric field like this.

And then our electric field would also put a force on these protons. In this case, I've drawn it in the same way so the electric field is pushing the protons out from here. So if I draw some more protons coming from a point source and I draw some trajectories going into the plasma, I'll have protons which are being bent upwards and downwards like this.

And so on my detector I could, for example, see a very similar pattern, where I have a void in the middle, I have some regions of increased fluence on the limbs, and then I have a region where there's undisturbed fluence because I've got particles which are just going around.

So this is a technique called proton imaging. It's a way of imaging electric and magnetic fields. But of course, it feels both the electric and the magnetic field. So that's one fundamental limitation with it, is that you never quite sure whether your deflection is due to electric or magnetic fields. There is a third form of proton imaging, which is technically called proton radiography.

Proton radiography, the radiography here is to make you think about X-rays and X-ray radiography, which is where you have your beam of particles, and you have some very, very dense plasma here. And because it's so dense, these particles don't stream through it and just fuel the electric or magnetic fields, the particles start scattering, and colliding, and maybe they never escape out the other side.

And then on your detector, you would have similar to an X-ray, an image which, for example, has a region which is a void where there are no protons, and that's because all the protons have been scattered. So again, this only happens at high densities. At lower densities, the particles should stream through.

Unfortunately a lot of people call this proton imaging technique proton radiography because that's what it was initially called, but it's not a radiographic technique. Radiography refers to your beam being attenuated by density in the way. So it's not really a right name, but you'll see a lot of people call this proton radiography. Some people have been trying to call it proton imaging instead.

Even in the case where you don't have such a high density, you may still end up with enough density in this plasma that it will knock a particle off course, and that will lead to some sort of blurring. So these weak collisions can lead to a blurring of the image. So you may still want to take into account the [INAUDIBLE] a little bit.

OK. And the references for this lecture are two papers. First one is by Hoogland. You can find it in *Review of Scientific Instruments, RSI,* from 2012. A lot of the mathematics we'll be using is based on this paper. And very recently, there was a review article by Schaeffer. It hasn't been published yet. It's on the archive. And that was published last year. And this review article is really, really good at the nitty gritty of how proton radiography is actually done, and we'll talk an awful lot, or a little bit at least, about how these sources of protons are made later on. For now, for the first bit, we're just going to assume there is some source of protons. So before we get on to a more mathematical treatment of this, does anyone have any questions? Yes.

AUDIENCE: [INAUDIBLE]

PROFESSOR: Yeah, absolutely right. So at the edges here, where they have less distance to travel through, you could have something that gets knocked around, but still gets through. But maybe another particle traveling a very similar path doesn't get through, and so you'd have grayscale you'd have here. So just like with X-rays, yeah. Other questions. Any questions online?

OK, so mathematically this does look very similar to shadowgraphy, but there are some differences. So I'm going to go through the mathematics again. So you may notice some similarities, some differences in notation. That's all OK.

So we're going to start by making some assumptions. Our first assumption is that we have a point source. In reality this means that if we have some source size here, which has a size, say, D source, that has to be much, much less than a length scale the size of our plasma. Because if that's true, we have some finite source size here and some very big plasma, from the perspective of the plasma, this will roughly be a point. So we can make this more rigorous by introducing a dimensionless parameter and insisting that parameter is small. This is a pretty good approximation.

The next thing we need to assume is a uniform beam, which is to say that we have the same number of protons coming through every little infinitesimal solid angle unit here. So that in the absence of any plasma, when I put my detector here, I do, in fact, get a nice uniform signal on it. So I over I0 is just 1 here.

If my signal is not uniform like this, it complicates the interpretation. It turns out you can do something with a non-uniform beam of protons, but mathematically it's harder. So we're going to insist on a uniform beam. So we'll say the gradient of the beam intensity is equal to 0, at least over the target, over the plasma, I guess.

OK. Third approximation we'll make is the paraxial approximation from geometric optics. The paraxial approximation is basically saying that although these particles are following some path that we can call DL, our detector is relatively small. And so most of the particles are going almost parallel to dz hat here.

So this means we can approximate any path integrals as just integrals in the z direction, and this also means we can approximate angles like tan alpha to be approximately sine alpha to be approximately alpha. This makes the mathematics very easy as well.

And the final assumption we'll make is it all protons are test particles. So you may have seen a test particle formalism in some bits of plasma theory. The idea is that your test particle merely experiences the fields inside your plasma. It doesn't contribute to them. So the fact that we have this beam of protons streaming through here, we assume it has negligible perturbation on the plasma itself. So we have no deflection, for example, between protons within the beam.

And this is a statement that the average potential that the protons are creating divided by their kinetic energy is much, much less than 1. That is to say they're going so fast that even if they do feel a small electric field that deflects them slightly, it's negligible because they're moving so fast. It doesn't change their overall proton kinetic energy here. OK, any questions on assumptions? Yes.

AUDIENCE: [INAUDIBLE]

PROFESSOR: Yeah, the paraxial regime takes care of that. Yeah, exactly. But you're right, but we're really talking about less than a degree subtended. So it's very, very small angle.

AUDIENCE: [INAUDIBLE]

PROFESSOR: The only place that appeared so far is we've assumed that it's very, very hot. So these protons tend to be, and we'll get on to the generation mechanisms, but these tend to be mega electron volt energy protons here. So they're much, much faster than any of the other particles in our system generally.

And because the collisonality, the mean free path goes as-- I'm going to get this right-- velocity cubed, then these very fast particles here have a very long mean free path. Their collisonality is very low, so they're unlikely to collide with any particles in the path. We'll talk about that. Yeah, no, no, no. It's great.

For the purposes of this, we're going to do it in such a way that we will just solve for the-- there are some protons with path energy 1, and some protons of energy 2, and our solution is separable. And I guess that comes back to here-- the fact that beam doesn't interact with itself, but we'll talk a lot about that later. Yeah, Alan?

AUDIENCE: Why not use [INAUDIBLE]?

PROFESSOR: They're much lighter and so they'll scatter more easily. But people have started doing electron imaging as well. But then you need GeV beams and stuff like that, so the protons are better for this.

AUDIENCE: Would there be advantages to that path?

PROFESSOR: I don't know enough about the electron beam techniques at the moment. So a lot of what I'm going to show you is through very specific detectors that have been created for protons, and I don't know whether that detector technology exists for electrons in the same way. There's another question.

AUDIENCE: [INAUDIBLE]?

PROFESSOR: Yeah, it's very hard to make a collimated beam of protons. And when we talk about the generation mechanisms, they tend to make point sources or things with very small spot sizes. So it's a technological limitation. In the very early days people used particle accelerators to do this. But although particle accelerators can accelerate a lot of particles to high energy, it's not enough particles on the timescale of these experiments. These experiments are over in a nanosecond, and so you need a very bright burst of protons. And it turns out the techniques we have for making those bursts of protons make a nice point source. Yeah, was there a question?

AUDIENCE: When you say point source, you mean like just from a specific one location, not the point source hitting the plasma, correct?

PROFESSOR: Sorry, could you say that a different way?

AUDIENCE: Yeah, so the point source is the beams. And when you were talking about the particle acceleration, you said it was coming from a single area. Are they still doing that with however else they're generating the protons these days?

PROFESSOR: Yeah, we'll skip over that, and we'll get to how the protons are being generated later, and it might make a bit more sense. So now you can imagine this as a point source that, for example, is emitting protons in every direction. It just turns out that our plasma is only in one direction. And so from the point of view of the plasma, there's just a little point that's sending protons its way.

AUDIENCE: But in reality, that's not exactly happening. I see, OK.

PROFESSOR: OK, any other questions? OK, so let's set up the geometry of our problem. So we've got our point source over here. We've got our plasma here. The distance between the two of these is lowercase L.

Our plasma has some characteristic size, a, here. We have a detector some distance away, and we'll call that distance capital L. Within the plasma, we have a coordinate system and we label points within the plasma using the position vector, x0. Yeah if I have a position with a 0 subscript, that's somewhere within the plasma.

And then on the detector, I have a position vector, x. So what we're going to be doing is looking at how the protons are deflected at position x0 and they will end up somewhere on the detector at x. And what our job is, therefore, is to link what we see on our detector x back to the properties of the plasma at x0.

And we can think of a proton coming out like this and within the plasma undergoing some deflection. And it's deflected from its original trajectory by an angle, alpha. And this alpha, in general, can be a vector. So we can have an angle in this direction and we can have an angle in this direction here. I'll be drawing it mostly in 1D, but remember, the particles can be deflected in two dimensions as well.

So from this simple geometry, we can already write down what we're going to see on the detector x. So x is a location of a proton which streams through the point x0. And then there's a magnification factor, capital L over lowercase L. This is just similar triangles. This just says in the absence of any deflection, I would have ended up at this point here, and that point is magnified because capital L and lowercase L are different.

So far this is just what you'd get without any plasma. But when you put the plasma in, of course you get some deflection, alpha, and that alpha is times by the distance between the plasma and the detector here. So again, this is just geometry. It has nothing to do with plasmas, or protons, or anything in there.

So just to clarify what all these terms are, this is at the detector. This is the object. This term here is due to the divergence of the beam. We wouldn't have this term if we had a collimated beam like we had with lasers. Remember with the laser, we started out with a load of rays which parallel, and so this wouldn't have happened with a collimated beam. But we don't have that. We got a point source. We got a diverging beam. And then finally, this is to do with the deflection. So this is like shadowgraphy with a diverging beam.

OK, any questions on that?

Typically we set up our system so uppercase L upon lowercase L is much, much larger than 1. So that is to say we have our source, we have our plasma, and then quite a long distance away, we have our detector here. Remember, this is lowercase L, this is uppercase L.

This is for two reasons. Firstly, the plasmas tend to be very small. And so by setting it up like this, we get a massive magnification. So because we've got these diverging protons here mapping out over there, we're going to have a nice big image to look at. So if this is only 100 microns across, maybe on your image over here it's 10 millimeters across, which is still pretty small, but maybe you can actually see something on your detector.

The other reason is just practical. You cannot put your detector very close to your plasma. This is something like a laser-driven ICF implosion. You really don't want to have your detector close because it will get trashed, so you've got to put it a long way away. So this is typically the regime that we work in. And then, as you can see up here, that means that we have a term that looks like x0 1 plus capital L over lowercase L, and we can just drop that term there as being small compared to the second term.

And we can then convert that equation so that it reads x equals L x0 upon lowercase L plus alpha. So I've just taken the capital L outside the brackets here and now we have these two terms inside. So this first term, as I said, is simply magnification.

Very poorly written. And this second term here is distortion. Because the rays are being deflected. If we didn't have the distortion, this would just be an imaging system with magnification. Because the rays are being deflected, we have distortion. And because it's distortion, proton imaging is not imaging. So perhaps they should call it proton deflectometry. You can argue about the name for ages.

But this is not an imaging technique, like with shadowgraphy. If you see something on your detector, it doesn't have a one to one correspondence with what's going on in the plasma. Features are enhanced and enlarged. The void that we were producing here, that void, for example, is going to be larger than the real size of the plasma. The protons are being pushed outwards.

So mathematically what we're doing is we're taking some area inside the plasma, the s0, which has a certain number of protons going through it, and we're mapping that out onto some area on the detector, which does not have to be anywhere close to the same shape because of all the deflections going on inside here. And that area is just ds. So we're keeping our subscript notation here. This is the object. This is the image that's forming here.

And the way to link these is to say that ds is equal to the magnitude of this quantity, D at x0 times ds. And this is a quantity that some of you may know. It's the Jacobian.

And it has the form partial x and y over partial x0 y0. Of course, we haven't told you how to calculate that yet, but it's going to be related to this here. So this is just a general statement. When you're mapping some area to another area, you can do it using this Jacobian transform, and the exact way the Jacobian transform works will be related to this, and we'll solve it explicitly.

Sorry, the left hand side here. Thank you. Yes, didn't make much sense otherwise. And guess this is a vector again, but I've written it out explicitly in terms of the x and y components. Here I just put it in this more compact vector notation. OK, questions?

OK, we're going to assume that we can serve particles. Maybe this was another assumption up here, but none of our particles are scattered and lost. But if we can serve the number of protons, then the intensity on our detector is going to be equal to the intensity going through the object divided by this Jacobian. It's equivalent to the statement that we're conserving the area of this Jacobian transformation. Here we're conserving intensity here.

And this Jacobian is going to be equal to capital L squared upon lowercase L squared times 1 plus then we start doing a Taylor expansion of this equation here. L radiant of alpha plus L squared partial alpha x component partial x0 partial alpha y component partial y0. And then another term, which follows symmetrically from this, which is minus partial alpha x component partial y0 partial alpha y component partial x0. Plus some other terms that we're going to drop as being small here, but there's probably a more compact vector notation for this, but I just want to write it out more explicitly. This one is clearly just partial alpha x partial x plus partial alpha y partial y. And these are all 0 subscripts because we're doing the derivative inside the plasma. So this is looking at derivatives of how the angle changes inside the plasma.

So if you can calculate your angle alpha, and you might think, I can do that if I know the electric and magnetic fields in my system, and you'd be right, then you can now calculate how alpha changes within the plasma, how the protons get distorted, and now you can work out what your intensity is compared to your initial intensity. And it turns out that the sorts of images you get out of here, there's a very useful dimensionless parameter that you can write down to characterize the different images, and this parameter is called the contrast parameter.

And it's written as mu, and it is defined as lowercase L over a-- lowercase L was the distance from the point source to the plasma and a is the size of our plasma-- times the modulus of this deflection angle vector, so the size of this deflection angle. And it turns out if you're in a regime where this parameter is much, much less than 1, then you find out that your D, your Jacobian here, is approximately constant and so your intensity is approximately constant.

So we talked about this with shadowgraphy. This is a regime where we only have small intensity variations. And when you have small intensity variations, you have a chance of being able to undo this transformation, and work out what D was, and therefore, work out something about your plasma. But if you have a contrast parameter where mu is about 1, this corresponds to having your Jacobian with singularities or with zeros in it.

And you can see if you have zeros in D, then all of a sudden, you're going to have your initial intensity over 0. Your intensity will go to some very, very large number. And these are the caustic patterns we talked about in shadowgraphy.

I wish I had some more space, but I don't. Well, actually, maybe I have just about enough space. So in this case here, you can show that your intensity on your detector is equal to your source intensity times 1 minus L divergence of alpha like this. And this is equivalent to the equation we came up with for shadowgraphy, where we've implicitly assumed that all of these terms are very small.

If you look here, our contrast parameter has an L and alpha has an a. We've got an L, an alpha, and this gradient is going to be on the order of the size of the plasma like that. So we've implicitly assumed that this contrast parameter is small in order to get the solution. And so what we see is we have small variations in intensity because it's 1 minus a very small number.

If we have zeros here, then we actually have to solve fully for D everywhere inside the plasma. And this is where we start getting these singularities. So I've got some space.

So we have D equals 0. We get singularities in I. I is equal to I0 over the size of D. And this corresponds to proton trajectories crossing. So we have deflection within the plasma and we have two protons, which take different paths, but end up at the same place. And if you can imagine if there's multiple of these happening, you end up with a huge amount of fluence in one spot, and so you get very, very high intensity.

And this is usually called a caustic. So these caustic features are very, very strong. You can see them very, very easily, but they mean that there is no longer a unique reconstruction. So we can no longer uniquely take our modulation intensity, I, on our detector and work out the properties of the plasma through D.

So we want to avoid being in this regime. Avoid being in the regime where mu is approximately 1. And to avoid being in that regime, we just have to look at the definition of mu and try and make it as small as possible.

So we want L over a much, much less than 1. So again, that's the distance between the source-- I've got it here already. The source distance to the plasma is L and the size of the plasma is a. So obviously in this case, I haven't succeeded. L over a is roughly 1. But I could put the source much further away, and then L over a would be much smaller, and that would help me make mu smaller. And the other thing I can do is have the size of alpha be much, much less than 1. So that's effectively insisting that my deflections are small.

Now for a given plasma, there are some given electric and magnetic fields. I can't just ask the deflections to be small. What I can do, however, as we'll see in a moment, is use very fast particles or fast protons. Because if we make the protons go very fast, their deflections become smaller and smaller as we're about to show.

Now none of this really has talked about protons at any point. All of this applies just the same to shadowgraphy. We're just thinking about particles or rays that get deflected going through a plasma, and we've put some geometric formalism on top of it to tell us what we expect to see on our detector. So bearing that in mind, any questions before we go on and actually talk about protons, and plasmas, and electromagnetic fields?

I saw some folks still writing, but yeah, taking questions.

AUDIENCE: The L being [INAUDIBLE].

PROFESSOR: Oh, it looks like I got it the wrong way around, didn't I? Yes, L needs to be much less than a.

AUDIENCE: [INAUDIBLE].

PROFESSOR: No, I can still do that if the plasma is spherical, right? Because if I have, for example, a source here and a spherical plasma over here, this is a and this is L, and it's pretty clear that L over a is much greater than 1. Well, no, no, no, no. This is the condition that you want. What I said earlier is incorrect. You don't want this condition. You want to have your plasma very close to your source. So my words were wrong, but the algebra is right here. Yeah.

AUDIENCE: [INAUDIBLE].

PROFESSOR: Oh, I see. Yes, I take your point. Yeah, if your plasma is spherical. A lot of the time people are imaging plasmas which are quite thin. But yeah, you're right. OK, other questions? Yes.

AUDIENCE: [INAUDIBLE]?

PROFESSOR: Oh, radians. Everything's in radians.

AUDIENCE: Less than 1?

PROFESSOR: Yes, much less than 1 radian. It's in radians because we're using this approximation. So if we're using this approximation, alpha has to be in radians for that to be true.

AUDIENCE: [INAUDIBLE] there's nothing special about 1 radian?

PROFESSOR: No, no, no, no. No, there's nothing special about 1 radian. We want it to be as small as possible. 1 is a number that it can be small there, but guess could have raised it 10 to 6. Yeah, sure, sure, sure. In particular, we said that we can get a less than 1. So if we want to get mu much less than 1, that means that alpha has to be much less than 1 from that point of view. I think this is a reasonable [INAUDIBLE], but yeah. OK, any questions online?

OK, let's have a look at what the actual deflection, what this alpha, is here. Because that's what you need to in order to work out this quantity, which is D, and work out all the rest of the stuff. So which board should I use?

OK, so alpha for electric and magnetic fields together is simply the integral of that force, which is E plus v cross B along the path, which remember, we're approximating as dz like that. And the deflection angle has to do as the charge, of course, because that's what goes into the force. But there's also a factor of 2 and w out the front here. This w is, again, the kinetic energy of our proton m proton v proton squared.

You can work this out if you want to. I haven't proven this exactly. So what we notice is interestingly we got a w that depends on v and here we've got v inside this. And so we can separately write out that there's going to be a deflection due to the electric field, which is e over 2w integral electric field dz. That's pretty obvious. I've just taken the first-- ah.

And we have a deflection due to the magnetic field Alpha B equals E over square root 2 mw. We're taking this velocity and we're combining it with the velocity squared over there. Integral of dL crossed with B. Whereas of course this dL is really dz because of our paraxial approximation.

So we're going to have a deflection angle that depends on the cross product of the path and the magnetic field. What's interesting about these two is that you have different scalings.

One has a scaling with the particle energy. One has a scaling with the square root of the particle energy. So this suggests to us straight away how to distinguish between E and B.

Or should I call them alpha E and alpha B. So the deflection is due to electric and magnetic fields, and we distinguish between them by using two or more proton energies.

If we have a source that produces 1 MeV protons and 10 MeV protons, they will go through the same plasma, but the 1 MeV protons will be much more sensitive to-- I've got to get it right now-- lower energy. So this is a bigger number to the electric field than the 10 MeV protons.

And so we can use a differential measurement effectively to work out the contribution of alpha E and alpha B. There'll be two simultaneous equations and we'll have two things we want to solve for. So we'll be able to get it out. So this looks an awful lot like when we talked about two color interferometry to determine the difference between vibrations or neutrals in our plasma.

And people do this a lot because they feel doing an experiment you don't a priori know whether the electric fields are small compared to the magnetic field. Most people want to use this technique to measure magnetic fields. And usually it's the case of magnetic fields do dominate, but you still need to check, and you can do it with these two different energies.

So we've been talking a lot about alpha here, but there's a rather neat formulation, which says, well, instead of talking about this vector alpha, and that deflection angle alpha depends on where you are in the plasma, so it depends on your position x0 within the plasma. If this is a vector, then we can just write it as the gradient of some scalar. That's just generally true.

So we can say what if there is some scalar, phi, of x0 and alpha is just its gradient. And the reason you want to do this is can now write down an expression for phi, which works for shadowgraphy as well as proton imaging. And then all of the mathematics that you've done previously, you just do it in terms of phi, and it's agnostic to the exact technique that we use.

So for shadowgraphy you find that your deflection potential is equal to minus the integral of the logarithm of the refractive index n. And I'll explicitly write this out in terms of the position within the plasma. The z0. So the integral along through the plasma in the z direction. And this logarithm here, or this n here is, of course, the one where we have n squared equals 1 minus nE over nc that we saw in all our refractive index things.

So of course it could be whatever-- O modes, X modes-- but people don't do proton radiography [INAUDIBLE]. So the plasmas we're working with are mostly unmagnetized. This is fine. But E fields, this potential here is just equal to q over 2w. I use q over there? No, I switched to E, so I'll put it back to E. Integral of the real electrostatic potential, lowercase phi, x0 y0 z0 E z0.

So they are related. They don't have to be, but they are in this case related. The deflection potential is related to the electrostatic potential. And then the final one is the magnetic fields.

Capital phi of x0 is equal to E upon square root of 2mw integral of A dot dz 0. And this A is the magnetic vector potential. So B is equal to the curl of A.

So the idea is that we will seek techniques which will take our intensity variation, I, on our detector, and we will use them to infer some sort of deflection potential. And then the neat thing is, it doesn't matter whether we're looking at electric fields, or magnetic fields, or shadowgraphy. That's a detail that the end user has to use, but the algorithms are all the same. So this is very powerful. We can share techniques between very disparate looking diagnostics.

AUDIENCE: Professor?

PROFESSOR: Yes.

AUDIENCE: Does the B is A, where B equals the curl of A, is that from the Maxwell's law B-- like the divergence is 0? Is where that comes from?

PROFESSOR: Gosh, yeah? Can divergence free fields be written as the curl of another vector? I think so, yeah.

AUDIENCE: OK, then where does the potential come from? Is it just a regular electric potential?

PROFESSOR: Yeah, this is the electric potential. This is the potential that's defined by Poisson's equation.

AUDIENCE: I see. OK. I just wanted to check. Thank you.

PROFESSOR: Yeah, no worries. OK. Any questions on that? The next thing I'm going to cover is how do we make these beams of protons, so we're going to switch gears a little bit. So if you have any questions on what's happened so far, this is a good time to ask.

AUDIENCE: [INAUDIBLE].

PROFESSOR: These are contradictory, yes. So the paraxial approximation also makes it very hard to have your object very close. But if you were able to do that, you would reduce the contrast parameter, but you would also break all of the mathematics we've done, which is use the paraxial approximation so far.

So in practice, your best bet is to reduce alpha instead. And you reduce alpha by making your protons as fast as possible. Because the faster your protons are, the higher their energy, the lower their deflections. So this is what motivates us using MeV or higher beams of protons. Yeah.

AUDIENCE: [INAUDIBLE].

PROFESSOR: So the particle is being deflected a little bit, but I could approximate mostly in the same direction. It's certainly not being decelerated. Its velocity is constant. So the size of its velocity, its speed, doesn't change as it goes through the plasma. That's also consistent with our test particle picture, where the test particle is experiencing the field, but it's not being slowed down. Yeah.

AUDIENCE: Is that like when [INAUDIBLE]?

PROFESSOR: The particles are really, really fast. They don't scatter at all. They're way faster than everything else. So this is a completely reasonable approximation. You can treat the plasma as this static, unmoving thing on the time scale of these protons going through. And the protons barely see it apart from they get deflected a tiny amount. And it's only because we put our detector so far away that those tiny deflections show up as significant changes to the fluence. OK, any other questions? Anything online?

Yeah.

Yeah, the deflection potentials add linearly, which is neat as well. And then when you use two different energies, you can solve separately for the two deflection potentials and then see how big they are. OK, let's talk about how to make a beam of protons.

This is actually quite frustrating. When I taught this in 2021, there was no good reference on this and I had to spend ages looking it up. And then Derek Schaeffer put his paper on archives and explains it all really straightforwardly. So if you want to understand it, you can just read his paper.

But yeah, it's interesting stuff because this technique is relatively modern. It's only within about the last 20 years that people have really been using it. And a lot of the development of this technique was led by the HED group here at MIT. So a lot of the things I'm going to tell you about are MIT diagnostic development.

So we need to have a source. And for each source, there is a detector. So the first source that I'm going to talk about is a technique called TNSA. This stands for Target-- and it doesn't really matter-- Normal Sheath Acceleration. You can't quite sing it to the tune of Teenage Mutant Ninja Turtles, sadly, but it's getting pretty close.

So the idea of TNSA, and I will never say target normal sheath acceleration again-- is you have a metal foil. And it's thin-- tens of microns thin. And any metal that you have is going to have absorbed on its surface lots of hydrocarbons, which means lots of little protons.

So again, we're not accelerating copper or something like this here. We're still accelerating protons, it just turns out there's lots of little protons absorbed in the structure at the front here. And we take our laser beam, and we focus it down, and hit the back side of this target. And our laser beam is ultrashort pulse.

So this tends to be something like a 50 Joule laser in 1 picosecond, 10 to -12 seconds. So this is over 100 terawatts of laser power. Or if you've got a really short pulse, you can do 1 Joule in 50 femtoseconds. A femtosecond is 10 to the -15 seconds. So these are seriously short laser pulses and this is a seriously intense focal spot here down to about 10 microns, we can focus the laser down to. So that's a lot of electrical energy being focused into a very small spot on a very short time scale.

And what that does is it initially blasts electrons off the foil. So there is some heating, there are some strong electric fields. For reasons that we're not going to go into very much this drives electrons off the foil at a high speed, and they form a little cloud going outwards. And because there's been electrons ejected, we then have an electric field. And that electric field drags these protons off the surface like that. And this is how the protons are accelerated.

So this technique, some good things about it, it gives us many protons. It's a very efficient way of accelerating the protons here. It gives us a range of energies. Now remember, we said we'd like several different energies for telling difference between electric and magnetic fields.

The spot size was around about 10 microns. So as we said, that's a nice small spot. That's something we wanted in order for all our paraxial approximation and stuff to work. And it's a beam. It's in one direction. And we'll see why that's important when we compare it to other [INAUDIBLE] experiments.

The big disadvantage of this technique is you need a petawatt class laser or higher. So you need to have one of these ultrashort pulse lasers. Not every facility has that. These are very expensive things to build. So it's not like you can just go down to the shop and get this. I've thought about trying to get one of these for the PUFFIN facility, and we got a quote for about $2 million for a laser just to do not very good TNSA. So these are very expensive. [INAUDIBLE].

So that's your source. Your detector--

Is something which is called radiochromic film.

Another acronym I'm not going to repeat, we'll call it RCF from now on. Now RCF changes color when it's hit by protons. That's the chromic part of it. And the more protons that hit it, the more it changes color. It sort of starts off quite clear, and it turns this beautiful ghostly blue, and then goes into a very dark, deep blue. They're very beautiful raw proton radiographic film images.

Now what you end up doing is you have stacks of this film. You have multiple sheets. So imagine these are squares of film and I've just made a stack out of lots of them like this. And the reason you make lots of stacks out of these is due to a peculiarity of charged particle stopping, and this peculiarity is called the Bragg peak, which some of you may have come across before.

The idea of the Bragg peak is your charged particles tend to stop in a very specific place for material, which is to do with their energy. So for example, if this is the stopping location x, we'll call this the x-coordinate. I guess I've called it z everywhere else, but whatever. You tend to have a lot of deposition of your particles all at one place, and this is energy-dependent. So this is energy-dependent deposition.

The reason this is peculiar is you remember that for photons we just had this exponential decay here that was to do with the opacity of it. But that's not what we get for particles. The fact that all the particles of the same energy roughly stop in the same bit of film means that each film corresponds to a specific energy.

Maybe the first film stack here corresponds to 1 MeV, and the next one to 2 3, 4, 5, 6, and so on. You can put different filters between these to select different proton energies, but it means that each of these bits of film now corresponds to a different energy, which is very useful if you want to do your multi-energy trick of unfolding the electric and magnetic fields.

So this first result of this is that we have we call it 1 energy per film. It's obviously not quite true because you have some bleed through, some particles which stopped early. So there's a little bit of crosstalk between them.

The other neat thing about this, if you don't want to use these in order to back out the difference between electric and magnetic fields, you can make a different argument. And you can argue, in fact, that my particles were born here, and they were born at different energies, and they streamed through this plasma here. But that means that a particle going at 10 MeV reaches the plasma at time T0.

So instead of 10, I'll write 6 because I've got 6 here. So these particles all stream through at T0. But a particle at 1 MeV is going more slowly, going six times more slowly modulo, some relativistic stuff. And so that means that this particle arrived at T0 plus delta T.

And so not only did the different energies maybe give you a way of unfolding the electric magnetic fields, the different energies are different slices in time. So if this is energy in this direction, it means that if you read the films back, they correspond to time in this direction. And so you can make a little movie of how your plasma evolves in time.

So that's really cool. You get time resolution. And the more different bits of film you have, and the wider range of energies you have, the better time resolution you can get. Questions?

Yeah.

AUDIENCE: [INAUDIBLE].

PROFESSOR: Yeah, the radiographic film isn't sensitive to other particles. So not to neutrons, and gammas, and things like that. In this case, I think it's almost that the lower energy particles and photons you could filter out and the high energy ones, like gamma rays, will just go straight through without interacting. So this is pretty much just sensitive to the protons. Yeah, that's a good question. Yes.

AUDIENCE: [INAUDIBLE].

PROFESSOR: It's the same thing. So the protons are all emitted in a very, very narrow burst. Yeah, that's great. Thank you. Let's have a little figure here of time and fluence. So at time 0 all of the protons are emitted. They're very narrow. Remember, this is picosecond or femtosecond here. So I can say this is picosecond.

And maybe I've got two energies here the blue energy, which is 1 MeV, and the purple energy, which is 10 MeV. They have to travel some distance from the source to the plasma, and they will go through it at different times. The 10 MeV one will get there first and the 1 MeV one will get there second.

And then finally, they will travel through to the detector. And they'll arrive there much later, but we don't really care. The detector is time integrating. So it will see protons, which sampled the plasma at an earlier time. Sorry, the 10 MeV film will see protons that sampled the plasma earlier than the 1 MeV film. But you do actually have to have that requirement that you have a very, very short burst of photons. Yeah.

AUDIENCE: [INAUDIBLE].

PROFESSOR: Yeah, so you can only do one or the other. You can either claim that there are no electric fields, and you know it's all magnetic fields, and then you get a time series. Or you can claim that this plasma doesn't change in time, and therefore, you can use a different energy. So you've got to be a little bit careful when you see someone claiming this proton radiography. It's difficult to do both.

But you might have a simulation or some other experiment that suggests the electric fields are minimal, in which case you can just say, OK, everything I see is due to magnetic fields. Now I have a time series. People do that and it may be reasonable. Was there another question do I see? OK, let's talk about this second method, which is an imploding capsule.

The second method would be, for example, a D helium-3 implosion. So this is literally a little inertial confinement fusion target here filled with deuterium and helium-3. And you get a load of direct drive lasers pushing on it.

I'm making a nice symmetric-ish implosion of this. And then when this implodes, it's going to send out all of the particles that come from the fusion reaction between the deuterium and the helium-3. So just to say for this, you need to have multiple, I'm going to write many, kilojoule class beams with a 1 nanosecond pulse. 1 nanosecond ir the laser world is considered a long pulse. So these are much longer than picoseconds and femtosecond, but these are long pulse lasers.

So the interesting thing is that this reaction produces two different energies from it, but only two. We have the 3 MeV DD protons. Remember, we're not interested in neutrons. There may be neutrons coming out, but they're not being used for this diagnostic. And we have the 14.7 MeV D helium-3 protons as well.

So this could be a positive or a negative. The positive is you know exactly what your particle energies are. They're set by fusion. They're going to be shifted a little bit because there's thermal motion here, but roughly what the energies are exactly. But it's good so the positive is we know the energy.

The negative is there's only two. People have recently add a little bit of spice in the form of some tritium, and then you also get the tritium helium-3 reaction, which gives you a proton at 12 MeV. So that gives you a tri particle source. So that's nice. Now you have three particles. So that's pretty good.

Another negative here is the spot size. These implosions tend to get down to slightly larger sizes than you can reach with the focal spot for TNSA, so the spot size is rather about 40 microns or so. It's not too much worse, but it is significantly larger than the TNSA size.

The other problem is that we have isotropic emission. So the nice thing about TNSA is all the particles are going roughly in the direction you want to. Here, if your plasma is over here, most of your particles are just flying off in completely random directions, and you don't get to capture them at all. And so this means that we have few particles.

This is in contrast to TNSA, where we were able to create a very large number of particles. But the fact that we have very few particles also leads to a change in detector. And this is the big workhorse of the MIT HED group because they realized that they could use a detector called CR-39.

Now CR-39 is a polymer. The interesting thing about it you have a sheet of CR-39, you have a proton going through it, is It causes a little area of damage, a little track as a proton goes through. And you can then dip your polymer after the shot in an etching solution. And it turns each of these tracks into little holes.

So now if you look at your CR-39, there's all sorts of little holes on it. It turns out the size of the hole is in some way related to the energy. So you can tell the difference between the 3 MeV and the 14.7 MeV. And theoretically, though again I'm not sure that anyone has done this since it was first suggested, if you have multiple pieces of CR-39 and protons are just going through it, you should be able to correlate the tracks in different bits of film and go, aha, a track in this bit of film is now over here and I should be able to work out the angle of the particles.

So you may be able to correlate tracks. But I'm not sure anyone's actually used that as a serious diagnostic. Just in one of the early papers.

So what do you actually do with all these tracks here? Well, you set up a very good microscope, and you put one of these bits of CR-39 in it. And the microscope looks at a small square here, and it counts all of the holes in this little square. And this square represents a pixel, and it outputs, for example, a hundred holes. And now it goes to the next one and it outputs 102.

So it's effectively reading off the number of protons, one by one, individually, automated, but still individually, and building up that intensity. Whereas the radiochromic film, we don't know the exact number of protons, we just have a different darkness of the film depending on the proton fluence here. So I did a scientific poll at APS DPP 2021. Three out of three physicists preferred-- I probably spelled preferred wrong-- PNFA plus radiochromic film.

However, there are many facilities which do not have a sufficiently powerful short pulse laser, but they do have an awful lot of kilojoule class laser beams floating around that they don't have to use. So for example, on omega or on NIF, you have lots of these beams. You can use some of the beams to drive your target plasma, and the other beams to drive your imploding capsule, and you'll still be able to do proton radiography. So there's definitely a place for this technique. It's just that it seems like people prefer, in general, TNSA. OK, questions? Yes.

AUDIENCE: [INAUDIBLE].

PROFESSOR: I don't know whether people have done that, but yeah, possibly. You need to have magnetic fields in this. And so in general, people don't think too much about the magnetic fields in ICF, but they might be there. There are mechanisms which could self-generate the field like the [INAUDIBLE] battery.

I don't know if anyone's done that, but it could be done. I imagine it's then complicated. You have to work out exactly what you're measuring. But yeah, it's an interesting idea. Yeah, sure.

AUDIENCE: You mentioned [INAUDIBLE]. Why not ELF particles?

PROFESSOR: Why don't we do ELF particles?

AUDIENCE: Because they are lower energy [INAUDIBLE].

PROFESSOR: Yeah, I would have thought that the velocity is a fair bit lower because of the higher mass. I don't know exactly, so good question. I mean, in general, the reason why people haven't put tritium in this, is you don't necessarily want to be playing with tritium. So this is relatively easy to fill this capsule, and this is just a pain in the ass. So it's not like everyone has rushed out to start doing the tri particle thing. Yeah. OK, other questions? Anything online?

OK, now we'll go through some issues with doing this diagnostic practically. We've got our source, we've got our detector, we understand how to make a map of the intensity after the plasma, but are there any problems with doing that? Yes.

So issue 1. This condition, but our beam was uniform. Remember, we need that because we're trying to determine from I equals I0 over the size of the Jacobian. And remember, the Jacobian is the thing that has all the physics in.

If we want to work out what the size of the Jacobian is, we are measuring I, but we need to make some assumption about what I0 is. We can't measure it because we do the target normal sheaf acceleration through the plasma. We can't put a beam splitter in and measure what the protons look like because we don't have beam splitters and protons.

So knowing I0 and knowing that it's uniform is very, very difficult. And so you could say, well, what if I have reproducibility? What if I do the TNSA over and over again and I measure it without any plasma and I see that it's uniform? Well, the trouble is we see that it's not uniform. So we have poor reproducibility.

So a solution to this is that you include a grid in your system. You still have your point source and your protons streaming out through your plasma, but on the other side of the plasma you put a grid like this. So in the absence of the plasma, this splits up your beam into a series of beamlets.

So for example, we have regions where the protons can pass through the grid-- I'm just going to draw nine of them here-- and we effectively have little points on a grid like this. This is the case without plasma.

Now when the plasma is present, these protons are going to be deflected in different ways, and we'll see these points move. So for example, this point might move to here. This point might move to here. This point might move to here.

And actually, we can now directly calculate the deflection angle, alpha, and therefore back out the electric and magnetic field from this technique. So this is very good because we can calculate alpha directly.

But the downside of it is we have very low spatial resolution now. Because you've gone from having a continuous image into a discrete image instead. But this technique is still very powerful because it does give you a direct angle on alpha without needing to know what I0 was. OK. The second issue I want to talk about.

Is if we have a uniform magnetic field as well as some varying magnetic field. If we have a uniform magnetic field all of the particles are going to be swept in the same direction as well.

It's actually extremely hard to align these detectors and know exactly where the center is because we're talking about submillimeter precision. So if you see this grid initially--

If you see a grid like that, that could be a grid that's been formed without any background magnetic field or it could be a grid that's been displaced some distance by a background magnetic field. You're not going to be able to tell the difference between those two, so you cannot measure this background magnetic field. And in many experiments where this is externally applied with some magnetic coils, they really want to be able to measure that background magnetic field externally applied.

So a very neat technique that's come up recently is to use a second detector, which is sensitive to X-rays here. So the idea, once again, is that we have our source of protons, but alongside the protons we're also going to have a source of X-rays because this thing is hot.

And in this case, I drew the mesh afterwards. Some of you may have realized I think the mesh needs to be before this part. Now we have our mesh again here and we have our plasma. And the neat thing is we have, for example, our RCF, which is sensitive to the protons, and we have some image plate, which is sensitive to the X-rays.

Then although our protons will be swept up by magnetic fields and do all sorts of strange things, the X-rays are just going to go in straight lines, which are completely unaffected by any magnetic fields here. So we're going to use high energy X-rays here, such that the refractive index at 10 kilo electron volts is roughly 1, and so we don't see any refraction of the X-rays.

And so that means what we end up with is we'll have a grid of the X-ray points. In the absence of any background magnetic field and in the absence of any plasma, we should see all of the protons end up in the same place as the X-rays, if there is some uniform magnetic field that will shift all of the protons like this, this is uniform. And then if there's a uniform magnetic field plus a perturbed magnetic field, it will further shift them on top of that.

So the X-ray grid acts as a really nice fiducial. It allows us to directly measure the deflections without having to worry about the uniform magnetic field screwing things up. So this is very nice bit of work by Johnson and others. And this is in *Review of Scientific Instruments* published last year.