MARKUS KLUTE: Welcome back to 871. So in this section of our discussion of instrumentation, we talk about accelerators, and I'll do this in a little bit of an historic way showing you some of the developments over the last up to 100 years. We use electromagnetic fields in order to accelerate charged particles, and so the developments in electromagnetic and understanding electromagnetism led to then the technical developments or the technological development of accelerators and the availability of devices, which can be used in order to accelerate or modify particles.

And so this goes back to Maxwell and Hertz discovering electromagnetic waves towards JJ Thomson, who was able to use cathode rays and the classical Lorentz force in order to understand the electromagnetic fields. If we study particle accelerators, we can see three different historic lines-- direct voltage accelerators, resonant accelerators, and transformer accelerators, and we go through those three different subjects one by one. The energy limits of our accelerators, they are typically given by the maximum possible voltage available.

When you think about accelerators used for colliding beams, it's not just the energy which is the limiting factor, but you also need a sufficient number of particles to be accelerated and brought to collisions. And those particles need to be in some sort of beam, which is narrow such that collisions are possible. Requirements change depending on whether or not you have colliding beams or fixed target experiments, whether or not you actually study lepton collisions, or hadron collisions, whether or not you're using secondary particles as the means of what you're going to learn from this. But the concepts are very comparable across individual fields of study.

So let's start with the van der Meer-- Van de Graaff accelerator. So you basically have to be able to create large voltages, and for the Van de Graaff accelerator, it's been doing this, creating this large voltage, by just moving particles from on one level-- separating particles to create this large voltage. You can typically get up to megavolts and tens of megavolts of voltages, but you need to make sure that you don't enter a breakdown kind of regime. And so it depends on what kind of insulating materials you use. If you are using insulating gas under certain environmental conditions, you get up to 17.5 megavolts, which then can be used in order to accelerate.

We can use the fact that you can use the electric fields twice in the tandem accelerators by changing the direction of the voltage. Large potential differences have been field of studies in the 1920s and '30s, and one not so-- and it's just noteworthy that this is a dangerous field. So Brasch and Lange, they use potential from lightning in the Swiss Alps, but this was fatal for Lange, who was electrocuted fatally by a lightning strike.

So then you need to think about how can you make large voltages available, and how can you make them available for acceleration? Cockcroft-Walton accelerators use a sequence of a cascade generator in order to reuse the voltage in order to create a larger potential for acceleration. The max generator is very-- conceptually is very, very similar. Those are still used today, so we know why those developments are 80 or 90 years old.

If you go to a *Physics Today* article from 2003, you see that a machine like this is being used in order to create an initial confinement for fusion reactors, and the total power is rather fascinating. It's four terabytes, which can be released in 100 nanoseconds from a larger number of those Marx generators. In modern particle physics accelerators, we use resonant acceleration quite a lot, and the idea is really like it's shown in this picture here, that the charged particles, they're kind of being accelerated on a wave. So basically, they're surfing on electromagnetic waves.

And this can be seen here. You just place them correctly in your waveform on a specific point, and then they can be accelerated over some distance. So the key point here is that you have a proper or correct phase relation to the accelerating voltage, and the set up can be varying. And historically, there's various attempts to do this in an optimal way.

The first one is the cyclotron, which has a static magnetic field, and in each turn, your particles are being injected, and then in each turn, your particle's getting a kick here and a kick here. And because their velocity is increasing, the radius in this fixed magnetic field is increasing as well. So after some time, the particle is accelerated and leaves the cyclotron as a specific velocity.

Focusing here is important. You don't want to just inject particles and then they spray all over the place, an accelerator's focus and having the right optics for the particle is a key part of the work needed. There's a number of techniques. I don't want to go into too much detail, but what you typically see is if you compress the beam in one direction, it decomposes in the other direction.

And so quadruple magnets can be used in order to get them focusing, and use fringe field and edge field in order to make sure that the beam itself stays in a compact form. You can also do techniques where you have initial focusing in one direction and then in the other direction, so the result can be made smaller. Accelerators are not just important today in particle physics, but they have specifically found their place in medical applications, in tumor therapy specifically.

And the history here is very long. You see those initial ideas or methods where neutrons are used-- [INAUDIBLE] neutrons are used in order to treat tumors. We haven't discussed this in nuclear physics too much, but when you use ions as a radiation form, you can really pinpoint where energy is deposited. The so-called Bragg peak is used in order to precisely figure in a three-dimensional way where the energy of the ions is being deposited.

This is in contrast to radiation therapy with photons, which just basically spray a larger part of the light material and just destroy the cancerous cells but also the ones which are still healthy. Any given large hospital nowadays has a small accelerator, and so there's thousands and thousands of those available. And the work and the maintenance of those is [INAUDIBLE].

But continuing the discussion of accelerator concepts, these kind of racetrack accelerators are quite interesting. You basically have a couple of fixed-- you have your particles being injected, and it's getting, like in the cyclotron, larger and larger kicks, and then, at some point, can be injected in order to do experiments. Again, this is not the technology which is not new anymore. MAMI is an accelerator at the University of Mainz, and it's-- the next generation is using-- the next generation of accelerators at this facility is using a similar technology.

The question is what kind of conditions you have to fulfill in order to keep the particles in place, and here because the particle moves along, it, in each turn, takes more time in order to make one circulation. So what you want to make sure is that your phase and the acceleration stays in sync, so you want to make sure that the particular event comes around again, gets another kick, and it's not deaccelerated. And so that explains why in those machines the particles are bunched. They come in little blocks of particles instead of just being a continuous stream of particles, and you can work out the conditions necessary in order to fulfill the requirement that particles are being continuously accelerated.

So then there's-- over the history a number of technologies which try to make use of the fact that when you accelerate, the velocity of the particles increases, and so initially, at a specific time, with one sequence, the particle gets a kick. And then in the next time, it's already faster. It travels further, so you can-- [INAUDIBLE] a linear accelerator structure, so you just increase the length of each accelerator structure in order to make sure that you, again, can give particles the necessary kick.

Nowadays, they use cavities, and we use superconducting cavities in order to make them energy efficient in order to have large gradients. The general idea is, again, that you place your particle in here, and you place it such in your face in your electromagnetic field that it always gets a kick instead of being on the other side and being deaccelerated. Again, the Alvarez Linac is a very similar concept, so the advantage here is that you only have one power input, which then you couple and the walls of the machine don't dissipate energy.

So then next, once you have an accelerator structure in place, you also want to make sure that the structure itself doesn't interfere with a beam, that the power transfer is as efficient as possible, such that you can get more for your buck. All right, I mentioned it a few times already, the fact when you have an electromagnetic wave of this form and you put your particle here, the question is what happens to these particles which have a slightly higher energy over these particle which have a slightly lower energy?

And it turns out that this kind of wave has a self-focusing kind of structure in a sense that the particles were a little bit behind, they get a little bit larger kick. Particles which are a little bit in front, they get a little bit lower kick, which means overall in energy you focus your bunch. In energy and space, you focus the bunch.

You can go one step further using RF quadrupoles. Again, no details given here. You use this unit in order to further squeeze the beam and reduce the footprint in energy and space, the phase space your particles are occupying.

All right, the next level here is then to use a betatron, and the idea of the betatron is that you change the magnetic field as you go. Instead of changing the size of the structure, you change the magnetic field, so you can use the same structure in order to confine your beams. And the next level to this is that you don't just use one magnet. You use many magnets, and this is done in synchrotrons, modern synchrotrons.

So here, again, the large line in history, but the point is that when you use the same orbit for the particles, the way you accelerate them, your magnet structures can become much, much smaller. So you have many small magnets instead of one large magnet, and only one or few accelerator sections are needed. So the particle passes by here as being accelerated, and then you have magnets, of course, a link, the ring, which are able to change their field strength. Again, if you have constant field strength, the radius changes, but if you're modifying the field strength accordingly to the speed of the particle, you can keep particles in the same circular structure.

More words on the focusing, again, if you space a magnet such that there's gradient in the fields between-- depending on the position, you can use that fact in order to have particles which are further out being bent more inwards. Particles which are further inwards, bend more outwards. This is called refocusing, and you can do this not just once, but twice, by changing the rotation. And that's called strong focusing.

Synchrotrons have limitations. There's two which are rather important. The first one, the radius of the synchrotron is determined by the momentum of the particle and your magnetic field. So at some point, you run into technical limitations on the magnetic field strength. Modern superconducting magnets, they get up to in the order of eight, nine tesla. We are able to produce accelerator-grade magnets up to 14 tesla using superconducting materials.

And so that then was a fixed plot size of your tunnel of your ring limits the amount of momentum you can give or energy you can give to your particle. And so for the LHC, we accelerate protons up to 75 TV in one beam, and we use the magnetic field of 8.4 tesla. So that's really the maximum the machine can actually deliver, and we haven't actually demonstrated that we can get up to this point.

Right now the center of mass, the proton energy is 6.5 TV. The previous concept and construction had started in Texas in the United States in the so-called SSC tunnel, which was much, much larger, had 87 kilometer tunnel. The idea was to get protons to center at energies of 20 TV with magnets of 6.8 tesla. OK, this is one limitation, the size of your tunnel.

The second one is when you bend a charged particle with the magnetic field, it radiates, and it radiates proportional with the energy proportion energy over mass to the fourth power, which means that you, at some point, are limited by the power you have to invest in the beam to even just keep it at a specific energy. So this is e over m and to the fourth power, and this also gives you a clue why we actually accelerate protons in the LHC and not electrons. Electron mass is to low, and this goes to the fourth power here. The [INAUDIBLE] of electrons in the LHC tunnel is just a limiting factor. At some point, you don't have enough power anymore in order to give that to the electrons or the particles in order to accelerate that.

All right, so as I was saying initially, so you need focusing, you need accelerating, and you need all kinds of additional components to accelerate in order to make good colliding beams, and so it's much easier to just dump a beam into a fixed target and study what's coming out. So colliding beams as a source for input into particle physics experiments came a little bit later. First concepts came to fruition in Frascati in the 1960s, and then we had SPEAR, a electron positron collider. It sent off mass energy of four GeV, which then led to the discovery of the J/Psi.

And then later, we had a five GeV electron positron collider, which was then designed for eight GeV. This then continued, as you know, to machines like [INAUDIBLE], which had a center of mass energy of up to 110 GeV. And the LHC, the center of mass energy of design of 14 GeV.

So the collider elements, what do you need? You need to inject particles, and so you have to have a source of electrons and a source of positrons. Producing positrons is just, technologically in large numbers, much more complicated than electrons. Here you can-- in order to get sufficient electrons, you need to actually produce them with some kind of an accelerator structure as well. And so then they need to be focused. They need to be cooled down in order to have them as a beam being injected in the structure.

So you've got-- you need as additional components, you need your RF generators. You need magnets to bend the beam in and out. You need to have magnets in order to bend the beam around, so we need bending magnets. You need focusing magnets to keep the beam in orbit, and then you want to-- before you bring them to the collision, we want to further focus the beam such that you have more actual particle collisions available. And then you have interaction points where you will put your particle for the experiment.

What's being done here in this facility is you inject, you accelerate, and then you store the beam to make sure that you can fully exploit the structure, so those rings are called storage rings. You avoid having a one kind of shot kind of mentality as you have, for example, in linear machine. Sometimes you do this in separate rings. Sometimes you do this in the same ring. It depends on the design of the machine.

The challenges are if you have particles travel around for hours that they shouldn't interact with the gas, for example, in your accelerator structure. [INAUDIBLE] by a very, very good vacuum in order to not lose the beam as you have it stored. The fields of your accelerator structures need to be very stable, and that stable-- they have to be stable for many, many hours. That, for example, there's some requirements on your electric grid, for example, such that you have the stability and voltage which don't end up changing the actual field strength of your magnet as you go along.

Yeah, so again, I already mentioned this, the further development of those machines. In the '80s at CERN, stochastic cooling was used for the first time in an antiproton machine, and that machine led to the discovery of the w and the z bosons and first really deep study of the weak interaction at the scale of the weak interaction. At the TEVATRON close to Chicago, protons and antiprotons were brought to collision at the Fermilab at the Fermi National Accelerator Laboratory. And the lab started in the late 1980s in the same tunnel as we find today the LHC.

At DESY in Hamburg, HERA was used to collide electrons with protons, and those results led to our understanding of the structure of the proton. So you see that the reason why I show you this history here is that the progress we did in particle physics at the energy frontier, each of the energy frontiers, was very much tied to the progress in accelerator structures. And rightfully so, Simon van der Meer recieved the Nobel Prize in physics as an accelerator physicist for the discovery of the w and z boson. He was working on the machine and made the machine possible together with Carlo Rubbia.

And interesting, if you look at the history of the particle accelerators, it's interesting to see how we may move the energy frontier forward. So what you see in this plot here is the available energy of the machine, and what you see here is line. And this project is called the Livingston Project. See the logarithmic scale, and you saw that for a very long time it was this logarithmic increase in available energy.

So this line is now turning over. You're Already in 2020, and we haven't made any progress here. So focus here on this. However, interesting discussions on going somewhere-- going to high, going somewhere here with the next machine and being able to probe further higher energies. And the way this is proposed for proton-proton collision was just making a structure similar to the LHC but with a radius about four times larger, about 100 kilometers compared to the 27 kilometers the LHC as today.

And so you can compare this with the hadron machines, but also the electron machines, and also on the electron machines, this trend is not as pronounced as for the proton machines. But basically, here, the highest energy electron positron collider [INAUDIBLE] has just been decommissioned at the end of the last century, and we are thinking about the next machine. Sometimes you see those acronyms as a linear machine, international linear collider or future circular collider. It's electron and positron collisions, which would be hosted in the very same tunnel as this machine, which is called FCCPP or HH. HH was 100 kilometer circumference.