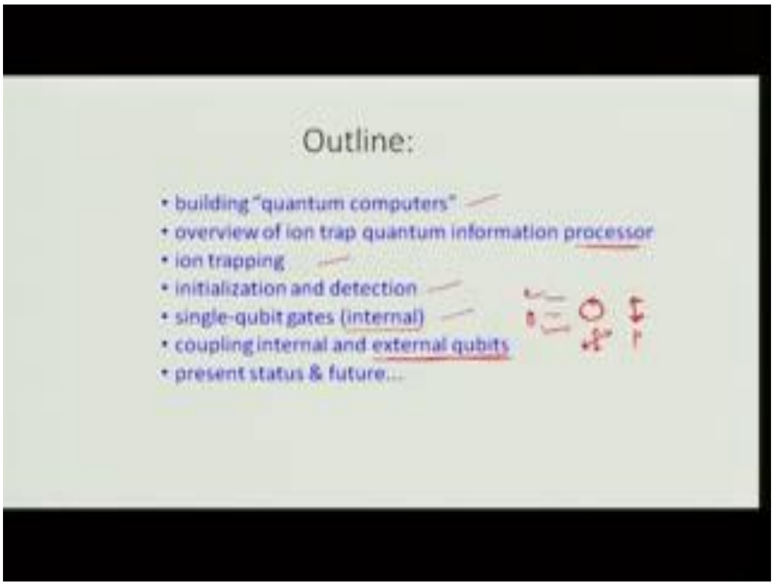
Implementation Aspects of Quantum Computing
Prof. Debabrata Gowswami
Department of Chemistry
Indian Institute of Technology, Kanpur

Lecture – 23
Basics of Ion Traps

This week as we have been looking at the quantum implementation part, we will explore another approach of quantum computing which has been very popular, which is known as the ion trap quantum computing. Now in this ion trap method the principles that will be using, will introduce you at the beginning and then we will look into the aspects that are necessary for ion trap quantum computing.

(Refer Slide Time: 00:47)

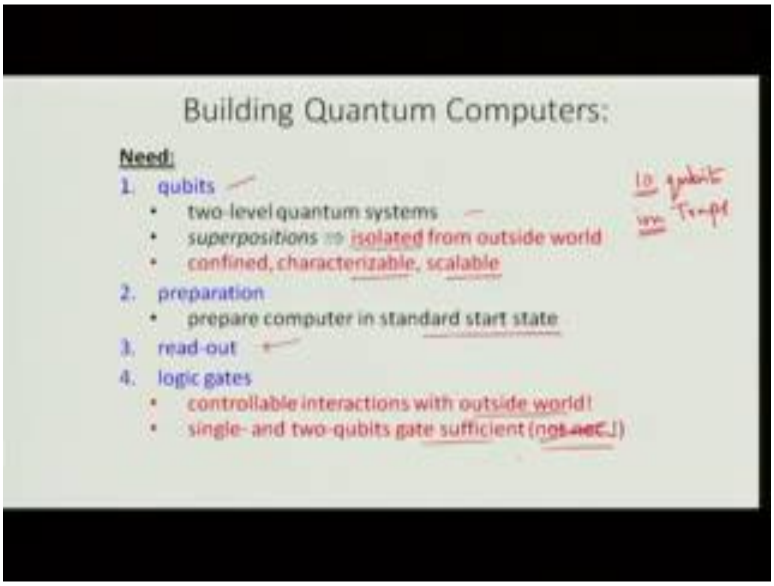


In this case, we are doing the ion trap implementation of quantum computing. I have set up a small outline that it is easier to look at how we are going to do. The principles of quantum computers as we have been discussing is the process that we are looking at here. The overview of the ion trap quantum information processor is the first thing that we are going to look at. In that respect we have to understand the concept of the ion trapping that we do.

Once we have seen that, then we are interested to get into the initialization and detection part of the problem. One or two small single qubit gates internal will be looking at. There are 2 aspects, one is the internal aspects and the other one would be the consolidated together approach. We will discuss those two aspects of this particular ion trap case. And the coupling of internal external qubits as we discuss that this will become clear. In nutshell we are basically talking about in one case the principle of polarization and in the other case the principle of the motion.

In one case the polarization is one particular aspect and the other one could be the state of the system whether it is in ground or excited and the third one could be the motional. All these 3 things can be looked at, while we look at ion trap case. This could be momentum aspect which is the emotional thing, the other one could be polarization aspect. And finally, the third one and the other very important one could be the state of the system, that we are looking at whether it is the ground state or the excited state.

(Refer Slide Time: 02:41)



Now, in terms of building the quantum computer as we have been looking at from the very beginning, we need the qubits to work and in most cases this 2 level quantum systems the way we look at it.

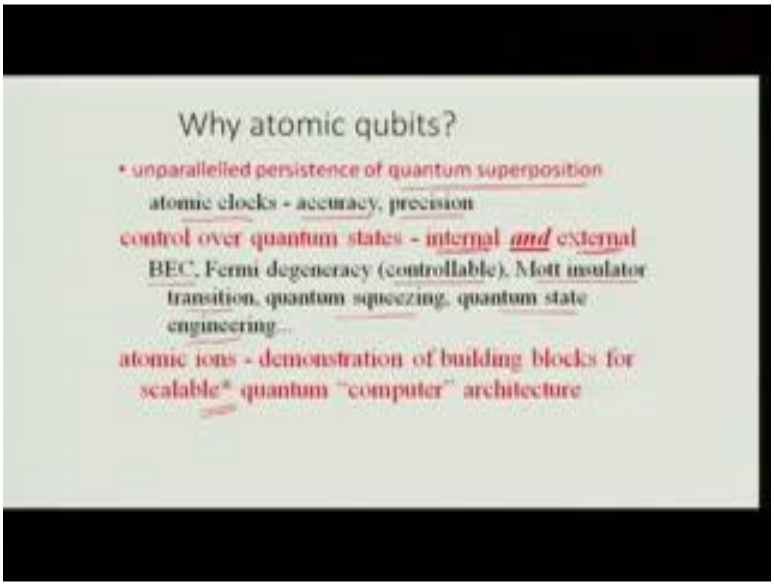
There are super position aspects which are isolated from the outside world and are confined characterizable and scalable. These are the issues that we are really looking at. And let me tell you while we go ahead with this area that trap time quantum computing has been quite successful in the sense that we have managed to and make up to; I mean the groups which work on this have managed to make 10 qubits available in terms of ion trap cases. In case of ion trap, as we know 10 qubits have been achieved.

We looked into the N M R case, where we showed that 8 qubit was the maximum, which would achieved. In that sense, the numbers of qubits in case of ion traps have been slightly higher, but all of them have their problems, that are why we will be discussing in detail as to how to look at them.

In case of the preparation, the preparation of the computer is in is the standard start state that we have to put it up and then comes the read outs and the logical gates which are associated with this, would be the once where the controllable interactions can occur with the outside world and that could be through single or 2 qubit gates. Sometimes, most of these cases that will be discussing here, single and 2 qubit gates are sufficient in the set of problems that we have first looking at. It is not yet necessary to get very high number of qubits to start with.

That is why, it is perhaps not very important to say all this. But, generally speaking at this point of time will be looking at the single and 2 qubit gates and for the preliminary operations to prove the point.

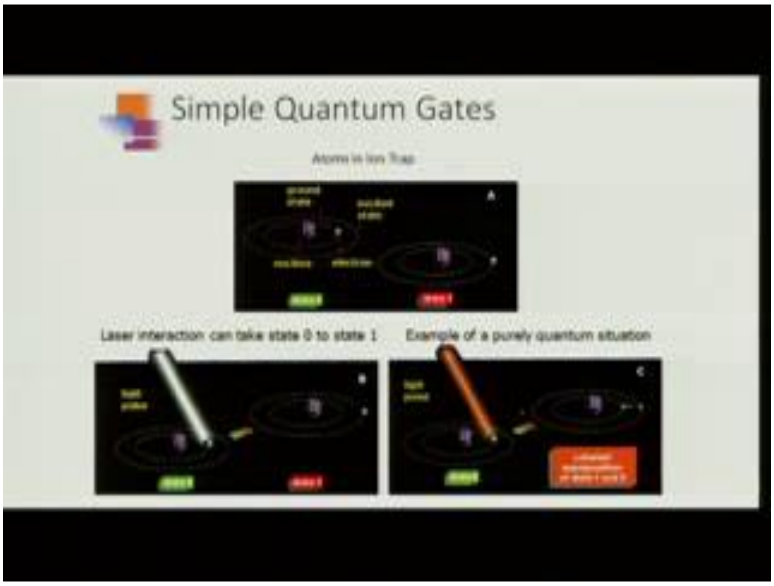
(Refer Slide Time: 04:55)



Why atomic qubits? Atoms and ions are used in conjunction here. That is because atomic qubits have certain advantages. They are unparalleled persistence of quantum superposition, that is one of the best features of having atomic qubits because we know that we have the most precise and accurate clocks which are available in terms of the atomic clocks. This also provides control over quantum states, both internal as we mentioned as well as in external. And there are many versions available Bose Einstein condensate and it allows Fermi degeneracy which is controllable and then there is this Mott insulator transition that we can look at, quantum squeezing, quantum states engineering. There are many other properties to work on and get them to explode as we look into this particular concept of atomic qubits.

Atomic ions demonstration of building blocks of scalable quantum computer that is what the effort has been in terms of get into scalability of our quantum architecture.

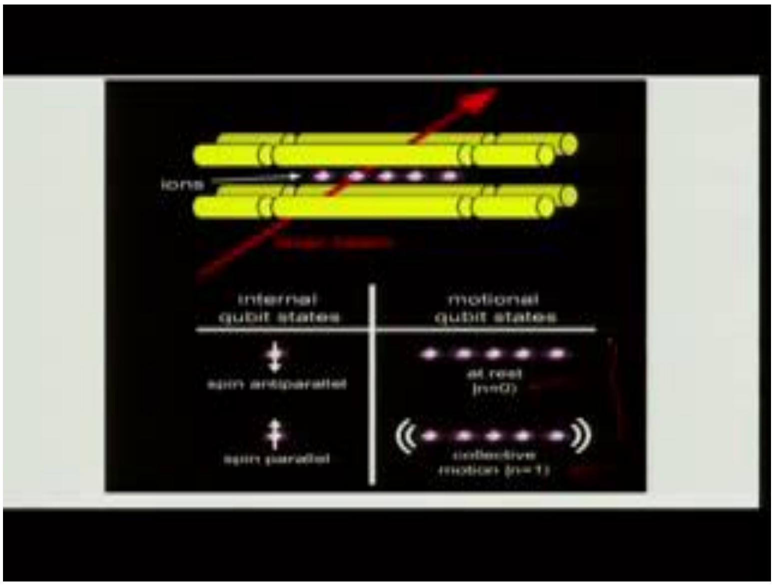
(Refer Slide Time: 06:10)



Here is an example of the simplest possible atoms that we talk about. Atoms in a trap on more precisely atomic ions or atoms in traps can be looked at as if the state of the system can be changed, where the ground state and the excited state can be considered as the state 0 and state 1. This is roughly what we are we are talking about the internal state of the system for instance. And the laser interaction can takes state 0 to state 1 and this is an example of how we can understand the concept of quantum.

This I think I had opened with this kind of demonstration at the very beginning of this course, where we have shown this particular example. Where we had showed how we can take a light pulse to produce coherence position of states 1 and o. By shinning a light so that a superposition occurs between the states 1 and 0 instead of being only in 1 or in 2 state. Classically, you can only be in state 0 or state 1, whereas in case of quantum mechanical aspects you can produce this particular state which is coherent super position of states 1 and 0. That was the basic idea behind bringing up this concept of quantum gates.

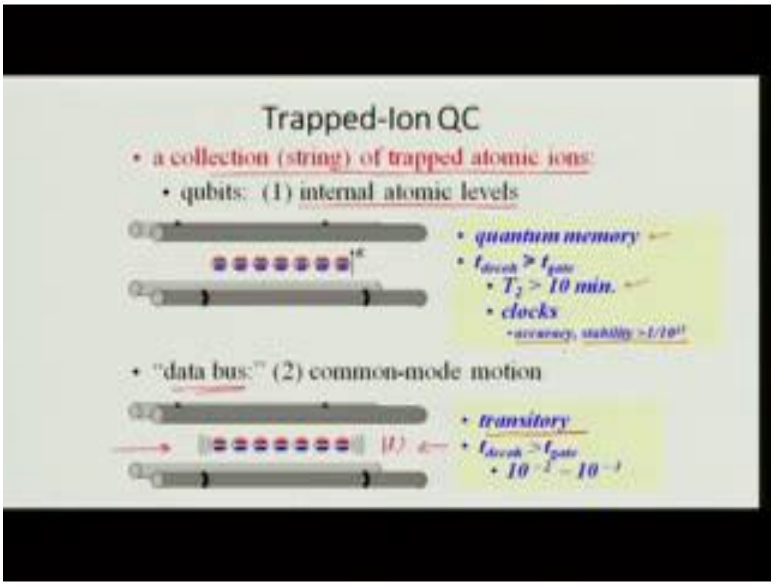
(Refer Slide Time: 07:42)



Now, making it go forward what we are looking at is not just a single atom, but several of them which can be put together in a space which is controllable under the conditions of the environment provided which will is what we will be discussing today. And under that point there are 2 different cases one is the say the internal qubits state, which could be when the spin of these individuals ions are in the anti parallel case or when they are in the parallel case with respect to each other.

Whereas, the motional qubits states could be while they are having at rest which one we treated as N equal to 0 state. Or there is a collective motion which can be treated as N equal to 1 state. It is almost like a simple harmonic motion of these collective states, which can be then looked at as a qubit condition for this case. That is how this is working.

(Refer Slide Time: 08:51)



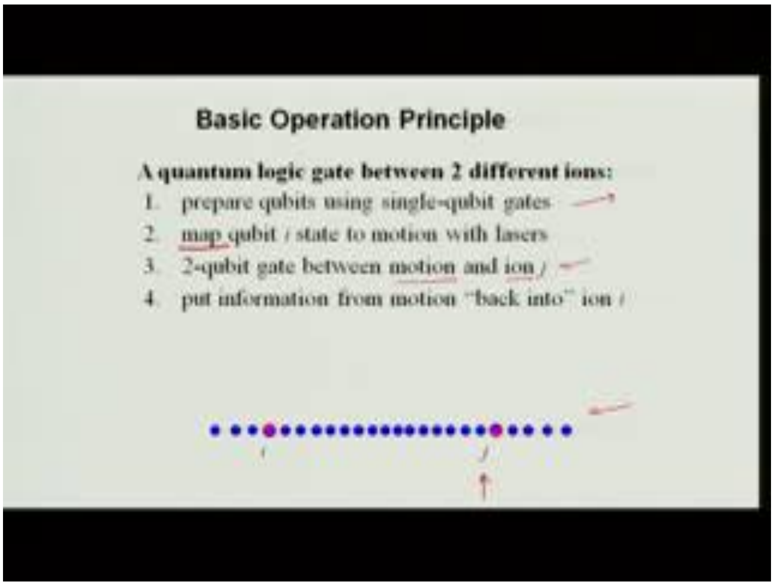
A little bit detail now as we go into this basic principle of this. We are talking in terms of a collection or string of trapped atomic ions and which forms our qubit in terms of 2 conditions as we discussed. One is the internal atomic levels and that has to do with the principle that the de coherence has to be long enough compared to the gate operation that we want to do with these things. So, that comes to our principle of quantum memory which is raise to the requirements that you need that the face delay has to be long enough. So, that the face of the system does not decay or the coherence is long live, so that is how embedding the T 2 structure of the story.

This is something which comes, which has appeared earlier in N M R, if you remember. And in terms of the other applications, it has been very highly applied in the; as I mentioned before in terms of clocks because it has high accuracy and stability as high as 10 to the power stability has to be quite high and that is what is being provided, stability has to be greater than 1 over 10 to the power 15. Once you apply an electric field in this particular case, the state can either be in the round case which is the 0 state for instance, or once the field is applied as we have discussed it could also go to the state 1 and we have the 2 different possibilities.

This is the internal atomic state the other one which is sought of like a entire data set which has been once loaded can undergo common mode motion, and therefore have the applications of properties or discussions or it can actually undergo changes or it can be actually utilized, say for doing operations then we would like to have the common mode motion in that case. For example, we can have all of them under the same condition. Once again in this transitory condition it has to also satisfy that the decoherences to be greater than the gate timing and which is in this order. And here looking at the condition where they are moving, which is our state 1 let us say versus the case where it is in the initial condition.

The total system going between these initial conditions where all of them are in one kind versus the other case where they have been moved closer together. Once again, when they are separated out is our state 0 and then once we composite a little bit, and then it becomes our state one. But this is as we have been trying to value more and more times is that is the entire bunch; this is like the data bus, the entire bunch which is undergoing a motion and that is why this is a transitory condition which is what we are looking at. These are the 2 different conditions of the trapped ions that will be utilizing when we discuss the application of ions for doing quantum processing informations and all that.

(Refer Slide Time: 12:20)



The basic in some sense the basic operation principle of this quantum system which we are going to utilize for a quantum information processing or computing with their would therefore involved these kinds of principles. Say quantum logic gate between 2 different ions let us say, I and J or our 2 ions that we are looking at and we are going to look at their basic operations here. So, let us look at how we can get them to operate. First is to prepare the qubits using single qubit gates. As we have mentioned before preparing single qubit gate means addressing individual elements. This is for example, addressing the individual element I and individual element J. This is our preparation where we have producing the qubits using the single qubit gate principle. We can take the view that; we have essentially taken these 2 particular cases under the applied field condition to make them go to state 1 for example, where anybody else in this entire set is still remains a state 0.

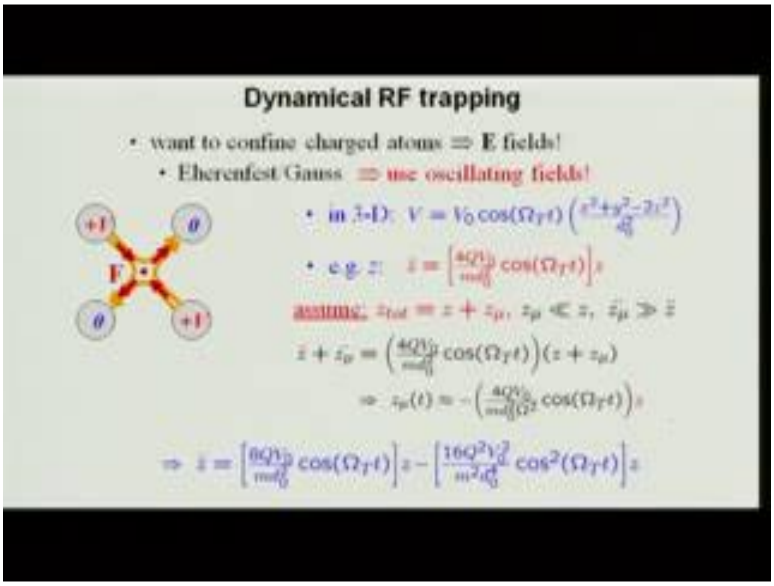
Next when this is been prepared by using single qubit gates we can map the qubit I state to the motion with lasers. Now, that this has been achieved in terms of labeling or preparing the preparation has been happened, and then we can actually utilize the principle of collectiveness to map qubit I state to motion with lasers. And for that we can actually provide a laser which will then give some sort of a movement as we have just now shown here in this case with respect to the state I. In this case for example, when the laser is on the operative on I specifically, to make sure that is the one which undergoes a change in this particular case due to the motional aspect, whereas the J state remains the same.

This one therefore, has a different case because of the selective application of the mapping that we just date. Which this means that we have a 2 qubit gate between the motion and the ion J now, because the ion J has been prepared from the principle of the internal condition, whereas the state I has been put back to this other motional condition and the 2 qubit gate between the motion and the ion J is therefore created because the rest of the gates are all the same.

Finally, what we have done is that now created a gate which is specific, created a set which is now 2 qubit set because of the condition of J. We can put the information from motion back into ion I by putting the laser back on I state and we can essentially have the interaction go between that different conditions. It is like saying that we can prepare by using internal qubit states for both for single qubit conditions, then we can map one of them with the motion with lasers and then we can get back to the case were we now have the 2 different conditions available for J, whereas the I has gone back to the original case. And this 2 qubit gate between motion and ion of the J can then do its job and then put the information from the motion, because it has now come back to the original case, back to back into ion I.

This is basically the set procedure that can be applied to get multi qubit operations going in terms of both the motional and the collective mode versus the individual ions that we are talking about.

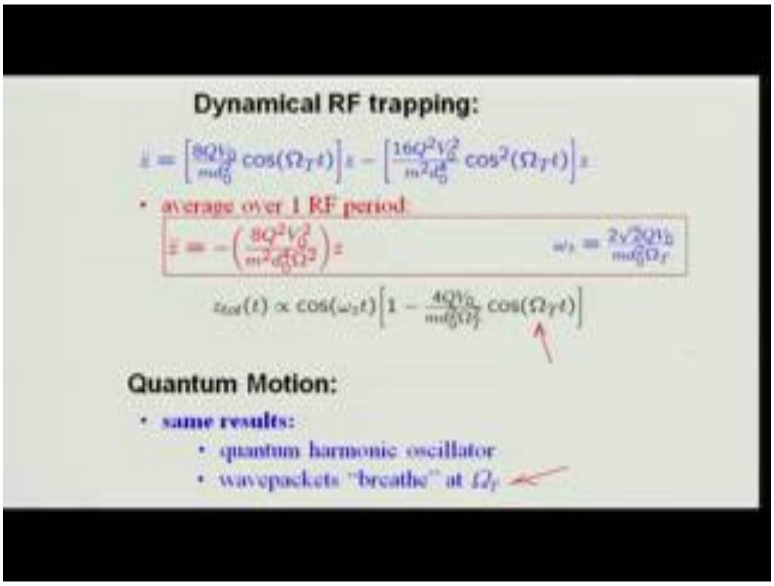
(Refer Slide Time: 16:33)



Now for studying these kinds of ions states and to be able to do something with how we are going to apply them eventually. We would like to have dynamical trapping of this entire process and that is typically attained with R F trapping and the applied field of the laser is used for doing the addressing. The dynamical R F trapping, it helps us because we want to confine the charged atoms in the field and we can use the Ehrenfest and the Gauss principles and we know that we cannot simply use static field because they are not going to help us in this particular condition when we have this charged atoms which were going to have their own fields. And we are going to also apply lasers from outsider's individual fields.

So we have to use oscillatory fields because, if you want to confine them in 3 dimensions, it is best to use the oscillatory field. And in 3 D we have a form of the potential which has to be of a certain kind. We are not going into the details of this, but these essentially provides us the relative motional condition or the exhilaration and the associated force which are provided and to balance this entire process. And we can undergo the mathematical transformations here to kind of see how the reduced mass motion of the system is finally going to be coupled to the applied frequency of the fields that we are going to provide for this to operate.

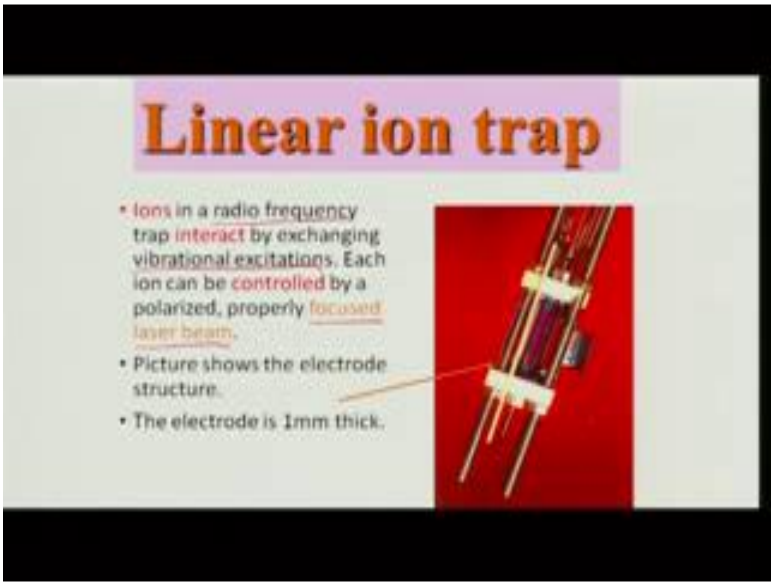
(Refer Slide Time: 18:23)



This dynamical R F trapping therefore, can be see how they map with respect to the positional variance as well as the frequency as a result of this. And that would give raise to the oscillatory motion that we are expecting from this trap system. The quantum motion of this is equivalent to the quantum harmonic oscillator motion and which gives raise to the wave packet breathing at about the same frequency as these particular motion that we have just now discussed.

And so this particular dynamical trapping concept helps us in providing the oscillatory quantum like features that we are able to utilize.

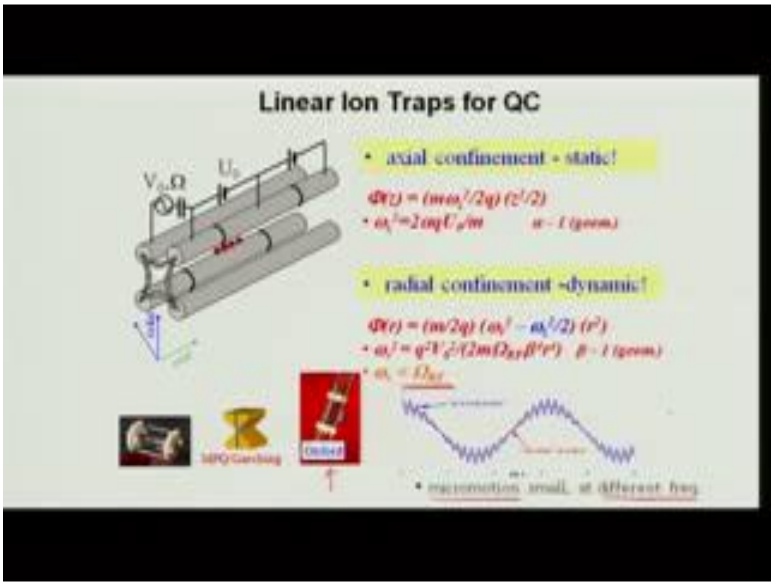
(Refer Slide Time: 19:09)



A coupling of this particular approach along in the linear ion trap allows us to make use of the principle. And so this linear ion trap which is been the main principle here utilizes the R F field as we just discuss. In this radio frequency field this R F ions would interact by exchanging vibrational excitations and that is because of the principle that we just discussed were the; oscillatory motions almost may make the simple harmonic principles shown by the harmonic oscillator mode of a quantum system almost.

Each of the ions can be controlled by polarized properly focused laser beam in addition to what we just now discussed in terms of the R F so that we can have the coupling that we just discussed before that. The picture here shows how the electrode structure typically looks for a particular linear ion trap experimentally. And the electrodes are roughly about millimeter thick which is what is used for making this systems work.

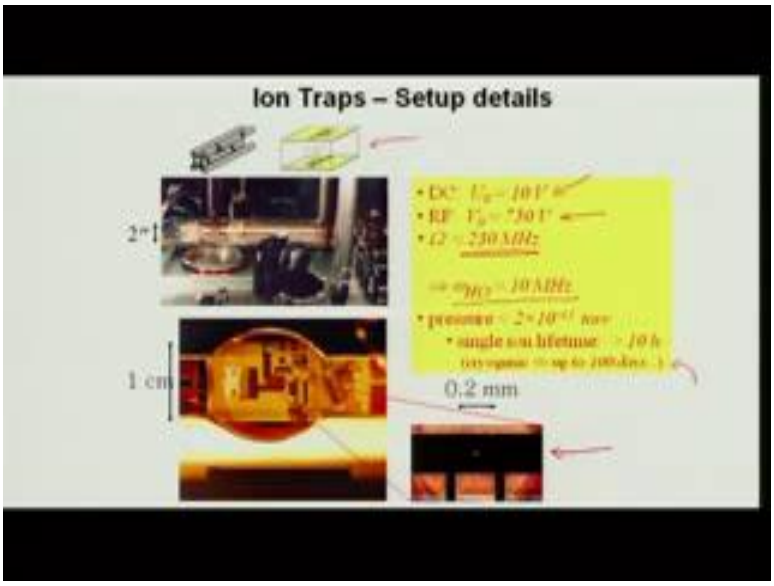
(Refer Slide Time: 20:19)



In practice or in schematic case this is how the picture looks like. We are applying the oscillatory field as we discuss before, because we know that static field will not work for it. This actual confinement parties static and the radial confinement part is dynamic. There are many different places were this particular approach of linear traps has been used. One of the pictures that I showed you as from which has been used mostly in Oxford. Then there are these other places were similar traps have been very successful in Max Planck and Gashing as well as this hand book as well as in many places nest and in US and in many places including Maryland and others.

This micro motion which we show in terms of the R F frequency is the one which is on top of the oscillatory motion that is there for these things. Now these are very small at a different frequency, so they do not really affect one or the other but they can be actually utilize in the way these confinements have been done. We have to very careful in terms of making sure that our applied radio frequencies always much much larger than the internal confinement the dynamical principle that exists. But as you can see in the diagram, because of the large difference in the 2 frequencies we applied R F always is consistent version that can be utilize with respect to the other micro motions that are that are already existing in the system.

(Refer Slide Time: 22:18)

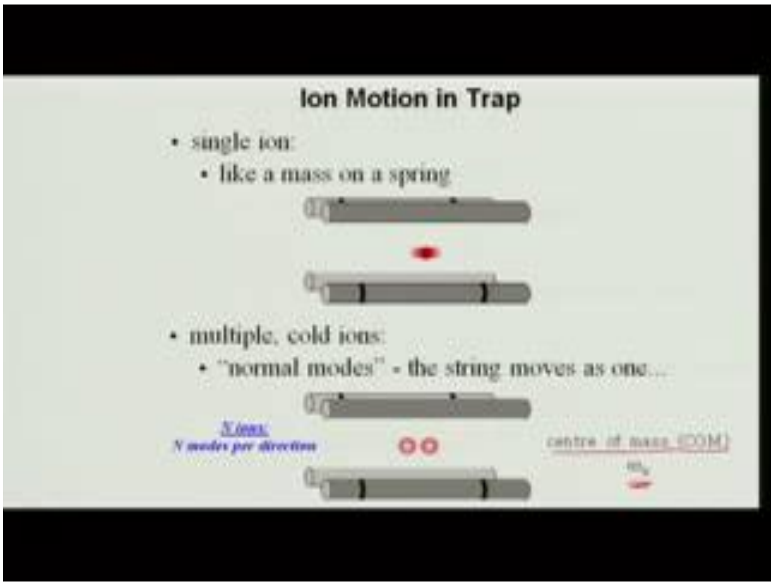


There are various different ion traps set ups has been discussed. Typically, the applied fields are of the range where we have about 10 volts of D C volts and then the R F is about 750 volts. As I have mentioned before the ratio of the 2 are quite different and the frequency oscillatory part is about 230 megahertz which is the very high frequency. So what we are talking about here as you can see are the 3 different frequencies which are extremely different from each other, and they are not going to actually create any problem with respect to the different applications.

We have the megahertz coming in one hand, the radio frequency coming in the other and the applied field coming in the other hand. We have these 3 different kinds of oscillatory motions, and this is our harmonic oscillator which is essentially working at about 10 megahertz and conditions. Here is a micro expanded blow up picture I do not know how where you can see here, but these are the few trapped ions which have been depicted inside the actual experimental set up which is what we have essentially earlier used and blown up in the cartoons to show you exactly how they look. And the single ion life time is can be pretty high and under cryogenic conditions it can almost always staying there.

Given all this backgrounds ion traps have some very useful advantages. As now has we have been talking about that their properties and conditions can be maintained with very high accuracy and precision over a very large number of days.

(Refer Slide Time: 24:20)

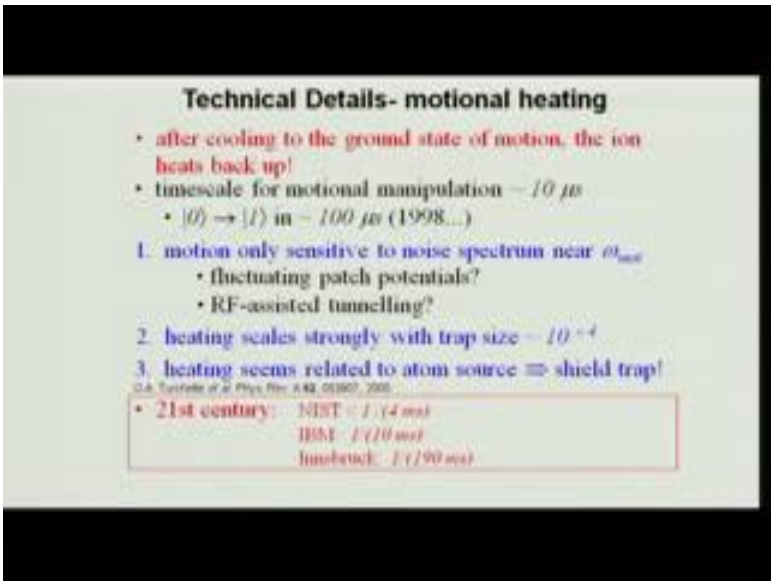


In terms of the motion inside the trap, a single ion is almost like a mass on a spring as we were discussing and it can be seen like this. And there are multiple cold ions which are simultaneously used. The normal modes of the string moves as 1, there are N ions so there are N modes of the direction. That depends on the center of mass and that gives raise to the overall frequency omega X which we have seen here oscillatory frequency.

This is how this whole picture looks like, where if you look at the single ion it is like a mass on a spring where it has all these probabilities of being finding an overview certain range, which is your frequency of the oscillator. In the multiple cold ion conditions, the normal modes the string moves as 1, and the whole picture is essentially looking like this where you can take the center of mass of the entire process and provide the frequency associated with this.

And so there are N modes per direction that this can be associated with. Depending on the applied laser and the properties as we go along we can actually make this and do it this way. The other important aspects are that we could also have different properties such as the stretch mode. One as we discussed was a combined motion which is center of mass, then the other one would be like a stretch mode which will be like the harmonic oscillator conditions. And so there are different kinds of modes and oscillation that we can discuss in this particular case.

(Refer Slide Time: 25:54)



There are however important aspects to remember that in terms of the technical details. There is motional heating which can happen and for extract of particles which are like this been set to a state in cold conditions it might not be possible for it remain under the same condition. Although the life time can be high, but after cooling to the ground state of motion, the ion can heat back up and the timescales of motion manipulations are roughly in the range of 10 micro seconds. And this has been consistently becoming better with the number we also have experiments.

For example, they have been cases which this has been improved upon the number of B E R, so that these difficulties can be made better. And also the motion can be made to be sensitive to the noise spectrum which is not going to hurt it or do something about it. However, there are issues which have still to be addressed and these are the few points that I thought I will point it out. These have all been presented in the previous work and in the most recent developments in the current times, we have this few wonderful developments which have been shown were this bolder has been running the best possible condition with less than 1 over 4 milliseconds timescale, so they have the longest level life time.

Whereas, the others are also getting closer, but they have their own difficulties and they have been trying to do their work quite well. With this starting point of our discussion on ion traps with some connection to how these become useful to quantum computing let me close this lecture, because this is a new area that we have been en blocking on for this particular application. And so I thought I will give you some of the background material which goes into understanding the ion trap principles which we have just discussed here. In the next class we will be detailing further on the application of the ion traps into making of quantum information processing and further more.

Thank you. See you in the next class.