Title
COURSE IN THE THEORY AND DESIGN OF PARTICLE ACCELERATORS - LECTURE I

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Course in the Theory and
Design of Particle Accelerators

LECTURE I
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(Notes by R. Avery, A. Bermingham)

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INTRODUCTION TO COURSE

This course will cover the mechanical engineering design aspects of particle accelerators. The subjects to be covered are:

Beam Dynamics

High Voltage Supplies

Magnet Design

R.F. Systems

Vacuum Systems

Controls and Instruments

Shielding

BEAM DYNAMICS

Generally speaking, the mechanical parts of particle accelerators do not move, the rotary condenser of the 184" cyclotron being an example of exception. Atomic particles may be considered the moving parts of accelerators. Pistons, the moving parts of an automobile engine, are held in confined paths by cylinder walls, while atomic particles are held in their path by what may be considered hypothetical springs which are actually electrical or magnetic fields. The shape of these fields among other factors determines the path of the particle. The general word for the restraint of particles to the desired location is called focusing or stability.

The mechanical engineer is concerned with the mechanical design of machines whose output is electrical, i.e., the particle beam. The design of ordinary machinery is not concerned with the increase in mass of bodies as explained by The Theory of Relativity. However, particle accelerator design must take into account the increase of mass with velocity, and the functioning of accelerators is the obvious proof of Einstein's theory.

BASIC PRINCIPLES OF ACCELERATORS

The following principles are common to almost all particle accelerators.

ELECTRIC FIELD. - In electric fields, a charged particle is accelerated in the direction of the field gradient with a force proportional to the product of the voltage gradient and the charge.

MAGNETIC FIELD. - In magnetic fields, a charged particle is accelerated at right angles to the direction of its motion and at right angles to the direction of the magnetic field. The force on the particle is proportional to the product of its charge, its velocity and the component of field perpendicular to the direction of motion. Note that this is the same effect that occurs to the current-carrying wires in the magnetic field of a motor or dynamo.

CHARGE. - In order to be accelerated by machines, particles must carry an electric charge. A charge may be considered as a handle - something by which to grasp particles. Neutral particles can only be accelerated indirectly, for example the acceleration of a charged ion that contains neutrons or the acceleration of a target neutron due to the collision of a high energy particle with the target.

FOCUSING AND STABILITY. - In order for a particle to stay in the path necessary for controlled acceleration, it must be stabilized or focused. Lateral focusing or stability pertains to concentrating the beam into a small cross-section. If the path of the beam is short enough, lateral focusing may not be required.

Another attribute of stabilization is phase stability or focusing. In equipment which depends upon rapidly changing polarity used many times in succession to build up high energy, the particles must be at the right place at the right time or they will "see" fields of the wrong polarity and instead of being attracted will be repelled with a loss rather than gain of energy. There must be, therefore, a tendency to pull the particle into phase with the accelerating voltage. Here again if the path of the beam is short, it may be out of the machine before getting out of phase.

SOURCE. - The source of a particle depends upon its nature. Electrons may be emitted from a filament heated cathode, while heavier particles may be made to originate inside or outside of a machine in the form of ions.

VACUUM. - A high vacuum is necessary in order to obtain high energy particles. If there were many gas molecules in the tank in which particles are being accelerated, there would be collisions causing the particles to be stopped or to fall out of focus or phase.

TARGETS. - The product of accelerators, the beam, is used to bombard various targets and the effects of this bombardment are analyzed in various ways, e.g., visual, biological, zoological, chemical, physical, and electronic. This is not of importance to mechanical engineers and will not be discussed further since "an eggbeater designer does not need to know much about cooking."

TYPES OF MACHINES TO BE COVERED

The following types of machines will be considered in discussing beam dynamics.

1. Statitron
2. Linear Accelerators
3. Cyclotron
4. Betatron
5. Synchrotron
6. Microtron

First we will take a look at these machines from a qualitative viewpoint and see the important distinguishing features of each type. After this we will take a more detailed look at the beam dynamics of each machine.

STATITRON

The term "Statitron", although not widely used, includes machines that use a single high voltage accelerating stage. The Van de Graff and Cockroft-Walton machines are examples. Statitrons were the first machines that accelerated particles to high enough energies to obtain artificial disintegration. The high voltages are obtained by an electrostatic machine in the Van de Graff and by a voltage multiplier in the Cockroft-Walton.

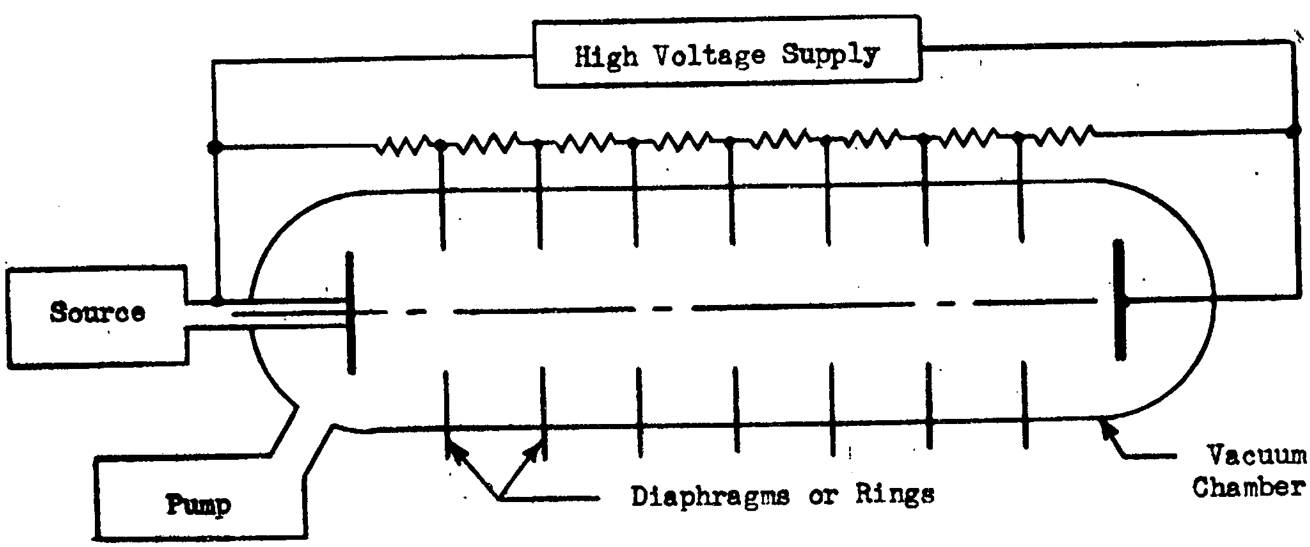

FIGURE 1-1
ELEMENTS OF A STATITRON

Figure 1-1 is a diagram of a statitron. It consists essentially of a vacuum chamber with oppositely charged electrodes at each end. Charged particles are introduced at one electrode by means of a source. The voltage gradient between electrodes causes the acceleration. In order to provide improved resistance to arcing (and also provide lateral focusing), diaphragms or rings are placed along the side walls. (NOTE: A small gap can withstand a higher voltage gradient than a large gap). A uniform voltage gradient between diaphragms is obtained by having small leakage currents flowing from one diaphragm to the next. This leakage current can be provided by resistors connected between diaphragms (as in Figure 1-1) or by corona discharge. Most statitrons over 500,000 volts are encased in a pressurized chamber containing nitrogen and freon in order to improve resistance to arcing.

FOCUSING IN THE STATITRON. - Lateral (radial) focusing, i.e., concentrating the beam toward the centerline, is obtained in the statitron by means of a phenomenon known as velocity focusing. To understand velocity focusing let us take a look at a section of the statitron between two diaphragms (Ref. Figure 1-2). The electric field lines are approximately as shown. As mentioned previously, the force due to

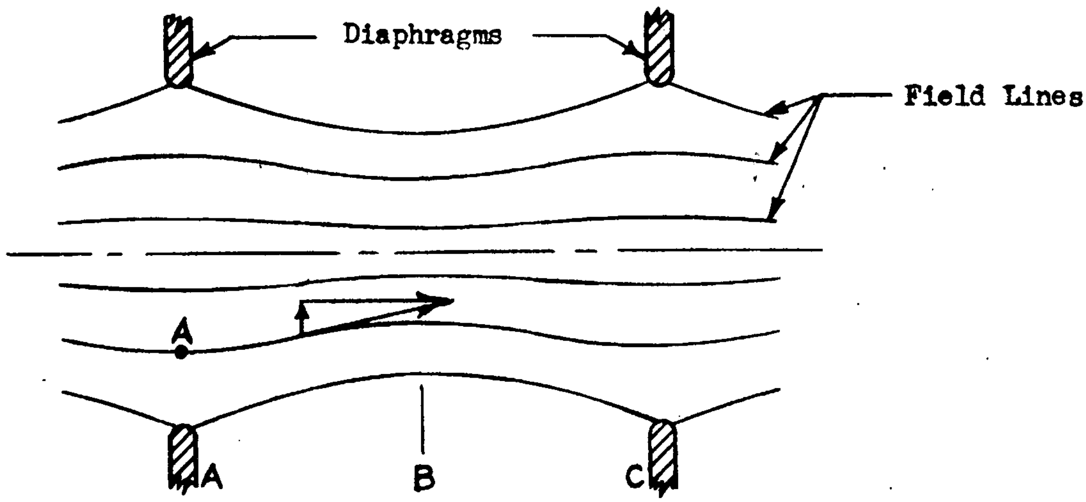

FIGURE 1-2
VELOCITY FOCUSING IN A STATITRON

an electric field acting on a charged particle is directed along the field lines. Consider a charged particle starting at A and travelling to the right. While travelling from section A to section B, an inward directed (focusing) force is exerted on the particle and while travelling from section B to section C, an outward directed (defocusing) force, approximately equal to the focusing force, is exerted on the particle. However, there is a net focusing force on the particle while travelling from section A to section C due to the fact that the particle is accelerating and spends more time in the focusing region than in the defocusing region. This net focusing effect could also be explained by considerations of momentum. If some of the particles at section A have outward directed velocities, the net velocity focusing effect may not be sufficient to cause focusing.

LINEAR ACCELERATOR

One type of linear accelerator is the resonant type in which radio frequency (R.F.) alternating voltages are used for acceleration. Figure 1-3 shows the current and electric field conditions for the four stages of the R.F. cycle.

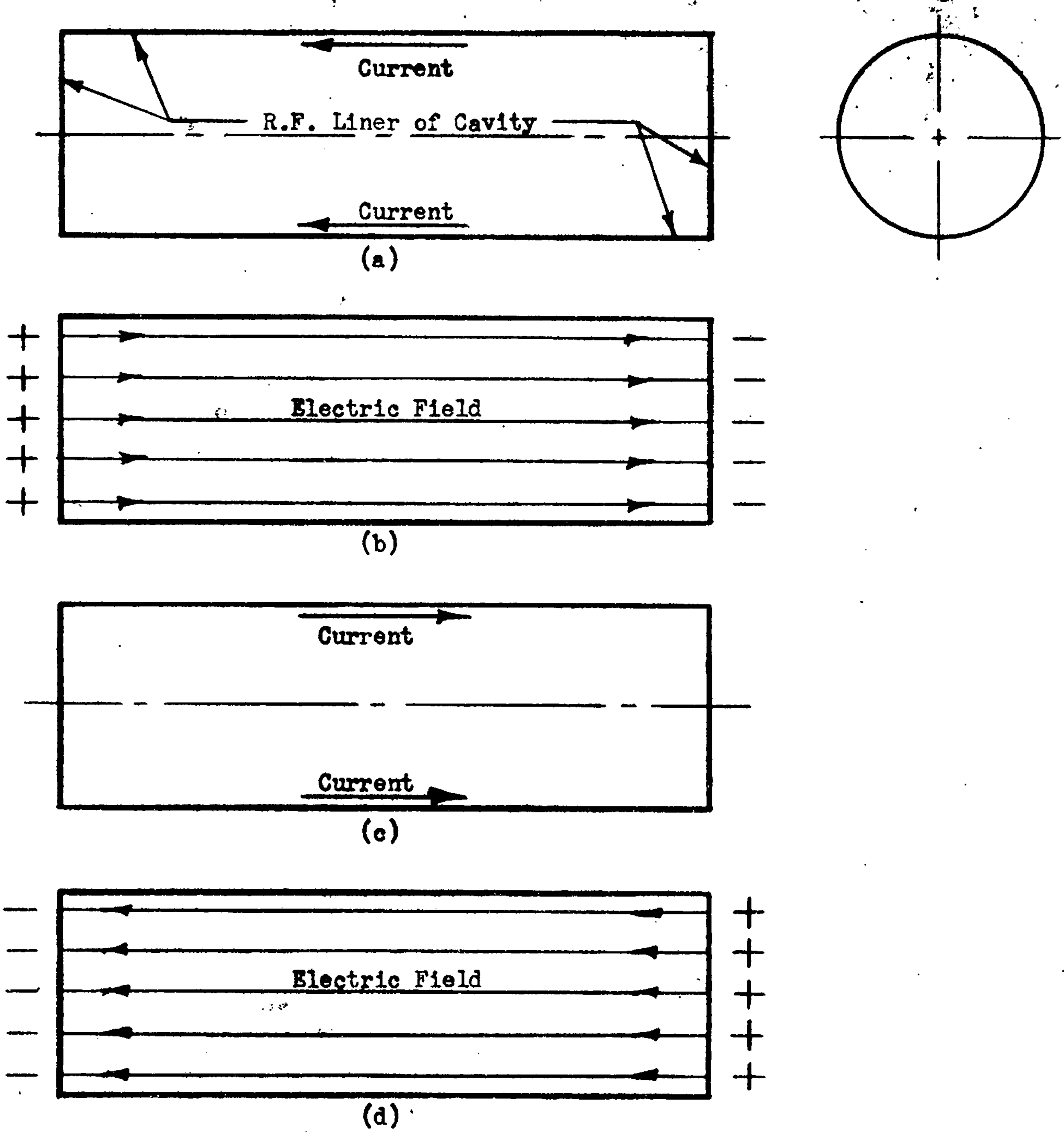

FIGURE 1-3
FOUR STAGES OF R.F. CYCLE IN LINAC

The condition shown at (b) is the only condition that will cause acceleration of positively charged particles. The beam must be protected from the action of the adverse electric field shown at (d). This is accomplished by means of drift tubes in which the beam may coast during periods of adverse fields. The drift tubes become longer as the velocity increases so that the particles spend the same time in each drift tube. These are shown diagramatically in Figure 1-4. The particles are in the gap between drift tubes only when the electric field is favorable for acceleration. More detailed explanation of beam dynamics in the linear accelerator will be given later in the course.

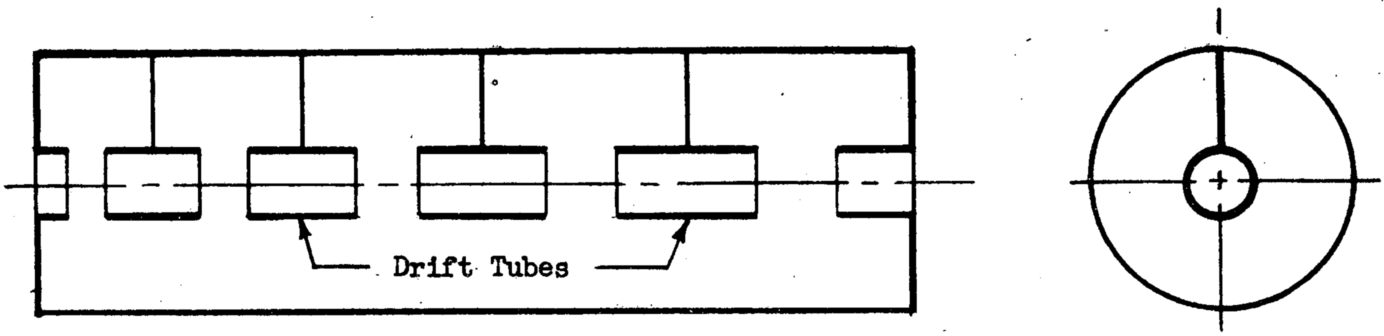

FIGURE 1-4
DRIFT TUBES IN LINAC