# Conceptual and technological evolutions of particle accelerators

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**Abstract** We give here an ordered list of all types of particle accelerators and exhibit how each type evolves conceptually and/or technologically from the preceding. This is in contrast to the usual “history of particle accelerators” in which unrelated accelerator types are listed in the chronological order. It is hoped that this discussion and understanding of the rationale and logic in the evolution of one accelerator type to the next will help to educe future inventions.

**Key words** Acceleration concept, technology evulotion, beam dynamics, technological application

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## 1 Introduction

Today I will not report on any technical work. Instead, I will discuss with you the more important factors involved in understanding how progress is made in the field of particle accelerators. These include the thought-processes leading to the creation of new concepts and the technological advances that make possible their realization. It is natural to first annotate the sequence of development by a series of “milestones”. However, instead of achievements, these “milestones” denote recognitions of something wanting or mystifying which need be understood or resolved. The technological evolutions necessary to resolve a milestone are listed under the same milestone but with a letter-subscript added. They are, of course, of no less importance in the overall development of accelerators. Dates are deliberately left out. Although important to historians they have no bearing on either the substance or the logic of the conceptual on technological evolutions.

In the following I will first list the milestones and later, attach brief explanations.

## 2 Milestones

Ⅰ) Recognizing the need of accelerating particles (Ernest Rutherford)

Ⅱ) Recognizing that charged particles can be accelerated by electric forces in the desired magnitude

Ⅲ) Recognizing the need for repeated acceleration, hence the need for accelerating structure with field confined

Ⅳ) Recognizing two modes of repeated acceleration: Repeating accelerating structure (cavity) or Repeated passages of beam through same cavities

Ⅴ) Repeating cavities—Two types of cavities, hence linacs: “Microwave linac” and “Induction linac”

  Ⅴa) High-efficiency, high-power microwave supplies

  Ⅴb) High-efficiency, high-current pulsing supplies

Ⅵ) Repeated passage through same cavities (E. O. Lawrence)

Ⅶ) Birth of modern Beam Dynamics (dynamics of beam motions guided by electromagnetic forces)

  Ⅶa) Phase stability

  Ⅶb) Alternating Gradient (AG) focusing

  Ⅶc) Beam cooling

Ⅷ) Application of general technological advances

## 3 Brief explanations

### 3.1 (Milestone Ⅰ) Recognizing the need of accelerating particles

The first particle physics experiment was performed by Ernest Rutherford. He used α-particles

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emitted by radioactive elements to bombard different atoms and found that an atom has a small charged central core containing almost all the mass of the atom. He then expressed the desire of having as projectiles different particles with higher and controllable energies. Thus was born the science and engineering of Particles Accelerators.

### 3.2 (Milestone II) Recognizing that charged particles can be accelerated by electric forces in the desired magnitude

The most rudimentary accelerator is the set-up of an electrostatic field between two electrodes. Charged particles are then accelerated by the electric force to fly from one electrode to the other. However, the strength of the electric field, hence the top energy of the particles is limited by electric breakdown. To reach higher energies repeated acceleration is necessary.

Later it was appreciated that of all the forces known in nature the electromagnetic force is the only one useable for particle acceleration.

The force $f$ between two particles can be expressed approximately in terms of their separation $r$ by the formula

$$f = \frac{S}{r^2}e^{-r/R},$$

where the two parameters $S$ and $R$ are the strength and the range. The $1/r^2$ factor comes about from the spreading of the field over the area $4\pi r^2$ of a sphere with radius $r$. For the 4 types of forces known today between 2 "up"-quarks, the parameters are listed in Table 1.

Tabel 1. The ranges and relative strengths of the four types of forces in nature.

| force type | strength $S$ (relative unit) | range $R$/m |
|---|---|---|
| electromagnetic | 1 | $\infty$ |
| strong nuclear | 24 | $-33\times10^{-18}$* |
| weak nuclear | 1.1 | $3.2\times10^{-18}$ |
| gravitational | $10^{-41}$ | $\infty$ |

*A negative range indicates that the force increase with $r$, hence there can be no free quark.

The only force with reasonable Strength and Range for use in particle acceleration is the electromagnetic force.

### 3.3 (Milestone III) Recognizing the need for repeated acceleration, hence the need for accelerating structure with confined field

The electrostatic field between electrodes extend spatially to $\infty$. For repeated acceleration the field must be localized, hence non-static.

The Maxwell equations for static field in vacuum are

$$\text{div } E=\rho, \ \text{div } B=0,$$
$$\text{curl } E=0, \ \text{curl } B=J.$$

Hence, $E$ must extend spatially to $\infty$.

The device developed—the cavity—is a metallic (high conductivity) enclosure which supports on the inside a time-varying electromagnetic field with zero field on the outside. Two general types are used. The "resonant cavity" is operated at a microwave frequency and is appropriate for high energy application. The "induction cavity" is loaded inside with ferromagnetic material so that the field can be ramped over a wide range. Such a cavity has a low $Q$ and is appropriate for high current application. Several variances of both types cavity have been developed and used for special applications.

### 3.4 (Milestone IV) Recognizing two modes of repeated acceleration

(1) Repeating cavities

One can string a series of cavities in a line. Going through $n$ cavities the particles will gain $n$ times the energy.

(2) Repeated passage through same cavities

One can bend the particle beam around back to repeatedly pass through the same cavities $n$ times thereby gaining $n$ times the energy.

### 3.5 (Milestone V) Repeating cavities

Depending on the cavity type, we have two types of linear accelerator (linac)

(1) The Microwave Linac is a string of phase coupled Microwave cavities and is needed to accelerate particle beams to high energies. The SLAC 2-mile long linac is a string of 80,000 cavities and has accelerated electrons to over 50 GeV.

(2) The Induction Linac is a string of synchronized induction cavities. Depending on the cavity loading design induction linacs can accelerate beam currents from 100 to 10,000 A.

(Milestone Va) Microwave linacs need high-efficiency high-power microwave supplies. In these supplies the microwave power is generally excited in cavities by pre-formed election beams. They have the names: Magnetron, Klystron, Gyrotron etc. For the CLIC linac developed at CERN the power supply cavities is also a linear array running alongside the array of accelerating cavities.

(Milestone Vb) The power supplies for induction linacs are high-current pulsers. The high current pulse is generated by gas-filled tubes such as thyratrons and shaped by a properly designed pulse-forming-network (PFN).

### 3.6 (Milestone Ⅵ) repeated passage through same cavities (E. O. Lawrence)

To transport the beam around back to passing through the same cavities over and over again, using the magnetic field $B$ is best (only deflection, no acceleration). The resulting circular accelerators fall into two categories: Cyclotron (fixed $B$) and Synchrotron (time-varied $B$).

### 3.7 (Milestone Ⅶ) birth of modern beam dynamics

For either fixed or time-varied beam transport field we need the precise knowledge of the beam motion. Thus, the science of beam dynamics has been advanced to a high degree. In the following we list the major discoveries in beam dynamics.

(Milestone VIIa) Phase stability—Longitudinal focusing action supplied by properly shaped accelerating electric field. (V. I. Veksler 1944 and E. M. McMillan 1945)

(Milestone VIIb) Alternating-gradient focusing — Transverse focusing action supplied by properly shaped beam-transporting magnetic field

(AG Cyclotron: L. H. Thomas 1938)
(AG Synchrotron: N. C. Christofilos 1950 and E. D. Courant, M. S. Livingston, H. S. Snyder 1952)

(Milestone VIIc) Beam cooling—Emittance reduction, essential for storage rings and colliders

(Electron cooling: G. I. Budker 1966)
(Stochastic cooling: S. Van der Meer 1972)
(Ionization cooling, Laser cooling etc.)

### 3.8 (Milestone Ⅷ) application of general technological advances

This is more like a subscripted milestone, namely technological advancements in support of conceptual evolutions. Most prominent are the following:

(A) Advancement in fast electronics, massive memory units and computer technology. This has revolutionized beam sensing, manipulation and control.

(B) The development of superconducting materials. This has been applied to both superconducting cavities and superconducting magnets, and has resulted in large power savings and great increases in attainable fields.

## 4 Final remark

Particle accelerators is by now a well developed field. It is hoped that an analysis of this type for the past development will serve to motivate and guide future endeavors.