A BRIEF HISTORY AND REVIEW OF ACCELERATORS

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ABSTRACT

The history of accelerators is traced from three separate roots, through a rapid development to the present day. The well-known Livingston chart is used to illustrate how spectacular this development has been with, on average, an increase of one and a half orders of magnitude in energy per decade, since the early thirties. Several present-day accelerators are reviewed along with plans and hopes for the future.

1. INTRODUCTION

High-energy physics research has always been the driving force behind the development of particle accelerators. They started life in physics research laboratories in glass envelopes sealed with varnish and putty with shining electrodes and frequent discharges, but they have long since outgrown this environment to become large-scale facilities offering services to large communities. Although the particle physics community is still the main group, they have been joined by others of whom the synchrotron light users are the larges and fastest growing. There is also an increasing interest in radiation therapy in the medical world and industry has been a log-time user of ion implantation and many other applications. Consequently accelerators now constitute a field of activity in their own right with professional physicists and engineers dedicated to their study, construction and operation.

This paper will describe the early history of accelerators, review the important milestones in their development up to the present day and take a preview of future plans and hopes.

2. HISTORICAL ROOTS

The early history of accelerators can be traced from three separate roots. Each root is based on an idea for a different acceleration mechanism and all three originated in the twenties.

2.1 The main "History Line"

The first root to be described is generally taken as the principal "history line", since it was the logical consequence of the vigorous physics research programme in progress at the turn of the century. Indeed, particle physics research has always been the driving force behind accelerator development and it is therefore very natural to also consider high-energy physics as the birth place.

The main events along this "history line" are listed in Table 1. The line is started at the end of the last century to show the natural progression through atomic physics to nuclear physics and the inevitable need for higher energy and higher intensity "atomic projectiles" than those provided by natural radioactive sources. In this context, the particle accelerator was a planned development and it fulfilled its goal of performing the first man-controlled splitting of the atom. It was Ernest Rutherford, in the early twenties, who realised this need, but the electrostatic machines, then available, were far from reaching the necessary voltage and for a few years there was no advance. Suddenly, the situation changed in 1928, when Gurney and Gamow independently predicted tunnelling[1] and it appeared that an energy of 500 keV might just suffice to split the atom. This seemed technologically feasible to Rutherford and he immediately encouraged Cockcroft and Walton to start designing a 500 kV particle accelerator. Four years later in 1932, they split the lithium atom with 400 keV protons. This was the first fully man-controlled splitting of the atom[2] which earned them the Nobel prize in 1951.

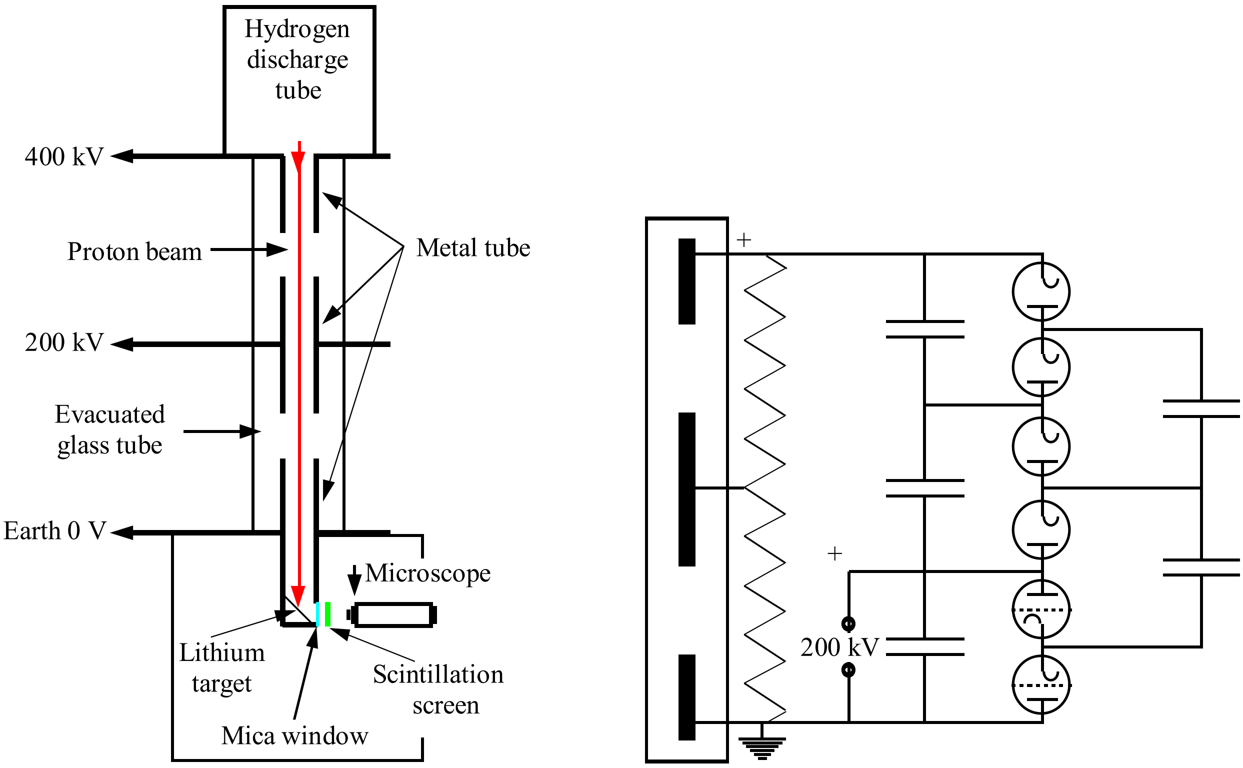
Figure 1(a) shows the original apparatus, which is now kept in the Science Museum, London. The top electrode contains the proton source and was held at 400 kV, the intermediate drift tube at 200 kV and final drift tube and target at earth potential. This structure can be seen inside the evacuated glass tube in Fig. 1 above the curtained booth in which the experimenter sat while watching the evidence of nuclear disintegrations on a scintillation screen. The voltage generator, Fig. 1(b), was at the limit of the in-house technology available to Cockcroft and Walton and the design voltage of 800 kV was never reached due to persistent spark discharge which occurred at just over 700 kV. However, the famous atom-splitting experiment was carried out at 400 kV, well within the capabilities of the apparatus. The Cockcroft Walton generator, as is became known, was widely used for many years after as the input stage (up to 800 kV) for larger accelerators, since it could deliver a high current.

At about the same time Van de Graaff, an American who was in Oxford as a Rhodes scholar, invented an electrostatic generator for nuclear physics research and later in Princeton, he built his first machine, which reached a potential of 1,5

MV[3]. It took some time o develop the acceleration tube and this type of machine was not used for physics research until well after the atom had been split in 1932. The principle of this type of generator is shown in Fig. 2.

Table 1
Main "History Line"

1895	Lenard. Electron scattering on gases (Nobel Prize).	<100 keV electrons. Wimshurst-type machines.
1913	Frank and Hertz excited electron shells by electron bombardment.	
1906	Rutherford bombards mica sheet with natural alphas and develops the theory of atomic scattering.	Natural alphas particle of several MeV
1911	Rutherford publishes theory of atomic structure.	
1919	Rutherford induces a nuclear reaction with natural alphas.	
	… Rutherford believes he needs a source of many MeV to continue research on the nucleus. This is far beyond the electrostatic machines then existing, but…	
1928	Gamow predicts tunnelling and perhaps 500 keV would suffice…	
1928	Cockcroft & Walton start designing an 800 kV generator encouraged by Rutherford.	
1932	Generator reaches 700 kV and Cockcroft & Walton split lithium atom with only 400 keV protons. They receive the Nobel Prize in 1951	



(a) Accelerating column (b) DC generator
Fig. 1 Cockcroft and Walton's apparatus for splitting the lithium nucleus

Two new features appeared in later versions of the van de Graaff generator. Firstly, the sparking threshold was raised by putting the electrode system and accelerating tube in a high-pressure tank containing dry nitrogen, or Freon, at 9-10 atmospheres, which enables operation typically up to 10 MV. The second was a later development, which has the special name of the tandem accelerator (see Fig. 3).

The new feature in the Tandem accelerator was to use the accelerating voltage twice over. First an extra electron is attached to the neutral atoms to create negative ions. In recent years, a great deal of developments has been done and it is now possible to obtain negative ion sources for almost all elements. The negative ion beam is injected at ground potential into the Tandem and accelerated up to high-voltage terminal where it passes through a thin foil which strips at least two electrons from each negative ion converting them to positive ions. They are then accelerated a second time back to earth potential. The Van de Graaff generator and the Tandem provide beams of stable energy and small energy spread, but they are unable to provide as high currents as the Cockroft-Walton generator.

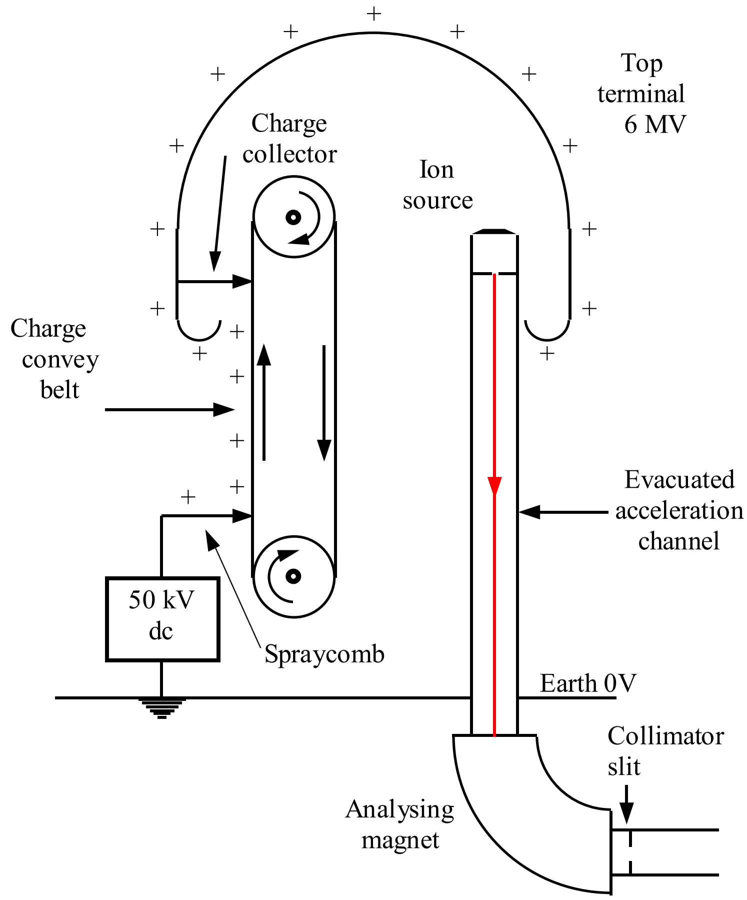


Fig. 2 Van de Graaff electrostatic generator

The highest energy Tandem is at Oak Ridge National Laboratory and routinely operates with 24,5 MV on the central terminal. However, developments is not at a standstill and there is a project (the Vivitron) underway at Strasbourg to build a Tandem operating at 35 MV.

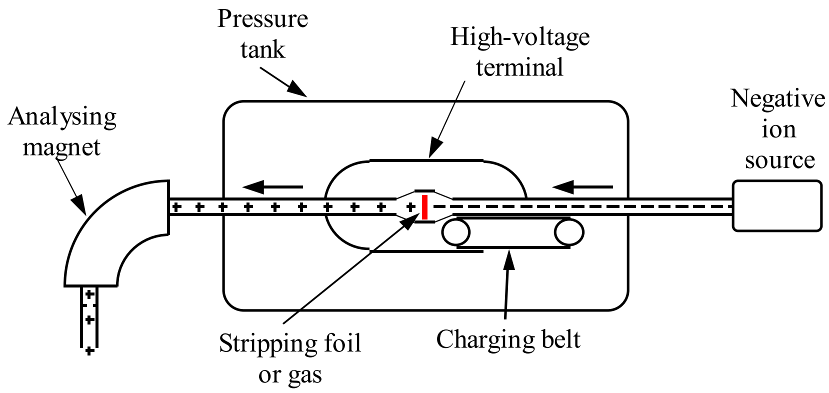


Fig. 3 Two-stage Tandem Accelerator

2.2 The second "History Line"

The direct-voltage accelerators were the first to be exploited for nuclear physics research, but they were limited to the maximum voltage the could be generated in the system (except for the astute double use of applied voltage in the Tandem). This limitation was too restrictive for the requirements of high-energy physics and an alternative was needed.

In fact, al alternative had already been proposed in 1924 in Sweden by Ising[4]. He planned to repeatedly apply the same voltage to the particle using alternating fields and his invention was to become the underlying principle of all today's ultra-high-energy accelerators. This is known as resonant acceleration. The main events along this "history line", starting with Ising, are given in Table 2.

The difference between the acceleration mechanism of Cockcroft and Walton and Ising depend upon whether the fields are static (i.e. conservative) or time varying (i.e. non-conservative). The electric field can be expressed in a very general form as the sum of two terms, the first being derived from a scalar potential and the second from a vector potential,

$$\vec{E} = -\nabla\phi - \frac{\partial}{\partial t}\vec{A} \tag{1}$$

where

$$\vec{B} = \nabla \times \vec{A} \tag{2}$$

Table 2
The second "History Line"

1924	Ising proposes time-varying fields across drift tubes. This is "resonant acceleration", which can achieve energies above that given by the highest voltage in the system.
1928	Wideröe demonstrates ising's principle with a 1 MHz, 25 kV oscillator to make 50 keV potassium ions.
1929	Lawrence, inspired by Wideröe and Ising, conceives the cyclotron.
1931	Livingstone demonstrates the cyclotron by accelerating hydrogen ions to 80 keV.
1932	Lawrence's cyclotron produces 1,25 MeV protons and he also split the atom just a few weeks after Cockcroft and Walton (Lawrence received the Nobel Prize in 1939).

The first term in (1) describes the static electric field of the Cockcroft-Walton and van de Graaff machines. When a particle travels from one point to another in an electrostatic field, it gains energy according to the potential difference, but if it returns to the original point, for example, by making a full turn in a circular accelerator, it must return to its original potential and will lose exactly the energy it has gained. Thus a gap with DC voltage has no net accelerating effect in a circular machine.

The second term in (1) describes the time-varying field. This is the term that makes all the present-day high-energy accelerators function. The combination of (1) and (2) yelds Faraday's law,

$$\nabla \times \vec{E} = -\frac{\partial}{\partial t}\vec{B}$$

which relates the electric field to the rate of change of the magnetic field. There are two basic geometries used to exploit faraday's law for acceleration. The first of which is the basis of Ising's idea and the second "history line", and the second is the basis of the third "history line" to be described later.

Ising suggested accelerating particle with a linear series of conducting drift tubes and Wideröe built a 'proof-of-principle' linear accelerator in 1928[5]. Alternate drift tubes are connected o the same terminal of an RF generator. The generator frequency is adjusted so that a particle traversing a gap sees an electric field in the direction of its motion and while the particle is inside the drift tube the field reverses so that it is again the direction of motion at the next gap. As the particle gains energy and speed the structure periods must be made longer to maintain synchronism (see Fig. 4).

Clearly, as the velocity increases the drift tubes become inconveniently long, unless the frequency can be increased, but at high frequencies the open drift-tube structure is lossy. This problem is overcome by enclosing the structure to forma cavity (in a circular machine) or series of cavity (in a linear machine), working typically in the MHz range. The underlying principle remains unchanged, but there are several variants of the accelerating structure design.

Ising's original idea can be considered as the beginning of the 'true' accelerator. Indeed, the next generation of linear colliders, which will be in the TeV range, will probably still be applying his principle of resonant acceleration, except that the frequency will probably be in the tens of GHz range.

Technologically the linar accelerator, or linac as it is known, was rather difficult to build and, during the 1930's, it was pushed into the background by a simpler idea conceived by Ernes Lawrence in 1929[6], the fixed-frequency cyclotron (see Fig. 5). Lawrence's idea was inspired by a written account of Wideröe's work and M. Livingston demonstrated the principle by accelerating hydrogen ions to 80 keV in 1931. Lawrence's first model worked in 1932[7]. It was less then a foot in diameter and could accelerate protons to 1,25 MeV. He split the atom only weeks after Cockcroft and Walton. Lawrence received the Nobel Prize in 1939, and by that year the University of California had a 5-foot diameter cyclotron (the 'Crocker' cyclotron) capable of delivering 20 MeV protons, twice the energy of the most energetic alpha particles emitted from radioactive sources. The cyclotron, however, was limited in energy by relativistic effects and despite the development of the synchrocyclotron, a new idea was still required to reach yet higher energies in order to satisfy the curiosity of the particle physicists. This new idea was to be the synchrotron, which will be described later.

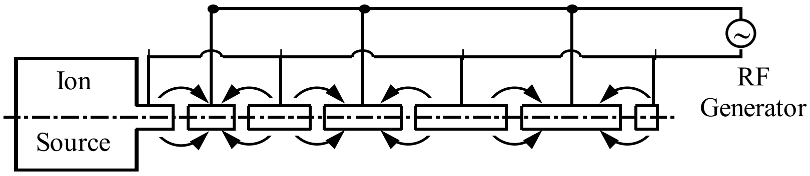


Fig. 4 RF linac

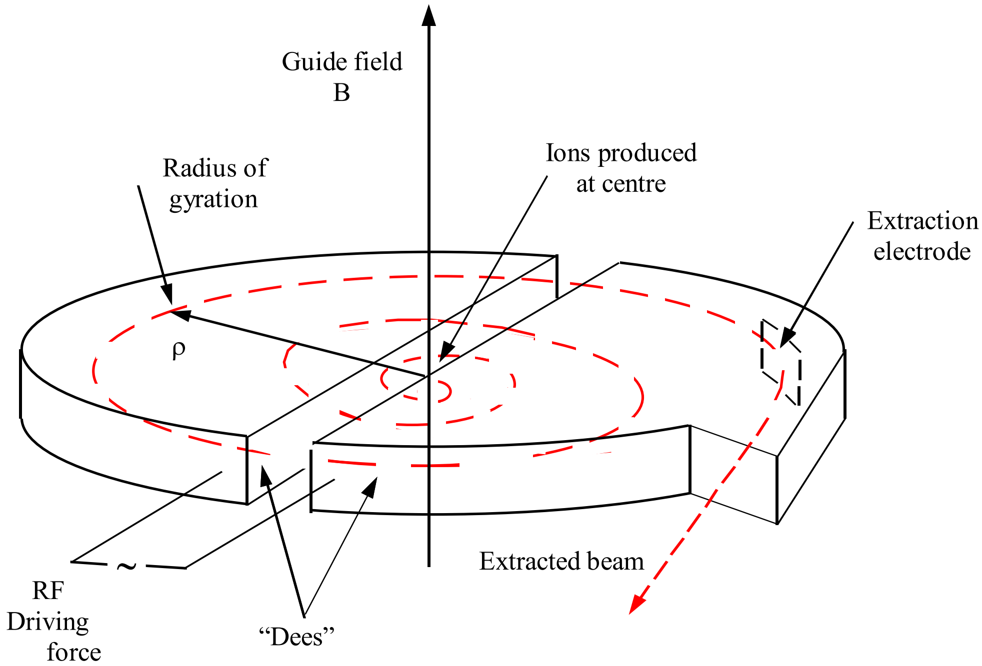
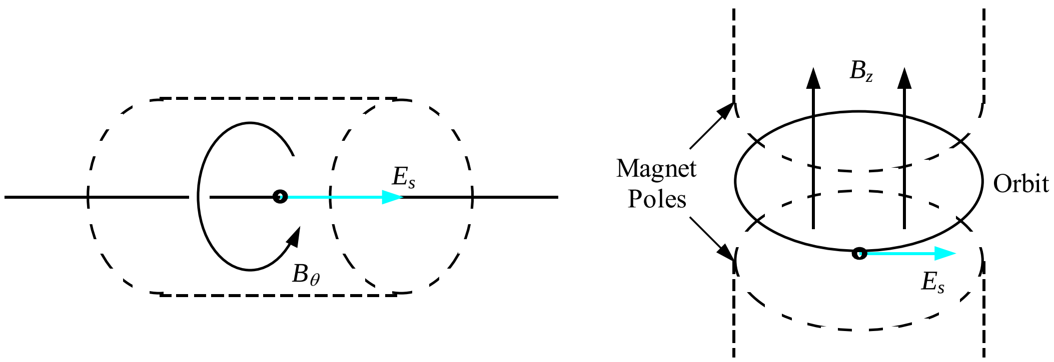


Fig. 5 Schematic cyclotron

2.3 The third and fainter "History Line"

In the previous sections, it was mentioned that there were two equipment configurations for exploiting Faraday's law for acceleration. First, consider the application of faraday's Law to the linac, which is made more evident by enclosing the gaps in cavities. For simplicity the fields in a single RF cavity are shown schematically in Fig. 6(a).



(a) (b)

Fig. 6 Acceleration configurations

The azimuthal magnetic field is concentrated towards the outer wall and link the beam. Faraday's law tell us the periodic rise and fall of this magnetic field induces an electric field on the cavity axis, which can be synchronised with the passage of the beam pulse.

Suppose now that the topology is transformed, so that the beam encircles the magnetic field as shown in Fig.6(b). Wideröe[8,9] suggested this configuration and the acceleration mechanism, now known as "betatron accelartion". He called his idea a "strahlung transformator" or "ray transformer", because the beam effectively formed the secondary winding of a transformer (see Figs. 6 and 7). As the flux through the magnet core is increased, it induces an azimuthal e.m.f. which drives the charged beam particles to higher and higher energies. The trick is to arrange for the increase in the magnetic field in the vicinity of the beam to correspond to the increase in particle energy, so that the beam stays on the same orbit (known as the Wideröe condition, or 2-to-1 rule). This device, the betatron, is insensitive to relativistic effects and was therefore ideal for accelerating electrons. The betatron has also the great advantages of being robust and simple. The one active element is the power converter that drives the large inductive load of the main magnet. The focusing and synchronisation of the beam energy with the field level are both determined by the geometry of the main magnet. As noted in the third "history line" in Table 3, Wideröe put this idea in his laboratory notebook, while he was a student, but it remained unpublished only to re-surface many years later when Kerst[10] built the first machine of this type. When in 1941 Kerst and Serber published a paper on the particle oscillation in their betatron[11], the term "betatron oscillation" became universally adopted for referring to such oscillation in all devices.

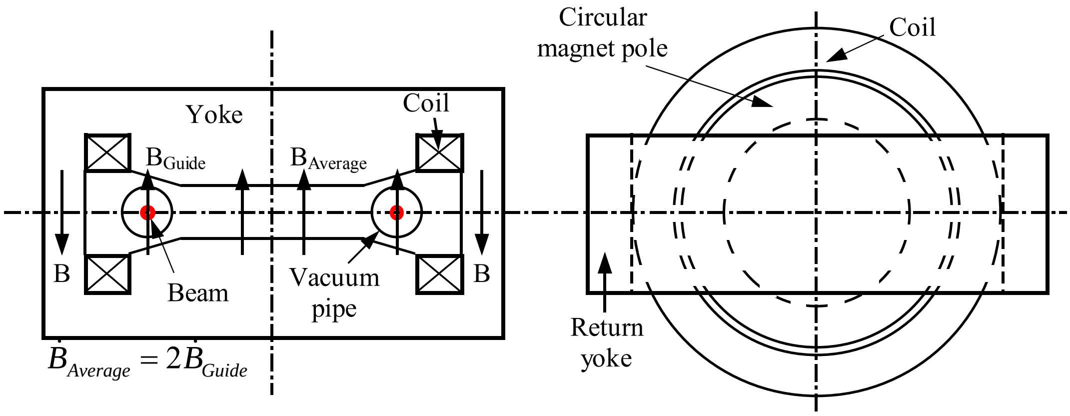


Fig. 7 Strahlung transformator or betatron

Table 3
The third "History Line"

1923	Wideröe, a young Norwegian student, draws in his laboratory notebook the design of the betatron with the well known 2-to-1 rule. Two years later he adds the condition for radial stability but does not publish.
1927	Later in Aachen Wideröe makes a model betatron, but it does not work. Discouraged he changes course and builds the linear accelerator mentioned in Table 2.
1940	Kerst re-invents betatron and builds the first working machine for 2,2 MeV electrons.
1950	Kerst builds the world's largest betatron of 300 MeV.

The development of betatrons for high-energy physics was short, ending in 1950 when Kerst built the world's largest betatron (300 MeV), but they continued to be built commercially for hospitals and small laboratories where they were considered as reliable as cheap. In fact the betatron acceleration mechanism is still of prime importance. In the present-day synchrotron, there is a small contribution to the beam's acceleration which arises from the increasing field in the main dipoles. If an accurate description of the longitudinal motion is required, then the betatron effect has to be included.

3. THE MAIN DEVELOPMENT

By the 1940's three acceleration mechanism had been demonstrated: DC acceleration, resonant acceleration and the betatron mechanism. In fact, there were to be no new ideas for acceleration mechanism until the mid- 1960's, when collective acceleration[12] was proposed in which eavy ions are accelerated in the potential well of an electric ring and the 1980's when there were several Workshops devoted entirely to finding new acceleration techniques. However, the acceleration mechanism is not sufficient by itself and other equally important developments are needed.

In order to accelerate particles to very high energies, it is also necessary to have focusing mechanism in the transverse and longitudinal (energy) planes. This was not always appreciated. In the early cyclotron, for example,, the field was made as uniform as possible only to find that the beam was unstable. Livingston[13] who was the Lawrence's research student, told how they shimmed the magnet for each small step in energy to keep the beam stable, thus ending up with a field shape for transverse stability that decreased with radius. Theory has later shown that this decrease should be an inverse power law of the radius between zero and unity.

The cyclotron is limited by relativistic effects, which cause the particles to slow down and lose synchronism with the RF field. At firs glance it would appear that one would only have to reduce the frequency in order to maintain synchronism, but this is a little too naïve since the spread in revolution frequency with energy would quickly exploit the natural energy spread in the beam and disperse the particle away from the peak of the RF voltage. In this case a longitudinal focusing mechanism is needed. This problem was overcome by E. McMillan[14] and independently by V. Veksler[15] who discovered the principle of phase stability in 1944 and invented the synchrotron. Phase stability is general to all RF accelerator except the fixed-frequency cyclotron. The effect is that a bounce of particles, with an energy spread, can be kept bunched throughout the acceleration cycle by simply injecting them a suitable phase on the RF cycle. This focusing effect was strong enough that the frequency modulation in the synchro-cyclotron did not have to be specially tailored and was simply sinusoidal. Synchro-cyclotrons can accelerate protons to about 1 GeV, a great improvement on the simple cyclotron, but the repetition rate reduces the particle yeld.

In the synchrotron[14,15] the guide field increases with particle energy, so as to keep the orbit stationary as in the betatron, but acceleration is applied with an RF voltage via a gap or cavity. In 1946 F. Goward and D. Barnes[16] were the first to make a synchrotron work, and in 1947 M. Oliphant, J. Gooden and G. Hyde[17] proposed the first proton synchrotron for 1 GeV in Birmingham, UK. However, the Brookhaven National Laboratory, USA, built their 3 GeV Cosmotron by 1952, just one year ahead of the Birmingham group.

Up to this time the only mechanism known for focusing in the transverse plane was called weak, or constant-gradient focusing. In this case, the guide field decreases slightly with increasing radius and its gradient is constant all around the circumference of the machine. The tolerance on the gradient is severe and sets a limit to the size of such an accelerator. The aperture needed to contain the beam also becomes very large and the magnet correspondingly bulky and costly. In the early fifties the limit was believed to be around 10 GeV.

In the same year as the Cosmotron was finished (1952) E. Courant, M. Livingston and H. Snyder[18] proposed strong focusing, also known as alternating-gradient (AG) focusing. The idea had been suggested earlier by Christofilos[19] but it was not published. This new principle revolutionized synchrotron design, allowing smaller magnets to be used and higher energies to be envisaged. It is directly analogous to a well-known result in geometrical optics, that the combined focal length F of a pair of lenses of focal lengths f_1 and f_2 separated by a distance d is given by

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{1}{f_1 f_2}$$

If the lenses have equal and opposite focal lengths, $f_1=-f_2$ and the overall focal length $F=f^2/d$, which is always positive. In fact, F remains positive over quite a large range of values when f_1 and f_2 have unequal values but are still of opposite sign. Thus within certain limits a series of alternating lenses will focus. Intuitively one sees that, although the beam may be defocused by one lens, it arrives at the following lens further from the axis and in therefore focused more strongly. Structures based on this principle are referred to as AG structures.

The synchrotron quickly overshadowed the synchrocyclotron and the betatron in the race for higher energies. The adoption of alternating gradient focusing for machine and transfer lines were even quicker. CERN for example immediately abandoned its already-approved project for a 10 GeV/c weak focusing synchrotron in favour of a 25 GeV/c AG machine, which it estimated could be built for the same price.

The next step was the storage ring collider. In physics experiments, the useful energy for new particle production is the energy that is liberated in the centre-of-mass system. When an accelerator beam is used on a fixed target, only a fraction of the particle's energy appears in the centre-of-mass system, whereas for two equal particles in a head-on collision, all of the particle's energy is available. This fundamental drawback of the fixed-target accelerator becomes more punitive as the energy increases. For example, it would have needed a fixed-target accelerator of over 1 TeV to match the centre-of-mass energy available in the CERN ISR (2×26 GeV proton collidings rings).

The storage-ring collider now dominates the high-energy physics field. Single-ring colliders, using particles and antiparticles in the same magnetic channel, were the first type of collider to be exploited at Frascati in the AdA (Anelli di Accumulazione) project (1961). The first double-ring proton collider was the CERN ISR (Intersecting Storage Rings), 1972-1983. The highest-energy collisions obtained to date are 2×900 GeV in Fermilab, single-ring, proton-antiproton collider.

Colliders have been very successful as physics research instruments. The J/ψ particle was discovered at SPEAR by B. Ricther and at the same time by Ting at BNL – they shared the 1976 Nobel Prize. The CERN proton-antiproton storage ring was also the source of a Nobel Prize for C. Rubbia and S. van der Meer in 1984, following the discovery of the W and Z particles. The proton-antiproton colliders were only made possible by the invention of stochastic cooling by S. van der Meer for the accumulation of the antiprotons[20].

The use of superconductivity in proton machine has made the very highest energies possible. There has also been another change taking place, which has been called the Exogeographical transition (a phrase coined by Professor N. Cabibbo at Workshop held at Frascati in 1984). This refers to the arrangements that have made it possible to bury the very large machines such as LEP and HERA deep under property which does not belong to the laboratory concerned. Without such agreements, Europe could not have maintained its leading position in the world accelerator league.

In order to fill in some of the bigger gaps in this brief history, it is now necessary to jump back in time to mentionsome of the other accelerators, which may not have featured as a high-energy machine, but have found their place as injectors or as being suitable for some special application.

The microtron, sometimes known as the electron cyclotron, was an ingenious idea due to Veksler (1945). The electrons follow circular orbits of increasing radius, but with a common tangent. An RF cavity positioned at the point of the common tangent supplies a constant energy increment on each passage. The relativistic mass increase slows the revolution frequency of the electrons, but by a constant increment on each passage. If this increment is a multiple of the RF oscillator frequency, the electron stay in phase, but on a different orbit. Microtrons operates at microwave frequencies and are limited to tens of MeV. They are available commercially and are sometimes used as an injector to a larger machine.

The radio-frequency quadrupole (RFQ) suggested in 1970 by I. Kapchinski and V. Telyakov is useful at low energies and is increasingly replacing the Cockcroft-Walton as injector. The RFQ combines focusing and acceleration in the same RF field.

The electron storage rings have given birth to the synchrotron radiation sources, more usually referred to as light sources. These machines are now the fastest growing community in the accelerator world and the first commercially available compact synchrotron light source for lithography has just come onto the market.

The linear accelerator was eclipsed during the thirties by circular machines. However, the advances in ultra-high frequency technology during the World War II (radar) opened up new possibilities and renewed interest in linac structures. Berkeley was first, with a proton linear accelerator of 32 MeV built by Alvarez in 1946. The Alvarez accelerator has become very popular as an injector for large proton and heavy-ion synchrotrons all over the world with energies in the range of 50-200 MeV, that is essentially non-relativistic particles. The largest proton accelerator to date is the 800 MeV ‘pion factory’ (LAMPF) at Los Alamos.

The first electron linear accelerators were studied at Stanford and at the Massachussetts Institute for Technology (MIT) in 1946. This type of accelerator has also had a spectacular development, up to the largest now in operation, the 50 GeV linear accelerator at the Stanford Linear Accelerator Centre (SLAC). Like betatrons they have become very popular in fields outside nuclear physics, particularly for medicine.

The Livingston chart (see Fig. 8) shows, in a very striking way, how the succession of new ideas and new technologies has relentlessly pushed up accelerator beam energies over five decades at the rate of over one and a half orders of magnitude per decade. One repeatedly sees a new idea, which rapidly increases the available beam energy, but only to be surpassed by yet another new idea. Meanwhile the first idea continues into saturation and possibly into quasi-oblivion.

This brings the section on the main development t almost up to date, except for the Stanford Linear Collider (SLC), but this will be mentioned under future accelerators where fits more naturally.

4. THE CURRENT SITUATION IN HIGH-ENERGY PARTICLE PHYSICS ACCELERATORS

Table 4 contains a section of the main operating high-energy physics machines, those under construction and those under study. The latter two groups encompass the extremes of machines like RHIC[22], which are partially constructed and the linear colliders, which are very futuristic.

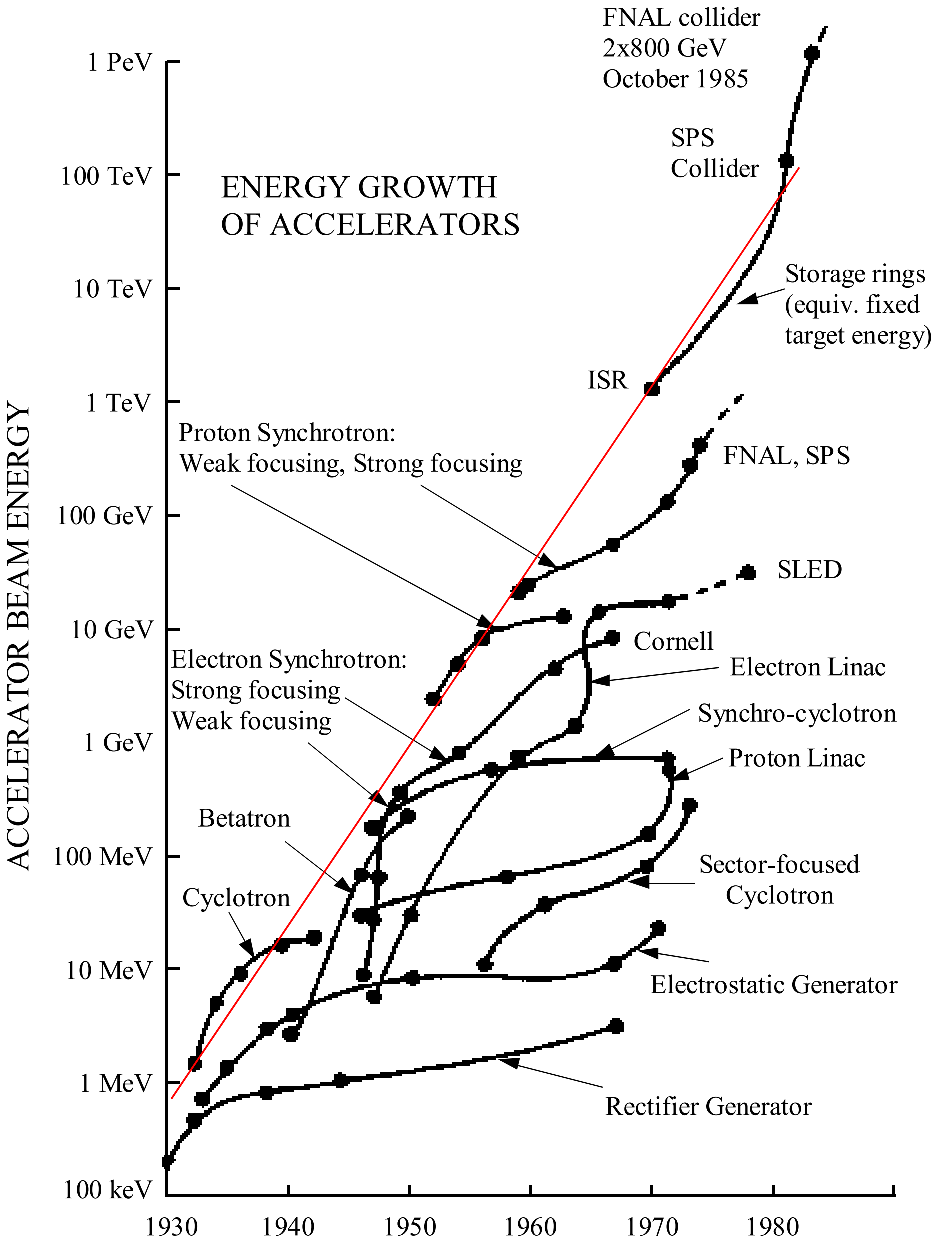


Fig. 8 Livingston chart[21]

In the present situation circular colliders dominate the high-energy filed. The proton-antiproton colliders are now mature machines and it is unlikely that the USA or Western Europe will propose further facilities of this type. The technologies of stochastic and electron cooling that were developed for this class of facility are now being applied in smaller storage rings.

Once LEP[23] has been upgraded to around 100 GeV, it will almost certainly be the highest energy electron ring to be built, since the penalty to be paid in RF power to compensate the synchrotron radiation loss is already prohibitive at this energy. The solution is to change to linear electron colliders; a solution that was already foreseen in 1965 by Tigner[24]. The Stanford Linear Collider (SLC)[25] is a test bed for these future machines.

At the moment, the proton community is poised to build the SSC (Super Superconducting Collider) in Texas[26] and the LHC (Large Hadron Collider) in CERN[27]. Both machines are superconducting and of very large dimensions. At present there is no hard limitation on the size of hadron colliders, except of course cost. However, synchrotron radiation is already a bothersome heat load in these machines and will be a very real problem in machines of the size of Eloisatron[28] for example. The LHC is a high technology project, which will use high-field magnet (approaching 10 T) with probably ‘niobium-titanium’ technology at 2 K in the arcs and niobium-tin technology at 4 K in the insertions. The magnets will also be of the twin-bore design first proposed by Blewett[29].

Table 4
Operating high-energy physics accelerators

Accelerator	Particles	Beam energy [GeV]	c.m. energy [GeV]	Luminosity [$cm^{-2}s^{-1}$]	Remarks
KEK Japan	p	12	5	-	Fixed target
AGS Brookhaven	p	33	8	-	Fixed target Polarised p
PS CERN	p e^+, e^-, p^-, ions	28 (p) 3,5 (e)	7 -	- -	Fixed target Injector
CESR Cornell	e^+, e^-	9	18	10^{32}	Collider
Tevatron II FNAL	p p, p^-	800 (p)	40 -	- -	Fixed target Injector
SPS CERN	p, e p, p^-	450 (p), 20 (e) 2×315	30 (p), - 630	- 3×10^{30}	F. target, injector Collider
SLC SLAC	e^+, e^-		100	6×10^{30}	Linear Collider
Tevatron I FNAL	p, p^-	900	1800	10^{31}	s.c. collider
TRISTAN In Japan	e^+, e^-	32	64	8×10^{31}	Collider s.c. cavities
LEP I CERN	e^+, e^-	55	110	$1,6\times10^{31}$	Collider
HERA DESY	e, p	30 (e^-) 820 (p)	310	3×10^{31}	Collider s.c. p-ring

High-energy physics accelerator under construction

UNK I USSR	p	400	28	-	Fixed target Conventional
SSC USA	p, p	20	40	~ 10^{33}	s.c. collider
LEP II CERN	e^+, e^-	100	200	10^{32}	Collider, s.c. cavity upgrade
RHIC Brookhaven	p to Au	0,25 to 0,1/amu	0,5 to 0,2/amu	3×10^{30} $1,2\times10^{27}$	s.c. collider for heavy ions

High-energy physics accelerator under study

UNK II USSR	p, p p, p^-	3	6	~ 4×10^{32} ~ 10^{37}	s.c. collider for 1996
LHC CERN	p, p	8	16	~ 10^{34}	s.c. collider
CLIC CERN	e^+, e^-	1	2	~ 10^{33}	Linear collider
SC Stanford	e^+, e^-	0,5 (1)	1 (2)	~ 10^{33}	Linear collider proposal 1990
VLEPP USSR	e^+, e^-	0,5 (1)	1 (2)	~ 10^{33}	Linear collider for 1996
JLC Japan	e^+, e^-	0,5	1	~ 10^{33}	-

5. CONCLUSION

Led by the example of the SLC, accelerator builder are now tackling formidable theoretical and technological problems in all stage of the accelerator design. In the next generation of proposed linear electron colliders the typical values required for the normalised emittance are of the order of 10^{-7} rad.m. Beam sizes at the interaction point will have to be around 1 to 30 nm high with pulse lengths of 200-800 μm. With a few 10^{10} particles per bunch and a repetition rate of over 1000 Hz the beam power is then a few MW. The luminosity in such design is around a few times 10^{33} $cm^{-2}s^{-1}$, far higher than anything that has yet been achieved. Stability of the supporting structures and power converters driving the final focus become critically important with such small beam sizes and the fabrication of elements such as the final focus quadrupoles requires new techniques.

At present the linear collider design are called quasi-conventional. For example, the CERN CLIC study[30] assumes the use of warm copper accelerating structure operating at 29 GHz giving 80 MV/m. If this sounds easy, then consider that the structure will be powered from a superconducting drive linac- Such high-gradient, high-frequency structures have never before been used and neither has a superconducting linac been used in this way to drive a second accelerator. In fact, the term "quasi-conventional" is really a misnomer.

The future holds many challenges for the accelerator engineer both in the gigantic superconducting hadron machines now proposed and in new generation of electron linear colliders.

* * *

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BASIC METHODS OF LINEAR ACCELERATION

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1. EARLY DAYS

In principle a linear accelerator is one in which the particles are accelerated on a linear path. Then the most simple scheme is the one which uses an electrostatic field as shown in Fig. 1. A high voltage is shared between a set of electrodes creating an electric accelerating field between them. The disadvantage of such a scheme, as far as high energies are concerned, is that all the partial accelerating voltages add up at some point and that the generation of such high electrostatic voltages will be rapidly limited (a few ten MV). This type of accelerator is however currently used for low energy ion acceleration, and is better known as the Van De Graaff accelerator.

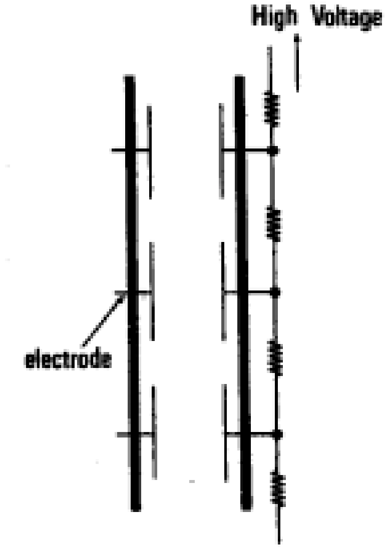


Fig. 1 Electrostatic accelerator scheme

In the late 1920's propositions were made, essentially by R. Wideroe, to avoid the limitation of electrostatic devices due to voltage superposition. The proposed scheme, later on (early 1930's) improved by E. Lawrence and D. Sloan at the Berkeley University, is shown on Fig. 2.

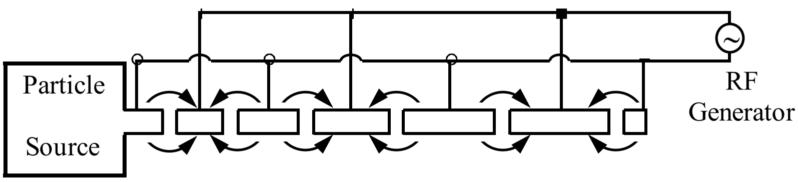


Fig. 2 Wideroe-type accelerator

An oscillator (7 MHz at that time) feeds alternately a series of drift tubes in such a way that particles see no field when travelling inside these tubes while they are accelerated in between. The last statement is true if the drift tube length L satisfies the synchronism condition:

$$L = \frac{vT}{2}$$

where v is the particle velocity (βc) and T the period of the a.c. field. This scheme does not allow continuous acceleration of beams of particles.

2. IMPROVED METHODS FOR NON-RELATIVISTIC PARTICLES

Consider a proton of 1 MeV kinetic energy entering the previous structure. At a frequency of 7 MHz such a particle, with $\beta = v/c = 4{,}6\ 10^{-2}$, will travel a distance of roughly 1 meter in half a cycle. Clearly the length of the drift tubes will soon become prohibitive at higher energies unless the input RF frequency is increased.

Higher-frequency power generators only became available after the second world war, as a consequence of radar developments.

However at higher frequencies the system, which is almost capacitive, will radiate a large amount of energy; as a matter of fact if one considers the end faces of the drift tubes as the plates of capacitor, the displacement current flowing through it is given by

$$I = \omega C V$$

where C is the capacitance between the drift tubes, V the accelerating voltage and ω the angular frequency in use. It is therefore convenient to enclose the gap existing between drift tubes in a cavity which holds the electromagnetic energy in the form of a magnetic field (inductive load) and to make the resonant frequency of the cavity equal to that of the accelerating field (Fig. 3). In that case the accelerator would consist of a series of such cavities fed individually with power sources.

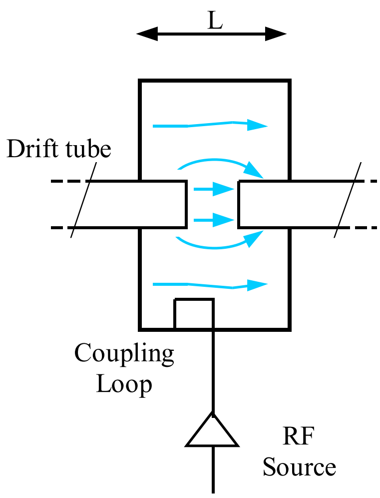


Fig. 3 Single-gap accelerating structure

Such single-gap cavities could also be placed adjacent to each other as shown on Fig. 4. In the 2π mode case, since the resulting wall current is zero, the common walls between cavities become useless. Then a variant of that scheme consists of placing the drift tubes in a single resonant tank such that the field has the same phase in all gaps. Such a resonant accelerating structure was invented by L. Alvarez in 1945 and was followed by the construction of a 32 MeV proton drift tube linac (Fig. 5) powered by 200 MHz war surplus radar equipment.

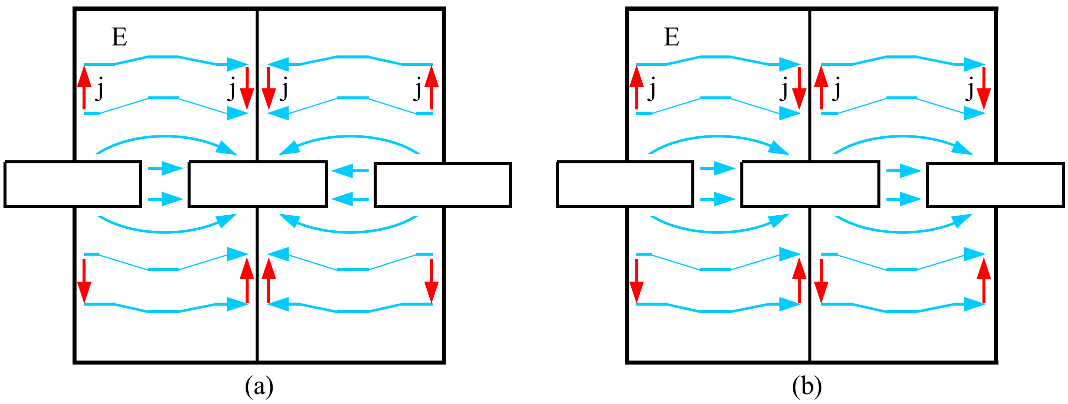


Fig. 4 Adjacent single-gap cavities: a) π mode, b) 2π mode

In the 2π mode of operation the synchronism condition is :

$$L = vT = \beta\lambda_0$$

where λ_0 is the free space wavelength at the operating frequency. Notice that in Fig. 5 the drift tubes are maintained by metallic rods to the tank walls.

The Alvarez structure is still used for protons, as well as heavy ions, operating mostly at 200 MHz. Most of our present day proton linear accelerators are used as injectors for circular machines such as synchrotrons and their energy lies from 50 MeV to 200 MeV. At 200 MeV protons are still weakly relativistic with β=0,566.

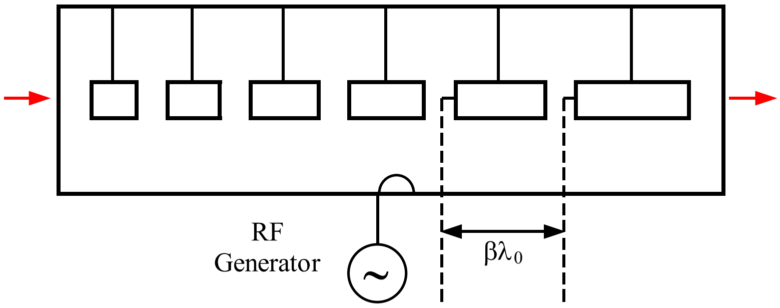


Fig. 5 Alvarez-type structure

Note: Since the progress in method of acceleration came from the resonant structures which can provide high accelerating field with less power consumption, the new definition of a linear accelerator or "Linac" implied machines in which particles are accelerated on a linear path by radio frequency fields. Then electrostatic devices no more appear in this definition, but it is worthwhile mentioning that they are used as front-end proton linacs.

3. THE CASE OF ULTRA-RELATIVISTIC PARTICLES

While β is getting closer to unity for protons of 10 GeV kinetic energy, β is almost unity for electrons of 10 MeV. Hence above these energies the particles will have a constant velocity v=c and yhe length of the drift tubes will remain constant as well. The higher velocity needs higher frequencies. However triode and tetrode tubes could not handle high RF power at high frequency. The invention of the klystron in 1937 and its successful development during the war led to high power sources at 3000 MHz. At this frequency the free-space wavelength is 10 cm, small enough that the perspective of accelerating electrons to high energies soon become an aim.

At the same time emerged the idea that ultrarelativistic particles could be accelerated by travelling guided waves. It is matter of fact that in a resonant structure the standing wave pattern can be expanded into two travelling waves, one which travels in synchronism whit the particle and the backward wave which has no mean effect on the particle energy.

However TM modes (with an electric field in the direction of propagation) in rectangular or cylindrical guides have phase velocities bigger than c. Then it was necessary to bring the phase velocity at the level of the particle velocity (v_p~c) and to do so the simplest method consist of loading the structure with disks as shown on Fig. 6, where the size of the holes determines the degree of coupling and so determines the relative phase shift from one cavity to the next. When the dimensions (2a, 2b) have been tailored correctly the phase changes from cavity to cavity along the accelerator to give an overall phase velocity corresponding to the particle velocity.

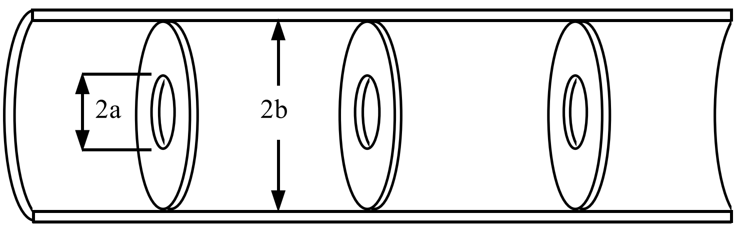


Fig. 6 Disk-loaded structure

This type of structure will continuously accelerate particles as compare to the drift tube structure which gives a discontinuous acceleration corresponding to the successive gaps.

Figure 7 is a more complete drawing of such a travelling-wave structure showing both, the input coupler which matches the source to the structure and the output coupler which matches the structure to an external load (resistive load for instance) to avoid the backward wave.

These structure generally operate in the π/2 mode or the 2π/3 mode. For the former the height of each cell is equal to λ/4 while is equal to λ/3 for the latter. The interesting thing with travelling-wave structures, in which the energy propagates relatively fast, is that the RF power source can be pulsed during a short period corresponding to the filling time of the structure. In this pulsed mode of operation much higher peak power pulses can feed the structure, increasing the accelerating field. As a consequence only pulsed beams can be accelerated leading to small duty cycles.

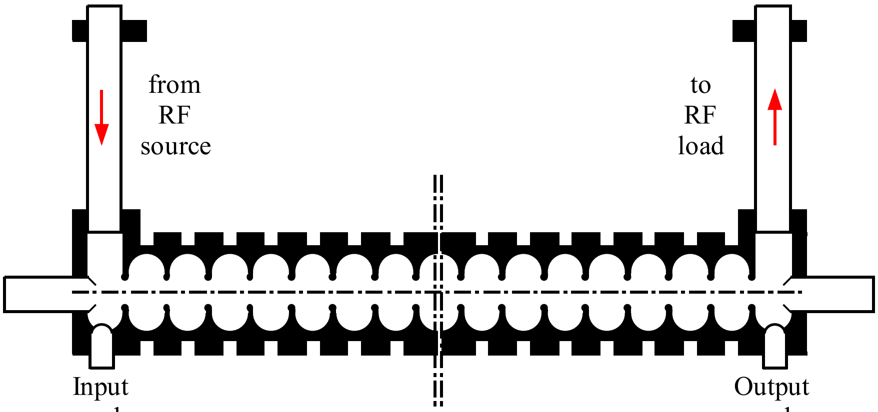


Fig. 7 Travelling-wave accelerating structure

Standing-wave structures can also be used for ultrarelativist particles. In that case the π mode of operation is efficient, where the field has opposite phase in two adjacent cells. This type of structure as shown on Fig. 8, often called "nose cone structure", is very similar to the drift tubes one in which the length of the tubes has been made very small. A variant of this scheme is used in the high energy proton linac (E=800 MeV) at Los Alamos, where the coupling between cavities has been improved by adding side coupled resonant cavities as sketched on Fig. 9.

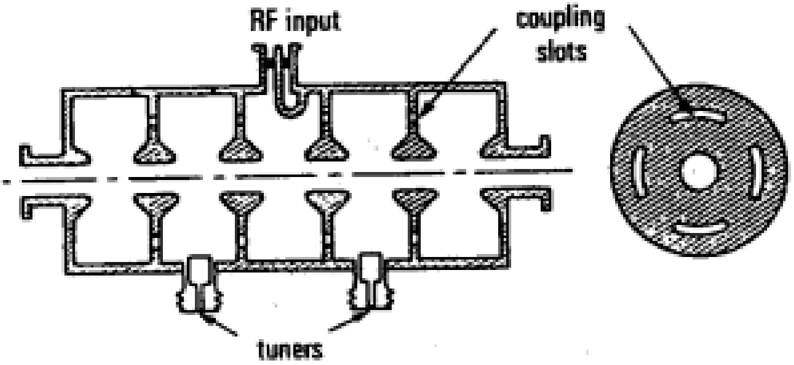


Fig. 8 Nose-cone structure

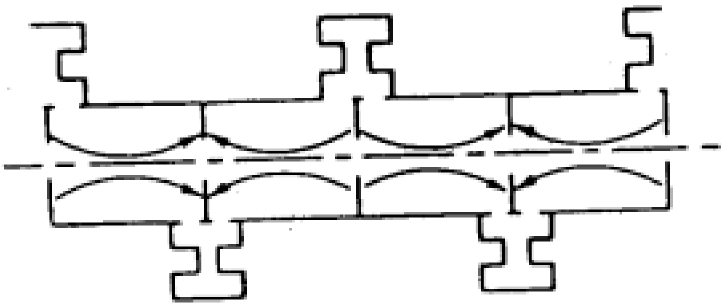


Fig. 9 Side-coupled structure

4. INDUCTION LINAC

Resonant structures as described previously cannot handle very high beam currents. The reason is that the beam induces a voltage proportional to the circulating current and with a phase opposite to that of the RF accelerating voltage. This effect known as "beam loading" disturbs the beam characteristics and can even destroy the beam by some instability. Mechanism.

A cure for such an effect in the case of very high currents consists of producing an accelerating field with a very low Q resonator. This is obtained with an induction accelerator module (Fig. 10) in which a pulsed magnetic field produces an electric field component, according to Maxwell equations, just similar to the betatron principle.

The accelerator will consist of an array of such modules triggered at a rate compatible with the particle velocity, and fed by high power short pulse generators.

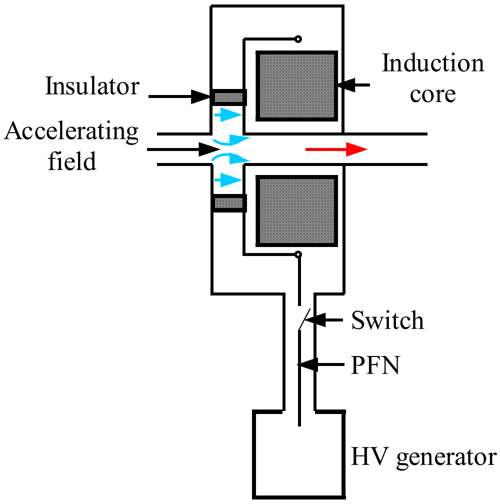


Fig. 10 Linear induction accelerator module

5. RADIO FREQUENCY QUADRUPOLE (RFQ)

Ai quite low β values (for example low energy protons) it is hard to maintain high currents due to the space charge forces of the beam which have a defocusing effect.

In 1970 I.M. Kapchinski and T.V. Teplyakov from the Soviet Union proposed a device in which the RF fields which are used for acceleration can serve as well for transverse focusing. The schematic drawing of an RFQ is shown on Fig. 11. The vanes which have a quadrupole symmetry in the transverse plane have a sinusoidal shape variation in the longitudinal direction. In recent years these devices have been built successfully in many laboratories making it possible to lower the gun accelerating voltage for protons and heavy ions to less than 100 kV as compared to voltages above 500 kV which could only be produced earlier by large Cockcroft-Walton electrostatic generators.

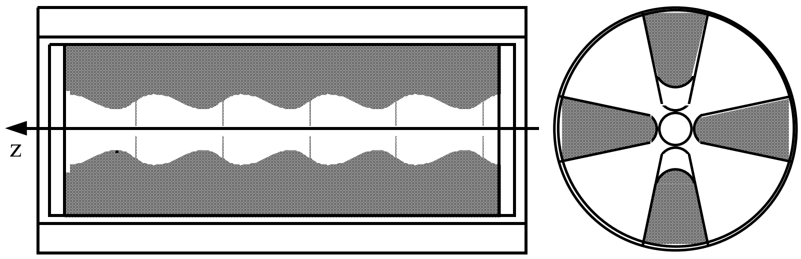


Fig. 11 Schematic drawing of an RFQ resonator.

A SHORT DEMONSTRATION OF LIUVILLE'S THEOREM

M. Weiss
CERN, Geneva, Switzerland

ABSTRACT

A brief demonstration of Liuville's Theorem is given by applying the Hamiltonian.

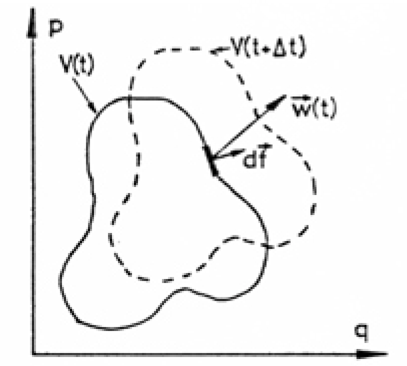
An ensemble of particles evolving in a system of external forces (space and velocity dependent) and self forces (space charge) is described by two families of canonically conjugated variables (coordinates) q and p. The equation of the motion form a system of first-order differential equations of the coordinates $\dot{q}$ and $\dot{p}$ where the dot indicates derivatives with respect to time.

If the system is non-dissipative, one can obtain the equations of motion from a function called Hamiltonian:

$$\begin{cases} \dot{q} = \dfrac{\partial H}{\partial p} \\ \dot{p} = -\dfrac{\partial H}{\partial q} \end{cases}$$

The Hamiltonian is in general also a function of time H(q,p,t).

An ensemble of particles, at a given moment t, occupies a volume V(t) in the (q,p) space called the phase space.



$d\vec{f}$ … vector of surface element

$\vec{w}(t)$ …phase space velocity of surface element $\vec{w} = \begin{pmatrix} \dot{q} \\ \dot{p} \end{pmatrix}$

At the time t+Δt, the particles occupy another volume V(t+Δt). It can easily be shown that these volumes are the same:

$$\frac{dV(t)}{dt} = \int \vec{w} \cdot \overrightarrow{df} = \int \left(\nabla \cdot \vec{w}\right) dv = \int \left(\frac{\partial}{\partial q} \dot{q} + \frac{\partial}{\partial p} \dot{p} \right) dv = 0$$

Surface integral → Volume integral (Gauss Theorem)

$$\left(\frac{\partial^2 H}{\partial q \partial p} - \frac{\partial^2 H}{\partial p \partial q} \right) = 0$$

(Hamilton)

The volume V(t) remains constant, if the motion can be represented by a Hamiltonian. This is true also when H is an explicit function of time. We conclude: *In non-dissipative systems, the particles move like an incompressible fluid in phase space.* This is Liuville's Theorem.

AMORTISSEMENT ADIABATIQUE DES OSCILLATIONS

Le théorème adiabatique d'Ehrenfest stipule :
Si les paramètres définissant un oscillateur varient lentement, les variables canoniques du mouvement évoluent de sorte que l'intégrale d'action

$$I(t) = \oint p\,dq = \text{const} \tag{1}$$

l'intégrale étant étendue sur une période de l'oscillation.
On supposera que les trois modes d'oscillation en x, z et θ d'une particule sont indépendants et on choisit comme paire de variables canoniques l'éenergie H et le temps t.

L'OSCILLATION BETATRON

La loi d'évolution de l'élongation y(t) d'un oscillateur harmonique de masse m et de fréquence angulaire ω_y dérive très généralement de l'hamiltonien :

$$H(y, p_y) = \frac{m\omega_y^2 \hat{y}^2}{2} + \frac{p_y^2}{2m}$$

(Ici ω_y a la signification de la fréquence d'oscillation.)
On suppose que m et ω_y varient lentement par rapport à la période d'oscillation

$$\Delta t = \frac{2\pi}{\omega_y}$$

de sorte que :

$$H = \frac{m\omega_y^2 \hat{y}^2}{2} = \text{const} \qquad \text{pendant } \Delta t$$

et en vertu de (1) :

$$I(t) = \int_t^{t+\Delta t} H\,dt = \pi m \omega_y \hat{y}^2(t) = \text{const}$$

d'où s'ensuit

$$\hat{y}(t) \propto \frac{1}{\sqrt{m\omega_y}}$$

Pur l'oscillation bêtatron on a m=p/v ; ω=υ(v/R), υ étant le nombre d'ondes.
L'amplitude de l'oscillation bêtatron évolue donc comme :

$$\hat{y}(t) \propto \sqrt{\frac{R}{\upsilon p}}$$

Dans un synchrotron pulsé on a R=const, υ=const, p∝B et

$$\hat{y} \propto \frac{1}{\sqrt{B}}$$

Name of Linac: New 50 MeV Injector Linac
Injection for: CERN Accelerator Complex (800 MeV Booster, 28 GeV PS, 300 GeV SPS)
Location: CERN, Geneva, Switzerland
Person in Charge: G. Plass **Date:** March 1980
Data Supplied by: D. Warner

HISTORY AND STATUS
Construction Started (date): Nov. 1973
First Beam Obtained, or Goal (date): Sept. 78
Total Cost of Facility: 23 MFr.
Funded by: CERN Member State
Total Accelerator Staff (now): 26 my/y incl. Old Linac
Annual Operating Budget: 1.6 Mfr. Incl O. L. (without salaries)
Annnual Operating Time: 7000 h
"Beam On": 99% of scheduled time

ACCELERATOR PARAMETERS
Physical Dimensions[1]
Total Length: 33,6 m **No. Tanks:** 3
Tank Diam.: Note[1] **No. Drift Tubes:** 125 + 6(½)
Drift Tube Lenghts: 48 mm to 316 mm
Drift Tube Diameter: 180 mm (Tank 1), 160 mm (rest)
Gap/Cell Length: 0,22 – 0,31; 0,20 – 0,29; 0,26 – 0,32
Aperture Diam.: 20 mm to 25 mm (Tank 1); 30 mm (rest)

Ion Source
Type: Duoplasmatron (with expansion cup)
Output : 250 mA
Emittance: - (Emittance = Area x$\beta\gamma$ at 90% current)

Injector
Type: High gradient column with Cockroft-Walton
Output: 250 mA at 750 keV
Emittance: 2 π mm·mrad (Emittance = Area x$\beta\gamma$ at 90% current)

Bunchers
Type : Three buncher system
Modulation: 37 keV **Drift:** *l* 950 mm at 202,56 MHz
16 keV **Drift:** *l* 800 mm at 405,12 MHz
35 keV **Drift:** *l* 160 mm at 202,56 MHz

Acceleration System
RF Freq.: 202,56 MHz
Field Mode: TM010 **Q:** 6000
Equil. Phase Note[2] **Accel. Rate:** 1,48 MeV/m
Repetition Rate: 1 pps (normal); 2 pps (Max)
Duty Factor: 0,03% (RF); 0,01% (Beam)
Pulse Length: 300 µs (RF); 110 µs (Beam)
Effective Shunt Resist.: 36 MΩ/m
Filling Time: -
RF Power Input Peak: 10 MW **Mean:** 0,002 MW

Focusing System
No. Quads: 131 **Type:** Pulsed **Order:** FD
Gradients: 100 to 20 T/m
Other: Pulse flat top ~ 220 µs

Vacuum System

Material Chamber:	Copper (Accelerating Tanks)
Average Pressure:	$2 \cdot 10^{-7}$ torr
Pumps (No., Type, Speed):	10 Ionisation Pumps each 1000 ls^{-1}

Published Articles Describing Machine

"The New CERN 50 MeV Linac", Proc. 1979, Linear Accel. Conf. (Montauk, Sept 1979)
"Performance of the New CERN 50 MeV Linac", Proc. 1979, Particle Acceleretor Conf., IEEE Trans. NS-26 No. 3, p 3674.
Ancillary Systems described in Proc. 1979 Linac Conf. (Ibid.) and Proc. 1976 Linac Conf. (AECL-5677)

ACCELERATOR PERFORMANCE[3]

	Normal (or Goal)	Maximum Achieved
Output Energy (MeV):	50	-
Energy Spread ΔE/E (%):	± 0,25	-
Current (mA):	125	150

Emittance: 5 π mm·mrad (Emittance = Area xβγ at 90% current)

Other Relevant Parameters or Notable Features

1) 3 Accelerating Tanks 0,75 – 10,4 – 30,5 – 50,0 MeV of Dia. 0,94 m, 0,90 m, 0,86 m resp.
2) Post Coupled Alvarez Accelerating System: Equilibrium Phase -35° to -25° (Tank I), -25° (rest); RF parameters quoted are total or mean for 150 mA accelerated current at 1pps.
3) Performance is quoted after debunching (85 m).

Recent Improvement or Modification to Machine

-

Name of Synchrotron: Proton Synchrotron Booster (PSB, four rings stacked vertically)
Injection for: CPS
Location: CERN, Geneva, Switzerland
Person in Charge: K. H. Reich **Date:** -
Data Supplied by: K. H. Reich, K. Schindel

HISTORY AND STATUS
Construction Started (date): January 1968
First Beam Obtained, or Goal (date): May 1972
Total Cost of Facility: 60 MFr. (Swiss)
Funded by: CERN Member State
Total Accelerator Staff (now): ~ 50
Annual Operating Budget: 1.7 Mfr. (without salaries)
Annnual Operating Time: 6300 h
"Beam On": 98,4% of scheduled time

ACCELERATOR PARAMETERS
General
Accelerated Particles: Protons
Energy: 0,8 GeV
Ring Diam.: 50 m **Tunnel Sect. (W×H):** 4,05 × 5,15 m

Injector
Type: New CPS Linac
Output (Max): 140 mA at 50 MeV
Emittance: H: 7; V: 7 π mm·mrad (Emittance = Area xβγ at 90% current)
Injection Period: Up to 100μs, or 4 × 15 turns
Inflector Type: Magnetic

Magnet System
Focusing Type: A. G. Sep. Func. **Filed index:** n= -
Focusing Order: $L_1/2 – B – L_2 – F – L_3 – D – L_3 – F – L_2 – B – L_1/2$
Betatron Freq.: υ_H: 4,30 → 4,17; υ_V: 5,45 → 5,23
No. Magnets: 32 **Length (ea):** 1,62 m
Bending Field: At inj.: 0,1254 T; at max: 0,5920 T
No. Quads 16/32 (D/F) **Lenght (ea):** 0,88/0,50 m
Grad.: At inj.: 0,81 T/m; at max: 3,83 T/m
No. Short Straight Sect.: 64 **Length:** 0,37/0,65 m
No. Long Straight Sect.: 16 **Length:** 2,65 m
Rise Time: 0,6 s **Flat Top Time:** 0,06 s
Power Input Peak: 5,6 MW **Mean:** 1,64 MW

Acceleration System
No. Cavities: 1 per ring **Length (ea):** 2,22 m
Harmonic Number: 5
RF Range: 2,997 to 8,033 MHz
Energy Gain: 1 keV/turn
Radiation Loss: -
RF Power Input Peak: 4 × 7,5 kW **Mean:** 4 × 4 kW

Vacuum System
Material of Vac. Chamber: Inconel 750, 316 L
Aperture of Vac. Chamber: 132 × 61 (bending) mm
Average Pressure 10^{-8} torr
Pumps (No., Type, Speed): 58 sputter ion – 400 *l*/sec, 22 mech, 250 m^3/h, 3 TI-subl. 4000 *l*/sec

Extraction System
Type: Fast. Vertical recombination of beams from the four rings

Length of Spill: 2,5 μs

Published Articles Describing Machine

The CERN PS Booster, a flexible and reliable injector, the PSB staff (reported by K. H. Reich, V All-Union Acc. Conf. Dubna 1976, Vol. 2, p.221, and references quoted.

Beam dynamics experiments in the PS Booster, J. Gareyte, L. Magnani, F. Pedersen, F. Sacherer, K. Schindl, IEEE, NS-22, No. 3 (1975), p. 1855-1858.

ACCELERATOR PERFORMANCE

	Normal (or Goal)	**Maximum Achieved**
Energy (GeV):	0,8	-
Resolution ΔE/E (%):	± 0,19	-
Repet. Rate (pulse/s):	0,83	-
Pulse Width at Peak E:	4 × 0,622 μs	-
Duty Factor, Macroscopic (%):	2×10^{-4}	-
Internal Beam (part/pulse):	1×10^{13}	-
(part/s):	$0{,}83 \times 10^{13}$	-

Beam Emittance: H: 55, V: 28 π mm·mrad (Emittance = Area xβγ at 90% current)

Beam Lines to: CPS, measurement line

Other Data: -

Other Relevant Parameters or Notable Features

-

Recent Improvement or Modification to Machine

-

Name of Synchrotron: CERN Proton Synchrotron (CPS). See Linac I, Linac II, PSB, AA and LEAR.
Institution: European Organization for Nuclear Research
Location: Meyrin, CH-1211 Geneva 23, Switzerland
Person in Charge: G.L. Munday **Date:** March 1980
Data Supplied by: E. Brouzet

HISTORY AND STATUS
Construction Started (date): 1955
First Beam Obtained, or Goal (date): Novembre 24, 1959
Total Cost of Facility: 200 MSFr. (1954 – 1959)
Funded by: CERN Member State
Total Accelerator Staff (now): 117
Annual Operating Budget: 6.8 MSw.Fr. (without salaries)
Annnual Operating Time: 6300 h
"Beam On": 96% of scheduled time

ACCELERATOR PARAMETERS
General
Accelerated Particles: Protons
Energy: 26 GeV
Ring Diam.: 200 m **Tunnel Sect. (W×H):** 6 × 6 m

Injector
Type: Linac or Booster
Output (Max): 150/1280 mA at 50/800 MeV
Emittance: H: 8; V: 8 / H: 55; V: 28 π mm·mrad (Emittance = Area xβγ at 90% current)
Injection Period: 20/2,5 μs, or 3/1 turns
Inflector Type: Electrostatic dc and pulsed magnetic kicker or septum and pulsed kicker

Magnet System

Focusing Type:	A. G.	**Filed index:**	n=288
Focusing Order:	FOFDOF		
Betatron Freq.:	υ_H: 6,25; υ_V: 6,25		
No. Magnets:	100	**Length (ea):**	4,26 m
Bending Field:	At inj.: 0,0147 T; at max: 1,4 T		
No. Quads	-	**Lenght (ea):**	-
Grad.:	-		
No. Short Straight Sect.:	80	**Length:**	1,6 m
No. Long Straight Sect.:	20	**Length:**	3 m
Rise Time:	0,7 s	**Flat Top Time:**	0,5 – 0,7 s
Power Input Peak:	41 MW	**Mean:**	2,8 MW

Acceleration System

No. Cavities:	11	**Length (ea):**	-
Harmonic Number:	20		
RF Range:	2,8 to 9,55 MHz		
Energy Gain:	220 keV/turn		
Radiation Loss:	-		
RF Power Input Peak:	100 kW	**Mean:**	50 kW (with beam)

Vacuum System
Material of Vac. Chamber: Austenitic steel
Aperture of Vac. Chamber: (146 × 70) (178 × 67) mm
Average Pressure 2×10^{-8} torr
Pumps (No., Type, Speed): 136 ion pumps (200 *l*/s ÷ 400 *l*/s)

Extraction System

Type:	Fast Extraction (FE). Slow Extraction (SE). Radial Shaving on several turns.
Length of Spill:	0,1 to 2,1µs 300 to 500ms 6,3 to 21µs

Published Articles Describing Machine

- E. Regenstreif, CERN 59-29, CERN 60-26, CERN 62-3.
- Y. Baconnier et al., VIIth Int. Conf. On High Energy Acc., Erevan, 1969, pp 565-575.
- PS Staff, Ixth Int. Conf. On High Energy Acc., Stanford, 1974.
- PS Staff, All Union Acc. Conf., Moscow, 1974.
- PS Staff, VIIth Nat. Acc. Conf., Chicago, 1977.
- PS Performance Committee, Xth Int. Conf. On High Energy Acc., Serpukhov, 1977.
- R. Gouiran, Vith Int. Conf. On Magnet Technology, Bratislava, 1977.

ACCELERATOR PERFORMANCE

	Normal (or Goal)	Maximum Achieved
Energy (GeV):	26	28
Resolution ΔE/E (%):	± 0,05	-
Repet. Rate (pulse/s):	0,5	1
Pulse Width at Peak E:	2,1 µs	-
Duty Factor, Macroscopic (%):	10^{-4}	-
Internal Beam (part/pulse):	$1 - 15 \times 10^{12}$	18×10^{12}
(part/s):	5×10^{12}	15×10^{12}

Beam Emittance: H: 60, V: 30 π mm·mrad (Emittance = Area xβγ at 90% current)

Other Data: -

SECONDARY BEAMS

Particle	Momentum Range	No. of Beams	Other Inform.
$\bar{p}$	< 1,5 GeV/c	1	Electrostatic septum (SE, East Hall)
$\bar{p}$	≤ 1,0 GeV/c	2	
π, p	3 – 14 GeV/c	1	
π^+	≤ 2,5 GeV/c	1	
p,	≤ 18 GeV/c	1	
p, π	≤ 2,0 GeV/c	2	(FE) South Hall, int. target operation for tests
p, π	≤ 4,5 GeV/c	1	
p, π	≤ 13 GeV/c	1	

RESEARCH PROGRAMME

Total Experimental Areas:	2: $(4+2,8)\cdot10^3$ m^2
No. Internal Targets:	1 — **No. Ext. Targets:** 5 – 6
No. Separated Beams:	4
No. Beams Served At Same Time:	all
Total Power Used (Average) for Research:	6 – 8 MW
No. User Groups:	-
Total Research Staff:	-
Ann. Research Budget:	-
Annual Research Time:	5600 h

Other Relevant Parameters or Notable Features

In normal operation, several kinds of beams are accelerated from pulse to pulse:

- 1,5 to 1,7 10^{13} ppp for SPS
- 3×10^{12} ppp for ISR
- 6×10^{12} ppp for slow extraction
- other beams for machine studies.

The longitudinal emittance is adjustable between 8 and 80 mrad.

Recent Improvement or Modification to Machine

- Several turns extraction for SPS (10 – 5 or 3) with prebunching at 200 MHz to allow bunch-into-bucket injection in SPS
- Vertical and longitudinal recombination of the 20 Booster bunches, resulting in more than 10^{13} ppp in 5 bunches for antiproton production
- RF modification to accelerate the antiprotons from 3,5 GeV/c up to 26 GeV/c on harmonic 6, and to decelerate them from 3,5 GeV/c down to 0,6 GeV/c on harmonic 10
- Deceleration from 800 MeV down to 46 MeV for studies in ICE
- Deuterons a..d alpha particles acceleration for ISR
- Ultraslow extraction (stochastic)
- Adjustment of the working point and chromaticities all along the acceleration, by means of 3 current poleface winding system.

Name of Synchrotron: Super Proton Synchrotron (SPS)
Institution: CERN
Location: Prévessin (France)
Person in Charge: G. Brianti **Date:** April 1980
Data Supplied by: E. de Read

HISTORY AND STATUS
Construction Started (date): February, 1970
First Beam Obtained, or Goal (date): May, 1976
Total Cost of Facility: 625 MSF (in 1970 SF)
Funded by: 12 Member State
Total Accelerator Staff (now): 500
Annual Operating Budget: 45 MSF (without salaries)
Annual Operating Time: 5500 h
"Beam On": 85% of scheduled time

ACCELERATOR PARAMETERS
General
Accelerated Particles: Protons
Energy: 400 GeV
Ring Diam.: 2200 m **Tunnel Sect. (W×H):** 4 × 3 m

Injector
Type: Proton Synchrotron
Output (Max): 250 mA at 10000 MeV
Emittance: 30 π mm·mrad (Emittance = Area xβγ at 90% current)
Injection Period: 2 × 11,5 μs, or 2 × ½ turns
Inflector Type: Fast kicker

Magnet System
Focusing Type: Sep. function **Filed index:** -
Focusing Order: FODO
Betatron Freq.: υ_H: 26,6; υ_V: 26,6
No. Magnets: 744 **Length (ea):** 6,26 m
Bending Field: At inj.: 0,045 T; at max: 1,8 T
No. Quads 216 **Lenght (ea):** 3,05 m
Grad.: At inj.: 0,05 T/m; at max: 20 T/m
No. Short Straight Sect.: 216 **Length:** 2,3 m
No. Long Straight Sect.: 6 **Length:** 128 m
Rise Time: 3 s **Flat Top Time:** 2 s
Power Input Peak: 130 MW **Mean:** 40 MW

Acceleration System
No. Cavities: 4 **Length (ea):** 20 m
Harmonic Number: 4620
RF Range: 199,4 to 200,2 MHz
Energy Gain: 3000 keV/turn
Radiation Loss: -
RF Power Input Peak: 1500 kW **Mean:** 500 kW

Vacuum System
Material of Vac. Chamber: Stainless steel
Aperture of Vac. Chamber: 150 × 50 mm
Average Pressure 10^{-8} torr
Pumps (No., Type, Speed): 500 sputter-ion pumps 35*l*/s

Extraction System

Type:	Fast
	Slow resonant
	Slow 1/3 Int. resonance
Length of Spill:	5 to 23µs
	1000 to 5000 µs
	0,5 to 2 s

Published Articles Describing Machine

CERN/1050, 14 January, 1972

ACCELERATOR PERFORMANCE

	Normal (or Goal)	Maximum Achieved
Energy (GeV):	400	450
Resolution ΔE/E (%):	± 0,1	± 0,05
Repet. Rate (pulse/s):	0,1	0,1
Pulse Width at Peak E:	2	2
Duty Factor, Macroscopic (%):	20	20
Internal Beam (part/pulse):	2×10^{13}	$2{,}5 \times 10^{13}$
(part/s):	2×10^{12}	$2{,}5 \times 10^{12}$

Beam Emittance: 50 π mm·mrad (Emittance = Area xβγ at 90% current)

Other Data: -

SECONDARY BEAMS

Particle	Momentum Range	No. of Beams	Other Inform.
υ	~ 30GeV/c	1	Wide band
υ	≤ 275 GeV/c	1	Narrow band
hadrons	≤ 200 GeV/c	2	H3, H6
hadrons	≤ 350 GeV/c	4	H2, H4, H8, H10
had. sep	≤ 40; ≤150	2	S1 ÷ S3
p	250 ÷ 450	3	P1 ÷ P4, P8
µ	≤ 280 GeV/c	1	M2
e	≤ 80; ≤ 150	3	E1 ÷ E4, E12

RESEARCH PROGRAMME

Total Experimental Areas:	~ 34000 m^2		
No. Internal Targets:	0	**No. Ext. Targets:**	14
No. Separated Beams:	2		
No. Beams Served At Same Time:	12		
Total Power Used (Average) for Research:	40 MW		
No. User Groups:	In house mixed with outside 40		
Total Research Staff:	In house 110, outside 1000		
Ann. Research Budget:	-		
Annual Research Time:	4500 h		

Other Relevant Parameters or Notable Features

-

Recent Improvement or Modification to Machine

The SPS in being modified for $p\bar{p}$ colliding beam operation.

Name of Linac:	Fermilab 200-MeV Proton Linac		
Injection for:	8-GeV Booster Synchrotron		
Location:	Batavia, Illinois		
Person in Charge:	C. D. Curtis	**Date:**	March 1980
Data Supplied by:	C. D. Curtis		

HISTORY AND STATUS

Construction Started (date):	December. 1968
First Beam Obtained, or Goal (date):	Novembre, 30, 1970
Total Cost of Facility:	$ 12,7M
Funded by:	USAEC
Total Accelerator Staff (now):	8 (part of Accel. Div.)
Annual Operating Budget:	$ 650 k (without salaries)
Annnual Operating Time:	7500 h
"Beam On":	97% of scheduled time

ACCELERATOR PARAMETERS

Physical Dimensions

Total Length:	144,8 m	**No. Tanks:**	9
Tank Diam.:	0,84 – 0,94 m	**No. Drift Tubes:**	286
Drift Tube Lenghts:	47 mm to 446 mm		
Drift Tube Diameter:	180 mm, 160 mm		
Gap/Cell Length:	0,21 – 0,47 mm		
Aperture Diam.:	20 mm to 40 mm		

Ion Source

Type:	Magnetron H^- Source	
Output :	50 mA at 18 keV	
Emittance:	-	(Emittance = Area xβγ at 90% current)

Injector

Type:	Cockroft-Walton
Output:	50 (normal) 25 – 75 mA at 750 keV
Emittance:	0,8 × 1,5 π mm·mrad (Emittance = Area xβγ at 90% current)

Bunchers

Type :	Single gap reentrant cavity		
Modulation:	~ 25 keV	**Drift:**	*l* 750 mm at 201,25 MHz

Acceleration System

RF Freq.:	201,25 MHz		
Field Mode:	TM010	**Q:**	$50 – 60 \times 10^3$
Equil. Phase	-32°	**Accel. Rate:**	1,4 MeV/m
Repetition Rate:	15		
Duty Factor:	0,2% (RF); to 0,1% (Beam)		
Pulse Length:	150 µs (RF); to 60 µs (Beam)		
Effective Shunt Resist.:	27 – 15 MΩ/m		
Filling Time:	120 (70 – 160)		
RF Power Input Peak:	35 MW	**Mean:**	0,075 MW

Focusing System

No. Quads:	295	**Type:**	Pulsed mag.	**Order:**	FDFD
Gradients:	70 to 7 T/m				
Other:	-				

Vacuum System

Material Chamber:	Copper-clad steel

Average Pressure: $5 \cdot 10^{-8}$ torr
Pumps (No., Type, Speed): 52 1000 ls^{-1} Ion pumps

Published Articles Describing Machine
Particle Accelerators 1, 51 (1970).
1968 Linear Accelerator Conf. Proceedings, BNL 50120.
1970 Linear Accelerator Conf. Proceedings.
1972 Linear Accelerator Conf. Proceedings, LA 5115.
1976 Linear Accelerator Conf. Proceedings, AECL 5677.
Proceedings of the Fourth All-Union Nat. Conf. on Part. Accelerators, Vol. I, p. 136 (Moscow, 1974).
IEEE Transactions on Nuclear Sciences, NS-18, No. 3, 517(1971).
IEEE Transactions on Nuclear Sciences, NS-26, No. 3, 3760(1979).
IEEE Transactions on Nuclear Sciences, NS-26, No. 3, 4120(1979).

ACCELERATOR PERFORMANCE

	Normal (or Goal)	Maximum Achieved
Output Energy (MeV):	201	-
Energy Spread ΔE/E (%) :**	0,35	-
Current (mA):	35	46

Emittance: 4 π mm·mrad at 35 mA (Emittance = Area xβγ at 90% current)

Other Relevant Parameters or Notable Features
** Energy spread adjustable to optimize performance of a three-cell debuncher, with reduces the energy spread at the input of the booster synchrotron.
The linac now delivers only H^- beam, which is time shared between high energy physics, cooling ring experiments and neutron cancer therapy.

Recent Improvement or Modification to Machine
The major modification in the last few years involved the switch over in March, 1978, to a negative ion source for routine operation to provide multiturn injection into the booster via a carbon stripping foil.
In the period from 1975 to 1978, high current duoplasmatron sources were used to provide short linac beam pulses of 150 to 300 mA for a single-turn injection into the booster.

Name of Synchrotron:	Fermilab 8-GeV Booster		
Injection for:	Fermilab 400-GeV Synchrotron		
Location:	Batavia, Illinois 60510		
Person in Charge:	C. W. Owen	**Date:**	March 1980
Data Supplied by:	B. C. Brown, J. R. Lackey, C. W. Owen		

HISTORY AND STATUS

Construction Started (date): 1969
First Beam Obtained, or Goal (date): 1971
Total Cost of Facility: $ 17 M
Funded by: USAEC
Total Accelerator Staff (now): Part of FNAL Accel. Div.
Annual Operating Budget: -
Annnual Operating Time: 4800 h
"Beam On": 96% of scheduled time

ACCELERATOR PARAMETERS

General

Accelerated Particles:	Protons		
Energy:	8 GeV		
Ring Diam.:	151 m	**Tunnel Sect. (W×H):**	3 × 2,4 m

Injector

Type: Linac (Negative Ions)
Output (Max): 46 mA at 201 MeV
Emittance: 3,8 π mm·mrad at 35 mA (Emittance = Area xβγ at 90% current)
Injection Period: 2,8 μs/turn, or 1× 20 turns
Inflector Type: Injection w/orbit bump & Stripper foil (Charge Exchange Injection)

Magnet System

Focusing Type:	Alternating Gradient	**Filed index:**	n= -
Focusing Order:	FOFDOOD		
Betatron Freq.:	υ_H: 6,72; υ_V: 6,78		
No. Magnets:	96	**Length (ea):**	3,04 m
Bending Field:	At inj.: 0,0490 T; at max: 0,67 T		
No. Quads	-	**Lenght (ea):**	-
Grad.:	-		
No. Short Straight Sect.:	24	**Length:**	1,2 m
No. Long Straight Sect.:	24	**Length:**	6 m
Rise Time:	-	**Flat Top Time:**	Biased 15 Hz sinusoid
Power Input Peak:	1,8 MW	**Mean:**	1,3 MW

Acceleration System

No. Cavities:	18	**Length (ea):**	2,4 m (140° Electrical)
Harmonic Number:	84		
RF Range:	30 to 52,8 MHz		
Energy Gain:	800 (peak) keV/turn		
Radiation Loss:	-		
RF Power Input Peak:	~ 1800 kW during acceleration cycles	**Mean:**	~ 500 kW

Vacuum System

Material of Vac. Chamber: Epoxy impregnated, laminated steel magnets in stailess steel envelope.
Aperture of Vac. Chamber: Chamber enclose magnets
Average Pressure 5×10^{-7} torr
Pumps (No., Type, Speed): 60, Ion Pumps, 600 *l*/sec plus roughing system in the synchrotron proper.

Extraction System

Type: Single turn, fast kicker and magnetic septum
Length of Spill: 1,6 μs

Published Articles Describing Machine

Reviews:

- B. C. Brown and C. Hojvat, Fermilab Memo FN-317 or Proceedings of the Kaon Factory Workshop, Ed. M. K. Craddock TRIUMF TRI-79-1, p. 178.
- E. L. Hubbard, Ed., Fermilab Memo TM-405 (unpublished).

Articles in Proceedings of Particle Accelerator Conference:

- IEEE Trans. On Nuclear Science for associate years.
- NS-26 (1979) p. 3149, 3173, 3337, 3373, 3586, 3953, 3974, 4009, 4061, 4111.
- NS-24 (1977) p. 1263, 1282, 1423, 1449, 1455, 1561, 1698, 1768, 1770, 1830.
- NS-22 (1975) p. 1234, 1283, 1242, 1458, 1897, 1900, 1904.
- NS-20 (1973) p. 351, 409, 404, 570, 863.
- NS-18 (1971) p. 244, 246, 424, 427, 654, 978, 979, 989, 991.
- NS-16 (1969) p. 510, 969.

ACCELERATOR PERFORMANCE

	Normal (or Goal)	**Maximum Achieved**
Energy (GeV):	8	10
Resolution ΔE/E (%):	0,1	-
Repet. Rate (pulse/s):	15	-
Pulse Width at Peak E:	1,6 μs	-
Duty Factor, Macroscopic (%):	-	-
Internal Beam (part/pulse):	-	$3,0 \times 10^{12}$/p
(part/s):	-	$4,5 \times 10^{13}$/s

Beam Emittance: -

Beam Lines to: 1 beam line to Fermilab 400 GeV PS

Other Data: -

Other Relevant Parameters or Notable Features

-

Recent Improvement or Modification to Machine

- Conversion to charge exchange injection
- RF, Extraxtion & magnet power supply upgrade for 10 GeV operation
- (vertical) bunch to bunch super dampers
- Improved low level Rf system