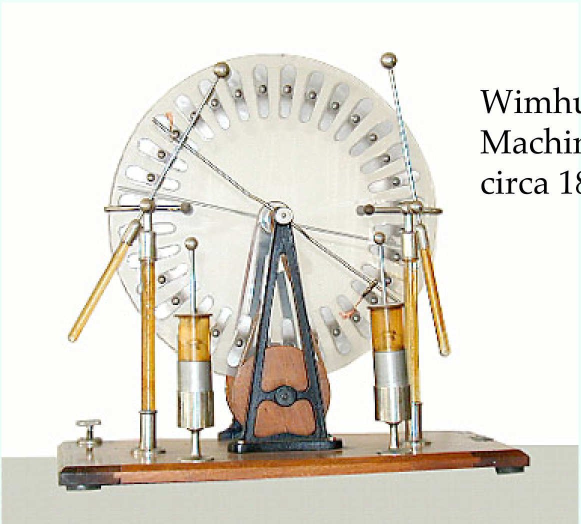
Short History of Particle Accelerators

The pre-history : generation of electric potential differences

1775 Volta's electrophorus

B. Le Roy type machine

II half 18th century



Wimhurst Machine circa 1880

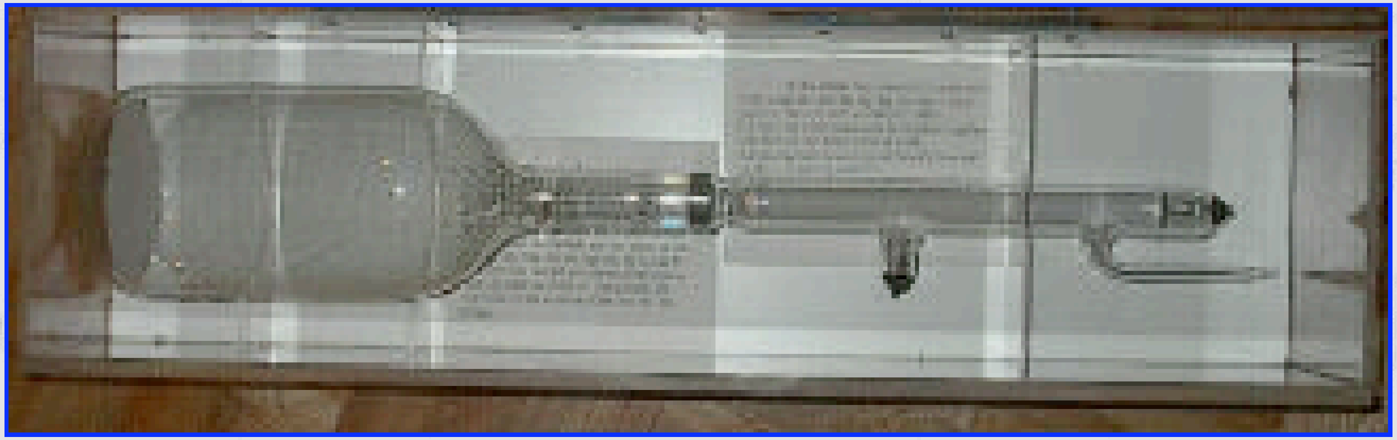
≈ few tens *KV*

Winter machine

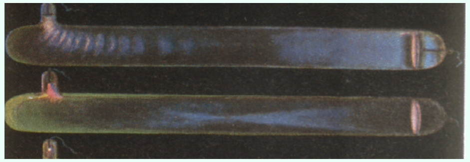
mid 19th century

1897

Ferdinand Braun Cathode Ray Tube



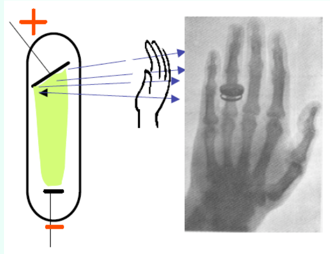
Utilization of voltage generators → Discoveries



1879 **W. Crookes** : Discharges in gas:

1845-1923

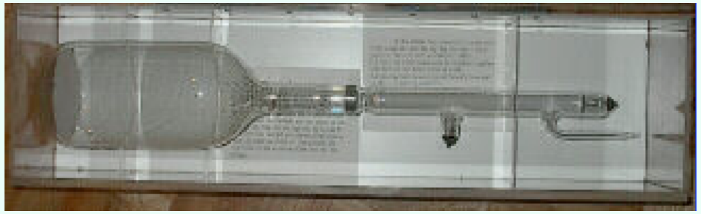
1895 **W.C. Röntgen** discovers X-ray production in discharge tubes when sufficiently high voltage is applied.



1896 **A.H. Bequerel** discovers radioactivity (of U), further studied by **Pierre** and **Marie Curie** .

1850-1918

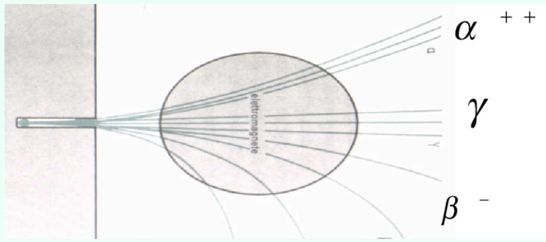
1897 **F. Braun** builds cathodic ray tube



1897 **J.J. Thompson** measures the ratio q/m of cathodic rays : they are **electrons**

1900 **E. Rutherford** finds there are different species of radioactive products :

α : He nuclei
β : electrons
γ : neutral (e.m.) radiation



1904 What do we know.......

First we must ask what is positive electricity and the answer is still we do not know ……….

But concerning negative electricity we know a great deal more.

This exists in excessively minute particles, sometimes called electrons and sometimes called corpuscles: these are thrown off the negatively charged terminal in a vacuum tube, and they fly with tremendous speed till they strike something. When they strike they can propel as well as heat the target, and they can likewise make it emit a phosphorescent glow: especially if it be made of glass or precious stones. If the target is a very massive metal like platinum, the sudden stoppage of the flying electrons which encounter it causes the production of the ethereal pulses known as X-rays. Electrons are not very easy to stop however; and a fair proportion of them can penetrate not only wood and paper, but sheets of such metals as aluminum, and other moderately thin obstacles. That is because they are extremely small, much smaller than the atoms of matter.

If a magnet be brought near a stream of flying electrons they are deflected by the magnetic force, as a rifle bullet is deflected by a wind; they will then miss the target at which they were aimed, and nay strike another. By measuring their deflection when their speed is known it is possible to estimate the mass of each particle; and if any stream consisted of particles of different masses it would be possible thus to sort or fan or winnow them out: the massive ones keeping nearly straight and the lighter ones being blown aside, somewhat as a cork projectile is more easily deflected than a bullet.

Determinations made in this sort of way, supplemented by many other refined and most ingenious measurements conducted in the Cavendish Laboratory, Cambridge, England, have resulted in the following knowledge:.........

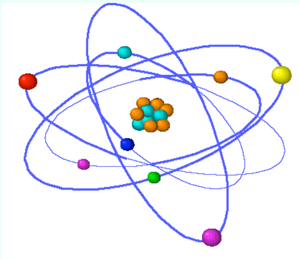
O.Lodge, *Harper Magazine 1904*, http://www.oneillselectronicmuseum.com/index.html

X-ray tubes

Villard Tube (1898-1905)

http://www.orau.org/ptp/collection/xraytubes/x-raytubes.htm

Physics motivations for man-made accelerators



1 913 H.Geiger & E. Marsden, working under E. Rutherford, show, by bombarding atoms with 5 to 10 MeV α particles, that they have a massive nucleus, very small compared to the atom size but not pointlike ($r \approx 3 \cdot 10^{-12}\ m$) .

According to the indetermination principle, to probe the inside of a nucleus of that size one needs a probe particle with energy >> than $E \approx \hbar c/(\beta \cdot r) \approx 70/\beta\ KeV$

A rough classical calculation shows that an α particle needs a kinetic energy of about 3 MeV to just overcome the Coulomb barrier of a $_3Li^7$ nucleus.

1 927 E. Rutherford says, addressing the Royal Society :"... *if it were possible in the laboratory to have a supply of electrons and atoms of matter in general, of which the individual energy of motion is greater even than that of the alfa particle, ... this would open up an extraordinary new field of investigation....*"

But bright sources with such energies were not yet available: man-made devices, mainly built as earlier seen, to produce X-rays, operated at the time in the hundred KV range.

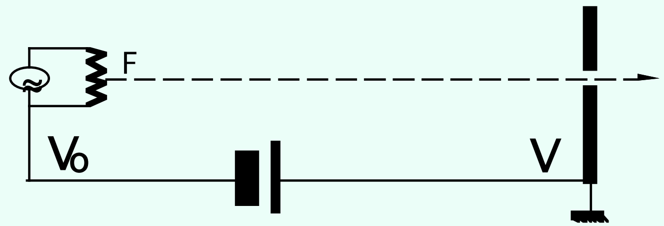
1929 G. Gamow shows that in quantum mechanics there exists a finite probability for lower than 1 MV energy particles to tunnel through the Coulomb barrier of light nuclei. This encouraged J. Cockroft and E. Walton, E. Rutherford's collaborators, to start studying methods to accelerate a particles beam to energies of hundreds of KV. They finally produced, in 1932, what is believed to be **the first true particle accelerator**, delivering a **400 KV collimated beam**.

E. Rutherford, Proc. Roy. Soc., **A97**, 374 (1920) dbserv.ihep.su/~elan/src/rutherford20/eng.pdf

Principle of electrostatic accelerators

The simplest method to accelerate charged particles ::

Charged particles produced by a source (elettroni from a hot filament, protons produced by stripping H atoms, ...) are accelerated across a **static** potential difference ΔV



The particle kinetic energy gain is $\Delta T = q\,\Delta V$

Because $\text{rot}\,\vec{E} = 0 \longrightarrow \oint \vec{E}\cdot d\vec{s} = 0$

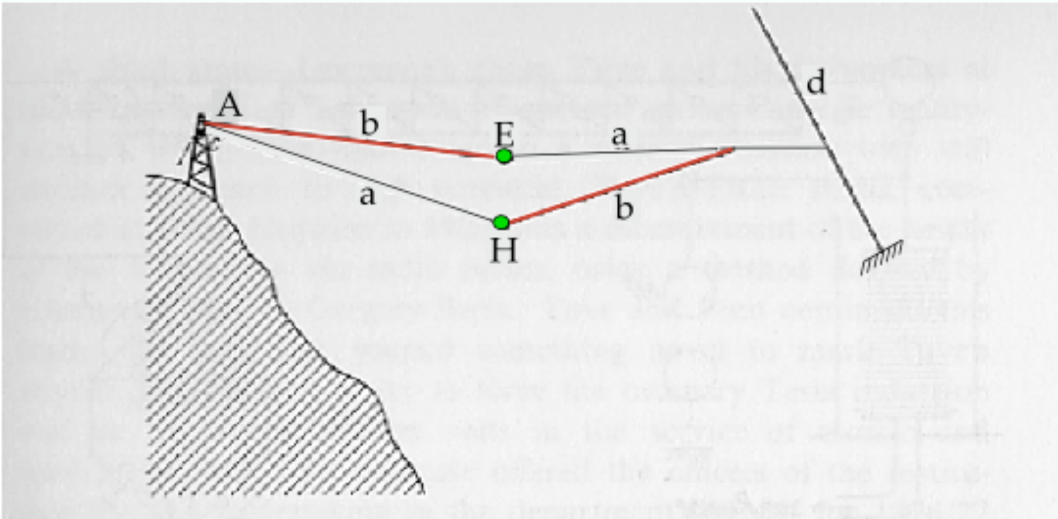
one pass only

Highest possible energy gain → **Highest possible ΔV**

First, impulsive, high voltages

A curious example:

1928-1930 - **C. Urban, A.Brasch** and **F.Lange,** experimenting in the italian Alps, succeeded in using potential differences between storm clouds and ground to produce huge voltage drops between two suspended spheres:



Brash and Lange's lightning catcher. E and H are the spheres between which the discharge occurs; AE, the antenna; a,a, insulators; b,b, conductors; d, a grounded wire. A.Brash and F.Lange, *Zs. F. Phys.,70 (1931), 17*

The experiments were dangerous: in their course C. Urban was killed by lightning

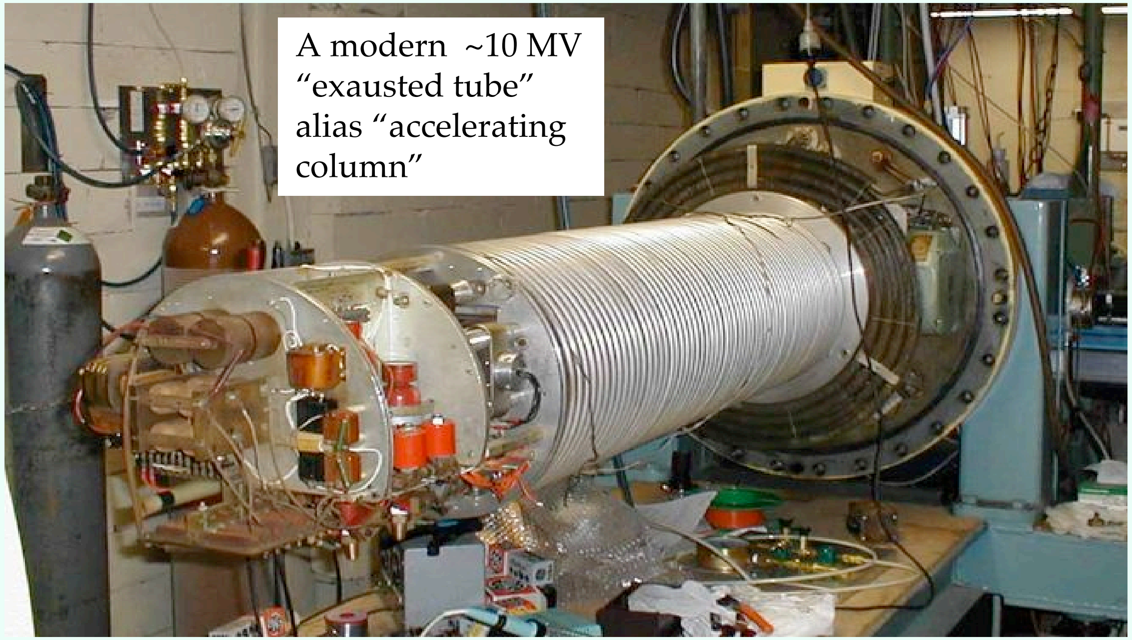
About physics needs and electrostatic accelerator technology

Energy is crucial but <u>not the only requirement</u>….

1930 E. Rutherford farsightedly says :

"What we require is an apparatus to give us a potential of the order of 10 million volts which can be <u>safely</u> accomodated in a reasonably sized room and operated at a few kilowatts of power.
We require too <u>an exausted</u> (*evacuated*) <u>tube capable of withstanding this voltage</u>…….I see no reason why such requirements can not be made practical."

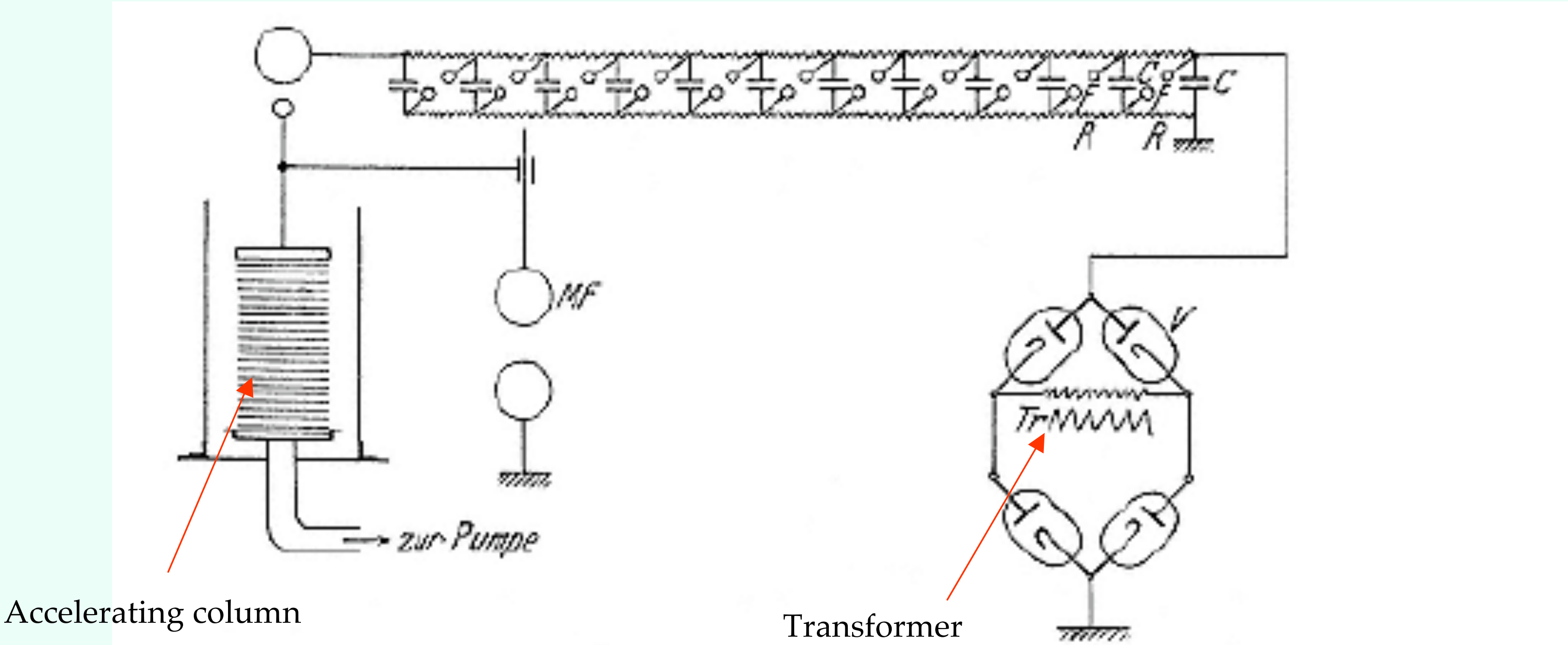
http://content.cdlib.org/xtf/view?docId=ft5s200764&chunk.id=d0e2505&toc.depth=1&toc.id=d0e2505&brand=ucpress



A modern ~10 MV "exausted tube" alias "accelerating column"

Next Brash and Lange impulsive apparatus

Spark-gap like



Voltage from the transformer multiplied by the string of capacitors discharges across evacuated laminated tube. *Zs. F. Phys.,70 (1931), 30*

http://content.cdlib.org/xtf/view?docId=ft5s200764&chunk.id=d0e2505&toc.depth=1&toc.id=d0e2505&brand=ucpress

Definition of a particle accelerator

A device that accelerates particles producing a beam that has **controllable**

- Intensity (number of particles / unit time)
- Energy
- Energy spread
- Transverse (with respect to its velocity) size
- Angular spread

The beam intensity may also be modulated in time in a controllable way.

One can say that, like for light beams, beam quality (brightness) is proportional to the ratio :

$$\text{Brightness} \propto \frac{\text{Intensity}}{\text{Transverse size} \cdot \text{Angular spread} \cdot \text{Energy spread}}$$

The first "high energy" accelerator

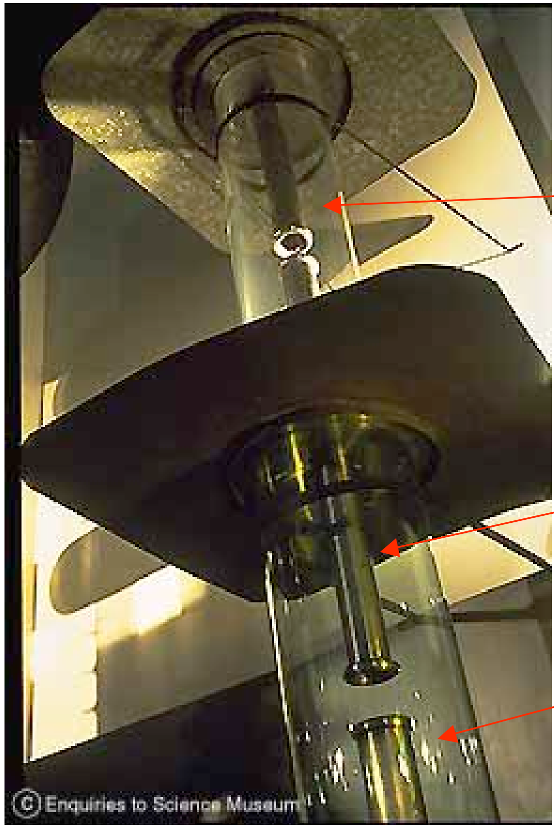
Using this device to accelerate protons produced by a discharge in H gas ,

G. Cockroft and E. Walton obtained the first nuclear transmutation via the reaction :

$$ {}_3Li^7 + {}_1H^1 \ (p) = 2 \ {}_2He^4 \ (2\alpha) $$

This earned them the Nobel Prize.

400 KV



1932

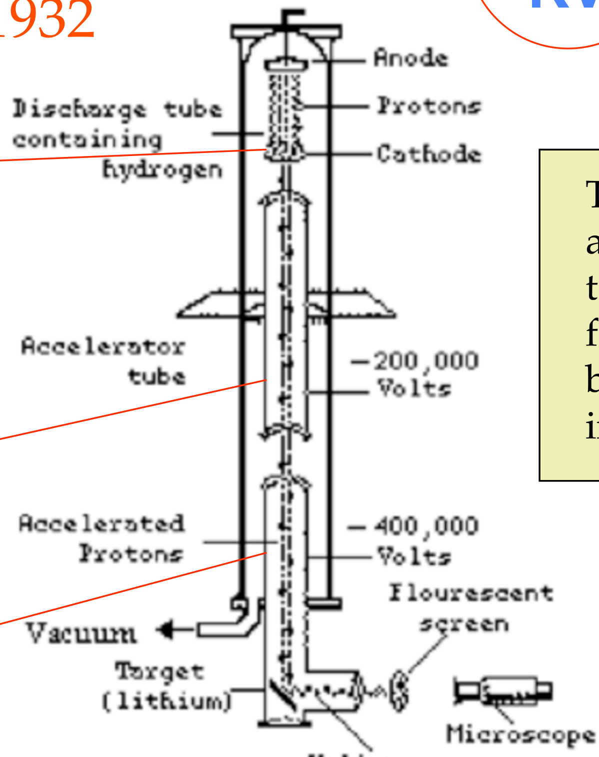


Figure 1.2

This type of accelerator takes its name from that of both its inventors

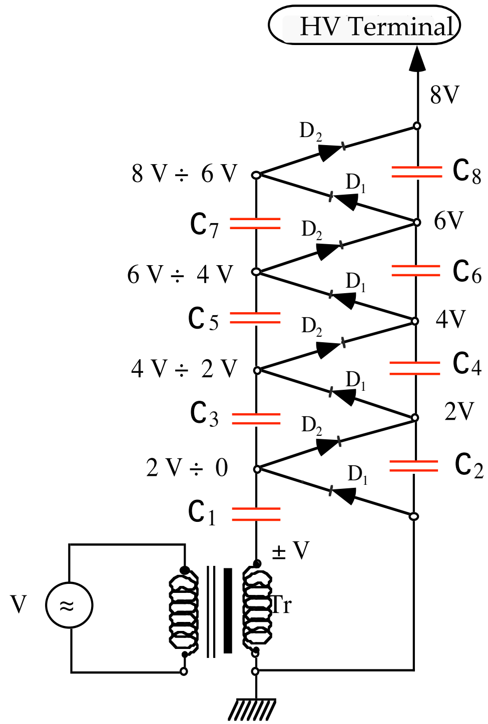
Cockroft & Walton voltage multiplier

Supplies a DC voltage.

$$V_N = 2\,N V_o - \left[\langle i \rangle / (12\, f_o C\ )\right] \cdot \left[8N^3 + 9\,N^2 + N\right]$$

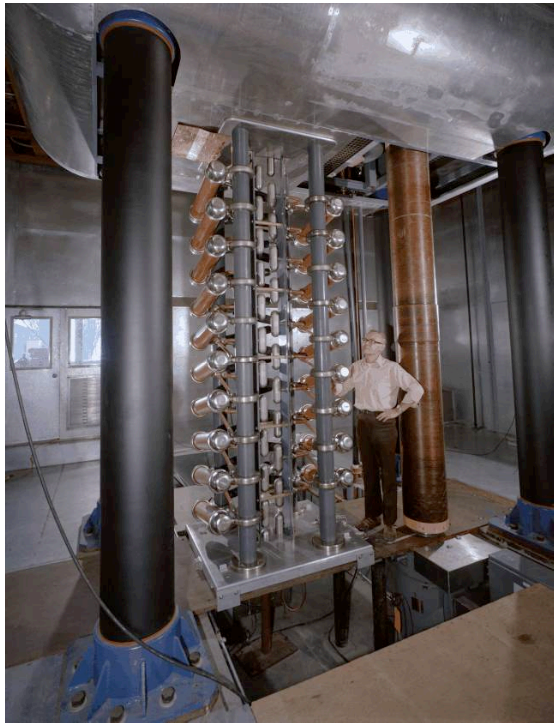
Main limitation is V ripple

$$\Delta V_N = \frac{(1/2)\ N\,(N+1)\langle i \rangle}{Cf}$$



E. Fermi - E. Amaldi first C&W
ISS, Roma, 1936-1946

Now an exibit in Frascati



C&W machine at LBL

C&W accelerators are still in use as pre-injectors into larger ion accelerators but are rapidly being replaced by smaller, e.m. type machines (RF quadrupoles)

Technology drive

Further improvement on e.s. devices voltage are essentially driven by technology of :

- **charging system**

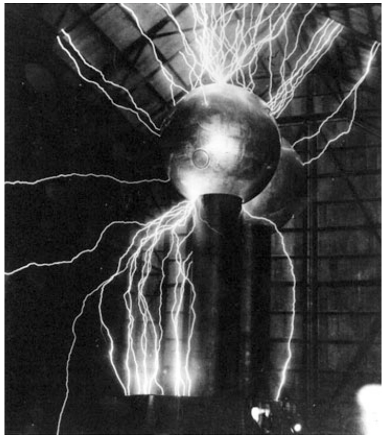
and

- **insulation**

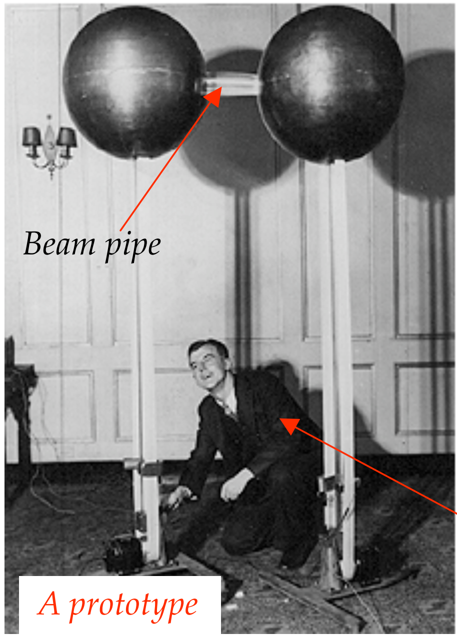
→ The **Van de Graaff** accelerator

@ M.I.T. A new idea: the first Van-de-Graaff accelerators 1931

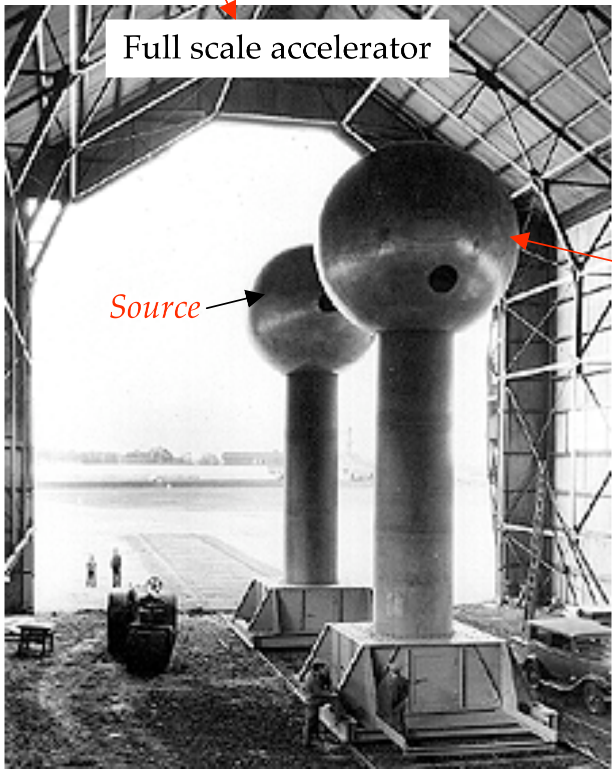
Air-insulated

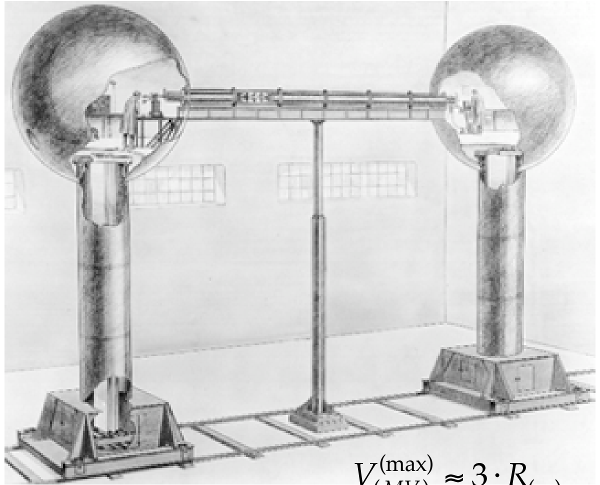


High voltage problems !



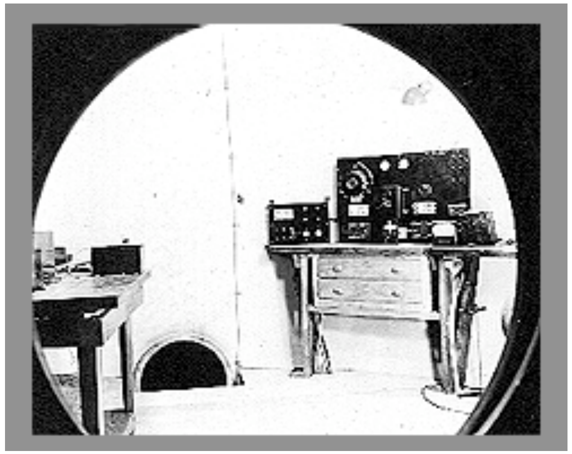
5 MV





$V^{(max)}_{(MV)} \approx 3 \cdot R_{(m)}$

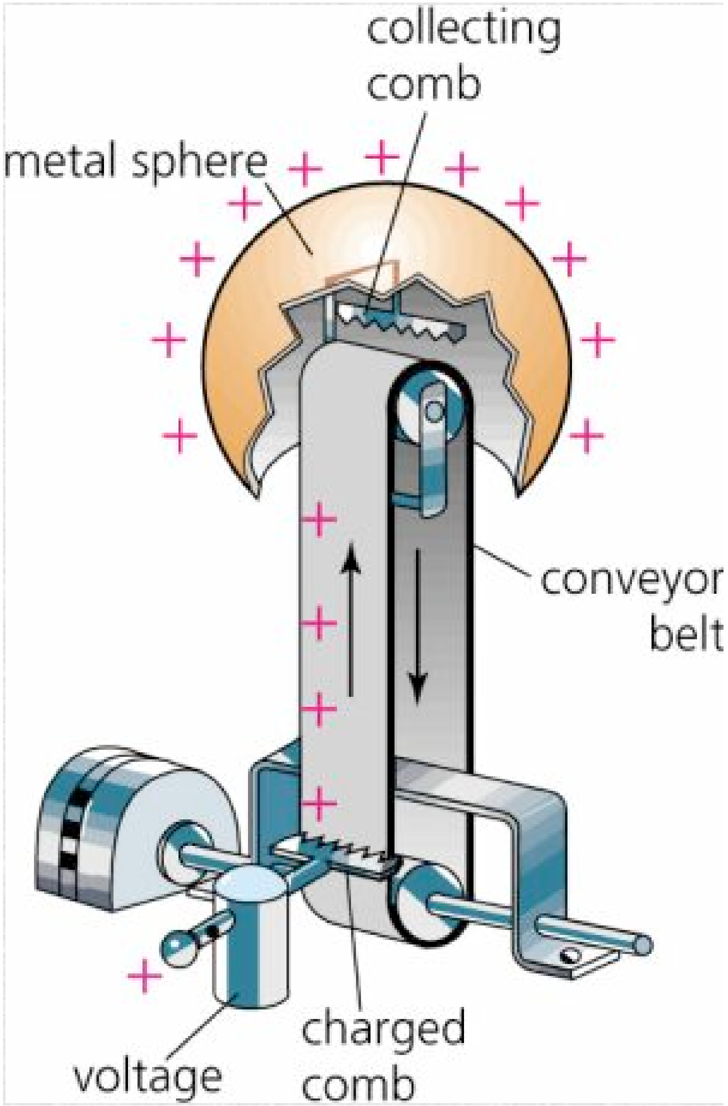
Laboratory



R. J. Van de Graaff

www.mos.org/sln/toe/history.html

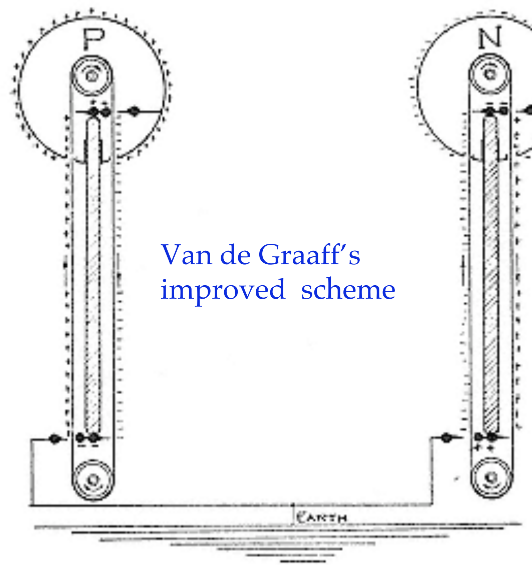
VdG charging scheme



A non conducting conveyor belt picks up charge at the low end, by corona discharge from a sharp pointed "comb" facing it and connected to a dc power supply.

The belt penetrates inside a metal sphere, where there is no electric field, and discharges through a second comb connected to the inside surface of the sphere.

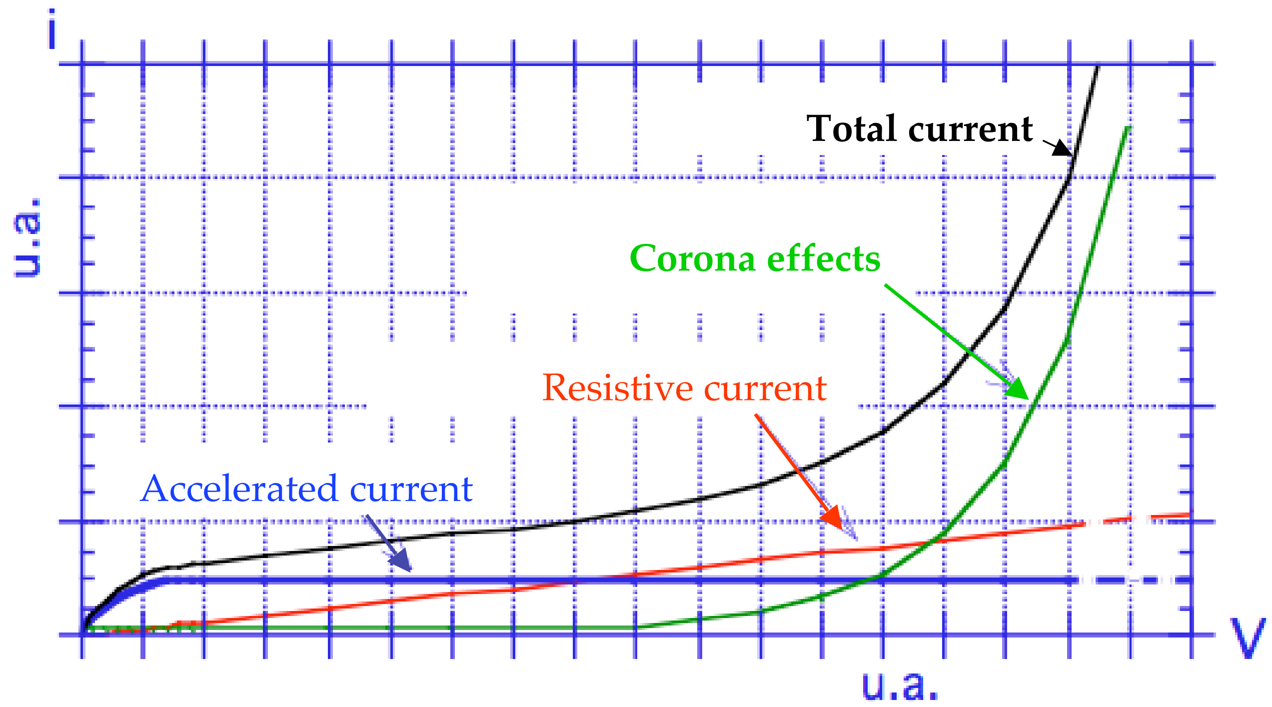
Of course the belt motor has to provide the work to bring enough charge per unit time to the top, to compensate the extracted desired beam current, plus all other current losses.



Van de Graaff's improved scheme

content.cdlib.org/xtf/view?docId=ft5s200764&chunk.id=d0e2505&toc.depth=1&toc.id=d0e2505&brand=ucpress

Van de Graaff: ultimate voltage limit



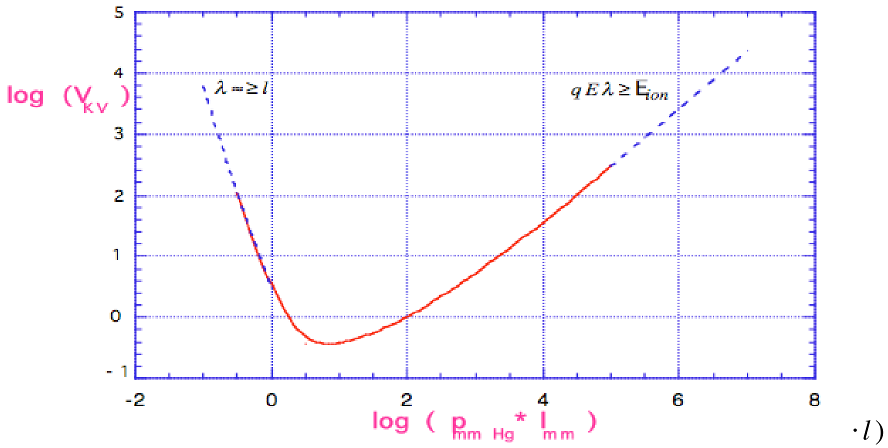
The ultimate voltage, for given radius of the terminal, is mainly determined by discharges, current losses, the power of the belt driving motor, the belt (subject to very large forces) mechanical resistance.

In practice < ~ 25 MV

Higher voltage VdGs

Pressurized

Paschen's Law: $\Delta V_{disch} = f(P \cdot l)$

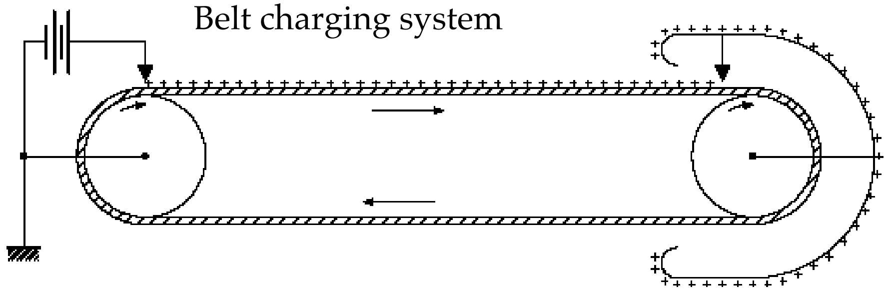


Across (infinite) parallel plates

In air $\Delta V_{disch} \approx 30 \ \ W/cm$

In SF6 @ 7 atm $\Delta V_{disch} \approx 360 \ \ W/cm$

Belt charging system



Pressure tank

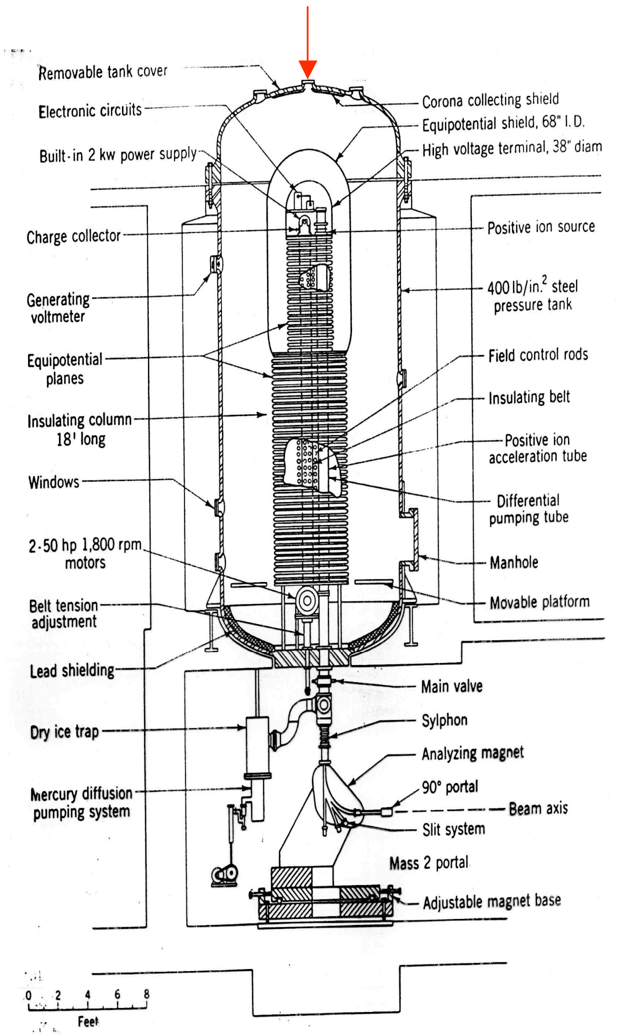
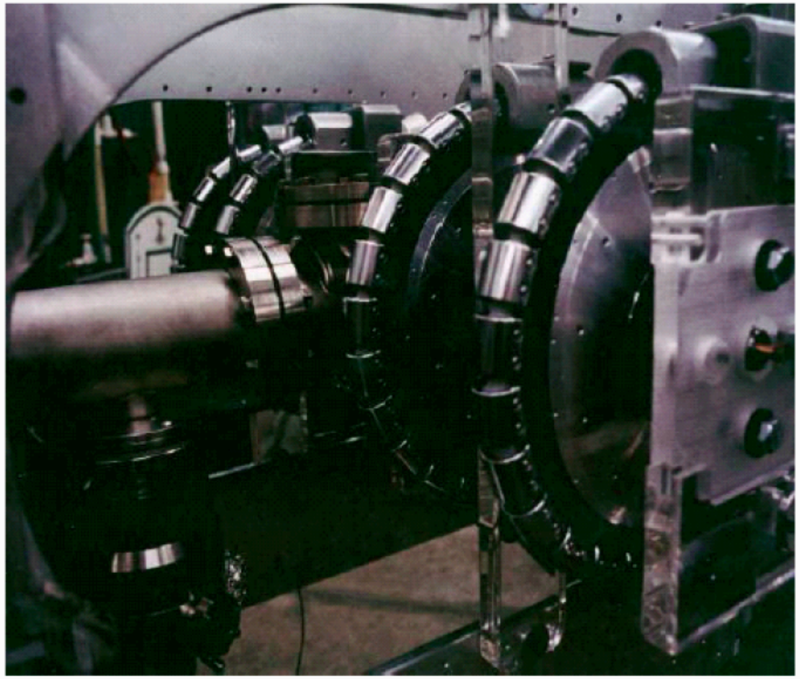


Fig. 3-15. 9-Mv electrostatic generator at MIT. (Courtesy of J. G. Trump.)

Van de Graaff charging sistems : belt, "pelletron"

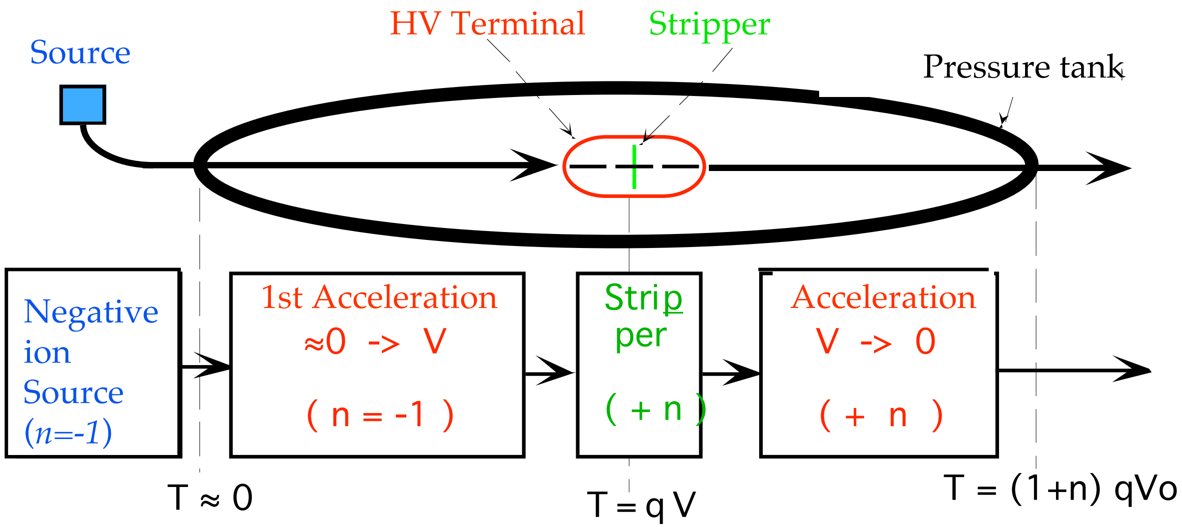
Charging belts

Pelletron Chain from NEC



Van de Graaff “Tandem” - A clever idea

A variant of the VdG, a "**Tandem**" (TVdG) allows, by using a **negative ion source**, to utilise a same terminal potential difference **twice** over (whence its name). In addition, by playing on the ion charge it can produce **ions much higher final energies** .



Negative ions with charge $-e$ are first accelerated by the positive terminal voltage V to an energy eV. They are then passed through a stripper (thin foil, gas jet,..) that strips away $n+1$ of their electrons; the positively charged ions are then again accelerated to ground potential to an energy $(n+1)\,eV$.

The stripper can be a thin foil of light material (e.g. C, Al, ..) or, more frequently, a gas jet. The latter is preferred because foils are very delicate and must be frequently replaced. Stripping efficiency is a function of material and ion energy.

E.G. : *with a 15 MV terminal voltage, Au^- ions can be stripped to a positive charge of up to $q=13$ e. Their final energy is therefore ~ (13+1)x15 MV ~200 MeV*

Tandem - Curve di stripping

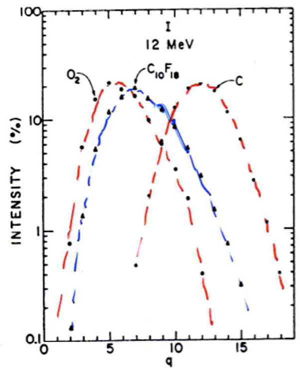


Fig. 1. Charge-state distributions for ^{127}I at 12 MeV with O_2, $C_{10}F_{18}$ and carbon foil strippers.

are shown in fig. 1 for 12 MeV I ions[9]) and in fig. 2 for 10 and 15 MeV U ions[10]). If one assumes that the charge-state distribution at equilibrium thickness is Gaussian, then according to Bell[11])

$$F(q) = (2\pi d^2)^{-\frac{1}{2}} \exp[-(q-q_0)^2/(2d^2)]. \quad (1)$$

If one takes the values of Dmitriev and Nikolaev[2])

$$d = d_1 Z^\alpha, \quad (2)$$

where $d_1 = 0.32$, $\alpha = 0.45$ for nitrogen and $d_1 = 0.38$, $\alpha = 0.40$ for carbon one obtains the curves superimposed for the carbon and oxygen cases of fig. 2. The curves are in quite reasonable agreement with the data.

For lower values of Z such as I the expression of Betz and Schmelzer[12])

$$d = 0.27 Z^{\frac{1}{2}} \quad (3)$$

is a good approximation for gases as well as solids. The charge-state distributions over the energy range useful in tandem accelerator terminals is to a good approximation energy independent. Some representative distributions are listed in table 1 and shown in fig. 3.

TABLE 1

Width of equilibrium charge-state distributions.

$q-\bar{q}$ \ Z	20	30	40	50
0	0.330	0.269	0.234	0.209
1	0.234	0.214	0.197	0.182
2	0.084	0.108	0.118	0.121
3	0.015	0.035	0.050	0.061
4	0.001	0.007	0.015	0.023
5		0.001	0.003	0.007

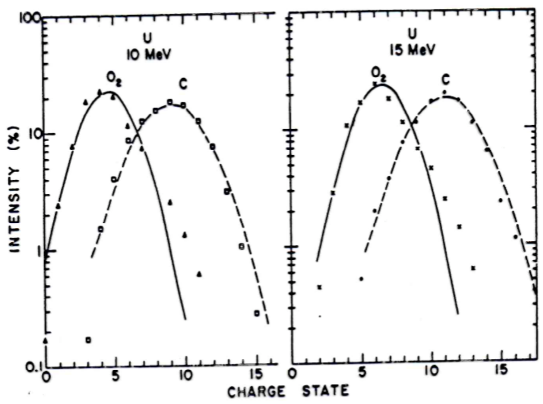


Fig. 2. Charge-state distributions for U ions at 10 and 15 MeV for O and C strippers together with distribution curve calculated from eqs. (2) and (1). The O_2 curve is shown with the parameters listed for N_2 in the text.

TABLE 2

Average charge state of heavy ions stripped by O and C foils.

E (MeV)	^{32}S gas	^{32}S foil	^{35}Cl gas	^{35}Cl foil	^{79}Br gas	^{79}Br foil	^{127}I gas	^{127}I foil	^{238}U gas	^{238}U foil
8	5.1	7.45	5.2	7.5	4.8	9.7	5.0	–	4.1	7.9
10	5.6	7.80	5.8	8.1	5.5	10.4	5.5	10.4	4.5	8.9
12	6.5	8.4	6.4	8.6	6.1	11.2	6.1	12.1	–	–
14	–	–	–	–	6.5	–	–	–	–	–
15	–	–	–	–	–	11.4	–	–	5.44	10.8
20	8.1	9.45	8.0	–	7.2	–	–	–	–	–

Betz[1]) has compiled the experimental information on the average equilibrium-charge state. Table 2 summarizes the information over the range from 8.0 to 20 MeV for stripping in O_2 and carbon foils. Semi-empirical formulae for computing the average equilibrium-charge states have been given by several authors. For carbon foils a good approximation can be obtained from the formula of Nikolaev and Dmitriev[4])

$$\bar{q}/Z = \{1 + [v/(v' z^\alpha)]^{-1/k}\}^{-k}; \quad (4)$$

when $v' = 3.6 \times 10^8$ cm/s, $\alpha = 0.45$ and $k = 0.6$.

Representative values derived from eq. (4) are given in table 3. Excellent agreement exists with the experimental values listed in table 2 for ^{32}S. For ^{79}Br and ^{127}I the calculated values are about 1.5 charge units below the experimental value and one may expect the calculated values for ^{58}Ni to be similarly too low. For ^{238}U the calculated values are 0.5 charge units higher than the experimental values.

For gases in the range $\bar{q}/z < 0.3$ which is the range of interest in tandem accelerator terminals, Dmitriev and Nikolaev[2]) have given the relation

$$\bar{q}/Z = AvZ^{-\frac{1}{2}},$$

where $A = 0.18$ for argon and nitrogen and v is

TABLE 3

Average charge state for foil stripping for eq. (4).

Ion \ E (MeV)	7	8	10	12	15	20
^{32}S	6.97	7.32	7.93	8.43	9.05	9.84
^{40}Ca	7.39	7.79	8.50	9.09	9.85	10.84
^{48}Ca	6.86	7.24	7.95	8.50	9.24	10.21
^{58}Ni	7.77	8.24	9.07	9.79	10.7	12.0
^{79}Br	7.72	8.21	9.07	9.84	10.84	12.24
^{127}I	7.84	8.36	9.29	10.12	11.23	12.8
^{238}U	7.88		9.39	10.06	11.43	13.1

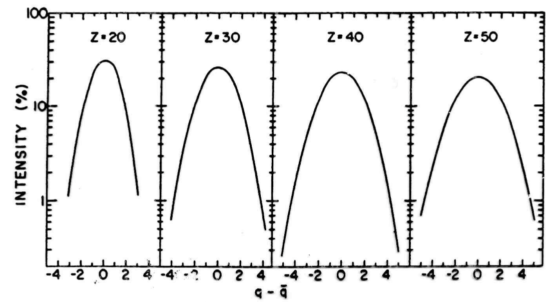


Fig. 3. Charge-state distributions calculated for $Z = 20$, 30, 40 and 50 with eqs. (3) and (1).

NIM, 122, (1974)

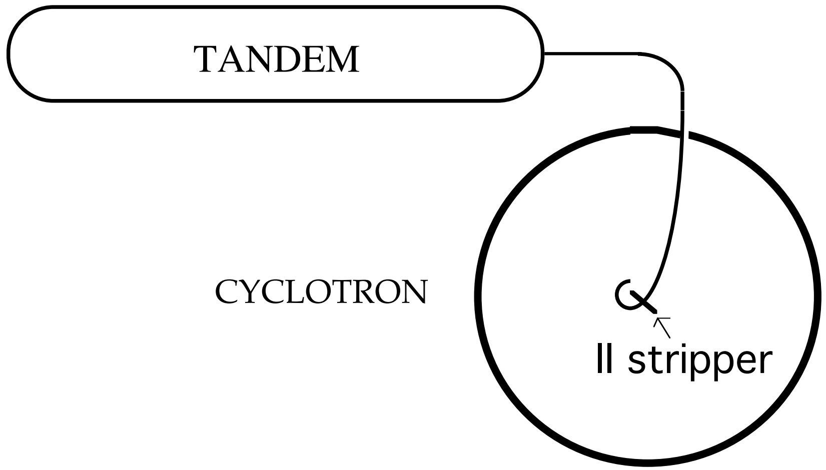
Tandems

Laboratori Nazionali di Legnaro (Pd, It), 16 MV
In operation.

Daresbury Laboratory (UK), 20 MV
Decommissioned

Laboratori Nazionali del Sud (Ct, It), 16 MV
In operation.

Further acceleration :Tandem + cyclotron, a typical arrangement



v. LNS

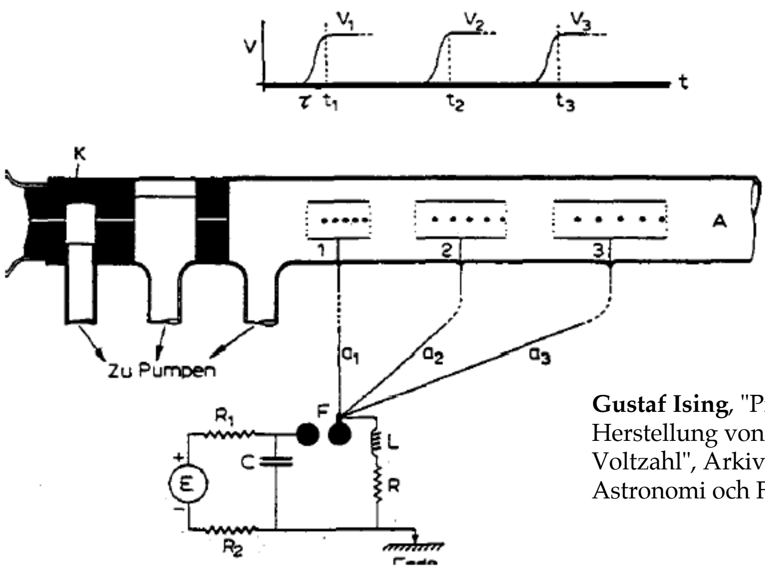
Further ion energy increase through :
- further acceleration
- further charge increase

N.B. : a tandem can provide very good, ~ 10^{-4}, energy resolution (mainly due to voltage ripple at the terminal)

G. Ising : the principle of electro-dynamic (multiple) acceleration

Overcoming the limits of electrostatics by using non-conservative electric fields.
G. Ising's contribution in the words of Nobel Prize E.O. Lawrence:

"....Professor G. Ising, who in 1924 published this important principle .
It was only after several years had passed that I became aware of Professor Ising's prime contribution.
I should like to take this opportunity to pay tribute to his work for he surely is the father of the developments of the methods of multiple acceleration."



Gustaf Ising, "Prinzip einer Methode zur Herstellung von Kanalstrahlen Hoher Voltzahl", Arkiv för Matematik, Astronomi och Fysik, Band 18 (1924)

Fig. 1. Diagram of linear accelerator from Professor G. Ising's pioneer publication (1924) of the principle of multiple acceleration of ions.

E.O. Lawrence's Nobel lecture

At about the same time: R. Wideroe's "ray transformer" idea

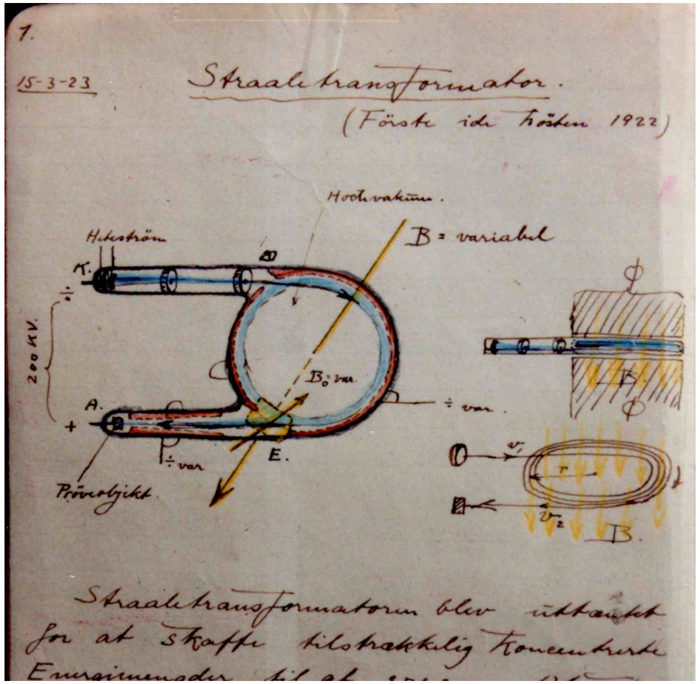
1923 **R. Wideroe** invents the principle of the circular induction accelerator nowadays called "Betatron" (but will not actually succeed in building a functioning one because *"…the theory of stabilizing forces acting on the orbit had not yet been developed sufficiently."*

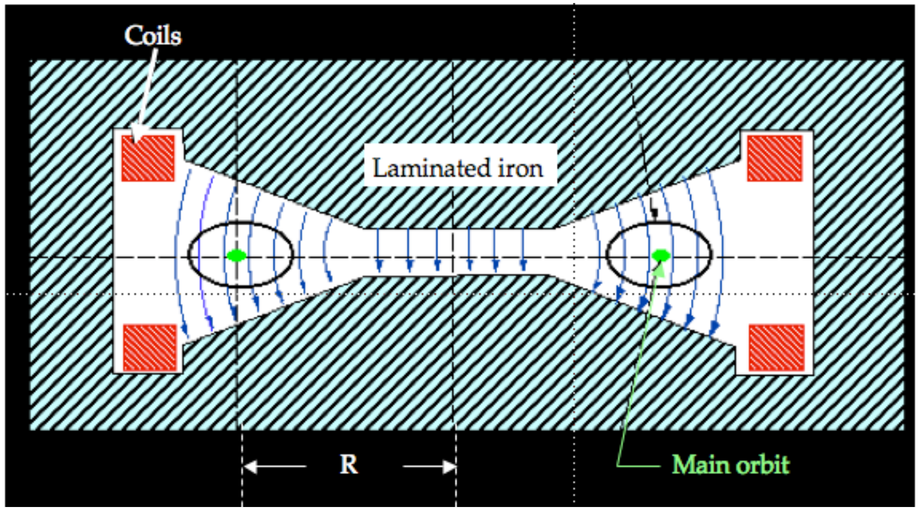
I. Einleitung.

Schwierigkeiten in der Beherrschung hoher Spannungen.

Bekanntlich liegen alle Schwierigkeiten bei der Herstellung hoher Spannungen in der Beherrschung der elektrostatischen Felder. Alle technischen Isoliermaterialien haben eine begrenzte Isolierfähigkeit, bei einer gewissen Feldstärke schlagen sie durch und werden leitend. Die Höhe der erzeugten Spannung wird deswegen hauptsächlich durch die stark zunehmenden Dimensionen der Isolierung begrenzt.

Es besteht nun aber die Möglichkeit, diese Grenze der erzeugten Spannungen wesentlich zu erhöhen, indem man elektrostatische Felder weitgehend vermeidet und die Hochtransformierung mit Hilfe schnellbewegten Elektronen und Ionen vornimmt.



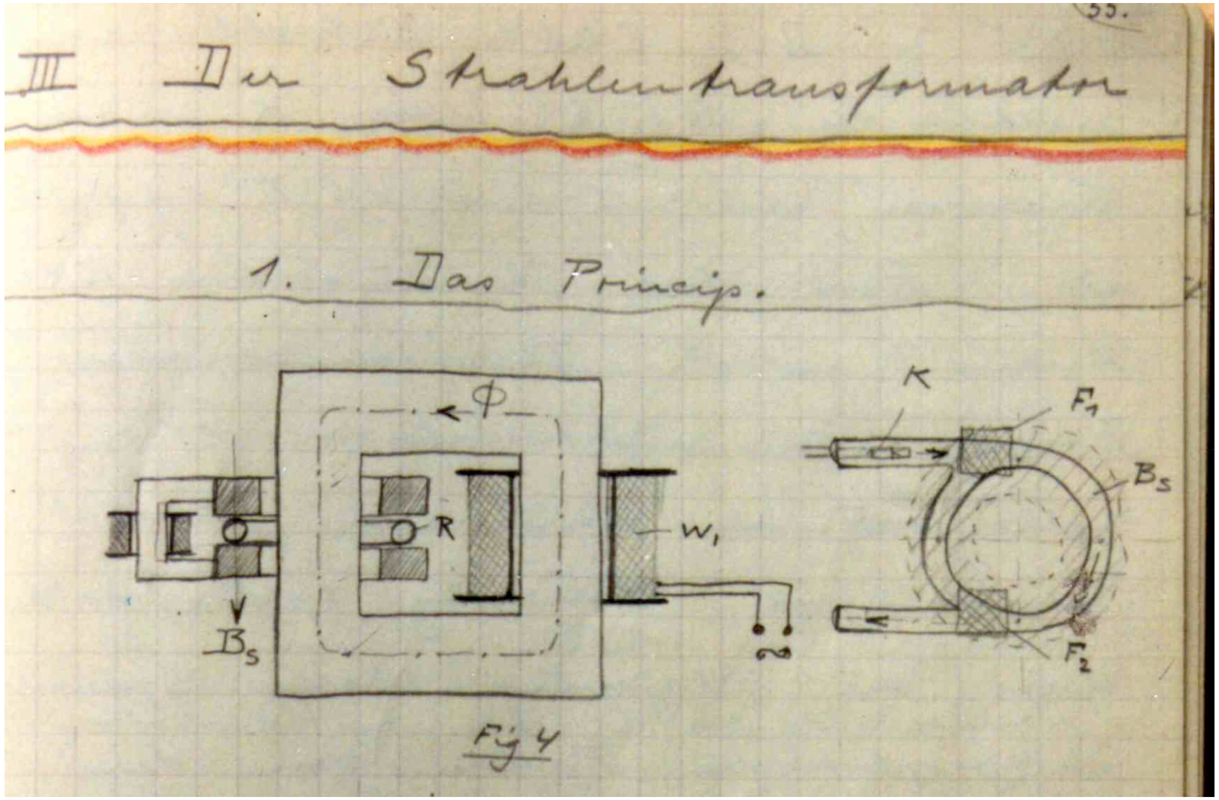


$$\frac{dB(R)}{dt} = \frac{1}{2}\left[\frac{1}{R}\int_0^R B(r)\cdot dr\right] = \frac{1}{2}\frac{d\bar{B}}{dt} \rightarrow B(R) = \frac{1}{2}\bar{B}$$

"The Infancy of Particle Accelerators", DESY-Report 94-039.

R. Wideroe's "ray transformer" idea

1923 **R. Wideroe** invents the principle of the circular induction accelerator nowadays called "Betatron" (but will not actually succeed in building a functioning one because *"…the theory of stabilizing forces acting on the orbit had not yet been developed sufficiently."*



$$\frac{dB(R)}{dt} = \frac{1}{2}\left[\frac{1}{R}\int_0^R B(r)\cdot dr\right] = \frac{1}{2}\frac{d\bar{B}}{dt} \rightarrow B(R) = \frac{1}{2}\bar{B}$$

"The Infancy of Particle Accelerators", DESY-Report 94-039.

D.W. Kerst builds the first working betatron

1940

Phys. Rev. 58, 841, 1940

Kerst did develop the theory of beam focusing, essential to have a stable circulating beam.

He studied and found the beam stability condition :

$$1/2 \le |n| \equiv \left|\frac{dB/B}{dR/R}\right| \le 1,$$

$n : negative$

His accelerator was industrialized for use as a X–ray source.

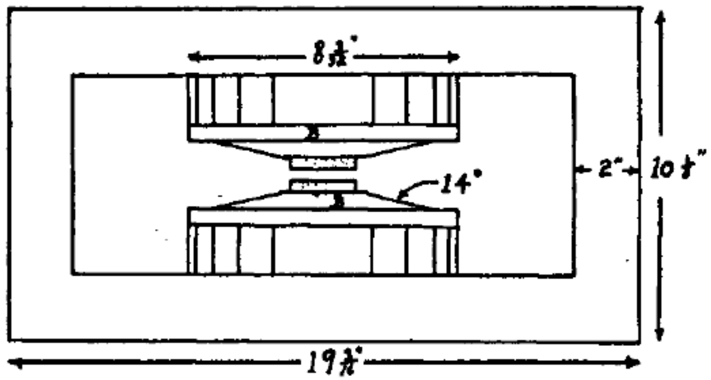
The Acceleration of Electrons by Magnetic Induction

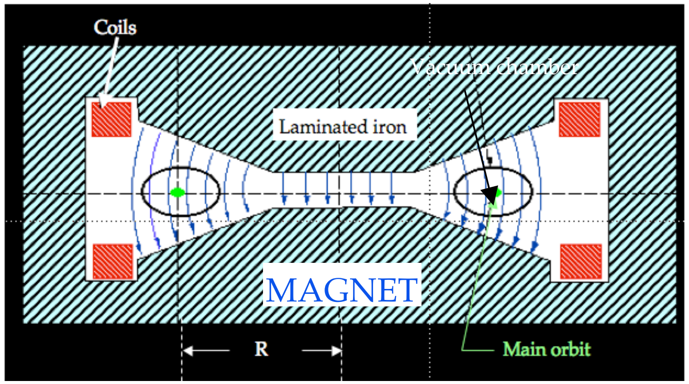
D. W. KERST[1]
University of Illinois, Urbana, Illinois
(Received April 18, 1941)

Abstract

Apparatus with which electrons have been accelerated to an energy of 2.3 Mev by means of the electric field accompanying a changing magnetic field is described. Stable circular orbits are formed in a magnetic field, and the changing flux within the orbits accelerates the electrons. As the magnetic field reaches its peak value, saturation of the iron supplying flux through the orbit causes the electrons to spiral inward toward a tungsten target. The x-rays produced have an intensity approximately equal to that of the gamma-rays from one gram of radium; and, because of the tendency of the x-rays to proceed in the direction of the electrons, a pronounced beam is formed.

Phys. Rev. 60, 47, 1941





$$B(R) = \frac{1}{2}\bar{B}$$

1944 : a first betatron is built in German industry; to its development collaborated B. Touschek

The Betatron is in practice usable only for electrons

Using $P_{\max} = q\ R\ B_{\max}$ one obtains [1]

$$(\beta\gamma)_{\max} \frac{E_0}{c} = qRB_{\max} \quad \Rightarrow \quad (\beta\gamma)_{\max} = \frac{q\ c\ R\ B_{\max}}{E_0}$$

Given a maximum magnetic field, the maximum obtainable energy is inversely proportional to the accelerated particle mass.

e. g. :
Take a 0.7 m orbit radius betatron whose magnet reaches a *1 T* maximum field and is powered by a *10 Hz* sinusoid.

- According to equation [1] when accelerating **electrons**, in the ultrarelativistic approximation $cP_{\max} \approx E_{\max}$, one finds $E_{\max} = 210\ MeV$.

For protons, using a non relativistic approximation, one obtains

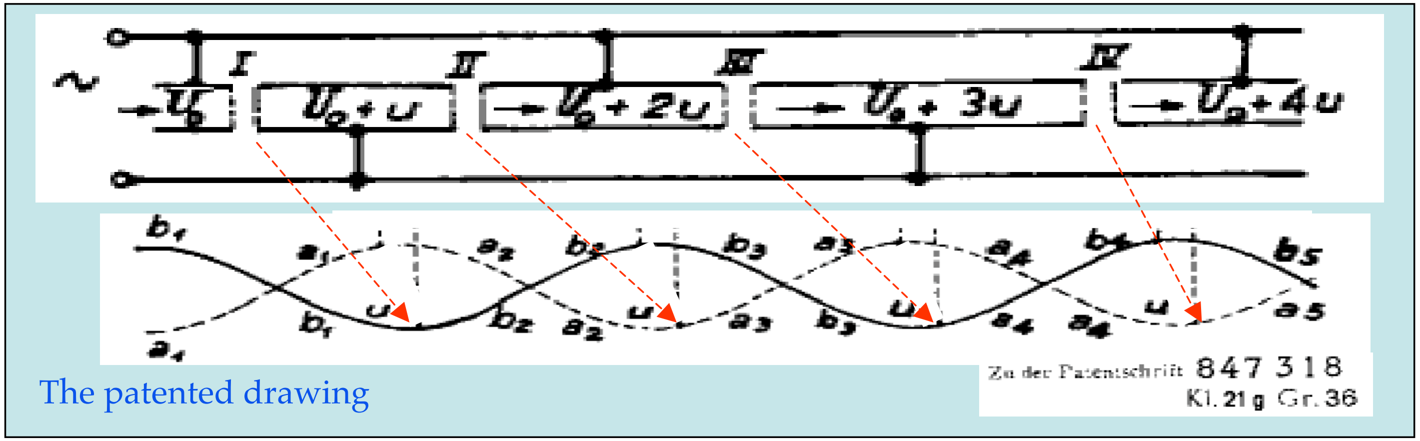
$$T \approx P^2c^2/(2E_o) = 23.5\ MeV.$$

A Cyclotron of same radius can do much better !

One can also easily derive that the maximum accelerating electric field is

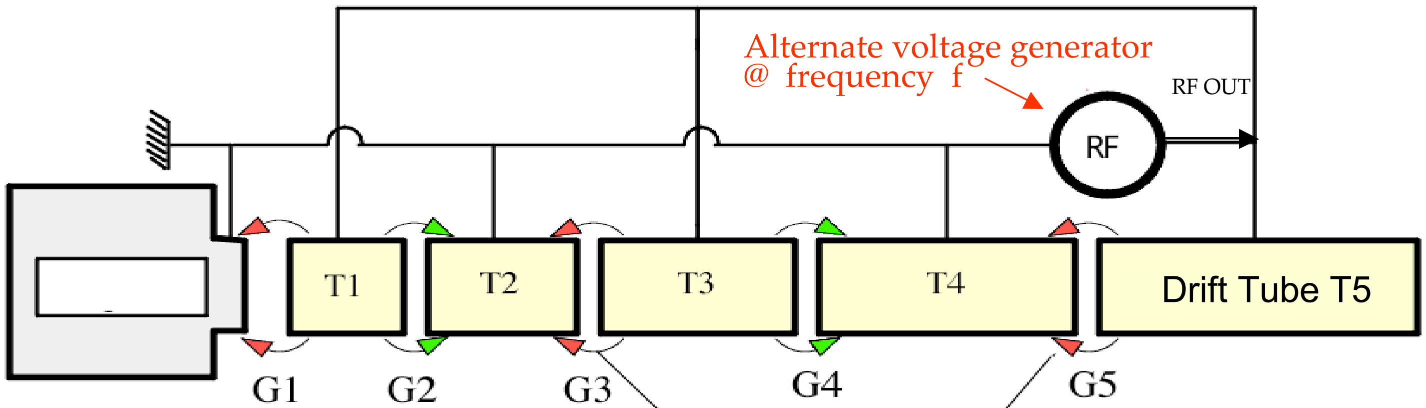
$$E_{acc} \approx 44\ \ V/m \quad \text{only.}$$

1927 Abandoning for the time the "ray transformer", Wideroe invents and builds a small, 2 section resonant linear accelerator with which he verifies the principle by accelerating ions to 50 KV using a 25 KV, 50 Hz generator.



The patented drawing

R.Wideroe's sketch in: "*The Infancy of Particle Accelerators*", DESY-Report 94-039.



Wideroe quotation on his linear, drift-tube accelerator

"As I speak about my life……… what always comes to my mind first is the Aachen drift-tube. Proving that it was possible to accelerate electrically charged particles with alternating potentials and without having to use the restricted possibilities of the (at that time usual) d.c. voltage, appears to me as my most fundamental piece of work. This was the major result which I presented in my dissertation **in 1927** and it does appear to have had the most far-reaching consequences."

R.Wideroe in: "*The Infancy of Particle Accelerators*", DESY-Report 94-039, 143, 1994.

First high energy drift-tube linac

Following
Ising
&
Wideroe

PhysRev.38.2021 (1931)

The Production of Heavy High Speed Ions without the Use of High Voltages

D.H. Sloan and E.O.Lawrence

A method has been developed for the multiple acceleration of ions to high speeds without the use of high voltages. The ions travel through a series of metal tubes in synchronism with an oscillating electric potential applied alternately to the tubes such that the electric field between tubes is always in a direction to accelerate the ions as they pass from the interior of one tube to the interior of the next. The ions are thereby successively accelerated to speeds corresponding to voltages as many times greater than the high frequency voltage applied to the tubes as there are tubes.

In the present experiments a high frequency voltage of 42,000 volts at a wave-length of 30 meters applied to 30 such accelerator tubes in line resulted in the production of a current of 10^{-7} amp. of 1,260,000 volt singly charged Hg ions. The surprising effectiveness of this experimental method for the generation of intense beams of high speed ions is due to the development of simple, convenient and effective methods for focusing and synchronizing the ions as they pass through the accelerating system.
The present experiments show that ions having kinetic energies in excess of 1,000,000 volt-electrons can be produced in this way with quite modest laboratory equipment and with a convenience surpassing the direct utilization of high voltages, that the limit to the attainable ion speeds is determined mainly by the length of accelerating system and the size of the high frequency oscillator system, and consequently that the production of 10,000,000 volt ions is an entirely practicable matter.

30 m → *10 MHz*

Received 19 October 1931

URL: http://link.aps.org/abstract/PR/v38/p2021

Wideroe's linac limitations

Given the frequency f_{RF} of the driving oscillator, the length L_i $(i = 1, 2, ...n)$ of the $i\ th$ drift tube, and v_i the velocity of the accelerated particle when entering it, a "resonance" condition is established whenever

$$L_i = \frac{v_i}{2 f_{RF}} \quad \Rightarrow \quad L_i = (\beta_i c) / 2 f_{RF}$$

in the sense that that the particle will always meet the same RF phase at every accelerating gap.

The main limitation of the device stemmed from the RF technology of the time, based on lumped–constants drive circuits and therefore restricted to low (tens of KHz) frequencies:

- at such low frequencies the drift-tubes lenghts become unmanageable unless $\beta << 1$

E. g. : $f_{RF} \approx 10 \quad MHz$ → $2L_i \approx 30 \cdot \beta_i \quad m$ → Way out

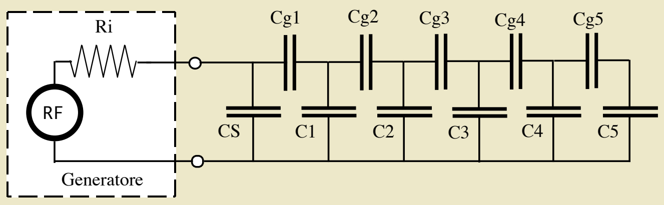
↓

Increase the frequency

↓

but : very high frequency transmitter techniques developed only during and after II world war, in the **1940's**, for radar applications.

↓



Drift tube Linac equivalent circuit

Non-radiating, "closed" resonators (accelerating cavities) and power drivers for them (HF power tubes, klystrons..) were first developed.

Alvarez type drift-tube linac (19…)

Drift-tubes are part of closed resonating structure.

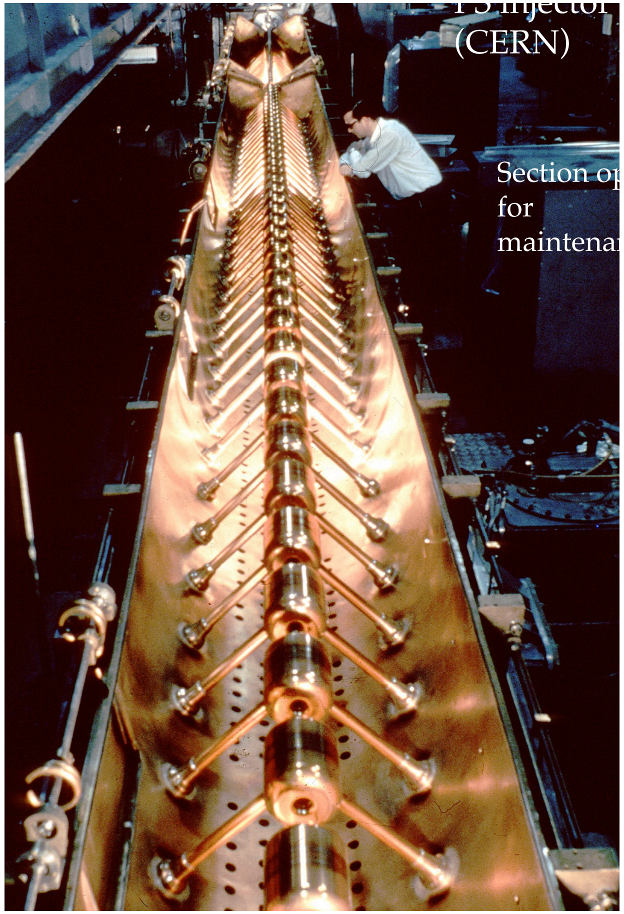
Such devices are still used to accelerate low energy protons and ions.

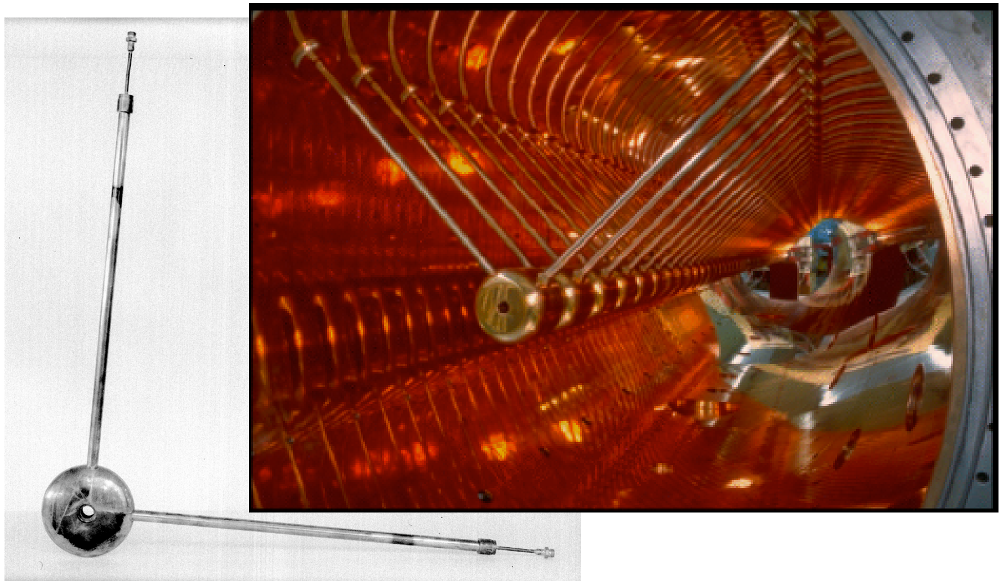
The resonant frequency is usually around a few hundred MHz, satisfying the condition

$$2L_{i(m)} \approx \beta_i \quad .$$

In practice, their useful range is

$$\beta <\approx 0.5$$





← 108 MHz

Cavity Resonator

The simplest schematization of a resonator is thin gap across which an oscillating voltage

$$V(t) = V_o \sin(\omega_{RF} t + \varphi) \qquad (3.8.2)$$

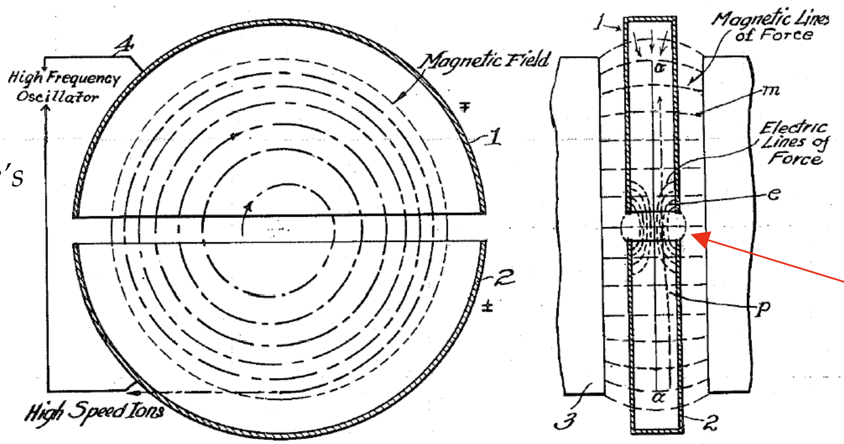
exists, f being an arbitrary phase constante and there being no special a-priori constraints on the oscillation sulla frequency ω_{RF}.
Whenever a charged particle crosses the gap its energy increases by

$$\Delta T(t) = qV_o \sin(\omega_{RF} t + \varphi) \qquad (3.8.3)$$

1929 - 1932

Once the possibility of multiple acceleration was discovered, the idea of accelerating particles by passing them several times through a same accelerating "gap" rather than once through many different gaps came to the mind of several researchers in slightly different form. It was E.O. Lawrence, inspired by Wideroe's "ray transformer", that first presented, pursued and patented the scheme later named "cyclotron".

Lawrence's patent claim design.



$$T_{max} = 2\pi^2 m_o f^2 R_{max}^2 = \frac{q^2 R_{max}^2 B^2}{2 m_o}$$

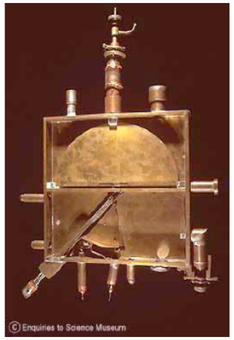
N.B. : the vertical focusing effect of the gap electric field is first recognised

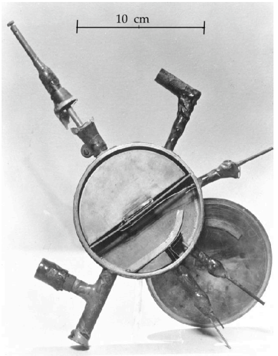
The driving a.c. voltage generator, is connected across two cylindrical metallic half boxes separated by a gap and immersed in an axial magnetic field. Particles to be accelerated are introduced inside them, the boxes functioning as curved drift "tubes", perform half circular orbits under the action of the magnetic field and, in a classic regime ($\beta \ll 1$), experience the accelerating field every time they cross the gap in either direction.

The latter, nature dictated, peculiarity is due to the time a particle takes to cover a half-orbit being independent from the particle energy and therefore from the orbit radius so that, provided it initially meets the field in a proper (accelerating) phase, it will stay in phase with it throughout.

http://upload.wikimedia.org/wikipedia/commons/3/39/Cyclotron_patent.png

The first operating cyclotron and other LBL ones

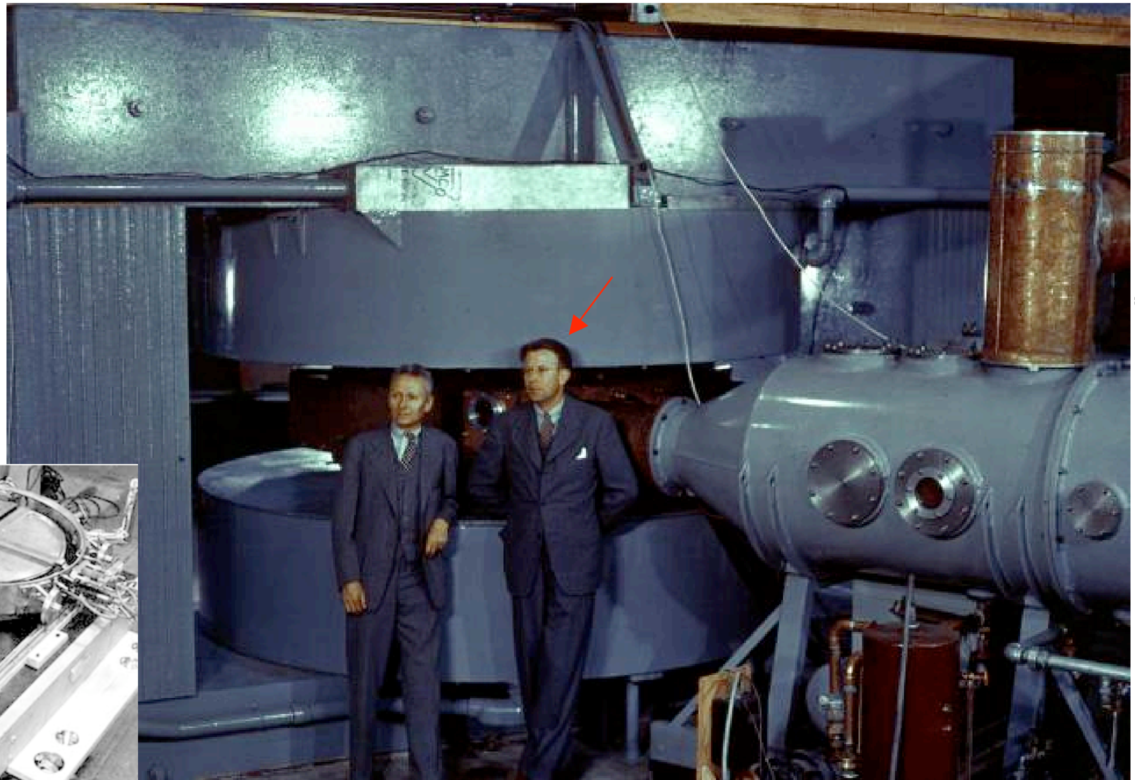




1931 E.O. Lawrence and his graduate student M.S. Livingston build the first successfully operating cyclotron. It accelerated a few hydrogen molecule ions to an energy of 80 KeV. *"Each ion that reached full energy and fell into a Faraday cup placed 4.5 cm from the center of the instrument had made no fewer than forty turns"*.

Result reported at the January 1931 APS meeting

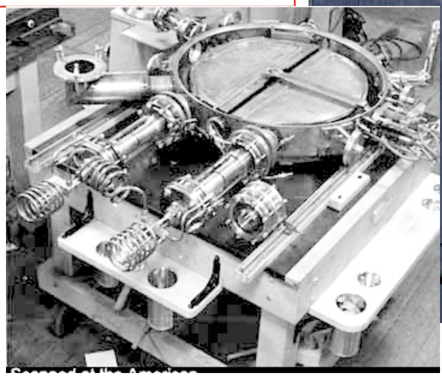
A series of other larger ones followed, at LBL, between 1935 and 1938



60" diam
220 ton magnet
11 ft high

8 MeV
$\approx 0.1 \div > 1\ mA$

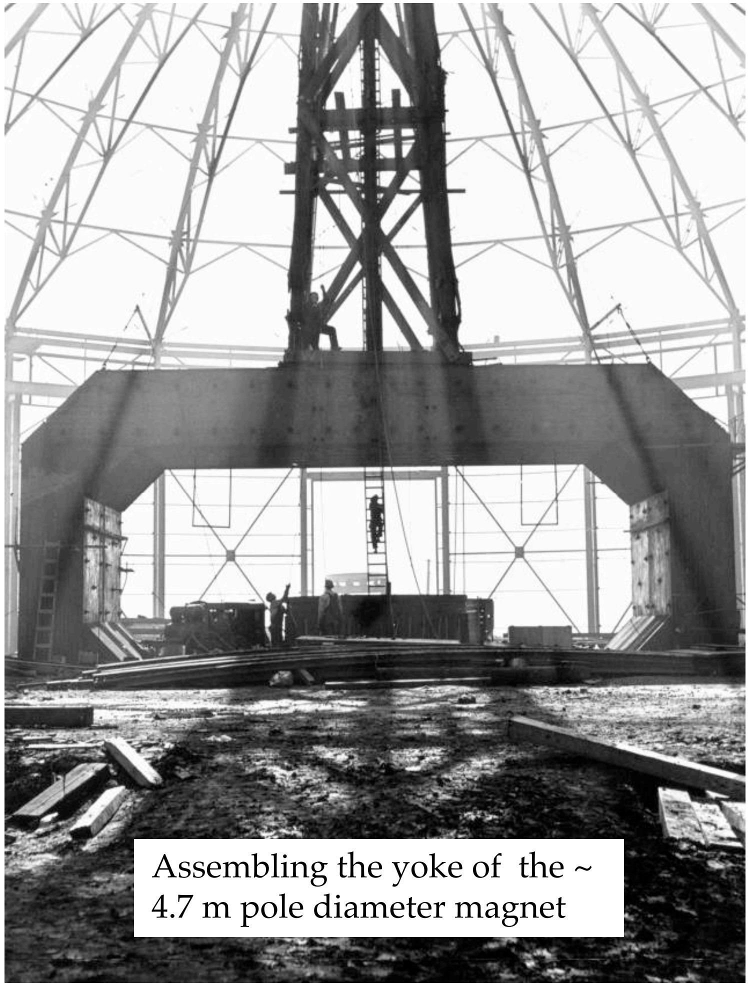
153 cm beam



E.O.Lawrence and his Laboratory, www.lbl.gov/Science-Articles/Research-Review/Magazine/1981/

Lawrence's 184" Cyclotron

1940

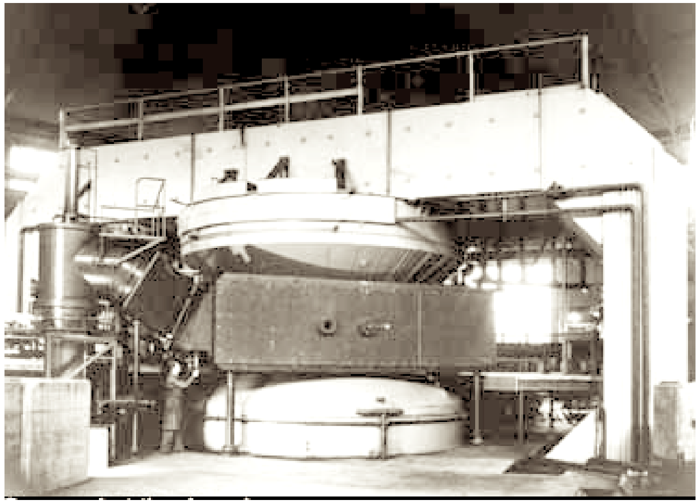


Assembling the yoke of the ~ 4.7 m pole diameter magnet

Because of the war the machine was first completed in 1946.
With an **energy for D_2 of 200 MeV**, it became the first over one hundred MeV accelerator.

The machine was thus the first able to produce, identify and precisely investigate mesons (**1948**).

In **1950** it was upgraded to produce 350 MEV protons as well as 200 MeV deuterons and 400 MeV alpha particles.



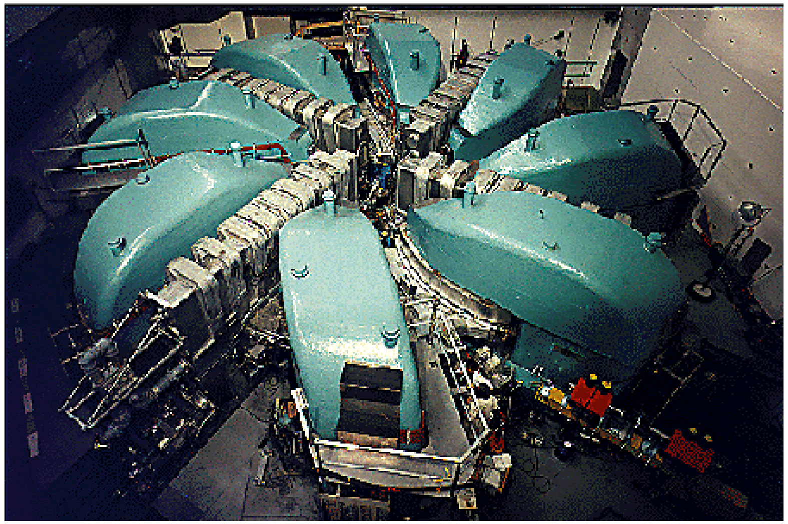
- Relativistic cyclotrons

In view of reaching higher energies the classic cyclotron has two drawbacks :

- the failure of isochronicity in the relativistic regime
- the magnet diameter increasing, at constant B, like $\sqrt{T_{\max}}$, the magnet volume and cost increase like $\propto T_{\max}^{3/2}$;

Modern cyclotrons still in use for basic science and medical applications incorporate one or both of the following techniques:

- superconductivity, to obtain much higher magnetic fields for a given radius (SC cyclotrons)
- shaping of the magnet poles to maintain isochronicity and focusing even in a moderately relativistic regime (sector-focussed cyclotrons, *L.H. Thompson 1938*).



PSI (CH) Sector-yclotron for protons, normal conducting 590 MeV , average current up to 1.9 mA '.

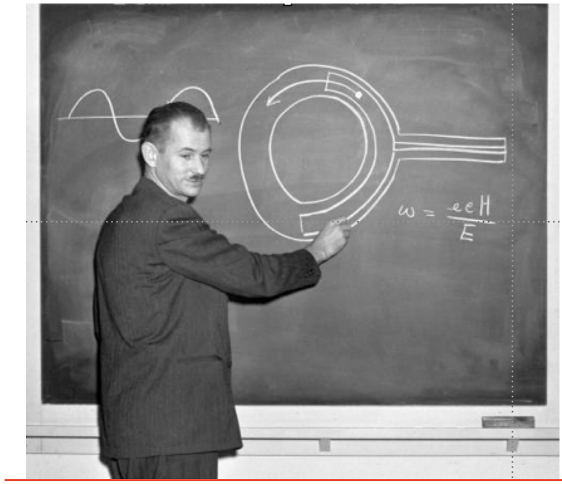
Pole of the Catania (It) SC sector cyclotron for heavy ions. B=5T, R=1m, Max energy for protons : 600 MeV

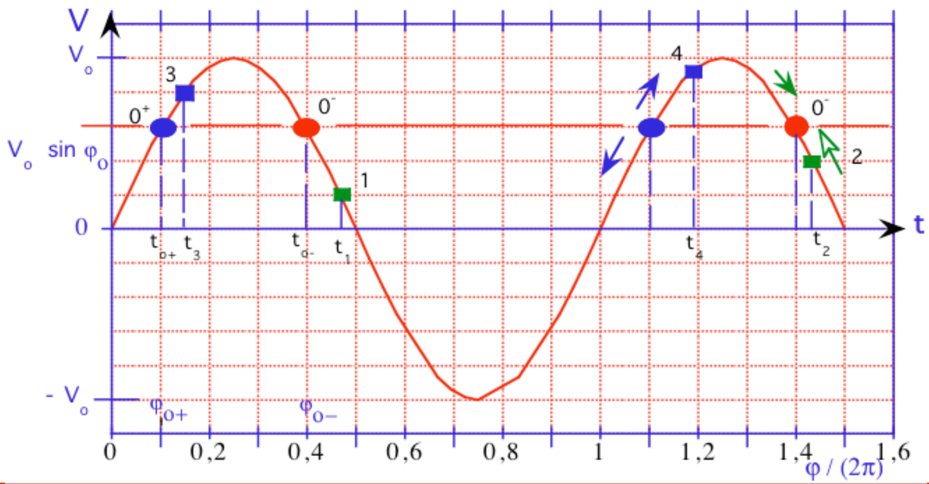
The Synchrotron

1943 Cost of scaling a conventional cyclotron to higher energies and acceleration of relativistic particles (electrons) , were probably the topics that prompted **M. Oliphant**, a british scientist then working on weapon-oriented research in the USA as E.O.Lawrence's deputy, to come up with the concept of the "**synchrotron**". He in fact writes, in a memo to the UK Directorate of Atomic Energy:

> *"Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field ... which would be varied in such a way that the radius of curvature remains constant as the particles gain energy through successive accelerations by an alternating electric field applied between coaxial hollow electrodes."*

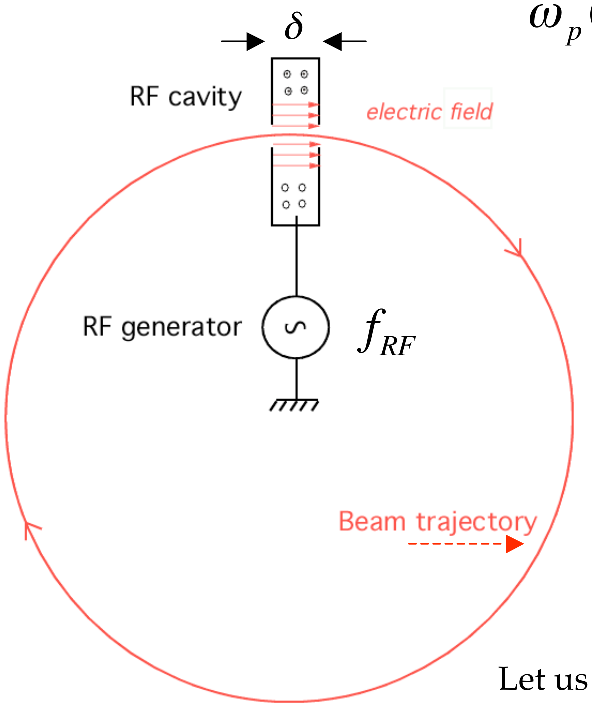
The problem of beam (*longitudinal*) stability in the presence of different trajectory lengths of particles starting with different initial conditions, in particular with finite initial energy spread, solved itself when V.I. Veksler and and E. McMillan, working on cyclotrons, independently formulated the "phase stability" principle (and applied it to "Synchrocyclotrons").





E. J. N. Wilson, "*Fifty Years of Synchrotrons*", CAS; J.D. Lawson, "*Early Synchrotrons In Britain and Early Work for Cern*", CAS

Synchrotron principle and a few formulae



$\omega_p(t)$ Particle angular velocity

δ cavity gap width

$$\mathcal{E}(t) = \mathcal{E}_o e^{i[\omega_{RF}(t)\cdot t + \varphi_o]}$$ Average electric field in the gap

$$q\,\Delta V_{RF}(t) = q\,\delta \cdot E(t)$$ Energy supplied per turn

The final energy is then

$$T_{fin} = T_{in} + \sum_n q\,\Delta V_{RF}(t_n)$$

Showing that in order for the sum to be non zero the particle must remain in phase with the Rf electric field. One must therefore have:

$$\omega_{RF}(t) = k\,\omega_p(t)$$

Let us now take $k=1$ and also assume we are in the ultra-relativistic regime so that $\omega_p = \omega_{RF}$ = constant.

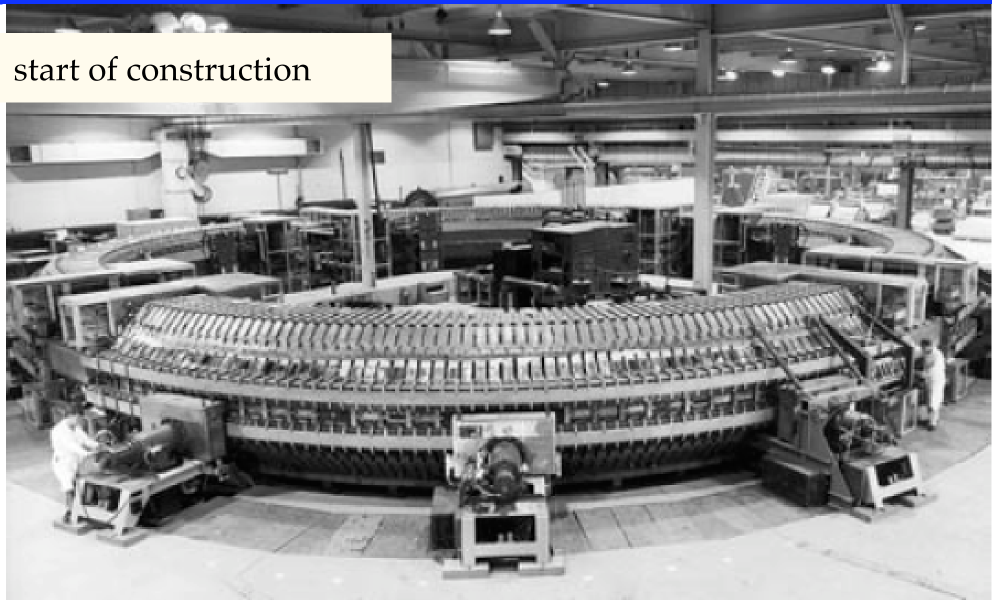
Calling the initial field phase φ_o and the orbit circumference L, the electric field seen by the particle can then be written :

$$\mathcal{E}_n = \mathcal{E}_o\, e^{i\left(\omega_o t - \frac{\omega_o nL}{\beta c} + \phi_o\right)} = \mathcal{E}_o\, e^{i\,\omega_o\left(t - \frac{nL}{\beta c}\right) + \phi_o)}\,.$$

Note that this exspression has the same form as that of a **wave travelling with velocity** βc .

Weak focusing synchrotrons

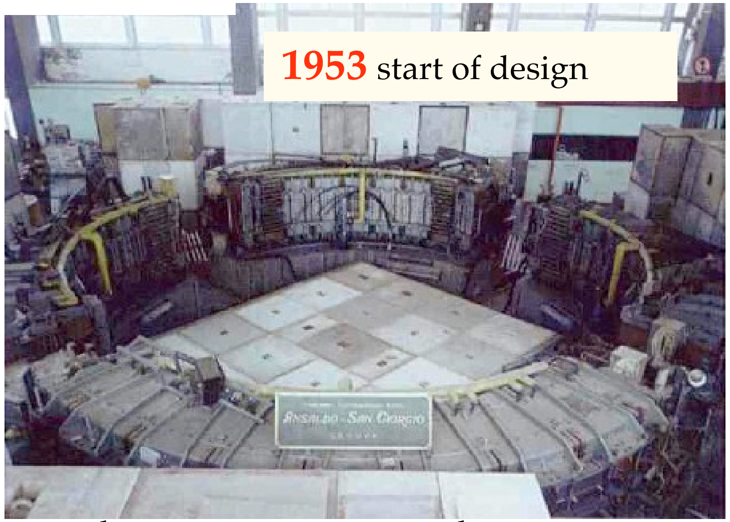
1951 start of construction



The BNL 3 GeV p-synchrotron

> *“....even a few years later (*after discovery of strong focusing principle*) wise and experienced people decided to construct two large synchrotrons, Nimrod in the UK and the ZGS in the USA, based on the weak focusing scheme.*
> *It was believed that alternating-gradient machines, if they worked at all, would produce beam currents considerably smaller than the classical weak focusing ones, which had a much larger aperture.”*
>
> G. Brianti, “The CERN Synchrotrons” CAS, CERN-97-04

1953 start of design



The 1 Gev Frascati e-synchrotron

Weak and strong focusing in the 1950's

The early synchrotrons relied on focusing provided by magnetic field lines according to Kerst's stability condition

$$1/2 \le |n| \equiv \left| \frac{dB/B}{dR/R} \right| \le 1, \quad \text{with negative } n$$

(**negative sign field gradient**)

Kerst' limits on n derive from the fact that a magnetic restoring force component acts only in the vertical plane while in the radial plane the force component has the the wrong direction and is over–compensated by the effect of the particle orbit curvature only provided the field gradient $(R/B)\cdot(dB/dR)$ stays inside the above limits.

The resulting focusing is "**weak**" which entails relatively large beam sizes, large pole widths and therefore a costly magnet in addition to expected stability problems at energies exceeding ~ 10 GeV.

This picture was changed dramatically at around **1952** when **E. Courant, M. Livingston** and **H. Snyder**, at Brookhaven, proposed **strong focusing**, or **alternating-gradient** (AG) magnetic lattices consisting of bending magnets with alternating sign of the gradient or of properly spaced quadrupole magnets with opposite polarities, which solved the above problems allowing for much higher energies per given price.

Why : given two lenses with focus $f_1$and f_2 separated by a distance d , their combination has

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

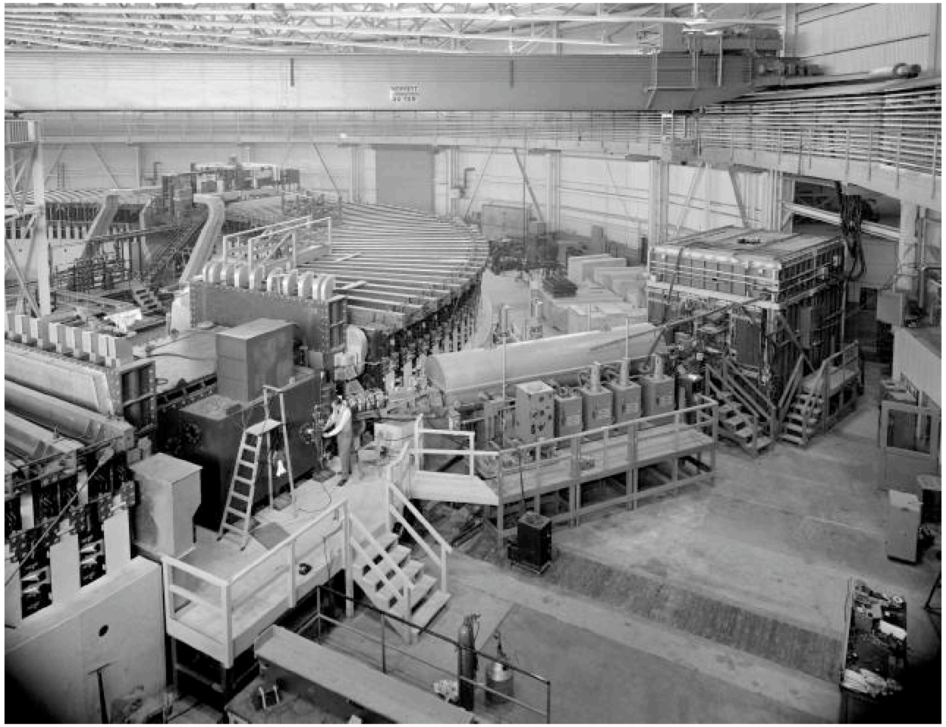
always positive if $f_1 = -f_2$ (and in a range around it),

else: the beam defocused by one lens arrives at the following (focusing) lens further from the axis and is therefore focused more strongly.

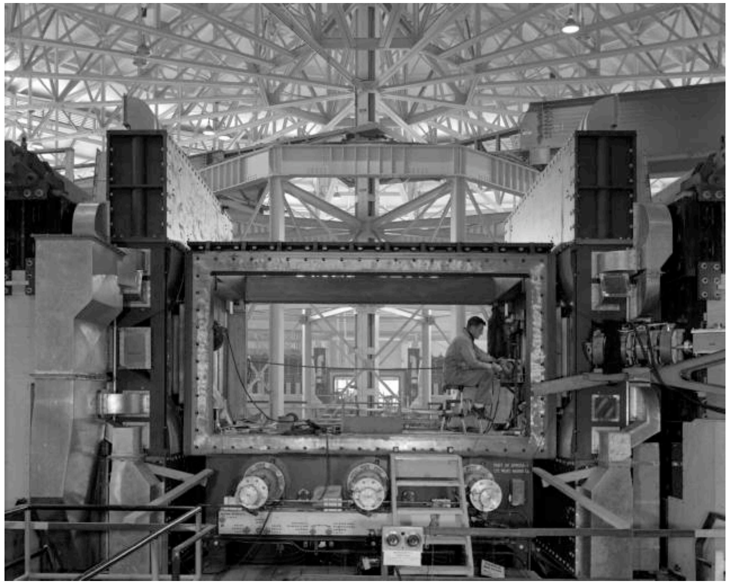
All modern synchrotrons are strong-focused

P.J. Bryant, *A brief history and review of accelerators, CAS* ; E. J. N. Wilson, "*Fifty Years of Synchrotrons*", CAS

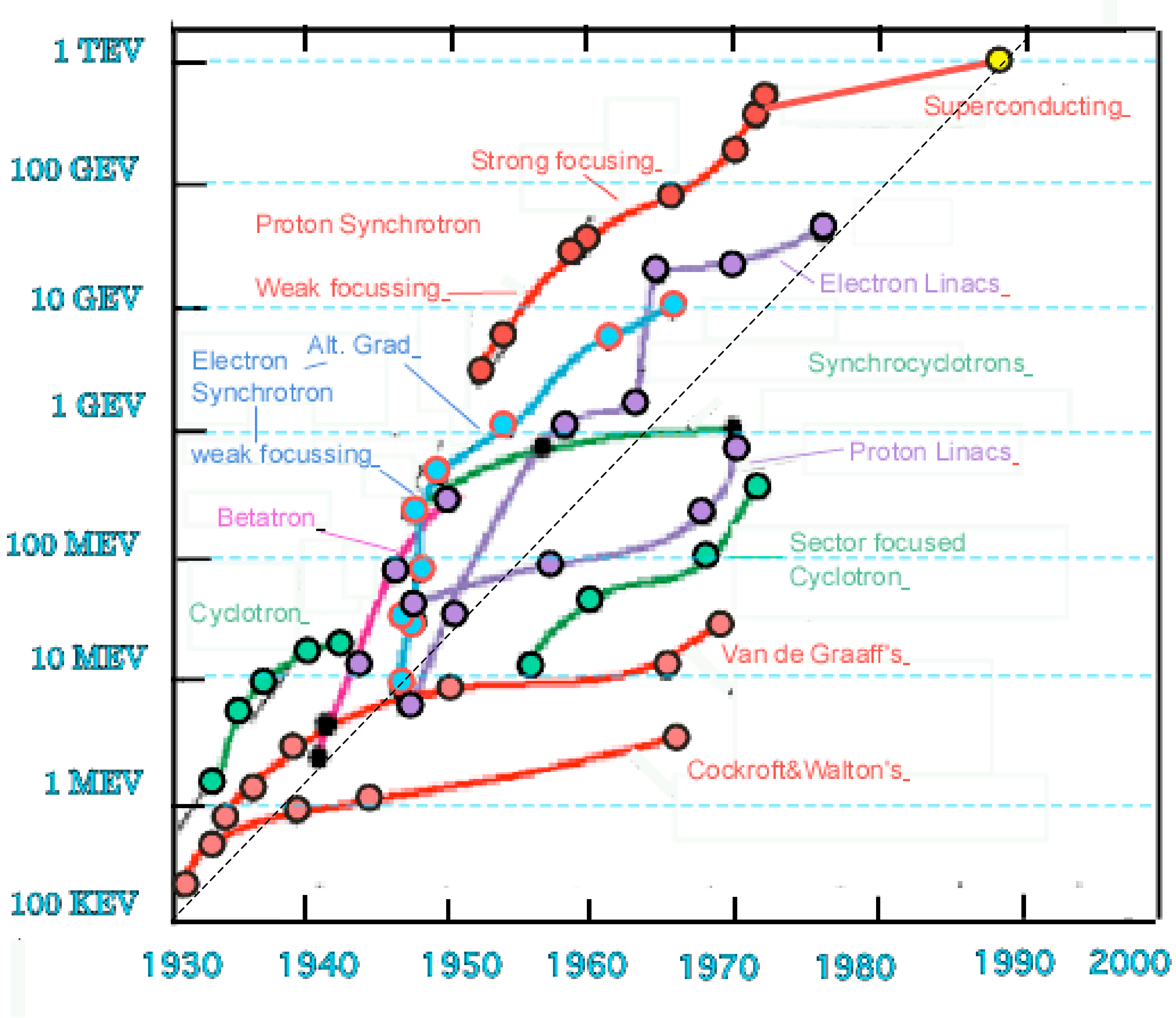
Weak focusing synchrotrons - Cosmotron



The Cosmotron vacuum chamber

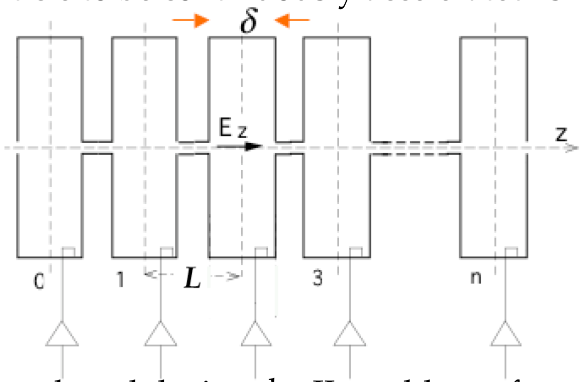


Synchrotron progress in time



Back to linacs in the ultra-relativistic regime *(mainly electron linacs)*

Take a sequence of identical equally-spaced cavities centered on a straight trajectory, spaced by L.
It can easily be seen that the argument made in the previous slide still holds so that the condition for the particle to be continuously accelerated is

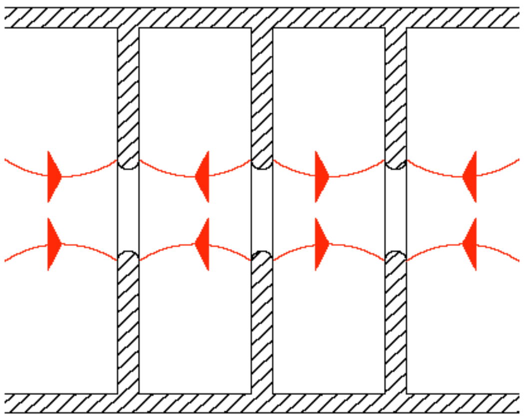


$$\mathcal{E}_n = \mathcal{E}_o\, e^{i(\omega_o t - \frac{\omega_o nL}{\beta c} + \phi_o)} = \mathcal{E}_o\, e^{i\,\omega_o\left(t - \frac{nL}{\beta c}\right) + \phi_o)} .$$

If therefore one can produce a wave travelling trough the structure here schematised a particle injected will be accelerated throughout to a final energy one can write as

$$T_{fin} = T_{in} + q\left\langle \mathcal{E}_o\, e^{i\,\phi_{acc}} \right\rangle_L nL$$

With the development of high frequency (in the GHz, S-band region or higher) power electronics, mainly developed during the II world war for radar applications, closed structures (waveguides) can be built and powered that can carry waves travelling at speeds less than c . They are used in all “warm” e-Linacs.



Storage Ring and Linear Colliders

Colliding beams

1943

R. Wideroe again.. *"…I had thus come upon a simple method for improving the exploitation of particle energies available .. for nuclear reactions. As with cars* (collisions)*, when a target particle (at rest) is bombarded, a considerable portion of the kinetic energy* (of the incident particle) *is used to hurl it (or the reaction products) away.*

Only a relatively small portion of the accelerated particle's energy is used to actually to split or destroy the colliding particles. However, when the collision is frontal, most of the available kinetic energy can be exploited.

For nuclear particles, relativistic mechanics must be applied, and .. the effect .. be even greater ".

In fact, relativistically, for a same amount of energy available in the center of mass system, the energy of the incident particle in a fixed target experiment , γ_F , and that of each of two particles in head-on collision , γ_C , obey the equation:

$$\gamma_F = 2\gamma_C^2$$

In addition :

"… If it were possible to store the particles in rings for longer periods, and if these 'stored' particles were made to run in opposite directions, the result would be one opportunity for collision at each revolution.

Because the accelerated particles would move very quickly they would make many thousand revolutions per second and one could expect to obtain a collision rate that would be sufficient for many interesting experiments."

The storage ring-collider concept

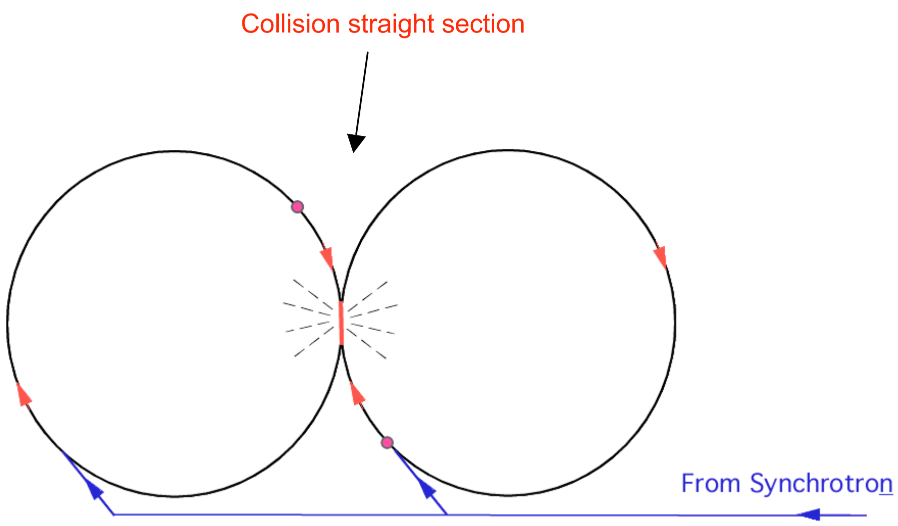
1956

D.W. Kerst et al *"The possibility of producing interactions in stationary coordinates by directing beams against each other has often been considered, but the intensities of beams so far available have made the idea impractical.*

*…………… accelerators offer the possibility of obtaining sufficiently intense beams so that it may **now** be reasonable to **reconsider directing two beams** of approximately equal energy **at each other**."*

D. W. Kerst et al., Phys. Rev. 102, 590 (1956).

G. K. O'Neill, interested in p-p collisions, introduces the idea of injecting the beam extracted from a high energy proton synchrotron in two "**storage rings**" in which particles would be accumulated and stored for a long time. Typically in a figure-of-8 configuration they have a common section in which the two stored beams collide head-on.



The storage rings concept

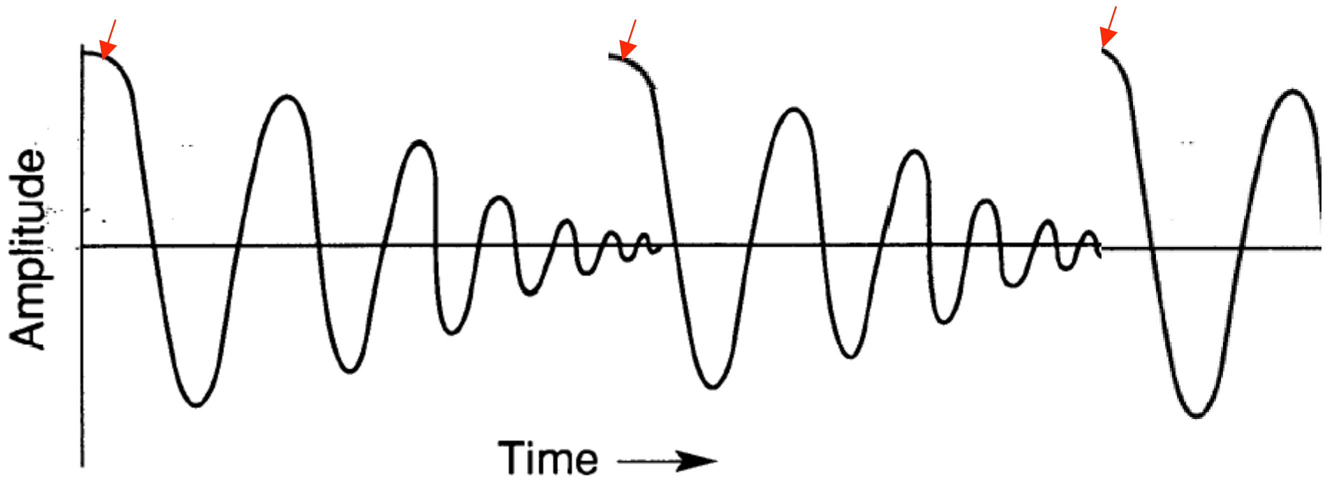
1956 Some time later, **G. K. O'Neill** also observed:

"The use of storage-rings on electron synchrotrons in the GeV range would allow the measurement of the ***electron-electron*** *interaction at center-of-mass energies of about 100 times as great as are now available. The* ***natural beam damping in such machines might make beam capture*** (and accumulation) ***somewhat easier*** *than in the case of protons."*

Proc.CERN Symposium on H.E.Accelerators and Pion Physics , Geneva (1956), p. 36

Bunches of particels coming from the injector are injected at some distance from the equilibrium orbit and start oscillating around it. Because electrons (but at the time not protons) constrained on a curved path radiate energy away it can be shown that the **amplitude** of the oscillations **is damped** so that all injected particles end up in the vicinity of the equilibrium orbit. Injections can thus be frequently repeated without disturbing the stored beam and adding the the newly injected particles to it

Phase Space not conserved

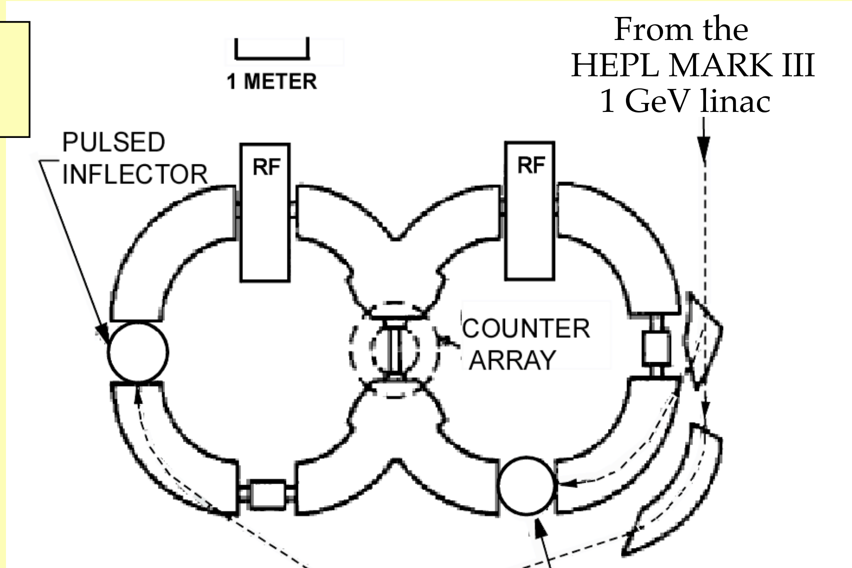


The first collider: Princeton-Stanford e-e experiment

1957 **G.K. O'Neill, B. Richter, W.C. Barber , B. Gittelman** start building the e^-e^- Princeton-Stanford colliding beam accelerator, still weak focusing, *500 MeV* per beam

The group, (Richter in particular), became interested in performing e-e scattering experiments study the at that time much discussed problem of possible breakdowns of quantum electrodynamics at high energy. The proposed collider energy would reach a center of mass energy by far higher than that obtainable at other accelerators and could be a model for a future p-p collider.

First stored beam in **1962.**



First Stanford e^--e^- collider

Technical problems solved:

-the world's largest ultra-high vacuum system (two cubic meters at 10^{-9} *torr*).

- injection kicker magnets faster than anything that existed at the time (80 ns pulse width, including a reasonable flat top).

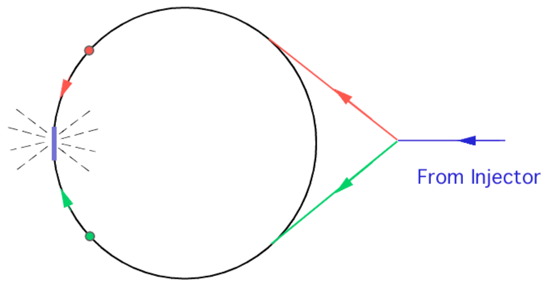
- stored beam currents in the *100's* of *mA* range.

SLAC-PUB-6023, June 1992

B. Touschek , the lead theoretician in Frascati, did not believe in QED breakdowns but *"...conceived electron-positron annihilation as the best tool to transfer "pure" energy - that is without unwanted quantum numbers such as charge or too large angular momentum or some other hadronic property - to the vacuum. "*

In **1960** he gave a seminar in Frascati presenting the main features of **e^+e^- annihilation** physics and proposing the construction of a small single ring injected from the 1.1 GeV Frascati electron synchrotron in which two bunches, one of electrons and the other of positrons, would circulate in opposite directions in a same vacuum chamber and collide once per turn.

A week later, ". .*given that preliminary studies have not shown insurmountable barriers*......", the machine was approved and named , funding made available, and construction started, to be completed one year later.



Quotations from

BT's seminar

On The Storage Ring.

The following is a very sketchy proposal for the construction of a storage ring in Frascati. No literature has been consulted in its preparation, since this invariably slows down progress in the first stage, necessary though it may be in the consecutive stages of the development. I shall present you here all I have thought about it and much, which others have suggested to me and to anticipate the question: No, I have not properly read O'Neil, but I hope that somebody will.

Let me first explain why a storage ring is an important instrument, particularly when fed with electrons and positrons. The first suggestions to use crossed beams I have heard during the war from Wideröe, the obvious reason for thinking about them being, that one ~~wasted~~ a considerable amount of energy by using 'sitting' targets - most of the energy being wasted to pay for the motion of the centre of mass. If one wants to study electrodynamics one should try to use particles, which interact weakly except electromagnetically. This automatically cuts one down to electrons (and positrons) since μ-mesons are hard to come by in large numbers. To use a crossed beam consisting of electrons and positrons has the further advantage that in all interesting processes the particles of the initial state (i.e. the electrons and the positrons) disappear: Experiments made in this way can only depend on two parameters (the energy and the angle, the first being given by the machine). This means that much more information can be gained by much fewer events.

At this stage it appears necessary to define the project a little better: I prefer to think of it as an experiment rather than as a machine - a fact which may change considerably our attitude to the project. As I think I will be able to demonstrate the project is closer to an experiment than to a machine in two important respects: in cost and in the limited range of applicability of the ironware. Talking of it as an experiment I propose to study the reactions

(1) $$e^+ + e^- \rightarrow \begin{cases} 2\gamma & (A) \\ \mu^+ + \mu^- & (B) \\ \pi^+\pi^- \ (2\pi^0) & (C) \end{cases}$$

and I admit that I think that there is nothing else of importance, which can be studied with the same set up.

The first of the processes listed is two quantum annihilation. The process is predominantly backward-forward in the C.M. system and in these preferred directions no 'radiative corrections' are to be expected. The cross section for this process is

(2) $$\sigma(A) = 6.3.10^{-30}\ \text{cm}^2$$

at 250 Mev and it diminishes a little less than quadratically with rising energy.

I propose to use (1A) as a monitoring process. This is a

On The Storage Ring.

The following is a very sketchy proposal for the construction of a storage ring in Frascati…No literature has been consulted in its preparation, since this invariably slows down progress in the first stage…I shall present you here all I have thought about it and much, which others have suggested to me and to anticipate the question: No, I have not properly read O'Neill, but I hope that somebody will […]

I prefer to think of it as an experiment rather than as a machine […]

Talking of it as an experiment I propose to study the reactions

$$e^+ + e^- \rightarrow \begin{cases} 2\gamma & (A) \\ \mu^+ + \mu^- & (B) \\ \pi^+ + \pi^- & (C) \end{cases}$$

And I admit that I think that there is nothing else of importance, which can be studied with the same set up.

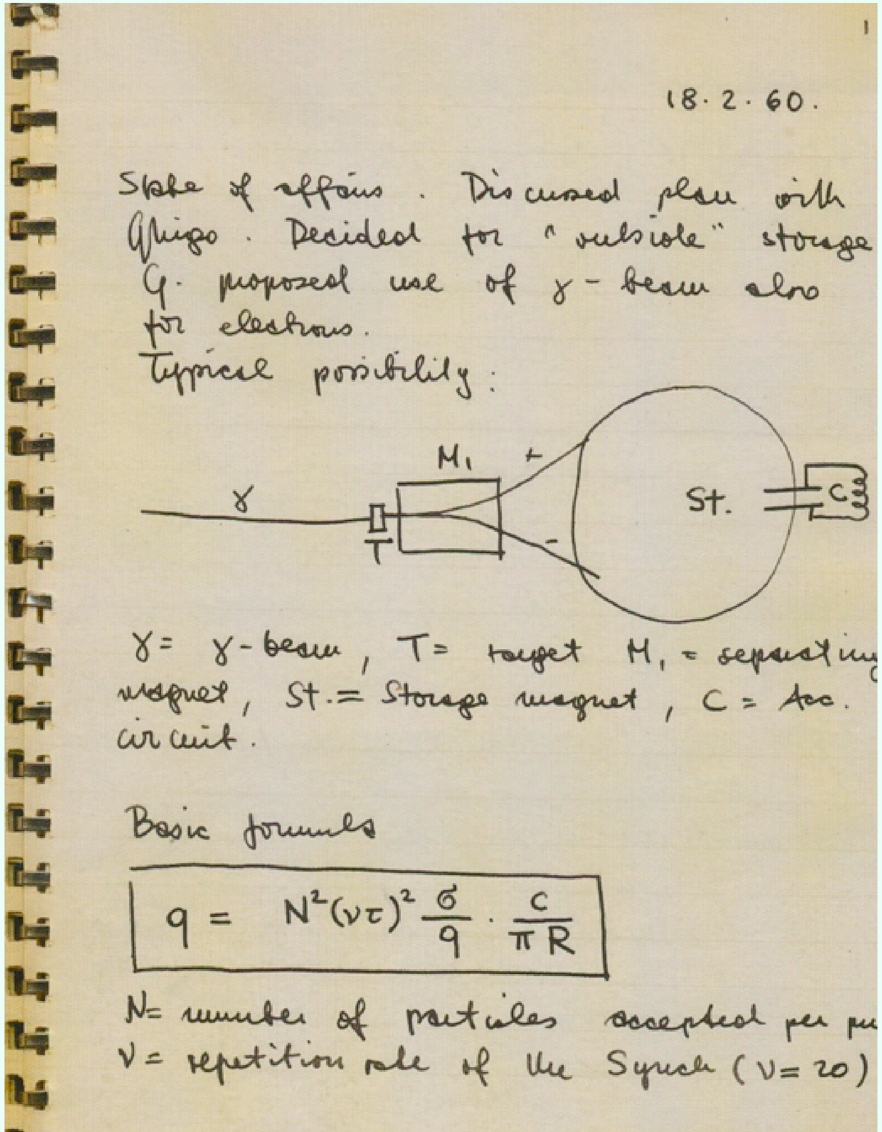
The first of the processes listed is two quantum annihilation. The cross section for this process is

$$\sigma(A) = 6.3.10^{-30}\text{cm}^2$$

At 250 MeV[…]I propose to use (1A) as a monitoring process[…]

C.Bernardini, Phys. Perspect. 6 (2004) 156–183

B. Touschek's notebook: birth of the first e^+e^- collider



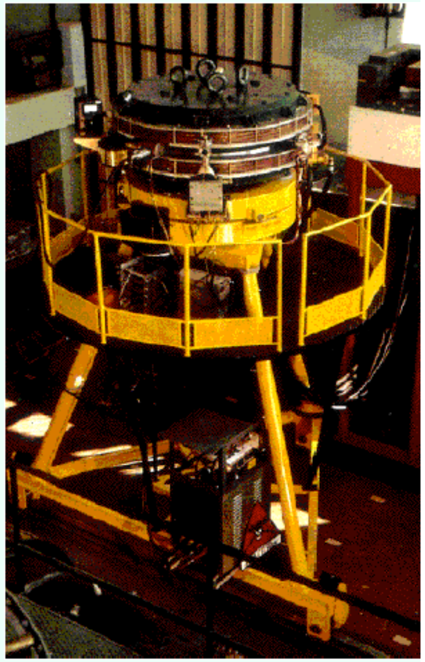
Archivio B. Touschek, Dip. di Fisica, Università "la Sapienza,", Roma

The first page of Bruno Touschek's notebook. The day before , during a meeting in in Frascati, he had proposed to build an accelerator to accelerate two particle beams and collide them head-on, to study the basic constituents of matter. The drawing shows a principle sketch of a ring collider.

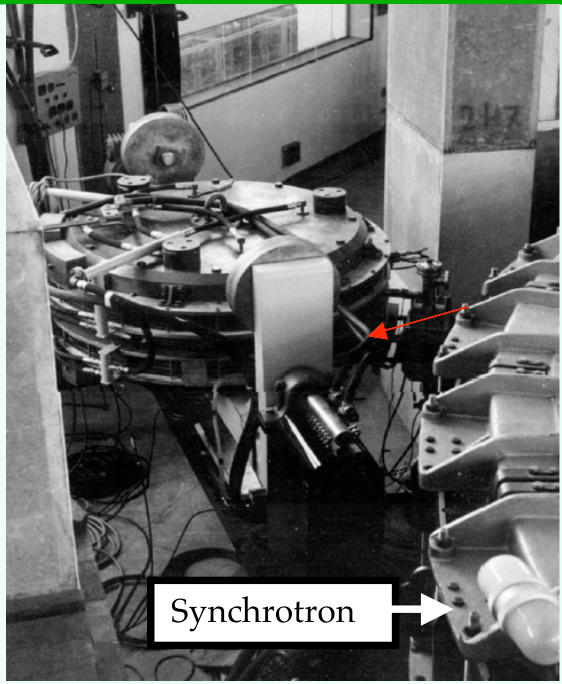
"State of affairs. Discussed plan with (G.) Ghigo. Decided for "…side"storage. G(higo) proposed use of γ -beam also for electrons. Typical possibility:

AdA
the ancestor of
today's e+e- and
pp_{bar} colliders .

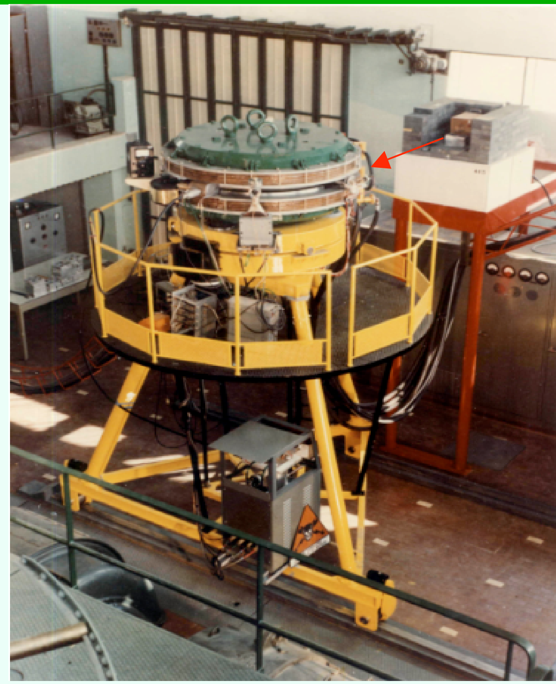
Injection by gamma's from the synchrotron producing pairs in internal thin targets

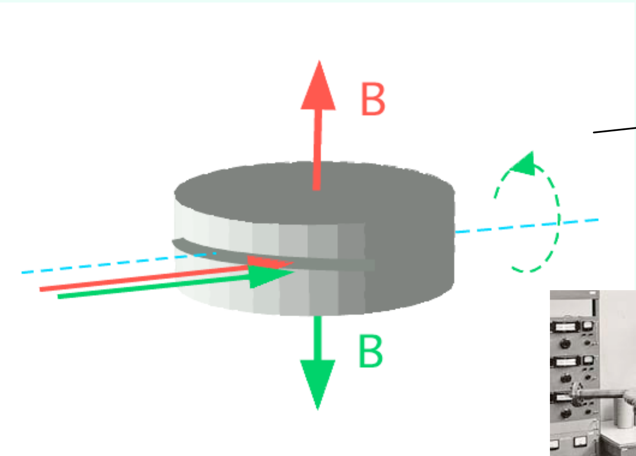


ADA in Frascati - the first e^+-e^- collider

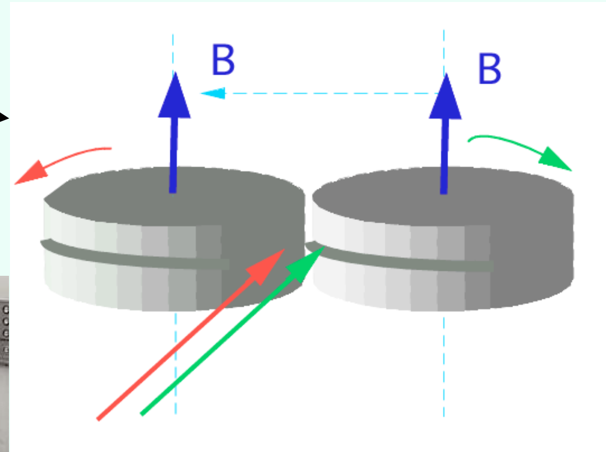


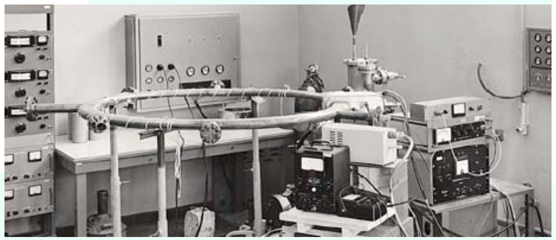
Nobody could tell which were positrons and which electrons !



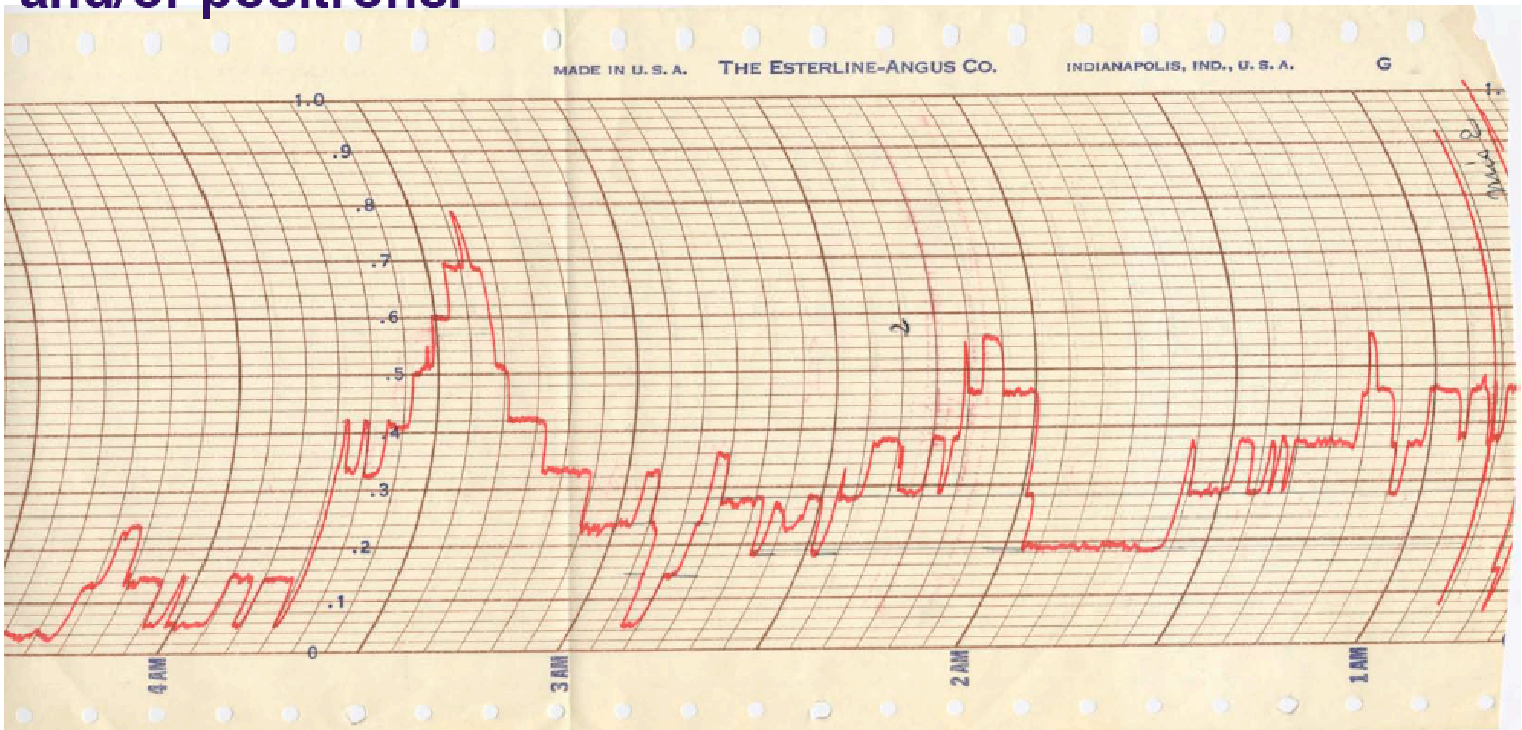


Beam loss due to falling dust





On February 27, 1961, just less than a year after Touschek's seminar, we got the first stored electrons and/or positrons.



The phototube record showing steps that correspond to single electrons entering or leaving AdA.

C.Bernardini, Phys. Perspect. 6 (2004) 156–183

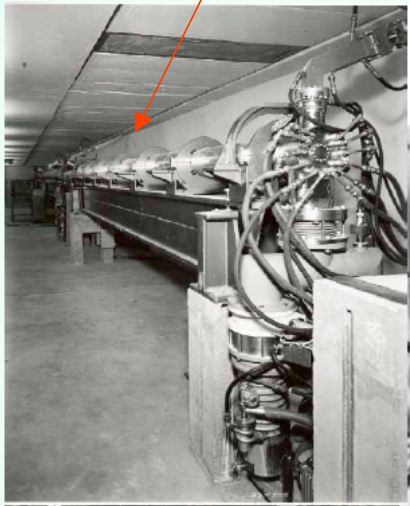
ADA in Orsay

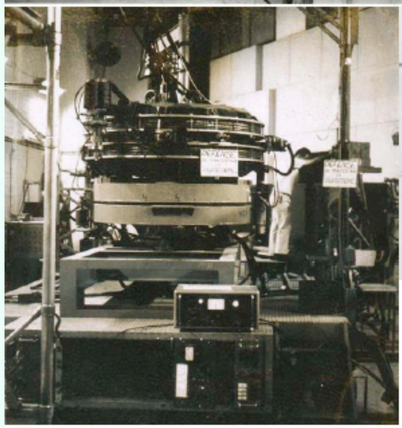
But the synchrotron intensity was not high enough and

following P. Marin's proposal, AdA was transferred to Orsay.

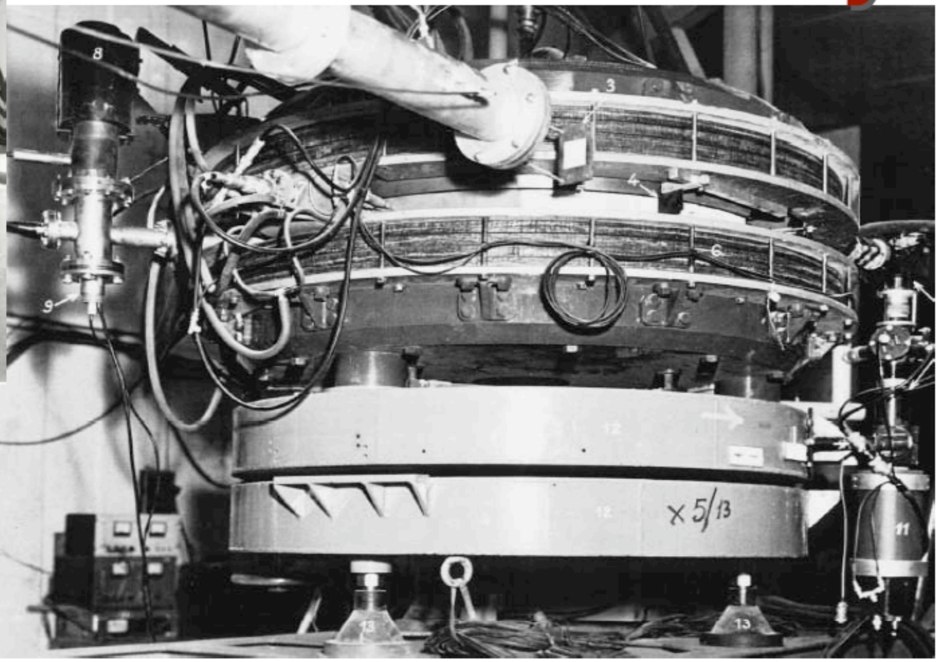
Injected by the 2 GeV Orsay electron/positron Linac

J. Haissinski
P. Marin





AdA at Orsay



AdA on the rotating and translating platform at Orsay. The injector beam channel is visible on the left.

C.Bernardini, Phys. Perspect. 6 (2004) 156–183

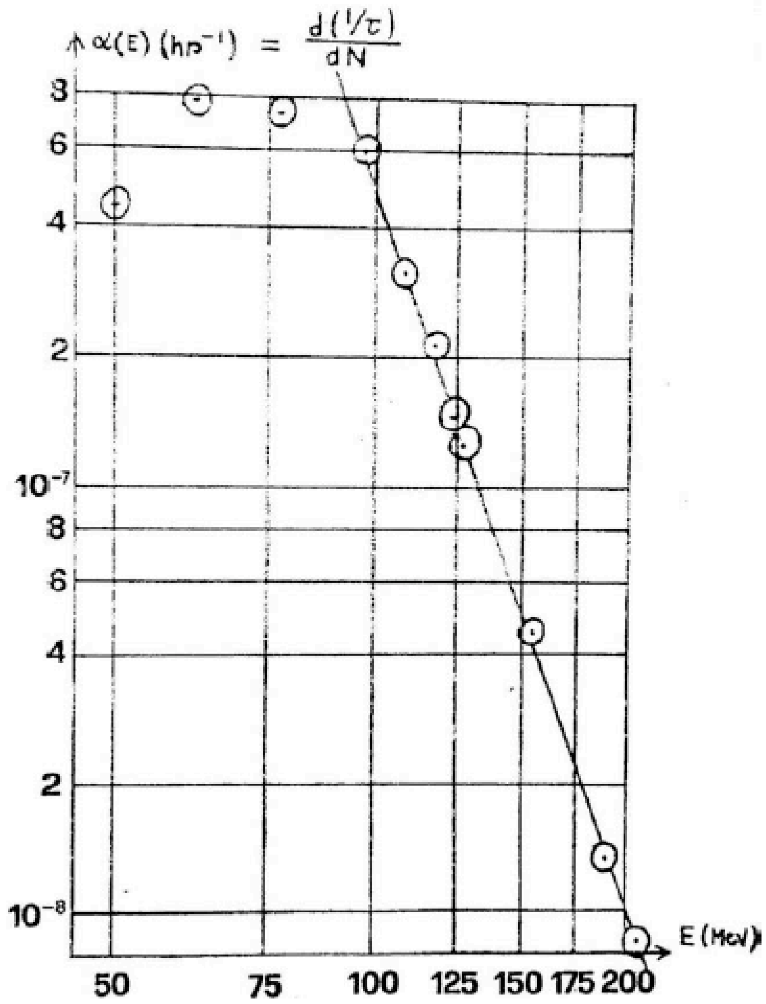
The Touschek effect

...at a certain point, we noticed that the injection rate was decreasing, and sometime later the stored current increased no further – it had reached saturation."

A few hours later :

".....Bruno reappeared announcing: "I got it! It is Møller scattering in the bunch!"

He then exhibited a formula, explaining that he had calculated that saturation should occur at the beam intensities we had reached because electron-electron scattering in the beam's bunches was transferring energy from the betatron oscillations in the transverse directions into the longitudinal stability zone, which was limited in the amount of energy it could accept."



Steep energy dependence

AdA achieved a peak luminosity of of 10^{25} cm^{-2} s^{-1}

Adone design: choices and open questions

1961 Study group under F. Amman **1963** First orders **1968** First physics runs
1991 Decommissioned ⟶ DAFNE

Main open questions at the time of design:

- Beam-beam limit
- Positron production
- Radiation effects in a strong focusing lattice
- Ultra high vacuum in a large chamber and gas load from radiation desorption.

1.5 GeV beam energy,
a nice round number but
J/ψ a few tens of MeV higher !

Adone design: early discoveries (= problems but learnig too)

Accelerator physics and technology:

- Head tail instability setting in at injection energy at the level of 100 μA circulating current
- Strong longitudinal instabilities due to (hundreds of) higher order modes in our four huge 10 MHz cavities.
- Single kick high voltage injector failures (eventually replaced), ...

Other : Physics runs started in **1968 !**

Discovery of multi-hadron production, ...

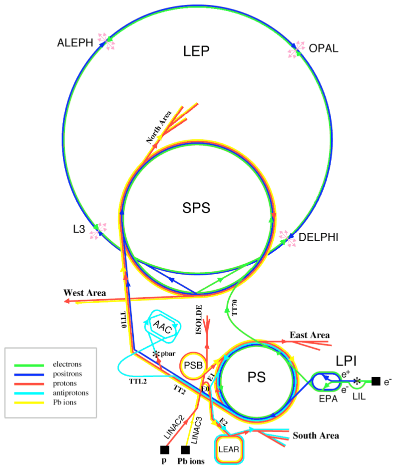
LEP (Large Electron Positron) - aerial view

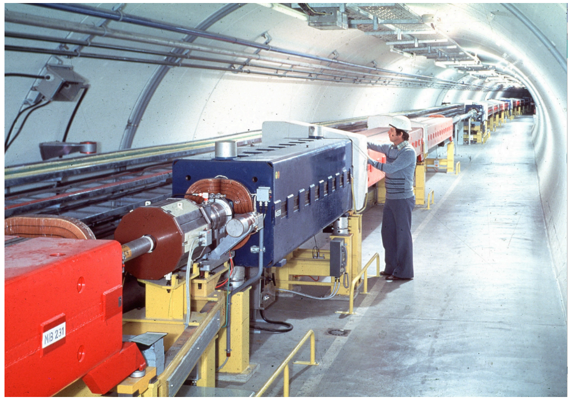
LEP (Large Electron Positron)

1981 approved, **1989** **LEP 1** first collisions at **46 GeV**/beam, at the Z_0

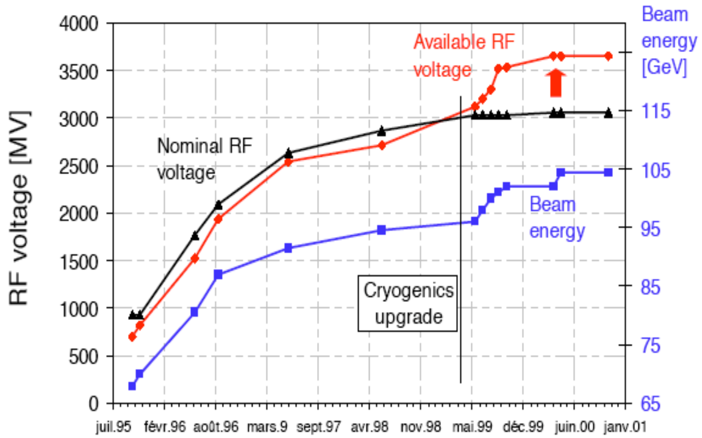
LEP 2 **1995** Upgraded operation starts with first installed of **SC** cavities

2001 Decommissioned





LEP Tunnel, 27 Km circumference



"A number of technical challenges had to be met by innovative designs such as the following.

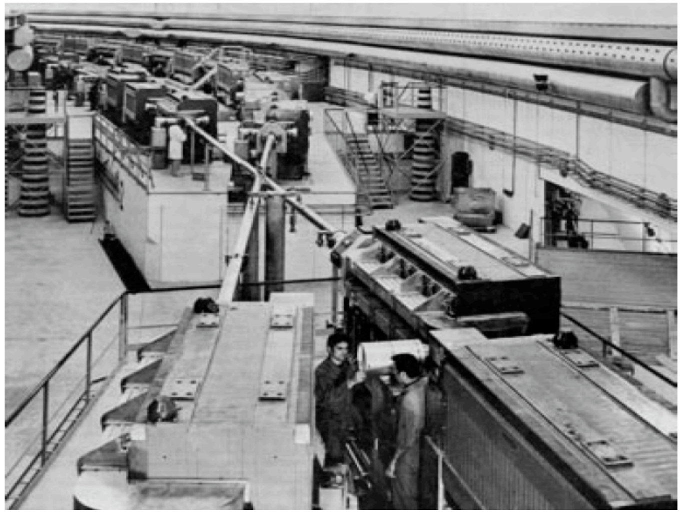
- *The cheap and rigid steel-concrete dipole magnets consisted of spaced iron laminations cement with mortar in between (27% steel filling), kept together by four pre-stressing rods running the whole length of 6 m. Concentration of the magnetic field in the laminations avoided reproducibility problems at injection where the average dipole field was only 240 G.*

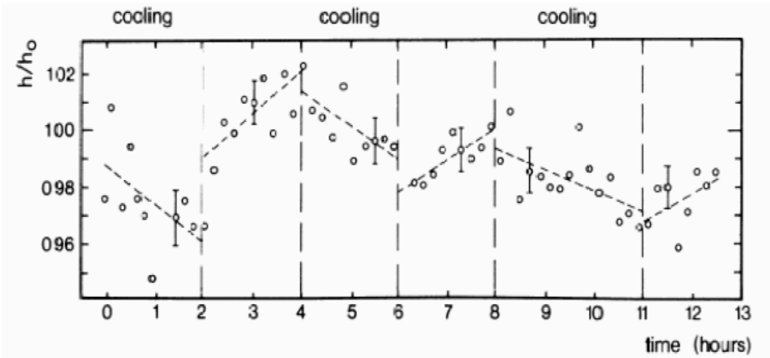
- *In order to avoid disturbance of the solenoid field in the detectors, warm-bore, iron-free superconducting low-beta quadrupoles had to be developed."*

K.Hübner, *50 Years Of Research At Cern: From Past To Future. The Accelerators*, CERN-AB-2005-031

From ISR, the first p-p colliders, to the $Spp_{bar}S$

1965 : approved **CERN** **1971** : in operation





Two 31 GeV, ~940 m circumference rings intersecting in eight places.

Proton bunches from the PS synchrotron were injected at 25 GeV, stored next to each other using a "stacking in momentum space" technique first developed by Kerst's group, accelerated to the final energy and de-bunched.

The main challenge for the ISR was to accumulate high-enough currents and maintain small-enough beam dimensions to achieve the high luminosity required by physics.

During actual physics runs it did store and collide world record currents, up to *57 A* per beam, and luminosity of $1.4\ 10^{32}\ cm^{-2}\ s^{-1}$.

The vacuum chamber pressure dictated by the desired beam lifetime also reached record values in the range of 10^{-11} *torr*.

The ISR, first of its kind, was quite obviously faced with many unexpected problems (resistive wall insatability, pressure bumps…) whose solution contributed significantly to the advancement of the field.

Most significantly, S. Van der Meer invented for the ISR "**stochastic cooling**", a terchnique that senses stochastic density fluctuations in the beam and damps them out by an active feedback system, which earned him the Nobel Prize shared with C. Rubbia.

Developed for and applied to the accelerator to improve its performance, it was the key to the realization of the Sp$\bar{p}$S proto-antiproton collider completed in **1981** .

The first e-p collider : HERA at DESY

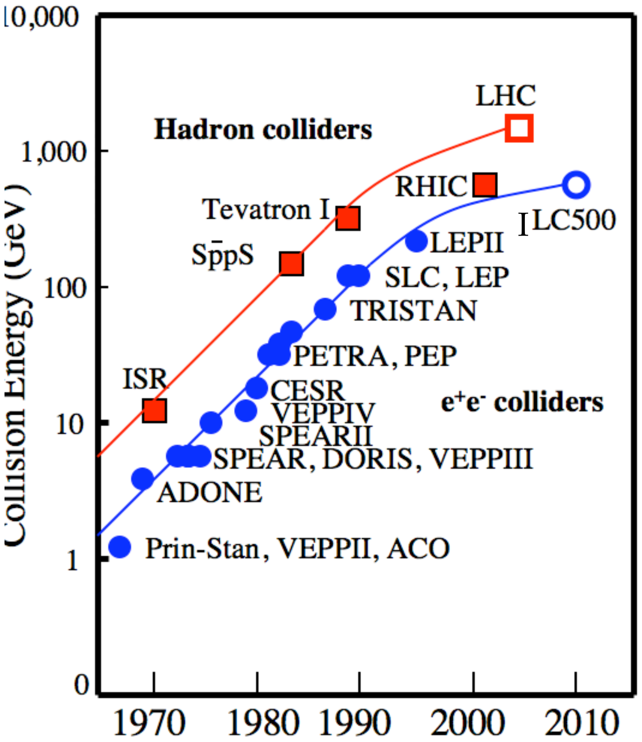
19.. : approved **19..** : in operation

From AdA to LHC.

Rings in the world

1961 AdA, Frascati
1964 VEPP 2, Novosibirsk, URSS
1965 ACO, Orsay, France
1969 ADONE, Frascati, Italy
1971 CEA, Cambridge, USA
1972 SPEAR, Stanford, USA
1974 DORIS, Hamburg, Germany
1975 VEPP-2M, Novosibirsk, URSS
1977 VEPP-3, Novosibirsk, URSS
1978 VEPP-4, Novosibirsk, URSS
1978 PETRA, Hamburg, Germany
1979 CESR, Cornell, USA
1980 PEP, Stanford, USA
1981 Sp-pbarS, CERN, Switzerland
1982 Fermilab p-pbar, USA
1987 TEVATRON, Fermilab, USA
1989 SLC, Stanford, USA
1989 BEPC, Peking, China
1989 LEP, CERN, Switzerland
1992 HERA, Hamburg, Germany
1994 VEPP-4M, Novosibirsk, Russia
1999 DAΦNE, Frascati, Italy
1999 KEKB, Tsukuba, Japan
1999 PEP-II, Stanford, USA
2003 VEPP-2000, Novosibirsk, Russia
2007 LHC, CERN, Switzerland

Energy frontier Accelerators



Effective constituent collision energy of Colliders (Physics Today, Jan. 2001)

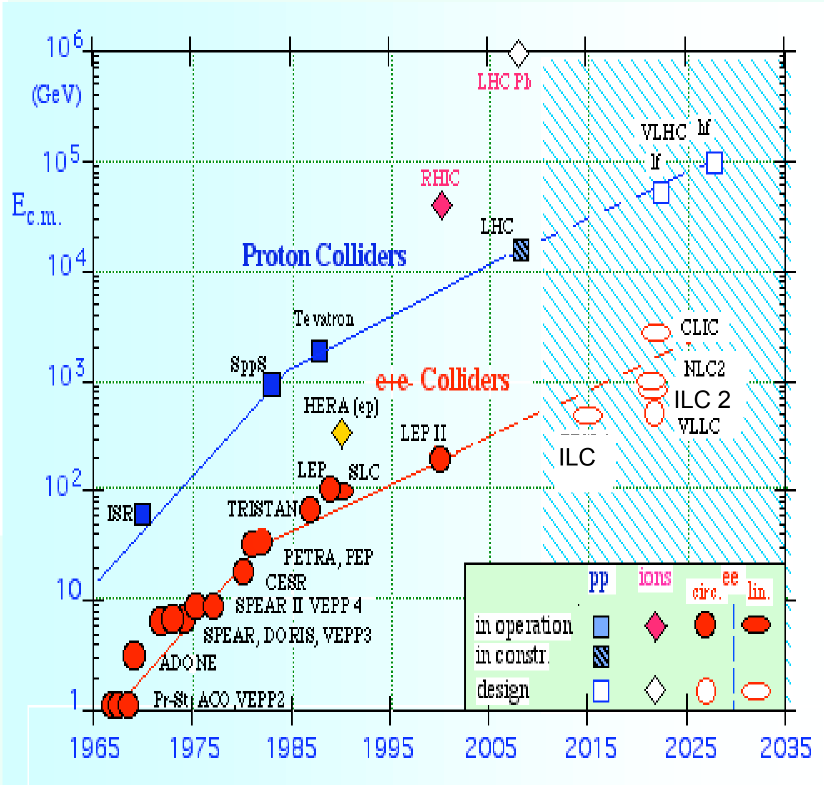
C.Bernardini, Phys. Perspect. 6 (2004) 156–183

From AdA to LHC.

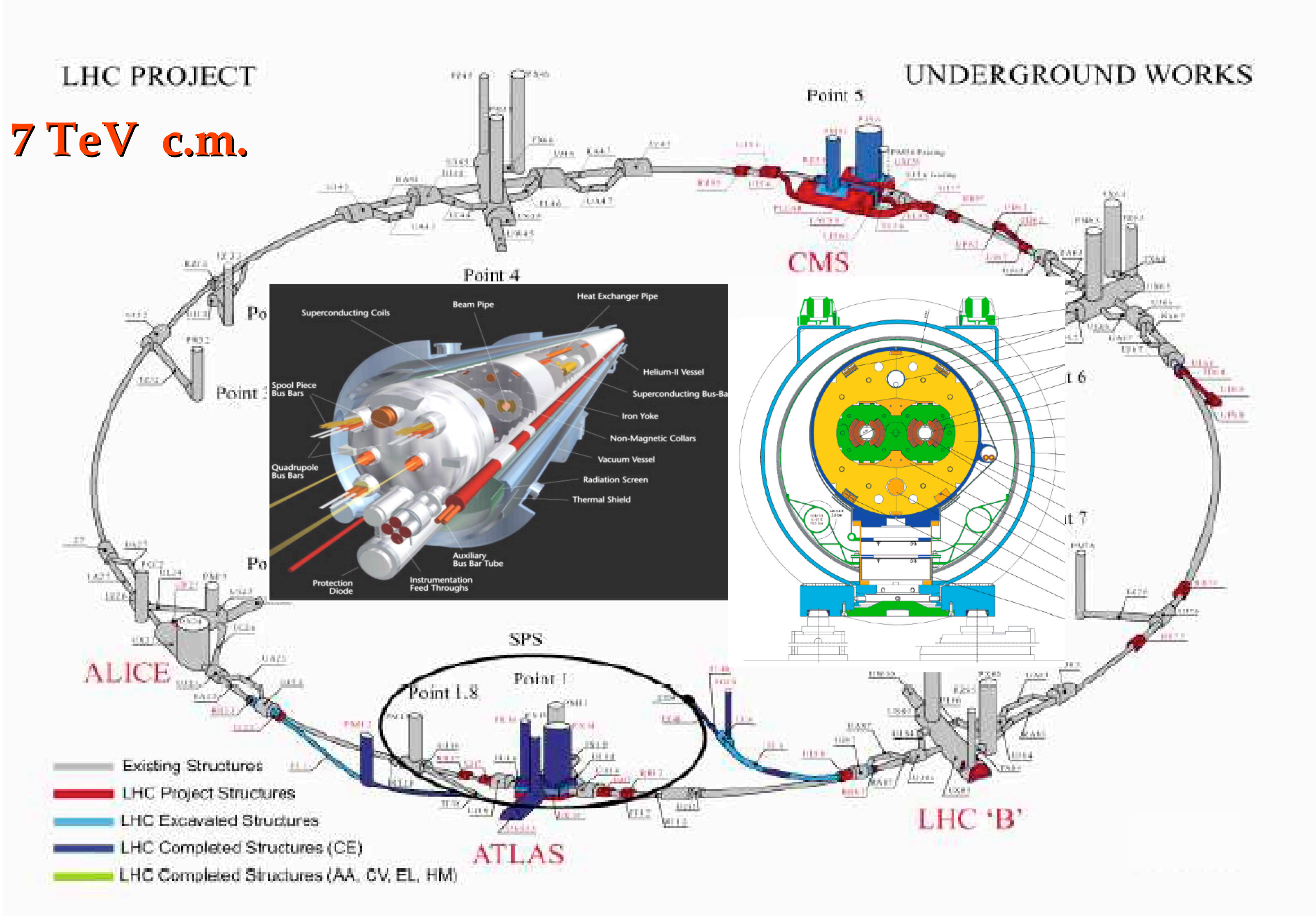
Rings in the world

1961 AdA, Frascati
1964 VEPP 2, Novosibirsk, URSS
1965 ACO, Orsay, France
1969 ADONE, Frascati, Italy
1971 CEA, Cambridge, USA
1972 SPEAR, Stanford, USA
1974 DORIS, Hamburg, Germany
1975 VEPP-2M, Novosibirsk, URSS
1977 VEPP-3, Novosibirsk, URSS
1978 VEPP-4, Novosibirsk, URSS
1978 PETRA, Hamburg, Germany
1979 CESR, Cornell, USA
1980 PEP, Stanford, USA
1981 Sp-pbarS, CERN, Switzerland
1982 Fermilab p-pbar, USA
1987 TEVATRON, Fermilab, USA
1989 SLC, Stanford, USA
1989 BEPC, Peking, China
1989 LEP, CERN, Switzerland
1992 HERA, Hamburg, Germany
1994 VEPP-4M, Novosibirsk, Russia
1999 DAΦNE, Frascati, Italy
1999 KEKB, Tsukuba, Japan
1999 PEP-II, Stanford, USA
2003 VEPP-2000, Novosibirsk, Russia
2007 LHC, CERN, Switzerland

C.Bernardini, Phys. Perspect. 6 (2004) 156–183



LHC - pp



LHC PROJECT
UNDERGROUND WORKS
7 TeV c.m.
Point 5
CMS
Point 4
Superconducting Coils
Beam Pipe
Heat Exchanger Pipe
Spool Piece Bus Bars
Helium-II Vessel
Superconducting Bus-Ba
Iron Yoke
Non-Magnetic Collars
Quadrupole Bus Bars
Vacuum Vessel
Radiation Screen
Thermal Shield
Auxiliary Bus Bar Tube
Protection Diode
Instrumentation Feed Throughs
SPS
Point 1
Point 1.8
ALICE
ATLAS
LHC 'B'
Existing Structures
LHC Project Structures
LHC Excavated Structures
LHC Completed Structures (CE)
LHC Completed Structures (AA, CV, EL, HM)

The Future of Colliders

"On the proton line, one has gone from the first bold initiative, the ISR at CERN which used conventional magnets, to the superconducting magnets that are used in all of the proton colliders built today."

"On the electron line, one can see a kind of complete cycle in accelerator technology, from the birth of the colliding-beam storage ring to its ***culmination in LEP II*** *and the beginning of the* ***next technique*** *for high-energy electron collisions,*
the linear collider*."*

(B.Richter, *The rise of colliding beams*, SLAC-PUB-6023, 1992).

The case of electron colliders

- Using B. Richters semi-empiric e+e- collider **cost-optimization law**: $\rho \approx R \propto E^2$

because : $R \propto E/B$ one has $B \propto E/R \propto 1/E$ **1st Problem**

For any **fixed radius**, the average power radiated-away per turn, P is :

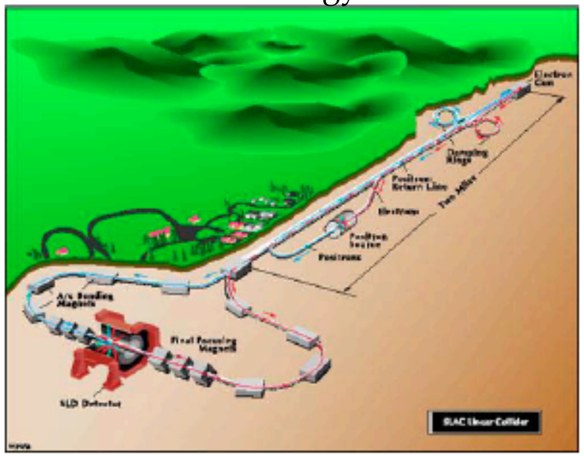
$P \propto E^4/R$ $\frac{P}{E} \propto E^3$ **2nd Problem**

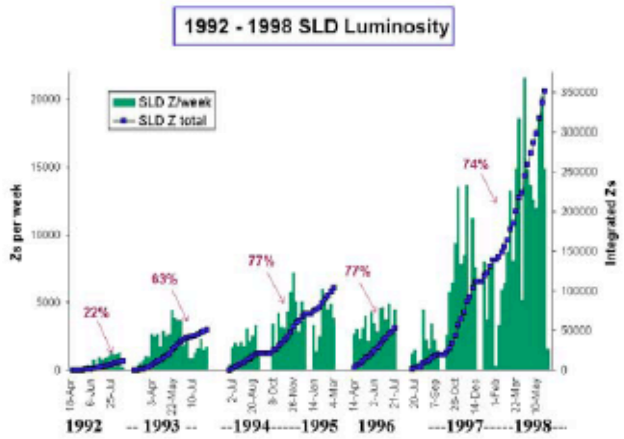
In practice : a circular collider to gain a factor of the order of 10 in energy w.r. to LEP can not be envisaged.

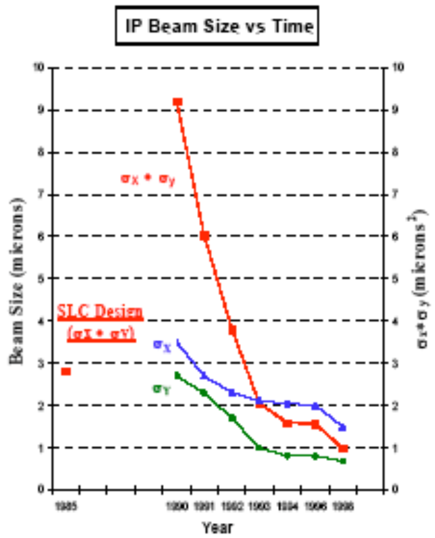
The first "linear" collider : SLC (SLAC Linear Collider)

1983 Start construction **1987** start commissioning **1990** start experiments

50 GeV cm energy





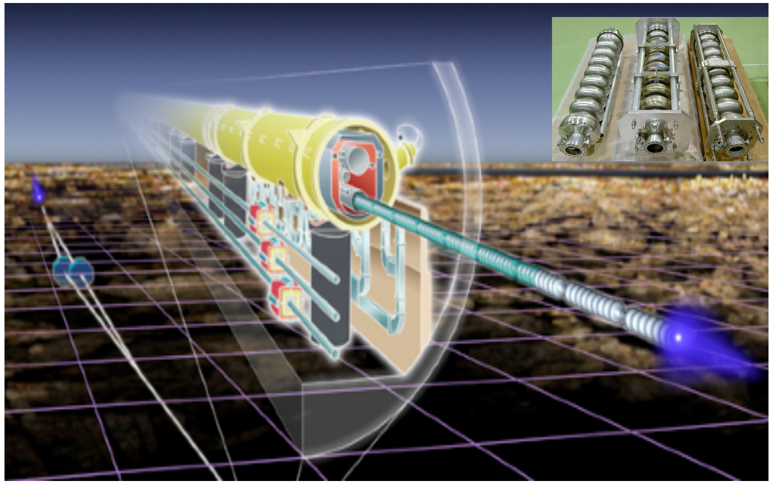


New Territory in Accelerator Design and Operation

- Sophisticated on-line modeling of non-linear beam physics.
- Correction techniques (trajectory and emittance), from hands-on by operators to fully automated control.
- Slow/fast feedback theory and practice.

Courtesy of C. Pagani

ILC 2015 ? CLIC



Superconducting Linacs approach

1990 *TESLA* Collaboration
(over 40 Institutions)
TTF test Facility

2005 Decision: choice of SC technology

International Linear Collider
Worldwide collaboration

~2015 500 GeV c.m. → 1TeV

f_{RF} =1.5 GHz V_{acc}= 35 MV/m

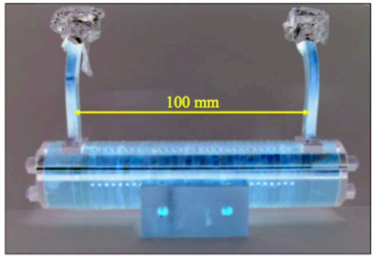
Warm Linacs approach → **NLC ,** SLAC-KEK Collaboration

↓

CLIC 3 TeV c.m.

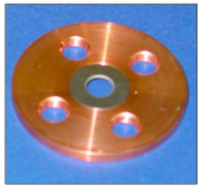
@ CERN

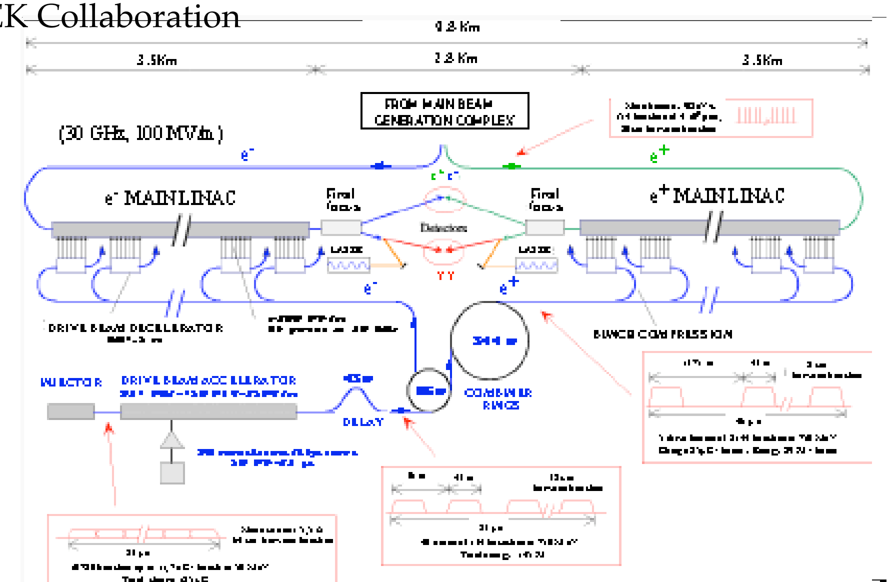
f_{RF} = 30 GHz V_{acc}~ 100 MV/m



193 MV/m peak accelerating field
426 MV/m peak surface field

2π/3 phase advance
3.5 mm aperture
Ês/<Eacc> = 2.84
4.6% v_g/c
T_{fill} 8.3 ns

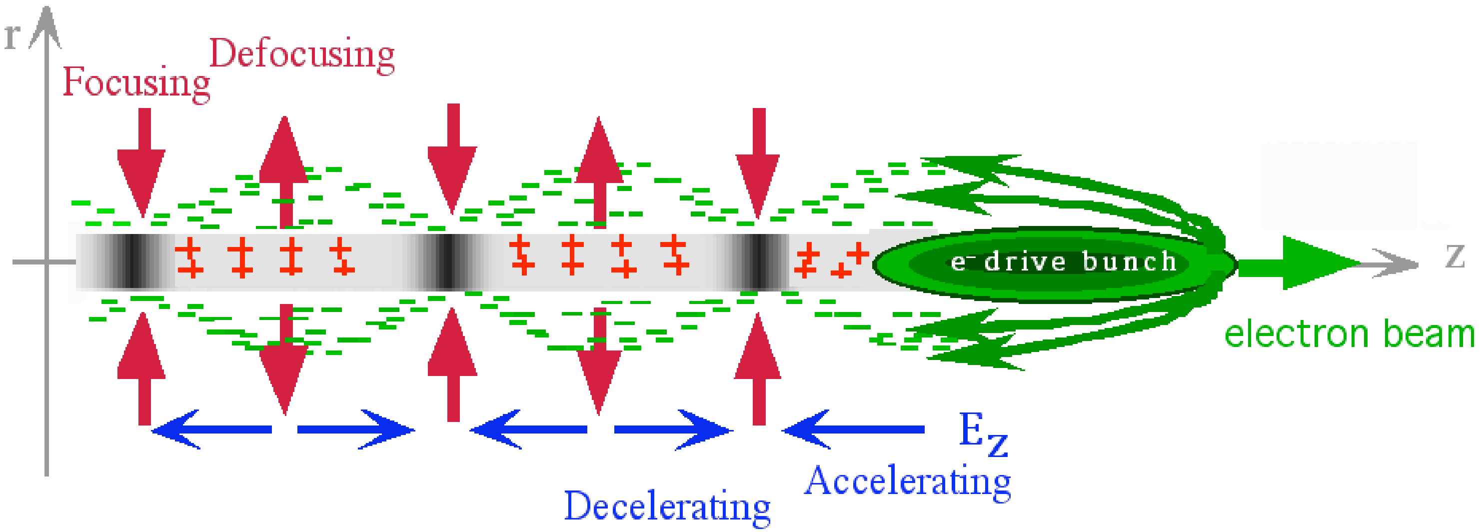




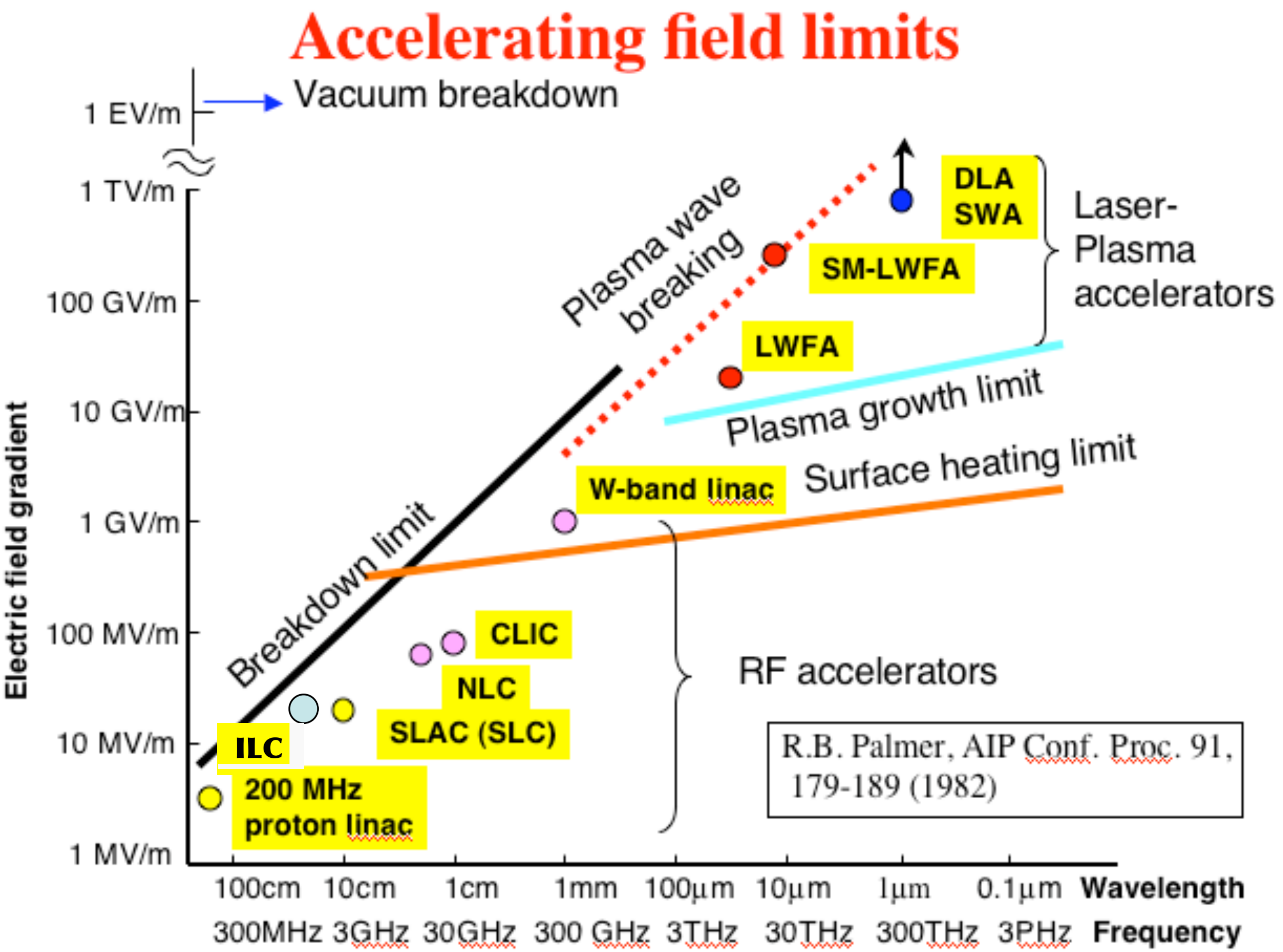
OVERALL LAYOUT OF THE CLIC COMPLEX AT 500 GEV C.M

CLIC Test Facility

Drive bunch excited plasma wake acclerator



A NEW GENERATION : Laser-Plasma acceleration



LWF :Laser Wake Field

Laser-Plasma acceleration : early work

Started in the early **1960's** with the work of **J.M. Dawson**

1983 *"Recently there has been a great deal of interest in using laser-plasma interactions to accelerate particles to high energies more rapidly than the 20 MeV/m to which linear accelerators are currently limited."*

*"The **beat-wave accelerator** is one scheme proposed by **Dawson and Tajima** to excite large amplitude electrostatic plasma waves which can accelerate particles."*

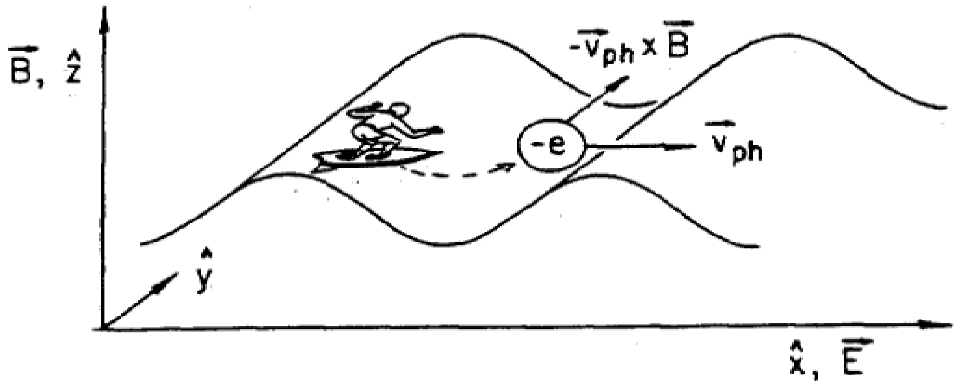
but

"...... particles in the beat-wave accelerator can gain only a finite amount of energy before they become out of phase with the beat wave...."

*"The limitation on the total energy gain ... with recent plasma accelerator schemes such as the beat-wave accelerator ..... is overcome by the **Surfatron**.*

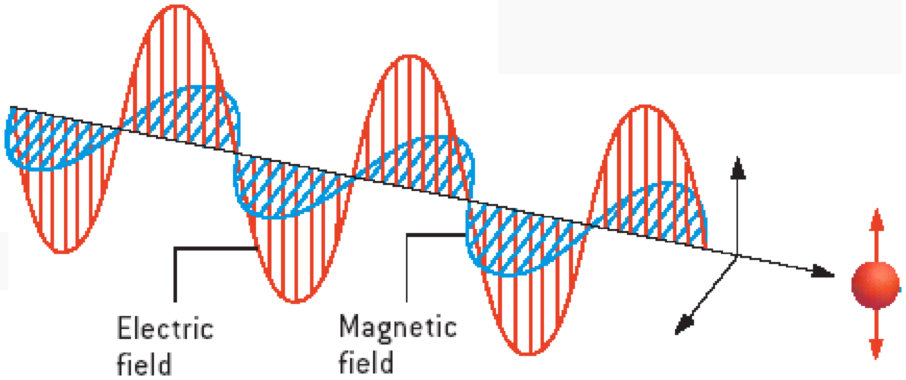
By introducing a perpendicular magnetic field it is possible to keep particles in phase with the laser-induced plasma waves and hence accelerate them to arbitrarily high energy.

The particles may be accelerated to arbitrarily high energy as they ride across the wave fronts like surfers cutting across the face of an ocean wave..."



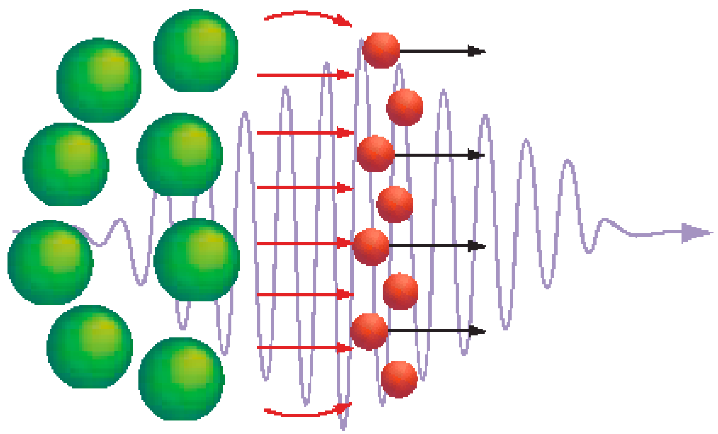
T. Katsouleas and J. M. Dawson, "*A Plasma Wave Accelerator - Surfatron 1*", IEEE Trans. Nucl. Science, Vol. NS-30, No. 4, August 1983

Laser excited plasma wake



For laser light of **TYPICAL INTENSITY**, striking the plasma, the light's electric field (red wave) makes plasma electrons oscillate at relatively low speeds so that the light's magnetic field (blue wave) does not appreciably affect them.

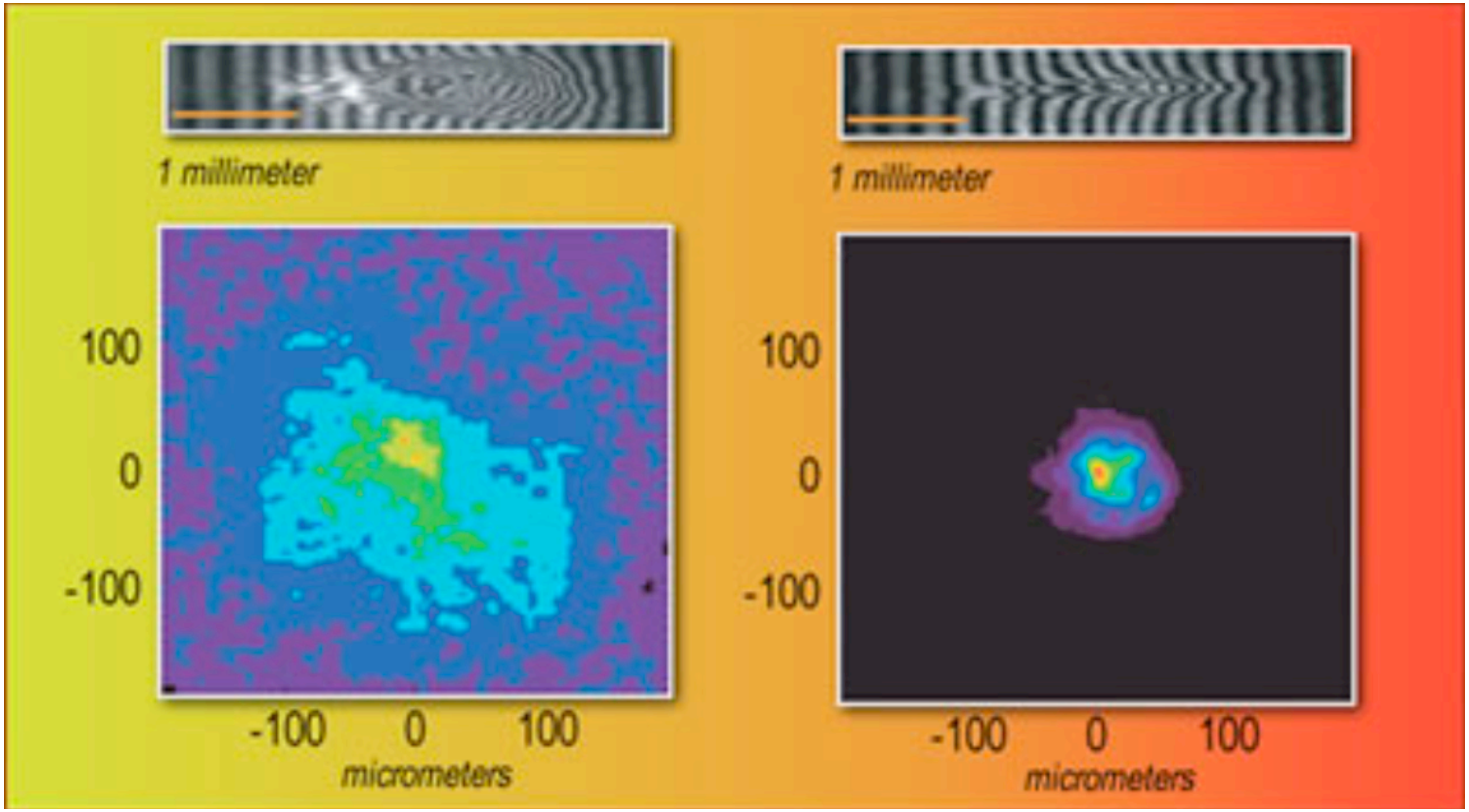
At **MUCH HIGHER INTENSITIES** the light striking the plasma makes the plasma electrons oscillate at velocities close to *c* do that the light's magnetic field makes them fly forward at high speed leaving the heavier positive ions behind.
This produces very high electric fields in between the now separated charges (red arrows).



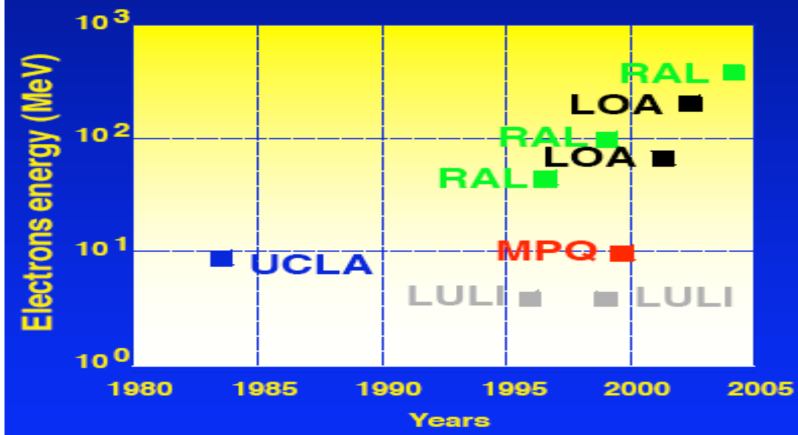
The gap between charges and the associated electric field trails along in the light wake and can accelerate other charged particles to very high energy

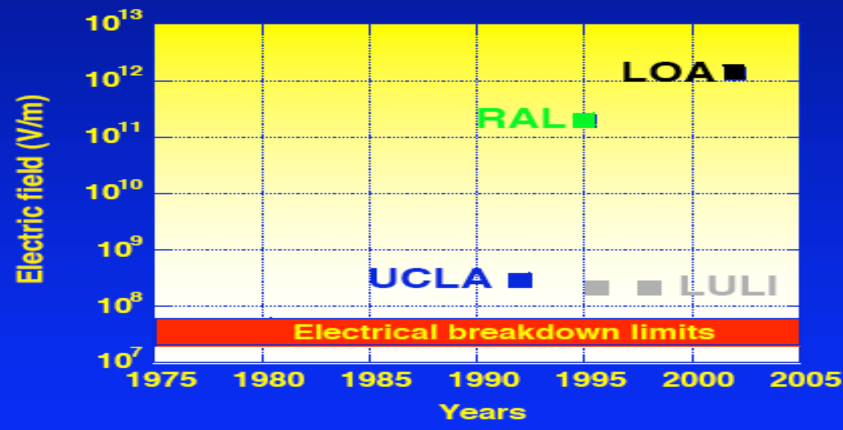
Channeled electron beam

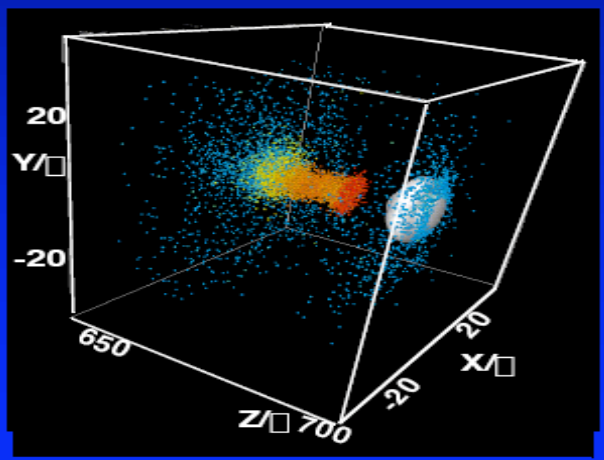
Laser propaga without and with plasma channel

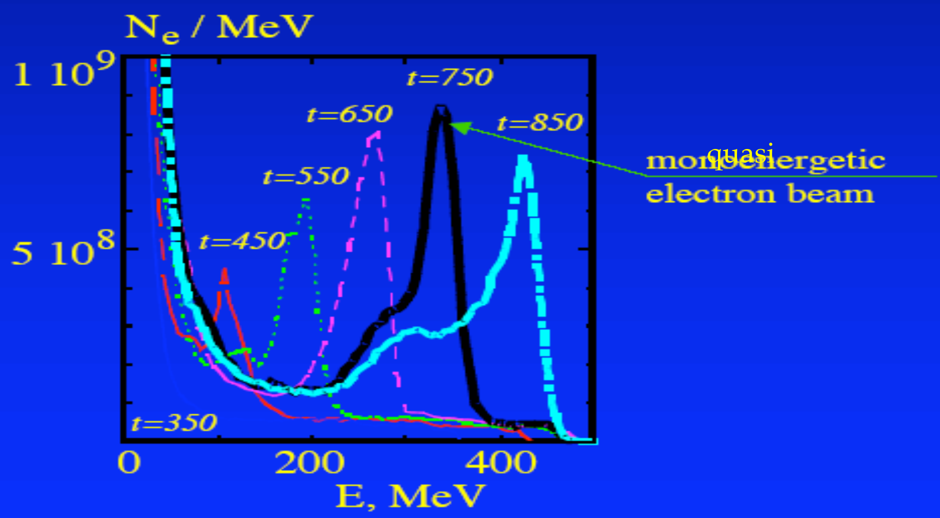


Progress in Laser acceleration









L O A

V. Malka et al , “Optically Induced GeV Electron Beams: The LOA Strategy , (2006),

Conclusion and future of laser particle acceleration

- •Laser particle acceleration has been demonstrated
  - •Energy gains of 1 MeV to 200 MeV
  - •E-fields of 1 GV/m to 1000 GV/m
  - •GeV energy gains are expected
  - •Good quality
- •Electron sources up to ~ 1 GeV (nC, <1 ps)
- •Electron beam duration has to be measured
- •Very high energy gains mainly rely on guiding
  - •Different schemes are being tested

V. Malka et al , "Optically Induced GeV Electron Beams: The LOA Strategy", (2006),