Limits of Conventional Techniques

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Abstract

At present, the highest particle energies are reached with synchrotrons and linear accelerators; the highest center of mass energies are produced in storage rings and linear colliders. The maximum energy of these devices is only limited by economical restrictions. For optimized machines, scaling laws can be derived which relate cost to energy. Advanced technologies such as superconducting magnets, superconducting rf resonators, ultra high power rf-sources etc. affect the constants in these scaling laws.

Progress in particle accelerator technology over the last 50 years has resulted in an increase of particle energy by a factor of about 35 every ten years. Fig. 1 is the famous Livingston chart showing the evolution of the different types of accelerators. For the last 30 years the high energy records were held by synchrotrons and electron linear accelerators. Both types of machines are not limited in their peak energy for physics reasons but only by reasons of economy. Progress over the last 25 years is mostly due to the perfection and economizing of these two types of accelerators.

The only qualitative new idea in the last 25 years in the area of accelerator technology has been that of colliding beams: By directing high energy beams against each other instead of directing them against a stationary target a very large factor in center of mass energy for the collision can be gained. The reason for this is the very large relativistic mass of high energy particles in modern accelerators, which is large as compared to the rest mass of the particles. Fig. 2 shows the center of mass energies which one can reach with colliding beams and in collisions where high energy particles from conventional accelerators hit stationary targets. One can define an "equivalent energy" E_{eq} for storage rings as that energy which would be necessary for a high energy particle to produce the same center of mass energy in a collision with a stationary target. Only by plotting these rather astronomical, but from the point of view of physics meaningless numbers on the Livingston chart, is it possible to satisfy the empirical rule of the factor 35 in energy increase every ten years up to the present time.

Colliding beam experiments can be done with storage rings or linear colliders. Storage rings are essentially synchrotrons with counterrotating currents of electrons and positrons or protons and antiprotons. Colliding beam experiments with particles of the same kind are done with two intersecting rings. Linear colliders are linear accelerators aiming the high energy particles against each other. Synchrotrons and storage rings, linear accelerators and linear colliders are the modern machines of high energy physics. The energy limit of these devices is economical and not technical. The maximum energy which can be reached with a given budget will depend to some extent on new technologies such as superconducting magnets and superconducting radio frequency resonators, but more so on the simplification of design to its absolute minimum in cost. In this area large advances have been made in the last 25 years.

Let us first consider proton accelerators. Costs of large proton machines are dominated by the tunnel and its installations and the magnet system. One would expect both to scale linearly with the radius R. That in turn is given by the maximum strength of the magnetic deflecting field B and the particle energy E

$$R = \frac{E}{c\ B} \quad (c = \text{velocity of light})$$

Considering that iron magnets saturate at 2 Tesla, and that only some 70 % of the circumference can be filled with deflecting magnets (the rest is needed for focusing, injection and ejection, acceleration and correction elements), one finds E to be about 400 GeV per kilometer of machine radius. We expect the costs of large proton accelerators to increase linearly with energy.

The prices for high energy proton synchrotrons are listed in the "Register of High Energy Physics Machines", but one must be careful in interpreting them: Listed are the prices for the "installation" which includes experimental halls, injectors, probably even machine shops and laboratory buildings. What is included in each listed price may be quite different for the different projects. I have escalated these prices to the equivalent 1982 level, Fig. 3a. If one divides these prices by the energy, one finds a dramatic decrease of unit costs with time, Fig. 3b. In a similar analysis L. Teng finds that unit costs go down like $E^{-2/3}$. I believe that there are certainly reasons why large machines can be built more cost efficient than small synchrotrons. But I also believe that the main effect is the time dependence: Accelerators today are built much more economically than in the past. Understanding of accelerator physics has matured to the point where technical design decisions are much better understood in their conceivable effect on machine performance; and people are willing to take bigger risks, because they are more confident about their ability to solve problems, should they arise.

Nobody will build airconditioned accelerator tunnels anymore with cranes running all the way around, magnets with sophisticated magnet foundations, complex surveying systems etc. Cutting out all these unnecessary frills has resulted in large savings, perhaps by one order of magnitude as related to unit cost, Fig. 4. I believe that these savings are much larger than those which we can expect from new technologies such as the superconducting magnet technology f.i. And this development toward progressively cheaper machines may not yet have reached its ultimate possibilities. We heard recently of ideas at Fermilab on how to build a very large proton accelerator which, of course, would also be used as a proton-antiproton collider: It would be built in a desert, where real estate would be cheap. The very long tunnel would be formed by a small diameter sewer pipe and would be installed with earth moving machines like sewer pipes are installed. The machine would no longer be in a plane but would follow the contour of the land. Magnets would have conventional steel yokes, but superconducting coils. They would be assembled during installation in large lengths. I guess such a machine would resemble the cybernetic accelerators which have been discussed for many years. The magnet aperture is so small and the magnet alignment is so poor that there is no chance that a beam will go around when the machine is turned on for the first time. But a computer will measure the beam displacement and watch where the beam gets lost. By calculating and turning on the required correction the computer will thread the beam around until the first turn is complete. Steering the beam with the last coils on the circumference such that the positions and angles of the first turn are reproduced should establish a closed orbit, good for many turns. The number of betatron oscillations in one turn Q of course also has to be determined and if necessary corrected. During the subsequent slow acceleration the computer has to keep track of orbit and Q-variations and correct them correspondingly.

All this has not been worked out in detail nor has it been brought to a proposal. But thoughts along these lines indicate to me that people have correctly realized that in the area of economizing accelerator design gains in unit costs are still easier to obtain than with fundamentally new technologies. It would be hard to predict by how much unit costs could still be reduced. I personally would guess that a factor of 3 does not sound too unrealistic.

These large factors have to be kept in mind when one looks at the advantage of the superconducting magnet technology: At Fermilab, superconducting magnets have been developed with fields of 4.6 T. The new Brookhaven ISABELLE-magnet reaches (at temperatures of 3° K) even more than 6 T. And design work on a 10 T magnet is going on at Berkeley, at Fermilab and at the KEK laboratory near Tokyo. The advantage of a higher field seems to be obvious: The machine size can be correspondingly smaller, resulting in hopefully lower costs. The other aspects are power costs: Superconducting magnets themselves need almost no electrical power, but power is needed for the refrigerator which keeps the magnets at the temperature of liquid helium. This power consumption - in the case of the 1000 GeV Fermilab doubler project estimated to be of the order of 10 to 20 MW - is considerably smaller than the power consumption of a machine with conventional magnets would have been. But then superconducting magnet refrigerators must work around the clock for most of the year, because the cool-down time of a superconducting machine would be quite long and the cool-down itself requires a large amount of electrical energy. Conventional accelerators on the other hand require only energy when used for acceleration, which typically is not more than half of the time. The power consumption of a conventional magnet depends on the design of the magnet and can be kept small by having large coil cross sections. In a properly designed machine power consumption over a certain number of years is balanced with capital costs such as to make the total expense over the expected life time of the accelerator a minimum. The power argument alone looses its meaning: What matters are the capital costs plus the operations costs over a certain number of years.

Capital costs of superconducting magnet systems are difficult to estimate, because no such system exists yet or has been put into operation. Furthest advanced is the Fermilab doubler project. Its design also served as the basis for the design of the HERA-magnet. Fig. 5 shows the estimated costs of the HERA magnet system including refrigeration per meter of machine circumference. Also shown are the costs of a comparable conventional magnet and the tunnel costs for various large projects which have been recently finished or have been proposed. If one takes the average tunnel costs to be 3800 US Dollars/meter and also takes into account that the ring is only filled with magnets for 70 % of its circumference, the price of a superconducting ring may be 30 % smaller than that of a larger ring with conventional magnets and the same energy. Considering the uncertainties of these estimates, one could almost say that the superconducting system has no economic advantage over the conventional system.

Would this picture change with superconducting magnets with higher fields? The highest strength which has been considered so far, is 10 T. Since the current carrying capacities of a superconducting wire decrease with increasing magnetic field strength, higher field magnets need more superconducting material and therefore will certainly be more expensive (the superconductor itself accounts for 25 % to 50 % of the magnet price). A major technical problem are the magnetic forces acting on the conductor, which increase quadratically with the field strength. The 10 T KEK design seems to be at the mechanical limit of strength. There is no estimate of the cost of a magnet system with these magnets, but I doubt very much that there is a real advantage as compared to a ring with conventional magnets and larger radius. The strongest argument for superconducting magnets is given where the site in question is limited and does not allow a very large installation, but where at the same time the peak energy of the proton synchrotron is of paramount importance.

Let us turn to electron synchrotrons and electron storage rings. The scaling law for large proton rings, in which size and costs are proportional to maximum energy, does not hold here. The reason being the synchrotron radiation losses in electron rings, which make the installation of very costly rf acceleration systems necessary. The energy losses W per turn are

$$W = .088 \frac{E^4}{R} \text{ [MeV]}$$

where E is the energy in GeV and R is the radius of curvature in the magnetic guide field measured in meters. Those losses amount to 58 MeV in PETRA at 19 GeV and require a peak accelerating field of about 100 MV. In proton machines such losses are smaller by the fourth power of the mass ratio of electron to proton. Even in such a large machine as the DOUBLER/SAVER at Fermilab the synchrotron radiation loss will be only 10 eV per turn, with protons having an energy of 1000 GeV. Synchrotron radiation only becomes significant in superconducting proton accelerators at energies higher than 100 TeV.

Because of the large synchrotron radiation losses, size and costs of circular electron machines scale with the square of the maximum energy. This scaling law can be easily understood in the following way: The cost of the machine (without injector, experimental halls etc.) consists mainly of that of the tunnel (length L), the rf system (length L_{rf}), the magnets with a bending radius of R and a fill factor of k in the arcs, and vacuum systems, cables etc. with a length of L.

Let c be the unit prices (price per meter) where

c_t = tunnel price

c_{rf} = price of rf-system (incl. klystrons, power supplies etc.)

c_m = price of the magnet (incl. power supplies)

c_v = price of the vacuum system, cables and other components of which the price goes with the length of the tunnel,

then the overall cost can be written as

$$C = L_{rf}\, c_{rf} + L\,(c_t + c_v) + 2\,\pi\, R\, c_m$$

The total length is

$$L = L_{rf} + 2\,\pi\, R\, k^{-1}$$

The length of the rf-system L_{rf} multiplied with the average gradient G must equal the voltage required to compensate the synchrotron radiation loss

$$L_{rf}\, G = a\, E^4\, R^{-1}$$

The constant a includes the necessary overvoltage for stable phase oscillations.

$$C = a\, E^4 R^{-1} G^{-1} (c_{rf} + c_t + c_v) + 2\pi\, R\, (c_m + k^{-1}(c_t + c_v))$$

The cost minimum is given when the derivative dC/dR is zero.

This yields the dependence of R on E:

$$R = E^2 \sqrt{\frac{a(c_{rf} + c_t + c_v)}{G\ 2\pi(c_m + k^{-1}(c_t + c_v))}}$$

The length of the rf-system is then

$$L_{rf} = a\ E^4\ R^{-1}\ G^{-1} = E^2 \sqrt{\frac{a\ 2\pi(c_m + k^{-1}(c_t + c_v))}{G\ (c_{rf} + c_t + c_v)}}$$

From these equations one can see the following:
R and L_{rf} are both proportional to E^2. This also means that the costs scale like E^2.
The ratio of R to L_{rf} is independent of energy or rf-gradient and depends only on the various unit prices.
R and L_{rf} scale inversely with the gradient$^{+0.5}$ and so do the costs. For a given amount of money the maximum energy will go up with $G^{+0.25}$.

These derivations are very much simplified, the conclusions, nevertheless, are qualitatively correct. Fig. 6 shows the costs vs. E dependence. If the pure machine costs are only considered, PETRA and LEP (phase II) scale in their costs approximately like the square of the energy (curve I). The gradient in normal conducting cavities is approximately 1 MV m^{-1}. If it were possible to maintain a gradient of 3 MV m^{-1} in superconducting cavities, curve II would follow. The storage ring CESR II f.i. would be on curve II.

Some of the unit costs which form the basis to Fig. 6 are shown in Fig. 7. In order to reach the highest electron storage ring energies, it is obviously advisable to strive for the highest rf-gradients (without increasing the rf unit costs c_{rf} of course). But before one starts with a heroic effort, one has to realize that the maximum energy will only go up with the fourth root of the gradient. This aspect is slightly discouraging. But the effort nevertheless is necessary, because we are still talking about large amounts of money.

One way of rf-power saving and thereby reducing rf-unit costs is to have the cavity voltage on only when one of the electron bunches passes by. It looks like this should be possible in very large electron machines when the time for one turn becomes long as compared to the filling time of the cavities. Ideally one would like to have a switch which would allow rf-power from a low-loss rf-storage device (f.i. a superconducting cavity) to enter the accelerating cavity at the right moment and a way to feed unused power back into the storage device. Unfortunately such a switch has not yet been developed. Another way which is not quite as efficient, is one in which one couples the accelerating cavity with a low loss storage cavity. This is being proposed for LEP and will lead to some power saving of the order of 40 %.

The most attractive way of increasing the gradient G and at the same time reducing c_{rf} through long range power savings would certainly be the use of superconducting accelerating cavities. Work toward that goal has been going on for at least 2 decades with disappointing results. During the last two years there seems to be some real progress though, through a better theoretical understanding of voltage limiting multipactor effects and a much larger attention to technological aspects (f.i. cleanliness and smoothness, chemical cleaning etc.). By shaping these resonators correctly, multipactor effects are suppressed. Present limitation seems to be field emission, which is easily enhanced by irregularities in the niobium material or by dust and chemical residues.

Single cells in the frequency range from 500 to 1500 MHz have reached gradients up to 11 MV m^{-1}. Multicell structures have exceeded 3 MV m^{-1} but so far there are only two cases of superconducting cavities which also have been tested in actual storage rings. At Cornell a 1500 MHz structure with an active length of 1 meter reached an accelerating field of 1.8 MV m^{-1} and allowed the storage of 7.4 mA of circulating beam at energies of 3.5 GeV. At about the same time a single 500 MHz cell built by the KFA Karlsruhe together with DESY and CERN reached in the PETRA storage ring an effective accelerating field strength of 2.3 MV m^{-1} and allowed the storage of 2 mA at an energy of 5 GeV. This cavity was kept in the storage ring for several months without loosing its qualities. It is difficult after such a long history of broken promises and disappointed expectations to make predictions. It looks to me like a system of 3 MV m^{-1} resonators should be feasible. 10 MV m^{-1} is certainly the outside limit of what could realistically be hoped for. The cost vs. energy for both cases are plotted in Fig. 6 (curves II and III).

Because of these voltage limitations I do not believe that superconducting resonators have any chance in the competition for high energy when used in pulsed linear accelerators. The cost vs. energy scaling law for linear accelerators is self evident: All costs increase linearly with length. Unit prices for superconducting and conventional structures are comparable. What matters then are only the achievable gradients in linear accelerator structures and here the conventional linacs are far ahead. They run with typical gradients of 10 to 20 MV m^{-1}; and this field is only limited by the available rf-power sources and not by break-down problems. S-band structures have been tested up to gradients of 50 MV m^{-1} with short (1 μs) rf-pulses without showing indications of break-down. This is probably one order of magnitude higher than superconducting structures will ever be able to handle. The use of superconducting linear accelerators will be limited to lower energy machines with high duty cycles. This is not what linear colliders ask for: In these installations intense single bunches are accelerated in linear accelerator structures and are brought to collision with single bunches from an opposing linac. The principal advantage of such an arrangement over electron storage rings is the lack of synchrotron radiation losses. This makes the dimensions and the costs of these machines scale linearly with energy. Taking present unit prices for linacs one would have a cost vs. energy curve as shown in Fig. 6. In the race for high energy these machines are certainly going to win. They are more economical even with today's technology at center of mass energies higher than approximately 300 GeV. But at that point the costs for either type of machine are so high that it is questionable whether such a machine would ever be funded. It is essential for linear collider projects to lower the unit prices for the rf-structure or to increase the accelerating gradient by a large factor. Otherwise they may never be in the position to enjoy their cost advantage over storage rings.

Work on high rf-power sources (tubes with pulsed power output of 150 MW to 1 GW and high efficiency), power doubling schemes (SLED), rf-power storage and switching devices, and investigation of new accelerating structures, is being pursued at various laboratories. The problem of building cost efficient linear accelerators seems to be the most important one for the future of $e^+ - e^-$ - physics.

Fig. 1: The Livingston chart, showing the evolution of various types of accelerators with time.

Fig. 2: Center of mass energy E_{CMS} in colliding beam devices and in conventional experiments with stationary targets as function of particle energy. E_{eq} is the "equivalent energy" of colliding beam devices.

Fig. 3a: Prices of accelerator "installations" as quoted in the "Register of High Energy Physics Machines", but escalated to 1982 dollars.

Fig. 3b: The same as in Fig. 3a but now prices divided by energy.

Fig. 4: Accelerator technology 1960 and 1975: Tunnel cross-sections are drawn to the same scale.

Fig. 5: Prices per meter for superconducting magnets (incl. refrigeration and installation), for conventional proton synchrotron magnets, for the "super ferric" magnets (this is a wild guess) and for tunnels built by different technologies.

Fig. 6: Prices for electron storage rings with various rf-systems and prices of linear colliders (present day technology). Prices do not include injectors, exp. halls, access tunnels, i.e. items not included in the scaling law.

Fig. 7: Prices per meter of rf-systems for electron storage rings and electron linear accelerators incl. power costs for 20,000 hours of operation.

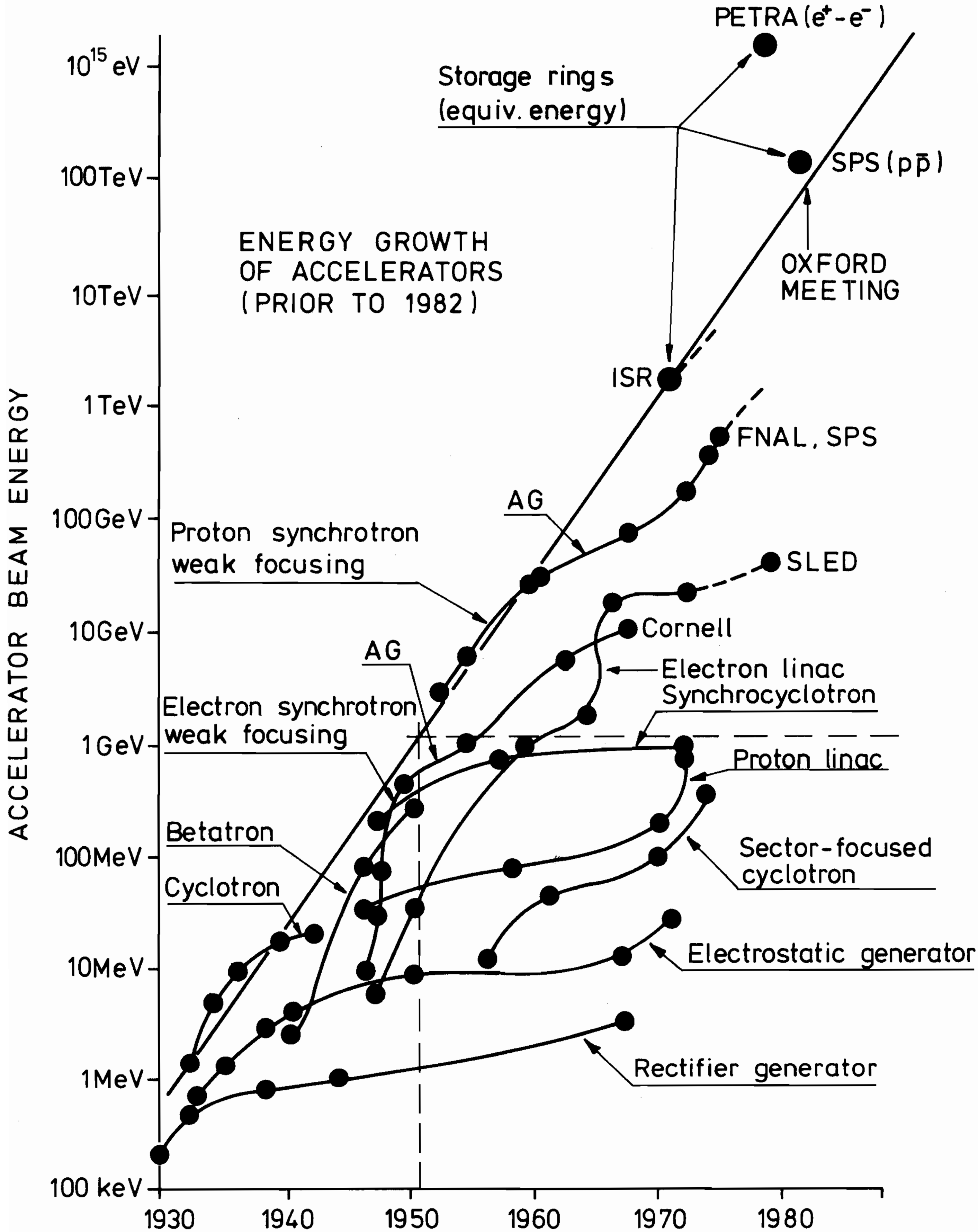


Fig. 1 Livingston Chart

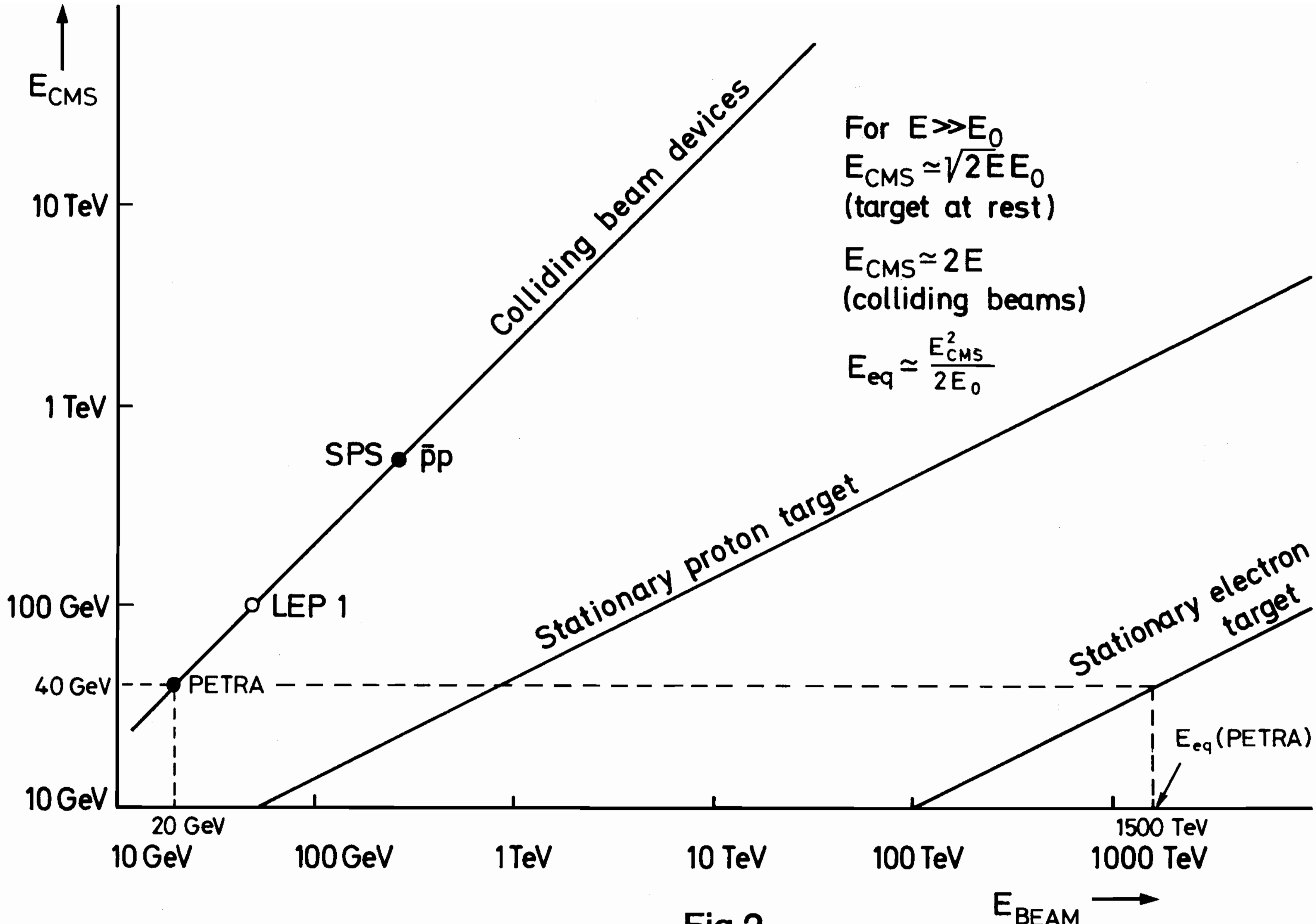

E_CMS
10 TeV
1 TeV
100 GeV
40 GeV
10 GeV
Colliding beam devices
SPS
p̄p
LEP 1
PETRA
Stationary proton target
Stationary electron target
For E≫E_0
E_CMS ≃ √(2E E_0)
(target at rest)
E_CMS ≃ 2E
(colliding beams)
E_eq ≃ E²_CMS / 2E_0
E_eq (PETRA)
20 GeV
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
1500 TeV
1000 TeV
E_BEAM

Fig.2

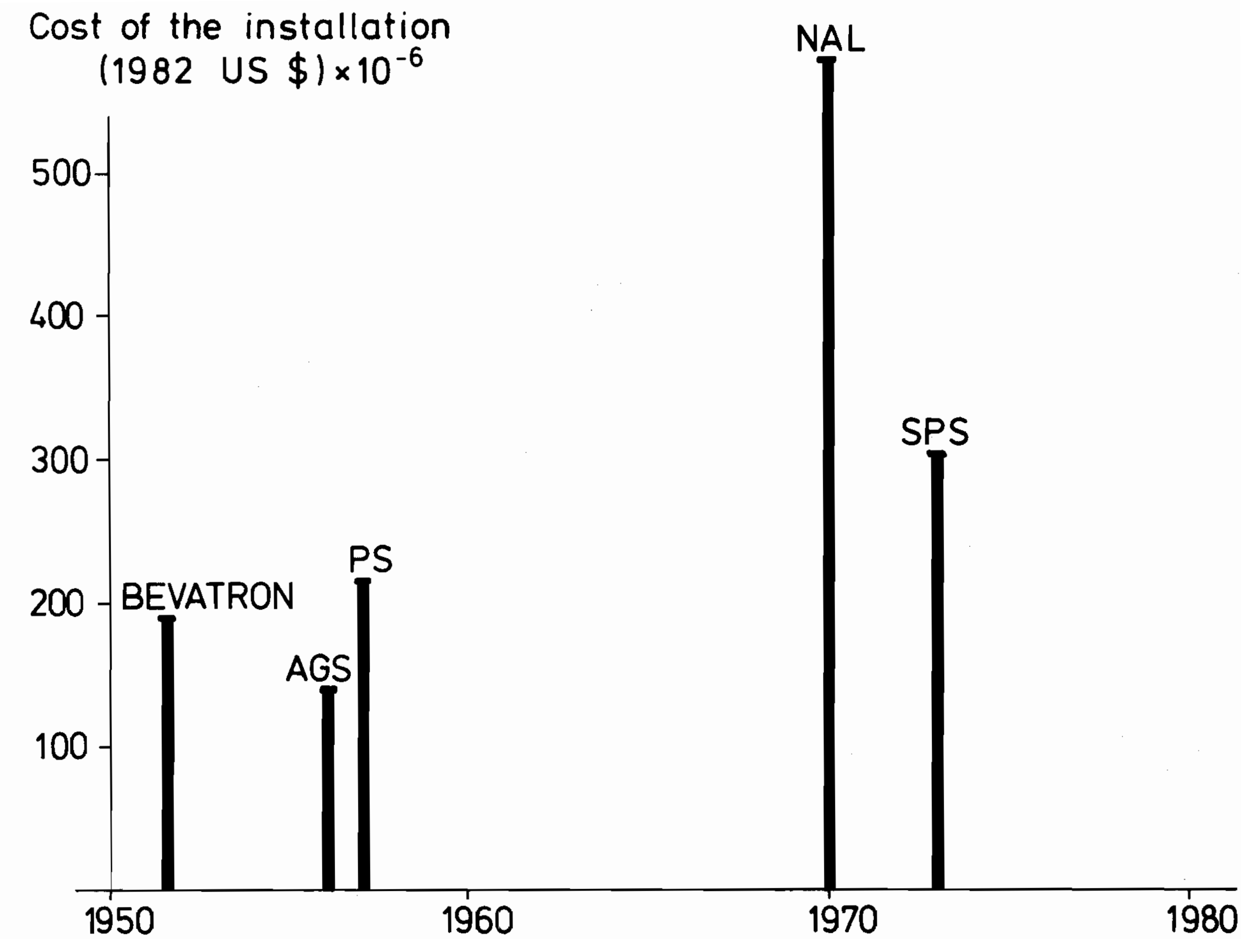

Cost of the installation
(1982 US $)×10⁻⁶
NAL
SPS
PS
BEVATRON
AGS
500
400
300
200
100
1950
1960
1970
1980

Fig. 3a

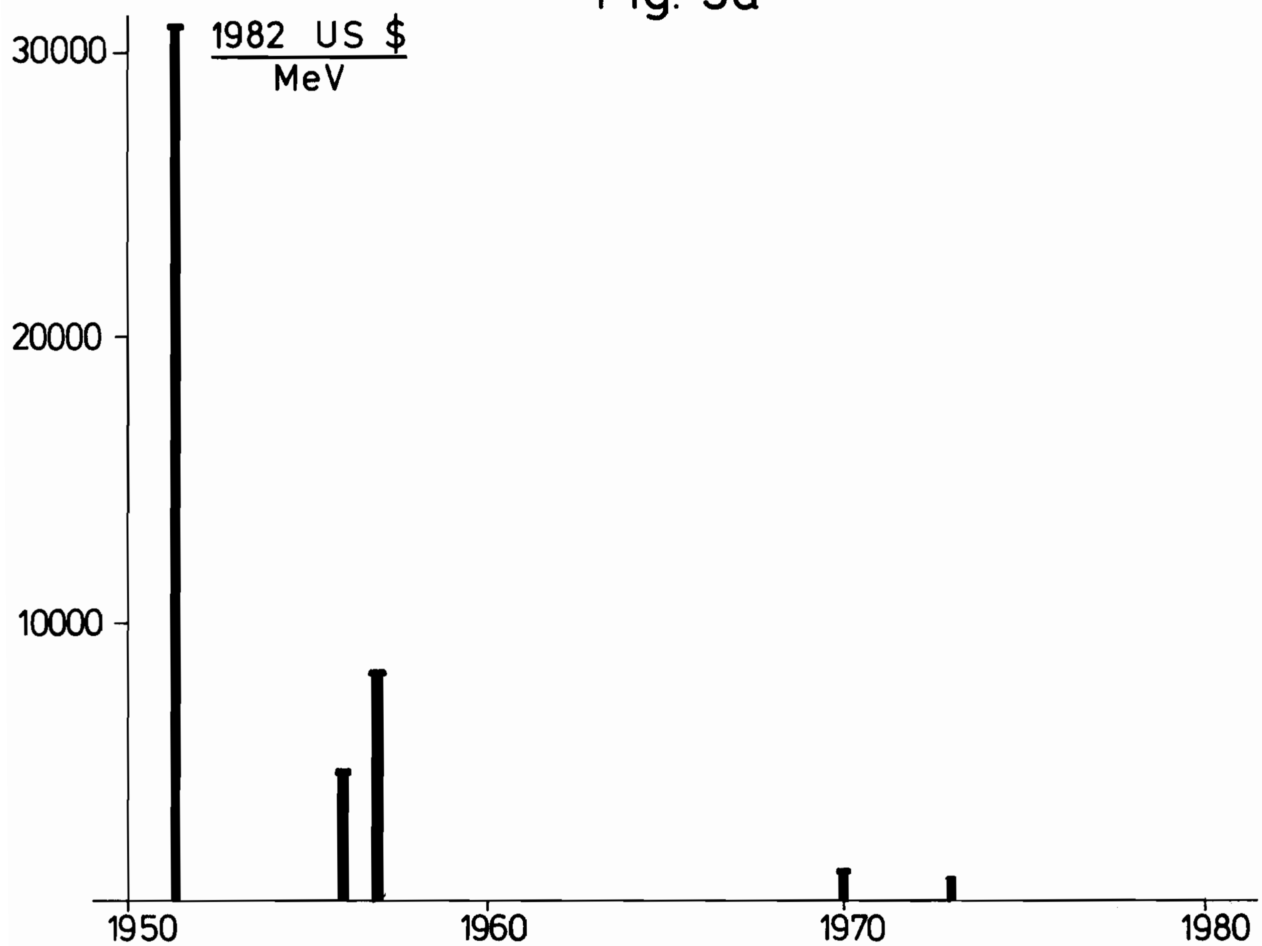
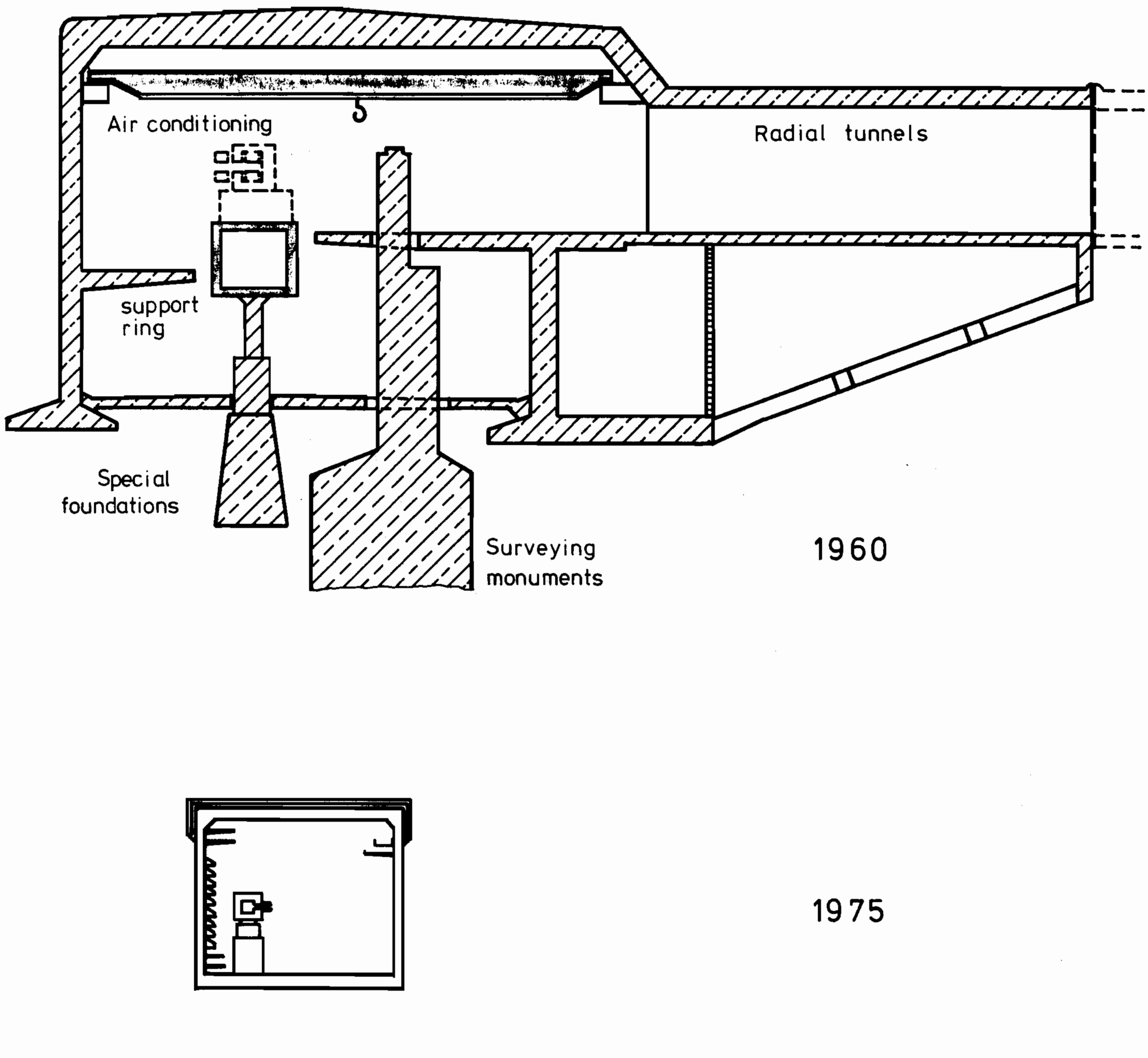

1982 US $ / MeV
30000
20000
10000
1950
1960
1970
1980

Fig. 3b



Air conditioning
Radial tunnels
support ring
Special foundations
Surveying monuments
1960
1975

Fig. 4

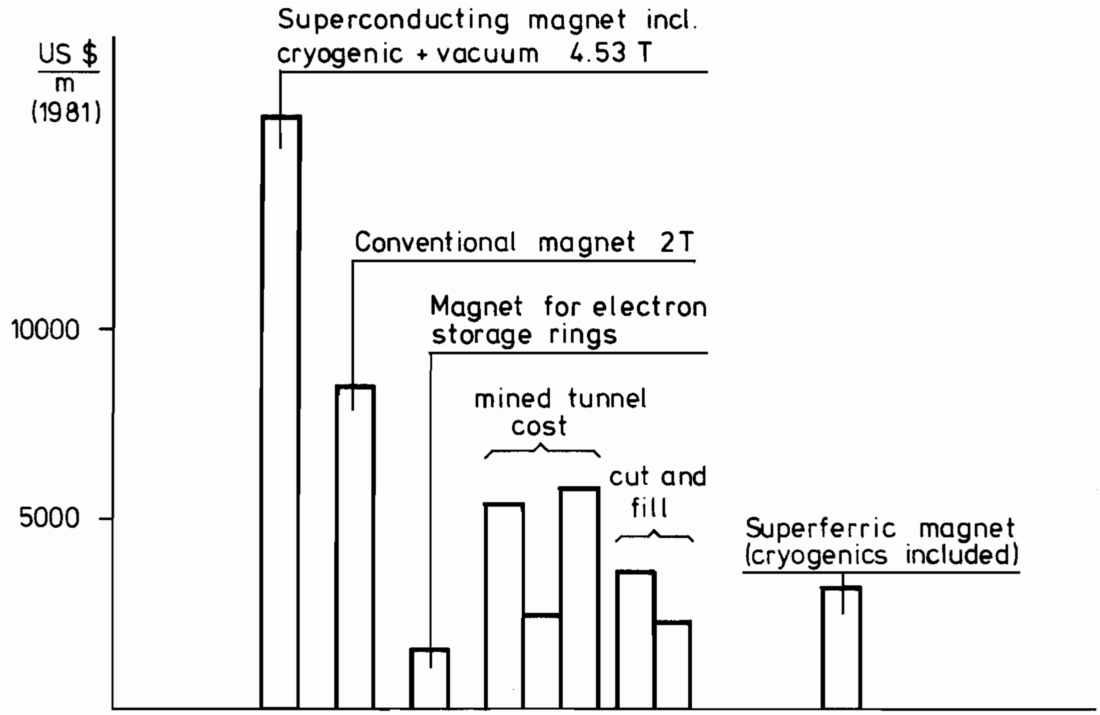
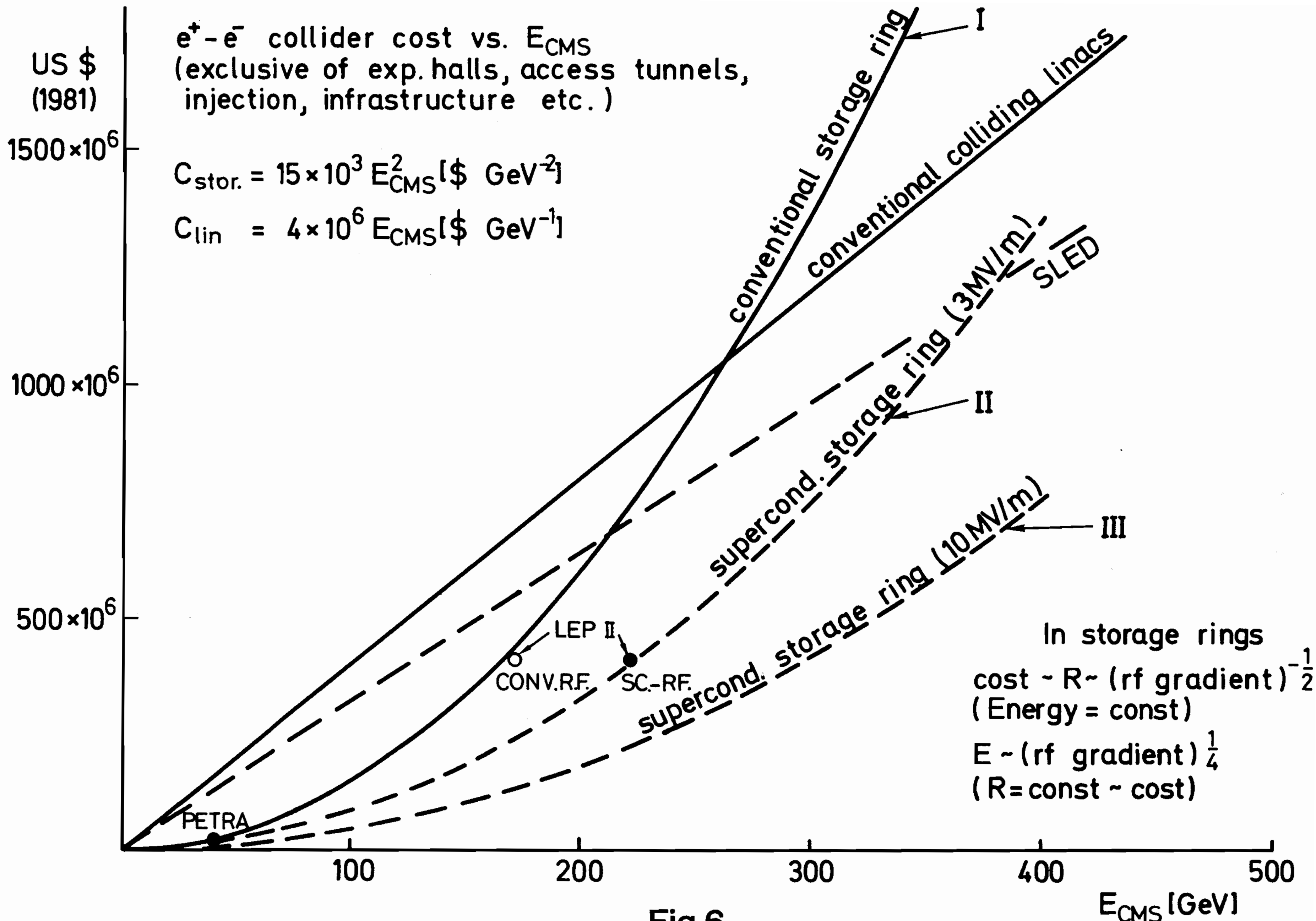
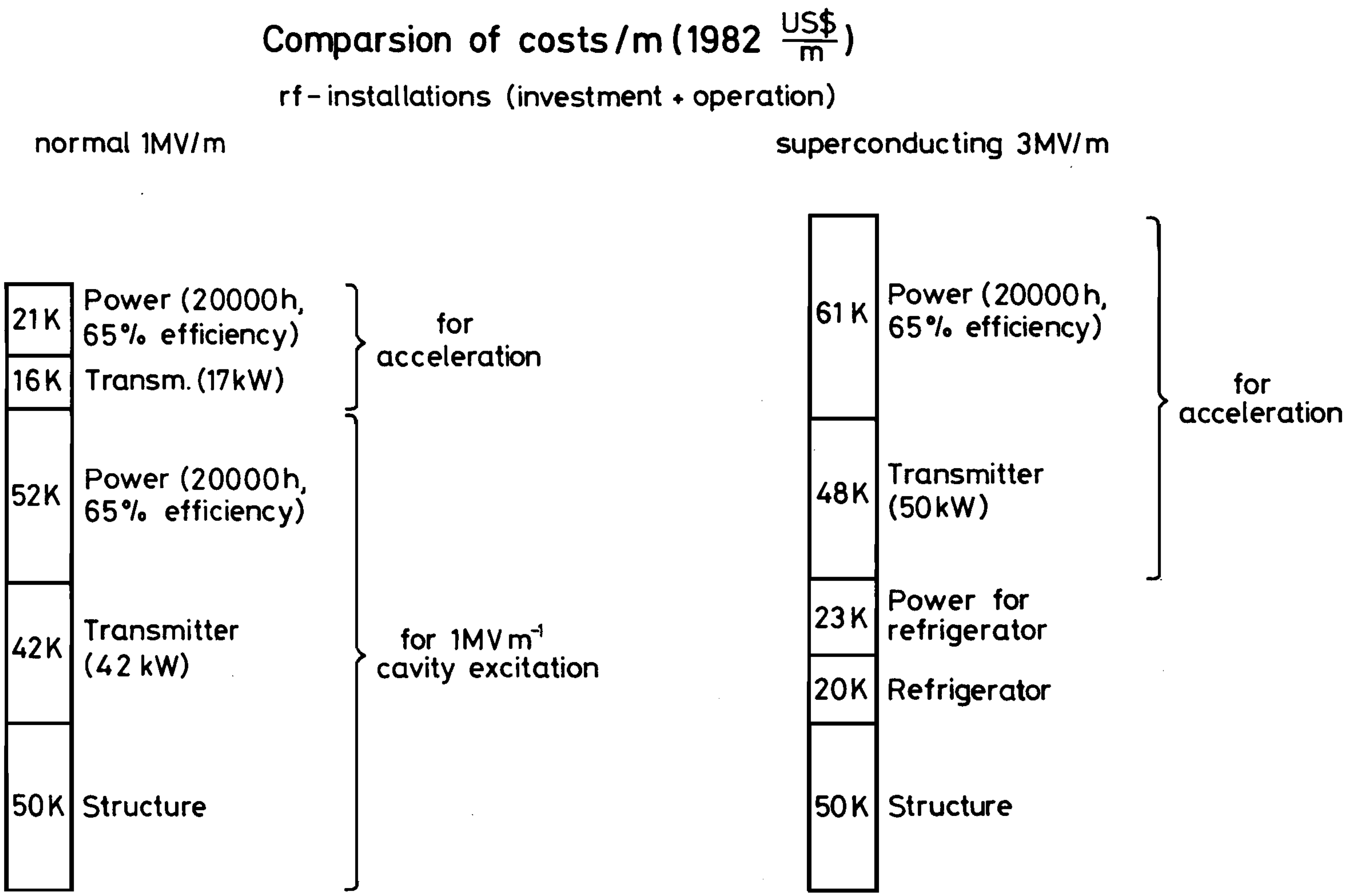

US $
m
(1981)
10000
5000
Superconducting magnet incl.
cryogenic + vacuum 4.53 T
Conventional magnet 2T
Magnet for electron
storage rings
mined tunnel
cost
cut and
fill
Superferric magnet
(cryogenics included)

Fig. 5



US $
(1981)
$e^+ - e^-$ collider cost vs. E_{CMS}
(exclusive of exp. halls, access tunnels, injection, infrastructure etc.)
$C_{stor.} = 15 \times 10^3 E_{CMS}^2 [\$ \; GeV^{-2}]$
$C_{lin} = 4 \times 10^6 E_{CMS} [\$ \; GeV^{-1}]$
1500×10^6
1000×10^6
500×10^6
conventional storage ring
I
conventional colliding linacs
supercond. storage ring (3MV/m)
SLED
II
supercond. storage ring (10MV/m)
III
LEP II
CONV.R.F.
SC.-RF.
PETRA
In storage rings
cost ~ R ~ (rf gradient)$^{-\frac{1}{2}}$
(Energy = const)
E ~ (rf gradient)$^{\frac{1}{4}}$
(R = const ~ cost)
100
200
300
400
500
E_{CMS} [GeV]

Fig.6



Comparsion of costs/m (1982 US$/m)
rf-installations (investment + operation)
normal 1MV/m
21K Power (20000h, 65% efficiency)
16K Transm. (17kW)
for acceleration
52K Power (20000h, 65% efficiency)
42K Transmitter (42 kW)
50K Structure
for 1MV m⁻¹ cavity excitation
superconducting 3MV/m
61 K Power (20000h, 65% efficiency)
48K Transmitter (50kW)
for acceleration
23K Power for refrigerator
20K Refrigerator
50K Structure

Fig. 7

DISCUSSION

Palmer. As one appraches energies appropriate to a 'desert' machine, it is possible that a machine with pulsed magnets which are only switched on when the particles come by might have power and unit costs much cheaper than those of a superconducting machine. This idea, although discussed, has not been written up.

Willis. Studies at Brookhaven have shown that the superferric magnet design has some nasty problems. But if you do have such magnets there is no need to restrict them to 2 Tesla, why not 4 or 5 Tesla?

Voss. Above 2T the fields are no longer determined only by the steel profile; non-linearites arise from steel saturation.

Palmer. Superconducting magnets have many horrible problems, but shaping the fields is not one of them. Placing the conductors is not significantly more difficult than shaping iron surfaces. I don't think that sextrpole field components are a problem.

Amaldi. If one considers intensity rather than energy the arguments are somewhat different. For colliding linacs luminosity is proportional to beam power, and thus more luminosity is obtainable with a superconducting colliding beam linac than with a normal linac. If you want both energy and luminosity you may need to go to superconductivity, which is more expensive.

Richter. I think this is wrong, and the problem is not one of principle but one of cost. If you take account of gradients now achievable with superconducting linacs they get to be monstrously long and very expensive. If, alternatively, you say that we can improve the gradients, the Q obtainable at a few degrees K puts so much power into the refrigerators that the plant costs more to run than a conventional one. Superconductivity is not the cheapest way to get high power.