PARTICLE ACCELERATORS — OUTLOOK FOR THE TWENTY-FIRST CENTURY

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Abstract

An outlook for the development of particle accelerators in the twenty-first century is gleaned from extrapolations of the experiences collected during the latter part of the last century. This perspective, somewhat personal, will be discussed relative to the needs in different fields of science and in conjunction with the many accelerator projects, on-going and proposed.

1 INTRODUCTION

With a title like this, I have a choice. I could survey the R&D of accelerator technologies such as laser-plasma acceleration for high beam energy, high-power rf source for high beam current, or low-β and beam cooling schemes for high beam brightness. But at this conference you have already heard many excellent talks on these subjects. So, I will take a step back to look at the requirements on beam characteristics imposed by various fields of science and applications, and examine how and to what extent these requirements are being met.

During the latter half of the last century, a majority of physics experiments were "beam experiments" in which a beam of particles was shot at a sample target (which may also be an opposing beam), and the outgoing particles were investigated. This technique has also been extended to chemistry using molecular beams to study the dynamics of chemical reactions. To get particle beams, one needs accelerators.

2 PARTICLE PHYSICS

The principal goal in particle physics is the discovery of new particles. For this one needs high energy and high luminosity. At these high collision energies, one uses almost exclusively "colliders."

2.1 Livingston Chart

For the historical progression of highest energies reached one generally looks at the celebrated Livingston chart shown in Fig. 1. The most prominent and oft-cited feature is the slope of the asymptotic straight line, which gives an increase in top energy reached by an order of magnitude in roughly seven years, a very fast rate indeed. But it is important to observe that this fast rate is accomplished by the introduction of new accelerator technologies at frequent intervals. These are indicated by green circles. Only ion accelerators are circled since it is difficult to compare electron accelerators with ion accelerators. The energy progressions of each type of accelerator follow curves with much lower slopes. For colliders the "equivalent energies" are plotted. These are the energies of hypothetical single beams on stationary targets to yield the same center-of-mass energies as those of the colliders. Because of the relativistic transformation, these "equivalent energies" are inordinately high. For measures of research utility and machine technology, one should plot instead twice the center-of-mass energy. The factor two gives the corresponding single-beam energy that is plotted for all single-beam accelerators. These are shown in red. The red collider curve joins smoothly with the AG-synchrotron curve showing that they both use the same technology. It flattens away from the asymptotic straight line despite the rapidly increasing investment worldwide in particle physics. It also shows plainly that since 1960 (or 1970 if one counts collider as new technology) there has been no new accelerator technology introduced with, perhaps, the exception of the superconducting magnet. New ideas and technologies are sorely needed. However, we will discuss below what can best be done to at least provide reasonable upgrade rates of energy and luminosity even if no new technology is forthcoming.

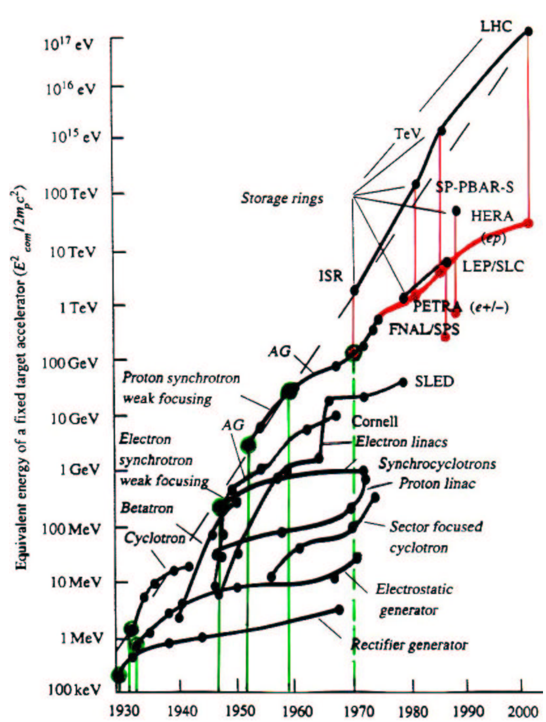

Figure 1: Livingston chart.

2.2 *"Reach"*

We will be comparing lepton and hadron colliders. For this we have to introduce the concept of "reach" (M) defined as the highest mass particle that can be produced in the collider. For lepton colliders, because leptons are point particles, the reach just equals the center-of-mass energy E or

$$M = E \qquad \text{(M in energy units).}$$

When selection rules, phase-space volume, etc., are glossed over, the production cross-section of M is given simply by the Feynman propagator as $\sigma \propto E^{-2}$, namely the integrated luminosity required is

$$\mathcal{L} \propto \frac{1}{\sigma} \propto E^2 .$$

The constant of proportionality can be scaled from the experience at LEP. This gives

$$\mathcal{L}\,(\text{pb}^{-1}) = 0.005\, E^2(\text{GeV}).$$

For hadron colliders, because hadrons are composite particles, the center-of-mass energy E is distributed over the ball of quark-gluon plasma composed of the valence quarks and all the virtual quarks and gluons. The cross-section for the production of M is

$$\sigma \propto \frac{1}{E^2} f(M/E) \quad \text{or} \quad \mathcal{L} \propto \frac{E^2}{f(M/E)},$$

where f gives the probability of having energy M out of the total center-of-mass energy E concentrated at one point and is, therefore, dependent on the distribution function in a nucleon. f is expected to be a sharply falling function of M/E and is, in principle, given by QCD. As an approximation, we take $f(M/E) \propto (M/E)^{-6}$, which gives

$$M \propto E^{2/3} \cdot \mathcal{L}^{1/6},$$

showing that M is weakly dependent on the integrated luminosity $\mathcal{L}$. Scaling from the Fermilab top-quark discovery we get

$$M(\text{GeV}) = 0.7\, E^{2/3}(\text{GeV})\, \mathcal{L}^{1/6}(\text{pb}^{-1}).$$

Table 1 gives the reach M for various colliders. For the hadron colliders, a run of one year (10^7 seconds) is assumed.

In Table 1 we have omitted the non-search colliders like the B-factories and the far futuristic machines like the μ-collider. The inclusion in Table 1 of the proposed e^+e^- linear colliders Next Linear Collider (NLC) and Japan Linear Collider (JLC) reflects the outcome of the recent U.S. HEP Workshop in Snowmass, Colorado held in July 2001, which stated, "We, therefore, recommend the expeditious construction of a Linear Collider as the next major international High Energy Physics project…." The inclusion of the proposed machines Very Large Hadron Collider (VLHC) and Very Large Lepton Collider (VLLC) indicates my own personal preference.

Table 1: Reaches of Colliders

Collider Name	Particles	COM Energy (GeV)	Luminosity ($cm^{-2}s^{-1}$)	Reach (GeV)
ISR	p p	63	6.5×10^{31}	33
S$p\bar{p}$S	p $\bar{p}$	630	6×10^{30}	100
Tevatron	p $\bar{p}$	1,900	2×10^{32} (10^{33})	380 (500)
LHC	p p	14,000	10^{34}	2,770
VLHC	p p	40,000 200,000	10^{35}	8,200 24,000
LEP	$e^+ e^-$	210	10^{32}	210
SLC	$e^+ e^-$	100	2.5×10^{30}	100
NLC JLC	$e^+ e^-$	500–1500	2×10^{34}	500–1500
VLLC	$e^+ e^-$	400	10^{34}	400

2.3 *Recurrent Use of Tunnels*

I now discuss what, in the absence of new ideas and technologies (which is likely the case), is the most advantageous project to undertake for particle physics in the twenty-first century.

First, I make the observation that nearly all the circular accelerators have had several modifications or upgrades housed in the same tunnel. Table 2 lists samples of tunnels and their past usages for substantiating this thesis. All the tunnels have housed several different types or variations of ring accelerators or colliders, with the latest tenant still engaged vigorously in physics research. Two members deserve special mention. The Fermilab tunnel has been in existence for more than 30 years, and the present resident Tevatron is and will remain to be the highest energy machine in the world until the inauguration of the LHC in 2006, which is itself housed in the 27-km tunnel of the decommissioned LEP. The last entry in Table 2 is what I consider the most advantageous project to undertake for particle physics in the twenty-first century. The 230-km tunnel is less than 2.7 times the defunct SSC tunnel. Based on the unit cost of the SSC tunnel and incorporating some expected reduction, we may expect the 230-km tunnel plus access shafts and halls to cost not much more than $1 billion.

The 400-GeV VLLC with a 100-MW rf system and 250-G dipoles designed for low cost and full production line construction should also cost not much more than $1 billion. The construction of such a machine requires only existing technology and can, therefore, commence immediately. The early attainment of its design performance is virtually assured.

Table 2: Recurrent Use of Tunnels

Laboratories and Machines (given are beam energies)		Year Built	Total Length (km)
Cornell	e^- synchrotron (12 GeV) CESR (6 GeV e^+e^-)	1966	0.77
SLAC	PEP (16 GeV e^+e^-) SLC (50 GeV e^+e^-, Lin. Coll.) PEP II (9 GeV e^-, 3.1 GeV e^+, B-factory)	1976	2.20
KEK	TRISTAN (31 GeV e^+e^-) KEKB (8 GeV e^-, 3.5 GeV e^+, B-factory)	1982	3.02
BNL	ISABELLE/ISA (200, 400 GeV, p p) RHIC (100 GeV/u Au Au)	1979	3.83
FNAL	synchrotron (400 GeV) TEVATRON (950 GeV $p\ \bar{p}$)	1969	6.28
CERN	LEP (105 GeV e^+e^-) LHC (7 TeV p p)	1983	26.66
New Collider	VLLC (200 GeV e^+e^-) VLHC (20 TeV p p, 2T) VLHCII (100 TeV, p p, 10T)		233

The first follow-up machine would be a 40-TeV VLHC with 2-T hybrid single-yoke duo-aperture dipoles energized by a single superconducting cable. The next stage is a 200-TeV VLHC-II with 10-T superconducting dipoles. In Fig. 2, these machines are shown in cross-section installed in the same tunnel. As shown in Table 1, this succession of machines is the only hope of extending the "reach" one decade beyond that of LHC. This program of staged assault on the energy and luminosity frontiers will probably occupy a major portion of the twenty-first century.

I should include here at least one diagram of the Linear Collider. Figure 3 gives the diagram of the NLC.

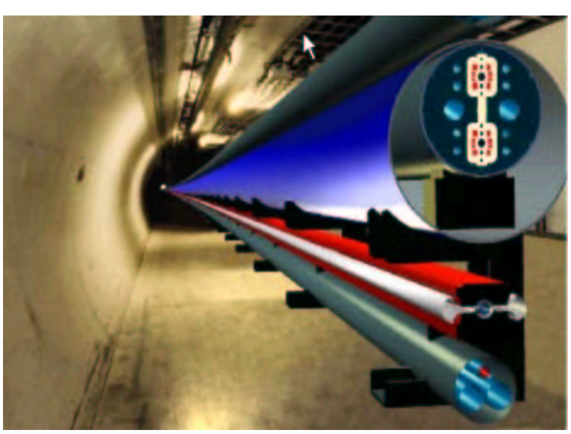

Figure 2: VLHC and VLHC-II in same tunnel.

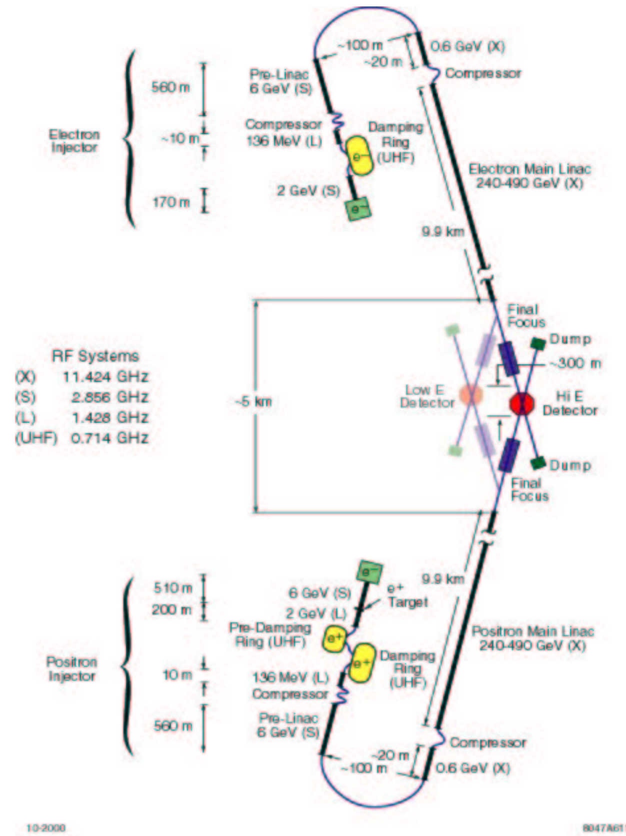

Figure 3: NLC diagram – 1-TeV center-of-mass (not to scale).

I have not mentioned the R&D work on "advanced acceleration techniques" because no consideration of luminosity has so far been included in this work. Neither have I alluded to the muon-collider because, in my opinion, there is still a great deal of R&D work to do before the design can be considered realistic. In addition, the advantage of a muon collider over other machine types has yet to be confirmed.

3 NUCLEAR PHYSICS

Standard studies of nuclei—forces and structures—using tens to hundreds of MeV protons and deuterons (neutrons) have largely been done. Special-purpose machines with special designs and accelerating special particles are being proposed, built, and operated. All of these facilities are very productive for nuclear physics research. For these special-purpose machines, I will mention two categories.

The high-current CW, GeV electron beams from CEBAF designed, constructed, and operated by the Jefferson Laboratory provide a unique electron probe. The GeV energies are needed to make the electrons small enough for probing atomic nuclei.

Heavy nuclei provide distinctive projectiles. Different types of heavy-ion accelerators are operated in various laboratories, for example: ANL (ATLAS), GSI (SIS), IMP (HIRFL), IU (IUCF), RIKEN, etc. A unique facility that accelerates ions of rare (short-lived and radioactive) isotopes is proposed by ANL and MSU. The proposed Rare Ion Accelerator (RIA) shown diagrammatically in Fig. 4 has a unique and clever design. Unfortunately, we do not have time to go into it. The Relativistic Heavy Ion Collider (RHIC) at BNL collides 100 GeV/u gold ions to study the properties of the resultant quark-gluon plasma. If a blob of high energy quark-gluon plasma can be considered as a big nucleous in a highly excited state, then RHIC can be classified as a collider for nuclear physics.

It is difficult to foresee where specialized needs will arise, but based on past experience, we can be fairly certain that these needs will arise and that most of them can be fulfilled by accelerators with clever designs using existing technologies.

4 EXTRANUCLEAR SCIENCES

We live outside the nucleus. The only areas in which intranuclear events touch our daily lives are the use of nuclear energy to power ships and electric power stations, and some minor applications of nuclear radioactivity (therapy, medicine, tracer, dating, etc.). The research goals of extranuclear sciences are very broad and extensive, but can be grossly described as investigations of the dynamics and structures of atoms, molecules (especially proteins, polymers viruses, etc.), and materials (such as crystals, catalysts, superconductors, surfaces, thin films, etc.). The outcome of this research intimately affects our daily life.

The desired characteristics of the beams used for these studies are:

- Preferably electric charge neutral so as not to be affected by Coulomb barriers. This means that the beam particles should be either neutrons or photons.
- The momentum of the particles should be matched to that of the bound structural electrons, which generally have binding energies of the order of eV. The binding momentum p is related to the binding energy T by $T = \frac{p^2c^2}{2mc^2}$. This then gives $pc = \sqrt{2mc^2T} \sim \sqrt{(\mathrm{MeV})(\mathrm{eV})} \sim \mathrm{keV}$. For photons, this means keV x-rays or synchrotron radiations. For neutrons, this gives a kinetic energy of $T = \frac{(\mathrm{keV})^2}{\mathrm{GeV}} \sim \mathrm{meV}$, namely thermal neutrons from reactors or as moderated spallation neutrons.

4.1 Spallation Neutron Sources

Spallation neutrons, being derived from the proton beam, can be produced in much shorter and cleaner pulses than neutrons from reactors and are, therefore, more suitable for time-resolved experiments based on neutron scattering. Table 3 gives a list of the more widely known spallation neutron sources (by no means exhaustive). Since the flux of the neutrons produced depends primarily on the power of the incident proton beam, the accelerator beam power is given as the major parameter. Most of the modern dedicated neutron sources have proton energies of ~1 GeV and time-averaged beam currents of a few milliamperes. For these high average power beams, the superconducting linac emerges as the favored accelerator. To generate higher peak intensity and short, clean pulses, the beam is accumulated several thousand turns in an accumulator ring and fast extracted in a single turn. The highest power facility in construction is the SNS with a beam power of 2 MW, 2½ times that of the highest power operating facility LANSCE, and with the capability of upgrading to 5 MW in the future. An artist conception of the SNS facility is given in Fig. 5.

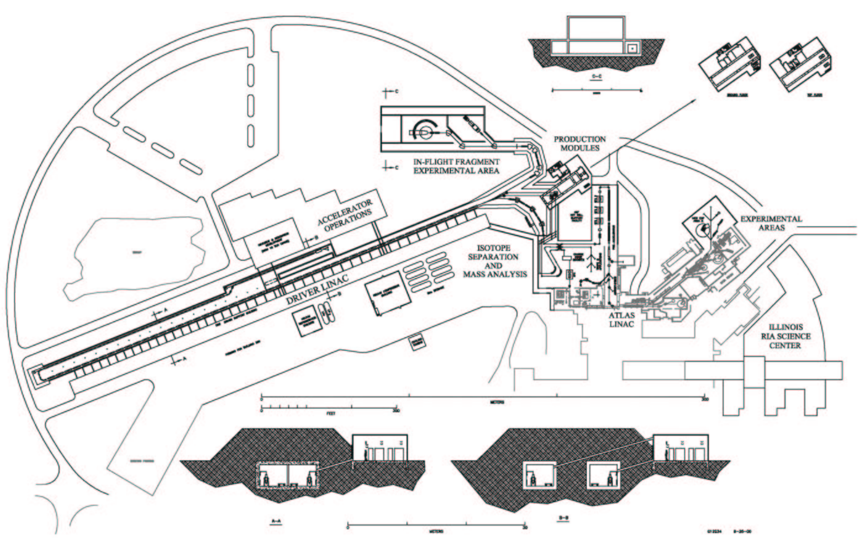

Figure 4. Schematic layout of RIA on the ANL site.

Table 3: Spallation Neutron Sources

Facility Name	Machine Type	Beam Power	Status
IPNS (ANL)	RCS[*]	0.5 GeV × 16 μA = 8 kW	operational
MMF (Moscow)	Linac	0.5 GeV × 120 μA = 60 kW	
ISIS (RAL)	RCS	0.8 GeV × 190 μA = 150 kW	operational
LANSCE (LANL)	Linac + Accumulator	0.8 GeV × 1 mA = 0.8 MW (6×10^{13}p, 0.25 μs pulse)	operational
HIPA (JAERI)	RCS	3 GeV × 1/3 mA = 1 MW (also as injector for 50 GeV, 15.5 μA K-Factory)	constructing[1]
SNS (ORNL)	SC Linac + Acc.	1 GeV × 2 mA = 2 MW (5 MW)	constructing[2]
ESS (Europe)	SC Linac + Acc.	1.33 GeV, 2 × 5 MW	proposed[3]

[*]Rapid Cycling Synchrotron
[1]Approved December 2000, Completion 2007.
[2]Cost $1.4 B, Completion June 2006.
[3]Cost $1.7-2.0 B, Multipurpose Accelerator – Decision June 2003, Completion 2010.

Figure 5: Artist conception of SNS.

Figure 6: The APS at ANL.

4.2 Synchrotron Radiation Facilities

Most of the modern synchrotron radiation storage rings are of the "third generation." This means that the primary radiation sources are the undulators inserted in the straight sections, and the storage ring magnet lattice, radio frequency and vacuum systems are designed to optimize the radiation from the undulators. The unavoidable radiation from the bending magnet is only used as auxiliary. Depending on the electron beam energy, the facilities can be classified as for hard x-rays (6-8 GeV), for midrange x-rays (2-3 GeV), and for VUV and soft x-rays (<1 GeV).

The three operating hard x-ray facilities are:

ESRF (Grenoble, France)	6 GeV
APS (Argonne, USA)	7 GeV
SPring-8 (Harima City, Japan)	8 GeV

In units of photon number per second, per 10^{-3} frequency bandwidth, per $(mm)^2$ source area, per $(mrad)^2$ solid angle, the peak brilliance of the undulator radiations from these facilities are all of the range of 10^{22}. (In comparison, the brilliance of a 100-W light bulb filament is $\sim 10^{8}$). Figure 6 gives an aerial view of the APS facility at Argonne.

All midrange x-ray facilities are listed in Table 4; most of them are also of the third generation and with peak brilliance above 10^{20}. At this conference we have heard talks of many of these facilities.

4.3 Coherent Radiation Sources

The synchrotron radiation from a storage ring is incoherent, for which the radiated power is proportional to the electron number n. If the electrons could be made to radiate coherently, the radiated power would be proportional to n^2, a gain of a very large factor n. To get coherent radiation one must resort to the interaction between an undulated electron beam and the coherent part of the radiation it emits. This interaction has two effects on the beam.

- It tends to bunch the electron beam at the zero-phase of every wavelength of the radiation, thereby increasing the coherency and hence the intensity of the radiation. This leads to exponential growths of coherency and intensity. At maximum bunching—called "saturation," when further interaction will overbunch or debunch the beam—the peak radiation

Table 4: Intermediate Energy Synchrotron Radiation Storage Rings

Location	Name	Energy [GeV]	Status
Australia	Boomerang	3	proposed
Canada, Saskatoon	CLS	2.9	constructing
China, Shanghai	SSRF	3.5	proposed
France, Orsay	SOLEIL	2.5-2.75	constructing
Germany, Karlsruhe	ANKA	2.5	operational
India, Indore	INDUS-II	2-2.5	constructing
Italy, Trieste	ELETTRA	2-2.4	operational
Japan, Tsukuba	PF	2.5	operational
Japan, Tsukuba	PF II	4	proposed
Korea, Pohang	PLS	2-2.5	operational
Spain, Barcelona	LLS	2.5	proposed
Switzerland, Villigen	SLS	2.4	operational
Taiwan	SSRC-II	3~3.5	proposed
UK, Daresbury	SRS	2	operational
UK, Daresbury	DIAMOND	3	constructing
USA, Stanford	SPEAR-III	3	constructing
USA, Brookhaven	NSLS X-ray	2.5-2.8	operational

brilliance could be as high as 10^{30}. For this self-amplified spontaneous emission (SASE) process to proceed, an electron beam with stringent properties must be made to copropagate with its own radiation in a long (tens to hundreds of meters) undulator. Figure 7 is a photograph of the pilot set-up at Argonne National Laboratory, which gave saturated emission at the ultraviolet wavelength of 265 nm. Several proposals have been made by different laboratories for facilities to supply hard x-rays.

- Interaction of an undulated electron beam with coherent radiation also results in an energy exchange between the radiation and the beam. This stimulated emission radiation is in phase with the radiation but is generally rather weak. Thus, the stimulated radiation must be confined in an optical cavity and accumulated over many passages of beams through the cavity. This is the free-electron laser (FEL). The highest power facility in operation is the 1.7-kW infrared FEL at Jefferson Laboratory. The wavelength of the FEL is limited to not much shorter than the ultraviolet by the availability of the appropriate material for the cavity mirrors.

Figure 7: SASE pilot facility (LEUTL) at ANL.

Both the spallation neutron and the synchrotron radiation facilities are in great demand around the world for doing R&D work for the advancement of human lives.

5 APPLICATIONS

We heard already at this conference several interesting talks related to applications of small low-energy accelerators. I will, therefore, limit the discussion here to only a few major applications, some of which are still at the development and studies stage.

5.1 Radiation Therapy

Different types of accelerators and radiations (particles) have been used for therapy. The choice of particles is based on the relative biological efficiency (RBE), the Bragg peaking and, of course, the ease of handling of the beam. Charged particles, electrons and protons, and photons (γ-ray) change biological cell molecules by ionization and have low RBE. Neutrons destroy cells by nuclear interactions and have higher (as much as tenfold) RBE. Heavy charged particles such as protons have Bragg peaking and deposit most of their energies at the end of their ranges, which is most suitable for treating deep-seated tumors. Heavy ions in which neutrons ride on protons may have both high RBE and Bragg peaking advantages. A heavy ion accelerator, HIMAC, has been operated for therapy in NIRS, Chiba, Japan for some time. But the clinical data for comparison with other radiation types are still being collected.

The choice of accelerator types depends on the available characteristics of their external beams—collimation, energy and easy variability, intensity uniformity and controllability, etc.—and, of course, on the cost.

With a well-collimated extracted beam, fast energy variability, and responsive intensity control, one can use 3-dimensional scanning irradiation to cover the entire tumor field. So far, however, the clinically available irradiation technique is to first enlarge the beam by scatterers, and then use boles masks to stop the radiation outside the tumor field. Energy variation is accomplished by putting absorbers across the beam.

For all these facilities, either a rotational mounting for the entire accelerator or a gantry that rotates the beam transport is needed so that the beam can be directed onto the tumor from many portals to distribute the dosage on the surrounding healthy tissue. The gantry must be designed as a part of the beam transport. Figure 8 shows the gantry of the proton therapy facility at the Loma Linda University Proton Facility.

5.2 High-Current, GeV, Proton Linac

A typical high-current, GeV, proton linac could provide, for instance, a 2-GeV proton beam at 300 mA, i.e., a 600-MW beam. Historically, similar machines have been recurrently proposed for different applications.

Figure 8: Gantry for the Loma Linda Proton Therapy Facility.

- Uncertain of the uranium reserve in the United States, E. O. Lawrence proposed in 1945 to breed fissile fuel using moderated spallation neutrons via e.g., the reaction

$$\mathrm{Th}^{232}_{90} + \mathrm{n} \xrightarrow{-2\beta} \mathrm{U}^{233}_{92} \text{ (fissionable).}$$

- When nuclear disarmament talks seemed to be leading to the shut down of all reactors, such a linac was proposed for a tritium factory. Tritium is in perpetual demand for thermonuclear weapon stockpile stewardship.
- Recently, studies are being made to use these machines to induce transmutations of long-lived fission reactor waste to more manageable short-lived elements. This is being investigated at LANL and, as we learned at this conference, also in Ukraine and in Korea.

5.3 Heavy Ion Inertial Fusion

The national ignition facility at LLNL will use terawatt laser beams to compress and ignite mm-size, deuterium-tritium (d-t) fusion pellets. Because of the long recharging time of the lasers, the operation cannot be repeated within hours. Heavy ion beams from rapid cycling accelerators can be used instead of laser beams. The pellets can then be exploded at a sustained fast repetition rate to provide fusion energy. This provides an alternative to magnetic fusion energy. For a 1-mm d-t pellet, depending on the design, the parameters of the beam pulse required are:

Duration	1 ns
Energy	4 MJ
Power	400 TW

For $^{2+}\mathrm{Bi}^{209}$ ions (mc^2 ~ 200 GeV) for example, this requires:

Kinetic energy	10 GeV (5-GeV linac)
Total pulse current	80 kA (electric).

This high current can be provided by an induction linac. For example, two 40-A, 1-μs beam pulses can be injected in parallel. With combined velocity and gradient compression factors of 1000, we get at 2 GeV the desired 1-ns beam pulses of 40 kA each. These beams will then be transported to impinge on the pellet in opposite directions. This approach is being pursued by LBNL and at CAEP, China.

Much more is known of the operations and capabilities of rf linacs. But since the current carrying capacity of an rf linac is considerably lower, it must be followed by several stages of circular accelerators that will take up the additional pulse compressions needed. A possible scenario of compression is the following:

Injection energy = 1 MeV
No. of beamlets injected = 16
Beamlet current = 400 mA
Velocity compression factor = 100
Compression factors in three stages of
circular accelerators = 5 × 5 × 5 = 125

Total compression factor = 200,000
Output energy = 10 GeV
Output current = 80 kA

This approach is being pursued by GSI. An old conceptual layout (HIBALL) of theirs for a power station with four reactors is shown in Fig. 9.

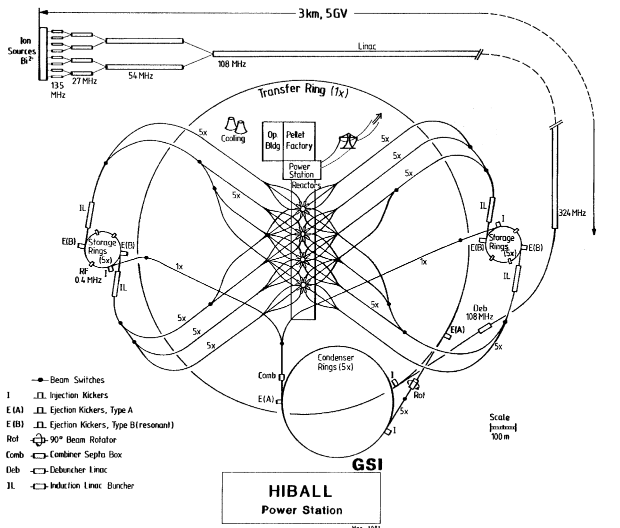

Figure 9: The conceptual diagram of a HIF power station by GSI.

Although far from realization, heavy ion fusion (HIF) power may not be much farther away than magnetic fusion power.

6 CONCLUSION

Particle accelerators, taken as a whole, are and will continue to be in great demand. As a field of endeavor, particle accelerators have a bright future. The construction and R&D of particle accelerators will be energetically pursued, and the rapid advances are expected to continue, at least through the twenty-first century.

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