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REVIEW OF MESON FACTORIES

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Abstract

The development of meson factories is briefly summarized. Present facilities are described and compared with the design goals they set out to meet. Further developments and limitations are discussed.

1. Introduction

Since the last National Accelerator Conference in 1973 Pion Factories have come into their own. The most powerful installation of its kind built at Los Alamos and completed in 1972 has supplied beams for an extensive physics programme since the beginning of 1974. Last year also saw the start-up of the Swiss ring-accelerator and it ended with the first successful beam tests of the H^- accelerator built at Vancouver.

These accelerators are designed for fields of application much wider than those of elementary particle and nuclear physics and with their completion we may find ourselves at the threshold of a new and exciting period in which short-lived nuclear particles will become tools for scientists in many disciplines.

This is therefore a good time to glance at the history of meson factories, to look at their present state and to attempt some comparisons.

2. History

2.1 The Role of Pions in Physics

The discovery of the pion by Powell and his colleagues[1] in 1947 opened a new era in nuclear science. The strongly interacting, short-lived meson predicted twelve years earlier by Yukawa[2] promised to supply the key to the understanding of forces between nucleons which had so long been lacking. Cosmic rays had provided the first pions, but for a detailed study of their properties a plentiful supply of pions of known momentum was required. Accelerators provided the answer to this need.

To produce a pion of rest-mass energy 139 MeV in a collision with a proton at rest an incident proton requires a kinetic energy of 290 MeV, which was far beyond the reach of the classical cyclotron. By a fortunate coincidence the energy limit of the classical cyclotron had been breached and the frequency-modulated 184" synchro-cyclotron completed at Berkeley in 1946 by E. O. Lawrence and his team[3] was able to accelerate alpha particles to 360 MeV.

The first artificially produced pions were observed at the 184" machine in 1948[4] and soon pion beams were available at several synchro-cyclotrons. Within a few years the intrinsic and interaction properties of the pion and of the muon produced by its decay were established. These unstable, subnuclear particles and the neutrinos formed in their decay constituted a remarkable set of tools for particle and nuclear physics, permitting entirely novel ways of studying the strong, electromagnetic and weak interactions of nucleons and nuclei.

The effect of these researches on elementary particle physics was spectacular. Within ten years of the availability of pion- and muon-beams at accelerators, the discovery of meson and baryon resonances had led to a systematic classification of elementary particles. Furthermore parity violation in weak interactions and the separate nature of muon and electron neutrinos had been established.

However, the accelerator-builders who had made this progress possible, did not rest on their laurels. While many worked to reach ever higher energies others considered the possibility of making much more intense pion-beams than those available in the fifties. Such beams had typically fluxes 10^5 pions/sec. in a few percent momentum band.

It was recognized that many experiments involving slow or stopping pions or muons were, in fact, intensity limited. This applied e.g. to studies of rare decay modes or capture processes of mesons and to scattering experiments performed with the precision necessary to distinguish the effects of nuclear levels. To make progress in these fields a gain of one or two orders of magnitude over existing meson fluxes was required. Even more exciting possibilities would be opened up if three or four orders of magnitude could be achieved. One might then hope to reach beyond the limits of particle- and nuclear-studies into atomic physics, into hot-atom chemistry, into solid-state studies and even into radiation biology, where the possibility of using negative pions for cancer-therapy had been analyzed by Fowler and Perkins[5].

2.2 The Meson Factory

The desire to overcome the intensity-limitations of pion and muon physics gave rise to the concept of a "meson factory":- An accelerator designed to produce mesons in the energy region spanning the 3-3 resonance, i.e. between 100 and 300 MeV and in quantities exceeding those furnished by synchro-cyclotrons by several orders of magnitude. To meet these requirements about 100 μA of 500 to 800 MeV protons were needed.

Mesons are expensive in terms of primary protons. About a million nuclear interactions of 700 MeV protons in a carbon target are needed to make a pion for a typical pion beam. A meson factory is therefore primarily a proton-factory, and the radioactivity induced in the accelerator and in the production target constitutes the major problem of such machines.

A very high proton extraction efficiency was therefore a first design requirement. The economic use of protons was a second. Isotope and neutron production in beam dumps were obvious extensions of the role of the meson factory. The study of proton interactions with nuclei and, in particular, of the nucleon-nucleon interaction were further means of enlarging its research-potential, but its specification had to be refined for this purpose. A variable proton energy, proton-beams of high quality and energy resolution and the possibility of accelerating polarized protons are necessary for such work.

Electronic particle detection introduced a further constraint: In coincidence-measurements the duty cycle becomes of primary importance since it determines the rate of random coincidences in those experiments in which the background is due to the accelerator. The problem posed by the duty cycle of a high-current accelerator has been extensively discussed (see e.g. Refs. [6] and [7]), and the response-time of electronics may even limit the use of an accelerator whose macroscopic duty cycle is unity. In the case of a pulsed accelerator the time taken for a given measurement becomes ultimately independent of the beam intensity and depends only on background, resolving time and the duty cycle. Very efficient shielding therefore becomes an added requirement.

The Specification for a Meson factory could therefore be summarized as follows:-

- Proton energy 500-1000 MeV
- Primary beam current $\gtrsim 100\ \mu A$
- High extraction efficiency
- High duty-cycle
- and, preferably, Variable proton energy

2.3 Meson Factory Projects

While these requirements were being formulated the challenge was taken up by accelerator designers.

A study for a 600 MeV proton linac was started in Britain in 1952 and showed the possibilities of new structures needed to replace the Alvarez linac at proton energies above 100 MeV. Although the accelerator which resulted from this work was limited to 50 MeV the authors concluded that "there seems to be no major technical obstruction to the acceleration of protons to any energy"[8].

The progress in the understanding of relativistic cyclotrons during the 1950's led Livingston and his colleagues at Oak Ridge to consider the possibilities of a meson-producing isochronous cyclotron[9,10] of 850 MeV, which would overcome the duty-cycle limitation of linacs. Studies with an electron-model showed the possibility of an efficient extraction using the $\nu_r = 2$ resonance.

The interest in meson factories grew rapidly and by 1962 many types of accelerator were being put forward as possible candidates. Apart from cyclotrons and normal linacs they included the Fixed-Field Alternating Gradient Accelerator[11], fast-cycling synchrotrons, superconducting linacs[12], separated orbit-cyclotrons[13] and a sector-focused cyclotron accelerating H^- ions[14]. The various types of accelerator were compared by Lloyd-Smith[15] who concluded with a prophetic foot-note "It is, however, fairly certain that the linear accelerator will continue to run ahead of the others". He referred to cost.

Proposals were made by Oak Ridge[16] and UCLA[17] in 1963, followed by the Federal Polytechnic of Zurich[18], Los Alamos[19], Yale[20] and Chalk River[21] in 1964.

It was a case of many being called but few being chosen[22]; in fact a first reaction from an AEC Advisory Panel on High Energy Physics[23] recommended the construction of a high energy FFAG accelerator in preference to a pion factory from the standpoint of high energy physics, but left the question of a pion factory for nuclear structure research open. This was taken up by a panel appointed by the U.S. Office of Science and Technology under the chairmanship of H. Bethe[24], who pointed out the great possibilities offered by meson factories in the advancement of the knowledge of nuclear structure and recommended the construction of a meson factory in the United States. As a result the Los Alamos proposal was partially funded in 1968. Also the Zurich project received preliminary approval in 1966 and was fully funded in 1967. Meanwhile the University of British Columbia had, in collaboration with two and later three other Canadian Universities, taken up the UCLA proposal for an H^- accelerator, whose unique characteristics as an intermediate-energy facility had been pointed out by the Bethe Panel. A proposal for a 500 MeV H^- accelerator was made in 1966[25] and construction was started in 1968.

So the first entrants for the Meson Factory Race were LAMPF, the Los Alamos Meson Physics Facility, SIN, the newly-formed Swiss National Institute for Nuclear Research at Villigen and TRIUMF, the Tri-University Meson Factory. Work on a meson factory project, based on a 600-1000 MeV proton linac, and provided with storage rings is also in progress in the USSR[26,27,28]. Acceleration of protons in a superconducting, helix-type linac has been achieved by Citron and his colleagues in Karlsruhe[28,29], who aim ultimately at an accelerator capable of furnishing several hundred microampêres of protons above 500 MeV.

These contestants were joined by several outsiders, the synchro-cyclotrons whose potential for improvement had been studied in the intervening years. Details of these projects are given in Refs. [30] to [34].

However, it is unlikely that these accelerators will be able to compete with full-fledged meson factories and they will not be considered in the context of the present survey. In the following we shall only examine the three meson factories so far completed. Fortunately each is based on a different design-principle and represents a different compromise between the various technical and physics requirements.

3. Present Meson Factories

3.1 LAMPF

3.11 General Characteristics. The Los Alamos Meson Physics Facility (LAMPF) is a complex of four accelerators: two Cockcroft-Walton Injectors furnish protons and H^- ions to an Alvarez type linac via two bunchers. A third injector will provide polarized H^- ions from 1976. The Alvarez injects particles of 100 MeV into a side-coupled cavity structure which provides acceleration to 800 MeV.

Table 1 lists some of the design parameters of LAMPF.

Table 1 - LAMPF Parameters

Ion Source	Duoplasmatron
Injection Energy	750 KeV
Linac Structures	Post-coupled drift tube,201.25MHz 4 tanks to 100 MeV Side-coupled cavity, 806 MHz 44 modules to 800 MeV
Length	794 m.
Macro-pulse length	500 (1000) μs
Repetition rate	120 s^{-1}
Micro-structure	0.25 μs pulses separated by 5 μs
Average RF power	[illegible] MW
Peak design energy	800 MeV
Peak design current	17 μA
Average beam currents	H^+ 900 μA H^- 100 μA polarized 60-600 μA
$\Delta p/p$	0.14%
Emittance	0.25 mm. mrad horiz. and vert.

Construction of the accelerator started in 1968 and it reached full energy in June 1972. In many respects it is a notable achievement in accelerator technology. While the injectors are largely conventional, three of the four tanks constituting the drift-tube section are fitted with post-couplers developed at Los Alamos and operate in the $\pi/2$ cavity mode[35]. This development of the drift-tube structure ensures field flatness and stability and is now used in many new Alvarez type linacs. However, the most important progress in accelerator design was the development of the side-coupled cavity-structure which made it possible to bridge the gap between the low velocity drift-tube accelerator and the wave-guide used for relativistic particle velocities[36]. This structure is illustrated in Fig. 1. Adjoining cavities resonate in the $\pi/2$

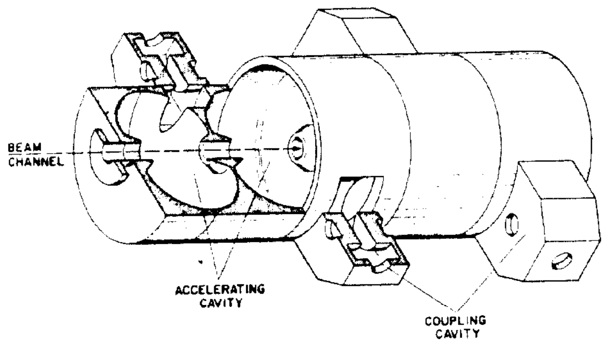

Fig. 1: LAMPF 805 MHz Side-Coupled Cavities

mode, but the intermediate side-couplers store no power. The cavity length can be adapted to the phase velocity and the cavities can be individually tuned to correct the effect of dimensional variations. In the 805 MHz accelerator they are grouped in 44 modules. Individual tanks within the modules are joined by bridge couplers. These are placed above the column of accelerating cavities and so allow room for focusing elements. The bridge couplers also serve to feed power into the structure from 44 1.25 MW klystron amplifiers developed for the project. With increasing phase velocity the shunt-impedance of the side-coupled cavity structure rises from about 20 to 50 megohms/m.

The accelerator has a macro duty-cycle of 6%. By reinforcing the amplifiers in the 201 MHz section this can be raised to 12%.

The design provides for H^+ and H^- acceleration in alternate half-cycles. A matching section between the 201 and 805 MHz accelerators corrects the phase of the H^- ions.

The accelerator is controlled by an extensive computer network, interfaced with it through 64 modules, each carrying 50 analogue voltages, 13 set-point controls, 55 binary indicators and 12 relay controls. Beam diagnostics employing a variety of sensors is performed on-line.

The 800 MeV beam provides particles simultaneously to ten experimental stations in five areas. In a switchyard H^+ and H^- beams are separated. The H^+ beam is directed to the Beam Area A where two successive target stations supply mesons to four beam-lines. A further target produces pions for the Biomedical Facility. The beam stop serves for isotope production and for neutrino beams. The H^- ions are used for nucleon beams. A fraction is converted to protons in a first stripper-foil and is directed to a large spectrometer in area C; the remainder is used after a further stripping to produce neutrons and for proton work in area B. An overall layout is shown in Fig. 2 and some details of the meson area A are indicated in Fig. 3. A first target A-1 produces pions for the low energy pion channel and for EPICS, a pion spectrometer of 10^{-4} momentum resolution. Target A-2 supplies the high-energy pion channel P^3 and the stopped muon channel.

Some data on meson fluxes are given in Table 2.

Table 2

Channel	Target	Particle	p(MeV/c)	$\Delta p/p$(%)	Flux/μA.s Observed [37] [63]	Flux/μA.s Calculated [38]
LEPC	3 cm C	π^+	200	± 3	1.2×10^6	1.2×10^6
P^3	6 cm C	π^+	400	5	3×10^6	4×10^6
Muon[37]		μ^+	93	± 3	1.5×10^4	

The high resolution proton spectrometer (HRS) in area C and the Biomedical Channel are of particular interest. The spectrometer, shown in Fig. 4, is housed in a concrete dome and can be rotated about a vertical axis through the target chamber. With a design resolution of 30 keV at 800 MeV proton energy it will permit detailed studies of proton-nucleus interactions over a wide range of energies and scattering angles.

The Biomedical Channel shown in Fig. 5 captures pions from 8 cm C or Al_2O_3 targets and conveys them via a vertical beam to the specimen or patient placed in a bunker below the proton beam line[39]. Fluxes of $2 \times 10^6 \pi$/s.μA with p= 170 MeV/c, $\Delta p/p$ = 2% RMS have been obtained from an 8 cm carbon target[40] corresponding to a peak dose rate of about 0.85 rad/min. μA. History was made when on October 21st, 1974 the first pion irradiation of a human tumour was performed with this beam.

Great efforts have been made at LAMPF to deal with radiation problems. Beam spill in the accelerator is monitored along its entire length and the design aim is a transmission exceeding 99%. Radiation hardened magnets are used in the beam switchyard and close to production targets. In the A-area the primary beam line is surrounded by 15 to 20 feet of iron and concrete and secondary beam lines are curved in the vertical or horizontal planes to reduce neutron background in the experimental areas. The pion production targets consist of radiation-cooled graphite rings which can be removed and replaced remotely. Maintenance in the target areas will ultimately be performed by a 200 ton shielded mobile remote-handling facility named Merrimac[41] which moves above the proton beam-line and which is equipped to replace damaged beam elements and to transport them to hot cells.

3.12 Status. Since reaching full energy in June 1972 the accelerator performance has been steadily improved. During the third quarter of 1974 LAMPF operated at an average current of 12.5 μA for prolonged periods and briefly at currents up to 200 μA. The current limitation in the accelerator is imposed by beam losses which are regarded as unacceptable if they reach 2%. 100 μA operation is foreseen for the second half of 1975 when adequate shielding will have been installed in the experimental areas. The total beam emittance at 800 MeV is 1.4π mm.mrad.

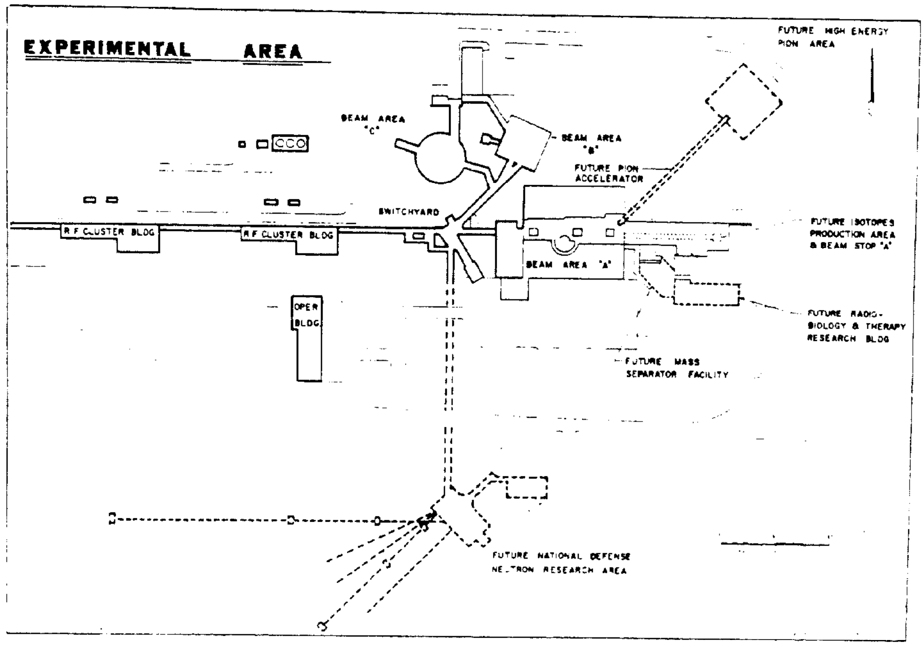

Fig. 2: LAMPF Experimental Areas

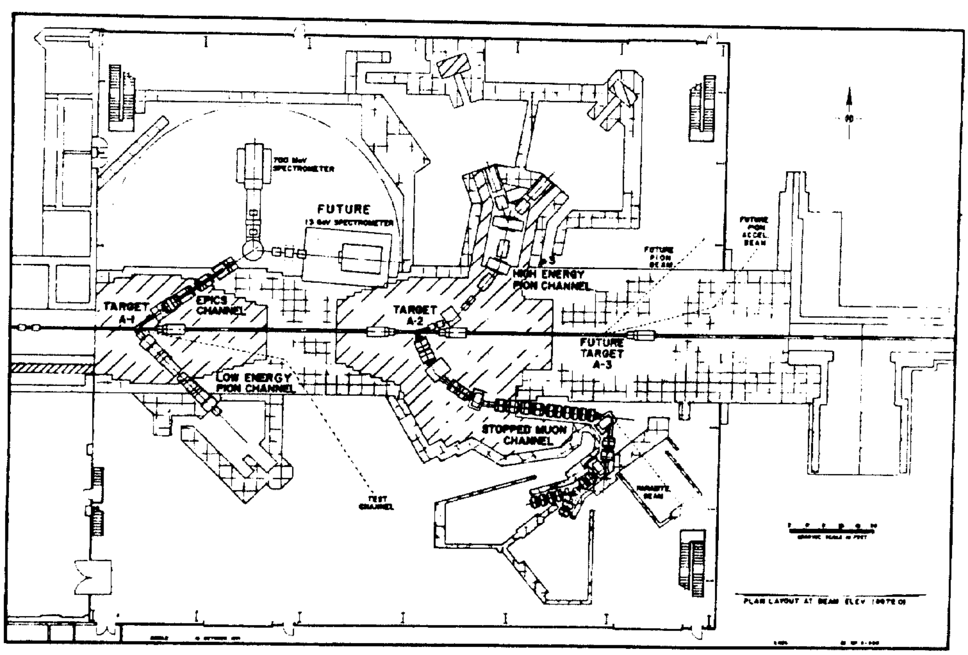

Fig. 3: LAMPF Experimental Area A with Secondary Meson Beams

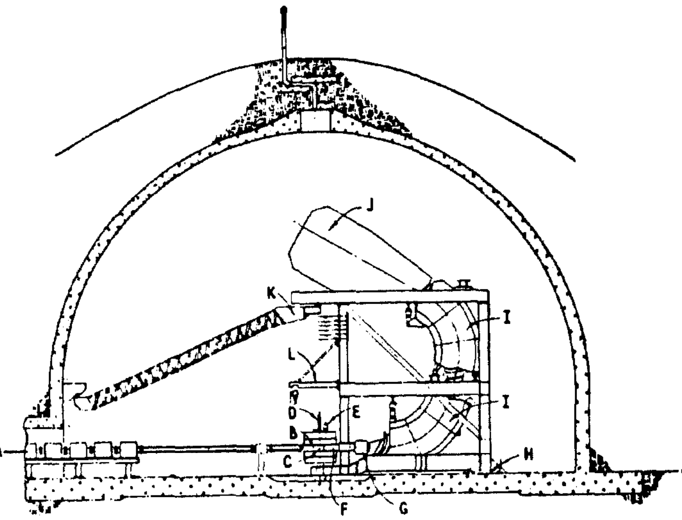

Fig. 4: **The high resolution spectrometer system, for 30 keV proton resolution at 800 MeV, at LAMPF. A beam; B scattering chamber; C target position; D target transfer mechanism; E vacuum pump; F sliding vacuum seal; G quadrupole magnet; H air pads; I bending magnet; J shielding for detectors; K cable tray system; L scattering chamber handling crane.**

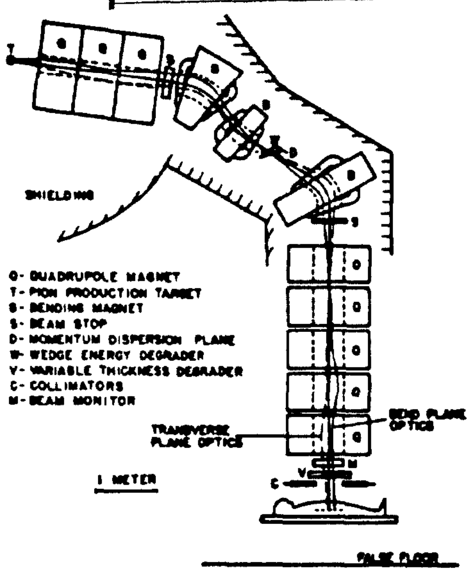

Fig. 5: **The Los Alamos Meson Physics Facility Biomedical Pion Channel.**

Dual beam acceleration has been demonstrated but beam losses were high. These were due to alignment-errors and to the reduction of the longitudinal acceptance of the 805 MHz side-coupled structure[42]. Accordingly the matching section between the two linacs, the 805 MHz linac and parts of the switchyard were re-aligned and the realignment of the remaining parts of the accelerator is in progress. Precise measurements of the effect of each module on beam-energy and phase have shown that the loss of acceptance is due to small errors in the length of the modules and of the drift spaces between them. By a proper choice of the RF amplitude and phase for each module the effect of these errors can be minimized and the acceptance increased.

The measurements required to improve the accelerator performance have been facilitated by sophisticated instrumentation and by the use of the computer system to interpret results and to calculate the necessary corrections.

In the experimental area A the stopped muon channel, the low and the high energy (P^3) pion channels are fully operational. The EPICS channel and the pion spectrometer associated with it are due for completion late in 1975. Beam area B is fully equipped; beam line C to the high resolution spectrometer is almost complete, but the work on the spectrometer has been delayed by a water leak in one of the dipole magnets, which are now undergoing final shimming.

The Biomedical Facility is operational although development work on targets, beam and dosimetry continue in order to make this installation as safe and efficient as possible for medical work.

The Radiation Effects and Isotope Production Facility in the beam stop area is under construction and will eventually contain equipment for the remote handling and observation of irradiated targets. Meanwhile irradiations of targets have been carried out at various temporary beam stops.

Although operation for research started little more than a year ago forty experiments received beam time in the third quarter of 1974 during a total of 878 hours. They cover a wide range of topics from proton-proton spin correlation effects and the study of muonium to nuclear spectroscopy and medical physics. It is probably in the medical field and in that of high resolution spectrometers where we may look forward to the most significant contributions from LAMPF.

Looking back at the proposal for LAMPF made eleven years ago one may feel confident that the promise it contained will be met. Instantaneous proton beam intensities are steadily climbing towards the design value. Some pion beams are a little below, others above the forecast yield per microampère of protons. The open question seems not to be how many protons the machine can deliver but how many the shielding, the targets and the experiments can stand. Activation and background will be the main obstacles. The simultaneous use of H^+ and H^- ions may prove difficult in the near future, but the exclusive use of H^- for physics appears satisfactory up to about 15 μA.

The experimental areas are much more varied and sophisticated than those planned in 1964. The builders of LAMPF must be congratulated on having enrolled their users at an early stage and having worked with them to achieve this result. However, they do not intend to rest but are considering improvements and extensions. A proton storage ring for producing intense neutron bursts by single-turn ejection is under study and the Kaon Factory, using LAMPF as injector, is a distant but possible goal.

3.2 SIN

The Swiss Institute for Nuclear Research at Villigen has constructed an isochronous cyclotron facility consisting of a sector focused Injector Cyclotron for 72 MeV protons, followed by a 590 MeV ring cyclotron with eight separated sector magnets and four high-voltage accelerating cavities. Construction was started in 1967 and the first protons were accelerated to the design energy of 590 MeV in January 1974. The project has been described in a number of papers[43,44] and a status report will be presented at this conference[45]. Only a brief description of the facility will therefore be given here.

Some basic parameters and performance data[46] of the SIN cyclotrons are listed in Table 3.

Table 3

	Injector	Ring
Pole Face diam. (cm)	250	360 - 930
Max. orbit radiux (cm)	105	445
Gap (cm)	22 - 42	5
Average field at R. max.(T)	1.65	0.87
AVF Sectors	4	8
B max./ <B>	1.25	2.4
Magnet weight (to)	400	2,000
Power MW	0.4	0.65
Ion source, internal external	Livingston Duoplasmatron pol. proton	
Accelerating system	180° dee	4 cavities H_{101} mode
RF (MHz)	50.63	50.63
Phase width (deg)	20	20
Harmonic no.	3	6
Max. accel. pot. (kV)	70	4 x 600
RP power (kW)	200	4 x 180
Extraction efficiency (%)	75	90 - 95
Energy (MeV)	72 ± 1	588 ± 1
$\Delta E/E$ (% FWHM)	0.17	0.3
Emittance H) (mm. mrad) V)	5π	5π

The design is determined by a need for a high extraction efficiency of the 590 MeV protons. By removing the centre of the ring cyclotron an open structure can be used which allows space for large and efficient RF cavities producing an energy gain of 2.4 MeV/turn.

Fig. 6 shows a layout of the two accelerators and of the experimental hall.

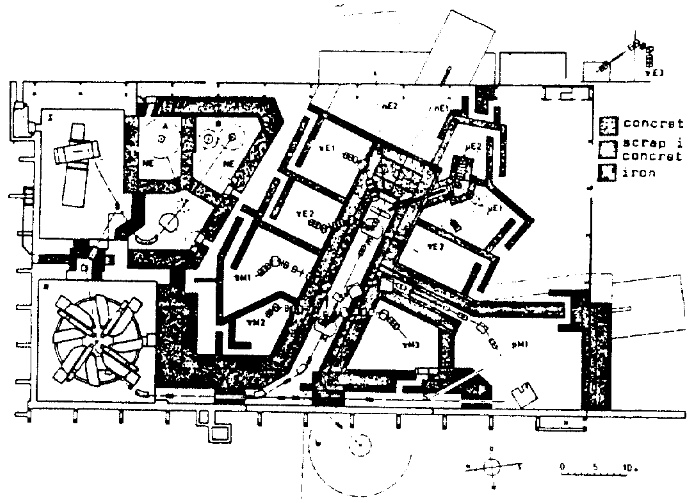

Fig. 6: Layout of SIN Experimental Hall

The injector cyclotron was designed and manufactured by Philips, Eindhoven and has been described by Bean et al.[47] Proton acceleration is effected with the dee tuned by a shorting-bar and excited by a 250 kW driven amplifier. A resonant extraction system provides the turn separation necessary to clear an electrostatic septum and permits the protons to pass via a deflecting coil and a focusing channel into the transfer-line to the ring.

The injector can also be fitted with a tunable self-excited RF system and is then used to accelerate different ions to energies variable up to $135q^2/A$ MeV. Variable-energy beams are deflected into beam areas NE-A and NE-B equipped for low-energy work.

A schematic view of the ring accelerator is shown in Fig. 7 which illustrates its modular construction

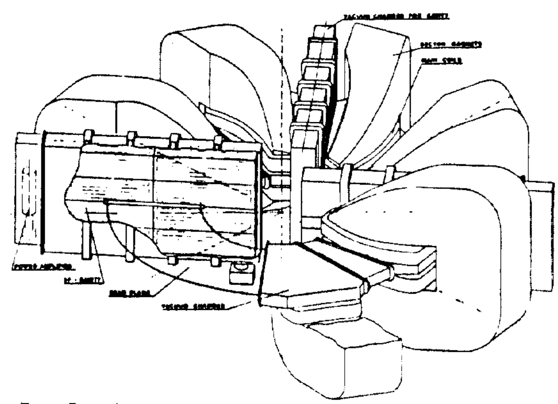

Fig. 7: Isochronous Ring Accelerator for 500 MeV Protons - Schematic View

designed to ease access and maintenance. Each magnet unit is separately demountable; the vacuum chamber is composed of sectors and pumped through the RF cavities. The cavities operate in the H_{101} mode; each is driven by a separate amplifier and tuned by mechanical deformation. Phase stability is 1°.

Injection occurs via an inflector magnet followed by a 120 kV electrostatic septum. The extraction is non-resonant and relies on the large energy gain per turn, which enables the beam to clear a 0.05 mm.thick, 1 m. long molybdenum septum producing a deflecting field of 70 kV/cm. This is followed by a 19 mm. aperture, 40 cm. long focusing magnet and by an extraction magnet.

A number of sensing devices control the beam position in the injection line and in the accelerator and permit the accurate centring required to reach a high extraction efficiency.

The present injector limits the performance of the accelerator both via beam quality and intensity. SIN are therefore studying the design of a new injector, which would improve the performance of the ring and free the Philips cyclotron for low energy research. A cyclotron with four 26° sector magnets and an 800 keV pre-injector is the most likely choice[48].

Thanks to the CW operation the 590 MeV proton-beam has 100% macroscopic duty cycle, but the 20° phase acceptance of the RF produces a 5% micro duty cycle with 1 ns pulses separated by 19 ns intervals. At electronic counting rates exceeding about 10 MHz, i.e. just in the range where the secondary beams become superior to those obtainable from improved synchrocyclotrons, the problem of counting losses and random coincidences reappears. SIN are therefore planning to stretch the beam by the addition of a fifth accelerating cavity operating at 150 MHz, but it is recognized that this will only be effective if the amplitude and phase of the third harmonic relative to the first are accurately controlled. The design provides for a phase error below 0.05°. Installation of the 150 MHz cavity is foreseen for 1976. It will improve energy resolution and extraction efficiency[49].

Figure 6 indicates the disposition of the experimental areas. The extracted beam passes two target stations, E and M, before reaching the beam dump. The targets are conical discs made of graphite or beryllium. The beam strikes the mantle of the truncated cone, which rotates slowly and is radiation-cooled. Each target assembly carries four cones and can be withdrawn from the beam with its support for replacement. The beam-stop consists of a series of water-cooled copper plates slotted in the beam plane so as to distribute the heat-load. It has to be wide enough to permit the beam displacements caused by an analyzing magnet downstream of target E and is in beam vacuum.

Five pion channels, a muon channel, a neutron channel and a channel for scattered protons supply ten experimental areas. Noteworthy installations are the πM1 channel, which will supply a large, single arm pion-spectrometer, the πE3 biomedical channel shown in Fig. 8, the neutron time of flight beam nE1 and the muon channel which consists of an eight-metre long superconducting solenoid. Some measured meson fluxes are listed in Table 4.

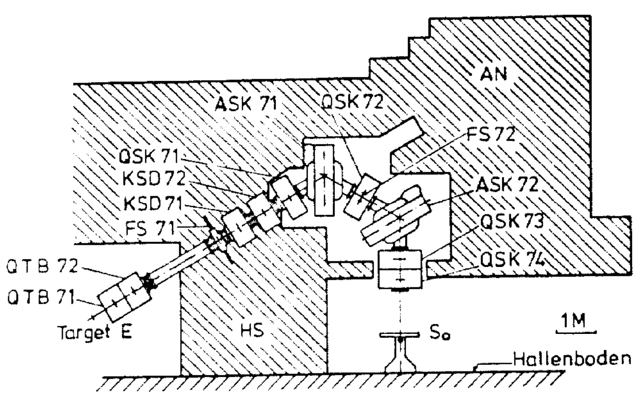

Fig. 8: SIN Biomedical Channel

Table 4

Channel	Target	Particle	p (MeV/C)	$\Delta p/p$ %	Flux μA.s
πE3	3 cm Mo	π^-	150	$\pm$ 7.5	10^6
μ	12 cm Be	μ^-	115	$\pm$ 7	2×10^5

The observed values agree well with earlier estimates[50] and a similar agreement is found in the other pion channels tested so far[51]. The pion dose rate in the πE3 channel is comparable to that observed at LAMPF.

The accelerator shows every promise of fulfilling the expectations of its designers. Its present maximum beam current of 25μA is entirely dictated by radiation safety and the ring appears capable of accelerating any beam obtainable from the injector. The limit of the present installation lies near 300μA and is given by the power of the RF amplifiers. Doubling them will raise the limit to about 1mA.

3.3 TRIUMF

The design for an H^- accelerator first developed by UCLA[17,51], and later taken up by a collaboration of Canadian universities[52], looks at first sight the ideal choice for a meson factory, combining the high duty-cycle of the isochronous cyclotron with the high extraction efficiency and the variable proton energy of a linac. The possibility of simultaneous extraction of several proton beams and its ability to accelerate polarized H^- ions are further points in its favour[53].

However, the Stark-effect stripping of the loosely bound second electron determines the maximum value of V x B which can be used and thereby either limits the energy or it makes the machine exceedingly large and thereby increases the ion loss by gas stripping, unless the residual pressure can be reduced at the same time. The choice of energy and dimensions therefore represents a compromise which has finally led the designers to accept a 20% loss of ions during acceleration and to adopt the set of parameters shown in Table 5[54,55].

Table 5: Principal Parameters of the TRIUMF H^- Accelerator

Pole face diameter	1717 cm	Accelerating system	2 x 180° resonators
Maximum orbit radius	780 cm	RF	23.1 MHz
Gap	52.8 cm	Phase width	35°
Maximum field	0.58 T	Harmonic no.	5
Average field at R_{max}.	0.46 T	Max. accel. pot.	2 x 200 kV
AVF sectors	6	RF power	1.65 MW
Magnet weight	4200 to	Vacuum	5×10^{-8} torr.
Magnet power	2 MW	Extraction	H^- stripping by two independent foils
Ion source external, axial inj. at 300 KeV	Ehlers H^-	Proton energy	165 - 520 MeV

The accelerator has been described in earlier publications[55 56 57] and a status report will be given at this conference. We shall therefore point out only a few particularly interesting features.

The H^- ions are produced in an external Ehlers source placed at 300 kV above ground and are injected via a 40 m. transfer line fitted with a double-gap buncher and with purely electrostatic bending, focusing- and switching-elements to avoid spin precession of the polarized ions. Ion injection into the cyclotron is effected by a spiral inflector. This is designed into a 50 cm. diameter stainless-steel centre post which also supports the cantilevered pole-faces.

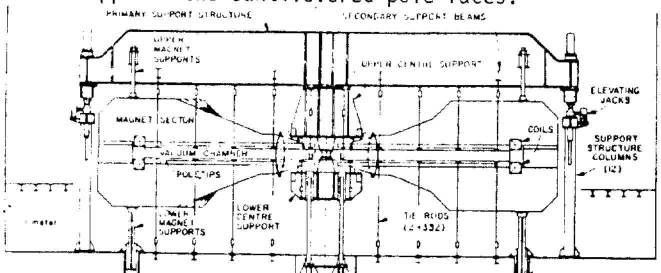

Fig. 9: TRIUMF Magnet and Support Structure.

Fig. 9 shows a cross-section of the 17 m. diameter - 4000 ton magnet, whose tailoring for isochronism proved difficult and necessitated cutting the pole-faces and reinforcing the yokes [58]. The vacuum chamber is a pill-box; its two halves meet in the median plane and are sealed with a circular joint. Diffusion pumps and cryo-panels cooled to 20°K by helium provide the required vacuum.

The upper pole-faces and the top of the vacuum chamber can be lifted by a support structure to allow access to the machine for servicing from a mobile bridge. The support frame also holds the tie rods necessary to prevent the collapse of the vacuum chamber under atmospheric pressure.

The accelerating system has been described by Erdman et al.[59] It consists of four sets of quarter-wavelength resonators aligned above and below the mid-plane on either side of a diameter of the vacuum tank (see Fig. 10). They are tuned to resonance and

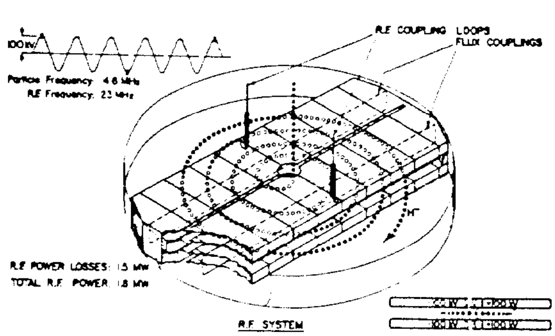

Fig. 10: TRIUMF Dee Resonators

powered by a three-stage amplifier via two single coupling loops. The same cavities will be excited in the third harmonic mode via a second amplifier-chain, permitting doubling of the micro duty cycle and an increase of the capture phase. The vertical alignment of the resonators near the centre is critical; they are shimmed by correcting plates.

Carbon foils of approximately 25 μm (1 mil.) thickness will act as strippers and cause extraction of the proton beam. By moving them radially the proton energy can be varied but the emerging proton beams all pass through a common dipole magnet which deflects them into the extracted beam line.

The accelerator is placed below ground and between two experimental areas as shown in Fig. 11. The Proton Area is equipped for nucleon beams and houses a proton-spectrometer. A liquid-deuterium target, specially designed to absorb the heat dissipation caused by a 10 μA proton beam, is used to produce mono-energetic neutron beams. The beam dump contains an irradiation facility.

The Meson Area has an achromatic pion beam for pions up to 240 MeV emerging from a thin (4 gm/cm^2)C, Be or water target at 2.6°. Fluxes of order 10^6 π^+ / MeV.sec.μA are expected. A second, 24gm/cm^2 target produces a medical pion beam capable of yielding maximum dose rates of about 10 rad/min, a stopping pion or muon beam and a further muon beam (not shown in the diagram) built by a Berkeley-Osaka collaboration.

Machine performance will principally be determined by beam losses. At 520 MeV and a residual pressure of 7×10^{-8} torr, 4% of the beam is lost by gas-stripping and 16% by electromagnetic stripping and a current of 100 μA is regarded as an upper limit. At 450 MeV the electromagnetic losses are much smaller and one may be able to exploit the maximum ion-source yield of about 500 μA.

Construction of TRIUMF was started in 1968; a proton beam at full energy was obtained in December 1974.

3.4 Other Projects

Design and development work is in progress on the meson-factory project in the USSR referred to earlier[26] but details have not yet been published. It is based on a proton-linac of characteristics similar to LAMPF. The injector stage has been defined and studies of accelerator structures have been reported, involving the development of the side-coupled cavities into ring-structures.

The maximum energy will be 600 or 1000 MeV. The machine is to be equipped with two storage rings[27], one capable of single turn ejection and producing an intense particle burst of 200 ns duration. A second storage ring is intended as a beam stretcher and is similar to the concept developed by Brianti and Skarek[60].

4. Comparisons and Conclusions

While none of the three accelerators described has yet been pushed to the limits of its performance, our present knowledge allows us to make some interesting comparisons. Some data for such an exercise are listed in Table 6. In all three cases beam loss and the resulting induced radio-activity are seen to be the principal limitation. At LAMPF a 4 μA beam loss in the accelerator is considered excessive and this limits its beam to about 200 μA at present. Progress in realignment will probably raise this limit in the near future. SIN has reached 95% transmission and has operated at 25 μA internal beam. An improvement of the extraction efficiency is expected from the installation of the fifth, third-harmonic accelerating cavity which should produce a better turn-separation in the extraction

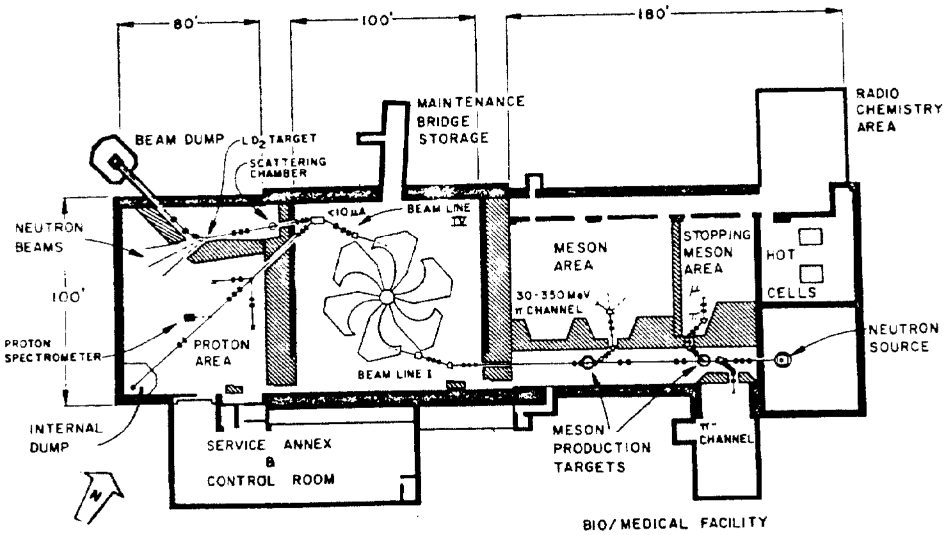

Fig. 11: TRIUMF Experimental Areas

Table 6: Comparison of Facilities

	LAMPF	SIN	TRIUMF
1. Location	Los Alamos	Villigen (CH)	Vancouver (BC)
2. Type	Linac	Ring cyclotron	Cyclotron
3. Accelerated particles	p. H^-	p	H^-
4. Particle energy (MeV)	$\leqslant$ 800	588	160-520
5. $\Delta E/E$ %	$\pm$ 0.4	0.3	($\pm$ 0.1)
6. Emittance (mm mrd)	1.4 π	5 π	(1.2 π)
7. Design current (µA)		100	
p	900		100
H^-	100		400 at 450 MeV
8. Transmission (%)	99	$\lesssim$ 95	~ 80
9. RF (MHz)	201.25 805	50.63	23.075
10. Macro duty cycle %	6	100	100
11. Micro pulse			
length (ns)	0.25	1	4
period (ns)	5	20	44
12. RF power (MW)	3	Injector 0.2 / Ring 0.72	1.8
13. Magnet weight (to)		Injector 400 / Ring 2000	4200
14. Magnet power (MW)		Injector 0.4 / Ring 0.65	2
15. Total power (MW)	3	2	3.7
16. Beam limitations:			
Injection		100 µA (1 mA)	500 µA
RF loading		300 µA (1 mA)	
Space charge		3 - 5 mA	
Induced activity	1 mA	200 µA	500 µA at 450 MeV
17. Best π^+ beam (design)			
Target (gm cm^{-2})	12 C	24 C	4 C
p (MeV/c)	400	364	254
Δp (MeV/c)	40	18	1
Flux (s^{-1})	1.8×10^{10}	1×10^{10}	2×10^8
Flux/ Δp	4.5×10^8	5.5×10^8	2×10^8
18. Experimental stations	10	10	8
simultaneously usable	10	8	6
19. Special features	Variable energy High resolution Spectrometers	Supercond. Muon channel Variable energy injector	Variable energy Simultaneous p-beams of different energies
20. Cost			
Accelerator	21 M$	50 MSFr	11 MC$
Site and buildings)	32 M$	50 MSFr)	15 MC$
Services)		20 MSFr)	
Experimental installations	12 M$	30 MSFr	6 MC$ + 2 per year
Total	65 M$	150 MSFr	36 MC$
21. Annual budget	13 M$	30 MSFr	4.9 MC$

region. The limitations of TRIUMF are more fundamental: higher beams will necessitate a lowering of the proton energy.

Radioactivity in the target areas is already a serious problem at LAMPF and SIN. With its Merrimac LAMPF is best equipped for the future.

Only LAMPF has so far furnished data on reliability. It achieved 69% machine availability during the third quarter of 1974. One would expect a linac with its close tolerances on RF amplitude and phase to be more vulnerable than a cyclotron, and it is interesting to note that the first and a good many subsequent runs at SIN were performed while only three cavities were operating. However, as a modular, stretched out machine the linac has obvious advantages over the cyclotron as regards maintenance. Cyclotron engineers are forever condemned to repair a prototype!

Its duty cycle will limit the useful beam in LAMPF except for experiments not involving electronic counting or those in which the background events are not produced by the accelerator, e.g. neutrino experiments. Count-rate limitations will also affect the cyclotrons when count rates in individual detectors approach the pulse frequency. In this respect TRIUMF is better placed than SIN. Not only can it excite the existing resonators in the third harmonic but a reduction of the energy gain with radius may ultimately be used for phase expansion.

A comparison of the best obtainable pion fluxes shows that the differences between the various installations is not as large as raw data might suggest. The peak in the pion spectrum moves to higher momenta as the energy of the incident protons increases but the calculated pion fluxes per unit of momentum interval are of the same order, although the assumed primary proton flux is ten times higher at LAMPF than at SIN and TRIUMF. The reason for this seems to lie in the use of zero-degree emission in the two latter cases. This not only benefits from the forward peaking of the pion production cross-section but equally from the greater effectiveness of a long target at forward angles.

In its experimental equipment each institution seems to have concentrated most effort on the field where it can be most effective. With its intense beams at relatively low duty cycle, LAMPF is clearly best suited for high-resolution single-arm spectrometry and with HRS and EPICS is working to equip itself with the best that can at present be achieved in proton and pion spectrometry. The variable energy nucleon beams available at LAMPF are of impressive quality but varying the proton-energy will not always be welcomed by pion-beam users and this may cause scheduling problems.

With its fixed energy SIN is more oriented towards mesons than towards nucleons and has made a great contribution by the development of its superconducting muon channel which is capable of producing ten times more stopping muons per proton than any other installation.

The strength of TRIUMF will be in its simultaneous proton beams of variable energy, which will avoid conflicts of interest between different users and will make it a very attractive facility for nucleon-nucleon studies. Its relatively low energy will favour the use of stopping pions, and it has been frequently pointed out that much of the research potential of a meson factory lies in this region.

All three accelerators possess biomedical pion beams giving roughly similar dose-rates per primary proton. The installation at LAMPF has been most thoroughly studied and is best equipped.

Attempts to compare costs founder on definitions, inflation and exchange-rates; while accelerators and buildings are reasonably well defined and identifiable the partial use of operating budgets to equip experimental areas renders the final figures uncertain. Comparing the site and accelerator costs to the estimate contained in the original proposals and quoted, e.g. by Livingston[61], one notes that LAMPF and SIN stayed closer to their estimates than TRIUMF. Even so the cost of TRIUMF is about half that of LAMPF.

The choice of any future meson factory will certainly benefit from the fact that three machines based on different design principles and of different characteristics are now available. While the USSR seems to be inclined to follow the U.S. lead into the field of linacs, the discussion does not appear to be closed and the protagonists of the strong-focusing cyclotron[62] are making their voices heard.

While duty cycle, cost and power consumption militate against a linac its high transmission and the possibility of increasing its energy by the addition of new modules are great points in its favour. Before contemplating a second generation of meson factories we ought therefore to watch the progress of the Karlsruhe Group towards a superconducting proton-linac[28 29].

It is clearly much too early to draw any conclusions from research at meson factories but a few interesting points emerge.

When physicists in the late 1950's called for orders of magnitude increases in meson beams, they were obviously aware of the limitations imposed by electronic detection methods. However, in the preceding decade these methods had made a spectacular advance, and microsecond resolving times had been reduced to nanoseconds. It did not seem unrealistic to hope for another order-of-magnitude gain before meson factories came into operation. However, while electronics have been perfected in many ways they have not become substantially faster, and the count-rate limitations have remained.

So far researchers have therefore tended to exploit the capacities of meson factories by other means, most usually centring on higher momentum resolution but rather wasteful in the use of mesons.

These are clearly exceptions to this, notably in the biomedical use, in weak interaction research and in the isotope production by mesons, but it seems that in the traditional field of nuclear and particle research the best way of living with a meson factory has still to be found.

For biomedical work higher dose-rates give quicker results, but even here some caution seems to be indicated. Present biomedical beams furnish dose-rates of about 1 rad per minute per microampère of protons. Considerations of safety would probably not permit going up by more than two orders of magnitude. So even in this field much remains to be done before the full potential of a meson factory can be exploited.

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