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CONTEMPORARY STATUS OF ACCELERATOR PHYSICS AND TECHNIQUE

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I. INTRODUCTION

THE present review consists mainly of the material presented at the VII International Conference on High Energy Accelerators, which took place August 27–September 2, 1969 in Erevan (Tsakhkadzor). We thought, however, that it would be appropriate to distribute the material thematically, without strictly following the order in which it was presented at the conference.

The review consists of two main sections, the first of which (Sec. II) is devoted to a discussion of the state of the art and the plans for the development of traditional acceleration methods, while the second (Sec. III) describes new acceleration methods. Such a division is, of course, somewhat arbitrary. Thus, the method of colliding beams, which we have classified as a traditional method, is in fact quite new and has been first proposed only thirteen years ago. It seems to us, however, that the main consideration for classification in our field should be the following: whether or not a given method of acceleration is used basically for the proposal and carrying out of experiments in the field of elementary particle and high-energy physics. So long as the development of a method proceeds in an internal manner with respect to experiments with accelerated particle beams, it may be regarded as new. From this point of view the method of colliding beams, which has already given a number of brilliant experimental results, may be looked upon in spite of its youth as a tried acceleration method forming part of the equipment of the experimental physicist. On the other hand, the development of conventional accelerators makes use of new methods or their applications. This is particularly true of cryogenic and low-temperature methods, which find more and more applications in the plans for the perfecting of existing accelerators, and in projects for the construction of new ones. Ever wider use in accelerator technique is also found for computers and for automation. Nevertheless the division into traditional and new methods is convenient and sufficiently justified by the existing practice of the workers in the accelerator field.

We do not touch in this review on experimental work carried out on accelerators, nor on problems of high-energy physics and their influence on the prospects for remote-future accelerators, but confine ourselves to the problem of presenting the contemporary picture of the state of the art in the accelerator field. This review, however, would lose something of its value if we failed to mention the very interesting report by Okun'[1], in which a number of experimental problems is discussed, whose solution in accelerator experiments is awaited by high-energy physics. Thus, a problem of prime importance for accelerators such as the one at Serpukhov is, aside from the study of hadrons and their interactions, the discovery of purely leptonic processes—the scattering of the electron neutrino by electrons and the muon pair production by muon neutrinos in the Coulomb field of a nucleus. The discovery of a neutral weak current (for example in the decay of a neutral kaon into two muons) would also be of great interest.

Of special interest are questions about the energy dependence of lepton weak interaction cross sections and the discovery of the region in which the "cutoff" of the cross section growth for such processes occurs. An indication that this growth should stop is given by the so far unexplained smallness of higher orders of weak interaction. Clearly, it is fundamental for the understanding of weak interactions to find effects in which higher order influences are seen, or experiments with colliding lepton beams with energies in the hundreds of GeV. Other problems of equal importance, which await for their resolution experiments on accelerators, are also discussed in the report[1], which constitutes a systematic review of elementary particle interactions.

Also of interest for the characterization of the contemporary state of accelerators is the comparison of large electron and proton accelerators from the point of view of the yield of secondary particles, their purity and dimensions, and from the point of view of other experimental possibilities. This was discussed in the report of Rees[132] and in the discussion that followed. The main conclusion of these discussions is that each of the different accelerator types has definite advantages over others; the yield of secondary hadronic beams is larger for proton accelerators, electron accelerators have advantages in the purity of neutral beams and in the density of the secondary lepton beam. However, experiments which have previously traditionally been assigned to proton or electron accelerators are now successfully carried out on either type of accelerator.

II. TRADITIONAL METHODS OF ACCELERATION

At this time the traditional acceleration methods (by external self-phasing electric fields at room temperatures) are the only methods utilized by all existing and projected high-energy accelerators. The demands of experimental physics for ever higher energies are still satisfied by the direct route—the construction of ever more grandiose (in dimensions and power) accelerators; the technical and economical difficulties involved in the creation of such accelerators are overcome in one or another manner.

1. The Status and Modernization of Operating Accelerators

a) Synchrotrons. The data for all proton and electron synchrotrons now operating or under construction

Table I. Proton synchrotrons

Location	Status constructed/ project	Beam			Injector		Magnet									HF system				Experimental possibilities	
							field				ring			weight							
												aperture									
		Energy, GeV	pulse/sec	10^{12} p/sec	energy, MeV	current, mA	indicator index	injection, G	at maximum, kG	maximum power, MW	diameter, m	h, cm	W, cm	kt Fe	t Cu	repetition rate	HF range, MHz	energy increase	maximum power, kW	total area, 1000 m^2	total power, MW
CERN																					
1. Geneva	1959	28	1/2	0.75	50	135	288	147	14	41	200	7	14.6	3	130	20	2.9—9.55	79 (max.)	375	11	33
2. Geneva	Project	(300)	1/3	(10)	8000		4780	355	12	180	2400	6	10	29	2100	4620	182.5—183.6	7500	6000	—	—
France																					
3. Saclay	1958	3	1/3	0.1	3.6	5	0.6	326	14.9	24	22	10.5	36	1.08	55	2	0.76—8.44	1.16	4	4.2	18
4. Saclay	Project	45	2/1	1	100	88	0	174	18	9.4 (mean)	300	12.2	6.8	3.4	240	96	13—31	240	—	—	—
Germany																					
5. Karlsruhe	»	(60)	1/2	5	2000	—	—	82	18	36	360	4.8	85	—	—	120	30.2—31.9	365	347	—	—
USSR																					
6. Dubna	1957	10	1/10	0.015	9	1	0.66	150	12.6	140	72	35	120	36	2700	1	0.2—1.45	2.4	500	2.7	26
7. Moscow	1967	1	1/2	0.005	1	5	190	250	10	—	17	1.6	2.1	0.016	2	5	1.25—25	2 (max.)	—	—	—
8. Moscow	1961	7	1/6	0.01	4	10		90	9.5	25	80	8	11	2.7	—	7	0.65—8.3	4.4	500	—	—
9. Moscow	Project	(1000)	1/3	(10)	18 000	—		—	—	—	5400	4	6.6	20	—	—	—	56 000	20,000	—	—
10. Serpukhov	1967	76	1/8	0.18	100	100	440	76	13	100	472	17	11.5	20	700	30	2.6—6.1	180	300	—	—
England																					
11. Birmingham	1953	1	1/4	0.0025	0.46	1	0.68	210	12.5	7	10	10	33	0.8	9	1	0.22—9.26	0.2	10	0.28	0.8
12. Rutherford	1963	7	1/4	2.0	14.9	45	0.6	229	14	160	53	100	20	7	250	4	1.4—7.98	5.5	45	7.3	24
USA																					
13. Argonne	1963	12,7	1/2	1—1/2	50	30	0	482	21.5	110	55	13.3	81.3	4.7	68	8	4.4—14	10	60	12.6	40
14. Brookhaven	1960	33	1/2.5	3	51	60	357	121	13	30	257	6.4	13.3	4	400	2	1.4—4.46	100	300	15	36
15. Brookhaven	Project	(1000)	1/1	(10)	25 000	0.002		1500	60	—	1500	5	12.5		—	—	—	30 000	—	—	—
16. Berkeley	1954	6.2	1/5	1.5	19	25	0.67	417 346	15.5	121	19.3	25	112	9.7	347	1	0.3—2.3	1.5	100	7	21
17. Berkeley	Project	(1.4)	60/1	(13)	3	10	28	1545	10	1	32	4	10	0.8	8,2	8—100	1.6—32	—	800	—	—
18. NAL, Batavia	—	Under construction (200—500)	1/4	(15)	8000	0.010		495	9—22.5	13	2.000	5	12.5	9.8	860	1000	52	3460	2000	—	—
19. Princeton	1963	3	19/1	1	3	4	0.6	278	13.8	2.5	25	6	18.9	0.4	15	8	30	61	320	3.5	20

Table II. Electron synchrotrons

Location	Status constructed/ project	Beam			Injector		Magnet									HF system				Experimental possibilities	
							field				ring			weight							
												aperture									
		energy, GeV	pulse/sec	10^{12} sec	energy, MeV	current, mA	index	injection, G	At maximum kG	mean power, MW	diameter, m	h, cm	W, cm	Cu, t	Fe, t	repetition rate	frequency, MHz	energy increase, keV/rev	maximum power, kW	total area, 1000 m²	total power, MW
Germany																					
1. Bonn	1967	2.3	50	2	25	250	23	100	10	0.55	22.2	4	9	17.4	133	116	500	330	80	1	2
2. Hamburg	1964	7.5	50	5.6	40	180	70	42	7.9	1.7	50.4	7	12	77	570	528	500	1250	360	6.4	23
Italy																					
3. Frascati	1959	1.1	20	0.4—1	12.4	30	0.61	110	10.2	0.15	8.74	5.7	19.2	10	100	4	43	4.5	16.5	0.4	2.5
Japan																					
4. Tokyo	1961	1.3	22.5	0.8	9	100	14.8	80	11	0.402	10.9	3.5	11	7,9	53	16	138	10	20	0.45	0.45
Sweden																					
5. Lund	1960	1.2	12.5	0.045	6.45	40	10.6	59	11	0.185	10.8	3.6	6.5	11.2	24	45	399	60	4	0.3	0.8
USSR																					
6. Erevan	1967	6.1	47.4	3.5	50	170	115	66	7.95	1.9	69	3	9.8	27	400	96	133	720	520	1.8	8.0
7. Erevan	Project	100—50	50—400	200	—	—	$4\cdot10^3$	360	1.8—1.2	—	2360—6800	—	10—12	—	—	$0.95\cdot10^4$—$0.75\cdot10^5$	800	$0.77\cdot10^6$—$4.15\cdot10^6$	$28.5\cdot10^3$—$310\cdot10^3$	—	—
8. Tomsk	1964	1,3	2	0.04	5,5	50	0,58	43	12	0.8	10.7	8.4	23	3	120	4	36.5	1.5	120	0.6	1.1
9. Moscow	Under construction	1.2																			
England																					
10. Danesbury	1966 r.	5	53	6	40	500	47	64	8	0.95	70.2	6.7	11.5	40	360	300	408	470	480	3.2	12
11. Danesbury	Project	15—20			3000		516	83.4	0.556		421	1.8	5			3600	816		1120 (GeV/mA)		
USA																					
12. Cambridge	1962	6.28	60	9	130	100	91	150	7.6		75	3	16	36.6	3006	360	476	6000	400	2	5.5
13. Cal. Tech.	1952	1.53	1.5	0.05	10	500	0.6	90	13.3	0.28	9.6	6	18	18	155	4	40	0.7	300		0.25
14. Cornell	1964	2.1	30	0.9	10	50	26	55	10	0.25	32	2.8	6.4	2.7	60	75	433	35	20	5.4	1.7
15. Cornell	1967	10	60	1.2	150	100	432	50	3.3	0.77	250	2.5	5.5	26	200	1800	714	10^4	425	1.1	2

and projected, with energies above 1 GeV, are given in Tables I and II.

In the Serpukhov proton synchrotron, a whole complex of secondary channels, generated from internal targets, has been constructed[22]. The distribution of channels in the experimental room, which measures 150 × 90 m, is shown in Fig. 1. The channels have been so designed that the beams that are formed can be deflected to several experimental setups. The momentum working range is 40–60 GeV/c in channel 2 and 25–40 GeV/c in channel 4. The channels $1K^0$ and $2K^0$ are designed for experiments with kaons and neutrons. Finally there is channel 6 of positive particles with momentum in the range between 0.8–20 GeV/c.

Projects for fast[23] and slow[24] proton extraction have been worked out for application to external targets on the accelerator. In the latter project, extraction is planned during the flat part of the cycle, whose length may reach 1.5 sec. The calculated efficiency of extraction amounts to 90%. Such an efficiency for slow extraction has been experimentally confirmed on the CERN proton synchrotron (PS). The measured value 90.7 ± 3.1%[25] is in good agreement with the theoretical calculations. The efficiency of fast extraction on that synchrotron equals 100%. A system of three-turn proton extraction with efficiency close to 100% has been calculated for the Brookhaven strong-focusing synchrotron (AGS)[26].

Two photon beams of 2 msec duration have been obtained in the Erevan synchrotron, and an electron beam was extracted of 2.5 msec duration at the beginning of 1970.

At the Cornell accelerator, use is made at this time of four photon beams and there is access to the internal beam in the long rectilinear interval[32]. An external electron beam is planned for the future.

More detailed information about the status of operating synchrotrons can be found in[2,4,8-14,20]. The paper[21] is a catalogue of accelerators, issued for the conference.

The setting up of ever more refined experiments for the study of processes with ever smaller cross sections, the incorporation of fast-acting detection instruments, as well as the increase in the possibilities of analysis of the experimental material connected with the joint use of automation and computer techniques, make ever new demands on operating synchrotrons regarding the increase in the efficiency with which these machines are used. In this connection in most laboratories there is either going on or being planned a modernization and perfection of the accelerators, whose aim is the increase of the average and instantaneous intensity, reliability, experimental area and power of the experimental magnets, number of extracted beams and their duration, and efficiency of extraction and purity of secondary beams.

The increase in the intensity of a synchrotron beam (as well as that for other types of accelerators) is theoretically limited by space-charge effects and the interaction of the beam with the accelerator system. However, the complexity and indeterminacy of the calculation of these effects makes it impossible to assert that a limiting of the current due to these effects is observed in any of the operating machines, although the limit should not be substantially higher than the intensities already achieved in the synchrotrons. Moreover, it is clear a priori that this limit may be shifted by increasing the energy of the injected particles and increasing the power of the accelerating system.

The Brookhaven AGS was stopped in June, 1969. In a period of five months the tunnel will be reconstructed in order to unite it with a new future injector and with additional already-constructed experimental areas, and the shielding and power supply for the magnets and the accelerating field have been increased. This will make possible the increasing of the cycle repetition rate to 1 Hz (without a flat part in the cycle) or increase the duration of slow extraction to 1 sec. In 1971 a new 200 MeV linear accelerator will be put into operation, which will increase the AGS beam intensity by a factor of 5[27].

Another approach was chosen for the modernization of the CERN PS—the construction of a special booster accelerator[28]. This was due to the desire to not only

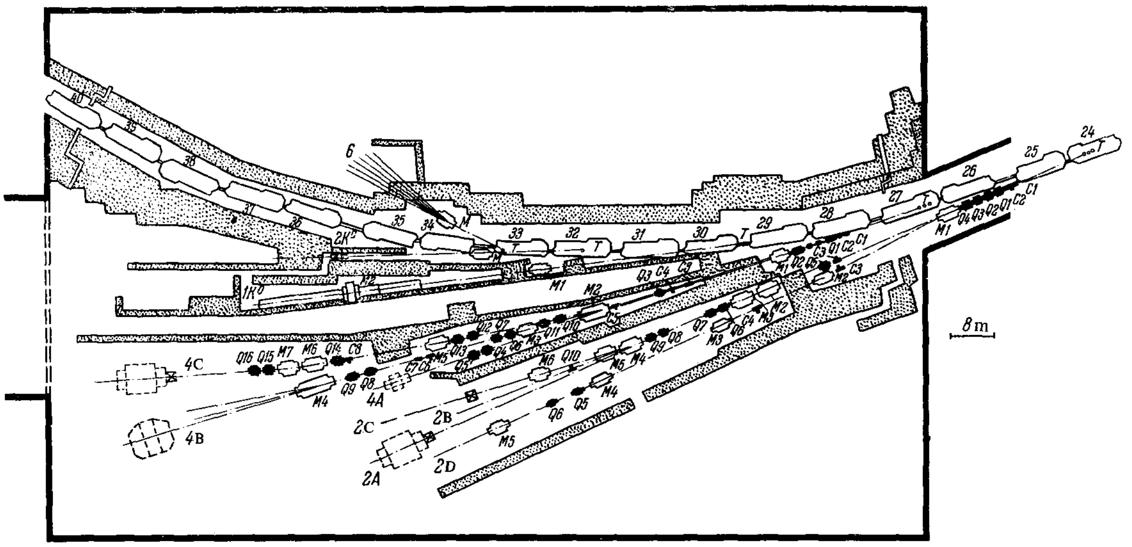

FIG. 1. Secondary beams location scheme of the IFVÉ synchrotron (Serpukhov) [22].

increase the intensity of the accelerator, but also to decrease the admitance of the CPS beam, which will be utilized as the injector for the intersecting storage rings (ISR, see below). The construction of the booster, which consists of a strong-focusing four-way synchrotron with divided functions for 800 MeV energy, has already been started and will be concluded in 1972.

The main parameters of the booster are given in Table III[27]. During last year's stoppage of the CPS the tunnel was reconstructed, the shielding was increased and the magnet power supply was increased. This ensures the creation of a flat part of the magnetic field curve of 0.4 sec duration for a repetition rate of 0.5 Hz. To increase the beam intensity to 10^{13} p/pulse it is also necessary to rebuild the high-frequency power supply system. This reconstruction will also be completed by 1972. Finally, a new experimental room with area of 10^4 m^2 has been built, which is used at present for putting together elements of the ISR.

The plans for the modernization of the Princeton-Pennsylvania accelerator (PPA)[20] also include the construction of a high intensity 75 MeV booster. It will make possible raising the intensity to 2×10^{13} p/sec. In the pursuit of the same goal it is planned to use non-sinusoidal accelerating voltage, to increase the energy of the Van de Graaff injector from 3 to 4 MeV, and to perfect the correction system at injection. A unique system for the formation of a flat peak field 50 msec in duration with a constancy of $\pm 0.001\%$ for a repetition rate of 10 Hz, constructed on hard valves, became operational at the end of 1969.

The improvements in the "Saturn" synchrotron (Saclay) include the passage from a 4 MeV Van de Graaff injector to a 20 MeV linear accelerator (a beam with intensity of 15 mA with an emittance of 2×10^4 rad-cm in the energy interval ± 150 keV was obtained), the accelerating of deuterons to an energy of 2.3 GeV (the beam contains 2×10^{11} particles), the creation of a polarized proton (or deuteron) source and their acceleration[4].

The zero-gradient Argonne accelerator (ZGS) should have its intensity doubled with the new vacuum chamber and pole windings, which will soon become operational.[27]

A 130 MeV linear accelerator has been constructed for the Cambridge electron synchrotron and is now in use.[29]

Virtually all large electron synchrotrons (except for Cornell) have plans for the construction of new injectors, and in Cambridge and Hamburg these injectors for energies of 250 and 400 MeV are already being built[30,31]. This will make possible not only increased intensity of the synchrotrons, but beams of accelerated positrons, and also their storage for experiments on colliding electron-positron beams (in Cambridge by means of a bypass, in Hamburg by an already constructed double storage ring). The Erevan synchrotron will, in addition, receive a new ceramic chamber and a second experimental room with extracted additional electron and photon beams.

Table III. Main parameters of the CPS booster

Energy	800 MeV
Injector energy	50 MeV
Critical energy	4.5 M_p
Intensity	10^{13} protons/pulse
Path number	4
Mean radius	25 m
Radius of curvature	8.3 m
Structure	$DO_2FBO_1BFO_2D$
Magnet gap cross section	7 × 14 cm^2
Voltage per turn (max.)	12 kV
High frequency range	3–8 MHz
Number of accelerating intervals per path	1
Average energy gain per revolution	1 keV
Chamber pressure	10^{-8} torr
Minimum cycle duration	1.2 sec

b) Linear accelerators. The data on electron and proton high energy or high intensity linear accelerators, including also certain synchrotron injectors, are given in Table IV.

The most efficient (and effective) is the SLAC accelerator. In 1968 during 5700 of full-time working hours of the accelerator the experimentors received 13000 hours [sic!]. 80% of the full-time was devoted to elementary-particle physics, 12% to nuclear physics, and only 8% to accelerator physics[33].

In addition to a rather intensive primary electron beam with 1.8×10^{14} electrons/sec, the accelerator also yields accelerated positron, muon, pion and kaon beams, as well as photons.

The burst instability, discovered in the Stanford accelerator in 1966, is now suppressed during startup (up to a current 50 mA for a 1.6 μsec pulse duration at the end of acceleration) by application of strong focusing and selective microwave tuning of certain accelerator sections[74].

All presently operational linear accelerators possess a significant fault from the point of view of the possibilities for their use in physical experiments: small duration of the accelerated-particle pulse, which gives rise to a large overloading of the electronic detecting apparatus. This fault may be overcome by supplying the accelerator with a storage ring for stretching the beam. Such work is being carried on at Saclay[34], where the ALIS setup has been proposed, and at Stanford where the projected storage ring may also be used for this purpose[35].

A direct method is also possible—the construction of linear accelerators with a small duty ratio. Such linear accelerators have been constructed in the U. S.[36] and in France[37]. These accelerators give beams with 400–450 MeV energy with an approximately 2% duty ratio.

It is to be expected that a cardinal resolution of the problem will be obtained by construction of continuous action superconducting linear accelerators. The first such accelerator, with an energy of 2 GeV, has been constructed at the high energy laboratory at Stanford[38]. The success achieved with this accelerator gave rise to plans for transforming the SLAC accelerator to superconducting sections, in which case it could reach energies of 100 GeV[30]. The cost of such a rebuilding is being estimated at 60–70 million dollars (for comparison we note that lengthening SLAC by only a factor of 2 would require 175 million dollars)[33].

Finally we note that linear accelerators (conventional as well as superconducting) constitute part of the projects for a large number of accelerators[6,40,41-44], where they are used as accelerating stations in place of resonant cavities.

Table IV. Linear accelerators

Location	Status operating/ under construction	Beam						Accelerating system						
		energy, GeV	Intensity, 10^{12} particle/sec	pulse duration, μsec	pulse/sec	emitance rad·mm	beam diameter, cm	sections numbers	group velocities ratio	filling time, μsec	frequency, MHz	number of klystrons	total HF power, MW	energy increase, MeV/m
France														
1. Orsay (*e*)	1959	2.3	40—120	1.5	50—150	0.5	0.8	1+37	0.05—0.01	0.7—0.9	2999	38	840	10
2. Saclay (*e*)	1968	0.64	600 μA	10	1000—2000	0.4	0 5	30	0.05—0.01	1	2998	15	12	3.3
USSR														
3. Khar'kov (*e*)	1964	1.8	5	1.4	50	0.4	0.3	49	0.04	0.4	2797	49	850	9 (max.)
4. Moscow (*e*)	Under construction	0.06	(5000)	5.5—0.01	50—900	—	1	6	0.022	0.3	1818	6	120	7
USA														
5. MIT (e)	Under construction (1971)	0.4	940	9.0	2000	0.02	0.5	24	0.01—0.024	1.2	2856	10	40	2.5
6. Stanford (e)	1952	1.2	1000	0.006—0.275	0.1—23		0.6	31	0,006—0,02	0.83	2856	31	600	12
7. Stanford (e)	1966	21.5	180	1.67	360	0.1	0.4	960		0.83	2856	245	4000	7
8. Stanford (e)	Under construction	2				0.1	0.1	24	0,02		1300	24	0.36	14
9. Los Alamos (p)	Under construction (1972)	0.8	6000	500	120	10	3	4		100	201	4	9	1—1.9
Injectors														
CPS (p)	1959	0.05	100 mA	200		23		3		150	202.5		8,4	1.71
AGS (p)	1960	0.05	60 mA	100		10		1		200	201.5		4,5	1.8
NAL (p)	Under construction	0.2	75 mA	100	15	10		9		200	201.3		37	1.4

Table V. Proton synchrotrons

	USSR Acad. Sci [45]	JINR [21]	CERN [21]
Beam put into operation	1968 r.	1953 r.	1957 r.
Energy, MeV	1000	680	598
Internal beam intensity:			
particle/sec	$2 \cdot 10^{12}$	$1.4 \cdot 10^{13}$	$8 \cdot 10^{12}$
current, μA	0.5	2.3	1.3
Cycle repetition rate, Hz	50—100	110	54.1
Magnet:			
pole diameter, cm	685	600	500
magnet gap, cm	50	60	45
extraction radius, m	316.5	277	226
magnet weight, t	7500	7000	2500
magnet power supply, kw	1200	1000	800
Accelerating system:			
number of resonant cavities	1	1	1
aperture	—	12	12
hf interval, mHz	13.18—28.88	13.8—26.3	16.6—30.6
energy increase, keV/rev	—	10	2.7—10
hf power, kW	400 (max.)	50 (max.)	20 (mean)

c) Proton synchrotrons and cyclotrons. The latest major event in this field consists of the turning on of the worlds largest synchrocyclotron of the Physicotechnical Institute of the USSR Academy of Sciences (Gatchina) with 1 GeV proton energy[45]. The main parameters of this machine are given in Table V. A number of reports were given at the conference, describing the characteristics of the construction and operation of the accelerator itself, as well as of its individual parts[46-48]. We have also listed in Table V the main parameters of operating synchrocyclotrons.

The introduction of periodic variations into the cyclotron magnetic field has given new life to this method of acceleration. The development of cyclotron acceleration methods, as can be seen from the reports of the conference, is going in two directions[49].

1) Relativistic cyclotrons with strong focusing for protons with energy up to 1 GeV and intensity up to 100 mA. Two accelerators of this class—in Zurich[50] and Canada[51]—are to be realized. An electron model of a relativistic strong-focusing cyclotron is operating at Dubna[52].

2) Isochronous cyclotrons with proton energy of the order of 100 MeV, but with an extremely highly monoenergetic accelerated beam ($\sim 10^{-4}$). A number of proposals for such accelerators has been worked out[53-56]. Certain problems of the cyclotron acceleration method are discussed in[57]. The basis of a project for a 300 MeV 4-sector cyclotron for accelerating heavy ions is outlined in[58].

In Tables VI and VII are given respectively the main parameters for relativistic cyclotrons under construction and being projected, and the parameters of the monoenergetic JINR cyclotron[49], they provide an idea about these machines.

2. The Construction and the Development of New Large Accelerators

In recent years a rather large number of projects has been proposed for proton synchrotrons with ener-

Table VI. Relativistic cyclotrons

	Zurich [50]	Vancouver [51]	Oak Ridge [58]
Status	Under construction (1973)	Under construction (1972)	Project
Beam:			
energy, MeV	585 (p)	200—500 (p)	300 (p)
internal beam intensity, mA	100	100	
particle/sec	$6 \cdot 10^{14}$	—	
Magnet:			
pole diameter, cm	930	813	1070
magnet gap, cm	50	50	7.5
extraction radius, cm	445	375	318
number of sectors	8	6	4
Magnet weight, t	8 × 245	3200	1900
Winding weight, t	8 × 3.5 (Cu)	3 (Al)	
Magnet power supply, kW	560	2500	850
Accelerating system:			
number of resonant cavities	4	2	4
aperture, cm	5	10	5
high frequency, MHz	50	23.58	29.34
energy gain, keV/rev	1400	400	1000
hf power, kW	600	1200	1600

Table VII. Parameters of the monoenergetic cyclotron (MC)

Accelerated particles:	
maximum energy, MeV	80; 60; 120; 120; 180
extracted beam energy variation range	0.25—1.0
energy scatter	$1 \cdot 10^{-4}$
extracted beam (protons) intensity, μA	100
Mean intensity on final radius, e	3292; 3985; 3960; 3460; 3967
Field intensity at center, e	3037; 3861; 3837; 3317; 3844
Final orbit mean radius, cm	400
Orbit mean radius at injection, cn	54
Injected ion energy, MeV	1.29; 1.045; 1.045; 1.03; 1.043
Frequency of free oscillations:	
axial	0.8—0,9
radial	1.07—1.17
Frequency of revolution, MHz	4.638; 2.948; 2.948; 3.377; 2.948
Accelerating field repetition rate	2
Number of main dees	2
Accelerating field amplitude on the main dees, kV	55
Number of additional dees	2
Energy gain per turn, keV	200
Final radius orbit pitch, cm	0.44; 0.6; 0.6; 0.6; 0.6
Magnet system sector number	4
Magnet system weight, t	1000
Electromagnet gap height, cm	16
Electromagnet power supply (max.), kW	1500
Power loss in the hf system, kW	140

gies from a few tens to a thousand GeV[3,5-7,15,59-62]. The rapid increase in radiation losses by electrons and the absence of any deep physical motivation have prevented the development of electron synchrotrons with energies somewhat above 10 GeV. However now a noticeable increase in interest in large electron synchrotrons has occurred, due in part to the successes of the colliding-beam method and cryogenics, and in part to a shift in the center of gravity in elementary-particle physics interests from strong to weak interactions.

a) Proton synchrotrons. Table I lists the main characteristics of four most developed projects for proton synchrotrons with energy in the interval 10^{11}–10^{12} eV. Only one of these is being constructed at this time—the NAL 200 GeV accelerator (Batavia). An interesting feature of this accelerator is its large mean radius (1 km) and correspondingly low maximum field value (about 9 kG). A relatively inexpensive modernization of the magnet power supply and cooling systems and of certain other stations (in particular, hf) will make possible a future increase of the accelerated beam energy to 400 GeV or slightly higher[16]. The accelerator possesses an 8 GeV booster, working at a 15 Hz repetition rate[17,18]. A 200 MeV linear accelerator, whose first sections are already operational, serves as the injector for the booster[63]. The relative location of the various accelerator components is shown schematically in Fig. 2.

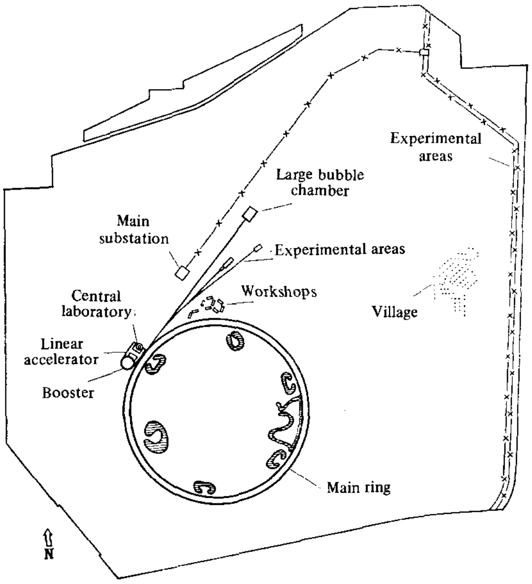

FIG. 2. Schematic plan of the National Accelerator Laboratory [18].

In the first stage of operation the accelerator will have one extracted proton beam[19], which will be sequentially split in order to irradiate all experimental areas (Fig. 3). One of the experimental areas (in the direct beam) is intended for a 25-foot hydrogen chamber, to be utilized mainly for neutrino experiments. A second experimental room, 7,500 m^2 in area, is intended for long-time use of six neutral and charged particle beams with momenta in the interval from 20 to 200 GeV/c. The construction of this room will be finished before that of others, in the spring of 1972.

The final decision on the construction of the 300 GeV proton synchrotron at CERN is expected in 1970. An already created construction directorate, headed by J. Adams, is actively working at this time on the possible influence of this project of recent achievements obtained in cryogenics in the development of other accelerators (in particular the cybernetic accelerator)[64].

b) Electron synchrotrons. In Orlov's report (see[41]) the possibility is considered of constructing an electron synchrotron with particle multiplication (by means of electromagnetic cascade) and colliding electron-positron beams with energies of the order of 100 GeV for particles of each sign. In Fig. 4 is shown the scheme for particle multiplication and their acceleration, first to 400 MeV in a linear accelerator, then to 10–20 GeV in a booster and, finally, in the main accelerator ring.

The construction of a large 15 GeV electron synchrotron is considered also in the Daresbury laboratory project[40]. The NINA synchrotron in this project serves as a 3 GeV electron source. An original scheme has been developed for filling the entire orbit of the large synchrotron (whose orbit length is 6 times the perimeter of the NINA synchrotron)[65]. As accelerating stations it is proposed to use two traveling wave linear accelerators. The existing experimental area could be used also for the large accelerator, thus reducing the cost of the project.

Although not one of the large electron synchrotron projects has yet been approved, and it is not yet clear whether sources for financing them will be found, it is to be expected that under pressure of new facts the interest in them will grow very rapidly. The main parameters of both of the above-mentioned synchrotrons are given in Table II.

c) Linear accelerators. The "meson factory" being constructed at Los Alamos—a linear proton accelerator with variable energy[86]—offers the best prospect for utilization. Its construction was started in October, 1968. The cost of the entire complex is estimated at 26 million dollars. At this time the preparation of the platform and the construction of a number of buildings (including the injector building) are nearly concluded. The tunnel is 75% constructed.

The main characteristics of the accelerator are: maximum energy 800 MeV, intensity 6×10^{15} protons/sec, duty cycle 6%.

The data on the secondary particle beams expected from the accelerator are shown in Table VIII. The first accelerated beam is expected in July, 1972. The efforts of laboratories interested in the development of electron linear accelerators are concentrated at this time on the perspectives for the use of cryogenic methods (see Sec. III).

3. Colliding Beam Accelerators

The situation in the field of colliding beam accelerators is exactly opposite to that existing for synchrotrons. Here electron and positron storage rings dominate in comparison with storage rings for protons and other particles. Whereas the former are already providing valuable results in colliding-beam experiments, the latter are only being built. One may point out two-main reasons for this situation:

1) The colliding-beam method is efficient only for colliding-particle energies many times in excess of their rest energy. For heavy particles such energies have become accessible comparatively recently and the achievement itself of such energies is connected with the construction of rather expensive accelerators.

2) The absence of radiative energy losses in the acceleration of heavy particles (which makes the construction of proton synchrotrons so much easier) means that in the heavy particle storage ring the incoherent damping mechanism is generally speaking absent. The storage of particles is achieved by the filling of ever new regions of phase space. In order to

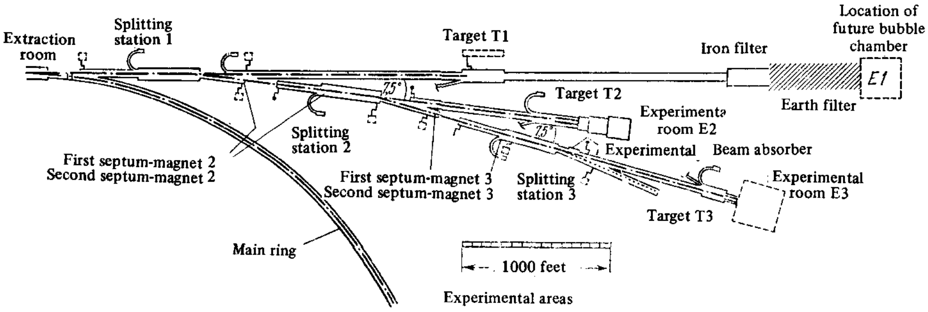

FIG. 3. Extracted beam distribution scheme of the National Accelerator synchrotron Laboratory [27].

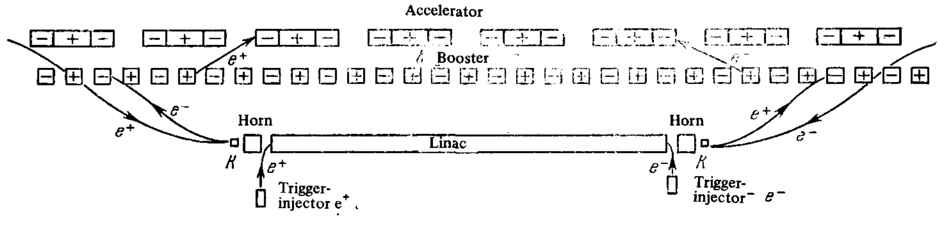

FIG. 4. Particle multiplication scheme in the 10-20 GeV electron-positron synchrotron project [41].

achieve true storage (into one and the same volume of phase space) it is necessary to create an artificial incoherent mechanism for energy loss—electronic cooling[66-67]. The leader in the field of electron as well as proton storage is without any doubt the Nuclear Physics Institute of the Siberian Division of the USSR Academy of Sciences, where a whole family of storage rings was and is being constructed under Budker's leadership, and where processes occurring during storage are also being studied[68-71]. The leading position of this institute is clear from Table IX, in which the main characteristics of existing, storage rings of high-energy light and heavy particles and those under construction and projected are shown.

a) Electron and positron storage rings. The vigor-period in the history of storage rings, connected with the discovery, understanding and overcoming of all possible beam instabilities, may now be considered to be over. The stable performance of the storage rings at Novosibirsk[68] and Orsay[72], which allowed colliding electron and positron beam experiments with remarkable results, shows that the theory and practice in this field are in sufficiently good agreement with each other, as well as with the dynamic characteristics of particles in storage rings. At the same time the experience with storage in the region of hundreds of MeV makes it possible to pass to the construction of storage rings for 1.5–3.5 GeV.

Table VIII. Los Alamos "meson factory" beams

Particles	Current particle/sec	Beam cross section, cm²	Energy, MeV	E_0/E, %
p	$6\cdot10^{15}$	6	800	0.75
π^+	$2\cdot10^{10}$	12	300	7.0
π^-	$4\cdot10^{9}$	12	300	7.0
μ^+	$4\cdot10^{9}$	200	250	25.0
μ^-	$8\cdot10^{8}$	200	250	25.0

The report of Amman et al.[73] was devoted to the performance of the storage rings of the National Laboratory at Frascati (Adone) with two beams. The experimental data on the luminosity measurement of the setup are shown in Fig. 5. The luminosity turned out to be approximately twice that estimated from the size of the current and the transverse dimensions of the beams. The lifetime corresponds to the theoretical estimate assuming constant transverse dimensions of the beams. The shift $\delta\nu$ of the number of betatron oscillations, due to the interaction between the beams, was also calculated from the data on the luminosity and the transverse dimensions. The value of $\delta\nu$ (which turned out to be between 0.05 and 0.1) is close to or somewhat larger than theoretically expected (0.04)[75]. At this time the construction of the 3.5 GeV VÉPP-3 storage ring at Novosibirsk has been completed[69], the work on the storage of electrons and positrons with ~3.5 GeV energy in the Cambridge accelerator ring is being completed[30], and this year construction will start and orders will be placed for the 3 GeV storage ring DORIS in Hamburg[31].

The general scheme of the VÉPP-3 storage ring is shown in Fig. 6. The setup consists of the following: a) a pulsed fore-injector ÉLIT with 3 MeV energy and 3 A current in a pulse of one μsec duration, b) a synchrotron injector B-4 with spiral storage followed by acceleration (betatron operation up to 10 MeV, synchrotron—to 500 MeV), c) electron-optical channels for the transportation of the injected beams, d) an $e^- \rightarrow e^+$ conversion system and e) the storage ring proper, consisting of a strong-focusing system of two semi-rings 802 cm in radius and two rectilinear intervals 12 m in length. The storage ring magnets are

Table IX. Electron and proton storage rings

Location	Status (under construction/ project)	Particles	Energy, MeV	Number of rings	Diameter, μ	Aperture, cm²	Number of intersections	Magnetic field fall index n	Radius of curvature	Maximum field, kG	Frequency, MHz	Repetition rate	Irradiation per revolution, keV/rev	Luminosity, cm⁻² sec⁻¹
CERN														
1. Geneva 1502	Under construction (1972)	p, p	28 000	2	300	5×15	8	240	79	12	9.5	30	20	$4\cdot10^{30}$
France														
2. Orsay, ACO	1965	e^-, e^+	540	1	7	6.5×15	1	0.5	1.11	16.2	27.24	2	5.5	$3\cdot10^{28}$
3. Saclay	Project	e^-	600	1	Ellipse 31×17	—	0	0.5	—	8	—	—	—	—
Germany														
4. Hamburg	Project (1974)	e^-, e^+	3000	2	Ellipse 110×55	4×11	—	—	—	8.06	500	480	520	$7\cdot10^{32}$
Italy														
5. Frascati	1969	e^-, e^+	1500	1	33.4	6×22	6	0.5	5	10	8.6	3	90	$3\cdot10^{29}$
USSR														
6. Kharkov	1963	e^-, e^-	100	2	2	4×10	1	0.27	0.5	10	52	1	1	
7. Novosibirsk, VEDP-1	1963	e^-, e^-	130	2	1	3×4	1	0.62	0.43	10		2		$4\cdot10^{27}$
8. Novosibirsk, VEDP-2	1966	e^-, e^+	700	1	3.5	8×14	1				18			$3\cdot10^{28}$
9. Novosibirsk, VEDP-3	Under construction (1969)	e^-, e^+	3500	1	24	3×7	2		8		4.03 and 76.57	1 and 19		$1.5\cdot10^{30}$
10. Novosibirsk, VEDP-4	Under construction	p, $\bar{p}$	25 000	1+1	115									
USA														
11. Cambridge	(1970)	e^-, e^+	3500	1	75	3×14	1	91		7.6	476	360		10^{31}
12. Stoughton, Wis.	1968	e^-, e^+	240	1	3.2	2×5	1	—	0.64	12.3	32	1	5	
13. Stanford	Project	e^-, e^+	1500—3000	2	71.8	6×25	2	—	—	7.8	50	36	560	$(1-2)\cdot10^{32}$
14. Batavia	Project	p, p	100 000	2	667	2.5×6.3	6	—	168.5	20	53,1			10^{32}

*Storage in the CEA accelerator ring.

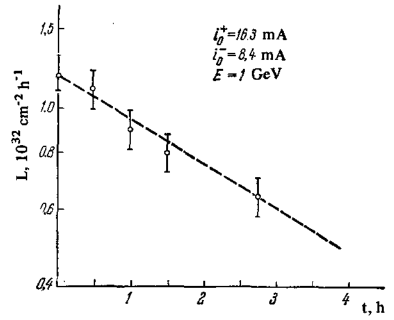

FIG. 5. Experimental measurement of the Adone storage ring luminosity L with one bunch in the beam.

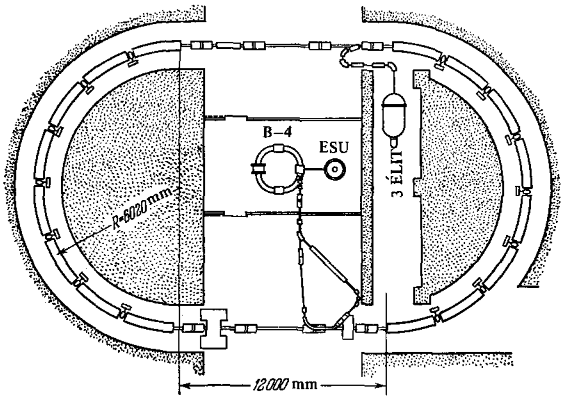

FIG. 6. Schematic plan of the VÉPP-3 storage ring [69].

hung from the ceiling of the tunnel (Fig. 7). At this time the main systems of the setup are completed, located in place, and adjusted. The storage ring has been marked out by 1.5 MeV protons. Work has begun on storage of electrons in the B-4 synchrotron.[69]

Up to now work in the storage ring of the Cambridge accelerator[30] has been carried out with an electron beam. Experiments have been performed on the filling of the ring for a large number of cycles with acceleration and deceleration of electrons (30 mA of instantaneous current has been stored), on the retention of the beam in the accelerator ring (the retention time at 2.5 GeV was 2.5 hours, the intensity e-folding time was 45 min), on the transferring of the beam to the bypass and back. In Fig. 8 (upper two lines) are shown oscillograms of the beam current in the bypass and in the main ring. It is seen that the transfer is achieved with practically no losses. However the lifetime in traversing the bypass turns out to be substantially less due to limitations in the horizontal apperture and to the increase in the beam width. The observed decay time of the beam equalled 25 sec.

At the end of the present year a new 130 MeV positron injector will be put into operation (it can also accelerate electrons up to 250 MeV energy). Next year experiments are planned on the storage of positrons and the study of beam-beam interaction.

A distinguishing feature of the DORIS storage ring consists of the presence of two separate paths for the electrons and positrons, located above each other. The beams will intersect in the vertical plane in the middle of two rectilinear intervals 60 m in length. The injection and storage may be achieved either from the DESY synchrotron, or from the new 400 MeV linear accelerator. The relative location of the accelerator and the DORIS ring is shown in Fig. 9. The planned luminosity of the storage ring (for 1 A currents in each beam) amounts to 10^{33} cm^{-2} sec^{-1} at 3 GeV energy. Termination of the construction and turning on of the storage ring is planned for 1973[31].

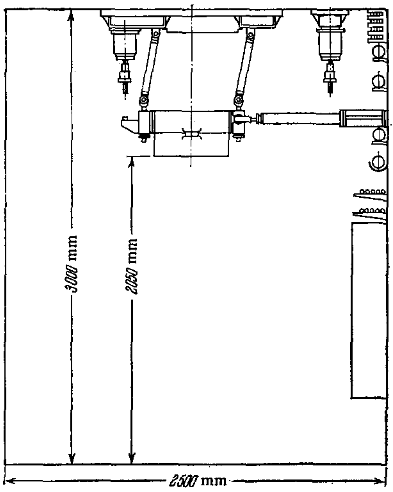

FIG. 7. Tunnel cross section of the VÉPP-3 storage ring [69].

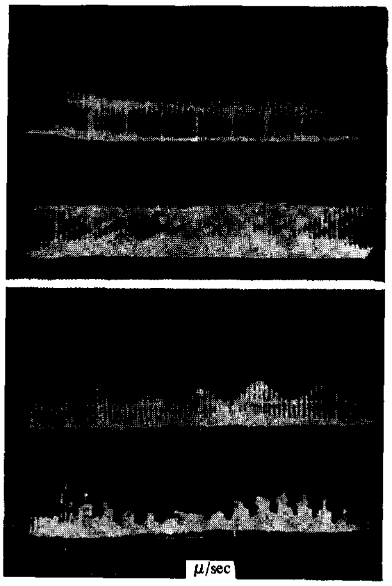

FIG. 8. Beam oscillograms in the CEA ring and bypass [30]. 1—current in the bypass; 2—current in the synchrotron; 3—vertical beam displacement in the synchrotron; 4—horizontal beam displacement in the synchrotron.

Other applications have also been found for electron storage rings. The Saclay group has worked out an interesting project for utilization of a storage ring to stretch the beam in a linear accelerator[34]. We shall not stop to discuss this project, nor other interesting proposals (the project for asymetric storage rings at Stanford[35], the Orsay project for a storage ring with space-charge compensation[76], and others).

b) Proton storage rings. At this time construction has started on two proton storage systems—a proton-

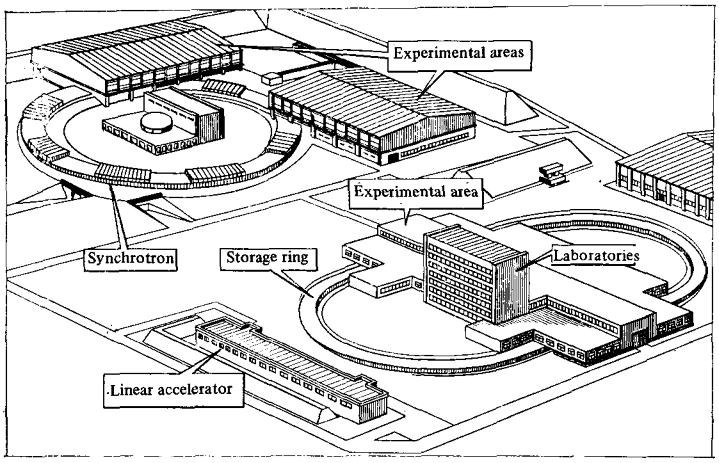

FIG. 9. Location plan of the accelerator and storage ring DORIS [31].

antiproton storage at 25 GeV in Novosibirsk[77] and intersecting proton rings ISR at 28 GeV in Geneva[78].

The project of the latter accelerator did not undergo any substantial changes in comparison with the state which was reported at the VI International Conference on Accelerators[97]. We shall therefore not repeat here its description, but will confine ourselves to mentioning its present state and certain characteristic details which did not receive previously sufficient attention.

The construction of ISR was started in 1966, the completion of the project is planned for 1971. By now, nearly the entire tunnel has been constructed, and construction has been completed around approximately half of its perimeter. Two thirds of the magnets have been put together, and their characteristics have been measured (all of the magnets were within the allowed tolerances). The magnet power supply system is ready and undergoing testing. It should be available by the end of 1969. To avoid loss of the stored beam the power supply system must guarantee a high degree of current stability in the windings ($\pm 2.5 \times 10^{-5}$ during two months and $\pm 7.5 \times 10^{-6}$ during two minutes).

All main parts of the high-frequency system have been obtained and are being mounted. Their emplacement should start in September 1969. The accelerating resonant cavities have been supplied with a new feedback system for the suppression of the beam-induced voltage (the signal is obtained from the broad-band induction electrodes). The vacuum system components have also been obtained. Each stage is evacuated and tested before being put in place. Without out-gassing, the pumps guarantee a vacuum of up to 10^{-8} torr. The first out-gassing of the ring guaranteed a vacuum of 2×10^{-10} torr. In October, 1969 the vacuum chamber was set up in the first interaction region. Four titanium pumps with liquid nitrogen, refrigeration should guarantee a pressure of 10^{-11} torr. The construction of the tunnels for the transportation of the beams is approximately 2/3 complete. The construction of the transportation channels has been started in them.

Great importance is given to the beam observation and control system. The rings will be supplied with the following observation devices: approximately 100 pick-up electrodes[80], one (for each ring) broad-band beam current transformer (with a band from 0 to 50 MHz)[81] and two gas screens for observing the beam profile. Some of the beam data for the transportation and injection system has been worked out[82]. The setup for automatic measurement of horizontal and vertical betatron oscillation frequencies has been worked out[83].

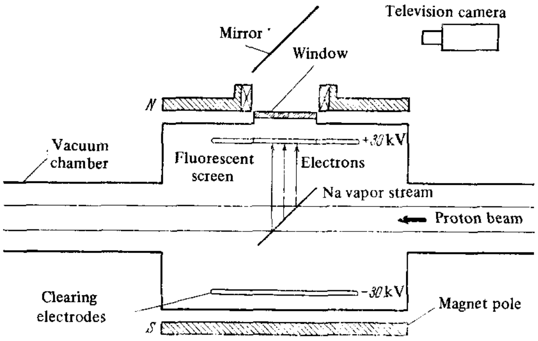

FIG. 10. Operation scheme of the setup used at CERN to measure the transverse dimensions of the proton beam [78].

The gaseous screen is, apparently, the most original arrangement utilized on the IRS. The operating scheme of this arrangement is shown in Fig. 10. A plane stream of sodium vapors (70 × 1 mm in dimension) is emitted by a supersonic nozzle on one side of the vacuum chamber, and the unused part of it (99.9%) is condensed on the other side. Electrons, torn from molecules in collisions with the circulating proton beam, are accelerated by a vertical electric field (4 kV/cm) and focused by a magnetic field (300 G) onto a fluorescent screen. The brightness of the beam image, whose horizontal as well as vertical dimensions will be measured, will be comparable to the brightness of one candle for the projected beam current (4×10^4 protons). The expected resolution is of the order of 1 mm.

The project for the intersecting proton storage rings of the US National Accelerator Laboratory for a 100 GeV in each beam[84] resembles the ISR in many respects. Certain differences (six intersection regions instead of eight, 50 mrad intersection angle instead of 15° and others) are rather secondary. The main parameters of this storage ring are shown in Table IX.

In conclusion it seems to us interesting to note the original project for a setup to observe pion-pion and muon-muon collisions—the so called pracetron[85]. The idea of this arrangement is illustrated in Fig. 11. A

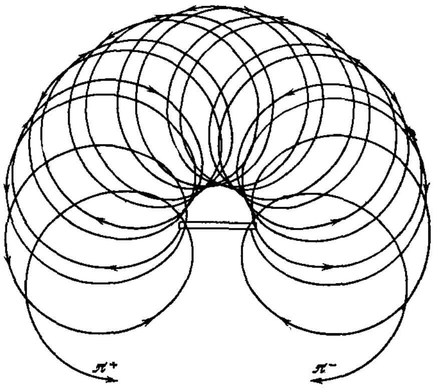

FIG. 11. Scheme of particle motion in the pracetron—the proposed instrument for observation of pion and muon collisions.

short 800 MeV proton pulse of 6×10^{15} protons intensity produces in the target in excess of 10^{13} π^+ and π^- mesons with momenta in the 310—350 MeV/c interval. The target is located in the center of a pulsed magnetic field of 400 kG intensity in a region ~5 cm in radius. During their lifetime the pions perform approximately 100 revolutions.

To obtain a significant number of collisions it is essential that the accelerator have a very high instantaneous beam power. Estimates show that for an accelerator with instantaneous power 60 times that of the Los Alamos meson factory[86] (for the same average power), one may expect two $\pi\pi$ interactions per hour. Analogous conditions will be fulfilled for collisions of decay muons.

III. NEW ACCELERATION METHODS

The difficulties in the construction of new high-energy accelerators are due in final analysis to the limitations in the values of the electric and magnetic field intensities which can be achieved by traditional methods (at reasonable expense). This limitation leads to an increase in accelerator dimensions, and consequently to an increase in the cost and the precision requirements in the preparation, setting up and maintenance of various accelerator stages and parameters.

One may point to three main directions of development, in attempting to overcome these difficulties and to construct accelerators cheaper; these constitute the meaning of the term "new methods":

1) the utilization of collective fields of plasma or plasmoids;
2) the utilization of low temperatures;
3) the utilization of cybernetic methods.

Each of these directions has advantages and successes, as well as disadvantages. It should be noted, however, that already now the cost of the accelerator itself constitutes approximately half of all its maintainance and outfitting expenses. For this reason the development of new accelerator methods should go in parallel with development of new methods also in the field of detection and registration of superhigh energy particles.

1. Acceleration by Collective Fields

At the basis of such acceleration methods is the idea of utilizing fields of dense particle formations (bunches, currents, plasmas). The intensities of such fields can be made one-two orders of magnitude larger than is possible by conventional methods. The main difficulty which must be overcome in such methods is the instability of dense bunches or plasmas, arising from the interparticle interactions.

The research on collective acceleration methods started to develop after the publication of Veksler's work on coherent methods[87], Budker's on self-stabilized beams[88] and Faĭnberg's on acceleration in plasma[89], although certain ideas[90] have arisen long ago. We shall mention here only the results obtained from the most highly developed acceleration methods, and refer the reader to the reviews by Rabinovich[91] and Faĭnberg[92], where a variety of so far poorly developed modifications of the collective acceleration method are described (scattering of an electron beam by the magnetic field of a plasmoid, the leading acceleration in the breakdown fringe field, acceleration by scanning or rotating electron rays, acceleration in magnetic plugs moving along the beam; see[93,94]), and where all possible instabilities and methods of their suppression are also described (see also[95]).

a) Accelerators with electron rings. The main principles of the construction and operation of such an accelerator have been outlined in[96]. In this method ions are captured by the potential well of a dense bunch of relativistic electrons, toroidal in shape. Successful formation and compression of the rings, as well as their filling with ions, have also been reported.

At the conference, Sarantsev[97] reported on a new success of his group—the rings were extracted from the adhesion-producing device and accelerated in a falling magnetic field together with nitrogen ions contained in them. An estimate of the lower limit of the ion energy and intensity was obtained from the production reaction of α-radioactive Tb as a result of nitrogen bombardment of Ce. The ion energy was > 60 MeV (4 MeV/nucleon), and their intensity was $\geq 10^8$ ions/pulse.

To insure stability of the electron bunch during the first stages of its acceleration a method of additional focusing by image forces in the screen was developed and used[98]. The bunch moves in a metallic tube, with cuts along the direction of motion of the ring. Such a system moves the electron oscillation frequency away from the most dangerous resonance and sustains constancy of the bunch dimensions, necessary for ion containment.

An analogous setup for obtaining heavy multi-charged ions is being constructed at Berkeley[99]. Work goes on there at this time on the formation and compression of electron rings and a new high-current linear induction accelerator is being erected. So far this group has successfully obtained stable electron rings with 4×10^{12} electrons, and has loaded them with ions. Work in this field has also started at Karlsruhe and Munich.

The possibility of obtaining high-energy ions or accelerators with electron rings depends on the character of energy loss by the ring bunch as it passes through the accelerating system. For the moment the theoretical studies of this question[100-103] do not agree with each other[104], giving a wide spectrum for the dependence of energy loss on the particle energy (from E_0 to E for a single resonant cavity).

The prospects are that accelerators with electron rings will make possible the construction of compact proton high-energy accelerators. They also offer great promise as intense sources of multiply-charged heavy ions.

b) Obtaining powerful electron currents. The further development of collective acceleration methods is connected with the development of techniques for obtaining super-powerful electron currents. At this time pulsed electron currents are obtainable with power in the beam up to 10^{12} W*. The pulse duration of such a current amounts to a few hundreths of a msec, and the electron energy amounts to a few MeV, the current being a few hundreds of kA[106].

In the review[107] the prospects of obtaining and utilizing intensive currents for particle acceleration are discussed, and possible mechanisms for ion acceleration by the collective field of high electron currents are also analyzed. In[108], 5-MeV protons, 9-MeV He ions and 20-MeV N ions were observed, accelerated by pulsed electron currents of the order of 50 kA with 1.3 MeV energy for a pulse duration of 40 nsec.

The ionic current pulse was substantially shorter (3—10 nsec) and corresponded to the acceleration of a single ion for each 3×10^3 electrons. Other workers have obtained analogous results.

The following were considered as ion acceleration mechanisms: 1) Cerenkov radiation by plasma wave ions, 2) space-charge wave acceleration. The results of the calculations for both mechanisms are not in contradiction with experimental data, but both theory and experiment are still in a very rough state.

Estimates indicate the possibility of obtaining accelerating fields of order 10^6 V/cm and accelerated ion kinetic energies of the order $(\gamma_0 - 1)Mc^2$, where γ_0 is the relative electron energy and Mc^2 is the ion rest energy.

c) Plasma methods of acceleration. The second avenue of collective acceleration methods, being intensively developed mainly by Ya. B. Faĭnberg's group, is ion acceleration in a plasma. When certain definite conditions are fulfilled, the charge-density wave propagating through the plasma can capture and accelerate part of the plasma ions. The advantages of such a method are: 1) absence of relativistic transverse electron motion results in an increase of the effective accelerating field, 2) the particle acceleration is in principle quasicontinuous, and not in ultrashort pulses as is the case in an electron ring accelerator. On the other hand plasma acceleration requires a substantially larger electromagnetic energy stored in the beams or in the plasma, since it turns out to be distributed over the entire wave propagation region (for equal accelerating field intensities).

The waves essential for the acceleration may be excited in the plasma by either electron currents or external high frequency fields. Theoretical and experimental studies indicate that ~ 30% of the beam energy goes into excitation of the oscillations. The passage from 10 kW beams to beams with the power of the order of several MW does not change the relative amount of energy that goes into wave excitation. At this time experiments have started with even more powerful beams of 30—50 and 300—800 MW, with pulse duration of 200—500 nsec[92].

One of the main difficulties which must be overcome for successful utilization of plasma accelerators is the appearance of instability of the plasma itself, as well as the accelerated particle beam. As was shown in the work[92], an effective method for dealing with beam instabilities consists of preliminary modulation of the electron currents. Control of intense oscillations may be achieved by imposing at the input of the system a regular signal with power amounting to 10^{-5} of the excited oscillations power. The results of the nonlinear theory of the interactions between modulated electron beams and plasma are given in[94]. Important results have also been obtained on the suppression of plasma drift instability by external high-frequency electric fields.

The phenomena observed in the work[109] may, apparently, also be classified as belonging to the plasma acceleration field. In it, 10—20 MeV ions were observed in the production of electron current pulses of order 10^3—10^4 A from the plasma. At that the electron energies were only 200—300 keV. Each pulse contained 10^{11}—10^{12} accelerated ions.

2. Low-temperature Methods in Accelerators

The use of cryogenics not only makes it possible to lower operating costs by reducing energy dissipation, but also substantially increases the magnitude of field intensities and correspondingly decreases the dimensions and cost of accelerator equipment. This method of reducing accelerator expense in also effective in that it may be used to reduce the cost of the experimental equipment and correspondingly the size and cost of the experimental areas.

a) Cryogenic and superconducting magnets. The development of alloys, capable of maintaining their superconducting state at superstrong magnetic fields (tens of kG) has stimulated intensive studies of the possibility for constructing superconducting magnets for accelerators. The main difficulty here consists in decreasing the dissipative losses of the alternating current. These losses in accelerators with rapidly varying magnetic fields require a substantial increase in the cryostat power and the economic advantage is lost.

Studies, first started in the Rutherford Laboratory[110], and then in other laboratories[111-113], have shown that this problem is, possibly, close to being solved. The construction of experimental coils filled with thin (of order of tens μ) niobium-titanium superconducting threads armored with normal metal, gave intensities of order 40—60 kG in a volume 4—9 cm in diameter, and allowed changing the field with a frequency of once every 2—5 seconds, as needed for synchrotron operation. Even more promising conductors have been developed, consisting of superconducting threads separated from the copper by a resistive barrier.

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*Electron beam generators with power of the order of 10^{10} W are being manufactured industrially [105] (10^4 A current, energy up to 2 MeV, pulse duration up to 50 nsec).

Another more radical approach for eliminating losses in the pulsed power supply of superconducting magnets was considered in[114,115,116]. There an accelerator is proposed, whose magnetic field is varied by rotation of superconducting magnets with constant fields. In each magnet pair the fields are directed in opposite directions at low-field levels, and then the field increases as they turn toward each other. In[117], the possibility is considered of constructing an accelerator whose magnet system consists of a combination of constant superconducting magnets and variable conventional magnets. No less and perhaps even more promising is the construction of magnets (both with and without) with normal windings, whose resistance is thousands of times smaller than usual. The resistance of extremely pure aluminum at 4.2°K is 14,000 times smaller than its resistance at room temperature (300 (300°K).

Cryogenic iron magnets with high current density may turn out to be more applicable than the superconducting ones since: 1) they require cheaper cryostats, 2) they require fewer ampere-turns for excitation, 3) they have lower stored energy, and 4) it is easier to obtain with them the required spatial distribution of the field.

Experiments performed on models of cryogenic magnets with current densities 10—20 kA/cm^2 show that Al at 15°K may easily compete with a niobium-titanium superconductor[118]. Cryogenic magnets are also promising for use in beam extraction and separation.

Although the research is still at the stage of using small models and a number of important questions remain unclear (reliability, material purity requirements, passage from small specimen to large etc.), it isn't hard to foresee that in the not too distant future proton* accelerators will change over to low-temperature magnets, and new accelerators will be planned with superconducting magnets.

b) Superconducting resonant cavities. Interest in the development of superconducting resonant cavities is easily understood, since their use will lead to: 1) a decrease in the power and cost of high-frequency accelerating systems due to elimination of energy dissipation in the resonant cavity walls, 2) a decrease in the dimensions and cost of accelerators due to an increase in the accelerating field intensity (limited by the size of the above-mentioned losses) and 3) an increase in the relative beam pulse duration up to 100% (continuous beam), also limited by the size of the losses in the walls.

At the conference, reports were given on the experimental study of the surface resistance of niobium[119] and lead[120-121] resonant cavities for various power levels and various high-frequency oscillation types in the 400—4,000 MHz frequency range and 1.5—4.2°K temperature range, as well as on the excitation of a superconducting resonant cavity by a continuous electron beam[122].

Encouraging results were obtained in experiments with a single resonant cavity: field intensity of 27 MeV/m and a Q-value of 10^{11}. A technology has been worked out for developing a niobium resonant cavity not requiring a super-pure material: the resonant cavity is heated at high vacuum up to 2,000°C, then cooled, and a 10 μm layer is removed from the working surface. Superconducting resonators, will be, apparently, very effective in high frequency particle separators[123,124].

c) Linear superconducting accelerators. The greatest progress in the construction of superconducting linear accelerators has been achieved by the staff members of the high-energy accelerator at Stanford, where a 2 GeV linear electron accelerator is nearing completion[38]. The accelerator parameters can be found in Table II. The prototype of this accelerator at 1.5 MeV was built with lead resonant cavities. A current of 140 μA was obtained on it, and it was shown that a current of 100 μA can be obtained in a pulse interval $\pm 10^{-4}$.

The tunnel construction is at this time complete. In the middle of next year the first niobium section of the accelerator for 30 MeV energy will be put into operation. The putting into operation of the entire accelerator is planned for the end of 1971.

The Illinois University group[43] is constructing a 30 MeV linear superconducting accelerator, which will be a part of the 600 MeV microtron. The frequency of the accelerating voltage is 1.3 GHz. A model of a 20 MeV proton linear superconducting accelerator is also being constructed at Karlsruhe[125].

We have already mentioned the plans for the rebuilding of the Stanford 2-mile linear accelerator to make it superconducting[32]. The maximum projected energy is 100 GeV (for an average accelerating field intensity of 33 MeV/m). The filling coefficient varies from 100% at 25 GeV to 6% at maximum energy. The average beam power at 100 GeV is 300 kW.

Finally, we mention the project of a superconducting linac for pion acceleration[126]. The pion beam with intensity of 5×10^{10} particle/sec from the Los Alamos meson factory will be accelerated from 300 MeV to 1.2 GeV in 9 five-meter superconducting sections. The accelerating field frequency is 402.5 MHz, the beam diameter is 8 cm. Estimates of the accelerated pion yield give the quantity of 3×10^9 particle/sec.

3. Accelerators and Cybernetics

Automatic parameter maintenance systems and control and guidance systems, which include computers and servomechanisms, are successfully utilized in many accelerators, improving the reliability of their operation and increasing the intensity of the accelerated beams and the efficiency of their utilization.

The CPS and AGS synchrotrons are equipped with a feedback system which suppresses coherent synchrotron oscillations. The Argonne ZGS accelerator has a programmed control system, which distributes the extracted proton beam to various targets. Similar systems of varying complexity are being installed in projected accelerators and those under construction[86,127]. In the last years work has been in progress at the Radiotechnical Institute of the USSR Academy of Sciences on the construction of a 1,000 GeV proton accelerator[7], whose cost should be reduced by the

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*Synchrotron radiation in large electron synchrotrons prevents the use of high magnetic field intensities. For this reason application of cryogenic magnets in high-energy electron accelerators is pointless.

development of systems controlling the beam location and oscillations. The decrease in the transverse dimensions of the working field achieved by these means leads to a decrease in the magnet cross section, and consequently, a decrease of the magnet power supply system and the tunnel.

To test experimentally a whole complex of problems arising in the development of such an accelerator, a 1 GeV operating model has been constructed[128]. The work on automatic regulation of transverse beam displacement in this model by means of an electronic guidance machine has been reported in[129]. The report[130] contains the description of a developed numerical system for synchrotron guidance.

IV. CONCLUSION

In the two years since the previous International Accelerator Conference remarkable results have been obtained in the development of new acceleration methods, opening prospects for the development of accelerators in a new energy interval of the accelerated particles. At the same time it is sufficiently clear that none of the new methods will by themselves guarantee the resolution of the entire complex of problems existing in this field. Apparently, the direction in which accelerator physics will go will consist of a synthesis of all these new methods. This is confirmed by the development of projects which contain elements of various approaches[41,73,117,131]. The realization of these projects encounters grandiose difficulties, which can be overcome only under conditions of extremely close collaboration of various laboratories. The search for new fruitful ideas and acceleration methods remains the main task of accelerator physics and technique.

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