Fermi National Accelerator Laboratory

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High Intensity Hadron Accelerators*

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HIGH INTENSITY HADRON ACCELERATORS

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This rapporteur report consists mainly of two parts. Part I is an abridged review of the status of all High Intensity Hadron Accelerator projects in the world in semi-tabulated form for quick reference and comparison. Part II is a brief discussion of the salient features of the different technologies involved. The discussion is based mainly on my personal experiences and opinions, tempered, I hope, by the discussions I participated in the various parallel sessions of the workshop. In addition, appended at the end is my evaluation and exposition of the merits of high intensity hadron accelerators as research facilities for nuclear and particle physics.

Part I Review of Status of Projects

(In descending order of certainty of funding)

A. ISIS (RAL) 50 Hz, 800 MeV, (operating since 1985). The intensity records are as follows:

Highest per pulse intensity = 1.64×10^{13} p/p (= 136 μA)

Normal operation intensity ~ 1.3×10^{13} p/p ($\gtrsim$ 100 μA)

Highest one-day average current = 97 μA

Highest injection intensity = 2.68×10^{13} p/p

The machine is down at the moment for repair of damage caused by beam accidentally hitting the vacuum pipe.

B. <u>AGS (BNL)</u> 1/2 Hz, 30 GeV, (being modified for higher intensity).

The modifications and the expected intensity gains are as follows:

- Present operation: ~ 0.9 μA
- Add booster (7.5 Hz, 1.5 GeV, ~ 2 x 10^{13} p/p) and AGS modifications - complete in 1991

  Resulting operation: 4 booster pulses injected into AGS on ~0.5 sec front-porch, 3 sec AGS cycle time with 1.5 sec flat top,

  4 μA (50% duty).
- Add beam stretcher ring (racetrack having AGS circumference and housed in separate tunnel, with d.c. solid core magnets and no RF, cost ~ M$ 57, proposal just submitted)

  Resulting operation: 1.5 sec AGS cycle time with no flattop,

  8 μA (100% duty).

C. <u>KAON (TRIUMF)</u> 30 GeV, 100 μA, 5 rings, polarized p.

- Rings are:

  A (accumulator, d.c.), B (booster, 50 Hz)

  [A and B in same circular tunnel]

  C (collector, d.c.), D (driver, 10 Hz), E (extender, d.c.)

  [C, D and E in same racetrack tunnel]
- M$ 11 for R & D in 1988, 1989. Topics include:

  Accelerator design

  Cyclotron beam extraction

  RF cavities: both perpendicular & parallel biased (with LANL)

  Beam pipe & vacuum (with SAIC)

  Magnet prototypes and power supplies

  Controls and instrumentation

Beam manipulation devices

Experimental areas

- Expecting construction start in 1990 and seeking foreign participation.

D. MKF (Moscow Kaon Factory, TROITSK)

- Architecture (using KAON terminology)

Linac: 0.6 GeV, 100 Hz, (inject every other pulses)

B: 7.5 GeV, 50 Hz, 250 μA

(with C) 12.5 Hz, 250μA.

D+E: 45GeV

(with C) 6.25 Hz, 125μA.

- Schedule

1989		1992		1994		1999
	R&D		Design		Construction	
			(10×10^6 rouble)		(500×10^6 rouble)	

E. JHF Compressor/stretcher ring

As so far proposed the project consists only of a d.c. storage ring which can be used either as an Extender ring or as a compressor ring for a spallation neutron facility. Future extension into a full fledged hadron facility is possible.

Injector: 1 GeV H^- linac

Compressor circumference = 174.88 m

Repetition rate = 50 Hz

Injector linac pulse duration = 400 μsec

Pulses in compressor = 2 x 200 nsec (charge exchange injection)

As pulse stretcher: slow extraction to give high duty factor (essentially 100%) & high efficiency (10^{-3} loss) beam spill.

As compressor: One or both pulses can be compressed to 20 nsec and fast extracted.

F AHF (LANL)

- Historical evolution

This project has gone through a number of transfigurations, with each transfiguration the capability in terms of energy and/or intensity was extended. The top energy has risen from 30 GeV to 45 GeV and now, to 60 - 100 GeV in response mainly to the desire of studying the Drell-Yan processes. The capability of the facility considered now also consists of a super-intense spallation neutron source driven by proton pulses from a 1.6 GeV compressor.

- The single ring scenario now being discussed is shown in the following diagram:

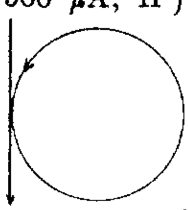
(800 Mev, 1 mA, H^-) {presently available from LAMPF}

[800 MeV SCC linac section]

(1.6 GeV, 500 μA, H^-) → {compressor ring for spallation n source}

[600 MeV SCC linac section]

(2.2 GeV, 500 μA, H^-)



[6 Hz Driver synchrotron with charge-exchange injection and flattop]

(60-100 Gev, 25 μA, p) {50% duty factor beam spill}

• Two different sitings of the Driver synchrotron are being considered: If located on the Mesa Top, at least a part of the present LAMPF experimental areas can be used for 60 GeV experiments. But the limited space available on the Mesa Top would require 2.2 T bending dipole field at 60 GeV. If located on the Mesa Bottom one will need a long transport (called the waterfall) for the 2.2 GeV injection beam from the Mesa Top down to the Bottom. But then one can use the more leisurely field of 1.4 T even for 100 GeV. The various dipole field strengths required are summarized below.

	2.2 GeV	60 GeV	100 GeV
Mesa Top	0.11 T	2.2 T	3.6 T
Mesa Bottom	0.042 T	0.84 T	1.4 T

• For the Mesa Top siting 100 GeV does not look feasible. For the Mesa Bottom siting the 0.042 - 0.84 T for 60 GeV is almost optimal for the cost of the bend magnets and power supplies.

Discussions of technology will appear in Part II. It is however timely to provide the following comments here.

• Although possible, it is difficult to provide a flattop for a 6 Hz synchrotion at 2.2 T. Problems include the regulation and stability of power supplies, the necessity of shorting out the RF cavities on the flattop, the debunching and the stability of the beam etc. It is simpler to add a d.c. Extender ring, E. Advantages are:

1. Factor ~2 increase in average beam intensity and spill duty factor.

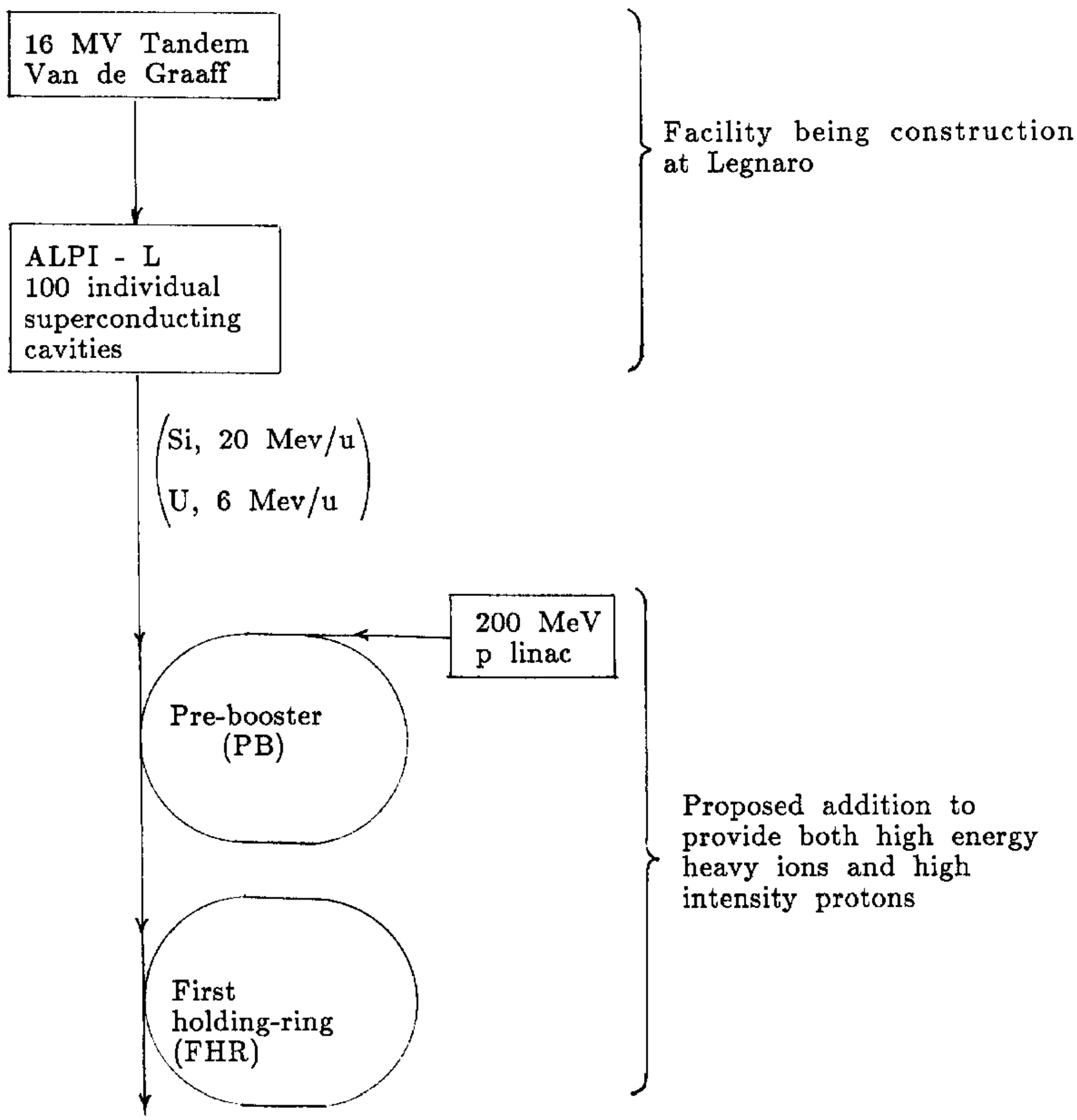
2. Much better regulation and stability obtainable by the d.c. power supply.
3. Need to short out the Driver RF cavities eliminated.
4. Beam debunching & stability in E much better controlled.
5. Beam loss and radioactivity more easily coped with in E.
6. High efficiency slow extraction system easier in E.

The cost of the d.c. Extender could be minimal especially since it is offset by cost savings due to the simplifications mentioned above.

• In extending the capability of a multipurpose facility the increased complexity of operation and scheduling, and the reduced availability for each purpose must be considered and weighed against the cost savings from adding separate single or a-few purpose facilities.

G. EHF-at-Legnaro (Italy)

The original 45 GeV, 100 μA EHF did not receive support and was replaced by the EHF-at-Legnaro which is described by the following diagram.



- Proton parameters of PB (B in KAON terminology)

  Racetrack synchrotron

  Circumference = 256 m

  Repetition rate = 50 Hz

  Peak kinetic energy = 1.26 GeV

  Intensity = 1.25×10^{13} p/p (100 μA)

- FHR (C in KAON terminology)

  D.C. storage ring to store beam from PB and inject into future next-stage high energy synchrotion.

Circumference and lattice same as those of PB.

Part II Evaluation of Technology

This part contains expositions of my own personal formulation of design considerations and principles, evaluation of important factors and assessment of technological requirements and difficulties for the component systems of a High Intensity Hadron Facility. For a list of component systems and technologies I will simply use the headings of the workshop groups.

1. Architecture

For beams of tens of GeV and tens of μA the only viable Driver, D (main accelerator), is a rapid cycling synchrotron. If a high current injector such as a linac is available which can fill the driver (generally by charge exchange injection) in a time much shorter than the cycle time, then the basis structure is simply

BASIC: Linac → D → E

where the Extender, E, is added to provide a 100% duty factor for experiments.

If the momentum (magnetic field) range required of D is much larger than a ratio of, say, 40 or if the application desires the availability of an intermediate energy one will want to add a Booster (B), and the boostered structure becomes

BOOSTER: Linac → B → (C)D → E

where a Collector, C, is needed to collect the pulsed from B for injection into D.

If furthermore, only a cyclotron is available as injector one must add an accumulator, A (a collector) to collect pulses from the cyclotron for injection into B.

CYCLOTRON: Cyclotron → (A)B → (C)D → E

and we have the "5-ring circus". The architecture of a high intensity hadron facility is, thus, seen to be entirely logical, straightforward and unique.

The energy stops after the injector and the booster are chosen to optimize cost and experimental utilization. Generally, the ranges of field strength required in the synchrotron do not impose any limitation on the choice. It is desirable to avoid transition crossing in the synchrotrons. This can always be accomplished fairly readily by appropriate lattice design.

2. Magnet and Power supply

Technologically conventional magnets can be made applicable over a very wide range of field strength. The lower limit can be pushed down to 200 G or lower and the upper limit can be pushed way into saturation, say, beyond 2.5 T by using shaped and cranulated poles, and pole-face coils. However cost optimization gives $B_{max} < 1$ T for fast cycling magnets. Thus the choice of B_{max} depends largely on economic, utility, and other non-technical factors.

Economic and operational factors should be considered also in the choice of power supplies. Magnet ramp gymnastics such as asymmetric up-and-down pulsing and flattopping can certainly be done by switching between power supplies of different frequencies, but the gain/loss of these arrangements should be evaluated. For example, the cost, complexity and reliability of the dual frequency power supply for asymmetric pulsing should be weighed against the savings in RF, and the cost savings of a, say, 50% duty factor flattop arrangement should be compared to the factor 2 higher intensity and 100% duty obtainable from an Extender ring.

3. RF System

Next to the slow extraction system the rf system is perhaps the most demanding. On the other hand, the LANL/TRIUMF rf research and development program is progressing well. Both the perpendicular and the parallel biased ferrite tuners are being studied and compared. There is, so far, no unsurmountable problems for either configuration. For example, it was shown that the leakage field from the perpendicular biased ferrite can indeed be adequately shielded from affecting the beam.

Damping of the higher-order-modes in the cavities must be studied and carried out with a great deal of care.

4. Beam Instabilities

It appears that only transverse instability (principally vertical) will be present. This implies that the transverse coupling impedance (Z/n) budget should be strictly controlled during construction. Even then, the use of vertical feed-back damper is likely to be unavoidable. But the over all problem of high current beam instabilities is not expected to be troublesome. Compared to electron machines the peak bunch-current of the hadron facility accelerator is still rather low.

The instability due to trapped electrons is present only for an unbunched beam. Clearing field may be necessary for the Extender ring.

5. Injector Linac

The by-now "standard" linac seems to be quite adequate. This is shown in the diagram below:

S ------- RFQ ---------- DTL ----------- SCC ---------------

	S–RFQ	RFQ	RFQ–DTL	DTL	DTL–SCC	SCC	After SCC
Beam parameters:							
Energy =			2.5 MeV		100 MeV		800 MeV (1600MeV)
Current =	33 mA		32 mA		30 mA		30 mA
RF parameters:							
Frequency =		400 MHz		400 MHz		1200 MHz	
Power =		0.25 MW		6.1 MW + beam		40 MW + beam	
Length =		2.9 m		45 m		326 m	

6. Polarized Beam

Full and partial Siberian snakes can be applied to suppress depolarizing responances in all synchrotrons. The effectiveness of these Siberian snakes will be demonstrated and studied in an experiment soon to be performed at the Indiana University Cyclotron Facility. If the actions of full and partial snakes are as expected the acceleration of polarized beam will be simple and straight forward.

Efforts are being spent in developing high current polarized proton sources. It appears that milliampere currents may be feasible. The availability of high intensity polarized beams will greatly enhance the usefulness of the hadron facility.

7. Beam Pipe and Vacuum

The R&D effort by LANL/SAIC has resulted in some very good metal coated ceramic beam pipes which should be entirely satisfactory in all aspects: electromagnetic, structural and vacuum properties.

8. Slow Extraction

This remains to be the most difficult problem. The solutions so far proposed are either unrealistic or at best marginal and difficult to implement. All of these schemes employ some kind of pre-septum to reduce the beam loss.

- The magnetic pre-septum discussed by MKF needs a great deal more detailed study. It is not clear at all how the magnetic pre-septum which is simply a very small aperture quadrupole, works.
- The electrostatic pre-septum discussed by KAON works in a straightforward manner. To make the effective thickness small it is clear that the septum must be short and the wires must be thin. The KAON design attains a 20 μm effective thickness with 10 μm diameter wires and 1/2 m septum length. With a 10 mm step-size this should give a beam loss of only 0.2% (The experiences at Fermilab, however, show an unexplained factor of 2 to 4 greater beam loss than calculated in this manner). Even for 0.2% we have a beam loss of 0.2 μA at 30 GeV which is larger than the total AGS beam current before the upgrade.

This points out clearly that

1. New ideas and more efforts are needed.
2. It is likely that remote handling is necessary.

3. It is perhaps easier to cope with the beam loss in the d.c. Extender ring than that in the Driver synchrotron.

Appendix The Need for High Intensity Hadron Accelerators

Historically, as the energy of accelerator increases the intensity or luminosity that can be provided decreases as one goes from linac to cyclotron to synchrotron to colliding beams. With the 1 mA and 1 cm^2 cross-section beam of LAMPF on a 1 mole target one gets a luminosity of ~ $4x10^{38}$ $cm^{-2}sec^{-1}$. This should be compared to the 10^{30}-10^{31} $cm^{-2}sec^{-1}$ luminosity of high energy colliders. With the 100 μA, 10 mm^2 cross-section beam, say, of KAON on a 1 mole target we can get back the luminosity of ~ $4x10^{38}$ $cm^{-2}sec^{-1}$ thus covering the so far unexplored parameter space of energies up to 30 GeV and luminosities up to ~$4x10^{38}cm^{-2}sec^{-1}$.

To obtain higher energies, one needs to go to higher field strength or larger size. With SSC one will have reached the practical limits in both directions. One is then left with the only option of going to higher precisions. For this one needs higher luminosities and more sophisticated experimental designs and detectors.

It is interesting to note that even if one's interest is to reach high mass-scales, incident luminosity can be traded for energy. For hadron interactions at high energies the cross-sections vary roughly as

$$\sigma \sim \frac{1}{E^2} f\left(\frac{M}{E}\right) \sim \frac{1}{E^2}\left(\frac{M}{E}\right)^{-6} = \left(\frac{E^{2/3}}{M}\right)^6$$

where

E = center-of-mass energy

M = mass-scale reached

f = rapidly decreasing function which is related to the quark-gluon structure function in the hadron. The inverse 6th power dependence is the approximate scaling suggested by Llewellyn-Smith.

The luminosity L required is inversely proportional to σ or

$$\mathcal{L} \sim \frac{1}{\sigma} \sim \left(\frac{M}{E^{2/3}}\right)^6$$

Solving for M we get

$$M \sim E^{2/3} \mathcal{L}^{1/6} \sim E_L^{1/3} \mathcal{L}^{1/6}$$

where $E_L \propto E^2$ is the laboratory energy. Thus we see that luminosity trades as $E^{1/4}$ or $E_L{}^{1/2}$ even for reaching high mass-scale (energy) phenomena. For experiments aimed at high precision observations of minute effects, with all other factors equal, precision (hence the value of the experiment) is directly proportional to luminosity.