REVIEW ON HIF ACCELERATORS

Yasuo Hirao
Institute for Nuclear Study, University of Tokyo
3-2-1, Midori-cho, Tanashi-shi, Tokyo 188, JAPAN

Introduction

Heavy ion driven inertial confinement fusion (HIF) is one of the latest contenders in the controlled thermonuclear research. It is generally expected that the properties of the reactor concept required in this approach would be quite different from those we have met in the usual magnetic fusion approach. Furthermore, even within the category of inertial confinement fusion the characteristics of heavy ion beams differ in many respects from other candidates of energy drivers such as lasers or light ion beams.

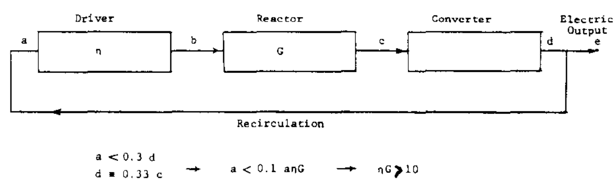

Fig.1 General Scheme of Power Circulation

Generally speaking, the requirement for economical feasibility is essentially that the recirculating power supplied to the driver be less than about 30% of the total generated power. Assuming a thermal-to-electric power conversion efficiency of 33%, this requires a product of driver efficiency times target gain of ten or greater, as shown in Fig.1. From the target yield vs input energy in Fig.2 based on the gain curves by R. Bangerter et al.[1], a 300 MJ output requires the input of 5 MJ by using single shell target within the condition of $\eta G > 10$. The yield of 300 MJ and one pulse per second could give an output power of 100 MWe. Assuming a 25% of accelerator efficiency, , and 5 MJ of beam power per pulse, the recirculated power is 20 MWe and then the system would have a net output of 80 MWe. Considering a much higher repetition rate and /or a number of reactor chambers with one accelerator, the system would result in net power produced in the range of GWe.[2]

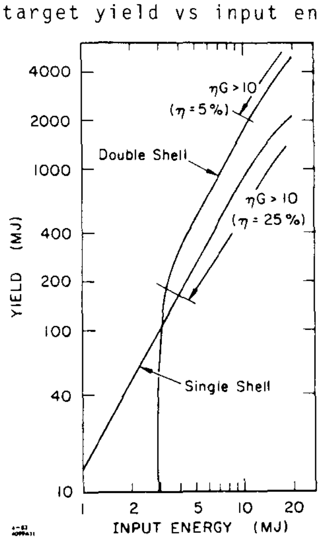

Fig.2 TARGET YIELD vs INPUT ENERGY

Summary of the advantages for HIF is given as follows:

a) physical separation between driver and reactor chamber which simplifies the engineering as compared with magnetic fusion,
b) higher driver-efficiency (20-30% attainable) than of lasers (∿5%),
c) abililty to employ the simpler single shell target,
d) high repetition rate of accelerator,
e) higher beam energy than for light ion considering the stopping range in the target, which allows low beam current and good energy deposition in the target pellet,
f) high reliability in accelerator technology based on the extensive world-wide experience using large accelerators.

On the other hand, there seems to be following disadvantages:

a) very big and complex accelerator system associated with relatively small reactor chambers,
b) big area of site and long beam lines to be handled,
c) large investment cost for construction.

Since 1976, studies in this direction have been done and a series of workshops and symposia was held four times in United States, and then in West Germany and in Japan.

In this paper, I would like to introduce the recent status limited to accelerator studies in this direction.

§ 1 HIF System Studies

The two types of accelerator system for HIF are proposed, so far. They are as follows:

a) the rf linac which supplies the energy to the system, injecting into a system of storage rings which perform the function of current multiplication, and
b) the induction linac which performs the dual functions of energy gain and current multiplication in the same structure.

So far there are several system studies in the world. These are the following.

Westinghouse - The study was completed in 1981. It uses Xe^{+1} or Xe^{+2} ions at 10 GeV. The total beam power is 3 MJ. The reactor employs a dry-wall design.

HIBALL-2 - The HIBALL design was completed by the collaboration of several West German governmental laboratories, groups at West German universilties and a group at the University of Wisconsin, USA in 1981, and was modified later to use Bi^{+1} ions, instead of Bi^{+2} previously, at 10 GeV and to avoid some instability problems. The total beam power is 5 MJ. The metallic wall of ferritic steel of the reactor chamber is protected by an array of porous Si·C tubes through which liquid Pb Li is flowing.[3]

HIBLIC-1 - The study was completed in 1983 by the collaboration of Japanese groups of several institutes, universities and private companies. It employs Pb^{+1} ions at 15 GeV. The total beam power is 4 MJ and the reactor chamber has a Li-curtain for the first wall.[4]

Rutherford Appleton Laboratory - The design of 4 MJ storage ring driver was made that gives a different version of the ring system from ones of above two systems.

Recently, the major emphasis of the United States program in HIF research is put on developing and understanding induction linac systems that employ multiple beams of high-current heavy ions, as described later.

Some details of driver systems in the HIBALL-2, HIBLIC-1 and RAL design are described in the following sections.

§ 2 The driver concept of HIBALL-2

HIBALL (Heavy Ion Beams and Lithium-Lead) is a conceptual design of HIF power plant. The driver part of the design is mainly in hands of GSI together with German university groups.[5]

The beam, pellet and reactor parameters are given in Tables 1, and 2. The concept of driver system is shown in Fig.3. A single charged Bi beam is chosen with a current of 165 mA at the end of the linac. In order to avoid space-charge limitations at its front end, the linac starts with sixteen parallel channels of multi-aperture ion sources and RFQ accelerator structures which are successively fed by funneling like a tree. The RFQ is followed by a Wider e structure and finally, the main part of the accelerator consists of Alvarez structures with a total length of about 5 km. The final energy is 50 MeV/nucleon, and the necessary momentum spread, $\Delta p/p$, is 5 ± 10^{-4} at the end of accelerator. After funneling between the low-velocity branches and main acceleration at the long stem of linac system, a first cuurrent multiplication is performed by horizontal stacking of ten turns in two transfer rings operated in parallel. After combining the two beams and rotating the beam by 90°, ten stacked storage rings are filled successively with five turns each. Another stack of ten superconducting storage rings is provided for the final bunching. The radii of these storage rings are 1/5 as large as of the transfer rings. After 4 ms, the cycle of filling and extracting is finished. Twenty beam pipes of less than 1 km each are feeding the reactor. The pulse current is 125 A at the exit of the final storage rings and attains 1250 A in each beam line at the target by final bunching.

Table 1. BEAM AND PELLET PARAMETERS

Ion species		Pb, Bi
Ion energy	50 MeV/Nucleon ≙	10 GeV
Pulse energy on target		5 MJ
Pulse duration		20 ns
Pulse current per beam-line		1.25 kA
Number of beam-lines		20
Fuel mass per pellet		4 mg
Pellet diameter		8 mm

Table 2. HIBALL REACTOR PARAMETERS

Target gain	80
Target yield	400 MJ
Number of reactor chambers	4
Number of beam-lines per chamber	20
Repetition rate per chamber	5 Hz
Net electric power (total)	3.8 GW_e
Coolant and Breeder	Pb(83%)Li(17%)
Maximum Coolant Temperature	500° C
Tritium breeding ratio	1.25
Chamber diamter	14 m
Chamber height	12 m

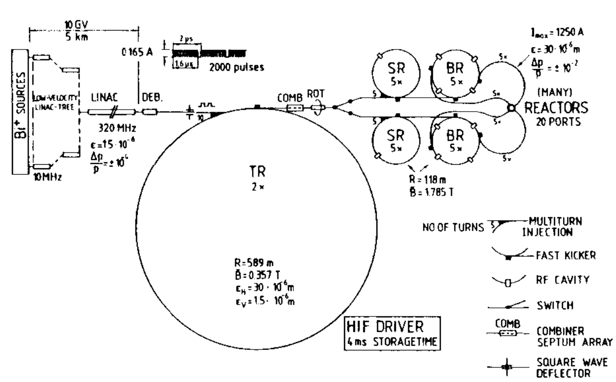

Fig.3 Concept of HIBALL System

§ 3 The driver concept of HIBLIC-1

The design study on the driver part was performed mainly at INS.[6] In the case of HIBLIC-1 (Heavy Ion Beam and LIthium Curtain) as well as of HIBALL, the driver system consists of a tree of rf linacs (RFQ linacs, IH linacs and Alvarez linacs, with four steps of beam funneling procedure), storage rings (one accumulator ring and three buncher rings) and linear beam compressors (induction linacs) as shown in Fig.4. Main parameters are given in Table 3. This accelerator complex provides six beams of $^{208}Pb^{+1}$ ions at 15 GeV to be focused simultaneously on a target pellet. Each beam carries 1.78 kA current with 25 ns pulse duration, i.e, the total beam power on the target becomes 4 MJ, 160 TW per shot. Superconducting coils are used in most parts of the magnet systems to reduce power consumptions.

To obtain such high peak current of heavy ion beam, the current at the end of the linac is multiplied by the function of two stage storage ring system.

The rf linac tree is similar to the one of HIBALL-2, while the output is 520 mA which is three times as large as of that. Momentum spread is ± 7 × 10^{-5} after debuncher following to the linac. A current multiplication is started by horizontal stacking of five turns in the accuumulator ring at first. Through an X-Y rotator, the beam is transfered from accumulator to three buncher rings successively with five turns each. The circumference of the former is just five times as large as of the latter. These buncher rings have also the function of bunching factor of 0.07. Finally, through linear compressors of induction linacs, six beams are fed to final transport lines. At the target position the bunching factor reaches to the value of 0.007. Therefore, the combination of stacking factor, 5 × 5, and bunching factor, 0.007, gives the current multplication of 3600, which gives then 1.78 kA with 25 ns

Table 3 Beam Parameters of HIBLIC

Ion species	$^{208}Pb^{1+}$
Total beam energy	4 MJ
Beam power	160 TW
Pulse duration	25 ns
Total beam current	10.7 kA
Ion kinetic energy	15 GeV
Number of beams	6
Radius of beam spot	3.2 mm
Repetition rate	10 Hz
Beam emittance	80 πmm·mrad
Momentum spread	± 0.01

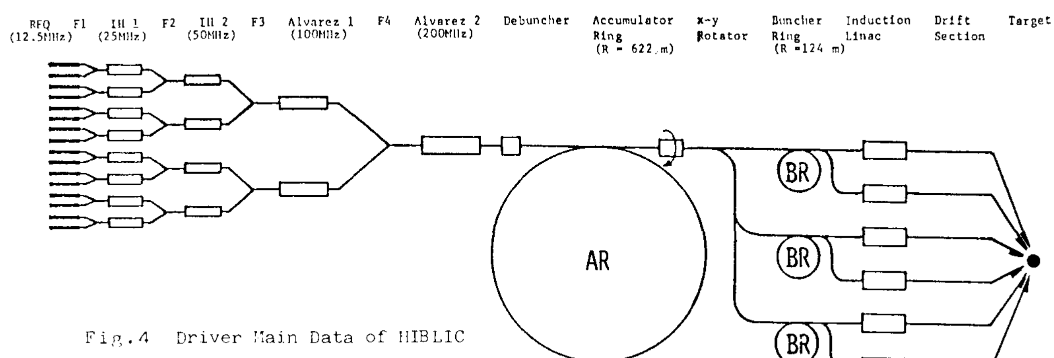

Fig.4 Driver Main Data of HIBLIC

Kinetic Energy(MeV/u)	0.3	1.16	4.51	17.78	72.12	72.12	72.12	72.12	72.12	72.12	72.12
Stack Factor	2	2	2	2		5		5			
Dilution Factor						2.67		2.67			
ϵ_x (mm·mrad)	27.19	19.03	13.19	9.12	6	80	6	80	80	80	80
ϵ_y (mm·mrad)	27.19	19.03	13.19	9.12	6	6	80	80	80	80	80
Bunching factor						0.99		0.96→0.07→0.06→0.007			
Bunch length								±196m→±14m→±12m→±1.4m			
Momentum Spread (ΔP/P)	$\pm 3.12 \times 10^{-3}$	$\pm 1.61 \times 10^{-3}$	$\pm 8.32 \times 10^{-4}$	$\pm 4.21 \times 10^{-4}$	$\pm 2.07 \times 10^{-4} \rightarrow \pm 7 \times 10^{-5}$	$\pm 7 \times 10^{-5}$		$\pm 7 \times 10^{-5}$	$\pm 1 \times 10^{-3}$	$\pm 1.1 \times 10^{-2}$	$\pm 1 \times 10^{-2}$
Peak Current (A)	32×10^{-3} (16x)	64×10^{-3} (8x)	128×10^{-3} (4x)	255×10^{-3} (2x)	510×10^{-3}	2.54		12.7→178→210→1780 (per Channel)			
Revolution Time (μsec)						35		7			
Maximum Beam Residence Time(μsec)						175		3200 (filling time = 530 μsec)			
-Δν(tune shift due to space charge)						0.174		0.048→0.67			

pulse duration. Maximum beam residence time in the ring system is 3.2 ms.

The structure and most of beam parameters are very similar between both systems, HIBALL and HIBLIC, and different points are mainly resulted from the beam energy difference between 10 and 15 GeV.

§ 4 Design concept at RAL

An rf-linac and storage ring concept was made as follows at Rutherford Appleton Laboratory.[7]

A high current single charged 10 GeV heavy ion beam is provided by a linac tree with five stages of funneling. For a 4 MJ system, current in the linac is typically 0.75 A. Use of such a high current allows rapid filling into rings so that there is insufficient time for the longitudinal microwave instability to develop significantly.

A debuncher between linac end and ring system is installed to obtain a momentum spread of $\pm 10^{-4}$. The ring system consists of accumulator and storage rings into which the beams are injected by low-loss five turn mode. Storage rings have a function of bunch compression by a factor of five. Additional bunch compression factor of ten is provided in the transfer line to the target.

Special feature of the design concept is in the ring system. All of five accumulators and eight storage rings have same radius of 90 m and use superconducting magnets to minimise the mean radius. First, the linac beam is injected by five turns in the horizontal space of each of five accumulator rings, and then the five accumulators are discharged in succession to provide five turn injection in the vertical space of one of the eight storage rings. The scheme is repeated to fill each of the five accumulator rings again. Finally, all of the eight storage rings are filled up by 5 × 5 turns both in horizontal and vertical spaces. The value of this current multiplication together with the bunch compression factor of 1250, which gives the bunch length of 30 ns.

The layout, as shown in Fig.5, seems to provide a method for reducing the very costly bending requirements of the final beam lines.

§ 5 Approaches to HIF

Through various design studies, necessary experimental subjects to make HIF scenario more feasible became clear. Several experimental

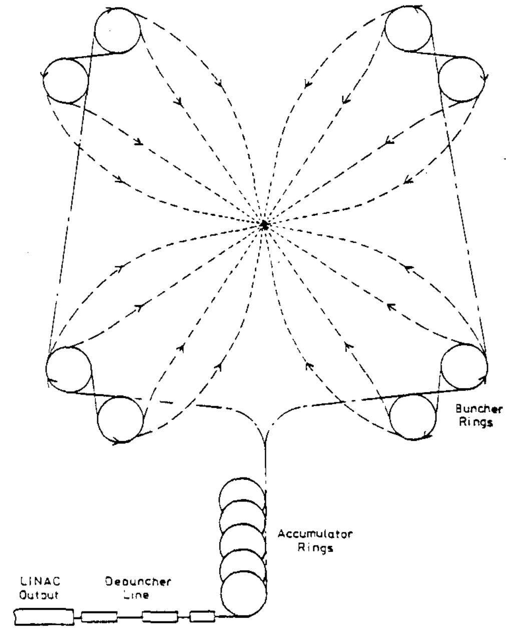

Fig.5 Concept of 4 MJ Driver System at RAL

studies by the existing facilities and also accelerator constructions for their purposes are proceeding, as follows.

West Germany - Beam and target experiments will be performed on SIS-18 and ESR-9 in GSI.[8] This facility is scheduled for 1988. Figure 6 shows schematic arrangement of this new facility to be added to the present UNILAC. The SIS ring has a Bρ value of 18 Tm and the maximum energies are 2 GeV/u for Ne and 1 GeV/u for U. Those energies are not necessary for HIF experiments. Instead, stripping between UNILAC and SIS is avoided and then higher intensities can be obtained. A high current injector including an RFQ is under development and UNILAC is expected to deliver high brilliance beams for very heavy ions as well in future.

Concerning the RFQ development, recently, the split-coaxial resonator type achieved the success of 6 mA acceleration of Ar^{+1} in GSI. Together with the big progress of RFQ development in several other institutes, the problem of acceleration at very low velocities seems to be essentially solved.

As an new aspect, electron cooling of heavy ions became an important program issue. In addition to developing cooling technology of heavy ion beam as an element in a driver system, it is considered as a promising way for increasing the energy density in a target experiment by synchrotron beam. ESR-9 is designed to have the Bρ-value of 9 Tm and six long dispersion-free straight sections of about

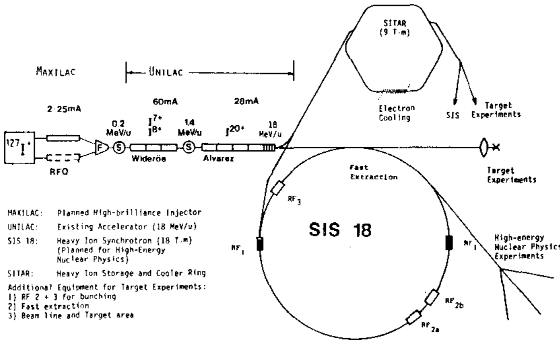

Fig.6 Schematic Layout of SIS-18, SITAR-9 System

7 m which provide enough space for various beam experiments including electron cooling. With electron cooling this facility should be able to provide a beam of 1 kJ energy and 0.02 TW power which can heat a target to 20 eV temperature. The preliminary parameter list of the experimental storage ring is given in Table 4.[8]

Table 4

PRELIMINARY PARAMETER LIST OF THE EXPERIMENTAL STORAGE RING WITH B·ρ = 9 T·M

MAXIMUM PARTICLE ENERGY

PARTICLE	P	NE	AR	KR	XE	U
ENERGY IN MEV/U	1900	(2+) 38 (3+) 84 (10+)708	(18+)599	(33+)480	(20+) 86 (48+)421	(72+)307 (78+)353 (92+)467

LATTICE

CIRCUMFERENCE	98.175 M
AVERAGE DIAMETER	31.25 M
BENDING RADIUS	5.00 M
FOC. STRUCTURE	ODFBFBFDO .
NUMVER OF FOC. PERIODS	6
LENGTH OF FOC. PERIODS	16.36 M
STRAIGHT SECTIONS	6 x 8 M
TOTAL LENGTH OF DIPOLES	31.42 M
TOTAL LENGTH QUADRUPOLES	22.5 M

RF

REVOL. FREQUENCY	0.46 - 3.10 MHz
HARMONIC NUMBER	2
ACCEL. FREQUENCY	0.92 - 6.20 MHz
EFFECT. ACCEL. VOLTAGE	0.49 kV FOR 1 T/s

INJECTION AND EXTRACTION

EL. STAT. SEPTUM	E · ρ = 1.7·10' V
MAGN. SEPTUM	B · ρ = 9 T·M

MAGNETS

12 DIPOLES A 30°, L_{EFF} = 2.62 M
24 QUADRUPOLES L_{EFF} = 0.75 - 1.0 M

United States - The HIF researches are now concentrated at LBL on induction linac and at LANL on target studies. Multiple beam experiments (MBE) and high temperature experiments (HTE) will be carried out on the induction linac being built at LBL which is expected to accelerate Na^{+1} ions to 125 MeV. Sixteen beams with 3.75 kJ, 30 ns are expected for HTE. The recent development of the induction linac for fusion at LBL is presented in this Conference by Dr. T. Fessenden. Figure 7 shows an example of 3 MJ induction linac driver.[10]

Three high-current beam transport experiments were carried out concerning the HIF driver research as shown in Table 5.[9]

Table 5 Experimental configuration and beam parameters of the three USA beam transport experiments

	BNL	LBL	UoM
Species	Ar^+, Xe^+	Cs^+	e^-
Kinetic Energy (keV)	1 - 2	80 - 160	0.5 - 5
Current (mA)	0.06	23	220
Pulse Duration (μs)	dc	~10	~5
Focussing Scheme	Electrostatic Quadrupole	Electrostatic Quadrupole	Interrupted Solenoid
Number of Lattice Periods	25	41	12(a)
Period Length (mm)	38.1	304.8	136
Aperture Radius (mm)	4.08	25.4	18.3
Minimum σ/σ_0	0.02(b)	0.1(c)	0.08(d)

(a) This value will be increased to 36.
(b) This value is estimated for a measured beam emittance after the publication of Ref. (1).
(c) This value is for the equivalent Kapchinskij-Vladimirskij beam (which has the same beam current, has twice the rms radius, and has four times the rms emittance) of the laboratory beam. Stable beam transport was observed for σ_0=60°, σ=8°.
(d) Emittance growth of 50 percent was reported for σ_0=60°, σ=5°. The final emittance was measured and compared with the theoretically estimated initial emittance.

United Kingdom - It is planned to commence a first HIF simulation experiment at SNS, RAL, by the end of 1984. Commissioning of the SNS synchrotron has just started and the first acceleration of 2.8 × 10^{12} protons was achieved on April 11, this year. Diagnostic equipments for the first HIF experiment are being prepared by GSI group. The aim of the experiment is to find the momentum distribution of the circulating proton beam of 70.4 MeV in the ring operated by storage ring mode and compare it with the momentum spread of the linac beam. The effect of the longitudinal space charge is of interest and also the momentum distribution in the ring is required for subsequent studies of longitudinal instabilities.[7]

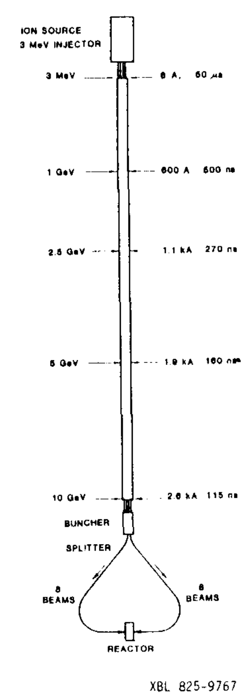

Fig.7 Concept of 3 MJ IL System at LBL[10]

Japan - INS, University of Tokyo has a test accumulation ring, named TARN, which is constructed in 1979 to study accelerator physics and technology. By use of this facility, beam accumulation in transverse and longitudinal phase spaces and then stochastic cooling of the beam were carried out successfully. An upgrading project of TARN is now proceeding, named

Table 6. Parameter List of TARN-2

Parameter		Value
Maximum Beam Energy	proton	1300 MeV
	ions with ε=1/2	450 MeV/u
Circumference		69.908 m
Average Radius		11.650 m
Radius of Curvature		3.820 m
Focusing Structure		FBDBFO
Superperiodicity		6
" for Cooler Ring Mode		3
Betatron Tune Value		around 1.75
" for Cooler Ring Mode		ν_H " 2.25
Transition γ		1.87
Repetition Rate		1/2 Hz
Maximum Field of Dipole Magnets		18 kG
Deflection Angle of Dipole Magnets		15°
Maximum Gradient of Quadrupole Magnets		70 kG/m
Revolution Frequency		0.38-3.75 MHz
Acceleration Frequency		0.76-7.50 MHz
Harmonic Number		2
Maximum RF Voltage		6 kV
Vacuum Pressure	better than 10^{-10}	Torr

TARN-2. Commissioning of this facility will be 1987. The list of main parameters is shown in Table 6. Improved point is a conversion to the synchrotron which has larger space of six long straight sections for beam experiments including electron cooling, while the present TARN is essentially small and DC ring of 10 m in diameter. Figure 8 shows the layout and lattice structure. Many features is very like to of the SIS-18 and ESR-9 system at GSI.

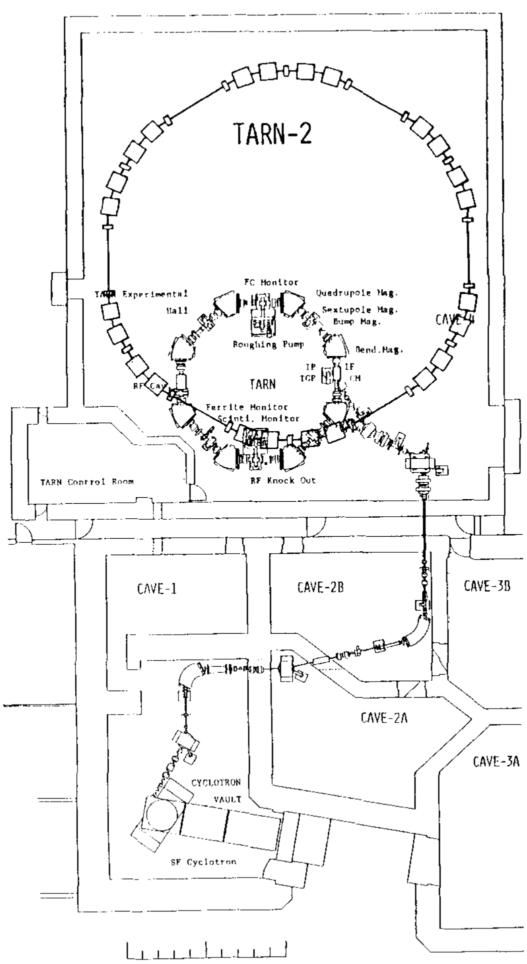

Fig.8 Layout of TARN-2

§ 6 Concluding remarkes

On the end of the last Symposium, Jan. 1984, Dr. Lee Teng summarized about accelerator for HIF. About issues for the induction linac approach, alignment for sixteen multibeam, related high current beam transport and beam compression in strongly influenced motion by space charge forces are important to be studied. For the rf linac and storage ring approach, effects on momentum spread induced by beam deflection during the initial funneling, dilution factor during multi-turn stacking, effects of space charge forces during debunching and compression, effects of crossing resonances during compression, coherent instabilities of the high current beam and transport in space-charge dominated situations are to be studied carefully. Some of these issues are being surmounted by theoretical studies and /or experimentally, and some new facilities are expected to provide ways not only for driver but also for targeyt studies.

Dr. Pierre Lapostolle remarked in his closing address on the same Symposium, that much work has still to be done and it is still so big that an international cooperation remains an essential issue.

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