Parameters and Requirements of Superconducting Focusing Quadrupoles for Heavy Ion Fusion

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***Abstract*—In a heavy ion fusion driver, arrays of superconducting quadrupoles will transport parallel beams through a sequence of induction acceleration cells. The development of such arrays is a unique and challenging task. Since magnetic transport is one of the most expensive subsystems, economy of fabrication is a primary consideration. A compact design is essential to limit the size and cost of induction cores. Special edge coils have to be implemented to adjust the field in outer cells and terminate the magnetic flux. The development of superconducting magnets for both near term experiments and the ultimate driver application is actively pursued by the U.S. Heavy Ion Fusion Program. The main parameters and requirements are discussed, and the R&D status and plans are presented.**

***Index Terms*—Superconducting magnet, heavy ion accelerator.**

I. Introduction

INERTIAL FUSION ENERGY (IFE) driven by heavy ion beams requires the deposition of several MJ beam energy in a 10 ns pulse, on a small target with spot radius of a few mm. The corresponding total ion current is on the order of hundreds of kA, at ion energies of 2–5 GeV. Space charge limits the current in a single focusing channel to much lower values, dictating the use of tens to hundreds of parallel beams at different stages in the fusion driver. Target ignition also demands that the beam energy is delivered in multiple components, with a particular geometric and time distribution. Fig. 1 shows the main parameters and beam manipulations envisioned in a Heavy Ion Fusion (HIF) driver to meet these requirements. Acceleration of the ions is achieved by a sequence of induction cells surrounding the entire cluster of beams. Induction linacs have demonstrated the capability to accelerate high current beams with very good efficiency. After a low-energy section based on electrostatic focusing, superconducting quadrupole arrays transport the beams throughout the accelerator, drift compression and final focus. The choice of a superconducting magnet system is determined by efficiency requirements in a power plant. Systems studies show that magnetic trasport accounts for a large fraction of the cost of the driver, making economy of fabrication a primary objective, along with compactness to limit size and cost of the induction cores [1].

The HIF program is progressing through a series of physics and technology demonstrations leading to an IFE power plant [2]. A set of scaled experiments carried out during the past several years has confirmed theoretical calculations of space charge dominated beam transport. In order to determine if these results can be extended to the power levels required by HIF targets, experiments with high current beams are currently underway in the areas of injection, transport and final focus. The next step involves source-to-target experiments to demonstrate that all beam manipulations required by the driver can be carried out in an integrated manner, thus setting the basis for a IFE demonstration power plant.

Superconducting magnet development for HIF is carried out by a collaboration of Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), MIT Plasma Science and Fusion Center, and Advanced Magnet Lab (AML). Several design concepts have been explored, and prototype cells have been fabricated and tested. These cells are suitable for use in near term single-beam experiments, as well as modules in multi-beam arrays. Following a design selection aimed at focusing the available resources on a single development path, present activities involve optimization of the module cell, design of a prototype quadrupole array and fabrication and test of a cryostated focusing unit. This unit will be installed in the High Current Experiment (HCX), currently underway at LBNL, to gain operational experience and perform initial beam measurements. Successful results in the present phase will make superconducting magnets a viable option for the next generation of integrated beam experiments. Although electrostatic and pulsed magnetic quadrupoles may provide more effective focusing in some parts of the accelerator, these experiments represent an important opportunity to develop the superconducting technology base required for effective beam transport in a large portion of the fusion driver.

The paper is organized as follows: in Section II, the design requirements of quadrupole arrays for fusion applications are discussed; in Section III, the magnet parameters for present experiments are presented, along with expected values for future experiments and the fusion driver; in Section IV, the magnet R&D status and plans are reported.

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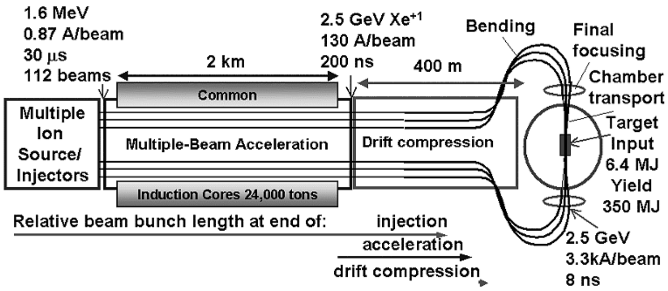
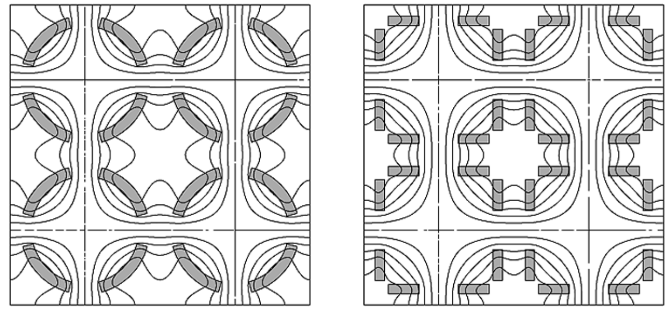


Fig. 1. HIF driver concept.



(a) (b)

Fig. 2. Array configurations using (a) shell or (b) block coils.

II. Design Requirements

The HIF multi-beam array approach and the requirements of induction acceleration lead to different optimization strategies compared to focusing quadrupoles developed for high energy physics applications. Achieving the highest gradient and field quality is generally given a lower priority, while new challenges arise in the areas of compactness, coil layout, edge termination, alignment, cryogenics and vacuum.

A key design issue is the optimization of the number of channels vs. aperture and field gradient. Accelerator physics considerations favor increasing the number beams and decreasing the current per beam. This corresponds to increasing the number of channels in the array, and decreasing the aperture. However, a larger number of channels results in higher number of parts and fabrication steps. A very small aperture results in a larger fraction of space allocated to coils and support structure, and stringent alignment requirements. Understanding the design limits and tradeoffs which contribute to determine the optimal parameters of the fusion driver is a fundamental objective of the magnet development effort.

A. Compactness

The acceleration voltage produced by an induction core with flux swing ΔB during a time τ is given by $V = A \cdot \Delta B/\tau$, where A is the cross-sectional area of the core material. The core has cylindrical geometry, with inner radius r_i and outer radius r_o. The cross-sectional area is proportional to $(r_o - r_i)$, while the mass of the ferromagnetic material is proportional to $(r_o^2 - r_i^2)$. Therefore, the cost to achieve a given accelerating voltage is a rapidly increasing function of the inner radius of the core. Since the core must surround the entire cluster of beams, and in some cases the magnet cryostat, the transverse size of the focusing array has important implications on the cost of the acceleration system. Strategies to achieve high average current density in the array include reducing the transverse space required for superconducting coils, mechanical structure and thermal insulation; developing schemes for compact return of the magnetic flux; and increasing the aperture fill factor.

Longitudinal compactness is also an issue, in particular at low-energy, where space charge effects are stronger and magnetic focusing less efficient. In order to provide high-voltage gaps for induction acceleration, each quadrupole array has to be housed in a separate cryostat and the cold mass supports, cryogenic services, and magnet electrical leads must be supplied near the midplane. Warm gaps between cryostats are also needed for diagnostics access and pumping ports. Short cryostat terminations and compact coil ends are therefore essential. The design solutions adopted in HCX to confront these issues are described in Section IV.

B. Coil Layout

A magnetic configuration based on square unit cells with alternating polarity is selected for optimal magnetic efficiency. In this configuration, the return flux from each cell increases the flux in adjacent cells, with enhancement factors of about 30% in practical configurations (Fig. 2). Design goals for the coil and its mechanical support are reliable operation up to the conductor limit with no training, cost effective fabrication, minimum overall thickness and good field quality.

Both shell and block type coils can be considered for this application. A shell-type ($\cos 2\theta$) configuration using keystoned Rutherford cables has the advantage of a self-supporting Roman-arch structure, and provides high magnetic efficiency [3]. However, it features complex geometries, in particular at the coil ends. Conversely, accelerator magnets based on block-coils have received considerable attention in recent years due to their simplicity and cost-effectiveness [4]. Double-layer racetrack windings are of particular interest. Racetrack coils are well suited to the square cell layout of the array [5]. They can be arranged back-to-back improving flux sharing, and they require less structural support since the outwards components of the magnetic force are balanced between cells. Neighboring coils can in fact be combined using a wider cable, with significant reduction of the number of parts, conductor joints, and inductance. Finally, block-type coils are well suited to brittle superconductors, due to the use of flat cables with low degradation, and planar coil geometry. Although the properties of conventional NbTi are adequate to meet HIF accelerator requirements, high critical currents and temperature margins in advanced conductors like Nb_3Sn and HTS may eventually improve the performance and cost-effectiveness of the driver. In addition, strong quadrupoles based on high-field conductors are needed to achieve small spot size in the final focus.

Coil designs based on round cables individually supported by grooved cylinders or plates have been actively explored by the HIF program, with the goal of reducing cost and improving design flexibility [6]. At the present stage of development, conventional approaches are still favored in achieving high coil-pack current density and minimum training. Special magnets like corrector packages and adiabatic bending dipoles, where fields are relatively low and several design variations are required, may provide an opportunity for further development of the new design concepts.

C. Flux Termination

In order to meet gradient and field quality specifications in quadrupole cells located at the boundary of the array, special edge coils are required, so that the same boundary conditions as for the inner cells can be obtained (flux normal to the sides of each cell). In addition, termination of the magnetic flux within the shortest radial distance is desired. Magnetic coupling between quadrupole array and induction cores results in a loss of efficiency of the core, generation of field errors in the array, and power dissipation in the 4.2 K system.

An effective strategy for flux termination has been presented in Ref. [7]. A current sheet along a parallel-flux boundary (magnetic pole axes), with linearly increasing current density, provides the desired boundary condition with no flux leaking to the outside. To obtain this condition, a layer of sub-unit cells ($1/4, 1/2$, and $3/4$ quadrupoles) surrounds the peripheral cells, achieving flux termination within a distance corresponding to half of the cell size. For an array based on shell-type coils, matching the $\cos 2\theta$ winding with the linear current distribution in the termination sub-cells is an issue. The implementation of termination coils may be simplified in a block-type design, where all coils have planar geometry.

A more efficient array termination scheme has also been derived [8]. It is based on two layers of coils to provide a flux containment channel, and achieves termination within one quarter of the cell size. However, improvements in compactness need to be evaluated against the cost of auxiliary coils. The use of magnetic iron appears as the most cost-effective solution for flux termination in near term single-beam experiments. A magnetic shell surrounding the array may also be used to complement and simplify the edge coil design.

D. Aperture Filling Factor

In order to achieve high average current density in the array, the beams must fill a substantial fraction of the available aperture. This requirement has implications in the areas of field quality, vacuum, alignment and steering. The field quality required to avoid emittance growth and particle losses (a few parts in 10^3) has to be maintained up to 80% of the coil radius. High vacuum is required to reduce beam loss, the associated energy deposition in the superconducting coils, materials activation and electron-induced instabilities. A cold bore with slotted liner can be used to improve the vacuum, at the expense of higher refrigeration cost.

A fraction of the aperture has to be allocated to beam centroid oscillations due to misalignments. The loss of efficiency can be large, especially in configurations with many small-aperture channels. Corrector coils nested to the main winding package are not easily implemented in the array. Because of flux sharing between channels, a correction applied to one aperture will cause errors in the neighboring apertures. Separate low-field corrector packages with iron shielding between channels are considered to be the most viable option. The required frequency of the correctors in the lattice is directly related to the alignment accuracy in the array [9].

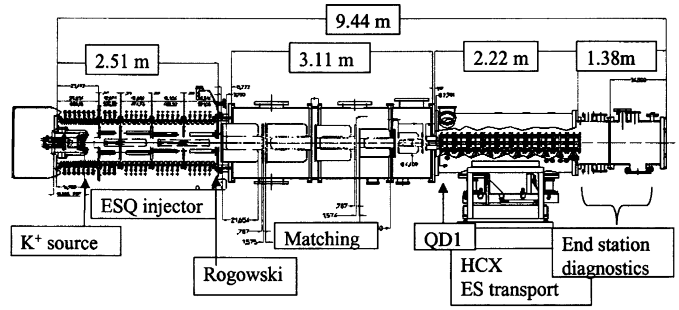


Fig. 3. HCX experiment.

III. Magnet Parameters

A. High Current Experiment (HCX)

HCX is designed to explore the physics of intense beams with driver-scale line-charge density (0.2 μC/m) and pulse duration ($\tau \geq 4\,\mu$s) [10]. The present configuration (Fig. 3) incorporates a 1–1.8 MeV K^+ injector delivering 0.2–0.6 A, a matching section and a transport lattice of 10 electrostatic quadrupoles (to be expanded to 40 quadrupoles). The electrostatic quadrupole electrodes are cylindrical conductors and the design is readily extended to multiple beam arrays for transport at low kinetic energy [11].

Magnetic transport experiments are also planned, in particular to study effects due to electrons trapped in the potential well of the ion beam. Magnetic quadrupoles lack the strong sweeping fields associated with electric focusing. Due to the low beam energy, the lattice has a short period of 45 μcm, leading to a challenging packing. Lattice syncopation (unequal drifts between F and D quads) is used to gain sufficient axial space for cryostat terminations at each focusing period. A quadrupole gradient of 84.2 T/m over a magnetic length $l_q = 10.1$ cm has been specified [12]. The nominal coil aperture is 70 mm, resulting in 59 mm (warm) vacuum chamber aperture. Although a 45 mm bore may be sufficient to accommodate the HCX beam parameters, additional margin is provided for experiments involving beam steering, mismatch and halo. The field quality is specified in terms of axial integrals of the magnetic field components. For any longitudinal field integral calculated at 25 mm radius and $0 < \theta < 2\pi$, a maximum deviation of 0.5% from the ideal quadrupole field at that location is allowed. The use of integrated field errors is well suited to short magnets with strong longitudinal field variations, and implicitly allows field error compensation between the magnet straight section and ends. Simulation studies of intense beams have shown that minimization of local field errors is desirable but not needed provided the integrated error is in the range specified.

B. Integrated Beam Experiment (IBX)

The purpose of the IBX is to integrate in a single experiment all beam manipulations required in a driver, including injection, acceleration, compression, bending and final focus, at significant line-charge density [13]. Magnetic focusing was selected throughout the accelerator to reflect the medium to high-energy part of the driver. The basic parameter range being considered is 1–4 beams, 7–20 MeV final energy, 0.2–1 μs initial pulse length, 1–2 μC/m final line-charge density. Two pre-conceptual designs were developed [14], [15]. A syncopated lattice with HCX doublets is used in [14] for the low energy section. As the ions gain velocity, focusing requirements are reduced and the period can be progressively increased. For beam energy above 4.58 MeV, each quad is housed in an individual cryostat, doubling the number of accelerating gaps per period. All magnets have equal length, but the gradient is adjusted to obtain a constant phase advance per period. In Ref. [15], a longer initial lattice period is chosen to accommodate separate cryostats for superconducting magnets, resulting in a larger beam size and magnet aperture. By removing the constraint of a constant phase advance, the same period, gradient and magnetic length can be maintained throughout the accelerator. This allows a single type of magnets powered in series and operating at the optimal design point. However, this choice lowers the average acceleration gradient and requires a larger number of periods to achieve the same energy. The drift compression section also uses magnets of fixed length and gradient, but the aperture increases from 4 cm to 6 cm as the transverse space charge force increases. A 90-degree bend is superimposed to the drift compression section. Smooth variation of the dipole field is required to minimize emittance growth. At the center of the bend, the dipole field reaches a maximum value of 0.54 T. Magnet parameters for both designs are summarized in Tables I (accelerator) and II (drift compression and final focus). The two pre-conceptual designs will represent the parameter range being considered.

C. Integrated Research Experiment (IRE)

The IRE will be a multiple beam induction linac with prototypical driver technology. It will allow the study of beam-beam magnetic coupling effects at high energy and in plasma-filled chambers near final focus. It will also provide substantial target heating and explore areas of target physics which are unique to ions. The scale of this facility is about $1/10$th of the driver in ion energy. A design with 200 MeV energy, 32 beams of K^+ ions, 30 kJ final pulse energy was presented in Ref. [16]. Recent considerations suggest that the final pulse energy may be increased to 250 kJ using 800 MeV Rb^+ ions, which provides more substantial target heating [17]. The heavy-ion beam specific energy deposition can also be increased by reducing the focal spot size. The final focus parameters in Ref. [16] call for quadrupoles with 14 cm bore diameter and 10 T peak field to achieve a spot size of 7 mm. A two-stage system has been recently proposed to obtain a focal spot size of 1 mm [17]. It consists of 16 large bore quadrupoles with 10–12 T peak field, followed by a short focal length plasma lens in the vicinity of the target. Magnet development for this application is a step toward more powerful final focus magnets required by the HIF driver, and may benefit from the R&D effort currently underway to develop second-generation Nb_3Sn quadrupoles for the LHC Interaction Regions [18].

TABLE I
IBX MAGNET PARAMETERS
(ACCELETATOR).

Parameter	Unit	Ref. [13]		Ref[14]
		Doublet	FODO	
Half lattice period (hlp)	cm	22.5	31.8 - 45	30
Number of hlp's		18	60	94
Syncopation factor		0.251	0.5	0.5
Clear bore radius	cm	2.95	2.95	4.0
Operating gradient	T/m	84.2	60.0 - 80.4	40.9
Magnetic length	cm	10.1	13.2	13.5

TABLE II
IBX MAGNET PARAMETERS (DRIFT COMPRESSION AND FINAL FOCUS).

Parameter	Unit	Drift compr.		Final focus	
		[13]	[14]	[13]	[14]
Half lattice period		45	50	-	-
Number of hlp's		60	48	-	-
Clear bore radius	cm	6.1	4 - 6	10	15
Oper. Gradient	T/m	65.4	26	30	12
Magnetic length	cm	13.2	13.5	25	70

TABLE III
HIF FINAL FOCUS: INNER TRIPLET MAGNET PARAMETERS [19].

Parameter	Unit	Last	2nd to last	3rd to last
Dist. from target	cm	600	755	1035
Beam pipe radius	cm	17.5	25.3	20.7
Winding radius	cm	24.5	32.3	27.7
Oper. Gradient	T/m	25.0	19.1	19.4
Magnetic length	m	1.25	2.5	1.25

D. Enginneering Test Facility (ETF) and the HIF Driver

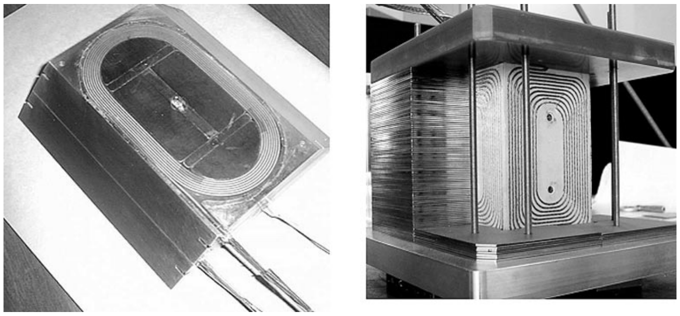
The IRE, together with the National Ignition Facility (NIF), will provide the basis for a high average fusion power Engineering Test Facility (ETF). ETF will incorporate all the major systems needed for a IFE power plant (HIF driver, target production, fusion chamber). The large scale of the machine, with final energy of a few GeV, will require fully optimized superconducting quadrupole arrays. A recently proposed design calls for field gradients of 75 to 122 T/m and coil apertures of 3–5 cm at different stages in the accelerator [19]. In the final focus, high gradient quadrupoles with large bore are required. Preliminary magnet parameters for the final focus inner triplet are shown in Table III.

IV. MAGNET R&D PROGRAM

A. HCX/IBX Magnet Development

The High Current Experiment provides an opportunity to address key magnet design issues like maximum achievable gradient, design simplicity and cost-effectiveness, optimization of the conductor parameters, field quality, modularity, and compact cryostats. Two design approaches were proposed in 2000 by LLNL and AML. The LLNL design uses two layers of double-pancake coils, wound around iron cores and preloaded using stainless steel holders and keystoned wedges (Fig. 4, left). In the AML approach, grooved plates surround a round 7-strand (6×1) cable (Fig. 4, right).

Fabrication and test of two prototypes of each design followed [20], [21]. Table IV shows a summary of the training performance of the four prototypes. All magnets surpassed the nominal operating current ($I_{\rm op}$), defined as 85% of the short



(a) (b)

Fig. 4.

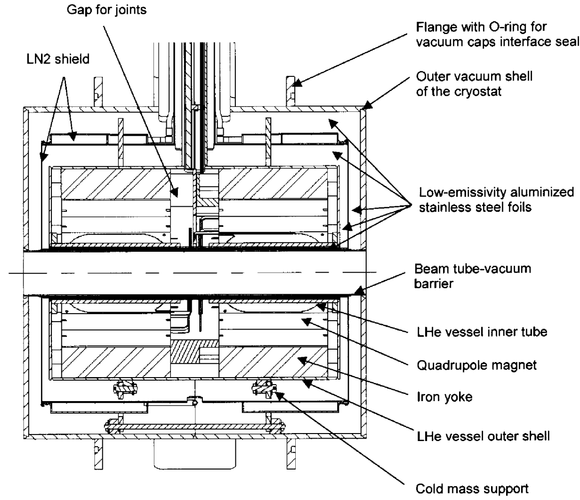


Fig. 5. HCX prototype cryostat.

TABLE IV
HCX PROTOTYPE TRAINING PERFORMANCE.

Prototype	1st Quench $I_q^{(1)} / I_{ss}$	Mx. current $I_q^{(max)} / I_{ss}$	No. quench to reach I_{op}
LLNL#1	0.75	1.0	3
LLNL#2	0.98	1.0	0
AML#1	0.78	0.97	4
AML#2	0.65	1.0	12

sample limit. The first LLNL prototype had relatively low initial quenches but rapidly trained to short sample. The second prototype reached short sample at the first quench. The AML prototypes showed slower training, and the maximum current achieved by the first prototype was a few percent below the expected short sample limit. No significant retraining after thermal cycles was observed in all prototypes. Ramp rate dependence was well within the HCX operational requirements. At the end of 2001, the LLNL design was selected as the baseline. Further design optimization of the baseline design has led to significant improvements of integrated gradient, field quality, coil mechanical support and cost with respect to the first series [22]. A prototype quadrupole of the optimized LLNL design is presently being fabricated by AML and will be tested at LBNL in the fall of 2002. The expected short sample gradient is 132 T/m, with an effective magnetic length of 105.4 mm. The integrated harmonics (in 10^{-4} "units" of the quadrupole component at 25 mm reference radius) are $b_6 = -7.3, b_{10} = -19.8$. The test will include magnetic measurement to confirm that the prototype meets field quality specifications.

The cryostat design for a quadrupole doublet, compatible with lattice requirements and induction acceleration, has been completed by LLNL and MIT [23]. A first prototype is being fabricated and additional modules are planned, to optimize the design and reduce cost. Installation of these units in HCX will allow to gain operational experience, and provide reliable performance and cost figures needed to select the magnetic focusing technology for the IBX and future experiments. Details of the cryostat design are shown in Fig. 5. The module contains two quadrupole magnets mounted on an alignment tubing, the 4 K cold mass container, LN2 thermal shields and radiation shields, a vacuum vessel, and a shielded straight chimney enclosing a pair of Nb_3Sn bus bars connected to the coil leads. The chimney is needed to maximize the space available for induction acceleration cores surrounding the transport line. In order to minimize the radial space between beam pipe and LHe vessel in the magnet bore, special low-emissivity aluminized stainless steel foils ($\varepsilon = 0.002$) are used for radiation shields, with no active thermal shields [24].

The HCX magnet development is directly applicable to IBX. In fact, HCX-type magnets are used for most of the accelerator in pre-conceptual design [14]. The magnet requirements for the accelerator in Ref. [15] can be met by a modified HCX design using a single layer of coils, with significant cost saving potential. In the combined drift compression and bend section, the lattice period is sufficient to accommodate separate function magnets for focusing and bending. The requirement of a slowly varying dipole field can be met using coil modules of a few different types powered in series, surrounded by shells where different distributions of magnetic and nonmagnetic materials allow for fine adjustment of the field. In the final focus, large beam envelope excursions require magnets with very wide bore (and comparatively low gradient). Shell-type coils may be favored for this application.

B. Quadrupole Array Prototype

The design of a prototype quadrupole array has started at AML with funding from a DOE SBIR Phase I grant. The main technical objectives are the comparison of different coil layouts, the design of edge coils to both terminate the flux and adjust the field quality, the development of a suitable mechanical design and quench protection scheme, and the design of a cryostat compatible with induction acceleration. The cryogenics and vacuum issues related to the use of a warm vs. cold beam tube will also be addressed. The magnet aperture will be selected to optimize the average transportable current. The Phase I study is expected to provide a conceptual design for a prototype quadrupole array, to be fabricated during Phase II. Four channels will be used in the first prototype, consistent with the possibility of an IBX upgrade to four beams. The principal array design issues can be addressed using a limited number of channels, as long as proper termination is provided. Termination schemes for the four-aperture configuration are being developed at MIT [25].

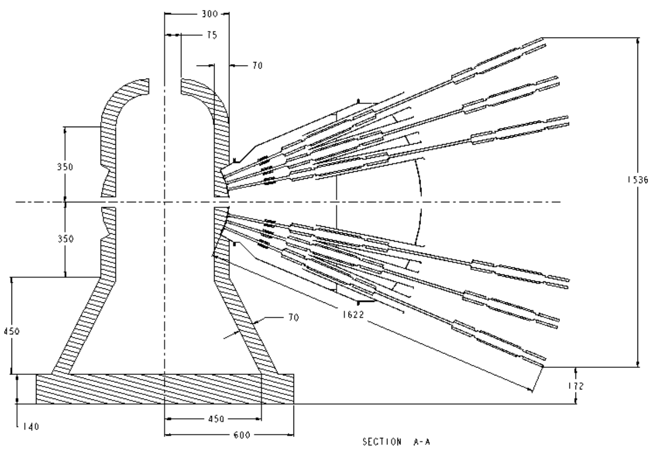


Fig. 6. Final focus triplets (6 beam lines) and HIF reaction chamber. (dimensions in cm).

C. HIF Driver Final Focus

In the final focus, the combined requirements of target ignition and radiation protection result in significant challenges. Target designs for ion energy of 2–5 GeV demand a large number of beams (~ 100) with limited divergence (less than 24° half-angle) resulting in a tight space budget to accommodate wide-aperture beam chambers, super-conducting coils, mechanical support structures, cryostats and shielding materials. Key considerations are the total radiation dose to the insulators, and production of radioactive waste due to fast neutron flux to the conductor.

At present, Nb_3Sn is the most suitable conductor to meet the magnet requirements (Table III), which result in a $\sim$10 T coil peak field. The maximum stress is within the limit to avoid permanent degradation of the conductor properties. The stored energy per unit length in each channel is significantly higher than in any high-field Nb_3Sn prototypes built to date, making quench protection a critical issue. A possible layout is shown in Fig. 6. The inner focusing triplet is the most challenging due to proximity to the chamber and the converging beam arrangement. The use of sub-arrays of block-type coils is being considered in order to simplify the magnet design.

V. Conclusion

Accelerators for fusion energy production will require arrays of superconducting quadrupoles to transport multiple beams in the accelerator and focus them on the target. The development of superconducting magnets for both near term experiments and the ultimate driver application is being actively pursued by the U.S. Heavy Ion Fusion Program. The main parameters and requirements have been discussed, and the R&D status and plans have been presented.

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