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FUTURE DEVELOPMENT OF HIGH-CURRENT DC INJECTORS FOR ACCELERATOR-BASED BREEDING SYSTEMS

Développement futur d'injecteurs CC à forts courants pour les systèmes de surrégénération recourant aux accélérateurs

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Chalk River, Ontario

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Résumé

Les Laboratoires nucléaires de Chalk River examinent actuellement la faisabilité technique et économique de la production de combustible nucléaire dans un surrégénérateur à spallation qui serait un accélérateur de protons de 300 mA, 1 GeV ayant un facteur d'emploi de 100% et produisant des neutrons dans une cible où se trouverait une matière fertile. On précise dans ce rapport les besoins de la section de l'injecteur à courant continu d'un tel accélérateur et on constate que les injecteurs actuels ne peuvent pas répondre à ces besoins.

On donne l'essentiel des critères conceptuels pour les colonnes d'accélération en cc lesquels sont fondés sur une enquête faite dans la littérature et sur des résultats expérimentaux. On compare les systèmes d'accélération mono-étagés et biétagés et on démontre que les systèmes biétagés sont préférables pour l'injecteur d'un surrégénérateur à spallation.

On décrit un concept pour l'injecteur et on donne un aperçu du banc d'essai qu'il faudrait pour faciliter sa réalisation. Dans l'injecteur un faisceau d'ions d'hydrogène de 750 mA est extrait à ~ 50 kV, puis magnétiquement analysé pour enlever les ions H_2^+ et H_3^+ du faisceau H^+ Le faisceau H^+ est alors focalisé et débarrassé de son halo et autres composants ayant un grand pouvoir émissif, ce qui donne un faisceau de 500 mA de haute qualité prêt pour la focalisation et l'accélération dans la colonne principale d'accélération.

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ABSTRACT

The Chalk River Nuclear Laboratories are examining the economic and technical feasibility of producing nuclear fuel in a spallation breeder, which would consist of a 300 mA, 1 GeV, 100% duty factor proton accelerator producing neutrons in a target assembly of fertile material. This report discusses the requirements for the dc injector section of such an accelerator and finds that present day injectors cannot satisfy them.

Design criteria for dc accelerating columns, based on experimental results and a literature survey, are summarized. One- and two-stage acceleration systems are compared, and the two-stage approach is shown to be preferable for the spallation breeder injector.

A conceptual design for the injector is described, and a brief outline of an Injector Test Stand required for design tests is given. In the injector, a 750 mA hydrogen ion beam is extracted at ∿ 50 kV, then magnetically analyzed to remove H_2^+ and H_3^+ ions from the H^+ beam. The H^+ beam is then focused and scraped of halo and other high emittance components, giving a high quality 500 mA beam ready for bunching and acceleration through the main accelerating column.

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TABLE OF CONTENTS

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1. INTRODUCTION

One method of increasing the amount of fissile isotopes available to nuclear power reactors is to convert fertile material to fissile by capture of neutrons produced by bombarding a target of high atomic number material with high energy protons. AECL has been interested in such systems for many years[1,2], as have laboratories in the United States where investigations have recently been renewed[3]

Much useful experience has been gained on dc accelerators at CRNL and elsewhere (see section 3). However, none of the high current dc accelerators developed so far meet the spallation breeder accelerator injector requirements on beam current, energy, quality, or stability. Indeed, the experience gained on these accelerators indicates that much development will be required to meet the requirements.

A conceptual injector design based on present understanding of injectors, and an injector test stand to test and develop this design, are described.

2. INJECTOR REQUIREMENTS FOR A SPALLATION BREEDER ACCELERATOR

The present accelerator concept[2] specifies a 300 mA, 1 GeV proton accelerator consisting of dc injector, low energy linear accelerator, and high energy linear accelerator, coupled to a liquid metal target surrounded by a fertile blanket.

For 300 mA on target, allowances for beam spill, accelerator capture efficiency, and buncher efficiency imply that 500 mA of protons is required from the injector. About 70% of the total ion beam is H^+ ions (the remaining 30% being unusable H_2^+ and H_3^+ ions), and about 5% of the H^+ beam is scraped off as beam halo and other high emittance components, so 750 mA total beam is required from the ion source. The injector voltage is expected to be $\gtrsim$ 250 kV if an alternating phase focused linear accelerator can be used4), or $\sim$ 750 kV if a conventional Alvarez linear accelerator is used5).

In the spallation breeder, a large, slow increase in beam current is required during start-up, because target heating dynamics require a slow run-up6) ($\gtrsim$ 1 hour) of beam power. Even if the target did not restrict run-up, the linear accelerator is 90% beam loaded and beam current must be increased gradually (over $\sim$ 1 second) to allow proper tracking of rf power by the control system.

The economic production of fissile material will require a high capacity factor from the accelerator. The number of interruptions (even short ones) in proton beam production must be minimized, because the requirement for slow beam turn-on will force a delay in recovering full neutron production. Two types of reliability can be defined: component reliability, which refers to hardware failures, and beam reliability, which refers to short ($\lesssim$ minutes) interruptions in beam production. Component redundancy, and design development, can improve component reliability. Beam reliability is strongly dependent on the injector - sparkdowns and momentary variations in beam energy cannot be tolerated by the downstream accelerator components, target heating dynamics, or by the high capacity required. However, these are the most common faults that occur on existing dc accelerators.

3. STATUS OF HIGH CURRENT ACCELERATOR TECHNOLOGY

Table I lists the design and achieved performances of five high voltage (> 150 kV) high current (> 10 mA) dc accelerators, and the LAMPF injector. The latter, although it operates in a pulsed mode, is included because many of its design features appear in dc accelerators. RTNS-II is still being commissioned.

The table heading "best run" refers to the longest period of continuous beam production, and "accelerator type" states whether the acceleration takes place in a one- or two-stage system. In a single-stage system the ion source emits ions directly into the high voltage column, hence all ions are accelerated. In a two-stage system the beam is extracted from an ion source, magnetically analyzed to remove molecular ions, focused, then the H^+ beam is injected into the high voltage column.

Of the accelerators listed in Table I, none approach all the requirements for the spallation breeder injector - the DCX-II injector is perhaps the closest. However, the beam quality in this machine is not known; it has been dismantled and further tests are not possible, and the factors which made it reliable are not understood, even by those who built it[11)]. The current on RTNS-I is limited by the power supply. In all the accelerators, beam-induced high voltage column sparkdowns are the major factor reducing reliability.

Experiments at CRNL on the FINS and HCTF accelerators, on a 100 kV electrode test assembly and on an ion source test

TABLE I

Compendium of High Current Accelerator Designs and Performances

Accelerator	FINS (Mk I)	FINS (Mk II)		HCTF		DCX-II		RTNS-I	RTNS-II[b]	LAMPF	LANCELOT	
Laboratory	CRNL	CRNL		CRNL		ORNL		LLL	LLL	LASL	Valduc,France	
Reference	7,8	7,8		5,9		10,11		12	12	13,14	15	
Design Current, total (mA)	43	43		120		∿ 300		-	-	-	200	
proton (mA)	30	30		90		-		22	150	∿1.5 avg	-	
Voltage (kV)	300	300		750		600		400[a]	450[c]	750	160	
Achieved Current, total (mA)	5	16	12	40	6	100	300	-	-	-	160	180
proton (mA)	-	10	6	-	-	-	-	20	-	∿1.5 avg	-	-
Voltage (kV)	250	250	250	700	700	600	600	350	-	750	160	200
Best Run	2 h	2 h	6.5 h	1 h	8 h	days	hours	days	-	hours	$\gtrsim$3 h	$\gtrsim$0.5 h
Accelerator Type, stages	one	one		one		one		two	two	one	one	

a) Includes pre-accelerator voltage of 70 kV.
b) This accelerator is still being constructed.
c) Includes pre-accelerator voltage of 50 kV.

stand have identified some of the causes of high voltage column sparkdown. The major causes are backstreaming electrons and the X-rays they produce. Maximum reliability on the HCTF is achieved by adjusting ion source parameters to minimize beam spill on the electrodes, and by keeping gas flow through the ion source as small as is feasible - failure to make these adjustments results in high radiation fields and a loss of reliability. A study done on the FINS column using an electron emitting filament placed at the bottom of the column showed that, if the filament emission current was adjusted to give the same external radiation field as would be produced by some given ion beam current, the sparkdown rates were the same for electron and ion beams in the column. It was also shown that the effect takes place on ceramic insulator surfaces (in vacuum) as installation of heavy copper electrodes that shield the ceramics greatly increased reliability with ion beams. A study of electrode materials, done on a 100 kV test stand, showed that the presence of an electron current, of magnitude similar to typical backstreaming currents, drastically increased the sparkdown rate. The effect varied for different materials. Efforts to reduce electron backstreaming in the ion source test stand have resulted in improved reliability.

A problem, known to arise in single stage accelerators10), occurs if electrons can be stably trapped in some region by column electric fields suitably overlapping ion source stray magnetic fields. The problem is made worse when the ion source extraction electrode is mounted on ceramic posts - the trapped electrons can be intercepted by the support posts, which results in voltage breakdowns. On the FINS accelerator, stray magnetic fields were reduced, and the extractor was replaced by a shaped, passive focus plate. These changes increased column reliability.

The foregoing discussion indicates the main problem of present accelerators - the presence of electrons inside the high voltage column. The following section shows that two-stage accelerator systems can be designed to avoid much of the in-column electron production inherent to single-stage designs, thus giving the potential for reliable operation at currents higher than presently possible.

In many of the accelerators described in Table I, ion optics constraints require that the source be operated over a limited range of output current; changes to source geometry are required to change the current range. This would make achievement of the large dynamic current range required in the spallation breeder injector difficult in existing accelerator designs.

4. COMPARISONS OF ONE- AND TWO-STAGE ACCELERATION IN THE INJECTOR

4.1 Introduction

The following sections compare two basic approaches to production of high voltage, high current dc beams - a single-stage acceleration arrangement, and a two-stage arrangement. The HCTF, FINS, LAMPF, LANCELOT and DCX-II accelerators have a single stage, while RTNS-I is a two-stage accelerator.

4.2 Interaction of Ion Source and Accelerating Column

One of the major problems in designing the electrode geometry for a single-stage system is to match the beam extracted from the source to the column, for all ion species. This match can be found for only a small range of output current (for given geometry)[9)], because beam divergence varies as the extracted current varies. When the ion source and main accelerating column are separated, as in a two-stage system, the pre-accelerator column can be designed for optimum extraction; focusing and beam filtering elements can be incorporated in the drift regions; and the main accelerating column can be optimized for accelerating a beam of chosen size, divergence and ion species. This reduces beam spill, electrode heating and electron backstreaming in the column. Also, the well-defined beam emerging from the main column of a two-stage system is easier to transport, because only H^+ ions with low emittance are present in the beam.

In operation, the single-stage injector has only one dynamic focus control parameter available for matching the beam to the column - the extraction (focus) electrode potential. The two-stage system has this plus independent focusing elements located between the two accelerating columns, hence the two-stage system is more versatile. The single-stage system has two mechanical adjustments for changing the beam current and focusing ranges available for the source: plasma aperture diameter and extraction electrode spacing. (Dynamic variation of these parameters does not seem feasible, because the components concerned are in a hostile environment and small misalignments can greatly reduce beam quality.) The two-stage system has these plus: drift distances, bending magnet focusing and magnetic lens positions.

4.3 Beam Filtering

Beam filtering is the removal of undesirable portions of the beam - various ion species, halo, and high emittance components. Molecular ions (H_2^+ and H_3^+) must be removed from the beam before injection into the linear accelerator to prevent radiation production and intense heating in the drift tubes. Furthermore, experience at both CRNL and LAMPF shows that emittance filtering may be required[13,16)

Table II shows the power requirements for 250 and 750 keV beams for the two possible accelerator systems, showing the power losses arising from mass selection (30% of the total beam current consists of unusable molecular ions), and emittance filtering (5% of the H^+ beam must be scraped off). The two-stage system is clearly superior; this approach would reduce the total power required by 50 kW at 250 keV total energy, and 165 kW at 750 keV.

If the beam current cannot be varied sufficiently by ion source control, another technique of current control would be to defocus the beam and dump some of it on a cooled aperture. This would be most easily achieved in a two-stage system - beam filtering and intensity scraping at low potential eases the design and construction of dumps for the undesired portion of the beam. Experience on the HCTF shows the difficulty of scraping and dumping high power dc beams in the confines of a bending magnet. The present HCTF bending magnet beam dumps are now handling 7.5 kW - extrapolation to 12.5 kW seems reasonable but extrapolation to 187.5 kW is not. Furthermore, the design of a pre-accelerator (ion source, 50 kV column, and bending and scraping system) for a two-stage system remains unchanged if the required beam energy from the complete injector is changed.

4.4 Gas Flow, and Electron and X-ray Production

In a single-stage arrangement the entire source gas flow is pumped through at least part of the main accelerating column. The resulting pressure leads to increased electron generation in the column, which contributes to high voltage breakdowns. Also, the backstreaming electrons can

TABLE II

Power Requirements and Losses in Injector Systems

Injector Beam Specification	System Type	Power Supplies Required	Total Power (kW)	Beam Power (kW)	Power Lost in Beam Filtering* (kW)
250 keV, 500 mA	single-stage	250 kV x 750 mA	187.5	125	62.5
	two-stage	50 kV x 750 mA 200 kV x 500 mA	137.5	125	12.5
750 keV, 500 mA	single-stage	750 kV x 750 mA	562.5	375	187.5
	two-stage	50 kV x 750 mA 700 kV x 500 mA	387.5	375	12.5

---

* Rejection of molecular ions and high emittance H^+ beam components.

lead to erosion and melting of ion source components, as has occurred on both the HCTF and FINS. In a two-stage system the number of electrons generated can be reduced by pumping the ion source gas load upstream of the main column, thus allowing a low pressure to be maintained in this column. Electrons backstreaming in the main column can be dumped in a low-Z target just upstream of the main column, preventing ion source damage, reducing X-ray production and X-ray shielding. Electrons backstreaming in the pre-accelerator column are of low energy, hence are less of a problem.

4.5 Emittance

Measurements on the HCTF have shown emittance growth in magnetically bent beams16). Even at low current levels where the ion source emittance is one-fifth that expected at full current, about 10% of the HCTF proton beam is outside the predicted Alvarez accelerator acceptance. The growth appears to be caused by magnetic dispersion of beam components with energy slightly lower than that of the main beam. Possible causes of this momentum spread include high gas pressure in the accelerating column (which degrades beam energy by charge exchange) and beam-plasma instabilities in the space-charge neutralized beam17). (The mixture of high-energy ions and low-energy electrons can be treated as a plasma.) The latter process, which requires a beam particle velocity greater than some characteristic plasma velocity such as the electron thermal velocity, suggests that emittance growth may not occur in low-energy beams. Measurements done at Livermore on a magnetically analyzed 100 mA, 20 kV beam did not indicate any emittance growth18).

In a two-stage system the proton beam is formed, analyzed, focused and scraped of high emittance components at an energy where emittance growth does not seem to occur. This beam can then be accelerated to full energy and injected directly into a linear accelerator. Thus any momentum spread generated in the main accelerating column is not converted into transverse beam growth - it should be noted that a linear accelerator can tolerate momentum spread better than it can tolerate large beam diameter and divergence.

4.6 Dome Layout and Column Geometry

A single-stage system is more compact, thus allowing the use of a smaller high voltage dome, but the more open layout of the two-stage system permits easier servicing. The low-energy drift space in a two-stage system also allows the installation of a pre-buncher, before final dc acceleration, if it proves advantageous. In the two-stage system, the ion source extraction region and the main accelerating column geometries can be independently optimized. Designs of high gradient columns usually require highly re-entrant geometry; design of a single-stage accelerating column is compromised by the size of the ion source.

4.7 Other Considerations

An advantage of the single-stage system is that it does not require the high-power pre-accelerator supply needed on the two-stage system. On the other hand, this supply operates at a low enough voltage that a modulator can be used with it to interrupt the beam if either column is beginning to spark down. When a single-stage system needs servicing, the entire vacuum system must be vented, with an accompanying loss of high voltage and current conditioning 9). The two-stage system allows selective venting of the vacuum system, with a reduction in the amount of reconditioning required.

Ripple and poor regulation of a power supply, or column microdischarges, result in energy modulation of the beam; this is seen as an oscillation in beam position after the beam is magnetically analyzed or bent. If any scraping of beam halo is done after the magnet, the spatial oscillation is converted into a current ripple on the beam. This current ripple would complicate rf control in a heavily beam loaded structure. (For small instabilities in beam energy, this effect could possibly be overcome by use of an achromatic bending magnet system.) It is feasible, with a two-stage system, to do all beam handling at low energy and inject straight into the linear accelerator from the main accelerating column. This means that only the low-voltage ($\lesssim$ 50 kV) pre-accelerator supply need be well regulated.

4.8 Operating Experience

The above discussion favours the two-stage system with low-energy beam filtering. However, the discussion in section 3 shows that the DCX-II and LANCELOT single-stage systems have had good reliability (at voltages and currents substantially less than those required for a spallation breeder). These designs may not be suitable for spallation breeder injection because neither design required an analyzed H^+ beam, and beam quality is unknown. The two CRNL single-stage accelerators have had reliability problems. A two-stage system (RTNS-I) at Livermore has been successful, and the new 150 mA version of this neutron source (RTNS-II) uses the two-stage concept.

It must be resolved whether or not the apparent success of the Livermore system is a result of the choice of a two-stage system or results from some other design choice. Changes made to the HCTF and FINS columns have led to gradual improvement in operation, but no major breakthrough in reliability appears likely. Experiments to incorporate further DCX-II injector design features into FINS are underway.

The spallation breeder injector requirements are much beyond present accelerator performance, so it seems unlikely that any present single-stage designs can be used to produce the 500 mA H^+, 750 keV beam required. (Suitable APF linear accelerator designs for 500 mA beams have not yet been calculated, so a conventional Alvarez linear accelerator is assumed to be necessary.)

5. CONCEPTUAL DESIGN OF A SPALLATION BREEDER INJECTOR

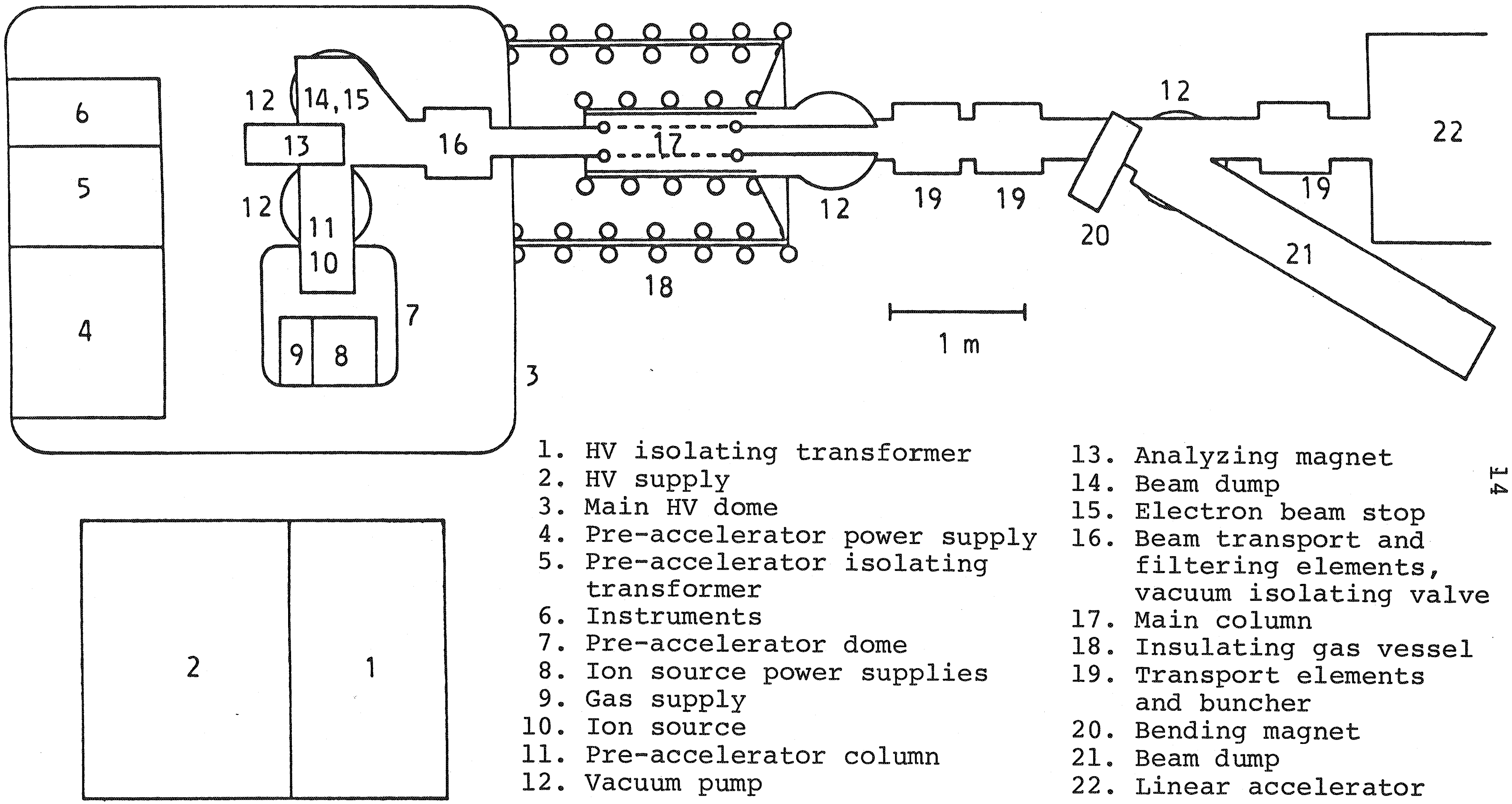
The conceptual design of the injector is shown in plan view in Figure 1. Two-stage acceleration is used.

While details of the ion source, extraction column, and main column will depend on the results of present and future test stand experiments, the features of the injector portrayed in Figure 1 now thought to be important to good reliability are described in Table III.

6. DEVELOPMENT PROGRAM

Development of the injector design shown in Figure 1 will require preliminary studies on an Injector Test Stand. Such a stand would resemble the layout shown in Figure 1, but should be built to maximize flexibility and ease of experimental changes to all components. Tests performed on such a test stand would:

- confirm ion source operation, as developed in the existing ion source test stand.
- study low-energy beam transport and beam filtering.



1. HV isolating transformer
2. HV supply
3. Main HV dome
4. Pre-accelerator power supply
5. Pre-accelerator isolating transformer
6. Instruments
7. Pre-accelerator dome
8. Ion source power supplies
9. Gas supply
10. Ion source
11. Pre-accelerator column
12. Vacuum pump
13. Analyzing magnet
14. Beam dump
15. Electron beam stop
16. Beam transport and filtering elements, vacuum isolating valve
17. Main column
18. Insulating gas vessel
19. Transport elements and buncher
20. Bending magnet
21. Beam dump
22. Linear accelerator

Figure 1. Conceptual layout of a spallation breeder dc injector.

TABLE III

Discussion of Injector Design Features shown in Figure 1

Item No. in Fig. 1	Description	Factors Important in Design
2	HV supply	700 kV, 500 mA, moderate regulation (∿ 0.5%) and low stored energy, controlled to compensate for different settings of pre-accelerator voltage to give fixed total voltage.
3,7	HV domes	both domes air insulated.
4	Pre-accelerator supply	50 kV, 750 mA, good regulation provided by modulator tube, tube used to cut off supply if either column starts to spark.
10	Ion source	duoPIGatron type, multiple aperture.
11	Pre-accelerator column	contains extraction electrode and electron suppression.
12	Vacuum pump	∿ 20,000 ℓ/s total capacity in four pumps with the main column, ion source, and both beam dumps pumped independently.
13	Analyzing magnet	selects and focuses H^+ beam.
14	Beam dump	can handle straight-through beam, or ions rejected by analyzing magnet (H^0, H_2^0, H_2^+, H_3^+, heavy ions from contamination).

TABLE III (cont'd)

Item No. in Fig. 1	Description	Factors Important in Design
15	Electron beam stop	use of a low-Z stop and local shielding reduces the effect of electrons accelerated through the main column.
16	Transport and filtering elements, vacuum isolating valve	scrapes off halo and other high emittance components, focuses H^+ beam, valve to allow selective venting of vacuum system.
17	Main column	low gradient on ceramics (< 1.5 MV/m), moderate accelerating gradient (~ 2.5 MV/m), convoluted ceramic inner surface, ceramic-to-metal joint well shielded, ~ 125 kV per ceramic and electrode, large aperture electrodes, heavy water cooled electrodes to shield the ceramics, small diameter beam line in and out to allow good vacuum when pumped on its own pump, water resistors for ~ 10 mA grading current.
18	Gas vessel	contains gas to insulate exterior of main column, graded independently of the main column.
19	Beam transport	contains buncher.
20	Bending magnet	off in normal operation.
21	Beam dump	contains diagnostic devices for testing injector.
22	Linear accelerator	in-line with main column.

- study column designs.
- test non-destructive beam measurement devices.
- test high power beam dumps.
- compare one- and two-stage accelerator operation.

Information gained from such an Injector Test Stand program could be used to upgrade the existing FINS and HCTF dc accelerators.

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