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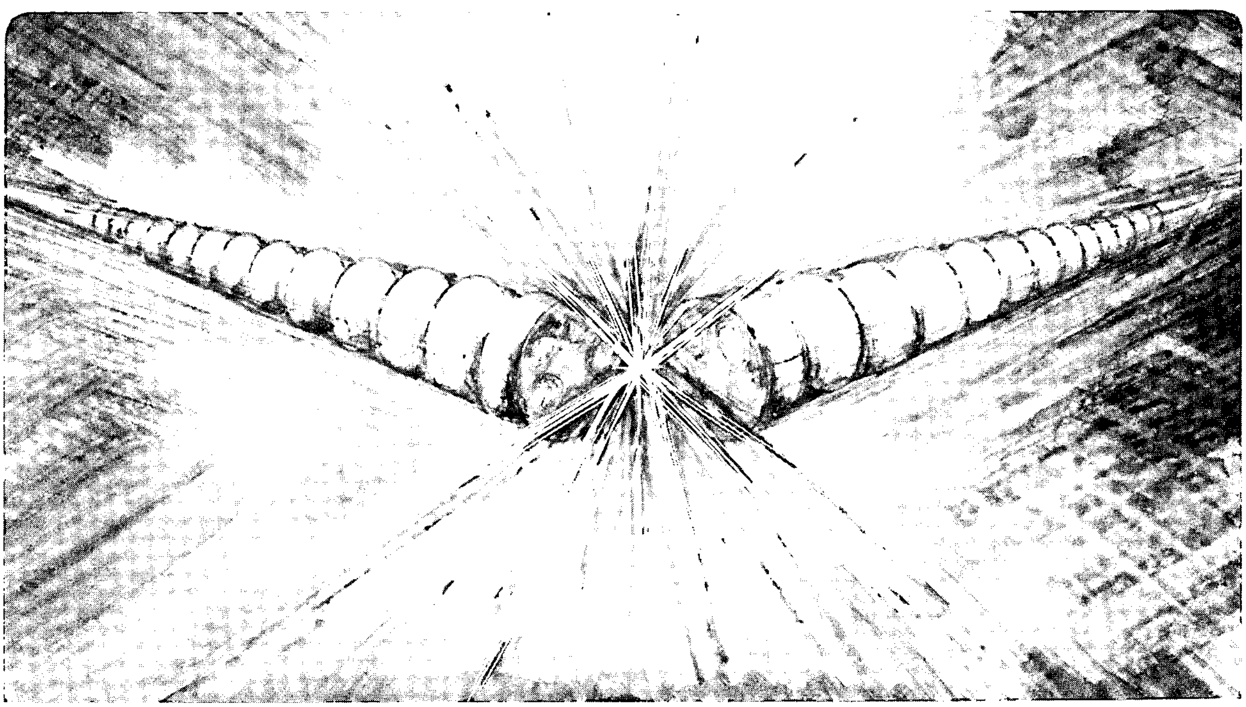

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LBL-27424

THE GIANT ION SOURCES OF NEUTRAL-BEAM INJECTORS FOR FUSION*

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ABSTRACT

All large tokamak fusion experiments today use auxiliary heating by multi-megawatt beams of neutral isotopes of hydrogen injected with energies in the neighborhood of 100 keV per atom. This requires reliable operation of large ion sources, each delivering many tens of amperes of protons or deuterons, and soon even tritons. For meaningful experiments these sources must operate with pulse durations measured in seconds, although the duty factor may still be small. It is remarkable that the successful sources developed in Europe, Japan and the U.S. are all very similar in basic design: the plasma is produced by diffuse low-pressure high-current discharges in magnetic multipole "buckets" with distributed thermionically emitting cathodes.

This paper briefly reviews the principal considerations and the basic physics of these sources, and summarises the collective experience to-date and describes the impressive recent performance of the U.S. Common Long Pulse Source, as a specific example.

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I. INTRODUCTION

Today's large tokamak experiments, JET in Europe, JT-60 in Japan, and TFTR at Princeton as well as DIII-D at General Atomic in La Jolla, use multimegawatt neutral-beam injection of atomic hydrogen or deuterium for auxiliary heating of the magnetically confined plasma. The energies involved amount to tens of megajoules since the pulse lengths used lie typically between one and ten seconds. The particle energies used so far have ranged from 40 to 140 keV per atom. This translates to particle fluxes equivalent to many tens or even hundreds of amperes. Although such injection is always divided up among several beamlines, we still end up needing ion sources that put out tens of amperes of protons or deuterons, and soon probably also tritons. These ions are accelerated to the desired energy and subsequently converted to neutral atoms via electron capture in gas-containing neutralizer channels. Not all ions end up as neutrals, however, because a fraction get stripped again. At a D^+ energy of 120 keV, for example, only 40% neutralization can be expected, the remainder needs to be deflected and dumped. Thus, the sources have to yield 2.5 times the ion flux that is ultimately utilized as injected particles. Furthermore, these ion flows have to meet certain stringent criteria of purity, species mix, thermal energy, and so forth, to be suitable for this application. All this has been discussed before in the literature where neutral-beam injectors are described(1)(2) and is therefore only summarized here briefly, for completeness sake.

This paper is a short review of the topic and a summary of the current status, with emphasis on the remarkable performance of the U.S. Common Long Pulse Sources (CLPS), so called because they were designed to fit--with only minor modifications—the neutral-beam injectors (NBI) of several different thermonuclear experiments in the United States.

II. REQUIREMENTS

To be usable for the purpose described above, the ion sources must satisfy the following criteria:

1. Long-pulse operation. The sources must be capable of running essentially in the steady state. During a pulse that is several seconds long, almost everything comes to an equilibrium, except perhaps the temperatures of certain large and massive components of the vacuum system. All parts with significant dissipation must be actively cooled. This limits the power density deposited on the source surfaces. As a consequence the ion current density produced in these sources is generally restricted to $j_i \leq 0.25$ A/cm^2.

2. Uniform current-density profile. The need for total current yield of tens of amperes combined with the above current density limit calls for very large multiple-aperture ion-acceleration structures (see Table 1). For example, at $j = 0.25$A/cm^2 a total current $I = 75$A requires 300 cm^2 of emitting surface. A multiple-aperture grid that is 60% transmitting must have an area of 500 cm^2. In the interest of good ion optics the ion current density must be the same over this entire area. This is one of the most difficult criteria to meet.

3. Low fluctuation level. Electric discharge plasmas tend to be characterized by noise and fluctuations. The same ion-optics considerations that call for spatial uniformity also place a limit on the acceptable temporal variations of ion flux density. Spatial and temporal variations of $\pm$ 5% are generally considered acceptable.

4. Low ion temperature. Since the beams are ultimately converted into streams of neutral atoms that cannot be refocussed or guided, the beam divergence is a matter of concern. The irreducible lower limit of the beam divergence is determined by the initial ion random energy, which should never exceed a few eV.

5. Ion species mix. Ideally, in most applications, we would like to have sources that produce 100% pure atomic ions. Diatomic and triatomic hydrogen ions break up in the neutralizer to form atoms of 1/2 and 1/3 of the acceleration energy. These are usually unwanted because they do not penetrate far enough into the target plasma. Maximization of the atomic fraction has therefore become an important consideration.

6. Low impurity level. Originally there was considerable concern about high-Z contaminants accompanying the ion beams which would then accumulate and degrade the fusion plasma. However, this has not been a major problem so far, perhaps because long-pulse operation with large gas thru-puts tends to reduce the impurity level simply by dilution. Furthermore, tokamak plasmas have been found to be flooded by contaminants from many other sources anyway.

7. Efficiency. Electrical efficiency is generally not an important issue since the total power is dominated by the high energy imparted to the accelerated ions. However, gas efficiency, often called gas-utilization, is crucial since the pumping requirements for steady state operation at the hundred ampere level are formidable. In addition, high gas density in the accelerating region leads to undesirable or even intolerable scattering which degrades the beam quality and which may even result in unmanageable power deposition on parts of the beam-forming structure. On the other hand, since the residual gas in this application is used as charge exchange

medium in the neutralizing channel, there is a practical upper limit to the gas utilization here, in the neighborhood of 30%.

8. Reliability. Electric discharges in gases tend to be temperamental and hard to control because there often exist several modes in which they can operate and they flip from one to another in an unpredictable manner. Nonsteady behavior is the rule rather than the exception. To be useful as ion sources for neutral beam injectors reliable and predictable performance are absolutely essential. More than that: the operation of these plasma generators should not only be stable but relatively insensitive to variations in gas flow, driving voltage and cathode power input, so that they are "forgiving" and easy to handle.

9. Ruggedness and durability. Finally, the design must be moderately simple, and the components must be sufficiently rugged, so that dependable and acceptable performance can be expected for thousands of "shots". Some upkeep or servicing may be required (such as replacement of filaments), but this should be a fairly easy and routine procedure rather than a delicate and sophisticated matter. High-precision alignments and other expertise only available in the developer's or manufacturer's shop should not be needed for routine maintenance. In short, in order to be practical, the sources should be robust and dependable tools, available for use by the fusion physicists for their experiment, rather than major components of the investigation requiring as much attention as the confinement study itself.

The sum total of the above requirements seems forbidding. It is to the credit of the neutral-beam development teams and the manufacturers that the mission seems to be essentially accomplished. The remainder of this paper describes and discusses the salient features and summarizes the current status.

III. LARGE AREA SOURCES

Large area multiple aperture ion sources were first successfully developed in connection with space exploration as so-called ion-motors or ion-thrusters.[3][4] The specifications required for the fusion application listed in the preceding section are considerably harder to meet, however. In particular, the needed currents and current densities, and above all, the beam quality and ion optics are much more demanding. As implied in item 2 above, the ion current density in an optimized space charge flow is uniquely determined by the accelerating voltage and the physical dimensions of the accelerating structure, the Child-Langmuir relation.[5] Thus a large area array of identical apertures, all having the same beam-forming conditions, i.e., the same accelerating voltage and the same spacings, etc., gives good ion optics only if the current density is the same in each of the apertures. This is not compatible with the usual density profile in plasma that tends to peak in the center and invariably decreases with decreasing distance from the side walls. Good beam quality thus required either modifying the accelerating structure, making it a function of position to match the predicted nonuniform ion current density (this is not really practical) or developing ion sources with uniform current-density profile.

An early successful although electrically not very efficient version with a flat profile was the so-called "field-free" 10 ampere ion source[6][7] developed at LBL for the magnetic mirror program at Livermore. It was based on a simple idea that may be termed "brute force": the specified extended ion extraction region was surrounded by as many emitting cathode filaments as needed and the entire pill-box shaped volume was flooded uniformly with primary ionizing electrons. The copper chamber walls were kept electrically floating so that the primary electrons were reflected a few times by the wall sheath. The anode was limited to a relatively narrow ring. In a low-pressure gas ($p \leq 10$ mTorr) with long mean-free-paths this produces a stable uniform quiescent plasma of almost arbitrary size. Here it was about 14 cm in diameter (see Fig. 1). But it required 1000 A of arc current to yield a deuterium ion current density of 0.5 A/cm^2. At this power the pulse length was limited to 30 ms. However, the main shortcoming of this system was the species composition, in which the atomic component was at most 75% at the highest power densities, and dropped to 60% when the current density was lowered to 0.25 A/cm^2.

The arrangement may be described as a pulsed diffuse low-pressure high-current hot-cathode discharge in which the primary electrons are supplied by a distributed set of tungsten filaments and fill the entire chamber essentially uniformly. It is this large diffusivity of the primaries that assures the uniformity of the plasma density, because the power input into the discharge proceeds via these primaries, and much if not all of the ionization taking place in the gas is caused by the energetic primaries. The word "arc" frequently used for these discharges is therefore not really appropriate. It has become popular, however, because the currents are large (many hundreds of amperes, at least) and the cathodes are hot.

Care has to be taken that the magnetic fields from the filaments and from the discharge current itself do not interfere with the uniformity of the plasma density profile. Strictly speaking, the term "field-free" sources is probably a euphemism. It is instead, essential to provide for rigorously controlled symmetry in the discharge arrangement lest the unavoidable self-fields ruin the uniformity of the density profile.

It is also important that the anode area is as small as possible but large enough so that the random electron current available from the adjacent plasma exceeds the total discharge current. In other words, the plasma potential near the anode should be <u>positive</u> with respect to the anode, or at the very least equal to the anode potential. The reverse situation, when the plasma potential is lower than that of the anode, tends to lead to fluctuations and noise, both in current and voltage. The cathodes, on the other hand, can be operated in either the space-charge limited mode or in the emission limited mode, depending on cathode temperature. In the latter case the discharge voltage can be raised, which may be desirable, possibly leading to more favorable ionization conditions. Care has to be taken, however, that the formation of high-emission arc spots is avoided. This would not only lead to violation of item 8 of the requirements listed in Section II, but it could lead to permanent damage of the affected cathode.

IV. MULTIPLE APERTURE ACCELERATORS

The ion-beam forming systems for the fusion application have to be much more carefully designed than those for space propulsion because excellent ion optics is crucial for this application. In most versions a large number of identical parallel beamlets are accelerated by grids with precision-machined and carefully aligned circular holes. The Japanese JAERI design, for example, has no less than 1020 holes of 0.4 cm diameter in a 12 cm x 27 cm rectangular grid structure.[8] These grids need to be water cooled to prevent heating and warping in long-pulse or steady state operation. The first grid (sometimes called "plasma grid") is vulnerable because it is exposed to the source plasma and full radiation from the cathode filaments. The other grids, on the other hand, invariably intercept a small fraction of energetic particles due to ion-optical aberrations as well as to some unavoidable collisions with the residual gas. In any case, the required cooling channels tend to limit the transparency of these beam-forming structures to about 40%.

A higher transparency, about 60%, is achieved in the slot design favored by the Lawrence Berkeley Laboratory group (see Fig. 2). Very effective cooling is achieved by passing water through the hollow grid rails. The large number of parallel slots present a good match to the rectangular shaped ion sources and to the elongated ion-beam cross section needed for injection through rectangular access ports between neighboring coils of the tokamaks.

It should be noticed that the words "ion extraction" are not used here since this terminology is misplaced. Positive ions are generally "emitted" by plasmas, literally expelled by the positive plasma potential. They need not be "extracted" but only accelerated.

V. MAGNETIC MULTIPOLES

The introduction and judicious use of small-sized strong permanent magnets permits considerable improvements in the performance of these sources. In particular, the loss rate for the energetic primary electrons on the chamber walls can be drastically reduced by lining the walls with rows of magnets arranged to produce high-order multipolar fields, as illustrated in Fig. 3. The effective collection area for electrons can in fact be made small enough in this manner to permit the entire wall to be kept at anode potential. Small spacing between adjacent magnets ensures that the boundary layer where the fields are strong is narrow and most of the interior volume contains only very weak magnetic fields, justifying the frequently used term "multicusp" bucket. This configuration is thus similar to the field-free sources described above, except that the wall losses are reduced and the electrical efficiency can be expected to be noticeably higher.

Two beneficial effects are immediately obvious: Higher efficiency means lower discharge current, which in turn means lower troublesome self-fields, i.e., better control over the uniformity of the ion-current-density profile, and less sensitivity to disturbing external fields. Better primary-electron confinement also implies more freedom in placing the emitting cathode filaments. This latter feature turns out to be important not only for the uniformity of the density profile but also for the species control, i.e., for maximizing the monatomic ion component. It is found quite generally and not unexpectedly that the percentage of monatomic ions increases with increasing power density of the discharge, as well as with increasing volume to surface ratio. Good confinement of primary electrons makes it easier to increase the power density and thereby the level of dissociation of the gas.(9)(10) The maximum atomic-ion fraction reached in this manner, when the ion current density is around $0.25 A/cm^2$, approaches 80% in these rectangular chambers. [In buckets with larger volume-to-surface ratios higher proton ratios can be achieved.[11]]

VI. MAGNETIC FILTERS

It is readily understood why an ordinary magnetic bucket hydrogen ion source must be expected to emit a certain fraction of H_2^+ (or D_2^+). All ions and most atoms recombine to form molecules when they strike the chamber walls, and particularly the cooled grids of the accelerator. A fraction of these backscattered molecules become ionized not far from the plasma grid where the gradient in the ambipolar potential drives them necessarily towards the grid structure. This process is responsible for an irreducible flux of molecular ions from the source regardless of the size and power density of the discharge, as long as ionizing electrons are present in the vicinity of the grids. However, if we arrange the magnetic fields in the source in such a manner, that the primary electrons (and heated bulk electrons) are prevented from reaching this region, so that only "cold" electrons are there and no fresh ions are formed, this contribution to the H_2^+ (D_2^+) ions from the source is suppressed. This is the basis of the concept that has become known as the "magnetic filter" effect.[12] It has been very effective, and atomic ion fractions in excess of 80% are routinely achieved in this way (see Table I).

Direct internal magnetic filters are usually produced by mounting small permanent magnets in water-cooled tubes inside the source chamber, effectively dividing the discharge into two regions: the hot region, where the ionization takes place, and the cold, or drift region, where only secondary reactions can occur. Such configurations have become popular for negative hydrogen ion sources,[13] and may be called tandem discharges.

Both the surrounding multipoles and the magnetic filters can take on a variety of shapes and configurations. In the U.S. most multipoles are aligned parallel to the ion beam direction, i.e. normal to the plane of the acceleration grids. In Japan, and certainly at JAERI, the orthogonal orientation is chosen, i.e., the multipoles are arranged in hoops that are parallel to the beam forming planes. In this way the interior fields tend to be higher, but the symmetry of the arrangement is simpler. Above all, however, the magnetic filter action discussed above occurs naturally, as demonstrated by a computer analysis of electron orbits.(14) In the U.S. Common Long Pulse Source (CLPS) the magnetic filter field must be superimposed to help the species mix.(15)

The European source has thin multipoles arranged in a so-called "checker board" fashion, i.e., neither axial nor azimuthal, but mixed.(10) In this way the best uniformity was achieved in the PINI source. The superimposed filter in this case is produced by a special "magnetic tent" arrangement, where a complete hoop of north poles is mounted near the accelerator end and the corresponding south poles all lie along a line in the center of the back plate.(10) All these systems work roughly equally well, as may be inferred from Table I.

VII. THE U.S. COMMON LONG PULSE SOURCE

Based on the successful demonstration of 30s long pulse operation of the large bucket plasma generator (LPS) and the matching 10 cm x 40 cm water-cooled Long-Pulse-Accelerator (LPA) the LBL design was chosen as the basis for the U.S. Common Long-Pulse Source (CLPS). The CLPS derives its name from the fact that a common design would fit with only minor modifications the neutral beam injector systems of three different large U.S. fusion experiments: the TFTR at Princeton, the DIII-D at La Jolla, and the MFTF at Livermore. The pulse length of 30s was required for the MFTF, the large tandem mirror facility, but this was abandoned before the injectors were constructed. The specifications for the other two systems are shown in Table I.

The CLPS was designed at LBL with input from the users, and RCA won the bidding for the manufacturing contract. The details are described in proceedings of several conferences,[16][17][18] and the performance tests have recently been published in the *Review of Scientific Instruments*.[19] A summary is presented here supplemented by a report on the operating experience at Princeton.

Figure 4 shows the narrow cross section of the CLPS , complete with corona shield and accelerating structure. The bar magnets on the sides that provide the multicusps are clearly visible. Not so obvious are end magnets which produce superimposed longitudinal magnetic fields linking the end plate with the rim near the accelerator plane somewhat like the "tent" filter in the PINI sources for JET. This externally generated magnetic filter is needed if an atomic ion fraction higher than 80% is desired. The resulting atomic-ion fractions H^+ and D^+ as a function of the power in the discharge are plotted in Fig. 5, as observed during testing of the 10 x 40 cm^2 LBL "prototype".[15]

A total of 22 production units of the CLPS were built by RCA, 13 for Princeton and 9 for General Atomic. The accelerators for the two users differ only in their source grid mask, alignment shims and replaceable waterlines The plasma generators are identical. At the TFTR a very substantial performance record has been accumulating during the last four years, culminating in a 20-week run from May to October 1988. After the initial learning period the sources turned out to be remarkably dependable and relatively easy to operate. For example, once conditioned, they need very little reconditioning after an interruption of the run. In general, other components of the system, such as power supplies, control units, or diagnostic equipment need at least as much attention as the ion sources.

Table II and Figure 6 show a summary of the performance statistics of the neutral-beam-heating system of TFTR as reported by M. Williams.[20] The "shot performance" here is defined as the normalized average "source performance factor"

$$P_{shot} \equiv \sum_{s} P_s \Big/ N$$

where N is the number of ion sources requested for a particular shot, and $\sum_s P_s$ denotes the ion source performance factors summed over all N sources, with

$$P_s \equiv \left(V_s / V_r\right) \cdot \left(\tau_s / \tau_r\right)$$

Here, V_s is the ion source voltage actually used, and V_r is the operations-imposed voltage limit, while τ_r is the requested pulse length, and τ_s is the actual on-time, i.e., the pulse duration minus the interrupts. These factors thus include the functioning of all components: the power supplies, the controls, the diagnostics and the sources themselves.

The neutral-beam system "availability" is defined as

$$P_{syst} \equiv \sum_{s=1}^{12} P_s \Big/ 12$$

where the summation is over all twelve existing sources, and inoperable sources (i.e., those out of commission) are assessed at $P_s = 0$, while operable sources not requested for a particular shot are entered with their most recent value of P_s. The demonstrated NB system availability is high enough not to be limiting the tokamak experimental schedule. This is important for the planned future D-T phase, where the use of tritium and the increased neutron activation make remote handling mandatory.

A similar positive experience is reported by the researchers at General Atomic's DIII-D experiment. They are in the process of increasing the acceleration voltage above the initially specified 80 kV. The lower atomic ion yield in this instance (see Table I), is intentional for their own operational reasons. It should be noted also that DIII-D has concentrated more on the use of H^+ rather than D^+.

VIII. CONCLUSION

The large high-quality hydrogen-ion sources that have been developed in Europe, Japan and in the United States for the neutral-beam injectors for the large tokamaks have much in common. Their operation is based on the same principles, they have similar dimensions, and their performance is quite comparable. It should also be pointed out that at present they are key components in the operation of these experiments.

The American embodiment, the so-called CLPS, has been produced by an industrial manufacturer (RCA) based on a design developed at the Lawrence Berkeley Laboratory, following extensive testing of a prototype designed and constructed at LBL. The process represents a highly successful example of technology transfer from a National Laboratory to the private sector. The performance of the CLPS on the two large tokamaks in the U.S., the TFTR at Princeton's Plasma Physics Laboratory and the DIII-D tokamak at General Atomic in La Jolla, California, has been impressive. At this point, these ion sources have been accepted as usable experimental tools that are no longer in the developmental or trial stage, but that can be depended upon, almost as we are accustomed to from reputable commercial products.

TABLE I

Large Ion Sources for Fusion

Tokamak	JET	JT-60	TFTR	DIII-D
Ion Source	PINI	JAERI Source	CLPS	CLPS
Pulse length (sec)	$\leq 10^{*}$	≤ 10	$\leq 2^{**}$	$\leq 5^{**}$
Current (A)	$\leq 60\ H^+$ $\leq 30\ D^+$	$\leq 35\ H^+$	$\leq 74\ D^+$	$\leq 83\ H^+$ $\leq 68\ D^+$
Current density (A/cm^2)	$\leq 0.20\ H^+$	$\leq 0.28\ H^+$	$\leq 0.23\ D^+$	$\leq 0.23\ H^+$
Accel. Size (cm x cm)	16 x 45	12 x 27	12 x 43	12 x 48
Transparency (%)	40	40	60	60
Apertures (type & number)	262 holes	1020 holes	45 slots	55 slots
Aperture size	1.2 cm diam.	0.4 cm diam.	$0.6 \times 12\ cm^2$	$0.6 \times 12\ cm^2$
Bucket type	checkerboard	azim. line cusps	axial line cusps	axial line cusps
Atomic ion fraction	≤ 87%	≤ 91%	≤ 85%	≤ 74%

* Limit of system; source has been desinged and tested at 15s pulse length

** Limit of system; source has been designed for and tested at 30s pulse length

TABLE II

TFTR

NEUTRAL BEAM HEATING SYSTEM*

PERFORMANCE SUMMARY[20]

05/88 - 10/88

Total Number of Injection Shots	1363
Number of Shots > 20 MW	504
Number of Shots > 25 MW	157
Number of Shots > 30 MW	17
Overall Shot Performance	90%
Overall System Availability	83%

* 4 beamlines were used with a total of up to 12 sources.

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FIGURE CAPTIONS

Figure 1. Field-Free "10-Amp" ion source.

a) Front view, accelerator grids removed.

b) Current-density profiles for H^+ and D^+.

Figure 2. 10x40 cm^2 Long-Pulse Accelerator showing multiple slot, rail type plasma grid facing upward.

Figure 3. Magnetic multipole arrangement with magnetic-field plot in one quadrant of CLPS.

Figure 4. U.S. Common Long Pulse Source, cross section of short side, including accelerator assembly.

Figure 5. CLPS 10x40 prototype H^+ and D^+ fractions as function of arc power.

Figure 6. Neutral beam injection performance in TFTR in 1988.[20]

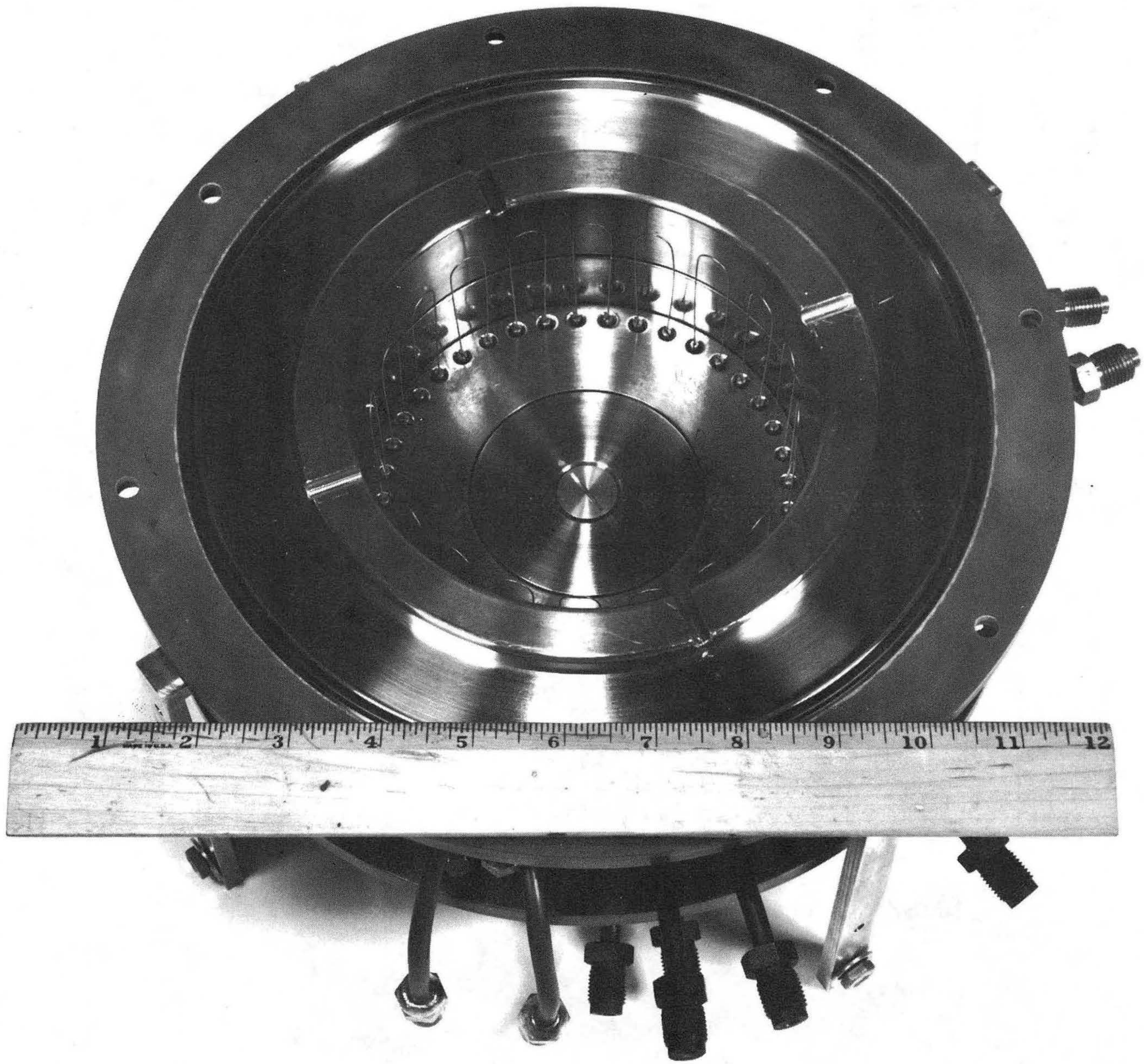

Fig 1a

CBB 727-3593

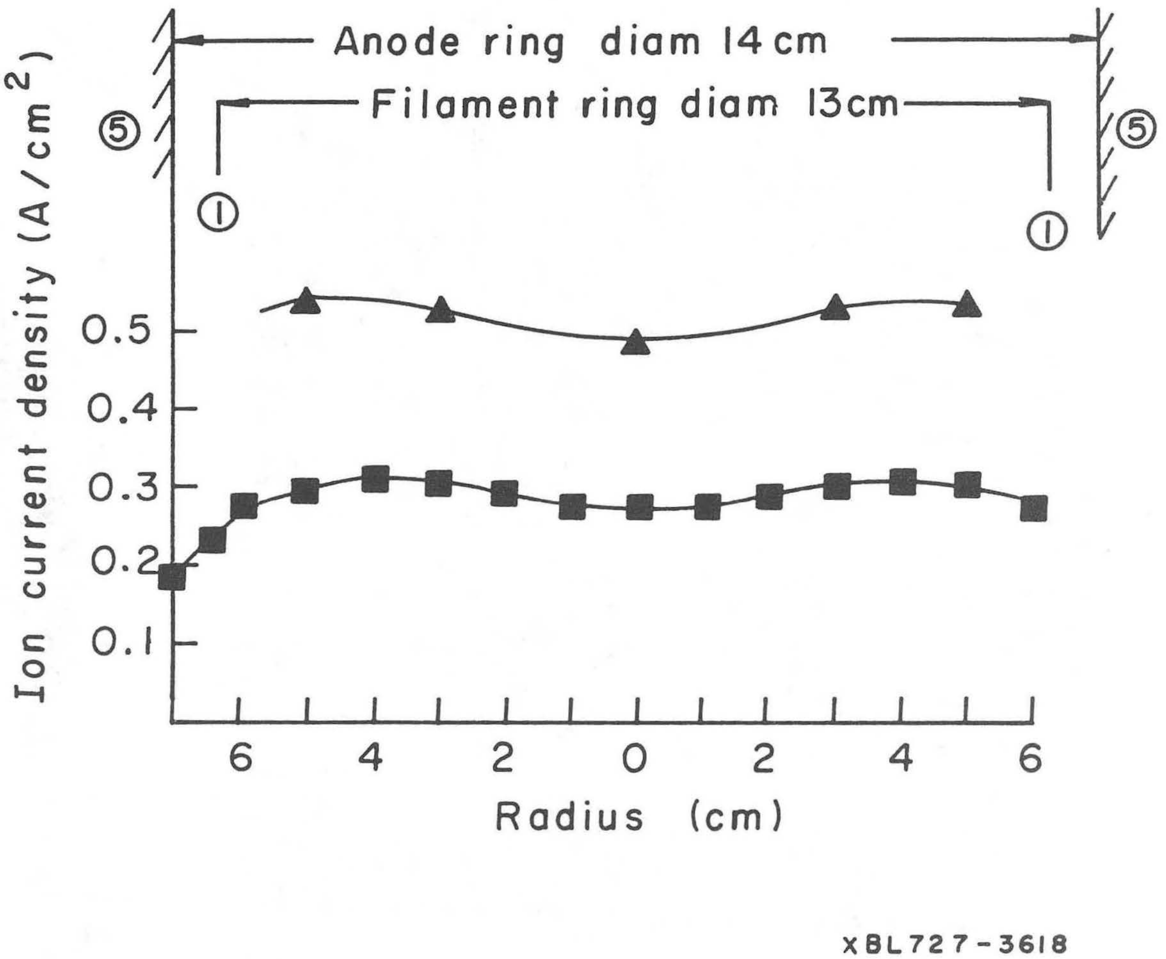
Anode ring diam 14 cm
Filament ring diam 13cm
⑤
⑤
①
①
Ion current density (A/cm^2)
0.5
0.4
0.3
0.2
0.1
6
4
2
0
2
4
6
Radius (cm)
XBL727-3618

Figure 1b

CBB 810-10862

Fig. 2

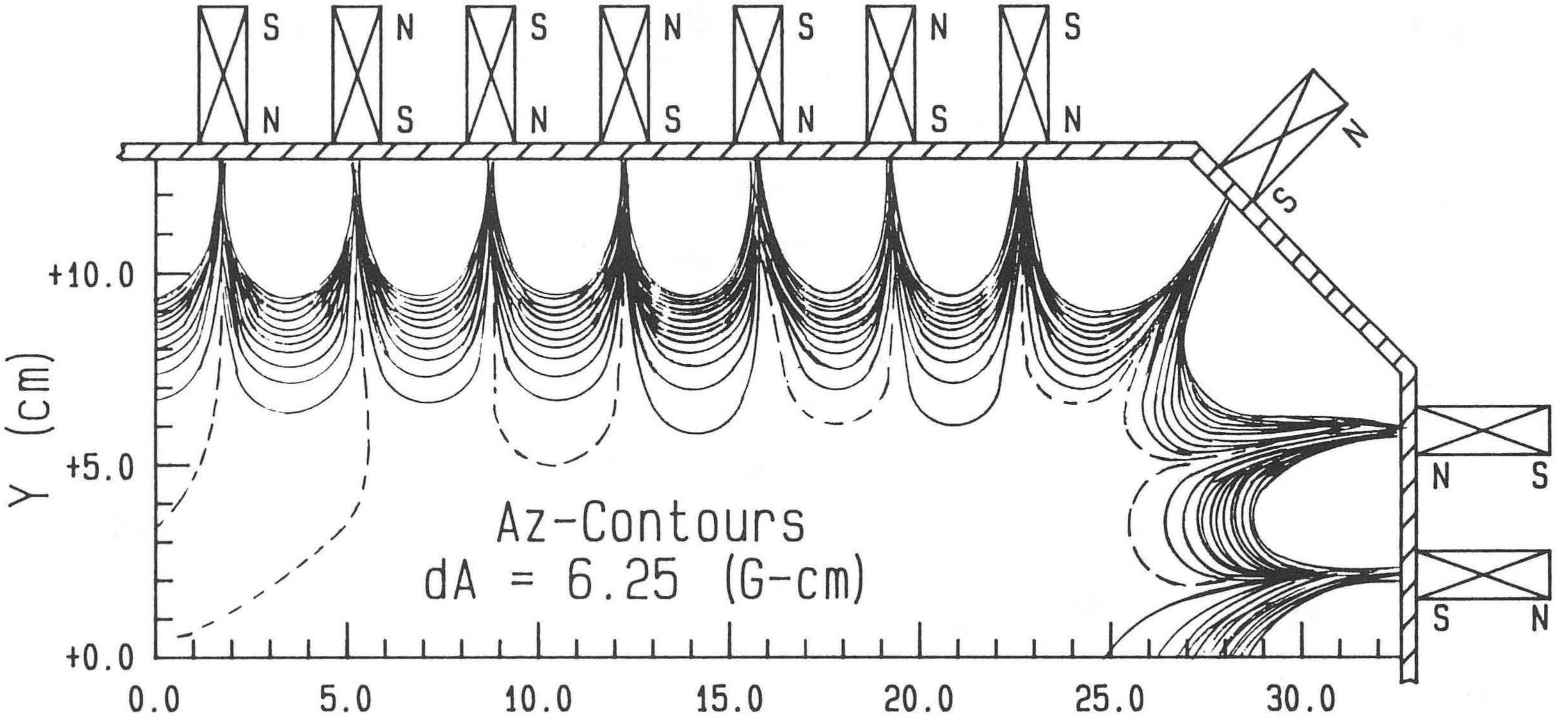

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Figure 3

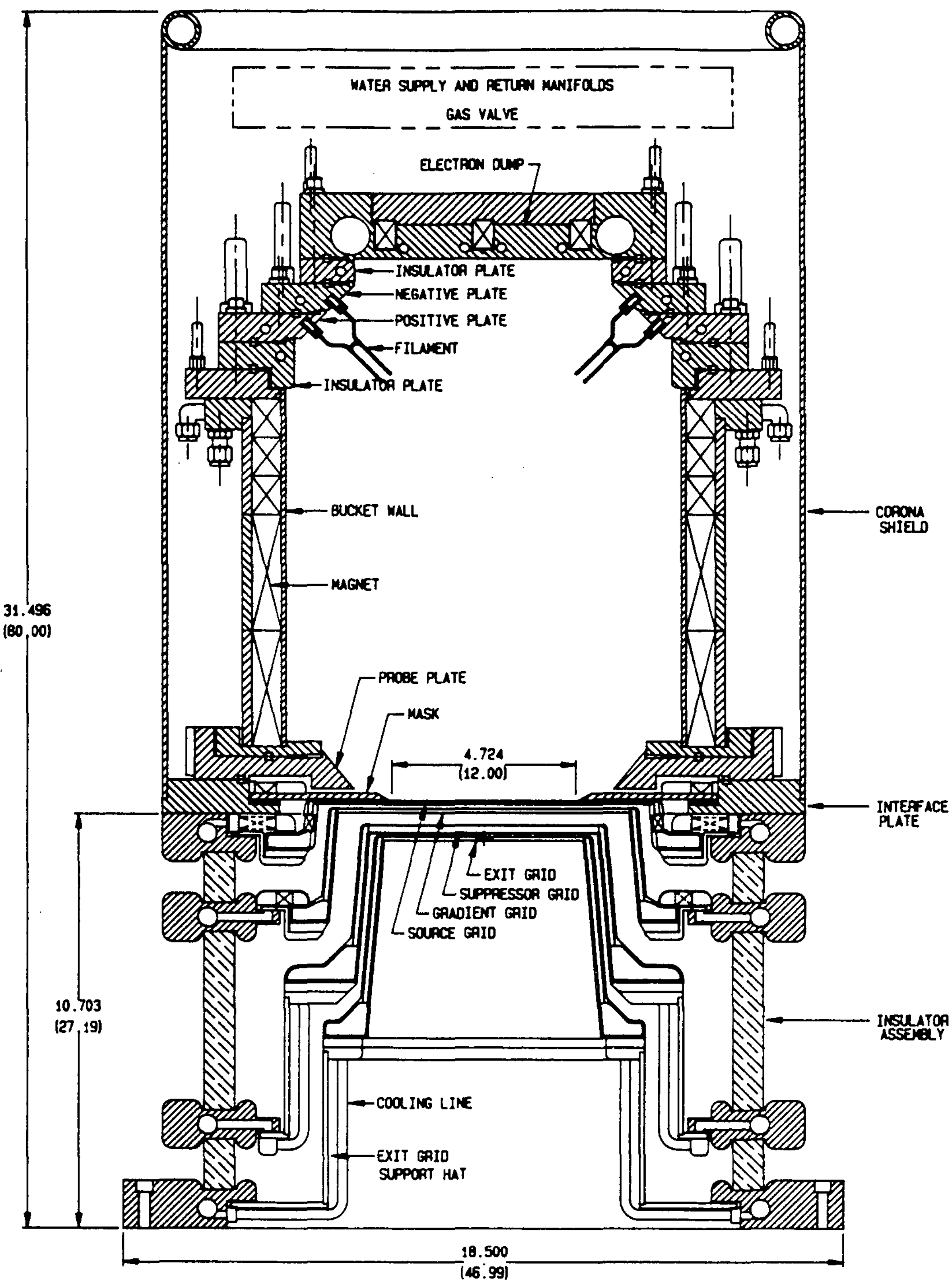

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Figure 4

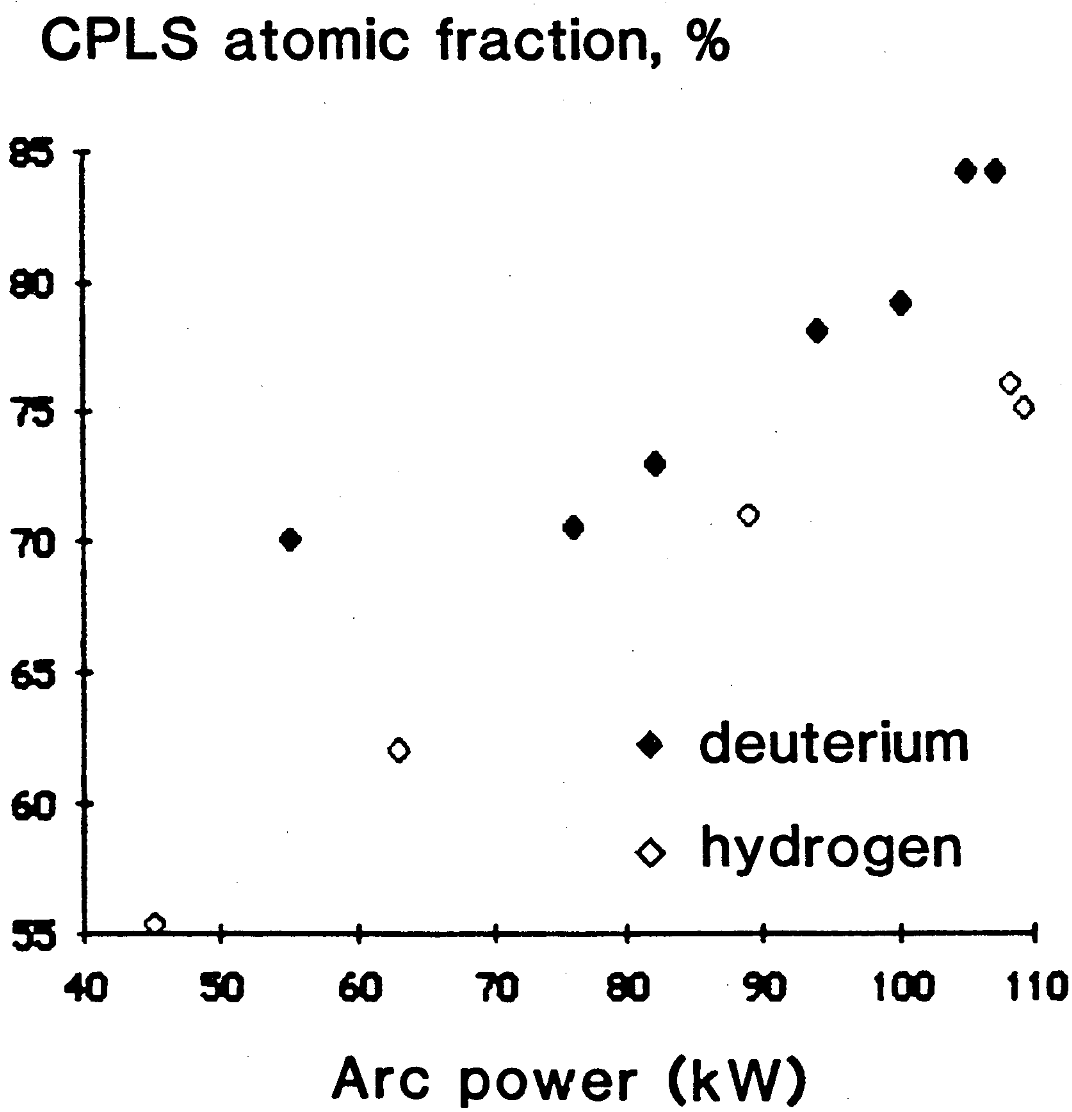

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Figure 5

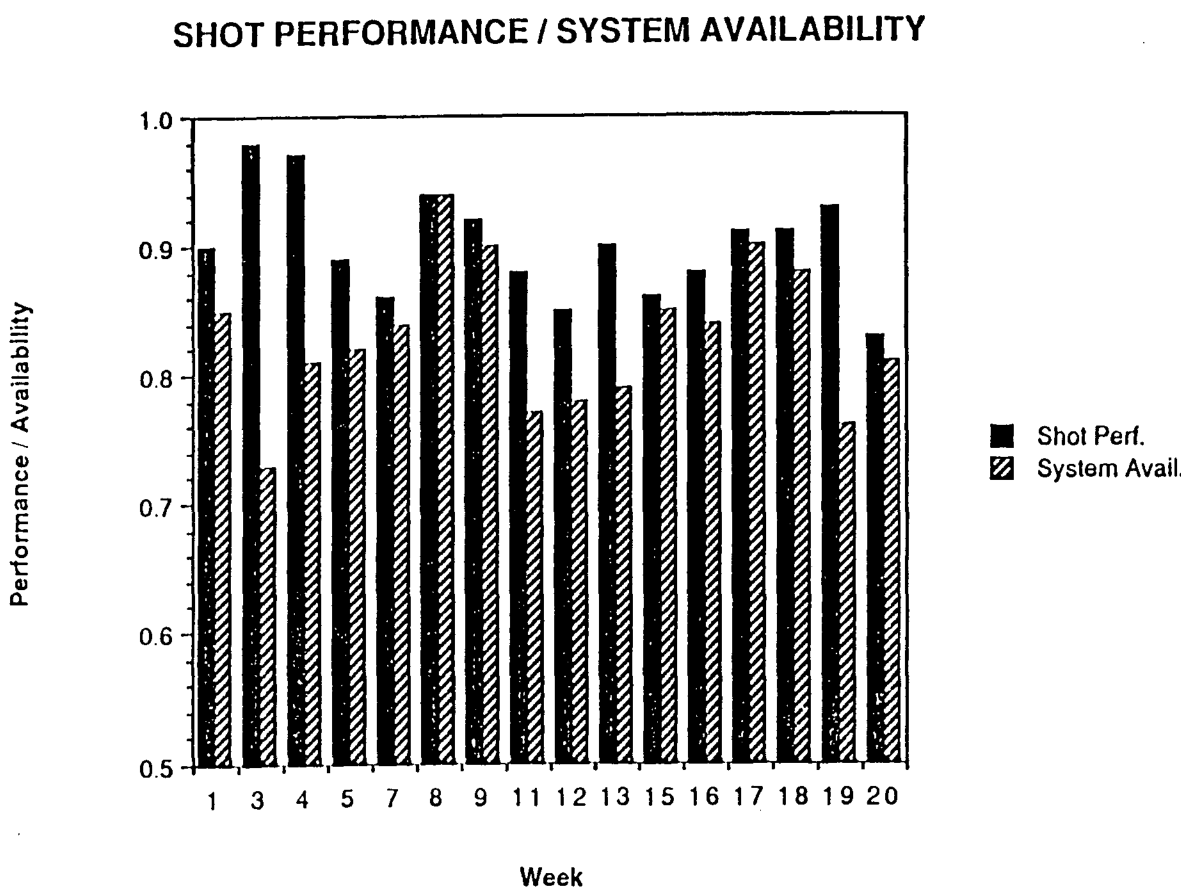
SHOT PERFORMANCE / SYSTEM AVAILABILITY
Performance / Availability
1.0
0.9
0.8
0.7
0.6
0.5
1 3 4 5 7 8 9 11 12 13 15 16 17 18 19 20
Week
Shot Perf.
System Avail.

Figure 6

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BERKELEY, CALIFORNIA 94720