**Title**
HIGHLIGHTS OF THE ZEPHYR NEUTRAL BEAM INJECTION SYSTEM CONCEPTUAL DESIGN

**Author**
Cooper, W.S.

**Publication Date**
1981-10-01

LBL-13432

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

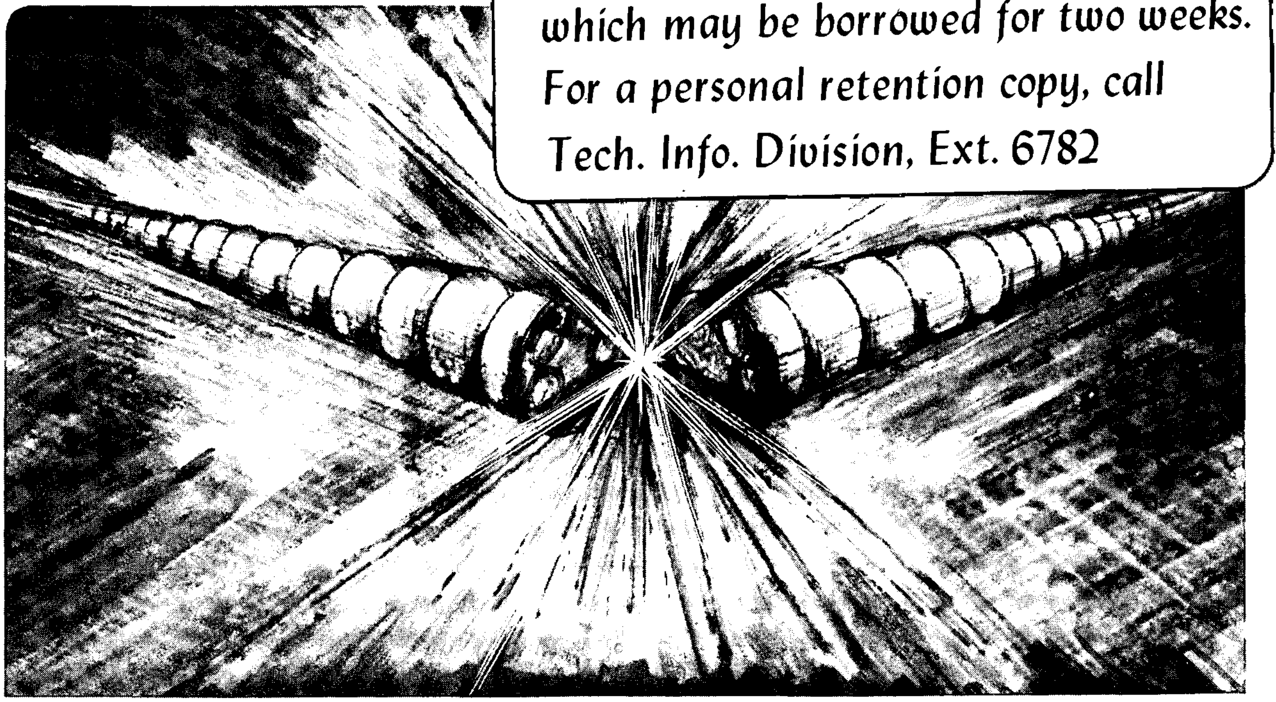
# Accelerator & Fusion Research Division

Presented at the Ninth Symposium on Engineering
Problems of Fusion Research, Chicago, IL,
October 26-29, 1981

# HIGHLIGHTS OF THE ZEPHYR NEUTRAL BEAM INJECTION SYSTEM CONCEPTUAL DESIGN

W.S. Cooper, O.A. Anderson, V.P. Elischer,
D.A. Goldberg, D.B. Hopkins, V.L. Jacobson,
K.H. Lou, and J.T. Tanabe

October 1981



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

LBL-13432

# HIGHLIGHTS OF THE ZEPHYR NEUTRAL BEAM INJECTION SYSTEM CONCEPTUAL DESIGN*

W. S. Cooper, O. A. Anderson, V. P. Elischer, D. A. Goldberg, D. B. Hopkins
V. L. Jacobson, K. H. Lou, J. T. Tanabe

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

## Summary

In June, 1980, the Lawrence Berkeley Laboratory (LBL) began a conceptual design study for a 160 keV, remotely maintainable neutral beam injection system (NBIS) for the ZEPHYR ignition tokamak proposed by the Max-Planck-Institut für Plasmaphysik (IPP). The ZEPHYR project was cancelled, and the LBL design effort concluded prematurely in January, 1981. This report describes the conceptual design as it existed at that time, and gives brief consideration to a schedule, but does not deal with costs. A more detailed description of this work is provided by Ref. 1.

## Introduction

In January 1979, IPP proposed a major new tokamak ignition experiment called ZEPHYR.[2] U.S. involvement was solicited by IPP in design of the NBIS, which was chosen by IPP as the primary heating mechanism. The ZEPHYR neutral injection requirements were:

| | |
|---|---|
| Beam Energy | 160 keV |
| Gas | $D_2$ |
| Pulse Length | 1.5 sec |
| Neutral Power into Plasma | 15 MW of 160 keV $D^0$<br>25 MW of all energies |

A summary of some of the most important ZEPHYR NBIS requirements is given in Table 1. In most cases these requirements significantly exceeded existing capabilities (as typified, for example, by the TFTR injection system).

Table 1: ZEPHYR Neutral Beam System Requirements

| | |
|---|---|
| Number of beam lines | $\leq 6$ |
| Reliability | $\geq 75\%$ of shots to give $\geq 25$MW to plasma |
| Duty Factor | $\geq 1.25\%$ |
| Availability | $\geq 80\%$ |
| Maintenance | By remote means |
| Minimum maintenance interval | $10^3$ plasma shots |
| Lifetime | $>2\times10^5$ beam pulses for all components except source filaments |
| Principal power source | Motor-generator set |
| Radiation exposure | $10^9$ rads (neutron and gamma) |
| Tritium purging | Beam line bakeable to 150°C |
| Modularity | All critical components separately and independently replaceable |
| Beam line materials | Chosen for low activation |

## Design Approach

We decided that, given an extremely aggressive ZEPHYR start-up schedule, the ZEPHYR injection requirements could best be met by an upgraded and improved version of the TFTR beam line, coupled with a new and very simple power supply design tailored to the ZEPHYR motor-generator set (a ZEPHYR requirement). The Neutral Beam System Test Facility (NBSTF) at LBL, which is the prototype TFTR beam line, has been operating since June, 1979. We would therefore be able to examine actual construction costs and operating experience for a very similar system. These thoughts led to the following guidelines for the technical design of the ZEPHYR NBIS:

1. The design would be based on the TFTR design, simplified, reduced in costs, and improved wherever possible.
2. Existing industrial components would be used wherever possible.
3. The design should require minimum extrapolation from existing technology.

Early in the project, we generated a list of all important specifications that could influence the initial mechanical and electrical conceptual designs. The principal ones among these are shown in Table 2. The data were derived from calculations and from reasonable extrapolations of TFTR (NBSTF) and Doublet-III beam line experience, and, of course, from ZEPHYR requirements. The data were sufficient

Table 2: ZEPHYR Beam Line Working Specifications

| | |
|---|---|
| Beam cross-section at source | 10x40 cm |
| Orientation (40-cm dimension) | Vertical |
| Number of sources per beam line | 3 |
| Angle between beams | 5.20° |
| Current per source ($D_2$ operation) | 50 A |
| Energy | 160 keV |
| Pulse length | 1.5 sec |
| Composition | |
| Percent $D^+$ | 80% |
| Percent $D_2^+$ | 15% |
| Percent $D_3^+$ | 5% |
| Beam divergences | |
| 1/e Angular half-width perpendicular to rails | 0.8° min<br>1.6° max |
| 1/e Angular half-width parallel to rails | 0.25° min<br>0.50° max |
| Minimum center-to-center source spacing | 88 cm |
| Minimum $D_2$ gas flow | 8 Torr-l/sec |
| Total length of neutralizer | 2.5 m |
| Typical beam powers (after traversing neutralizer, $\Pi = 1.2\times10^{16}$ cm$^{-2}$) | |
| Positive ion power | 5320 kW |
| Negative ion power | 25 kW |
| Neutral power | 2655 kW |
| Total beam power | 8000 kW |

---

*This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division, of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

to permit examination of beam layouts, power densities on dumps and scrapers, pumping requirements, vacuum tank dimensions, and power supplies.

Two "environmental" factors also had a major impact on the design. The first of these was the stray magnetic field of the tokamak. Preliminary calculations showed that the stray field was strong enough to have a marked influence on the ion trajectories at the downstream end of the beam line. These fields would vary with time in a manner that was not accurately calculable, and it would have been extremely difficult to shield against them. Hence we opted for a sweep magnet of the reflection type to remove unneutralized ions from the beam since for such a design the ion trajectories are farther removed from the region of high magnetic field. (Because of the tight time schedule, we decided against trying to develop a "direct recovery" scheme for disposing of the remaining ion power.) The second "environmental" consideration was radiation, which led to the requirements, shown in Table 1, on tritium purging, modularity, remote handling, and beam line materials.

## Summary of the Conceptual Design

At the end of the design effort we had examined all major sub-systems and had found conceptual designs for all of them that satisfied both our internal guidelines and the ZEPHYR requirements. It appeared that no unreasonable extrapolation would be required from existing experience and technology except in the areas of remote maintenance and reliability.

Plan and elevation views of the proposed beam line design are shown in Figs. 1 and 2 respectively, the former view also showing the positioning of the beam line relative to the tokamak. Each beam line consists of three independently operated beam channels. The usual neutral beam line components - ion source, neutralizer, ion removal system, and neutral beam dump - are clearly seen in Fig. 2. The source is of the so-called "magnetic bucket" type and is coupled to a conventional electrostatic accelerator similar to that used on the TFTR beam lines. The large structure directly below the source is a "core snubber" whose function is to protect the accelerator in the event of sparkdown.

The overall beam line is 10.96 m from the exit grid to the center of the plasma; an additional 2.05 m is required for the $SF_6$ housing enclosing the source and core snubber. The estimated weight of the beam line (exclusive of its support carriage) is about 93 tonnes.

Mechanical highlights of the conceptual design may be summarized as follows:
1. All critical components--all cryopanels, the ion and neutral dumps, the magnet, and the three source assemblies--are directly and independently accessible by overhead crane and remote handling equipment.
2. Water cooling lines for the ion dump and the neutralizer are outside the vacuum envelope.
3. Both the ion and neutral dumps are single, simple "Vees" of copper. The designs are inertial (not actively cooled), and are conservative for 1.5 sec pulse operation.
4. The ion sweep magnet is of a new reflection type that defocuses the ion beam to reduce the power density on the ion dump, and does not require water cooling.
5. A readily available and easily welded aluminum alloy (5254) was found for the vacuum vessel which would exhibit only minimal long-lived radioactivity following neutron irradiation.
6. A mounting system was devised whereby beam lines could be removed and replaced without requiring alignment adjustments to be performed in the radioactive environment.
7. The design permits installation of up to 50 $m^2$ of cryopumping, if necessary.
8. The cryopanel design permits bake-out to 150°C for tritium removal, yet does not need bellows in the vacuum to accommodate thermal expansion.

Electrical highlights of the conceptual design may be summarized as follows:
1. All power supplies (PS) use solid-state circuitry exclusively, with the exception of ignitrons in the accelerating (accel) PS crowbar circuit, and a tetrode switch tube in the suppressor PS.
2. Use of an unregulated accel PS is made possible by a tracking arc-current modulator, which adjusts the beam current to compensate for the effects of small accel voltage variations on the beam optics.
3. A solid-state star-point controller in the accel PS primary circuit performs the filtering and ON/OFF

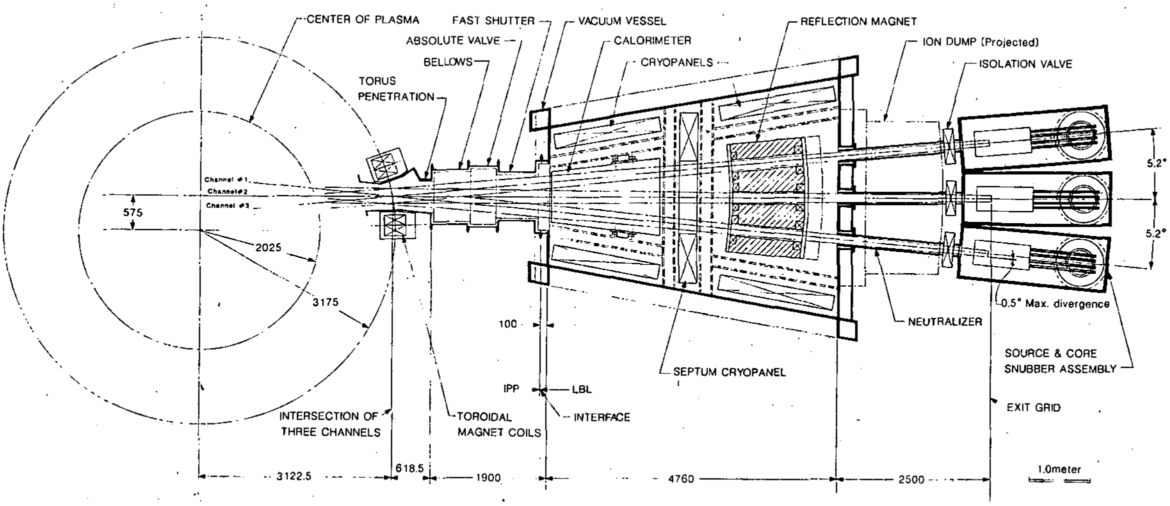


Fig. 1 Plan view of proposed ZEPHYR neutral beam line.

XBL 814-9234

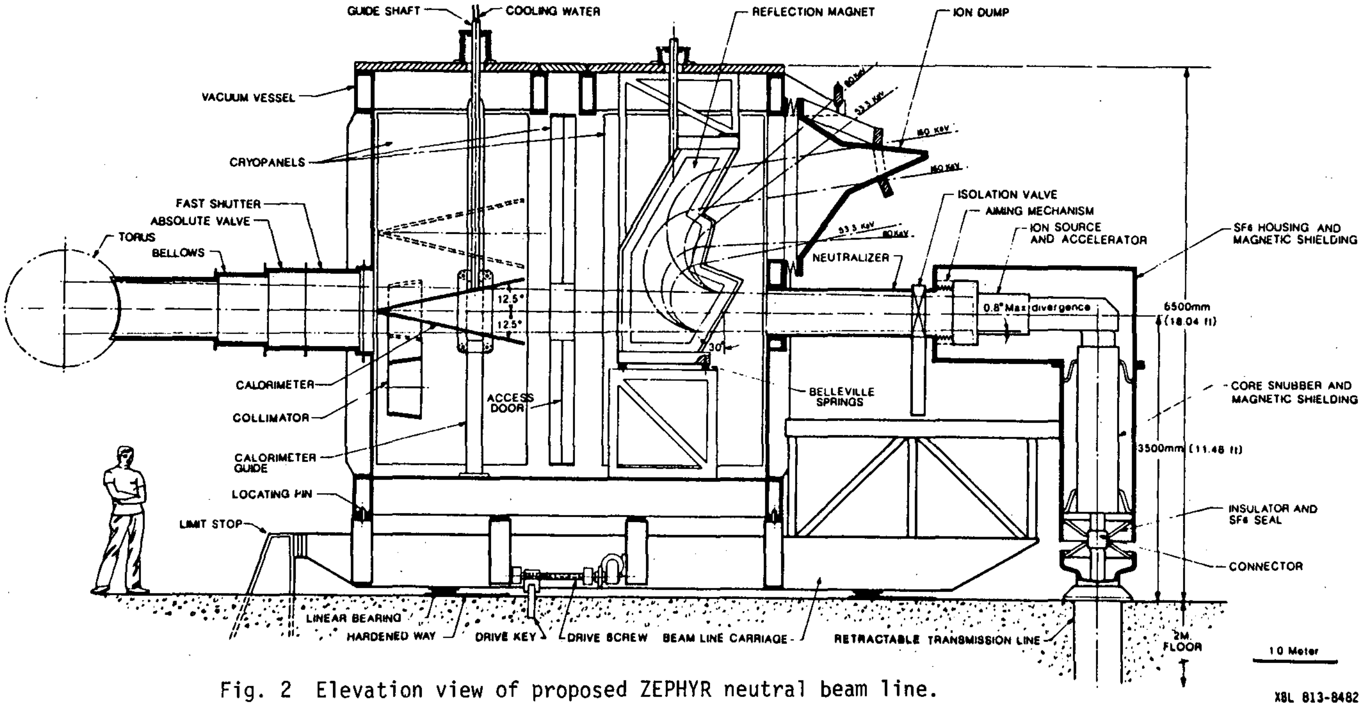


Fig. 2 Elevation view of proposed ZEPHYR neutral beam line.

XBL 813-8482

switching functions, thereby eliminating a capacitor bank and the usual complex switching circuitry from the high voltage secondary (see Fig. 3).

4. The turn-on of the accel PS is phase-synchronized relative to its last turn-off, thereby eliminating unbalanced transformer saturation and the resulting undesirable transient behavior in the dc secondary.

5. The "promptly" available stored energy in the accelerator and cabling is well below 5J, to prevent deterioration of accelerator performance following a high-current spark.

6. The accel PS has the ability to turn off and restart several times (if necessary) during a single beam shot, in the event of a spark-down in the accelerating grid structure. The current in the primary circuit exhibits negligible increase during spark-down and recovery.

7. Electrically symmetric extended-delta secondary windings are used in the accel PS transformer rectifiers to produce 12-pulse ripple and minimize the required filtering.

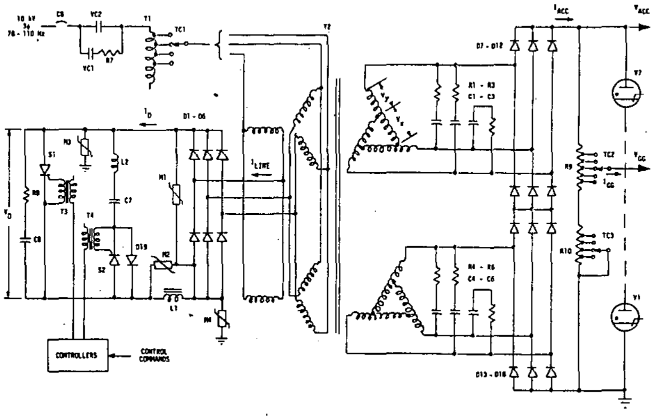


Fig. 3 Simplified schematic diagram of accel power supply.

XBL 814-9191

8. All major power supply components are well within present industrial fabrication capability.

A listing of the most pertinent power system and accel supply specifications is given is Table 3.

Virtually all the control and diagnostic hardware and software necessary for the ZEPHYR NBIS either has been developed already at LBL or is being developed for NBSTF and its upgrade, NBETF. Since this control system has been in use for some time and has been extensively tested, a substantial saving in costs and time would have been realized by using this investment also for ZEPHYR.

Table 3. Major NB Power System Specifications

| | |
|---|---|
| General | |
| Number of NB Sources | 18 |
| MG Power Required at 10 kV, $3\phi$ | 206 MVA; 0.95 P.F. |
| Auxiliary Power Required | 5 MVA |
| Component Lifetime | $2 \times 10^5$ shots |
| Accel PS (One of 18) | |
| Voltage Range | 40 to 176 kV |
| Voltage Regulation, peak-peak | ≤2% |
| Voltage Ripple, peak-peak | ≤4% |
| Voltage Risetime, 0-90% | ≤10 msec |
| Voltage Risetime, 0-97% | ≤250 msec |
| Current, Max. | 60 A |
| Pulse Width Range | 1 ms to 5 sec |
| Duty Cycle, Max. | 1.25% |
| AC Primary | 10 kV ±1%, $3\phi$, 78-110 Hz |
| Arc Modulator | |
| Voltage Range | 20 to 85 V |
| Current Range | 150 to 1500 A |
| Regulator Current Range | 0 to 150 A |
| Regulator Closed-Loop Bandwidth | ≥500 Hz |
| Auxiliary PS's (18 of Each) | |
| Gradient Grid | 0.75-0.9 $V_{accel}$, ±1 A |
| Filament | 8-11 V, 3750 A |
| Arc | 20-85 V, 1500 A |
| Suppressor | 2-6 kV, 30 A |
| Magnet | 15-50 V, 100 A |

## Schedule and Cost

We used our NBSTF and TFTR experience as a guide in estimating development and construction times for the ZEPHYR NBIS. Preliminary scheduling studies indicated comparable figures for ZEPHYR, meaning the beginning of neutral beam operation on ZEPHYR early in 1988, roughly one year later than desired by IPP.

It was apparent, however, that the reliability and remote maintenance requirements would introduce large uncertainties in this schedule, and necessitate the development of a prototype. It was also apparent that, although massive industrial involvement and coordination of the entire project was the most desirable way to transfer neutral beam technology to industry, it probably would not produce beam lines on the shortest time scale or at the lowest cost. Because these issues were not resolved, we considered even our preliminary schedule to be aggressive and optimistic.

Although cost constraints were constantly kept in mind in the conceptual design phase, trade-off studies for cost minimization would only have been performed in the latter half of the project, along with schedule studies. The largest uncertainty in estimating costs would have been in the area of remote handling.

## Remaining Technical Questions

In a number of technical areas, we identified problems that would have required careful study at an appropriate point in the project. We list below those questions which needed to be resolved before completion of the conceptual design. A similar list was drawn up for questions needing to be resolved before completion of the project (principally requiring model studies of the tokamak stray field, the ion-removal magnet and the accel supply), as well as for areas in which supporting research and development was required (principally extending the ion source cathode life and investigating operation of the 160 kV accelerator).

1. Complete computer code development, specifically for better calculation of power densities on the ion dump.
2. Study thermal stress and fatigue of the ion dump and calorimeter.
3. Study cryopanel heating due to eddy currents and neutrons.
4. Apply NBSTF cryopump experience and measured performance to ZEPHYR design.
5. Complete cost study of NBSTF construction.

## Conclusion

Although this project did not continue to completion, we were able to draw a number of conclusions from our work, and we list them below. Some of these relate specifically to the ZEPHYR design; other are more general in nature.

1. It appeared that a ZEPHYR NBIS could be designed and built using what were, for the most part, reasonable extrapolations from existing technology. A major exception was the area of remote-handling capability, which would likely require substantial additional development.
2. It appeared unlikely that the ZEPHYR NBIS could be delivered in time to meet the proposed ZEPHYR start-up date of spring, 1987. The uncertainty was mainly due to the unknown difficulty in achieving high reliability and remote maintenance capability, and the unknown degree of industrial involvement.
3. Construction of a prototype beam line and associated power supplies was regarded as virtually essential. The remote handling features constituted a sufficiently major innovation that their development on a prototype system was required. Also, the amount of power in an NBIS is so large that even a small unaccounted-for fraction of stray beam or electrical power is capable of doing considerable damage; to guarantee reliable operation of the final system, such situations must be identified and corrected, and this is by far most efficiently done in the prototype stage.
4. Industrial involvement, if it were eventually to be substantial, should have occurred at an early stage in the project. Since the process of selecting an industrial partner would probably take over one year, maximizing his degree of participation would mean delaying much of the detailed design work.
5. Laboratories involved in NB development need to maintain an on-going program of system design studies. Notwithstanding the large number of highly competent individuals at such laboratories, design teams cannot be assembled and/or educated on short notice, nor can design tools be developed or resurrected quickly. In addition, on-going programs in research and development are needed to come up with and incorporate cost-reducing innovations wherever possible.

## Acknowledgements

We would like to acknowledge the valuable contributions of the following colleagues who, while not members of the design team, participated significantly in this study: W. R. Baker, C. F. Chan, J. V. Franck, K. Halbach, G. P. Harnett, L. T. Jackson, H. Kim, H. M. Owren, and L. Soroka of LBL, and J. H. Feist of IPP.

## References

1. W. S. Cooper, et al., A Conceptual Design for the ZEPHYR Neutral Beam Injection System, LBL-12383.
2. ZEPHYR, Proposal for a Compact Ignition Experiment, IPP Study Group, January 1979, revised June 1979.