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STEADY STATE NEUTRAL BEAM INJECTOR

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Abstract

Learning from operational reliability of neutral beam injectors in particular and various heating schemes including RF in general on TFTR, JET, JT-60, it has become clear that neutral beam injectors may find a greater role assigned to them for maintaining the plasma in steady state devices under construction. Many technological solutions, integrated in the present day generation of injectors have given rise to capability of producing multimegawatt power at many tens of kV. They have already operated for integrated time $>10^5$ S without deterioration in the performance. However, a new generation of injectors for steady state devices have to address to some basic issues. They stem from material erosion under particle bombardment, heat transfer > $10\mathrm{MW/m}^2$, frequent regeneration of cryopanels, inertial power supplies, data acquisition and control of large volume of data. Some of these engineering issues have been addressed to in the proposed neutral beam injector for SST-1 at our institute; the remaining shall have to wait for the inputs of the database generated from the actual experience with steady state injectors.

1. Introduction

Neutral beam injection have demonstrated their capability in providing novel plasma configurations in short pulse confinement devices. These plasmas have demonstrated improved stability and confinements. The role of neutral beam injection as a sustaining device for thermal, particle and momentum influx to the plasma have therefore assumed prominence among all the options available for heating systems in steady state machines. The experimental objectives are simulation of ITER relevant experimental regimes.

To minimize the design efforts on all the components, this injector system design has relied on the existing database on the operating systems. The technological complications associated with the design of a neutral beam injector system however intensifies when long pulse operation is considered. The complications are component based and they are summarized in Table I below.

TABLE I. STEADY STATE ISSUES

Component	Issues
Back plate	Fatigue induced damages
Grids	Material erosion induced beam property degradation
Cryopumps	Requirement of frequent regeneration
Magnet	Inadequate space charge compensation
Heat removal system	Material erosion
Duct	Uncertain duct conditions at long operational pulses
Data acquisition system	Management of large volume of data accumulated during a shot
Power supply system	Steady state transmission of multimegawatts of power

These issues have been studied and recommendations have emerged on the design, fabrication and operation of specific systems for long pulse compatibility. Some of these recommendations have been incorporated in the design, while others shall have to wait until a data base on the performance is generated. These have been discussed in this paper.

The paper begins with a basic description of the system in Section 2, the problems associated with the beam formation system, transportation system and with the transmission and supply of multimegawatt of power and the management of a large volume of data are discussed in Section 3 . The concluding Section 4, presents a summary of the long pulse issues and ends with a discussion of the physics objectives that this technology mission is expected to make.

2. System description

For the SST-1 machine with parameters listed in Table II, the power required in neutral beam injection in the low and high density phases are 0.5 MW and 1.7 MW respectively. As shown in Fig.1, this requirement is accommodated through a tangential injection of the beam corresponding to a maximum absorption at the .98 m radius of tangency in the plasma. The beam parameters and its effect on the plasma have been modeled using the 1D transport code BALDUR, these have been summarized in Table III. The injection is expected to raise the ion temperature to ~1 keV, contribute to a fueling of ~ 4 torr lit/sec, impart a toroidal momentum of ~ 10^5 m/sec, drive a current of ~ 40 kA at the core of the plasma.

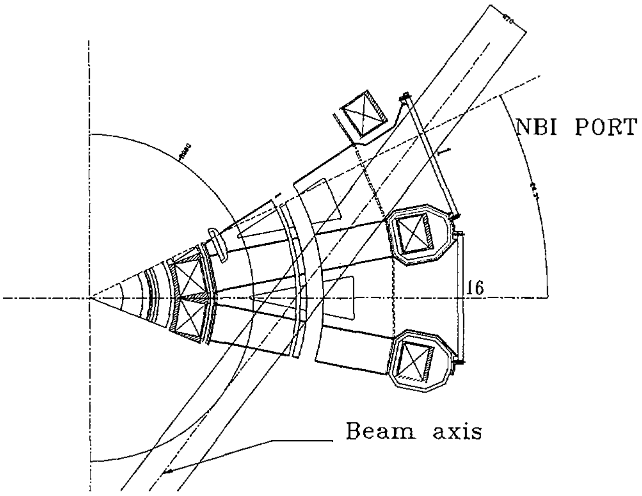
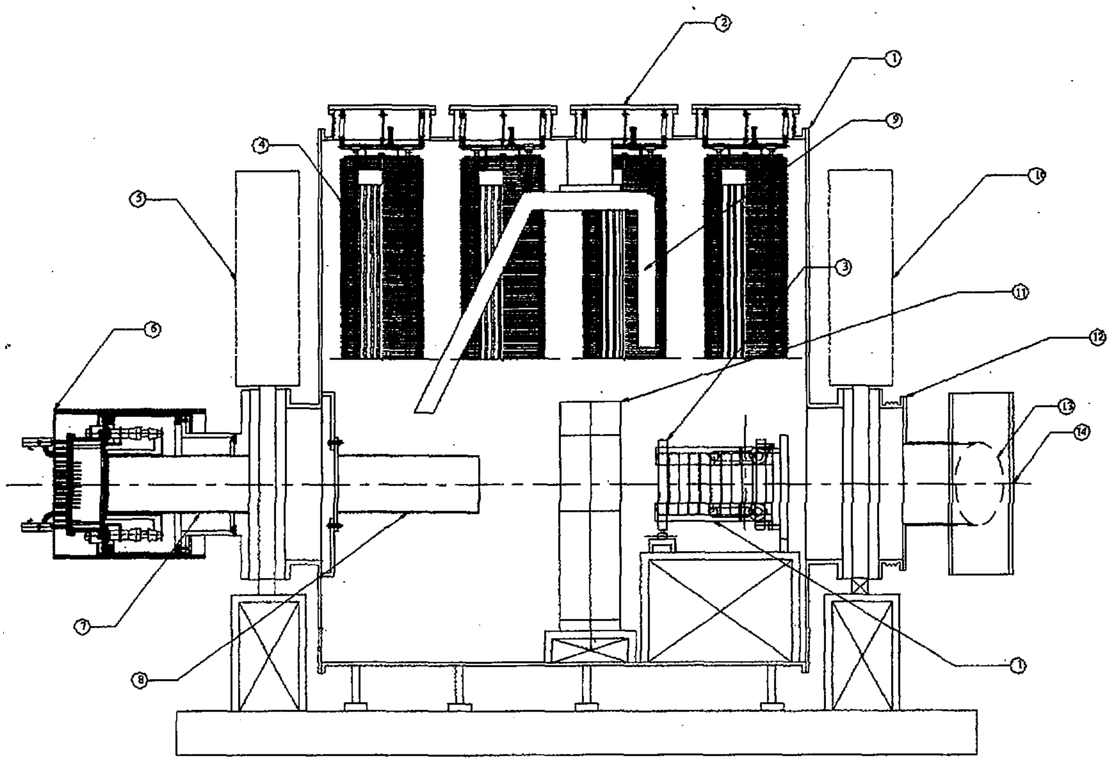


FIG.1. Tangential injection of the beam.

The beam-formation system in the injector is based a multipole bucket type plasma source where option of both checkerboard and supercusp magnetic geometry can be exercised. The extractor system is based on a shaped circular aperture geometry. The grid system is supported on the grid holders and the whole assembly is electrically isolated and mechanically supported by a set of three post insulators. The ion source is mounted on a ion source flange on the injector box with an isolation valve in between. The neutralizer is equipped with a provision of feeding gas up to 50 Torr lit/sec. The magnet system qualifies in its uniqueness through a short pathlength design. The field in the iron circuit is high ~2 T. The ion dump, scraper and the V-target assembly is based on the modular concept of a heat removal system elements. The V-target also acts as a preduct scraper in the synchronous mode of operation.

The vacuum system is designed for a reionization loss of < 5 % along the total path length. The data acquisition and control system for the injector system handles data from 600 channels and the data management system acquires, stores, displays and archives about 1 GB of data per shot.



COMPONENTS:

1.INJECTOR BOX VACUUM VESSEL
2.CRYOPUMP SUPPORT FLANGE
3.MAGNET AND V-TARGET PLACEMENT PORT
4.CRYOPUMP
5.ISOLATION VALVE-1
6.ION SOURCE ASSEMBLY
7.NEUTRALISER FIRST STAGE
8.NEUTRALISER SECOND STAGE
9.ION DUMP
10.ISOLATION VALVE-2
11.MAGNET
12.BELLOW
13.TOKAMAK CONNECTIONG PIPE
14.TOKAMAK COUPLING FLANGE

FIG. 2. Elevation view of injector system.

TABLE II. PARAMETERS OF SST-1

R (m)	A(m)	n_e (m^{-3})	κ	δ	T_e(keV)	I_p(kA)	τ_E(ms)	T_p(S)
1.10	.20	2×10^7	1.7	0.67	1.0	220	14	1000

TABLE III. PARAMETERS OF NEUTRAL BEAM

Species	Energy(keV)	Power(MW)	Power density to plasma(MW/m^2)	% shine through	Focal lengths (m)	Diverg--ence
H, D	30–80	0.5–1.7	15–40	<5	7.1(h),5.4(v)	<1°

TABLE IV. PARAMETERS OF THE INJECTOR SYSTEM

Component	**Description**
Plasma source	Multipole bucket. 24 filaments independently controlled. Density ~10^{12} cm^{-3}
Extractor system	Circular multi-aperture system. Extraction current density 230 mA/cm^2.
Neutralizer	2 stages. Length 2 m. $\int ndl \sim 10^{20}$ mol/m^2
Ion deflection magnet	Transmission typr. Maximum field 0.3 T in air & ~2.0 T in iron. Liner dissipation ~200 kW.
V-target	Movable. Designed to dissipate 2.5 MW of neutral beam power, at maximum flux of 10 MW/m^2.
Duct	Designed for a transportation current of ~100 A.
Vacuum system	Based on cryopumps. ~15 m^2 of active pumping area at 3.8 K.
Power supply system	Solid state modular supplies based on PSM. Filament supply independently controlled for the 24 sets.
Data acquisition system	Designed to handle 2 GB of Data over 500 channels. Real time display incorporated.

The power shall be delivered from a single beamline and the dynamic range of voltage shall be accommodated in a single source[1]. An elevation view of the beam line is shown in Fig. 2. The summary of the system design elements and the components therein are listed in Table IV.

3. Steady state issues

Steady state in the thermal effects are said to have been established in the actively cooled components of the injector systems operating in the range ~10-20 sec as these pulse lengths are two orders of magnitude greater than the thermal diffusion time scales. The real challenge in the steady state operation stems from the degradation in the material properties over long pulse lengths of ~1000 s. The important effects are erosion, fatigue induced creep, transition of the material into the plastic domain etc. Effect of these degradation on the material properties have been studied for the different components of the injector system. They are discussed below.

3.1. Beam formation system:

The back plate, the extractor system and the first stage of the neutralizer cell are the critical elements in the beam forming system.

3.1.1. Backplate

The backplate in the present design is based on the concept of the system operating in the JET PINI's [2]. However, there have been reports of failure of this component whenever there is an attempt to increase the power extracted from the ion source. The failures have been ascribed to a rise in the temperature of the copper surface under higher heat fluxes. This issue has been examined and its impact on the long pulse operation of this component have been assessed. The results of a 2D finite element analysis using ANSYS shows that surface temperature enhancement can be arrested with an enhancement in the flow rates by ~20% from the existing 8 gm/s along with a modification in the configuration of the flow channel where mixing of coolant is allowed [3]. The results of this analysis is presented in Fig. 3.

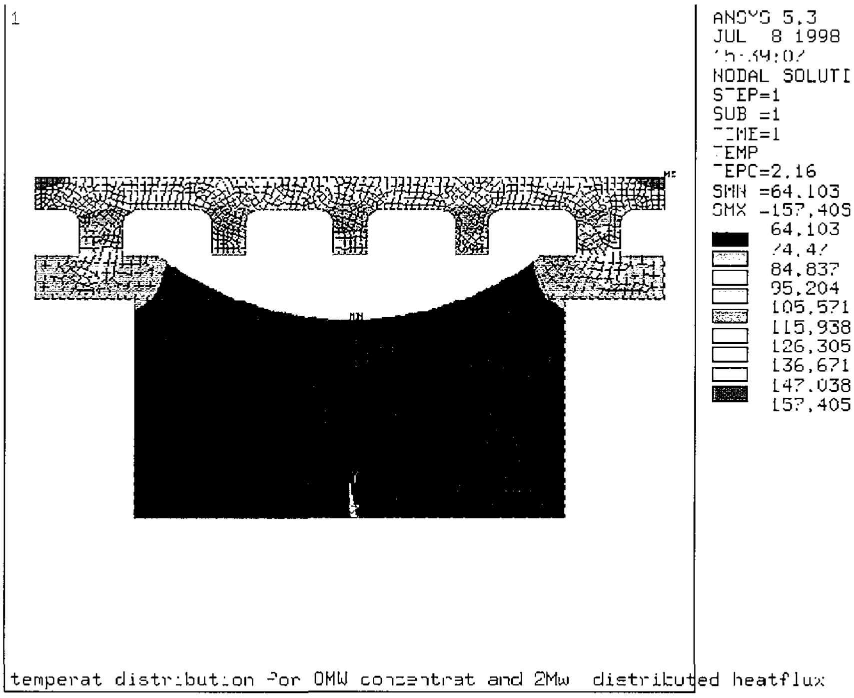


FIG. 3. Flow channel configuration of back plate (ANSYS Analysis).

3.1.2. Extractor grids

Material erosion induced degradation in the beam properties have been studied in relation to the performance of the grids. As evident from Fig 4, OFHC grids shows that beam divergence degrades by ~ 30% from an original value of 1° after 10^6 seconds of operation in Deuterium, when ~100 μm of material has eroded from the surface due to the incidence of 100 eV ion beams on the accelerator grid. The situation does not improve when Molybdenum grids are used, since the sputtering database predicts erosion rates comparable to that of copper at lower energies. The erosion effects are significantly reduced for both copper and molybdenum at lower voltages of the ion beam incident from the plasma source. This however, is accompanied by an increase in the divergence of the beam, the effect is represented in Fig. 5. Incorporating the recommendations of this study, for the long pulse operation of the grids, the beam line components have been designed to accommodate higher values of beam divergence.

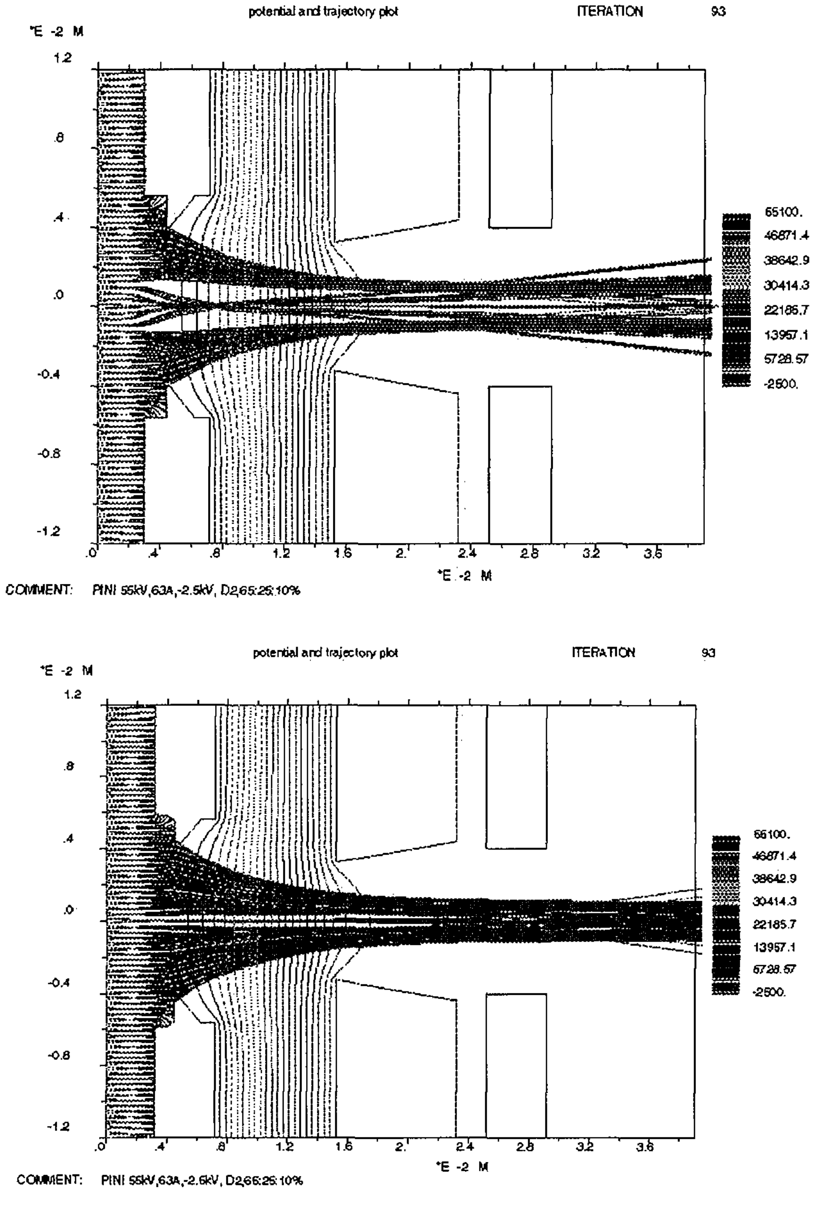


Fig. 4. Erosion effects in Extractor grid system.

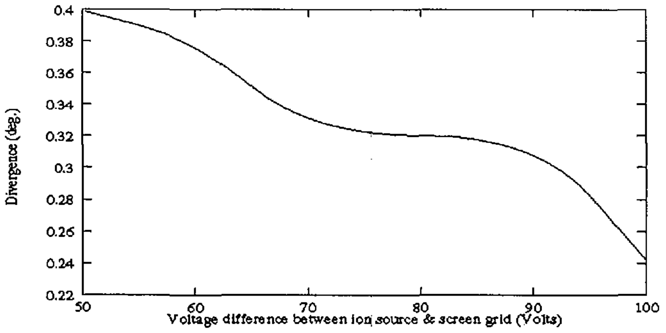


FIG. 5. Divergence as a function of voltage.

3.1.3. First stage of neutralizer

The first stage of the neutralizer, housed inside the earth grid holder has an access limitation for accommodating cooling provisions. However power dissipation estimates show ~70 kW of heat may be dissipated in this inaccessible section. This thin walled inertial structure has therefore been cooled through a set of embedded channels on this structure to dissipate ~100 kW of heat, this is shown in Fig 6.

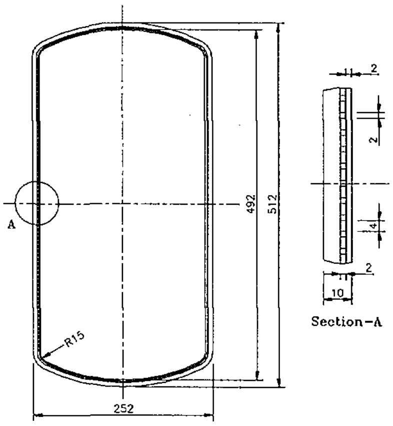


FIG. 6. Embedded cooling channels for neutralizer.

3.2. Beam transportation system

The magnet in the ion removal system, the heat transfer elements, the duct and the supporting vacuum system are the critical elements of the beam transportation system. The transportation system has been designed with the primary objective of compactness in its dimensions [4]. This objective has been met under the constraints of minimization of power density on the scrapers and the beam intercepting elements and minimization of the power loss inside the duct. The system design has utilized three numerical codes on beam transmission, magnetic fields and Monte Carlo simulation of the pressure profile.

3.2.1. Ion deflection magnet

The performance database on the magnet indicates that there is considerable reduction in the power dissipation on the magnet liner for a short path length magnet. The magnet design accommodates this need through a compact ~ 45 cm length. The ion beam traversing the magnet shall however be subjected to space charge expansion of the beam, which is proportional to the operation of the beam. Experimental database does indicate a reduction in this loading when excess gas is made to flow within the pole pieces [5]. The long pulse design of the magnet has included these additional features of active liner cooling to dissipate up to 120 kW, and provision of additional gas feed up to 10 torr lit/sec within the magnet. In addition, to prevent excess loading on the LN_2 panels due to an estimated 26 kW of power in the devious particles, provisions of a high conductance ~10^6 l/s protection baffle the region between the magnet exit and the cryopump has been made in the beam line design.

3.2.2. Heat transfer elements

The limits of operation of the heat dissipation system are imposed by considerations of material erosion. Estimates suggests that ~ 2 mm of the beam facing surface erodes in 10^6 s which implies that these elements shall be replaced within a year of its operation. The operational experience with Hypervapotron in JET and their projected use during the initial phase of TPX corroborates this apprehension. Use of molybdenum or its copper alloy on the other hand enhances the lifetime of the panels by a factor of 8. Though molybdenum should have been a natural choice for the heat transfer elements, the present design is based on Cu-Cr-Zr alloy as it is felt that its reliability in long pulse operation, and cyclic loading conditions have not been established. Molybdenum is also associated with the problem of oxygen induced embrittlement. The water quality and the operating vacuum environment demand additional stringency. A database in this matter is necessary. Fabrication difficulty in molybdenum is another deterrent.

3.2.3. Duct

Duct design is one of the most critical areas of system design for tangential injection geometry. The pressure profile and therefore the possibility of reionized power loading on the duct walls enhanced by the focusing due to the vertical field poses serious hurdles for long pulse injection. In the present system an unique concept has been incorporated in the design of the duct where the tokamak port wall has itself been lined with a thin walled heat transfer system made of OFHC to dissipate the incident power flux and increase the conductance. The pressure profiles shown in Fig. 7 clearly indicate the reduction in the background pressure with the incorporation of this geometry. The scraping of the beam for the purpose of injection is carried out by the in-situ V-target in its partially open configuration.

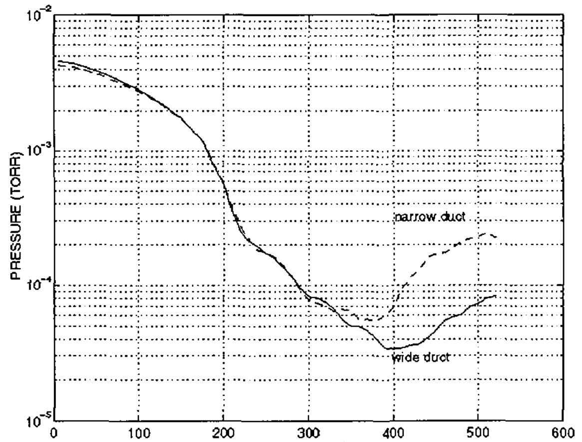


FIG. 7. Background pressure in duct.

3.2.4. Vacuum system

The vacuum system is based on cryocondensation pumping with the panels operating at 3.8K. Safety requirements for operation in hydrogen which limits the maximum pressure build up to 12 torr of partial pressure for hydrogen gas. This limits the accommodation of gas for a maximum of 4 shots of 1000 S in hydrogen or 5 shots of 1000 S in deuterium before the panels need to be regenerated. During

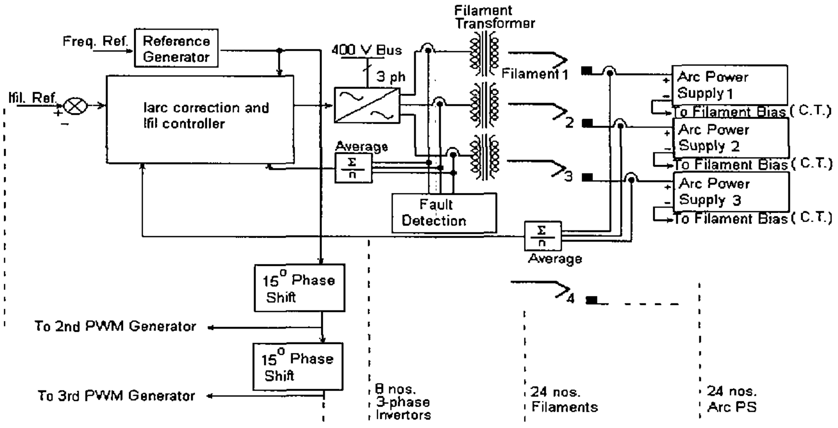


FIG. 8. Integrated arc and filament power system.

regeneration the panels are cycled to 77 K from 3.8 K. The flow channels in the LHe panel have therefore been optimized to accommodate a minimum quantity of LHe. Another related issue is the effect of hydrogen ice on the pumping performance of hydrogen. A prototype experiment designed to study these effects is expected to yield the desired data.

3.3. Power supply system

The HV regulated DC power supply for extraction is a wide dynamic range (4-80kV) and fast transient response (~20μS voltage rise time and ~5μS turn off time). The solid state power supply uses high frequency pulse step modulated switching [6]. Technical problems that are resolved are: transient free fast switching, efficient heat dissipation from semiconductors and low stored energy in the load side of the system. The multisecondary transformers are designed for very low stray capacitance of the secondary windings. The transmission line (~50m long) stores about 30 J energy, which is removed by a passive snubber on occurrence of grid sparkover. The arc and filament system is a closed loop system (Fig. 8) for controlling the discharge current by control of the actual heating current of each filament. The focus is on obtaining steady plasma density with temporal and spatial homogeneity.

3.4. Control and data acquisition system

For acquisition of about 600 data channels for each 1000 S injection shot, a data acquisition and control system based on VXI is used. Logical subsystems (e.g., vacuum, power supply, diagnostics, etc.) has been defined to build a structured distributed system where part of the system can run independent of the others. The volume of data acquired per shot is ~1GB. The data base manager is written with postgre.

4. Conclusions

The long pulse operational issues have been presented in this paper. Material erosion is one of the main concern. The design has incorporated some of the modifications necessary in the magnet and the cryopumps, as the indicators from the present database could be extrapolated over long pulse lengths. In the case of other components where predictions have emerged sufficient support from the database is not available. The present injector in its test stand operational mode is expected to generate the necessary database. The injector in is installation on the SST-1 machine is expected to yield a considerable database not only on the heating and fueling of a long pulse plasma but also on the experiments on locked modes, hot ion H modes, high beta plasma, neutral beam injection controlled post Greenwald density limits, which shall be useful for deciding on the ITER relevant regimes.

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