

Estimation of Electron Temperature on Glass Spherical Tokamak (GLAST)

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Abstract. Glass Spherical Tokamak (GLAST) is a small spherical tokamak indigenously developed in Pakistan with an insulating vacuum vessel. A commercially available 2.45 GHz magnetron is used as pre-ionization source for plasma current startup. Different diagnostic systems like Rogowski coils, magnetic probes, flux loops, Langmuir probe, fast imaging and emission spectroscopy are installed on the device. The plasma temperature inside of GLAST, at the time of maxima of plasma current, is estimated by taking into account the Spitzer resistivity calculations with some experimentally determined plasma parameters. The plasma resistance is calculated by using Ohm's law with plasma current and loop voltage as experimentally determined inputs. The plasma resistivity is then determined by using length and area of the plasma column. Finally, the average plasma electron temperature is predicted to be 12.65eV for taking neon (Ne) as a working gas.

1. Introduction

Spherical tokamak is an evolutionary extension of conventional tokamak with additive advantages of low aspect ratio, low field, and tokamak confinement to achieve high beta. Glass Spherical Tokamak (GLAST) is a small spherical tokamak indigenously developed in Pakistan with an insulating vacuum vessel (Pyrex glass). The design parameters of GLAST are $R=15\text{cm}$, $a=9\text{cm}$, $\kappa=2.5$, $I_p=50\text{kA}$, $B_T=(0.1-0.4)\text{Tesla}$, $\tau_p=10\text{ms}$, and $T_e=(300-400)\text{eV}$.

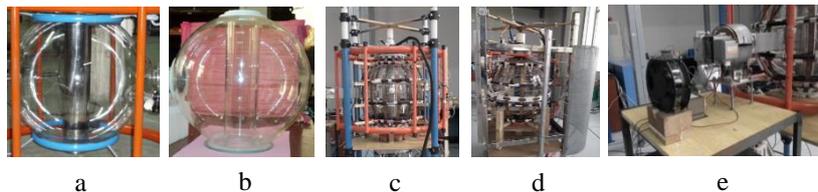


Figure 1. a) Vacuum vessel for GLAST-1 b) Vacuum vessel for GLAST-2
c) GLAST-1 d) GLAST-2 e) 2.45GHz waveguide system for pre-ionization

There are two tokamak devices (Fig.1c, 1d) currently operating at NTFP named GLAST-1 (having central tube of steel) and GLAST-2 (having central tube of glass). The toroidal field coil system consists of sixteen coils made from 1.5mm thick copper strip. In GLAST-1, a special ring (Fig.2) is used to join the coils in series, keeping inner legs straight while in GLAST-2, the inner legs are tilted at certain angle to join in series. This scheme provides an effect of additional pair of coils that helps to stabilize the plasma. The ohmic heating system consists of a central solenoid and two pairs of compensation coils connected in series. This system provides the necessary loop voltage for the startup and also deflects the unnecessary magnetic flux (due to the solenoid) out of the vacuum vessel. The size and the number of turns in these coils were determined experimentally with the help of double flux loops. The vertical field coil system, consisting of three pairs of coils, is currently being used to provide small vertical magnetic field to support the plasma current startup.



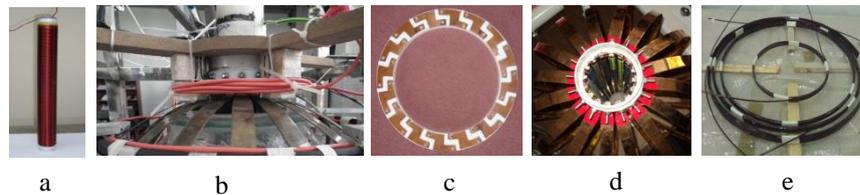


Figure 2. a) Central solenoid b) Compensation coils c) Support ring for TF coils on GLAST-1 d) TF coils of GLAST-2 e) Vertical field coils

The magnetic diagnostics such as induction coils, flux loops and Rogowski coils (Fig.3) are installed on the devices for the measurement of magnetic flux and the plasma current.

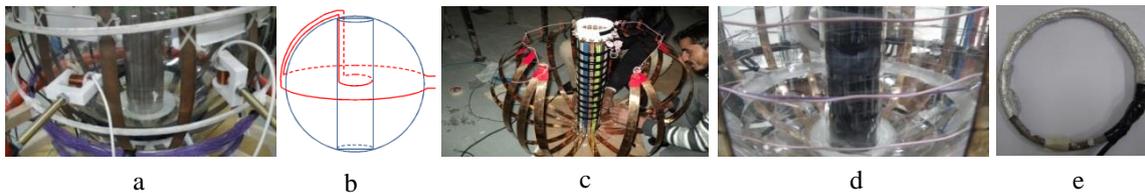


Figure 3. a) Magnetic induction coils b) Scheme of double flux loop c) Inner side of double flux loops d) Outer side of double flux loops e) Rogowski coil

The plasma diagnostics installed on GLAST (Fig.4) are two high speed cameras, fast photodiode, Langmuir probe, Ocean Optics spectrometer HR4000 and a high resolution spectrometer JOBIN YVON THR1000.

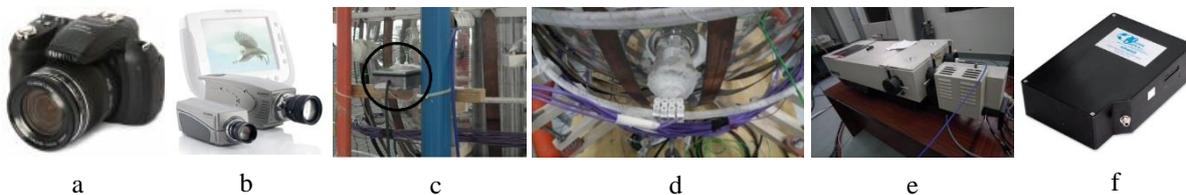


Figure 4. a) Fujifilm camera HS-10 b) Olympus high speed camera ispeed-2 c) Fast photodiode d) Langmuir probe e) Spectrometer THR1000 f) Spectrometer HR4000

A commercially available 2.45 GHz (0.8kW) magnetron source was modified for generating a microwave pulse of 4msec with enhanced output power of about 1.5kW. This pulsed waveguide microwave system is used as a source of pre-ionization for plasma startup in GLAST. In our initial studies neon was used as working gas with optimum pressure ranging from 1.0 mTorr to 0.5 mTorr. A plasma current of 5 kA for 0.5 msec have been generated in GLAST-2. The recorded experimental signals of microwave pulse, loop voltage, photodiode and of Rogowski coils are shown in Fig.5.

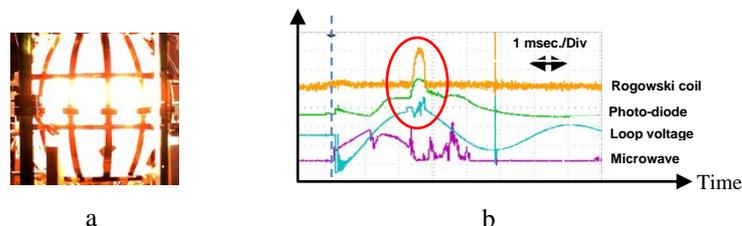


Figure 5. a) Image at maximum plasma current recorded with high speed camera ispeed-2 b) Experimental signals

An image of the device recorded with high speed camera (5000fps) at the time of maxima of the plasma current is shown in Fig.5a. The intense glow has filled the whole space of the tokamak vessel

giving effect of shining star. The temporal evolution of the plasma current, light intensity and the corresponding variations in the loop voltage and in the microwave pulse are clearly evident.

2. Estimation of Electron Temperature

In this work, Spitzer resistivity formula is exercised for estimating the plasma electron temperature using the measured values of plasma current and the variations in the loop voltage. The plasma inside GLAST-2 is assumed to be in Coulomb phase. The specific resistivity of such fully ionized plasma only depends on its electron temperature ' T_e ' and effective charge number ' Z_{eff} ' and this dependence is quantified by the Spitzer formula [1]. Through these considerations, an estimation of the average electron temperature ' T_e ' can be obtained.

The plasma resistivity, using Spitzer resistivity formula, is given by

$$\eta_p = 5.23 \times 10^{-5} T_e^{-3/2} Z_{eff} \ln \Lambda \quad [\Omega m, eV] \quad (1)$$

$$\text{where,} \quad \ln \Lambda = \begin{cases} 16.34 + 1.5 \ln T_e - 0.5 \ln n_e & ; (T_e < 1.16 \times 10^5 \text{ K}) \\ 22.81 + \ln T_e - 0.5 \ln n_e & ; (T_e > 1.16 \times 10^5 \text{ K}) \end{cases}$$

and for tokamaks, $\ln \Lambda \approx 17$ [2].

The effective charge number ' Z_{eff} ' is determined by the amount, composition and state of impurities in the plasma. For GLAST plasma the effective charge number is assumed to be $Z_{eff} = 1$.

Using these values in Eq. (1), the electron temperature ' T_e ' is calculated as

$$T_e = \left(\frac{8.9 \times 10^{-4}}{\eta_p} \right)^{2/3} \quad [eV, \Omega m] \quad (2)$$

The plasma resistivity ' η_p ' can be calculated by using experimentally determined plasma parameters as

$$\eta_p = R_p \frac{A_p}{l_p} \quad [\Omega m, \Omega, m^2, m] \quad (3)$$

where, ' l_p ' and ' A_p ' are the length and area of the plasma loop/column respectively and for GLAST, their values are determined as

$$\begin{aligned} l_p &= 0.97 \quad [m] \\ A_p &= 0.032 \quad [m^2] \end{aligned} \quad (4)$$

The plasma resistance ' R_p ' is calculated as

$$R_p = \frac{U_{loop}}{I_p} \quad [\Omega, V, A] \quad (5)$$

where, ' U_{loop} ' and ' I_p ' are the loop voltage and plasma current respectively and for a typical shot of GLAST-2, their values are experimentally determined as

$$\begin{aligned} U_{loop} &= 3 \quad [V] \\ I_p &= 5 \times 10^3 \quad [A] \end{aligned} \quad (6)$$

Using the values from Eq. (6) and Eq. (4), we get

$$\begin{aligned} R_p &= 6 \times 10^{-4} \quad [\Omega] \\ \eta_p &= 19.7 \times 10^{-6} \quad [\Omega m] \end{aligned} \quad (7)$$

Resultantly, Eq. (2) gives the edge plasma electron temperature ' T_e ' as

$$T_e = 12.65 \quad [eV]$$

It must be noted that this is a rough estimate of the edge plasma electron temperature basically for three reasons:

1. Plasma in the GLAST is not fully ionized, which makes us overestimate the plasma resistivity ' η_p ' and resultantly underestimate the electron temperature ' T_e '.
2. Due to the presence of impurities, $Z_{eff} > 1$ but for GLAST, ' Z_{eff} ' is assumed to be unity with large uncertainty, which again makes us overestimate the plasma resistivity ' η_p ' and resultantly underestimate the electron temperature ' T_e '.
3. Adsorbed gases are released from the surface of plasma facing components during the discharge. These atoms enter the plasma and cool down it, thus making us underestimate the electron temperature ' T_e '.

The central plasma temperature is also estimated using the equilibrium temperature profile and found out to be 34.6 eV. This value is considerably higher than the estimated average value of the edge electron temperature because center of the plasma has lower resistivity with higher current density.

In our future work we are planning to estimate the electron temperature and the number density with better accuracy and also using other diagnostics like spectroscopy and interferometry.

[1] Spitzer L and Harm R 1953 *Phys. Rev.* **89** 977

[2] Woods L C 2006 *Theory of Tokamak Transport* (WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim).