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Analysis of Tokamak fusion device parameters affecting the efficiency of Tokamak operation

Nour El-Houda El-zmeter [1*], Ben Schmiga [2], Alicia Murphy [3], Brendan Boyd-Weetman [4]

University of Technology Sydney, P.O Box 123, MaPS, Broadway NSW 2007.

1 E-Mail: Nour.E.El-zmeter@student.uts.edu.au
2 E-Mail: Benjamin.R.Schmiga@student.uts.edu.au
3 E-Mail: Alicia.Murphy@student.uts.edu.au
4 E-Mail: Brendan.Boyd-Weetman@student.uts.edu.au

* Author to whom correspondence should be addressed;
E-Mail: Nour.E.El-zmeter@student.uts.edu.au

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Abstract: Nuclear Power has been available as a relatively clean and reliable energy source for several decades. While tokamak engines have been in existence almost as long as successful fission-powered nuclear generators, they have not yet reached operational success for energy generation. This meta study collates key fusion device parameters and determines ideas on the applicability of fusion devices for energy. This paper supports the argument that toroidal tokamaks are not limited by volume whereas spherical designs have a potential volume limit, spherical tokamaks use a lower magnetic field current than toroidal tokamaks. Further scientific and engineering progress is required before tokamak devices can be a viable technology to be used for energy generation.

Keywords: Plasma, fusion, Tokamak, Magnetic field, plasma current, toroidal, spherical

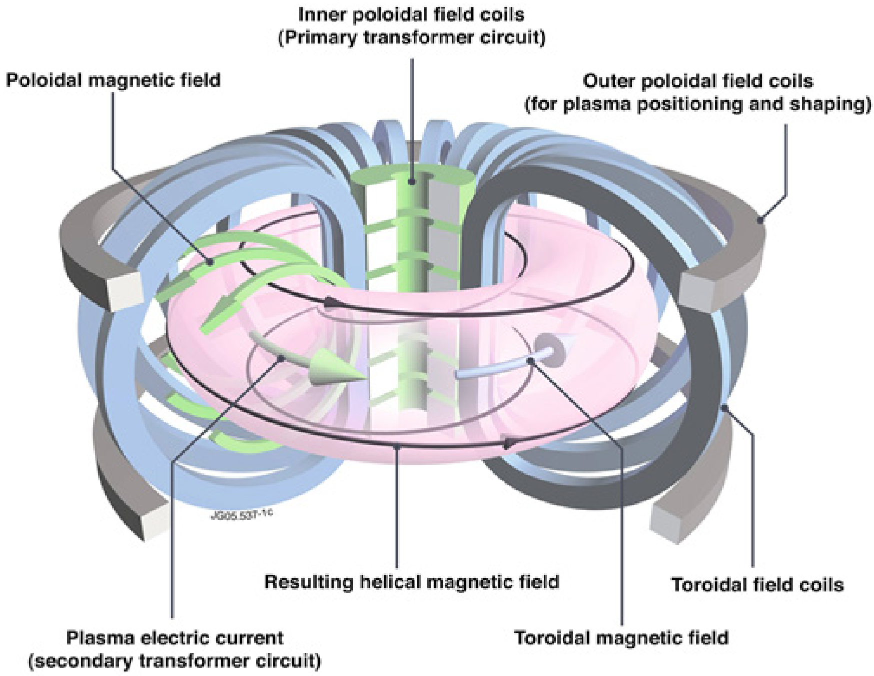
1. Introduction

Tokamak reactors are experimental power generators that use thermonuclear fusion to generate energy [1, 2]. While progress on the technology is slow due to many factors, achieving fusion power is highly desirable because its fuel, hydrogen, is functionally limitless as hydrogen is the most plentiful element in the universe [3], it has no hazardous by-products [4, 5], and if it malfunctions, the reaction would simply destabilise and stop [6, 7].

Nuclear fusion was discovered to be possible in the 1930's [8], and has been heavily studied and applied in areas such as energy generation [9, 10, 11] and weapons development [12, 13] with varying success. The idea that would later become the tokamak reactor was first suggested by Oleg Lavrentiev, and later made reality by Soviet physicists Igor Tamm and Andrei Sakharov in the 1950's [14].

In a tokamak reactor, the fusion reaction takes place within a steel constructed vacuum chamber [15, 16, 17], either toroidal or spherical in design. This chamber is surrounded by magnetic coils in toroidal and poloidal configurations, which generate the magnetic field with sufficient strength to contain the plasma, the combination of the two magnetic field orientations causes an induced magnetic field in the form of a directional plasma current, maintaining the plasma flow within the magnetic field (as seen in diagram 1) and preventing collision with the outer wall [18, 19, 20]. The inside of the chamber is usually lined with a heat-resistive element, such as lead, lithium, and boron to help the chamber withstand the intense heat generated by the plasma [21, 22, 23]. Tokamak reactors use the isotopes of hydrogen, deuterium and tritium, in a fusion reaction to produce helium. [24, 25, 26] The reaction is initiated by firing a neutron beam into the chamber to heat, and thus excite the hydrogen ions for fusion to take place, while also accelerating the particles further. [27, 28, 29] The reaction is initiated and maintained by applying immense atmospheric pressure inside the chamber, this forces the atoms together in a similar fashion as gravity in a naturally occurring fusion reaction within a star [30, 31, 32]. Continual engineering and scientific challenges that face the design of fully operational tokamaks for energy generation are extensive. Major examples include issues such as the interior coatings used are not currently able to withstand the extreme plasma temperatures for extended periods [33, 34], the magnetic confinement field is difficult to keep strong enough whilst still able to dynamically change with the continuous plasma reaction [35, 36] and the pressure inside the chamber is unstable largely for similar reasons [37, 38].

Diagram 1. *basic image of a toroidal tokamak reactor [14]*



While tokamaks show great potential, there are many hurdles associated with the technology. These problems not only affect the confinement of the plasma; they also affect the stability of the plasma. The viability of this technology is under debate [39, 40], as while these generators have been tested since the 1950's [41, 42], a fully functional reactor, that being one that can sustain an economically viable amount of energy production, has never been successfully built.

High confinement mode plasma (H-Mode) plasma is the most stable type of plasma [43, 44], while it has been achieved, it cannot be sustained for more than a few minutes at most in tokamak fusion devices [45]. H-mode is when magnetically contained plasma is heated until it goes from a state of low-containment (L-Mode) to H-Mode state and becomes more stable [46, 47]. This stability of the reaction is also what causes the plasma to destabilise as the fusion of hydrogen creates helium, which is heavier than hydrogen, and throws off the balance of the pressure in the chamber [48].

2. Methods

The meta study into the applicability of fusion reactors as a technology for energy generation was undertaken with the decision made that magnetic confinement fusion devices would be the main focus of our investigations.

The scientific databases used to search for reactors includes Scopus, ResearchGate, Google Scholar and Web of Science Core collection using keywords such as 'tokamak', 'fusion' and names of operational tokamaks found in preliminary research. The data collected only includes measured tokamak design parameters from papers on experimentally built tokamaks and excludes theoretical data. We did not discriminate devices based upon year in which they were built or published, however referenced background information was preferred to have been published within the past fifteen years.

To proceed with the research on the tokamak design parameters, the data was compiled into a spreadsheet and sorted based upon either spherical or toroidal plasma chamber designs. The parameters were then analysed to determine any correlations that could be found between them with particular emphasis on Plasma Current, Volume and applied magnetic field. A study into the significance of the vacuum chamber as a variable in other aspects of the design parameters was undertaken with the assumption that all devices had uniform geometry. The equations that follow illustrate what geometrical assumptions were made for toroidal and spherical geometries respectively.

$$V_{Toroidal} = (\pi a^2)(2\pi R^2)$$
$$V_{Spherical} = \left(\frac{4}{3}\pi R^3\right) - \left(\pi a^2(2R)\right)$$

Where ‘R’ and ‘a’ are considered the major and minor radii respectively. All calculations were performed in Microsoft Office Excel 2016.

3. Results

3.1 Toroidal and Spherical Tokamak data points

The tokamak design parameters obtained are listed against their respective device in order of the calculated assumed volumes. Tabulated data has been included for selected parameters to increase the clarity of the results and to match said parameters with their respective device without reducing the visibility of the graphical results. Parameters listed include name of the tokamak fusion device, major device radius R measured in metres, minor device radius a measured in metres, toroidal magnetic field strength B_T measured in Teslas, Plasma current I_P measured in mega amperes and calculated assumed volume V in cubic metres. In addition to the data set listed below, additional parameters including fusion power, mean electron density and calculated aspect ratio were obtained how they have not been included as there were not analysed for the purpose of inclusion in this meta report.

Table 1. *Table volume, toroidal magnetic field and plasma current of Toroidal Tokamaks [49-72]*

Device	R (m)	a (m)	B_T (T)	I_P (MA)	V (m^3)
GOLEM	0.4	0.085	0.8	0.025	0.057046
EGYPTOR	0.3	0.1	1.2	0.1	0.059218
ISTTOK	0.46	0.085	0.6	0.1	0.065603
STOR-M	0.46	0.12	0.15	0.004	0.130753
IR-T1	0.45	0.125	1	0.04	0.138791
COMPASS	0.56	0.21	2.1	0.4	0.48748
Alcator C-Mod	0.67	0.22	8.1	2	0.640103
SST-1	1.1	0.2	3	0.22	0.868525
ADITYA	0.75	0.25	0.9	0.08	0.925275
TEXT	1.05	0.255	1.8	0.16	1.347719
FTU	0.935	0.3	8	1.6	1.661054

Device	R (m)	a (m)	B_T (T)	I_P (MA)	V (m^3)
HT-7	1.22	0.29	2.5	0.25	2.025282
EAST	1.75	0.4	2	0.5	5.526978
TCV	0.88	0.7	1.4	1.2	8.511547
KSTAR	1.8	0.5	3.5	2	8.882644
DIII-D	1.74	0.56	1.9	1.1	10.77098
ASDEX	1.65	0.8	3.1	2	20.8446
Tore Supra	2.25	0.7	9	1.7	21.76248
TFTR	3.1	0.96	6	3	56.39413
UCLA-ET	5	1	0.25	0.045	98.69604
JET	2.96	2.1	3.45	3.2	257.6677

Table 2. *Table volume, toroidal magnetic field and plasma current of Spherical Tokamaks [73-93]*

Device	R (m)	a (m)	B_T (T)	I_P (MA)	V (m^3)
Medusa-CR	0.14	0.1	0.5	0.04	0.02029
GUTTA	0.16	0.084	1.5	0.15	0.024251
GLAST	0.2	0.1	0.4	0.05	0.046077
ST25	0.25	0.125	0.2	0.02	0.089994
LATE	0.25	0.2	0.12	0.004	0.128282
ETE	0.3	0.2	0.8	0.44	0.188496
HIT	0.3	0.2	0.46	0.15	0.188496
CPD	0.3	0.2	0.3	0.15	0.188496
SUNIST	0.3	0.23	1.15	0.05	0.212811

Device	R (m)	a (m)	B_T (T)	I_P (MA)	V (m^3)
START	0.32	0.26	0.4	0.25	0.273176
Globus-M	0.36	0.24	0.65	0.5	0.32572
UTST	0.39	0.24375	0.3	0.31	0.394066
LTX	0.4	0.27	0.4	0.4	0.4513
FBX-II	0.47	0.33	0.5	0.1	0.756485
Pegasus	0.45	0.375	0.18	0.3	0.779311
QUEST	0.68	0.4	0.25	0.02	2.0007
KTM	0.9	0.45	1	0.75	4.198739
NSTX-U	0.934	0.6227	1	2	5.688485

3.2 Plasma current against toroidal magnetic field strength analysis

Data points contained in the following series of graphs depict parameters listed in the above tables for each respective tokamak fusion device.

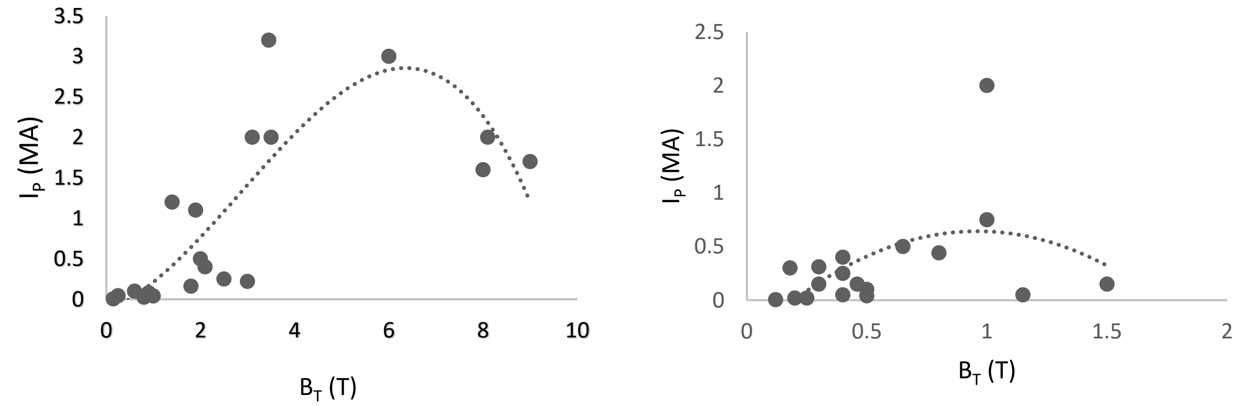


Figure 3. *Plasma Current (I_P) vs Toroidal Magnetic field (B_T) where the Plasma current is measured in mega Amps (MA) and magnetic field in Teslas (T). Graph 3a, which is on the right, is based on conventional tokamaks whereas 3b, which is on the left, is based on spherical tokamaks. The outlier in 3b is NSTX-U with an I_P of 2MA.*

3.3 Volume against plasma current analysis

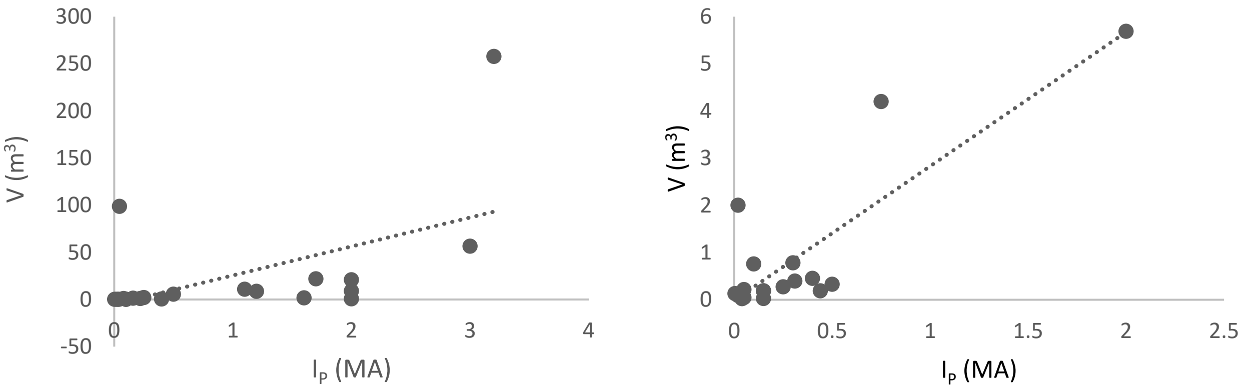


Figure 4. *Toroidal Tokamak Volume vs Plasma current with I_P in (MA) and V in (m^3). Graph 4a, which is on the right, is based on conventional tokamaks whereas 4b, which is on the left, is based on spherical tokamaks. The outliers for 4a are UCLA-ET with an I_P of 0.045MA and a volume of 98.7m^3.*

4. Discussion

The tokamak machine radius parameters for often varied between journal articles by around ±0.05m, this increases the uncertainty in our volume assumptions however based on the variety of results any observed trends should only be affected by a negligible amount. In addition to the assumption that all geometries of both spherical and toroidal geometries are the same throughout their respective machine type designs, the assumption was also applied that any inserts or technology differences such as Langmuir probes or variances in materials used for the chamber coating or heat shield.

In addition to the varying measurements, data on the tokamaks often had to be taken from more than one paper as the required parameters were not always reported from a singular source. Additionally, it should be noted that spherical tokamaks have not been practically researched to the same degree as traditional torus shaped designs, this is not represented in our research as we have obtained an amount of data on the parameters of spherical designs that is similar to the torus tokamak data obtained. Furthermore, the data used is not indicative of the parameters of the machines at the present but it only an indication as to the parameters of the machine used in the research papers listed, this means that any changes to the parameters over time are not represented in our analysis but could be the subject of further research.

During the fusion reaction in the tokamaks, there is an increasing change in enthalpy as the hydrogen is converted to helium and neutral beams, or electron cyclotron heating, increase the speed and temperature of the reaction which also increases the density and pressure. The reaction speed is also increased by the magnetic field coils as the current in the magnetic coils is increased until it reaches a maximum [94]. The variation between the time taken for the tokamaks to reach the maximum coil current is dependent on each tokamak design parameters and varies between them.

4.1 Plasma current and toroidal magnetic field

4.1.1 Conventional tokamak

The trend suggested Figure 3a shows a possible parabolic relationship between the plasma current and the magnetic field, with a maximum magnetic field turning point around 6 Tesla's with an equivalent current of 3 MA. This correlates with the theoretical aspect of plasma physics in which to maintain the plasma current, it operates in pulse mode until the poloidal coils reach their maximum current. When the maximum current is reached, induction of the plasma current ceases. To increase the current induction efficiency for conventional tokamaks, superconducting coils are used, as seen in the Tore Supra [32] which has a B_T of 9T.

4.1.2 Spherical tokamak

The tighter magnetic field of spherical tokamaks compared to conventional tokamaks seem to point to an outcome that spherical tokamaks can achieve a higher plasma pressure. This is seen in Figure 3b where the spherical magnetic field range of the coils is between 0.12-1.5T, whereas in comparison to the conventional tokamak in Figure 3a, the toroidal magnetic field range is between 0.15-9T.

However, the outlying plasma current factor tokamak NSTX-U does not follow the trend as it has a plasma current of 2MA which is greater than the more frequently observed values of plasma current strength in spherical tokamaks. This could potentially be because the NSTX-U has a greater volume and can therefore allow for a greater plasma current.

4.2 Plasma current and volume

4.2.1 Conventional tokamaks

Torus shaped tokamaks have a larger area from their inherent shape, than a spherical tokamak. As seen in figure 4a, the increase in plasma current for volume is linear. The equation for this is $y=30.729x-5.173$, hence the increase is measurable at about 30 cubic meters for every Mega Ampere.

For this reason, it is recommended that future generation tokamaks be larger size to for a larger desired plasma current output.

The exception to this being the UCLA-ET, with the second largest measured volume of currently operational Tokamak. Although it has a large volume of 98.7m^3, due to parameters such as its weaker magnetic field strength of 0.25T, UCLA-ET has a lower induced plasma current of 0.045MA. JET however, is the world's largest tokamak for its volume as seen in the upper right corner of figure 4a, is a perfect example of proportionality expected with volume and plasma current.

4.2.2 Spherical tokamak

Spherical tokamaks are designed to operate using smaller chamber volumes. Since the coils need to be cooled to maintain efficiency, if the volume is too large, the coils will not be cooled sufficiently as they pass through the narrow core and the plasma current will not be maintained well due to decreased efficiency of the magnetic coils. In figure 4b, the volumes are between 0.2-5.7m^3 which differ greatly to conventional tokamaks which range between 0.13-258m^3. Although the relationship seems linear, that is due to the lower volumes used for the spherical tokamaks. Increasing the volume further than what has been shown in figure 4b will likely show a curved graph with the gradient decreasing until it reaches a point where the heat affecting the coils passing through the narrow core is too great and the combined magnetic fields are no longer at angle to maintain the motion of the plasma inside the reactor, inhibiting the reactor's operation.

The points on the graph that appear to be outliers are not deemed as outliers as the parameters per tokamak differ, affecting the plasma current induction and maintenance. Not all the parameters that affect the plasma current are mentioned in the tables above, such as the temperature of the system. Another point to be noted is due to the vast difference in range between spherical and conventional tokamaks, the graph points for spherical tokamaks will appear to have greater variance than what is expected. It would be recommended to accommodate for the overheating of the coils in order to manage spherical tokamaks with larger volumes.

5. Conclusion

Energy generation via the use of nuclear technology has been a triumph of modern science however fusion based nuclear power from tokamak reactors has not yet been accomplished with any large scale practical application outside scientific research. There is a trend of spherical tokamak fusion devices to be developed with small scale operating parameters. Tokamaks of the traditional torus design have a peak in their ability to generate plasma current as the size increases, supporting the argument that toroidal tokamaks are not limited by volume whereas spherical have a potential volume limit. Further scientific engineering needs to be developed further upon before tokamak devices will be a viable technology to be used for energy generation.

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