Design and construction status of the TPM-1U tokamak

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Abstract. TPM-1U is a small size tokamak, with a vacuum vessel of 0.15 m minor radius and 0.4 m major radius, with an expected magnetic field in the torus centre of 0.5 T and a plasma current above 150 kA. One of the goals of the TPM-1U is to establish the scientific and technological base for the study of magnetically confined high temperature plasmas in Mexico, and help bring cohesion to the efforts in this field that have been scattered to date. Another goal is to contribute to the generation of high level human resources that can help the community grow in size. In addition to these two strategic goals, the machine will also have technical and scientific goals such as plasma-wall interaction studies, development of new diagnostics and exploration of new magnetic topologies. In this work, the design for the pulsed power system that will be used to feed the set of toroidal coils and design considerations for the central solenoid will be presented. Calculations for the dimensioning of the central solenoid used for ohmic heating are also presented, as well as preliminary considerations for the implementation of microwave power injection into the plasma.

1. Introduction

During the last 50 years, there has been steady progress on the road to generate thermonuclear fusion on earth, and the main approach that has been pursued to achieve this goal has been magnetically confined plasmas. Today, very large machines with long pulses have already demonstrated that it is possible, and the next step is to build a device that can demonstrate net energy generation, and this prototype is already being constructed [1]. Despite this tremendous advance, not all issues have been resolved and there are still many scientific and technological challenges to make controlled nuclear fusion a reality. The study of some of these open questions, in particular those where the risk of experiment is too high to be run in a large facility, is better suited for small experimental facilities, where the necessary reconfiguration might be easier to achieve and implement, the number of people affected by a malfunction is low and the cost of recovery is modest. Hence, small machines still play an important role in the path towards energy from nuclear fusion [2], as testbed of new ideas, development and improvement of diagnostic techniques and as training instruments for the development of human resources.

In the particular case of Mexico, previous efforts have been done to build and operate a small tokamak [3-6]. However, this machine had many operational issues that made it unreliable and it ceased to operate around the year 2000. Parallel to that effort, a larger machine was also designed and built, but due to a shortage of both funds and personnel that machine was only partially constructed and was left unfinished. Recently, the infrastructure of this machine was transferred to CICATA-IPN,
where there is an active group in the field of magnetically confined plasmas and where there are better opportunities for obtaining funding.

2. The TPM-1U tokamak

Figure 1 shows a rendering of the TPM-1U vacuum vessel, which has a 0.15 m minor radius and a 0.5 m major radius, formed by four 90° elbows, two of which are electrically isolated from each other by use of a Viton O-ring to make the seal and plastic washers on the bolts joining these two sections. The vessel has 10 ports of 3.75 cm in diameter, oriented in different positions, and one port for pumping which mates into an 8” CF flange. The vacuum is achieved using a Pfeiffer Balzers TPU-520 turbomolecular pump, with a nominal pumping speed of 520 liters per second for nitrogen; this pump is backed by a Balzers DUO 016 mechanical pump. Monitoring of the vacuum environment is done with an Accu-Quad quadrupole mass spectrometer, with a range of 1 - 100 amu. Preliminary measurements of the achievable vacuum level show that a vacuum of $5 \times 10^{-7}$ Torr can be achieved without any conditioning of the chamber, and the main impurities are water and air.

For supplying the necessary power to the tokamak, there are 60 Maxwell capacitors, with a maximum charging voltage of 7.5 kV and a capacitance of 20 µF each, so a maximum total energy of 33 kJ can be stored in this capacitor bank. To charge it, a 20 kV DC power supply with up to 500 mA current capacity is available. In the following sections it will be shown that this power is sufficient to drive the toroidal field of the machine for pulses of up to 10 ms, as well as providing the ohmic transformer power used to drive the plasma current.

![Figure 1. Rendering of the TPM-1U vacuum vessel with one of the sectors removed, and a schematic with dimensions (access ports not shown).](image)

3. TPM-1U Subsystems

3.1. Toroidal field

In order to confine high temperature plasmas, it is necessary to create a magnetic field in the machine along the largest curvature, known as the toroidal direction. To generate this field in TPM-1U, a set of 16 coils 40 cm in diameter is being considered. Each coil has 6 layers with 6 turns each of 5 AWG magnet wire with double insulation. Each coil requires 8 m of wire, which translates into approximately 8 kg of wire per coil. The field produced by this coils is shown in figure 2, both in the equator plane and in a vertical plane. The magnetic field generated by the addition of a plasma column with 12 cm radius and a parabolic current density profile with 5 MA/m² in the centre and vanishing right at the vessel wall. For these conditions, the current in the defined plasma column is on the order of 150 kA, and the calculated radial safety factor in the midplane and across the plasma column is shown in figure 3. It can clearly be seen that for the chosen plasma current profile, the stable portion of the plasma is bounded by the peak in safety factor at a plasma radius of 4 cm, which is 1/3 of the set value. In order to achieve a good safety factor value in the edge, the current would have to drop by a factor of 10, to 15 kA, reducing the ohmic heating significantly.
The main requirement for the toroidal field is a maximum intensity of 0.5 T in the centre of the torus for at least 2 ms. Hence, a suitable pulsed forming network (PFN) needs to be constructed. The PFN has two main advantages: 1) it can store the energy required, and 2) this energy can be delivered as a rectangular pulse [7]. The PFN consists of capacitors and inductors connected in a ladder configuration, and the values of the different elements in it have an effect on the pulse shape and duration.

For the generation of a rectangular pulse, the network consists of inductors and capacitors with the same values connected in cascade [7, 8]. The capacitor bank used to store the energy is charged up to 7.5 kV, and the inductance of the set of 16 toroidal coils is estimated to be 250 μH. Simulations were performed using the ATP software, and a particular case of these simulations is shown in figure 4, where the left panel shows the circuit used and the right one shows the current pulse obtained. As it can be seen, the network can generate a pulse with a rise time of only a few μs with duration of a few ms.

The load resistor affects the value of the peak voltage output. To achieve the power output of the pulse forming network, a Marx generator is attractive because it multiplies the voltage, so that the PFN will produce the waveform and the Marx generator can multiply the output voltage. For the PFN-Marx configuration, the output pulse parameters as a function of network parameters can be expressed by the equations in table 1.

Figure 5 shows different pulses of current obtained for different load inductance values. It can be seen that larger load inductances damp the initial oscillations of the pulse, at the cost of increasing the
initial rise time. A plateau starting at \( t = 1 \) ms can be seen, and it has a duration of 1 ms; the addition of more stages to the PFN may allow the extension of the pulse to the desired 2 ms.

![Figure 4](image1)

**Figure 4.** The pulse forming network (left) and the resulting current pulse (right).

| Parameter          | Expression                      |
|--------------------|---------------------------------|
| Pulse length       | \( \tau = 2k \sqrt{LC} \)      |
| Characteristic impedance | \( Z_M = n \sqrt{L/C} \) |
| Pulse voltage      | \( V = \frac{nV_0}{2} \)        |
| Delivered power    | \( P_L = \frac{nV_0^2}{4 \sqrt{L/C}} \) |

**Figure 5.** Effect of load inductance on pulse shape for the PFN shown in figure 4.

3.2. **Ohmic heating.**

The solenoid is a part of the TMP-1U prototype, and it is the component responsible for inducing high currents (> 100 kA) in the plasma confined within the torus, in order to achieve heating to several tens of millions of degrees for a short time (microseconds). As a starting point, it is assumed that the maximum available space is a circular area of 101.6 mm in diameter; the reason for this limitation is the internal space available on the toroidal vacuum chamber already available. Another consideration is that the signal for the solenoid power will have the minimum rise time to maximize flux swing. Even though a trapezoidal signal is used as a first approximation, the more realistic and easily
achievable sine wave is used, considering only half the cycle. It is assumed that this waveform is obtained by discharging an 800μF capacitor bank. In figure 6 a comparison between the trapezoidal and sinusoidal signals shows the similarity between the two signals. A better approximation of the trapezoidal signal can be obtained using Fourier series, which gives the infinite series that approximates the desired waveform; this is valid considering that only half cycle of the sine signal is used, and that the signal is generated by a single-shot capacitor bank discharge.

Some parameters for solenoid construction are still free, such as the number of turns that must carry the density at which the coil works the type and size of conductors and their insulation, and the material of the core. According to Faraday's law, the voltage induced in a coil wound on set of a magnetic core is given by:

$$e_{ind} = -N \frac{d\phi}{dt}$$  \hspace{1cm} (1)

where $N$ is the number of turns carrying the winding and $\phi$ is the magnetic flux flowing through the core. This equation is valid for an induction coil which experiences a magnetic field effect; the same equation allows us to represent the case when a voltage $V(t)$ is applied to the coil, the only difference being the sign, since in the case of an induced voltage it is negative according to Lenz's Law; the flux, however, remains the same in both cases. For the case of a solenoid to which a potential $V$ is applied, the expression is then:

$$V(t) = N \frac{d\phi}{dt}$$  \hspace{1cm} (2)

However, in the case of a time-changing voltage, the result will be a circulating magnetic flux in accordance with the implementation of the Right Hand Rule and this in turn will vary with time in the same way as the applied voltage. If the voltage applied is a sine function with frequency $\omega$, the magnetic flux is:

$$\phi(t) = \phi_{max} \sin(\omega t)$$  \hspace{1cm} (3)

Substituting the magnetic flux in equation (2) yields:

$$V(t) = N\phi_{max} \omega \cos(\omega t) = N\phi_{max} (2\pi f) \cos(2\pi ft)$$ \hspace{1cm} (4)

In the above equation, the maximum magnetic flux is given in Wb. Considering that the application of the maximum potential generates the maximum flux, that condition determines the maximum solenoid area required to drive the peak magnetic flux. Instead of using instantaneous values, effective values are used, which allow the comparison between a sinusoidal signal and its equivalent direct
current. This is indicative of how much energy the signal carries. Writing the maximum values in terms of effective values and removing the cosine variation with time, the above equation becomes:

\[ V = \sqrt{2\pi N\phi} \]  

(5)

If this last equation is written in terms of the flux density \( B \) instead of the magnetic flux, then it takes the following form:

\[ V_i = \frac{\sqrt{2\pi BA}}{2} \]  

(6)

where \( A \) is the area where the magnetic flux will flow, and \( V_i \) is the volt-per-turn value, defined as the potential induced by each of the N turns \( (V/N) \). Rearrangement of the equation finally yields an expression for the solenoid cross sectional area:

\[ A = \frac{V_i}{\sqrt{2\pi B}} \]  

(7)

If we apply this equation to our case where the input is the half cycle of a periodic signal with a 200 μs period, or a frequency of 5 kHz, the flux density and the volts per turn value are still free to be set, with the restriction that the maximum cross sectional area available for the solenoid is roughly a 100 mm diameter circle. This means that the number of layers needs to be low, so a large number of turns would imply a long solenoid; this is advantageous in this case, since a long solenoid would have low impedance and hence be more efficient in energy transfer.

The power of a coil is given by the product of voltage between its terminals and the current flowing through it, i.e.:

\[ S = VI \cos(\theta) \]  

(8)

This formula allows us to calculate the apparent power, in this formula the power factor depends on the load that will be powered by the coil, with three distinct cases: it is unity in the case of resistive load, less than one for highly inductive loads with a delay on the current waveform with respect to the voltage, and also less than one for capacitive loads with the current waveform ahead in time with respect to the voltage. The power factor really is nothing more than a way to quantify the effect of the phase shift of current with the voltage; the coil power can be estimated using any of the two windings, either the primary (solenoid) or secondary (plasma); as the plasma is a very complicated impedance when subjected to high currents, the only thing assumed initially is that the current to be circulating in the secondary is 150 kA.

### 3.3. Microwave heating considerations

The proposed mechanism to inject power into TPM-1U is electron cyclotron resonant heating (ECRH). Heating using X mode is complicated due to both the requirement of inboard launching to avoid deposition near the edge and the frequency required to achieve the resonance (14 GHz) [9]. Since the plasma density is expected to be low, injection from the outboard is simpler and sources at a lower frequency are less expensive, the natural decision is to perform ECRH using the O mode initially. The heating efficiency will be then dictated only by the plasma density, and interesting experiments regarding wave mode conversion to achieve Bernstein wave heating [10] may be possible. Microwave generators on the S band (2.45 GHz) are relatively cheap and readily available due to their extensive commercial application; even though this frequency range may not be very well suited for plasma heating, its price and hardware availability enables a relatively quick implementation of relevant research activities regarding interaction of microwaves with magnetically confined plasmas. Such activities may include microwave diagnostic development, non-inductive current drive studies or fundamental studies on mode conversion and wave propagation at lower field and no plasma current [11], as well as power deposition (lower hybrid [9]) at this frequency. For the X-mode heating and higher field operation, which for our central field value falls on the K_a band, the VTX5783G3
TWT from CPI [12] seems like a good prospect, with a 100 µs pulse length and an operating frequency of 10 GHz (resonant at 0.4 T); but being many times more expensive than the S band sources its implementation will be a long term project. Overall, it is deemed that microwave heating will be more likely implemented once good operation with just ohmic heating is achieved, and only once the planned diagnostics for the machine (and in particular the Thompson scattering setup) come online in order to have the necessary tools to measure power deposition via microwaves.

4. Conclusions
The TPM-1U tokamak has begun construction at CICATA Queretaro. It is a small machine with high aspect ratio similar to ISTTOK and TORPEX. It is expected to provide up to 150 kA of plasma current and 0.5 T of magnetic field in the centre. Vacuum and power infrastructure is already available to drive the toroidal field and the central solenoid, and a PFN to obtain a long toroidal magnetic field pulse has already been designed. Basic parameters for a prototype toroidal coil prototype are currently being evaluated.

Acknowledgments
The authors wishing to acknowledge assistance from COFAA-IPN for providing partial funding that allowed the attendance of authors to the meeting where this work was presented.

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