Study on technology of RF ion source for compact neutron generator

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Abstract. The technology of RF ion source for compact neutron generator has been studied. Compact neutron generator is a neutron generator with a relatively small size compared to conventional neutron generator; therefore it is very convenient to be used for field applications. Although the size is relatively small, compact neutron generator has the capability to produce neutrons with high neutron yield and the long operational lifetime which are the requirements of neutron generator for field applications. The main parts of the compact neutron generator are constructed in a small chamber of 2 – 5 cm diameter, 30 – 50 cm length. One of the main parts is ion source to produce positive deuteron ions which will bombard the target to produce fast neutrons. There are some types of an ion source for a compact neutron generator, one of which is radio frequency (RF) ion source. The advantage of the RF ion source is that most of the produced ions (> 80%) are atomic ions. Therefore the efficiency of the ion source is greater and subsequently the neutron yield is greater, small ions beam spot without overheating at the target. RF ion source requires an RF generator/RF power supply. The operating frequency of the RF generator is usually of 13.56 MHz. The output impedance of the RF generator is adjusted to the impedance of the transmission line (50 Ohm). A matching network is used to match the impedance of the RF antenna (0.5 – 2 Ohm) in order to maximize the transfer of RF power and to protect the equipment.

1. Introduction
The compact neutron generator is a kind of neutron generator whose dimension is relatively small compared to conventional neutron generator. Compact neutron generators have been developed for several kinds of field applications which are difficult to be done using conventional neutron generators. Some examples of compact neutron generator applications are detection of explosive materials and drugs at airport and harbors, detection of corrosion, crack and impact damage using neutron radiography method, analysis and mapping of mining minerals, exploration of oil and uranium, quality control of coal using PGNAA technique, cancer therapy using BNCT method, etc[1].

The requirement of the neutron generator used for field applications is that the neutron generator must be easy to be transported so that the neutron generator must be portable (compact). Besides that, the neutron generator has a high neutron yield and long-life operation. The compactness of the neutron generator can be realized when the parts of the neutron generator are constructed in a small tube, therefore it called a neutron tube or sealed tube. The neutron production of neutron tube per second (neutron yield) is determined by the accelerating voltage and intensity of ion source. Neutron yield of \(10^8\) ns\(^{-1}\) - \(10^9\) ns\(^{-1}\) can be produced by a neutron tube based on a D-T fusion reaction[2]. The neutron tubes of several technical specifications dedicated for certain applications are already produced commercially.
by some fabricants like Adelphi Technology (USA), EADS Sodern (France), Hotwell GmbH (Austria), Thermo Fischer Scientific (USA), and VNIIA All Rusia Research Institut of Automatics (Rusia). These commercial neutron tubes are shown in Fig.1[3].

![Figure 1. Some commercially produced neutron tubes [3].](image)

D-D fusion reaction-based compact neutron generators have been developed whether at university laboratories or national laboratories like Lawrence Berkeley National Laboratory (LBNL), in California, USA. While the commercial compact neutron generators use Penning type ion sources, the compact neutron generators developed by LBNL use RF type ion sources. By using RF type ion sources the neutron yield could be improved although the D-D reaction cross-section is smaller than the D-T reaction cross-section. Therefore it is interesting to study the technology of RF type ion source for compact neutron generator. This paper describes the results of the study.

2. Methodology
The study is done by learning the literature related to compact neutron generator and RF ion source covering its composition which consists of RF power supply (RF generator), impedance matching circuit, RF antenna, plasma chamber, and also by learning the plasma formation using RF field, deuteron ions formation and subsequently deuteron ions extraction from plasma chamber and deuteron ions beam formation. D-D and D-T fusion reactions in which product fast neutrons are also discussed in this study.

3. Result and discussion
There are 2 types of compact neutron generators developed by LBNL i.e. axial and coaxial compact neutron generators as shown in figure 2 [4].

![Figure 2. Axial (left) and coaxial (right) compact neutron generators developed at LBNL, California, USA[4].](image)
3.1. The axial compact neutron generator
Axial compact neutron generator uses RF ion source with external RF antenna (outside ion source), plasma chamber made of quartz and plasma electrode made of molybdenum. Deuterium target is set up in a vacuum tube made of aluminum and isolated from ground potential. The average neutron yield produced by the axial compact neutron generator is \(10^8\) ns\(^{-1}\) depend on the ions beam current.

3.2. The coaxial compact neutron generator
Coaxial compact neutron generator uses RF ion source with an internal RF antenna (inside ion source). The ion source is constructed in the center of a compact neutron generator in such a way that its extraction slits are around the plasma chamber. The deuterium target is set up around the ion source. The average neutron yield produced by the coaxial compact neutron generator is \(10^9\) ns\(^{-1}\) depend on the ions beam current.

3.3. RF ion source in compact neutron generator
In general neutron generator needs ion source for producing deuteron ions that will be bombarded to deuterium or tritium target. It will induce D-D or D-T fusion reactions that produce fast neutrons as shown in the following reaction equations:

\[
D + D \rightarrow n + ^3\text{He} \quad (E_n = 2.45\text{ MeV}, \ E_{\text{He}} = 0.82\text{ MeV}) \tag{1}
\]

\[
D + T \rightarrow n + ^4\text{He} \quad (E_n = 14.1\text{ MeV}, \ E_{\text{He}} = 3.5\text{ MeV}) \tag{2}
\]

The energies of fast neutrons produced from each fusion reaction are 2.45 MeV and 14.1 MeV, respectively.

There are several ion sources usually used in compact neutron generators, e.g. cold cathode or Penning ion source, hot cathode ion source, magnetron ion source and RF ion source[1]. Penning ion source usually used in commercially produced compact neutron generators like Thermo Electron, Sodern, Schlumberger, etc. The neutron yield around \(10^8\) ns\(^{-1}\) up to \(10^{11}\) ns\(^{-1}\) can be produced from the D-T fusion reaction[5].

RF ion sources as well as compact neutron generators are developed by LBNL. The good characteristics of RF ion sources are the long-life operation, high gas efficiency, high plasma density, and it produces mostly atomic ions than molecular ions. Thus, the neutron yield becomes higher without overheating on target although the beam spot is small enough. The schematic diagram of the RF ion source is shown in Figure 3[6].

![Figure 3. The schema diagram of RF ion source [6].](image-url)
The components of the RF ion source basically consist of RF power supply, impedance matching circuit, RF antenna, plasma chamber, and plasma electrode.

3.4. RF power supply

RF power supply is the component of ion source used for generating an RF field that will be used to induce plasma. RF power supply operates at a frequency of 13.56 MHz. The output impedance is usually standard (50 Ω) in order to match the impedance of the coaxial transmission line used to deliver RF power to the RF antenna. The impedance of the RF antenna in the RF ion source is typically from 0.5 Ω up to 2 Ω. The components of the RF power supply consist of:

3.4.1. RF power amplifier. It is a high-efficiency power amplifier because the efficiency is greater than the normal power amplifier for the same application. The high-efficiency power amplifier belongs to power amplifier class D which theoretically has efficiency up to 100%. But practically it only achieves around 85% up to 90%. The example of an RF power amplifier is power MOSFET hybrid DRF1300; this is a push-pull hybrid that has 2 independent channels. Each channel consists of a high power gate driver, MOSFET 500V 30A and internal bypass capacitor as shown in figure 4[7][8].

![Figure 4. Diagram of MOSFET push-pull hybrid DRF1300][7][8].

By using the DC power supply of 250 V the power MOSFET hybrid DRF1300 can produce RF power up to 2000 W. Bypass capacitors C1 and C2 are used for reducing the internal loop parasite inductance. DRF1300 is designed to provide more flexibility for the system designer, higher performance, and cheaper cost.

3.4.2. Pulse generator. It is a component for providing pulse signals to the RF power amplifier so that the RF power amplifier generates plasma pulses. The pulse generator circuit is as shown in Figure 5[7][9]. This circuit works at a voltage of 3.0 up to 5.5 V. The signal from 27.12 MHz crystal is divided into 2 parts of 13.56 MHz and separated by U2B into 2 signals of 180 degrees out of phase. U2A and U3A make the possibility to tune the pulse width of 2 input signals for DRF1300. Each signal pulse width can be tuned from 15 ns up to 35 ns using potentiometer R9 and R16, respectively.
3.5. Impedance matching network

Impedance matching network is a component of the RF ion source which is used to maximize the RF power delivery from RF power supply to RF antenna. There are 2 types of impedance matching network i.e. inductive and capacitive impedance matching networks as shown in figure 6 [10].

Figure 5. Pulse generator circuit [7], [9].

Figure 6. Impedance matching network for RF ion source :(a) inductive, (b) capacitive [10].
Inductive impedance matching network uses a ferrite transformer in the primer to drive a series resonant circuit in the secondary i.e. L1, C1 and antenna represented by L_{antenna} and R_{antenna}. The 50 Ω output impedance of the RF power supply is matched to the antenna by adjusting the transformer turn ratio and tuning the capacitor. This type of matching network has poor efficiency due to the losses in the transformer especially at high RF power level.

Capacitive impedance matching network uses a capacitive voltage divider for matching the RF power to the antenna. It is arranged by C1, C2 dan C3 which are connected to antenna represented by L_{antenna} and R_{antenna}. L1 stabilizes the resonance frequency of the matching network. At low RF frequency (2 MHz) capacitive impedance matching network has much higher efficiency than the inductive one.

3.6. RF antenna

RF antenna is used for delivery RF power to the plasma. It is an induction coil made of copper or stainless steel coated with electrical isolative material (e.g. porcelain or quartz). This aims to protect the antenna from colliding and sputtering by charged particles in plasma so that the antenna becomes more reliable. There are 2 kinds of antenna form i.e. transversal loop antenna and axial loop antenna as shown in figure 7 [10].

![Figure 7. RF antenna for RF ion source: transversal loop antenna (left) dan axial loop antenna (right) [10].](image)

The RF antenna can be installed inside the plasma chamber (internal) or outside the plasma chamber (external) of the ion source. The advantage of external antenna installation is that the plasma becomes cleaner since there is no contamination caused by antenna materials.

3.7. Plasma chamber

The plasma formation by the RF field is occurring in the plasma chamber of the RF ion source. It is a cylindrical chamber that is closed off at both ends by a plasma electrode on one side and a back flange on the other side as shown in figure 8 [10].

![Figure 8. Plasma chamber of RF ion source [10].](image)
The plasma electrode is used for the extraction of deuteron ions from the plasma chamber. The back flange is used for the installation of gas inlet, a pressure gauge, feed-throughs for RF antenna and magnetic filter. The back flange is also equipped with a small diameter quartz window for viewing the plasma in the ion source during operation. Permanent magnets (cusp magnets) made of samarium cobalt are installed around the plasma chamber for plasma confinement. This leads to the extension of colliding electrons trajectories in plasma and subsequently increases the ionization probability. While magnetic filters installed at the back flange are used for protecting feedthroughs [10].

3.8. Plasma formation using RF field
Plasma is an ionized gas where ions and electron are in quasi-neutral equilibrium so that the overall electric charges of plasma nearly zero (neutral). However plasma is different from neutral gas. Plasma is a good electrical conductor due to freely moving charged particles in plasma, while neutral gas is not a conductor.

In general, plasma is formed by the collision of energetic electrons with electrons in neutral atoms so that ionization occurred, i.e. electrons escape from atoms and subsequently the atoms become positive ions. This is the simplest method to ionize neutral gas, because the cross-section of electrons collision is great enough. There are several methods for plasma formation in the ion source, among others by using DC discharge, RF field and microwave.

Plasma formation using the RF field is done by flowing RF current through RF antenna into the plasma chamber filled by gas to be ionized. RF current generates a sinusoidal magnetic field that subsequently generates a sinusoidal electric field. The electric field accelerates free electrons in neutral gas so that its energy is high enough for gas ionization (plasma forming).

There are 2 methods of RF field coupling through the RF antenna, namely capacitive coupling and inductive coupling:

- In capacitive coupling, an oscillating high voltage at RF frequency is applied between antenna and electrode. The produced plasma by this coupling usually has a low density which is characterized by purplish glimmer (for hydrogen gas).

- In inductive coupling, RF current in the antenna is varied so that varies magnetic field is produced in the plasma chamber, subsequently an electric field is induced to accelerate electrons in the plasma chamber and plasma formation begin. The produced plasma has a high density which is characterized by redness bright light (for hydrogen gas). This kind of coupling is frequently used because it can produce high ion current density and higher atomic ion fraction. The shape of the RF antenna for inductive coupling can be flat spiral or cylindrical spiral as shown in Figure 9[11].

![Figure 9](image_url). The shape RF antenna for inductive RF coupling in RF ion source: flat spiral (left) and cylindrical spiral (right) [11].
Most of the positive ions in plasmas are created by bombarding neutral gas with energetics free electrons. The kinetic energy of electrons comes from electric field $F$ induced by a magnetic field. If ionization occurs in monoatomic gas (e.g. noble gas), usually there are only singly charged ions in the plasma. The ionization process can be written as:

$$A + e \rightarrow A^+ + 2e$$

(3)

If ionization occurs in molecular gas (e.g. diatomic gas), there are some possibilities of ionization process:

$$A_2 + e \rightarrow A_2^+ + 2e$$

(4)

$$A_2 + e \rightarrow A^+ + A + 2e$$

(5)

$$A_2^+ + e \rightarrow A^+ + A + e$$

(6)

$$A + e \rightarrow A^+ + 2e$$

(7)

$$A_2^+ + A_2 \rightarrow A_3^+ + A$$

(8)

The kind of ions that most probably created by the above ionization processes is affected by parameters of gas pressure, RF power and configuration of the magnetic field. At high gas pressure, the ionization process (4) and (8) tend to produce $A_{3+}$ ions. Whereas at low gas pressure, light ions are most probably created. At high RF power $A_{3+}$ ions are easily broken into $A^+$ and $A_{2+}$ ions. The number of atomic ions extracted from the plasma chamber can be increased by using the transversal magnetic field in front of the extraction slit inside the plasma chamber.

Hydrogen gas is an example of molecular gas. The hydrogen ions can be created through the following reactions:

$$H_2 + e \rightarrow H_2^+ + e$$

(9)

$$H_2^+ + e \rightarrow H^+ + H + e$$

(10)

$$H + e \rightarrow H^+ + 2e$$

(11)

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

(12)

$$H_3^+ + e \rightarrow H^+ + H_2 + e$$

(13)

Proton can be created efficiently from hydrogen gas through reaction (12) and (13). In the neutron generator, deuteron ions are needed for bombarding Ti-D or Ti-T target. Deuteron ions can be created by the ionization of deuterium gas in RF ion source. The ionization energy of deuterium is 14.9 eV.

3.9. Ion beam extraction system

Ions created in the plasma chamber are extracted and shaped as ions beam in such a way that beam divergence is as small as possible. Hence the beam loss can be minimized and most of the extracted ions reach the target. Therefore, an extractor is installed in front of the plasma electrode (slit) and it must have potential lower than the potential of the plasma electrode. The ions beam extraction system of the RF ion source is as shown in figure 10 [12].
The ions trajectory is affected by extracting the electric field and plasma meniscus. The shape of plasma meniscus is determined by the electric field around the plasma electrode (slit) and the density as well as the mobility of plasma which are related to plasma temperature. The profile of plasma meniscus plays an important role in the ions beam trajectory. After the Child Langmuir-Schottky law of space charge, ions are emitted perpendicular to the plasma meniscus surface. This law determines the maximum current density which can be extracted between 2 flat electrodes one of which is charged particles emitter (source). The maximum space charge limited current density is expressed as [12]:

\[
J = \frac{4\varepsilon_0}{9} \frac{2q}{m} \frac{U^{3/2}}{d^2} \left[ \frac{A}{m^2} \right]
\]

(14)

where \( J \) ions beam current density (A/m²), \( \varepsilon_0 \) vacuum permittivity (8.8 x 10⁻¹² F/m), \( q \) ion charge (coulomb), \( m \) ion mass (kg), \( U \) accelerating potential between 2 electrodes (volt) and \( d \) electrodes distance. If the equation (14) is fulfilled, then we get a flat plasma meniscus surface, this is related to the flat ions emitting source. But if \( J \) is smaller than the right side of equation (14), then ions extraction occurs in emission limited condition where extracting electric field can extractions more than available.

There are 3 types of plasma meniscus usually found in the plasma electrode of the ion source, i.e. planar, concave and convex plasma meniscus as shown in Figure 11[10].

[Figure 10. Ions beam extraction system of the RF ion source [12].]

[Figure 11. The shapes of plasma meniscus at the plasma electrode of ion source: (a) concave, (b) planar, (c) convex [10].]
Flat plasma meniscus is an ideal condition that can occur when ions current density and extracting electric field are in equilibrium state as expressed in equation (14). In this case, the ions beam is extracted nearly parallel to the beam axis[11].

4. Conclusion
From the study of RF ion source technology for compact neutron generator it can be concluded that RF ion source is suitable used for compact neutron generator. It is supported by the favorable characteristics of RF ion source, i.e. long operation lifetime, high gas efficiency, high plasma density and it produces atomic ions more than molecular ions. Hence the ion source efficiency becomes high and subsequently the neutron yield becomes higher, the size of the beam spot is small and there is no overheating on the target. If overheating occurs on the target, then deuterium or tritium ions that have been implanted on target will be knocked out from the target surface and it causes the reduction of neutron yield of compact neutron generator[13].

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