Study of the multi-driver decoupling model of RF negative ion source

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Abstract. According to the latest physic design of the China Fusion Engineering Test Reactor (CFETR), radio-frequency (RF) driven negative ion source was selected as the preferred ion source for CFETR neutral beam injection (NBI) system. In order to solve the key problems of the CFETR, a big scientific project, the Comprehensive Research Facility for Fusion Technology (CRAFT) has begun. Since the RF driven negative ion source of CRAFT is a high-current beam source with large area, multi-driver negative beam source was employed. When multiple RF drivers of the same type work at the same time, there may be mutual coupling and interference between themselves, which results in an asymmetric distribution of the RF magnetic field in the driver, thereby affecting the extraction of ion current of the RF negative ion source. This study investigated some possible solutions, which would provide theoretical support for CRAFT's RF negative ion source to achieve stable operation.

INTRODUCTION

Compared to filament driven hot cathode ion source, the radio-frequency (RF) driven ion source do not need to consider filament life, and it has the advantage of simplicity, reliability, and longer lifetime, which is most likely to achieve steady-state operation. The ion source of the neutral beam injection (NBI) can be selected between the negative and positive ion source, although it is easier to produce positive ions, the neutralization efficiency reduces sharply when the beam energy higher than 100 keV. When the beam energy is higher than 200 keV, the neutralization efficiency of positive ions decreases to less than 20%, which is of negligible engineering practical value. In contrast, even if the beam energy goes up to 1 MeV, the neutralization efficiency remains at about 60% for the negative ions beam [1]. For large-scale fusion devices like International Thermonuclear Experimental Reactor (ITER), Comprehensive Research Facility for Fusion Technology (CRAFT), and fusion demonstration power plant (DEMO), the required injection beam energy is larger than 200keV/amu to attain more power deposition in the core plasma. At such high beam energy, a negative ion-based neutral beam injection (NNBI) system is inevitable[2]. The RF negative ion source was initially driven by a single driver in the development route of IPP, and multi-driver RF ion source was proposed then due to the higher beam power requirement for NBI system. In 2006, an RF ion source, which of the full width but half the length of the ITER reference source, with four drivers, was commissioned in IPP[3]. In 2012, Kraus et al. proposed that the ITER ion source in Padua will use eight cylindrical drivers for plasma generation[4]. Since the RF negative ion source of CRAFT is a high-current beam source with a large area, multi-driver negative beam source was employed. According to the window size of the current multi-driver ion source for fusion devices, their drivers are often close to each other. When these drivers of the same type work simultaneously, there may be mutual coupling and interference between them, which results in an asymmetric distribution of the RF magnetic field in the driver, thereby affects the extraction of ion current of the RF negative ion sources. In 2012, the researchers from IPP also pointed out that some mutual inductance occurs between the two drivers [4].Therefore, it is urgent to carry out a study of the multi-driver decoupling model of the RF negative ion source to realize the stable operation for CRAFT negative beam source.

RF BASED NEGATIVE ION SOURCE DEVELOPMENT ROUTE

The development route of ITER RF based negative ion source is indicated in Fig. 1. In the beginning, the IPP prototype source is equipped with one driver. Then, the ELISE (Extraction from a Large Ion Source Experiment), which is regarded as an important intermediate step from IPP prototype source to the ITER source with 8 drivers[5], went into operation in November 2012 with the first plasma in February 2013[6]. The ultimate goal is to build the ITER source with 8 drivers.

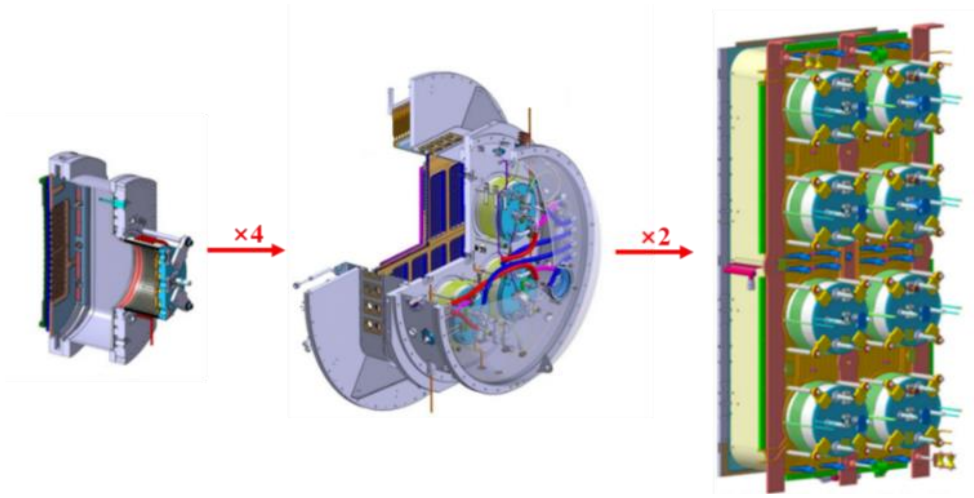


FIGURE 1. Development route from the IPP prototype source with one driver to the ITER source with 8 drivers[7].

Fig. 2 shows the development route of CRAFT's RF based negative ion source in ASIPP. ASIPP chooses to develop an RF negative ion source in the first step, it is equipped with one driver[8]. In the future, the source size will be increased, and there would be more drivers on the negative ion source of CRAFT.

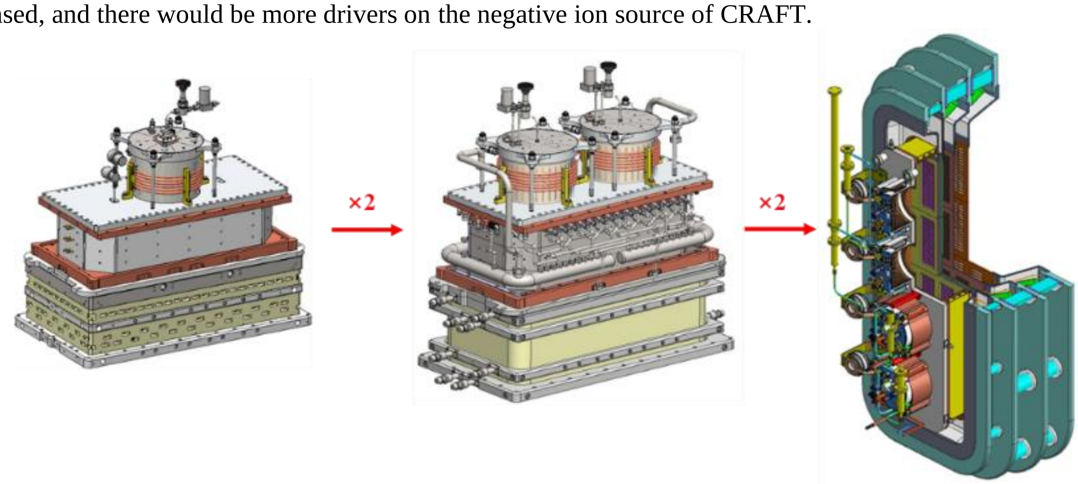


FIGURE 2. Development route from the IPP prototype source with one driver to the ITER source with 8 drivers[9].

Due to the different window scale of the ion source, there is a slight difference in the development route of RF negative ion source between ASIPP and ITER, which is shown in Table 1. The power supply mode of ELISE is that each of the generators drives a pair of two horizontal drivers in series, the same as the case for the ITER NBI sources while CRAFT NBI source will adopt the mode of one generator supply to one driver[10]. Determined by the shape of the ion source window of CRAFT, its driver is intended to be designed as mode of four vertically distributed drivers. However, this distribution mode needs to consider the uniformity of generated plasma, which will be further explored in future studies.

TABLE 1. COMPARISON BETWEEN ITER, ELISE AND CRAFT

Device name	Power supply mode	Distribution mode of driver
ITER	One RF generator supplies to two drivers, which are connected in series.	Symmetric distribution
ELISE	One RF generator supplies to two drivers, which are connected in series.	Symmetric distribution
CRAFT	Each driver is supplied by one RF generator.	Vertically distribution

METHODS OF SOLVING MUTUAL COUPLING OF DRIVERS AT PRESENT

According to the study of Fantz et al. in 2012, when the two drivers in series were shielded by a copper plate between the drivers or a cylinder around each driver, the mutual inductance between them vanished[4]. After the first RF ion source test facility was successfully developed in KAERI[11, 12], as shown in Fig.3, Doo-Hee Chang et al. pointed that outside of the driver region of the test LAHP-RaFIS was shielded by using a metal housing, which could prevent the leakage of RF power[13, 14]. In 2014, the study about ELISE proposed that a copper RF shield was used to avoid asymmetries of the RF magnetic field in the driver[10]. In 2017, Kraus et al. proposed a method of replacing a driver in series with one larger racetrack-shaped driver, which was shown in Fig.4, this way could simplify the design, as well as solve some problems including driver coupling.

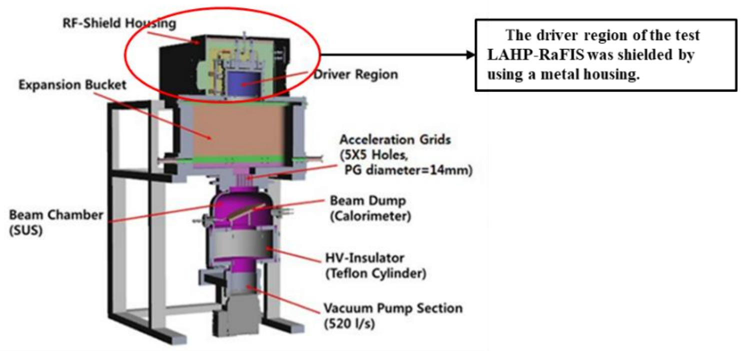
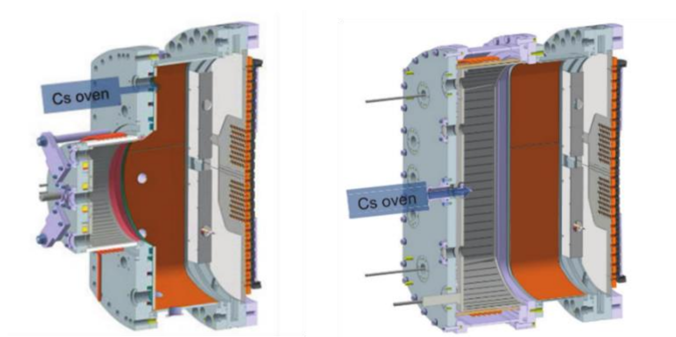


FIGURE 3. Photo of the test RF ion source system at KAERI[14].



(a) (b)

FIGURE 4. Drawing of the BATMAN source with (a) cylindrical driver and (b) racetrack shaped driver[15].

OTHER POSSIBLE WAYS

The flux chain in coupling inductance is not only related to the applied current but also related to the tight and thin degree of coil coupling determined by coil structure, mutual position, and magnetic medium. k is used to represent the coupling factor of coupling inductance, the mathematical expression of k is shown in Equation (1):

$$k \overset{\text{def}}{=} \frac{M}{L_1 L_2} \leq 1 \tag{1}$$

If the position between coupling coils is changed, it is possible to change the coupling factor of coupling inductance. When L_1 and L_2 are fixed, M will change. We can try to change the distribution of drives within a limited window size range to determine an optimal distribution pattern.

Another method has been applied to eliminate the coupling of the antenna array: using the reactance component to compensates the coupling induction between the antenna elements[16]. The driver structure of the RF ion source is a spiral coil therefore, capacitors could be applied to eliminate inductive coupling between the drivers. A possible circuit is shown in Fig. 5: suppose the mutual inductance between the two independent drivers is M_{12}, C_d represents the decoupling capacitance between them， ω represents the operating frequency of the driver. The decoupling circuit needs to satisfy the condition as Equation (2):

$$\frac{j}{\omega C_d} = j\omega M_{12} \tag{2}$$

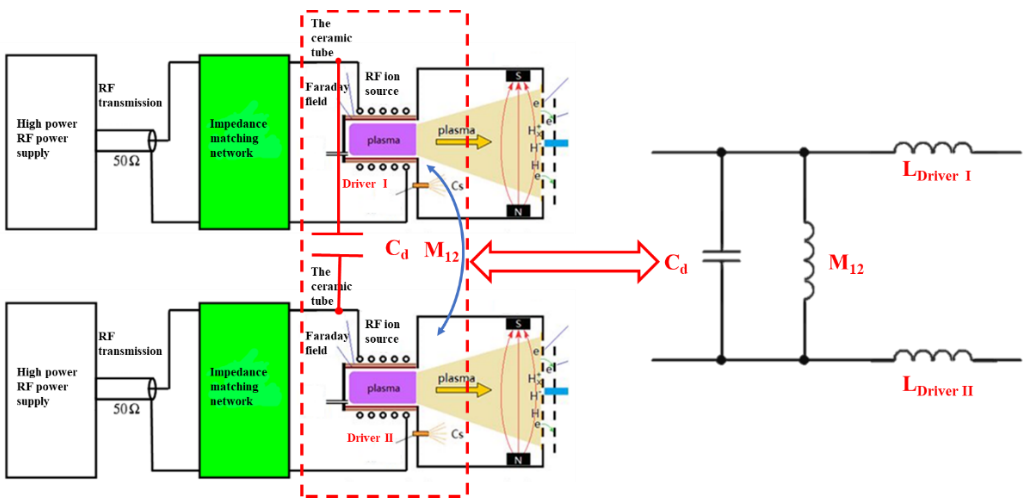


FIGURE 5. A kind of decoupling method in the case of two drivers and the simplified circuit.

Similarly, when the number of multiple drivers becomes larger, decoupling capacitors can be added between each two drivers to eliminate mutual inductance. However, its effectiveness remains to be studied, which will be further explored in the future. Fig.6 briefly shows the connections of the decoupling capacitor between driver I and II， so do driver III and IV.

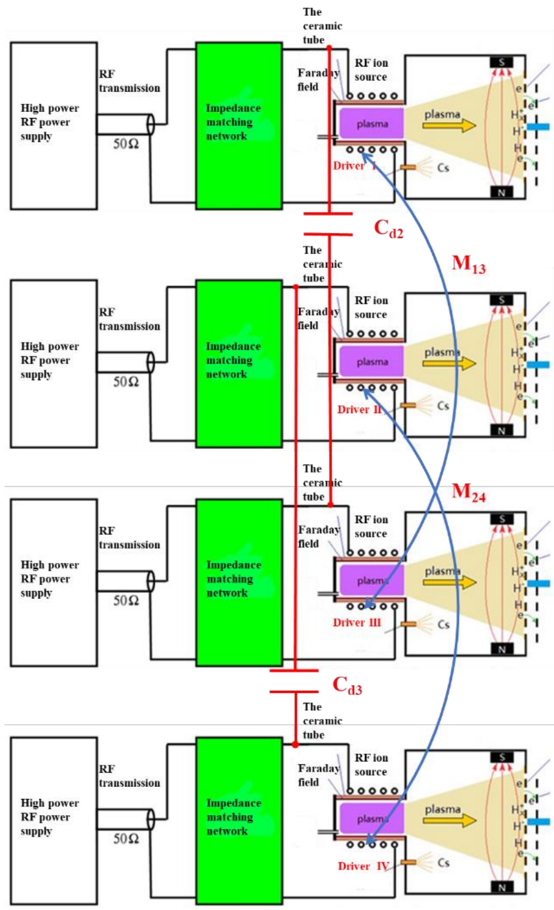


FIGURE 6. Part of decoupling capacitor connection mode in the case of four drivers.

SUMMARY

The distribution mode with the least mutual coupling and interference between the drivers would be further studied. Under this mode, the effectiveness of different decoupling methods will be compared in the decoupling model, such as adding metal shielding on the periphery of the driver, adding decoupling capacitors in the driver circuit, replacing multiple drivers with larger drivers, and so on，which would greatly support CRAFT's RF negative ion source to achieve stable operation.

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