Comparative study on cost evaluation and network visualization of particle accelerator components for heavy ion inertial fusion

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Abstract. By visualizing accelerator system components in heavy ion inertial fusion, the connection between the components becomes clear. We clarify an influential component on the entire cost by the relation of node connections due to the visualization result. Since a low cost component affects a high cost component, not only the cost estimation but also the relation between the components is considerable and important issue. A cost estimation result changing with an induction core cost indicates no influences in the rate of details.

1. Introduction

Inertial confinement fusion (ICF) is a method for realizing a fusion energy system. Several energy drivers such as laser, pulsed-power discharge induced X-ray, and charged particle beams are candidates for an ICF system. Heavy ion inertial fusion (HIF) is one of the methods for ICF driven by intense heavy ion beams. To accelerate heavy ions, we must consider the space charge effect, because of the high-current beams are required in the HIF system. For this reason, as methods to accelerate the heavy ions, various accelerator concepts are proposed as the HIF driver [1]. However, all the methods require a huge particle accelerator. Moir [2] has estimated the cost of HIF system "HYLIFE-II", and compared the costs in the cases for lasers and heavy ion beams as the energy driver.

Figure 1 shows the typical system with a linear accelerator (linac) [3]. In this system, each component is connected to the linac. In the case of recirculator as shown in Fig.2, several accelerator components such as an injector, induction units, bending magnets, injection and extraction kicker systems, and so on, are included in the system. After the acceleration of the heavy ions by using the small circular accelerator, the heavy ions transit to next circular accelerator (medium energy ring), and are further accelerated. Figures 3 and 4 indicate the connection between the components at each system. However, these costs and connections are difficult to design the HIF system because of the unclear and complex connections of the each component.

In this study, we researched the cost evaluation and the visualization of system network. To visualize the HIF systems and the cost weights proposed by Meier et al [4] and Newton et al [5,6], we have used Gephi [7], which is software to visualize the network connections. The cost of the HIF system has been suggested various estimations including the details. However, the relation between the components in HIF system is unclear. To understand the relations, we considered a correlation diagram of HIF system using Gephi.
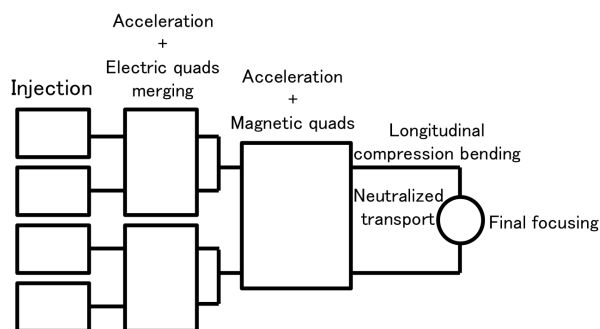
Figure 1. HIF system with linac [3]
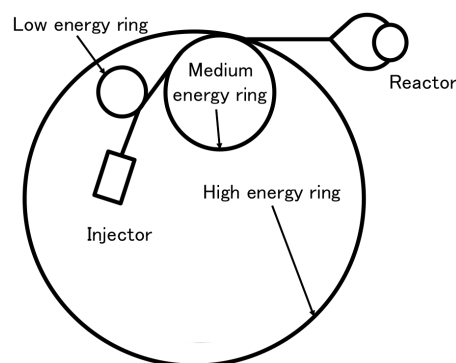
Figure 2. HIF system with recirculator [5]
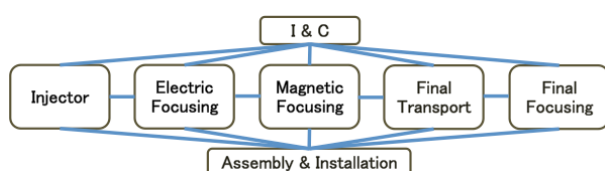
Figure 3. Component model of linac system
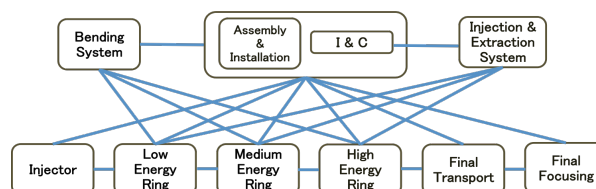
Figure 4. Component model of recirculator system

2. Classification of cost and components

Table 1. Meier's system (Linac) cost

Component		Cost [M$]	Rate [%]
	Assembly and Installation	322.0	23.0
Operation Cost	I&C	112.0	8.0
Total Accelerating System Cost	Electrostatic Focusing	140.0	10.0
	Magnetic Focusing	672.0	48.0

Table 2. Newton's system (Recirculator) cost

Component		Cost [M$]	Rate [%]
	Administrative	38.5	7.7
	Controls	18.3	3.7
Operation Cost	Engineering	38.5	7.7
	Facilities	54.4	10.9
	Installation	38.5	7.7
	Alignment system	30.6	6.1
	Focus magnet system	44.7	8.9
Total Accelerating System Cost	Prime power system	45.0	9.0
	Vacuum system	52.0	10.4
	Accelerating system	67.1	13.4

We show the details of "Operation cost" and "Total Accelerating System Cost" in Tables 1 and 2. Tables 1 and 2 show the cost details of Operation and Total Accelerating System at each system. Because each HIF accelerator system has different components for the above cost estimations, we categorized the individual element costs as "Operation cost" and "Total Accelerating System Cost." The cost and the rate (percentage of the individual element cost to the total cost) were cited from Refs.[4] and [5,6] in the tables.

3. Visualization of cost and connection between components for accelerator system

3.1. Visualization of connection between components of accelerator

Figure 5 shows the visualization of both HIF systems, according to the cost estimation summarized in the previous section and the component models as shown in Figs.3 and 4. The circle size shows the cost, and the circle color shows the number of in-degree, which is the incident number of arrows into the node. In the higher value of in-degree, the color becomes thick. It implies that a starting point node (component) of an arrow affects a terminal node of the arrow.

(a) Meier's system (Linac)   (b) Newton's system (Recirculator)
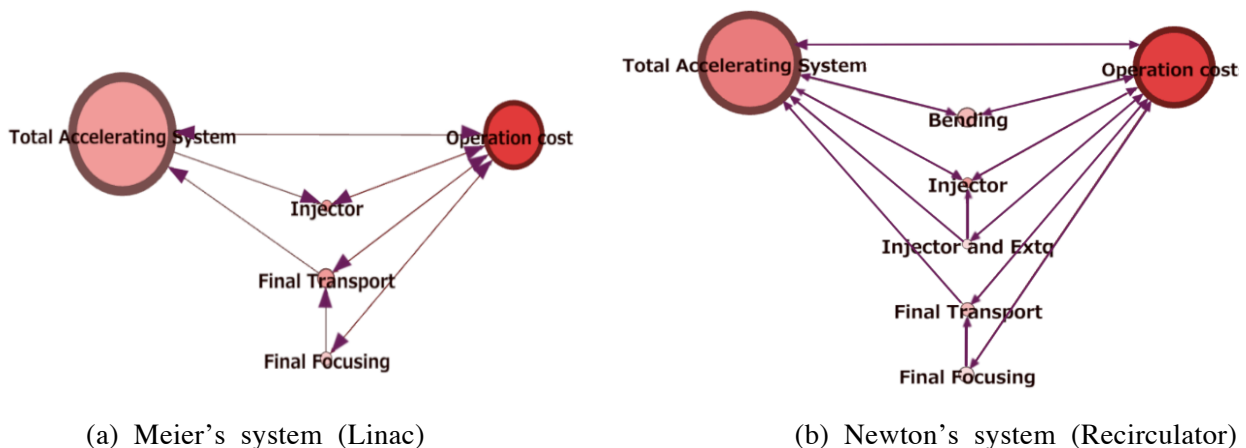
Figure 5. Visualization of connection between accelerator components for linac and recirculator systems.

We assume that the HIF accelerator system is designed by the requirements from the fuel pellet side. The Total Accelerating System is the highest in all the costs, and the Operation cost is the second component. The number of connected nodes in the Total Accelerating System and the Operation Cost is almost same.

In the Meier's system model, the number of nodes connecting with the Total Accelerating System is three, and the number of nodes connecting with the Operation cost is four. On the other hand, the number of nodes connecting with the Total Accelerating System is five, and the number of nodes connecting with the Operation cost is five in the Newton's system model. Because, the Newton's system model has the components for the Bending and the Injection and Extraction due to a recirculator configuration, while the Meier's system model has no component for the Bending and the Injection and Extraction, which the system consists of a linac. As shown in Fig.5(a), in the Meier's system model, the cost of the Final Transport component is small. However the Final Transport affects the Total Accelerating System, which is the highest cost component. It is predicted that the modifications of the Final Transport design give the changes of the Total Accelerating System. As a result, a cheap component such as the Final Transport may control an expensive component.

In the case of Newton's system model, as shown in Fig.5(b), the bending and the Injection and Extraction components are extra equipment in comparisons with the linac system. The Injection and Extraction component affects directly the Total Accelerating System and the Injector components. For this reason, the Injection and Extraction component affects indirectly the Total Accelerating System

via the Injector. Consequently, although the cost of the Injection and Extraction is cheap, the influence is not low impact on the entire system design and cost.

In both the systems, the Total Accelerating System and the Operation costs are high, and have large number of nodes connecting to the other components. As a result, both the components are critical in the HIF system. However, as mentioned above, a node with the low cost such as the Final Transport affects the high cost component such as the Total Accelerating System. Consequently, not only the cost estimation but also the relation between the components is considerable issue.

3.2. System cost estimation for induction core cost

Figure 6 shows the total cost and the details at each system. The two graphs at the left side show the original costs in Refs. [4] and [5,6]. The Total Accelerating System and Operation cost are accounted for the majority of the total cost. The two graphs at the right side show the details of costs after changing the cost of the induction core. The cost of induction core in the Newton's system model was 5 $/kg. On the other hand, the cost was estimated as 20 ~ 150 $/kg [8]. For this reason, we also estimated the total system cost when the cost of the induction core quadrupled. In comparison with the estimations, the total cost increases, however it was found that the rate of cost details is similar.
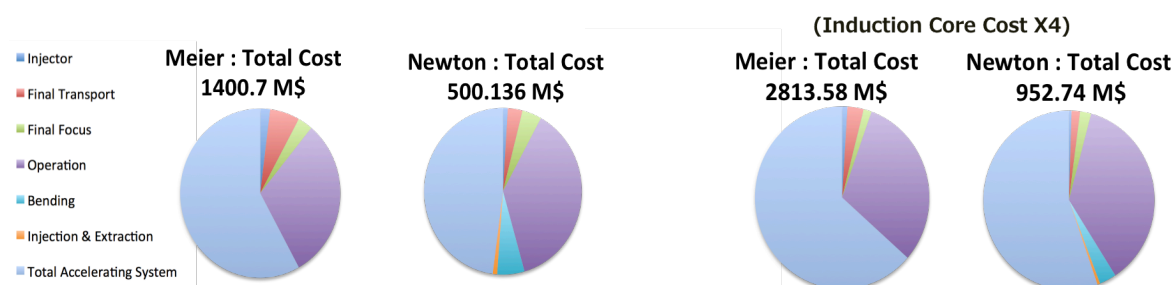
Figure 6. Comparison of cost as a function of induction core cost at each system model

4. Conclusion

By visualizing the components of accelerator system in the HIF using Gephi, the connection between the components became clear. Because it was difficult to understand from the only cost estimation, the component network visualization has a possibility to find the unclear fact.We clarified an influential component on the entire cost by the in-degree of the node. Because the Operation cost is connected to many nodes, it is considered particularly important element to determine the total cost. In addition, element number of system is also important. The Newton's system has more components than that for the Meier's system. It suggested that each component is closely related to other components. Not only the cost estimation but also the relation between the components was considerable and important issue. The induction core cost was main for the HIF accelerator system. The cost estimation changing with the induction core cost indicates no influences in the rate of the details. Considerations of any other costs in the above, such as social cost, public relation cost, and ethical education cost, are in our near future work for the economics in the HIF system.

References

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