HIGH-CURRENT ELECTRON BEAM POWER MULTIPLICATION BY CONVERGING THE BEAMS[1]

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This paper is devoted to research and development of the techniques of multiterawatt electron beam generation in pulsed multimodular systems. Three methods of beam convergence/overlapping have been studied numerically and experimentally. Experiments showed efficiency of three beam energy addition equal to (93±3)%.

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1. INTRODUCTION

In the multimodule facilities, that have been built to present day and designed to generate multiterawatt charged particle beams, electric power as produced in each module is summed up on the general diode generating one beam of super-high power. However, for generating high-power pulsed bremsstrahlung flows with a multimodular facility it may be preferred to converge/overlap the electron beams generated by each module separately. This approach for high-power beam generation presupposes availability of a section for every beam to be transported from the diode to the point where they are to combine, as well as of a region where the beams are to partially overlap or combine into one common beam. The only method for megampere electron beam transport that has been realized by now is electron grad-B drift transport in the outer azimuthal magnetic field induced by a current carrying conductor. In this transport method, the azimuthal magnetic field creating conductor is positioned along the beam axis. The beam self-fields are compensated by plasma produced by the beam when being injected into the drift chamber. For that the drift chamber is filled with background gas at several Torr pressure before the beam is injected into it. Successful use of this method for 1.1-MA, 0.9-MeV beam transport was reported in [1].

This work was aimed at finding some schemes of overlapping several electron beams transported by grad-B drift to be combined into one common beam with minimal electron loss in the transition region.

2. BEAM CONVERGENCE METHODS AND RESEARCH RESULTS

As long as simple joining of conductors transmitting separate beams results in the excessive electron loss and considerable increase of the common beam cross-section, several possible convergence schemes have been analyzed and chosen to be further studied using the created computer model. As a result three feasible schemes providing potentially minimum electron loss and insignificant increase of the common beam diameter have been chosen to be verified experimentally.

2.1. EXPERIMENTAL EQUIPMENT

Experimental testing of the beam convergence schemes was carried out on “Nadia” electron accelerator providing the beam pulsed current of 100 kA and particle energy of up to 1.0 MeV. To form three separate beams three cathodes were attached to the accelerator high-voltage output electrode which together with three separated output windows formed three parallel diodes each generating an electron beam with the current of about 30 kA.

To study the electron beam energy characteristics x-ray diagnostic facilities together with calorimeters were used. To visualize the beam shapes and their position in the transport channels as well as to measure the electron density distribution over the cross-section thin tantalum strips were arranged along the beam trajectories and the bremsstrahlung induced by electrons in these strips was recorded by pin-hole cameras and pin-diodes.

2.2. BEAM CONVERGENCE BY BENDING GUIDE CONDUCTORS

Let us consider the process of electron drifting along the bent conductor. In the curvature region magnetic field around the conductor becomes asymmetric and the electrons are pushed away from the stronger field region into the weaker one. In other words, if the straight conductor is the beam axis, then, when it is bent the beam is biased aside and drifts beside the conductor. Complete “sliding” of the beam from the conductor is observed when the electron velocity azimuthal components are negligible (cold beam). However, the real high-current beams are generated with a wide velocity angular spread, which prevents the beam from complete separating from the conductor. This was experimentally verified in [2]. Nevertheless, the beam axis displacement might be used for electron beam partial overlapping. In this case one should exclude combining of magnetic fields induced by separate guide conductors. To meet this requirement thin current carrying planes should be placed between the guide conductors.

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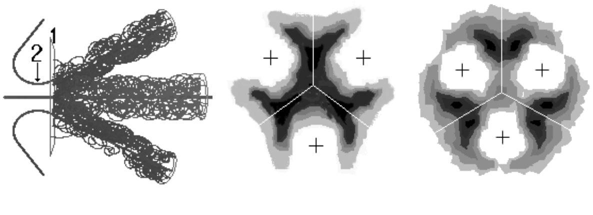


a **b** **c**

Fig.1. Computer simulation results on three electron-beam convergence in the curved channels:
a – examples of electron trajectories;
b, c – total beam structure in the planes 1, 2 of Fig.2,a

Numerical simulation results for three-beam convergence by this method are summarized in Fig.1.

As the beams approach the system axis the electrons from the beam outer bounds start crossing the transport channel division planes. Then, the electrons scatter in the current carrying boundary material and also due to the drastic jump of the magnetic field vector direction at these bounds. Due to scattering more and more electrons pass outside the guide conductors resulting in the total beam expanding. Thus, there is an optimal point on the convergence system axis where the total beam cross-section is minimal. The electron energy loss in the separating current carrying planes can be utilized if these planes are used as the bremsstrahlung target component.

Fig.2 is the picture of one of the beams made by a pin-hole camera using thin tantalum strips.

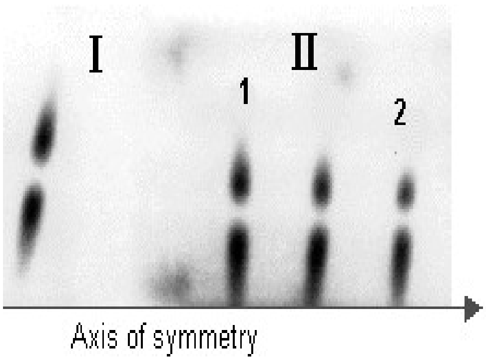
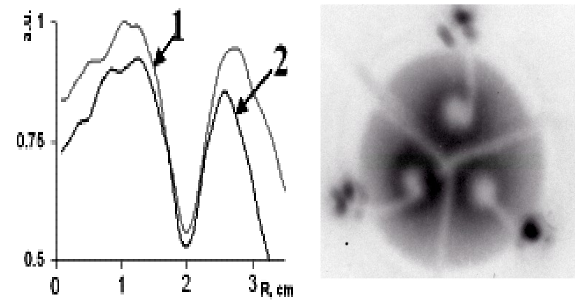


Fig.2. Photograph of the beam trace on tantalum strips

As the x-ray photograph shows, the beam has an azimuthal-symmetric electron density distribution around the guide conductor at the section of the straight trajectory of the beam (area I). The beam center in the area of the guide field azimuthal symmetry breakdown (II) is biased to the convergence system axis.

Digitally processed x-ray tracks on foils 1 and 2 of Fig.2 are summarized in Fig.3,a. Fig.3,b presents an x-ray photograph of the bremsstrahlung target for three beams.



a b

Fig.3. Radial profiles of electron density – a;
b – bremsstrahlung target x-ray image

Calorimetric measurements have shown the total energy of the overall beam in its narrowest cross-section point to be 60% from the sum of three-beam energy. 40% of the energy is lost in the copper wires that separate the transport channels.

As these figures show, for this beam convergence scheme one might speak about partial overlapping of the beams.

2.3. BEAM CONVERGENCE ONTO A COMMON CONDUCTOR

The convergence scheme presented in Fig.4 is more attractive.

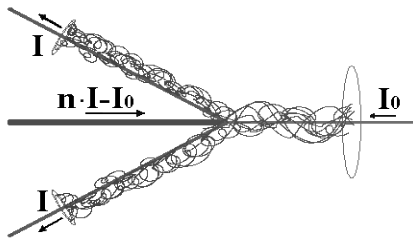


Fig.4. Scheme of beam convergence onto a common conductor

In this scheme, all the guide conductors are combined into the common one, and in order to hold the necessary common conductor current I_0, its major portion $n{\cdot}I{-}I_0$, where n is the number of the converged beams, and I is the current of each channel conductor, is fed back through an additional conductor. The feedback conductor role in this scheme is very significant. The magnetic field induced by the feedback conductor provides for the field azimuthal asymmetry around the guide conductors of separate beams, especially, in the region upstream of the point of junction of all the conductors. The magnetic field strength from the direction of the convergence system axis, increasing as the electrons move to the common conductor, causes the beams displacement outside the guide conductors (relative to the system axis), thus improving conditions for all the beams to pass to the common conductor. Besides, the magnetic field induced by the reverse current eliminates the zero field areas between the guide conductors, thereby eliminating the channels of the electron loss.

It should be noted that the combined beam diameter is determined by the structure of the magnetic field induced by the conductors, and does not change, virtually, with changing of the number of the beams combined. By changing the guide conductor current ratio I/I_0 one may adjust the common beam diameter. Experimental results of studies on the common beam diameter variation depending on the current ratio I/I_0 are presented in Fig.5.

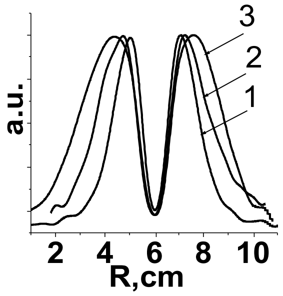
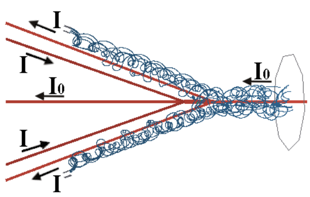


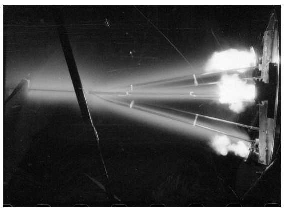
Fig.5. Electron beam density profiles: 1 – a single beam in the transport channel at the guide conductor current I = 40 kA: 2, 3 – total beams at the common conductor current I_0 = 31 kA, and 40 kA, respectively

As can be seen from comparison of the curves *1* and 2 in this figure, the combined beam cross-section area is twice as large, so, when two beams are converged the common beam density does not grow. On the other hand, each additional beam increases proportionally the electron density of the total beam.

Careful calorimetric energy measurements for all the beams have shown this scheme to provide (93±3)% efficiency of the beam energy summation.

Another version of the beam convergence system is presented in Fig.6. This scheme is a modified version of the previous one.





a b

Fig. 6. Scheme of several beam convergence with the guide field azimuthal asymmetry over the full length of transport channel (a); a photo of three beams in the air with transport chamber housing off (b)

This scheme requires two current generators for magnetic field generation. The first generator provides pulsed magnetic field for separate beams transporting. In this case the current of each channel *I* runs through the guide conductor and is fed back through the parallel one which is placed closer to the convergence system axis. Electron beams are injected from the outer side of the guide conductors, and due to the magnetic field azimuthal asymmetry over all the transport channel length they propagate up to the top of the cone at the outer side of the conductors, and are combined on the common conductor positioned along the system axis. This conductor is fed with a current pulse I_0 from a separate capacitor bank. The possibility to vary more flexibly the current ratio I/I_0 facilitates adjusting the total beam diameter.

A photograph of three beams converged by this method, and propagated in the air at the atmospheric pressure is presented in Fig.6,b.

Fig.7 represents radial distributions of the beam electrons for a single channel, and for the total beam.

As these figures show, the back current carrying parallel conductor does not provide for the complete expelling of the electrons outwards the guide conductor. A portion of electrons propagates between the parallel conductors. At the same time, the outside weaker field forms the beam more stretched outside what results in a larger total beam diameter against that in the previous scheme at the same currents in the appropriate guide conductors.

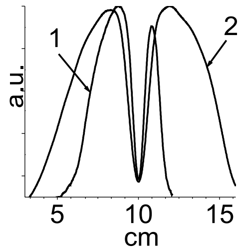


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Fig.7. Radial distribution of electron densities in the beams: a – x-ray images; b – digital processing data images in x-rays. 1 – the single beam, 2 – the common beam

The beam energy summation efficiency for both of the above studied schemes is nearly the same within the limits of the measurement error. The major electron loss (about 7%) occurs at the top of the cone at the joint of separate channel guide conductors.

3. CONCLUSIONS

The results of the numeric simulations and R&D have shown that for the beams transported by grad-B drift in azimuthal magnetic field, a configuration can be created for the guide magnetic field providing convergence of several high-power electron beams into a common one without considerable loss, using relatively simple methods.

Several problems, related to the beam self-field compensation have been left out beyond the scope of this work. The challenge is such that if the net currents of the beams transported separately are much below their Alfven limits, then, when the beams are combined, the net currents are summed up too, and the total beam net current may exceed the Alfven limit. This fact requires the initial beams having a high level of current compensation.

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УМНОЖЕНИЕ МОЩНОСТИ СИЛЬНОТОЧНЫХ ЭЛЕКТРОННЫХ ПУЧКОВ ПУТЕМ ИХ СЛОЖЕНИЯ

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Исследованы и разработаны методы генерации мультитераваттных электронных пучков в многомодульных импульсных системах. Три метода сведения/сложения пучков были исследованы численно и экспериментально. Эксперименты показали эффективность сложения энергии трех пучков равной (93±3)%.

УМНОЖЕННЯ ПОТУЖНОСТІ СИЛЬНОСТРУМОВИХ ЕЛЕКТРОННИХ ПУЧКІВ ШЛЯХОМ ЇХ СКЛАДАННЯ

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Досліджено і розроблено методи генерації мультитераватних електронних пучків у багатомодульних імпульсних системах. Три методи зведення/складання пучків були досліджені чисельно та експериментально. Експерименти показали ефективність складання енергії трьох пучків рівною (93±3)%.