POLISH INPUT TO BEAM DYNAMIC RESEARCH FOR A SUPERCONDUCTIVE LINEAR ACCELERATOR IN THE EARLY NEUTRON SOURCE PROJECT*

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DONES, which is a deuteron–lithium source of high-energy neutrons, has been designed to test materials for a proposed fusion reactor. DONES will produce a 125 mA deuteron beam, which will be accelerated to 40 MeV energy and will hit a liquid lithium curtain, causing intensive neutron production, sufficient to simulate neutron radiation in fusion reactor. Those neutrons enable experimental probes of materials in a test cell. The general aim of our research was superconducting radio-frequency linear accelerator optimization. The specific aim of our calculations was to find phase values for each accelerating cavity separately, and to achieve a deuteron beam that matched each of two criteria simultaneously: the energy of the beam had to reach at least 40 MeV at the end of the accelerator, and energy losses of the beam have to be less than 1 W/m (in the 1-meter section where losses were the highest). A further complication occurred when changes in the accelerator design were made during the course of our research. The first change was the redesigning of existing criomodules and addition of one more criomodule. The second change was an extension of the spaces between criomodules. We found proper optimisation after the first change, however, our optimisation before the change was not sufficient. We are working on optimisation after the last design modification.

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1. Introduction

DONES — DEMO (DEMOnstration Power Station) Oriented Neutron Source is a part of the Early Neutron Source (ENS), one of the EUROfusion program, which is a consortium of thermonuclear fusion institutes from 28 European countries. The consortium was founded in 2014 as a successor to European Fusion Development Agreement (EFDA). The aim of the consortium is to build a functional prototype of fusion reactor by 2050. This project

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is funded under the Horizon 2020 European program. DONES is envisioned as a successor to the Linear IFMIF Prototype Accelerator (LIPAC) and simplification of International Fusion Material Irradiation Facility Engineering Validation and Engineering Design Activities (IFMIF/EVEDA) [1].

DONES, which is a deuteron–lithium source of high energy neutrons, has been designed to test materials for the proposed fusion reactor. The intensity of the neutrons should be sufficient to simulate neutron radiation in a fusion reactor. DONES will produce a 125 mA deuteron beam, which will be accelerated to 40 MeV energy and will hit a liquid lithium curtain, causing intensive neutron production. Those neutrons enable experimental probes of materials in a test cell [2].

DONES contains three main components: Accelerator Systems, Test Systems and Lithium Systems (see Fig. 1). The Accelerator Systems contain a deuteron injector, Low Energy Beam Transport (LEBT), Radio Frequency Quadruple accelerator (RFQ), Medium Energy Beam Transport (MEBT), Superconducting Radio Frequency Linear accelerator (SRF-L) and High Energy Beam Transport (HEBT).

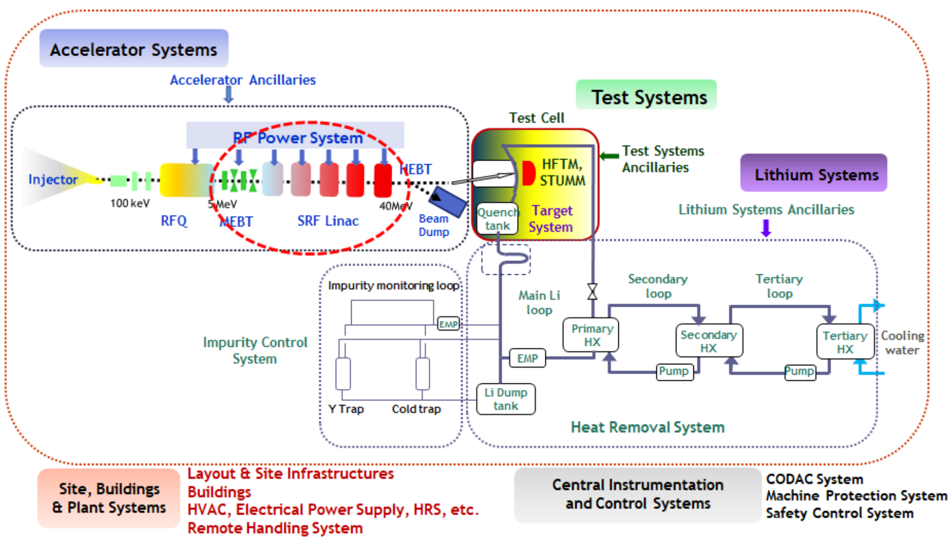

Fig. 1. DEMO-oriented neutron source. A part interesting for us is marked with the dashed line. Courtesy of Prof. W. Królas.

2. Polish research on DONES

The general aim of our research was SRF-L optimization following modification of the accelerating cavities. However, initial calculations of SRF-L alone were not sufficient. To obtain reliable results, we calculated Accelerator Systems from the end of RFQ to the beginning of HEBT (MEBT and SRF-L sections).

A further complication occurred when changes in SRF-L design were made during the course of our research. The initial accelerator contains four criomodules. The first change was the addition of a fifth criomodule and redesigning of modules from two to four. The second change was an extension of the spaces between criomodules.

The specific aim of our calculations was to find phase values for each accelerating cavity separately, and to achieve a deuteron beam that met each of two criteria simultaneously: the energy of the beam had to reach at least 40 MeV in the end of SRF-L and energy losses of the beam had to be less than 1 W/m (in the 1-meter section where losses were highest).

We checked the beam energy, value and localisation of losses. We also searched those sections where particle acceleration was suboptimal — where some deuterons began to exhibit energy that was too low, or phase that was too high in comparison to the rest of the beam. We could also change phase value of cavities and some other parameters (*i.e.* quadruple settings or value of solenoid fields), in SRF-L and MEBT.

All calculations were performed using two codes. The first one, TraceWin was written in CEA Saclay. This code was designed for linear and non-linear, 2D and 3D calculations of a charged particles beam and for optimization of beam parameters [3]. The second one, General Particle Tracer (GPT) was designed by van der Geer and de Loos [4]. This code is based on full 3D technics of charged particle tracing in an electrical field.

3. Four-criomodules accelerator

We checked 66 main variants of accelerator settings. These variants differed with the phase settings of each accelerating cavity. Our method was to maintain beam energy over 40 MeV and minimize beam energy losses.

In the first variant we assessed, losses were over 550 W/m at the site of the greatest loss. The best case variant beam energy we found was 40.185 MeV (calculated with TraceWin, see Fig. 2) and 40.176 MeV (calculated with GPT), while energy losses in the worst place were 8.35 W/m (TraceWin) and 23.57 W/m (GPT). Localisation of the losses calculated with either code was similar. The section with the highest losses was 15.3–16.3 m (TraceWin) and 15.5–16.5 m (GPT). Total losses of the beam were 18.96 W (TraceWin) and 62.34 W (GPT). Therefore, the aim was not reached. When the beam energy was over 40 MeV, the loss level was unacceptably high.

Figure 3 shows phase density (general view) of the beam, while Fig. 4 shows the envelopes (X-direction, Y-direction and phase envelope) of the beam.

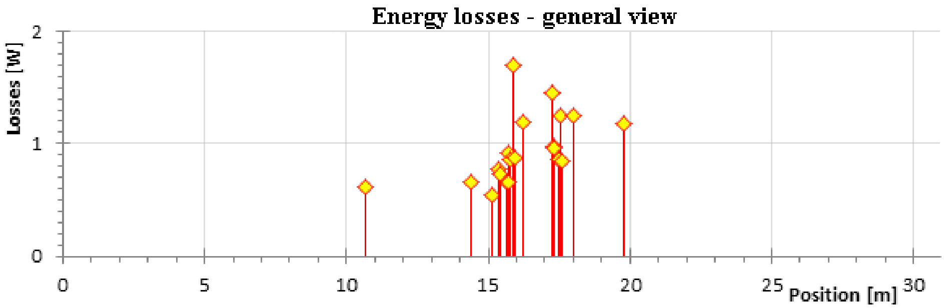

Fig. 2. Localisation of beam energy losses for the best variant calculated with TraceWin.

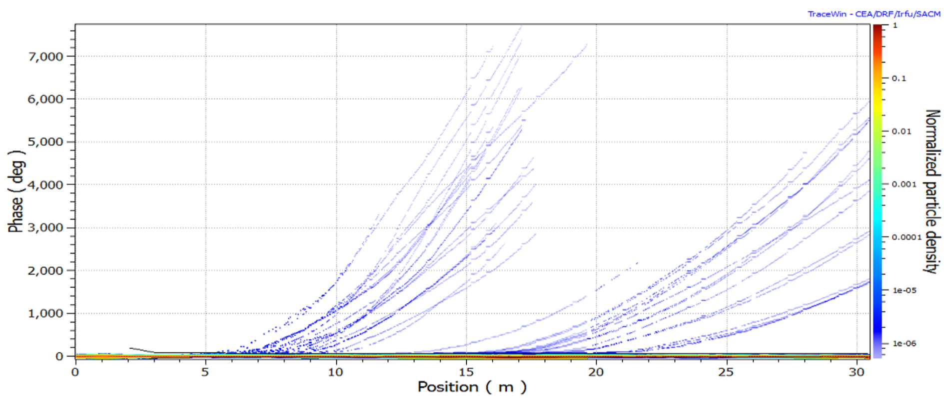

Fig. 3. Phase density of the deuteron beam.

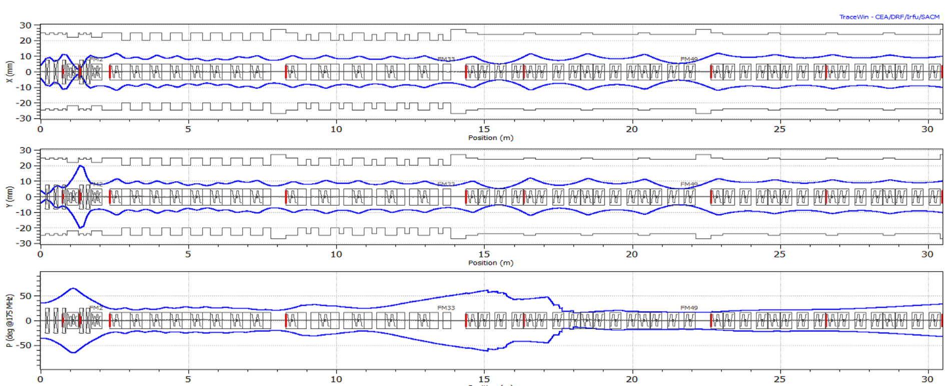

Fig. 4. Envelopes of the deuteron beam. Upper: X-direction; middle: Y-direction; bottom: phase envelope.

None of the losses were caused by an inappropriate focusing of the beam. Exact analyses show that disorders in phase and energy of the deuteron beam begins at the $5^{\rm th}$ meter of calculation (in the first criomodule) leading to energy losses about 10 meters further along.

4. Five-criomodules accelerator

The SRF-L was redesigned to reduce the size of the beam cross section and to reduce beam losses in the accelerator. The second, third and fourth modules were redesigned and a fifth criomodule was added. Total length of the accelerator was extended by about five meters.

We examined 13 main variants of the modified accelerator. For the best variant, energy of the beam was 40.21 MeV (calculated with TraceWin) or 40.41 MeV (GPT). There were no losses observed in calculations with either code. In Fig. 5, we present phase density of the beam and Fig. 6 shows the envelope of the beam (X-direction, Y-direction and phase envelope).

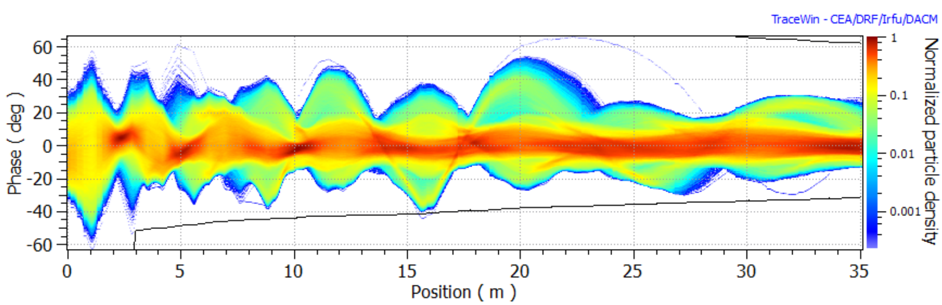

Fig. 5. Phase density of the deuteron beam.

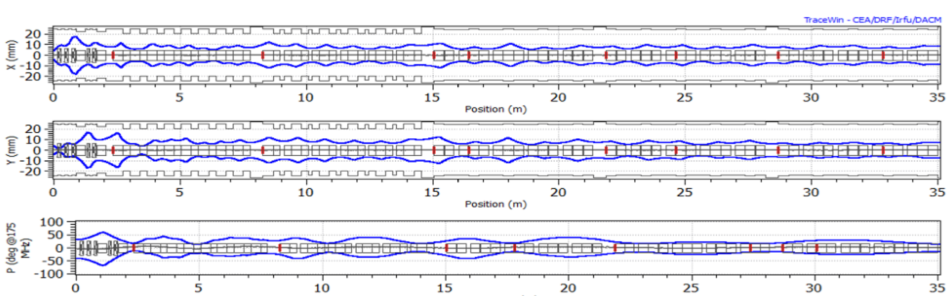

Fig. 6. Envelopes of the deuteron beam. Upper: X-direction; middle: Y-direction; bottom: phase envelope.

We then performed statistical errors analysis, where errors were defined as imperfect positioning (shifting or rotating) of particular elements. We calculated 1500 variants with various, random sets of such errors. There were no variants which failed to fulfil requirements. Highest total losses were 0.87 W when the beam energy was over 40 MeV.

We were given results obtained by the CEA Saclay group for comparison purposes. This group, working in parallel with ours, used only one calculation code: TraceWin. We recalculated their results using the same parameters and using both the TraceWin and GPT codes. The beam energy we calculated with TraceWin was 39.98 MeV and with GPT it was 39.95 MeV. Our calculations showed no losses, neither with standard calculations nor in analysis of statistical error.

5. Summary

For the 4-criomodules design, we did not find an optimisation that fulfilled both criteria. For the best variant, the beam energy was 40.18 MeV, but energy losses were 8 W/m in the worst place and total losses were 19 W.

After modification to a 5-criomodules SRF-L, we found optimisation. For our best variant, beam energy was over 40.2 MeV and there were no losses. Statistical error analysis showed only minimal losses, none of which exceeded requirements.

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