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Polish Contribution to final Beam Dynamic calculations for accelerator system analysis in the Early Neutron Source project

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ABSTRACT

The DEMO Oriented Neutron Source (DONES; DEMO – DEMOnstration Power Station) is part of the Early Neutron Source (ENS), one of the EUROfusion work packages. The DONES system is designed to provide an accelerator-based D-Li neutron source that produces high energy neutrons at sufficient intensity to simulate the first wall neutron spectrum of future nuclear fusion reactors.

The aim of this work was to optimise the superconducting linear accelerator (SRF-L) to meet two requirements at the same time: (a) deliver sufficient energy of the beam at the end of the linac, (b) minimize energy losses. To obtain reliable results, we used two calculation codes: TraceWin and GPT (General Particle Tracer) to simulate the accelerator system. Based on technical data provided by CEA (French Alternative Energies and Atomic Energy Commission), we investigated 66 variants of the accelerating system. The results were not satisfactory, so the design of the accelerator was changed and subsequently we calculated 13 variants of the new system.

Calculation results for beam energy losses, statistical parameters of the beam and beam density in analysed phase spaces were obtained and compared in both codes. At present, the best result obtained is a beam energy of 40.4 MeV with no losses.

KEY WORDS

Beam dynamic, linear accelerator, superconductive, DONES.

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1. INTRODUCTION

The DEMO Oriented Neutron Source (DONES; DEMO – DEMOnstration Power Station) is part of the Early Neutron Source (ENS), one of the EUROfusion work packages. DONES is the successor to the Linear IFMIF Prototype Accelerator (LIPAC) and represents a simplification of International Fusion Material Irradiation Facility Engineering Validation and Engineering Design Activities (IFMIF/EVEDA)[1]. DONES is intended to test materials for suitability for use in a fusion reactor.

The DONES plant will produce a 125 mA deuteron beam, which can be accelerated up to 40 MeV and shaped to have a nominal cross section of 100 mm x 50 mm (20 mm x 10 mm, after an accelerator design modification), that impinges on a liquid lithium curtain. The stripping reactions generate a large number of neutrons that interact with material samples located behind the lithium target[2].

The accelerator (Fig. 1) consists of the deuteron source, Low Energy Beam Transport line (LEBT), Radio Frequency Quadruple accelerator (RFQ), Medium Energy Beam Transport line (MEBT), Superconducting Radio Frequency Linear accelerator (SRF-L) and High Energy Beam Transport line (HEBT).

1.1. Objectives of the work

Our goal was to optimize a part of DONES, the SRF-L, and to perform beam loss studies. A secondary objective was to compare results obtained with two calculation codes.

Optimization required finding optimal RF field phase values separately for each accelerating cavity. The optimized system have to meet two requirements at the same time: the beam energy (delivered with 5 MeV in the entrance of MEBT) of at least 40 MeV in the end of the SRF-L and energy losses lower than 1 W/m in each arbitrary selected one meter long section of the accelerator.

1.2. Calculation codes

Two beam dynamics simulation codes were used: TraceWin and General Particle Tracer (GPT).

TraceWin code was developed by CEA Saclay for linear and non-linear, 2D or 3D, charged particle beam dynamics calculations and optimization of beam parameters[3]. Calculation in TraceWin were performed with PARTRAN method. GPT was developed by dr. S.B. van der Geer and dr. M.J. de Loos, based on full 3D particle tracing techniques, and is used for 2D and 3D calculations of charged particles in an electric field[4].

All calculations with both codes were based on technical data provided by CEA Saclay.

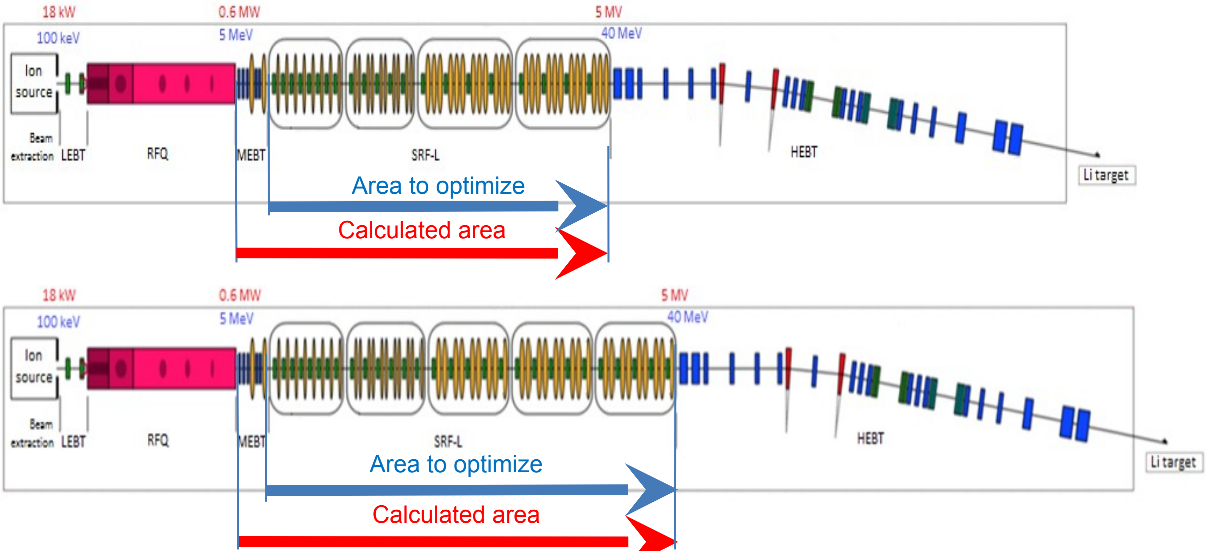


Fig. 1. 4-cryomodules (up) and 5-cryomodules (bottom) design of the DONES accelerator.

2. FOUR-CRYOMODULES DESIGN

Our goal is to optimize only a SRF-L, but to obtain reliable results, we started calculation with the MEBT. The MEBT consists of five quadruple magnets and two bunchers (Error: Reference source not found, upper).

Inside the SRF-L are four accelerating modules. These modules consist of accelerating cavities and solenoids. First two modules have identical low-β cavities, each one (in the first module) or each two (in the second module) separated by a solenoid. The remaining two modules have high-β cavities, each three separated by a solenoid.

For calculation both in TraceWin and in GPT we used 1 054 757 particles.

2.1. Results

We investigated 66 main variants of the accelerating system. These variants differed in phase values for each accelerating cavity.

We maintained energy at the exit of SRF-L above 40 MeV and minimized losses. For the best variant, beam energy was 40.185 MeV for the TraceWin result and 40.176 for GPT calculations. Total losses were 18.96 W for TraceWin (Fig. 2 left) and 62.34 W for GPT (Fig. 2 right).

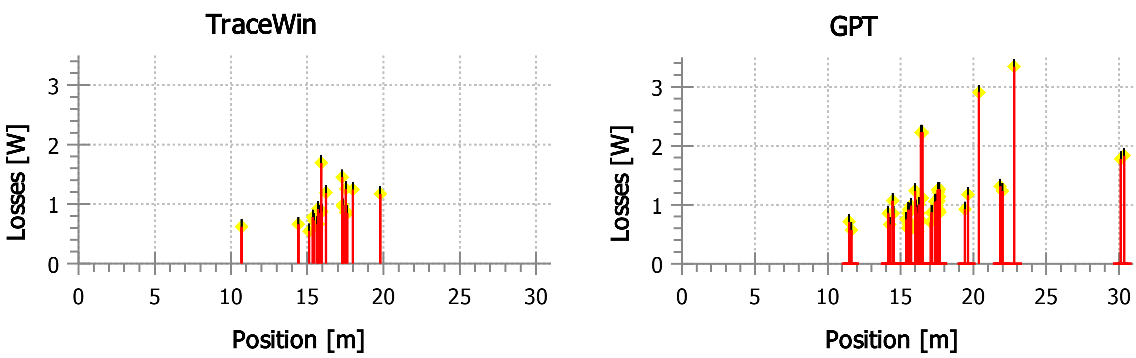
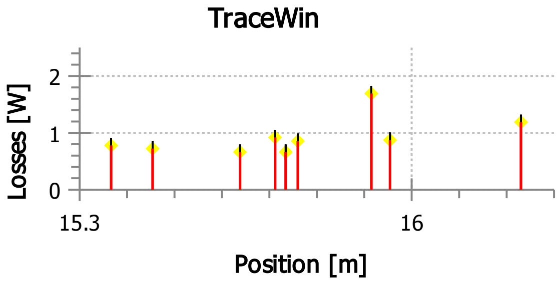


Fig. 2. Total losses for best variant (left: TraceWin calculation; right: GPT calculation).

Losses in the worst-case 1m sector were 8.35 W/m for TraceWin (Error: Reference source not found left) and 23.57 W/m for GPT (Error: Reference source not found right), although the positions of the sectors were nearly the same: 15.3 – 16.3 m for TraceWin and 15.5 – 16.5 W/m for GPT. In the first analysed variant, losses were over 550 W/m in the worst-case sector.



Losses: 23.57 W/m

Fig. 3. Losses for the best variant in the worst 1 m long sector calculated with TraceWin (left) and with GPT (right).

Energy losses calculated in GPT are three times higher than losses calculated in TraceWin. In both cases the losses did not meet a pre-established requirement of 1 W/m.

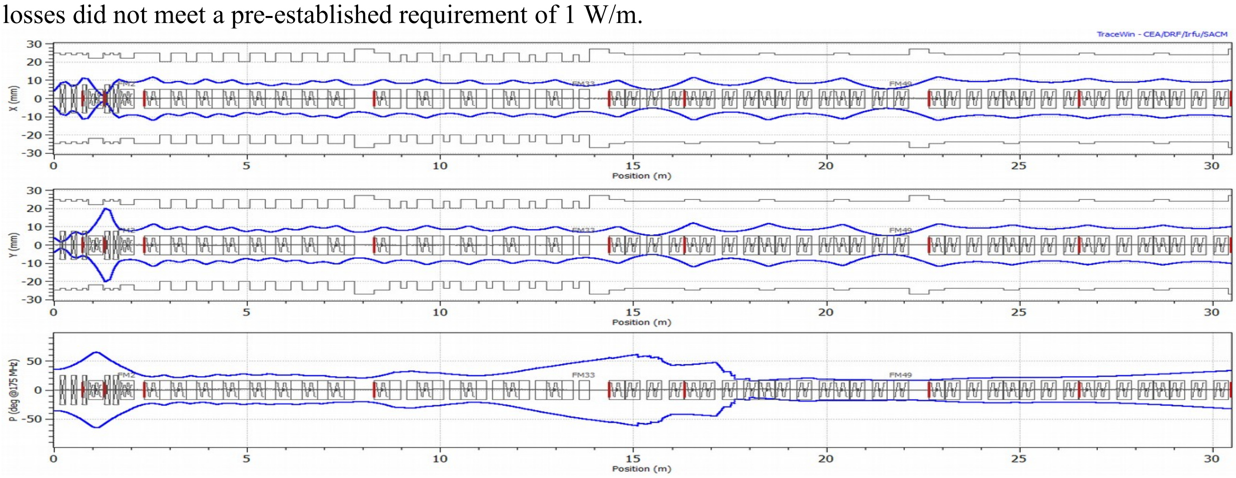


Fig. 4. Envelope of the beam. Top: envelope in X direction; middle: envelope in Y direction; bottom: phase envelope.

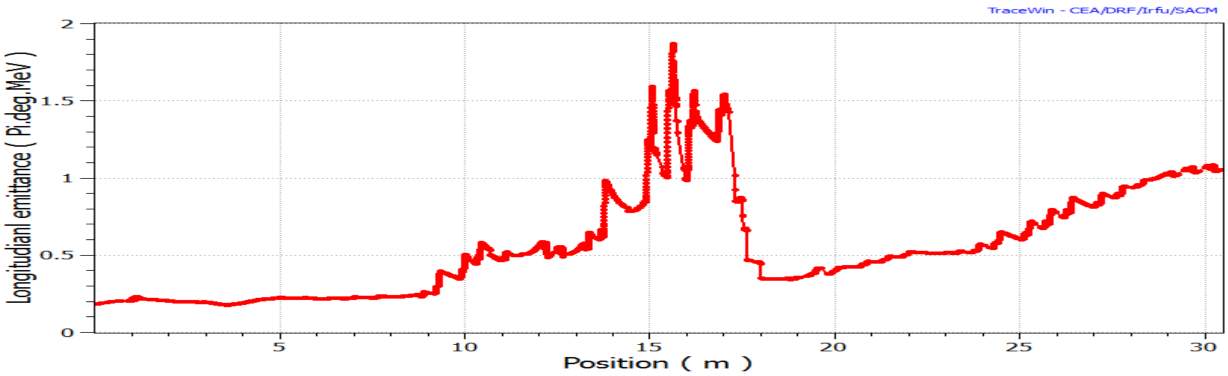


Fig. 5. Longitudinal emittance of the beam across the calculated area.

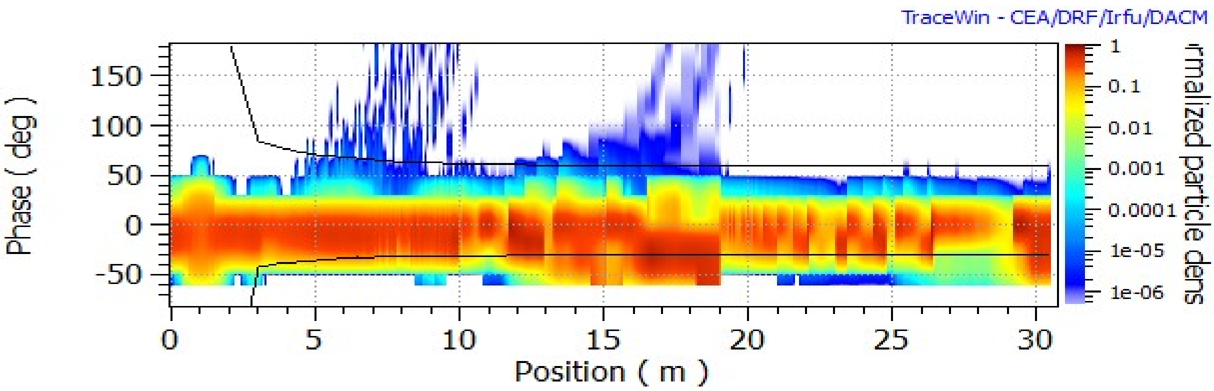


Fig. 6. Density of phase deviation of the beam across the calculated area.

None of the losses we observed could be attributed to improper focus of the beam. A careful analysis of the beam envelope (Fig. 4), longitudinal emittance (Fig. 5) and phase density of the beam (Fig. 6) performed to compare energy losses confirmed that a phase mismatch of macro-particles beginning in the 5th meter (in the middle of first cryomodule) led to beam losses ten meters further in the structure.

We also checked whether both codes produced a similar particle distribution at the HEBT entrance. This geometrical distribution is shown in Fig. 7 (left side for TraceWin calculation and right side for GPT calculation).

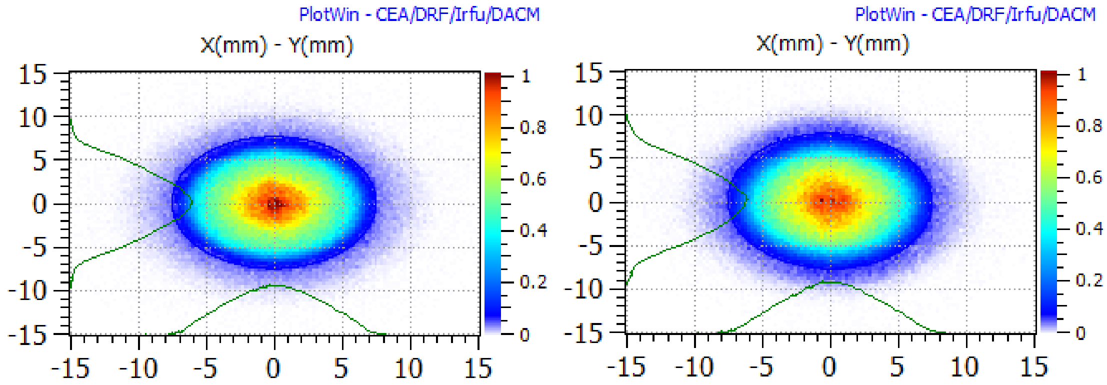


Fig. 7. Geometrical particles distribution in the entrance to HEBT - TraceWin (left) and GPT (right) calculation.

Deuteron distribution in X and Y direction (position vs. angle chart) at the HEBT entrance is shown in Fig. 8 for both the TraceWin and GPT calculations.

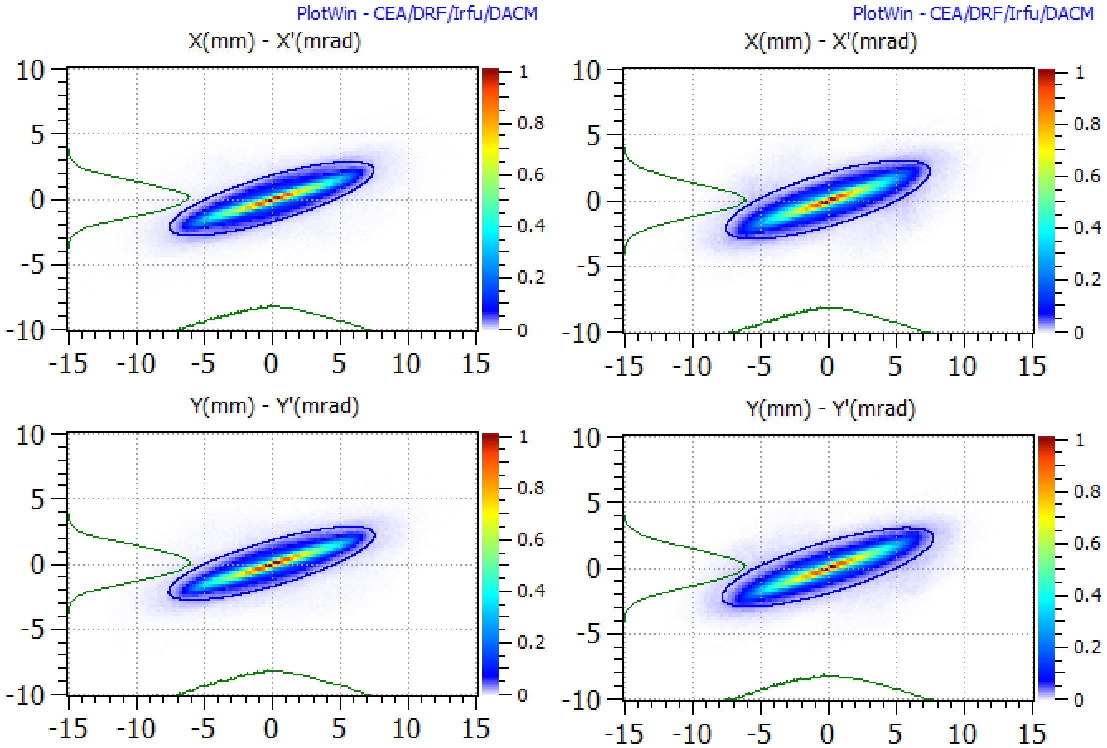


Fig. 8. X-direction (up) and Y-direction (bottom) particles distribution (position vs. angle chart) – calculation with TraceWin (left) and with GPT (right).

Phase vs. energy distribution chart at the HEBT entrance presented in Fig. 9, again with TraceWin shown on the left side, and GPT on the right side.

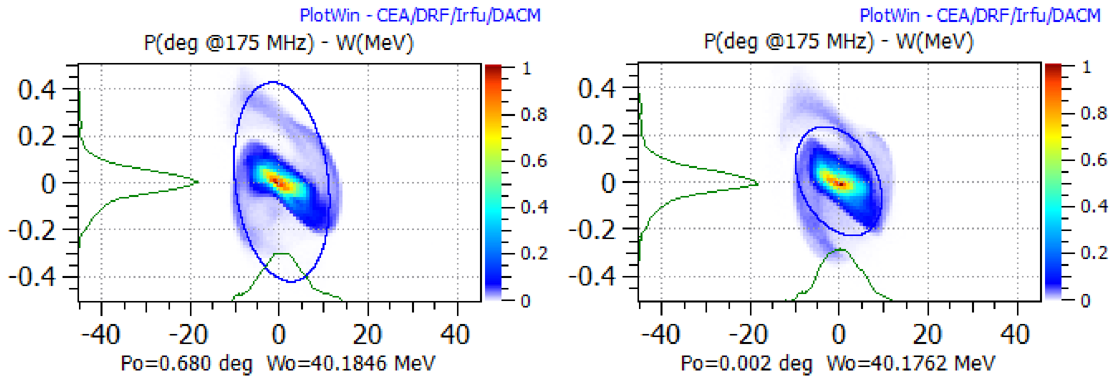


Fig. 9. Phase vs. energy distribution. Left: TraceWin calculation, right: GPT calculation.

We were not able to find sufficient optimisation for the four-cryomodule accelerator, the energy losses were unacceptably high.

3. FIVE-CRYOMODULES DESIGN

The modification of the accelerator design was prepared subsequently to reduce the size of the beam cross-section size and reduce beam losses in the accelerator. The design solution prepared by the CEA Saclay group took the form of a new, five-cryomodule accelerator. The first module was unchanged from the previous design we tested, but an accelerating cavity was added to the second module. High-beta modules were redesigned – with each two cavities separated by a solenoid. A fifth module was added. Total length of the accelerator to be studied was extended by about five meters (Fig. 1).

3.1. Results

We investigated 13 main variants of the redesigned accelerating system. As previously, the variants differed in phase values for each accelerating cavity. For the best variant we tested, beam energy was 40.4 MeV and we observed no loss of deuterons. Analysis of envelope (Fig. 10), longitudinal emittance of the beam (Fig. 11) and, especially, density of the phase (Fig. 12) across the calculation suggest it may still be possible to find a better, more stable solution.

Analysis of the particle distribution (Fig. 13) show that the beam in the accelerator's exit is focusing slightly.

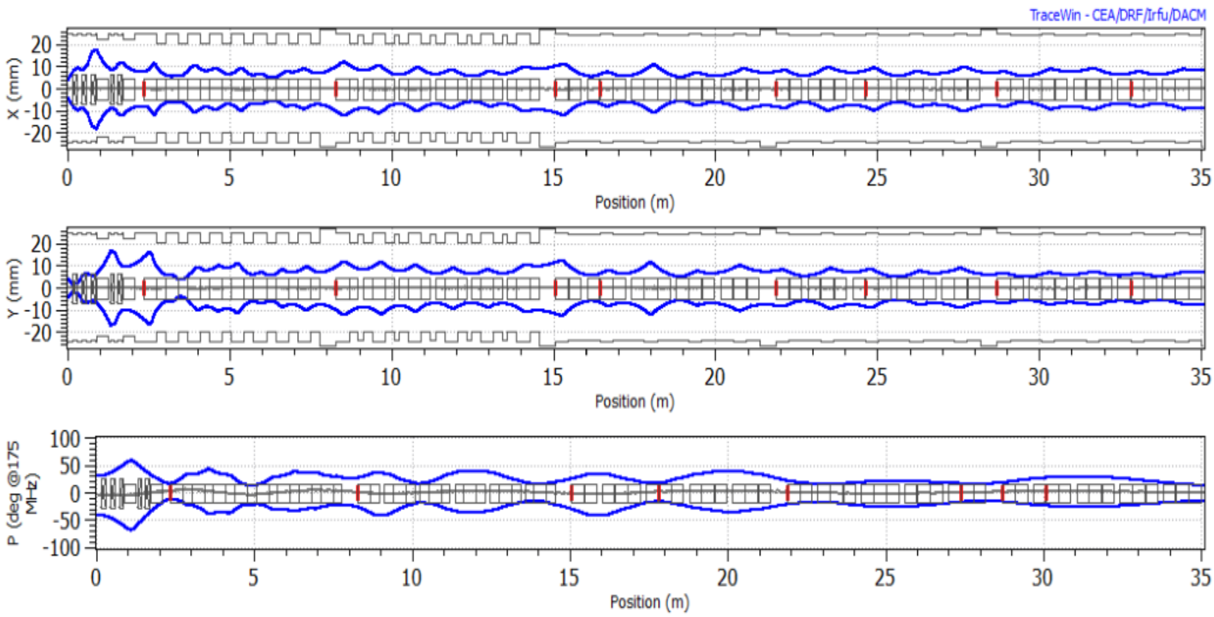


Fig. 10. Envelope of the beam. Top: envelope in X direction; middle: envelope in Y direction; bottom: phase envelope.

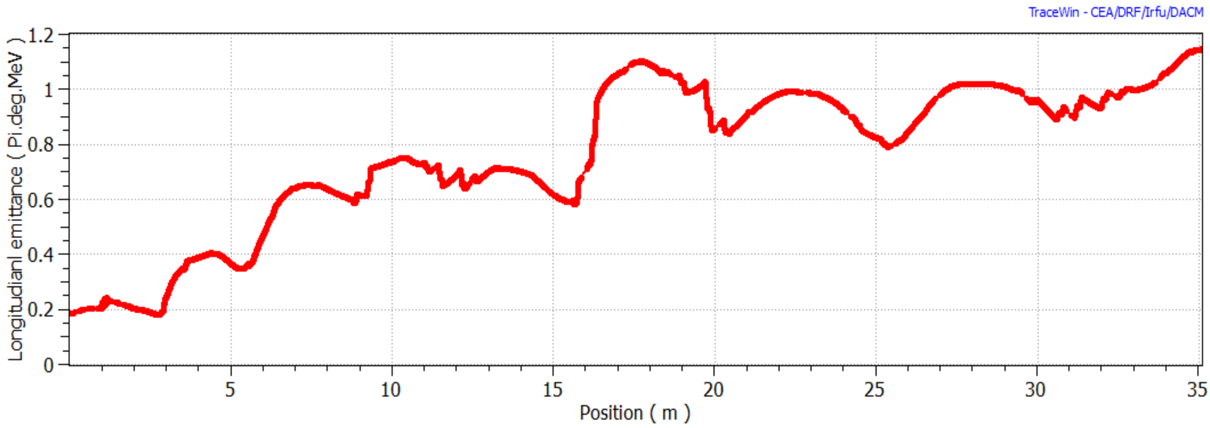


Fig. 11. Longitudinal emittance of the beam across the calculated area.

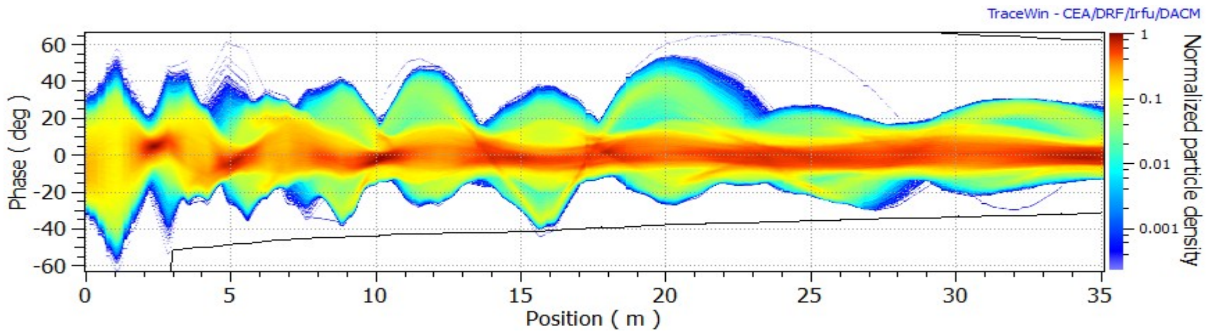


Fig. 12. Density of phase deviation of the beam across the calculated area.

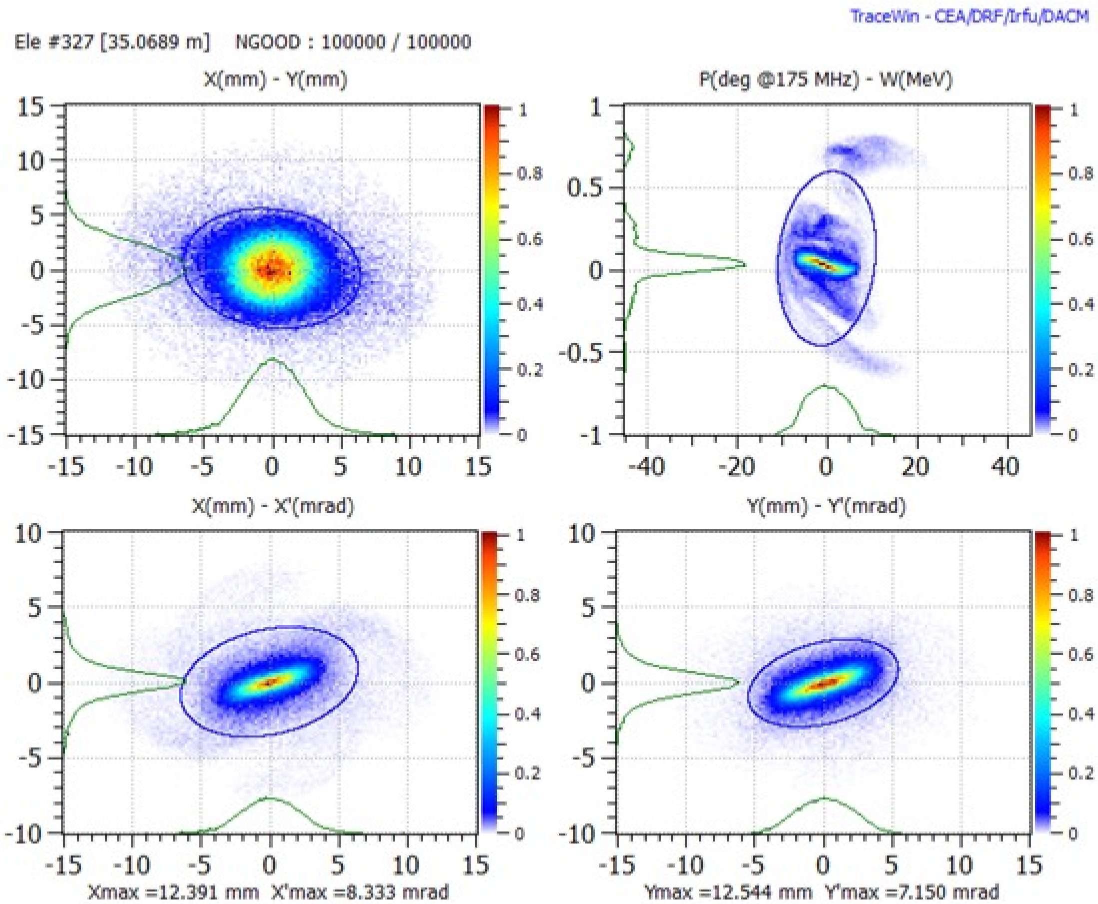


Fig. 13. Deuterons distributions in the exit of the accelerator obtained with TraceWin code. Top left: X-Y distribution; top right: phase vs. energy distribution; bottom: X-direction (left) and Y-direction (right) particle distribution (position vs. angle chart).

4. SUMMARY

Calculations for a four-cryomodule design accelerator showed an unacceptable level of the beam energy losses. We were unable to optimize the SRF-L sufficiently, which required that the SRF-L be redesigned[5].

Our initial results were confirmed in calculations performed separately by CEA Saclay team. We had maintained energy over 40 MeV and attempted to minimize losses, while the CEA team focused on maintaining low losses while maximizing energy. The obtained energy was lower than needed[6].

The SRF-L was therefore redesigned with five cryomodules, adding about five meters to the length of the structure[7].

For best calculated variant of RF field phase settings in the five-cryomodule accelerator structure design, achieved beam energy was 40.4 MeV with no beam losses in calculations with both TraceWin and GPT code.

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