THE IFMIF 5 MW LINACS

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Abstract

The International Fusion Materials Irradiation Facility (IFMIF) is based on two high power cw accelerator drivers, each delivering a 125 mA deuteron beam at 40 MeV to the common lithium target. The present design of the 5 MW IFMIF Linacs, as well as the description of the prototype accelerator to be built in Japan are presented: the injector including the 140 mA ion source and the magnetic focusing LEBT, the RFQ for the bunching and acceleration to 5 MeV, the MEBT for the proper injection into the Drift-Tube-Linac where the beam is accelerated to the final energy of 40 MeV. Recently, the Alvarez type DTL was replaced by a superconducting Half-Wave Resonator Linac to benefit from the advantages of the SRF technology, in particular the rf power reduction, plug power saving, ability to accelerate high intensity cw beams with high flexibility and reliability. Last, a HEBT section transports and tailors the beam as a flat rectangular profile on the flowing Lithium target. The design and technology choices will be validated during the EVEDA phase, which includes the construction of one full-intensity deuteron linac, but at a lower energy (9 MeV) at Rokkasho Mura in Japan.

INTRODUCTION

The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator driven neutron source for the investigation of the fusion plasma facing materials [1]. The accelerator consists of two high power linacs, each delivering 125 mA deuteron beams at the energy of 40 MeV to the common lithium target. The Engineering Validation and Engineering Design Activities (EVEDA), launched in the framework of a bilateral agreement between Euratom and the Government of Japan in the middle of 2007 aims at producing the detailed design file enabling the further construction of IFMIF, as well as the construction and test at full current of the low energy part of one accelerator at Rokkasho in Japan. The components of the prototype accelerator are provided by European institutions (CEA, INFN, CIEMAT): the injector, the RFQ, the transport line to the 1.2 MW beam dump, the 175 MHz RF systems, the matching section and the DTL, the local control systems and the beam instrumentation, required for tuning, commissioning and operation of the accelerator. The building constructed at Rokkasho Broader Approach site, the supervision of the accelerator control system, as well as the RFQ couplers, are provided by JAEA. From the IFMIF Conceptual Design Report [2], technical updates have been brought in order to optimise the design of the entire linac. In addition to the RFQ, which looks now shorter, the major change is the switch from the room temperature DTL to superconducting technology for the high energy portion of the linac and a linked complete redesign of the RF system.

INJECTOR

The injector has to deliver a 140 mA, low emittance deuteron beam with high reliability. An ECR type (Electron Cyclotron Resonance) ion source has been selected owing to its intrinsic high efficiency, high availability and limitless lifetime. Starting from the SILHI source, developed at CEA-Saclay, with a frequency of 2.45 GHz at 875 Gauss, the extracted energy has been increased from 95 keV to 100 keV, then the extracted intensity from 150 mA to 175 mA in order to meet the 140 mA D^+ requirement (26 mA D_2^+, 9 mA D_3^+). Simulations have been carried out to optimize the electrode number, electrode shape, aperture diameter and to minimize the electric field (Figure 1). A four electrode extraction system was finally chosen since it allows an easy tuning with minimum beam losses and back-streamed electrons. In order to decrease the risk of sparking, the maximum electric field has been kept around 100 kV/cm.

The Low Energy Beam Transport (LEBT) is a dual solenoid transport system with space charge compensation. The total length was minimized to about 2 m to restrain the emittance growth, but even so it allows to include classical diagnostics (movable Faraday cup and insulated screens associated with cameras, current transformers, emittance measurement unit) as well as non destructive optical diagnostic based on residual gas fluorescence to measure steadily the species fraction by Doppler shift analysis. Numerical simulations [3], using a back-and-forth process between the TRACEWIN code and a specially developed code, capable of calculating the space charge compensation, showed that the emittance at the RFQ entrance could come close to the challenging requirement (0.25 π.mm.mrad for the total current of 175 mA) provided that a Krypton gas is injected in addition to deuterium in order to better compensate the space charge effect ($P_{D2} = 1.10^{-5}$ hPa, $P_{Kr} = 4.10^{-5}$ hPa). The loss rate of the incoming D^+ beam by neutralization on the gas is about 2.4% under these pressure conditions.

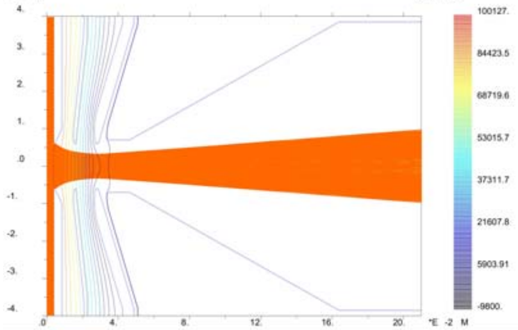

Figure 1: Plot of trajectory simulation for the 4 electrode extraction system (175 mA, 100 kV).

RADIOFREQUENCY QUADRUPOLE

The RFQ is a four vane structure – due to the high beam current and CW operation – and is developed by INFN. It has to bunch the dc beam from the injector and to accelerate the beam from 100 keV to 5 MeV. The optimisation of the 175 MHz RFQ [4] resulted in reduced length (9.8 m) and power consumption, with beam losses along the RFQ under control. The criteria chosen for the shaper, gentle buncher and accelerator sections are:

- Analytic law for the voltage with a smooth increase in the accelerator section
- Larger acceptance in the accelerator section to reduce losses at high energy
- Physical aperture "a" minimal at gentle buncher end playing the role of beam collimation to prevent for beam loss downstream
- High focusing factor $B = qV\lambda^2 / mc^2 r_0^2$ to keep the beam in the linear part of the focusing fields.
- Peak surface electric field limited to the reasonable value of 1.8 x Kilpatrick's criterion.

The resulting parameters, modulation, vane voltage, average aperture and physical aperture along the RFQ are plotted in Figure 2.

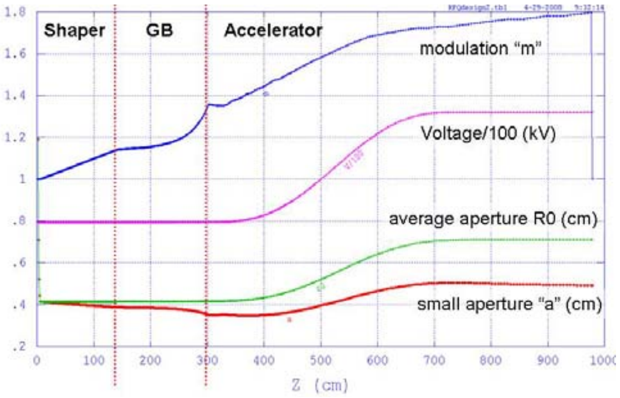

Figure 2: Main parameters along the RFQ.

As activation of the RFQ cavity is of main concern for maintenance, extensive multi-particle simulations [4] have been performed to evaluate the loss of particles along the RFQ. Assuming an input beam of 0.25 π.mm.mrad rms emittance with waterbag distribution, the output rms transverse and longitudinal emittances are 0.29 π.mm.mrad and 0.27 deg.MeV, respectively. The transmission is about 98.5% and the losses above 1 MeV are kept at a very low level (Figure 3). Any deviation from these ideal conditions will increase the losses in the RFQ and spoil the emittance. If one consider for example an input beam, of Gaussian distribution and 20% larger in emittance, the transmission drops to 92%, still acceptable.

An overall view of the RFQ with the location of the RF couplers and vacuum ports is shown in Figure 4. Although it offers a lower stiffness under vacuum, a square transversal section instead of circular shape was chosen because it presents some advantages, as a lower total amount of required RF power, large free surfaces for the positioning of all vacuum lines and tuning plungers, reduced request of raw material to obtain the final shape of the components.

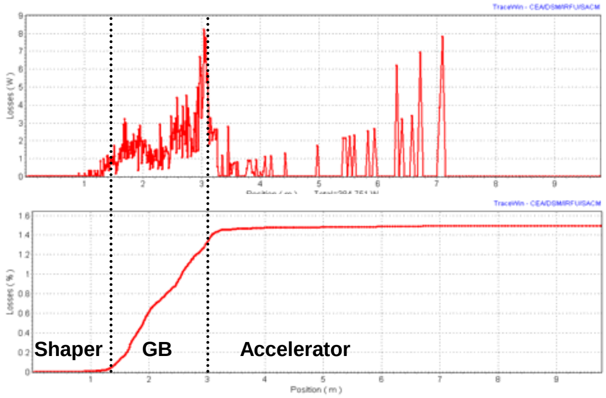

Figure 3: Beam losses along the RFQ with a waterbag input beam (130 mA @ 0.25 π mm.mrad).

The structure is made of 9 modules of 1.1 m each. The brazing technique has been chosen for the assembling of the different modules.

The total RF power required is about 1.6 MW and will be delivered by eight 200 kW RF power sources. Field stability should be provided by segmentation and finger dipole correctors. However, since simulations do not show a large gain from segmentation, mesurements will be made on a full scale cold model.

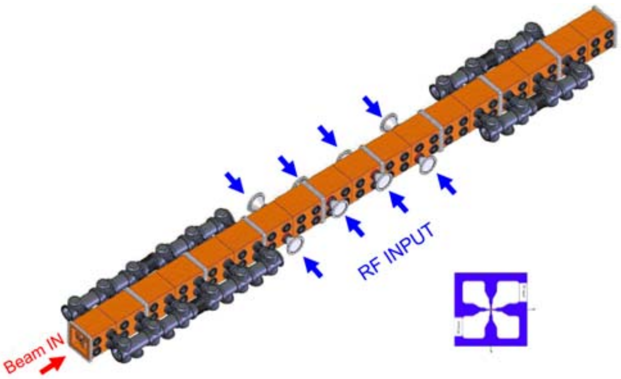

Figure 4: Overall view of the RFQ.

DRIFT TUBE LINAC

A Drift Tube Linac (DTL) has to accelerate the beam from 5 MeV to the final energy 40 MeV. While intensive activities on conventional Alvarez DTL have been carried out all around the world in the past decade, all these developments were done for lower beam intensity and pulsed operation, and therefore for much lower average dissipated power. Two options based on superconducting technology have been under investigation [5] since they offer many technological and financial advantages, as:

- RF power reduction, leading to 6 MW saving;
- higher flexibility and reliability;
- mature technology and better suited to existing teams and industries;
- less sensitive to all machining and assembly errors.

The proposal, based on Half Wave Resonators (HWR) and close to existing and widely used technology, was finally selected for the EVEDA phase. The baseline design is the result of a conservative approach for both resonators and focusing lattice. Moderate gradient at 4.5 MV/m and large aperture in the 40-50 mm range were chosen. As a result, the peak surface fields (Epk < 30 MV/m, Bpk < 50 mT) are much lower than the ones that can be achieved today by using well-tried methods developed in the last ten years, such as high-pressure rinsing, high-purity niobium and clean conditions. The phase advance per lattice period is always lower than 90° in order to avoid any structure instability. Four cryomodules for an overall length of 22 m housing a total of 42 resonators are used to cover the acceleration from 5 MeV to the final energy 40 MeV (Figure 8). Table 1 lists the main parameters of the HWR Linac and Figure 5 shows an overview of a possible cryomodule design.

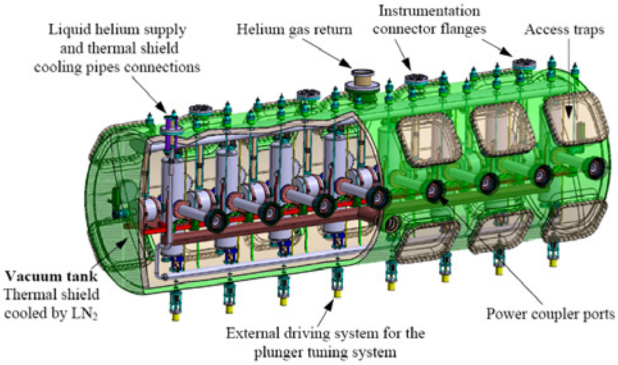

Figure 5: Overview of a possible cryomodule design.

Table 1: Main Parameters of the HWR Linac

Cryomodule	**1**	**2**	**3 & 4**
Cavity β	0.094	0.094	0.166
Cavity length (mm)	180	180	280
Beam aperture (mm)	40	40	48
Nb cavities / period	1	2	3
Nb cavities / cryostat	1 x 8	2 x 5	3 x 4
Nb solenoids	8	5	4
Cryostat length (mm)	4.64	4.30	6.03
Output energy (MeV)	9	14.5	26 – 40

Particle tracking simulations [6] have shown that the HWR scheme can sustain very conservative alignment and field errors, up to 1 mm misalignment and 10 mrad solenoid tilt while keeping a large safety margin between the beam occupancy and the pipe aperture (Figure 6).

The beam orbit correction relies on beam position monitors and steering coils located at the solenoid package. The beam phase space distribution at the exit of the linac is shown in Figure 7. After the linac, the beam has to be transported to the target through a long HEBT line, with very stringent beam footprint and homogeneity requirements on the liquid Li target. It was checked that, by injecting the beam output from the s.c. HWR linac into the present IFMIF HEBT, the beam footprint and homogeneity were similar to the results obtained with the room temperature DTL.

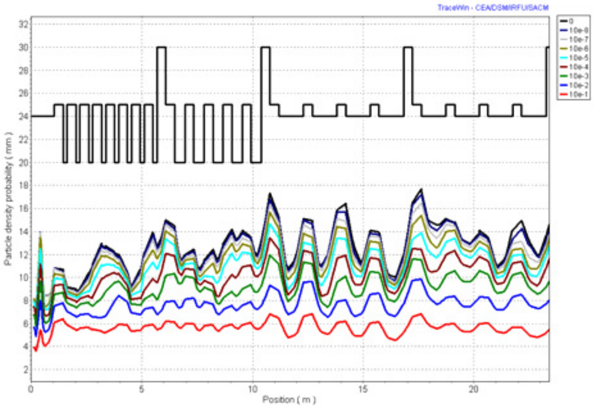

Figure 6: Plot of contour lines encircling 90% to 100% of Particles, with errors and beam orbit correction.

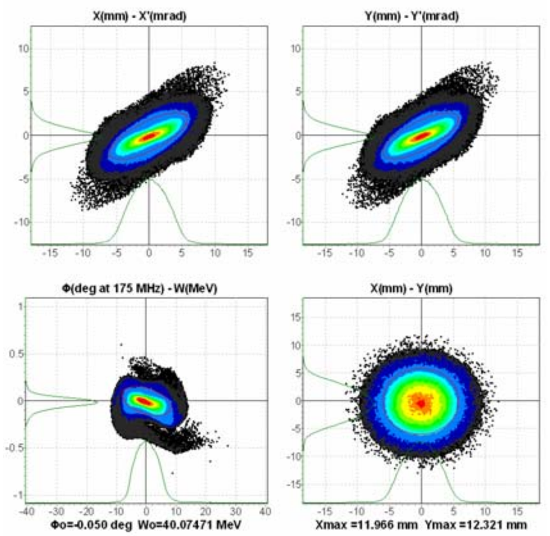

Figure 7: Beam space phase distribution at linac exit.

Further beam dynamics simulations are required to include a matching section between the RFQ and the cryomodule with realistic dimensions and to optimise the focusing scheme, as well as matching between sections.

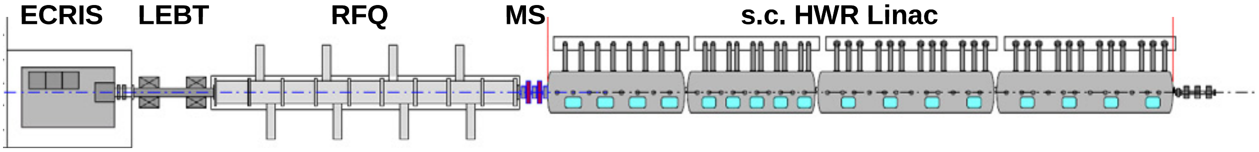

Figure 8: Layout of the superconducting Linac for IFMIF.

RF POWER SYSTEM

Following the change from normal to superconducting DTL, the RF Power System [7] can be made simpler and more reliable, based on smaller and more conventional power units using tetrodes: 18 units of 105 kW and 24 units of 220 kW (Figure 9).

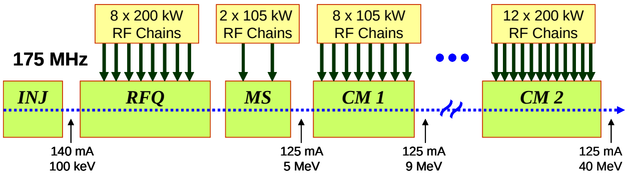

Figure 9: Identical RF power stations for the accelerator.

As a positive side effect, these 220 kW units will also be used for the RFQ, standardizing the whole accelerator. In addition, the same RF chain is used for all power sources, only the high voltage power supply changes: one 400 kW HVPS feeds one 220 kW RF amplifier or two 105 kW RF amplifiers. In order to optimize space, maintenance and availability, a symmetric modular system, composed by removable modules with 2 complete RF chains each, has been proposed (Figure 10).

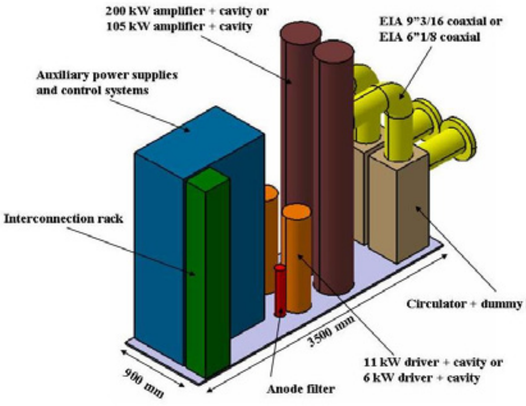

Figure 10: Removable RF power module.

The LLRF system is designed for CW mode operation but also for pulsed mode operation, needed during the commissioning and tuning of the prototype accelerator. The main requirements of the LLRF system are :

- Field error 1% in amplitude, 1deg. in phase
- Field ramp up with a predefined time profile
- Switch off the RF power in case of abnormal operation or upon request from other subsystem.
- RF signals monitoring to control performance and prevent failures.

HIGH ENERGY BEAM TRANSPORT

The 50 m long HEBT transports the 40 MeV, 125 mA beam to the target. The present design from the CDR [2] includes two twenty degree achromatic bends, FODO lattice, a final focus and a final 9° achromatic bend before reaching the lithium target, in order to avoid neutron back-streaming into the accelerator beam pipe. The required beam spot on target, a rectangle of 20 x 5 cm^2, with a uniform distribution is achieved by a nonlinear focusing beam expander scheme (Figure 11). The main issues (uncontrolled beam losses in the non-linear magnets, complex beam tuning procedure requires a robust nonintercepting beam profile monitor for tuning the 2 x 5 MW beams, beam-on-target jitter due to dynamic errors, very sensitivity to the input beam distribution) remain to be studied. An alternative solution could be the raster-scanning technique, widely used in medical applications, but the impact of the high power beam sweeping on the target (risk of shock-wave excitation) and on the condition of material irradiation has to be carefully analysed.

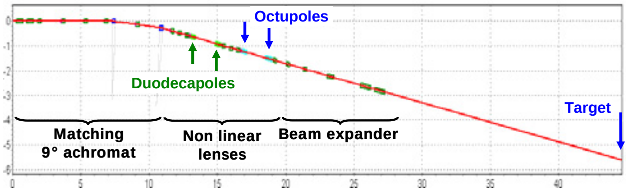

Figure 11: Layout of the HEBT (nonlinear focusing beam expander scheme).

PROTOTYPE ACCELERATOR

In order to test and to validate the technical options, the prototype accelerator is identical to one IFMIF accelerator running at full beam current (125 mA) but the high energy portion includes only the first cryomodule, resulting in the lower output energy of 9 MeV. It will comprise the ion source and LEBT, the RFQ, the matching section and the DTL, the transport line to a 1.2 MW beam dump, as well as the 175 MHz RF system and the beam instrumentation, required for the tuning, commissioning, operation. The layout of the prototype accelerator integrated in the IFMIF/EVEDA accelerator building of the Rokkasho BA site is shown in Figure 12. The figure shows also the implementation of the high voltage power supplies and RF amplifiers of the RF Power system, the cryogenic plant and the water cooling circuits.

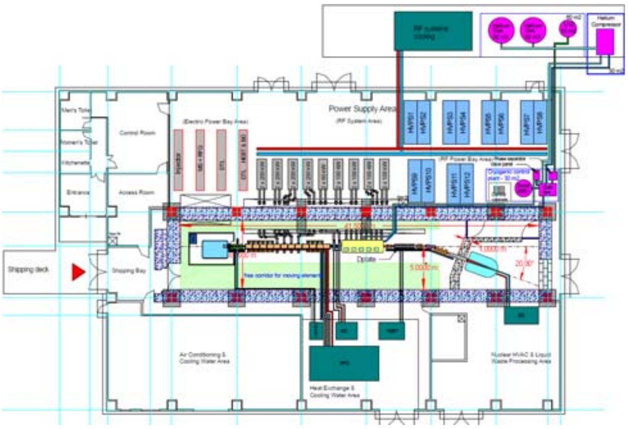

Figure 12: Layout of the prototype accelerator in the IFMIF/EVEDA accelerator building.

HEBT and Beam Dump

The High Energy Beam Transport [8] of the prototype accelerator has to transfer the beam to the beam dump with the required beam spot (rms size of 40 mm rms divergence of 16 mrad) while enabling the full beam characterization by means of the so-called Diagnostics Plate (Figure 13). A first triplet focuses the beam through the 3 m diagnostics plate; a doublet is able to compensate the variations of the first triplet during the emittance measurement with the quad-scan method; a bending magnet (angle 20°) prevents neutron from streaming back into the accelerator and can be used as spectrometer for the energy spread measurement; the last triplet expands the beam towards the downstream beam dump.

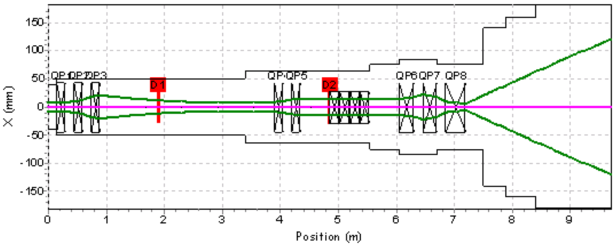

Figure 13: Layout of the HEBT of the P.A.

The EVEDA beam dump has to stop deuteron beams with a maximum power of 1.125 MW. Figure 14 shows the profile of the beam power deposition on the wall facing material, assuming a 2.5 m long Cu cone. This choice was infered from thermal stresses calculations [9].

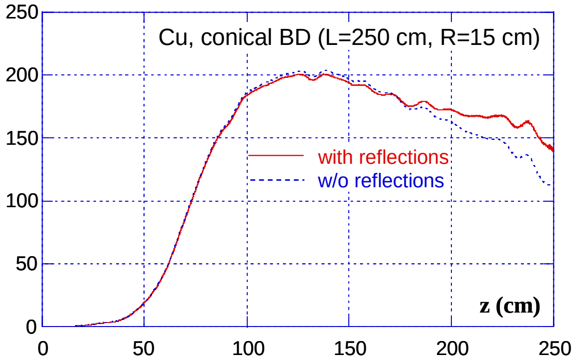

Figure 14: Power density at BD surface (W/cm^2).

Diagnostics

Beam instrumentation is essential to tune the linac and monitor the beam from the ion source to the beam dump, to minimize the beam loss and to characterize the beam properties. Furthermore, a complete set of diagnostics will be implemented at the exit of the HWR Linac on the Diagnostics Plate, for the measurement of the main beam parameters [10]: current, phase, position, transverse profile, energy, transverse halo, transverse emittance and longitudinal profile. Non interceptive transverse profile monitors, based on fluorescence and ionization of the residual gas, are specially developed for the prototype accelerator [11] and will be the first step towards the IFMIF diagnostics, required for the proper characterization of the beam shape near the target.

CONCLUSION

One year after the start of the project, substantial technical updates have been brought in order to optimise the design of the entire linac. In addition to the RFQ, which looks now shorter and less prone to beam loss, the major change is the switch from the room temperature DTL to superconducting technology for the high energy portion of the linac and a linked complete redesign of the RF system, based on conventional RF amplifiers.

The beam dynamics studies, even if they are far from being completed (next steps: optimisation of the linac focusing, end-to-end simulations with errors, beam tuning strategy, analysis of the IFMIF HEBT line, etc), have shown that the acceleration of the full beam looks feasible with reasonable emittance growth and beam loss.

The components of the prototype accelerator, starting with the injector, the RFQ and the RF power system, enter now into the manufacturing phase. Most of them will be tested in Europe before the shipping, installation, check-out, commissioning and operation at Rokkasho.

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