Proton drivers for neutrino beams and other high intensity applications

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Abstract. CERN, Fermilab, J-PARC and RAL tentatively plan to have proton accelerators delivering multi-MW of beam power in view of enhancing their physics reach especially in the domain of neutrinos. These plans are described, together with their benefits for other applications.

1. Introduction

High power proton accelerators ("proton drivers") have a wide range of applications including spallation neutron sources, radioactive ion sources, rare decay experiments, muon and neutrino production, etc. Among the existing laboratories equipped with medium power (100 kW-class) proton accelerators, CERN, Fermilab, J-PARC and RAL have a declared interest in neutrino physics, including the potential implementation of high power (MW-class) proton accelerators.

2. Plans at Fermilab

2.1. Project X

Fermilab is planning to build Project X [1] with operation beginning around 2021. Project X will be a high intensity proton machine capable of supporting several different experiments at the same time that could later be used as a starting point for a proton driver for a Neutrino Factory. Project X (figure 1) will consist of a low energy (up to 3 GeV) continuous wave (CW) linac and a higher energy (3 to 8 GeV) pulsed linac. The CW linac will deliver up to 3 MW of beam power at 3 GeV, principally for the study of rare muon and kaon processes, while the pulsed linac will provide beam to the Main Injector and increase its beam power for the Long Baseline Neutrino Experiment (LBNE). At a later stage in the 2020s, these new linacs may be upgraded to serve as the proton driver for a possible future Neutrino Factory and/or Muon Collider.

The front end of Project X will consist of a negatively charged hydrogen ion source, a low energy beam transport system, which will bunch the beam at 162.5 MHz, and a programmable chopper system that will form different desired pulse trains for the different experiments. For the initial configuration of Project X, the ion source will be run at 5 mA. The CW linac will initially be able to support an average beam current of 1 mA, thus requiring the above-mentioned chopper system to intercept more than 80% of the beam. The CW linac will consist of superconducting RF systems operating at 325 (up to 160 MeV) and 650 MHz (between 160 MeV and 3 GeV).

After the CW linac, the majority of the possible 3 MW of beam power will be sent to an experimental campus. A transverse RF splitter system will direct beam pulses to different experiments.

The programmable chopper will determine whether a beam pulse is present at different phases of the RF splitter system at the desired frequency for each experimental area: the chopper system can send either pulse trains or every n^{th} pulse as long as the average CW linac beam current is less than 1 mA. A minor fraction of the beam from the CW linac will be diverted away from the 3 GeV experimental area by a pulsed dipole and sent into the pulsed linac.

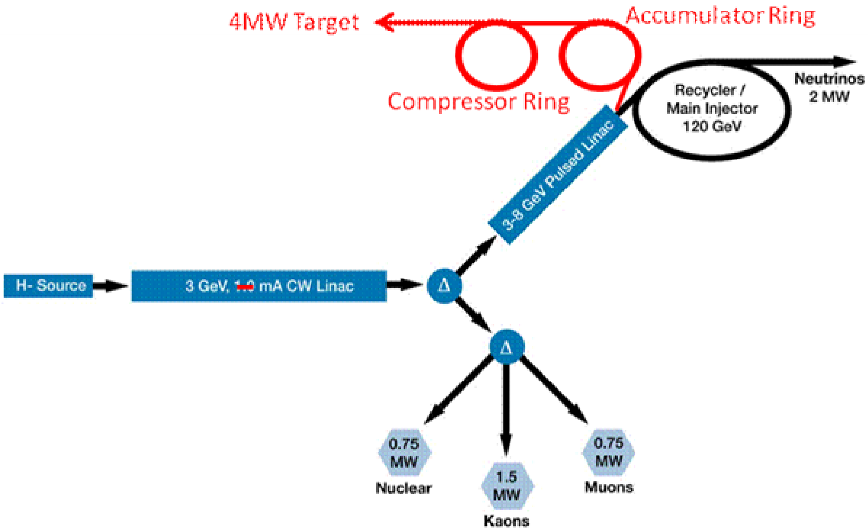

Figure 1. Schematic of Fermilab Project X with additional rings for beam formatting for a Neutrino Factory.

The 3–8 GeV pulsed linac will use 1.3 GHz superconducting RF cavities using technology developed for the ILC. Accelerating 4 ms long beam pulses every 100 ms, the pulsed linac will deliver approximately 300 kW of beam power at 8 GeV to the Main Injector/Recycler. Project X foresees upgrades to the Main Injector/Recycler rings for accumulation and subsequent acceleration of the intense beam: more than 2 MW can then be delivered to LBNE.

2.2. Future Project X upgrades

With the Neutrino Factory proton driver requirement of 4 MW of beam power between 5 and 15 GeV, it is natural to use the output of the 8 GeV pulsed linac. The necessary increase of beam power by an order of magnitude will be obtained by boosting the ion source beam current, the average CW linac beam current, and the length and repetition rate of pulse trains diverted to the pulsed linac. The Project X ion source is capable of operating at 10 mA. The associated chopper system and beam dump are being designed to handle 10 mA. The CW linac is being designed to handle an average 5mA beam current; there will have to be additional RF power purchased. The pulsed linac will require an upgrade of the power couplers and more RF power for longer pulses of nearly 7 ms at a repetition rate of 15 Hz. The cryogenic capacity will have to be increased by approximately 50% to support both linacs; the layout of utilities is being done with future expansion in mind.

An upgrade of Project X outlined above will deliver 4 MW of beam power at 8 GeV; however, the pulsed linac output does not satisfy the desired short-intense beam bunch on target as required for a Neutrino Factory. The beam will have to be accumulated and RF manipulations must be performed in new accelerator rings (see figure 1) to achieve the few-ns bunch length. A new accumulation ring (200–250 m circumference) is being designed. The programmable chopper will send beam that will only be injected at the correct RF phase for easy capture. Due to the beam power, stripping the hydrogen ions of electrons to form a proton beam is a concern and is being studied. Several bunches at a time will be transferred to a second ring for final bunch length compression. RF bunch rotation will be performed to reduce the bunch length to the desired few-ns length and then each bunch will be extracted towards the target with the desired time interval. For example, accumulation is done at 15 Hz into $h = 12$ buckets; three bunches are transferred to the second ring and undergo bunch rotation; then the three bunches are extracted to the target separated by 120 μs. This example results in three bunch trains of desired bunch length and repetition rate of 60 Hz. Design and simulations of these rings are in progress.

3. Plans at RAL

The Rutherford Appleton Laboratory (RAL) is home of ISIS, the world's most productive spallation neutron source. ISIS has two neutron producing target stations (TS-1 and TS-2), driven at 40 Hz and 10 Hz, respectively, by a 50 Hz, 800 MeV proton beam from a rapid cycling synchrotron (RCS), which is fed by a 70 MeV H^- drift tube linac (DTL) [2]. Potential upgrades of the ISIS accelerators to provide beam powers of 2–5 MW in the few-GeV energy range could be envisaged as the starting point for a proton driver shared between a short pulse spallation neutron source and the Neutrino Factory (NF). Although the requirements for the NF baseline proton energy and time structure are different from those for a spallation neutron source, an additional RCS or FFAG booster bridging the gap in proton energy and performing appropriate bunch compression seems feasible.

3.1. ISIS megawatt upgrades

The first stage of the upgrade path is to replace parts or all of the ISIS 70 MeV H^- injector in order to address obsolescence issues with the present linac, and ensure reliable operation for the foreseeable future. The more exciting, but more challenging, option is to install a higher energy linac (up to ≈180 MeV), with a new optimised injection system into the present ring, which could give a substantial increase in beam power (up to ≈0.5 MW) [3].

The next stage is a new ≈3.2 GeV RCS that can be employed to increase the energy of the existing ISIS beam to provide powers of ≈1 MW. This new RCS would require a new building, along with a new ≈1 MW target station. There are a number of possible candidates for the ≈3.2 GeV, 50 Hz RCS, but studies are presently focused on a 3.2 GeV doublet-triplet design with five superperiods (5SP) and a 3.2 GeV triplet design with four superperiods (4SP), both of which will include features required for fast injection directly from the existing ISIS RCS, together with the option for optimised multi-turn injection from a new 800 MeV H^- linac [4].

The final upgrade stage is to accumulate and accelerate beam in the ≈3.2 GeV RCS from a new 800 MeV linac for 2–5 MW beams [5]. It should be noted that a significant collimation section or 'achromat' would be required after the linac to provide a suitably stable beam for injection into the RCS. These upgrades to the ISIS facility are shown in figure 2.

3.2. Common proton driver

In a common proton driver for a neutron source and the NF, based on a 2–5 MW ISIS upgrade, bunches of protons are shared between the two facilities at ≈3.2 GeV, and a dedicated RCS or FFAG booster must then accelerate the NF bunches to meet the requirements for the NF baseline. Some possible bunch sharing scenarios are outlined in table 1.

It would appear that the 5SP design is most suitable, as it meets all the requirements of the NF baseline and provides more beam power to the neutron source, but its merits need to be established by thorough beam dynamics studies. In order to give some flexibility in case the total power at ≈3.2 GeV is somewhat less than 5 MW, 6.4–10.3 GeV RCS and FFAG booster designs will be considered. Figure 2 shows the conceptual layout of the common proton driver.

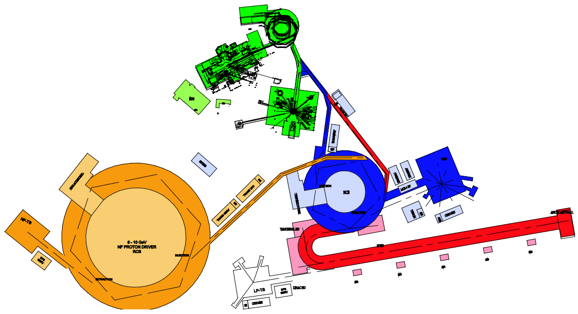

Figure 2. Conceptual layout of the NF proton driver with ISIS (green), ≈ 3.2 GeV RCS (blue), 800 MeV linac (red) and dedicated NF booster (orange) within the RAL site boundary.

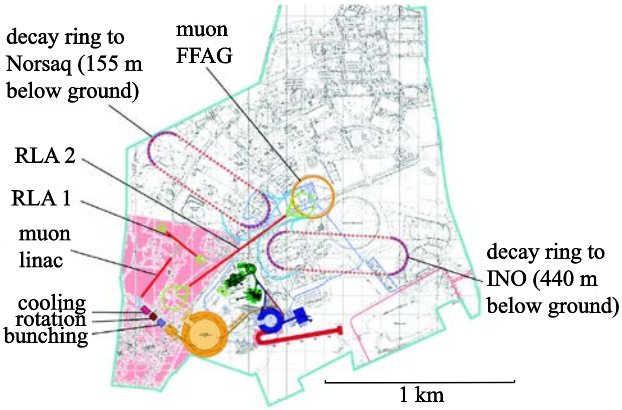

Figure 3. Schematic layout of the NF on the Harwell Oxford site. The proton driver is as shown in figure 2 and the Harwell Oxford site boundary is shown in light blue.

Table 1. Scenarios for bunch sharing between an upgraded ISIS and NF, assuming that bunches are transferred from the 3.2 GeV RCS and that 4 MW is required for the NF target.

≈3.2 GeV RCS design	Power at 3.2 GeV (MW)	Total number of bunches	Bunch spacing (ns)	Protons per bunch ($\times 10^{13}$)	Number of bunches to ISIS	Power to ISIS (MW)	Number of bunches to NF	NF booster energy (GeV)
4SP	5	5	280	3.9	2	2	3	4.3
4SP	5	5	280	3.9	3	3	2	6.4
5SP	5	9	140	2.2	6	3.3	3	7.7
5SP	4	9	140	1.8	6	2.7	3	9.6

Booster RCS designs [6] have concentrated on achieving the necessary acceleration and bunch compression with present-day, cost-effective RCS technology. Although the preliminary lattice design has been produced, a great deal of work remains to be done to produce a full conceptual scenario, and no consideration has yet been given to beam transport to the pion-production target. FFAG options are yet to be explored, and would be based on technology that remains to be fully tested, but in principle would offer the advantage of allowing all the bunches to be extracted to the NF target with the same energy (unlike the RCS where the ~120 μs sequential extraction delay required by the NF baseline would give time for the main magnet field to vary between bunches).

Optimised longitudinal muon capture in the muon front end of the NF requires compression of the proton bunch length from the ≈100 ns for the neutron source to 1–3 ns at the NF target. Several methods have been proposed in order to reach this goal, based on either adiabatic compression during acceleration or fast phase rotation at the end of acceleration (or in an additional compressor ring).

3.3. *Summary*

The site-specific design at RAL is in a preliminary stage, and will require extensive effort on beam dynamics and accelerator engineering (and strategic research and development in a number of key areas such as high power front ends, RF systems, stripping foils, kickers and diagnostics) before it can be regarded as viable. The common proton driver could fit onto the RAL site, on land already set aside for large facilities and research expansion, but the complete NF would require the use of part of the Harwell Oxford Campus. A possible schematic layout of the NF on the Harwell Oxford site is shown in figure 3. It is hoped that a new (up to ≈180 MeV) linac will be installed on ISIS between 2014 and

2020, but further upgrade stages are unlikely to be realised in the foreseeable future unless a decision is made to site the NF at RAL, and funding for the common proton driver is forthcoming.

4. Plans at CERN

Following a rich history of neutrino physics using the CERN proton accelerators, new proposals are being made for experiments requiring higher beam power and either exploiting the existing machines or assuming the availability of new dedicated accelerators.

4.1. Neutrino experiments with existing accelerators

The CNGS experiment [7] is currently operating using a 500 kW proton beam from the SPS and sending neutrinos to the Gran Sasso underground laboratory 730 km away. The SPS performance is expected to improve by the end of the decade, as a result of the ongoing upgrade programme of the LHC injectors [8]. The recently started LAGUNA-LBNO Design Study [9] is aimed at making use of the increased SPS beam power, tentatively set at 750 kW, for generating a conventional ν_μ beam and sending it to a new underground experiment located in Pyhäsalmi (Finland), at a distance of 2300 km. Beyond the upgrade of the SPS and PS complex, which is foreseen in the context of the High Luminosity upgrade of the LHC, this proposal only assumes the construction of a new transfer line from the SPS to a new target area and decay tunnel oriented towards Finland.

4.2. Future high power proton drivers

New accelerators have to be built for reaching a higher beam power. Two possibilities are being considered with different proton beam energies and therefore with neutrinos of different energy spectra. The first one delivers 4 MW of beam power at 4–5 GeV, the second one 2 MW at 30–50 GeV. Both make use of a multi-GeV Superconducting Proton Linac (SPL). The SPL is the subject of active R&D [10] in collaboration with external partners (ESS, CEA-Saclay, CNRS-IN2P3, University of Rostock, Cockcroft Institute) and with the support of the European Commission in the frame of its 6th Framework Programme. Its low energy part up to 160 MeV is based on Linac4 which is presently in construction [11].

4.2.1. Low energy (5 GeV) proton driver

In this option, the entire beam acceleration is obtained in a ~500 m long high power linac providing 10^{14} p/p in beam pulses of 0.4-0.8 ms at a repetition rate of 50 Hz. The superconducting linac part (160 MeV to 5 GeV) uses two types of 5 cell superconducting elliptical cavities [10]. They operate at 704.4 MHz and their main characteristics are given in table 2.

Table 2. SPL cavities.

Section	Low energy	High energy
Energy range [MeV]	160–790	790–5000
$\beta_{\text{geometrical}}$	0.65	1
Number of cells/cavity	5	5
Accelerating gradient [MV/m]	19.3	25
Number of cavities/focusing period	3	8
Number of cavities	60	200

The linac beam is accumulated in a 200–300 m circumference fixed-energy ring, using charge-exchange injection. To generate a conventional low energy ν_μ beam from π decay, the beam is fast ejected from the accumulator onto the target. In that case, a fraction of the linac beam (~200 kW) could be diverted to a radioactive ion production system of ISOL-type to generate a beta-beam [12].

For a Neutrino Factory [13, 14], the accumulator is isochronous so that the chopped linac beam can be accumulated in bursts filling fractions of the circumference and separated by gaps, without using any RF system. Once accumulation is finished, bursts are transferred successively to the compressor ring where rotation takes place in the longitudinal phase plane with the energy stored in RF cavities. A few (3–6) bunches of ~2 ns rms length are finally ejected one by one onto the target. The circumference ratio between accumulator and compressor is such as to guarantee the arrival of the successive beam bursts at the correct location in the compressor without any resynchronization.

4.2.2. Medium energy (30–50 GeV) proton driver

In the context of the LAGUNA-LBNO design study (DS) mentioned in section 4.1, a High Power Proton Synchrotron (HP-PS), which would deliver 2 MW of beam power onto the target and decay tunnel first used by the SPS and aimed at the Pyhäsalmi (Finland) experiment, will be studied. The exact energy and cycling rate will be defined in consultation with the experimenters within the LAGUNA-LBNO DS. Thereafter the accelerator will be designed using the work done for PS2 [15, 16] and its layout on the CERN site will be drawn (a preliminary sketch is shown in figure 4). The injector will be a slower cycling, and hence lower power, version of the Superconducting Proton Linac. Contrary to PS2, the HP-PS will be dedicated to neutrino production and will not be connected to the SPS.

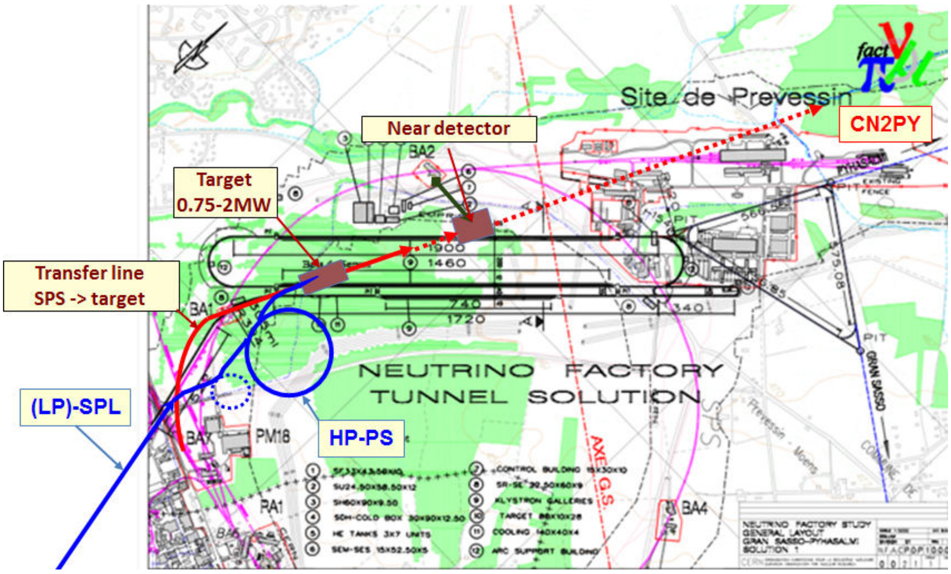

Figure 4. Conceptual layout of proton driver options at CERN.

5. Plans at J-PARC

5.1. Overview of J-PARC

J-PARC is the most recently built multi-purpose proton accelerator facility and it aims at megawatt-class beam power. A 3 GeV beam for neutron production was delivered for the first time in May 2008. The facility comprises an H^- linac, a 25 Hz rapid-cycling synchrotron (RCS), a slow-cycling main ring synchrotron (MR) and related experimental facilities. The RCS sends most of its beam pulses to neutron and muon targets in the Materials and Life Science Experimental Facility (MLF). A fraction of the RCS beam pulses is injected into the MR, which accelerates them up to 30 GeV and supplies particles to the hadron experimental hall using a slow extraction (SX) system, or to a neutrino production target using a fast extraction (FX) system. The neutrino beam is aimed at Super-Kamiokande, a large water Cherenkov detector located 295 km west from Tokai, for the long baseline neutrino oscillation experiment called T2K (Tokai to Kamioka). The layout of the MR is shown in figure 5. It has three-fold symmetry and a circumference of 1567.5 m. It is the first large proton accelerator using an imaginary gamma transition lattice. The three dispersion-free 116-m long straight sections, each of which consists of 3 FODO cells and matching sections to the arcs at the two ends, are dedicated to “injection and beam collimators”, “slow extraction”, and “rf cavities and fast extraction”, respectively.

For cost-saving reasons, only the first part of the linac has presently been built, which limits its beam energy to 181 MeV (400 MeV nominal) and its peak current to 30 mA (50 mA nominal). These parameters must be brought up to their nominal values to reach the nominal beam powers of 1 MW at the RCS and 0.75 MW at the MR. An additional linac section using Annular-Coupled Structure (ACS) linac has to be installed in the downstream part of the existing linac to bring the beam energy up to 400 MeV. The present ion source and RFQ have to be replaced for the beam current to reach 50 mA. Design and manufacture of the accelerator components for both energy and intensity upgrade are now well in progress.

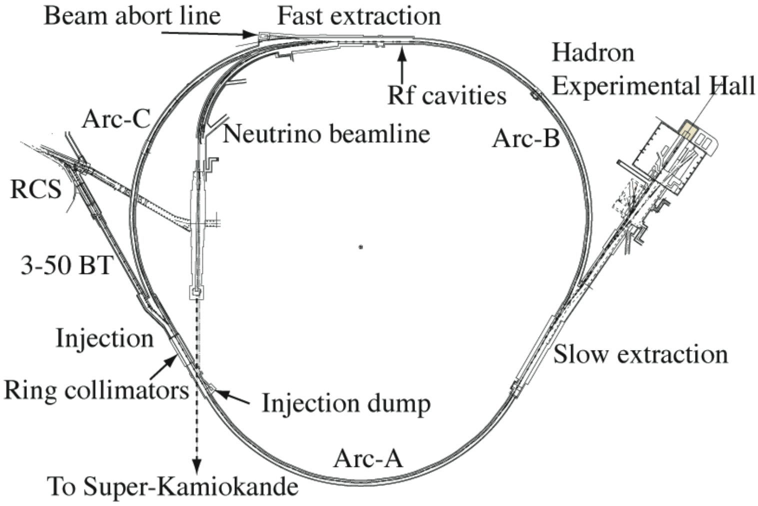

Figure 5. Layout of the J-PARC Main Ring and its experimental facilities.

5.2. Recent operating experience with the Main Ring

On March 7, 2011, the MR started operating with a cycle time of 3.04 s, delivering 145 kW of beam power to the T2K target until the morning of March 11, the day of the Great East Japan Earthquake. Since the start of physics data taking in January 2010, a total of $1.43x10^{20}$ protons has been delivered on the T2K target, 1.4 times the amount accumulated for K2K (KEK to Kamioka) during 4 years [17]. This has already led to an important physics result announced on June 15, 2011 [18]. Six electron neutrino candidate events have been identified, showing for the first time that muon neutrinos can transform into electron neutrinos through the quantum mechanical phenomena of neutrino flavour oscillation.

5.3. Consequences of the earthquake

According to the planned schedule, operation for physics was stopped in the morning of March 11. When the earthquake struck at 14:46 JST (Japan standard time), the linac was operating in an accelerator study mode while the RCS and MR were in maintenance. Lots of damage happened [19]. Subsidence occurred at many places. Underground water entered into the linac tunnels, but pumping with a diesel generator limited the water level to a maximum of 10 cm. The electrical and cooling infrastructures of the RCS were heavily damaged. In the MR tunnel, tens of cracks appeared and many of them let groundwater leak in. In contrast, most accelerator components, except linac beam monitors (BPMs and CTs), were not seriously hurt. Repairs are in progress and beam operation is planned to resume in December 2011 with a low current and a small duty cycle. The user program will then restart and 50 days of beam time are foreseen for the users until the end of March 2012.

5.4. Plans for the near future

Since the earthquake, the plan of the J-PARC intensity upgrade has been reconsidered. Both ACS and the new front-end part are now scheduled for installation during a 7-month shutdown corresponding with the 2013 summer maintenance period. Figure 6 shows the power upgrade plan for the RCS and the FX operation of the MR for the next three years, ultimately reaching the nominal specifications of 1 MW at 3 GeV and 750 kW at 30 GeV. Additional shields and new collimator units [20] will be installed for increasing the power loss capacity of the ring collimator section. More accelerating voltage will be obtained with the addition of 3 RF systems, bringing their total number up to nine.

For further increasing the MR beam power, a shorter cycle time of the order of 1 s is being considered. R&D has already started for the required magnet power supply and high-gradient RF cavity [21].

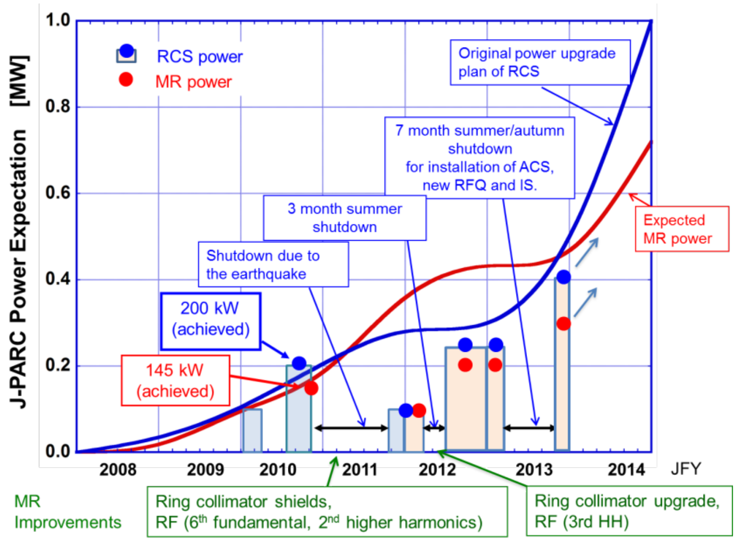

Figure 6. Power upgrade plan for the RCS and the FX operation of the MR for the next three years.

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