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ENGINEERING CHALLENGES OF FUTURE LIGHT SOURCES

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Abstract

We review some of the present engineering challenges associated with the design and construction of ultra-low emittance storage rings, the 4th generation storage rings (4GSR). The field is experiencing a growing interest since MAX-IV, followed by Sirius, started to build storage rings based on multi-bend-achromat (MBA) lattices. It was the recent progress in accelerator technology that allowed these facilities to base their designs on this kind of lattice. Although the challenges are starting to be overcome, many issues are still open and a lot of R&D is required until the 4GSR achieve optimal performance.

INTRODUCTION

Over the past few years an explosion of activities in the field of storage-ring based light sources has started, marking the beginning of a new generation in the history of storage rings, the fourth generation, where the electron beam emittance is reduced by at least an order of magnitude with respect to third generation machines, approaching the diffraction limit for multi-keV photons. The first audacious step was taken by the MAX-IV project in Sweden [1], a 3 GeV storage ring using a 7BA lattice that is based on quite a few new accelerator technological concepts. Following the path initiated by MAX-IV is the Sirius project in Brazil [2] with a 3 GeV 5BA lattice, similar emittance and circumference, but with its own set of particularities that reflects both a different user community and a different local industry condition. Both are green-field projects that are presently under construction. Other green-field projects that are being planned include BAPS in Beijing [3] and ILSF in Iran [4]. A big part of the recent activities in the field involve the plans of existing facilities in converting third generation machines into fourth generation ones. Some of these projects are well advanced, like ESRF [5], APS [6] and Spring-8 [7]; and others are at different conceptual stages, including ALS [8], Soleil [9], Diamond [10], SSRF [11], and others. Figure 1 shows a survey of emittances for some existing machines that are in operation for users, for machines under construction or in commissioning phase and for planned green-field or upgrade to existing machines.

The activity in the field can also be assessed by the great number of recent workshops [12-14] and special publications [15-16] on the subject.

The scaling laws in a storage ring that relate the emittance, the total number of dipoles, the beam energy and the ring circumference have been known for a long time. The first lattices based on MBA cells were proposed in the early 1990's [17], but their practical implementation had to wait for the technological advances that came about 20 years later. To understand the difficulties, we recall that the basic idea for emittance reduction using MBA lattices is that a large number of dipoles, and thus small deflection angle per dipole, allows the dispersion function to be kept focused to small values in the dipoles. The dispersion function plays an important role in determining the equilibrium emittance because it is directly related to the excitation of oscillations when a particle's energy is changed due to the emission of a photon. To keep the dispersion function small, strong focusing quadrupoles are needed between the dipoles. The strong quadrupoles and the small dispersion, in turn, require strong sextupoles to compensate for chromatic aberration effects. The strengths required have a big impact on the design of the magnets: the bore radius has to shrink and consequently the aperture available for the vacuum chambers is also reduced. The small vacuum chamber aperture has a big impact on the vacuum system because the conductance of the vacuum pipe is reduced (it scales as the cube of the pipe radius) and a new approach with distributed pumping is needed to keep the pressure low. Also the resistive wall impedance becomes an issue and may require a material with higher electrical conductivity for the chambers to minimize its effects.

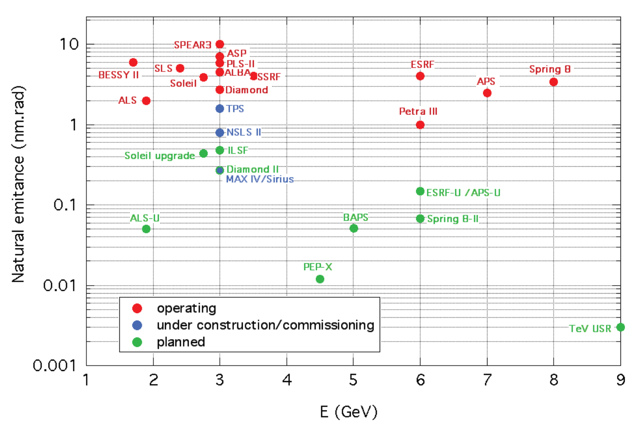

Figure 1: Survey of emittances versus energy for some existing machines that are in operation for users, for machines under construction or in commissioning phase and for some planned green-field or upgrade to existing machines.

The strong magnetic field gradients also imply high orbit amplification factors: the orbit amplitude becomes very sensitive to alignment errors of the magnets. The high amplification factors combined with the very small beam sizes impose stringent tolerance requirements for the magnets alignment and vibration amplitude, which translate into tight tolerances for the floor and girder vibrations. The high orbit stability requirement is also pushing the technology of beam diagnostics, fast feedback systems, special injection hardware to minimize

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perturbations on the stored beam during injection, as well as civil engineering and beamline optics development, among others.

The strong sextupoles introduce nonlinear effects that reduce the dynamic aperture and consequently the clearance for injection. The reduction maybe so drastic that the conventional beam accumulation scheme is not possible anymore. Clearly novel injection schemes are necessary in this case, such as the proposed swap-out scheme, in which the stored beam is ejected every time a new beam is injected on-axis to replace it. Even when accumulation is still possible, the small injection aperture imposes stringent requirements on the injection hardware geometry and pulse-to-pulse repeatability. A good quality injector, with emittance similar to those of third generation storage rings, is also desired for high injection efficiency.

In this paper we review some of the engineering challenges related to the construction of 4GSRs with emphasis on the difficulties and potential solutions that are being worked out for the Sirius project.

BEAM STABILITY

The small beam sizes that will be provided by the 4GSR light sources make stability for users one of the most important source quality parameters. Achieving the desired stability in beam position and angle around 5% of the beam size and divergence requires integrated state-of-the-art design of most subsystems, including the machine floor, the magnet alignment and support system, the beam position monitor mechanics and instrumentation, the stabilizing feedback systems, among others.

Machine Floor

The design of high stability machines is strongly affected by the characteristics of the construction site. Spring-8 in Japan is built on a virtually monolithic rock site and has the best vibration performance among synchrotron light sources worldwide, a dream for any machine designer. But since the choice for the machine site cannot always be based on purely technical factors, a high stability floor design has to take into account the local conditions to find a solution that minimizes the effects of existing vibration sources. Since the tolerances required for this class of machines is beyond what is normally required for civil engineering, the analysis of solutions used in similar facilities and their achieved performance is fundamental for a new design. Machines built at places where the soil is already well compacted, such as NSLS-II, MAX IV and Spring 8, tend to use the slab on grade solution, without piles. When the soil has low bearing capacity, the use of piles is essential, as in the case of Diamond, Soleil, Shanghai Light Source and others. At first, the clay-type soil at the Sirius site could use a solution similar to Diamond/Soleil. However, an analysis of the MAX IV solution that uses a large soil-cement bulk, moved us to a more detailed comparative analysis and to a decision to construct two floor prototypes: one similar to Diamond/Soleil solution with piles and another similar to MAX-IV's. A schematic drawing of the prototypes is shown in Figure 2.

Many measurements have been made to compare the performance of the two types of floor and, to make a long story short, the conclusions are that although both types have similar performance regarding vibrations generated far away from the floor, for vibrations generated on the floor itself, the MAX-IV-type has a considerably better behaviour. The Diamond-type floor is exclusively supported on the piles without touching the ground, and behaves like a waveguide, propagating the generated vibrations with little attenuation. The conclusion is that piles are important for soil stabilization, especially in the case of Sirius where the site has to be cut on one side and filled on the other, but the use of a large soil-cement bulk integrated with the concrete floor is also important to attenuate vibrations that are generated on the floor itself. The final choice for Sirius consists in an array of piles to increase the bearing capacity of the soil and a 4-meter thick layer of soil-cement on top of it covered by the concrete floor.

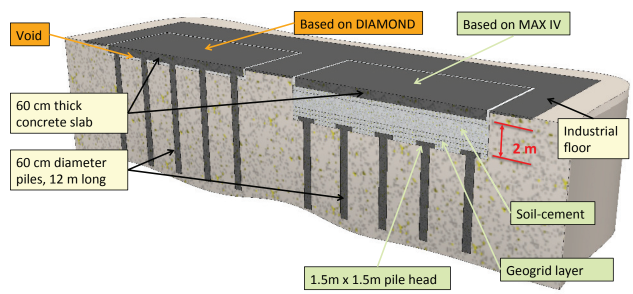

Figure 2: Two types of floor prototypes constructed at LNLS site to study and compare their performance. The concrete slab is supported exclusively on piles for the Diamond-type solution. In the MAX IV-type solution, a thick layer of soil-cement is interleaved between piles and concrete slab.

Magnet Supports

In 4GSR machines the compromise between alignment quality and vibration stability has to be seriously considered. The magnets supports have to avoid resonance frequencies that are normally excited in the floor, typically in the range from 2 to 100 Hz. This implies in high rigidity, which makes the required fine alignment adjustments difficult. The most common solution adopted so far consists in machining the girders so that the magnets can be positioned by construction, using shims in case some correction is needed. This solution has been used at Diamond, Soleil, ESRF, SLS, ASP, ALBA and at many other machines. A new magnet alignment level has been reached at NSLS-II, (less than 10 microns) with the vibrating wire technique and individual adjustment of each magnet position on the girder. A similar individual adjustment technique has been employed at Petra III, with the addition of a

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procedure to glue the magnets on the girders after the final alignment. For ESRF II a new individual magnet alignment procedure is being developed based on commercial wedge-type levelling systems and highly preloaded springs. The possibility of individual magnet adjustment reduces the required girder machining work, which reduces the costs involved. On the other hand, MAX IV chose the magnet block concept already used at MAX lab before, which consists in machining consecutive magnet elements out of a single solid iron block (some magnet poles can be detached) divided into top and bottom halves. The alignment tolerance is fixed by the machining process and no adjustments between magnets can be made later. Figure 3 summarizes the magnet girders and magnet positioning systems described. Regardless of whether individual magnet adjustments can be made or not, the quality required for the magnets themselves already demands manufacturing tolerances below 20 microns.

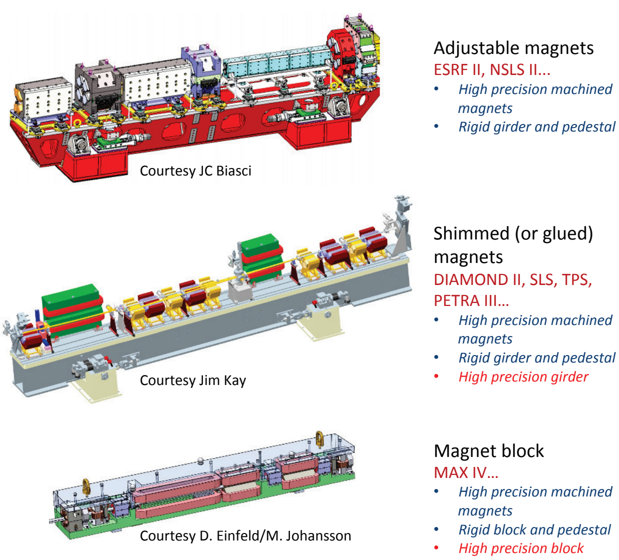

Figure 3: Different solutions adopted for magnet girders and magnet positioning systems.

For Sirius the girders will have a maximum length of 2.5 m and the project goal is to reach alignment tolerances by mechanical design, reducing the need for individual adjustments on the girder. The stability analysis for the assembly pedestal-girder-magnet usually begins with the individual component design. For Sirius the first prototype for the concrete pedestal showed a low horizontal stiffness in the region where the girder is supported and a new prototype is being designed. For the girder, the first prototype was based on the Petra III design, which is derived from the Diamond design, which, in turn, derives from the SLS design. Since measurements of this prototype show vertical vibration modes above 100 Hz, only minor modifications will be needed. The Sirius storage ring magnets are being designed with special attention to the optimization of fundamental resonance frequencies of the whole assembly of magnets and girders. The approach includes lowering the center of gravity of the magnets with respect to the fixing point in the girder and increasing the stiffness of the clamping fixtures (Figure 4). Preliminary finite element simulations and measurements show that first harmonic modes above 100 Hz can be obtained.

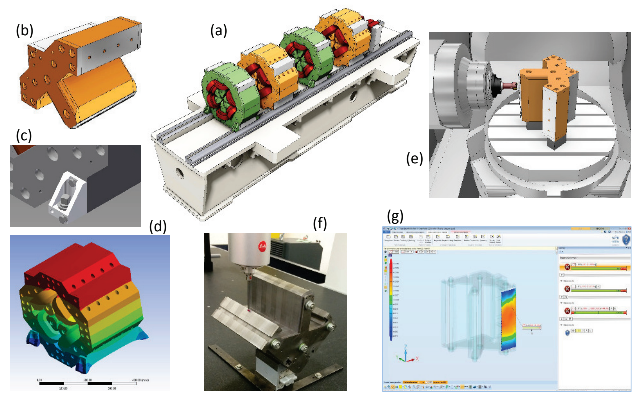

Figure 4: Proposed girder-magnet assembly for Sirius showing: (a) the girder with multipole magnets; (b) one pole of the quadrupole magnet with machine reference surfaces; (c) the designed clamping fixture; (d) structural analysis of the clamping fixture (>400 Hz vibration mode); (e) machining process developed for the quadrupole; (f) machined pole on CMM machine; and (g) results for the surface flatness measurements (< 8 µm).

Beam Position Monitors

The beam stability in storage rings depends very much on the quality of the BPMs. The usually short and highly intense circulating bunches can excite a significant heat flow into the BPM structure that can impair its performance. This still is one of the main issues in BPM design. The reduction in the size of vacuum chamber apertures caused the BPM buttons to reduce as well. Although this is helping to reduce the heat flow problem since the trapped mode frequencies are increased, further analysis of thermal and wakefield simulations [18] can considerably improve the BPM performance by reducing the beam power loss and optimizing the way the heat loads are drained. Some effective ways to reduce the loss factor are decreasing the gap size between button and housing and increasing button thickness [19]. For Sirius, a bell-shaped BPM button geometry has been adopted that shifts the trapped modes to frequency values higher than in the case of a cylindrical button, and also hides the ceramics from the beam [20]. The permittivity and the dimensions of the ceramic vacuum insulator also affect the trapped modes due to its coaxial cavity properties. Such properties are also present in the gap between housing and BPM body, which can be avoided by RF-shielding springs [21], bare-button design [22] or threads [20]. The power absorbed in the button can be reduced if a material with higher electrical conductivity as compared to the housing is used [23]. The load is drained more efficiently by increasing the contact area between the button and a high thermal conductivity ceramics. Figure 5 shows a comparison between different button shapes and

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ceramic sizes on the beam power loss for the Sirius beam parameters.

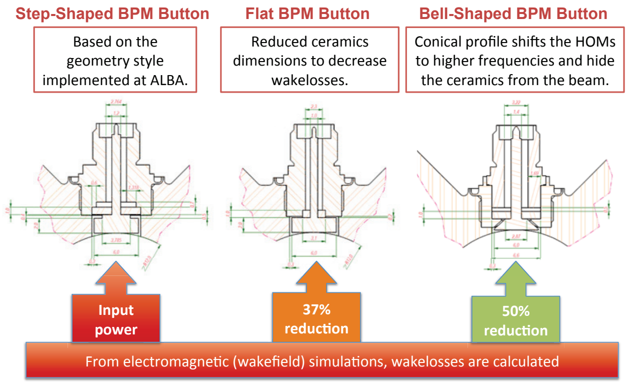

Figure 5: Effect of different button shapes and ceramic sizes on the beam power loss for the Sirius beam parameters. The buttons sensitivity is preserved in all cases.

Orbit Feedback Systems

The orbit feedback system plays a fundamental role in the operation of the storage ring at its performance limit as they actively fight the perturbations that cannot be controlled at the source. Stability requirements are often defined as a function of time scale and not surprisingly one of the main performance figures for fast orbit feedback (FOFB) systems is the highest frequency up to which the orbit distortions can be attenuated. Above this frequency, known as crossover frequency, the distortions can be amplified. Another figure-of-merit is the noise of the BPM system, which is inevitably injected into the beam through the feedback loop. Present day FOFB systems are reported to have crossover frequencies about 200 or 300 Hz [24-29], translating into an attenuation factor of around 10 in the range 20-30 Hz. At such bandwidths, modern BPM electronics have an integrated RMS noise around 30 nm for a 0.1-200 Hz bandwidth. To improve the FOFB performance, both the loop latency and the noise of beam position measurement have to be reduced to a minimum.

The latency limit is set today by the size of the network that distributes BPM and orbit corrector data to the feedback controller. As communication technology advances, the achievable data distribution latency has dropped to lower levels. Presently the combination of FPGA processing and multi-gigabit links running at 6.5 Gbps allows for an overall data distribution latency below 40 µs for medium-sized accelerators (~500 m) [30].

Detailed calculations taking into account data payload, processing overheads and light propagation over optical fibers show that this number can still be improved to a 10 µs level. In order to profit from this low latency data distribution, BPM electronics decimation filters latency have to be drastically reduced from the present ~200 µs to around 10 µs, which can be done by increasing the loop update rate from 10 to 100 kHz. To increase update rates more bandwidth is needed for the communication links as well as support for bigger load of the feedback algorithm.

Figure 6 shows the simulated FOFB crossover frequency as a function of data distribution latency for various FOFB update rates and steering coil bandwidths.

As the loop latency limitation is overcome, the crossover frequency can be extended to the 1-2 kHz level, corresponding to an attenuation factor of 10 in the range 100-200 Hz. At this point, the performance will be limited by BPM noise. The noise performance for state-of-the-art button BPM systems with RF channels switching electronics [31] is dominated by the BPM supports (at few micrometer level) for long term displacements and by electronics noise and pick-up vibrations (at 20-30 nm RMS level) for the frequency range from few Hz to 100 Hz.

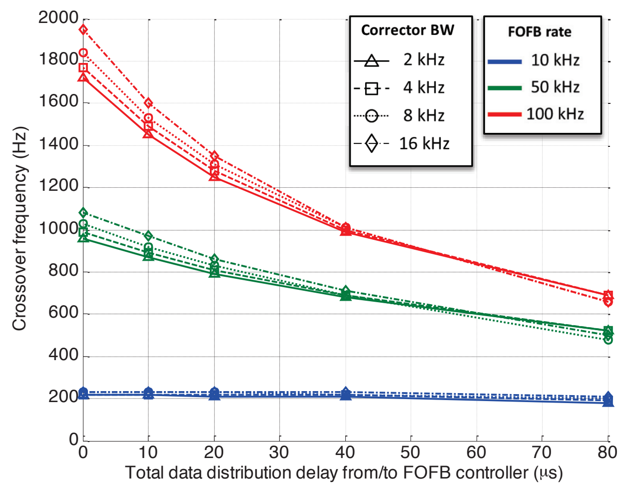

Figure 6: Simulated FOFB crossover frequency as a function of data distribution latency. Simulation considers a vacuum chamber with 15 kHz passband, BPM low pass filter delay of 3 times the FOFB sampling period, and PI controller tuned to guarantee maximum disturbance amplification below 5 dB. The present 10 kHz update rate limits the crossover frequency to a few hundreds of Hz due to large BPM group delay. Increasing the update rate to 100 kHz can extend the crossover frequency to the 1-2 kHz level.

VACUUM SYSTEM

Very low emittances are achieved using MBA lattices, which require the use of small aperture magnets. This has a big impact on the vacuum system since the conductance of the vacuum chamber is greatly reduced. To keep the pressure low requires placing the pumps closer, thus increasing the number of pumps, a solution that requires longitudinal space in an already compact lattice and also increases the impedance of the vacuum chamber. Although the conventional approach using discrete pumping is still considered in new projects [32-34], a distributed pumping approach based on non-evaporable getter (NEG) coating is increasingly being considered as an effective option for such compact lattices. NEG

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coatings can pump most gases that compose UHV systems and, in addition, present many desirable properties like low thermal outgassing and low photon stimulated desorption [35, 36]. The use of NEG coatings can also simplify the design of vacuum chambers since simpler cross sections without antechamber can be used. Besides the challenge to keep the pressure low, the small aperture chambers also make it difficult to deal with synchrotron radiation power deposited on the walls. This problem is greatly affected by the choice of the vacuum chamber material. For MAX IV and Sirius, copper has been chosen as the chamber material. The high thermal conductivity of copper allows the synchrotron radiation power to be distributed along the chamber walls, where water-cooling channels are welded to remove the heat load. In this way special absorbers are only necessary at few places with high power load.

Today NEG coating is a well-developed industrial technology, used extensively at CERN for LHC and at many other facilities for narrow gap insertion device chambers. Soleil was the first synchrotron light source to extensively use NEG coating [37], with 56% of the machine circumference coated. MAX IV [38] and Sirius [39] will be the first storage rings to base vacuum pumping mainly on NEG coatings, with more than 95% of the circumference coated.

The choice to use NEG technology has to be carefully planned from the start, as the vacuum system design has to be compatible with this option. Additionally, R&D has to be considered for complex chamber geometries. Figure 7 shows the result of a NEG deposition test for the Sirius dipole chamber with a narrow antechamber for radiation extraction.

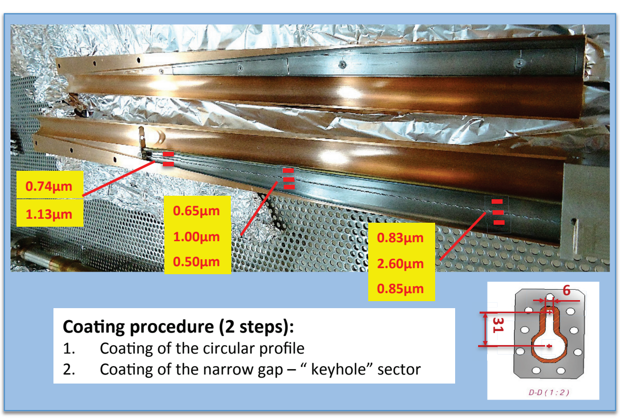

Figure 7: Development of NEG coating in a dipole chamber with a narrow (6 mm height) antechamber for radiation extraction. The picture shows the coating thickness variations for different positions inside the antechamber.

NEG activation is also an issue. In order to be activated the coated chambers have to be heated up to a temperature close to 200 ˚C for around 24 hours. Since the chambers cannot be vented after activation, this procedure clearly represents a challenge due to the small free space between the chamber and the magnet poles. At MAX IV an *ex-situ* solution has been adopted in which the achromat cell chamber is removed from the magnet assembly and is baked in an oven positioned above the magnets [38]. Sirius will use the *in-situ* bake-out approach for NEG activation by using a specially developed thin polyimide heater jacket with thickness of 0.4 mm [39].

Moreover, the vacuum chambers and components contribute to the machine impedance and thus can affect the machine performance by limiting the beam intensity. It is important that the vacuum components (e. g. flanges, bellows, BPMs, pumping ports) be designed to minimize their contribution to the machine's impedance.

RF SYSTEM

The RF system may be an important source of MTBF and effective emittance degradation in synchrotron radiation facilities. Although copper RF cavities are easier to maintain, they may have a significant contribution to the broadband impedance of the storage ring, compared to superconducting cavities, limiting the beam intensity. On the other hand, superconducting cavities usually degrade the MTBF compared to room temperature ones. The choice for superconducting or room temperature copper cavities is still a controversial decision that is heavily affected by the particular experience at each facility.

The choice of high power amplifiers is also an important item in the design of a storage ring. The use of solid-state amplifiers (SSA) has been increasing since the beginning of this century due to its reliability compared to klystrons and IOTs. The synchrotron light source at LNLS, for example, has been using SSAs since 2001 for the booster (2.2kW; 476MHz) and 2010 for the storage ring (2 x 50kW). In four years, only seven power modules, out of 324, have failed and no beam loss has occurred due to the SSAs.

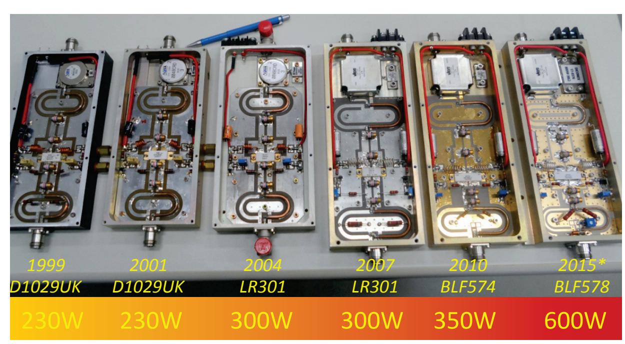

Figure 8: Evolution of the LNLS 476 MHz SSA modules showing the continuous increase of the output power over the last 15 years. The 600W module operates at 500 MHz.

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