REVIEW AND PROSPECTS OF RF SOLID STATE POWER AMPLIFIERS FOR PARTICLE ACCELERATORS

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Abstract

Thanks to the growth of high power semiconductor technology, solid state power amplifier (SSPA) systems with several hundred kW RF power are now available for various accelerator fields. Following the successful development at 352 MHz that took place at SOLEIL in the 2000s, the technology was transferred to industry and SSPAs at different frequencies, power levels, and pulse lengths have been widely adopted. In this paper we report about the SOLEIL experience with SSPAs and review the used or planned SSPAs in other accelerator facilities.

INTRODUCTION

Ti Ruan's team started to work on RF SSPA at LURE-Orsay in the 1990s. SSPA of 1.8 kW at 100 MHz and 1.5 kW at 500 MHz were designed and put into operation in 1997 on SUPER-ACO, replacing the previously used tetrodes [1]. Since then until the LURE shutdown, end of 2003, they have run without a single failure.

When the SOLEIL project studies started in the mid-1990s, it was naturally proposed to benefit from the experience acquired in that domain. The development of a 352 MHz - 2.5 kW SSPA prototype was launched with the goal to validate both the 330 W elementary module design and the power combination scheme. The successful results led to the decision of applying this technology for SOLEIL, at first to the 35 kW Booster (Bo) amplifier (147 modules) and then adapting it to the four storage ring (SR) 180 kW amplifiers (4 x 724 modules).

In synergy with these projects, 2 SSPA of 2.5 kW were built, following the same approach, one at 352 MHz for LNL (Laboratori Nazionali di Legnaro) [2], later expanded up to 10 kW for EURISOL [3] and another one at 476 MHz for the Booster of LNLS, the Brazilian light source, where it reliably operates since many years [4, 5].

In March 2004, the SOLEIL Bo SSPA could deliver up to 35 kW CW into a dummy load, a world record for a SSPA [6]. This record was broken, in May 2006, with the successful tests of the SR SSPA up to 190 kW [7].

These SSPA, which have now run for about eleven years, have shown excellent operational availability and MTBF and proved that they could advantageously replace the vacuum tubes in such application thanks in particular to their extreme modularity, the absence of high voltage and their very low phase noise. After commissioning its RF systems [8], SOLEIL has pursued R&Ds in this domain, which allowed improving the original 352 MHz design in compactness, reliability and efficiency and that was also extended to other frequencies [9]. This technology has now reached maturity, being adopted by many other accelerator facilities and taken up by the industry for applications ranging from the FM to L Band with power from a few tens up to a few hundreds kW.

SOLEIL 352 MHz SSPA

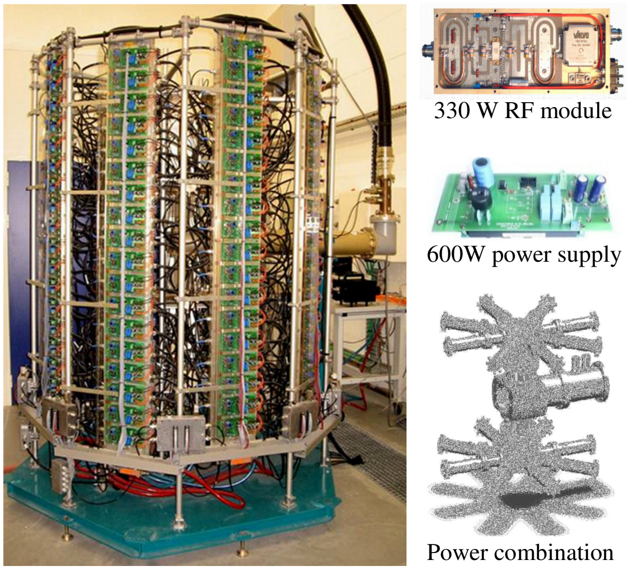
Using SSPA, instead of the conventional vacuum tube (klystron or IOT) amplifiers to provide the high CW RF power required at 352 MHz for SOLEIL, 1 x 35 kW in the Bo and 4 x 180 kW in the SR, was quite innovative and challenging. These SSPA consist in a combination of a large number of 330 W elementary modules (1 x 147 in the Bo and 4 x 724 in the SR), based on a design developed in house, with MOSFET transistors, integrated circulators and individual power supplies.

A detailed description of their design and performance can be found in reference [10].

35 kW Booster SSPA

The 35 kW CW Bo SSPA (fig. 1) consists in a single tower comprising 147 amplifier modules (with VDMOS D1029UK05 from SEMELAB) and their power supply boards (with 600 W - 280 Vdc / 28 Vdc converters from TDK-Lambda), mounted on both sides of 8 water cooled dissipaters. In the centre of the tower stand the components for the power splitting and recombination.

The Bo SSPA was commissioned in July 2005 and since then it has run for about 65 000 hours, being responsible for a single trip in operation (relative down-time $\approx 2\ 10^{-5}$ and MTBF $\approx$ 32 000 hours), due to a loose connection on a monitoring cable; another trip from the SSPA was caused by a human mistake. Otherwise, only about 10 out of the 147 RF modules had minor problems, which could be quickly repaired during scheduled machine shutdowns and that did not impact at all the operation thanks to the modularity and redundancy inherent to this design.



330 W RF module

600W power supply

Power combination

Figure 1: The 35 kW SSPA of the SOLEIL Booster.

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180 kW Storage Ring SSPA

In the SR, each of the four superconducting cavities is powered by a 180 kW CW SSPA [11]. The SR SSPA are based on the same principle as the Bo one, extended to 4 towers of 45 kW (fig. 2), each of them comprising 10 dissipaters of 18 modules. The use of another MOSFET device, the LDMOS LR301 from POLYFET, with higher gain and better linearity is the main difference.

Figure 2: one of the four SOLEIL SR 180 kW SSPA.

So far, the SR SSPA have run for about 63 000 hours over 11 years, featuring excellent operational avaibility and MTBF, as shown in Table 1. These results also point out that it is still perfectible by curing the lack of redundancy at first in the ac/dc power conversion, which originally consists in a single 500 kVA rectifier per SSPA and also in the preamplifier (preA) stage, a failure of one of them automatically switching off the SSPA. Cures to both of these "weaknesses" were brought in our novel design (see next sections).

Table 1: Downtime and MTBF Cumulated by the 4 SR SSPA over 63 000 Running Hours (*failures from preA)

Equipment	**Downtime**	**MTBF**
4 RF amplifiers (a)	$1\ 10^{-4}$ *	~ 12 500 h*
4 x 500 kVA rectifiers (b)	$4\ 10^{-4}$	~ 8 000 h
4 RF transmitters (a + b)	$5\ 10^{-4}$	~ 5 000 h

On the other hand, the rate of RF module failures due to the transistors and their solders [11] remains significant, around 2.5 % a year on average. However, once again, the inherent redundancy makes it transparent for the operation, except the preA; it is only a matter of maintenance, typically 5 k€ and 3 man.weeks a year for the 4 SR SSPA.

In 2013, we undertook to start replacing our original LR301 (28 V) by the BLF574XR (50 V), a 6th generation LDMOS from NXP (now Ampleon), much more robust and with higher gain (+ 7 dB) than the former one. We are thus expecting from this refurbishment a drastic reduction in module failure rate and therefore in maintenance efforts. Moreover the higher power capability will provide the possibility of storing 500 mA with only 3 running SSPA. It is also worthwhile noting that the electrical power savings from the overall efficiency gain (from 49% up to 59%) compensate the investment cost in about three years. Besides, the insertion of a "divider-combiner" assembly cures the lack of redundancy in the preA stage.

One of our four SSPA is already fully refurbished and we intend to go on at a rate of two towers a year. We have not yet got a single failure with the new transistors.

SOLEIL R&D, COLLABORATIONS AND TECHNOLOGY TRANSFERS WITH SSPA

Following the success of the SOLEIL SSPA, several accelerator facilities expressed their intention of adopting this technology, including the CEA/DIF at 352 MHz for DEINOS [12], the Swiss (SLS) and Brazilian (LNLS) light sources at 500 MHz and 476 MHz, respectively.

In 2006, a 2.5 kW 352 MHz prototype was delivered to the CEA in anticipation of a batch of four 20 kW SSPA; however it was not followed up as DEINOS remained unfunded. The SLS has built on its own a 60 kW 500 MHz SSPA (fig. 3-a), based on the SOLEIL design, except for its control specificity [13, 14].

In 2007, a collaboration agreement was concluded with LNLS for the production of two 50 kW 476 MHz SSPA, relying on components designed by SOLEIL. These two SSPA were successfully commissioned end of 2010 on the LNLS SR (fig. 3-b) where they are operating quite satisfactorily [15]. This design is being taken up for the 500 MHz SSPA of SIRIUS, the new light source under construction in Campinas [16].

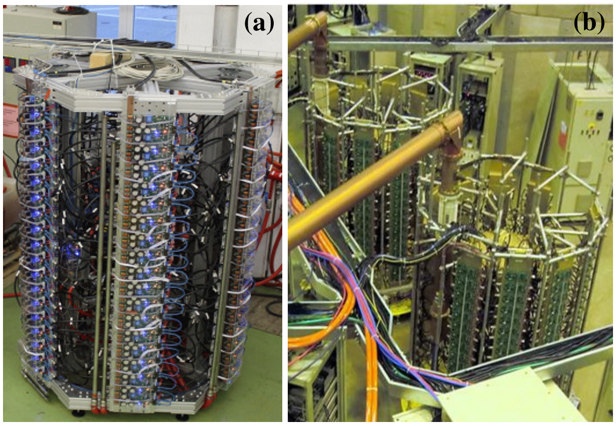

Figure 3: (a) SLS 60 kW 500 MHz SSPA; (b) the two 50 kW 476 MHz SSPA of the LNLS storage ring.

In parallel, SOLEIL has carried on with R&Ds. The acquired experience as well as the arrival on the market of the 6th generation LDMOS with 50 V instead of 30 V dc voltage has led to fast progress. A module of 700 W at 352 MHz was developed using the LDMOS BLF578. That represents a huge improvement as compared to the original SOLEIL LR301 modules: more than twice the power along with better performance in terms of gain (~ 20 dB instead of 13 dB), efficiency (> 70 % instead of 60 %), linearity and moreover much less thermal stress (ΔT_{max} of 50 °C instead of 105 °C), resulting in longer life time and lower failure rate. Similar performance was achieved with 500 MHz modules (see below).

Technology Transfer for the ESRF SSPA Supply

The growing interest in the SOLEIL SSPA technology and in particular the ESRF project of replacing its klystron amplifiers by SSPA of 150 kW at 352 MHz, led SOLEIL to conclude in 2009 an agreement of technology transfer with the French company ELTA, a subsidiary of AREVA TA. ELTA could thus tender and win the ESRF contract for seven SOLEIL type SSPA of 150 kW, four for the Bo and three for the SR [17]. They consist in two 75 kW towers (fig. 4), relying on the 700 W RF modules described before. All RF components, amplifier modules, directional couplers, power dividers and combiners, were designed by SOLEIL and then their mass production was contracted by ELTA to the Chinese company, BBEF.

The ESRF SSPA are running with an overall efficiency of 58 %, since Jan. 2012 in the Bo (2 trips over 5.5 years), since Oct. 2013 in the SR (2 trips over 3.5 years), without a single failure from the 1820 operating transistors [18].

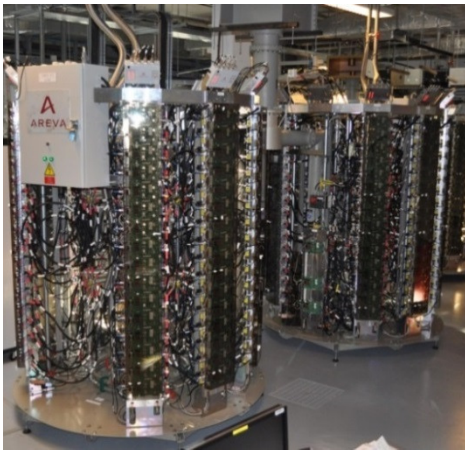

Figure 4 : ESRF 352 MHz 150 kW SSPA (2 towers with 8 dissipaters of 16 modules).

Last Generation of SSPA Developed by SOLEIL

More recently, within the frame of scientific collaborations, SOLEIL has built two 500 MHz SSPA, a 50 kW one with 6 dissipaters of 16 RF modules for ThomX, the Compton X-ray source under construction at Orsay in France [19] and a 80 kW one with 10 dissipaters of 16 RF modules for SESAME (fig. 5), the synchrotron light source, which is being commissioned in Jordan [20]. The main novelty is the use of very efficient (96 %) fully modular power supplies, 230 Vac / 50 Vdc converters, in 2 kW units, directly connected on the mains. Their remote voltage control allows optimizing the efficiency for any operating power: the overall ac-to-RF efficiency, which is 56% at nominal power, still remains 50% at half power. As shown in fig. 5, we changed from the tower to the cabinet assembly, which is better suited to the new power supply layout on top of the cabinet.

A new agreement of technology transfer was concluded with SigmaPhi Electronics (SPE), which became the unique SOLEIL licensee after termination of the ELTA license, in 2014. As SESAME needed four 80 kW SSPA for its SR, it was agreed with the first one being built by SOLEIL as a demonstrator and the three others by SPE on the same model. Two of them are operational in SESAME since December 2016 and the second pair was successfully commissioned a few weeks ago.

The ThomX SSPA is also completed and shall be soon installed and commissioned on site.

Figure 5 : SESAME 80 kW 500 MHz SSPA.

USED OR PLANNED SSPA IN OTHER ACCELERATOR FACILITIES

The successful operational experience with the SOLEIL 352 MHz SSPA has led many other accelerator facilities to adopt this technology and the industry to take it up and extend it to other frequencies. Here below is a non-exhaustive review of the main applications, classified in four frequency ranges.

UHF (350 - 509 MHz) SSPA

All above mentioned SSPA, for SOLEIL and ESRF at 352 MHz, LNLS at 476 MHz, SLS, ThomX and SESAME at 500 MHz, use several stages of coaxial combiners, similar to what is shown in fig.1. The EURISOL 10 kW 352 MHz [3] and Indus-2 100 kW 508 MHz SSPA [21] are also based on the same design.

In BESSY II, all klystrons were recently replaced with 500 MHz SSPA, 1 x 40 kW in the Bo and 4 x 75 kW in the SR (fig. 6) [22], from Cryoelectra GmbH. They are operating since end of 2015 with about 50 % overall efficiency. Their design is similar to the above ones, but the last stage combiner is coaxial-to-waveguide (fig. 7-a).

Figure 6: BESSY II 500 MHz 75 kW SSPA.

Fig 7-b shows another type of coaxial-to-waveguide combiner, designed by SOLEIL for use in 150 kW SSPA combining two units of 75 kW.

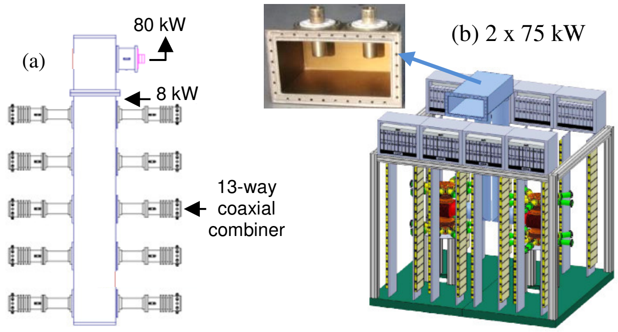

Figure 7: coaxial-to-waveguide combiners in SSPA (a) 10 x 8 kW (BESSY II), (b) 2 x 75 kW (SOLEIL).

A few years ago, ESRF started R&D on cavity combiners, which led to the 352 MHz 85 kW SSPA prototype shown in fig. 8 [17]. The cavity is made of 22 water cooled "wings" on which are mounted 6 RF modules of 700 W, magnetically coupled to the cavity by means of loops. The 50 V dc power supplies (22 x 8 kW) are hosted in a separate cabinet. Up to 85 kW could be reached with an overall efficiency around 56%. This approach has the advantage to eliminate RF power coaxial cables and to be quite compact. In return, the efficiency being highly sensitive to the coupling spread, a fine individual sizing of each loop is required to compensate for the cavity field non-uniformity (position dependence). It also proved hard preventing the cavity from RF leakage and, as compared to a phase adjustable coaxial combination, the tolerable VSWR is significantly lower [17].

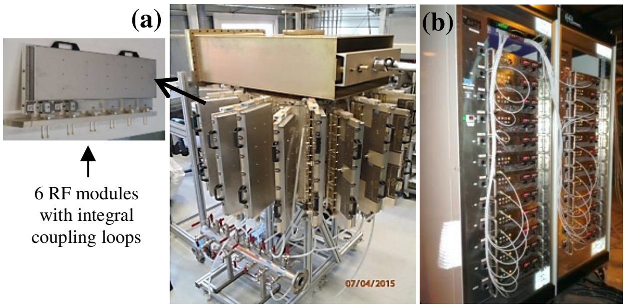

Figure 8: ESRF 85 kW 352 MHz SSPA prototype, based on a cavity combiner (a); (b) power supply cabinet.

SSPA, based on a cavity combiner, are also under study for APS (352 MHz) [23] and SPRING8 (509 MHz) [24], following slightly different approaches with the coupling loops, integral to the cavity. The former is designed to combine 108 RF modules of 2 kW; the areas of the coupling loops are adjustable (fig 9). The latter combines 2 cavities of 55 kW, on which are plugged 20 "wings", each of them including 4 RF modules of 600 W; the coupling loops are adjustable in angle (fig. 10).

Other facilities are about to use 500 MHz SSPA, like CLS, DIAMOND, DELTA, SIRIUS, ELETTRA, ALBA and R&Ds in this field are ongoing at other places, like ILSF [25] or NSRRC [26], for instance.

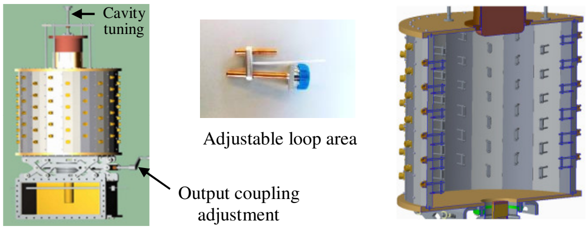

Figure 9: 200 kW 352 MHz APS cavity combiner

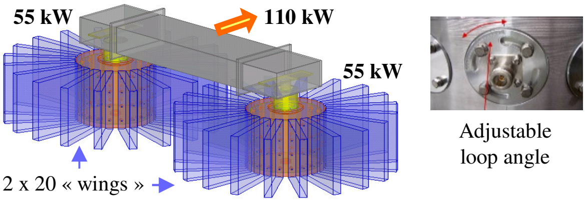

Figure 10: 110 kW 509 MHz SPRING8 SSPA.

UHF L-band (~ 1.3 GHz) SSPA

Bruker, now SPE, has pioneered the extension of SSPA to the L-band by supplying 10 SSPA of 10 kW at 1.3 GHz for ELBE where they perform very well with 47 % of RF efficiency and extremely low failure rate since early 2012 [27, 28]. They rely on 64 LDMOS-based RF modules of 160 W, combined in 2 stages, first coaxial, then coaxial-to-waveguide. The progress in LDMOS technology led to an upgraded version, intended to bERLinPro and presently used in HoBiCaT [29, 30]. It can provide 16 kW using 8 x 10 RF modules of 200 W (fig. 11). SPE is now producing 1.3 GHz SSPA, from 5 to 15 kW for TARLA [31], MESA [32] and Cornell with RF modules of 500 W.

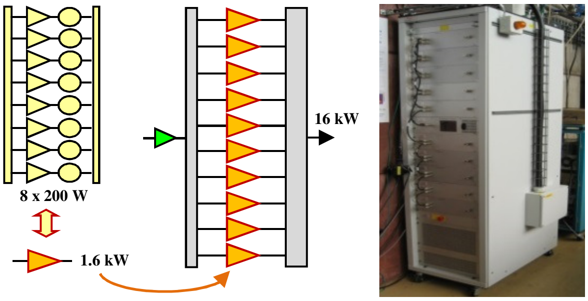

Figure 11: 16 kW 1.3 GHz SSPA for bERLinPro.

The Beijing university is using a 20 kW 1.3 GHz SSPA with LDMOS, built in cooperation with BBEF [33].

The production of 284 LDMOS-based SSPA of 3.8 kW at 1.3 GHz for LCLS is in progress [34]; 81 of them are already delivered [35].

In the frame of LUCRECE, a project of R&D about RF technology for CW Linac [36], SPE and SOLEIL collaborate to develop a 20 kW 1.3 GHz SSPA using GaN instead of LDMOS transistors. JLab is also carrying out R&D with the GaN at 1.5 GHz [37]. Above 1.3 GHz, the GaN, which has higher efficiency and power capability, is supplanting the LDMOS.

Generally, for UHF SSPA the use of a circulator per transistor is the key to success and that allows using low-cost low-loss non-isolated combiners of any type, coaxial, coaxial-to-waveguide or cavity.

VHF 175 MHz - 200 MHz SSPA

Recent works, made in collaboration between Valvo and SOLEIL have led to the availability of commercial compact circulators down to this frequency range. Using such circulators, SOLEIL has built RF modules, which can deliver 800 W at 176 MHz and 200 MHz. A 40 kW 204 MHz SSPA combining such modules is used in the SR of the Hefei light source [38]. A prototype of 160 kW at 176 MHz is being produced by IBA for MYRRHA in the frame of the MYRTE project [39].

For IFMIF, RAMI studies have shown that the use of SSPA would significantly improve the operational availability, as compared to the previously planned 200 kW 175 MHz tetrode-based transmitters; R&Ds with SSPA are ongoing in the frame of the LIPAc demonstrator [40].

CERN intends to replace its actual SPS 200 MHz tetrode transmitters by two SSPA of 2 MW peak (50% duty cycle). As shown in fig. 13, 16 SSPA of 140 kW will be combined by re-using the 4 stages of coaxial 3 dB hybrid, as already existing. A first 140 kW SSPA prototype, supplied by Thales, was recently tested and the fabrication of a second one was launched, aimed at a long test run [41].

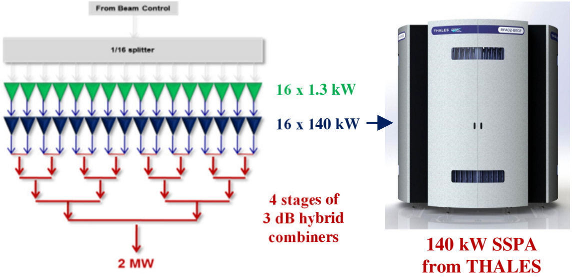

Figure 13: 2 MW 200 MHz CERN-SPS SSPA.

VHF Radio FM (≤ 100 MHz) SSPA

At frequency around 100 MHz, it is hard to build compact low-cost circulators at the kW level. This is not an issue for conventional Radio FM SSA, which provide few kW under matched conditions using isolated 3 dB hybrid combiners. SSPA up to few 10 kW for accelerator applications were recently built, following this approach, completed with a single power circulator at the SSPA output.

Bruker, now SPE, has supplied to GANIL - SPIRAL2 a batch of 88 MHz SSPA, 7 x 2.5 kW, 2 x 5 kW, 6 x 10 kW and 14 x 20 kW [42]. As shown in fig. 12, elementary RF modules of 900 W are combined by means of 3 dB hybrid in the 2.5 and 5 kW units while non-isolated coaxial combiners are used at higher power levels. It turned out that, even with the power circulator at the SSPA output, the residual VSWR was sufficient to limit its power capability. That was cured by oversizing the SSPA and inserting phase shifters both sides of the output circulator to minimize the VSWR effects. All SSPA have passed the site acceptance tests; their overall efficiency is around 66 % and they are being commissioned in SPIRAL2.

SSPA of 60 kW at 100 MHz, from Rhode &Schwarz, are used in Max IV [43] and SOLARIS [44] (Fig. 12b). A 3 dB hybrid combines 2 cabinets of 30 kW, each one consisting in six units of 5 kW.

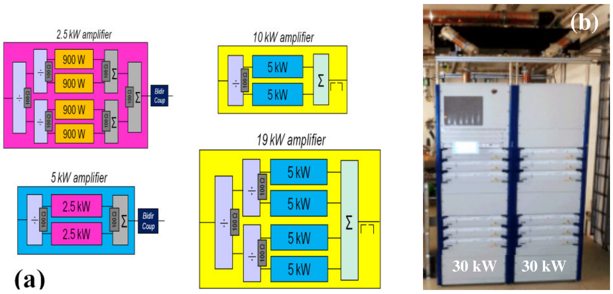

Figure 12: (a) SPIRAL2 88 MHz SSPA (left)
(b) MAX IV 100 MHz 60 kW SSPA (right).

SUMMARY AND CONCLUSIONS

SOLEIL has run for about 11 years with 352 MHz SSPA (1 x 35 kW in the Bo and 4 x 180 kW in the SR), developed in house; they have shown excellent operational availability, flexibility and MTBF. This experience has demonstrated that the SSPA can advantageously replace the vacuum tubes in such CW application, thanks in particular to their inherent modularity and redundancy, the absence of HV and their extremely low phase noise.

R&D carried out at SOLEIL allowed improving the original design in compactness, reliability and efficiency along with the extension to other frequencies. Overall (ac-to-RF) efficiency of 65% can be achieved at 352 MHz or lower frequencies, 56% at 500 MHz and 45% at 1.3 GHz.

Following the success of the SOLEIL SSPA, several accelerator facilities expressed their intention of adopting this technology, which led SOLEIL to share its experience in this domain through scientific collaborations and technology transfers to the industry (ESRF, LNLS, ThomX, SESAME, LUCRECE, ...). Since 2014, SigmaPhi Electronics is the unique SOLEIL licensee.

The SSPA technology has now reached maturity; in addition to SOLEIL, SSPA have run for more than 5 years in ESRF (352 MHz), LNLS (476 MHz), ELBE (1.3 GHz), from where the experience feedbacks are excellent. It is being adopted by many other accelerator facilities and taken up by the industry for applications ranging from the FM to L band with power from a few 10 to a few 100 kW. In the upper frequency range, the key to success is the use of one circulator per transistor. SOLEIL and Valvo have collaborated to develop commercial compact circulators at frequency down to 175 MHz. At lower frequency, the conventional Radio FM technique using isolated hybrid 3 dB combiners is applied, completed with a single power circulator at the SSPA output. This configuration remains very sensitive to residual VSWR.

At frequencies above 1.3 GHz the GaN is supplanting the LDMOS transistor.

R&Ds are carried out with cavity combiners, which could be an alternative to coaxial combiners; each of the two versions has its own advantages and drawbacks.

Although the SSPA are replacing the vacuum tube amplifiers in CW power applications as reviewed above, they cannot oust the klystron as far as very high peak power (tens of MW) and high frequency (S-band and above) are concerned.

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I also want to express my deepest respect and gratitude to our colleague, Ti Ruan, who passed away in 2014. He was **the** pioneer in the domain of RF SSPA, which would not have had such a fast expansion and success without his precursor work.

Ti Ruan
1936 - 2014

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