ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPTS057

SSPA UPGRADE PLAN DESIGN FOR CiADS *

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Abstract

Whether research or commercial ADS facilities require a significant amount of RF power to drive several megawatts of proton beam power, an appropriate RF power upgrade plan can reduce budgets at each stage of the upgrade process and add valuable engineering experience. For stability and maintainability considerations, CiADS (China Active Accelerator Drive System) is designed with SSPA (Solid State Power Amplifier) as the RF power source for future flexible configuration and upgrade. From an engineering point of view, if a suitable matching beam current is selected, a fixed-coupling input coupler is used, which sacrifices up to 10% of the RF power in the upgrade plan, which is acceptable for a 5 MW goal. The SSPA upgrade plan calculation begins with determination of matching beam current, then with the stability requirements to determine the bandwidth, then combines the other RF power requirements to select the output level, and finally checks how much of the remaining level of SSPA is available for detuning control. Calculations and evaluations of a 545 MeV physical design lattice show that some resonators have very limited residual RF power for detuning control, which provides the necessary optimization direction and guidance for physical design and SSPA placement.

INTRODUCTION

In high-energy particle accelerators, over 100 meters or even kilometers linear or storage ring structure are more and more widely used to acquire several hundred MeV to GeV of high-energy particle beams for nuclear physics experiments, for instance LHC in CERN [1]. The ADS (Accelerator Driven System) project is also one of the most typical examples. Currently, included CiADS (China initiative Accelerator Drive System) [2], there have several ADS experimental facility projects [3] planned or under construction around the world.

Most established facilities employed klystron or IOT (inductive output tubes) as their RF power source for high pulse or CW power (MW level) applications for light source or collider [4–6]. Comparing with klystron, Solid-State Power Amplifier (SSPA) has advantages of scalable, reliable, maintainable and easy to control, especially for aspect of maintaining and recovering time. Long RF failures for ESRF (European Synchrotron Radiation Facility) were klystrons, and in the worst case, it required about 8 hours to be replaced [7]. According to the experience of CiADS 25 MeV demo facility, for long recovering time and complex maintaining opererating considerations, one 200 kW electron tube type RF power source replaced with two 80 kW combined 160 kW SSPA as RFQ RF power source. Taking into account the upgrade complexity and decreasing initial budget, SSPA is proposed as RF power source for CiADS.

With the requirement of beam power multiplication plan from 1 mA to 10 mA, CiADS performs upgrade SSPA plan for 5 MW goal. Whether it is acceptable while only upgrade SSPA capacity under the fixed-coupling of input coupler for decreasing the complexity work of changing coupling factor, the answer is positive for following analysis. Based on that, it is necessary to determine the matching beam current during the upgrade process at first, then to calculate the bandwidth and the input coupler coupling factor value under that condition. To calculate the RF power requirement for each upgrade phase to arrange the SSPA capacity and design the upgrading plan.

METHOD

The RF power converted to beam power through a long travel and may loss some at somewhere. Firstly, with an analysis of upgrade process, the RF power requirements may come from several parts as shown in Fig. 1:

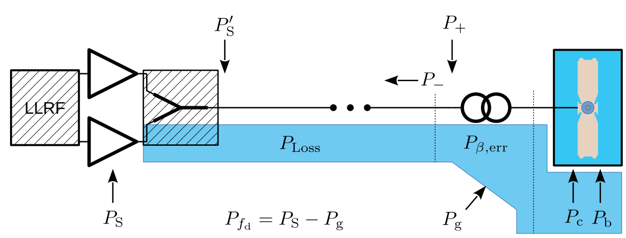

Figure 1: RF power flow.

Among those RF power which can not convert to beam power, the transmission loss and the error introduced RF power requirement must be satisfied undisputed. In the upgrade process, the combining loss among racks and the reflected power requirement should be considered carefully while under operating at mismatching beam current.

Basic Requirements and Parameters

From the calculation and simulation by physical design, cavity design, LLRF design and coupler design, together with the basic assumptions based on some thumb rules are shown in Table1.

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Table 1: Baseline Parameters

Parameter	Value	Comment
Stability for Amplitue	0.1%	Physical Design
Stability for Phase	0.1°	Physical Design
Tranmition Loss	10%	RF Design
Detuning control	10%	LLRF Design
Coupling Error	± 20%	Coupler Design

Fixed-coupling Introduced Reflected RF Power

For evaluating how much reflected RF power will be generate during upgrade on a fixed-coupling input coupler design, the matching beam current should be calculated first.

The matching beam current $I_{\mathrm{b,m}}$ is the condition of the cavity and the coupler working at matching status and without detuning. Since Q_{ext} satisfies $Q_{\mathrm{ext}} = V_c^2/(P_{\mathrm{b,m}} \cdot R/Q)$ at that situation, the input power P_+ is exactly equals to the matching beam power $P_{\mathrm{b,m}}$. The relationship between input power and arbitrary beam power P_{b} is [8],

$$P_+ \cong \frac{P_{\mathrm{b,m}}}{4}\left(1 + \frac{P_{\mathrm{b}}}{P_{\mathrm{b,m}}}\right)^2 \quad (1)$$

Here define beam power matching ratio $m_{\mathrm{P}} = P_{\mathrm{b}}/P_{\mathrm{b,m}}$ for any selected matching beam power $P_{\mathrm{b,m}}$, then the input power Eq. 1 becomes $P_+ = (1 + m_{\mathrm{P}})^2/(4m_{\mathrm{P}}) \cdot P_{\mathrm{b}}$, and the reflected power for arbitrary operating beam current is:

$$P_- = \frac{(1 - m_{\mathrm{P}})^2}{4m_{\mathrm{P}}} \cdot P_{\mathrm{b}} \quad (2)$$

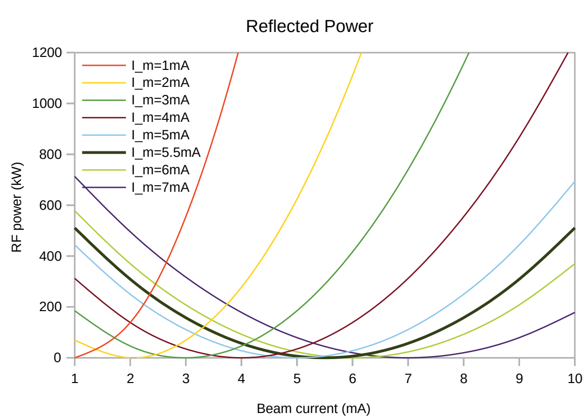

Figure 2: Reflected RF power ratio at different $P_{\mathrm{b,m}}$.

The reflected power versus $P_{\mathrm{b,m}}$ at varying matching beam current $I_{\mathrm{b,m}}$ from 1 mA to 7 mA were ploted in Fig. 2. To balance the RF power reflection during the upgrade process, that the reflected power at 1 mA should be equal to the reflected power at 10 mA under selected $P_{\mathrm{b,m}}$. It is determined that the $I_{\mathrm{b,m}}$ value is 5.5 mA for that the reflected power of the two at this condition are all 0.92 $P_{\mathrm{b,1mA}}$, that is no more than 510 kW in that physical design ($P_{\mathrm{b,1mA}}$ = 554 kW) theoretically. Comparing with around 5 MW beam power, maximum 10% reflected RF power is acceptable if fixed-coupling input coupler design was employed during upgrade procedure. And the SSPA upgrade plan can be simply devided as four phases, 1 mA, 2.5 mA, 5 mA and 10 mA for multiplication beam power upgrade plan.

Stability vs. Bandwidth

For the CW operating machine, the Lorentz force caused detuning is mainly present as static value, while for the pulse operating accelerators, that is dynamic detuning. The static detuning can be tuned by a slow tuner, but the dynamic detuning requires the LLRF system to compensate with RF power in some level. Another major source of dynamic detuning is the Microphonics, especially at the beam loaded increases, it will become more significant [9]. The Microphonics may generate from known and unknown mechanical vibration sources, liquid Helium pressure, etc., which can be compensated by LLRF system sacrificed more RF power or tuned by a fast tuner like PIEZO [10,11]. Some simulation shows that in order to achieve the stability requirement of amplitude and phase, the amplitude of the oscillation caused by the Microphonics should be limited at $\omega_{\mathrm{d}} < 0.1\delta\omega$. Some simulation results of Microphonics for CiADS listed in Table2 shows that the higher frequency the tighter detuning allowance [12]. Enlarging bandwidth can improve detuning control but scrifice more RF power.

Table 2: Maximum Detuning Under Different Microphonics Frequency For Each Segment Under Corresponding Bandwidth

f_{m} (Hz)	50	100	150	200
f_{d} @ 162.5, 100 Hz	10	5	4	3
f_{d} @ 325, 100 Hz	18	10	7	5
f_{d} @ 650, 50 Hz	18	10	7	5

RESULTS AND DISCUSSION

For instance, the RF power requirement calculation results and optimization suggestions for one physical design 545 MeV are shown as follows.

SSPA Upgrade Plan and Arrangement

For convenient of calculating and discussing, the subsequent calculation or description will be analyzed with the minimum unit of each segment, For example, Pssa555 is the minimum unit of 5 kW for 162.5 segment, 5 kW for 325 segment, and 10 kW for 650 segment, which the corresponding maximum output of the whole rack are 24 kW, 24 kW and 30 kW.

For the realization of engineering, the best combination scheme selected by using three kinds of single rack output power are 20 kW, 24 kW and 30 kW. Under the premise of maximizing the beam power, the rated total power is reduced as much as possible. The upgrade posible combination schemes are shown in Fig. 3 for those utilization

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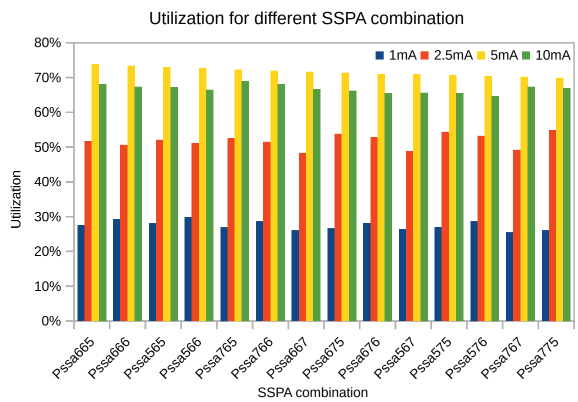

Figure 3: SSPA group utilization.

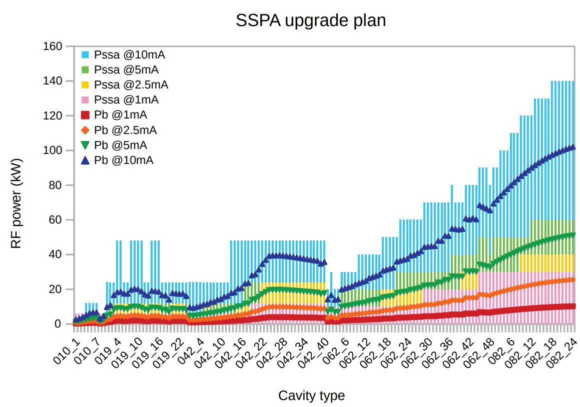

Figure 4: SSPA upgrade plan.

(P_b/P_S) larger than 70% at 5 mA phase of SSPA combination scheme, that the total rated power of the Pssa665 is the smallest at 5 mA. So the combination scheme of Pssa665 is determined as the minimum unit combination of the SSPA output level. If considering the phases of 2.5 mA and 10 mA, Pssa765 is better than Pssa665 for high utilization at these two phase, and not bad at 5 mA phase. The upgrade plan of SSPA for Pssa665 is ploted in Fig. 4, if the budget for initial phase is allowed, starting with 2.5 mA not required too much budget than 1 mA.

Availability for Detuning Control

Figure 5 shows the beam power and the corresponding SSPA availability for detuning control during the upgrade process. Under the beam current of 1 mA, only several SSPA's surplus is less than 10%. At 2.5 mA, some of both low and high energy segments have a small margin. Under 5 mA is mainly concentrated in the Spoke042 and Ellip082 segments, but at 10 mA, the power margin of the more cavities are seriously insufficient. For the medium and high energy segments (650 and above), the cavity voltage can be adjusted flexibly to balance the RF power requirement or directly increase one or two minimum combination unit, but for the low energy segment, the physical design adjustment space is very limited, and only the SSPA utilization of the individual cavity can be sacrificed to satisfy the physics design requirement.

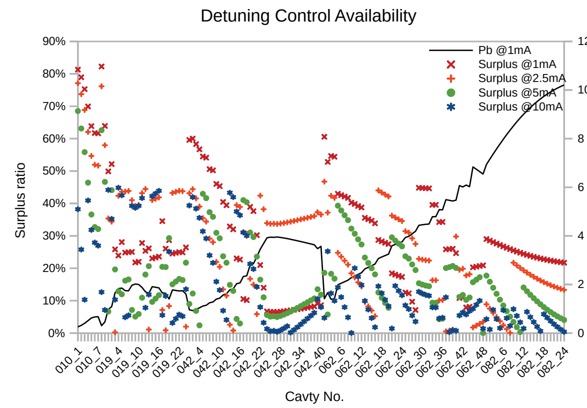

Figure 5: SSPA availability for detuning control.

CONCLUSION

For the selection and arrangement of SSPA, the author is firmly realized that the criteria chosen are not fixed on one hand , and more complex for upgrade plan desgin for CiADS. Budget is undoubtedly a key issue in balancing all phases requirements, trade-offs should be on some aspects. First of all, fixed-coupling input coupler for each cavity type were chosen to do quality control in assembly and installation procedure which can extremely decrease the complexity of customized input coupler for each cavity and the sacrificed RF power also can be acceptable. Here some high priority requirements must be garanteed such as RF loss on transmision line and combination between racks, the reflected RF power at mismatching phases, and some error introduced requirements. There is no bargain room for a confirmed safety level contruction design and upgrade plan. More friendly to detuning control RF power requirement for high energy segments but still very tight for lower energy segments if the strategy of tuning cavity voltage will be taken.

ACKNOWLEDGEMENT

I am grateful to L Hardy, who point out clearly the main availability in accelerator reliability issues for existing facilities, for the numerous and excellent experience of Klystron he wrote in the paper. Many thanks for the RF power source designers sttempt introduce SSPA into particle accelerators. I am also grateful CiADS leaders, cooperators and designers, many thanks for all the advice and suggestion from CiADS design colleagues, the valuable communication between us made a lot of help for these work, especially for the strategy of SSPA output power level selection and SSPA upgrade plan arrangement.

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