CONCEPTUAL DESIGN OF A MULTI-TURN ENERGY-RECOVERY LINAC FOR THE ADVANCED PHOTON SOURCE RING*

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Abstract

The Advanced Photon Source (APS) is a fully-developed 3rd-generation x-ray source with some 40 beam-lines for materials, condensed matter, and bio-molecular structure studies. The concept put forth in this paper can improve the source brilliance of the APS by three to four orders of magnitude and can shorten the x-ray beam pulse length from about 30 ps to the order of 100 fs by combining the existing APS ring with a multi-turn energy-recovery linac. The paper discusses one possible solution to a major difficulty associated with operation of a multi-GeV CW linac, namely how to minimize the cryogenic heat load. The cryoplant, using today's technology, for a multi-GeV CW linac could be extremely large and costly. The heat load issue could be solved by improving the cavity quality factor by an order of magnitude, which is one of the forefront topics in SRF R&D. In the meantime, we propose another possible solution to the heat-load problem by re-circulating the beam as is done in CEBAF in order to make the linac length shorter. We discuss implementation of this idea in the APS storage ring or at other 3rd-generation light sources in order to best preserve the excellent linac beam emittance.

INTRODUCTION

The photon beam brilliance of a storage-ring-based synchrotron radiation source is determined by the natural emittance (ε) of the ring lattice and by the ring energy (E). Since ε is proportional to E^2 and inversely proportional to the third power of the number of bending magnets in the ring, a 3rd-generation x-ray ring in the 6- to 7-GeV energy range tends to have a large periodicity to increase the number of bending magnets in the ring. Additionally, the brilliance, a conserved quantity, is inversely proportional to ε^2. It is very important to make ε as small as possible, which becomes increasingly difficult as the ring energy increases. This is a basic limitation of storage-ring-based x-ray sources.

Another limitation of storage-ring-based synchrotron sources is the bunch length of the stored electron beam, which directly translates to the length of the photon beam pulse. Typical bunch lengths are of the order of 20 ps with zero current in the bunch. Beam-loaded bunch lengths are usually longer than zero-current bunch lengths. The natural bunch length is determined by the natural energy spread of the lattice and by synchrotron motion of the particles in the bunch.

Beam emittance of a linac varies as 1/E, however, so its beam emittance can be made as small as needed by accelerating to higher energy. The other advantage of acceleration by a linac is that the beam bunch length can be made as short as a fraction of a mm by means of bunch compressors in the early stages of acceleration. Such bunch compression is performed routinely at the TESLA Test Facility, http://tesla.desy.de, for example.

The disadvantage of a linac-based synchrotron radiation source is that it needs very high beam power in order to be comparable to a storage-ring-based source of similar photon wavelength. For example, the Advanced Photon Source (APS) at Argonne National Laboratory, http://www.aps.anl.gov, is a 7-GeV storage ring with a beam current of 100 mA. If this level of beam current and energy were to be produced by a linac, the beam power would be 700 MW and the AC wall-plug power required to produce such beam power would be in the GW regime. Spent beam must be absorbed in a beam dump after use, and such a beam dump is not easily constructed. Therefore, a single-pass linac-based synchrotron source is not practical.

The solution to the above problem is to recover almost all of the energy from the spent beam before dumping it, using an energy recovery linac (ERL). M. Tigner proposed the energy-recovery scheme in connection with "clashing beam" experiments in 1965 [1]. Recently, Tigner, et al., proposed and studied a full-scope radiation source facility based on the energy recovery principle [2]. The recovered energy is in the form of radio-frequency power that is used to accelerate the incoming beam. The recovery mechanism utilizes the same accelerating structure to both decelerate spent beam and accelerate incoming beam. Deceleration is achieved by injecting the spent beam into the accelerating structure while shifting the bunch phase by λ/2 with respect to the new accelerated beam. Thomas Jefferson National Accelerator Facility (JLAB) personnel have performed a number proof-of-principle energy-recovery experiments, and have shown that energy recovery is feasible. These initial experiments recovered 98% of the beam energy [3].

The predicted superior performance of ERL-driven light sources is well known and well documented [2, 4]. Peak brilliance is typically four orders of magnitude better than at 3rd-generation storage ring sources.

There is, however, a technical difficulty associated with multi-GeV CW linacs resulting from the cryogenic heat load associated with the accelerating structures. This paper addresses consequences of radio-frequency stored energy loss into the liquid helium bath around the structure, commonly known as dynamic heat load. For a multi-GeV CW linac, assuming existing SRF-cavity technology, the dynamic heat load poses a problem that must be successfully addressed in order for the linac design to be practical.

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DYNAMIC HEAT LOAD FOR A CW LINAC

The TESLA Technical Design Report (TDR) [5] shows a detailed dynamic heat load calculation for the TESLA linac operating at gradient of 23.4 MV/m, quality factor of cavities, Q_o, of 10^{10}, and a linac duty factor of 0.5%. According to the TDR, the design dynamic heat load, including overhead, is about 1W/m. If this linac were to operate in CW mode, the dynamic heat load would become 200W/m or 1kW/5m.

The central helium liquefier (CHL) cost is about US$10M/kW based on recent procurement of the SNS CHL system. From this unit cost, one can estimate the CHL cost for a 1-km-long CW linac to be about US$2B for a linac gradient of 23.4 MV/m and Q_o, of 10^{10}.

Dynamic heat load per cavity length is proportional to the square of the gradient, but for a given energy linac, dynamic heat load is proportional to cavity gradient. Therefore, it would be possible to reduce the heat load somewhat with a trade-off between gradient and linac length, but the reduction would be minor.

The ultimate solution to the rf heat load issue associated with long CW linacs is to increase the cavity Q_o, i.e. reduce the residual resistivity of the cavity surface. At the present time, techniques to achieve a large reduction of the residual resistivity of Nb surfaces are not readily available, and intensive R&D work is still required.

RE-CIRCULATING ENERGY RECOVERY LINAC (RERL)

Perhaps a simpler solution to the dynamic heat load issue with a GeV-range CW linac is to make the linac shorter but attain the required energy by re-circulating the beam in a similar fashion as done by CEBAF. The dynamic heat load of the re-circulating linac could be as low as 1/N, where N is the number of turns circulated in order to attain the required final energy.

Fig. 1 is a schematic machine layout showing re-circulation arc beamlines. The figure shows a four-turn re-circulation to achieve a 6-GeV beam, which is then transported to the APS storage ring. The beam passes through the APS ring once and returns to the CEBAF-like structure as “spent beam.”

At the present, CEBAF operates with a modest beam current of about 100μA for its nuclear physics program. In order to make a re-circulating accelerator appropriate for light source usage, the beam current has to be increased to the range of 100 mA. As noted in the Introduction, in order for a multi-GeV 100-mA CW electron accelerator to be feasible, the energy must be recovered from the beam after the beam has been used for science.

In the proposed energy-recovery process, spent beam arrives at the linac from the APS ring, as shown in Fig. 1, and reenters the linac together with new beam from the injector but with a λ/2 phase shift in order to enter a decelerating bucket. Energy from the spent beam in the decelerating bucket is transferred to the incoming low-energy new beam in the accelerating bucket. When these two beams make 4 turns, the acceleration and deceleration cycles are complete and the low-energy spent beam is dumped into a beam dump.

CEBAF experience has shown [6] that the injection energy of a re-circulating linac can be as low as 25 MeV. Since the design current is 100 mA, the beam dump should either be able to accept 2.5 MW of beam power or it should have additional energy recovery by deceleration to lessen the required beam dump capacity. Daresbury Laboratory proposes the latter in their 4GLS light source design [7].

INTERFACING WITH THE APS RING

Fig. 2 schematically shows the interface between the

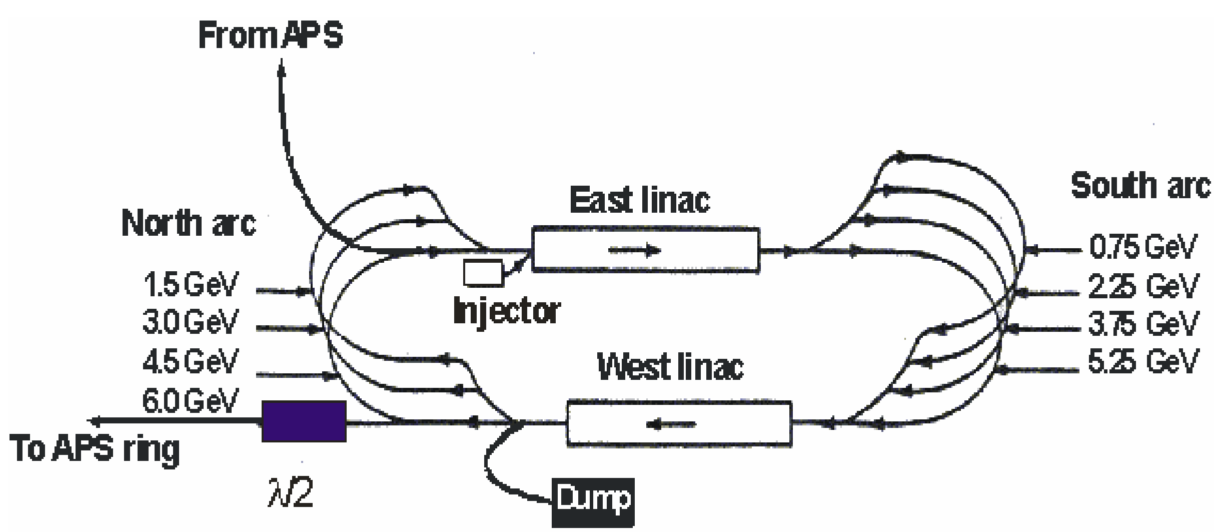

Figure 1: Schematic machine layout showing re-circulation arc beamlines.

RERL and the existing APS ring. The injected beam circulates four times in a clockwise direction in the RERL to achieve 6 GeV. The 6-GeV beam is transported to the APS ring as shown in Fig. 2 and circulates clockwise in the ring for one turn. Then the beam enters into the RERL and circulates clockwise to satisfy the energy recovery

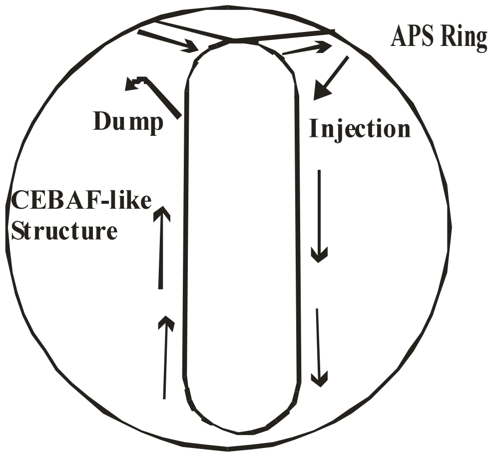

Figure 2: Schematic trajectory of beams from the RERL to the APS Storage Ring.

conditions: a) the new beam being accelerated and spent beam being decelerated must have a phase difference of $\lambda/2$, and b) both beams should travel in the same direction in order to avoid beam-beam collisions. The schematic trajectory shown in Fig. 2 satisfies these two conditions provided that the phase of the spent beam is adjusted to achieve the $\lambda/2$ phase difference. The particle trajectory between the RERL and the APS ring is a folded figure-8.

Fig. 3 shows a layout of the RERL in the APS infield. The actual connection between the RERL and the APS can be made at the APS booster tunnel as indicated in Fig. 3. The linkage between the old and new machines can be designed to minimize interference with the current APS scientific program. The APS infield diameter is about 180 m and can therefore accommodate two linacs of 110 m or less.

Since integrated dynamic heat load is proportional to the accelerating gradient for a fixed energy linac, lower gradient is preferred. If one chooses the RERL gradient to be 10 MV/m, and uses two 75-m-long linacs in the infield, the beam energy becomes 6 GeV after a 4-turn circulation.

RERL BEAM IN THE APS RING

The APS ring becomes a single-pass beam transport for the RERL beam, i.e. the beam enters into the ring and after passing once through the entire ring, returns to the RERL. In this way, the beam that creates x-rays for the users maintains its excellent linac beam properties without becoming degraded by the storage ring.

Since the beam trajectory within the storage ring is not changed by introduction of the RERL, the trajectories of photons emitted by the APS insertion devices and dipoles are also unchanged. There is no need to re-arrange any user experiments.

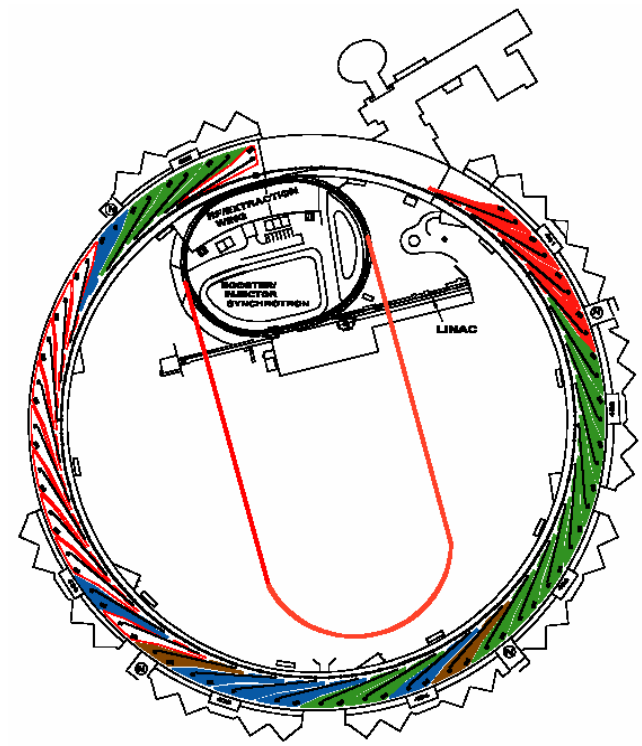

Figure 3: RERL layout in the APS Infield. The red line represents the RERL, interfaced at the present booster tunnel.

The performance of the APS ring with a RERL driver is the same as that shown in a paper at this conference by M. Liepe [4] on ERL performance. Fig. 4, obtained from Liepe [4], shows performance in terms of peak brilliance and pulse length for a 5- to 7-GeV ERL-driven synchrotron source. The figure shows that pulse duration could be as short as 100 fs with a peak brilliance that is 3 to 4 orders of magnitude better than 3rd-generation x-ray sources.

SUMMARY

The concept of a 100-mA, 6-GeV RERL is presented in order to solve the dynamic head load problems of multi-GeV CW linacs. The RERL is an ideal driver for the APS ring or other 3rd-generation x-ray rings to generate short-pulse, high-brightness undulator radiation for the synchrotron radiation research community.

Generating high-quality beam using the RERL, and using the APS storage ring as a transport and distribution system improves the APS photon source brilliance by 3 to 4 orders of magnitude. Furthermore, the APS would have the new capability of having 100-fs-long photon beam pulses for reaction timing and pump and probe experiments.

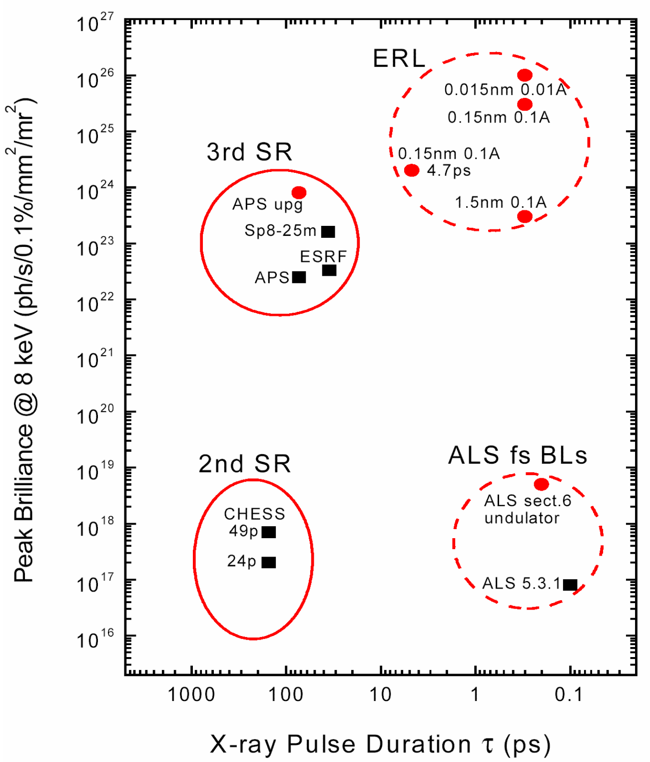

Figure 4: Performance in terms of peak brilliance and pulse length is shown for a 5- to 7-GeV ERL-driven synchrotron source, from Liepe [4].

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