EXPLOITING LINAC FLEXIBILITY TO PRODUCE A SUPERIOR X-RAY FACILITY

R. Talman, Laboratory of Elementary-Particle Physics, Cornell University, Ithaca, NY, USA

Abstract

The benefits to x-ray beam quality associated with the flexibility possible with a linac (as contrasted with a storage ring) are investigated. It is shown that comparable flux and far higher brilliance can be produced, in spite of far lower beam current. Specially tailored beta-functions, electron beam focusing, and collimation produce a monochromatic beam with no filters, mirrors, lenses, or any other material in the x-ray line. This preserves maximal coherence and, with it, the possibility of diffraction-limited focusing. A proposed reconfiguation of CESR as a dual mode (ERL/linac) light source is described and its performance compared to NSLS-II projections.

LINAC AND RING OPTICAL FUNCTIONS

Pros and cons of linacs and storage rings as light sources are listed in Table 1. That almost all light sources are based on storage rings rather than linacs is presumably due to their far greater average beam currents. But the table shows many advantages for linacs.

Table 1: Pros and Cons of Storage Rings and Linacs as X-Ray Sources

FAVORS LINAC	NEUTRAL	FAVORS RING
		large beam current
(potentially) large charge/bunch		
small ϵ_x	$\epsilon_x\epsilon_y$	small ϵ_y
high brilliance	flux density	high flux
flexible optics		
unsegmented, long undulator usable		
helical undulators usable over large E_γ range		
coherence preservation		
(potential) femtosecond bunch length		
flexible bunch pattern		
ultrahigh energy x-rays		

The useful narrow energy bandwidth (BW) x-rays are those emitted dead forward from an undulator (assumed here to be helical). The x-ray transverse distribution can be described by the beta functions (with name changed to "Rayleigh range functions") the electron beam *would have* if propagating into the drift space after the undulator. These distributions are shown, for both storage ring and linac cases, in Fig. 1. By design the beams have a waist at the undulator position in the storage ring case, but at the x-ray target in the linac case.

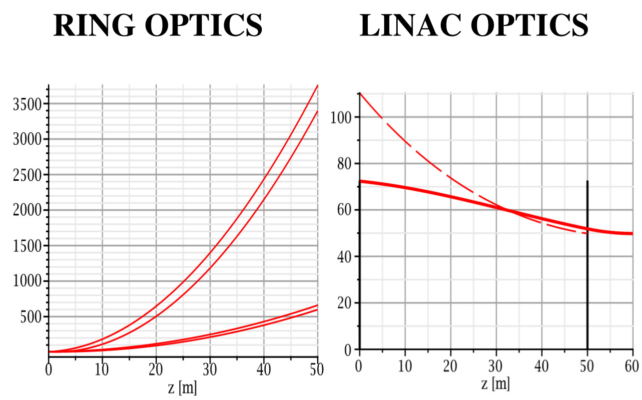

Figure 1: Beta functions (in meters) for ring and linac. The broken curve is the Rayleigh range factor (at the 60m downstream x-ray target) plotted at the z-value from which the x-ray emission occurs. For the ring case the range function coincides with the plotted curves (the dual curves indicate the range ascribable to position in undulator).

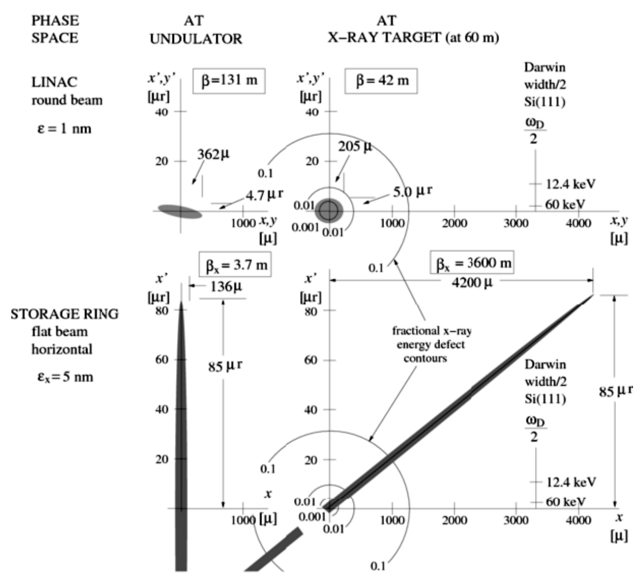

Figure 2: Horizontal phase space evolution from undulator position (on the left) to x-ray target position (on the right) for a linac (upper) a ring (lower). Vertical phase space evolution is identical in the linac case, and similar (though with both scales altered by a square root of emittance ratio of about ten) in the ring case.

Circles centered on the phase space origin at the x-ray target indicate contours of constant fractional energy deviation (away from the undulator spectrum edge). In the linac case the beam passing a circular collimator of, say, 0.5 mm ID, is monochromatic with BW considerably less than one percent. In the storage beam case, after convoluting with the electron distribution, the x-radiation is approximately white.

Only a small fraction of the x-ray beam shown in the storage ring case would pass through a 0.5 mm ID collimator. With a focusing mirror this fraction could be increased to near unity, but the angular divergence would still be of order 100 microradians, far larger than the Darwin width (shown on the plots) for a typical monochromator crystal. Furthermore mirror imperfections necessarily destroys the beam coherence, and with it any possibility of diffraction-limited focusing.

It can be seen that these comparisons strongly favor the linac case, especially for beam brilliance, which is inversely proportional to both angle and position spreads. This more than makes up for a hundred or so smaller average beam current in the linac case. The possibility of far longer undulators even enables competetive x-ray flux with the linac option.

RECONFIGURATION OF CESR AS RECYCLING ERL AND LINAC

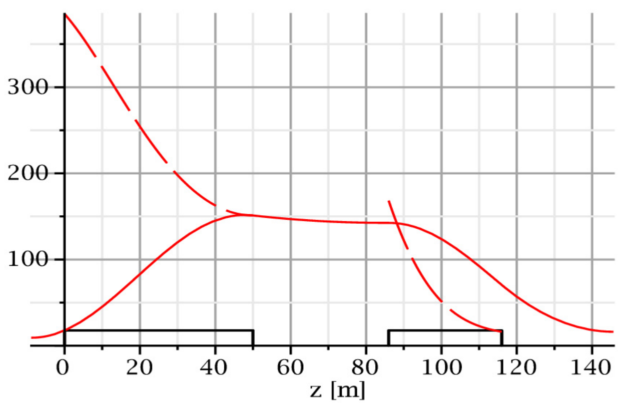

Figure 3: Beta functions (in meters) for a 150m long, two undulator insertion section. It is waist-to-waist matched to typical (few meter) arc lattice functions. As in Fig. 1 Rayleigh range factors at the two x-ray targets are shown as broken curves.

These advantages can be exploited in a proposed reconfiguration of CESR. Most of the x-rays lines are based on dual helical undulator optics[1,2] like those shown in Fig. 3. A tentative overall layout cartoon is shown in Fig. 4.

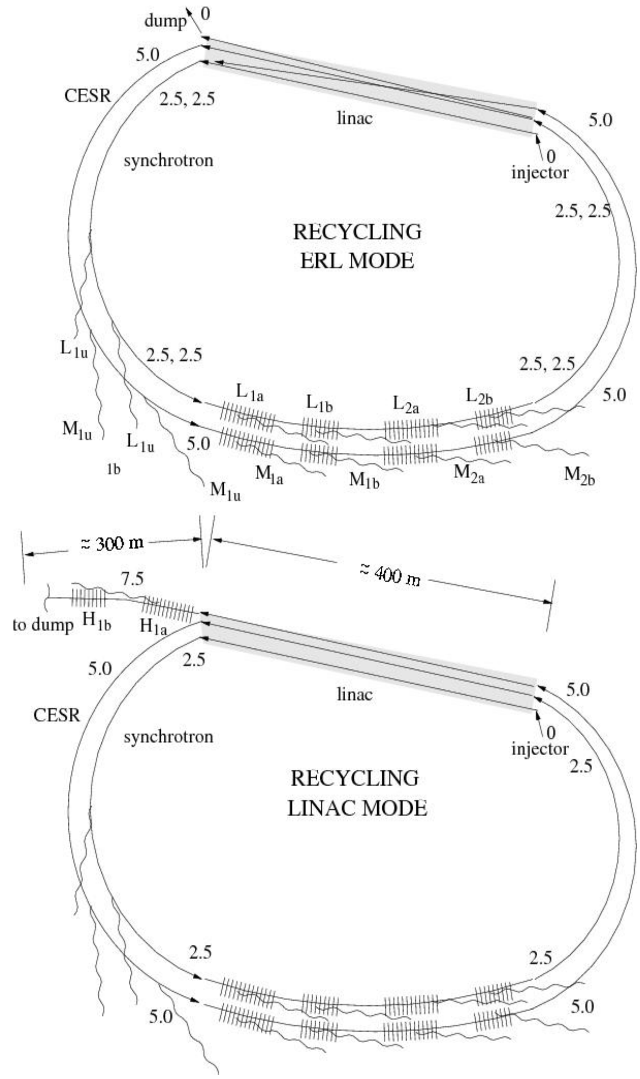

Figure 4: Reconfigured Cornell CESR/synchrotron complex as a dual, recycling ERL and recycling external linac light source, based on multiple insertion sections shown in Fig. 3. Beam energy sequencing in the two modes can be inferred from the numbers beside the arcs, which are energies in GeV units.

The basic linac is 400 m long and imparts 2.5 GeV per pass, for one, two, or three passes. In ERL mode beams are available at 2.5 and 5 GeV. In external linac mode a low current external beam is also available at 7.5 GeV. Prefixes “L”, “M”, and “H” on beamline labels refer to low, medium and high x-ray energies.

Projected performance, at 10 keV x-ray energy, for four of the beamlines, is shown in Table 2. Of course the “L” lines would be optimized for softer x-rays and the “H” lines for ultrahard x-rays. Note especially the extremely low beam power through collimator, even at extremely high brilliance. Projected performance of the most intense NSLS-II beam[3] is shown in the final column for comparison purposes.

Table 2: Parameters of X-ray beam lines (labels are in Fig. 4) are compared with projected performance of the highest flux (at 10 keV) NSLS-II beamline. [3]

parameter	unit	ERL M_a hi-flux	ERL M_b hi-brill.	LINAC H_a hi-flux	LINAC H_b hi-brill.	NSLS-II U19 CPMU
electron energy	GeV	5.0	5.0	7.5	7.5	3.0
electron current	mA	50	50	1	1	500
emittance, horz.	nm	0.1	0.1	0.01	0.01	2.1
emittance, vert.	nm	0.1	0.1	0.01	0.01	0.008
undulator length	m	50	30	50	30	3
undulator period	mm	16	16	25	25	
undulator parameter		0.69	0.69	0.69	0.69	2.0
beamline length	m	35	35	35	35	< 60
x-ray energy	keV	10	10	9.9	9.9	10
flux	§	3.1e16	1.9e16	1.4e15	0.85e15	0.9e15
flux density	§	1.3e18	5.0e18	1.2e18	1.9e18	
brilliance	§	2.6e23	3.1e24	1.1e25	2.1e25	0.8e21
total beam line power	kW	16.7	10.0	0.8	0.5	11.2
power through collim.	W	≈200	≈100	≈1	≈1	?

§ Standard units, 0.1% BW, mm, mr

Obviously Fig. 4 is much oversimplified. To preserve flexibility the undulators should be split into individually-powered segments. As drawn all undulators are helical, with undulator strength parameter K=0.7 (corresponding to K=1 for a planar undulator) both of which are unacceptably restrictive. The optics can also be matched with planar undulators for various K values[4] but trim quadrupoles (not shown) will be required for this and other flexibility. Fortunately they can be quite weak.

To simplify separating the x-ray beams the M lines need to be displaced vertically from the L lines. More serious are the bending magnets (also not shown) required to provide separation of successive beamlines. They can also be quite weak, but downstream elements may need to be shielded from their synchrotron radiation. If the undulators are superconducting they may have to have warm bores. Tentatively the inner diameter of the M-line undulators is 5 mm which, though small, is consistent with the assumed emittances.

There are many ways in which the facility will function very differently from, and less conveniently than, a conventional storage ring light source. The most important of these is that the undulator focusing is integral to the lattice optics---not just a perturbation as in a storage ring. Since the undulator gaps heights will need to be held fixed it is likely that small x-ray energy step sequences will be performed by changing the linac energy. This will, at best, be inconvenient for servicing multiple experiments.

On the other hand the simultaneous availability of three electron beam energies will provide unprecedented flexibility by permitting optimal x-ray beams over the full keV to MeV energy range.

REFERENCES

[1] J. Madey, J. Appl. Phys., 42, 1906, 1971

[2] J. Blewett and R. Chasman, Orbits and field in a helical wiggler, J. Appl. Phys., 48, 2692, 1977

[3] http://www.bnl.gov/nsls2/project/CDR

[4] J. Corbett and Y. Nosochkov, Effect of Insertion Devices in SPEAR-3, Proc. Of Part. Acc. Conf., New York, 2358, 1999