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Incoherent Thoughts About Coherent Light Sources

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Abstract

Jefferson Lab-specific issues related to the design of an SRF linac-driven coherent light source are discussed. A concept for a x-ray coherent light source driven by a 10 GeV linac is sketched.

Overview

Community consideration of “fourth generation” light sources frequently focuses on FEL-based coherent x-ray sources driven by high-energy electron linacs. In this note, we entertain the notion of a CW x-ray coherent light source at Jefferson Lab. A rough parameter set is presented, and machine topologies that may meet these design goals are discussed. In particular, the location of such a machine on the lab site is addressed. Cost/operability and source-related issues are broached, and a possible machine concept for a 10 GeV driver linac/FEL based coherent light source is presented.

Parameter Set

In this note, we want to investigate the possibility of using an SRF linac to drive a coherent x-ray source. SLAC has made significant investment in studies of similar devices (though driven by conventional linacs). Our discussion is therefore based on an adaptation of the SASE FEL design proposed for the SLAC LCLS [1]. Parameters immediately appropriate to the following discussion are presented in Table 1.

This parameter set implies single bunch performance consistent with that of the SLAC LCLS. Average performance will, however, be significantly higher inasmuch as the use of SRF technology will allow CW operation. Provided source limitations can be overcome (a discussion follows), an SRF linac-driven coherent light source could, in principle, out-perform copper linac driven sources in much the same manner that the JLab IR-FEL outperforms previous copper linac and storage ring based IR FELs.

Table 1: Baseline Parameters

Parameter	*Value*	*Rational*
Energy E	10 GeV	x-ray source
Normalized emittance ε_N	1 mm-mrad	FEL requirements*
Peak current I_{peak}	3400 A	“
Rms bunch length σ_t	67 fsec	“
Charge/bunch Q_B	500 pC	Consequence of peak current/bunch length*
#e^-/bunch N_e	$3x10^9$	Consequence of peak current/bunch length*
Repetition Rate	2 MHz	CW driver accelerator*
Average current I_{ave}	1 mA	Guesstimate of reasonable current in SRF structure
Undulator Length	100 m	FEL requirement – multiple coherence lengths
Type of driver accelerator	Energy-recovering SRF linac	Cost/performance optimization; RF power management; radiation management
Average accelerating gradient	10 MV/m	Projected SRF performance†
Average bending radii of transport arcs	100 m	Management of CSR-driven emittance degradation

* source limitations imply need for technology development

† gradient limitations imply need for technology development

Such a machine generically comprises a 10 GeV linac (with energy recovery to limit RF power and radiation management requirements) and associated beam transport to get the electron beam to and from a 100 m undulator, on which the FEL is based. Conceptual details of, and issues for, the machine design follow. We envision that the repetition rate is ~ 2 MHz to limit currents in the SRF structure to the order of the 1 mA values JLab experience has shown to be reasonable. Similarly, short bunch-lengths (high peak currents) are by implication to be generated *after* the SRF linac to avoid wake field driven instabilities in the high Q structures. This in turn implies that any beam transport system must support features intended to limit wake field effects (clean vacuum system), limit incoherent synchrotron radiation-induced emittance/momentum spread degradation, and manage, or perhaps even suppress, CSR-induced degradation of the beam phase space. The 100 m mean transport bending radii given in the table are assumed to allow design of a system that will meet these criteria and which, in addition, may provide, if needed, a large momentum acceptance for energy recovery.

Topologies/Siting

We may extract the following design requirements from the above discussion.

1) Machine energy ~ 10 GeV

2) Energy recovery is to be used as a means of limiting RF power requirements and managing radiation.

3) The machine must support a utility insertion to accommodate the ~100 m length of the FEL undulator. If an “undulator farm” is desired (for technicolor/multiuser operation) factors of two or more space must be allowed.

4) The transport to/from undulators and through linac must
    a) ensure beam quality preservation during acceleration
        i) Avoid impedance-driven instabilities
        ii) Manage quantum excitation
            (1) Incoherent synchrotron radiation dilution of emittance, momentum spread
            (2) CSR
    b) support bunch-length compression prior to the wiggler but after acceleration (to limit peak currents in the SRF structures)
    c) provide low-loss transport during energy recovery
        i) possibly support transport of relatively large momentum spread after the wiggler
        ii) allow for longitudinal matching

5) The electron source must provide a tight phase space with high single bunch charge at high rep rate/CW current.

The energy is set by FEL requirements to produce radiation in the x-ray regime. We assume continued development of CEBAF-style cavities (perhaps at lower frequency) to provide a “100 MV module”, or an average footprint gradient of 10 MV/m. A total of 1 km of acceleration length is thus needed. The use of energy recovery allows a significant reduction in RF power demands and aids in radiation management. Without energy recovery, the final beam power of 10 MW would require use of very robust beam dumps and would, in addition, demand significant development of RF windows for the accelerator modules. With energy recovery, the average forward RF power is significantly reduced (the energy recovered beam being used to drive the cavities), alleviating demands on windows and reducing linac power utilization. The dumped beam can, in principle, be brought to very low energies (~10 MeV) and directed to a simple, low cost dump.

The FEL itself will require use of a long undulator to allow for multiple coherence lengths. The available space must exceed 100 m (the nominal undulator length) to allow for matching and, if not done elsewhere, bunch length compression. Multiple undulators could be used if space is provided to switch amongst them; a total length of at least 200 m would be required for such an undulator “farm”. If bunch-to-bunch switching and “technicolor” operation is required, even more space would be need to accommodate CEBAF-like RF separation.

The transport system is subject to a variety of constraints imposed by both physical processes and operational demands. During acceleration, the electron beam quality must be preserved to maintain beam phase space brightness at the FEL. Degradation through processes such as impedance driven instabilities (BBU, wake-field effects) and quantum excitation (though either incoherent or coherent synchrotron radiation) must be properly managed, through use of an electromagnetically “clean” vacuum chamber and proper transport system design. The system must support bunch length compression prior to the wiggler but after the accelerator, to provide the required high peak currents at the FEL without generating impedance-driven instabilities in the linac. During energy recovery, beam losses must be limited. The system may have to manage large momentum spreads following the FEL during at least portions of the energy recovery process. Provisions for longitudinal matching (though adjustment of momentum compactions and path lengths/RF phases) may be required. We expect that a mean bending radius of ~100 m will be required to accommodate these constraints. We note that CEBAF uses arcs of 80 m mean radius; these are expected to allow simple beam transport with small quantum excitation of low peak current beams up to perhaps 20 GeV.

Source requirements for high-brightness bunches may represent the most significant technical challenge for machines of this type. A more extensive discussion is given in a following section.

Various machine topologies can meet these requirements. Each has its own cost/operability advantages. Here we consider four possible scenarios.

I. *Anti-parallel, single-pass linac pair*: This simple topology has a pair of linacs directed at each other with an undulator (farm) between the pair [2]. A bunch is accelerated in one linac, drives the laser, and is then decelerated in the second linac, driving it as well. As the system is essentially “linear”, it will lead to low quantum excitation (both coherent and incoherent), provides simple operation, and, in a sense, gives opportunity for “double barrel” operation, with a pair of undulators simultaneously lasing while driven by the linac pair. Beam transport between the linacs provides bunch compression prior to the FEL and, as it is essentially straight-line, can be readily designed to handle large momentum spreads.

The scenario has a significant disadvantage in that the cost is as much as a factor of two higher than machines with a single driver linac. In addition, it is very large, needing as much as 2 km of straight-line footprint. Finally, as will be discussed below, the beam-beam interaction between accelerating and decelerating bunches may affect the machine performance significantly. A siting scenario is presented in Figure 1.

II. *Anti-parallel, single-pass linac (“counter-rotated linac”)*: This topology is somewhat more complex than the previous one and involves more beam transport. It retains some of the advantages of Topology I, namely, limited quantum excitation and operational simplicity. It will have as much as a factor of two lower cost than Topology I. A conceptual layout is shown in Figure 2. The end-loop transport can provide bunch compression prior to a 200 m undulator farm in the backleg opposite the linac. Proper design of the return transport can provide proper management of large momentum spread beams.

As in the first case, the machine footprint is quite large, though Figure 2 illustrates that such a machine could fit on the Jefferson Lab site. In addition, beam-beam interactions between accelerated and energy-recovered beams can significantly influence performance; this will be discussed below. Management of quantum excitation becomes important, though not as significant as it will be in multiply recirculated machines.

> A. *Anti-parallel, folded single pass linac*: as a subcase of Topology II, we consider a “folded” single linac. Figure 3 illustrates this concept, which has basically the same advantages as the unfolded case, but fits more easily onto the laboratory site. It has, however, the same disadvantages as the unfolded linac and must, in addition, contend with the additional cost and quantum excitation imposed by the folding of the linac. The additional complexity is operationally undesirable, as is the additional cost; unless site constraints are of overriding importance, such a topology is not particularly attractive.

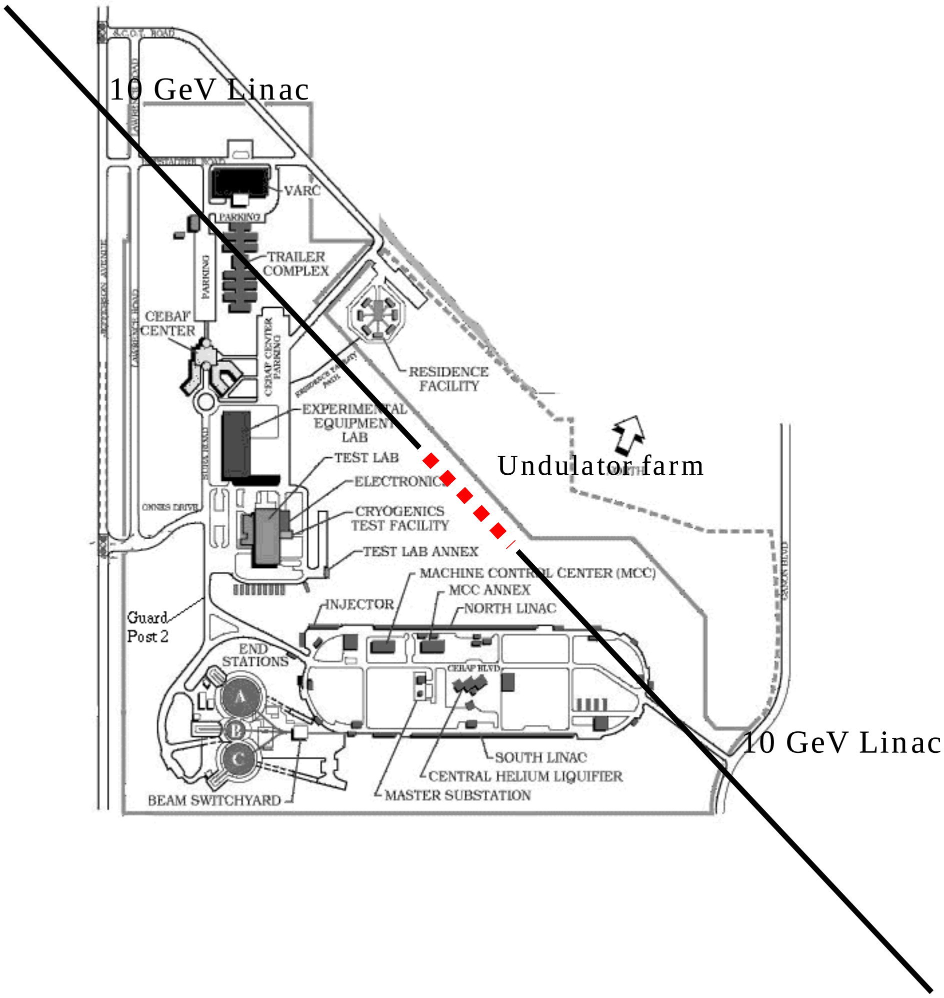

Figure 1: Opposed linac pair

__Beam-Beam Interactions in Counter-Rotated Linacs__: As noted above, machines using anti-parallel acceleration and deceleration for energy recovery can be seriously affected by the beam-beam interaction [3]. Such interactions are typically characterized by tune shifts Δν and disruption parameters D given by the following relations [4] in which r_0 is the classical radius of the electron.

$$\Delta u = \frac{r_0 N_e}{2p\, e_N}$$

$$D = \frac{2 r_0 N_e s_t c}{2p\, b e_N}$$

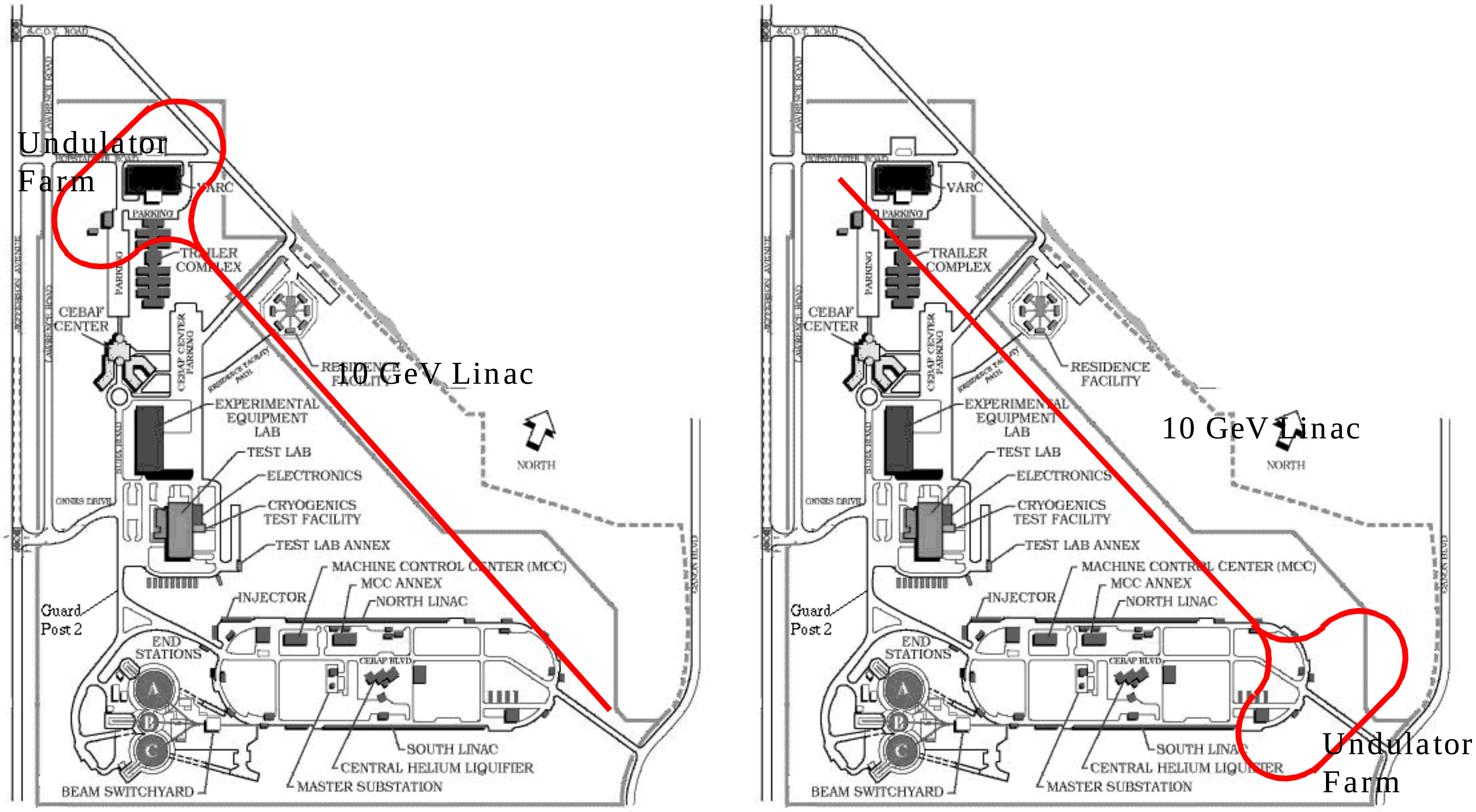

Figure 2: Two siting scenarios for “counter-rotated” single linac topology. A 200 m undulator farm is located opposite the linac in the recirculation loop. On the left, the machine could be buried on the Yorktown formation. On the right, the machine would have to lie (or below) the CEBAF tunnel, though it could still be below ground level with an overburden for radiation shielding.

Using Table 1 values gives $\Delta\nu \sim 1$ and $D \sim 3\ \sigma_t c/\beta << 1$. The former is a very large single-crossing tune shift. The latter is a small disruption parameter. This result not surprising inasmuch as in a collider, D is the ratio of bunch length to spot size at the crossing point; often D>>1. Here it is the ratio of bunch length to spot size in the linac, where the bunch is at most moderately long (by virtue of the small longitudinal emittance required for FEL operation) but may be vastly larger transversely than acceptable at the crossing point of a collider. Beam disruption thus does not appear to be an issue for operation of such machines. However, the large single crossing tune shift is a concern, particularly as (at 2 MHz) a bunch will experience a crossing every 75 m, or about 13 crossings, on each pass through the linac. Though *perhaps* not fatal for an aperiodic transport system (as opposed, for example, to a storage ring), this introduces design and operational complexity that is best avoided. Moreover, the large linear tune shift suggests nonlinear effects will be important, rendering the problem even more complex.

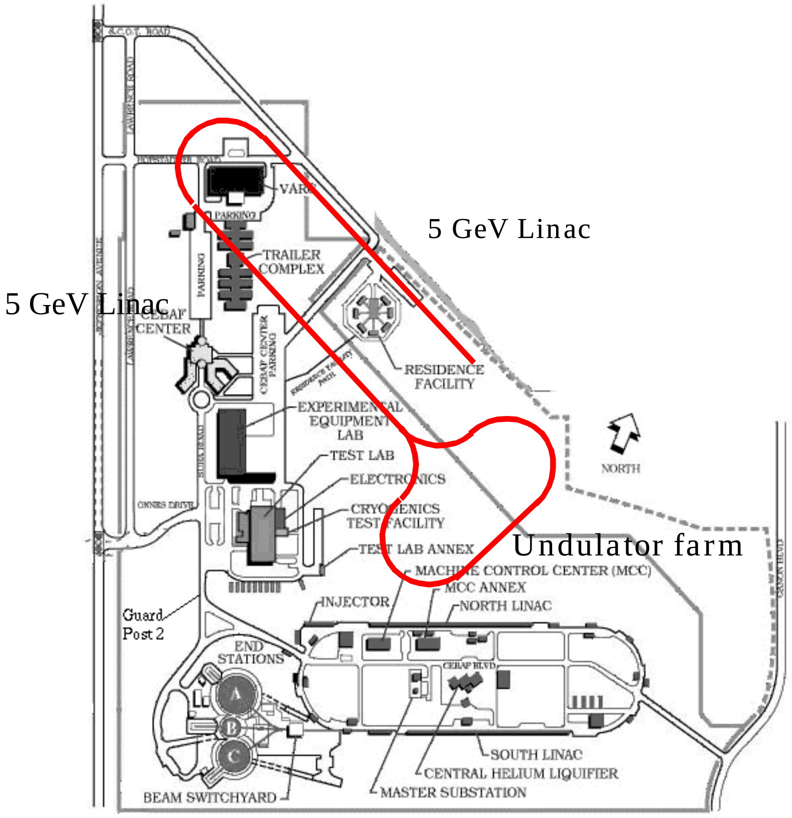

Figure 3: “Folded, counter-rotating half-linac pair”

III. *Recirculated Single-Pass Linac*: Beam-beam interaction driven issues in counter-rotated linacs can be avoided by adopting head-to-tail recirculated topologies such as that used in CEBAF. Figure 4 depicts perhaps the simplest of these configurations, that of a recirculated single-pass linac. In this topology, a single 1 km linac is recirculated though a backleg, in which an undulator farm can be located. Recirculation is for the purpose of energy recovery only. Such a machine will not suffer from beam-beam focusing due to collisions amongst accelerated and energy recovered bunches, and is relatively simple operationally. The long backleg provides adequate space for even a large undulator farm. However, as with Topology II, management of quantum excitation is an issue (though perhaps not as significant as in the above example), as are the more mundane problems associated with the design and operation of recirculated linacs. For example, the design must adequately manage transverse focussing despite the large mismatch of energy to focussing for one of the two (either accelerated or energy recovered) beams in the common linac structure. If designed as a single pass machine, it will be quite large, as is clear from Figure 4. The cost of such a machine may not be as well optimized as that of a multi-pass configuration.

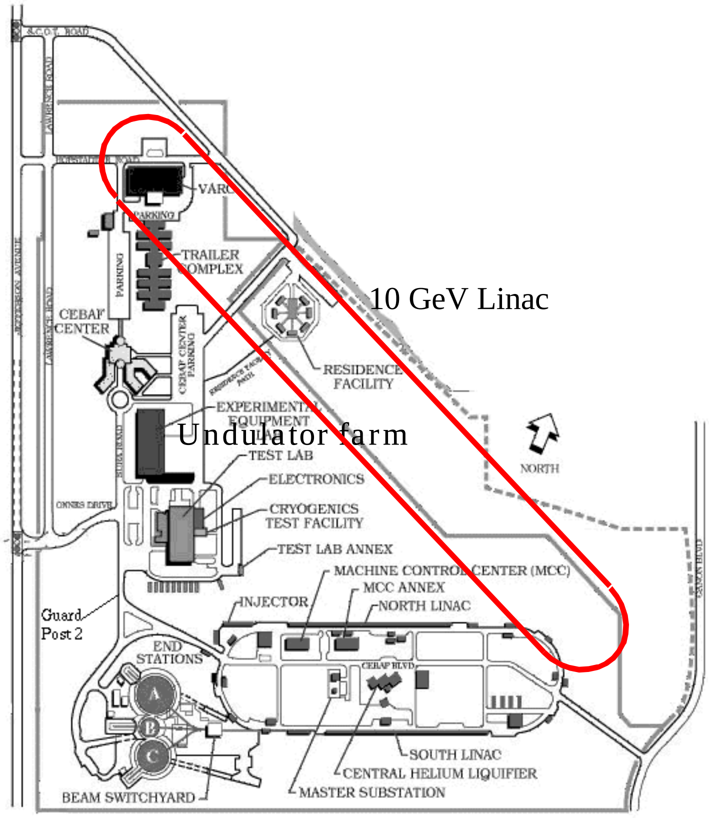

Figure 4: Recirculated single pass linac topology

A. *Recirculated Folded (Split) Single Pass Linac*: As in Topology IIA, folding produces a sub-case of the basic scenario. This system is shown in Figure 5. It has the basic advantages of the recirculated linac, and is significantly smaller. It does not provide as much space for an undulator farm, but can still in principle support technicolor operation. It suffers from the same disadvantages as the primary geometry, and, in addition, will require additional attention to both synchrotron radiation and momentum spread management issues.

IV. *Recirculated Multi-pass Linac*: The introduction of the concept of folding a recirculated linac (Topology III A) leads naturally to the concept of a multi-pass recirculated linac. Such a system, if feasible, has many advantages. The accelerated and energy recovered beams do not collide, so beam-beam interactions are not an issue. As with the single pass linac, adequate space is available for an undulator farm in the machine backleg or in a utility insertion. Use of multiple passes shortens the physical linac length (without reducing the acceleration path length), which alleviates energy/focussing mismatch somewhat. It also provides more opportunities for focussing beams independently, thereby operationally decoupling the beam/lattice matching process for each pass during acceleration and energy recovery. The multipass design process also allows cost optimization. The number of passes and the choice of a single or split linac can be selected as the outcome of a cost/performance analysis (an example of which follows). The overall footprint of a multipass machine may, in addition, be somewhat smaller than that in any of the preceding topologies, allowing easier siting of the machine.

Multipass machines do however require great attention to a variety of issues that are noted above as problems for any machine of this type. Beam quality preservation in the presence of various synchrotron radiation problems will be more challenging in this scenario. The principal design problem in such a machine may well be to address this single issue. In addition, various deleterious impedance driven effects (such as BBU instabilities) may be more severe in such a topology. The system is operationally significantly more complex than any of the above topologies; it will therefore require greater effort (with associated higher cost) to commission and operate.

A cost/operability analysis for this topology is given below. An example siting scenario will be discussed there.

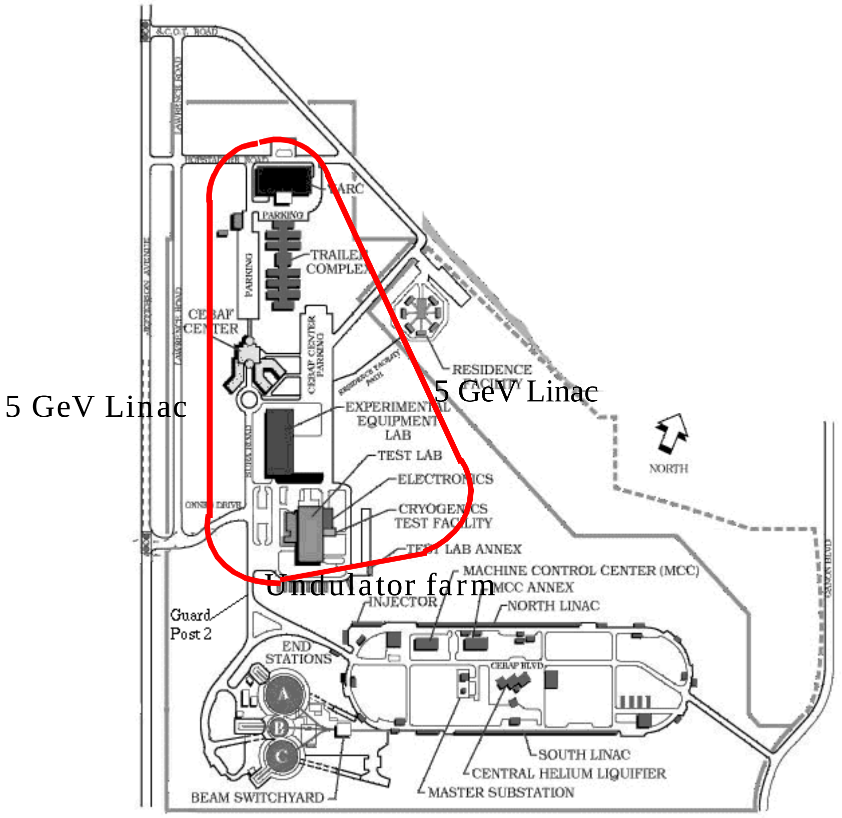

Figure 5: Recirculated, folded single pass (split) linac topology

Consideration of each of the above topologies suggests that the primary issues in the design of a coherent light source are cost/operability optimization, beam quality preservation (particularly with attention to impedance driven instabilities and synchrotron radiation effects) during acceleration, and momentum spread/beam loss management during energy recovery. Each is contingent on the availability of the same developmental technologies, namely, very high brightness electron sources and very high gradient superconducting cavities. With the advent of such components, a design solution and a siting scenario for a Jefferson Lab project could probably be developed.

Cost/Operability Analysis

The project cost for a coherent light source will be heavily influenced by the construction and commissioning costs of the driver accelerator. The construction costs, in turn, will evolve from the choice of machine topology. If the dependence of construction costs on machine configuration is known, a cost operability analysis can be performed to select a machine design path that will optimize the project cost from groundbreaking to completion of commissioning.

We have performed a rudimentary cost analysis for the construction of a recirculated, energy recovering linac. In this analysis, a unit cost was assigned to each of several accelerator subsystems (cryomodules, tunnel, transport system module) and the machine cost evaluated for each of several design scenarios (number of passes, single vs. split linac). The unit costs are presented in Table 2; the results are shown in Figure 6.

Table 2: Unit Cost Basis

Component	Projected Cost (M$)	CEBAF 1988 Actual Cost (M$)	Comments
Cryomodule	4 (@ 10 MV/m)	1 (@ 2.5 MV/m)	development, escalation
Spreader/Recombiner	5	2.5	escalation
Arc Beamline	5	2.5	escalation
Tunnel, per m	0.01	0.005	escalation

The analysis reveals that the minimum cost driver accelerator is a four-pass single linac. It shows, moreover, that the minimum is relatively shallow and broad, and it is not strongly influenced by the choice of single vs. split linac. The primary cost reduction comes from moving from a single pass to a two pass machine; the single pass machine cost is SRF system dominated while multipass machines spread the cost more uniformly amongst the SRF and the beam transport. The machine cost increases again as the configuration becomes more complex, driving transport system costs higher.

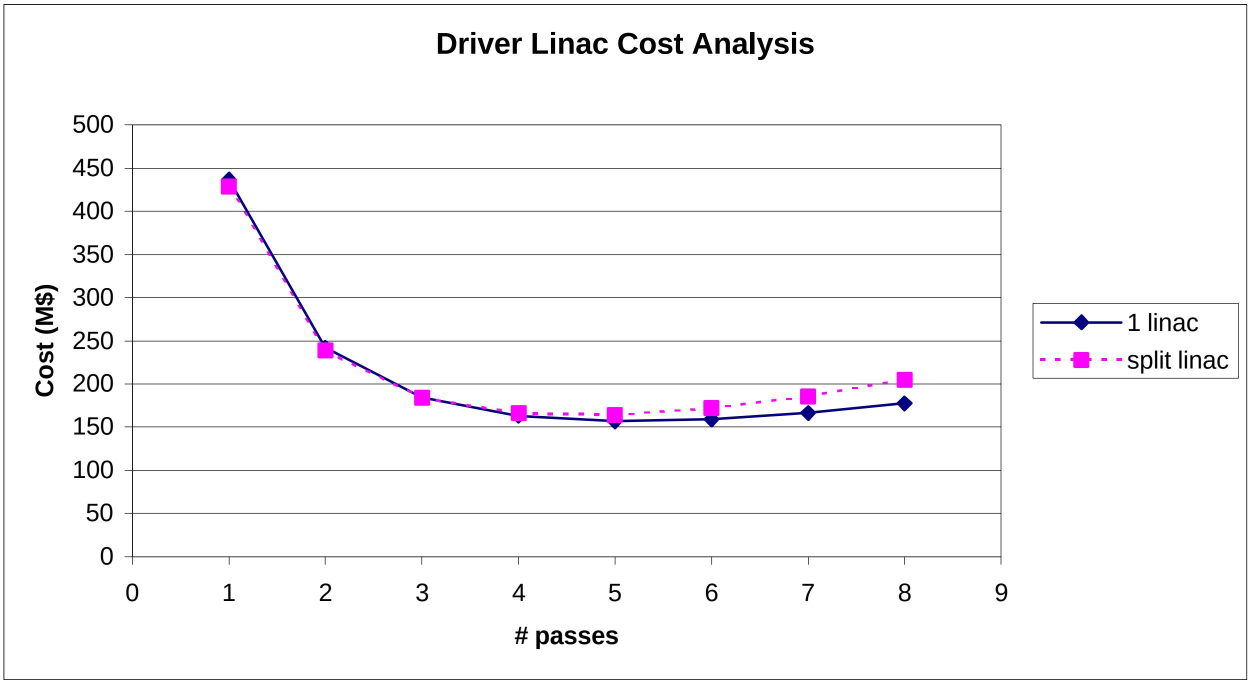

Figure 6: Cost analysis for driver linac

We note that a more complex machine will have higher commissioning costs than simpler configurations. CEBAF experience [5] indicates that the final passes of a many pass machine may in fact incur a significant fraction of the commissioning burden. Thus, incremental savings gained in moving this design from two to three or four passes may be eliminated by increased commissioning costs. A very crude scaling suggests that the commissioning time may go quadratically in the number of passes; this might suggest a three month commissioning period for a two pass machine but a one year commissioning period for a four pass machine. The differential commissioning cost thus corresponds to nine months of laboratory operation, or 40 – 50 M(FY98)$. With escalation over the next ten years, this could shift the minimum of Figure 6 upward by 100 M$ in actual year dollars. Coupled with the additional impact of beam transport induced synchrotron radiation effects, such considerations strongly argue for a simple multipass geometry. We have sketched a two-pass topology, which will be presented in the Conclusions/Concept section, below.

Compression Scenarios and Source Issues

Two technological developments are needed to construct machines of this type. The first is a "100 MV SRF module". We anticipate that this will occur as a consequence of CEBAF upgrades to 12 GeV and beyond. The second is the advent of a very high brightness electron source. Such a source must generate high charge state bunches with good longitudinal and transverse emittance. Either DC or RF guns may be considered as potential candidates; the Jefferson Lab IR FEL uses a DC gun in a not dissimilar application while the SLAC LCLS proposal calls for a RF gun [6] (though not at 2 MHz).

We note that the 67 fsec rms bunch length needed at the coherent light source wiggler is to be generated in a bunch of order $2x10^{-4}$ rms relative uncorrelated momentum spread [7]. This implies a rms longitudinal emittance of order $2 \times 10^{-4} \times 10^{10}$ eV $\times 67 \times 10^{-15}$ sec $= 134 \times 10^{-9}$ eV – sec is required of the 500 pC bunch, in a beam of average current 1 mA. This may be compared to the longitudinal emittance achieved in the Jefferson Lab IR FEL, in which a bunch of rms length ~0.4 psec was generated in 60 pC bunches using a 1 mA average current beam with rms momentum spread of order ¼%. The corresponding rms longitudinal emittance value is of order $2.5 \times 10^{-3} \times 4 \times 10^{7}$ eV $\times 0.4 \times 10^{-12}$ sec $= 40 \times 10^{-9}$ eV – sec. One may conjecture that the additional factor of 8 in required charge per bunch may use the available factor of 3 – 4 in longitudinal emittance to manage space charge driven emittance degradation at low energy.

We note that the IR FEL gun, when performing to specification, is intended to produce 135 pC/bunch at 37.5 MHz in a 5 mA average current. The total average current is, with 500 pC/bunch at 2 MHz, significantly *lower* in the coherent light source than that required in the IR FEL. Achieving the target transverse emittance is a somewhat greater challenge. The IR FEL gun delivers of order 5 mm-mrad normalized emittance; the coherent light source requires 1 mm-mrad. This clearly remains a developmental issue; however, DC gun development could potentially yield a source of sufficient brightness to be used in this application. A parallel track of RF or SRF gun development could similarly provide the required source.

Given the advent of the required high brightness source, it remains to develop a longitudinal matching scenario producing the requisite short bunch at the FEL undulator. A multi-pass machine concept allows numerous opportunities for differential phasing and compaction management in each of the several available beam transport lines. Successful operation of the Jefferson Lab IR FEL in energy recovery mode will provide a fiduciary scheme that could be extended to higher energy and shorter bunches.

Conclusions/Concept

The above discussion suggests that it may be possible to site a 10 GeV SRF driver linac for a x-ray FEL at Jefferson Lab. The primary technological challenges for such a machine are to develop high brightness sources and SRF components with “real estate” gradients of 10 MV/m. The cost/performance optimum for the machine seems to lie on a design path of a single, two-pass recirculated linac with energy recovery. Accelerator physics challenges for the design include beam quality preservation during acceleration in the presence of impedance driven instabilities and synchrotron radiation effects, and beam loss minimization during energy recovery of beams with potentially large momentum spreads.

Figure 7 presents a siting scenario for this concept. A single 5 GeV linac is used to accelerate the electron beam through two passes; the beam is delivered to an undulator farm in the backleg, and thence is energy recovered using two passes through the linac.

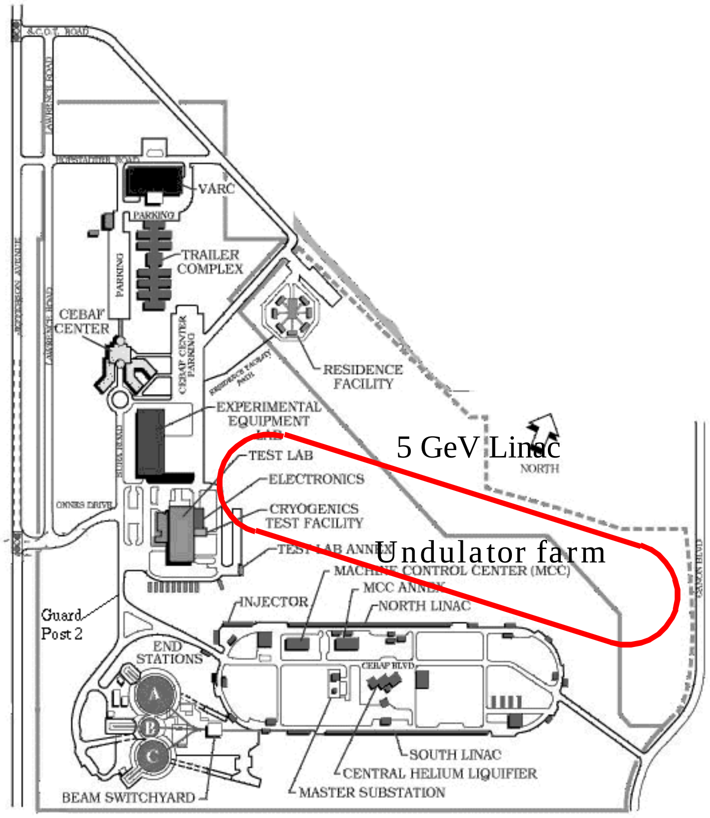

Figure 7: Two pass, recirculated energy recovering single linac.

Acknowledgements

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References

[1] The LCLS Design Study Group, “LCLS Design Study Report”, SLAC-R-21, UC-414, April 1998.

[2] A. Hutton suggested such a machine concept for the IR FEL.

[3] Thanks to Christoph Leemann for pointing this out.

[4] J. Bisognano, “Comments on Linac-Ring Colliders”, 15 July 1998 (unpublished).

[5] The first 3 passes of CEBAF were commissioned relatively quickly; the final pass was significantly more difficult.

[6] The LCLS Design Study Group, *op. cit.*

[7] *ibid.*