# A SCRF LINAC AS A FEL DRIVER AND STORAGE RING INJECTOR

J. Rose, B. Podobedov, J. Murphy, T. Shaftan, B. Sheehy, X.J. Wang, L.H Yu

BNL, Upton, NY 119733, USA

*Abstract*

A 5 GeV Super-conducting Radio Frequency (SCRF) linac for the dual application of FEL driver and top-off injector for a storage ring is described. Starting from the FEL drive beam requirements of sub-picosecond bunch lengths and kiloamp peak current the choice of frequency, gradient and operating modes of the linac are presented. Magnetic optics and RF system descriptions follow to provide the specified beam parameters. Accelerator design issues are identified for future studies.

## INTRODUCTION

Next generation light sources may include or be based on Free Electron Lasers (FEL) driven by super-conducting radio frequency (SCRF) linacs. The NSLS at BNL undertook a design study of a linac driven FEL in which we looked at the trade-offs in the of choice linac cavity frequency, pulsed vs. CW operation and bunch repetition rates. We then present the conceptual design of a pulsed 1300 MHz SCRF linac that provides ultra-short bunch length and high peak current while preserving the low emittance required by the FEL. In addition, a method of performing top-off injection into a storage ring in the same macro-pulse as the FEL bunch train is described. This method allows the frequency of the linac and ring to be independent over hundreds of kHz bandwidth.

## FEL BEAM REQUIREMENTS

As part of the conceptual design of a FEL user facility at NSLS [1] a cascaded High Gain Harmonic Generation (HGHG) FEL was produced, utilizing the so-called “fresh bunch” technique [2]. This technique uses a short ~100 fs electron pulse seeded with a ~20 fs laser pulse overlaid at the front of the electron bunch to produce HGHG FEL laser pulse. A magnetic chicane is used to delay the electron bunch and a harmonic of the HGHG is used to seed a fresh portion of the bunch. This process is repeated several times and can produce very short wavelength FEL light at relatively low electron energies. The electron beam requirements to produce 4.5 Angstrom FEL light are given in Table 1.

Table 1: Electron bunch parameters for 4.5 Angstrom cascaded HGHG FEL.

| | |
|---|---|
| Electron Energy | 4.75 GeV |
| Electron bunch length | 100 fs rms |
| Energy Spread | 0.01% rms |

## CHOICE OF LINAC FREQUENCY

Design studies incorporating 700 MHz and 1300 MHz cavities were compared. Three cases were considered: TESLA like cavities [3] at 1300 MHz and 20 MV/m, the same cavity shape scaled to 700 MHz at 16 MV/m and the case with 700 MHz and 20 MV/m. The lower gradient was included due to the realization that the larger cavities may not be able to operate at as high a gradient due to the larger surface area and corresponding higher statistical defect probabilities, and susceptibility to microphonics. Identical cavity designs were used in each case to preserve the integrity of the frequency scaling, changes in one case could in most cases be made in the other, increasing iris diameter for instance, with the same effect in both cases. Beam loading can be neglected if either the average current is low or if the time between bunches is long enough to allow the rf generator to replace the energy in the cavity before the subsequent bunch arrives. In this case the power required by the rf system is dominated by the microphonics and is approximated by the product of the stored energy of the cavity and the maximum frequency deviation bandwidth of the cavity resonance. Since the 700 MHz cavities have nearly four times the stored energy they require four times the installed rf power for equal microphonics bandwidth.

Clearly the lower frequency favours very high current machines due to the lower loss factor translating into higher single and coupled bunch instability thresholds. However, the lowered frequency results in higher cost, driven by higher rf power requirements, greater material costs (primarily the high purity niobium), and higher civil construction costs (longer linac). This, coupled with the lower technical risk associated with the well-developed TESLA design leads us to the choice of 1300MHz.

A cost benefit analysis was performed for CW vs. pulsed operation of the linac. It was clear that the pulsed linac could deliver more electron bunches at a lower installation and operating cost than the CW linac. The cryogenic and RF costs dominate the scaling, and the lack of a CW electron gun to meet the FEL requirements today or in the foreseeable future led us to choose pulsed operation. The recent successes of SCRF Electron Recirculating Linacs [4] may change this economics if a CW electron gun can be developed. Relevant parameters of the pulsed mode of operation are given in Table 2.

Table 2: Pulsed linac operation. The AC power estimates were made assuming a 50% AC to RF efficiency and 500:1 ratio of AC watts to $2^{o}$ K W.

| | |
|---|---|
| 5GeV Linac | 1.3 ms pulse/10 Hz |
| Gradient | 25 MV/m |
| # Cavities | 192 |
| # of Klystrons | 6 (10 MW) |
| Average rf power | 780 kW |
| Cryo load @$2^{0}$K | ~350 W +static losses |
| Linac Length | 288 m |
| Bunch Rate | 100 kHz (10 MHz for 1 ms x 10 Hz) |
| AC Power (Cryo + rf only) | ~2 MW |

## LONGITUDINAL DYNAMICS

The conceptual design of a SCRF linac with two magnetic chicanes to provide the FEL bunch requirements is shown schematically in Figure 1, and the parameters of the linac in Table 3.

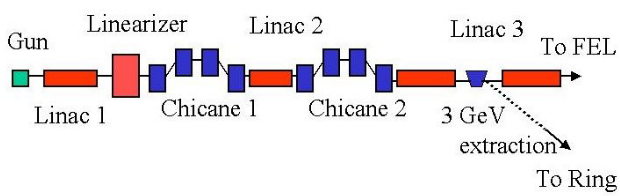


Fig. 1: Layout of 4.75 GeV FEL driver linac.

Table 3: 4.75 GeV SCRF linac parameters.

| Parameter | Unit | Value |
|---|---|---|
| Injector energy | MeV | 10 |
| Bunch length | ps | 2 |
| Energy spread (rms) | % | 0.2 |
| $1^{st}$ linac maximum energy gain | MeV | 150 |
| $1^{st}$ linac phase | Deg | 28.7 |
| Beam energy after $1^{st}$ linac | MeV | 141.6 |
| $3^{rd}$ harm. linearizer max energy gain | MeV | 25 |
| $1^{st}$ Chicane R56 | mm | 50 |
| Bunch length (rms) | ps | 0.32 |
| Energy spread (rms) | % | 0.83 |
| $2^{nd}$ Linac maximum energy gain | MeV | 600 |
| $2^{nd}$ linac phase | Deg | 41 |
| Beam energy after $2^{nd}$ linac | MeV | 716.0 |
| $2^{nd}$ Chicane R56 | mm | 41 |
| $3^{rd}$ linac maximum linac gain | MeV | 4241.1 |
| $3^{rd}$ linac phase | Deg | -18 |
| Final beam energy | MeV | 4750 |
| Final bunch length (rms) | ps | 0.1 |
| Final energy spread (rms) | % | 0.0085 |

The photo-injector is pulsed at 10 Hz with 1 ms macropulses with a bunch frequency of 10MHz. These are accelerated in the first linac to a high enough energy to avoid space charge blow-up of the bunch in subsequent beam manipulations. The beam passes through a linearizer to take out the RF induced curvature in longitudinal phase space before going through the first chicane. Two chicanes are used to compress the beam in stages separated by an energy gain in the second linac. This allows for the natural reduction in rms energy spread due to the energy gain. Finally the beam is accelerated to the final energy of 4.75 GeV for the FEL. Since the beam is not always on crest in order to chirp the beam for compression, the installed linac energy gain has to be 5 GeV.

## RF SYSTEMS

The proposed photocathode gun is a 3.5 cell gun operating at 1300 MHz. With the combination of proper cell shaping to increase the shunt impedance and over-coupling the cavity to decrease the fill time at the expense of installed RF power a preliminary design with 60 MV/m gradient on the cathode and 60 W/cm$^2$ has been achieved.

The SCRF linac is powered by eight high-power klystrons. There is one each for the first two linac sections, consisting of 6 and 24 9-cell cavities respectively. The final linac section consists of 170 cavities and requires 6 klystrons. The first 150 MeV linac section before the linearizer could in principle have a 2.5 MW klystron. The remaining klystrons are 10MW klystrons.

## RING INJECTION

Electron bunch quality of the linac greatly exceeds the requirements of a ring injector, and injected bunch will filament in the storage ring to an equilibrium emittance determined by the ring lattice.

The electron bunch is extracted from the linac at the 3 GeV of the beam energy, where a fast extraction kicker is placed in a gap between cryostats. The 1.75 GeV of linac beyond this point in the FEL line is sufficient to vary the FEL linac energy from 1.25 to 4.75 GeV without affecting ring energy or phase. The ring extraction energy can be varied over a small range and likewise compensated by the remaining FEL linac tanks.

The proposed storage ring RF system would utilize CESR II SCRF cavities at 500 MHz. This produces a somewhat awkward frequency ratio of 2.6. Although it is possible to lock the frequency of the ring by providing a variable path length chicane, and cogging by adjusting phase to fill different ring buckets the following novel approach has been adopted.

The ring RF system would be designed to be several hundred kHz from 500 MHz, in fact the first NSLS upgrade lattice resulted in an RF frequency of 499.97 MHz. The resulting frequency ratio instead of being rational is now irrational and there arises a beat frequency between the respective RF systems of 300 kHz. This allows the ring buckets to “precess” past the linac rf system. In 3.3 μs any given ring bucket will precess 2π radians, and line up with an injected bunch. This is shown in Fig. 2.

A separate photo-cathode laser locked to the linac RF and triggered at a zero of the phase error between the linac and ring creates a bunch at the tail end of the FEL beam macro-pulse (Fig. 3). This bunch is separated from the FEL bunches by a minimum of the extraction kicker rise time and by up to 3.3 microseconds which is the time it takes any given bucket to precess past the injection point.

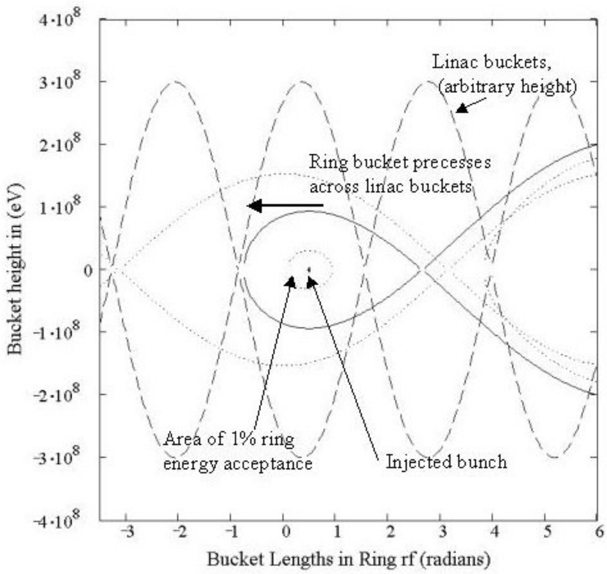


Fig. 2: Bunch and bucket traces for 499.97 MHz ring buckets and 1300 MHz linac bucket.

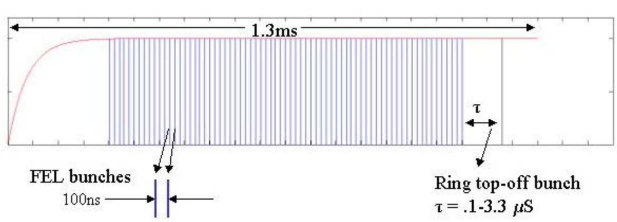


Fig. 3: Bunch pattern in macro-pulse showing the creation of the ring pulse on the tail end of the FEL bunch train.

## CONCLUSION

Next generation light sources, which may include short-wavelength FEL's as well as storage rings with top-off injection, can use the same SCRF linac for both purposes. The linac has to be optimised for the FEL beam, but easily meets the requirements for the ring. Bunch "stealing" at the end of the FEL macro-pulse with asynchronous linac and ring frequencies insures independent operation of the two machines.

## REFERENCES


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