ELECTRON BEAM COLLIMATION FOR THE NEXT GENERATION LIGHT SOURCE*

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Abstract

The Next Generation Light Source will deliver high (MHz) repetition rate electron beams to an array of free electron lasers. Because of the significant average current in such a facility, effective beam collimation is extremely important to minimize radiation damage to undulators, prevent quenches of superconducting cavities, limit dose rates outside of the accelerator tunnel and prevent equipment damage. This paper describes the early conceptual design of a collimation system, as well as initial results of simulations to test its effectiveness.

INTRODUCTION

A collimation system is necessary in the NGLS to deal with the beam halo which will be generated due to dark current in the injector and in the accelerating modules, scattering from residual gas particles, Touschek scattering within the main bunches, as well as off-energy beam tails caused by coherent synchrotron radiation in the bunch compressors and beam spreader, and several other smaller effects. If not collimated, this beam halo can demagnetize permanent magnet undulators, cause Bremsstrahlung co-axial with the photon beams, cause quenches in superconducting cavities and can activate the components of the facility. Collimating the beam halo at the lowest possible beam energy, which means as near as possible to the various sources is preferred as this reduces the overall radiation levels in the machine. Figure 1 shows the layout of the NGLS with some beam parameters. One can see the location of the bunch compressors, as well as the spreader arcs, where the horizontal dispersion allows for effective collimation of off-energy particles.

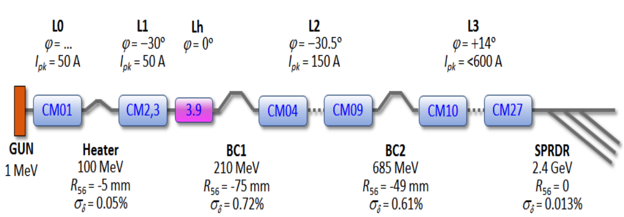

Figure 1: Schematic layout of NGLS injector, linac, bunch compressors, and undulators with key parameters listed for 1 MHz operation with 300 pC per bunch.

The baseline beam power of the NGLS is just below 1 MW at maximum energy. Results at FLASH [1], an FEL facility with lower beam energy and lower average beam current, as compared to NGLS, has demonstrated that without halo collimation significant demagnetization of the undulator permanent magnets can occur very quickly even for kW beam powers. The collimation scheme for NGLS will therefore be optimized to keep any losses away from undulators, superconducting cavities or other sensitive areas. Compared to FLASH there will be more collimators, which can be better adjusted. There also is the deflection of the final spreader arcs, which helps to separate secondary showers from the collimators from the main beam and keep them away from the undulators. However, there are also different options being pursued in terms of potentially more radiation hard permanent magnet undulators or superconducting undulators. In fact, at the moment superconducting undulators are the preferred design choice, which would likely relax the requirements for the collimation system.

In addition to removing the beam halo continuously, the collimation system must also provide protection against mis-steered beam or element failure scenarios without being damaged itself. This is planned to be achieved by a combination of collimator design, cooling, as well as beam loss detectors and the machine protection system.

Collimation Strategy and System Layout

NGLS will employ a distributed collimation system, starting with the injector area where collimators will be located to remove dark current from the gun. Even though there is no dispersive area in the injector, it is expected that focusing mismatch in the strong solenoids might be sufficient to separate particles with large energy offsets on those collimators as well. The next stage consists of multiple (energy) collimators in the middle of each of the bunch compressors as well as the laser heater chicane to reduce beam losses in the superconducting linac and achieve collimation at the lowest beam energy feasible.

The post-linac collimation removes the beam halo particles in a transverse collimation section with approximately 90 degree phase advance between horizontal and vertical collimators. Finally there is another energy collimation section that makes use of the dispersion at the beginning of each of the spreader arcs. The geometry of the spreader also allows to keep any particle showers after the collimators away from the undulator sections, which has proven effective with collimation systems at 3rd generation light sources.

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DARK CURRENT TRANSPORT

Dark current from the gun (as well as potentially from other accelerating, bunching, or diagnostic cavities) usually is the major source of beam halo. Any collimation system at a minimum has to be effective in containing this halo such, that losses in superconducting cavities and the undulator section can be minimized. To study the effectiveness of the conceptual NGLS collimation system, simulation techniques very similar to what has been successfully used for FLASH, XFEL [1] and LCLS [2] have been employed. The dark current model has been calibrated with measured data from the APEX gun. Initial measurements at APEX show relative cw dark currents of up to 8 μA at full accelerating gradient. It is expected that this will be improved significantly over time, however, it provides a conservative starting point for the collimation design and dark current tracking. Based on the calibrated predictions using the Fowler-Nordheim equation,

$$I_F = \frac{1.54 \cdot 10^{-6} \beta_e^2 A_e E_{RF}^2}{\phi} 10^{4.52\phi^{-0.5}} e^{-\frac{6.53\cdot 10^9 \phi^{1.5}}{\beta_e E_{RF}}} \quad (1)$$

dark current emission is then simulated in ASTRA [3], generating a large ensemble of macro-particles at the exit of the injector. The distribution has a very large energy spread and part of the particles has spread over multiple linac buckets. In our simulations, we generate about 250,000 macroparticles around the cathode, of which about 50,000 survive in the simulation all the way to the end of the injector at about 90 MeV.

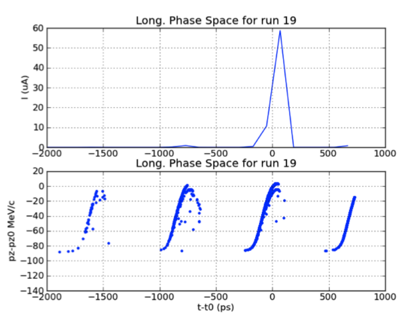

Figure 2: Longitudinal phasespace (simulated with ASTRA based on fit of Fowler-Nordheim formula to APEX measurements) of dark current from one rf-gun bucket at the exit of the injector section.

Afterwards, standard tracking codes have been used to track the trajectories of those dark current particles throughout the machine lattice. In our case we used both AT [4] (upgraded to treat linacs) and elegant [5]. This allows to determine loss locations (at or away from the collimators) as well as a comparison of the final distribution at the entry point to the undulator sections with the acceptance of the undulator chambers. The draft collimator layout described above generally appears effective to localize losses of dark current particles from the gun away from the undulator sections as well as most other parts of the accelerator. Further improvements are necessary to reduce the losses in the first linac sections.

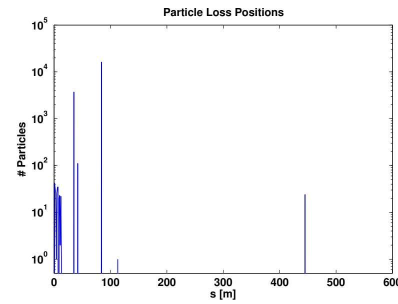

Figure 3: Loss location histogram from dark current tracking of the CD0 lattice of NGLS with a conceptual energy collimation system. Trajectories are calculated with a modified version of AT [4].

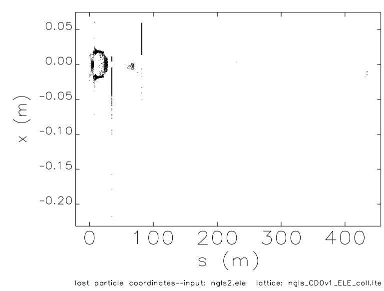

Figure 4: Transverse location of lost particles as calculated with elegant [5] (for same case as above two plots from AT).

Other Sources of Beam Halo

Measurements at FLASH and LCLS indicate that background radiation in the undulator sections cannot be fully explained with just dark current production from the gun. This will likely be true for NGLS as well. Studies will be carried out simulating gas and Touschek scattering in the linac, spreader and undulator sections. Based on scaling results from storage rings, no show stoppers are expected, but results could have impact on required vacuum pressures in spreader and undulator sections and therefore the vacuum system design. Tails produced by collective effects (e.g. CSR, impedance) on the main bunch could also be relevant and will be included.

COLLIMATOR DESIGN

The machine protection issues at NGLS include the collimation system itself, which of course is designed to prevent damage to other parts of the facility. Potential damage sources could be synchrotron radiation, wakefields, as well as beam losses. Because of the lower beam current compared to ring based light sources, synchrotron radiation is

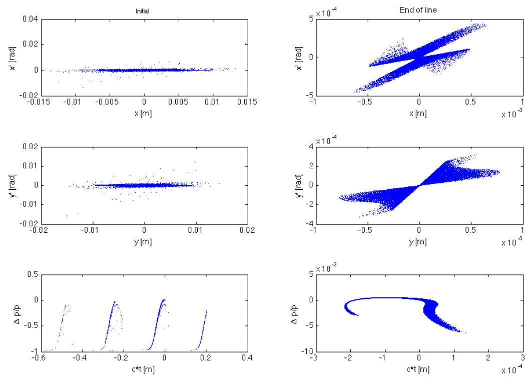

Figure 5: Phase space of dark current distribution at the exit of the injector, as well as after all collimations, i.e. at the entry point into the FEL undulator section. The remaining phase space is small compared to the planned acceptance of the undulator chambers.

the smallest concern of theses three. Wakefields can be a more significant challenge and will require care in the design and likely cooling. The much lower beam current is compensated by much shorter bunchlengths so that overall heating of collimators due to wakefields will likely be similar to 3rd generation sources. In those cases water cooling of collimators/scrapers is necessary but no other special solutions. The final design consideration are beam losses due to equipment failure. These could in a worst case reach the full 1 MW beam power. However, it is envisioned that the machine protection system would react quickly in such a case to shut off the beam (or reduce the repetition rate). At 1 MHz repetition rate, the machine protection system could possibly react within a few bunches, limiting the deposited energy to a few Joule. However, this is not necessary from a collimator standpoint. If the machine protection system would react within 1 ms, the deposited energy would be limited to $<$ 1 kJ. This is the same as the stored energy in a 3rd generation light source, where simple water-cooled collimator designs easily withstand such beam losses [6]. As part of the machine protection system it is planned to add beam loss monitors at all collimator locations.

Impedance

The impedance of the collimators is important in several regards. First there is the aforementioned heating due to wakefields which needs to be small enough to not damage the collimators. Secondly one wants to avoid any deterioration of the beam quality due to short or long range wakefields (acting back on the same bunch or following bunches). In LCLS the short range wakes were minimized by using a thin Titanium-Nitrite coating o the collimator jaws. Similar coating techniques are envisioned for NGLS, but in addition efforts will be undertaken to minimize geometric impedance and long range wakes. Whenever possible the adjustable collimators will be double sided to allow to center the beam and minimize impedance induced dipole kicks.

Dark Current Deflector

The dark current produced at the gun is quasi continuous with the rf-frequency of the gun as repetition rate (187 MHz). In contrast to this, the beam used to drive the FEL has a nominal repetition rate of up to 1 MHz. Therefore it is possible to reduce the dark current significantly at low energy by kicking any dark current in between nominal bunches into a dump or collimator. Such a system has been employed at FLASH and reduces the dark current intensity downstream by a significant factor. Depending on whether the beam losses on collimators and the effectiveness of the collimation system can be improved sufficiently over FLASH, a similar system is envisioned for NGLS as well. Because of the different pulse train structure, the system would be very different from FLASH. It would have to work with a high repetition rate (1 MHz) and need fast rise and fall times. However, a system with many of these characteristics is installed for a different purpose in the ALS [7]. It works with a repetition rate of 1.5 MHz, has rise and fall times of $<$ 40 ns and can kick the beam by tens of μrad at 2 GeV. For an application in NGLS, the pulse duration would need to be increased, which will require a reduction in kick angle. But the system would be used just after the gun, i.e. at a beam energy of 10s of MeV. So it is conceivable that a modified version of the ALS system could reduce the transported dark current by a factor of $>$ 10 just after the gun.

SUMMARY

Very early design studies for a collimation system for the NGLS have been completed. Using a conservative dark current model for the gun, start to end tracking simulations of dark current particles have been completed. Tentative results conclude that a standard set of energy collimators can effectively protect most of the linac and the undulator region with the lost beam power at the collimators well within the limits of simple water-cooled designs. Improvements are still necessary to reduce losses in the first superconducting linac module. Future work will include gas and Touschek scattered particles, sensitivity studies, detailed collimator design including impedance considerations, as well as a correct treatment of secondary particles after the collimators.

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