SYSTEM TRADE ANALYSIS FOR AN FEL FACILITY*

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Abstract

Designing an FEL from scratch requires the design team to balance multiple science needs, FEL and accelerator physics constraints and engineering limitations. A full multi-dimensional exploration of "design space" is not realistic using existing particle simulations. STAFF (System Trade Analysis for an FEL Facility) enables the user to rapidly explore a large range of Linac and FEL design options to meet science requirements. The code utilzes analytical models such as the Ming Xie formulas when appropriate and look-up tables (for example, emittance as a function of charge) when necessary to maintain speed, flexibility and extensiblity. STAFF allows for physics models for FEL harmonics, wake fields, cavity higher-order modes and aspects of linac particle dynamics. The code will permit the user to study error tolerances and multiple beamlines so as to explore the full capabilities of an entire user facility. This makes it possible to optimize the integrated system in terms of performance metrics such as photons/pulse, photons/sec and tunability range while ensuring that unrealistic requirements are not put on either the electron beam quality, undulator field/gap requirements or other system elements. This paper will describe preliminary results from STAFF as applied to a CW FEL soft X-ray facility. Point verifications against common FEL simulation codes will also be presented.

INTRODUCTION

The goals of the system trade analysis are to (1) optimize the integrated system performance of an X-ray FEL Facility, (2) predict photons/pulse, photons/sec, and tunability range for a wide range of system parameters, (3) evaluate optimization of the linac for multiple beamline facilities, (4) allow for performance metrics that can include both X-ray production and other project considerations, and (5) help guide R&D priorities and facilitate thinking about performance vs. risk. The tool is for parameter surveys; full simulations can confirm and explore specific design points.

The code must be able to evaluate hundreds of cases rapidly, using analytic relationships when available. These relationships include the Ming Xie formulas, emittance and energy spread scaling with bunch charge from photoinjector operational experience, and wiggler technology limits from the magnet groups. Many scaling laws are implemented in STAFF, although some require further validation and verification. The scaling laws include harmonic generation, wake fields, higher-order modes, seeded FEL power requirements (for various schemes), linac particle dynamics (e.g. microbunching), wiggler particle dynamics, accelerator cell performance, and injector performance. Many effects are in the process of being implemented. These include error tolerances, approximate radiation damage, and image current heating for SC wigglers. In some cases it will be necessary to use table-lookup or a best fit to simulations.

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SPECIFIC MODULES FOR LINAC AND FEL MODELING

STAFF is structured so as to contain individual modules for different parts of the machine. In this section, we describe the modules contained in STAFF. Beyond doing numerical calculations, the modules can also issue "warning flags" to the main framework. For example, the undulator module can issue a warning flag if the required undulator parameter is not achievable with the selected undulator technology.

Module for the Superconducting RF Linac

The module for the superconducting RF linac begins its calculation by preparing an ensemble of cavities with a distribution of parameters. This ensemble can be set up with gradient setpoints according to the process described in Ref. [1], and the needed refrigeration capacity can then be computed.

Module for Emittance Scaling

The emittance scaling module calculates the emittance from the bunch charge, based on studies of this dependence. The longitudinal emittance is chosen to scale as the 0.65 power of the total bunch charge. while the transverse emittance is chosen to scale as the 0.3 power of the total bunch charge.

Undulator Module

The undulator module uses scaling laws that give the peak magnetic field as a function of the ratio x=gap/period. It assumes the undulator is designed for maximizing the fields, and that the ratio x is less than unity but not too small. The relevant magnet technologies include pure permanent magnet (like SCSS, a good choice for an in-vacuum

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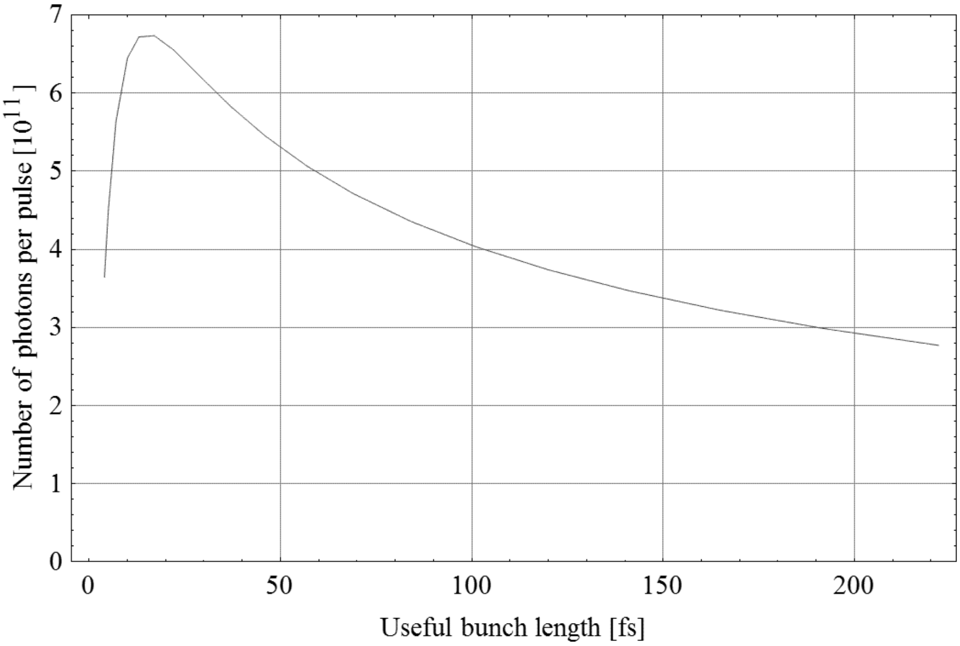

Figure 1: In this one-dimensional scan, the length of the bunch is varied at a constant bunch charge of 250 pC. It is assumed that 50% of the bunch is useful for lasing. As the bunch length gets smaller, the energy spread increases and eventually reduces the output. The beam energy is 1.8 GeV, and the output wavelength is 1.0 nm.

undulator) with a scaling

$$B_{\text{peak}} = 1.54\, B_r\, \mathrm{e}^{-\pi x} = 2\, \mathrm{e}^{-\pi x}\,, \tag{1}$$

hybrid permanent magnet with a scaling

$$\begin{aligned} B_{\text{peak}} &= 3.25\, B_r \exp\left(-5.08\, x + 1.54\, x^2\right) \\ &= 4.22\, \exp\left(-5.08\, x + 1.54\, x^2\right)\,, \end{aligned} \tag{2}$$

and superconducting magnet technologies. For normal conducting magnets we take $B_r \simeq 1.3$. The code also contains corrections that depends on the size of the magnetic blocks.

Module for Estimating Saturation Power of FEL Harmonics

The module that makes estimates for the saturation power of the various odd FEL harmonics is based on literature results, such as those in Ref. [4] and Ref. [5], but also contains original research and novel ways to approximate the production of FEL harmonics. With both shorter gain length and wavelength, it is expected that there will be a minimal effect due to diffraction on the harmonics. The fields are treated as dependent on the local current and bunching of fundamental, so only the local dE/dz matters. In the one-dimensional model, we can assume the radiation is produced by harmonic bunching equal to $b_h \simeq b_1^h$ Three-dimensional effects including higher sensitivity to slippage are included by multiplying some of the Ming Xie parameters by the harmonic number, specifically:

$$f \equiv \left(\frac{b_h}{b_1^h}\right)^2 = \frac{1 + \Lambda(\eta_d, \eta_\epsilon, \eta_\gamma)}{1 + \Lambda(\eta_d, h\eta_\epsilon, h\eta_\gamma)}\,, \tag{3}$$

where Λ is the function from Ref. [3] which characterizes the 3-dimensional effects of the fundamental wavelength of the FEL, according to $L_g = L_{1D}\left[1 + \Lambda(\eta_d, \eta_\epsilon, \eta_\gamma)\right]$. The nonlinear harmonic power then takes the form

$$\frac{P_h^{NL}}{P_1^{\text{sat}}} = C_h f \left[\frac{J_{(h-1)/2}(h\xi) - J_{(h+1)/2}(h\xi)}{J_0(\xi) - J_1(\xi)}\right]^2 \left(\frac{P_1}{P_1^{\text{sat}}}\right)^h, \tag{4}$$

where $\xi = a_u^2/2(1 + a_u^2)$, a_u is the rms undulator parameter, and C_h only depends on harmonic number (for example, $C_3 = 0.094$).

POINT RUNS, SCANS, AND OPTIMIZATIONS

A run of STAFF for a single set of input parameters is called a "point run," and typical output includes the following:

```
Calculations based on the Ming Xie fitting formula
==================================================
All quantities in mks unless otherwise stated.
Input quantities
  gamma                         3522.512452
  norm transv emit [micron]     0.600000
  current                       500.000
  energy spread [keV]           50.000000
```

```
  average beta in undulator    13.000000
  undulator period [mm]        18.500000
  output wavelength [nm]       1.000000
Output quantities
  aw_rms                       0.584308
  sigma_x [micron]             47.056653
  rho1D * 1000                 0.460258
  1D gain length               1.846716
  3D gain length               2.337523
  1D sat power [GW]            0.414232
  3D sat power [GW]            0.413668
  3D sat power [MW], 3rd harm 0.709717
  3D sat power [kW], 5th harm 8.351381
  3D sat power [W],  7th harm 267.567477
  LRayleigh                    27.826074
  etaD                         0.066366
  etaE                         0.304064
  etaG                         0.034845
  Lambda factor                0.265773
Calculations that use a formula for start-up noise
==================================================
  input power noise            18.314949
  3D sat length                44.717014 (und. only)
  3D sat length incl. FODO     67.075520
Calculations that use the rep rate and pulse length
===================================================
  repetition rate [MHz]        1.000000
  t_useful [ps]                0.250000
  pulse_energy [mJ]            0.051709
  number of photons per pulse 2.603067e+011
  photons/second               2.603067e+017
  number ph./pulse, 3rd harm   1.488667e+008
  photons/second,   3rd harm   1.488667e+014
  number ph./pulse, 5th harm   1.051046e+006
  photons/second,   5th harm   1.051046e+012
  number ph./pulse, 7th harm   2.405297e+004
  photons/second,   7th harm   2.405297e+010
```

An example of a one-dimensional scan done by STAFF is shown in Fig. 1. In this example, the length of the bunch is varied at a constant bunch charge of 250 pC. It is assumed that 50% of the bunch is useful for lasing. As the bunch length gets smaller, the energy spread increases and eventually reduces the output. The beam energy is 1.8 GeV, and the output wavelength is 1.0 nm. The undulator period is 18.5 mm. For this example, there is a further reduction in output power below about 4 fs because the light slips away from the electron pulse before saturation is achieved. STAFF uses an approximate formula that reduces the saturation power in such cases.

An example of a two-dimensional scan done by STAFF is shown in Fig. 2. In this example, Photons/s is plotted as a function of undulator period and beam energy. This is done at constant power going into the beam dump. The dots indicate regions that are not achievable with current undulator technology. The output wavelength is 1 nm, and the average beam power is 2.5 MW. The undulator gap is 6.0 mm. This type of plot allows one to easily see what the trade-offs are and which regions of parameter space are of interest.

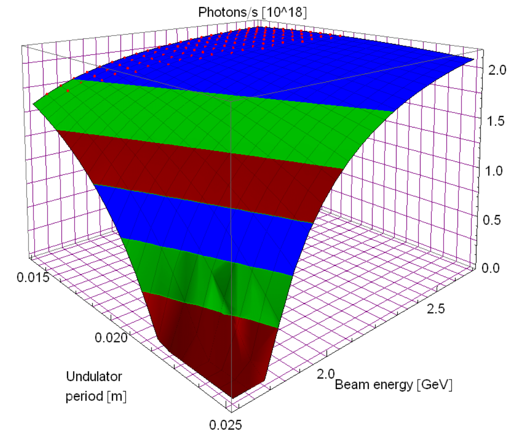

Figure 2: In this two-dimensional scan, Photons/s is plotted as a function of undulator period and beam energy. This is done at constant power going into the beam dump. The dots indicate regions that are not achievable with current undulator technology.

CONCLUSIONS

STAFF enables the user to rapidly explore a large range of Linac and FEL design options. The ability to generate cogent plots that guide the user to workable regions of parameter space is very useful for the design of an FEL facility. This makes it possible to optimize the integrated system in terms of performance metrics such as photons/pulse, photons/sec and tunability range while ensuring that unrealistic requirements are not put on either the electron beam quality, undulator field/gap requirements or other system elements.

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