TITLE: COMPARISON OF INTEGRATED NUMERICAL EXPERIMENTS
WITH ACCELERATOR AND FEL EXPERIMENTS

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Comparison of integrated numerical experiments with accelerator and FEL experiments

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ABSTRACT

Even at the conceptual level the strong coupling between the laser subsystem elements, such as the accelerator, wiggler, optics, and control, greatly complicates the understanding and design of an FEL. Given the requirements for a high-performance FEL, the coupling between the laser subsystems must be included in the design approach. To address the subsystem coupling the concept of an integrated numerical experiment (INEX) has been implemented. Unique features of the INEX approach are consistency and numerical equivalence of experimental diagnostics. The equivalent numerical diagnostics mitigates the major problem of misinterpretation that often occurs when theoretical and experimental data are compared. A complete INEX model has been applied to the 10- μm high-extraction-efficiency experiment at Los Alamos and the 0.6- μm Burst Mode experiment at Boeing Aerospace. In addition, various subsets of the INEX model have been compared with a number of other experiments. Overall, the agreement between INEX and the experiments is very good. With the INEX approach, it now appears possible to design high-performance FELs for numerous applications. The first full-scale test of the INEX approach is the Los Alamos HIBAF experiment. The INEX concept, implementation, and validation with experiments are discussed.

1. INTRODUCTION

A high-performance FEL is a complex and strongly nonlinear device. As such, the traditional approach of defining an interface between the various components of the system is difficult, at best, because FEL performance is affected by coupling between the accelerator, wiggler, optics, and control system. In fact, historically, FEL performance has been greatly reduced because this coupling was not properly taken into account during the design phase of an experiment.

An important contribution to the subsystem coupling is the evolution of the six-dimensional electron phase-space distribution. As a specific example, consider some issues associated with the electron beam accelerator, such as injector emittance and energy spread, longitudinal and transverse wakefields, cavity asymmetry, misalignments, and jitter. All these issues affect the electron distribution in a slightly different manner, but the effects are not independent of one another. In fact, the nonlinear sum of these effects determines the final state of the electron beam distribution function, which, in part, determines the FEL efficiency. Similar arguments apply to electron beam magnetic bunching and transport; wiggler transport, focusing, and field errors; electron beam to light conversion efficiency; wiggler and resonator interplay, including distortion and damage; and electron beam energy recovery.

Given the stringent requirements associated with a high-performance FEL, the coupling must be taken into account in the evaluation and design process. The integrated numerical experiment was proposed to address the strong coupling nature of an FEL.¹ In terms of the physics, INEX is a one-to-one numerical equivalent of an existing or planned FEL. Engineering and technology constraints are included in the model to ensure that a given design is realistic. In some cases, INEX is used to set control and alignment

tolerances. In addition to the self-consistent nature of the integrated model, INEX includes numerical diagnostics that are equivalent to the experimental diagnostics. In this fashion, the question of theoretical and experimental data interpretation, which is often a major source of discrepancy between theory and experiment, is avoided. Since validation against experiment is fundamental to the reduction of risk in a high-performance FEL design, the incorporation of numerical diagnostics has significantly enhanced our ability to accurately evaluate a number of physics and technology experiments.²⁻¹⁹

An INEX is constructed by linking a number of sophisticated physics programs, or codes, together in such a way that the evolution of electron phase space and light is determined in a self-consistent manner. Since precise knowledge of the electron beam phase-space distribution is required, the physics codes used in INEX are all particle tracking codes. Particle codes calculate the dynamics of a small volume of phase space that is represented as a point particle. This type of code provides the most realistic description of particle dynamics to the physical world and is used extensively to study complex problems in many areas of physics.²⁰ The three primary codes used in INEX are ISIS,²¹ PARMELAX,²² and FELEX.²³ In addition, there are a large number of secondary codes used to support the three primary codes, including T3,²⁴ TBCI,^{25,26} and SUPERFISH.²⁷

In section 2, an overview of INEX is presented. The physics in the three primary codes ISIS, PARMELAX, and FELEX is briefly discussed. The photoinjector is calculated with ISIS, a particle-in-cell code that solves Maxwell's equations with complex boundary conditions. The electron beam acceleration and transport is calculated with PARMELAX, while FELEX is used to calculate the conversion of electron beam energy into electromagnetic energy.

Most of the INEX effort has centered around verification of the integrated computational model. In section 3, a brief review of the comparison of INEX with the nine experiments is summarized, Table I. No doubt, this section will leave some readers with many questions about some aspects of a particular experiment. In most cases, this information can be obtained from the references. Here, the point is simply to provide the reader with some insight into the depth and breadth of the verification effort.

Finally, in section 4, a summary of the verification effort is presented. With the INEX approach it now appears possible to design a realistic high-performance FEL for numerous applications.

Table I. Summary of accelerator and FEL experiments compared with the INEX.

Experiment	Location
#1 Proof-of-Principle Photoinjector Experiment ^{2,3}	Los Alamos
#2 20-MeV Accelerator Experiment ^{4,5}	Los Alamos
#3 Harmonic Experiment ^{6,7}	Stanford
#4 10- μ m FEL Mode Media Experiment ⁸	Los Alamos
#5 Cavity Asymmetry Experiment ^{9,10}	Boeing
#6 10- μ m FEL High-Extraction-Efficiency Experiment ^{11,12}	Los Alamos
#7 Burst Mode 100-MeV Accelerator Experiment ¹³	Boeing
#8 0.6- μ m Burst Mode FEL Experiment ¹⁴⁻¹⁶	Boeing
#9 HIBAF 17-MeV Photoinjector / Accelerator Experiment ¹⁷⁻¹⁹	Los Alamos

2. INTEGRATED NUMERICAL EXPERIMENT OVERVIEW

The integrated numerical experiment is constructed by linking a number of sophisticated physics programs, or codes, together in such a way that the evolution of electron phase space and light is determined in a consistent manner. The three primary codes used in INEX are ISIS, PARMELAX, and FELEX.

2.1. ISIS

The photoinjector is calculated with ISIS, a code used extensively in plasma physics, accelerator, high power microwave, intense electron beam generation, and pulse power research. ISIS is a highly versatile implementation of the electromagnetic particle-in-cell method.²¹ In this method the full set of Maxwell's equations is solved as an initial value problem for the electric and magnetic fields subject to the appropriate boundary conditions. Charged particles are moved in the fields via the equations of motion. The procedure consists of alternately advancing the field and the particles in time to obtain the self-consistent evolution of the system. This procedure includes the important effects for the photoinjector, including self-consistent space charge and magnetic fields with image charges, wakefields, and time-and-space dependent electromagnetic fields.

An accurate treatment of complex boundary conditions is obtained through the use of body-fitted coordinates. In this option, the mesh on which the electromagnetic fields reside can be deformed to lie along the boundaries of the conductors. The entire particle-in-cell method is performed on an arbitrary quadrilateral, nonorthogonal grid.

ISIS is highly optimized to produce maximum performance on the most advanced Cray computers. Graphics are obtained from a rather sophisticated postprocessor, PEGASUS, developed in parallel with ISIS at Los Alamos. ISIS interfaces with PARMELAX through a translator code when operated in the INEX mode.

2.2. PARMELAX

The accelerator, magnetic buncher, and magnetic transport are calculated using PARMELAX (Phase And Radial Motion in Electron Linear Accelerators eXtended). Although similar to the PARMELA code used for years in the accelerator community PARMELAX has been greatly expanded in capability.²² For example, a fully three-dimensional space charge algorithm is implemented, along with azimuthally symmetric longitudinal and transverse wakefields, three-dimensional fields and wakefields resulting from cavity or vacuum vessel asymmetry, and three-dimensional tapered wiggler transport.²⁸

PARMELAX is a particle tracking code, but numerous approximations have been made to the equations of motion in order to calculate the entire accelerator in a reasonable time scale. The accuracy of some of these approximations in the high-brightness and high-current electron beam regime is unknown, although agreement with existing experiments has been very good. The primary emphasis of the HIBAF (High Brightness Accelerator FEL) experiment at Los Alamos is to verify the reduced set of physics models used in PARMELAX.

2.3. FELEX

FELEX (Free Electron Laser Emulation eXperiment) simulates realistic FEL oscillator and amplifier configurations.²³ The code incorporates detailed models of the wiggler and optical resonator

subsystems, and interfaces to the accelerator code PARMELAX through a translator code when operating in the INEX mode.

The basic technique used in FELEX is to follow the trajectories of a distribution of electrons through the wiggler, accounting for the self-consistent interaction with the optical field. The three-dimensional electron phase space distribution is from the accelerator code PARMELAX or through sampling from a Gaussian distribution with experientially measured moments. With this approach the electron distribution implicitly includes finite emittance, energy spread, and time structure through the micropulse. In other words, FELEX calculations include micropulse effects on the FEL interaction.

FELEX incorporates a detailed model of the wiggler subsystem. The model approximates the wiggler magnetic field near the geometric axis of the system by an analytic expression which takes into account the taper in the magnitude of the magnetic field, including two plane focusing forces due to parabolic pole faces or canted poles. Magnetic field errors are modeled as a random dipole impulse every one-half wiggler period. Wiggler errors in both the wiggle and magnetic plane are included.

A model of the wiggler electron beam steering system consists of periodic beam position monitor and a dipole steering magnetic. Algorithms have been developed to set the position of the dipole magnets from the beam position measurement data in order to steer the beam close to the magnetic axis of the wiggler. It has been found that the ability to steer close to the wiggler axis is dependent upon the level of magnetic field errors and the beam position accuracy.

In the wiggler region, FELEX models the self-consistent interaction with the optical field. The three-dimensional paraxial wave equation is solved with a source term representing the bunching of the electron beam in the combined wiggler-optical fields. The electron bunching is determined by solving the relativistic Lorentz force equation to determine the electron deceleration in the wiggler-optical field. The above analysis is performed on a three-dimensional grid which includes misalignments, optical guiding, electron slippage, and micropulse effects. The analysis includes the boundary effects of the wiggler vacuum tube which can intercept a fraction of the optical beam and generates wakefield deceleration of the electron beam at discontinuities.

At the end of the wiggler, the optical field is propagated through the resonator, in the case of the oscillator, or to a beam control system interface, in the case of the amplifier. For the resonator, the optical field is propagated back to the entrance of the wiggler where the electron beam interaction is reinitialized with a unperturbed electron beam distribution. FELEX propagates the optical beam by using fast Fourier transform techniques. Many optical elements can be included in the field solution, including apertures, realistic mirrors, transmissive couplers, and gratings.

Realistic mirrors are modeled as a phase sheet where the added phase includes such effects as the tilt and curvature of a mirror, aberrations due to surface imperfections, and thermal distortion of irradiance mapping. The three-dimensional algorithm for a grating rhomb includes astigmatism and pulse dispersion, both compression and expansion.

Multiple pass calculations are used to investigate oscillator performance. FELEX follows the build up of the optical pulse within the resonator from noise to saturation. Since the optical field can be significantly modified by the gain medium, algorithms have been developed to change the curvature, or equivalently displace, the mirrors to compensate for this gain.

2.4. Master-Oscillator Power-Amplifier Configuration

As a specific example of the INEX approach consider the MOPA (master-oscillator power-amplifier) FEL configuration illustrated in Fig. 1. The MOPA configuration uses two different accelerators with separate FEL wigglers. A complete INEX calculates the electron beam evolution from the injector to the electron beam dump. As shown, ISIS and PARMELAX are linked to calculate the injector, low energy accelerator, magnetic buncher, high energy accelerator, and transport to the wiggler. At this point, the electron phase space distribution is linked to FELEX to calculate the self-consistent interaction between the electron beam and light, in conjunction with optics configuration. After the FELEX calculation is completed, the residual electron phase space distribution is linked back to PARMELAX for the transport to the electron beam dump calculation. (For a more complemented configuration, an energy recovery decelerator calculation could be inserted at this point.) For the MOPA, a separate calculation is performed for both accelerators since there is no direct link between the electron distribution functions.

The link between the master oscillator and power amplifier is through the light pulse. FELEX provides the light link between the two wigglers. In this fashion, the FEL amplifier input signal includes the nonideal aspects of the light generated by the FEL oscillator. Although not presently a part of INEX, the evolution of light through the beam control system and output beam director could be calculated using a three-dimensional optics code.

Fig. 1. Illustration of the linking of ISIS, PARMELAX, and FELEX for a master-oscillator power-amplifier FEL system.

3. INTEGRATED NUMERICAL EXPERIMENT VALIDATION

When fully developed the integrated numerical experiment is intended to provide a credible and realistic design for high-performance FELs. In this context, a high-performance FEL refers to a laser with a high system efficiency relative to the intended application. Validation of the physics and technology models contained within INEX is crucial to successful application of the approach. The results presented in this section represent a subset of the INEX verification effort.

3.1. Proof-of-principle photoinjector experiment

A high-brightness and small-energy-spread electron beam source is required for high-performance FEL operation. Given this, a photoinjector is the appropriate choice for an FEL. The photoinjector uses a laser to generate a train of electron bunches from a photocathode that is located in an rf cavity. Because the laser pulse generates a bunch of electrons, the energy spread required to bunch electrons in a conventional electron injector is avoided. Moreover, in a photoinjector the electron bunch is rapidly accelerated resulting in reduced space charge emittance growth.

The proof-of-principle photoinjector experiment consisted of a single cavity with a solenoid used to control the downstream focus the electron beam.^{2,3} Located downstream from the solenoid was a pepper pot, a diagnostic used to determine the beam emittance. The function of the pepper pot is to generate a large number of small beamlets, each beamlet representing a fraction of the original electron beam. After the pepper pot, the beamlets drift downstream to a point where each beamlet diameter is measured. With a measured beamlet diameter and specified drift distance, the divergence angle associated with each beamlet can be determined. In addition, the beam diameter at the pepper pot position must be measured. Given the electron beam radial profile and divergence angle as a function of radius the emittance can be estimated. Using this technique, the emittance was found to be a function of the solenoid field strength. For each operation point, however, a minimum emittance was found.

Fig. 2. The electron beam radial profile in the horizontal plane at the entrance to the pepper pot.

In this case, there was a large disagreement between the theoretical prediction and the experimental measurement for the emittance. The predicted normalized emittance was above 100π mm-mrad, whereas the experimental measurement indicated an emittance of about 50π mm-mrad. In contrast, agreement between theory and experiment with all other parameters of interest was good.

Because of the importance of the photoinjector to a high-performance FEL, the first application of INEX was to evaluate the proof-of-principle photoinjector experiment. In this case, ISIS was used to calculate the experiment through the solenoid field while PARMELAX was used to calculate the remaining drift to the pepper pot, the pepper pot, and drift region to the measurement.

Rather than a significant disagreement between theory and experiment, the results of the INEX were in good agreement with the proof-of-principle experiment. In other words, the radial beam profile and beamlet divergence angles from the numerical diagnostic and experimental diagnostic were in very good agreement. The source of apparent disagreement was due to a misinterpretation of the pepper pot data, because of a large velocity shear associated with the electron distribution. The divergence measurement obtained from the pepper pot was associated with the core of the electron bunch, which only included about 50% of the electrons. From INEX calculations the emittance of the core of the electron beam was predicted to be about 50π mm-mrad, in agreement with the pepper pot measurements.

A comparison between INEX and the photoinjector experiment for the radial beam profile at the pepper pot is given in Fig. 2. In this case, the electron beam kinetic was 1 MeV with a peak current of 150 A. The Gaussian electron beam pulse was about 150 ps in duration.

3.2. 20-MeV accelerator model

With proper design the photoinjector can generate electron beam with small emittance and energy spread. Given the photoinjector, the next issue for high-performance FEL design is the control of emittance and energy spread growth in the accelerator, magnetic buncher, and magnetic bend. Space charge, micropulse energy spread, longitudinal and transverse wakefields, cavity and beamline asymmetry, alignment, and jitter contribute to emittance and energy spread growth.

As a first step toward the development of an INEX for the Los Alamos free-electron laser experiment, a model was constructed for the 20-MeV accelerator and magnetic buncher.^{4,5} This experiment did not have a photoinjector. A basic assumption of the accelerator model was that the current profile from the conventional electron gun is a half-cosine function, in reasonable agreement with the experimental measurement. At this point, only longitudinal wakefields were included in the INEX model. The emittance growth contribution from the transverse wakefield and beamline asymmetry were small relative to the initial emittance and energy spread. Thus, in this experiment the space charge, micropulse energy spread, and longitudinal wakefields are the primary source of emittance growth within the magnetic buncher.

With the optimum tuning of the conventional injector and accelerator, about 66% of the charge is contained within a 10 ps interval. The remainder of the charge is distributed into a lower energy tail, and some charge is even found in two following buckets. Initially, there was a disagreement about the distribution of charge predicted by the accelerator model. However, the accelerator model included a numerical equivalent of the wall current monitors. Given the response time and sensitivity of the wall current monitors, the calculated wall current signals are consistent with the experimental measurements. Again, the disagreement about the exact distribution of charge is an interpretation problem, as was the

case in the proof-of-principle photoinjector experiment. A problem which is mitigated with the use of equivalent numerical diagnostics.

In Figs. 3 through 5 the INEX model predictions are compared with the electron beam pulse width, the normalized emittance, and the electron beam diameter, respectively. In the experiment the magnetic buncher is located in the region 700-to-900 cm from the cathode. The wiggler entrance is at located at 1050 cm. In all cases, the open circles are the predictions of the accelerator model while the solid circles are the experimental data.

The FWHM electron beam bunch length is plotted as a function of distance for the cathode in Fig. 3. The agreement between INEX model and the experiment is good. In this case, the magnetic buncher reduces the pulse length over a factor of three. However, the electron beam brightness actually decreases because of emittance growth, which can be seen by comparing Figs. 3 and 4.

The normalized emittance is plotted as a function of the distance from the cathode in Fig. 4. The INEX accelerator model predicts significant emittance growth through the accelerator and magnetic buncher. Overall, the emittance data is in agreement with the prediction, both in scaling and in magnitude. In the accelerator the primary source of emittance growth is space charge, while in the magnetic buncher space charge, micropulse energy spread, and wakefields cause emittance growth.

The electron beam diameter is shown as a function of position along the accelerator in Fig. 5. The variation in the electron beam diameter is due to various matching conditions. Again, the overall agreement between INEX and the experiment is very good.

Fig. 3. Electron beam FWHM pulse width as a function of distance from the cathode. The electron bunch pulse width is reduced by about a factor of three in the magnetic buncher.

Fig. 4. The electron beam normalized emittance as a function of distance from the cathode.

Fig 5. Electron beam diameter as a function of distance from the cathode.

3.3. Harmonic experiment

The size of resonator mirrors is determined by damage and distortion limits. In the case of a high-performance FEL the harmonic power can contribute to mirror damage. As a result, the harmonic power spectrum must be known with some accuracy and the harmonic power must be included in the optics design.

A model for the harmonic radiation in plane polarized FELs has been implemented in a version of the three-dimensional FEL code FELEX called HELEX.⁷ This model includes the generation mechanisms for the odd and even harmonic frequencies and radiation effects caused by electron guiding center motion at angles to the wiggler axis. The model determines both the angular distribution and power level for the second through eleventh harmonics.

As part of the INEX verification effort, the experimental harmonic power levels measured in the Stanford Mark III FEL oscillator⁶ were computed, using the relevant wiggler, electron beam, and optical beam parameters defined from the experiment. The comparison between the experimental and HELEX results is summarized in Fig. 6. The seventh harmonic was the highest measured in the experiment. Although not an inherent assumption of the harmonic generation model, the HELEX simulations assumed a perfectly aligned electron beam through the wiggler. As a result, the predicted harmonic power is larger than measured experimentally, except for the second harmonic. The enhanced second harmonic power would be expected from electron beam misalignment with the wiggler.

Fig. 6. Comparison of the harmonic power spectrum with HELEX calculations.

Overall, the agreement with the experimental results is good, indicating that the basic model for harmonic generation is correct. The discrepancies between the experimental measurements and theoretical predictions appear to be caused by the inability to precisely measure the electron beam distribution and by wiggler field errors that cause electron beam wander within the wiggler. In a complete INEX calculation, both of these effects on harmonic generation are included. With improved experimental measurement of the harmonic power, coupled with the complete INEX description of the experiment, which includes micropulse effects, quite accurate predictions of the harmonic power appear to be possible. Moreover, with an INEX data base, the measurement of the harmonic radiation may prove to be a viable nonintrusive diagnostic of the electron beam.

3.4. Mode-media experiment

A series of experiments were performed to test optical guiding, which we refer to as the mode-media interaction.⁸ In long wigglers, theory predicts that the optical mode will be guided within the wiggler, in contrast to the usual diffractive spreading exhibited by a Gaussian beam during propagation. In short wigglers, the optical guiding effect will appear as a positive lenses, in place of the wiggler, in the resonator cavity.

Understanding the mode-media interaction is quite important in oscillator design because tapered wiggler designs are optimized for saturation. At the same time, increased mode distortion loss requires large small-signal gain for startup. Unfortunately, increased small-signal gain means decreased FEL efficiency. Thus, oscillator design is a sensitive trade-off.

The mode-media experiment tested the above effect by offsetting the optical axis of the resonator cavity relative to the fixed wiggler-electron-beam axis. It was expected that the larger the offset the greater optical mode displacement. Offsets parallel, type A, and perpendicular, type B, to the faces of the wiggler magnets were explored. Time integrated measurements were made of the optical mode shape outside the resonator cavity and the circulating cavity power. Finally, time resolved measurements followed the build-up and decay of the resonator power.

Calculations of the experiment were done with FELEX, using the electron beam phase-space distribution calculated with PARMELAX. Comparison between the INEX predictions and the experimental data is shown in the Figs. 7 and 8. At the output coupler and back reflector, type A offsets in which the optical axis is 1) offset or 2) offset and tilted are shown. The offset and tilt are relative to the fixed wiggler-electron-beam axis. The centroid displacements calculated with INEX are in reasonable agreement with the experimental data.

3.5. Cavity asymmetry

High-power FEL operation requires the generation of a high-power electron beam. If the accelerator is an rf linac, the coupling slot that connects the rf cavity to the waveguide feed supplying the rf energy must be large. A large coupling slot will introduce an appreciable asymmetry into the fundamental mode of the cavity that can lead to emittance growth.

The deflection shear was calculated using the T3 code, which can calculate a three-dimensional solution to Maxwell's equations in a complicated geometry.²⁴ As a support code, T3 is used to provide cavity asymmetry and three-dimensional wakefield information for PARMELAX. Thus, comparison of the T3 predictions with the cavity asymmetry experiment performed at Boeing⁹ validates an important component of the INEX model.

Fig. 7. Comparison of mode-media output coupler data and INEX.

Fig. 8. Comparison of mode-media back reflector data with INEX calculations.

A frequency-domain solution for an asymmetric cavity showed the presence of a TM_{110} -like deflecting mode. With the center of a beam bunch arriving at the center of the cavity for maximum acceleration, the transverse force is zero at the center of the bunch. However, the head of the bunch is deflected toward the coupling slot while the tail of the bunch is deflected away from the coupling slot. The differences in deflection between the head and tail of the bunch leads to a deflection shear. In Fig. 9 the magnitude of this deflection shear is plotted as a function of the coupling slot width in the MCTD (Modular Component Test Demonstrator) cavity for a 15 MeV electron beam with a bunch length of 25 ps. The time-domain solution obtained from T3 is in good agreement with the experimental data over the entire range of the coupling slot width.

Cavity asymmetry can be reduced to an acceptable level by placing a similar waveguide and coupler configuration diametrically opposite the power waveguide and coupler.¹⁰

Fig. 9. Comparison of cavity asymmetry experiment with T3 time-domain solution.

3.6. High-extraction-efficiency experiment

This is the most important INEX validation effort because 1) a complete INEX model was utilized and 2) the INEX model demonstrated predictive capability.

The high-extraction-efficiency experiment utilized four distinct wiggler configurations¹¹: 1) 12% linear taper in wavelength (12%), 2) 12% linearly taper in wavelength with a prebuncher (12% +), 3) 30% parabolic taper in wavelength (30%) and 4) a 30% parabolic taper in wavelength with a prebuncher (30% +). The same prebuncher was used both tapered wiggler configurations.

The prebuncher was an 8.75 cm long section of untapered wiggler with a 3.3 cm wiggler wavelength and a 0.11 T magnetic field strength. The purpose of the prebuncher, which is located upstream of the

main wiggler entrance, is to induce a velocity modulation on the electron beam. In the drift space following the prebuncher, the velocity modulation is converted into a density modulation on the scale length of the optical wavelength. This prebunching allows a greater fraction of the electron beam to be captured in the decelerating bucket of the main wiggler.¹² As a result, the extraction efficiency of the interaction can be increased.

Fig. 10 is a comparison of the high-extraction-efficiency experiment with the INEX predictions. Because the experiment used a conventional thermionic gun the ISIS code was not used. PARMELAX was used to calculate the electron phase space distribution to the entrance of the wiggler, see Figs. 3 through 5. The FEL interaction was calculated with FELEX.

As previously stated, the INEX predictions were made before the experimental data was available using a single operation point for the accelerator. In the experiment, the accelerator operation was varied somewhat for the different wiggler configurations. Nevertheless, for each wiggler configuration INEX predicted the FEL efficiency within, or close to, experimental error.

Fig. 10. Comparison between high-extraction-efficiency experimental data and INEX prediction.

3.7. Burst Mode 100-MeV accelerator experiment

Electron loss can lead to activation and wiggler magnet damage. Thus, an important issue for high power FELs is the electron beam loss in the accelerator and wiggler.

The development of the INEX model for the Burst Mode accelerator required a number of improvements in the accelerator code PARMELAX²². Most important was the development of a realistic algorithm for a traveling wave accelerator. Both longitudinal and transverse wakefields

associated with the accelerator cavities and limiting apertures are included in the accelerator model, through the use of a Green's function based upon TBCI calculations.

Three-dimensional wakefields, as well as azimuthally symmetric wakefields from bellows, flanges, and current monitors are not included in the initial model. The electrostatic fields of the electron gun, the subharmonic buncher fields, the fields of the traveling wave buncher, and cavity fields were calculated with SUPERFISH. The magnitude of the external magnetic field solenoids and quadrupoles were consistent with the experiment.

As with the photoinjector model, the space charge algorithm used to calculate the electron gun includes the image charges on the metal surface. Since the electron gun is pulsed, the leading and trailing edges of the electron bunch were overfocused relative to the center. As a result, the normalized emittance is about 30π mm-mrad, which is much larger than the normalized dc emittance of less than 10π mm-mrad.

The field amplitude for the subharmonic bunchers was determined from the experimental value, whereas the phase was set for bunching about the center of the micropulse. The traveling wave section of the accelerator was modeled by summing two standing waves. Again, the field amplitudes were chosen to correspond to the experimental values. The phase was chosen to minimize the micropulse energy spread.

A comparison of the accelerator model with experimental beam loss ¹³ is shown in Fig. 11. Overall, the agreement between INEX and the experiment is reasonable. As was the case in the 20-MeV Los Alamos accelerator, the Boeing burst mode accelerator exhibits significant emittance growth due to space charge and wakefields.

Fig. 11. Comparison of 100-MeV accelerator loss as a function of current monitor position.

3.8. 0.6- μ m burst mode oscillator experiment

In this experiment, the FEL is composed of a 110 MeV traveling-wave linac, a FODO array, a 180-degree magnetic bend, a matching section, a 5.0-m variable taper wiggler, and a near concentric two mirror optical resonator. The electron beam is formed using a thermionic gun. Each micropulse is then compressed in time using two subharmonic bunchers operating at 108 and 433 MHz, followed by a tapered phase velocity buncher at 1300 MHz. After bunching the micropulses are accelerated using six 1300 MHz traveling wave accelerator sections.

The accelerator has been extensively studied using PARMELAX. It is known that significant charge loss occurs before the electron beam enters the wiggler, as shown in Fig. 11. In addition, significant emittance growth occurs in the 180-degree magnetic bend. The three sources of emittance growth are nonlinear magnetic field components, space charge, and wakefields. Consequently, the emittance growth depends upon the electron beam radius and energy spread in the bend, as well as the peak current and charge in a micropulse.

For this experiment, the electron beam distribution function calculated by PARMELAX is used in FELEX to calculate the FEL efficiency without sidebands present. The efficiency prediction from the three-dimensional code FELEX is then corrected for the sideband instability using the one-dimensional code FELP. In this fashion, the nonideal character of the electron beam distribution, the three-dimensional effects on the FEL interaction, and the sideband instability are included into the efficiency prediction. In contrast to an untapered wiggler, the presence of the sideband instability reduces the efficiency when the wiggler is tapered.

Fig. 12. Burst Mode oscillator extraction efficiency as a function of macropulse shot number. Outcoupled laser power was used to derive the efficiency. The data has an error of ± 0.25 .

The comparison between INEX and the Burst Mode oscillator experiment ¹⁴ is shown in Fig. 12. The solid horizontal line is the INEX prediction without the sideband instability correction. When the system is properly tuned the extraction efficiency is in good agreement with the INEX prediction corrected for sidebands, indicated by the horizontal dashed line.

Based upon the wiggler taper the ideal efficiency should be about 2 %. In contrast, the efficiency predicted is only 1.25 %. Thus, the nonideal character of the electron beam distribution and three-dimensional effects reduce the efficiency below ideal by about 30 %. The sideband instability then reduces the efficiency another 30%. Taking these effects into account, the agreement of the experiment with INEX is excellent when the system is properly tuned. As a final point, the variation of the efficiency from macropulse-to-macropulse clearly demonstrates that proper FEL operation depends strongly on the control system.

3.9. 17-MeV Photoinjector / Accelerator Experiment

HIBAF is the first FEL experiment designed with INEX. In addition, it is the first experiment to incorporate a high-current photoinjector with an accelerator. When completed, it will be possible to operate HIBAF in a high-peak-current, single-accelerator master-oscillator power-amplifier FEL configuration. At present, the experiment is directed towards measuring the emittance and energy spread at 17 MeV.¹⁷⁻¹⁹

Tentative results from this initial experiment are shown in Fig. 13. Here, the solid line is the normalized 90% emittance as a function of micropulse charge. The curve was generated with the

Fig. 13. Comparison between HIBAF data, INEX prediction, and FELPPC emittance model.

FELPPC (Free Electron Laser Physical Process Code) correlated emittance model along with an uncorrelated emittance growth of 24π mm-mrad. The single INEX design calculation with an additional uncorrelated 24π mm-mrad emittance growth is indicated by the solid circle. Although more data is required before a final conclusion can be drawn, the four emittance data points appear to be in good agreement with INEX and FELPPC when the uncorrelated emittance growth is included. Here, the experimental data is shown with 10% error bars.

The initial conclusion from the HIBAF experiment is that an unknown source of 24π mm-mrad emittance is present, which is independent of micropulse charge. In short, the design INEX for HIBAF was incomplete because the calculation failed to predict the uncorrelated 24π mm-mrad emittance. It is now known that the cavity field asymmetry from the coupling slots is the source of the uncorrelated emittance growth. Initially, this source of asymmetry was thought to be negligible and not included in the INEX design calculations. However, when the asymmetry is included in INEX, the linac correlated emittance growth associated with the combined effects of space charge and magnetic field aberrations and coupling slot emittance growth are in good agreement with the experiment. To sum up, three-dimensional asymmetry cannot be neglected in FEL design.

4. CONCLUSION

It is important to understand the level of verification of the integrated numerical experiment since the credibility of the model will directly impact the design risk.

The most complete INEX model exists for the Boeing Burst Mode oscillator experiment.¹⁴ In fact, the INEX model and the Burst Mode experimental results are in very good agreement. More importantly, INEX has been used to predict modifications to improve FEL performance, especially with respect to the 180-degree magnetic bend. Subsequent modification to the experiment resulted in improved performance consistent with the prediction. Given this, the INEX approach has shown some predictive capability. On the other hand, for the most part, the Burst Mode INEX validation was performed after experimental data became available. As a result, the Burst Mode oscillator validation did not demonstrate sufficient predictive capability for the design of future high-performance FELs.

A complete INEX model exists for the Los Alamos high-extraction-efficiency experiment.¹¹ The FEL efficiency associated with four different wiggler configurations was predicted before experimental data became available, using a single operation point for the accelerator model in INEX. In contrast, the accelerator operation varied somewhat in the actual experiment. Despite the differences in the accelerator operation point the agreement between INEX and the experimental data is quite good, because INEX provides a consistent relationship between the electron beam current, size, emittance, and energy spread. In fact, consistency is the strength of the integrated numerical experiment approach.

The agreement of INEX with the Burst mode oscillator and high-extraction-efficiency experiments, as well as with other smaller experiments, shows that the development of the INEX approach is quite advanced. In some cases, the predictive capability of the model has been demonstrated. However, limiting physical effects that might be important in the high-performance FEL regime were masked in the Burst Mode oscillator and high-extraction-efficiency experiments, because the electron beam emittance and energy spread were both large relative to that required for a high-performance FEL in the optical regime.

The requirement for predictive verification of INEX in the high-brightness and high-current FEL regime was the motivation of the HIBAF experiment. HIBAF is the first experiment designed using the

INEX approach. Although tentative, the initial experimental results agree with the INEX design prediction for the micropulse energy spread and emittance, once the coupling slot asymmetry is taken into account. Thus, the only remaining accelerator physics issue is emittance growth control in magnetic bunchers and bends, which is a nontrivial problem. However, HIBAF has been designed to investigate these crucial issues.

In short, there is no evidence that important physics is missing in the present INEX model. It is expected that the integrated numerical experiment will remain under development for some time, as the model is first used to design and then later used to evaluate future FEL experiments. With the integrated numerical experiment approach it now appears possible to produce a credible and realistic design for high-performance FELs.

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