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Free electron laser physical process code (FELPPC)

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ABSTRACT

Even at the conceptual level, the strong coupling between subsystem elements complicates the understanding and design of a free electron laser (FEL). Given the requirements for high-performance FELs, the coupling between subsystems must be included to obtain a realistic picture of the potential operational capability. The concept of an Integrated Numerical Experiment (INEX) was implemented to accurately calculate the coupling between the FEL subsystems. During the late 1980's, the INEX approach was successfully applied to a large number of accelerator and FEL experiments. Unfortunately, because of significant manpower and computational requirements, the integrated approach is difficult to apply to trade-off and initial design studies. However, the INEX codes provided a base from which realistic accelerator, wiggler, optics, and control models could be developed. The Free Electron Laser Physical Process Code (FELPPC) includes models developed from the INEX codes, provides coupling between the subsystem models, and incorporates application models relevant to a specific study. In other words, FELPPC solves the complete physical process model using realistic physics and technology constraints. FELPPC can calculate complex FEL configurations including multiple accelerator and wiggler combinations. When compared with the INEX codes, the subsystem models have been found to be quite accurate over many orders-of-magnitude. As a result, FELPPC has been used for the initial design studies of a large number of FEL applications: high-average-power ground, space, plane, and ship based FELs; beacon and illuminator FELs; medical and compact FELs; and XUV FELs.

1. INTRODUCTION

A free-electron laser 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. The Integrated Numerical Experiment (INEX) was proposed¹ to address the strong coupling nature of an FEL. In terms of the physics, INEX is a self-consistent one-to-one numerical equivalent of a physical experiment. Engineering and technology constraints are included in the model to ensure that a given design is realistic. In addition to design, INEX is used to set requirements such as control and alignment tolerances. The integrated approach includes numerical diagnostics that are equivalent to the physical 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 any applied program, the incorporation of numerical diagnostics significantly enhanced our ability to accurately evaluate a number of physics and technology experiments.² The downside of the INEX approach is that it is very computer and manpower intensive.

FELPPC has been developed to overcome the disadvantages associated with the INEX approach. Basically, the INEX codes were used as a guide for the development of realistic models for the accelerator, FEL interaction, optics, and controls. Working with INEX as a reference point, these relatively simple models allow an accurate prediction of FEL subsystem elements. In turn, these subsystem elements are coupled to obtain a system-like model for the entire FEL configuration. Each subsystem model contains the detailed information required to estimate mass, cost, and size from a parts count.

FELPPC takes a system-oriented approach towards understanding a particular problem. However, FELPPC operates from a detailed physics description of specified hardware to obtain a very detailed design from which the performance, mass, cost, and size are then determined. In general, there is no guarantee that FELPPC can provide the performance required for a particular application. Since much of the interest in FELs is directed towards applications, the physics of the particular application of interest is incorporated as a subsystem element into FELPPC. The application subsystem element is then used as a metric to judge the physics and technology implications of a particular FEL configuration.

In section 2, a very brief overview of FELPPC is presented. The twelve subsystem elements of the laser system are discussed: radiofrequency (rf) power, injector, accelerator beamline, magnetic buncher, magnetic bend, electron beam dump, oscillator, frequency doubling crystal, amplifier, energy recovery decelerator, beam control system, and output beam director. Finally, a short discussion of the four application subsystem elements is given. In section 3, a comparison is made between the emittance predicted by FELPPC and 36-MeV accelerator experiment. The comparison with experimental data is an example of how FELPPC might be used in the physics mode of operation. A conclusion is given in Section 4.

2. FELPPC OVERVIEW

There are twelve laser subsystem elements associated with FELPPC: radiofrequency (rf) power, injector, linac, magnetic buncher, magnetic bend, oscillator, frequency doubling crystal, amplifier, energy recovery, electron beam dump, beam control system, and output beam director. Each problem investigated by FELPPC tends to be unique. Therefore, there are no defaults for the independent variables, and constraints between independent and dependent variables must be constructed for each problem. As such, a user must be knowledgeable in accelerator, FEL interaction, and optics, as well as in the particular application under investigation. Application subsystems are provided as a metric against which a particular FEL configuration can be evaluated. There are four application subsystems: 1) continuous-wave space-based FEL ICBM booster mission, 2) continuous-wave ground-based FEL cost, 3) sodium fluorescence, and 4) pulsed compact FEL cost.

A complex laser configuration can be constructed from the twelve subsystem elements. Each subsystem subroutine is indexed. The first index refers to the FEL configuration whereas the second index refers to the subsystem element within that FEL configuration. For example, consider a master-oscillator power-amplifier laser (MOPA) system that utilizes a separate FEL laser configuration for both the oscillator and amplifier. Typically, for a MOPA, the master-oscillator and power-amplifier FEL laser configurations are quite different. Thus, both the master oscillator and power amplifier must be specified as distinct FEL configurations in FELPPC.

The FELPPC construction of such a MOPA laser system is shown in Table I. The rf power source, beam control system, and output beam director subroutines are not indexed by element because each is utilized only once within a laser configuration. In this example, each laser configuration has a separate rf source subsystem element. With this construction, the rf power source is allowed to be different for the oscillator and amplifier configuration, subject to a constraint on the frequency ratio between the two sources. The beam control system for the oscillator configuration consists of transfer optics between the oscillator and the amplifier. No output beam director is required for the oscillator. The actual beam control system and output beam director are associated with the higher output power amplifier configuration.

Table I. Construction of a master-oscillator power-amplifier laser system. The oscillator contains six subsystem elements and the amplifier contains ten subsystem elements.

Laser Subsystem Element (Subroutine)	FEL Configuration (j)	Segment Number (k)
Oscillator rf power (RFEFFIC)	1	
Oscillator Accelerator Injector (PHOTO)	1	1
Oscillator Accelerator Beamline (BEAMLINE)	1	2
FEL oscillator (OSC)	1	3
Oscillator Electron Beam Dump (BEAMDUMP)	1	4
Oscillator Beam Control System (BCS)	1	
Amplifier rf power (RFEFFIC)	2	
Amplifier Accelerator Injector (PHOTO)	2	1
Amplifier Accelerator Beamline (BEAMLINE)	2	2
Amplifier Magnetic Bend (ABEND)	2	3
FEL Amplifier (AMP)	2	4
Amplifier Magnetic Bend (ABEND)	2	5
Amplifier Energy Recovery Decelerator (RECOVERY)	2	6
Amplifier Electron Beam Dump (BEAMDUMP)	2	7
Amplifier Beam Control System (BCS)	2	
Amplifier Output Beam Director (DIRECTOR)	2	

2.1. Radiofrequency source subsystem element

For each FEL configuration the efficiency associated with the specified rf source is determined using the RFEFFIC subroutine. At present, there are six sources that can be selected: 1) solid state, 2) tetrode, 3) klystron, 4) cross field amplifier, 5) lasertron, and 6) klystrode. The efficiency of each source is a function of the rf frequency. In addition, each source has a specific frequency range of operation. If the frequency falls outside this operational frequency range, the efficiency of the source becomes small. In this manner, during optimization, each source is effectively limited to the correct operational regime. For each source a risk value must be assigned: low, medium, or high. Generally, the higher the risk, the higher the source efficiency, specific power, and specific cost.

2.2. Accelerator subsystem elements

To calculate the accelerator with some precision, the accelerator lattice must be specified. In addition, the magnetic buncher and magnetic bend types must be specified. A thermionic injector or photoinjector must be specified. Given the lattice, the accelerator technology and associated hardware must be specified. It is possible to select pulsed or continuous-wave operation. The accelerator technology can be specified as cryogenic, conventional superconductor, or high-temperature superconductor. Room temperature operation is included as a subset of cryogenic technology. The accelerator cavity shape is a hardware option. At present, there are six basic cavity shapes in FELPPC, each with a data base generated by SUPERFISH, TBCI, or T3. All the cavity information is rf frequency dependent.

After the hardware is specified, the accelerator layout is calculated, taking into account the rf frequency, rf source characteristics, cavity coupling, micropulse charge, peak current, operating temperature, average current, focusing, magnetic bunchers, and magnetic bends. In addition, there are a number of design and

technology constraints determined from a low, medium, or high risk specification: 1) Kilpatrick-limited electric field gradient, 2) rf window power limit, and 3) rf power source safety and control margins. Finally, the method for determining the cavity phase and the method for determining energy gain per subsystem element are specified.

The electron beam kinetic energy, peak current, average current, emittance, and energy spread are calculated and updated as FELPPC moves from element to element within an FEL configuration. First, micropulse emittance growth due to nonuniform fields, wakefields, and space charge is calculated. Second, micropulse energy spread growth due to space charge, wakefields, and magnetic bunching is calculated. Third, the micropulse moments are modified to take into account jitter and misalignment. Finally, effective emittance growth resulting from cumulative beam breakup instability is determined. The cumulative beam breakup instability calculation includes jitter and misalignment, stagger tuning, focusing, and higher-order-mode coupler design.

2.3. Amplifier and oscillator subsystem elements

As with the accelerator subsystem elements, hardware options must be specified for the FEL subsystem elements. First, the type of laser system configuration must be selected: 1) oscillator, 2) amplifier, 3) spontaneous emission amplifier, 4) conventional laser driven amplifier, 5) master-oscillator power-amplifier, or 6) single-accelerator master-oscillator power-amplifier. FELPPC requires knowledge of the laser system configuration to update electron beam moments, determine transfer optics, and determine the input amplifier power correctly. Second, the type of wiggler, mirrors, and resonator configuration must be specified. At present, there are six wiggler options: permanent, hybrid, electromagnetic, superconducting, cryogenic, and pulsed. A metal or dielectric mirror can be specified. In some cases, the mirror information is frequency dependent. The resonator options are 1) simple concentric, 2) ring, and 3) ring with a grating rhomb.

The amplifier subsystem element first determines the resonance condition based upon the wiggler type and technology safety margins. The safety margins are not options. Using the nonideal electron beam moments determined by the accelerator subsystem elements, including emittance growth due to the beam breakup instability, the effective energy spread associated with the beam-wiggler combination is determined. The small signal gain is then determined from the solution of an integral equation. At this point, it is possible to calculate the nonlinear conversion efficiency of electron beam kinetic energy into electromagnetic using a particle trapping model, a calculation that includes the nonideal aspects of the electron distribution and micropulse effects. The ratio of the tapered-to-untapered wiggler length is determined from the nonlinear trapping model. If possible, a wiggler prebuncher is utilized to enhance efficiency.

The FEL interaction leads to large energy spread growth on the electron beam that depends upon the efficiency of the interaction. In the amplifier subsystem element the electron beam micropulse moments are updated for the energy recovery magnetic bends, energy recovery decelerator, and electron beam dump calculations.

The oscillator subsystem element is more complicated than the amplifier subsystem element. First, it must be determined if it is possible for the oscillator to startup. Because of mode mismatch resulting from gain, it is not sufficient that the small-signal gain simply exceed the resonator loss. Basically, depending upon

the small-signal gain and resonator loss at saturation a safety margin based upon mismatch is required to ensure startup.

If startup is possible, an iteration is performed to establish the oscillator operation point where saturated nonlinear gain equals resonator loss and outcoupling. As in the amplifier subsystem element, the nonlinear conversion efficiency is calculated using a trapping model, with a nonideal electron distribution and micropulse effects. Again, the ratio of the tapered-to-untapered wiggler length is determined from the trapping model, and, if possible, enhanced efficiency is obtained using a wiggler prebuncher.

The resonator type is a hardware option. Resonator loss is calculated from the number and reflectivity of elements in a particular resonator. The outcoupling efficiency is an independent variable. Both the resonator and outcoupling efficiency are taken into account in the saturation calculation. The mirror and resonator size are calculated taking into account distortion and mismatch.

Even if the oscillator interaction is weak, as occurs for a single-accelerator master-oscillator power-amplifier (SAMOPA) configuration, energy spread is induced on the electron beam. For a SAMOPA configuration, this induced energy spread is included in the oscillator subsystem element. In other words, the electron beam micropulse moments are updated for use in the amplifier accelerator, FEL amplifier, amplifier energy recovery, and amplifier dump calculations.

2.4. Energy recovery decelerator subsystem element

There are a number of hardware options for energy recovery. The accelerator and decelerator must have identical operation and technology: pulsed or continuous-wave operation and cryogenic, conventional superconductor, or high-temperature superconductor technology. To start, a same-structure or parallel-structure configuration must be specified for the decelerator. Here, same-structure energy recovery implies that the accelerator and decelerator are the same structure. Parallel-structure energy recovery implies that the accelerator and decelerator are separate structures but are coupled together in parallel. The cavity shape is a hardware option. Thus, in the parallel-structure configuration, the accelerator and decelerator can have different cavities.

At present, the energy recovery is composed of two parts. First, the fraction of the residual electron beam kinetic energy recovered is calculated. The residual electron beam power from the kinetic energy recovery process must be handled by the electron beam dump. Second, the fraction of the recovered kinetic energy available for rf power in the acceleration process is calculated.

As the electron beam kinetic energy is converted into electromagnetic energy, an energy spread is induced on the electron beam. The larger the FEL conversion efficiency, the larger the electron beam energy spread. A special energy recovery bend is used to disperse the electron beam along the direction of propagation in correlation with the electron energy. The FEL interaction and deceleration are distinct nonlinear processes. Consequently, it becomes more difficult for the decelerator to put the electron distribution back together as the FEL conversion efficiency increases.

The kinetic energy recovery efficiency depends strongly upon the cumulative beam breakup instability. In the decelerator the electron kinetic energy decreases as the beam propagates along the structure. As a result, the beam becomes more sensitive to transverse deflecting forces as the decelerator continues to

remove kinetic energy. Incidentally, with same-structure energy recovery the situation is more difficult because the magnetic focusing force is mismatched. At any rate, at some point the electron beam kinetic energy becomes too low, the beam cannot be controlled, and the deceleration must be truncated. The truncation energy determines the energy recovery efficiency.

Once kinetic energy is removed from the electron beam, the fraction of this energy lost to rf heating must be calculated. The rf heating depends upon the accelerator technology, cavity type, operation temperature, rf frequency, and deceleration electric field. In turn, the deceleration electric field depends upon decelerator design and the truncation energy determined by the cumulative beam breakup instability.

2.5. Electron beam dump subsystem element

The electron beam dump subsystem element is intended to calculate the residual electron beam transport and electron beam dump performance, mass, cost, and size. The electron beam dump performance is determined from the residual electron beam kinetic energy and average power, which depend upon the FEL efficiency, kinetic energy recovery efficiency, initial electron beam average power, and initial electron beam kinetic energy.

2.6. Beam control system and output beam director subsystem elements

The beam control system and beam director subsystem elements calculate the performance, mass, cost, and size of the beam control system and output beam director, respectively. The efficiency of the subsystem depends upon the number of mirrors, vignetting, and reflectivity. Metal or dielectric mirrors can be specified. In some cases, the mirror information is frequency dependent. Simple models for jitter, vibration, and alignment, which are important for some applications, have been implemented.

3. COMPARISON OF FELPPC WITH 36-MeV ACCELERATOR EXPERIMENT

Thermal emittance; residual cathode magnetic field emittance; three-dimensional coupling slot emittance; geometric, chromatic, and space charge emittance; and transverse wakefield emittance contributions are included in the FELPPC model. The model predicts the peak current, normalized emittance, and brightness as a function of photoinjector laser pulse length, cathode radius, micropulse charge, and acceleration gradient. In turn, the acceleration gradient depends upon the rf frequency, photoinjector cavity field enhancement factor, Kilpatrick limit, and cavity cooling.

3.1. Thermal contribution

The thermal contribution to the emittance resulting from the photoelectron emission is

$$\epsilon_n (\text{thermal}) = 2000 r_c (\text{mm}) (kT/mc^2)^{1/2} \pi \text{ mm-mrad},$$

where r_c is the cathode radius, kT is the photoelectron emission temperature, and mc^2 is the electron rest energy. For the standard model $kT = 0.3 \text{ eV}$, yielding

$$\epsilon_n (\text{thermal}) = 0.88 r_c (\text{mm}) \pi \text{ mm-mrad}. \quad (1)$$

3.2. Cathode external magnetic field contribution

The emittance contribution from a residual cathode magnetic field is

$$\epsilon_n(\text{bfield}) = e B_z r_c^2 / 2mc = 0.029 B_z (\text{gauss}) [r_c (\text{mm})]^2 \pi \text{ mm-mrad}, \quad (2)$$

where e is the electron charge and B_z is the residual magnetic field on the cathode.

3.3. Three-Dimensional Coupling Contribution

The off-axis coupling slot contribution to the emittance is

$$\epsilon_n(3d) = 0.96 [r_c (\text{mm})]^2 \pi \text{ mm-mrad}. \quad (3)$$

The leading coefficient depends upon the cell-coupling technique used in the accelerator. The coefficient of 0.96 has been found for the APEX linac. If the cavities are independently driven, the coupling coefficient is zero. Finally, even with a coupled structure, analysis indicates that the cell-coupling coefficient can be reduced significantly with an alternate design approach.

3.4. Geometric, Chromatic, and Space Charge Contribution

The geometric, chromatic, and space charge emittance is

$$\epsilon_n(\text{dynamics}) = 10 (r_c / r_0)^3 + 15 [(Q/Q_0) / (E/E_0)] / (r_c / r_0)^2 \pi \text{ mm-mrad}, \quad (4)$$

where Q is the micropulse charge, r_c is the cathode radius, and E is the electric field gradient at the cathode. The normalization constants Q_0 , r_0 , and E_0 are 5 nC, 5 mm, and 26 MV/m, respectively. The first term includes chromatic and geometric contributions, and the second term includes the space charge contribution.

3.5. Transverse wakefield emittance

The impact of transverse wakefields on emittance growth depends upon the cavity bore, misalignment, and focusing. In the APEX experiment, integrated calculations indicated a significant transverse wakefield emittance growth that is sensitive to both the micropulse charge and electron beam peak current. Emittance growth due to transverse wakefields would be expected to scale as

$$\epsilon_n(\text{transverse}) = \alpha_{t1} Q \langle x \rangle (Q / I f)^{1/2} / a^3 \pi \text{ mm-mrad}.$$

Here, α_{t1} is a coefficient that depends upon the cavity shape, accelerator lattice, and focusing; $\langle x \rangle$ is an average transverse displacement of the electron beam along the accelerator; I is the peak micropulse current; Q is the micropulse charge; f is the rf frequency; and a is the cavity bore radius. For a given accelerator and focusing technique, one would expect that f , a , and $\langle x \rangle$ would be constant. Then the basic dependence with micropulse charge and current is

$$\epsilon_n (\text{transverse}) = \alpha_{t2} Q^{3/2} / I^{1/2} \pi \text{ mm-mrad}, \quad (5)$$

where $\alpha_{t2} = \alpha_{t1} \langle x \rangle / f^{1/2} a^3$. However, the scaling predicted in Eq. (5) is inconsistent with integrated calculations. Based upon these more detailed calculations, it is found that

$$\langle x \rangle = \alpha_x Q^{1/2}. \quad (6)$$

Combining Eqs. (5) and (6), the transverse wakefield emittance growth contribution is

$$\epsilon_n (\text{transverse}) = \alpha_t Q^2 / (I f)^{1/2} a^3 \pi \text{ mm-mrad}, \quad (7)$$

which for the APEX experiment reduces to

$$\epsilon_n (\text{transverse}) = 28.8 Q^2 / I^{1/2} \pi \text{ mm-mrad}. \quad (8)$$

3.6. Combined photoinjector and linac emittance

The emittance contributions given by Eqs. (1), (3), (4), (5), and (8) are uncorrelated. Thus, the total accelerator emittance is

$$\epsilon_n = [\epsilon_n^2 (\text{thermal}) + \epsilon_n^2 (\text{bfield}) + \epsilon_n^2 (\text{coupling}) + \epsilon_n^2 (\text{dynamics}) + \epsilon_n^2 (\text{transverse})]^{1/2} \quad (9)$$

Many of the terms in Eq. (9) depend upon the cathode radius. Thus, minimum emittance is not obtained when the dynamic emittance, Eq. (4), is minimum. Rather, Eq. (9) must be solved as a function of radius. In most experiments the cathode radius and acceleration gradient remain fixed while the micropulse charge is varied. This fixed cathode experiment will yield a significantly higher emittance than if the cathode radius is varied. It is the matching of the cathode radius to the micropulse charge and acceleration gradient that leads to minimum emittance. The prediction of matched cathode radius was first suggested by FELPPC calculations.

In Fig. 1 the emittance is shown as a function of micropulse charge. As the micropulse charge was varied, the cathode radius was also varied in an attempt to achieve the minimum emittance. The change in the experimental cathode radius was somewhat coarse. However, the overall agreement with Eq. (9), in both magnitude and scaling, of the emittance with micropulse charge is very good.

A comparison between the predicted cathode radius and the experimental cathode radius is shown in Fig. 2. Considering the course nature of the change in the experimental cathode radius, the agreement between the data and the model is quite reasonable. Note that the relationship between the cathode radius and the micropulse charge shown in Figs. (1) and (2) only applies to the APEX experiment. In general, the relationship will be quite different for a linac that has each cell driven individually, a lower rf frequency, a lower gradient, and a larger bore cavity.

Fig. 1. FELPPC model compared with 36-MeV APEX data with a variable cathode radius.

Fig. 2. FELPPC model cathode radius compared with 36-MeV APEX cathode radius.

With the model, it is possible to break down the emittance contributions as a function of charge. As an example, the emittance contributions corresponding to 0.5 nC, 1.0 nC, and 5.0 nC are shown in Fig. 3. With a micropulse charge of 0.5 nC, the emittance is dominated by the dynamics contribution. When the micropulse charge is increased to 1 nC, the cathode radius is increased, and the cell-coupling emittance contribution becomes comparable to the dynamics contribution. Finally, at a micropulse charge of 5 nC, the transverse wakefield, dynamics, and cell-coupling contributions all contribute to the emittance. Above a micropulse charge of 5 nC, the emittance becomes swamped by transverse wakefields. By understanding the magnitude of the various contributions to the emittance, the photoinjector and linac can be systematically redesigned to achieve the lowest emittance for a desired operation point.

When the magnetic field is not zero on the cathode, the emittance can significantly increase. As an example, in Fig. 4 the emittance is shown as a function of magnetic field on the cathode for a micropulse charge of 0.5 nC. In this case, the emittance is dominated by the dynamics for this micropulse charge. Overall the trend is correct, but the measured emittance increases almost a factor of two faster than predicted by the FELPPC model.

Finally, the emittance is shown as a function of cathode radius in Fig. 5. The micropulse charge is fixed a 2 nC. Except for the data point at a cathode radius of 1.5 mm, the overall agreement is very good. The fact that there is a large discrepancy at a cathode radius of 1.5 mm is the most interesting aspect of the comparison. Is this discrepancy associated with a bad data point or is some new interesting physics entering the problem? Using FELPPC, a discrepancy has been clearly isolated, and the discrepancy can be resolved. In this case, the data point appeared to be bad.

Fig. 3. FELPPC model emittance contributions as a function of micropulse charge.

Fig. 4. Emittance as a function of residual magnetic field strength for a micropulse charge of 0.5 nC.

Fig. 5. Emittance as a function of cathode radius for a micropulse charge of 2 nC.

4. SUMMARY

Relatively simple, but realistic, models for the accelerator, FEL interaction, optics, and control have been developed using the Integrated Numerical Experiment model as a benchmark. These models have been incorporated into twelve subsystem elements: radiofrequency power, accelerator injector, accelerator beamline, magnetic buncher, magnetic bend, oscillator, frequency doubling crystal, amplifier, energy recovery decelerator, electron beam dump, beam control system, and output beam director. Each subsystem element provides the detailed information, and associated parts count, necessary to estimate mass, cost, and size. With these subsystem elements a system-like model for the FEL configuration can be constructed. FELPPC can calculate a number of FEL configurations: 1) oscillator, 2) spontaneous emission amplifier, 3) conventional laser driven amplifier, 4) master-oscillator power-amplifier, or 5) single-accelerator master-oscillator power-amplifier.

Since much of the interest in FELs is directed towards applications, the physics of the particular application of interest is incorporated as a subsystem element into FELPPC. With this approach, a relevant trade-off or initial design study is performed in the context of the application. Basically, the application subsystem is used as a metric to judge the physics and technology implications of a particular FEL configuration. FELPPC can be used in a physics scaling, technology assessment, or program development mode of operation.

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