PARAMETRIC MODELING OF ELECTRON BEAM LOSS IN SYNCHROTRON LIGHT SOURCES*

B. Sayyar-Rodsari†, C. Schweiger, E. Hartman, Pavilion Technologies, Inc., Austin, TX 78759, USA
J. Corbett, M. Lee, P. Lui, E. Paterson SLAC, Menlo Park, CA 94025, USA

Abstract

Synchrotron light is used for a wide variety of scientific disciplines ranging from physical chemistry to molecular biology and industrial applications. As the electron beam circulates, random single-particle collisional processes lead to decay of the beam current in time. We report a simulation study in which a combined neural network (NN) and first-principles (FP) model is used to capture the decay in beam current due to Touschek, Bremsstrahlung, and Coulomb effects. The FP block in the combined model is a parametric description of the beam current decay where model parameters vary as a function of beam operating conditions (e.g. vertical scraper position, RF voltage, number of the bunches, and total beam current). The NN block provides the parameters of the FP model and is trained (through constrained nonlinear optimization) to capture the variation in model parameters as operating condition of the beam changes. Simulation results will be presented to demonstrate that the proposed combined framework accurately models beam decay as well as variation to model parameters without direct access to parameter values in the model.

INTRODUCTION

Synchrotron light is used for a wide variety of scientific disciplines ranging from physical chemistry to molecular biology and industrial applications. The synchrotron light is radiated from a relativistic electron beam circulating in a storage ring particle accelerator [1, 2, 3]. As the electron beam circulates, random single-particle collisional processes lead to decay of the beam current in time. As the electron beam decays, so does the intensity of the synchrotron light resulting in detuned optics in the photon transport lines (*e.g.* mirrors, gratings, slits), changes in material properties of the experimental sample, degradation of detector performance and uncertainties in data reduction. Hence, at all synchrotrons, a premium is placed on delivering constant photon beam intensity to the photon beam lines [4].

Efforts to systematically model the electron beam loss in synchrotron light sources have therefore been of primary interest. At SPEAR3, for example, every two weeks, up to 48 hrs of beam time is allocated for machine development studies, including programs to measure, characterize,

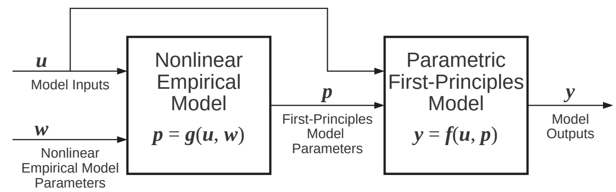

Figure 1: Block diagram of a PUNDA model. The PUNDA model is formed by the series connection of a *Nonlinear Empirical Model* (NEM) block and a *Parametric First-principles Model* (PFM) block.

and mitigate electron beam loss. In this paper a framework for the systematic modeling of electron beam loss is presented. This framework, known as **P**arametric **U**niversal **N**onlinear **D**ynamics **A**pproximator (PUNDA), consists of a series connection of a Nonlinear Empirical Model (NEM) block and a Parametric First-principles Model (PFM) block (see Figure 1). The parameters, $\vec{P}$, in the PFM block may vary as a function of process inputs, $\vec{u}$. For the beam loss model of interest in this study, the instantaneous electron beam current, Eq. (1), constitutes the PFM block, where the characteristic beam decay time constant is the varying parameter. A neural network (NN) model forms the NEM block. This NN model is trained to capture the variation in the characteristic beam decay time constant as a function of variation in vertical scraper position (Y_s), RF voltage (V_{rf}), initial beam current (I_0), and total number of bunches (M_b).

The ultimate goal of this study is to build accurate and computationally efficient models that quantify beam loss from electron-gas scattering (elastic and inelastic) and intrabeam scattering (electron-electron). Once such models are constructed, an optimization-based approach may be adopted to: *(a)* minimize beam loss in standard modes of operation, *(b)* optimize synchrotron performance based on forecasts of beam loss, *(c)* provide design guidelines for performance at high beam current and top-up mode of operation, and *(d)* provide design guidelines for installation of future small-gap undulators.

PHYSICS OF ELECTRON BEAM LOSS

The physics behind electron beam loss is conceptually straight-forward but nevertheless a highly non-linear process. In principle, the electron beam current decays in time due to (a) elastic electron-gas collisions (Coulomb scattering) (b) inelastic electron-gas collisions (bremsstrahlung scattering), and (c) intrabeam electron-electron collisions [5, 6, 7, 8]. In this section, global mod-

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† bijan@pavtech.com

els for electron beam loss are briefly described.

At any given time t, the instantaneous electron beam current may be written as:

$$I_t(t) = I_0 e^{\frac{-t}{\tau}} \quad (1)$$

where I_0 is the initial beam current, and τ is the characteristic beam decay time constant. Due to the uncorrelated nature of the collisional processes, the characteristic decay time depends on the individual contributions from Coulomb, Bremsstrahlung, and Intrabeam sources for scattering. Given that we can only measure the net beam decay time, (τ), the gas and intrabeam components must be inferred from an array of measurements under different experimental conditions. For the simulation study in this paper, τ is assumed to be a non-linear function of vertical scraper position (y_s), RF voltage (V_{rf}), initial beam current (I_0), and total number of bunches (M_b).

Over longer time periods of time, electron beam loss deviates from pure exponential and is governed by a more general rate equation:

$$\frac{dN_e}{dt} = \sum_i A_i \, N_e \, N_i \, \sigma_i \quad (2)$$

where N_e is the number of electrons, N_i is the number of scattering centers, σ_i is the scattering cross section for each type of collision, and A_i are characteristic proportionality constants. The cross sections σ_i quantify the probability of particle loss for each collision process. Note that integration of the rate equation, $\frac{dN}{dt} = -\alpha N^2$, yields a beam decay profile in time:

$$N(t) = \frac{N_0}{1 + N_0 \, \alpha \, t} \sim N_0 e^{-\frac{t}{\tau}} \quad (3)$$

for short times t. The long-term decay curve is more complicated than the exponential expression for instantaneous decay because the density of scattering centers is reduced roughly in proportion to circulating beam current.

The objective of the current study is to build PUNDA models that accurately predict the electron beam decay as a function of electron beam parameters and synchrotron operating parameters. The training of the NN block in the PUNDA model will be constrained by first-principles models (*i.e.* particle collision physics) for each scattering mechanism, and hence the trained model will be physically meaningful.

SIMULATION RESULTS

For the simulation study in this paper the following first-principles model is used to describe the electron beam loss:

$$I_t(t) = \frac{I_0 e^{-bt}}{1 + \left(\frac{a}{b}\right) I_0 \left(1 - e^{-bt}\right)} \quad (4)$$

where I_0 is the initial beam current, and a and b are parameters of the parametric model for electron beam loss that are functions of the beam operating conditions.

The parameter $a = a_T + a_B + a_C$, is affected by Touschek (a_T), Bremsstrahlung (a_B), and Coulomb (a_C) effects on beam loss [9] which in turn depend on gap voltage (V_{rf}), vertical scraper position (Y_{s}), dynamic vacuum pressure (P_{dyn}) and number of bunches (M_{b}). The parameter $b = b_B + b_C$ is affected by Bremsstrahlung (b_B) and Coulomb (b_C) collisions due to the base pressure.

For the simulation results shown in this section, four major parameters, *i.e.* Y_{s}, V_{rf}, M_{b}, and I_0 are varied over an operation range consistent with that at SPEAR3. Electron beam loss is simulated using Eq. (4). Random noise is added to the simulated electron beam current to reflect imperfect current measurements. The noisy electron beam current is then used to construct a PUNDA model where Eq. (4) constitutes the *Parametric First Principles Model* block, and a NN constitutes the *Nonlinear Empirical Model* block. The combined PUNDA model is trained via constrained optimization, identifying appropriate parameter values for the FP model (*i.e.* a and b), at the same time that the decay in electron beam current is modeled. Figure 2-5 capture typical simulation results.

CONCLUSIONS

PUNDA structure offers a framework in which both beam data and first principles models may be used to complement one another. The nonlinear empirical model block may be used to capture the less known aspects of the beam decay that is reflected in the operation data but is not fully explained by first-principles information. Once a PUNDA model is verified to capture the beam loss in a particle accelerator, the model can be used to identify potential sources of beam loss in real-time.

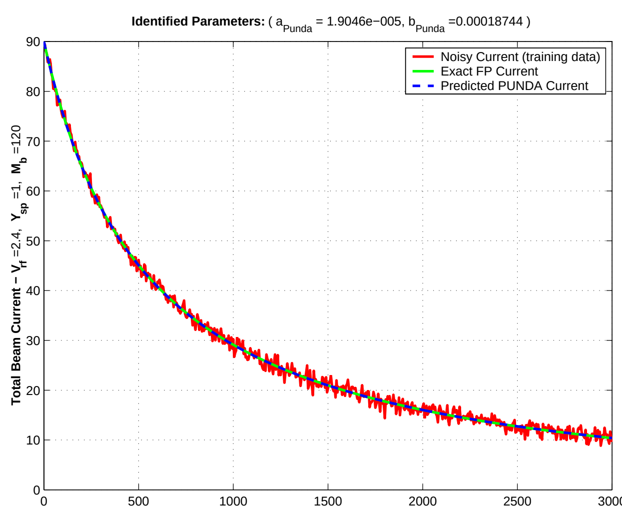

Figure 2: Prediction of electron beam decay using PUNDA model. The beam decay is accurately predicted while acceptable estimates of the decay model parameters are obtained. The actual parameter values used in the FP model of Eq. (4) are $a_{FP} = 1.8992e-005$ and $b_{FP} = 0.00018964$.

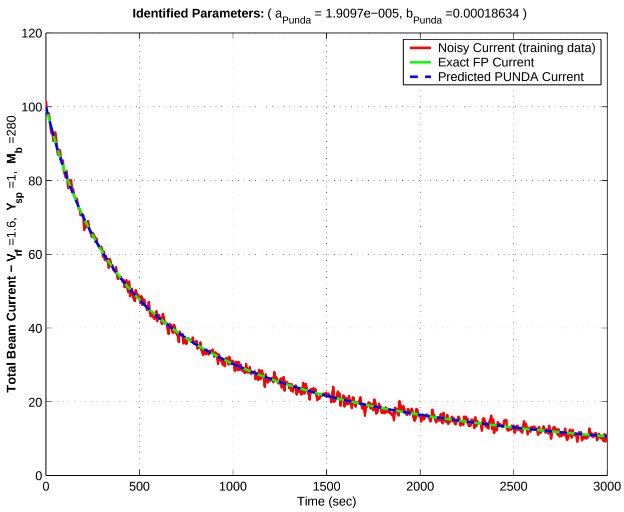

Figure 3: Prediction of electron beam decay using PUNDA model. The beam decay is accurately predicted while acceptable estimates of the decay model parameters are obtained. The actual parameter values used in the FP model of Eq. (4) are $a_{FP} = 1.882e - 005$ and $b_{FP} = 0.0001905$.

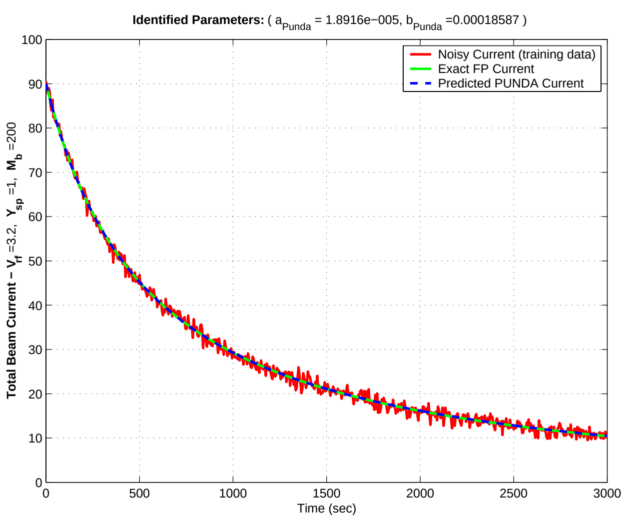

Figure 4: Prediction of electron beam decay using PUNDA model. The beam decay is accurately predicted while acceptable estimates of the decay model parameters are obtained. The actual parameter values used in the FP model of Eq. (4) are $a_{FP} = 1.9058e - 005$ and $b_{FP} = 0.00018842$.

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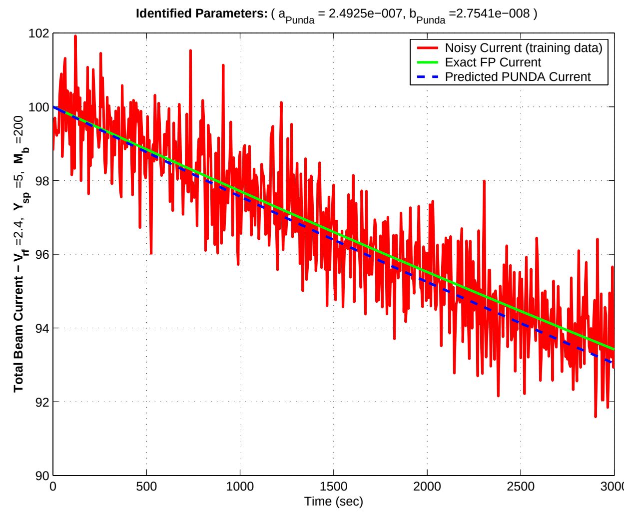

Figure 5: Prediction of electron beam decay using PUNDA model. The beam decay is accurately predicted while acceptable estimates of the decay model parameters are obtained. The actual parameter values used in the FP model of Eq. (4) are $a_{FP} = 2.4925e - 007$ and $b_{FP} = 2.437e - 006$.

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