

UPDATES TO QUINDI - A CODE TO SIMULATE COHERENT EMISSION FROM BENDING SYSTEMS

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Abstract

QUINDI has been developed to address the numerical challenge of calculating the radiation spectra from electron bunches in bending magnet systems. Since the introduction of QUINDI, many improvements and features have been added. QUINDI now supports a 3D model for bending magnets which includes fringing fields. A more modular approach has been achieved which allows better interoperability with other tracking and radiation codes. There have been many updates to the electric field calculation and spectrum processing, as well as to the post-processor, SpecGUI.

INTRODUCTION

While many previous codes support self-interaction by radiation between particles, few codes can accurately model what is seen by a detector in an actual experiment. QUINDI addresses this problem by simulating a detector or windowed port in an experimental setup. The observed fields are then Fourier transformed and integrated over the detector to produce the frequency spectrum.

The general flow of processes involves three major steps: trajectory calculation, electric field calculation, and spectrum calculation. The trajectory can be calculated using either a 1-, 2-, or 3-dimensional model for the magnets, with higher dimensionality usually yielding better results at the cost of extra processing time. Each particle's trajectory is then inserted into the Lienard-Wiechert potential formula to calculate the observed electric field at the point of observation for each integration step. The final step, the spectrum calculation, is a Fourier transform from the time domain into the frequency domain, which is recorded for each spot on the detector. The QUINDI post-processor, SpecGUI, is then used to display and manipulate the data. A more detailed description of the tracking, electric field calculations, spectrum calculations, and post-processing is presented in Ref.[1]. This paper only deals with the modifications and updates made to the code since PAC07.

QUINDI was originally developed to simulate the ATF compressor experiment at Brookhaven National Laboratory[2]. Since its introduction, QUINDI has gained many new features which increase the usefulness in modeling physical systems and extends the range of possible applications.

MODULARITY

QUINDI has been designed to be as modular as possible. The tracking and field calculations have now been completely separated: it is possible to have QUINDI only perform tracking or only perform field calculations, in addition to being able to perform both tasks sequentially in a single run. Depending on the situation, it can be useful to run the particle tracking in a code such as TREDI[3], which is a self-consistent tracking code, and then perform only the electric field and spectrum calculations with QUINDI.

Previously, QUINDI was limited to only recording the trajectory of the first particle, but now it is possible to run QUINDI and record the entire trajectory for all particles. This feature allows the user, at a later time, to use that output file as the trajectory for field and spectrum calculation with a new set of parameters. This approach allows the user to run the tracking a single time, while providing the ability to run the spectrum calculation many times with a different maximum frequency and frequency cuts.

QUINDI is now capable of producing its own tracking, importing the tracking from a prior TREDI run, or importing the tracking from a prior QUINDI run. These options have been added to the main input file.

UPDATES TO TRACKING

Originally, QUINDI only had the option to model the tracking 1- or 2-dimensionally. In these cases, the transverse momentum which is outside of the bending plane was constant, giving the particle a transverse drift that could not be altered by the unidirectional magnetic field. The 2D case does have a fringing field, however, it is a simple linear drop-off in strength, and still, only the primary magnetic field direction is taken into account. Realistic fringing fields will also have a longitudinal component, which can affect the transverse momentum which is outside of the bending plane. QUINDI is now capable of modeling this 3-dimensional fringing field. This effect results in a slight rotation of the bunch as it propagates through the magnets, causing the transverse phase spaces to appear slightly different between the 2D and 3D cases, as shown in Figure 1.

QUINDI uses a coordinate system where z - is the main direction of propagation, y - is transverse but lies in the predominant bending plane, and x - is the predominant direction of the magnetic field. The 3D case adds two parameters to the magnetic lattice input file describing the x -offset of the magnet and the gap between the magnet faces. The

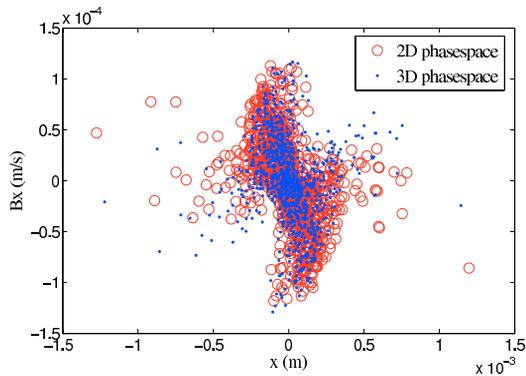


Figure 1: Comparison of 2D vs. 3D tracking. Shown here is the final transverse phasespace, the red circles are the 2D case, the blue dots are the 3D case. The slight rotation of the phase space is due to the fringing fields.

x -offset is the shift in the x -direction of the midpoint between the two magnetic faces. The gap, which is the distance between the two faces, is additionally used as the length of the fringing field. For the 3D case, these parameters are used to develop a polyhedron with 6 trapezoidal sides, with each face being described by its normal vector. By comparing these normal vectors to the position vectors of the particle, we can determine where inside or outside of the magnetic polyhedron the particle lies, and ultimately, which magnetic fields affect it at that position. In the 1- and 2-dimensional cases, the magnetic field is only modeled in the x -direction, while in the 3D case, the x -component still falls off linearly as before, but now certain locations inside of the fringe field can give rise to a magnetic component in the longitudinal or z -direction. The strength of this z -component is found by inserting the x -component formula into Maxwell's equation, $\nabla \times B = 0$, to obtain the relationship $B_z = -\frac{B_0}{g} \cdot \Delta x$, where B_0 is the strength of the magnet, g is the gap between the plates, and Δx is the particle's x -direction deviation from the midpoint between the plates.

Additionally, QUINDI can now perform a full trajectory dump to the HDF5[4] output file. This is an essential setting if the user plans on using the trajectory for field calculations at a later time. Full trajectory recording comes at the expense of approximately 1 gigabyte of data per 25000 particles using this HDF5 format. A setting has been added to the main input file to toggle this option.

UPDATES TO ELECTRIC FIELD

Previously, QUINDI utilized only the acceleration field of the Lienard-Wiechert potential[5]. Now, the electric field calculation includes the velocity field portion, so the new formula being used is

$$E(\tau) = \frac{e^-}{4\pi\epsilon_0} \cdot \left[\frac{\vec{n} - \vec{\beta}}{\gamma^2 R^2 \cdot (1 - \vec{n} \cdot \vec{\beta})^3} \right]$$

$$+ \frac{e^-}{c4\pi\epsilon_0} \cdot \left[\frac{\vec{n} \times [(\vec{n} - \vec{\beta}) \times \vec{\beta}]}{R \cdot (1 - \vec{n} \cdot \vec{\beta})^3} \right], \quad (1)$$

where \vec{n} is the unit vector and points from the particle's position along the trajectory to the detector point, R is the distance, and $\tau = t + \frac{R}{c}$. t is the laboratory time, c is the speed of light, e^- is the charge of the electron, and ϵ_0 is the permittivity of free space. $\vec{\beta}$ and $\vec{\beta}$ are the particle's velocity and acceleration, respectively, and γ is the particle's Lorentz factor. The addition of the velocity field can have an impact on the resulting spectrum, as the velocity field has stronger near-field effects, while the acceleration field has stronger radiative effects.

A pair of optional parameters has been added to the main input file, which allows you to restrict the field calculation to a limited region of space. These parameters, measured in meters and referring to z -position, cause the fields outside of the range to be set to zero. This allows the electric field calculation to ignore certain parts of the trajectory so the calculated spectrum has less uninteresting noise. This process is somewhat analogous to having a limited size window that only allows certain regions of the beam trajectory to influence what is seen on the detector.

Optimizations have been made to the memory handling abilities of QUINDI, allowing the user to specify finer detector meshing before experiencing memory issues.

UPDATES TO SPECTRUM

Users of QUINDI requested a way to gather more spectrum information at lower frequencies than at higher frequencies which avoids having to merely increase the total number of frequency samples. A setting to adjust the scaling was added to the main input file, and it can either be set to produce a linear sampling or a logarithmic sampling. Linear sampling refers to the old standard method of dividing the frequency in equally spaced slices. Logarithmic sampling means that there are more frequency slices at the lower end of the spectrum, and each subsequent slice is larger than the previous. This allows the user to gain more useful information about the lower frequencies than the higher frequencies, without increasing the run duration.

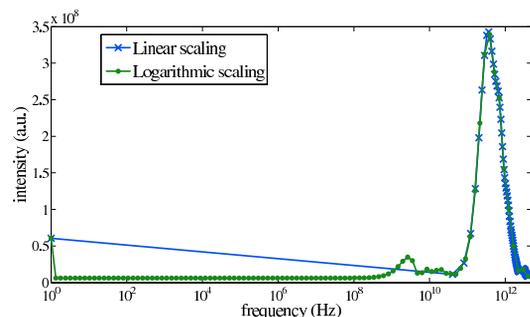


Figure 2: Spectrum comparing linear and log scaling. The frequency axis is displayed logarithmically to highlight the advantage of the log scaling setting.

As seen in Figure 2, the logarithmically sampled spectrum reveals more fine structure at low frequencies than the linearly sampled spectrum. Both graphs contain the exact same number of frequency samples and had identical run durations.

UPDATES TO SPECGUI

SpecGUI, the Matlab-based QUINDI post-processor, has undergone a major code overhaul. The software should run faster in general, as it has been completely rewritten and is now more optimized.

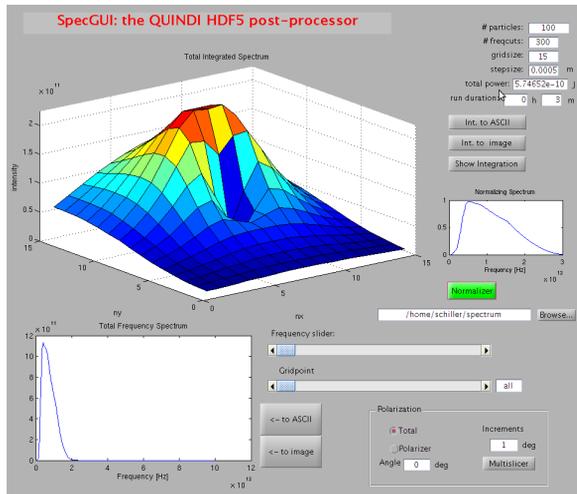


Figure 3: New version of SpecGUI, showing indicators and normalizer function enabled.

SpecGUI now displays helpful run information on the front panel, including particle count, number of frequency slices, number of gridpoints, tracking stepsize, and run duration. This information is useful when comparing runs, and precludes the need to manually look up these major values in the HDF5 output file.

A normalizer function has been added which allows the user to apply a mask or filter to the frequency spectrum. This can be useful if the user has an experimental setup with a known absorption involved. For instance, if the experiment has a certain gas in the transport with a known absorption spectrum, the normalizer can multiply this against the calculated spectrum to better match the experimental results. The selected graph need not match up in maximum frequency or in the spacing of the samples; SpecGUI will interpolate the normalizer graph to the same scale as the integrated spectrum, and it will pad any unknown frequencies with zeroes.

NEW BENCHMARKS

In the original QUINDI paper, QUINDI was benchmarked against the ATF experiment at Brookhaven National Laboratories. Since then, a new paper on this experiment was published in Physical Review Special Top-

ics - Accelerators and Beams[6]. An updated version of QUINDI was tested against the new experimental ATF results, a comparison of which is shown in Figure 4.

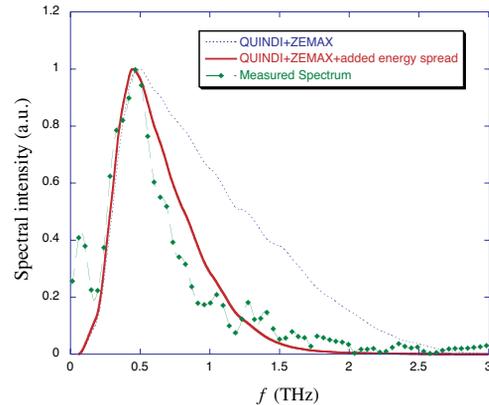


Figure 4: Comparison of experimental results with QUINDI simulation results[6].

Because the exact phase space of the electron bunch is unknown in the experiment, small modifications to the simulated input beam can adjust the output from QUINDI. With a small added energy spread to the input beam, the computed results from QUINDI match up nicely with the new experimental measurements.

OUTLOOK

There are additions we would like to make to QUINDI. We would like the ability to model other types of magnets, including quadrupoles and sextupoles, as well as have the ability to rotate the magnets in all axes of space. Second, there have been requests to add static and time-dependent external electric fields as possible beamline elements. Users have requested a way to get the beam to stop, such as in a material, so the radiation can be calculated in these types of situations. Finally, we would like to be able to calculate the incoherent part of the emission with shot noise canceling in order to achieve the correct power at higher frequencies.

REFERENCES

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- [6] G. Andonian, et al., "Observation of coherent terahertz edge radiation from compressed electron beams", Phys. Rev. ST Accel. Beams 12, 030701 (2009).