BBU_PROGRAM: Simulation of the Beam Breakup Instability

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1 Introduction

BBU_PROGRAM is a program which simulates the beam breakup instability [1]. The beam breakup instability occurs when a particle beam is recirculated through a cavity as in an Energy Recovery Linac. The bunches of the beam are kicked by the wakefields in a cavity and this kick generates an orbit distortion so that when the bunches return to the cavity, their off-axis orbit through the cavity will create additional wake fields. Given the right conditions, this regenerative feedback can lead to instabilities. BBU_PROGRAM works by direct simulation. A train of bunches is tracked though a lattice and the wakefields and orbit can be monitored.

2 Simulation technique

In order to correctly calculate the HOM fields, bunches are tracked through a given cavity in the correct time order. That is, BBU_PROGRAM "simultaneously" tracks a sequence of bunches that fill the lattice, starting and stopping bunches as appropriate to make sure that the bunches going through a cavity are tracked in the correct order.

In BBU_PROGRAM, time (t) is measured in "turns" (Abbreviated "T"). One turn is the time it takes a bunch to travel from the start of the lattice to the end. At the start of a simulation, at time equal zero, the HOM power in the cavities is set to zero. Bunches are then started at the beginning of the lattice and tracked through to the end. To minimize computation time, a single particle is used to represent each bunch.

Bunches that are initialized at a time between 0 and 1T are given a random transverse offset. The offset distribution is Gaussian in shape and the sigma is determined by the parameter bbu_param%init_particle_offset (see below). After the zeroth turn period (which is the period ($0 \le t \le 1T$) , bunches will be initialized with zero transverse offset. In the second turn period ($2T \le t \le 3T$), the averaged "maximum field strength", $V_{max}(2)$ which is the field strength of the strongest HOM mode in all the cavities, is taken as a baseline to determine whether the fields are growing or decaying. At the end of the simulation, after a set number of turn periods n, the beam is declared stable or unstable depending upon whether the ratio $V_{max}(n-1)/V_{max}(2)$ is less than or greater than 1. Additionally, in order to shorten the computation time, if $V_{max}(m)/V_{max}(2)$ for some turn period m is lower then a user defined limit, the simulation is aborted and the beam is declared to be stable. If $V_{max}(m)/V_{max}(2)$ goes above a user defined upper limit, the simulation is aborted and the beam is declared to be unstable.

2.1 Main input file

When BBU_PROGRAM is run, BBU_PROGRAM first reads the `main input file`. The main input file can be specified on the command line invoking BBU_PROGRAM. If not given, the default name for the main input file is "`bbu.init`". Example main input file:

```
&bbu_params
  bbu_param%lat_file_name = 'erl.lat'        ! Bmad Lattice file name.
  bbu_param%bunch_freq = 1.3e9               ! Bunch-to-bunch frequency in Hz.
  bbu_param%init_particle_offset = 1e-8      ! Initial particle offset sigma.
  bbu_param%limit_factor = 2                 ! Simulation unstable limit.
  bbu_param%simulation_turns_max = 11        ! Simulation time.
  bbu_param%hybridize = T                    ! Combine non-hom elements in the simulation?
  bbu_param%keep_overlays_and_groups = F     ! Keep when hybridizing?
  bbu_param%keep_all_lcavities = F           ! Keep when hybridizing?
  bbu_param%current = 20e-3                  ! Starting current (amps).
  bbu_param%rel_tol = 1e-2                   ! Final threshold current accuracy.
  bbu_param%write_hom_info = T
  bbu_param%drscan = F                       ! Do DR scan as in PRSTAB 7 (2004) Fig. 3?
  bbu_param%elname = 'T1'                    ! Element to step length for DRSCAN.
  bbu_param%nstep = 50                       ! Number of steps for DRSCAN.
  bbu_param%begdr = 5.234                    ! Beginning DR value for DRSCAN.
  bbu_param%enddr = 6.135                    ! End DR value for DRSCAN.
  bbu_param%use_interpolated_threshold = T
  bbu_param%nrep = 10                        ! Threshold or stable orbit calculation reps.
  bbu_param%ran_seed = 0                     ! Set specific seedd (0 uses system clock).
  bbu_param%ran_gauss_sigma_cut = 3          ! Limit ran_gauss values to within N sigma.
  bbu_param%stable_orbit_anal = F            ! Write out cavity orbit data.
/
```

Fortran namelist input is used. The namelist begins on the line starting with "`&bbu_params`" and ends with the line containing the slash "`/`". Anything outside of this is ignored. Within the namelist, anything after an exclamation mark "`!`" is ignored including the exclamation mark.

`lat_file_name`

The `lat_file_name` parameter specifies the lattice file to be used. Lattices are in Bmad standard format [2]. In order to simulate BBU, `multipass` lines which contain `lcavity` elements must be specified in the lattice. The long range wakes in the `lcavity` elements are responsible for the BBU instability. See the Bmad manual for more details.

`bunch_freq`
: The `bunch_freq` is the bunch-to-bunch frequency in Hz.

`init_particle_offset`
: This is the 1σ half width, in meters, of the distribution of the initial transverse coordinates for bunches initialized during the zeroth turn period.

`limit_factor`
: If the ratio $V_{max}(m)/V_{max}(2)$ goes above `limit_factor` the beam is declared unstable and if $V_{max}(m)/V_{max}(2)$ goes below `1/limit_factor` the beam is declared stable.

`simulation_turns_max`
: The `simulation_turns_max` parameter sets the duration of the simulation.

`hybridize`
: Hybridization is the process of combining all the elements between two cavities into one element. Tracking through a hybridized element is done using linear transport. This speeds up the calculation but there is a possible loss of accuracy.

`keep_overlays_and_groups`

`keep_all_cavities`
: When hybridizing, if `keep_all_cavities` is set to False, then `lcavity` elements that do not have HOM elements will be hybridized. If `lcavity` elements without HOMs are hybridized, this will speed up the simulation but can possibly lead to inaccurate results.

`current`

`write_hom_info`
: If this parameter is set true, the HOM parameters are written to the main output file.

`drscan`
: If enabled, the threshold current is calculated for over the range in return times corresponding to the range from `begdr` to `enddr` in `nstep` steps, lengthening the `elname` element in the lattice accordingly. If the toy lattice of Ref. [1] (see the Appendix) is used, then its Fig. 3 is reproduced.

`nrep`
: The BBU threshold current calculations are repeated `nrep` times. This is useful to estimate the effect of randomizing the HOM frequencies, since they are re-randomized for each calculation.

`ran_seed`
: Random number see used in by the random number generator. If set to 0, the system clock will be used. That is, if set to 0, the output results will vary from run to run.

`ran_gauss_sigma_cut`

Any randomized values in the lattice, such as HOM frequency spread or position jitter are limited to a maximum deviation of `ran_gauss_sigma_cut` rms deviations.

`stable_orbit_anal`

If this parameter is set true, then the output files stable_orbit.out and hom_voltage.out are written for each bunch train passage and each repetition, allowing the orbit deviations and HOM loading to be analyzed as the equilibrium level is reached.

3 Output files

3.1 Main output file

The standard output stream contains information on the progression of the job, including a calculation of total elapsed wall clock time at the end.

3.2 drscan.out

For each successive BBU threshold calculation convergence, a line is written to drscan.out containing the trtb variable [1], the analytic approximation to the threshold current, and the result for the threshold current, in standard format.

3.3 rep.out

The output file rep.out contains one line per threshold calculation which consists of the repetition number, the threshold current, and the index number, the ring position, the input file HOM frequency, the HOM frequency used after randomization, the input file R/Q value, the HOM Q value, and the HOM polarization angle. The format is (i6,e14.6,2i7

3.4 hom_voltage.out

The stable orbit analysis proceeds at a fixed current without iteration, calculating the for multiple bunch train passages the voltages excited in the HOM elements and the resulting orbit distortions. The output file hom_voltage.out contains one line for each train passage the reptition number, the passage number, the sum over HOM elements of the greatest HOM voltage excited by any of the HOM modes in that element, the total number of contributions to that HOM voltage, and the HOM voltage gain factor which would be used in a threshold current convergence calculation. The format is (2i10,e13.6,x,i8,x,e15.6). The successive values of this sum over maximum HOM voltages can be used to estimate when the equilibrium loading condition has been reached for this value of the beam current.

3.5 stable_orbit.out

The stable orbit analysis also writes output for each HOM element for each bunch train passage to the file stable_orbit.out. This line contains the HOM element ordinal number, the HOM arrival time, its maximum HOM voltage, the HOM frequency, the R/Q value, the Q value, and five statistical variables characterizing the orbit distortion: the number of orbits analyzed, the average orbit distortion, the rms orbit distortion, the minimum orbit distortion and the maximum orbit distortion. The latter five variables are repeated six times for each of the six coordinates of the orbit: x, px, y, py, z, and δ. The format is (i10,5(1x,e15.8),i10/,4(6(1x,e15.6)/)).

4 Appendix

The BBU threshold calculations produced by setting the parameter drscan true and using the default values of begdr, enddr and nstep reproduce the results of Fig. 3 of Ref. [1], writing them to the output file drscan.out when the following Bmad lattice file is used:

```
parameter[lattice] = "PRSTAB 7, 2004 Toy Lattice"
betaa=20
betab=20
alphaa=0
alphab=0
beginning[beta_a] = betaa
beginning[alpha_a]= alphaa
beginning[beta_b] = betab
beginning[alpha_b] = alphab
beginning[e_tot] = 5e9
parameter[lattice_type] = linear_lattice
rfw:  lcavity, l = 0, gradient = 0.0, lr_wake_file="prstab2004.dat",
lr_freq_spread=0.0E-3, rf_frequency = 1.3e9
m1:  match, beta_a1=betaa, alpha_a1=alphaa, beta_b1=betab, alpha_b1=alphab,
dphi_a=1, dphi_b=1, l=1.269, match_end=.true.
m12=-5e9*1.0e-6
t1:  Taylor, 1:  m12, 0 1 0 0 0 0, l=1.269
simple:  line[multipass] = (rfw, t1)
dual:  line = (simple,simple)
use, dual
```

The required HOM parameter file prstab2004.dat is

```
         Frequency            R/Q            Q          n      Polarization_Angle
           [Hz]           [Ohm/m^(2n)]                           [Radians/2pi]

&long_range_modes
 lr(1) =      2.0e9            8.78e4        10000      1         0.0
/
```

References

[1] G.H. Hoffstaetter, I.V. Bazarov, *Beam-Breakup Instability Theory for Energy Recovery Linacs*, Phys. Rev. ST-AB **7**, 054401 (2004)

[2] D. Sagan, *Bmad: A Relativistic Charged Particle Simulation Library*, Nuc. Instrum. & Methods **A558**, 356 (2006). The Bmad manual can be obtained at http://www.lepp.cornell.edu/∼dcs