

USPAS course on Recirculated and Energy Recovered Linacs

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Computer class: Linear Optics in JLAB: Longitudinal Dynamics and BBU





UV wiggler

Spreadsheet model of JLAB IRFEL includes:

- full first-order optics
- longitudinal phase space visualization
- beam break-up simulations





Download the spreadsheet and bbu code to a *single* writeenabled directory from

http://www.lns.cornell.edu/~ib38/uspas08/

Make sure macros are enabled. Start the spreadsheet (note: it may take a while to initialize all formulas).





The spreadsheet is organized into three main parts

- ---> elements matrices layout and lattice control products twiss ---> bbu bbu_latfile beam breakup simulation bbu_homs bbu_param ---> long_phase_space R56 longitudinal phase space Ζ
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Organization: layout and lattice

---> elements sheet contains optics controls





Spreadsheet: beam break-up

---> bbu controls execution of beam break-up code

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---> long_phase_space tracks a bunch in the long. p.s.





- first- and second-order correlation in longitudinal phase space
- second-order momentum compaction
- requirements for energy recovery



First- and second-order correlations



$$\delta = \delta_0 + \frac{\partial \delta}{\partial l} \bigg|_{l=0} l + \frac{1}{2!} \frac{\partial^2 \delta}{\partial l^2} \bigg|_{l=0} l^2 + \dots$$
$$\delta \cong \delta_0 + \alpha_{\delta} l + \frac{1}{2} \beta_{\delta} l^2$$

$$\sigma_{\delta} = \sqrt{\sigma_{\delta_0}^2 + \alpha_{\delta}^2 \sigma_l^2 + \frac{1}{2} \beta_{\delta}^2 \sigma_l^4} \qquad \qquad \varepsilon_{\delta-l} = \sigma_l \sqrt{\sigma_{\delta_0}^2 + \frac{1}{2} \beta_{\delta}^2 \sigma_l^4}$$

$$\alpha_{\delta} = -\frac{E_{linac}}{E_{final}} k_{RF} \sin \varphi \qquad \beta_{\delta} = -\frac{E_{linac}}{E_{final}} k_{RF}^2 \cos \varphi$$

 $k_{RF} = 2\pi / \lambda_{RF} = 31.5 \,\mathrm{m}^{-1} \,\mathrm{for} \, 1.5 \,\mathrm{GHz}$

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After acceleration

after the main linac:

$$\alpha_{\delta} \approx -k_{RF}\varphi$$
$$\beta_{\delta} \approx -k_{RF}^2$$

$$\begin{array}{ll} assuming \ large \ E_{\text{final}}/E_{\text{injection}} \ and \ small \ energy \ spread \\ \hline energy \ spread: & \hline longitudinal \ emittance: \\ \sigma_{\delta} \approx \alpha_{\delta} \sigma_{l} \quad \text{for} \ \left|\varphi\right| > \frac{1}{\sqrt{2}} k_{RF} \sigma_{l} \\ \varepsilon_{\delta^{-l}} \approx \frac{1}{\sqrt{2}} \beta_{\delta} \sigma_{l}^{3} \end{array}$$

$$\sigma_{\delta} \approx \frac{1}{\sqrt{2}} \beta_{\delta} \sigma_l^2$$
 for $|\varphi| < \frac{1}{\sqrt{2}} k_{RF} \sigma_l$

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Longitudinal transform

$$l^* = l + R_{56}\delta + T_{566}\delta^2$$
$$\delta^* = \delta$$

$$\alpha_{\delta}^{*} = \frac{\alpha_{\delta}}{1 + R_{56}\alpha_{\delta}}$$
$$\beta_{\delta}^{*} = \frac{\beta_{\delta} - 2T_{566}\alpha_{\delta}^{3}}{\left(1 + R_{56}\alpha_{\delta}\right)^{3}}$$

$$L = \int \sqrt{(1 + x/\rho)^2 + x'^2 + y'^2} \, ds$$

momentum compaction (times the path length):

$$R_{56} = \int \frac{\eta}{\rho} ds$$

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second-order momentum compaction:

$$T_{566} = \int \left[\frac{\eta_{(2)}}{\rho} + \frac{\eta^2}{2\rho} + \frac{\eta'^2}{2} \right] ds$$

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Compression

for maximum compression need

$$R_{56} = -\frac{1}{\alpha_{\delta}} \approx \frac{1}{k_{RF}\varphi}$$

for maximum compression need

$$T_{566} = \frac{\beta_{\delta}}{2\alpha_{\delta}^3} \approx \frac{1}{2k_{RF}\varphi^3}$$

actual (absolute) value of T_{566} can be smaller

$$\Delta T_{566,\sigma_l^{comp}} = \frac{\sigma_l^{comp}}{\sqrt{2}\alpha_\delta^2 \sigma_l^2} \approx \frac{\sigma_l^{comp}}{\sqrt{2}k_{RF}^2 \sigma_l^2 \varphi^2}$$

no T_{566} is needed beyond a certain off-crest phase angle

$$\varphi > \varphi_{T_{566=0}} = \frac{\sigma_l^2}{\sigma_l^{comp}} \frac{k_{RF}}{\sqrt{2}}$$



Achieving the right values of R_{56}







$$R_{56} = \int_{1}^{2} \frac{\eta_x}{\rho} ds$$



Achieving the right values of T_{566}



200 198 198 196 196 194 192 192 126540107 1.26560107 1.26560107 1.26560107 1.26560107 1.26560107

changing sextupoles strength in the Arc...

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$$T_{566} = \int \left[\frac{\eta_{(2)}}{\rho} + \frac{\eta^2}{2\rho} + \frac{\eta'^2}{2} \right] ds$$

 $\eta_{(2)}'' + K(s)\eta_{(2)} = -h + k_1\eta - \frac{1}{2}k_2\eta^2 + (h^3 + 2k_1h)\eta^2 + \frac{1}{2}h\eta'^2 + h'\eta'\eta + 2h^2\eta$



Bunch length in the Bates'





General rule of thumb for successful energy recovery is having the full recirculating arc isochronous to first and second order ($R_{56} = T_{566} = 0$).

In IRFEL, the main difficulty is an additional energy spread generated at the wiggler due to FEL interaction.

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Controlling Bates' quads

---> elements sheet, yellow region





Off-crest phase, FEL energy spread and T_{566}

---> long_phase_space sheet



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• Set the off-crest phase angle in the main linac to 0 and 'turn-off' laser interaction. Observe how the longitudinal phase space looks throughout the accelerator and at the beam dump.

• Set the off-crest phase angle in the main linac to -10° . Achieve the shortest bunch possible at the wiggler location using linear optics only (T₅₆₆ should be 0). Compare calculated R₅₆ with the value in the model.

• Use T_{566} to maximally compress the bunch at the wiggler. Compare calculated T_{566} with the value in the spreadsheet. How much shorter is the bunch length when both second- and first-order compaction is used, as opposed to only the first-order compression? Achieve less than 150 fs rms bunch duration.

NOTE: R_{56} from the linac to the wiggler consists comes from two parts: Bates' turn-around and a chicane





• 'Turn-on' the laser interaction (actual max. energy spread of 5 %). Observe the longitudinal phase space at the dump. Is the beam being successfully recovered?

- Adjust R_{56} in the second Bates' section to minimize energy spread at the dump. Note the smallest energy spread you were able to achieve.
- Use T_{566} to minimize energy spread at the dump. Note the values of R_{56} and T_{566} of the whole recirculating arc that allowed the result. What is the smallest energy spread you were able to achieve? Achieve less than 15 % max energy spread at the dump.





Higher order modes

Two basic concerns:

•Multipass beam breakup (dipoles)

•Resonant excitation of a higher order mode (monopoles)

monopole (m = 0)

$$E \qquad B$$

high energy losses, no kick





kick and losses when beam is not centered



kick, coupling and losses when beam is not centered



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BBU threshold for a single dipole mode



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Controlling BBU code

---> bbu controls execution of beam break-up code





Controlling BBU code: HOMs

bbu_homs spreadsheet

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	ac261	:	28.49501	2.88E+06	2115383900	0					
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• By commenting out modes in bbu_homs sheet, determine the worst mode (the one with highest threshold). How does the threshold due to the single worst mode compares to the situation when all modes are present?

• Work with the worst offending mode (for faster computing speed). Slightly change the frequency of the mode and obtain dependence of threshold vs. the mode frequency. Plot the dependency. What is the ratio of max over min threshold that you found in this manner? What is the frequency difference between the two adjacent maxima?

• Add 'fake' 1000 m to the recirculation length (---> bbu sheet) and repeat the steps from 2). What is the ratio of max over min threshold in this case? What is the frequency difference between the two adjacent maxima? Try to explain the result.

