Beam Dynamics in FLASH with 3rd Harmonic Module

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BD meeting, DESY
Present layout + ACC39 is considered in the talk

New layout

MAC Meeting
DESY, November 8-7, 2008

FLASH Upgrade 2009
Katja Honkavaara, DESY

Free-Electron Laser in Hamburg
3D simulation setup

M. Krasilnikov - Input Desk for ASTRA gun simulations for 1nC, 0.5 nC, 0.25nC
N. Golubeva – MAD optics for 1 GeV
3D simulation setup

GlueTrackM – a control script in Matlab.
S2E simulation time on Ferrari for 200k particles is about 10 hours.
1D (longitudinal phase space) simulation setup

accelerator

\[ E_1(s_1) = E_0(s_0) + V \cos(k_0 s_0 + \phi) \]
\[ s_1 = s_0 \]

compressor

\[ E_1(s_1) = E_0(s_0(s_1)) \]
\[ s_1(s_0) = s_0 - \left( t_{566} \delta_0^1 + t_{5666} \delta_0^2 + u_{56666} \delta_0^3 \right) \]

W1 - TESLA cryomodule wake
W3 - ACC39 wake
LS - space charge wake
W_{in}, W_{out} - wakes to simulate CS and edge radiation in BCs
1D (longitudinal phase space) simulation setup

function [P,C1,C12,C13,V11,V21,V31]=Flash(P0,q0,v,fi11,fi13, V13,fi21,V31,fi31,E1,r56_1,...
    t566_1,u5666_1,E2,r56_2,t566_2,u5666_2,...
    E3,r56_3,t566_3,u5666_3,see,wakes,lsc,M,savepart)
%global V11 V21 V31
if nargin<26, M=0.1; end;
if nargin<27, savepart=0; end;
PhysConsts;
sig0=std(P0(:,1));
k = 2*pi*f/c;lambda=2*pi/k;
P=P0;
subplot(4,2,1); PlotParticles2D(P,see,q0,v) ;title('after gun');
E0=P(1,2); dP11sc=0;dP13sc=0;
E01=E1-V13*cos(fi13);
if lsc==1,
    % L=11.3; beta=12.5; emit=1.9e-6;
    % [dP11sc, x, W] =AddLSC (P,q0,v,E0,E01,L,beta,emit);
    L=1.2; beta=15.33; emit=1.8e-6;
    [dP13sc, x, W] =AddLSC (P(:,1),q0,v,E01,E1,L,beta,emit);
    L=6; beta=15.33; emit=1.8e-6;
    [dP13_1sc, x, W] =AddLSC (P(:,1),q0,v,E1,E1,L,beta,emit);
    dP13sc=dP13sc+dP13_1sc;
end;
dP11w=0;dP13w=0; dPBC1_1w=0;if wakes==1,
    w0='Wakes/w0_11.txt';w1='0'; RLC='0';
    [dP11w, x, W] =AddWakeL (P(:,1),q0,v,w0,w1,RLC);
    w0='Wakes/w0_13.txt';w1='Wakes/w1_13.txt';
    RLC='Wakes/RLC_13.txt';
    [dP13w, x, W] =AddWakeL (P(:,1),q0,v,w0,w1,RLC);
    w0='0';w1='0';
    RLC='Wakes/RLC1_1.txt';
Matlab function for the S2E simulation of the FLASH.
Simulation time for 200k particles ~ seconds
1D (longitudinal phase space) simulation setup

clear all; close all;
PhysConsts;
M=0.05; % smoothing parameter
global P0 q0 v f E10 r56_1 E20 r56_2 see wakes lsc
global I0 C10 C20 emit0 t566_1 t566_2 u5666_1 u5666_2
global E30 r56_3 t566_3 u5666_3 V31 fi31
global V11 V21 V31
q0=1e-9; v=c;
see=1; %0-phase space; 1-current; 2-E_av and E_rms;
wakes=1; %0- no; 1-yes;
lsc=1; %0- no; 1-yes;
f = 1.3e9;
E10=127;   r56_1= -0.1808; t566_1= 0.295198; u5666_1= -0.437737;
E20=470;   r56_2= -0.048669; t566_2= 0.0733141; u5666_2= -0.0982712;
E30=1000;  r56_3=5.585e-4; t566_3=0.0588; u5666_3=-0.6417;
I0=1809;C10=7;C20=7;
infile='E:\S2E_3rdH\s2e\N1_Injecror_2m60_13m88\flash.0260.ast';
P0=LoadAstraParticles2D(infile); %n=length(P01);P0=P01(1:10:n,:);P01=[];
P0(:,1)= P0(:,1)-P0(1,1); n=length(P0(:,1));

[fi11,V11,fi13,V13,fi21,V21,fi31,V31]=FindFlashParameters(P0(1:4:n,1:2),E10,E20,..
E30,r56_1,t566_1,u5666_1,r56_2,f,1/C10,1/C20);
options = optimset('TolFun',1e-1);
par=fminsearch(@Optim3,[fi11,fi13, V13,fi21],options);
fi11=par(1);fi13=par(2);V13=par(3);fi21=par(4);
[P,C1,C12,C13]=Flash(P0,q0,v,f,fi11,fi13, V13,fi21,V31,fi31,E10,..
r56_1,t566_1,u5666_1,E20,r56_2,t566_2,u5666_2,...
E30,r56_3,t566_3,u5666_3,0,wakes,lsc,M,1);
1D analytical solution without self fields

\[ E_1 = 127 \text{MeV} \quad E_1 = 470 \text{MeV} \quad E_3 = 1 \text{GeV} \]

\[ r_{56} = -0.1808 \text{[m]} \quad r_{56} = -0.048669 \text{[m]} \quad r_{56} = 5.585 \times 10^{-4} \text{[m]} \]

\[ t_{566} = 0.295198 \quad t_{566} = 0.0733141 \quad t_{566} = 0.0588 \]

\[ u_{5666} = -0.437737 \quad u_{5666} = -0.0982712 \quad u_{5666} = -0.6417 \]

\[ C_1 = 7 \quad C_2 = 7 \]

\[ P_0 = \text{LoadAstraParticles2D(infile)}; \]

\[ [\text{fi11, V11, fi13, V13, fi21, V21, fi31, V31}] = \]

\[ \text{FindFlashParameters}(P_0(:, 1:2), E10, E20, E30, r56_1, t566_1, u5666_1, r56_2, f, 1/C10, 1/C20); \]
1D analytical solution without self fields
$E \text{[MeV]}$  

1D analytical solution without self fields
3D simulation without self fields. Optics.

Beam optics from 3D simulations

Design optics
3D simulation without self fields. Optics.

- $E[\text{MeV}]$
- $I[A]$
- $s[m]$

Diagram with labeled sections:

- ACC1
- ACC2/3
- ACC4/5/6
- BC2
- BC3
- LOLA
- Collimator
- SASE

Parameters:

- $\phi_1 = 14.5485^\circ$
- $\phi_3 = 193.8678^\circ$
- $\phi_2 = 23.4969^\circ$
- $\phi_3 = 0^\circ$
- $V_1 = 144.3381[\text{MV}]$
- $V_3 = 18.2405[\text{MV}]$
- $V_2 = 374.0126[\text{MV}]$
- $V_3 = 530[\text{MV}]$
3D simulation without self fields. Tails charge?
3D and 1D simulations with self fields.

1) space charge
2) space charge + cavity wakes
3) space charge + cavity wakes + self fields in BCs

1D model was checked through 3D. Working points are found by minsearch() in 1D and then checked by 3D. Finally, 1D model will be used to estimate RF tolerances.
3D and 1D simulations with self fields.

Work points from 1D optimization

<table>
<thead>
<tr>
<th></th>
<th>$V_1$, [MV]</th>
<th>$\varphi_1$, [deg]</th>
<th>$V_{39}$, [MV]</th>
<th>$\varphi_{39}$, [deg]</th>
<th>$V_2$, [MV]</th>
<th>$\varphi_2$, [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>without self fields, $I=2500$ A</td>
<td>144.34</td>
<td>14.549</td>
<td>18.24</td>
<td>193.87</td>
<td>374.01</td>
<td>23.497</td>
</tr>
<tr>
<td>+ space charge, $I=2500$</td>
<td>142.55</td>
<td>13.98</td>
<td>16.54</td>
<td>191.859</td>
<td>376.63</td>
<td>24.295</td>
</tr>
<tr>
<td>+ space charge +cavity wakes, $I=2500$</td>
<td>142.29</td>
<td>14.827</td>
<td>15.9</td>
<td>194.536</td>
<td>380.15</td>
<td>25.274</td>
</tr>
<tr>
<td>+ space charge +cavity wakes +BCself fields, $I=2500$</td>
<td>142.37</td>
<td>14.848</td>
<td>16</td>
<td>194.963</td>
<td>379.87</td>
<td>25.198</td>
</tr>
<tr>
<td>$I=1809$ with self fields</td>
<td>142.29</td>
<td>14.827</td>
<td>15.9</td>
<td>194.536</td>
<td>380.15</td>
<td>25.274</td>
</tr>
</tbody>
</table>
3D simulation with space charge in ASTRA. Optics.

Beam optics from 3D simulations

Design optics
3D simulation with space charge in ASTRA.

- 3D with SC
- 1D without SC

Graphs showing energy (E[MeV]) vs. position (s[m]) with and without space charge (SC).
3D simulation with space charge in ASTRA.

Current at $z=203$ m

SC wake between BCs
$E[\text{MeV}]$ 1D simulation with space charge.
$I[A]$

1D simulation with space charge.

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![Graphs showing 1D simulation results with space charge.](image)
1D simulation with space charge + cavity wakes.

$E[\text{MeV}]$
1D simulation with space charge + cavity wakes.
3D simulation with space charge + cavity wakes.

$E[\text{MeV}]$

1D with SC+CW

3D with SC + CW

$J[A]$

1D with SC+CW

2.5 kA

3D with SC + CW

$[\text{m}]$

$[\text{s}]$

$I[A]$

$[\text{A}]$

$2.5 \text{kA}$
3D simulation with space charge + cavity wakes + self fields in BCs.

\( E [\text{MeV}] \)

1D with BCs

3D with BCs

1D without BCs

3D with BCs

3D with BCs

1D with BCs

s [m]

s [m]
3D simulation with space charge + cavity wakes + self fields in BCs.

Optimized for I=2500A without BCs fields
Optimized for I=2500A with BCs fields

1D with BC’s fields
2.5 kA

3D with BC’s fields

1D with BC’s
2.5 kA

Optimized for I=2500A with BCs fields
1D with BC’s

3D with BC’s

s[m]
3D simulation with space charge + cavity wakes+ self fields in BCs.

$E[\text{MeV}]$
3D simulation with space charge + cavity wakes + self fields in BCs.

\[ I(A) \]
3D simulation with space charge + cavity wakes + self fields in BCs.
3D simulation with self fields for I=2500A.
3D simulation with self fields for I=2500A.

bunch with BC’s self fields.

bunch without BC’s self fields.
3D simulation with self fields for I=2500A.

front, side and top view of the bunch with BC’s self fields.
3D simulation with self fields for I=2500A.

front, side and top view of the bunch without BC’s self fields.

symmetrical shape
From $I=2500\, \text{A}$ to $I=1809\, \text{A}$.

Rectangular and Gaussian bunches with the same rms length
3D simulation with self fields for I=1809A.
3D simulation with self fields for I=1809A.
3D simulation with self fields for $I=1809A$. 
3D simulation with self fields for I=1809A.
3D simulation with self fields for $I=1809\,A$.

Current profile

$2 \, mm \times mrad$
3D simulation with self fields for I=1809 A.
1D model vs 3D model.

1D model agrees with 3D model.
We use the 1D model to estimate the RF tolerances.
Compression vs. RF parameters

\[ C = \frac{\sigma_{13m}}{\sigma_{203m}} \] - compression
RF tolerances

Tolerances (relative derivatives)

<table>
<thead>
<tr>
<th></th>
<th>$\frac{1}{C} \frac{\partial C}{\partial \phi}$,[deg$^{-1}$]</th>
<th>$\frac{1}{C} \frac{\partial C}{\partial V}$,[MV$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC1</td>
<td>2.23</td>
<td>0.16</td>
</tr>
<tr>
<td>ACC39</td>
<td>-0.73</td>
<td>-0.72</td>
</tr>
<tr>
<td>ACC2</td>
<td>0.18</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

Tolerances (10 % change of compression)

|       | $|\Delta \phi|$,[deg] | $|\Delta V|$,[MV]  |
|-------|----------------------|------------------|
| ACC1  | 0.045                | 0.62             |
| ACC39 | 0.14                 | 0.14             |
| ACC2  | 0.56                 | 4.6              |
How to improve? A phase shift between BCs.

\[ \Delta \psi = 300 [\text{deg}] - ? \]
How to improve? A phase shift between BCs.

Slice emittance
\( \Delta \psi = 300 \text{[deg]} \)

Slice emittance
\( \Delta \psi = 0 \text{[deg]} \)