TREND 2012: Nonlinear wave Dynamics in Charged Particle Beam Systems

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“... It is estimated that [since the early 1960s] accelerator science has influenced almost 1/3 of physicists and physics studies and on average contributed to physics Nobel Prize-winning research every 2.9 years.”


**Use of accelerators**

Water – Sterilization

Health – imaging, isotope production, cancer therapy

Energy – Controlled nuclear fusion

Environment – Radioactive waste treatment

Food – Sterilization to preserve

Information – Probing materials with neutron sources, FELs

Infrastructure – lithography, ion implantation

Transportation – Maglev Trains

Security – X-ray sources
Introduction: Beam Dynamics and Methods: Perturbations

Thermionic+ Photoemission

Ferrite

Glass Gap

laser

Resistors

Beam (100ns)

Perturbation (movable)

Beam in current space

Induction cell
\( \nu(z,t) : Particle\ Velocity(m/s) \)

\( I(z,t) : Current(A\ or\ C/s) \)

\( \Lambda(z,t) : Current\ Density(C/m) \)

\[
\frac{\partial \nu}{\partial t} + \nu \frac{\partial \nu}{\partial z} + \Lambda_0 \frac{\partial \nu_1}{\partial z} = 0
\]

**Linear approximation of current density**

\[
\frac{\partial \nu_1}{\partial t} + \frac{\partial \nu_1}{\partial z} \frac{\partial \nu_1}{\partial t} \approx \left( \frac{e^2}{4\pi^2 \varepsilon_0 \gamma^5 m} \right) \frac{\partial \Lambda}{\partial z} \frac{\partial \Lambda_1}{\partial z} = 0
\]

**Characteristic Solution (Sound Speed)**

\[
\frac{\partial \Lambda_1}{\partial z} = \left( \sqrt{\frac{2}{\gamma^5 \varepsilon_s \eta}} \right) \frac{\partial \eta}{\partial t} \frac{\partial \Lambda_0}{\partial t} \left( t - \frac{z}{\nu_0 \eta \gamma m} \right) \frac{\partial \nu_0}{\partial t} \left( \gamma - \frac{e^2}{4\pi^2 \varepsilon_0 \gamma^5 m} \right) \left( \frac{\partial \nu_0}{\partial t} \right)
\]

\( \nu_1(0,t) = \delta \nu_0 h(t) \)

\( I_1(0,t) = \eta I_0 h(t) \)

\( \Lambda_1(0,t) = (\eta - \delta)\Lambda_0 h(t) \)
Well Behaved (linear) perturbations

Proper tracking:
Crest follows Cs
With high fidelity

It takes time for the perturbation to reach its full amplitude

Velocity Perturbation @ delta= .0445
When amplitude is too great, the crest travels faster than the base causing steepening.

Velocity perturbation @ delta= .00127
Density perturbation set of two traveling waves with the same polarity in current space but opposite polarity in velocity space.

Eta: 0.9432
Velocity perturbations set off two traveling waves with opposite polarities in current space but same polarity in velocity space.
Pulse flattening is the first step toward total homogenization of a charged particle beam. Because our theory can describe the propagation of both types of perturbations, we are able to flatten one of these waves using a ratio of eta and delta described in the linear approximation solutions.

\[ \frac{\eta}{\delta} = 1 + \frac{\nu_0}{C_s} \]
Conclusions

- Characteristic solution accurately predicts steepening & deformation.
- Pulse flattening is predicted and experimentally confirmed.
- Nonlinear dynamics dominate the practical behavior of beam at long path lengths and large amplitudes.

Future work:

- Verifying the perturbations in velocity space using energy analyzer.
- Active pulse corrections as a manner of density regulation.
- Pulse flattening using multiple secondary perturbations.

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