Simulation of High Current Linacs

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430. WE-HERAEUS-SEMINAR
“Accelerators and Detectors at the Technology Frontier”
Outline

- The LORASR beam dynamics code
  ● A new space charge routine based on a PIC 3D FFT algorithm
  ● Tools for loss profile and machine error study calculations

- Description of the ‘Combined Zero-Degree Structure’
  (‘Kombinierte Null Grad Struktur – KONUS’) concept

- KONUS design examples

- Summary and outlook
LORASR Code Features - Overview

Longitudinal and radial beam dynamics calculations including space charge

- Multi particle tracking along drift tube sections, quadrupole lenses, short RFQ sections including fringe fields and dipole magnets.
- Running on PC-Windows platforms (Lahey-Fujitsu Fortran 95).

Available Elements:
- Magnetic quadrupole lens
- Solenoid lens
- Dipole bending magnet
- Accelerating gap
- RFQ section (constant rf phase, ‘Superlens’)
- 3D FFT space charge routine
- Error study routines

GUI:

[Image of LORASR software interface]
$E$-field shape distributions for 10 gap geometries with different $g/\varnothing$ ratios are stored as input parameter list.

The evolution of the single particle coordinates $x, x', y, y'$, $\Delta W$, $\Delta \Phi$, is performed in a 30 step per gap procedure for 4 different radial zones. The field components at the particles positions are linearly interpolated from the stored fields at the adjacent radial zones.
GAP Field Modelling: Upgrade Options

- Read in the RF field of each cell, as generated by MICROWAVE STUDIO™, from an external file.
  
  • Accuracy (mesh resolution)?

- Consideration of dipole and quadrupole content of IH- and CH-gaps).
Magnetic Quadrupole Lens

Hard edge approximation:

Focusing lens:

\[
\begin{pmatrix}
X_2 \\
X'_2
\end{pmatrix} = \begin{pmatrix}
\cos kL & \frac{1}{k} \sin kL \\
-k \sin kL & \cos kL
\end{pmatrix} \begin{pmatrix}
X_1 \\
X'_1
\end{pmatrix};
\]

Defocusing lens:

\[
\begin{pmatrix}
X_2 \\
X'_2
\end{pmatrix} = \begin{pmatrix}
\cosh kL & \frac{1}{k} \sinh kL \\
k \cdot \sinh kL & \cosh kL
\end{pmatrix} \begin{pmatrix}
X_1 \\
X'_1
\end{pmatrix};
\]

\[k = \left( \frac{q \cdot B' \cdot c}{\beta \cdot \gamma \cdot m_o} \right)^{1/2}\]
Space Charge Calculation by the “Particle-In-Cell” (PIC) Method

The Poisson equation is solved on the nodes of a Cartesian grid:

$$\Delta \varphi = \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \varphi = -\frac{\rho}{\varepsilon_0} \quad \text{on } G \subseteq \Omega$$

Boundary condition options:

a) \( \varphi = 0 \quad \text{on } \partial \Omega \)

b) \( \varphi = 0 \quad \text{on } \partial G \)

c) \( \varphi = 0 \quad \text{at } R \to \infty \)
Main Steps of a Particle-In-Cell (PIC) Algorithm

- Charge discretization on a 3D Cartesian grid and calculation of the charge density distribution \( \rho_{j,k,l} \)

- Solving the Poisson equation \( \Delta \varphi = -\rho / \varepsilon_0 \) on the grid

- Calculation of the electric field components on the grid from \( \vec{E} = -\text{grad} \ \varphi \)

- Interpolation of the grid field values to the exact position of each macro particle.
Main Steps of a Particle-In-Cell (PIC) Algorithm, Example

Gauß distr., $10^4$ particles, $L_x = L_y = 64$ mm, $L_z = 184$ mm, $I_{\text{bunch}} = 1$ mA $^{238}\text{U}^{28+}$
1.) Grid charge discretization \( (O(N_p) + O(N_G)) \)

2.) Solving the Poisson equation \( (O(N_G \cdot \log_2 N_G)) \)

3.) Calculation of the grid \( \vec{E} \)-field components \( (O(N_G)) \)

4.) Interpolation of the \( \vec{E} \)-field to the particle positions \( (O(N_p)) \)

Number of operations : \(~ (N_{\text{particles}} + N_{\text{meshpoints}} \times \log_2 N_{\text{meshpoints}})\)
Benchmarking of the New FFT Algorithm

Example: GSI Proton Linac preliminary design, LORASR Run on a 733 MHz, Intel PIII PC

<table>
<thead>
<tr>
<th>Macro part. no. $N_P$</th>
<th>Grid no. $N_G$</th>
<th>PP-routine (old) CPU time / call</th>
<th>PIC-routine (new) CPU time / call</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 000</td>
<td>32 768 (32×32×32)</td>
<td>1.307 s</td>
<td>0.103 s</td>
</tr>
<tr>
<td>10 000</td>
<td>32 768 (32×32×32)</td>
<td>34 s</td>
<td>0.294 s</td>
</tr>
<tr>
<td>100 000</td>
<td>262 144 (64×64×64)</td>
<td>3 500 s (58 min 20 s)</td>
<td>3.1 s</td>
</tr>
<tr>
<td>1 000 000</td>
<td>2 097 152 (128×128×128)</td>
<td>350 000 s (4 d 1 h 13 min)</td>
<td>28.8 s</td>
</tr>
</tbody>
</table>

919 space charge calls over total linac length (11 DTL’s + intertank quad. lenses).
Error Study Tools for LORASR:
Classification of Error Types

Static errors:
- Appear during design and running in phase. Can be detected and cured.
- Examples: quadrupole, cavity, drift tube misalignment, manufacturing errors (geom. lengths), field-flatness, quadrupole gradient errors.

Dynamic errors:
- Appear during operation. Are time-dependent. Remain often uncorrected.
- Examples: rf source instabilities (amplitude, phase), mechanical vibrations, transient beam loading.
LORASR Error Studies Analysis Tools
Loss Profile for Single Runs
KONUS Concept

- “Standard” linac design (up to \( \approx 100 \text{ MeV} \)) : Alvarez DTL + FODO beam dynamics.

Alternative :
- H-Type DTL (IH or CH) and KONUS beam dynamics, each lattice period divided into 3 regions with separated tasks:
  - Main acceleration at \( \Phi_s = 0^\circ \), by a multi-gap structure (1).
  - Transverse focusing by a quadrupole triplet or solenoid (2).
  - Rebunching: 2 - 7 drift tubes at \( \Phi_s = -35^\circ \), typically (3).
Transverse KONUS Beam Dynamics: Quadrupole Triplet Channel

IH cavity of GSI HLI injector: first built cavity containing several KONUS periods (op. since 1991)
Applications

- **Proton Injector for the GSI FAIR Facility**
  325 MHz, 70 mA protons, 3-70 MeV, 0.1% duty cycle.

- **Superconducting CH-DTL section for IFMIF (IAP proposal)**
  175 MHz, 125 mA deuterons, 2.5 – 20 MeV/u, cw operation.
FAIR Proton Linac Design

Source, LEBT, RFQ, Re-Buncher, CH-DTL, Diagnostic Insertion, to SIS18, to Dump

95 keV, 3 MeV, 70 MeV

transv. envelopes [mm]

relative $\varepsilon_{rms}$ growth

beam axis [m]
## FAIR Proton Linac Design: Machine Error Studies

<table>
<thead>
<tr>
<th>Error type</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>lens translations $\Delta X, \Delta Y$ [mm]</td>
<td>$\leq 0.1$</td>
</tr>
</tbody>
</table>
| lens rotations $\Delta \phi_x, \Delta \phi_y, \Delta \phi_z$ [mrad] | $|\Delta \phi_x| \leq 1$  
$|\Delta \phi_y| \leq 1$  
$|\Delta \phi_z| \leq 5$ |
| gap voltage variation $\Delta U_{ij}$ [%] | $|\Delta U_{gap}| \leq 1.0$  
$|\Delta U_{tank}| \leq 1.0$ |
| tank rf phase oscillations $\Delta \phi$ [$^\circ$] | $\leq 1.0$       |

![Graph](image-url)
S.C. CH-Linac for IFMIF

100% common beam envelopes of 100 runs, $10^6$ particles each

red: nominal run
green: error settings 1
blue: error settings 2

<table>
<thead>
<tr>
<th>Setting1</th>
<th>Setting2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta X_{lens} = \pm 0.1$</td>
<td>$\Delta X_{lens} = \pm 0.2$</td>
</tr>
<tr>
<td>$\Delta Y_{lens} = \pm 0.1$</td>
<td>$\Delta Y_{lens} = \pm 0.2$</td>
</tr>
<tr>
<td>$\Delta \phi_x = \pm 1.5$</td>
<td>$\Delta \phi_x = \pm 3.0$</td>
</tr>
<tr>
<td>$\Delta \phi_y = \pm 1.5$</td>
<td>$\Delta \phi_y = \pm 3.0$</td>
</tr>
<tr>
<td>$\Delta \phi_z = \pm 2.5$</td>
<td>$\Delta \phi_z = \pm 5.0$</td>
</tr>
<tr>
<td>$\Delta U_{gap} = \pm 5.0$</td>
<td>$\Delta U_{gap} = \pm 5.0$</td>
</tr>
<tr>
<td>$\Delta U_{tank} = \pm 1.0$</td>
<td>$\Delta U_{tank} = \pm 1.0$</td>
</tr>
<tr>
<td>$\Delta \Phi_{tank} = \pm 1.0$</td>
<td>$\Delta \Phi_{tank} = \pm 1.0$</td>
</tr>
</tbody>
</table>
- A new LORASR PIC 3D FFT space charge routine was developed and implemented to the LORASR code. It provides the ability to perform simulations with up to 1 million macroparticles routinely and within a reasonable computation time. This will give a strong impact to the design of high intensity linacs (e.g. GSI FAIR Facility Proton Linac, IAP-proposal for IFMIF Accelerator, …).

- Machine error settings routines and data analysis tools were developed and applied for error studies on the FAIR Proton Linac and the IAP IFMIF proposal.