Space charge studies in the HIPPI project

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Accelerator Physics Seminar, DESY, April 23, 2007

1. Introduction to Care-HIPPI
2. Code Benchmarking
3. Resonances in Linacs!
4. GSI/FAIR and UNILAC-Experiments
5. Comparison Measurement-Simulation (ongoing work)
6. Outlook
HIPPI Structure

- High Intensity Pulsed Proton Injectors (HIPPI) was set up in 2003 as a Joint Research Activity inside the CARE (Coordinated Accelerator Research in Europe) Integrated Activity partially funded by the EU.

- Main objective: Research and Development of the technology for high intensity pulsed proton linear accelerators up to 200 MeV (and starting from 3 MeV).


- HIPPI is a (temporary) coordination of the existing high-intensity linac R&D programs of 9 EU laboratories.

- Financial background: about 16 M€ total HIPPI cost (lab manpower included), including 3.6 M€ EU Contribution (22%).

- EU contribution mainly goes to: temporary staff, some hardware (mainly 700 MHz test stand), organization of meetings.
The 3 HIPPI Projects

Integrated Activities must result in upgrading of existing infrastructures: HIPPI aims at the upgrade of 3 accelerator facilities

<table>
<thead>
<tr>
<th></th>
<th>GSI-FAIR</th>
<th>CERN-Linac4</th>
<th>RAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Linac4 mode</td>
<td>SPL mode</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>70</td>
<td>160</td>
<td>180 MeV</td>
</tr>
<tr>
<td>Beam Current (pulse)</td>
<td>70</td>
<td>40</td>
<td>40 mA</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>4</td>
<td>2</td>
<td>50 Hz</td>
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<tr>
<td>Beam Pulse Length</td>
<td>36</td>
<td>400</td>
<td>720 µs</td>
</tr>
<tr>
<td>Average Current</td>
<td>10</td>
<td>32</td>
<td>1440 µA</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>324</td>
<td>352 - 704</td>
<td>324 - ? MHz</td>
</tr>
<tr>
<td>Transv. Emittance (100%)</td>
<td>2.8</td>
<td>2.1</td>
<td>µm, norm.</td>
</tr>
<tr>
<td>RFQ Energy</td>
<td>3</td>
<td>3</td>
<td>3 MeV</td>
</tr>
<tr>
<td>Overall Linac Length</td>
<td>~ 30</td>
<td>~ 80</td>
<td>~ 80 m</td>
</tr>
<tr>
<td>Accelerating Structures(s)</td>
<td>RFQ, CH</td>
<td>RFQ, DTL, CCDTL, SCL</td>
<td>RFQ, DTL</td>
</tr>
<tr>
<td>Average RE Gradient</td>
<td>2.3</td>
<td>2.0 (1.7 to 90 MeV)</td>
<td>~ 2 MeV/m</td>
</tr>
<tr>
<td>Installed RF Power (linac)</td>
<td>6 x 2.5 MW</td>
<td>13 x 1 MW + 4 x 4 MW</td>
<td></td>
</tr>
</tbody>
</table>
In the proposal a set of HIPPI Goals was established.

**Normal Conducting** Structures: $ZT^2 > 40 \ \text{M}\Omega/\text{m}$, $3 \ldots 100 \ \text{MeV}$, low cost

**Superconducting** Structures: $E_{\text{acc}} > 7 \ \text{MV}/\text{m}$, $Q > 10^{10}$, $5 \ldots 200 \ \text{MeV}$

**Chopper:** $\tau < 2 \ \text{ns}$, minimum emittance growth

**Beam Dynamics:**

- benchmarking of codes
- design for loss $< 1 \ \text{W}/\text{m}$ up to $3.5 \ \text{GeV}$
- do we have enough confidence in codes to optimize and verify design before construction?
- do we understand enough about sources of emittance growth, halo formation and beam loss in linacs?
The HIPPI Programme

Coordinator: J.M. Deconto, Grenoble

- Work Package 2
  - Drift Tube Linac
  - H-mode Linac
  - Side Coupled Linac
  - Cell Coupled DT Linac
  - Models for RF properties, drift tubes, alignment
  - Prototype for power tests, beam dynamics analysis
  - Model for RF properties
  - Prototype for power tests

Coordinator: S. Chel, Saclay

- Work Package 3
  - Elliptical Cavities
  - Spoke Cavities
  - CH Resonator
  - Prototypes for pulsed power test
  - Prototypes for power tests
  - Tuning system construction and test

Coordinator: A. Lombardi, CERN

- Work Package 4
  - Chopper A
  - Chopper Line
  - Chopper B
  - Prototype, hardware test
  - Assembling, testing with beam
  - Prototype, hardware test

Coordinator: I. Hofmann, GSI

- Work Package 5
  - Beam experiments
  - Diagnostics
  - Code development
  - Code benchmarking
  - Experiments at CERN (3 MeV) and GSI (UNILAC)
  - Prototypes
  - Preparation of codes and specific routines
  - Comparison of beam dynamics codes

Comparative assessment of NC structures
Comparative assessment of SC structures
Comparative assessment of chopper and chopper line performance
Design of the CERN Injector
Design of the GSI Injector
Design of the RAL Injector

Overall Coordinator: R. Garoby → M. Vretenar, CERN
Beam simulation code "Benchmarking" became a high-priority activity

"Nobody believes in simulation besides the simulationists
Everybody believes in experiment besides the experimentalist"

Simulation and experiments are complementary approaches to study the behaviour of beams:

**Simulations** are
- usually based on imperfect models missing part of the real behaviour
- give high flexibility, where particular interactions (particle-particle, particle-mean field, beam-beam, beam-wall, beam-rest gas, beam-electron clouds etc.) or boundary or initial conditions can be turned on/off and parameters can be varied
- allows identification of phenomena with particular physical effects
- diagnostics is "perfect" in the sense that unconstrained information can be extracted at any time.

**Experiments** have
- an underlying "perfect" model
- but the complexity of interactions in accelerators makes it often impossible to disentangle the main sources
- parameters can be varied only over a limited range
- diagnostics is usually quite imperfect and limited in resolution.
Participants "HIPPI Code Benchmarking Project"

A. Franchi, W. Bayer, G. Franchetti, L. Groening, I. Hofmann, A. Orzechkovskaya, S. Yaramyshev, X. Yin

GSI, Darmstadt, Germany
A. Sauer, R. Tiede, G. Clemente

IAP, Frankfurt am Main, Germany
R. Duperrier, D. Uriot

CEA, Saclay, France
G. Bellodi, F. Gerigk, A. Lombardi, T. Mütze

CERN, Geneva, Switzerland
D. Jeon

SNS, Oakridge, USA
Steps in "Benchmarking"

The first "trivial" step is that of "debugging", making sure the code does what it is written for. Thereafter:

1. **Verification:** The task is to prove that a computerized model of a beam in a well-defined environment agrees with a theoretical model, for which assured analytical solutions exist. Hence verification is
   • a quite precisely defined task and a test within the framework of the underlying model, and not under most general conditions as would occur in real beams
   • problems here are largely of mathematical or numerical nature due to algorithms, time steps, grids, and convergence problems and similar.

2. **Comparison:** A comparison with other (already tested) codes gives enhanced assurance.
   • often codes are not too rigorously comparable, especially if the underlying concepts differ, and one needs to learn where discrepancies might stem from.

3. **Validation:** Comparing code results with experimental data is crucial, but limited.
   • a realistic goal cannot be to validate a code as such, which is practically impossible
   • validation is always more vague – due to the limited representation of real beams and environments - and limited to a particular problem and its modelling
   • therefore validation is more a (possibly open-ended) process and not a unique task.

**GSI Unilac offers unique test-bed herefore:**
**space charge dominated, diagnostics, need improvement!**
**requested and obtained experimental beam-time herefore!**
Resonant process also in linacs (used to in rings)

- Here: \( p \) or ion linacs with direct space charge force main interaction
- Ideal linear forces: normalized emittances invariant
- Nonlinear forces due to space charge (also RF)
- 1990's: Halo is parametric resonance of single particles with mismatched beam core
- 1998 ff: Equipartitioning
- Aim is to demonstrate this on UNILAC – first experimental evidence of theoretical predictions
CERN SPL and the Neutrino Factory

"older Version": F. Gerigk/CERN, 2002

H⁺ RFQ1 chop. RFQ2 DTL CCDTL β 0.52 β 0.7 β 0.8 LEP-II dump

Source Low Energy section DTL Superconducting low-β Superconducting β=1

785 m

45 keV 13m 2 MeV 18MeV 237MeV 389MeV 357m
7 MeV 78m 18MeV 334m
120 MeV
1.08 GeV
2.2 GeV

Stretching and collimation line

PS / Isolde Accumulator Ring

Neutrino Factory schematic (isometric view)
“Stability Charts” for $\varepsilon_z/\varepsilon_{x,y} = 2$: CERN SPL study

(F. Gerigk/CERN, 2002)

major 2:2 resonance stopband driven by space charge „octupole“

emittance evolution for SPL IIb

SPL nominal design

emittance evolution for case 2

Test case 2
Fig. 6.2-2. Hofmann Chart for e_in/e_out=1.4, showing the intermediate RFQ trajectory for the shaper and from the EOS to the output, using pteqH1 including multipole and image-charge effects.
GSI heavy ion accelerator facility

UNILAC  Synchrotron SIS18  Cooler storage ring ESR
GSI: FAIR Accelerator Facility

- New: Cooled pbar Beams (15 GeV)
- Intense Cooled Radioactive Beams
- Parallel Operation

<table>
<thead>
<tr>
<th>Feature</th>
<th>Multiplication Factor</th>
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<tbody>
<tr>
<td>Primary Beam Intensity</td>
<td>x 100-1000</td>
</tr>
<tr>
<td>Secondary Beam Intensity</td>
<td>x 10 000</td>
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<tr>
<td>Heavy Ion Beam Energy</td>
<td>x 30</td>
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SIS100 Project Overview

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SIS18 upgrade
SIS100 R&D phase

Construction phase

Demonstration of U^{28+} operation in SIS18
Status – Uranium Beams

- U^{4+}
- U^{28+}
- U^{73+}

Beam current [emA]

- LEBT
- HSI
- Gas stripper
- Alvarez
- Single gap resonators
- Foil stripper
- SIS-Injection

- Dez. 01
- Jul. 02
- Au-02
- Okt. 02
- März 03
- Au-03
- Au-03 (2)
- Oct. 03
- Dec. 03
**UNIversal Linear ACcelerator**

*Machine Coordination: W. Barth, L. Dahl*

Diagram showing the layout of the UNILAC accelerator system with key components labeled:

- **MUCIS, MEVVA**
- **LEBT**
- **HSI (RFQ, IH1, IH2)**
- **HLI (ECR, RFQ, IH)**
- **36 MHz**
- **Gas Stripper**
- **108 MHz**
- **Poststripper (Alvarez, Cav.)**
- **Foil Stripper**
- **TK**
- **to SIS 18**

**High Current Injector HSI**

**ALVAREZ**

**Single Gap Resonators**
UNILAC Code Benchmarking for the HIPPI project


A. Sauer, R. Tiede, G. Clemente **IAP, Frankfurt am Main, Germany**

R. Duperrier, D. Uriot **CEA, Saclay, France**

G. Bellodi, F. Gerigk, A. Lombardi, T. Mütze **CERN, Geneva, Switzerland**

D. Jeon **SNS, Oakridge, USA**

– comparison and validation of 3D linac codes in the high current regime using the UNILAC structure
– several codes are available and currently run for such simulations
– static tests of Poisson solvers
– dynamical tests: are tune shifts calculated correctly?
– full tracking with "ideal" input and matching
– full tracking with measured input and matching
# Participating linac codes

<table>
<thead>
<tr>
<th>code (a.o.)</th>
<th>platform</th>
<th>GUI</th>
<th>parallel</th>
<th>particles</th>
<th>s. c. solver</th>
<th>boundary conditions</th>
<th>CPU time</th>
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<tr>
<td>DYNAMION</td>
<td>Windows</td>
<td>no</td>
<td>no</td>
<td>5x10^3</td>
<td>3D p-p</td>
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<td>1.3 days</td>
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<tr>
<td></td>
<td>(Li)Unix</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.5 days</td>
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<tr>
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<td>(Li)Unix</td>
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<td>yes</td>
<td>1x10^6</td>
<td>3D PIC</td>
<td>closed</td>
<td>1.0 day</td>
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<tr>
<td>IMPACT</td>
<td>(Li)Unix</td>
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<td>1x10^6</td>
<td>3D PIC</td>
<td>open</td>
<td>4.0 days</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>closed</td>
<td>2.5 days</td>
</tr>
<tr>
<td>LORASR</td>
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<td>1x10^6</td>
<td>3D PIC</td>
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<td>N.A.</td>
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<td>PARMILA</td>
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<td>post</td>
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<td>1x10^5</td>
<td>2D PIC</td>
<td>open</td>
<td>1.5 days</td>
</tr>
<tr>
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<td></td>
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<td>3D PIC</td>
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<td>7.0 days</td>
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<td>no</td>
<td>1x10^5</td>
<td>2D PIC</td>
<td>open</td>
<td>1.5 days</td>
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<td></td>
<td>2x10^4</td>
<td>3D p-p</td>
<td></td>
<td>1.5 days</td>
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</table>

Table 1: Summary table with an indication of the requested CPU time for different choice of solvers and boundary conditions. See text for the discussion on the choice of the number of macro-particles, the integration step and grid resolution. All the codes having a post-processor for the graphical analysis are labeled with "post" in the GUI entry.
Static tests of space charge field accuracy

**Figure 3** Field error $\delta E/E$ for DYNAMION and PIC codes with a grid resolution of $128^3 (129^3)$
Dynamical tests - ideal input (Gaussian distribution)

Figure 20: CASE 2: normalized transverse RMS emittance computed by all the codes along the DTL.

for most codes (except LORASR) < +/- 10% deviation in transverse emittance
→ good enough for comparison with experiment
Longitudinal: problem is bucket containment: lost particles treated differently

Figure 21 CASE 2: normalized longitudinal RMS emittance computed by all the codes along the DTL, before the code adjustments (left) and after (right).

Figure 23 CASE 2: Longitudinal phase space at the exit of tank 1 (left) and at the entrance of tank 2A (right), as simulated by IMPACT \((10^6\) macro-particles) and DYNAMION \((5\times10^6\) particles).
We found that inter-tank 1-2 is too long and causes lack of longitudinal focusing.

possible cures:

preferrable:
Parameters of UNILAC Alvarez DTL

- 5 independent rf-tanks + 2 bunchers
- 108 MHz, 50 Hz, 5 ms
- 192 rf-cells
- DTL based on F-D-D-F focusing
- dc-quads grouped to 13 families
- Inter-tank focusing: F-D-F
- Transv. acceptance (norm.): 15 μm
- Synchr. rf-phases: -(30°,30°,30°,25°,25°)
Overview of Beam Diagnostics Equipment

Stripper & matching section with selected beam diagnostics

Beam diagnostic devices:
- transverse emittance
- longitudinal emittance
- phase probe
- beam current transform
- beam profile grid
Results of HIPPI I (Sept. 2006): Transv. Emittance After DTL

Before optimisation:

After optimisation:
Results of HIPPI II: Beam Energy & Emittance
undesirable emittance growth → injection loss into SIS18

7.1 emA $^{40}$Ar$^{10+}$
Parmila simulations through UNILAC-Drift tube linac

\[ \sigma_{0,\text{trans}} = 90^0 \]

\[ \sigma_{0,\text{trans}} = 45^0 \]

just on exchange resonance!
4-th order structure resonance

\[ \sigma_{0,\text{trans}} = 90^0 \]

long.-trans. emittance coupling

\[ \sigma_{0,\text{trans}} = 45^0 \]
Predict minimum around $\sigma_{0,\text{trans}}=60^0$

preliminary confirmation by experiments – work in progress
Conclusion

- Code benchmarking (space charge effects) with UNILAC of mutual benefit for HIPPI and GSI-FAIR
- In principle "complete" set of diagnostics
- Code deviations sufficiently small (<10%) if no loss from bucket
- First experiments done – under evaluation
- Evidence for resonant emittance growth phenomena
  - Emittance exchange
  - Structure resonance
  - Mismatch emittance growth
- Need another cycle to eliminate uncertainty on longitudinal data