HIPPI WP5 CODE BENCHMARMINK FINAL ASSESMENT

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Abstract

In the frame of the CARE-HIPPI collaboration a working package was dedicated to beam dynamics investigations, both in terms of theoretical modeling as well as in terms of experimental investigations. In a first step major codes used in the linac community were compared one against each other and, in a second step, their predictions were compared with experimental campaigns performed at the GSI UNILAC. In parallel, codes developed by the participating laboratories were updated with new features dedicated to the evaluation of beam loss and space charge evaluation with numbers of particles up to 10^6.

This paper presents a general overview of the R&D activities performed during the HIPPI collaboration: in a first section a chronological overview of the whole collaboration period is presented describing the activities of each laboratory and, in the final part, the benchmarking campaigns between codes and experiments are described and commented

Introduction

The development of most recent high intensity linac has shown that phenomena associated with space charge and beam loss play a significant role in the design of high power proton accelerators. In particular, losses are mainly associated with mechanical and RF tolerances together with the appearance of beam halo. Those effects need to be modelled in terms of theory and simulations in order to minimize the risk of particles loss during high intensity operation. On the other side, a dedicated diagnostics system is required to protect the structure and to avoid activation beyond tolerated limits

The joint activity proposed in this work package combines infrastructures and resources from accelerator laboratories and universities and has been focused on three main topics.

1. Validation and Benchmarking of Simulation Codes.

The development of adequate 3D computer codes and the proper modelling of self-interaction by space charge is a crucial issue. Codes must be fast enough to allow large ensembles of particles in order to resolve very small loss fractions. Including the effect of errors jointly with space charge requires a significant enhancement of simulation capabilities. Benchmarking of computer simulation codes against each other and against analytical models represents the most effective way to increase the level of confidence in their predictions.

2. Experiments on Beam Halo and Emittance Growth.

At the starting point of the HIPPI collaboration, no satisfactory experiments on beam halo in high intensity linacs were performed in Europe; hence this topic was considered as a priority in the frame of the WP5. Beam experiments were performed at the UNILAC at GSI, where operational conditions, available intensities and diagnostics allowed to perform relevant and reliable measurements. At the same time several codes were used to interpret the outcoming results.

3. Diagnostics.

The acceleration and transport of high power beams also presents new challenges for beam diagnostics. While conventional methods continue to be needed, operating conditions at high intensity require a remarkable R&D effort. New measurement techniques are needed to diagnose the small fractional beam losses, which could cause serious damage to components and produce unacceptable levels of activation. Dedicated monitors for direct beam halo measurements are strongly required and needed to be designed, constructed and validated in existing machines.

1. Overview of the activities for each joining institute

1.1 2004

GSI

The space charge solver comparison between the different codes was started: an exact Poisson solver solution was developed in order to compare the space charge routines of different codes with the exact solutions in case of an ellipsoidal bunch.

Concerning the diagnostics development a first study was performed concerning fluorescence detection from the residual gas. The method was tested with a proof-of-principle experimental set-up detecting one transverse plane only at an external beam dump behind the UNILAC facility. This activity continued with the installation of an improved system behind the last module of the UNILAC for both transverse planes together with the development of the data acquisition and presentation systems which are needed for the planned prototype.

A first experimental campaign to benchmark different linac codes and the beam diagnostics was proposed and preliminary internal simulations were started.

IAP Goethe University

IAP-Frankfurt focused its activity on the further development of the existing LORASR code, which was used in former times only to design H-mode cavities. The main effort has been dedicated to the implementation of a faster PIC routine based on FFT (fast Fourier Transform) to allow simulations up to some million of particles. Besides this activity, Microwave Studio was used to model the "Alvarez-type" gap field distributions: the parameterization of the axial field component at different radial positions will be the base for the adaptation of the LORASR gap transformation subroutine to the Alvarez DTL. Finally, in parallel with the development of CH-DTL, a first investigation of the GSI Proton Injector was started.

CERN

The CERN activities were focused on the preparation of the 3 MeV test stand: a code for the 3 MeV line was prepared and validated. The first investigation regarded the setting the buncher phase to appropriate value by beam measurements, energy and energy spread measurements and emittance measurements via quadrupole scan. The other main activity regarded the halo measurement device: all components were prepared and ready for the final assembly.

FZJ

The activities in Jülich were focused on the preparations for the participation in the benchmarking campaign and on the assembly of the beam profile monitor for space charge dominated beams.

CEA

Saclay' s activity were also focused on the preparation of the benchmarking activity.

1.2 2005

GSI

A zero current code comparison was performed showing good agreement and the work progressed towards the inclusion of space charge in the UNILAC DTL structure simulations; due to the high level of communication between the different laboratories the level of agreement between different codes was visibly improved.

In preparation of the UNILAC experiments, studies to explore various focusing options using PARMILA were done. A special rms-matching routine was developed that includes bunchers, transverse defocusing effect of bunchers, and space charge effects.

Test experiments with different DTL tanks on/off in March 2005 have shown encouraging agreement with DYNAMION simulations (transverse emittances) even if the measured transmission was still below the calculated one.

The beam induced fluorescence method tests have been successful and the first prototype went under testing.

IAP Goethe University

The new version of the LORASR beam dynamics code was released. It included the new space charge routine based on a 3D FFT. An algorithm using closed boundary conditions

(Dirichlet cond. for the potential at the surface of a rectangular pipe, up to 128 x 128 x 128 grid points, up to 1 million macro particles) was implemented and a code extension for open boundary conditions is under discussion. This new version was included in the benchmarking activities at GSI and preliminary results on the Poisson solver were available within the year.

CERN

Beam dynamics studies for a new design for the SPL DTL have resulted in a shorter structure with stronger focusing, also avoiding the coupling resonance. At the same time the work on the codes for the preparation of the 3 MeV test stand was progressed together with an internal code comparison.

Error studies of the LINAC4 DTL were performed at LPSC with the CEA code TRACEWIN describing all tolerances in terms of mechanical construction and RF instabilities. In parallel, the work was continued towards a better understanding of the code limitations as it was noticed that TRACEWIN results depended strongly on the type of space charge routine chosen for the simulation. For that matter, collaboration was extended to new partners and cross-comparison with independent particle transport codes is now underway.

The prototype for halo measurement was completed.

FZJ

The activities in Jülich focused mainly on the development of the "slot+finger" structure. The electrodynamics including the fundamental mode distribution, the maximum field behaviour, the optimum geometry, the neighbouring modes etc. were investigated. This new kind of structure was compared with several other cavities in the range from 3 to 200 MeV: for half wave and spoke type cavities was observed a parametric resonance in the longitudinal plane due to the acceleration free “drift space” between cavities in the range 5-20 MeV. This resonance does not show up using the slot+finger structure. In the energy range from 50 to 200 MeV no severe differences were observed. The high intensity behaviour of the accelerators was investigated using the Jülich 3D space charge code. Currents up to 50 mA did not show losses in our calculations.

Finally, test measurements with gas scintillation photons were performed aiming to reduce the background and to improve the resolution.

CEA

Simulations with neutralization have been applied to solenoids and the IPHI LEBT; comparisons of PIC results with simple formula for rise times have been successful.

1.3 2006

GSI

The code benchmarking progressed further in tracking in the UNILAC Alvarez by extending to elongated rather than the idealized spherical bunches. After eliminating some misinterpretations the transverse emittances showed an improvement agreement. The longitudinal emittances were also in good agreement, except for Dynamion, up to tank 3, where a significant mismatch occurred. The role of a suitable buncher to cure the mismatch between tanks 1 and 2 was investigated.

An exhaustive HIPPI note was released about the benchmarking campaign.

The first bloc of the UNILAC experiments planned for HIPPI was successfully conducted. During the experiments it was verified that for a low intensity beam energy parasites lead to significant transmission losses and emittance growth. By optimizing RF parameters especially of the HSI RFQ and the second HSI IH structure, the phase correlation between HSI and Alvarez DTL, the settings of the gas stripper, and the matching of the beam to the first Alvarez tank a transmission of 99% and a minimum transverse emittance growth of about 1.2 was achieved. The experimental data started to be processed and compared with three different simulation codes.

Further tests of rest gas fluorescence yield have been carried out to optimize the non-destructive diagnostics by the "beam induced fluorescence method", also in the high energy beam line at 750 MeV/u. Longitudinal bunch profile measurements have been tested for resolution optimization. The online transmission control went in the testing phase.

IAP Goethe University

The new version of the LORASR space charge routine based on a 3D FFT was routinely used for simulations up to 10^6 simulation particles for verification, and 10^5 simulation particles for design. In order to make use of this new capability a breeding technique was developed and successfully tested that allows enhancing the small seed of particles (few 10^3) of the RFQ output distribution to seeds of 10^5 or 10^7 particles while maintaining the important phase space information. The design of the GSI proton injector advanced well and profited considerably from the development of the new version. In particular, the resonance frequency of the entire project was changed to 325 MHz from the original value of 352 and a new design was completed with the new LORASR version.

In the frame of the benchmarking activities, the preparation of the Alvarez input files was completed and transferred to GSI.

Finally, a new error study and loss profile routine started to be developed.

CERN

Beam dynamics studies for the high energy part of LINAC4 have been carried out on the basis of sc spokes cavities. Simulations with Tracewin (50.000 particles) showed anemittance growth between 3-5%, depending on the cavity voltage for designs where the longitudinal-transverse emittance coupling is avoided. The reference normal-conducting SCL design resulted equivalent from a beam dynamics point of view with the spokes cavity design.

In parallel the PATH code was extended to include possibility of doing statistical error studies and a firs comparison with TRACEWIN on LINAC4 DTL were successful. End-to-end simulations, starting from the source, were performed while a re-matching for the new conditions all along the LINAC4 together with a detailed beam dynamics simulations of the LEBT started.

FZJ

The activities in Jülich were still focused on the study of sc linacs based on slot structure cavities: calculations have shown that in the energy range of 3-21 MeV the slot-finger structure is promising, with a real estate gradient of 1.7 MV/m. Efforts have been made to lower the ratio peak / accelerating field. Stable bunch motion was verified with a current up to 40 mA. This investigation also showed that from 90 to 180 MeV, under the beam dynamics point of view, the slot structures offer similar behaviour to standard sc structures.

The beam profile monitor based on fluorescence was finally upgraded to read each of the 32 PMT channels individually, leading to a higher resolution. This change also results in a new

data analysis, the development of which was started. System enhancements for tailoring this beam profile monitor to be used in circular accelerators covered three issues: (i) measurements showed that the photocathode of the PMT must have optimum sensitivity for hydrogen photons. (ii) the vacuum chamber of the beam profile monitor has to be covered with a black surface. (iii) For low intensity applications (e.g. time resolved measurements) a local enhancement of residual gas pressure has to be considered.

CEA

General linac design optimization from a beam dynamics point of view was studied. The advantage of "smooth" designs was described, where frequency jumps and excessive matching sections are avoided. On this level the design of the cavity (spoke or elliptical) is found to have little impact on beam dynamics.

To implement the collisions processes into the code for ECR sources and neutralized LEBTs, several Monte Carlo method has been developed and checked. First hard sphere approximation were been used for modeling elastic and inelastic collisions (charged-neutral particle collisions), second, a partial differential cross section approach have been studied to more accurately simulate charged particles collisions. The routines have been checked with a simulation of a DC glow discharge.

1.4 2007

GSI

Experimental data on input/output distributions and rms quantities obtained at the UNILAC experiment in late 2006 have been evaluated. Some difficulties with interpreting the longitudinal measurements have been analyzed. The measured data have been extensively compared with simulation using PARMILA, with the help of Dr. D. Jeon from SNS/Oakridge, who visited GSI in March/April. Comparison with earlier results from the in-house DYNAMION code showed good agreement, in most cases within a few percent of deviation only as far as rms quantities are concerned.

Discrepancies with measurements are larger and currently analyzed to form a basis for further measurements.

IAP Goethe University

The new error and loss routine was finished and successfully tested. A first loss investigation was performed on the GSI Proton Injector based ion a breeding distribution (10^5 particles) generated from and RFQ output distribution made of 3000 particles.

CERN

At CERN a measurement of the EM compatibility of the Beam Shape and Halo Monitor was done, as recommended by the ESAC in the September review with positive results.

Beam dynamics simulations of the electron transport in the BSHM were performed in order to optimize the detector setting for time and space resolution. Studies on the optimal condition for a frequency jump (352 MHZ to 700 MHz) were continued, in collaboration with CEA.

A module has been coded to automatically steer a beam on its reference trajectories in a linear accelerator or a transfer line. This module is interfaced with the CERN code PATH and it will be used for steering LINAC4 in presence of machine and beam errors

FZJ

No major achievements were reported within 2007.

CEA

For CEA, new simulations of a neutralized LEBT with H- beams have been started. These simulations have been performed with the recent parallelized code and they show a good agreement with the previous simulations.

The investigation performed on frequency jumps in linac was extended in collaboration with CERN on the design of the new LINAC 4.

1.5 2008

GSI

Evaluations of UNILAC data on high intensity Ar^{10+} beam and comparison with codes has been continued and brought to final conclusion. The introduction of distributions in the codes close to those measured has improved the agreement and shown the importance of detailed equivalence beyond rms equivalence. PARTRAN, DYNAMION and PARMILA results have been included and the final deliverable as comprehensive document prepared.

IAP Goethe University

The development of the LORASR code continued with the implementation of solenoid lenses for beam focusing. This new features is particular important in the design of superconducting linacs based on CH-DTL cavities.

CERN

The design of LINAC 4 was completed including the new PIMS structure

FZJ

The development of residual gas monitor was continued and applied to several measurements with short beam pulse and coast beam at COSY, in Julich, and with a cyclotron cw beam in South Africa.

The non-destructive beam diagnostic system based on light radiation of atoms excited by the beam particles has been successfully tested in first proton beam experiments at low (3.1 MeV) and high (1.35 GeV) energies. The intrinsically very high time resolution could be demonstrated by resolving the beam profile of a single pulse. Even in synchrotrons the monitor has shown its capability to measure beam profile and position.

The first experience with the multi channel photomultipliers have shown that they are appreciably more resistive against injurious exposures to the bright light as well as beam and secondary particles than micro channel plates (MCP), which are applied usually for electron and ion registration. N_2 can be considered as possible scintillation substance, but also in environments with H_2 as main residual gas the presented method can be used to monitor the beam profile.

CEA

The main activity in CEA concerned the development of a code allowing to investigate plasma evolution coupled with Maxwell equations dynamically. For space charge compensated LEBT line, numerical investigations which are in a good agreement with

measurements showed how it is possible to reduce the emittance growth by playing with the nature and the partial pressure of the different gas in the vacuum pipe.

In parallel PARTRAN was used to evaluate the new experiments at GSI with Argon beam.

RAL

A recent aspect of work concerning the non destructive photo detachment diagnostics at RAL is the emittance reconstruction by moving the particle detector (which is in general used to determine the transverse angular momentum). This feature allows to measure beam profiles along a short drift length. Using a Bayesian statistics method called Maximum Entropy (MaxEnt) a relatively low (3...10) number of profiles is sufficient to reconstruct the missing 2dim projected view achieving a good agreement with the entrance distribution. Further studies about the necessary phase advance were also performed.

Another aspect was investigated experimentally concerning the ion source development where the laser was "simulated" by a movable slit. After a drift this collimated beam was then mapped with a scintillator allowing understanding the same slit--point transformation of the PD emittance instrument. Some of the measured features might be helpful to optimise ion source and sector magnet.

3 List of related HIPPI Notes

CARE-Note-2005-014-HIPPI "CCDTL design update for Linac4" M. Pasini.

CARE-Note-2005-016-HIPPI "Beam dynamics investigation of the first tank of a 70 mA CH-DTL proton injector" G. Clemente, H. Podlech, R. Tiede, U. Ratzinger, L. Groening, S. Minaev.

CARE-Note-2006-008-HIPPI "A 90-160/180 MEV Spoke Linac as an Option for the CERN Linac4/SPL"J.L. Biarrotte, G. Olry

CARE-Note-2006-009-HIPPI "Superconducting Spoke Linac Design as an Alternative Option for the CERN Linac4 High Energy Part"

CARE-Note-2006-011-HIPPI "Linac Code Benchmarking in Preparation of the UNILAC Experiment" A. Franchi, W. Bayer, G. Franchetti, L. Groening, I. Hofmann, A. Orzhekhovskaya, S. Yaramyschev, X. Yin, A. Sauer, R. Tiede, C. Clemente, R. Duperrier, D. Uriot, G. Bellodi, F. Gerigk, A. Lombardi, T. Muetze.

CARE-Note-2006-015-HIPPI "Particle-In-Cell Code with Monte Carlo Collisions for ECR Ion Sources Simulation" I. Rudskoy

CARE-Note-2006-022-HIPPI "Linac4 Technical Design Report" L. Arnaudon, P. Baudrenghien, M. Baylac, G. Bellodi, Y. Body, J. Borburgh, P. Bourquin, J. Broere, O. Brunner, L. Bruno, C. Carli, F. Caspers, S. Cousineau, Y. Cuvet, C. De Almeida Martins, T. Dobers, T. Fowler, R. Garoby, F. Gerigk, B. Goddard, K. Hanke, M. Hori, M. Jones, K. Kahle, W. Kalbreier, T. Kroyer, D. Küchler, A.M. Lombardi, L.A. Lopez-Hernandez, M. Magistris, E. Mahner, M. Martini, S. Maury, T.K. Meinschad, E. Page, M. Paoluzzi, M. Pasini, U. Raich, C. Rossi, J.-P. Royer, E. Sargsyan, J. Serrano, R. Scrivens, M. Silari, M. Timmins, W. Venturini Delsolaro, M. Vretenar, R. Wegner, W. Weterings, T. Zickler

CARE-Note-2007-003-HIPPI "Pi-mode 352 MHz scaled LEP cavities as an alternative accelerating structure for the energy range of 90 to 160 MeV in CERN Linac4/SPL" E. Sargsyan, A. Lombardi

CARE-Note-2007-009-HIPPI "Frequency change in the LINAC4-SPL: at 90 MeV or at 180 MeV?" E. Sargsyan, A. Lombardi

CARE-Note-2007-010-HIPPI "Comparative study of the beam dynamics in LINAC4 using CERN and RAL MEBT (Medium Energy Beam Transport) lines" C. Plostinar, E. Sargsyan

CARE-Note-2008-001-HIPPI "Beam diagnostics based on photo-detachment for the Front End Test Stand FETS" C. Gabor, J.K. Pozimski, A.P. Letchford, C.R. Prior
CARE-Note-2008-002-HIPPI "Using the chopper as emittance exchanger" JB. Lallement, F. Caspers, T. Kroyer
CARE-Note-2008-003-HIPPI "Consideration on field ramp for the LINAC4 DTL design" E. Sargsyan, A. Lombardi

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