



Code Benchmarking of Higher Order Modes simulation codes

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Summary

In order to compare simulation results performed with different codes a simulation test bench is defined and four different codes are compared with each other to validate their compatibility.

1 Introduction

A mini-workshop on the subject of Higher Order Modes (HOMs) in a superconducting proton linac was held at CERN on the 25th and 26th June 2009 [1, 2]. The purpose of this workshop was to discuss more specifically the effects of HOMs on beam dynamics in the SPL [3–5] and comparable accelerators and to provide guidelines for the specification of HOM dampers, if necessary.

Several beam dynamic studies [6–9] done with different codes (see Tab. 1) were presented. Most of the codes are based on [10], where a drift kick model is used to simulate the longitudinal beam dynamics. In this model the point-like bunches are accelerated and get an addition kick by a HOM. This causes an energy error which leads to an arrival time error in the next cavity since the particles are not highly relativistic. This dynamic behaviour from one cavity (m) to the next ($m+1$) can be expressed by the following equations

$$dE^{(m+1)} = dE^{(m)} + dU_{RF} + dU_H \quad (1)$$

$$dt^{(m+1)} = dt^{(m)} + (dt/dE)_E^{(m)} \cdot dE \quad (2)$$

where dU_{RF} is the RF-error caused by the arrival time (phase) error in the cavity and dU_H the effect of the HOM. The arrival time error depends on the energy error and causes a time of flight error which is given by

$$(dt/dE) = -\frac{L}{c \cdot m_0 c^2 \cdot (\gamma^2 - 1)^{3/2}} \quad (3)$$



using the relativistic γ , the drift space L between the cavity centre to the next cavity centre, and the particle rest mass m_0 . The effect of the HOM is

$$dU_H = q \left(\Re(V_H) \cos(\omega_H dt) - \Im(V_H) \sin(\omega_H dt) - \frac{1}{2} V_b \right) \quad (4)$$

where V_H is the HOM voltage, ω_H its angular frequency and V_b the voltage induced by the bunch itself. The HOM is excited by the beam itself and the evolution of V_H from bunch n to bunch $n + 1$ can be expressed as

$$V_H^{n+1} = (V_H^n + V_b) \cdot \exp(i\omega_H T_b) \cdot \exp(-\omega_H T_b / (2Q_{ex})) \quad (5)$$

with an nominal time between two bunches T_b and the damping of the HOM in terms of Q_{ex} .

Table 1: Benchmarked codes

Code	Author	Implementation	Code based on
JT	J. Tückmantel (CERN)	C, Cocoa	-
MS	M. Schuh (CERN)	C++, ROOT	JT
JB	J.-L. Biarrotte (IPN Orsay)	Matlab	JT
DK	D. Kaltchev (TRIUMF)	Mathematica	TALOBBU[11]

In order to compare and classify the results of the different codes a benchmark was performed. All codes were used to simulate a generic linac described in [10] with same set of input parameters and the same bunch pattern. Afterwards the output was compared bunch by bunch.

2 Benchmark setup

For the sake of simplicity a test setup with the generic linac model of [10] is used in all simulations. It consists of 150 equal cavities with a constant drift space L in between. Each cavity provides an accelerating voltage $V_{RF} = 20.7$ MV which correspond to $V_{acc} = 20.0$ MV in operation¹⁾. The focus is set to the beam HOM interaction and effects like changing $E_0 T$ with β or RF errors are neglected. One HOM with constant R/Q and Q_{ex} is present in each cavity. The HOM frequency has a certain cavity to cavity spread which is generated once using a random number generator with a Gaussian distribution ($f_{HOM}, \sigma_{f_{HOM}}$) and then used in all simulations. The same is done with the input charge error pattern²⁾ of the bunches. In total one pulse with 50,000 bunches is tracked through the linac with no deviation in energy and phase at the entrance. The output energy and phase error of each bunch in this pulse is then compared for all codes using separate scatter plots for energy and phase. All simulation parameters of this setup are listed in Tab. 2. In this setup only the longitudinal behaviour is tested and protons are used instead of H^- .

¹⁾The linac operates with a synchronous phase of $\phi = -15^\circ$: $V_{acc} = V_{RF} \cos(\phi)$

²⁾10% white noise bunch to bunch charge scatter.

Table 2: Benchmark setup parameters

	Parameter		Value	Variance
Cavity	cavities		150	-
	L	[m]	1.75	-
	f_{RF}	[MHz]	704.4	-
	V_{acc}	[MV]	20.7	-
	ϕ	[deg]	-15	-
HOM	f_{HOM}	[MHz]	2283.8	0.1
	(R/Q)	$[\Omega]^\dagger$	100	-
	Q_{ex}		10^8	-
Beam	bunches		50,000	-
	T_b	[ns]	$1000/352.2 \approx 2.84$	0
	I_b	[mA]	400	40
	W_{in}	[MeV]	150	0
	W_{out}	[MeV]	3150	0
	dt_{in}	[ps]	0	0

[†]linac definition

3 Benchmark results

In total 4 codes listed in Tab. 1 were compared with each other. The code *JT* is chosen as reference for this comparison. In case of perfect agreement of the codes there should be no deviation in the scatter plots (see. Fig. 1-3) which correspond to a straight line with slope equal one.

The output of code MS (Fig. 1) shows very small deviation in energy and phase which are most likely due to numerical imperfections in the implementation.

In the code JB (Fig. 2) the drift space after the last cavity is not modelled. The output data is generated at the last cavity. The drift space afterwards leads to a change in the arrival time (phase) error, but no change in the energy error. This explains the perfect match in the energy but mis-match in the phase.

All codes up to now are based on J.T.'s code. The code of DK is a modified version of TALOBBU [11]. TALOBBU was used at SNS³⁾ for such studies. Looking at the output of code DK (Fig. 3) shows, that this code behaves like the others and models the same physics⁴⁾. In this code also no drift space is modeled after the last cavity, which leads to a small deviation in the phase error.

³⁾Superconducting proton linac for the Spallation Neutron Source at the Oak Ridge National Laboratory

⁴⁾DK performed also a benchmark of TALOBBU against *R.L. Gluckstern et. al., "Cumulative Beam Breakup in RF Linacs"*. There was only a good agreement found, if the first bunch passes the linac unaffected. Further details see [12]

Comparing DK with JB shows a perfect match (Fig. 4). The relative error is in the order of 10^{-4} , which corresponds to the input value accuracy.

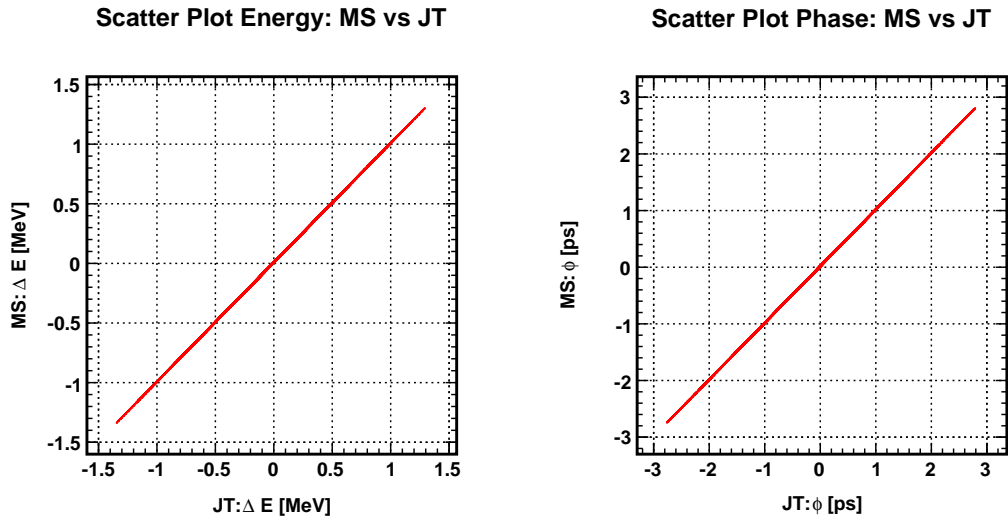


Figure 1: Comparison of the output phase space of MS against JT. Minor deviation in energy and phase visible. Relative error: 10^{-3}

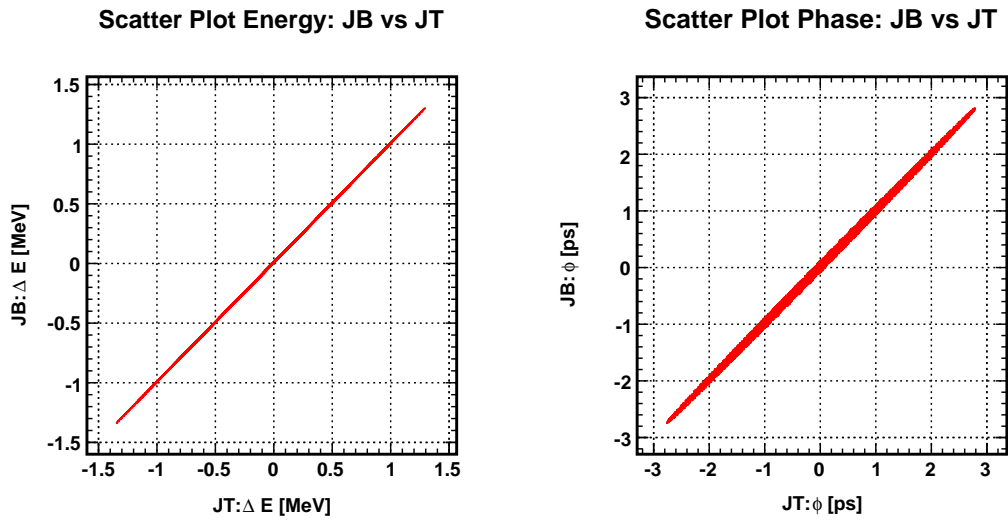
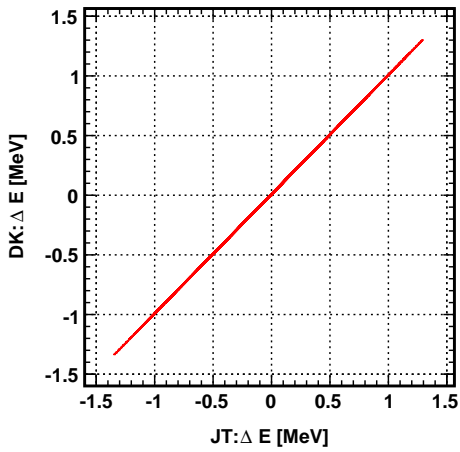


Figure 2: Comparison of the output phase space of JB against JT. No deviation in energy and only slight deviation in phase visible.

Scatter Plot Energy: DK vs JT



Scatter Plot Phase: DK vs JT

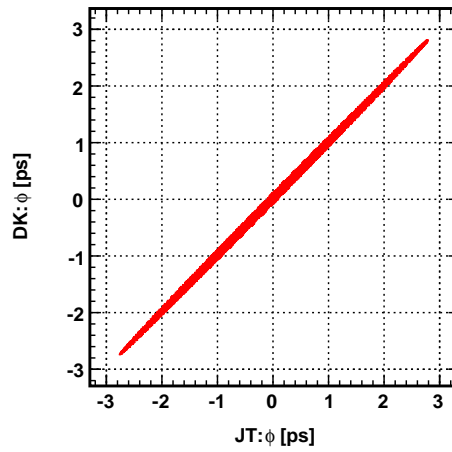
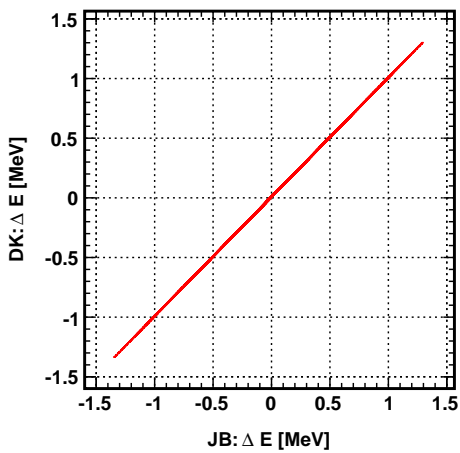


Figure 3: Comparison of the output phase space of DK against JT. No deviation in energy and only slight deviation in phase visible.

Scatter Plot Energy: DK vs JB



Scatter Plot Phase: DK vs JB

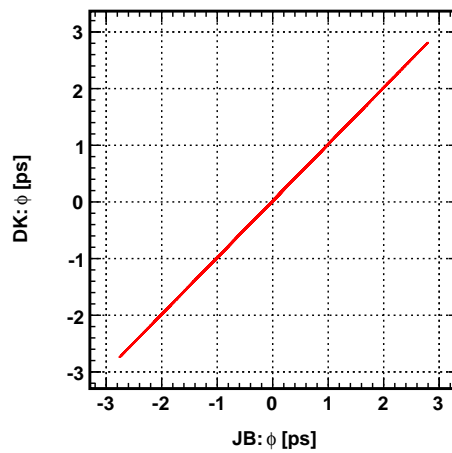


Figure 4: Comparison of the output phase space of DK against JB. No deviation visible. Relative error: 10^{-4}

4 Conclusion

All codes show the same behaviour and model the same physics in a very well defined test setup. The chosen input data for HOM spread and bunch pattern are irregular random choices, hence

it is reasonable to conclude that the codes would also agree for any other random choice. All results of these codes can be treated equally as long as the used input parameters and used linac geometry modelling is the same. The different results presented at the SPL HOM workshop are due to different input parameters and not due to differences in the codes.

This enables also the possibility of sharing future work between different groups with each group using their own well understood code. The defined test bench can also be used for further comparisons with other codes and can be easily extended to a test bench for transversal codes, which is not discussed here.

References

- [1] SPL HOM Workshop (CERN), <http://indico.cern.ch/conferenceDisplay.py?confId=57247>
- [2] A. Lombardi et al., "Summary of the workshop on HOM in SPL, held at CERN June 25-26.", CERN-sLHC-Project-Note-0003.
- [3] R. Garoby et al., "SPL at CERN", in Proceedings SRF 2009, Berlin, 2009.
- [4] F. Gerigk et al., "Higher Order Modes in the Superconducting Cavities of the SPL", in Proceeding of the Particle Accelerator Conference (PAC09), Vancouver, 2009.
- [5] M. Schuh et al., "Higher Order Mode Beam Breakup Limits in the Superconducting Cavities of the SPL", in Proceedings SRF 2009, Berlin, 2009.
- [6] J. Tückmantel, "HOMs", at SPL HOM Workshop
- [7] M. Schuh, "Studies for the SPL at CERN", at SPL HOM Workshop
- [8] R. Baartman, "Studies for the SPL at TRIUMF", at SPL HOM Workshop
- [9] J.-L. Biarrotte, "Studies for the SPL at IPN Orsay", at SPL HOM Workshop
- [10] J. Tückmantel, "Beam simulations with initial bunch noise in superconducting rf proton linacs", Phys. Rev. ST Accel. Beams 13, 011001
- [11] D. Jeon et al., "Cumulative Beam Break-Up Study of the Spallation Neutron Source Superconducting Linac", Nuc. Instr. A (2002) 495.
- [12] D. Kaltchev, "BBU Simulation Notes", <http://trshare.triumf.ca/~kaltchev/CERN-HOM/notes/>