Summary Report
SNS-Miniworkshop on Linac Space Charge

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Contents:

Talks see web site: `http://www.sns.gov/APGroup/workshops/linacSC_6_01/linacSC_6_01.htm`

1. Main Recommendations

The scope of the workshop with leading experts from the US (ORNL, BNL, LANL, LBL, U Maryland) and international scene (CERN, GSI, KEK, Milano, Saclay) including all major groups involved in high power linac projects has been to review machine design status, space charge beam dynamics and the adequacy of simulation codes, in particular to draw the necessary conclusions for proceeding with the next phase of detailed studies on errors and beam loss for the SNS as requested by ASAC.

- The workshop has expressed confidence that the present picture and understanding of sources of emittance/halo growth, and the simulation tools (with inclusion of a 3D Poisson solver into Parmila) are sufficiently complete to move towards enhanced mismatch and error studies; in particular, resonances of the bunch core due to space charge, which would lead to emittance transfer, appear *not to be of concern* for the design parameters. This conclusion must be revisited for the upcoming *extensive error simulation studies, which need to remain in close contact with beam dynamics interpretation* for several reasons: (a) to correlate cumbersome emittance growth and beam loss to their actual origin and propose suitable diagnostics; (b) to develop detailed predictive and corrective capabilities for later phases of the project; and (c), to be able to compare results with findings from other super-conducting linac projects. These studies also *need to enhance our confidence* in an emittance growth < 2 throughout the linac in view of the (possibly design dependent) 3-4 times larger factors for LANSCE and other linacs.
- On the code side, developing *a common device description format* to facilitate exchange of standardized input files is crucial; code comparison must continue to test approximations in modelling the linac, including additional physics needed to describe loss at the 10^{-4} to 10^{-6} level, like gas scattering/stripping, transverse cavity modes and RF coupler kicks and wall effects.
- Discussion of the LEDA experiment has shown the importance and at the same time the difficulties of experimental verification of theoretical/simulation prognosis. We *strongly recommend a study of the diagnostics tools needed for SNS to measure mismatch (in particular longitudinal) and halo into the DTL*, and in other critical positions. Possibilities for placing additional scrapers and chances for feed-forward schemes (on RF) should be discussed.

<u>The willingness of the Saclay group to host a similar mini-workshop around EPAC02 (Paris) to present and discuss progress was unanimously appreciated.</u>

2. Conclusions on Beam Dynamics

10 of the presentations have focused (in part or fully) on space charge beam dynamics issues under general boundary conditions as well as in the context of existing projects. The main emphasis was on the influence of space charge in the context of resonances and of halo/loss driven by mismatch and errors. There was broad consensus that worked performed over the last 6 months by the various involved individuals – interacting between laboratories - has brought visible progress in terms of applicability of the models to the SNS linac, and confidence that the phenomena described are sufficient and necessary to make predictions for the SNS. It has become clear, however, that efforts to model halo generation under *realistic linac boundary* conditions need to continue. Extrapolations from idealized models (ignoring acceleration, constant structures etc.) leave considerable uncertainty due to the transient situation in a linac, but they provide useful guidance to interpret the *realistic* simulations, relate emittance/halo growth to well-understood mechanisms, and allow comparison between different linacs. Simulation codes, on the other hand, have been seen fully adequate to model the phenomena, provided that they are upgraded to fully 3D space charge calculation as is now in process for Parmila, and already working for IMPACT (CERN-study) and the Saclay and Milano codes (for sc part). Comparison with experiments is still a difficult subject (LEDA, U Maryland), but the experience gained by these groups gives a very valuable input to future work related to the SNS and the other projects

2a. Phenomena

Space charge coupling resonances have been discussed with particular scrutiny as they are intrinsic to high current bunches (independent of the lattice type) and a possible source of rms emittance growth. The full linac simulations presented for the SNS, as well as for the CERN SPL, have confirmed earlier predictions - under more ideal conditions - that a longitudinal-to-transverse emittance ratio 2 leads to transverse rms emittance growth of 30-40% (due to double crossing of the leading resonance near tune ratio 1 in the SNS-DTL and SRF). For the design emittance ratio of 1.2, however, the SNS beam is not affected by this resonance; the other resonances near tune ratios 1/2 or 1/3 were found not to cause noticeable effect as they take much longer distance to develop; fully 3D Parmila simulations are needed, but they are not expected to change this conclusion for the SNS. Obviously, an increase of the nominal emittance ratio is to be avoided. While it was shown that the coupling resonance (if excited) would not lead to halo itself, it was also found that it can enhance the formation of halo, if an additional envelope mismatch is present.

The issue of envelope mismatch, and the proper definition of it in a normalized way to allow comparisons between different project studies were discussed extensively. While exciting single mismatch eigenmodes (of which there exist three) is an unambiguous way to model halo generation, evidence was given by 2D idealized simulations that a *mix* of eigenmodes might lead to the worst case in terms of halo intensity, due to providing more channels for resonant transport from the core to the halo. Likewise, there is indication that a pre-existent halo at entrance into the DTL could enhance the amount of halo developed in the rest of the linac. Also, initial longitudinal mismatch (into the DTL and elsewhere) has a potential to enhance transverse halo due to intrinsic space charge coupling. The possibility of longitudinal-transverse coupling within the halo was also discussed, which might, if excited, lead to loss out of the RF bucket. All these effects can be studied realistically only with the soon expected 3D Parmila version, which should lead to an extensive parameter study including initial mismatch (originating in the MEBT) and errors throughout the linac.

There was broad consensus that intrabeam scattering is not an issue in the real linac, though attention needs to be paid to unphysical collision effects in codes caused by insufficient number of particles or grid representation. It was generally accepted that the phenomena identified here would be well represented by typically $10^5 – 10^6$ simulation particles, and 16-32 grid cells in each direction over the extent of the bunch core.

2b. Requirements to Simulation

In terms of next steps it was agreed that an error study on the MEBT should deliver a worst-case scenario for mismatch input into the DTL, which needs to be further transported throughout the linac by assuming a realistic distribution of errors on RF amplitudes/phases and quad strengths/rotation angles. For such error studies (involving error sets of 200-500 samples) it would appear that 10^4 - 10^5 simulation particles are sufficient; cross-checks of some of the worst samples by 10^6-10^7 particles is advisable.

2c. Experimental Validation

Description of the LEDA beam-halo experiment at LANL has triggered off a very valuable discussion on the importance of proper diagnostics to relate expectations to findings in the real world. The observation of a significant shoulder in the transverse distribution at the exit of the channel – higher than expected from simulation - has underlined the difficulties to be encountered without diagnostics at the entrance. The 2:1 halo mechanism for a well-defined input beam should result in a halo size clearly correlated to intensity (due to a channel length shorter than needed for saturation of the halo size even for maximum current); this was, however, dominated by the shoulder effect. It is hoped that the experiment will be continued with adequate support (possibly further transverse and longitudinal diagnostics) to confirm this dependence and bridge the still open gap between theory and experiment. Exploring the origin of the initial shoulder will by itself be of interest for the SNS.

In a somewhat different direction (more space charge dominated “long” beams), the Maryland UMER e-beam ring experiment can be expected to yield important contributions to the basic understanding of space charge driven resonances and halo in the near future (continuing their experiment-simulation comparisons in space charge dominated e-beam transport).

3. Conclusions on Codes

Several codes used in the design and simulation of high intensity proton linacs were described. Considerations addressed in these codes include machine design, tuning and particle tracking. Typically, separate RMS envelope codes are used to perform matching (picking quad and RF values near structure transitions). Results from these models are subsequently used as input to the multi-particle tracking codes which calculate halo and particle loss. PIC models are the primary method used to model space charge effects in the multi-particle tracking codes. The PIC implementations include 2-D and 3-D approaches using FFT and multi-grid methods to solve the Poisson equation. Regarding the requirements on the numbers of cells and particles needed, a general prescription was suggested to use at least 10-20 cells per direction over the core region of the beam, with each cell populated by an average of 10-20 particles. However, some modellers believe a higher resolution is needed to model finer beam structure. Additionally, progress has been reported in using Hermite functions to solve Poisson´s equation; the method is presently implemented in a separate code (“Dynac”). Cavity gap treatments range from a

single gap kick per cavity to integrations through cavity fields. Options for field representation include both analytic expansions and externally generated representations. Most models neglect quad fringe effects, but one method was used to investigate the fringe field effect for an SNS DTL tank, and found to be unimportant. This result needs to be verified for the entire linac. Many particle tracking models include the ability to specify errors. The choice of error parameters is typically performed external to the particle tracking codes, in a simpler framework better suited for large sets of error distribution sampling. A benchmark comparison among five of the multi-particle codes for case of a well matched beam passing through the first tank of the SNS DTL showed excellent agreement in the core behaviour of the beam, despite many differences in the modelling approaches.
A number of recommendations for future follow-up on codes and simulations were made, including:

- The code comparison discussed above should be repeated for the case of mismatched beams, also including errors; it should be extended to super-conducting cavities to compare the beam & filed models used.

- The characterisation of beam mismatch needs to be studied. In particular there is a question as to whether characterising mismatch by specifying eigenmode amplitudes is sufficient, or whether there is too much downstream mode mixing for this to be useful, in particular in the presence of the statistical effect of errors.

- A set of figure-of-merits should be agreed upon for describing halo magnitude and for use in code result comparison. Proposals include the 90%, 99%, 99.9%, etc. radial and emittance extents as well as the Kurtosis parameter.

- Develop a common device description format to facilitate exchange of input files and code comparison.

- Approximations presently used in codes need to be validated, including: treatments of quadrupoles (fringe fields, chromaticity and imperfections), RF cavities (transit time approximations and transverse longitudinal coupling), the space charge solution resolution, and the symplecticity of integration schemes.

- Determine the additional physics needed to warrant investigating losses at the 10^{-4} to 10^{-6} level, including: gas scattering/stripping, transverse cavity modes, RF coupler kicks, intrabeam scattering and wall effects.

Annex 1: Description of codes used in different laboratories :

LANL/KEK - PARMILA (H. Takeda)

- Design, matching (with Trace 3D), multi-particle simulations,
- Errors (quad: grad, skew, tilt, misalignment; cavity: field, phase (static or dynamic)),
- SC routine: SCHEFF (2.5D),
- Cavity model: One gap at the middle of each cell, using transit-time factors model with S, Bessel function in transverse,
- Quad model: Thick linear lens, chromaticity (different matrix for each particle),

- Specificities: Linac design and multiparticle simulation non separated (It is impossible with PARMILA to run a linac generated with an other program).
- - Z code

LANL - LINAC (K. Crandall)
- Mutiparticle simulations,
- Errors (quad: grad, skew, tilt, misalignment; cavity: field, phase),
- SC routine: SCHEFF (2.5D), PICNIC (3D)
- Cavity model: One gap at the middle of each cell, using transit-time factors model with S, Bessel function in transverse,
- Quad model: Thick linear lens, chromaticity (different matrix for each particle), Octupolar fringe field model can be used.
- - Z code

LANL/BNL/CERN - IMPACT (J. Qiang/R. Ryne/F. Gerigk)
- Multiparticle simulations,
- Errors (quad: grad, skew, tilt, misalignment; cavity: field, phase),
- SC routine: PIC-FFT (3D), with open or closed boundary conditions,
- Cavity model:
    - Transit-time factor model, Linear in transverse,
    - Step by step integration in field.
- Quad model:
    - Thick linear lens, ?chromaticity,
    - Step by step integration in magnetic field map.
- The step by step integration is leap-frog,
- Mutiparallel code.
- Z code

LANL - PARMELA (L. Young)
- Multiparticle simulations,
- Errors
- SC routine: SCHEFF (2.5D) , FFT (3D),
- Cavity model: Step by step integration in field.
- Quad model: Step by step integration in magnetic field map.
- The step by step integration is ?leap-frog,
- t code.

INFN - SCDYN (P. Pierini)
- Design with DoLinac, matching (with ?Trace 3D), multiparticle simulations,
- No Errors,
- SC routine: Multigrid (3D) with squared boundary conditions,
- Cavity model:
    - Transit-time model, At the middle of the gap, Bessel in transverse;
    - Sin-like model (leap frog step by step integration),
- Quadrupole model: Thick linear lens,
- Z code

Saclay - TraceWIN/PARTRAN (N. Pichoff/ D. Uriot)

- Design with GenDTL/GenLin, matching with TraceWIN, multiparticle simulations with PARTRAN,
- Errors (quad : grad, skew, tilt, misalignment; cavity : field, phase, tilt, misalignment),
- SC routines : SCHEFF (2.5D), PICNIC (3D), GAUSUP (3D),
- Cavity model:
  - One gap at the position where the synchronous particle has the synchronous phase, using transit-time factors model without S (need T, T', T''), Bessel function in transverse,
  - Sin-like model (Runge-Kutta 4 step by step integration),
- Quad model: Thick linear lens, chromaticity (different matrix for each particle),
- Design and multiparticle simulations separated,
- Diagnostics + correction scheme included,
- Simulation of diagnostics (current, positions, sizes, emittances, diaphragm).
- Z code

WARP (U. Md. / LLNL, R. Kishek, A. Friedman)

- PIC space charge (3D)
- Cavity and quad models
  - Expansions in off axis coordinate
  - Detailed field maps
- T code

Annex 2: Program

Presentations at SNS-Miniworkshop on Linac Space Charge

June, 25/26 2001, Oak Ridge National Laboratory (SNS-building)

	Session I **Project & Exp.**	**Session II** **Beam Dynamics**	**Session III** **Codes**
Conveners/ Secretaries	**J. Stovall/E. Tanke**	**I. Hofmann/D. Jeon**	**N. Pichoff/J. Galambos**
Monday I 9-12am	Stovall, Mosnier, Ikegami, Gerigk, Pagani, Kishek, Bernal, Garnett		
Monday II 1.30-5.30 pm		Wei, Hofmann, Jeon, Pichoff, Qiang, Ruggiero + discussion	
Tuesday III 9-12am		Fedotov,	Nath,/Pichoff, Takeda, Ryne, Valero, Pierini + discussion
Tuesday IV 1.30-5.00 pm	General Discussion / Summary Remarks		
Talks:	J. Stovall: SNS overview (15+5 min)	J. Wei: HEBT/Ring Limitations to Linac Emittance & Halo (15+5 min)	S.Nath / N. Pichoff: Code Comparison (25+5 min)
	A. Mosnier: CONCERT (15+5 min)	I. Hofmann: Overview on Resonant Space Charge Effects (25+5 min)	H. Takeda: PARMILA code (25+5 min)
	M. Ikegami: The beam dynamics design for KEK/JAERI proton linac (25+5 min)	D. Jeon: Parmila Studies on Emittance Transfer & Mismatch for SNS (15+5 min)	R. Ryne: IMPACT code (25+5 min)
	F. Gerigk: Emittance Exchange in the CERN-SPL (25+5 min)	N. Pichoff: Coupling Resonances (25+5 min)	S. Valero:Solution of the Laplace-Poisson's equation for high intensity. (25+5 min)
	C. Pagani: TRASCO project (15+5 min)	A.V. Fedotov and R.L. Gluckstern: Halo Formation in High-Intensity Linacs (25+5 min)	P. Pierini: The SCDyn Code (15+5 min)
	S. Bernal/ R. Kishek: Studies of Energy Transfer in Space-Charge Dominated Beams (25+5 min)	J. Qiang: Emittance exchange in 3D PIC-simulation (25+5 min)	
	B. Garnett: Preliminary results of the LEDA Beam-Halo Experiment (25+5 m)	A.G. Ruggiero: Beam Dynamics in SCL BNL Project (25+5 min)	