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memorandum

Los Alamos Neutron Science Center
LANSCE-1, Accelerator Physics and Engineering

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SUBJECT: Transient Analysis for SNS Linac

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The memo describes a procedure for analyzing transient effects in the SNS linac during the beginning of its macropulse. The analysis includes simulations of the beam chopped structure with the pulse-width ramp, PID-feedback RF control model, and accounts for collective modes in a given RF module of the accelerator structure. The method application is demonstrated for the most complicated RF module of the CCL linac structure for the 2-MW design: its 1st RF module has N=17 segments, each with 8 identical accelerating cavities plus 8 coupling cavities. The module is about 15.6 m long and has the largest total number of cells per module in the CCL, equal to N_{cav}=17*16-1=271 [1]. In addition, the accelerating field in this module is ramped in the first 10 segments to provide a smooth longitudinal matching to the magnetic lattice of the upstream CCDTL module, that creates a problem of properly distributing the RF power provided by two 2.5-MW klystrons.

The following steps describe this procedure.

1. Start from the design data for the module: PARMILA and LINAC output files – *design.out*, *dynamics.out* (or *linac.out*), *power.out* plus RF partition table [2] – contain information about the structure, such as cavity radii, βs, quad strengths, segment-to-segment distances, etc. First, one should extract values of geometrical betas β_g for each segment in the RF module (17 values in the considered example).

2. Using the design data for representative cavities of the corresponding type (CCL, in our case), which are produced with a step of 0.01 in β [3], one should:

    a. Linearly interpolate the cavity parameters – g/(βλ), outer diameter (DIAM), and two corner radii (OUTER_CORNer radius and INNER_CORNer radius) to the design geometrical values β_g to generate cavities for each of N segments.
    b. Prepare the batch file for a CCLFISH (or CCDTLFISH) run [4] for the N different types of the generated cavities (Strictly speaking, there is some difference between middle and end cells of a segments, but we ignore it in the present model). The fields in the

SUPERFISH problems should be normalized to $E_0 = 1$ MV/m for the proper input into the PARMELA code [5].

c. After the CCLFISH run we get N output files *.T35 to use them as input for SF7 postprocessor [4], from which we finally obtain the cavity fields in files *.T7 that are ready to be used as PARMELA input.

3. Prepare a PARMELA input file using the design data of step 1 and the results of step 2, with all cavity fields in the input file normalized to $E_0 = 1$ MV/m. For the cavity lengths L_{cav} one can use data in the beginning of *.T7 files: the second number in the first line is the cavity half-length in cm, so that it should be multiplied by factor 2. The quadrupole strengths B' are contained in *dynamics.out*, and drifts between tanks, or segments, (DBT) are in *design.out*. The beam distribution parameters required in the PARMELA input ($\varepsilon_{x,y}$, $\alpha_{x,y}$, $\beta_{x,y}$, ΔW, $\Delta\phi$) at the entrance to the RF module can be obtained from the *linac.out* file. The resulting file should be named *input* and be placed in the folder where the WTRANS code (see below, step 5) runs.

4. Use LOOP [6] to calculate the frequencies of all N_{cav} collective eigenmodes in the RF module consisting of N_{cav} cavities. The code assumes a lumped-circuit model of N_{cav} cells.

   a. As the first step, the operating mode frequency is tuned to the desired value f_0=805 MHz by adjusting the frequencies f_a of the accelerating cells while keeping it equal to f_0 for coupling cells. The profiled (or flat) field distribution in the operating mode is achieved by a proper choice of the coupling constants for the end cells of the segments (or the module). If the field profile should be flat (i.e. the same in all segments), the frequencies of only two end cells of the module are adjusted by keeping them equal to $(f_0+f_a)/2$. For a profiled (ramped) field, one should adjust the coupling constants between cells where the field jumps, i.e. the ends of segments (see Appendix A for detail). The LOOP-calculated ramped field distribution for the operating $\pi/2$ mode in the 1st RF module of the CCL is shown in Fig.1. After the operating mode frequency is tuned and the required field profile is achieved, we proceed with calculating all other modes.

   b. The LOOP code has two executables *loop.exe* and *loopctn.exe*: the first one is used for tuning a given mode, and the second calculates all modes. LOOPCTN uses the same input file as LOOP, however, switching off the graphics output is recommended before running LOOPCTN, especially for a large number of modes. The mode parameters calculated by LOOPCTN – frequencies and current amplitudes – are recorded in the output file *tempfreq* which is later used by WTRANS (see step 5) and should be placed in the folder where WTRANS runs. The LOOP code has some (unpublished) documentation; for convenience, the LOOP input file for our example is described in Appendix A.

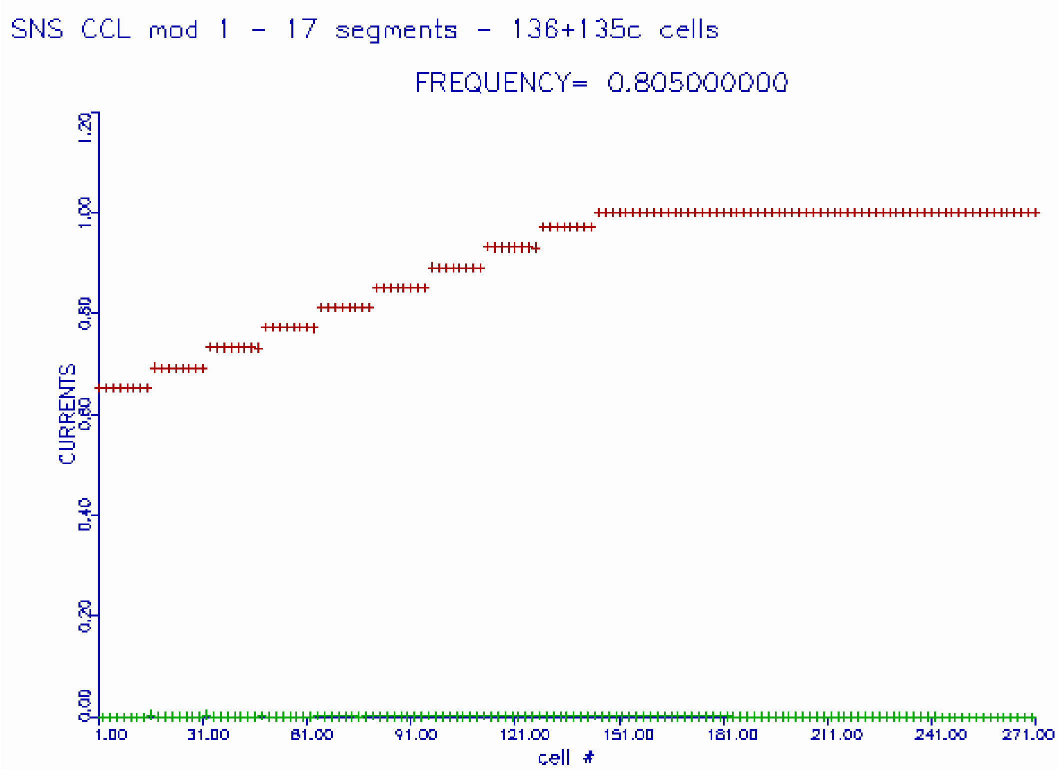

Figure 1: Fields in the operating ($\pi/2$) mode (not scaled) versus cell number: red crosses are for accelerating cells, and green ones, near zero, for coupling ones..

5. All previous steps were to prepare a WTRANS run, and now we use the results of steps 3 and 4 as an input to WTRANS code [7]. The code assumes a model for the RF PID feedback system, takes the collective modes produced by the LOOP code, and calls PARMELA to simulate the beam propagation through the module self-consistently. There is no documentation for the WTRANS, therefore we provide some description and examples of the input files in the Appendix B.
   a. With two input files for a WTRANS run – *input* and *tempfreq* – already prepared, we need one more, *linac.dat*. Additional input parameters required at this point are the klystron maximum power, klystron drive feed points, RF feedback parameters, and macropulse and ramp time structure. The values of Z*L/Q for each segment for a given coupling k_0=0.05 can be found from data in SUPERFISH output files *.sfo, produced during the step 2.
   b. After the first WTRANS run, when the required RF power is calculated, and the cavity beam load is found, one should adjust the waveguide-cavity coupling ($\beta_{opt}=2\beta_0$) and detune the cavity operating frequency f_0 by [8] $\Delta f=f_0*\tan\phi*(\beta_{opt}-1)/2Q_0$ to minimize the reflected power. In our example, see Figs.2-4 below, the value of $\beta_{opt}=1+P_{av}/P_{cav}=1.328$, where P_{av} is the average power delivered to the passing beam during the regular macropulse structure, $P_{av}= 0.65*I_{max}*\Delta W\approx 1$ MW (here 0.65 is the nominal duty factor after the ramp is over, I_{max}=56 mA is the beam peak current, and ΔW=106.76-79.19=27.57 MeV is the beam energy gain in the RF module), and $P_{cav} = P_{RF} - P_{av} \approx 3.05$ MW is the energy dissipated in the cavities. With f_0=805 MHz, the synchronous phase ϕ= -30°, and Q_0=16200, we get Δf = - 4710 Hz. Figures 2-4 show the transient process in the considered RF module in details.

c. For this particular module, with its ramped-up field profile, it was important to choose the RF-feed points in such a way that RF powers delivered by both klystrons are equal; that is why the RF feeds were moved further downstream from usual symmetric 1/4–3/4 points. Otherwise, the total required RF, which is already close to the allowed limit, would be about 8% above it.

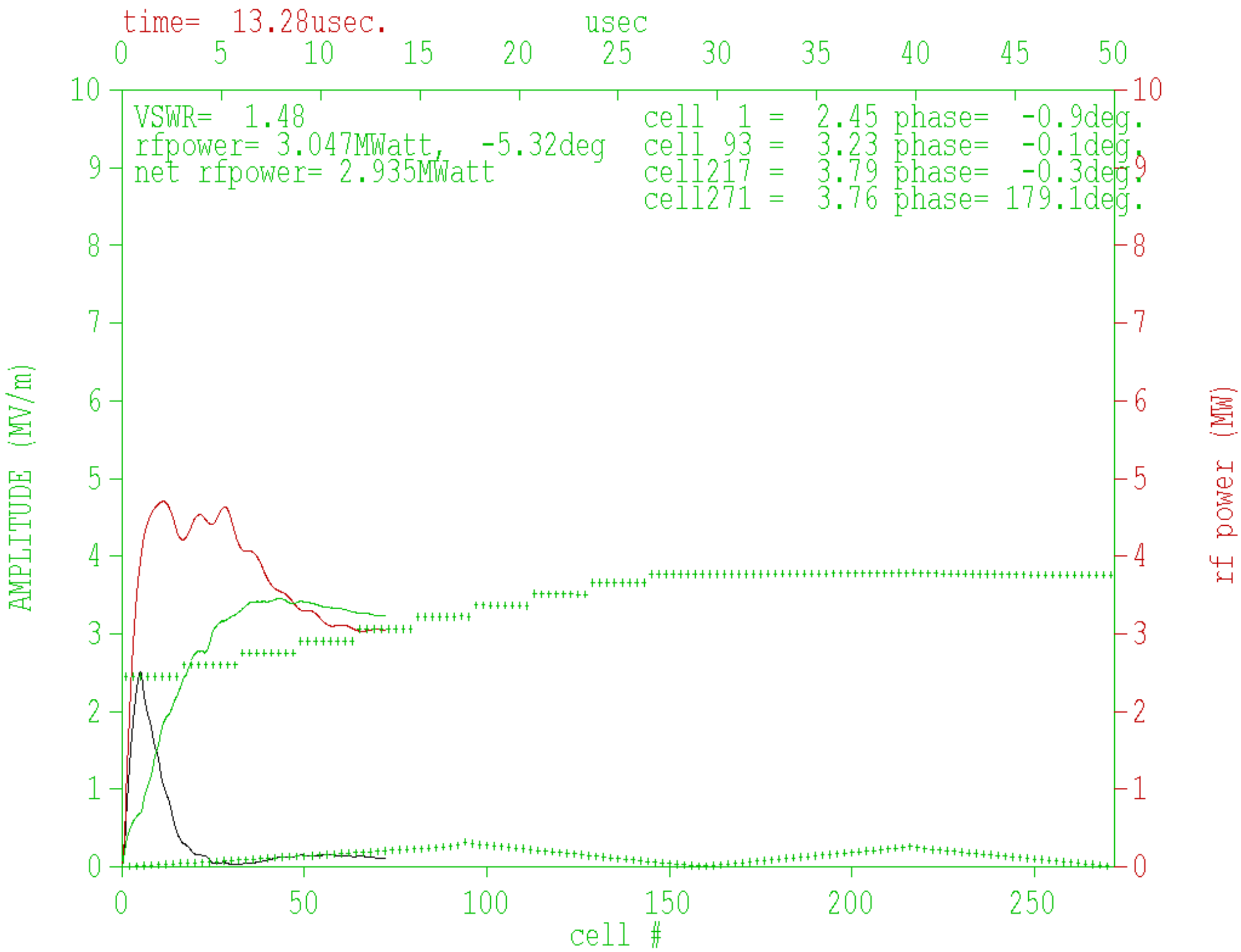

Figure 2: Just before the beam arrival. Pluses show the fields (left scale) versus the cell number (bottom axis). The profiled field distribution in accelerating cells is clearly seen, as well as low fields in coupling cells (two peaks are near the RF feed points in cells #93 and #217). The wavy red (top) line is for total RF power, and the black (bottom) one for reflected power (right scale) versus time (top axis). The green wavy line (in the middle) shows the field evolution in the 1st RF feed cavity (#93), versus time (in µs, top axis).

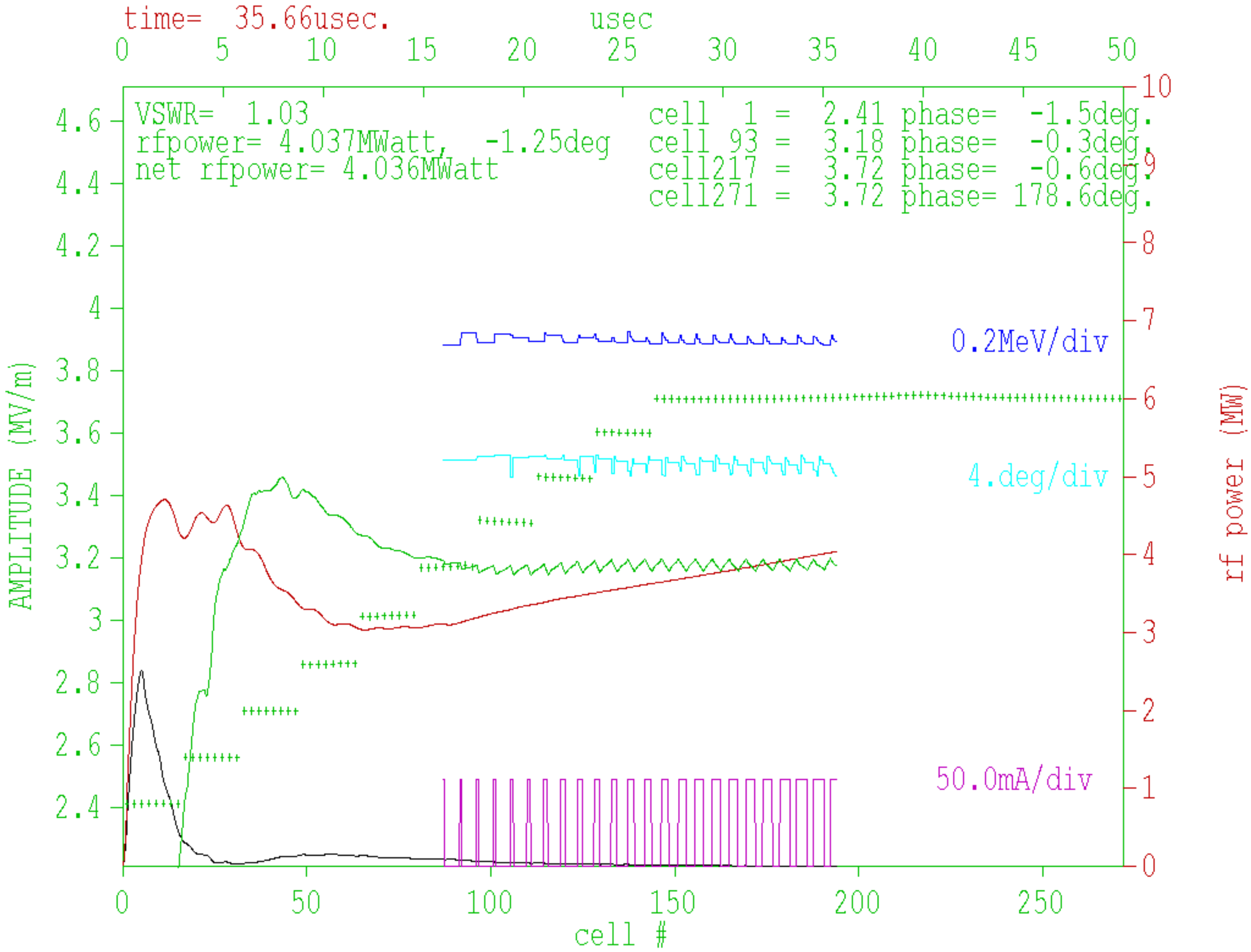

Figure 3. Near the end of the beam-pulse ramp-up that lasts from 16 μs to 36 μs. The field scale (left) is blown and shifted. The magenta peaks at the bottom show the pulsing beam current versus time, with the pulse width increasing during the ramp. The dark-blue line (near the top) shows the output beam energy (0.2 MeV per division of the right scale, with 0 corresponding to 105.4 MeV, see Appendix B). The light-blue line (in the middle) shows the beam phase at the last quadrupole after the RF module (4° per division of the right scale, 0 corresponds to –40°). The saw-tooth green line shows the field evolution in the cell #93 (left scale). The total RF power (red line, right scale) increases during the beam ramp, while the reflected power (black line near the bottom) gradually decreases.

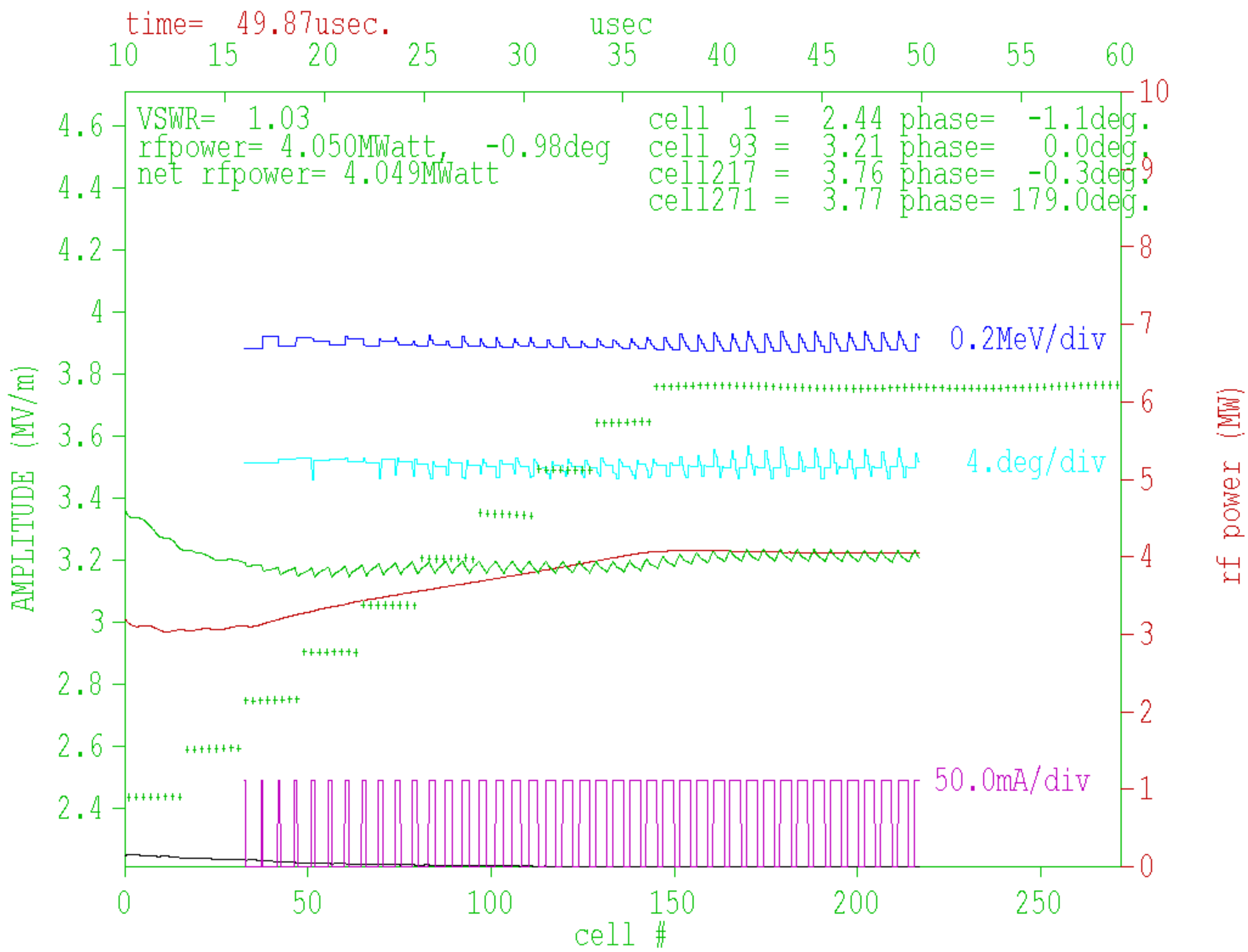

Figure 4. The stationary regime after the beam ramp is over (note the time scale shift compared to Figs. 2-3; the time scale starts here from 10 µs). The beam-pulse width, increasing during the ramp, remains constant (65% of the revolution period) after approximately t=36 µs. The total RF power (red line, right scale) also stays constant after the ramp, and the reflected power (black line) is kept small. The saw-tooth oscillations of the field in the monitored cavity (#93, the 1st RF feed point, green line) around its nominal value of 3.21 MV/m are about ± 0.45%.

During a WTRANS run, the PARMELA code (a part of WTRANS) produces an output file every time it is called; the output files are stored in the folder *out* and marked by the simulation time (in µs) when the PARMELA was called. One can visually check the beam quality by running the PARGRAF postprocessor [5] in the same folder where the WTRANS runs. Just for completeness, we reproduce one of the beam dynamics pictures in Fig. 5. The beam is well matched to the structure.

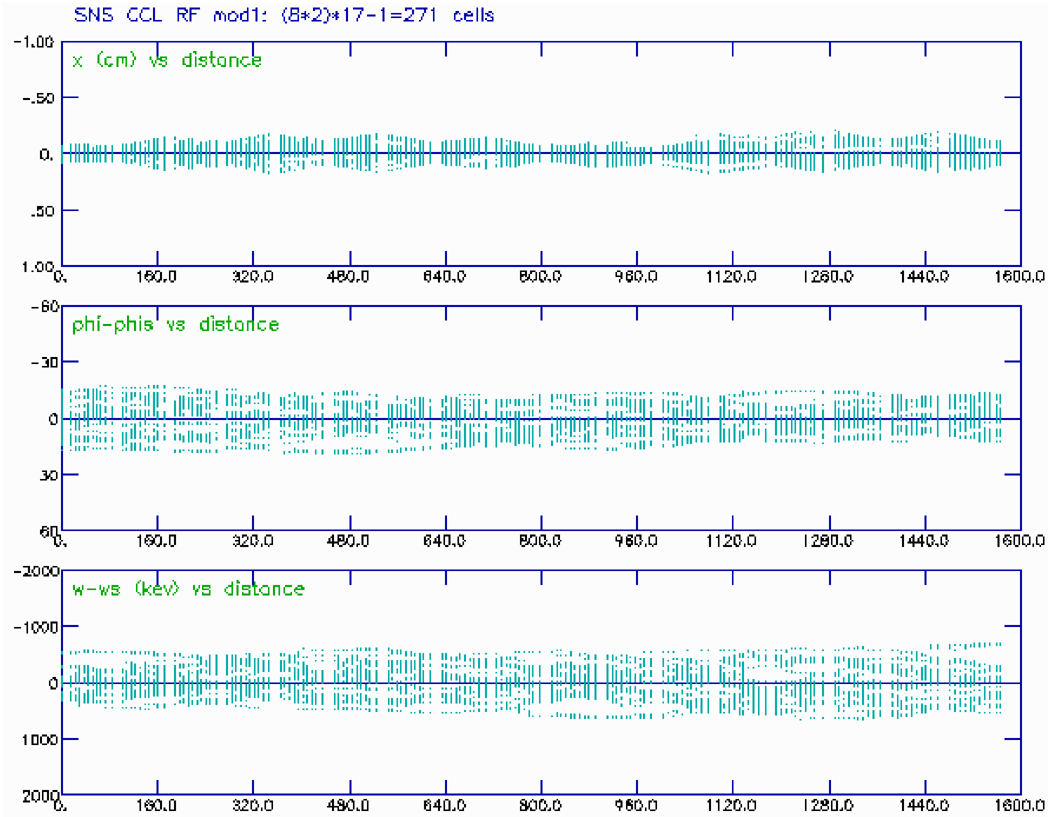

Figure 5: Beam dynamics in the 1st RF module of the SNS CCL linac for 2-MW design (only 50 particles are taken; PARGRAF output)

Conclusions

A procedure for the transient analysis in the SNS linac is described. The analysis for the 1st RF module of the CCL linac for the baseline 2-MW design is presented. Due to its ramped-up accelerating field profile, this 17-segment, 271-cell module requires a careful redistribution of the available RF power from two klystrons. Our analysis shows that with reasonable RF-feedback parameters the oscillations of the accelerating fields due to the pulsing beam loading in the module can be contained within a rather small range, $\pm 0.45\%$.

Some details of the code usage for the transient analysis are described in Appendices.

References

[1] Tarlochan Bhatia et al. “Beam Dynamics Design for the 1-GeV 2-MW SNS Linac”, 1999.

[2] Tarlochan Bhatia, Barbara Blind, private communications, Jan.-May 1999.

[3] James H. Billen, private communications, Jan.-May 1999.

[4] James H. Billen and Lloyd M. Young, “SUPERFISH/Poisson Group Of Codes”. Report LA-UR-96-1834, Los Alamos, 1996. Revised 1999.

[5] Lloyd M. Young, documentation by James H. Billen. “PARMELA”. Report LA-UR-96-1835, Los Alamos, 1996. Revised May 11, 1998.

[6] The initial LOOP program was written by S.O. Schriber, then adapted for PC by Lloyd M. Young.

[7] The WTRANS code for transients analysis was written by Lloyd M. Young. Some info on the code input is available in Appendix B.

[8] T.P. Wangler, “Principles of RF Linear Accelerators”, John Willey & Sons, NY, 1998. Chapter 10.

Appendix A: Input for LOOP Code

The LOOP code input file is named *input*, and its content is shown below for the considered example of 17-segment module with 271 cells and a profiled accelerating field, with some comments after semicolons.

```
title 271 1 5 0         ; # of cells = 271, periodicity – single (IPER=1), termination –
                        ; full-full (ITERM=5), IPRIN=0 (output only resonance data)
SNS CCL mod 1 - 17 segments - 136+135c cells      ; title line – up to 80 characters
accel .802985111 220000000             ; f(GHz) & Q for accelerating cavities*
coupl .805 220000000                   ; f(GHz) & Q for coupling cavities
kcons .05 .005   ; coupling constants accel-coupl (1st neighbor) and accel-accel (2nd one)
termin 0.8039925546 220000000 0.8039925546 220000000
                                       ; f(GHz) & Q for end cells **
drive 1                                ; driving cell # for normalization
oper 136                               ; operating mode
plot 0 0 0 0                           ; plot options ***
errk 15 0.05148 16 0.04852 31 0.05140 32 0.04860       ;corrected coupling constants
     47 0.05132 48 0.04868 63 0.05126 64 0.04874       ; for the end-segments cells
     79 0.05120 80 0.04880 95 0.05114 96 0.04886       ; to provide a profiled field
  111 0.05109 112 0.04891 127 0.05105 128 0.04895 ;of the operating mode ****
  143 0.05074 144 0.04926
begin
end
```

Comments:

* Q is taken to be very high to have narrow resonance lines

** f_{end} is kept to be $(f_{acc}+f_{coupl})/2$ to provide for a flat field distribution in the accelerating (operating) mode.

*** No screen output – use for LOOPCTN while calculating all N_{cav} modes. For adjusting the operating mode frequency and controlling visually its field distribution in LOOP runs use "plot 1 0 0 0".

**** These coupling are obtained from the accel-coupl constant k_0=0.05 as follows: if the required field in the n-th segment is E_n and in the (n+1)-th one is E_{n+1}, the couplings are $k_n=k_0*2E_{n+1}/(E_n+E_{n+1})$ for the last accelerating cell in the n-th segment and $k_{n+1}=k_0*2E_n/(E_n+E_{n+1})$ for the next (coupling) cell.

Appendix B: Input for WTRANS Code

The WTRANS code uses 3 input files. The first one is named *input*, it is essentially a PARMELA input file for the considered module with the field in all accelerating cells normalized to $E_0 = 1$ MV/m, see step 3 above. While the PARMELA is well documented [5], for convenience, an abbreviated version of *input* is shown below for our example of 17-segment module, with some comments.

File *input*.

```
run 1 1 805. -1.25 79.194 2 939.30163                  ; 805 MHz, W0=79.194 MeV, H-
title
 SNS CCL RF mod1: (8*2)*17-1=271 cells
; parmela input file
drift 0. 1.5 1
quad 4.0 1.5 0 1908.19                                 ; half-quad in the middle of 1st drift
drift 10.398 1.5 1
cell 7.22090170 1.5 1 0.000 1.00000 1 5. 0 0 0 0       ; start 1st segment
;  cell length,   radius (cm)     E0 (MV/m)
cfield 1
150g1.t7                                               ; file with fields for 1st segment, SF7 output
cell 7.22090170 1.5 1 180.0 1.00000 1 5. 0 0 0 0
cell 7.22090170 1.5 1 0.000 1.00000 1 5. 0 0 0 0
cell 7.22090170 1.5 1 180.0 1.00000 1 5. 0 0 0 0
cell 7.22090170 1.5 1 0.000 1.00000 1 5. 0 0 0 0
cell 7.22090170 1.5 1 180.0 1.00000 1 5. 0 0 0 0
cell 7.22090170 1.5 1 0.000 1.00000 1 5. 0 0 0 0
cell 7.22090170 1.5 1 180.0 1.00000 1 5. 0 0 0 0       ; end 1st segment
drift 10.485 1.5 1
quad 8.0 1.5 0 -1917.99      ; quad in the middle of the drift space between segments
drift 10.485 1.5 1
cell 7.26596366 1.5 1 0.000 1.00000 2 5. 0 0 0 0       ; start 2nd segment
cfield 2
150g2.t7                                               ; file with fields for 2nd segment, SF7 output
cell 7.26596366 1.5 1 180.0 1.00000 2 5. 0 0 0 0
cell 7.26596366 1.5 1 0.000 1.00000 2 5. 0 0 0 0
;...
; etc, etc
;...
cell 8.10054118 1.5 1 0.000 1.00000 16 5. 0 0 0 0
cell 8.10054118 1.5 1 180.0 1.00000 16 5. 0 0 0 0      ; end 16th segment
drift 12.2645 1.5 1
quad 8.0 1.5 0 1928.87
drift 12.2645 1.5 1
cell 8.16366518 1.5 1 0.000 1.00000 17 5. 0 0 0 0      ; start 17th segment
cfield 17
150g17.t7                                              ; file with fields for 17th segment, SF7 output
cell 8.16366518 1.5 1 180.0 1.00000 17 5. 0 0 0 0
```

```
cell 8.16366518 1.5 1 0.000 1.00000 17 5. 0 0 0 0
cell 8.16366518 1.5 1 180.0 1.00000 17 5. 0 0 0 0
cell 8.16366518 1.5 1 0.000 1.00000 17 5. 0 0 0 0
cell 8.16366518 1.5 1 180.0 1.00000 17 5. 0 0 0 0
cell 8.16366518 1.5 1 0.000 1.00000 17 5. 0 0 0 0
cell 8.16366518 1.5 1 180.0 1.00000 17 5. 0 0 0 0          ; end 17th segment
drift 12.3905 1.5 1
quad 4.0 1.5 1 -1922.13             ; half-quad in the middle of last drift
zout
input 5 50 -.124 241.1 6.19e-5 -.058 646.0 6.32e-5 18 0.6 0 0 0 0 0 0
; distribution 5, with only 50 particles
output 5
scheff 0.056 1.5 1600 10 2040 0 0 3 1.5 0 0
; current 56 mA
start -60. 20 100000 1 0
end
```

The second input file for the WTRANS code is ***tempfreq***, it is produced by LOOPCTN (see step4.b) and contains parameters of all N_{cav} collective modes in the module.

The third input file for the WTRANS code is called *linac.dat*. It contains the data for the main program of WTRANS, including parameters of the PID feedback, some cavity data, RF power and timing parameters. Since the WTRANS code is not documented yet, we show this input file below and describe it in details.

File *linac.dat*

```
&linacdata
 integain=.05, propgain=1., diffgain=4., propset=.35,
 nave=40, idel=28,
; PID parameters; idel is delay time in units of 16*T_RF
 numdrive=2, numres=1, ncav=271, nc=271, npar=5,
; # of driving klystrons, # of resonators, # of cavities, # of cells; how often PARMELA is called
 cl=0.077,                  ; an average cell length, in m
 zloverq=2.15e-4,           ; kind of an "average" Z*L/Q, in Mohms*m
 8*1.9387e-4,8*1.9537e-4,8*1.9697e-4,8*1.9863e-4,8*2.0038e-4,
 8*2.0221e-4,8*2.0411e-4,8*2.0608e-4,8*2.0813e-4,8*2.1023e-4,
 8*2.1233e-4,8*2.1443e-4,8*2.1652e-4,8*2.1859e-4,8*2.2065e-4,
 8*2.2268e-4,8*2.2469e-4
; Z*L/Q, in Mohms*m, for all 17 segments, for coupling k0=0.05 (from SUPERFISH results)
 it=1,93,217,271, ia=93,
; # of cells where the field is monitored (up to for); # of cell where the field scale is set
 f0=.804995290d9, beta0=0.664,
; the detuned frequency of the operating mode (here by –4710 Hz); waveguide-cavity coupling;
 beamfreq=805.e6,           ; RF frequency
 klypower=2.375, fwdphase=0.,
; power (in MW) per klystron, klystron phase
 xset=(3.21,0.)
; scaling factor for fields, equal to the nominal field in the cell 'ia' (see comment above)
 q0=16200.,1000.,
```

; unloaded Q for the 1st resonator (i.e., for the whole RF module); for the 2nd one (not used)

```
 ndrive=93,217,                    ; RF feed cell #s
cell=1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,
1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,
1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,
1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,
1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,
1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,
1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,
1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1
```

; for all N_{cav}=271 cells: 1 means an accelerating cavity, and 0 a coupling one

```
 ampscale=1., scalechange=4.,
```

; initial electric field amplitude scale per division (MV/m); new scale after scale change;

```
 timescalechange=14.,
```

; time of the field scale change (μs)

```
 engbase=105.4, engscale=0.2,
```

; energy value corresponding to y=0 in the screen output, energy scale per division (MeV)

```
 phasebase=-40., phasescale=4.,
```

; phase value corresponding to y=0 for the screen output, phase scale per division (degree)

```
 powerscale=1.,
```

; total RF power scale per division (MW)

```
 adjustf=.false.,
```

; frequency adjustment

```
 loopsolution=tempfreq,
```

; file name for mode parameters

```
 beam=.true., beamon=15., beamoff=100. , pulseing=.true.,
```

; beam on, beam-on time (μs), beam-off time (μs)

```
 xtintval=5.,
```

; time scale shifts (μs)

```
 ipulse=18, ipulseinc=18, ipulsemax=440, ipulsecyles=677 &
```

; 1st beam-pulse width, beam-pulse width increment during the ramp, max beam-pulse width
; at the end of the ramp, the revolution period (all in units of T_{RF}, here 1.2422 ns)