SPLINAC: COMPUTER SIMULATIONS OF SC LINAC RF SYSTEMS WITH BEAM

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Abstract

The beam in a proton linac is very sensitive to field perturbations in the cavities. Therefore a simulation program was written modelling longitudinal beam dynamics in a realistic composite linac RF system. Fast RF vector sum feedback loops control several cavities with β-dependent transit time factors driven by one transmitter. Modelling of feedback loops covers limited transmitter power and bandwidth and possible loop-delay. Vector sum calibration errors, power splitting errors and scatter in the coupling strength to the cavities are optional as well as beam loading of the pulsing beam. Different modes of mechanical cavity perturbations including Lorentz force detuning can be chosen. A multitude of phase-space representation of bunches as well as RF quantity plots are available, most of them can be assembled as a movie, showing the system dynamics in 'real time'

1 INTRODUCTION

The program, its capabilities and how to run it have been described with ample details including a user guide to run the program in [1]. Therefore we shall only summarise the essential features here and show a few examples, including the newly found spontaneous symmetry breaking effect.

For many accelerator calculations and simulations the main RF voltage is considered fixed and perturbations – e.g. beam loading – are treated as independent superposition. This approach is no longer valid for larger perturbations asking for *fast* RF vector feedback loops, which then are strongly influenced by this beamloading. Therefore the author has modelled in a first program [2] (for storage rings as LHC) an RF system with strong beam including the fast RF vector feedback loops with loop delay, transmitter power limitation and transmitter bandwidth.

For a superconducting proton *linac* also cavity microphonics and Lorentz force detuning become important and the new program 'SPLinac' has been developed to study these questions. Hence some features for each cavity in 'SPLinac' are

• different types of external mechanical perturbations (coherent and incoherent microphonics) as well as Lorentz detuning

• β-dependent transit time factors

• the possibility of driving several cavities via an RF vector sum with a single transmitter

• RF system errors

• pulsed operation mode, with or without beam loading

• a full longitudinal phase space representation of bunches.

The main purpose of the program was considered the examination of the beam dynamics in longitudinal phase space, tracking bunches from cavity to cavity along the whole linac with all possible system perturbations present. For these investigations several graphic displays are available for a representation of bunches in longitudinal phase space along the machine and at its exit, optionally superimposed.

Initially foreseen only for diagnostic means, for each single transmitter with all its driven cavities, controlled by a vector sum feedback (called 'family'), special plots are available:

• complex cavity voltages (I and Q-components), for each cavity and their vector sum, either without vector sum calibration errors (the true voltage as seen by the nominal beam) or with errors (the measured voltage as seen by the feedback system).

• transmitter incident and reflected powers and phase

• cavity detuning(s) – microphonics or Lorentz detuning.

These calculations can be executed without full beam simulation.

The program is designed interactive [1], i.e. the simulation progress can be displayed on the screen and, by user intervention, the execution can be held, cancelled or its operational mode changed at any time. The program can create series of pictures (from pulse to pulse) that can be used individually – e.g. pasted into a report as the present one (possibly after post-processing by a professional graphics program) – or assembled as movies showing the system dynamics. To build movies, the author uses QuickTime® [2], which assembles the pictures (built by simple vector graphics instructions) without transformation, so it does not produce storage wasting pixel maps – as some other video programs do exclusively working e.g. in MPEG format – and the picture quality even of thin lines is conserved.

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[1] Running on any Macintosh with PowerPC processor

[2] QuickTime for *displaying* the movies can be downloaded <u>free of charge</u> at <u>http://www.apple.com/quicktime/download/</u>. (<u>Macintosh</u> or <u>IBM-compatible</u> versions). To get the possibility to *assemble* a movie, a password must be bought for a small fee (the author paid $29.95 with credit card over the net)

2 EXAMPLES OF RESULTS AND PROGRAM CHECKS

In the following we shall show a few examples using data from the CERN SPL study [3][4]. First outputs (Fig. 1-3) will show the behaviour of a transmitter supplying four cavities with 'disabled' Lorentz force. On the left the RF is switched on, starting to load the empty cavities to the nominal field. Fig. 1 shows the RF power (red) rising with the highest speed possible with the given generator power and bandwidth, soon hitting its maximum power. Fig. 2 shows the cavity voltage real parts, i.e. in phase with the nominal voltage. Thin, light blue traces show all four cavity voltages rising (zero suppressed). The true sum voltage (normalised per cavity, resulting in the same graphic scaling) is shown by a thick dark blue trace and the measured and error prone sum voltage thick orange. The latter rises till the measured voltage approaches the set value (corresponding to the y=0 line). In parallel the reflected power in Fig. 1 (magenta), goes down while the cavities are loading. When the measured sum voltage approaches the set value, the generator power reduces and settles to an equilibrium necessary to keep the sum voltage at the set value. Since superconducting cavities do not really consume power, the reflected power settles on the same value. The β=0.8 cavities of this section have the parameters f=352.209 MHz, $Q_{ext}=3 \cdot 10^6$, R/Q=192 Ω and V_{nom}=15.3 MV per cavity (9 MV/m). Therefore analytically the power for four cavities comes to 203.2 kW, while Fig. 1 tells 203.8 kW in very good agreement (precise numbers obtained by 'info window' [1] with RF system errors switched off).
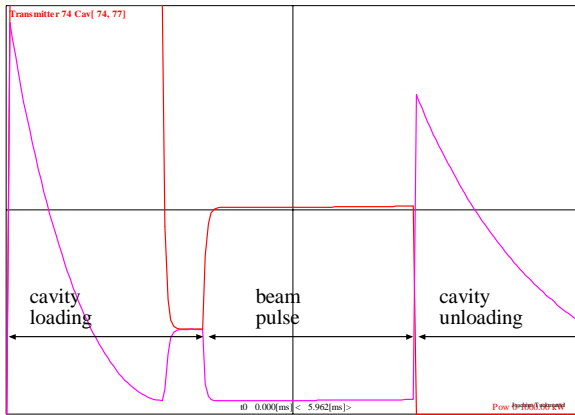

Fig. 1: Transmitter (red) and reflected (magenta) power, range 0-1 MW, 0-6 ms.

The quadrature voltages are shown in Fig. 3. When the *real* part of the *measured* sum voltage (orange in Fig. 2) arrives at the set value, the *imaginary* part of the measured sum voltage (thick cyan) approaches also its set-value zero. The true voltage (thick dark green) stabilises slightly off the set-value due to the calibration errors in the vector sum. The imaginary part of the four

cavity voltages (light green) shows distinct behaviour – changes to first order with a resonant frequency change - depending on cavity tune status.
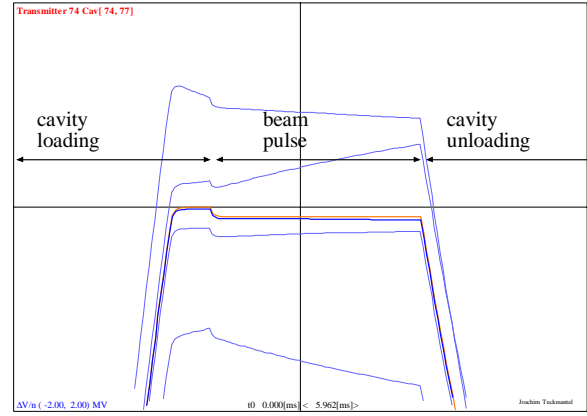

Fig. 2: Cavity voltages and vector sum voltages per cavity (real component, zero suppressed: the nominal value corresponds to zero, range ± 2MV, 0-6 ms) Light blue the four individual cavity voltages, dark blue true vector sum (per cavity), orange measured vector sum (per cavity) including calibration errors.
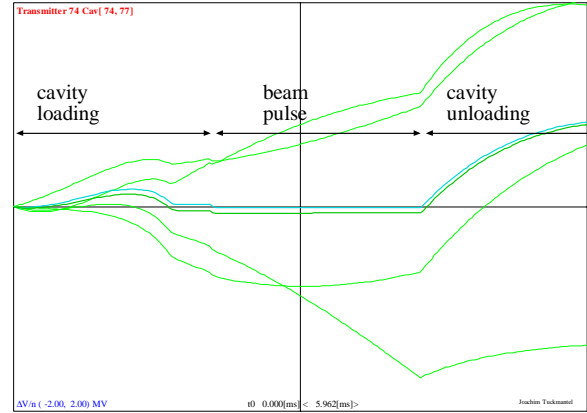

Fig. 3: As Fig. 2 but quadrature voltage component (imaginary part). Light green the four individual cavity voltages, dark green true vector sum (per cavity), cyan measured vector sum (per cavity) including calibration errors.

After 2 ms the beam is injected and all real parts of the cavity voltages show a fast decrease, while the transmitter power shows a fast rise to supply the new power demand. The particles arrive at the depicted cavities with 394 MeV and leave with 437 MeV; the average relative transit time factor amounts to 0.76 (see [1]). For a beam of 11 mA and a phase angle of -15° analytically we expect a transmitter power of 515 kW, from Fig. 1 (precise number by 'info window') we read 525 kW. Analytically the induced equilibrium voltage without feedback would be 9.63 MV per cavity. With a feedback gain of 100 and four cavities we expect a total

residual voltage drop of 0.385 MV and the measured sum voltage drops in fact by 0.364 MV ('info window'). The natural cavity filling time for the *field* is 2.7 ms and the feedback with gain g=100 shortens the reaction time by this factor to about 0.03 ms which corresponds also to the transient time for the sum voltages in Fig. 2. All four cavities execute *independent* microphonics movements. Therefore, despite the fact that the nominal vector *sum* is stabilised by the feedback system, individual cavity voltages drift with their natural filling time to the new equilibrium (four diverging light blue lines). Since the beam does not pass at the crest of the RF it induces also an imaginary voltage, the latter also drifting apart for the different cavities (Fig. 3)

At the end of the beam pulse the RF power is switched off instantly and the reflected power produces a power spike due to the sudden unloading of the cavities (magenta in Fig. 1). All cavity voltages decay, approaching zero with the apparent exception of the imaginary voltages in Fig. 3. The imaginary voltage increase is caused by the fact that the feedback is not active anymore and the complex voltage vector starts to turn due to the detuning. The initially mainly real vector now turns towards the imaginary direction and thus increases this component in the beginning, even while the *absolute* value of the vector decays. In a plot of this function for a longer time, the imaginary part also decays to zero, as it should do.
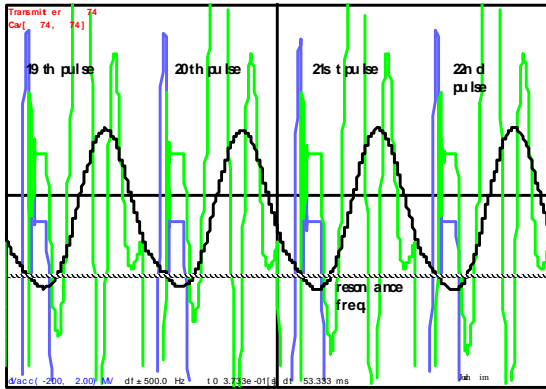

Fig. 4: Cavity with Lorentz detuning and pulsed beam, *one* transmitter per cavity. The cavity voltage real part (blue) and imaginary part (green) are shown together with the RF resonant frequency changes (movement) in black, range is ±500 Hz; the loaded bandwidth is about 120 Hz.

Fig. 4 shows a cavity with a Lorentz detuning of $-2 Hz/MV^2 = -0.75 \; Hz/(MV/m)^2$. The mechanical cavity resonant frequency is 100 Hz at a Q-value of 38, the linac pulse rate 75 Hz. The loaded bandwidth of the cavity is about 120 Hz, the displayed frequency range ±500 Hz. One (largely overpowered) transmitter supplies only this *single* cavity statically 'pretuned' by +200 Hz in such a way that it just oscillates through the resonant

frequency when 'RF on' is requested, i.e. when loading the cavity and during beam pulse. The plot shows the *dynamic* equilibrium status after the mechanical transients have just about died out.

2.1 Spontaneous symmetry breaking

During simulations with *more than one* cavity connected to a single transmitter, after a short start-up transient, all cavities settled to a dynamic equilibrium – cavity movements and fields repeating exactly from pulse to pulse – for medium fields. However, when increasing the field set value above a certain threshold (not much above the planned operational field for SPL), no equilibrium established anymore, cavity fields shaking completely out of control. Evidently such a system cannot be used in a real linac anymore. Disabling all voluntarily introduced system errors and inequalities (RF and mechanical) did not remove this effect and all program checks did not reveal any abnormalities. Thus it became apparent that this observation is in fact a true feature of any system with more than one (Lorentz detuning sensitive) cavity driven by a common transmitter, controlled by a vector sum feedback.

To obtain a heuristic demonstration of such a process, the field level (two cavities) has been adjusted corresponding to a very slow growth; otherwise the system takes off straight away into the chaotic state before establishing any apparent equilibrium[3]. Then this instability, growing out of the noise, does not reach visible size before the start-up transient of the cavities has died out and cavities seem to settle on equilibrium. Only few pulses later the instability takes over destroying system control completely (Fig. 5a-e)
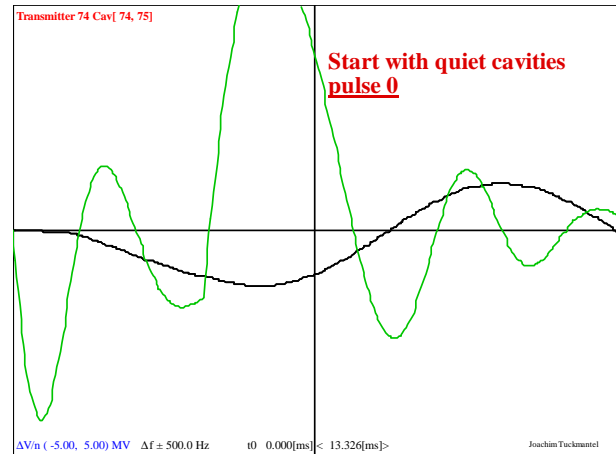

Fig. 5a: Starting with a motionless pair of cavities supplied by one transmitter. Voltage vector sum in blue (real part, not yet visible – zero suppressed plot – for first pulse above) and green (imaginary part), cavity movement in black, both movements graphically overlapping here.

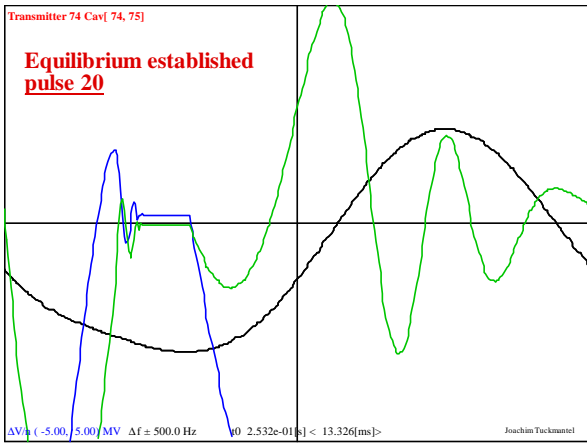[3] this was the main obstacle to the understanding of the mechanism

Fig 5b: As Fig. 5a after 20 pulses, each pulse apparently resembles the previous one. A dynamic equilibrium state, identical for both cavities, seems to be established.
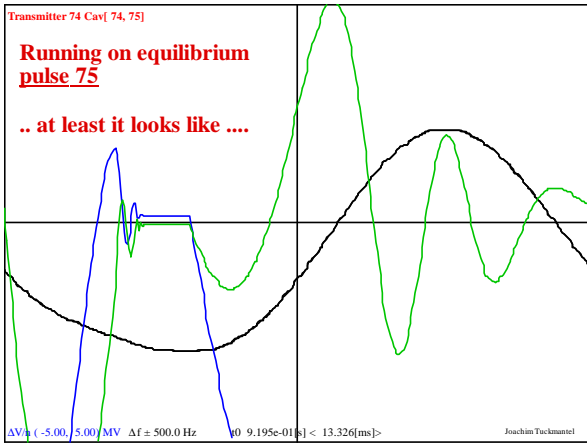

Fig. 5c: At pulse 75, looking exactly as Fig. 5b. It seems that the system will continue like this forever
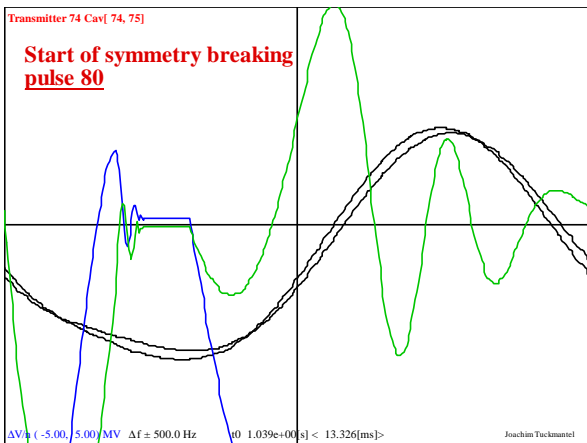

Fig 5d: As above at pulse 80, the movement of the two cavities start to split: spontaneous symmetry breaking takes place
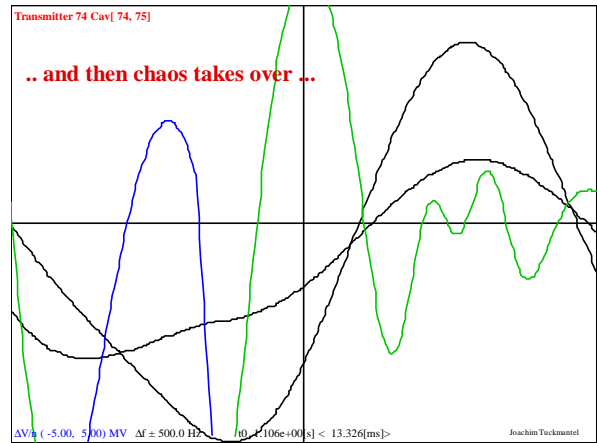

Fig 5e: As 5d for the following pulses, the system enters into an irrecoverable chaotic state.

The above simulation with adjusted field level leads to a first idea on the driving mechanism. We suppose a microscopic scatter in the mechanical movement of the cavities, in reality always present due to noise[4]. Then the RF tuning of the cavities differ microscopically and hence also the excited field levels, only the vector *sum* being forced constant[5]. Due to the scatter in the field levels, the mechanical excitations during the RF pulse, the 'Lorentz kick', are not uniform and hence also the additionally excited mechanical amplitudes. These are still present at the next pulse – reduced by the influence of the mechanical Q-value – and hence the amplitudes again will have a scatter, its size depending on the scatter at the previous pulse. Now it cannot be excluded that the scatter at the following pulse is larger than at the previous one, thus the scatter may grow from pulse to pulse, raising the initially microscopic noise to a macroscopic perturbation.

To demonstrate that the observations with SPLinac correspond to reality and develop comprehension for the decisive parameters and their critical values, a model very close to the real system was designed and analysed mathematically [5]. It shows exactly such behaviour, predicting under which conditions this effect should appear in the *real* system, agreeing with good precision the corresponding SPLinac simulations. In [5] also a demo-program (listing of a few lines) is attached modelling such a system with two cavities. With it one can demonstrate by a very simple numerical application – completely independent from the more painstaking mathematical analysis – that there exists in fact a sharp

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[4] This can be a problem in computer simulations when the calculations for all cavities may be absolutely identical up to the least significant bit, the system apparently remaining stable. Some tiny artificial noise must be introduced then as was done in the demo program in [5]

[5] The voltage sum is the only controlled system degree of freedom, otherwise we have no handle whatsoever on the individual cavity fields or mechanical amplitudes

threshold [6] above which the system starts to diverge, manifesting typical features of chaotic behaviour.

Under certain conditions there appears e.g. a bifurcation where the two cavities alternatively exchange their movement pattern for one pulse to come back again to the original pattern at the following pulse. For other conditions we first diverge and then converge against a state with dynamic equilibrium, repetitive from pulse to pulse, for both cavities, but despite *identical* static cavity parameters *not identical* movement pattern.

2.2 Beam Dynamics Simulations

The program is basically foreseen to simulate bunches in phase space as they travel along the linac through perturbed cavities till the end. Fig. 6 shows a phase space image of a bunch travelling along the linac just passing a certain cavity. The centre most part of the bunch is presented in red, the outer parts in more and more yellow shade. The (relative) cavity voltage as function of time is superimposed as red line, showing the position of the bunch relative to the RF wave. On the screen during the simulation (or in a separate movie) the 'shaking' of the voltage from cavity to cavity due to microphonics or RF system scatter can be observed.
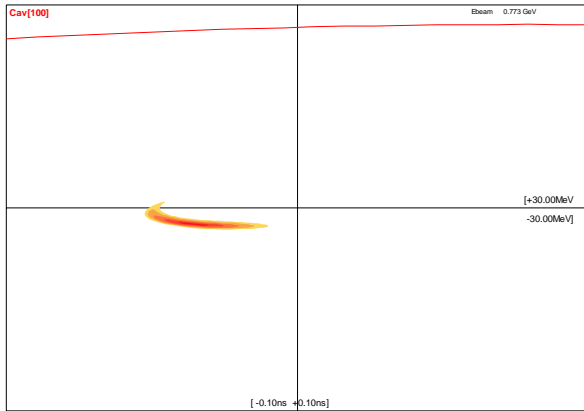

Fig. 6: Longitudinal phase space image of a bunch along the linac (at cavity 100), the RF waveform of this cavity with respect to the bunch is depicted(top) in red

Fig. 7 shows the longitudinal phase space image of such a bunch at the end of the linac (yellow/red) and for comparison the injected bunch (green/blue, flat close to the x-axis); the deformation in longitudinal phase space is clearly visible.

The program allows then plotting of dot maps of the centroids as shown in Fig. 8 or overlay plots of the full phase space area covered at the end of the linac as the example shown in Fig. 9 (the same conditions as Fig. 8).
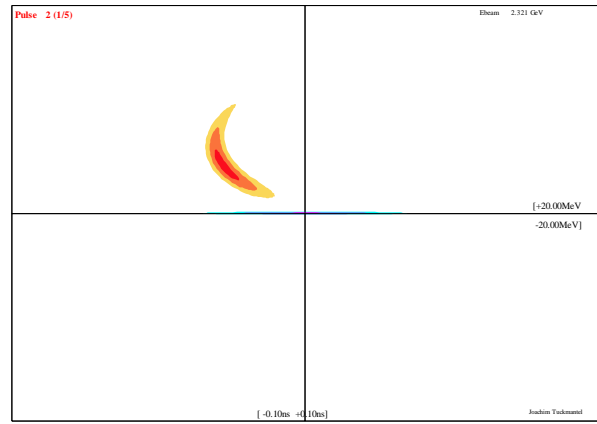

Fig. 7: Longitudinal phase space image of a bunch at the end of the linac (red/yellow) and the injected bunch (centred, green/blue)
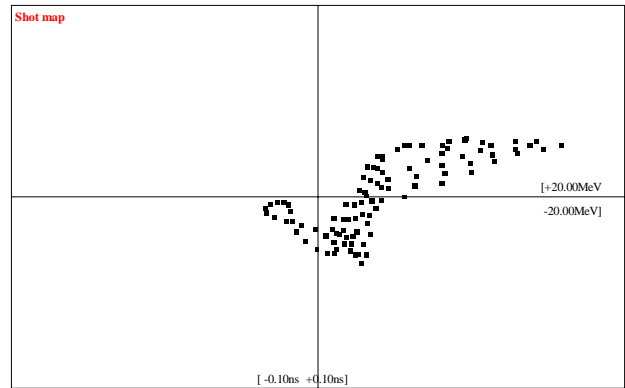

Fig. 8: Centroid dot map of bunches at the end of the linac. This plot pretends to show a much nicer pattern than the full truth as shown in the following figure.
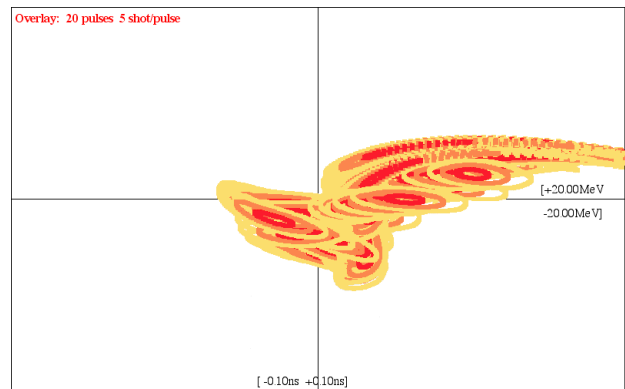

Fig. 9: Overlay plots for many bunches of many pulses depicting the full phase space area 'sprayed' at the end of the linac.

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[6] In fact its value can be predicted exactly by an expression developed in the mathematical analysis!

3 SOME PRACTICAL DETAILS

The program can be started simply clicking its icon. Data are entered using self-explaining panels (example in Fig. 10) and the complete data set for the run is conserved – transparent for the user – available as starter for the following run. Also data sets can be saved separately; clicking then the corresponding 'SPEC' icon (similar to the document of a word processor) will load program and data ready for execution, maybe after some parameter changes. Also pictures (PICT files) are saved keeping the run data set conserved 'in the background'[7] so that all run parameters are permanently linked to the picture. This makes archiving of pictures and their parameters automatic, simply clicking the 'PICT' icon loads the program and all parameters can be enquired. These PICT files can be read into all professional graphics programs allowing post-processing if desired, or can be pasted directly into papers.

Fig. 10: One of the available entry panels, here the one for the cavity and transmitter specifications for a linac section

4 CONCLUSIONS

A new simulation program exists modelling a linac with a realistic RF system and beam offering many different options. The linac is assumed to be composed of sections of different internal parameters, the cavities having β-dependent transit time factors. Fast RF vector (sum) feedback loops control one or several cavities driven by one transmitter. RF feedback loops include limited transmitter power and bandwidth and possibly

loop-delay as well as vector sum calibration errors, power splitting errors and scatter in the coupling strength to the cavities. Beam loading of a pulsing beam can also be considered. Coherent or incoherent mechanical cavity perturbations are possible with scattered or sharp values as well as Lorentz force detuning. Bunches can be defined in full longitudinal phase space representation or as a point bunch.

The program offers a multitude of graphic displays including phase-space images along the linac or at the exit, summary dot-map or overlay plot at the exit as well as all RF quantities of any transmitter or cavity. Precise numbers of voltages, powers, phases or phase-space points in plots can be obtained online at the cursor position in an 'info window'. All plots can be saved as standard graphic files, accessible to professional word-processors or graphic postprocessors and frames may be assembled to movies, showing the dynamics of the system.

The program is easy to use, offering explanatory panels for entering or changing data or options. Default sets of data are saved automatically – e.g. together with a picture file – or on user request, keeping an easy track of the different run parameter sets.

5 REFERENCES

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[7] in a so-called resource fork