Abstract

The beam in a proton linac is very sensitive to field perturbations in the cavities. Therefore a simulation program was written modelling a realistic linac RF system with beam. Fast RF vector sum feedback loops control several cavities with $\beta$-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 can be included as well as beam loading of the pulsing beam. Different modes of mechanical cavity perturbations including Lorentz force detuning and a full longitudinal phase space representation of bunches are possible. A multitude of phase-space and RF quantity plots are available, most of them can be assembled as a movie, showing the system dynamics ‘in real time’.
1. Introduction

For many accelerator calculations and computer 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 This approach is no longer valid for larger perturbations when fast RF vector feedback loops are necessary. In LHC for example the RF system will have to fight heavy beam loading with stepwise changes and thus the factual cavity voltages strongly depend on the loop characteristics. To learn about overall system stability under these conditions and for the specification of RF components that must be ordered it is essential to ‘operate’ the complete system long before the machine really exists. Therefore the author modelled in a previous program ‘RfSyst’ [1] the LHC machine\(^1\) with beam and complete RF system, including the fast RF vector feedback loops with loop delay, transmitter power limitation and transmitter bandwidth.

For a superconducting proton linac, such as SPL [2] at CERN, additional questions such as cavity microphonics and Lorentz force detuning – neglected in the above approach – become important and the degree by which these perturbations can be compensated by the RF loops is part of the feasibility of the machine design. Based on the experience gained with ‘RfSyst’ and adapting some parts of the above software (graphic display and the loop description), a new program ‘SPLinac’ has been developed to study these questions. Different modes of mechanical cavity perturbations, pulsed operation mode with or without beam loading, $\beta$-dependent transit time factors, the possibility of driving several cavities via an RF vector sum with a single transmitter, RF system errors and a full longitudinal phase space representation of bunches are some features of ‘SPLinac’ (version 2.0). Several graphic displays are available for a representation of the beam in longitudinal phase space along the machine and all bunch centres superimposed at its exit. Also cavity voltages and transmitter powers for each desired component are available. As ‘RfSyst’ the program is designed to be interactive, i.e. the ongoing simulation can be displayed on the screen like a movie and by user intervention, the execution can be held, cancelled or its operational mode changed at any time. The program can create series of frames that can be assembled as movies showing the system dynamics.

2. Perturbations of the Cavity Fields and their Influence on the Beam

In a linac with particles of constant speed – highly relativistic ones – a local lack or excess of acceleration will not influence the acceleration efficiency in the following parts of the linac and the final particle energy will simply be different by this amount. Things are worse in a linac with particles of $\beta$ significantly lower than unity, as is the case especially in the initial part of a proton linac. A local change of acceleration will modify not only the energy gained but also the speed of the particle. Therefore drift times to the subsequent cavities change, modifying phase angles and the acceleration in these cavities. A local perturbation modifies parameters globally.

The origins for field variations are multiple. Firstly, the resonant frequencies of the accelerating cavities are not stable due to external perturbations. Some are coherent for the whole linac due to a common origin – e.g. the cryogenic plant or

\(^1\) the program is also ‘general purpose’ and can simulate any synchrotron with any beam configuration
ground motions – some are \textit{incoherent} – \textit{e.g.} different vacuum pumps on different cryostats. Since the loaded bandwidth of superconducting cavities is generally small, even innocent-looking mechanical perturbations can produce a resonant frequency shift of a sizeable fraction of a bandwidth. Secondly, when the field is pulsed, the Lorentz force detunes the cavities with similar effect. Thirdly, the sudden onset of beam loading at the start of the beam pulse creates a fast transient of the cavity fields. In this context it is important to remember that beam loading is not uniform for all – otherwise equal – cavities since the transit time factor changes with the increasing speed of the particles from cavity to cavity, especially important at the beginning of a proton linac.

To fight the consequences of these field variations a vector (sum-) feedback has to be built around cavity and transmitter. However, this system is only capable of reducing the effect but not of eliminating it completely. The loop gain $g$ is limited due to unavoidable delays and noise so that the fraction $1/g$ of any original perturbation remains. Also all fast transients are only compensated within a time-scale of the cavity filling time divided by the loop gain $g$, and the bunch position in phase space as seen at the end of the linac varies rapidly along the beam pulse.

\textbf{2.1 Multi-Cavity Operation with one Transmitter}

An additional difficulty arises when (for cost reasons) a single transmitter drives several cavities via a vector (complex or amplitude and phase) \textit{sum} feedback. Mathematically the complex sum of individual cavity voltages, phase-adjusted for the particle’s time of flight, expresses the equivalent RF voltage as seen by the particles. In practice time of flight is defined for a design particle. The RF vector sum is built up from the measured, phase corrected, individual cavity voltages to give a signal imaging the equivalent RF voltage of the whole family of cavities. This signal is fed into the control loop as ‘measured cavity voltage’.

For particles with constant speed – \textit{i.e.} $\beta$ very close to 1 – the time of flight is invariant and the phase adjustments set into the summing device are always correct, thus the sum signal correctly images the total voltage independently of the individual components of the sum. However, for slower particles this is no longer completely true. Any change of cavity voltage also influences the speed of the particle and thus the time of flight for the following cavities. Therefore the phase adjustments in the summing device do not correspond to reality any more and the sum output signal does not image precisely the total voltage gain. However, the feedback loop will do its best to stabilise this erroneous signal, thus inducing residual voltage errors depending on the individual cavity voltages.

A vector \textit{sum} feedback only offers the same precision as for a single cavity when \textit{each} cavity is \textit{stabilised individually}. With a common transmitter this is only possible when all cavities show exactly the same perturbation, coherent and in phase. This is also important to keep in mind for the onset of beam loading where cavities may be charged differently. Then the vector sum is stabilised quickly by the feedback but the individual cavities will drift with their filling time – not reduced by $1/g$ as for the vector sum – towards their new equilibrium.
2.2 Real Life System Errors

Finally there are practical imperfections in the real hardware, particularly perturbing for families with several cavities per transmitter. Errors in the power splitting network result in cavities with unequal excitation in amplitude and phase. As we have seen above each deviation from the design voltage – for which the vector sum device is calibrated – leads to errors in the measured equivalent field. The scatter in the coupling strength of the main couplers causes a similar effect and additionally produces a non-uniform beam loading. Furthermore, the vector sum devices themselves will contain calibration errors. All these errors lead the feedback system to correct a slightly wrong signal, not the true equivalent voltage, thus leaving residual errors.

Also the Lorentz constant \( k_L \), expressing the static frequency shift per square of the accelerating field, may have a scatter over different cavities, important if one transmitter drives several cavities.

To study the influence of all these perturbations and system errors on the beam – including the RF feedback loops and their real life limitations – this computer program was written. It simulates the acceleration of bunches in full longitudinal phase space representation along the whole linac. To localise the origin of the worst perturbations, the measured and ideal RF vector sum, individual (complex) cavity fields including beam loading, frequency deviations, and generator and reflected power can be plotted for each transmitter family. Numerical values of any point in any plot can be read in a special window, simply setting the mouse cursor to it and clicking. Further information can be obtained from online ‘movies’ showing longitudinal phase space images of bunches travelling along the machine together with the jittering local RF voltage.

3. Short Description of the Working Algorithms

Each cavity is represented as an instantly accelerating centre plane between two drift spaces. These equivalent centre planes are positioned along the linac according to the machine specification and the RF parameter set-up takes place using a reference point bunch. Starting with the injection energy the bunch drifts to the first cavity centre plane. The phase of this cavity field is then adjusted to match the synchronous phase angle, this and the absolute field amplitude being part of the linac specifications. The bunch is accelerated instantly with this freshly defined cavity field and drifts with its new \( \beta \) to the next cavity centre, defining there the next nominal cavity field. This process is repeated till the end of the machine, thus fixing all nominal cavity field parameters. Then vector sum and power distribution network of all families consisting of one transmitter and its cavities are adjusted to obtain the nominal settings. Finally optional system errors are introduced. To avoid repeating identical calculations, sets of constants depending on stable parameters are established as far as possible and used later.

The feedback loops, transmitters and cavities apply the same algorithms as in [1] but use a vector sum instead of a single field value. Quantities oscillating with the RF frequency (e.g. the cavity field) are treated as time-dependent complex amplitudes changing slowly compared to \( \omega \). This allows analytical self-consistent solutions of the system proportional to \( \exp(i\omega t) \) with constant or exponentially moving RF amplitudes.
to be used. These are valid for a short (user defined) clock tick\(^2\), lasting several RF periods. After each clock-tick the feedback status is updated for each transmitter and its cavities thus defining new amplitude parameters. This clock-tick should be as long as possible for CPU time reasons but must be short compared to all other time scales (mechanical perturbations, cavity filling time, inverse transmitter bandwidth) except the RF period itself; the author worked with 500 ns for SPL. If a linear feedback loop delay is included in the simulation, the clock-tick must be shorter than, say, a quarter of the loop delay, thus in general much shorter than without this option and CPU time will be increased correspondingly. In practice it was demonstrated that the simulation of the loop delay does not change results provided other natural delays (e.g. the cavity filling time) are longer. Therefore a test run is recommended to show that parameters do not essentially change when loop delay is applied so this option should no longer be activated.

Since the mechanical oscillations are expected to be much slower than the basic clock-tick, the mechanical quantities and the corresponding tune-dependent RF quantities are updated with a ‘mechanical clock-tick’. The latter is also user defined, much longer than the basic clock-tick, but must be sizeably shorter than the mechanical period lengths; the author worked with 0.1 ms for SPL.

Beam loading – if the option is chosen – is assumed to be created by the nominal beam.

The time of flight of a bunch through the whole linac is very short (a few \(\mu\)s) compared to the time scale of the perturbations. Therefore, the mechanical quantities of the linac can be assumed to be 'frozen' while a bunch passes from cavity to cavity. All macro particles of a bunch in longitudinal phase space representation – or only the central particle for the simplified point bunch option – are tracked from cavity to cavity, being accelerated according to the actual perturbed cavity voltage and phase angle.

4. Parameters of the Simulation

In this section we will describe all necessary and possible data for the simulation and the variety of available options. Practically data are entered using (nearly) self-explanatory panels, avoiding input with cryptic text files. Each data set can be saved completely – by simply clicking the ‘Save specs’ button and naming it in a ‘file dialog box’. It can be re-used later by double-clicking the created SPECS icon (details see later). We introduce now the simulation parameters and show in parallel the corresponding panels avoiding describing parameters twice. To allow smooth handling of series of runs, the parameters of the last executed run are used as default when panels open (exceptions see later). The main panel always appears at start up of the program waiting for a user command.

\(^2\) which has nothing in common with the computer’s clock tick
4.1 Global Specifications

The particles used (protons or electrons) are chosen by radio button and a title for the calculations can be filled in. The basic (lowest) RF frequency (e.g. 352.209 MHz) appearing in the linac has to be defined – all RF systems will be forced to work at an integer multiple of this frequency. Linac pulse rate, beam pulse length, RF rise time before the beam pulse, average beam pulse current and injection energy have to be specified. The RF rise time has to be large enough to allow all sections of cavities to reach the design field. This condition can be checked using the corresponding display options (see later). For the full bunch presentation the longitudinal phase space ellipse of the injected bunch has also to be defined by ±dt and ±dE.

Furthermore the calculation’s basic clock-tick has to be specified. The latter will automatically be forced to become an integer multiple of the basic RF period (e.g. 500 ns forced to 496.86408 ns at 352.209 MHz). The (much slower) mechanical clock-tick has to be defined as well (e.g. 0.1 ms); this time lap will also be forced to become a multiple of the basic RF period. Beam loading and feedback modelling with loop delay may be chosen by a check-box.

The linac itself is considered a sequence of different sections. In the main panel each section considered to be part of the linac needs its ‘active’ check box (left) to be chosen. The linac starts logically from the top most checked section towards the
lowest checked one; any section not checked disappears. This allows ‘switching’ sections on or off, thus giving an easy reconfiguration of the linac for comparisons and tests. Detailed parameters for each section are defined in a sub-panel, described in the following chapter. Such sub-panels will only open (one after the other if several) if the ‘show’ box in the main panel was checked, otherwise the existing ‘old’ data will be used.

4.2 The Linac Section Definition

![Sub-panel to define parameters of a section of cavities](image)

The linac itself is considered as a series of sections, each with different internal parameters, installed one behind the other. Mechanically each section is made of a sequence of equidistantly spaced identical modules (i.e. cryostats), each module housing a fixed number of equidistantly spaced identical cavities. RF-wise the same section consists of a number of identical ‘families’, each with one transmitter, supplied cavity (or cavities) and the vector (sum) feedback. Each transmitter supplies a sequential series of cavities. A series may bridge modules, but not sections.

The sub-panel allows a mnemonic title to be defined in the top line. This will later appear again in the main panel in order to easily recognise if a section is active or not.

The allocation of cavities along the linac is defined by

- Number of modules in this section
- Number of cavities in each module
• Distance from cavity centre to cavity centre within the module

• Distance from the last cavity centre to the connecting plane of the next module. (Focussing elements have to be included in the latter distance.)

The cavity RF parameters are defined by

• Nominal $\beta$ of this cavity section (R/Q is defined for this $\beta$)

• Number of cavities per transmitter

• Nominal cavity frequency (forced multiple of the basic frequency)

• $Q_0$ (only important for normal conducting cavities, otherwise any very large number will do)

• Coupling strength expressed by $Q_{\text{ext}}$

• Cavity $(R/Q) = \frac{V^2}{2 \omega U_{st}}$

• Relative static detuning in df/f

• Nominal voltage, expressed for the nominal $\beta$

• Nominal RF phase angle

• Three pairs of $\beta$ and (relative) accelerating voltage, covering the expected $\beta$-range

If the total number of cavities in this section (number of modules times number of cavities in each module) is not an integer multiple of the number of cavities per transmitter, then the last few ‘overhanging’ cavities are supplied by a separate but otherwise equivalent transmitter.

The cavity frequency has to be an integer multiple of the basic RF frequency of the linac as defined in the main panel; if this is not the case it is slightly adapted to become the closest exact multiple. To define the dependence of the voltage on the speed ($\beta$) of the particles, a parabola is used as (fast) approximation and the three values of beta and relative cavity voltage have to be specified defining this parabola. It is preferential if the chosen points completely cover the used $\beta$–range. The factual accelerating voltage is determined to be such that for a particle with the nominal $\beta$ the nominal voltage is realised, others are scaled using the parabola. The external perturbations for this section are according to the checked options:

• The amplitude of the cavity vibration (i.e. the stroke of RF resonant frequency shift); if the check box ‘distr. vib. Ampl.’ is not checked, all amplitudes are fixed, otherwise the effective amplitudes are distributed at random between zero and this value.

• The frequency with which the cavities vibrate (coherent case)

• The scatter of these frequencies (incoherent case); if the check box ‘distr. vib. freq.’ is not checked, the unique frequency is applied, otherwise the vibration frequencies
used are scattered at random uniformly with this range (±) around the coherent case frequency.

- The phase of the vibration; if the check box ‘distr. vib. phase’ is not checked, the unique phase is applied, and otherwise the phases used are scattered at random uniformly between ±180°.

Externally driven cavity vibration can be switched off by choosing ‘vibr. freeze’

The Lorentz detuning parameters for this section are according to checked options:

- The (steady state) Lorentz detuning constant in Hz/MV².

- Scatter of this Lorentz detuning constant in Hz/MV²; if ‘distr. LorConst’ is not checked, the fixed value is applied, otherwise the Lorentz constant is scattered at random uniformly with this range (±) around the fixed value.

- The mechanical eigenfrequency of the cavities (important for resonant build-up with Lorentz detuning and pulsed beam)

The scatter of those frequencies; if the check box ‘distr. f₀.mech.’ is not checked, the unique eigenfrequency is applied, otherwise the mechanical eigenfrequencies used are uniformly scattered at random with this range (±) around the unique eigenfrequency

- The mechanical Q-value (important for resonant build-up); a scatter of this quantity is not very relevant, thus not foreseen.

If the check box ‘Lorentz freeze’ is chosen, no Lorentz detuning takes place.

The transmitter and the feedback loop are specified by

- The peak power

- The bandwidth

- The (complex) loop gain

- Optional: the loop delay

The latter should only be used for checks; the option has to be activated for all sections at once in the main panel. To obtain the desired set-value in reality, a correction by (1+g)/g of the desired value can be switched on. Mainly for tests or isolation of a problem, the nominal stable cavity voltages can be forced for a section, simulating a perfect section. Furthermore the feedback system can be switched off, the transmitter being driven at constant power to obtain the nominal fields if there are no perturbations and no beam.

The RF system errors for this section are specified according to the chosen options:

- The vector sum field error; the erroneous complex vector sums are scattered at random uniformly in a circle around the true complex vector, the relative radius of the
circle is specified here in %. If the check box ‘Vector Sum error’ is not checked, a perfect vector sum is assumed.

- The power splitter field (not power) error; the erroneous complex coupler currents are scattered at random uniformly in a circle around the true complex vector, the relative radius of the circle is specified here in %. If the check box ‘Power split error’ is not checked, perfectly equal splitting is assumed.

- The $Q_{ext}$ error in %; the erroneous coupling constants are uniformly scattered at random by this percentage ($\pm$) around the nominal value. If the check box ‘$Q_{ext}$ error’ is not checked, perfectly uniform coupling is assumed.

It is important to compare two otherwise identical machines but one with an additional type of error. To get an unbiased comparison, one has to avoid that activating a new type of error changes the random attribution of the errors initially already present. Therefore care has been taken that the sequence of random calls is invariant, i.e. errors depend only on the seed (or are zero if the option is not checked).

All detuning effects are switched off by checking ‘ignore all dyn. detuning’. The button ‘OK’ (or RETURN on the keyboard) accepts the specified data and returns to the main panel. ‘Revert’ scratches all modifications done in this panel and restores the initial settings. ‘Cancel’ abandons the whole run; all modified data in all panels are ignored.

4.3 Phase Space Plots

Coming back to the main panel we also find the run and output options. Bunches will be tracked through the whole linac if the ‘Pulses’ box is checked. The number of beam pulses considered is defined as well as the number of reference bunches – called ‘shots’ – equally distributed along a beam pulse, allowing the influence of beam loading to be studied. Also the sequence of $dt$ and $dE$ – i.e. the deviation from the nominal bunch – along the linac for each shot can be presented, choosing ‘$dt,dE$ along linac’; precise numbers can be obtained with the ‘info-window’ (see later). For practical reasons the program can be asked to wait (hold) at the end of each shot (restart for next shot by the user with Cmd-G, see later) or to continue immediately after a specified display time. When all shots are done$^3$ the centre particle of each bunch – which is not necessarily the centre of mass of the bunch if the latter is heavily distorted – will be displayed as a dot-map in longitudinal phase space.

Choosing the check box ‘Full bunches’, defining the number of particles per bunch (and having defined the injected bunch dimensions in $dt$ and $dE$), allows bunches in full phase space presentation to be tracked along the linac. If ‘PhSp along linac all . cav’ is checked, a longitudinal phase space plot each nth (to be filled in) cavity is displayed as an ‘online-movie’. The jittering RF voltage of the cavities can also be displayed (‘plot also Vacc’). The number of shots for which this display is done can be limited by ‘max. plot shots’ to avoid memory overflow.

Bunches in longitudinal phase space representation can have different display modes. If no option is checked, the specified number of points (macro particles) are scattered

---

$^3$ If no other plot is active each shot is displayed online to keep the user informed that things progress
uniformly in longitudinal phase space inside the specified injection ellipse. Each new run will apply another independent random set using the system clock as seed if ‘clock seed’ is checked, otherwise the user defined seed defines the (repetitive) starting point. The ‘regul. bunch’ option creates points sitting on equally spaced concentric ‘ellipses’ (number of ‘rings’ to be defined) at injection, allowing observation of the deformation of different bunch regions. These points are displayed using one of five ‘markers’ to be chosen by radio button; the size of the marker in pixels can be modified. The option ‘paint bun.’ does not display points but fills the area between adjacent ‘rings’ with different colours. Colours were chosen by the author for good visibility for the injected bunch (from violet to cyan) and the travelling bunch (from red to yellow). These choices may be changed using the option ‘choose col.’. The Macintosh ‘colour picker’ will open at the start to ask for the user request concerning these colours.

Also in phase space precise numbers in dt,dE can be obtained with the ‘info-window’ (see later).

4.4 Periodic Lorentz Detuning

The ‘periodic Lorentz force’ option is not yet operational.

4.5 RF parameter plots and Checks

The transit time factors of the different sections as a function of $\beta$ within the specified $\beta$-range can be verified (‘show TTs’); precise numbers can be obtained with the ‘info-window’ (see later). Other RF parameter plots show what is going on during pulsing in a family of transmitter with cavities and these plots are thus a strong diagnostic tool. A single transmitter in a section can be chosen (counting starts at zero for both) and voltages, powers, detuning and RF-phases for this transmitter and its supplied cavities can be plotted against time; several consecutive plots are possible. Again, precise numbers can be obtained using the ‘info-window’ (see later). These plots show points spaced by a multiple (e.g. 20) of the basic clock tick. RF may be pulsed with the predefined pulse rate; beam loading can be taken into account or not. This type of plot is designed to observe the parameters during ramping, injecting the pulse and the decaying field after RF switch-off. The cavity resonant frequencies will have only small changes during this short time, thus for a larger spacing the behaviour of the system can be observed for many mechanical oscillation periods; e.g. with Lorentz detuning the (possible) establishment of a stable dynamic equilibrium can be studied with multiple consecutive plots, best one pulse per plot.

The plot scaling is defined in the lower right part of the panel. For the longitudinal phase space plots minimum and maximum of dE and dt have to be filled in. The scale for RF voltages – in fact deviations from the set-values - the powers (zero at the bottom per default) and the (symmetric) frequency stokes are also defined there. The generator phase is plotted per default over ±180°.

These plots may have many traces but are easy to read while the different colours of the traces are distinguishable; it is, however much more difficult in a black and white presentation. The option ‘define traces’ allows a few of these traces to be picked out and the results to be displayed on a few separated plots. A secondary panel will open to define which quantities should be displayed in the following run.
4.6 Run Options

The interactive structure of the program allows two modes of operation. If ‘auto run’ is checked the program displays a requested plot, waits for the agreed time (‘wait sec.’) and continues; otherwise the program stops after each plot and has to be restarted manually. Using Cmd-H (hold) and Cmd-G (go one frame) or Cmd-A (auto-run) allows changes to be made online from one mode to the other (details see later).

4.7 Plot Outputs

Any plot displayed on screen will be lost for future use if not marked otherwise. Marking can be done by typing Cmd-P - a ‘camera click’ will be heard to acknowledge the ‘snapshot’ - while the plot is displayed on screen. A second possibility is to choose at start of the program the option ‘HC’ (hard copy) for this group, saving all plots of this group or, third, choosing ‘Hardcopy All’, saving any plot produced. The marked plots will be conserved for later printing/plotting or saving onto a PICT file. Attention: memory is limited, so very long series of blind ‘hard copy’ plots may force the program to abandon (there is no limitation for movie frames, they will be written to disk immediately).

The option ‘overlay mode’ (main panel) allows the assembly of full phase space representations graphically overlayed for many ‘shots’ to illustrate the whole swept-over phase space; also RF plots can be overlayed for comparison. Choosing this option, frames and text are omitted except in the first plot, thus the overlay has only one frame and no mixture of different texts.

All plots are created internally as vector graphics using a reference frame of several thousand pixels in both directions. When rendering, this picture is scaled to fit the screen or output device, producing high quality output on high resolution equipment. However, it is possible to force a different frame size internally and on the screen in checking in the main panel the option ‘frame’ and defining the new frame dimensions in x- and y-direction in pixels before starting the program. This does not change the storage requirements (vector graphics), but quality may be different and since text fonts are not scaled here, it may produce text overlap.

When all simulations are terminated – or abandoned by Cmd-. – a panel appears and the marked ‘snapshots’ will be treated in logical groups as they were created. Plots can be grouped in frames of 1, 2, 4, 6 or 8 plots per page (radio button). The author name is printed bottom right of the page. Frames can be previewed first on the screen; clicking into the displayed frame advances to the next one, clicking the ‘close box’ skips all plots of this group and goes to the next group (cyclic), identical to
choosing ‘Next Group of Plots’. They can also be saved on standard graphic (PICT) files or sent to the printer; ‘portrait’ or ‘landscape’ orientation will be determined in the printer driver panel. If ‘Assemble Overlay’ is checked, all plots of one group are displayed graphically on top of each other in a single frame, it is recommended that the ‘overlay mode’ be chosen on the main panel before execution (see above). ‘Exit Program’ finishes execution and ‘Save specs’ gives a last chance to conserve the actual run specifications.

Fig. 4: Panel to route and group final output

### 4.8 Movies

When the option ‘movie’ is checked, scaling is changed for the output format and colours will be adapted for increased contrast, e.g. the background will be black instead of white. Also here the option ‘frame’ can be checked, forcing the movie canvas size in x- and y-direction (pixels). Without ‘save frames’ there is only a preview run on screen; with ‘save frames’ a ‘file dialog box’ opens to choose the series name – a separate folder should be used for each series – and frame after frame are saved. The user may interrupt at any time. The file names are of the form name.xxxx, xxxx being consecutive 4-digit numbers starting with 0001. To avoid overwriting an existing series, the presence of the file name.0001 is checked. If it does not exist or the user decides to overwrite it, all existing files name.xxxx are overwritten without further checks. These frames are standard graphic PICT files. A resource fork with the run specifications will be added to file name.0001 but not the following ones.

These frames can be assembled to a movie by professional video programs, the author used QuickTime® for it. PICT files are a native format for it and thus it does not convert vector graphics into inefficient pixel maps (as some other video programs do producing MPEG) but keeps the compact vector graphics. Therefore, e.g., a phase space movie of a colour-ring bunch travelling along the whole linac with 230 cavities (i.e. 230 frames) needs only 325 Kbytes of storage. The resulting QuickTime®
movies can then be displayed off-line on any other computer\textsuperscript{4}. While discarding the series of files name.xxxx after movie-assembly, it is recommended that file name.0001 together with the movie, should be conserved, thus archiving the run parameters.

Instructive movies are

• A bunch in full phase space representation travelling along the linac from cavity to cavity executing synchrotron oscillations

• A sequence of bunches arriving at the end of the linac with vibrating cavities or Lorentz detuning

• Displays of dt and dE along the linac from ‘shot’ to ‘shot’ with vibrating cavities or Lorentz detuning, showing ‘bumpy’ areas of the linac

• RF parameters with Lorentz detuning, showing a view as seen on a multi-trace colour scope. In this case it is recommended that the length of the plot be chosen to be such that it corresponds to an integer multiple of linac pulses.

4.9 Starting Execution

Clicking ‘GO’ (or hitting the RETURN-key on the keyboard) starts execution or opens a sub-panel if one of the ‘show’ check boxes has been chosen. ‘Revert’ scratches all data modifications done in this session and offers the initial ones again, ‘Cancel’ abandons, the modified data are not saved.

5. Program Execution and Practical Features

The program is executed on a (Power-) Macintosh\textsuperscript{5}. It can be started by double-clicking either the application icon, or one of the document icons, i.e. a SPECS icon or a PICT icon. The main panel will open in any case, waiting for user request.

![Fig. 5: Application icon, specifications icon and picture file icon](image)

If we execute the program by double clicking the application icon, the specifications of the executed run are automatically saved at start of execution in a ‘hidden linked file’, the so-called resource fork, the operation being transparent for the user. When double clicking the application icon again the next time, these specifications are automatically default; the last run can be repeated identically or

\textsuperscript{4} Many web-browsers have already QuickTime installed since it can handle many graphic and video standards. If not, it can be downloaded free of charge at [http://www.apple.com/quicktime/download/](http://www.apple.com/quicktime/download/). Careful: there exist Macintosh and IBM-compatible 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)

\textsuperscript{5} The author has more than 10 years of experience with the Macintosh OS and developed as hobby programmer a lot of (more or less) useful software partly incorporated in several ‘official’ programs
settings may be modified in the panels. The specifications as executed are saved automatically into the resource fork, *overwriting the initial ones*.

Specifications can be archived by saving a SPECS (resource-) file by clicking the SAVE button in the main panel. (This button is also available in a few other panels.) A file dialog allows a name to be given and an icon will appear\(^6\). To recall these specifications in future, double clicking this SPECS icon loads the application with the archived parameters and opens the main panel waiting for user request. (This is like double clicking the document icon of a word processor text: it loads the word processor itself and opens a window with the text displayed.) On request the executed run specifications may be saved into the resource fork of the *application* – overwriting the existing ones - so that double clicking the application icon the next time will load *these* specifications; if this option is refused, the existing specifications in the application will be conserved.

Standard Macintosh graphics PICT files can be created from plots internally saved (see above) during execution. These files can then be imported into publications (‘Insert from file’) written with a standard word-processor such as MS-WORD® or post-processed by professional graphics programs (‘open file’) such as Claris Works®, Adobe Photoshop®, or GraphicConverter®. These PICT files also carry the resource fork with the specifications of the run (as the first movie file name.0001). Double-clicking a PICT file is then equivalent to double-clicking a SPECS file, the corresponding PICT file run parameter recordings are set ready to go or to be modified. Using this method of ‘book-keeping’, which picture was created under which conditions becomes trivial and a comparative run with slightly modified conditions can be started immediately without possibility of errors. Also here the run specifications may be saved in the *application* resource fork or not.

The following short cuts can be used interactively during execution (in the actual version there are no corresponding menus) interrupting execution and smooth continuation is foreseen for most requests.

- **Cmd-Q**\(^7\) Quit program completely, scratch saved ‘snapshots’ if they exist
- **Cmd-.** Stop simulation, go to plotting if saved ‘snapshots’ exist, else exit
- **Cmd-P** keep actual screen as ‘snapshot’ to be plotted or saved on PICT file later; a camera click sound confirms the action. If Cmd-P is typed several times for the same plot or together with the automatic ‘HC’ option, only one copy is kept.
- **Cmd-X** Abandon actual simulation group, go to the next group
- **Cmd-H** Hold simulation (allowing to study a screen plot if in ‘autorun’ mode)
- **Cmd-G** Go to simulation for next frame (after hold or without ‘autorun’)
- **Cmd-A** Continue simulation, switch to ‘autorun’ mode

\(^6\) This archiving feature can also be used to avoid storing lengthy plot (PICT) files on disk for long time if they can be recreated relatively easy from such a SPECS file.

\(^7\) ‘Cmd’ is the key with the ‘apple’ on it, to be held down while typing the second character
**Cmd-T**  Show panel to ‘tell’ static quantities of chosen family on screen.

After choosing on the panel a print-window opens displaying the desired quantities for the transmitter and connected cavities such as $Q_{ext}$ applied mechanical frequencies, …

![Fig. 6: Sub-panel for static data for a transmitter and/or cavity](image)

**Cmd-I**  Show ‘info window’ for dynamic quantities in a plot (see below)

### 5.1 The ‘Info-Window’

![Info Window](image)

Fig. 7: Info-window digitising the quantities under the mouse cursor
The ‘Info Window’ is a special feature available for all plots of the program. When hitting **Cmd-I** the simulation is frozen and an ‘info window’ opens empty. When the mouse cursor is placed on the screen in an RF plot and the mouse button is clicked, time, cavity RF-voltages, sum voltages and transmitter and reflected power values at the mouse x-co-ordinate are digitised. All data are printed in the ‘info window’, each with the same colour as the graph of the corresponding quantity in the plot. If longitudinal phase space plots are on screen, dE and dt in longitudinal phase space of the x and y mouse co-ordinate are digitised. At each mouse-click at another place the corresponding data are digitised and printed.

This feature allows precise numbers to be obtained at each instant – e.g. to determine peak voltages or powers, worst phase space deviations - and these results can also be compared with calculated data for simple cases and used for program checks. If accidentally the window covers an interesting region, taking the header bar allows it to be shifted elsewhere. Clicking in the ‘close box’ (top left) lets the window disappear again and simulation resumes, clicking in the ‘shrink box’ (top right) lets the window shrink to the header bar.

6. Examples of Results and Program Checks

In the following we shall show a few examples using data for the CERN SPL project. First diagnostic outputs will show the behaviour of a transmitter supplying four cavities.

![Diagram of Transmitter 74 Cav[74, 77]](image)

**Fig. 8:** Overview of all parameters in one plot. See text and following figures
Fig. 9 to 12 show these data; Fig. 8 contains the same data displayed together in a unique presentation. On the left the RF is switched on, starting to load the empty cavities to the nominal field. Fig. 9 shows the RF power (red) rising with the highest speed possible with the generator power and bandwidth, soon hitting its maximum power. Fig. 10 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 real parts change only to second order with the resonant frequency change; thus the real parts of the cavity voltages are nearly identical and all four are graphically on top of each other. The true sum voltage 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. 9 (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 cavities of this section have the parameters $f=352.209$ MHz, $Q_{\text{ext}}=3 \times 10^6$, $R/Q=192$ Ω and $V_{\text{nom}}=15.3$ MV per cavity. Therefore analytically the power for four cavities comes to 203.2 kW, while Fig. 9 (precise numbers by ‘info window’ with RF system errors switched off) tells 203.8 kW in very good agreement.

The quadrature voltages are shown in Fig. 11. When the real part of the measured sum voltage 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, the latter being traced in Fig. 12.

Transmitter 74 Cav[ 74, 77]

Fig. 9: Transmitter (red) and reflected (magenta) power, range 0-1MW. See text
Fig. 10: Cavity voltages and vector sum voltages (real component, zero suppressed: the nominal value corresponds to zero, range ± 2MV) Light blue the four individual cavity voltages, dark blue true vector sum, orange measured vector sum including calibration errors. See text

Fig. 11: As Fig. 10 but quadrature voltage component (imaginary part). Light green the four individual cavity voltages, dark green true vector sum, cyan measured vector sum including calibration errors. See text
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; thus the average relative transit time factor amounts to 0.76 as shown in Fig. 13 for this energy or beta range. For a beam of 11 mA and a phase angle of –15° analytically we expect a transmitter power of 515 kW, from Fig. 9 (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 (‘info window’, Fig. 10) the measured sum voltage drops in fact by 0.364 MV. 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. 10. Due to differences in transit time and phase angle, cavities are loaded differently by the beam. 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). At injection the transmitter power also rises quickly to supply the necessary power. 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. 11).

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 cavity (Fig. 9). All cavity voltages decay, approaching zero with the apparent exception of the imaginary voltages in Fig. 11. The imaginary voltage increase is caused by the fact that the feedback is not active any more 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 be.

Fig. 14 displays (as a unified plot) the same variables, however over a much longer time scale, showing several mechanical cavity oscillations. Beam loading does not exist and – apart from the first powering up – the RF is not pulsed. This plot allows studying how the cavity voltages with feedback follow the detuning and can be compared with theoretical expectations.

Fig. 15 shows a cavity with Lorentz detuning, $-0.75 \text{ Hz/(MV/m)}^2$ are assumed as Lorentz constant. 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 transmitter supplies only this single cavity and it was statically ‘pretuned’ by +200 Hz in such a way that it just oscillates through the resonant frequency when ‘RF up’ is requested, i.e. when loading and during beam pulse. The plot shows the dynamic equilibrium status after the mechanical transients have just about died out.
Fig. 12: The frequency drifts of the four cavities, range ±20 Hz, see text

Fig. 13: The relative transit time factor for $\beta=0.8$ cavities, see text
Fig. 14: Cavity oscillations and RF parameters over several mechanical periods (100 ms) no pulsing RF. Traces as in Fig. 8-12

Fig. 15: 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 in black, range is ±500 Hz; the loaded bandwidth is about 120 Hz.
Fig. 16: Longitudinal phase space image of a bunch at the end of the linac (red/yellow) and the injected bunch (centred, green/blue).

Fig. 17: A typical output assembly: Collection of 8 reference bunches (‘shots’) for one beam pulse.
Fig. 16 shows the longitudinal phase space image of the bunch at the end of the linac in yellow/red and for comparison the injected bunch in green/blue (flat close to the x-axis); the deformation in longitudinal phase space is clearly visible. Fig. 17 shows a typical display of eight such consecutive images assembled in one frame.

Fig. 18 follows the centre particle of this bunch as it travels along the linac. Plotted is the energy deviation with respect to the design bunch in red, the time deviation in green. The synchrotron oscillation of the bunch is clearly visible.

Fig. 19 shows the same bunch in a longitudinal phase space snapshot at cavity 100 (arbitrary choice). The red line close to the top is the RF voltage profile of this cavity. While the program is simulating and this option is active (graphics costs some CPU time!) the user can observe the bunch deformations and the RF voltage wiggle due to cavity perturbations along the linac as an online movie.

Fig. 20 finally shows as a dot map the points in longitudinal phase space where a collection of centroids of bunches arrives. Here five reference bunches were ‘shot’ equally distributed over each beam pulse; 50 beam pulses were simulated. There exist clearly two patches; the upper right one displays the ‘virginal’ bunches which pass first for each beam pulse not feeling any beam loading. Since the new and – despite the feedback loops - different equilibrium voltage establishes very rapidly, all following reference bunches in the same beam pulse (nearly) feel the same voltages and are thus grouped elsewhere. In reality the beam will sweep very rapidly from the point without beam loading to the one with full beam loading, and stay there till the end of the pulse.
Fig. 19: Longitudinal phase space images of a bunch along the linac (at cavity 100), the RF waveform of this cavity with respect to the bunch is depicted in red above.

Fig. 20: Shot map of 50 pulses, 5 reference shots per pulse. The upper right blotches are formed by the first bunches in the pulse where cavity fields are not yet modified by beam loading, the following bunches end up in the other blotch.
7. Conclusion

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 $\beta$-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.

The program is easy to use starting by simply clicking the program icon or a document icon. It offers 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. Frames can be assembled to movies, showing the dynamics of the system.

References
