Real Time Digital RF Control for the TESLA Test Facility

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Abstract

The superconducting cavities in the TESLA Test Facility [1] are operated in pulsed mode at gradients of up to 25 MV/m with each klystron driving multiple cavities. Significant Lorentz force detuning and control of the vector-sum are the main issues for the low level RF controls. A digital feedback system has been developed to provide flexibility in the control algorithms, precise calibration of the vector-sum, and extensive diagnostics and exception handling. The main features are the sampling rate of 1 MHz for the individual cavity signals, digital in-phase and quadrature detection, calculation of the vector-sum which includes gradient calibration and the correction of phase offsets, and the feedback algorithm. Measured performance results of the RF control system will be presented.

I. TTF RF SYSTEM

The acceleration section of the TTF Linac will consist of 64 superconducting cavities each providing an accelerating voltage of up to 25 MV. The first cryomodule with 8 cavities has been installed in April 97. The RF system must therefore supply up to 200 kW/m of pulsed RF power to the cavities to maintain the maximum accelerating voltage at the design electron beam current of 8 mA (25MV · 8mA = 200 kW). The accelerating field must also be stabilized to 0.5% in amplitude and 0.3 degrees in phase to achieve the desired low energy spread of 10^{-3}. An active feedback system is required to provide the necessary field control in presence of field perturbations caused by microphonics, Lorentz force detuning and beamloading.

The design of the RF feedback is complicated by fact that up to 32 cavities will be driven by a single 10 MW klystron. The RF control system must therefore control the vector-sum of the 32 cavities. Calibration errors of the individual cavity field vector can result in fluctuations of the vector-sum as seen by the beam, while the measured vector-sum is perfectly regulated. The residual fluctuations increase with the microphonic noise level and require that individual field vectors must be calibrated to better than 10% in gradient and 1 degree in phase for a microphonic noise level of ±10 degrees.

II. PRINCIPLE OF DIGITAL FEEDBACK

The digital feedback is based on the control of the in-phase (I) and quadrature (Q) component of the cavity field [2]. That means the real and imaginary part of the RF-field vector are controlled instead of traditional amplitude and phase control. The cavity probe signal is down converted to 250 kHz and then sampled with a sampling rate of 1MHz. These samples can be considered as the real and imaginary part of the complex field vector, called I&Q (fig. 1).

The sampled field vectors of each cavity are rotated and scaled to compensate phase differences due to different cable lengths and to calibrate the accelerating fields in the different cavities. The vector-sum is calculated and also rotated to adjust the overall phase in the control loop to ensure negative feedback. It seemed convenient to separate these rotations. The present feedback algorithm applies proportional gain to the error signal and uses a digital low-pass filter to reduce the sensor noise. For maximum flexibility setpoint and gain values are updated from tables every microsecond. Additionally, a feed forward signal is added to the correction signal. It is also read from a table. These feed forward tables are optimized by measurement of the average correction signal from the feedback loop such that the average feedback signals are close to zero. The I&Q-actuator signals directly control the I&Q component of the RF vector by the use of a vector modulator. Due to conversion and computation time the total delay in the digital feedback loop is in the order of a few μs. The maximum achievable feedback gain is limited by this delay.
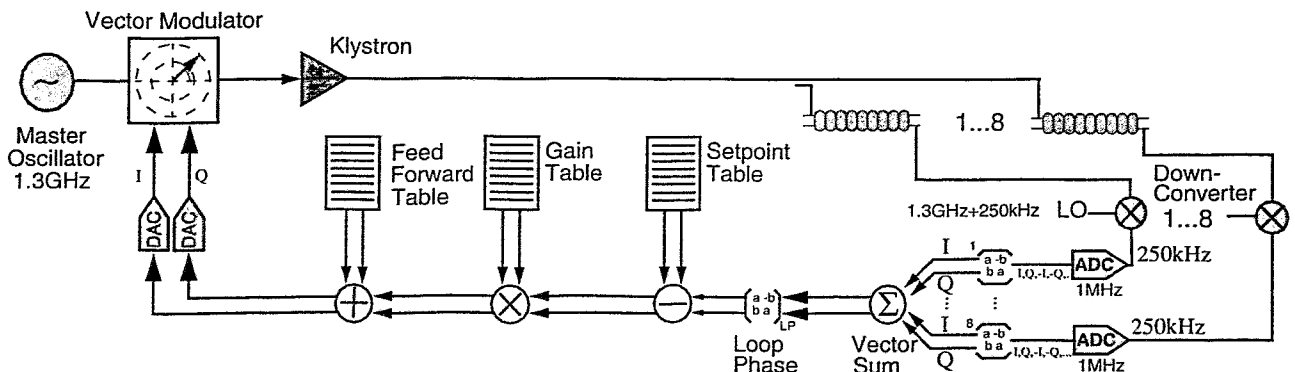

Figure 1: Scheme of the digital feedback system

III. REAL TIME FEEDBACK DESIGN

The real time RF feedback system consists of various hardware components as shown in fig. 2. The RF signal from the RF cavities is down converted to an intermediate frequency of 250 kHz and digitized on an in-house developed ADC board. The data are transmitted to a commercially available Digital Signal Processor (DSP) carrier board prior to the reconversion of the digital control signal to an analog signal on the DAC board. The local oscillator (LO) signal is generated from the 1.3 GHz signal using a vector modulator which is driven by tables synchronized with the master oscillator. An IQ driver board with VME interface allows to set the tables through the TTF control system.

A. *Hardware*

1) DSP System

The sampling rate of 1 MHz demands processors with high processing speed and high I/O capability in order to handle the high data rate. The DSP C40 (Texas Instruments' floating-point parallel Digital Signal Processor TMS320C40) with 32 bit address and data buses has been chosen. It provides six processor-to-processor communication interfaces, the so called communication ports. The DSP is mounted on a module following the TIM-40 norm. The carrier board DBV44 from Loughborough Sound Images (LSI) is a VME slave board with a modular architecture. Each DBV44 board can accomodate up to four modules. Three communication ports of each site are routed to front panel connectors the others are on-board links. The module type which is used for the TESLA Test Facility is the single module MDC40S2-40 with 40 MHz clock rate. The data transfer of the 32-bit words between the three DSPs is performed through on-board communication port links on a byte-to-byte basis at a maximum rate of 20 Mbyte/s. Data transmission is asynchronous due to FIFO (first-in-first-out) input/output buffers.

2) IQ Driver

The IQ Driver is a universal programmable two channel functional generator with VME interface. Each of the channels has a 16 bit D/A converter receiving the digital input from two 32k RAM blocks. Both memory blocks are controlled by common address register operating at 10 MHz in increment mode. In our case the IQ-driver generates a 250 kHz bipolar step signal with ±5V amplitude to switch the LO phase in 90 degree increments.

3) ADC and DAC Board

The ADC and DAC boards are in-house developed boards performed as 6U eurocards. Both of them have interfaces to the standard communication ports of Texas Instruments DSPs with handshake protocols.

The ADC board consists of four independent ADC channels with 14-bit A/D converters (Datel ADS 929, maximum sampling rate 2 MHz) operated at 1MHz sampling rate. Input amplifiers with a gain of 30 and a bandwidth of 9 MHz amplify the signal to the maximum sampling range of ±5V to get highest
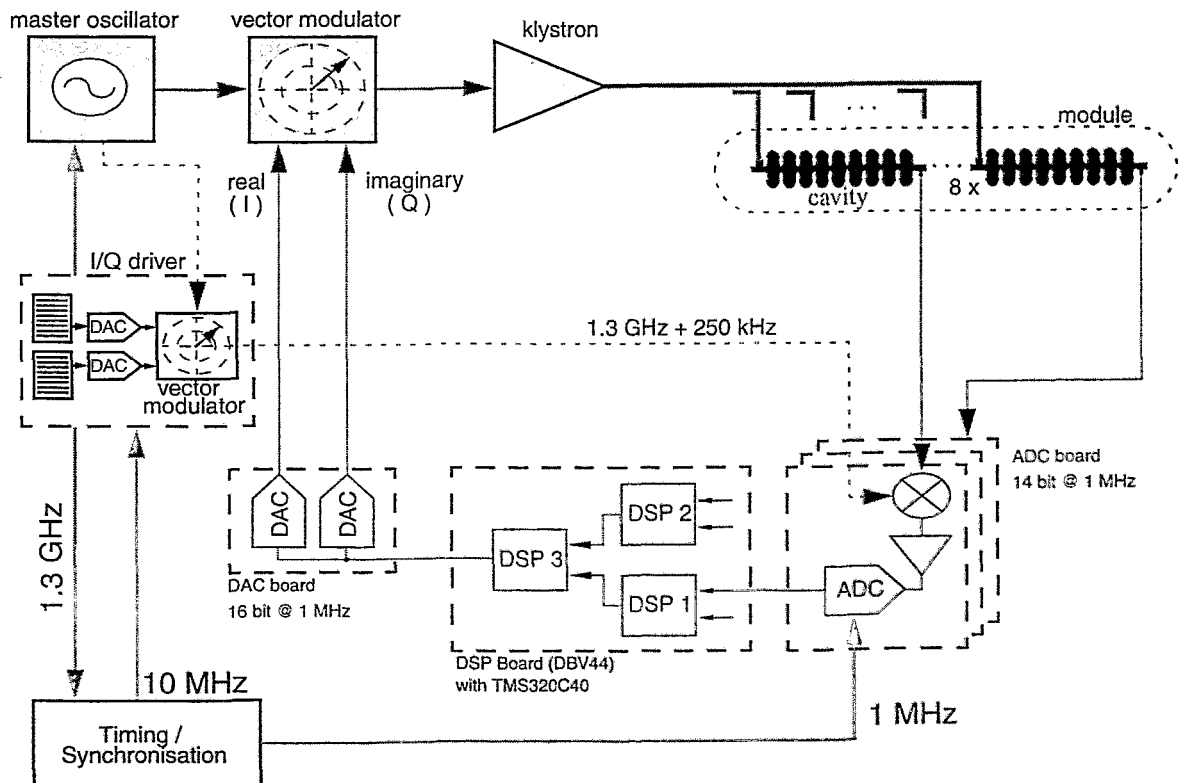

Figure 2: Overview of the TTF RF control system

resolution. Two ADCs transmit their data to a programmable logic device (PLD) respectively. This PLD is connected with the DSP through the communication port interface. Because of piplining data of two ADC channels only one communication port of the DSP is occupied. Therefore a total of six ADC channels could be connected to one DSP. To save conversion time from integer (ADC) to floating point (DSP) format this conversion is already performed in the PLD. The total delay time between ADC input and DSP input is approximately 900 ns.

The DAC board is a two channel board with 16-bit D/A converters (AD768). Similar as the ADC board it has a programmable logic device which is connected to the DSP through the standard communicated port. The received floating point data from the DSP are back converted to integer format which is necessary for the DAC. Thereby valuable computing time is saved in the DSP again. Additionally the PLD logic checks the incoming data and limits it to the valid input range for the DAC. The delay time through the DAC board is about 500 ns.

B. DSP Code

The TTF control algorithm has been implemented on the TMS320C40 parallel processor system and distributed over 3 DSPs (fig. 2) . The C40 internal communication ports are used to send signals among this group of processors. DSPs #1 and #2 read cavity data from the A/D converters with sampling period 1 μs, perform multiplication of the I/Q vector with the rotation matrix and calculate the vector-sum for 4 cavities. A more extensive set of computations are carried out in the DSP #3 which receives partial vector-sums from two DSPs and executes the feedback algorithm. The present feedback algorithm applies proportional gain to error signal and uses a digital low-pass filter to reduce the sensor noise. Finally the amplified errors for I and Q values are calculated and sent to the D/A converter.

All calculations must be done during a time shorter than the sampling period. This is possible for 40MHz DSP board which executes 20-40 instructions per 1 μs since multiplication and addition can be done simultaneously in a single 50 ns cycle. The interrupt service routines were implemented in all DSPs to read data from the communication ports thus allowing to scale and rotate matrices between pulses, correct DC offsets for the feed forward table and vary the length of the pulse. Due to time critical requirements all programs were developed in C4x assembly language to increase performance. The internal DSP timer was used in all DSPs to scale and rotate matrices in case of failure of the TTF timing system. Computation delay including ADC and DAC conversion is 4.2 μs.

IV. INTEGRATION WITH RF CONTROL SYSTEM

The TTF RF System is completely integrated in the Distributed Object Oriented Control System (DOOCS) to provide remote access to all RF data, parameters and controls. The architecture of DOOCS is based on an object oriented client/server model [3]. The whole system was designed as a set of reusable objects in shared libraries written in C++ programming language and is realized on Sun SPARC platforms in SunOS

4.*, SunOS 5.* and LINUX running on PCs environments. These libraries are used by the DOOCS servers and client applications and provide the tools to integrate the different subsystems into the whole control system. The RF front-end system consists of a few DOOCS servers: a server process to control the DSP hardware, a server to read fast ADCs for the measurement of the RF amplitudes and phases and servers to control the timing and local oscillators (fig. 3). The servers are stand-alone processes to control individual subsystems. Since data and commands are transferred in a standard way between clients and servers, the configuration and complexity are hidden from the user. The Low Level RF Real Time Digital System layout is described in a configuration file for the DSP server. When the DSP server starts it reads this configuration file and sets all required server data structures to customize the real system configuration. Control system developers can use the symbolic names of the DSP data in the clients applications to get/set data from/to the DSPs. The server allows to load required data structures and DSP programs into DSPs, start these programs and communicate with the DSPs via the Link Interface Adaptor (LIA) and common regions of DSP memory. Several client applications devoted to the RF system control were developed and realized for the users. These client applications communicate with the DOOCS servers over Ethernet and are used by the RF experts to control and investigate the system. These includes:

-ADC RF measurement tools for an on-line analysis of the RF behaviour,
-LabVIEW VIs provide the control over the Low Level Real Time Digital RF Control System,
-MatLab tools for
loop phase measurement and adjustment,
measuring indirect parameters for cavities,
saving and restoring system setup parameters,
feed forward table generation for optimal control,
calibration of gradient and phase measurement.
-software for operator knobs control.

The LabVIEW makes use of Virtual Instruments which implements the access to the DOOCS sever parameters and commands [4]. MatLab applications call external functions which were developed to send DOOCS requests to the servers.

V. RF SYSTEM PERFORMANCE

Fig. 4 and 5 show the acceleration gradient per cavity and the phase with respect to the beam during one RF pulse while no control loop is closed (e.g. constant RF klystron power). With closed feedback loop and a gain of 30 the rms error in gradient is about 4‰ and 0.2° in phase (fig. 6 and 7 respectively). Due to the high reproducibility of the cavity field without beam from pulse to pulse adaptive feed forward is able to reduce the remaining error further. The gradient is regulated to an rms amplitude fluctuation of less than 0.5 ‰ during the flat top. The pulse-to-pulse stability is better than 0.2 ‰. The according rms
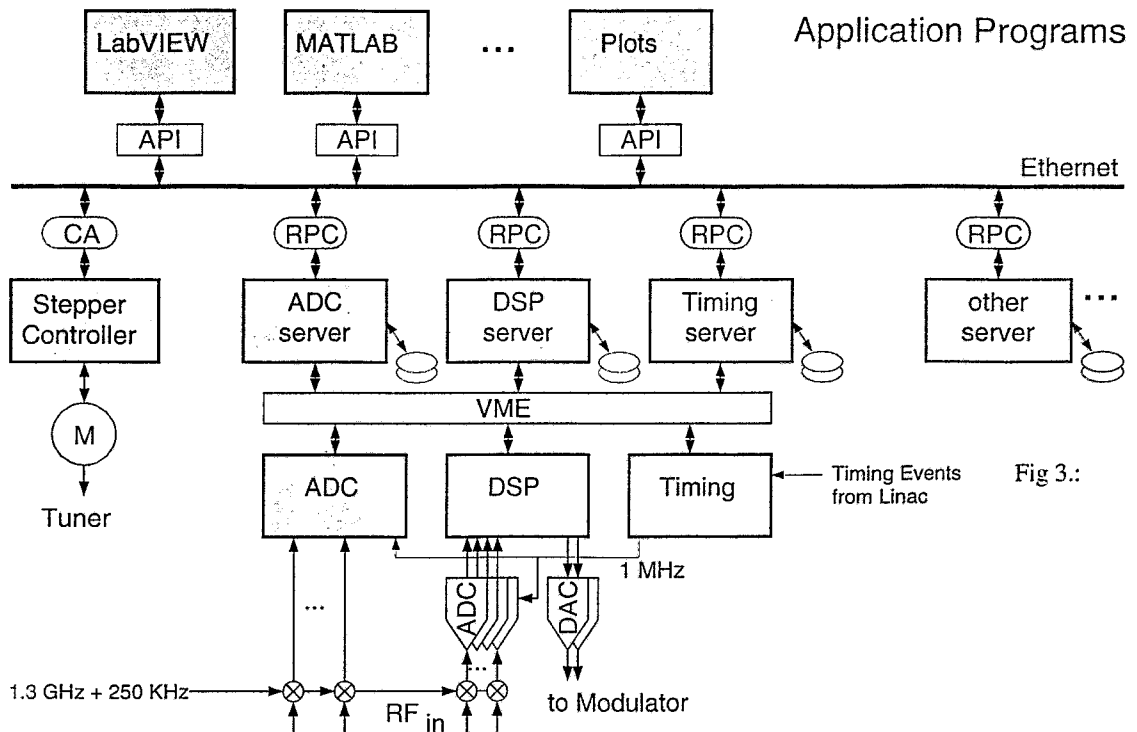
Figure 3: RF control system integration

error in phase of the accelerating field is less than 0.03°. The pulse-to-pulse phase stability is better than 0.02°.

VI. FUTURE PLANS

In 1998 two more accelerating modules will be installed in the TTF linac. Therefore the RF control system has to control 24 cavities instead of 8. The existing DSP modules will be replaced by the faster Texas Instruments TMS320C40 - 60 MHz modules. The new DSP configuration will consist of an array of 9 DSPs. This includes DSPs used for Kalman filtering of the measured data, DSPs which provide the basis for more complex feedback algorithms and time-optimal control and DSPs for ex-
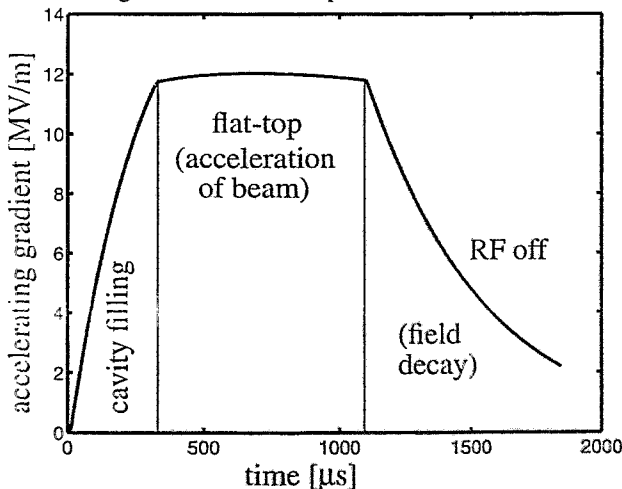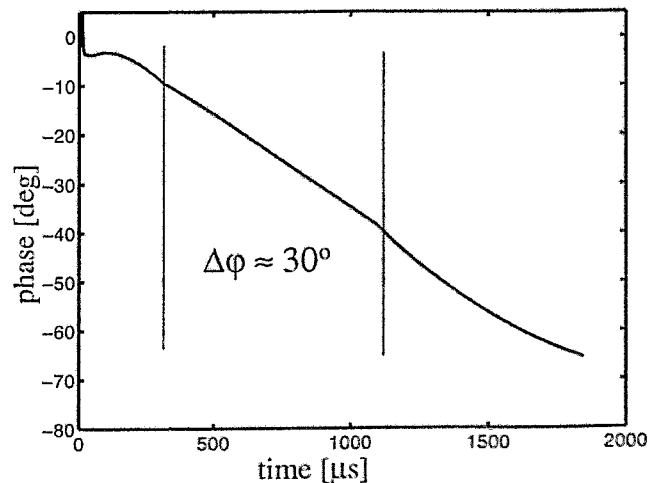

Figure 5: RF phase with constant forward power during 'flat-top' (open feedback loop)

ception handling as part of a fast security system. Sophisticated algorithms demand significant computation time. More studies in detail will answer the question of optimizing the control algorithm versus computational delay.

VII. CONCLUSIONS

The RF control system for the TTF requires tight control of the vector-sum of the accelerating fields in an ensemble of up to 32 cavities driven by one common klystron. The requirements for precise adjustment and calibration of the vector-sum, the long time constant of the cavities of several hundred microsec-
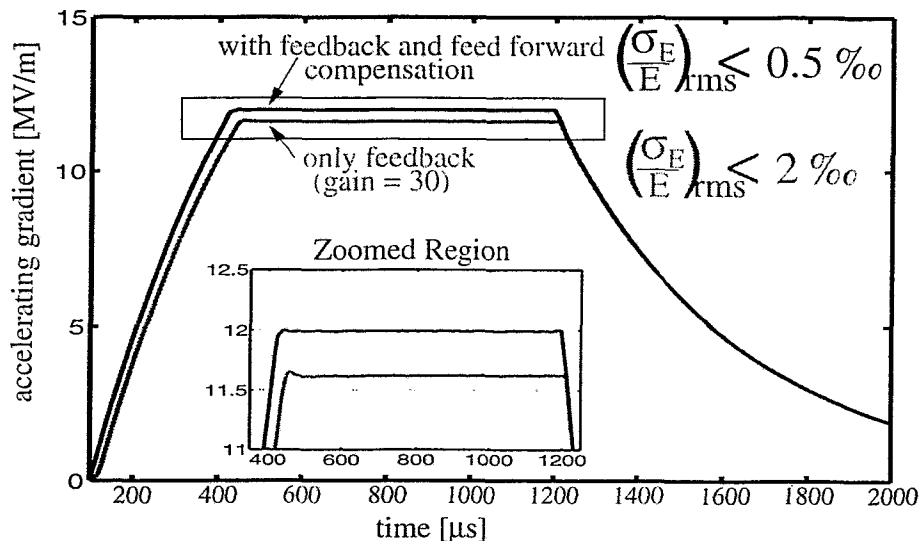

Figure 4: Accelerating gradient per cavity with constant forward power during 'flat-top' (open feedback loop).

Figure 6: Accelerating gradient per cavity with feedback and with feed forward respectively

In figure 6, text labels:
"with feedback and feed forward compensation", "only feedback (gain = 30)", "Zoomed Region"

$$\left(\frac{\sigma_E}{E}\right)_{rms} \lesssim 0.5\ \%_o$$
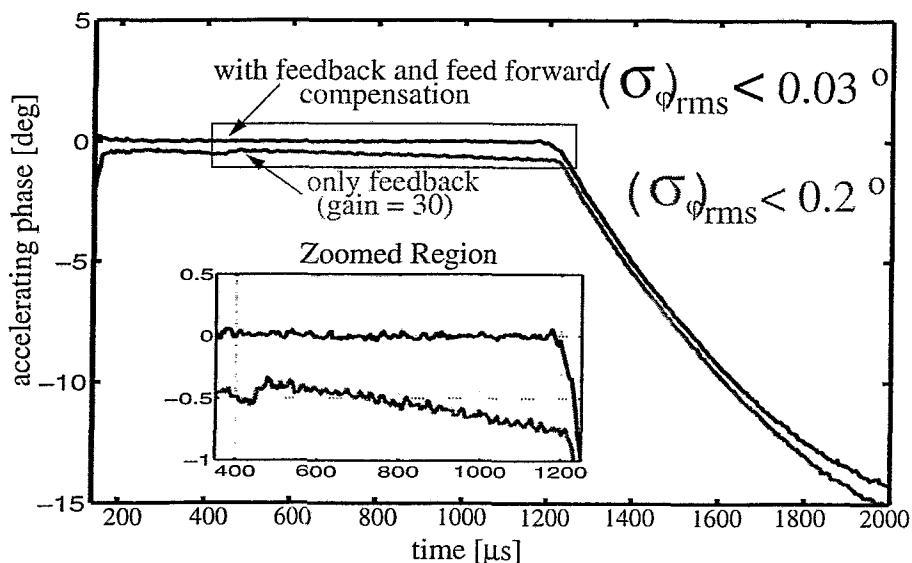
$$\left(\frac{\sigma_E}{E}\right)_{rms} \lesssim 2\ \%_o$$

Figure 7: Phase stability of vector-sum of the first cryomodule with feedback and with feed forward respectively (5 cavities operational)

In figure 7, text labels:
"with feedback and feed forward compensation", "only feedback (gain = 30)", "Zoomed Region"

$$\left(\sigma_\varphi\right)_{rms} < 0.03\ ^{o}$$

$$\left(\sigma_\varphi\right)_{rms} < 0.2\ ^{o}$$

onds, and repetitive perturbations due to the pulsed operation favoured a completely digital approach for the design of the RF control.

So far the controller for 8 cavities has been implemented and prooven to be successful. Within a few hours after turning the system on for the first time the beam has been accelerated at average gradients exceeding 15 MV/m. By now the cavity field has been stabilized to 0.5‰ in amplitude and 0.03 degree in phase respectively thereby exceeding the requirements. The extensive build-in diagnostics have greatly enhanced the operability of the system which includes adjustment of loop phase, calibration of the vector-sum, correction of the phases of the incident waves, and adaptive adjustment of the feed forward tables. Also the reproducibility and reliability of the system is remarkable.

VIII. REFERENCES

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