Multipurpose RF Field Vector Controller for Linear Accelerators

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***Abstract*—The paper describes the design and the implementation of the flexible, multipurpose RF (Radio Frequency) field Vector Controller for the linear accelerators based on the superconducting technology. The implementation is done for the FPGA (Field Programmable Gate Array) based LLRF (Low Level Radio Frequency) control systems. The full process of the requirement analysis and the library implementation is presented. It is followed by the description of the controller's applications and the results of the performance tests. The controller fulfills the requirements of the various accelerator facilities and hardware platforms and can be easily adapted for the planned experiments to decrease their cost by avoiding expensive research and development phase.**

***Index Terms*—LLRF system; RF field controller; superconducting linear accelerators; FLASH**

I. Introduction

The linear accelerator facilities based on the superconducting technology differ in terms of executed experiment type, but for all of them, the quality of the results of performed experiments is strongly correlated with the amplitude and phase stability of the provided electron beam. This stability depends on the several factors connected to different elements of the accelerator, but the most important is the quality of the accelerating RF (Radio Frequency) field. To minimize the field's amplitude and phase fluctuations LLRF (Low Level Radio Frequency) control system is used. The task of the system is to measure electromagnetic field inside accelerating structures, compare it with a required value, and adjust an output of an RF field source accordingly to ensure required field stability[1].

The central element of the system is a controller capable of executing chosen transfer function. The transfer function may vary from simple P-controller (Proportional), through PID-controller (Proportional/Integral/Derivative), to custom, flexible transfer functions. Traditionally, the controller is implemented as analog system, but during last years, the digital implementations are becoming more popular. In addition to the controller, the digital LLRF system is also equipped with down-converters - to prepare high frequency signals for sampling with low frequency ADCs (Analog to Digital Converter) - and up-converters - to prepare drive signal for RF amplifier chain.

These elements are common parts of many digital LLRF control systems [2,3]. Such structure is and will be used in the existing and planned experiments based on the superconducting linear accelerators at different research centers throughout the world not depending on the type of accelerating structures and mode of operation used. However, the digital algorithm and controller development efforts in different research centers are coordinated in very limited range or not coordinated at all.

The paper presents the structure and implementation of the flexible RF Vector Controller. The controller is capable of execution of various control algorithms and can be easily extended by additional user functionality. It can be used for the control of the RF field inside accelerating structures of linear accelerators with different design, work parameters and stability requirements. The controller has been permanently installed at FLASH [4] (Free Electron Laser in Hamburg) facility and is ready to be implemented for facilities such as XFEL or POLFEL. Moreover it may be used to speed up LLRF control system development in future experiments, by avoiding expensive research and development phase.

II. Requirements for the Vector Controller

To define the requirements for the vector controller, which can be used for different linear accelerators, the comparison of several LLRF systems is necessary. The results of such comparison are presented in Table I. The various parameters of the LLRF system for FLASH, SNS (Spallation Neutron Source) and VTS (Vertical Test Stand) facilities have been compared. Each parameter implies the specific controller requirement.

TABLE I. Comparison of different LLRF control systems [3,4]

Parameter	FLASH	SNS	VTS	Controller requirements
Type	digital	digital	analog	flexible to match digital platform
Communication	VME	VXI	-	flexible communication module
Cavities per klystron/amplifier	8-24	1	1	vector sum control
Cavity Loaded Q factor	10^6	10^6	10^9	frequency tuning
IF frequency	250 kHz	50 MHz	-	flexible IF frequency span
Transfer function	P	PI	VCO	adjustable transfer function
Mode of operation	pulsed	pulsed	CW	time management module
Bunch repetition	1 MHz	-	-	pipelined computations

A. Flexible enough to match digital platform

The controller must offer the wide range of functionality. In addition, it must be possible to use it in wide range of different digital systems. The most flexibility is offered by FPGA chips, therefore this chips are commonly used in different LLRF control systems. It has been decided that the design of the flexible vector controller should be made for this chips.

B. Flexible communication module

Hardware platforms support different communication channels. To allow implementation of the controller for different facilities, communication module of the controller must be flexible and support basic communication protocols. Moreover it should provide easy extension interface to allow users to add support for necessary protocols.

C. Vector sum control

The facilities use one RF field source to drive one or more cavities. In the second case the controller must provide the possibility to control the sum of vectors in individual cavities instead of single one.

D. Frequency tuning

Narrow bandwidth of the cavities, especially for high Q ones, requires special considerations while loading to and maintaining required RF field level. The controller must provide the possibility to change output frequency of the vector modulator or upconverter used. This will allow to match the driving frequency to the current resonance frequency of the cavity, therefore it will make the loading process possible even for large frequency offsets.

E. Flexible IF frequency span

The facilities use wide range of intermediate frequencies from several kHz to hundreds of MHz. The controller's field detection subsystem must accommodate this range and allow to correctly detect field components independently of the frequency used.

F. Adjustable transfer function

Different mode of operation, type of accelerating structures and requirements may need different transfer functions executed by the controller. It must support basic functions such as P-controller, PI-controller and PID-controller, but also give the possibility to adjust the transfer function according to the user needs.

G. Time management module

Support for different modes of operation (different duty cycle up to continuous wave) requires special timing management routines capable of controlling data acquisition system and managing control parameters. The module should also allow to switch control modes during operation

H. Pipelined computations

The time available for the computation in the feedback loop is limited by the time between concurrent updates of the controller output. The requirements concerning that time (correlated with bunch repetition rate and required bandwidth) differ from facility to facility. The controller must use pipelined computations to be independent of the necessary output update rate.

The analysis of the requirements led to the implementation of the Vector Controller Library, which contains components necessary to build specific Vector Controller.

III. Vector Controller Library

The library consists of several packages containing the modules for usage on different computation stages. The structure of the library is presented in Fig. 1.

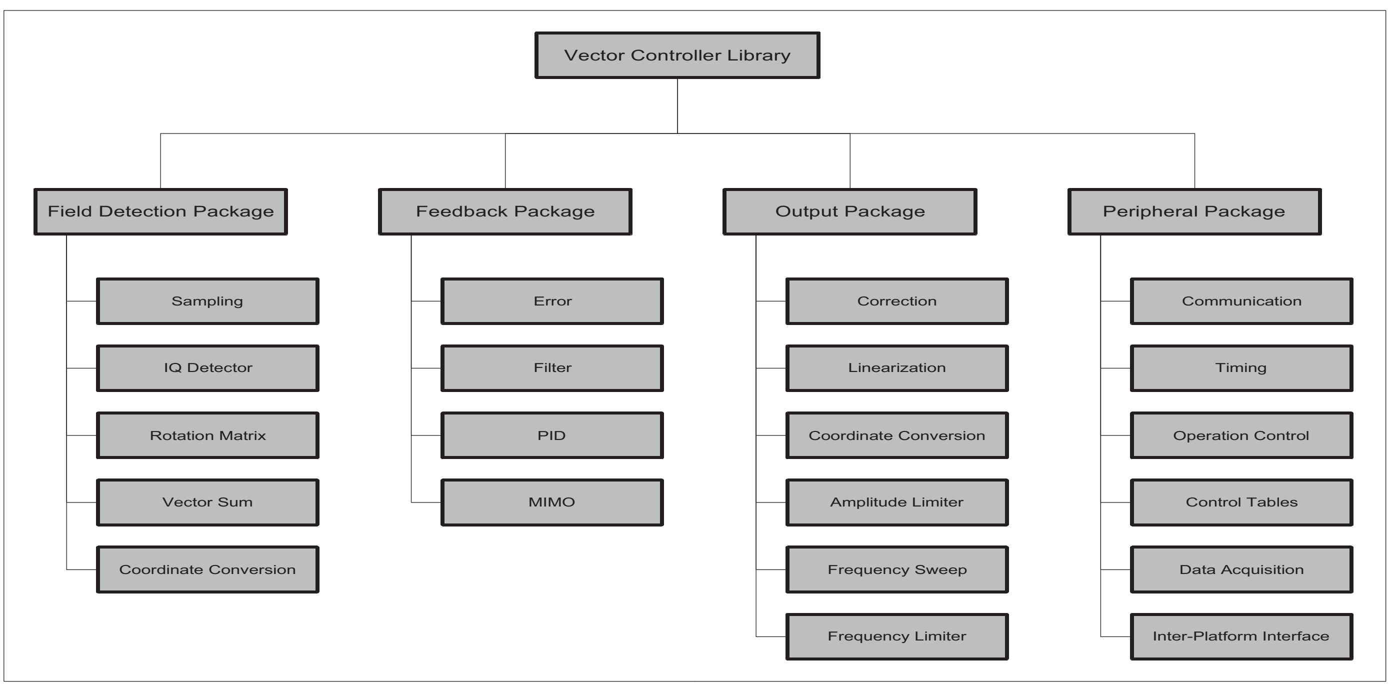

Figure 1. Vector Controller Library Structure

- Field Detection package

The package contains the modules related directly to the sampling, component detection and preprocessing of the input signals. They are meant to be used in the first computation stage of the application, which is responsible for gathering measurement data.

- Feedback package

The package contains the computation modules used to perform further data stream processing. They can be used to execute required transfer function and apply additional corrections for the signals. The modules are meant to be used in the middle stages of the application using the calibrated and initially preprocessed measurement data.

- Output package

The package contains modules which can be used in the last stage of the application to apply various corrections and modifications of the processed signal calculated in the previous computation stages. These tasks include offset compensations, domain exchange, digital upconversion, output linearization, etc.

- Peripheral package

The package contains various modules, which provide services and communication interfaces for other parts of the application. It also includes the modules for interfacing the embedded processing platform which can be used for FPGA chips equipped with PPC405 embedded processor.

The structure of the library and the flexibility of individual modules make the library universal tool for design of signal processing applications based on the FPGA technology. The parts of the library have been used during the implementation of several algorithms running currently at FLASH facility. The most important is the Vector Controller used for RF field control in accelerating modules.

IV. Vector Controller Implementation

The library presented in the previous section has been used to implement flexible Vector Controller, which is able to control accelerating RF field in the linear accelerators, which are using different types and designs of the superconducting accelerating structures. The architecture of the Controller can fit to wide range of digital FPGA based platforms.

A. Controller Architecture

The number of applications executed by the LLRF control system is large and is constantly growing as the new algorithms and field control concepts are developed. The hardware platform must provide computation power, which can accommodate all of them. Currently two different approaches for computation power distribution among the system are used: distributed and centralized. Each type of architecture has advantages and disadvantages, but the distributed hardware architecture is more general - the centralized approach can be considered as a special case of the distributed one (which is using only one computation board). The software architecture of the controller must match the hardware architecture, therefore, the distributed software architecture has been chosen. This way, the controller can be implemented for the hardware platforms of both types.

B. Computation Pipe

The core of the controller is computation pipe, which structure is presented in Fig. 2. The computation pipe is accompanied by the additional peripheral modules, which provide access to the DAQ system, communication medium and links amongst individual hardware components.

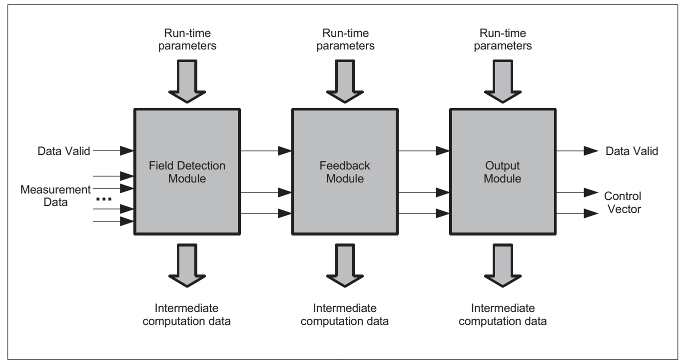

Figure 2. The structure of the controller's computation pipe

- Field Detection module

The main task of the module is to measure input signals proportional to RF field vectors in several sources, estimate actual vector and provide the preprocessed data for the following top level modules. The module is capable of compensating analog input stage non-linearities, phase shifts and channel attenuation according to the user-provided data. The resulting vector is a sum of partial vectors estimated for each channel. It can be provided in form of I-Q or Amplitude-Phase coordinates.

- Feedback module

The main task of the Feedback module is to calculate difference between the measured RF field and the user provided set-point value, apply correction filters and execute transfer function. It also gives the possibility to execute external slow and fast feedbacks and apply arbitrary signal corrections. The result of the processing is the correction signal, which can be provided using I-Q or Amplitude-Phase coordinates. The signal is used by the next module to calculate final controller output, which minimizes the RF field error.

- Output module

The task of the module is to calculate final output control vector by applying several corrections and coordinate conversion to the incoming vector provided by the Feedback module. The output signal is provided in the form most suitable for external devices. This includes I-Q vector for analog vector modulator, modulated signal for up-converter and digital output for other external subsystems.

C. Operation Modes

The controller can operate using vector in I-Q coordinates or Amplitude-Phase coordinates. The behavior can be changed during the operation. The proposed structure of the Vector Controller can be configured according to the specific application needs. This includes the selection of one or more of the available modes of operation. Each mode is suitable for different conditions and can be selected during controller operation if necessary:

- GDR (Generator Driven)

In the generator driven system, a RF reference frequency from the Master Oscillator serves as a drive signal for the cavity (amplified by the klystron). The GDR is usually employed if the resonance frequency remains close to the operating frequency (< bandwidth). In this case the accelerating fields can be established after a shutdown without initial cavity frequency tuning.

- SEL (Self Excited Loop) [5,6]
- VCO (Voltage Controlled Oscillator) [6]

The SEL and VCO modes are employed if the cavity resonance frequency is far from the operating frequency and changes in time. The modes are useful for low bandwidth, high Q cavities and can e used together with I-Q and A-P operation. The SEL operates using positive feedback loop, which drives the RF field source using amplified cavity signal. The VCO mode uses digital implementation of PLL (Phase Locked Loop) to phase lock drive signal with the measured cavity signal.

D. *Transfer function*

The most important part of the computation pipe is the controller module which executes specified transfer function. Wide range of the runtime and design time parameters offers the possibility to customize the function according to the application specific needs. Two general controller types are possible:

- PID controller

This type of the controller can be used in any configuration and mode of operation. The transfer function is executed independently with separate set of gain parameters on each vector coordinate.

- MIMO (Multi Input Multi Output) controller [7]

This type of the controller can only be used for GDR mode of operation using I-Q values. It consists of 4 biquadratic filters interconnected with each other. In this case transfer function is executed for the whole vector.

The available options and multiple configuration parameters create the possibility to implement the Vector Controller for wide range of hardware systems. It can be used to control accelerating field in the accelerating structures with large span of parameters.

V. Vector Controller Applications

The presented Vector Controller implementation has been installed and tested using several hardware platforms running in different accelerator facilities.

A. *VME based system at FLASH*

The VME is a bus standard, which was originally developed in 1981 for the Motorola 68000 CPUs. Later the VME bus was widely used for many applications. Finally, it has been standardized by the IEC. The physical dimensions and connectors of the VME card are based on the Eurocard, but the standard uses its own signal definitions. Due to the flexibility and leading position on the market, the standard has been chosen for the hardware platform for many linear accelerators. The old generation of the LLRF control system for FLASH is also based on this standard.

The distributed system used for the Vector Controller implementation is based on the SIMCON_DSP board family and is presented in Fig. 3. The system has been used to control accelerating field in ACC456 RF station. It is scalable, so it can be used for all RF stations at FLASH facility.

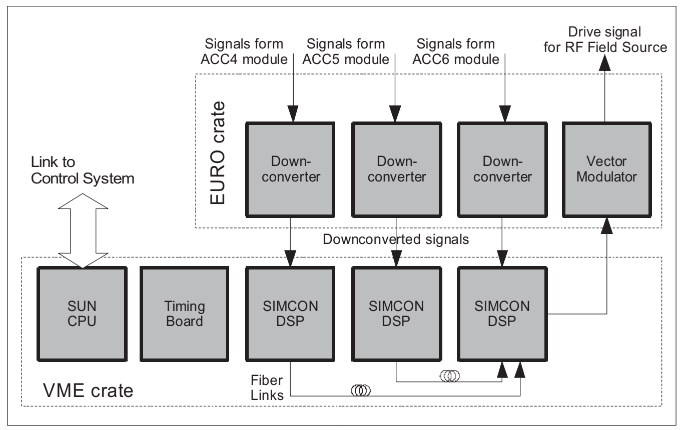

Figure 3. Distributed system for ACC456 RF station

To estimate the field control performance, the beam energy stability measurements has been performed and compared with the previous control system. The results of the measurements are presented in Fig. 4.

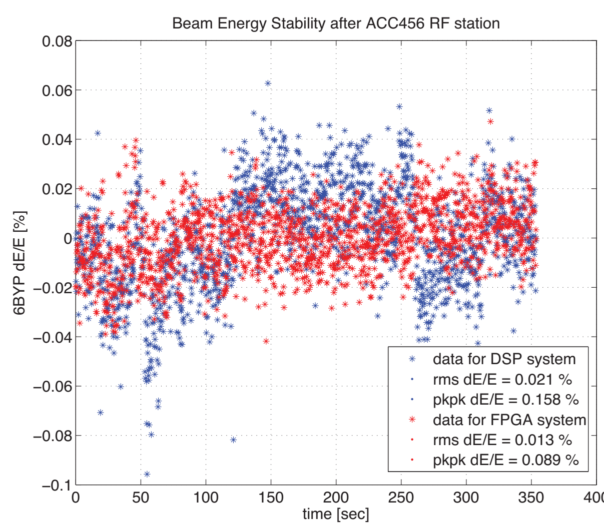

Figure 4. Beam energy stability measurements

The VME based system has been permanently installed in ACC1 RF station at FLASH and is used for the normal user operations [8].

B. *ATCA based system at FLASH*

Advanced Telecommunications Computing Architecture (ATCA) is a new standard used by many telecommunication applications. The work on the ATCA standard specification includes participation of more than 100 companies and is the largest specification effort in the history of the PCI Industrial Computers Manufacturers Group (PICMG) [9]. The specification incorporates the latest trends in high speed interconnect technologies (Gigabit ethernet and PCIe etc.), high performance processing units (FPGA, DSP etc.) together with improved Reliability, Availability and Serviceability (RAS).

The standard is considered as the hardware platform for the new generation of LLRF control systems. Despite the requirements and the standard specification are not yet complete, the first prototypes of such systems are being produced and tested. The described application of the Vector Controller is using ATCA based system build using commercially available solutions to drive the vector sum of 8 accelerating cavities at linear accelerator which is part of FLASH laser.

The ATCA demonstration system built at DESY is the first running LLRF system for the linear accelerator based on this standard. Despite the system has been built using commercial and previous generation component, it allowed to check the basic concepts and assumptions. The conclusions drawn from the online tests allowed to improve the development of the dedicated components, which is still in progress [10]. The structure of the system installed in ACC456 RF station is presented in Fig. 5.

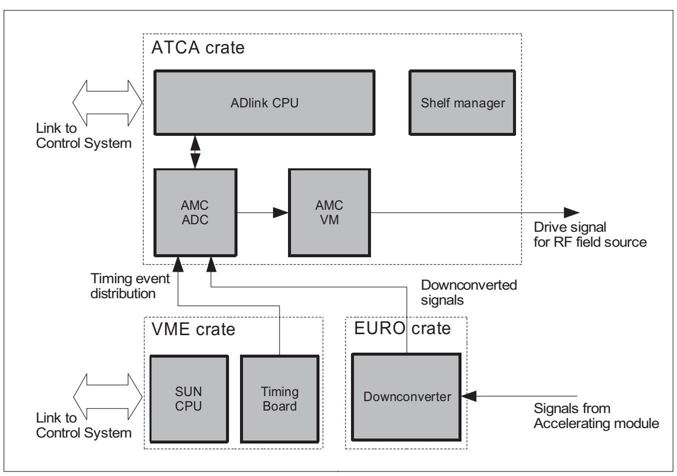

Figure 5. The structure of the ATCA based system

To evaluate the field control performance and stability of the feedback loop, the gain scans have been performed. The results are presented in Fig. 6. The achieved stability (minimum rms error) of amplitude and phase is 10^{-4} and 0.02 degree respectively. Due to the several limitations such as low resource availability or usage of the old generation components, it is not possible to draw conclusions concerning the control quality of the final ATCA based system. Nonetheless, the presented application proved the basic principles and allowed to improve ongoing system development process.

Both VME and ATCA based systems have been fully integrated with DOOCS (Distributed Object Oriented Control System) control system used at FLASH. The user interface for ACC1 RF station is presented in Fig. 7. The integration allowed to use external computation tools such as MATLAB to run additional algorithm improving field control quality.

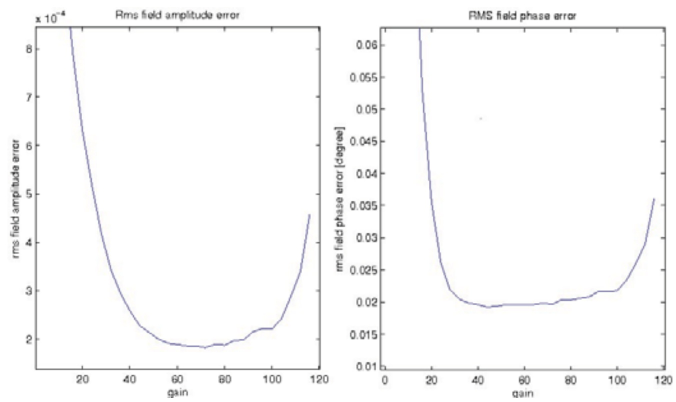

Figure 6. The results of gain scan performed by ATCA based system

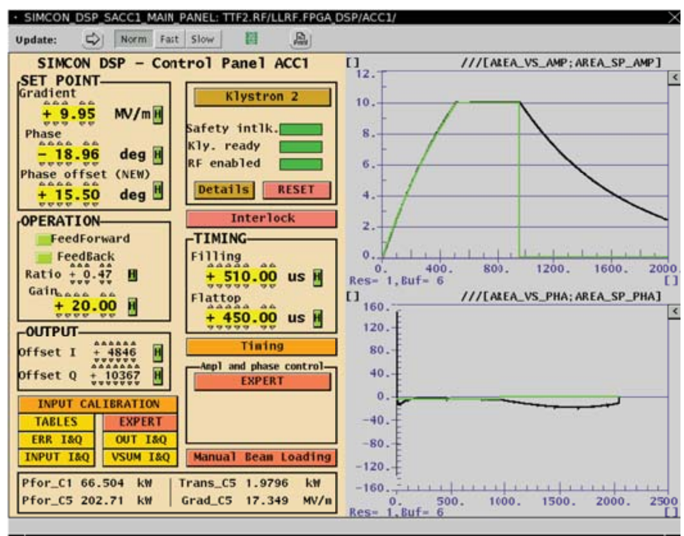

Figure 7. DOOCS panel for ACC1 RF station

C. *VME based system at VTS*

The Vertical Test Stand facility is the test device, which is used for the resonator cavity measurements. The measurements include such cavity parameters as quality factor, resonance frequency and coupling. They are performed for each resonating mode of the multi cell cavities. Due to the lack of the input coupler, the loaded Q parameter of the cavity is in range of 10^9. The bandwidth of such resonator is in range of several Hertz and requires implementation of frequency tuning mechanisms. The application of the Vector Controller based on the VME standard is using the same hardware architecture as for FLASH, but the software functionality includes VCO and

SEL modes of operation. The previous system for VTS has been implemented as an analog PLL (Phase Locked Loop), but the operation of such system is hard and time consuming. The digital system allows to reduce that time. The sample measurement results are presented in Fig. 8.

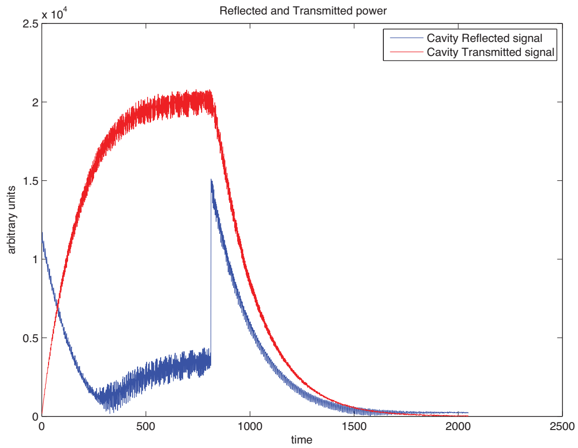

Figure 8. The results of the measurements performed at VTS

VI. Summary

The Vector Controller presented in the paper can be used with the accelerating structures characterized by different parameters and modes of operation. The test results for different accelerator facilities and hardware architectures proved its flexibility. The Controller can be easily extended by additional modules to accommodate new solutions, field control concepts and algorithms, but also changes and extensions to the hardware platform. The solution will be used as a base for XFEL controller.

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