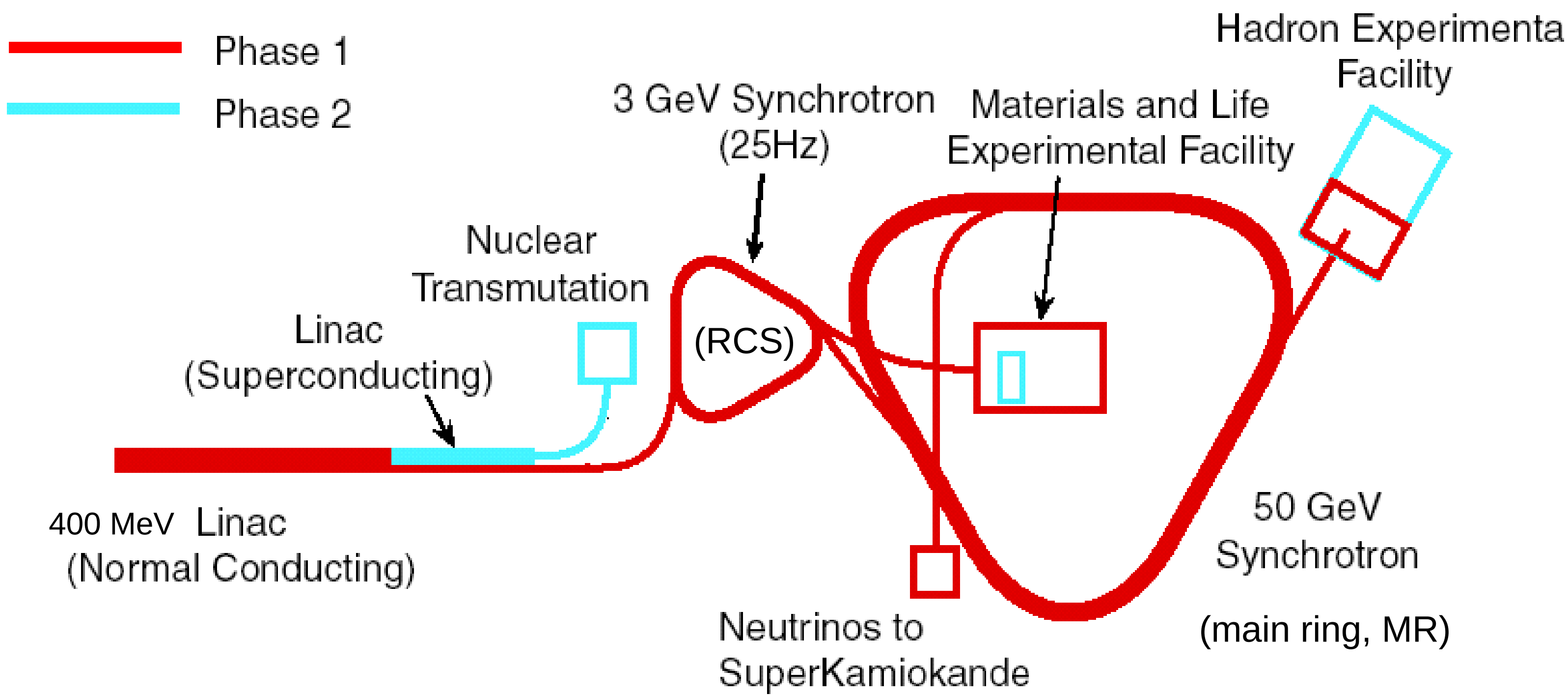
Performance of J-PARC Linac RF system

T. Kobayashi, E. Chishiro, S. Suzuki,
Japan Atomic Energy Agency (JAEA), JAPAN

S. Anami, Z. Fang, S. Michizono, S. Yamaguchi,
High Energy Accelerator Research Organization (KEK), JAPAN

Outline

Introduction ..(1) -- J-PARC Facility



The Japan Proton Accelerator Research Complex (J-PARC) will be one of the highest intensity proton accelerators in the world.

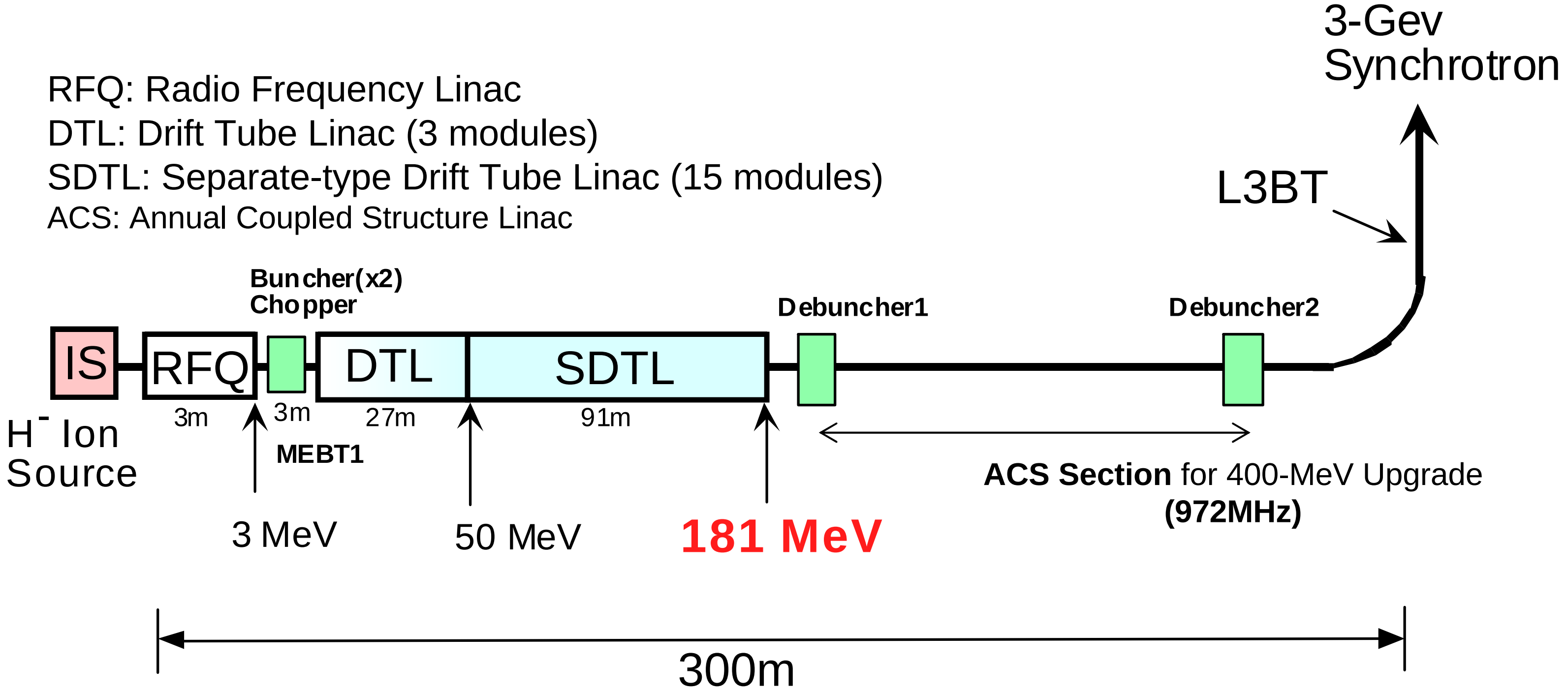
It consists of a **400-Mev** H$^-$ **linac**, a **3-GeV** 1-MW rapid-cycling synchrotron (**RCS**), and a **50-GeV** synchrotron (main ring, **MR**)

Introduction ..(2) -- J-PARC Linac

(Present State)

- \- Accelerated particles: H^- (negative hydrogen)
- \- Energy: 181 MeV (The last two SDTL tanks are used as debunchers)
  Upgraded to 400 MeV by using ACS cavity (in 2011?)
- \- Peak current: 30 mA (50 mA for 1MW at 3GeV)
- \- Repetition: 25 Hz
- \- Pulse width: 500 us (Beam), 650 us (RF including cavity build-up time)
- \- Acceleration Frequency 324 MHz

RFQ: Radio Frequency Linac
DTL: Drift Tube Linac (3 modules)
SDTL: Separate-type Drift Tube Linac (15 modules)
ACS: Annual Coupled Structure Linac



Introducton ..(3)

History of the Linac Commissioning

Oct. .2006: High-power operation of all the RF systems was started. All klystrons have successfully supplied power to the cavities.

Nov. 2006: RFQ&MEBT-1 beam commissiong
Dec. 2006: DTL beam commissiong.
Jan. 2007: SDTL beam test. (rough tuning)

Jan. 2007: **181-MeV acceleration** of 5-mA (20us) beam succeeded!
Feb. 2007: **181-MeV** acceleration of **26-mA beam** (50 us) was succeeded!

~ Fine beam commissioning ~

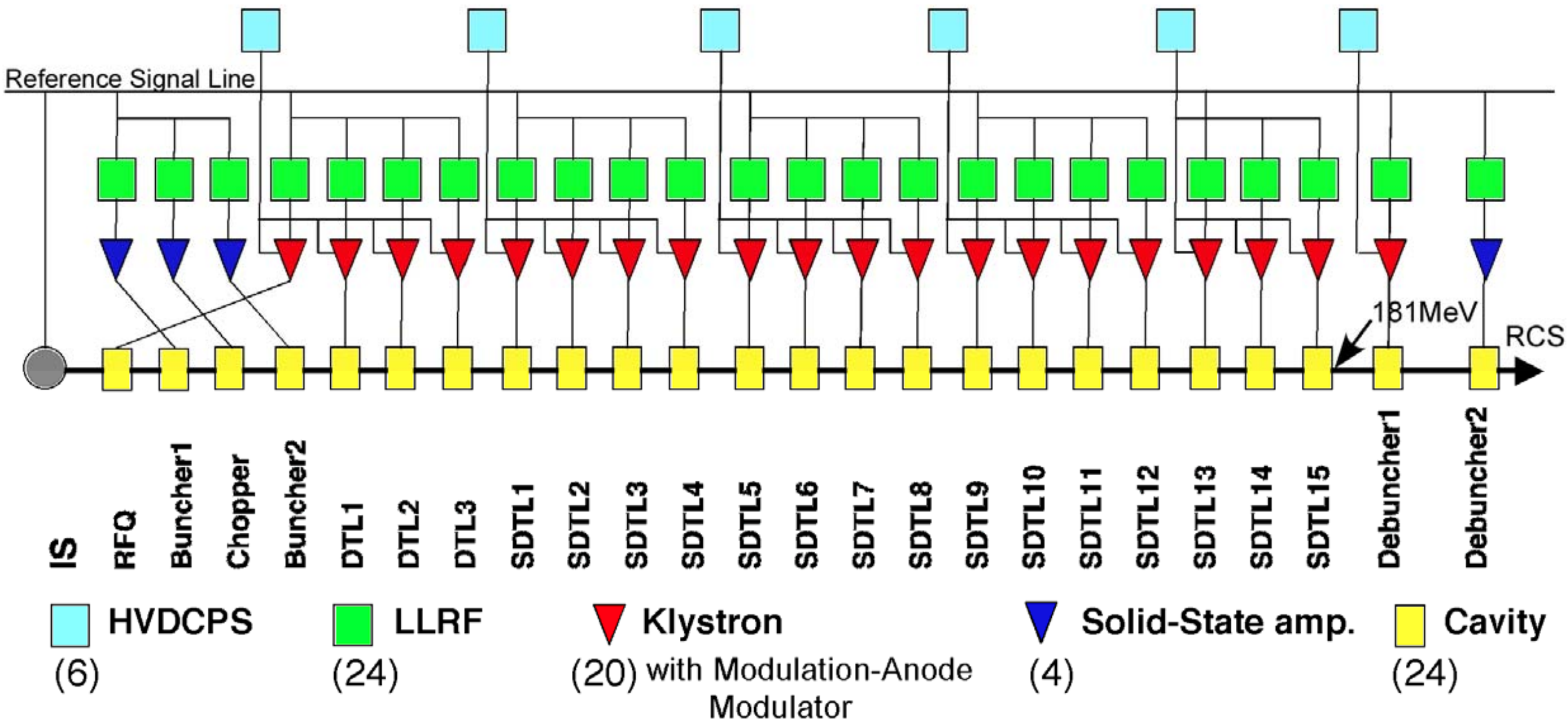
Jul. & Aug. 2007: Summer Shutdown

Oct. 2007: Injection into 3-Gev Ring (RCS) !
Now RCS commissioning is continued.

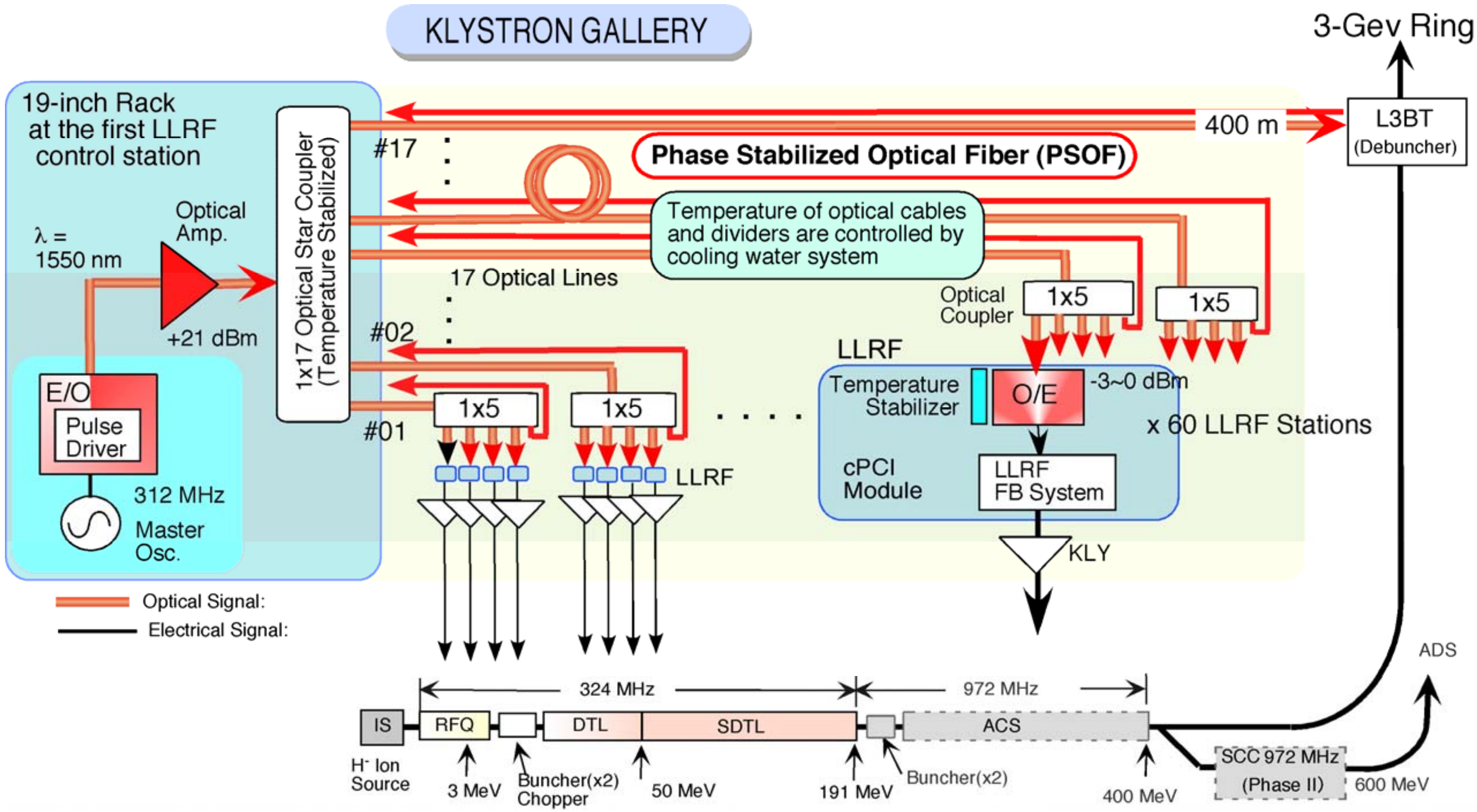
Linac RF System

- **181 MeV normal conducting proton linac**
- **Operation frequency: 324 MHz**
- **Total 20 klystrons (max.3 MW), 6 DCPS (#1~6)**
- **RF Pulse width: 650 us (25Hz)**

Requirements of cavity field stability
< +/-1% (amplitude), < +/-1 deg. (phase)



RF Reference Distribution System



312-MHz RF reference is distributed to all LLRF control systems through optical links.

The reference signal is optically amplified and divided into 17 transfer lines, then furthermore it is divided into 5; one of them is returned back to the first station for phase monitor.

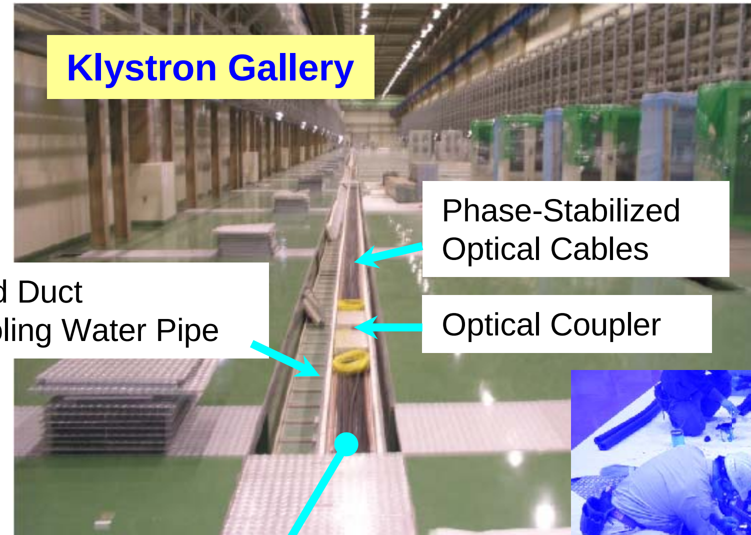
Optical cable is the Phase Stabilized Optical Fiber (PSOF). (The thermal coefficient is 0.4 ppm/ºC.)

Temperature of the optical components (E/O, O/E, cables, couplers) are controlled to be constant.

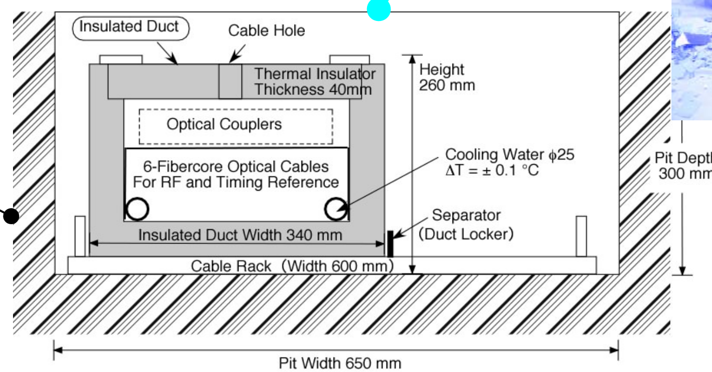
Installation of the Reference System

1x17 optical coupler
set in an oven

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



Insulated Duct
with Cooling Water Pipe



Cross section of the under-floor cable trench

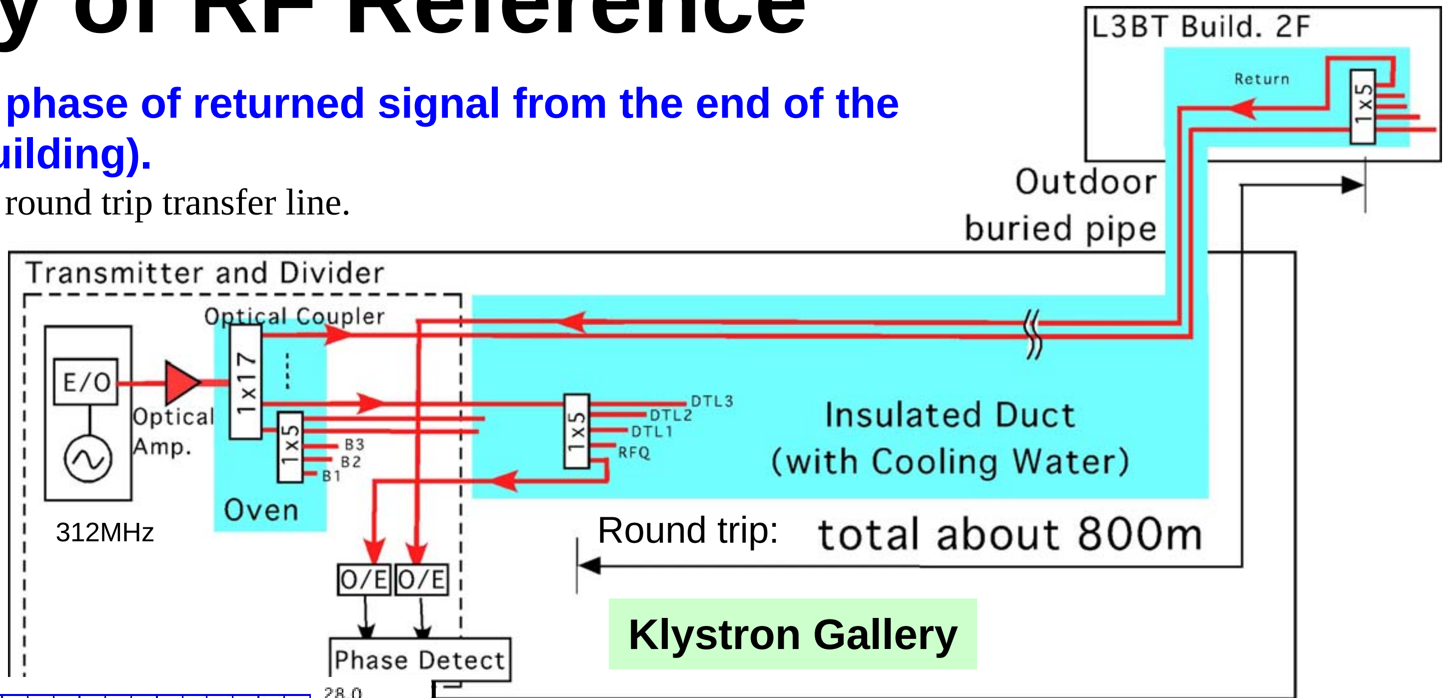
- Insulated duct set in the under-floor cable trench.
- Cooling water temperature is controlled to be 29±0.1 deg. C

An insulate duct is set in a cable trench under floor.
Optical cables and Optical couplers are installed into the insulated duct with cooling water pipe for the temperature stabilization.

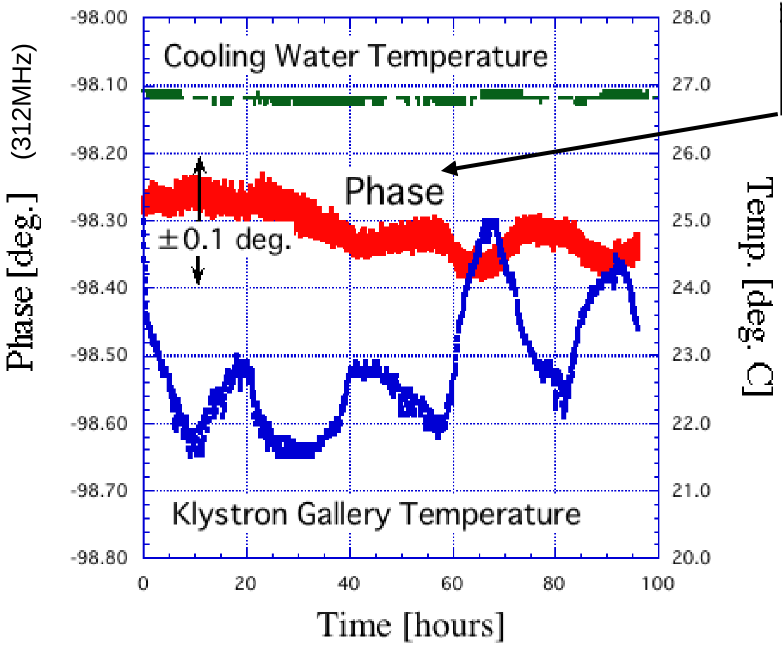
Stability of RF Reference

Measured the phase of returned signal from the end of the linac (L3BT building).

Total about 800-m round trip transfer line.



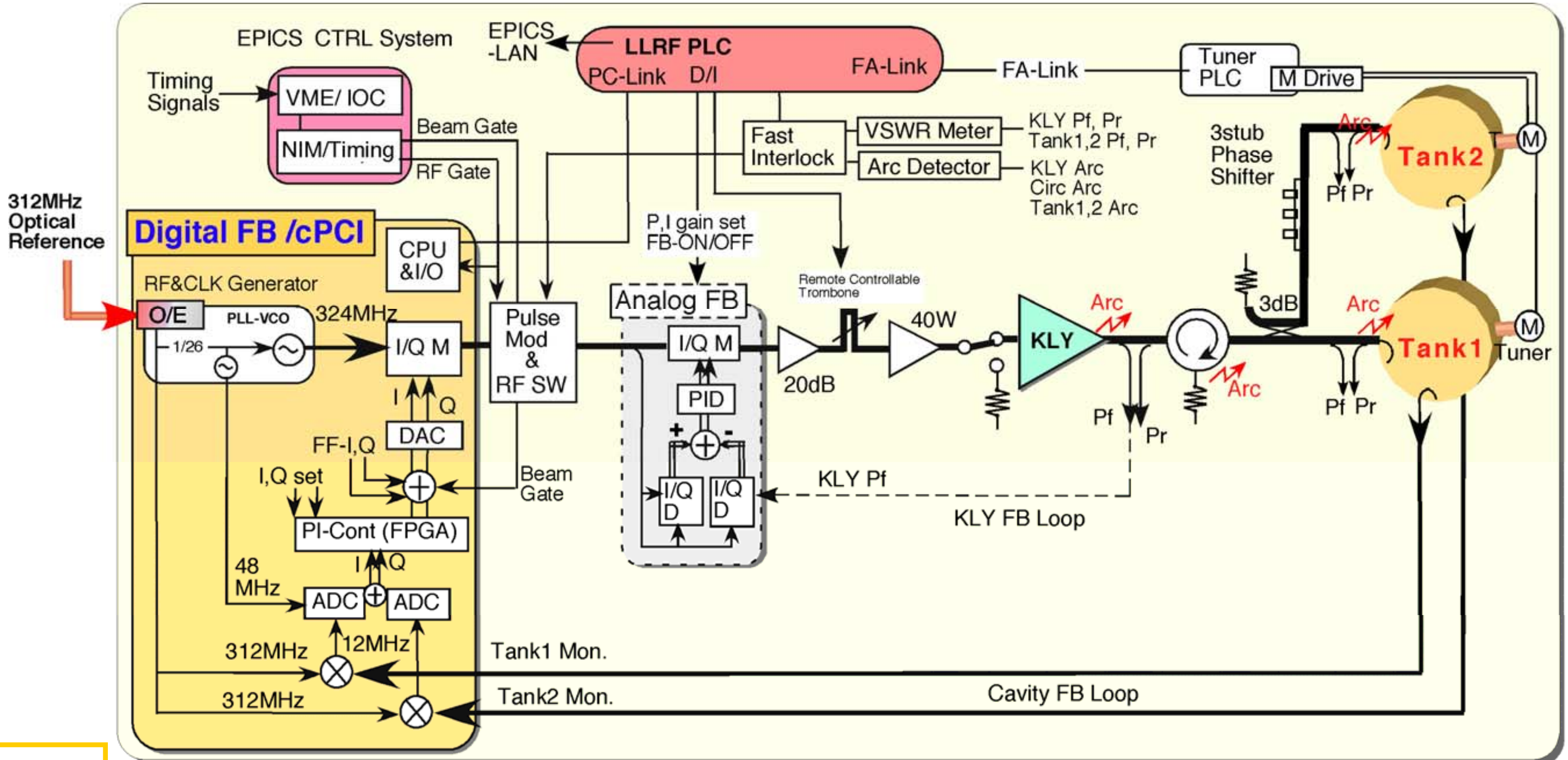
Phase trend for 4 days

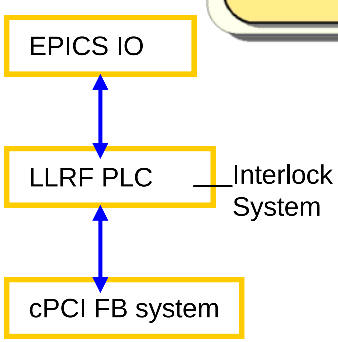


Stability	Measured Result	Spec.
Gallery Temp.	±1.7 °C	within ±2°C
Phase of Ref.	**±0.06°**	**within ±0.3°**

Required stability is satisfied.

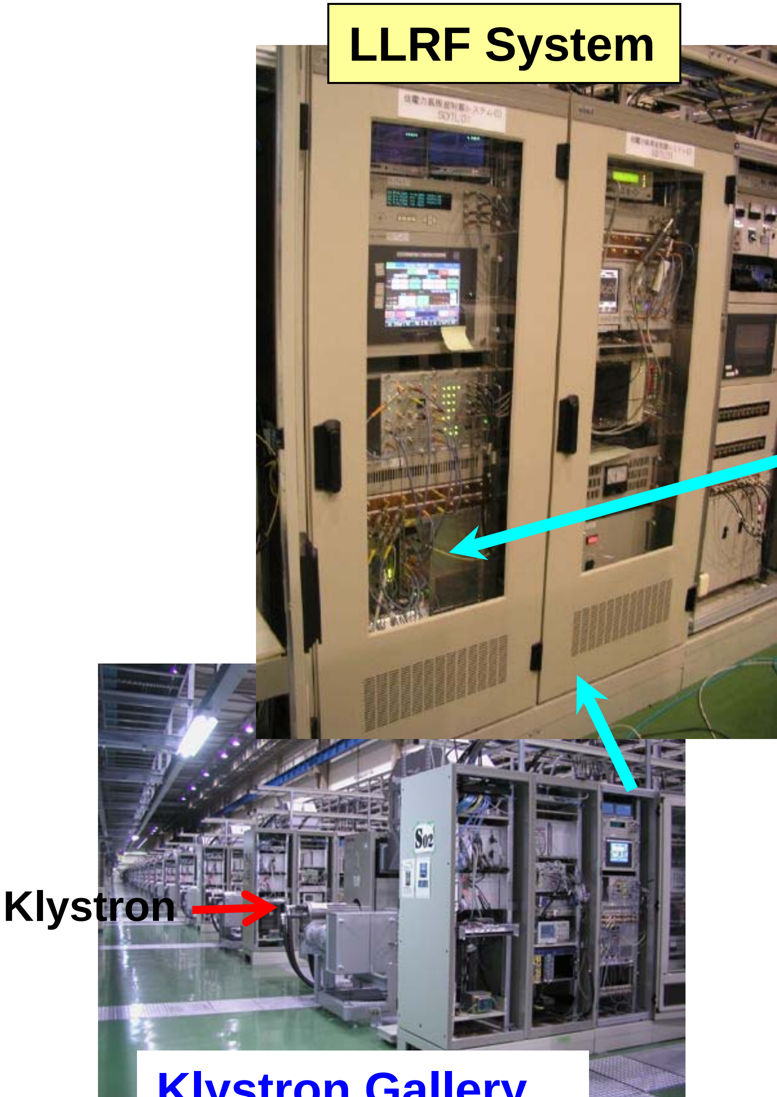
Low Level RF System

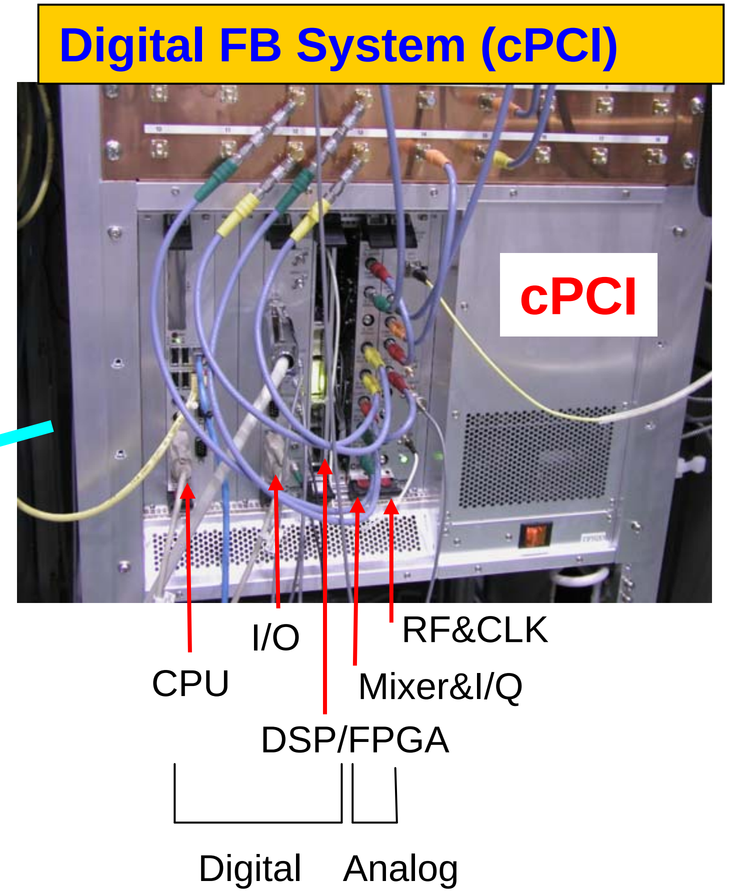




- **One klystron supplies power 2 cavities in the SDTL section.**
- **Digital FB system (FPGA & DSP) is used for the cavity field stabilization.**
- **The FB system controls the vector sum of the 2 cavity fields.**
- **The RF reference is 312-MHz optical signal (received by O/E converter) .**
- **Cavity-tuners are controlled from the digital FB system by way of PLC.**
- **Fast hardwire interlock is connected to RF switch outside the FB system.**
- **Analog fast FB will be used for klystron FB loop if necessary. (It is optional.)**

Low Level RF System ..(2)





Digital FB control system acts on a compact-PCI (cPCI) crate system.

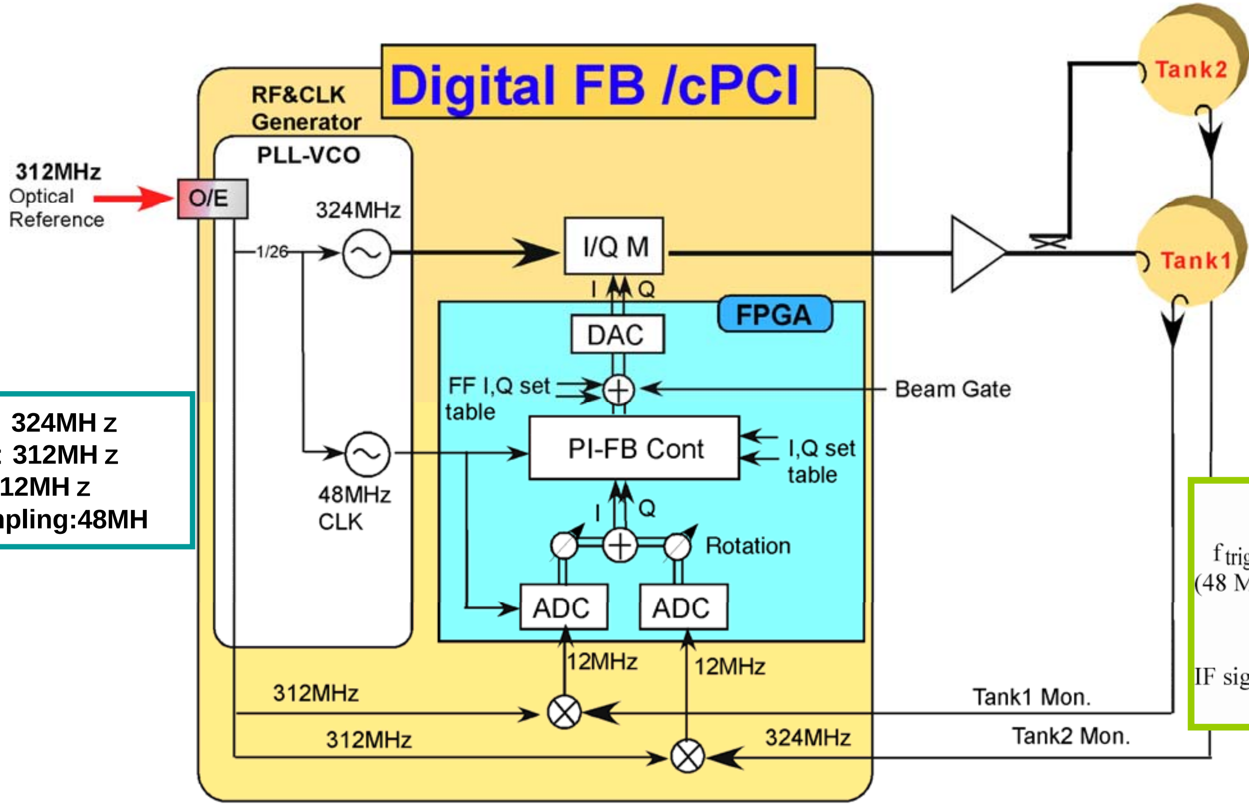
The FB and FF controls are performed by means of a combination of FPGA and DSP.

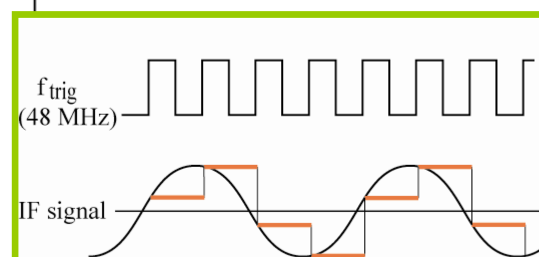
Digital FB Control System

cPCI digital FB system (FPGA & DSP)

- generates standard signals (48 MHz and 324 MHz).
- delivers I/Q modulated RF signals to 2 cavities.
- receives RF signals from cavities and down-converts to IF signal (12 MHz).
- samples the IF (12MHz) directly with 48 MHz.
- controls the vector sum of 2 cavity fields (PI-control).

RF : 324MHz
LO : 312MHz
IF : 12MHz
Sampling:48MHz





IF signals are directly read by ADCs.
The separated IQ signals are compared with set-tables and PI control is made with FF.

IQ Offsets Calibration of the IQ-modulator

We found that
the output of the **IQ-modulator** has **offsets** for I/Q set value (as Red Circle in the figure).

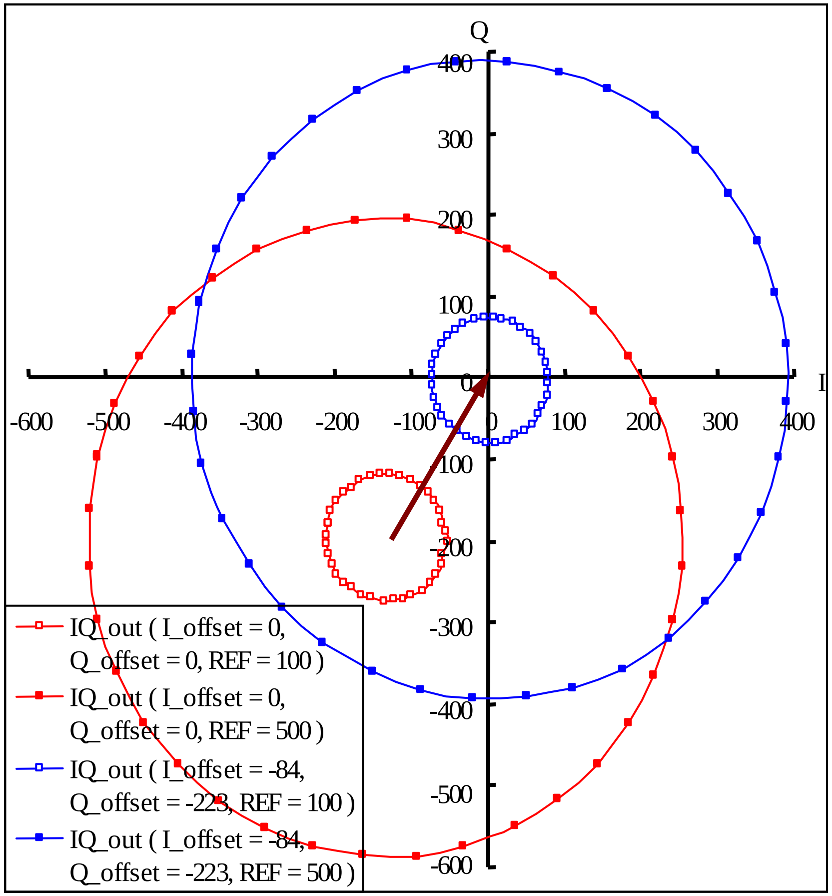
(Even if I and Q components set to 0, but the IQ-modulator still outputs a considerable signal.)

In order to cancel this undesired output,
we added I/Q offsets to the DAC out.

The offset values were measured for all the LLRF systems.

With calibration of the IQ offsets,
the performance of the IQ-modulator significantly improved (as Blue Circle)

With phase scanning, the amplitude of IQ modulator output varies by less than 1%.

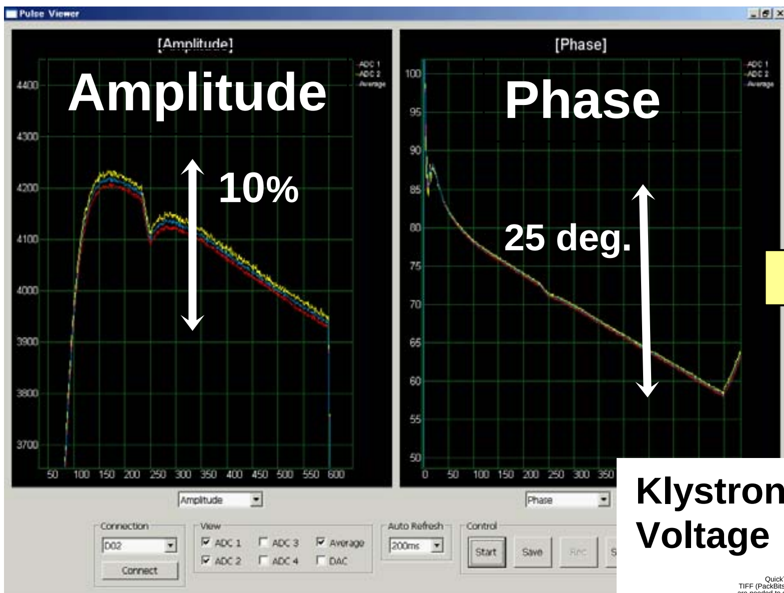


IQ modulator outputs at SDTL13 with or without IQ offsetting.

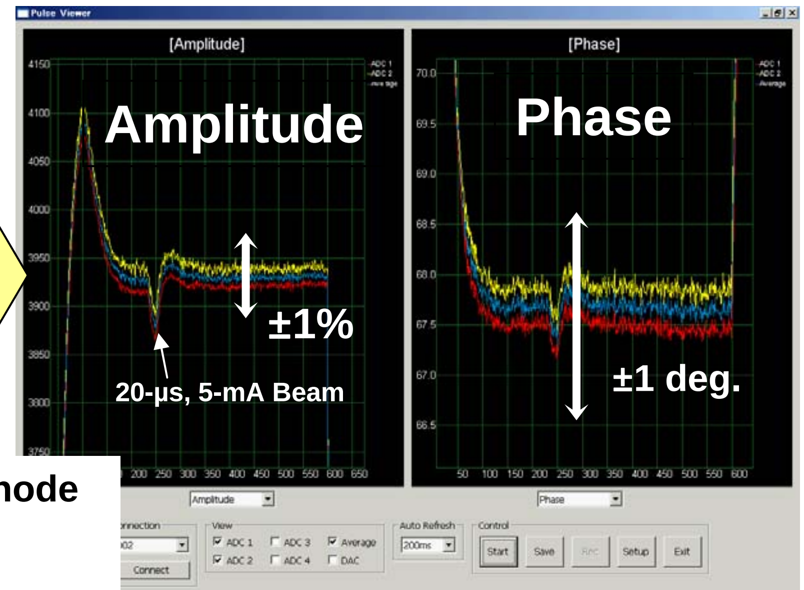
Performance of Feedback (FB) Control

Cavity field stabilization (in 600-µs pulse)

No FB Control



with FB Control **(Gain: P=5, I=5/1000)**



Klystron Cathode Voltage

QuickTime™ and a TIFF (PackBits) decompressor are needed to see this picture.

3.4% sag

25-degree phase sag is due to about 3.4% sag of the Klystoron DC voltage.

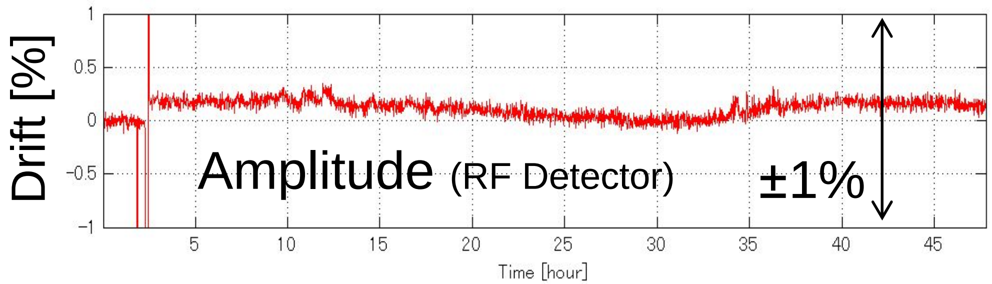
Amplitude and phase are stabilized to be less than ±0.15% and ±0.15 degrees, respectively.

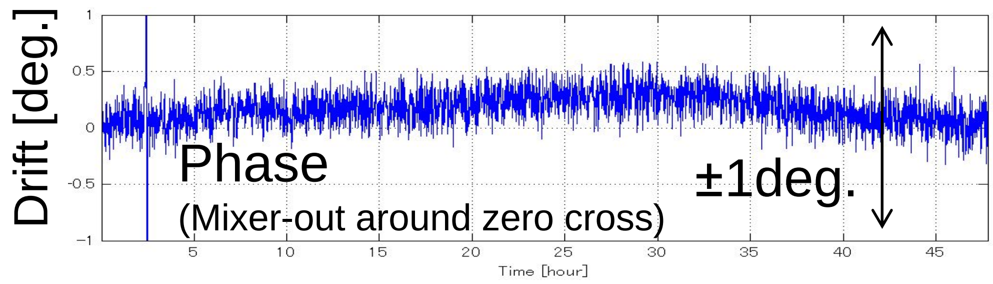
Beam loading (rising/falling ripple) is completely compensated with feed-forward control .

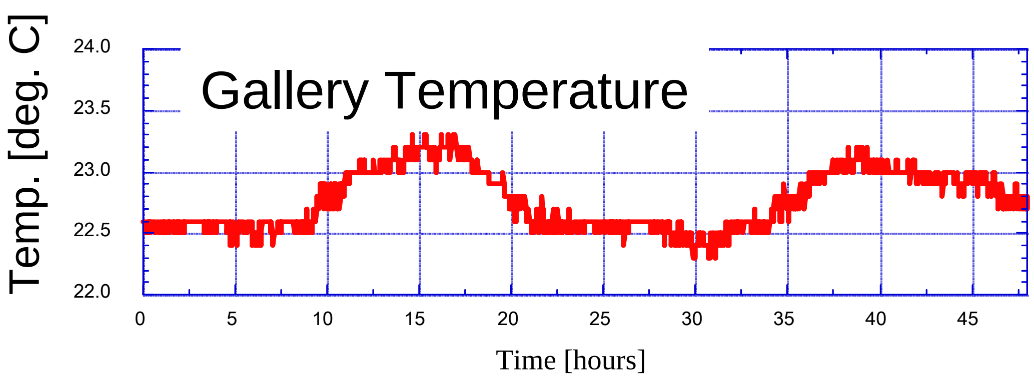
Long Term Stability

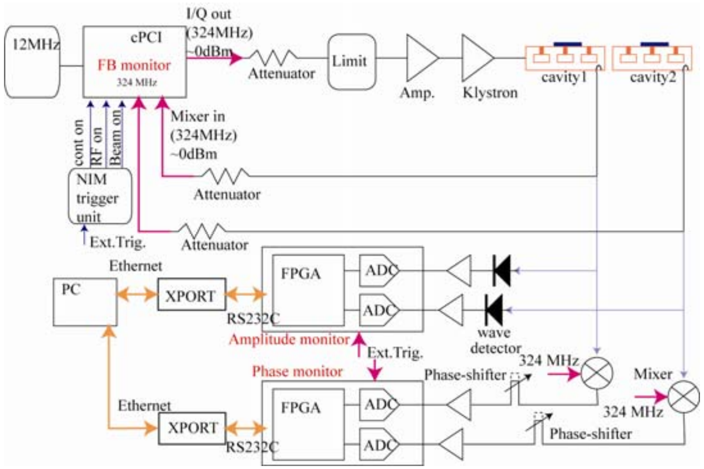
The stability of the FB system in long-duration operation was evaluated.

The trends of the amplitude and phase of the DTL2 Cavity (Input Power 1MW) were measured by external monitor (independent of FB system) **for 2 days**









(during 2 days.)

Amplitude drift is ±0.15%.

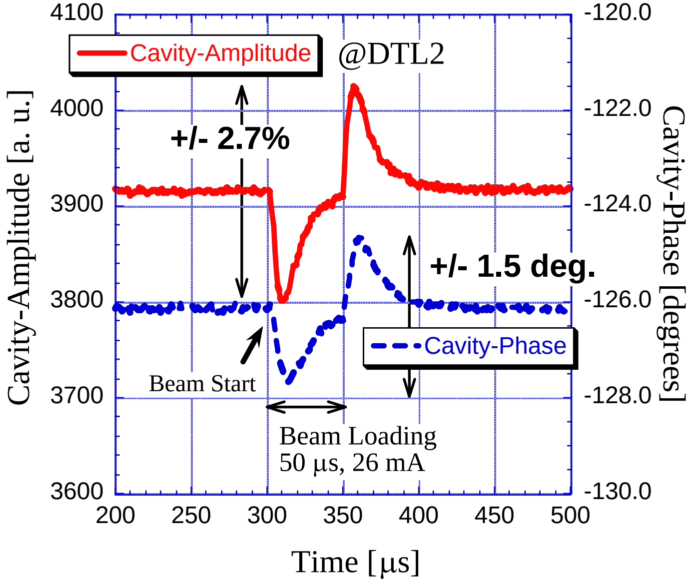
Phase drift is ±0.15 degrees.

These results are including characteristics of measurement system (detector, mixer and so on).
Therefore, cavity field is maybe more stable than observed values.

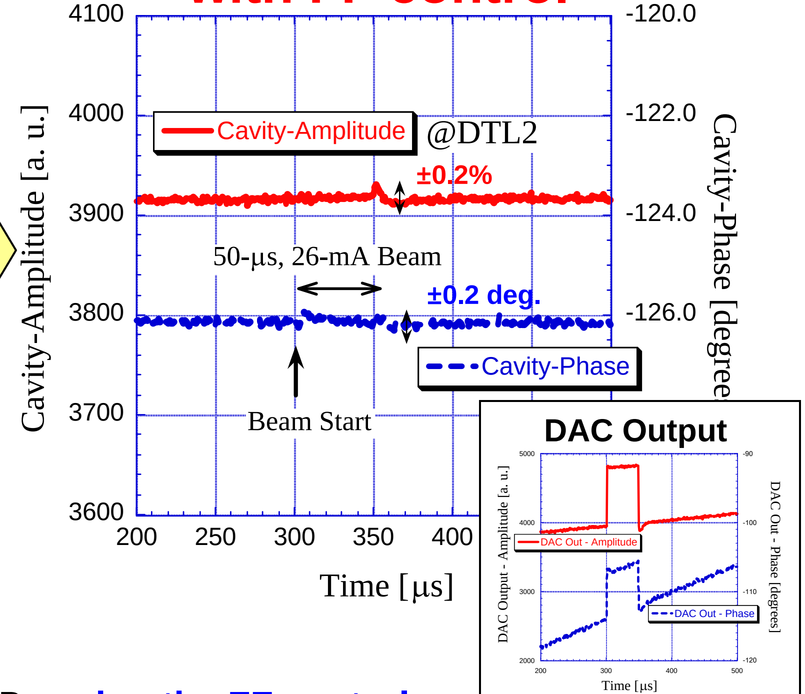
Beam Loading Compensation

with Feed-forward (FF) control

No FF control



with FF control



Beam Loading in DTL cavity field with only FB control.
Peak Current: **26 mA**, Pulse width: **50 us**,

The amplitude change: ±2.7% ,
Phase Change: ±1.5 degrees

By **using the FF control**
the beam loading was **successfully compensated**.
(Amplitude change: ±0.2% , Phase change: ±0.2 deg.)

However, it is necessary to adjust a timing of a control gate by 0.1-us step for optimization.

Optimum values of the FF amplitude and phase **depend on beam current**.

Summary

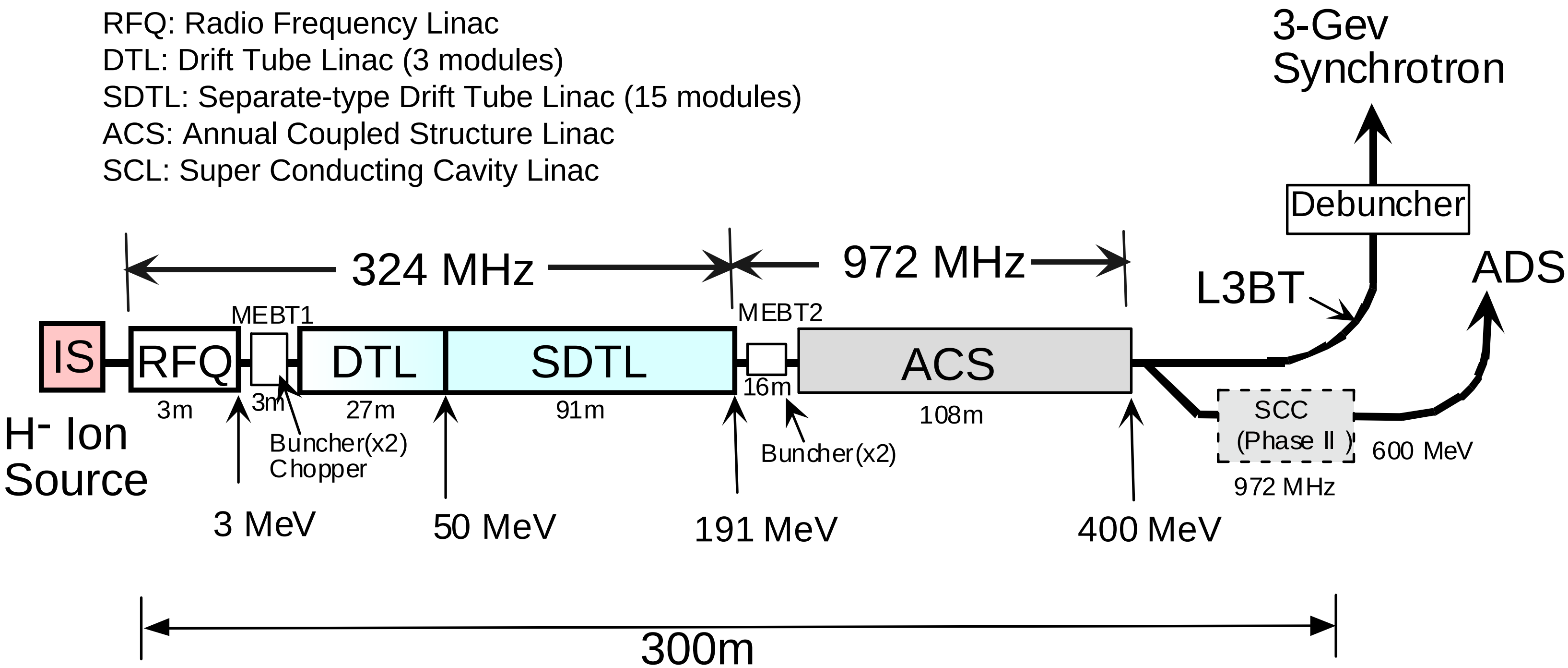
- High power operation was started in October 2006.
- RF control systems are working well without fatal problem.
- the 181-MeV acceleration was succeeded in January 2007.
- The digital FB control system is performing according to the expectation.
- Required stability is satisfied in duration of RF pulse and in running operation. (Amplitude change: < ±0.2%, Phase change of RF reference: < ±0.1° and FB control: < ±0.2°)
- The beam loading was successfully compensated with FF control.
- Now, beam commissioning has been steadily continued.

Introduction (3) -- J-PARC Linac

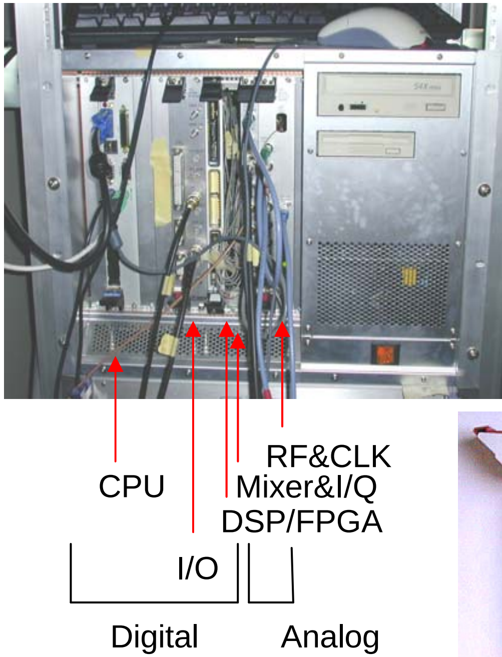
(Final Design)

Accelerated particles: H^- (negative hydrogen)	
Energy:	400 MeV for 3-Gev Synchroton
	600 MeV for Accelerator ADS
Peak current:	50 mA
Repetition:	50 Hz (including 25 Hz for ADS application)
Pulse width:	500 us (Beam), 650 us (RF)
Acceleration Frequency	324 MHz (~191MeV) , 972 MHz (~400 MHz)

RFQ: Radio Frequency Linac
DTL: Drift Tube Linac (3 modules)
SDTL: Separate-type Drift Tube Linac (15 modules)
ACS: Annual Coupled Structure Linac
SCL: Super Conducting Cavity Linac

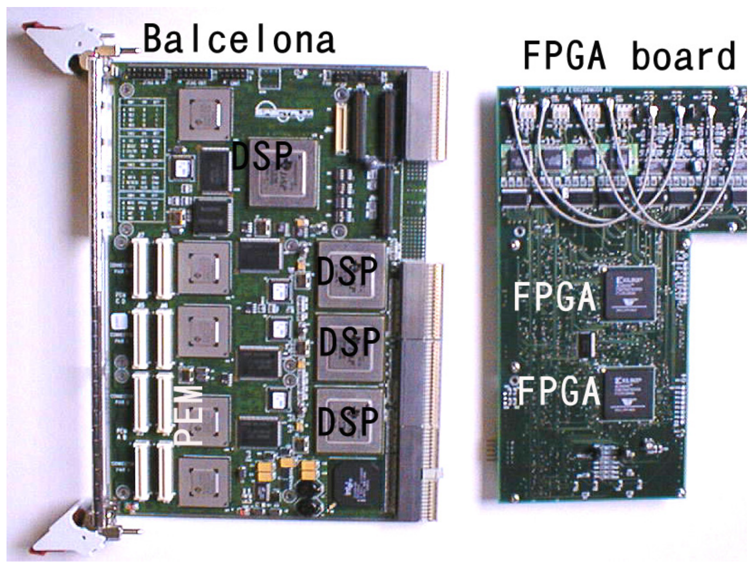


Digital FB Control System (Apendix)



cPCI is adopted for the crate.

FPGA based digital FB system
FPGA: Mezzanine card of the commercial DSP board



- **2-FPGAs (**2x VirtexII 2000) **are installed with 4x**14bit-ADCs and4x14bit-DACs at 48 MHz sampling
- DSP board enables to calculate complex diagnostics such as cavity control.
- FPGAs are used only for fast feedback.