Experiences on J-PARC LINAC LLRF Systems

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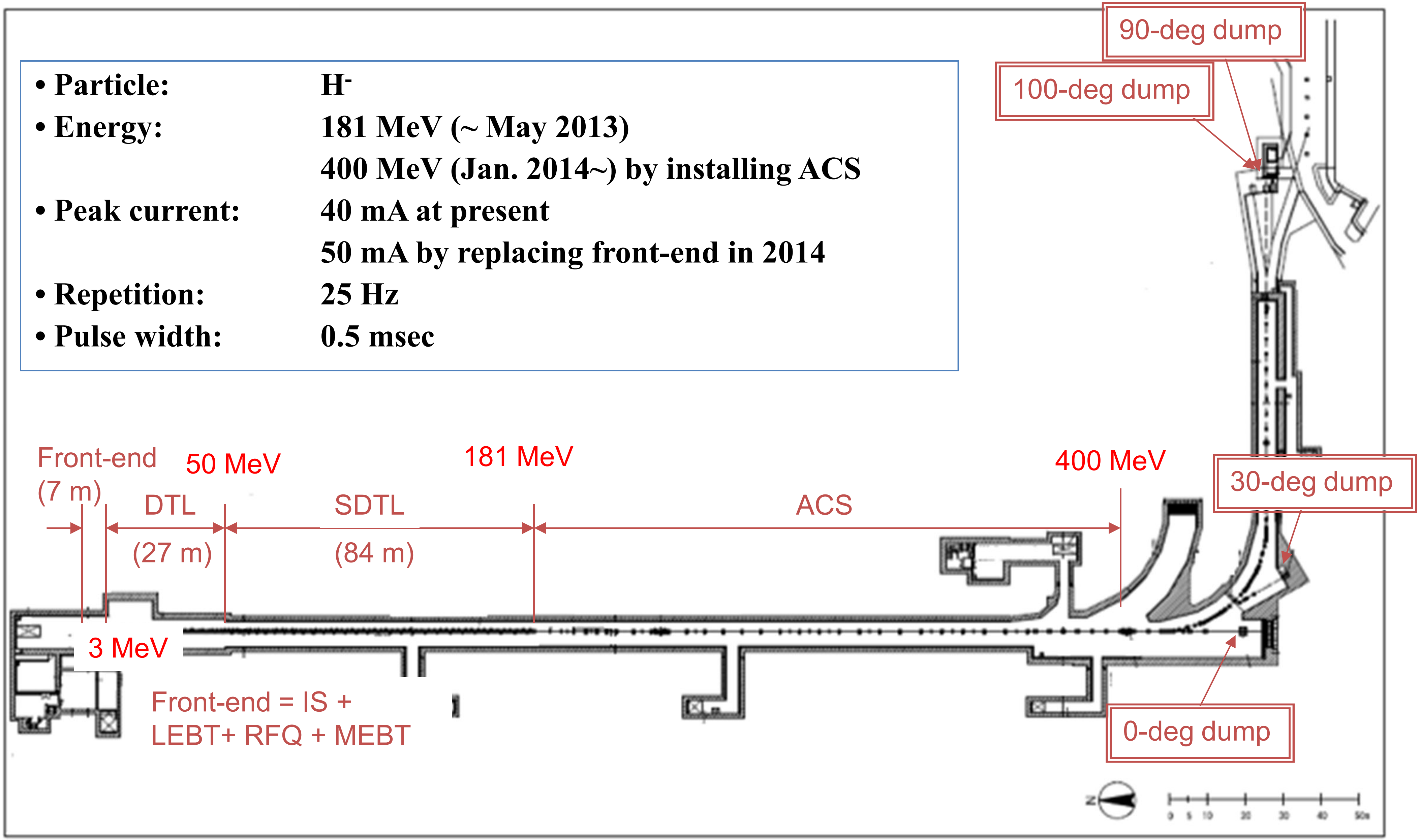
1 Introduction

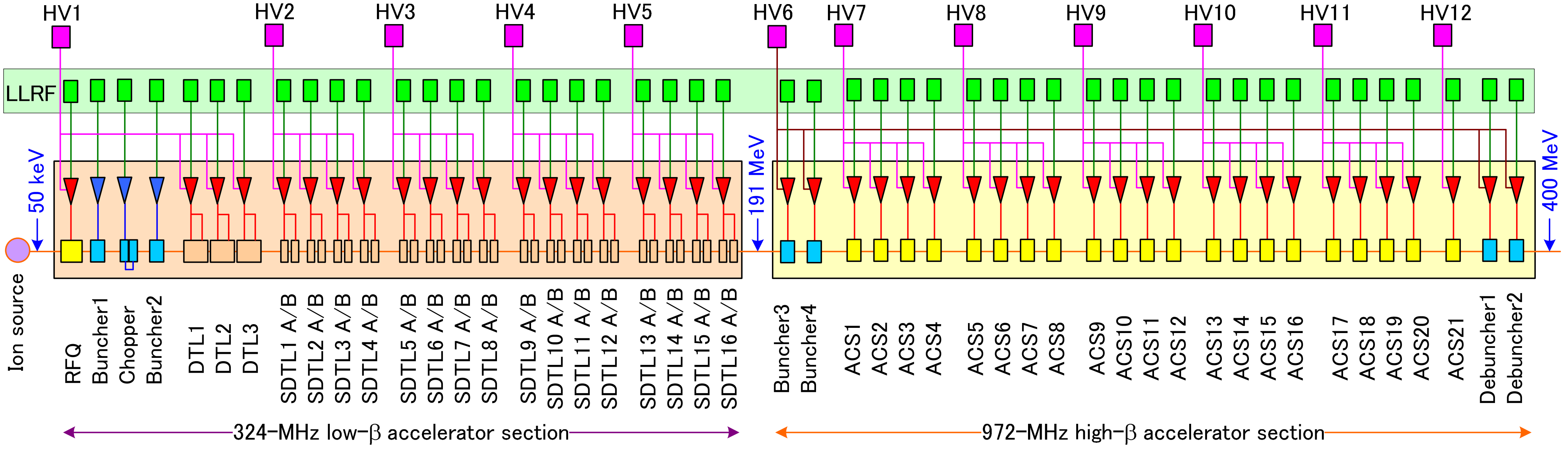
J-PARC LINAC

- **Particle:** H^-
- **Energy:** 181 MeV (~ May 2013)
  400 MeV (Jan. 2014~) by installing ACS
- **Peak current:** 40 mA at present
  50 mA by replacing front-end in 2014
- **Repetition:** 25 Hz
- **Pulse width:** 0.5 msec



From Prof. Tadashi Koseki, KEK

J-PARC LINAC



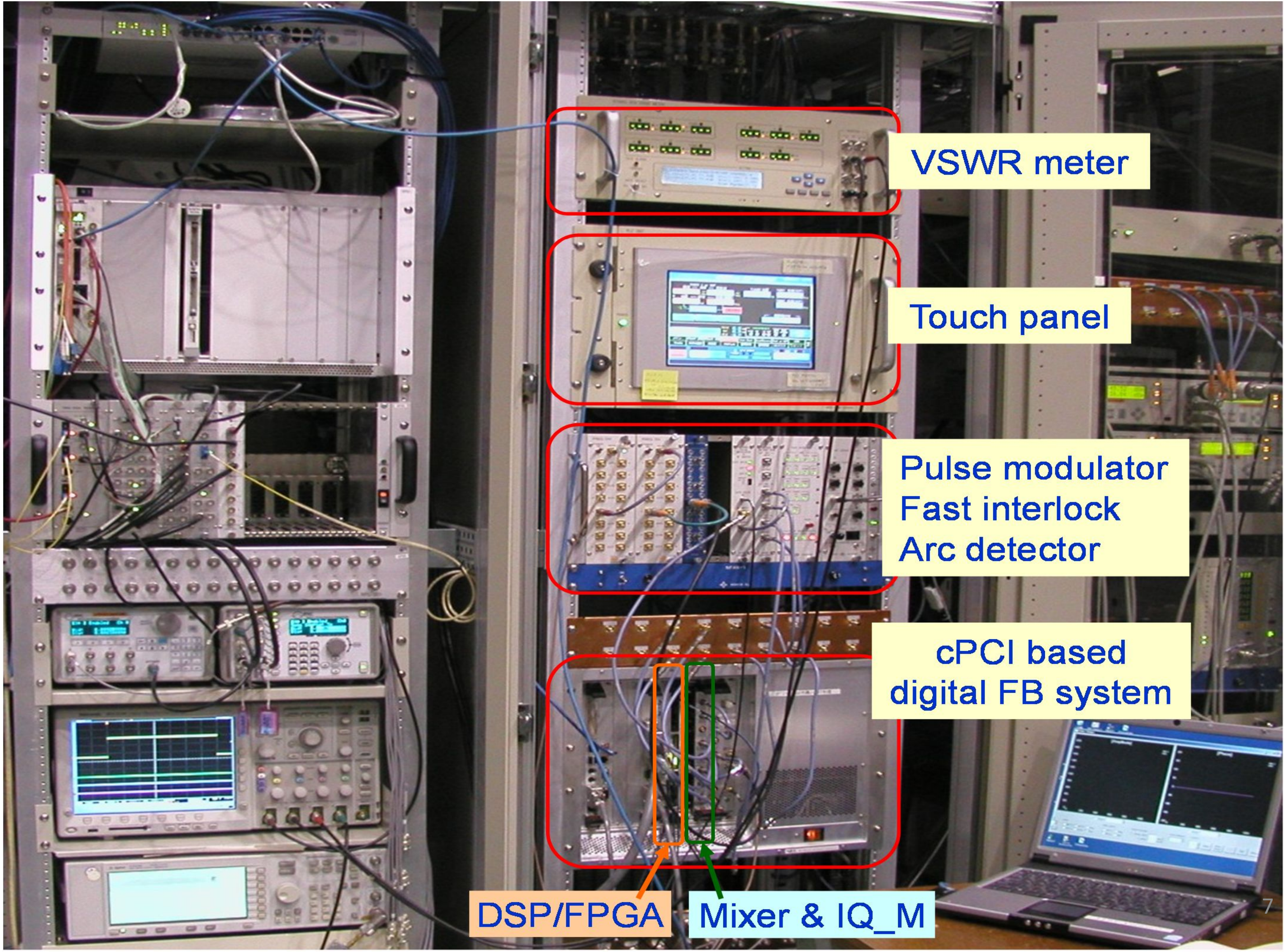

ACS


SDTL


DTL

J-PARC LINAC

J-PARC LINAC LLRF system



VSWR meter

Touch panel

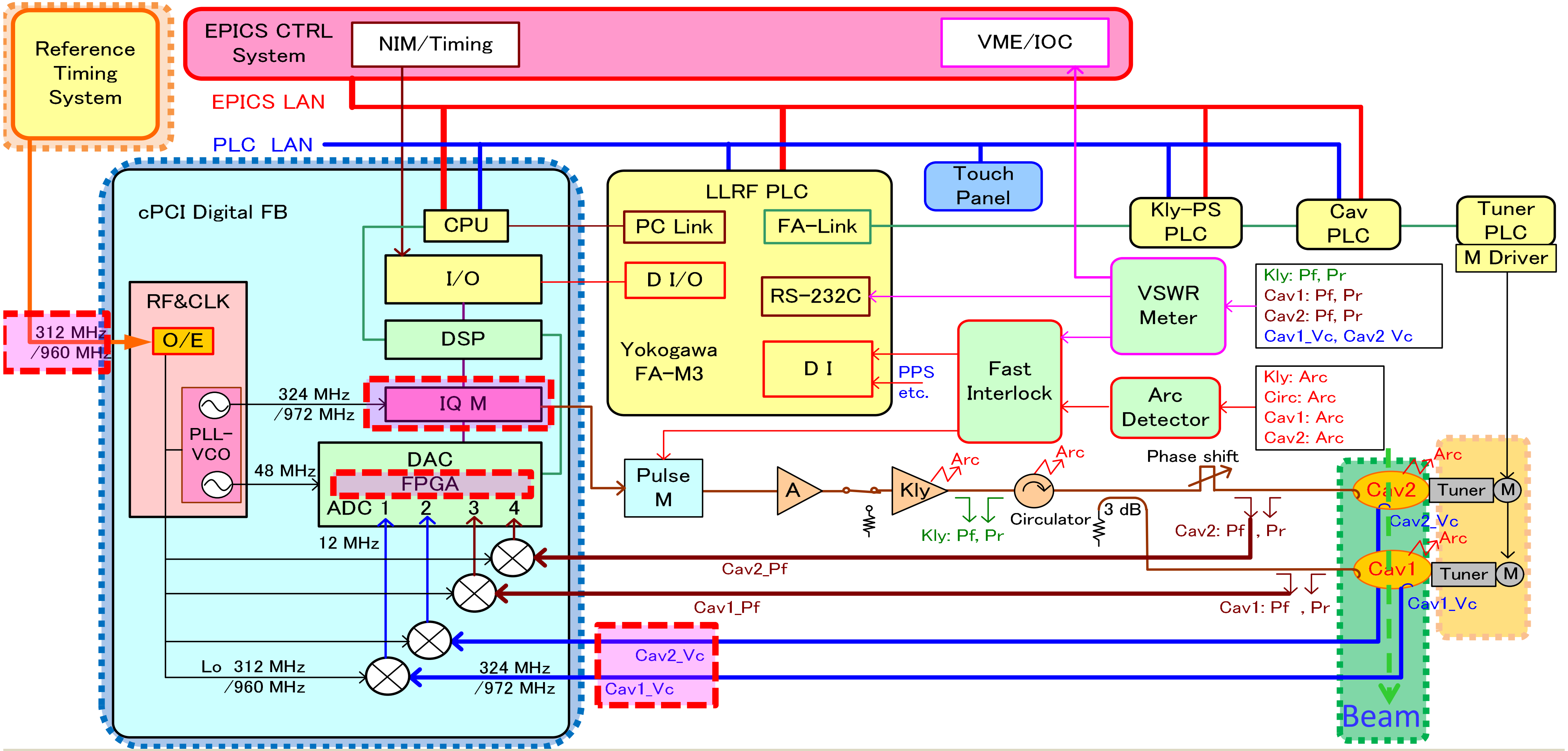
Pulse modulator
Fast interlock
Arc detector

cPCI based
digital FB system

DSP/FPGA

Mixer & IQ_M

Block diagram of J-PARC LINAC LLRF



Basic requirements of J-PARC LINAC LLRF:

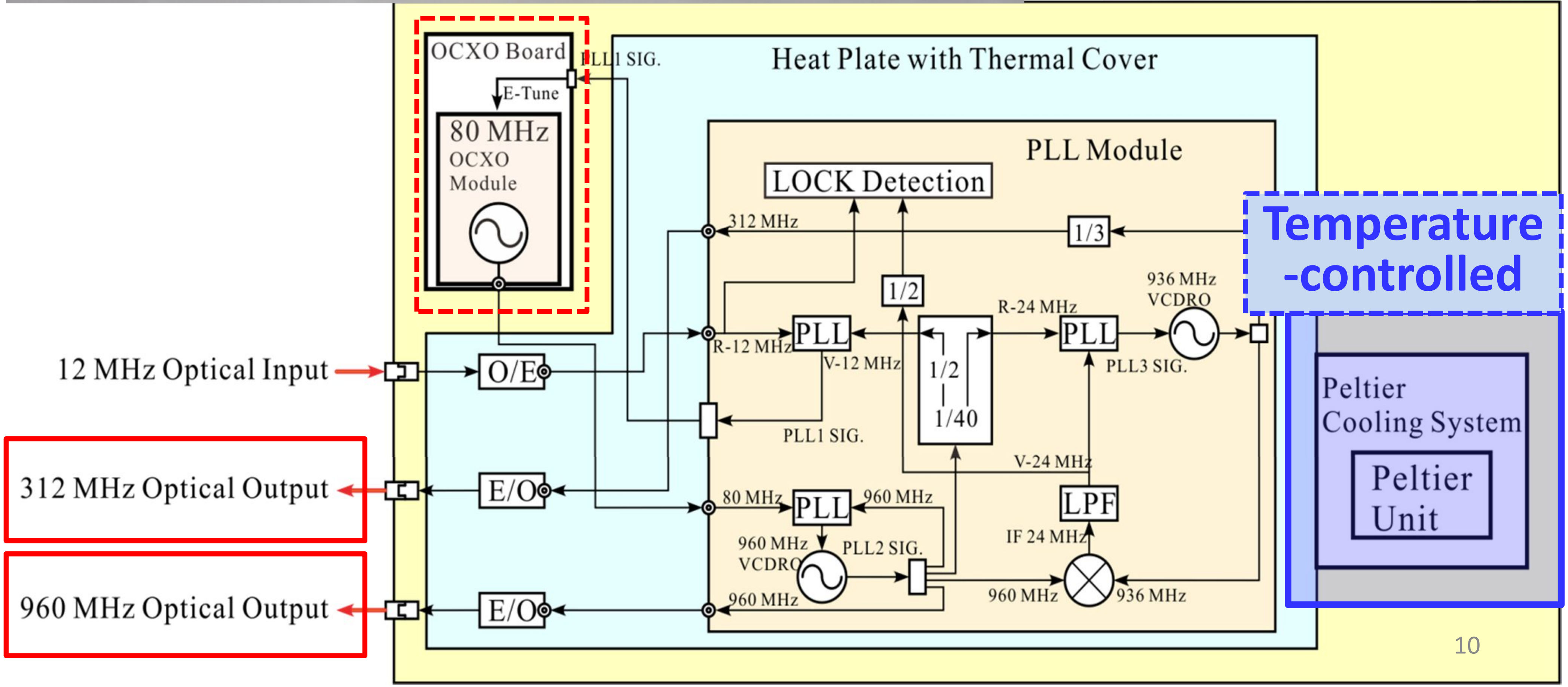
- Stabilities of rf field: ±1% in amplitude and ± 1° in phase.
- Auto-tuning of rf cavity.
- Interlock system.
- Operation system with a great convenience, high reliability, and fast response.

2 Reference timing system

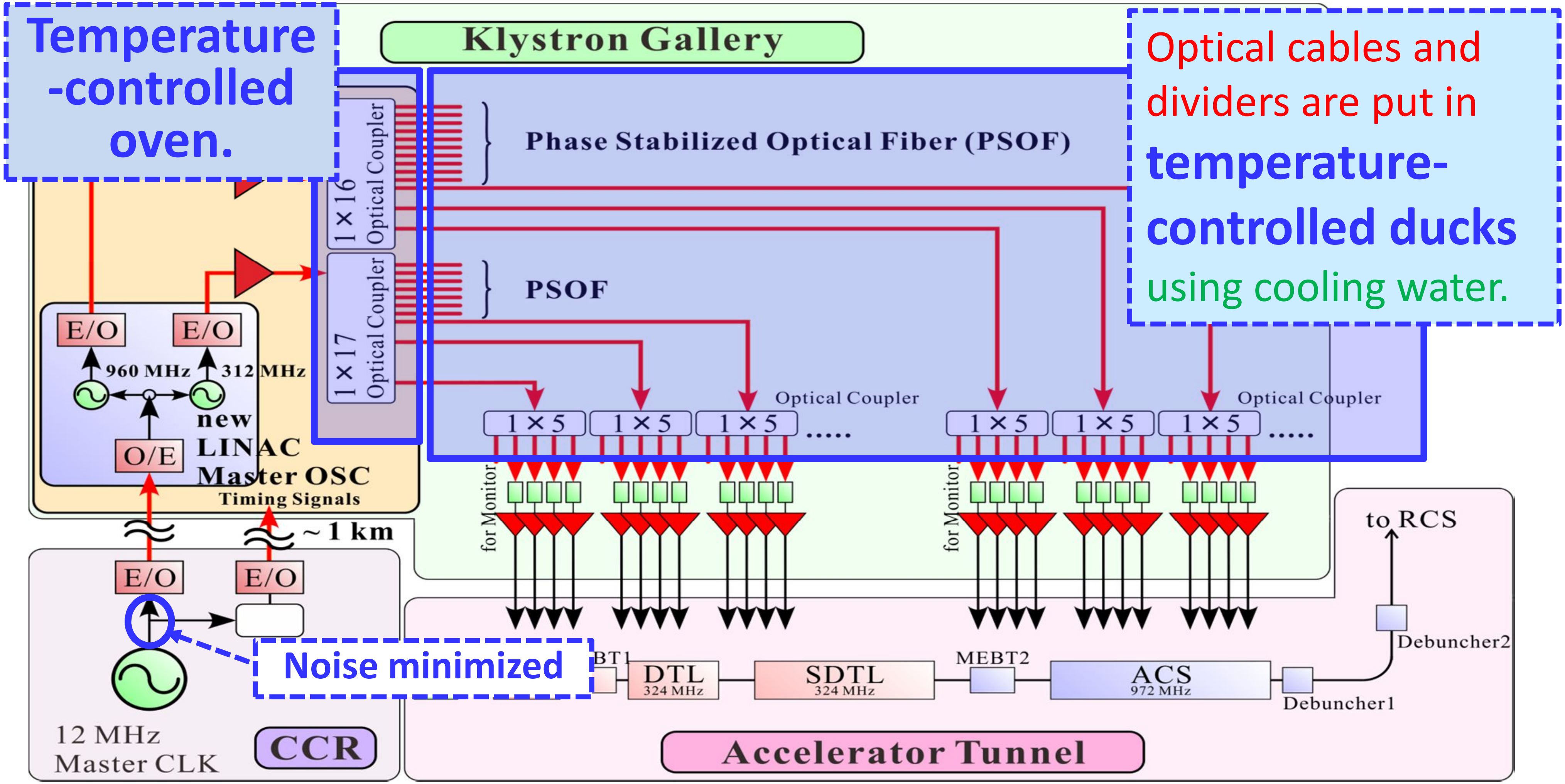
1) New master oscillator for LO signals
2) LO signal distribution system
3) 12MHz reference distribution system

1) New master oscillator for LO signals

Signal Source Analyzer E5052B (Agilent Technologies)



2) LO signal distribution system



Temperature-controlled oven.

Optical cables and dividers are put in **temperature-controlled ducks** using cooling water.

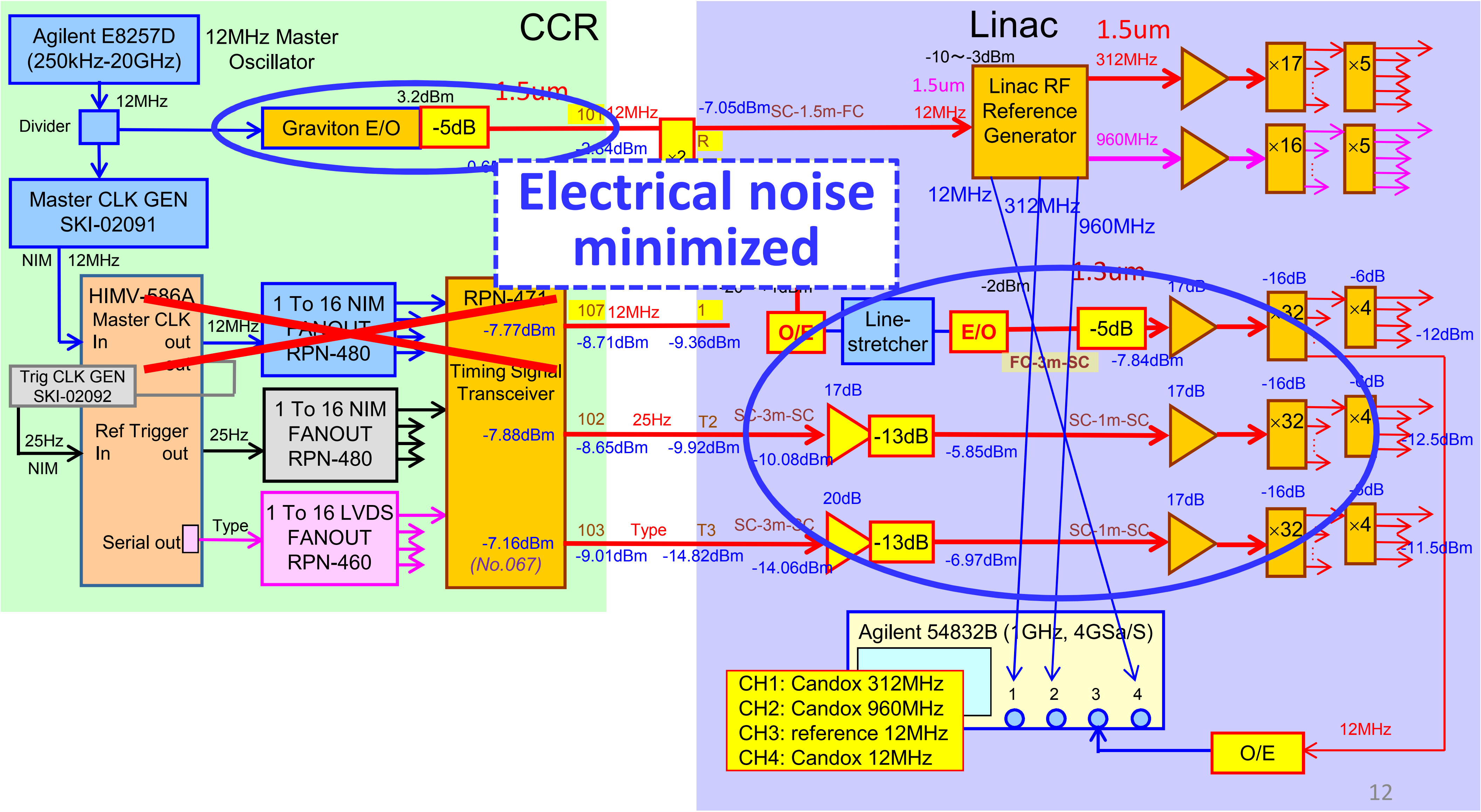
Noise minimized

The **LO signals** are **optically amplified and divided** into 17/16 lines, then **furthermore divided** into 5: one of them is returned to the front end for phase monitor; the others will be used for the LLRF systems at each station.

- The phase instability by monitoring the returned signals is about ±0.2 deg., better than requirements (±0.3 deg).

3) 12MHz reference distribution system

New system using **optical couplers**



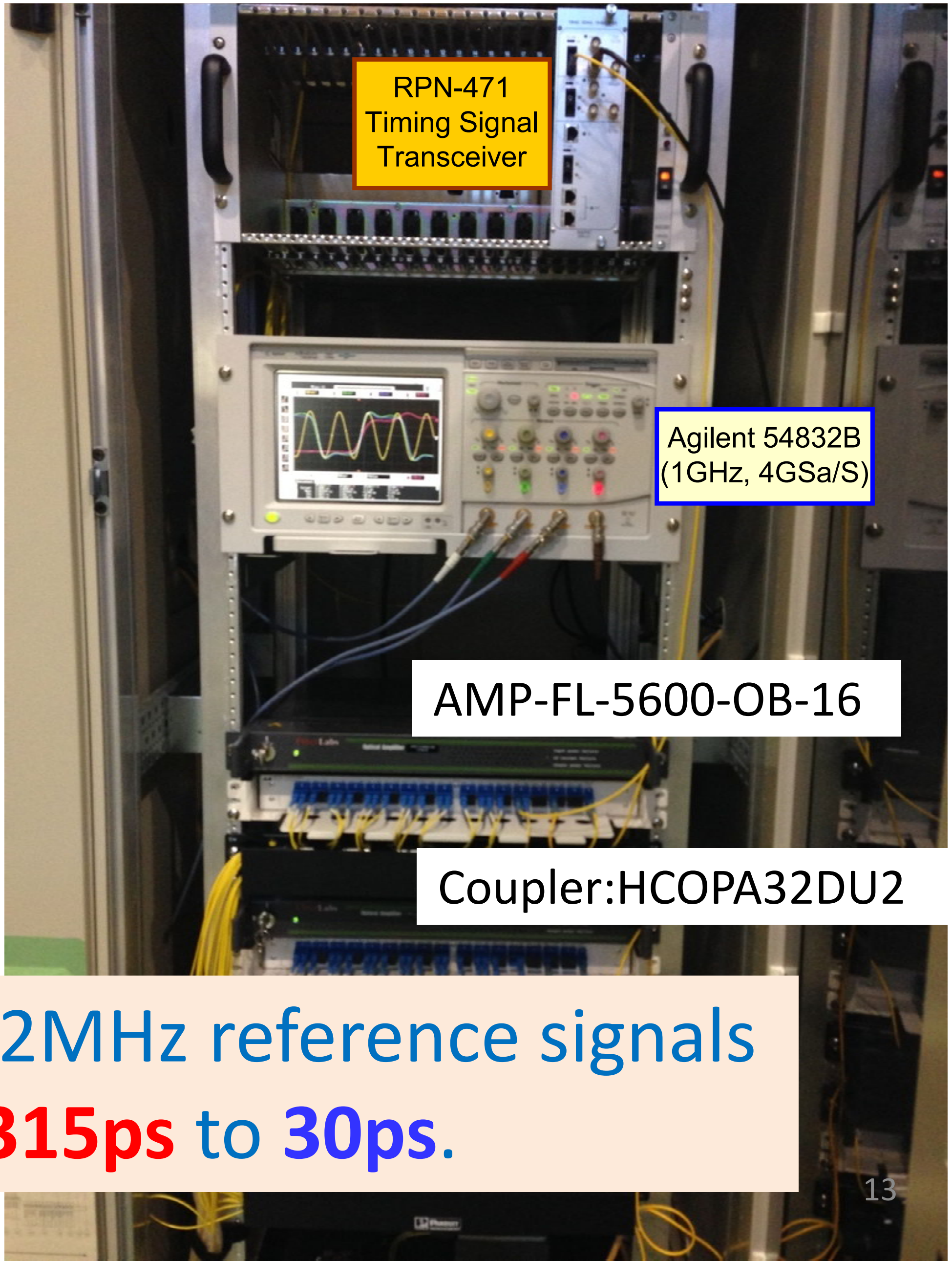
Electrical noise minimized

CH1: Candox 312MHz
CH2: Candox 960MHz
CH3: reference 12MHz
CH4: Candox 12MHz

New system using **optical coupler**


RPN-471 Timing Signal Transceiver

Line-stretcher


RPN-471 Timing Signal Transceiver

Agilent 54832B (1GHz, 4GSa/S)

AMP-FL-5600-OB-16

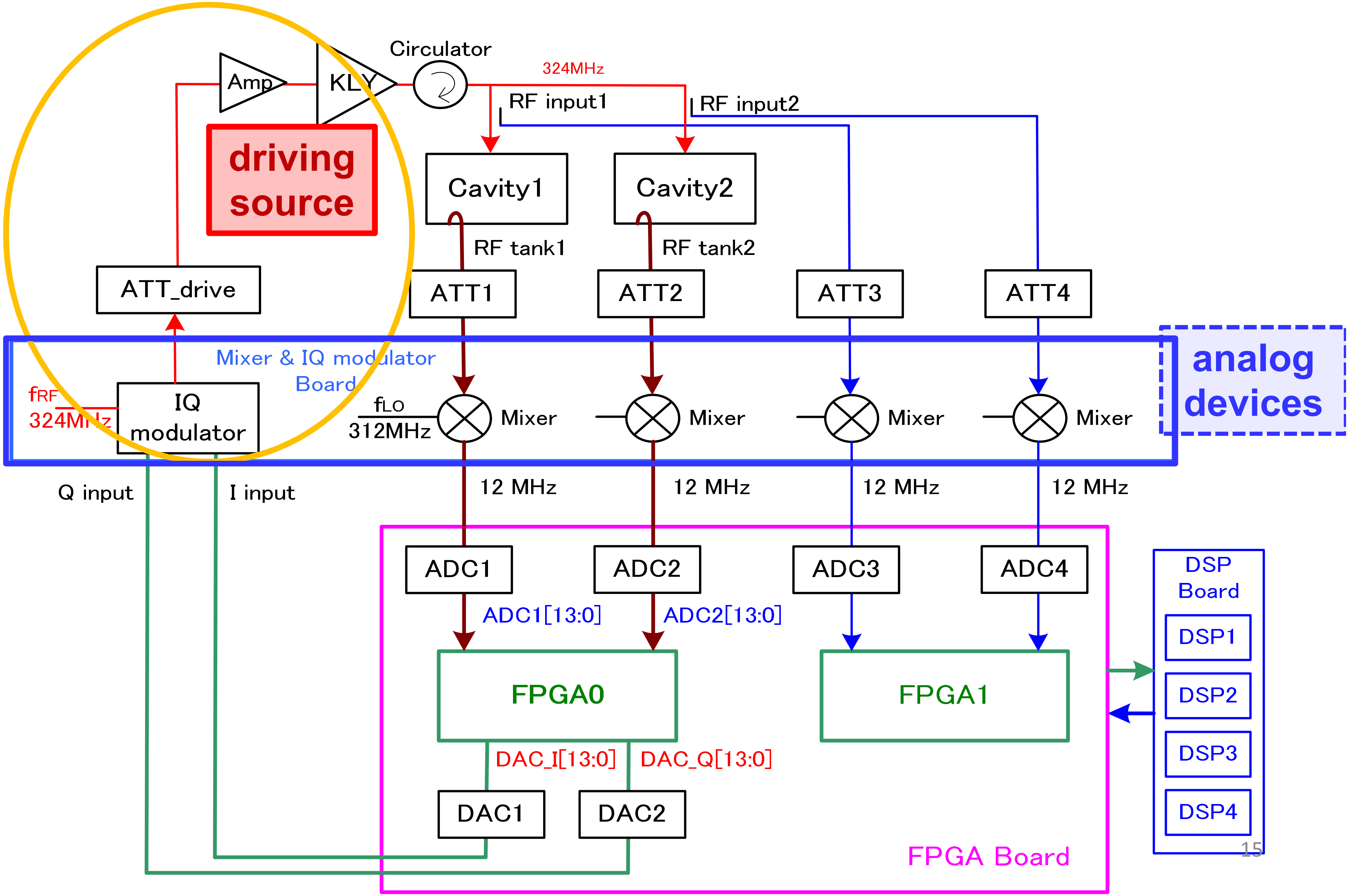
Coupler:HCOPA32DU2

Jitter between LO and 12MHz reference signals reduced from **315ps** to **30ps**.

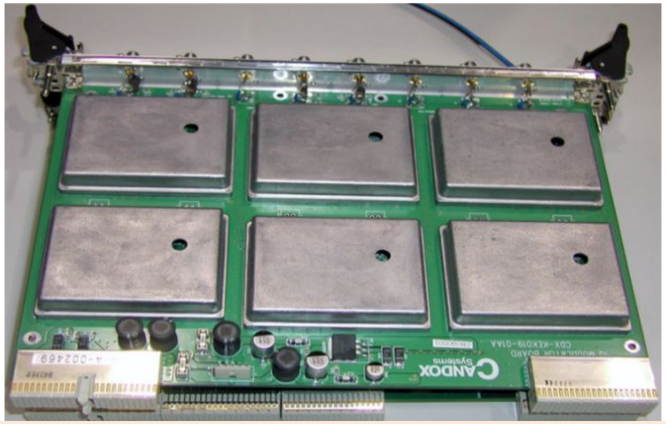
3 Digital feedback system

1) Feedback control circuits
2) Improvements of analog devices
3) Digital functions idealizing driving source
4) Optimization of feedback parameter setting

1) Feedback control circuits

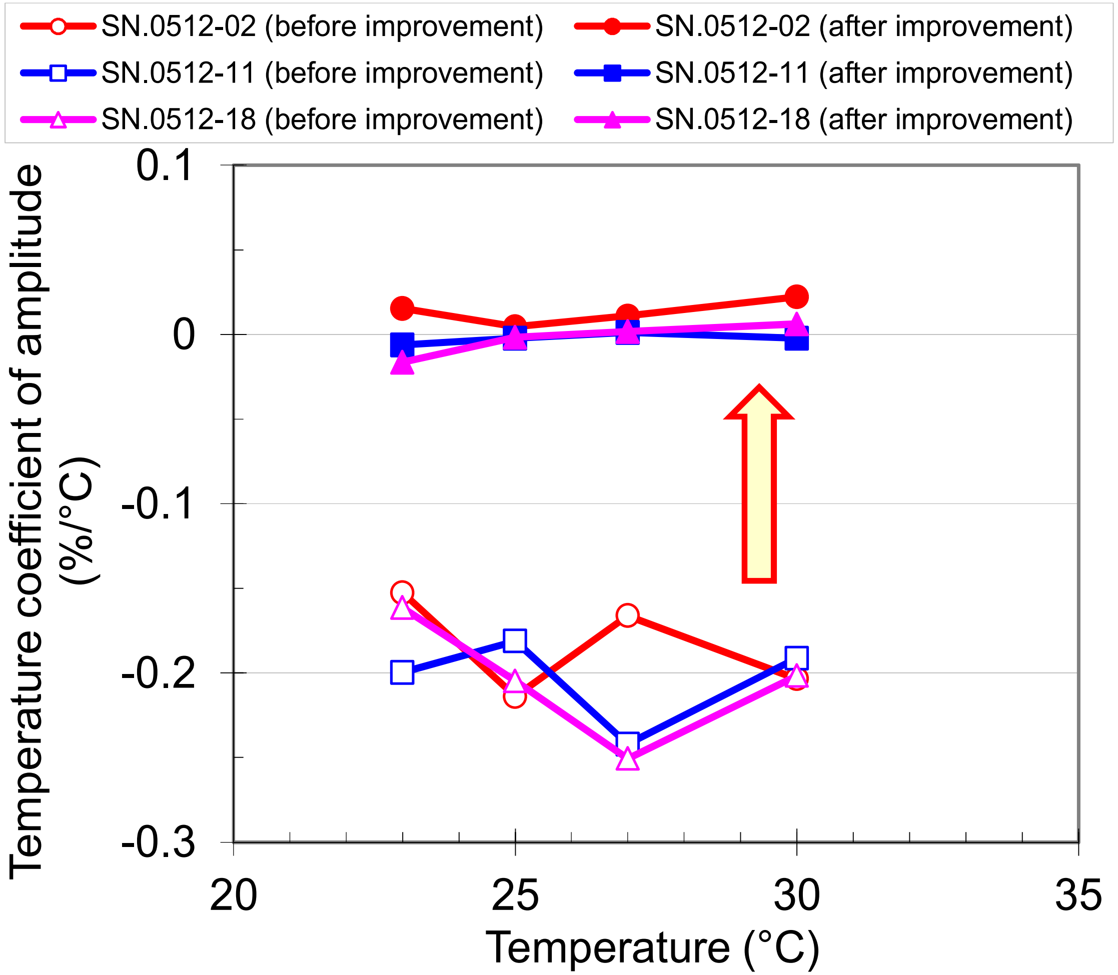


2) Improvements of analog devices

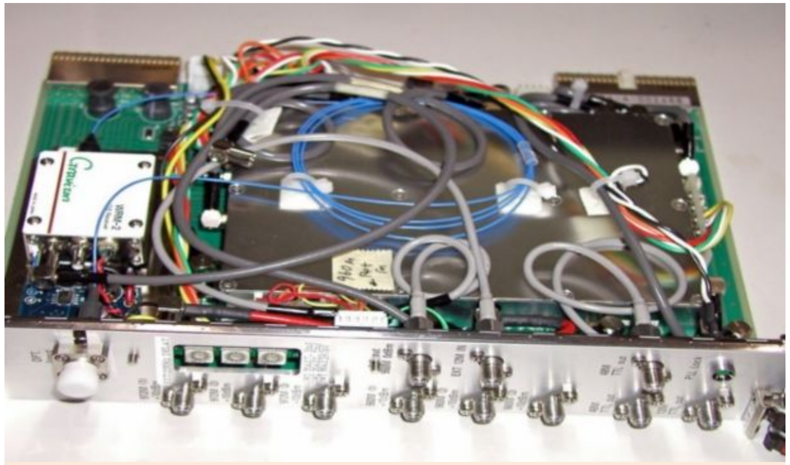


Mixer&IQ board

Introducing a **temperature-compensation attenuator** into the output circuits.

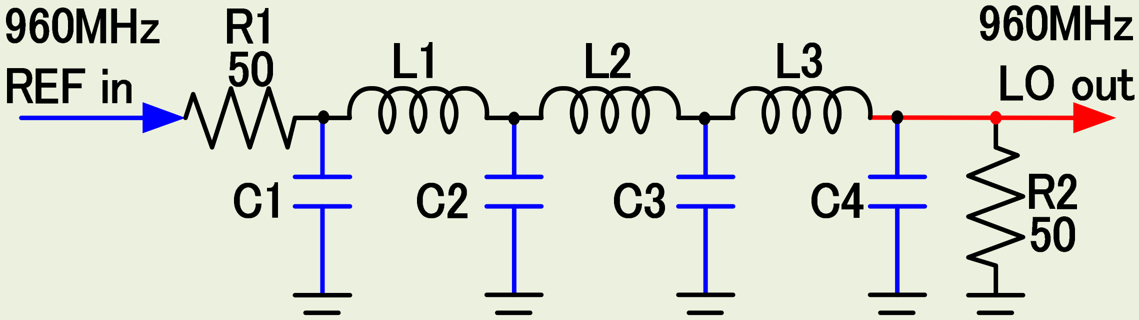


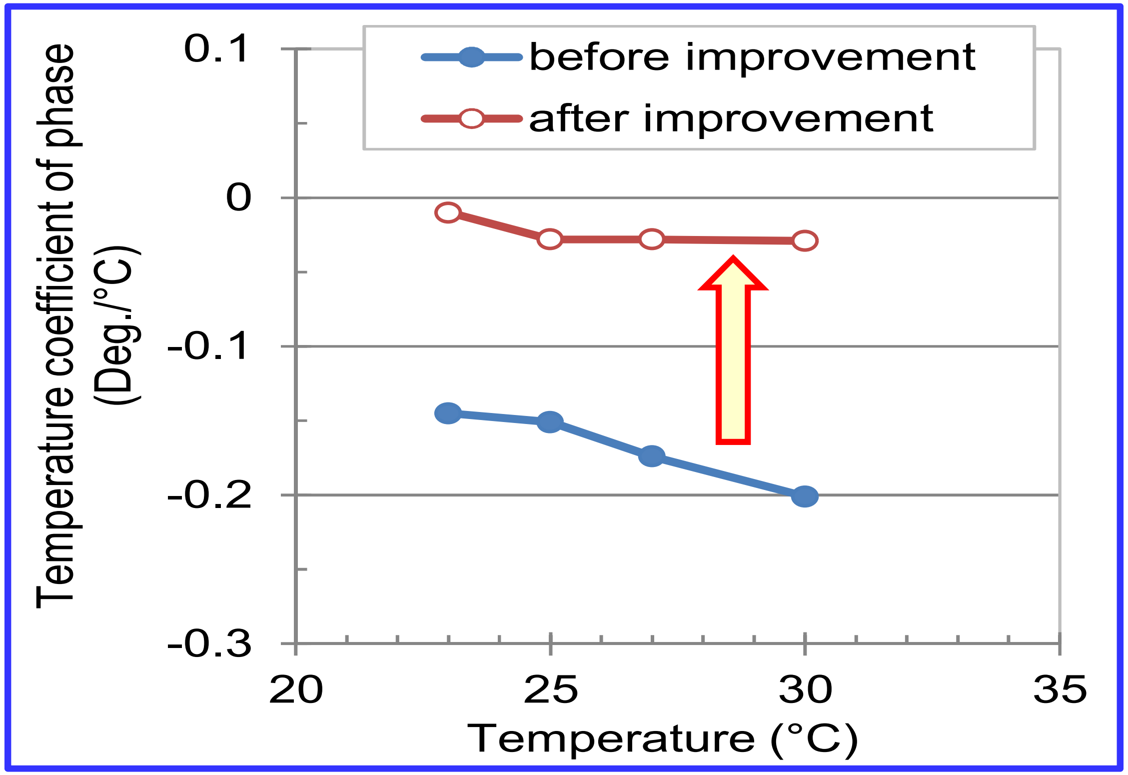
Temperature coefficient of amplitude of the down-converter output signal



RF&CLK board

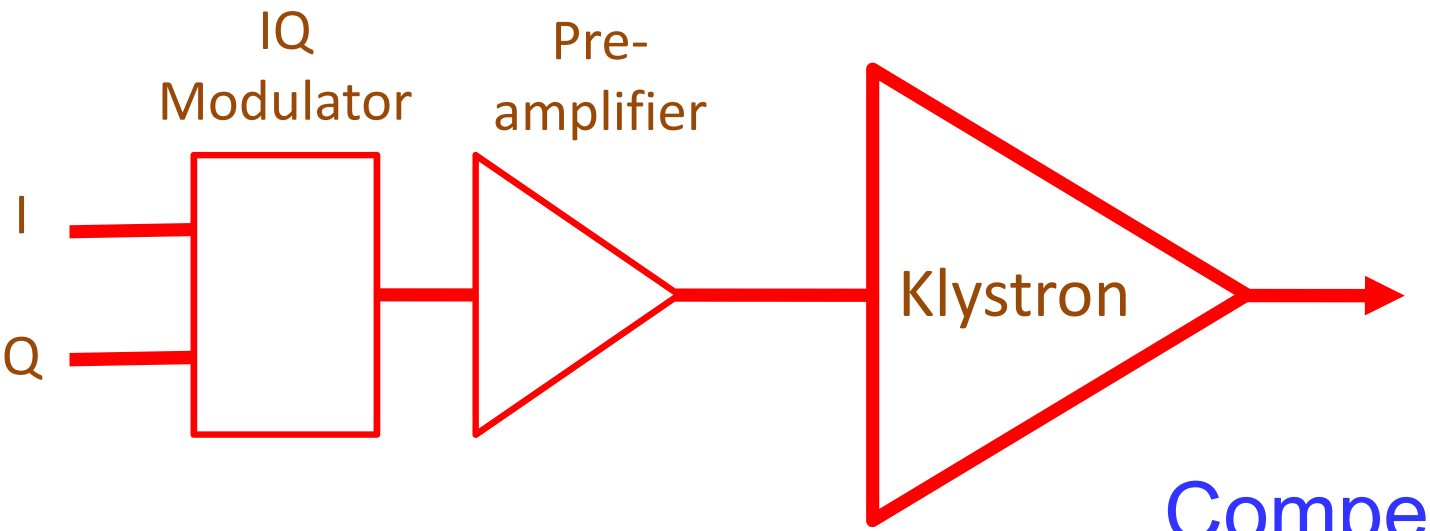
Using **temperature-compensation capacitors** in the Low-Pass Filter (LPF) of the LO output circuits.





Temperature coefficient of phase of the LO output signal

3) Digital functions idealizing driving source



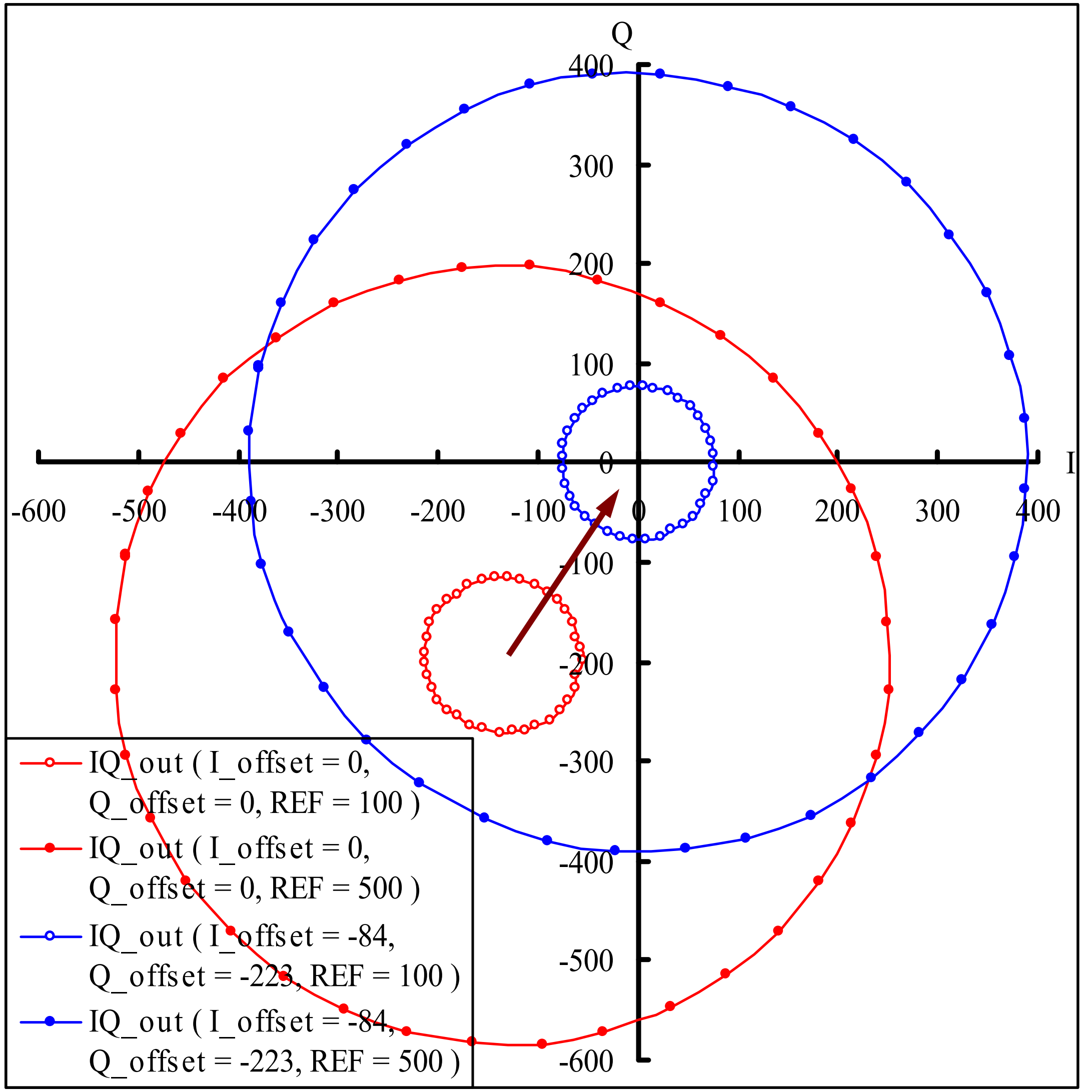
Compensation for

(1) Offset

(2) Sag

(3) Non-linearity

(1) IQ offset compensation



IQ modulator output at SDTL13 with or without IQ offset compensation.

(2) Automatic sag compensation

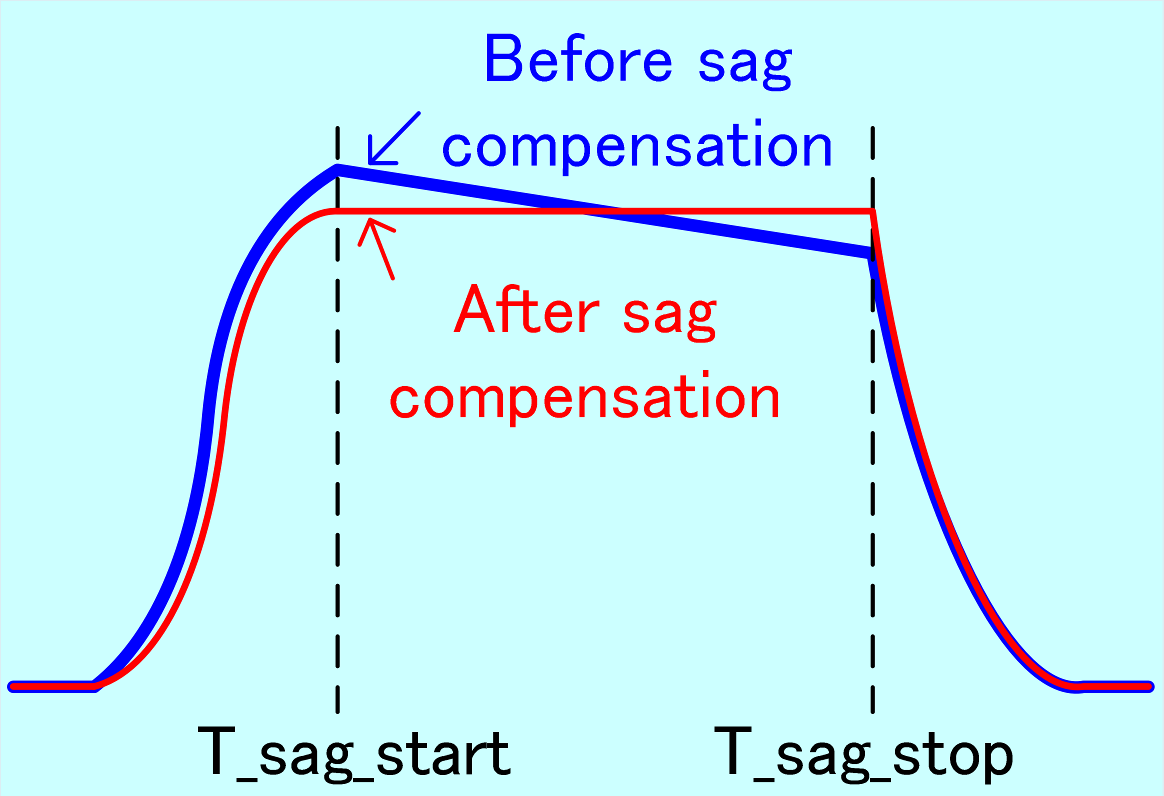
Sag compensation coefficient:

$$\Delta\alpha = \Delta\alpha_0 + \Delta\alpha\_test$$

$$\Delta\phi = \Delta\phi_0 + \Delta\phi\_test$$

$$\Delta\alpha\_test = \frac{\dfrac{A_{t2} - A_{t1}}{t_2 - t_1}}{\dfrac{A_{t1} + A_{t2}}{2}}$$

$$\Delta\phi\_test = \frac{\phi_{t2} - \phi_{t1}}{t_2 - t_1}$$



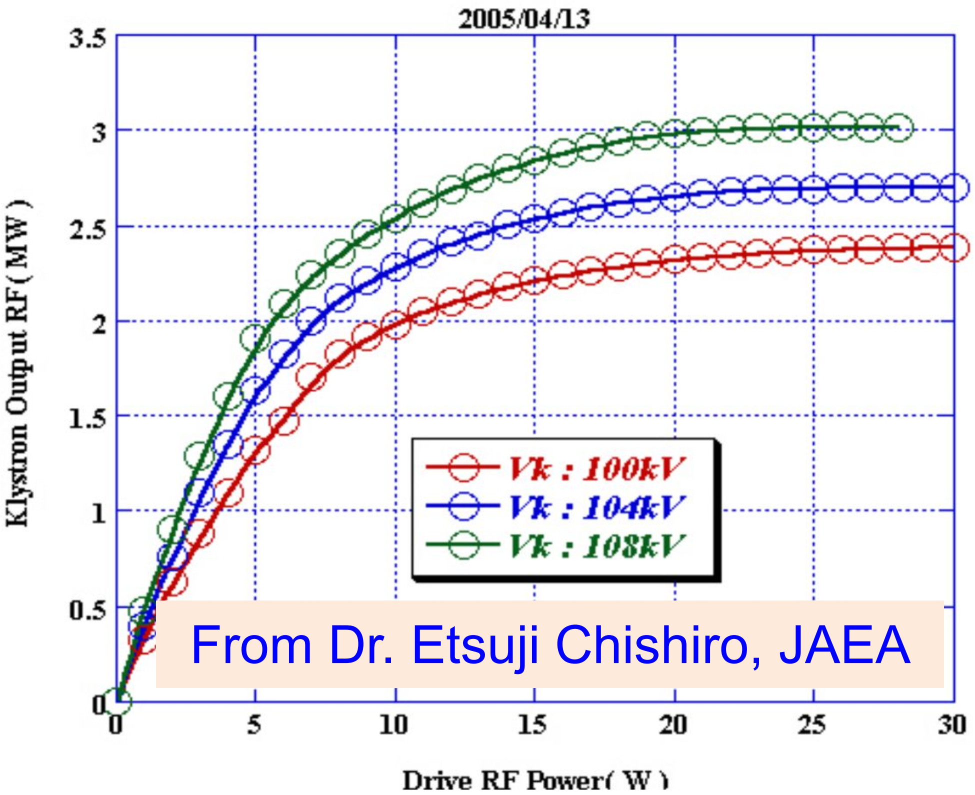
RF amplitude waveform with FB OFF

Feedforward tables:

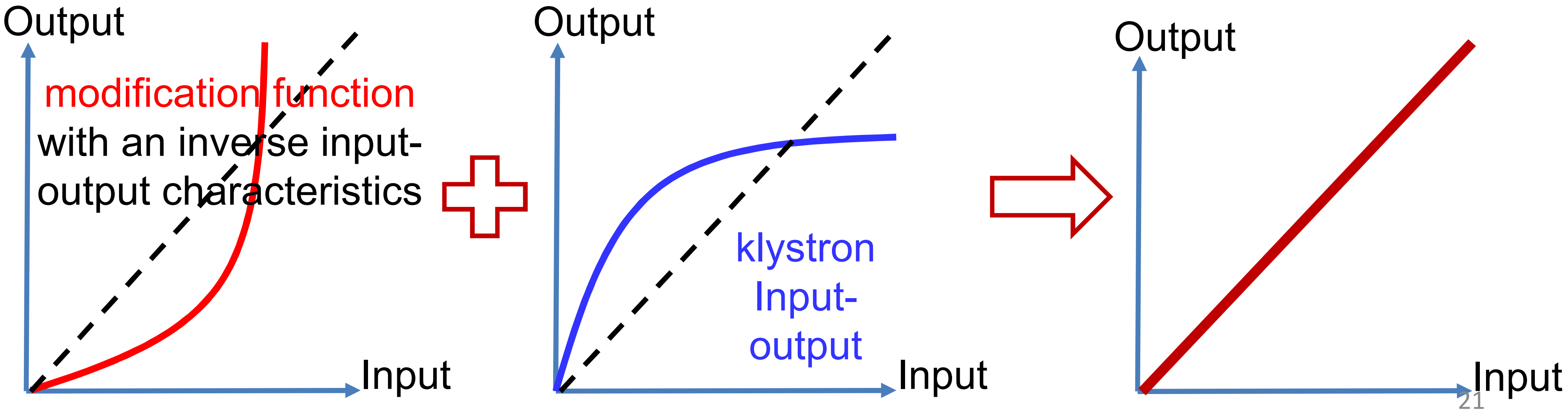
$$FF\_I\_t = A\_t \times \left[1 - \Delta\alpha\left(t - \frac{t_1 + t_2}{2}\right)\right] \cdot \cos\left[\theta - \Delta\phi\left(t - \frac{t_1 + t_2}{2}\right)\right]$$

$$FF\_Q\_t = A\_t \times \left[1 - \Delta\alpha\left(t - \frac{t_1 + t_2}{2}\right)\right] \cdot \sin\left[\theta - \Delta\phi\left(t - \frac{t_1 + t_2}{2}\right)\right]$$

(3) Non-linearity compensation of klystron input-output

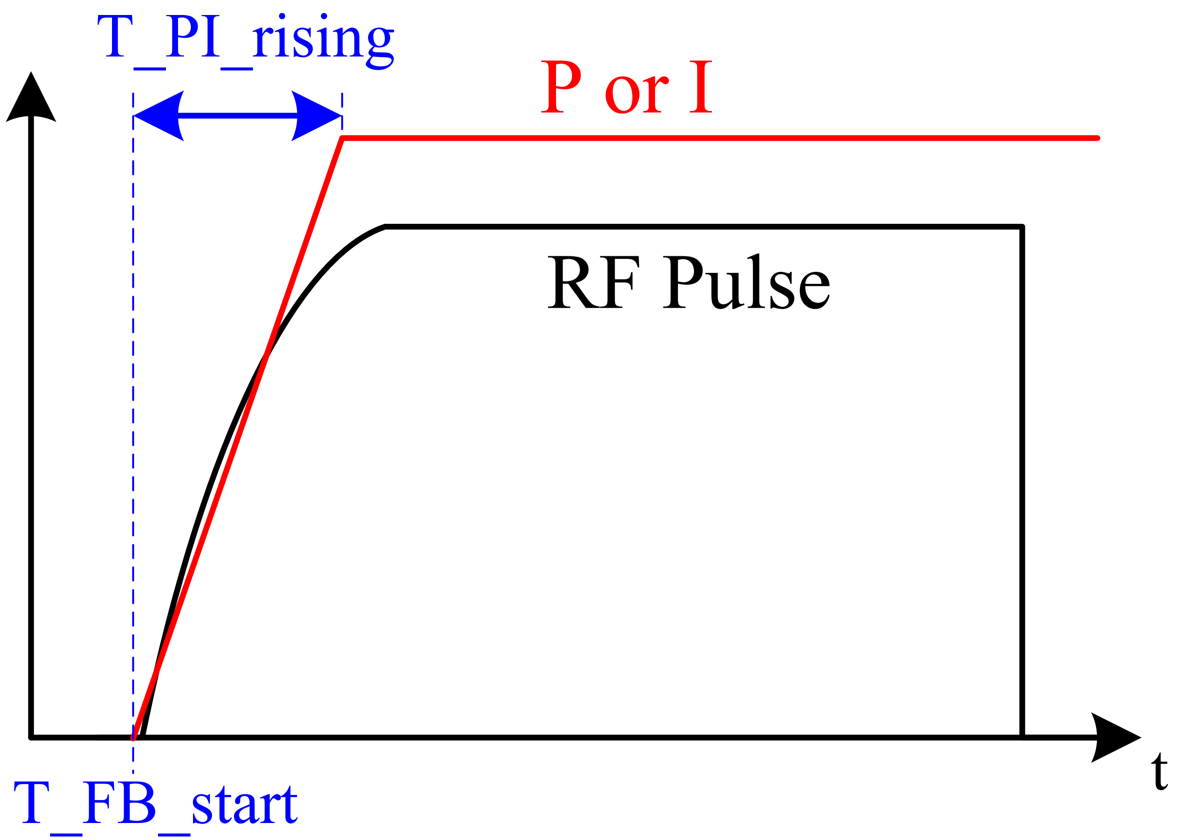


From Dr. Etsuji Chishiro, JAEA



4) Optimization of feedback parameter setting

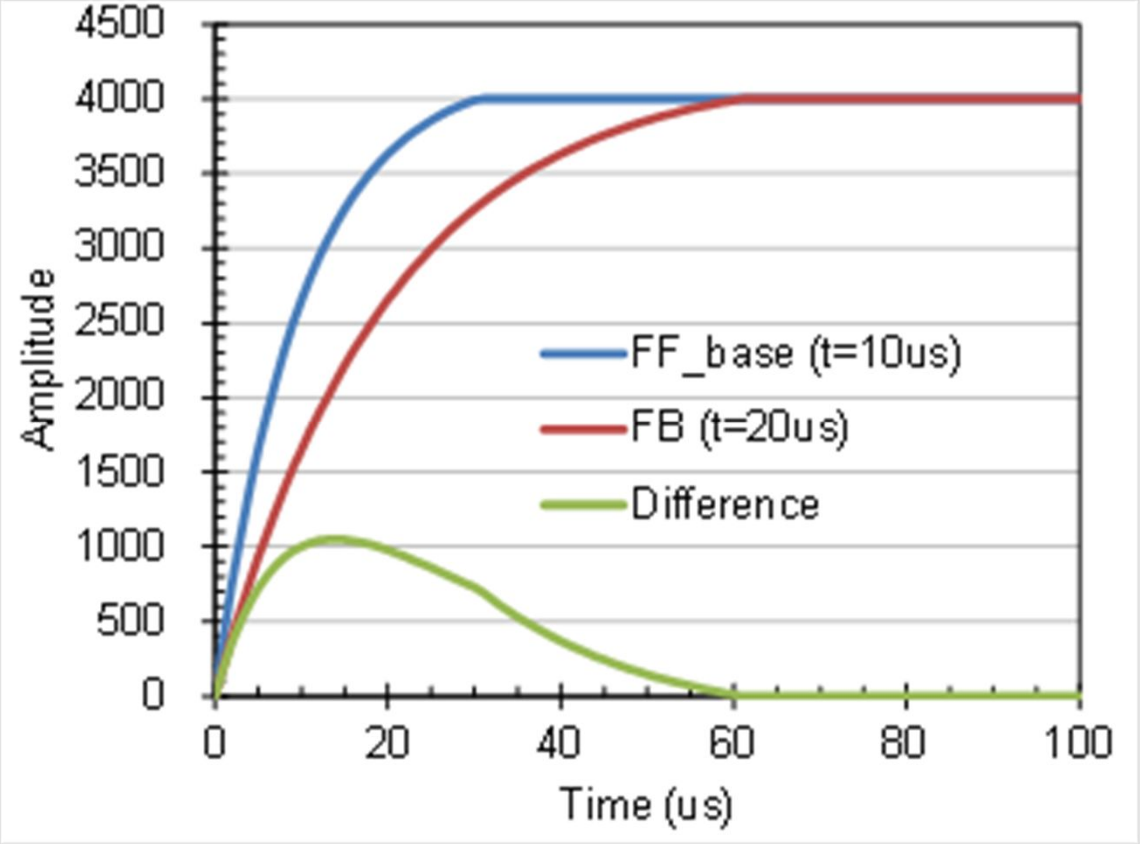
(1) Feedback gain gradually increased



Overshot and deformation of RF waveforms minimized.

Smooth RF waveforms obtained with feedback ON, especially during the rising time in the pulse.

(2) FF_BASE and FB_REF tables optimized



RF waveforms of both of the DAC and ADC **not changed much** between FB_OFF and FB_ON.

A long flat top obtained with **a good stability** of feedback system.

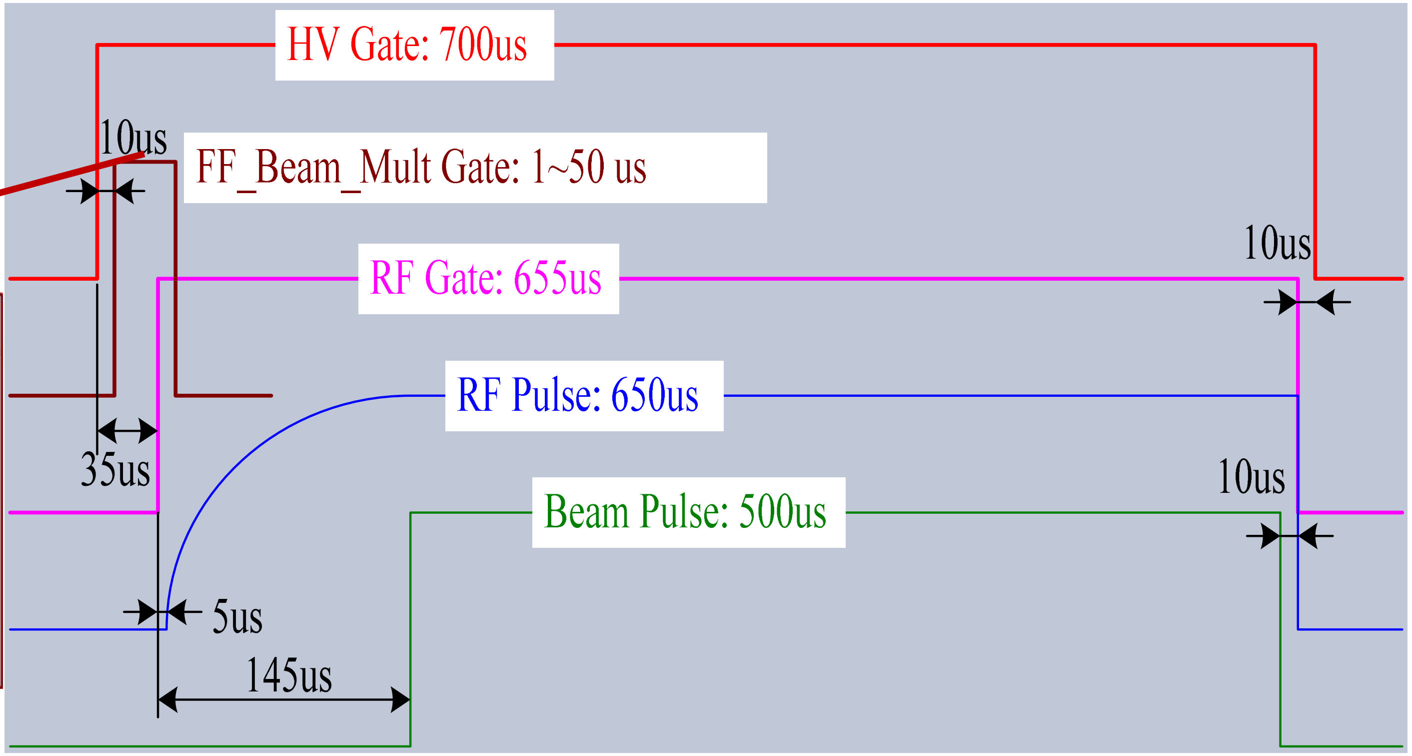
4 Beam compensation system

1) Automatic beam loading switching
2) Automatic FF_beam setting
3) Chopped beam compensation
4) Performances

1) Automatic beam loading switching

At J-PARC, several different beam operation modes are required, with different beam loadings.

Pulse width (us)	FF_beam
5 (04～06)	Amplitude_1 , Phase_1
10 (09～11)	Amplitude_2 , Phase_2
15 (14～16)	Amplitude_3 , Phase_3
20 (19～21)	Amplitude_4 , Phase_4
25 (24～26)	Amplitude_5 , Phase_5
Others	Amplitude_1 , Phase_1



- Add **a mode-exchanging signal** (FF_Beam_Mult gate), detected by the FPGA.
- In the FPGA program, the different value of FF_beam will be applied corresponding to its pulse width.

Switching the beam loading compensation could be realized in real time before beam coming.

2) Automatic FF_beam setting

Using DAC information before beam and in beam:

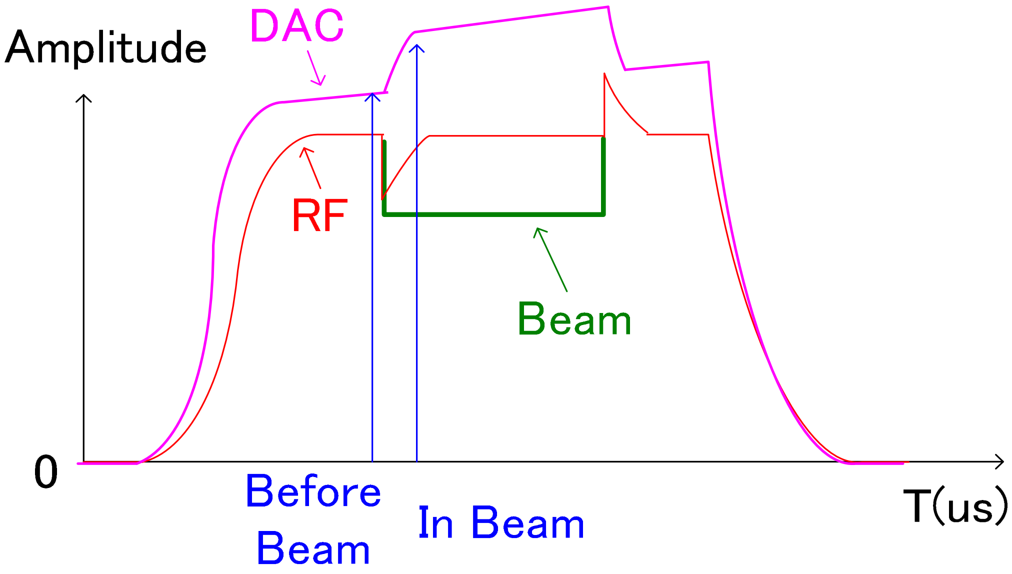
$$AMP\_beam = (I\_beam^2 + Q\_beam^2)^{0.5}$$

$$PHA\_beam = \mathrm{atan2}(I\_beam, Q\_beam) \times 180/3.1416$$

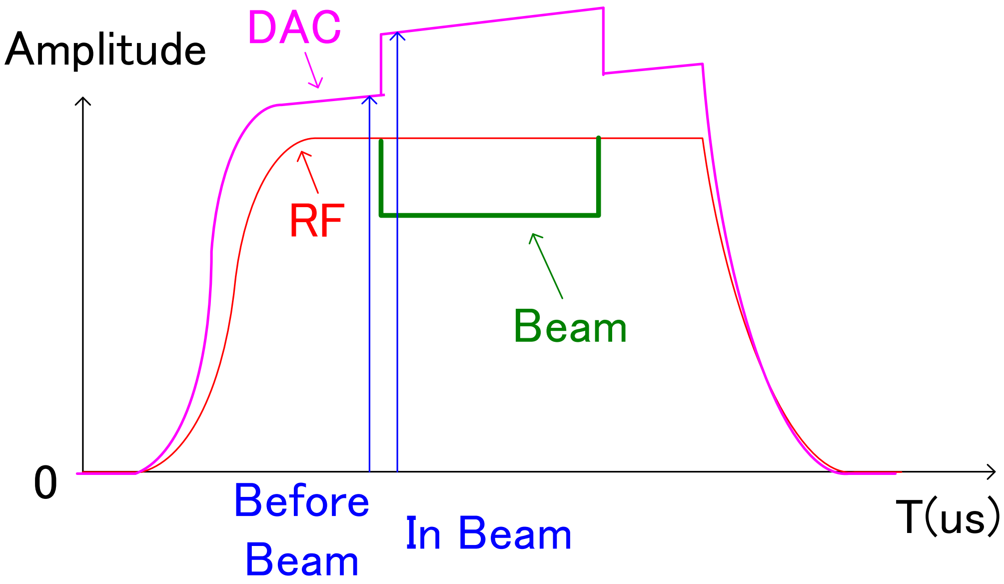
to obtain FF_beam:

$$AMP\_FF\_beam = AMP\_beam / DAC\_amp\_calibr$$

$$PHA\_FF\_beam = PHA\_beam - DAC\_pha\_calibr$$



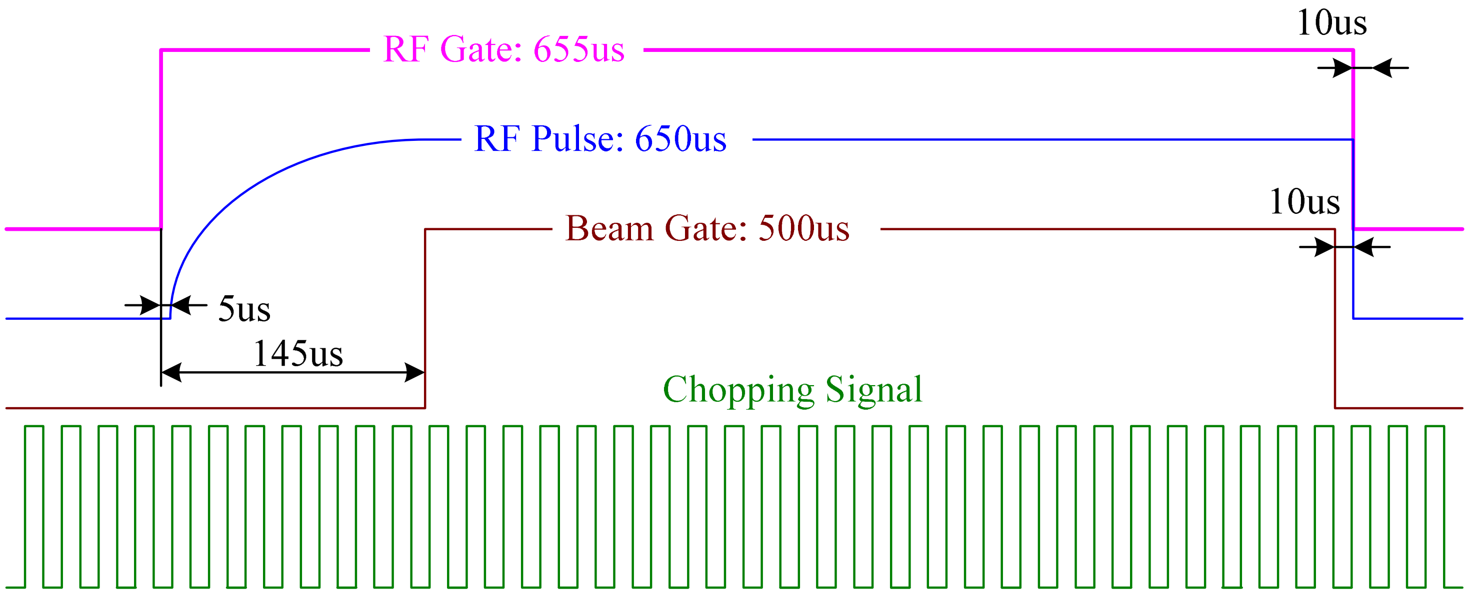
before automatic compensation setting



after automatic compensation setting

3) Chopped beam compensation

At J-PARC, chopped beam is accelerated after chopper station.
Chopped beam compensation is carried out.



Chopping signal and timing of the LLRF system.

- Add **chopping signal and beam_gate**, detected by the FPGA.
- In the FPGA program, the FF_beam is fed forward when the logical AND with inputs of the beam gate and chopping signal has the value 1.

4) Performances

Stabilities of amplitude and phase without/with beam operation

Without beam	**324MHz RF Cavities**	**972MHz RF Cavities**
$\Delta A_{(p-p)} / A$	∼±0.12%	∼±0.12%
$\Delta\phi_{(p-p)}$	∼±0.08°	∼±0.11°

16mA chopped-beam	**324MHz RF Cavities**	**972MHz RF Cavities**
$\Delta A_{(p-p)} / A$	∼±0.14%	∼±0.27%
$\Delta\phi_{(p-p)}$	∼±0.08°	∼±0.16°

30mA chopped-beam	**324MHz RF Cavities**	**972MHz RF Cavities**
$\Delta A_{(p-p)} / A$	±0.12%∼±0.31%	∼±0.45%
$\Delta\phi_{(p-p)}$	±0.09°∼±0.14°	∼±0.19°

50mA chopped-beam	**324MHz RF Cavities**	**972MHz RF Cavities**
$\Delta A_{(p-p)} / A$	±0.18%∼±0.69%	∼±0.94%
$\Delta\phi_{(p-p)}$	±0.15°∼±0.22°	∼±0.30°

5 Auto-tuning and auto-startup process

1) The first generation
2) The second generation
3) The third generation
4) Performances

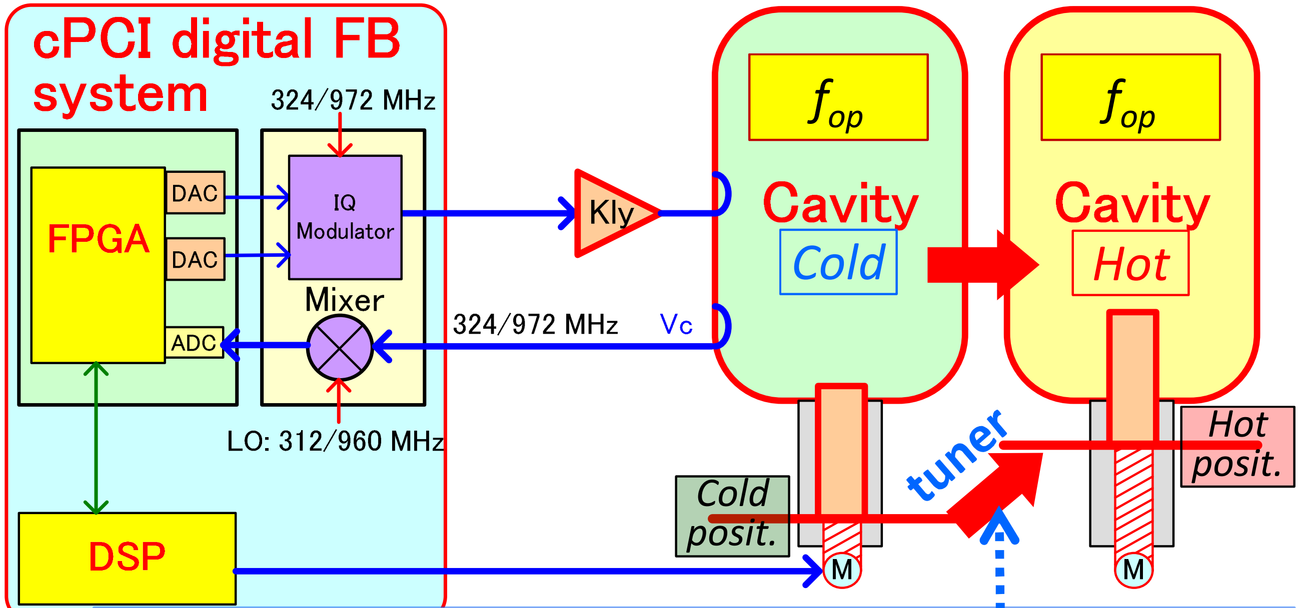
1) The first generation

(2006.10-2009.09)

When RF power feeds to a cavity, *cavity temperature* will increase, and its *resonance frequency* will change.
Auto-tuning system is very important for accelerator operation, especially during cavity warm-up.

The ***first generation*** of auto-startup process:

using a mechanical tuner controller by DSP.



During the RF start-up, ***for the rise in cavity temperature***, ***the mechanical tuner*** is used to tune the **cavity resonance to operation frequency.**

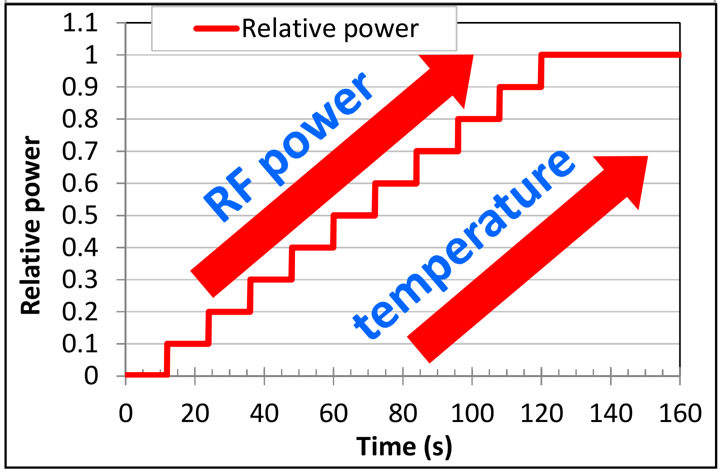
DSP: *ΔΦ (detuned phase)* can be obtained from phase-slope during rf field decay:

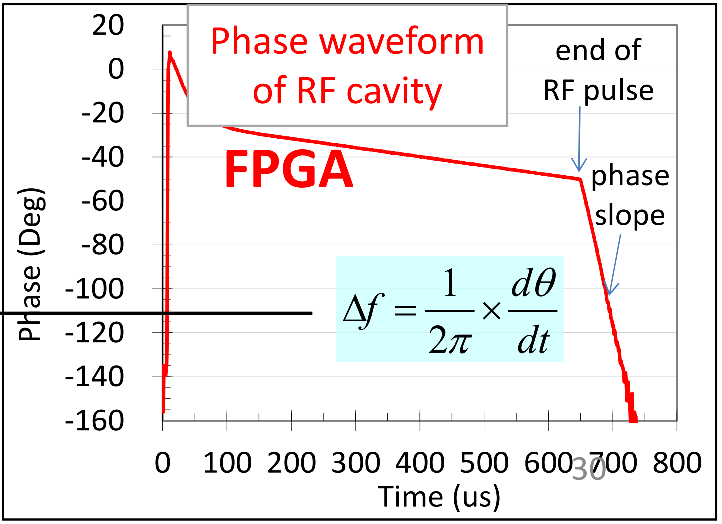
$$\Delta\Phi = \tan^{-1}(2Q_L \frac{\Delta f}{f_{op}})$$

ΔP(tuner position): $\Delta P = \Delta\Phi / k$

k: tuner sensitivity in degree/mm

Typical setting of RF start-up process



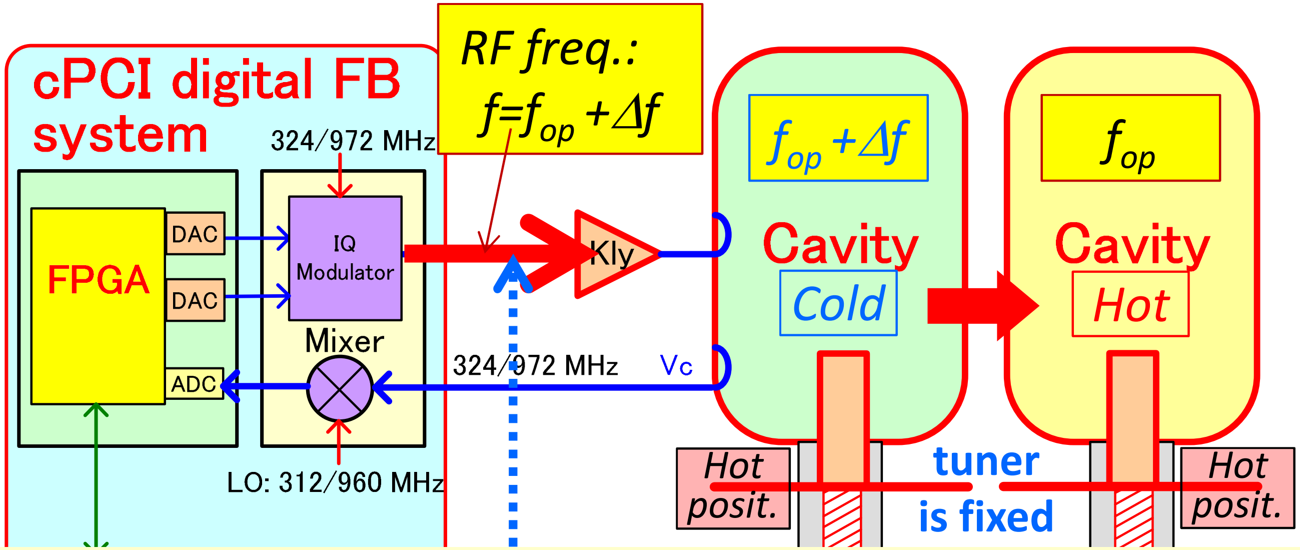


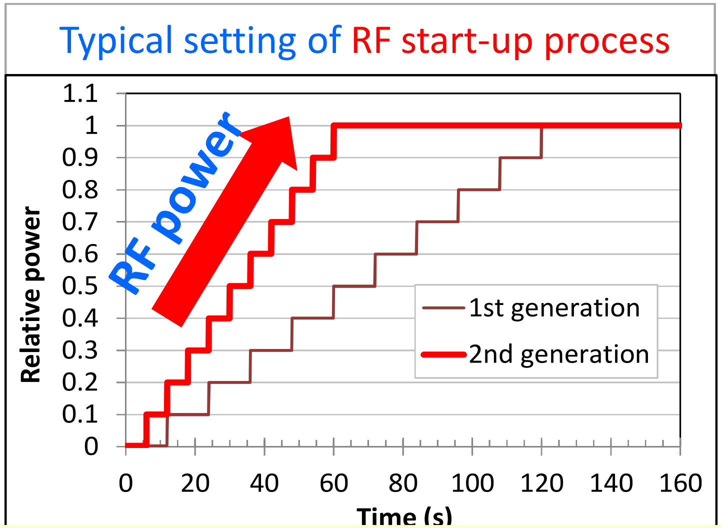
$$\Delta f = \frac{1}{2\pi} \times \frac{d\theta}{dt}$$

2) The second generation (2009.10-2013.11)

For cavity warm-up process, instead of using mechanical tuner controller, the ***second generation*** of auto-startup process:

using input RF frequency tuning by FPGA.




Typical setting of RF start-up process

Important advantages:

- ♦ We can ***restart RF operation very quickly***, *since now* it's ***not necessary to move*** the tuner from "hot position" back to "cold position".
- ♦ It also provides the tuner with ***a good protection*** from damage due to frequent movements.
- ♦ Now, RF power can be fed to RF cavity **more** ***smoothly*** and ***quickly***:
  Very good matching maintained between RF input and RF cavity in real-time,
  Time for RF startup reduced.

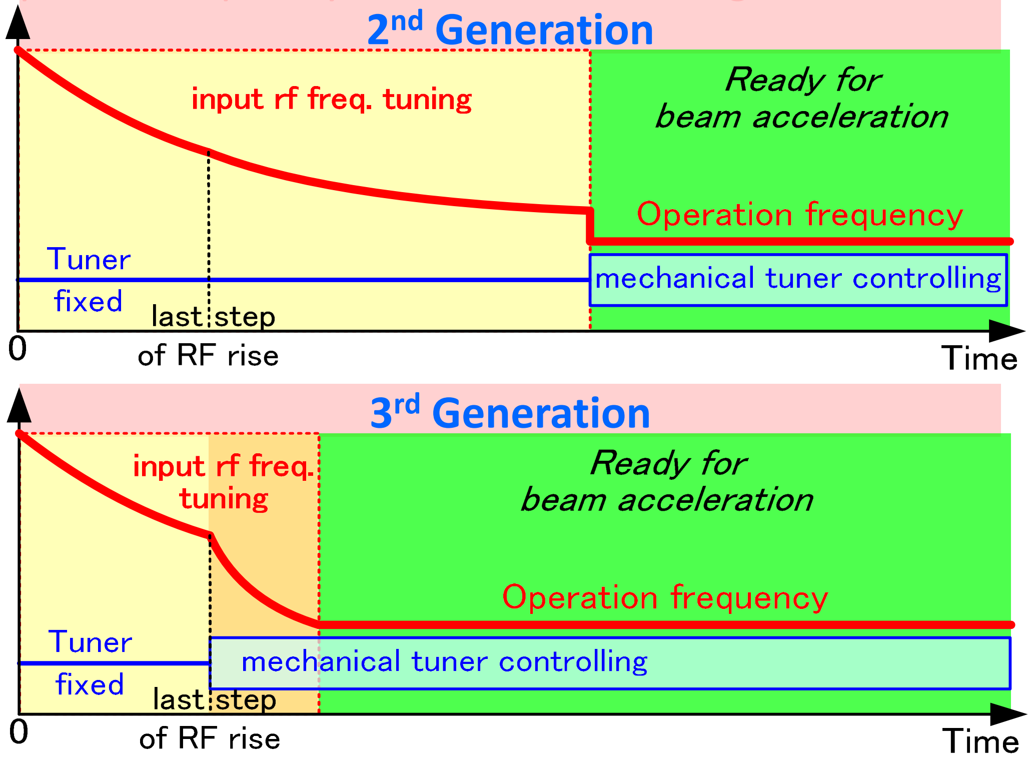
3) The third generation

(2013.12-now)

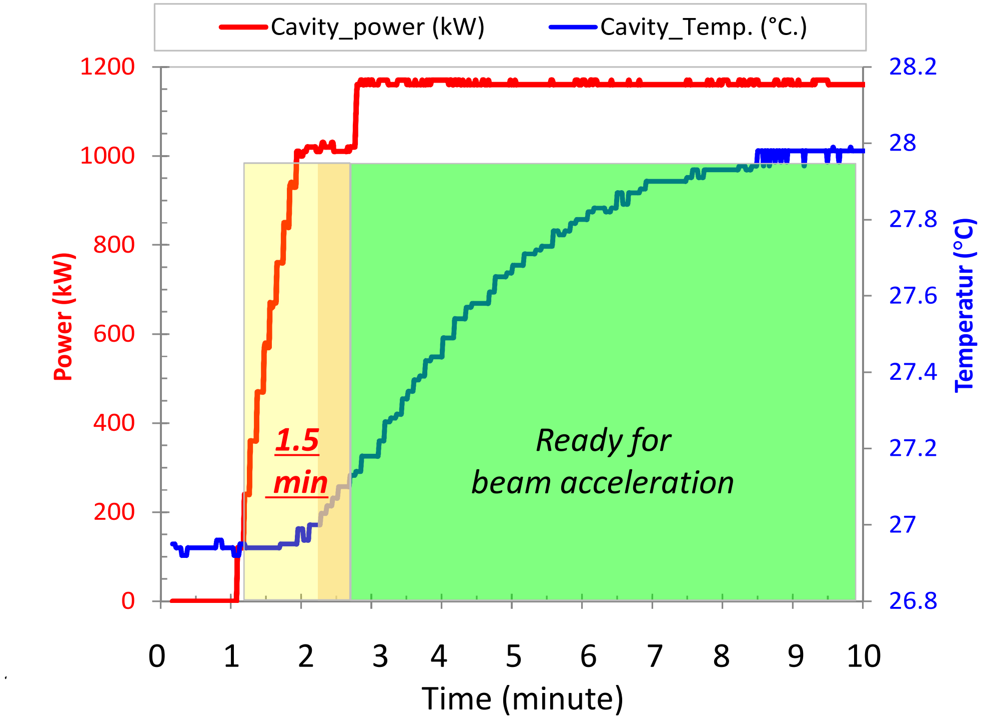
The ***third-generation of a novel auto-startup process***:

using input RF frequency tuning* + *mechanical tuner controller.

Input RF frequency and tuner controlling



RF start-up during actual accelerator operation:

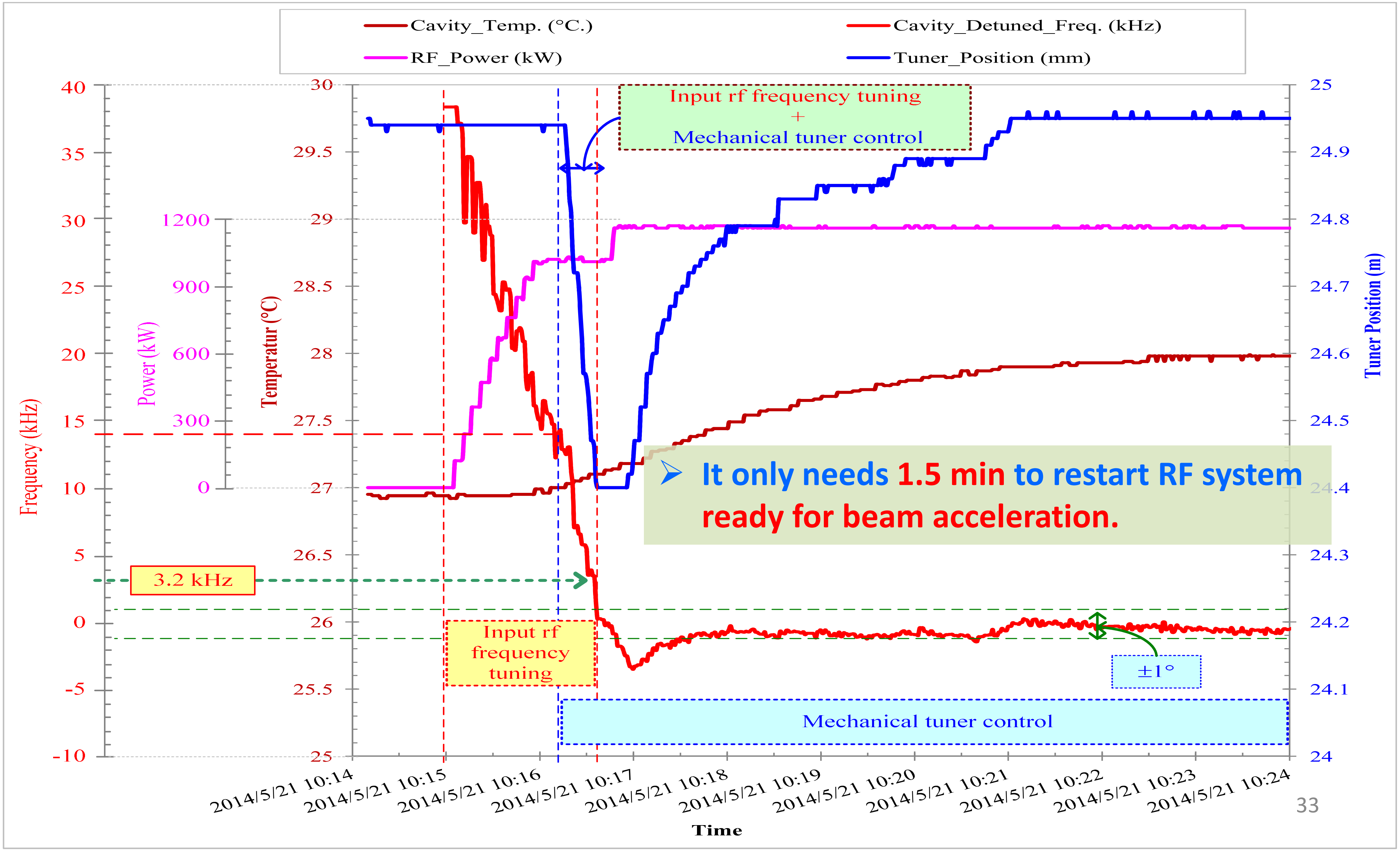


Two ***most important advantages***:

- ♦ ***Time for cavity start-up process*** will be ***shortened*** **furthermore**;
- ♦ ***A "perfect" matching*** between RF source and RF cavity will be ***obtained*** **during entire RF operation**.

4) Performances

Trend data during RF startup process using the third generation



- It only needs **1.5 min** to restart RF system ready for beam acceleration.

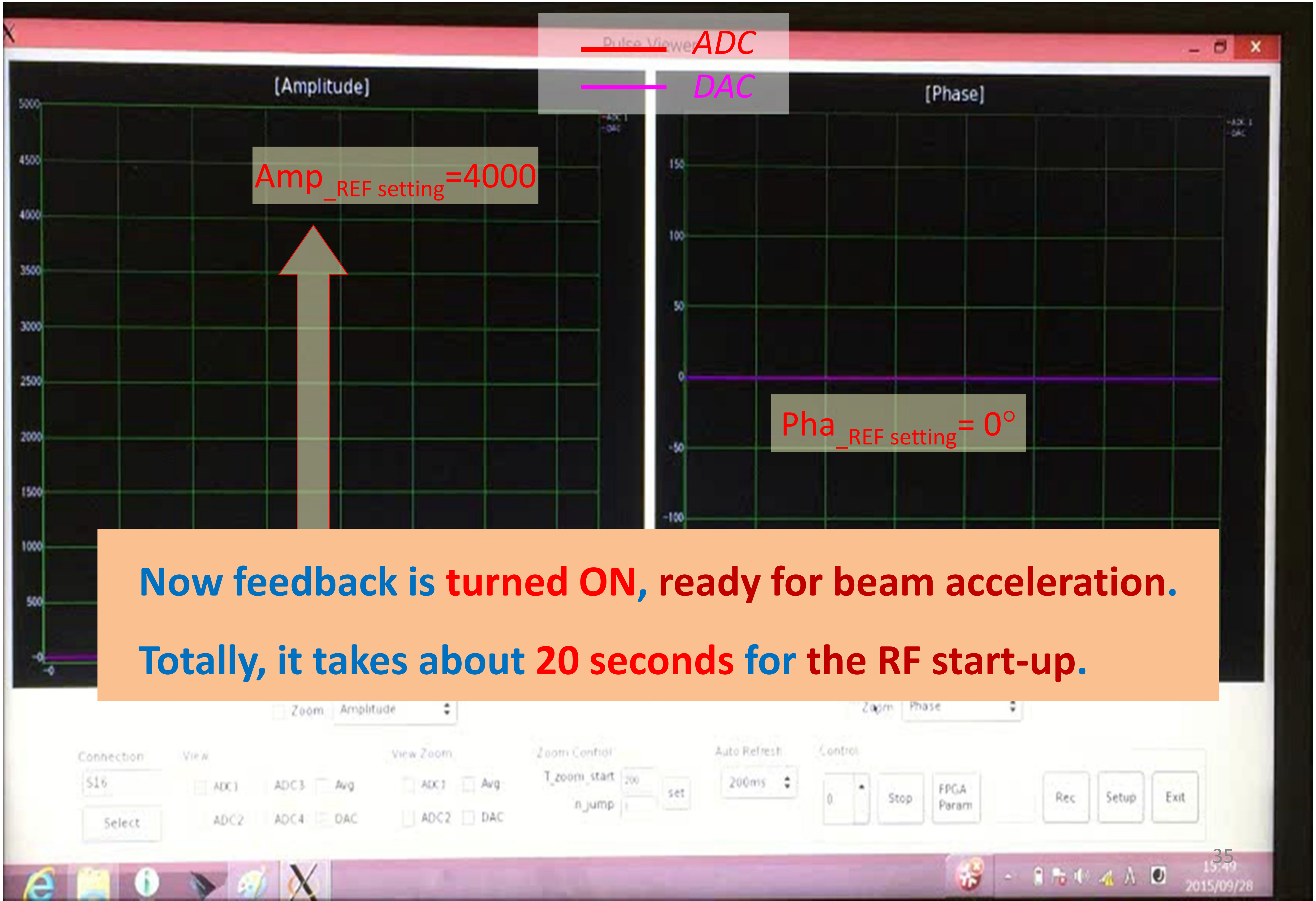
Movie for RF startup process using the third generation

- **In the actual operation, it took about 1.5 min to recover RF fields in RF cavities ready for beam acceleration even after a long-term shut down.**
- **Recently, the start-up time was reduced furthermore to about 20 seconds for all cavities.**

Movie for RF start-up

In our operation system, for RF start-up, we only need to push one button:

RF waveform during RF start-up process



ADC

DAC

$Amp_{\_REF\ setting}=4000$

$Pha_{\_REF\ setting}= 0°$

Now feedback is turned ON, ready for beam acceleration.

Totally, it takes about 20 seconds for the RF start-up.

6 Summary

1) Experiences and performances of J-PARC LINAC LLRF systems
2) Interface of LLRF operation system
3) Consideration for future
4) Spare information

1) Experiences and performances of J-PARC LINAC LLRF systems

- **Improvements and experiences on J-PARC LINAC LLRF:**

  Reference timing system

  Digital feedback system

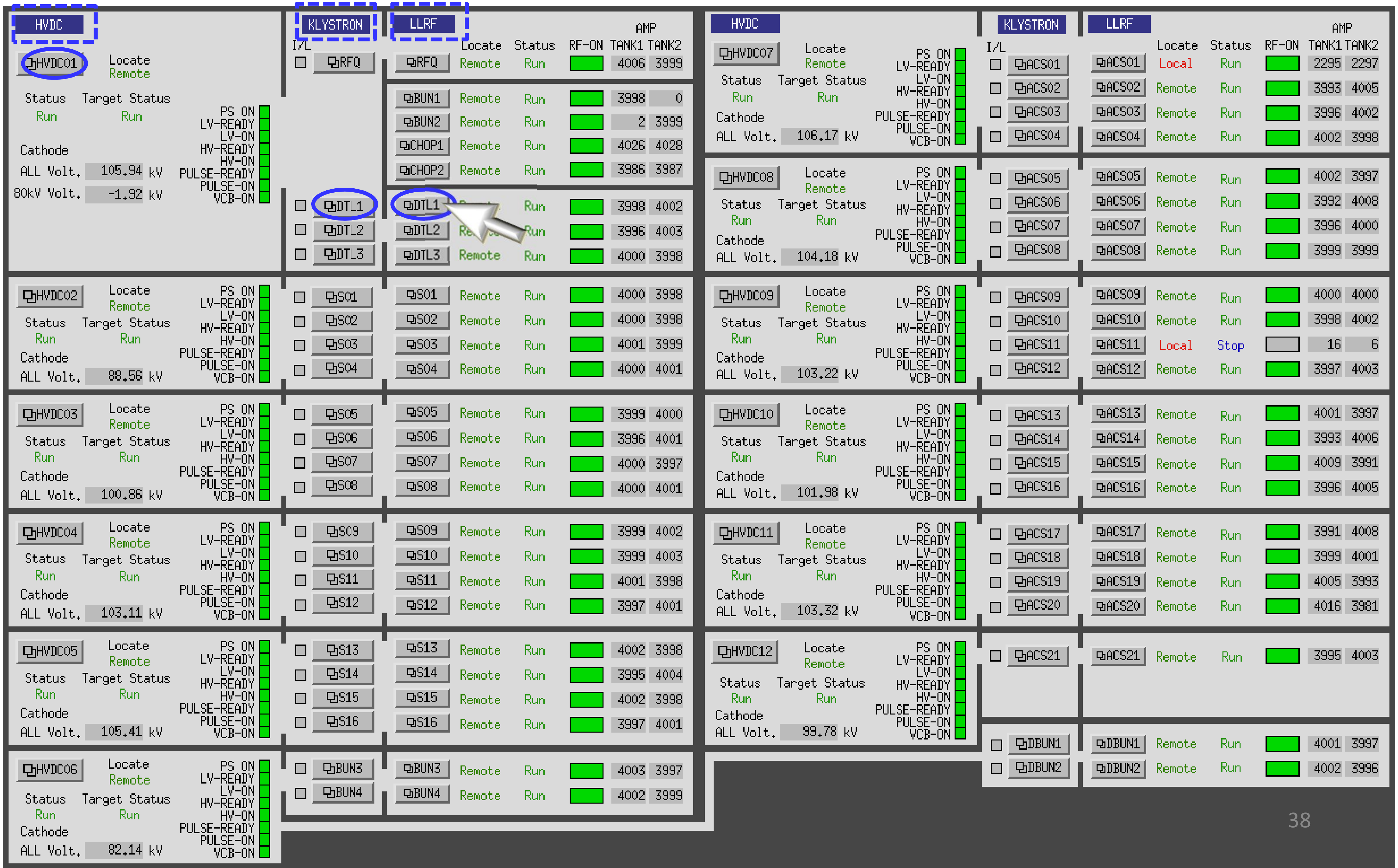
  Beam compensation system

  Auto-tuning and auto-startup process

- **Excellent performances**:
  - ***Very good RF field stabilities*** *are obtained with beam operation.*
  - ***A novel auto-startup process*** *is available with* ***"perfect" matching*** *between RF source and RF cavity* ***during entire RF operation****.*
  - ***An RF operation system*** *is achieved with* ***great convenience, high reliability****, and* ***fast response****.*

2) Interface of LLRF operation system

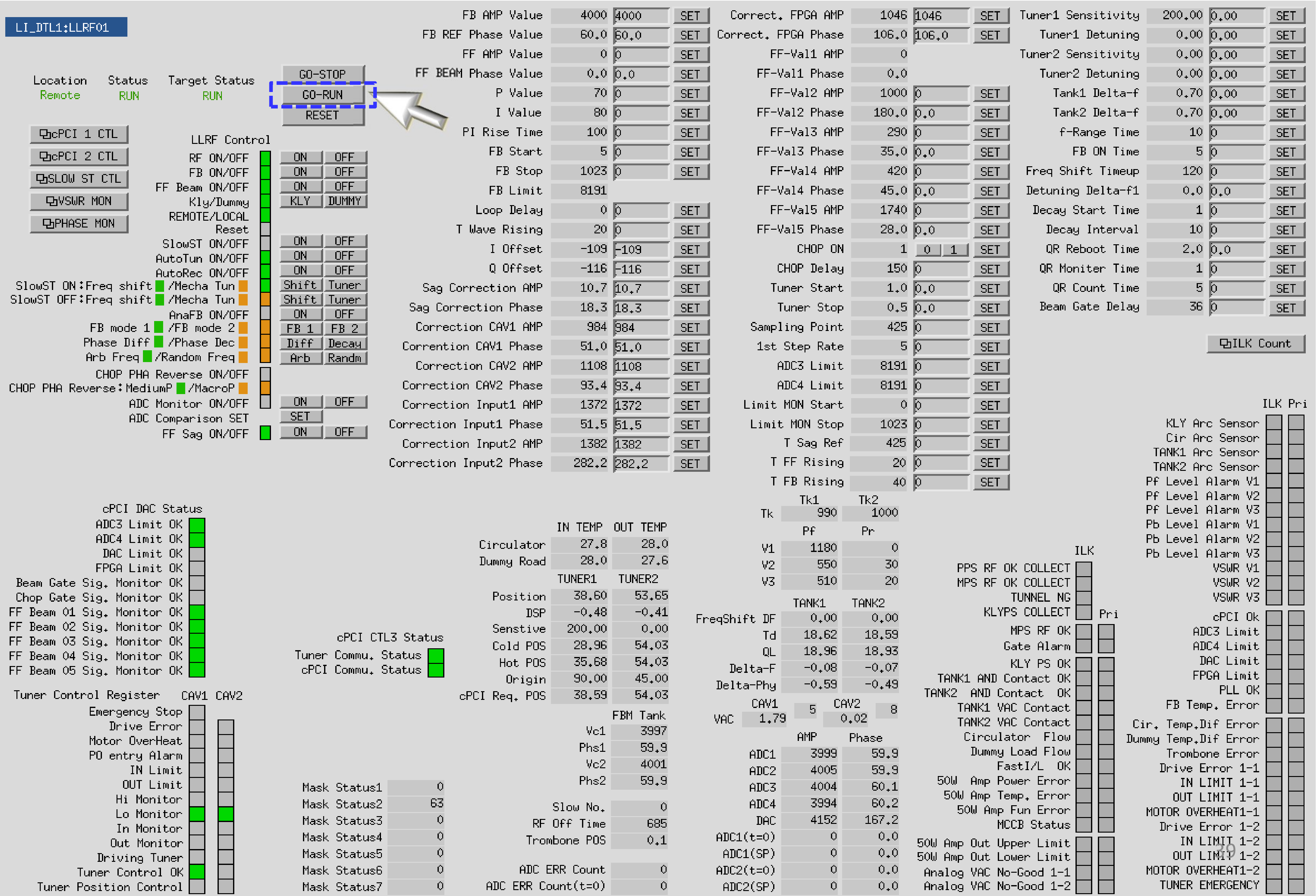
(1) All stations



HVDC	Locate	Status	Target Status	Cathode ALL Volt.	80kV Volt.	PS ON	LV-READY	LV-ON	HV-READY	HV-ON	PULSE-READY	PULSE-ON	VCB-ON
HVDC01	Remote	Run	Run	105.94 kV	-1.92 kV	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC02	Remote	Run	Run	88.56 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC03	Remote	Run	Run	100.86 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC04	Remote	Run	Run	103.11 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC05	Remote	Run	Run	105.41 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC06	Remote	Run	Run	82.14 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC07	Remote	Run	Run	106.17 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC08	Remote	Run	Run	104.18 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC09	Remote	Run	Run	103.22 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC10	Remote	Run	Run	101.98 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC11	Remote	Run	Run	103.32 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HVDC12	Remote	Run	Run	99.78 kV		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

KLYSTRON I/L	KLYSTRON	LLRF	Locate	Status	RF-ON	AMP TANK1	AMP TANK2
☐	RFQ	RFQ	Remote	Run	🟩	4006	3999
		BUN1	Remote	Run	🟩	3998	0
		BUN2	Remote	Run	🟩	2	3999
		CHOP1	Remote	Run	🟩	4026	4028
		CHOP2	Remote	Run	🟩	3986	3987
☐	DTL1	DTL1	[illegible]	Run	🟩	3998	4002
☐	DTL2	DTL2	[illegible]	Run	🟩	3996	4003
☐	DTL3	DTL3	Remote	Run	🟩	4000	3998
☐	S01	S01	Remote	Run	🟩	4000	3998
☐	S02	S02	Remote	Run	🟩	4000	3998
☐	S03	S03	Remote	Run	🟩	4001	3999
☐	S04	S04	Remote	Run	🟩	4000	4001
☐	S05	S05	Remote	Run	🟩	3999	4000
☐	S06	S06	Remote	Run	🟩	3996	4001
☐	S07	S07	Remote	Run	🟩	4000	3997
☐	S08	S08	Remote	Run	🟩	4000	4001
☐	S09	S09	Remote	Run	🟩	3999	4002
☐	S10	S10	Remote	Run	🟩	3999	4003
☐	S11	S11	Remote	Run	🟩	4001	3998
☐	S12	S12	Remote	Run	🟩	3997	4001
☐	S13	S13	Remote	Run	🟩	4002	3998
☐	S14	S14	Remote	Run	🟩	3995	4004
☐	S15	S15	Remote	Run	🟩	4002	3998
☐	S16	S16	Remote	Run	🟩	3997	4001
☐	BUN3	BUN3	Remote	Run	🟩	4003	3997
☐	BUN4	BUN4	Remote	Run	🟩	4002	3999
☐	ACS01	ACS01	Local	Run	🟩	2295	2297
☐	ACS02	ACS02	Remote	Run	🟩	3993	4005
☐	ACS03	ACS03	Remote	Run	🟩	3996	4002
☐	ACS04	ACS04	Remote	Run	🟩	4002	3998
☐	ACS05	ACS05	Remote	Run	🟩	4002	3997
☐	ACS06	ACS06	Remote	Run	🟩	3992	4008
☐	ACS07	ACS07	Remote	Run	🟩	3996	4000
☐	ACS08	ACS08	Remote	Run	🟩	3999	3999
☐	ACS09	ACS09	Remote	Run	🟩	4000	4000
☐	ACS10	ACS10	Remote	Run	🟩	3998	4002
☐	ACS11	ACS11	Local	Stop	⬜	16	6
☐	ACS12	ACS12	Remote	Run	🟩	3997	4003
☐	ACS13	ACS13	Remote	Run	🟩	4001	3997
☐	ACS14	ACS14	Remote	Run	🟩	3993	4006
☐	ACS15	ACS15	Remote	Run	🟩	4009	3991
☐	ACS16	ACS16	Remote	Run	🟩	3996	4005
☐	ACS17	ACS17	Remote	Run	🟩	3991	4008
☐	ACS18	ACS18	Remote	Run	🟩	3999	4001
☐	ACS19	ACS19	Remote	Run	🟩	4005	3993
☐	ACS20	ACS20	Remote	Run	🟩	4016	3981
☐	ACS21	ACS21	Remote	Run	🟩	3995	4003
☐	DBUN1	DBUN1	Remote	Run	🟩	4001	3997
☐	DBUN2	DBUN2	Remote	Run	🟩	4002	3996

(2) DTL01 LLRF



LI_DTL1:LLRF01

Location	Status	Target Status
Remote	RUN	RUN

LLRF Control

RF ON/OFF	🟩	ON	OFF
FB ON/OFF	🟩	ON	OFF
FF Beam ON/OFF	🟩	ON	OFF
Kly/Dummy	🟩	KLY	DUMMY
REMOTE/LOCAL	🟩		
Reset	⬜		
SlowST ON/OFF	⬜	ON	OFF
AutoTun ON/OFF	🟩	ON	OFF
AutoRec ON/OFF	🟩	ON	OFF
SlowST ON:Freq shift 🟩 /Mecha Tun 🟧	🟩	Shift	Tuner
SlowST OFF:Freq shift 🟩 /Mecha Tun 🟧	🟧	Shift	Tuner
AnaFB ON/OFF	⬜	ON	OFF
FB mode 1 🟩 /FB mode 2 🟧	🟧	FB 1	FB 2
Phase Diff 🟩 /Phase Dec 🟧	🟧	Diff	Decay
Arb Freq 🟩 /Random Freq 🟧	🟧	Arb	Randm
CHOP PHA Reverse ON/OFF	⬜		
CHOP PHA Reverse:MediumP 🟩 /MacroP 🟧	🟧		
ADC Monitor ON/OFF	⬜	ON	OFF
ADC Comparison SET		SET	
FF Sag ON/OFF	🟩	ON	OFF

FB AMP Value	4000	4000	SET
FB REF Phase Value	60.0	60.0	SET
FF AMP Value	0	0	SET
FF BEAM Phase Value	0.0	0.0	SET
P Value	70	0	SET
I Value	80	0	SET
PI Rise Time	100	0	SET
FB Start	5	0	SET
FB Stop	1023	0	SET
FB Limit	8191		
Loop Delay	0	0	SET
T Wave Rising	20	0	SET
I Offset	-109	-109	SET
Q Offset	-116	-116	SET
Sag Correction AMP	10.7	10.7	SET
Sag Correction Phase	18.3	18.3	SET
Correction CAV1 AMP	984	984	SET
Corrention CAV1 Phase	51.0	51.0	SET
Correction CAV2 AMP	1108	1108	SET
Correction CAV2 Phase	93.4	93.4	SET
Correction Input1 AMP	1372	1372	SET
Correction Input1 Phase	51.5	51.5	SET
Correction Input2 AMP	1382	1382	SET
Correction Input2 Phase	282.2	282.2	SET

Correct. FPGA AMP	1046	1046	SET
Correct. FPGA Phase	106.0	106.0	SET
FF-Val1 AMP	0		
FF-Val1 Phase	0.0		
FF-Val2 AMP	1000	0	SET
FF-Val2 Phase	180.0	0.0	SET
FF-Val3 AMP	290	0	SET
FF-Val3 Phase	35.0	0.0	SET
FF-Val4 AMP	420	0	SET
FF-Val4 Phase	45.0	0.0	SET
FF-Val5 AMP	1740	0	SET
FF-Val5 Phase	28.0	0.0	SET
CHOP ON	1	0 1	SET
CHOP Delay	150	0	SET
Tuner Start	1.0	0.0	SET
Tuner Stop	0.5	0.0	SET
Sampling Point	425	0	SET
1st Step Rate	5	0	SET
ADC3 Limit	8191	0	SET
ADC4 Limit	8191	0	SET
Limit MON Start	0	0	SET
Limit MON Stop	1023	0	SET
T Sag Ref	425	0	SET
T FF Rising	20	0	SET
T FB Rising	40	0	SET

Tuner1 Sensitivity	200.00	0.00	SET
Tuner1 Detuning	0.00	0.00	SET
Tuner2 Sensitivity	0.00	0.00	SET
Tuner2 Detuning	0.00	0.00	SET
Tank1 Delta-f	0.70	0.00	SET
Tank2 Delta-f	0.70	0.00	SET
f-Range Time	10	0	SET
FB ON Time	5	0	SET
Freq Shift Timeup	120	0	SET
Detuning Delta-f1	0.0	0.0	SET
Decay Start Time	1	0	SET
Decay Interval	10	0	SET
QR Reboot Time	2.0	0.0	SET
QR Moniter Time	1	0	SET
QR Count Time	5	0	SET
Beam Gate Delay	36	0	SET

cPCI DAC Status	
ADC3 Limit OK	🟩
ADC4 Limit OK	🟩
DAC Limit OK	⬜
FPGA Limit OK	⬜
Beam Gate Sig. Monitor OK	⬜
Chop Gate Sig. Monitor OK	⬜
FF Beam 01 Sig. Monitor OK	🟩
FF Beam 02 Sig. Monitor OK	🟩
FF Beam 03 Sig. Monitor OK	🟩
FF Beam 04 Sig. Monitor OK	🟩
FF Beam 05 Sig. Monitor OK	🟩

cPCI CTL3 Status	
Tuner Commu. Status	🟩
cPCI Commu. Status	🟩

Tuner Control Register	CAV1	CAV2
Emergency Stop	⬜	
Drive Error	⬜	⬜
Motor OverHeat	⬜	⬜
PO entry Alarm	⬜	⬜
IN Limit	⬜	⬜
OUT Limit	⬜	⬜
Hi Monitor	⬜	⬜
Lo Monitor	🟩	🟩
In Monitor	⬜	⬜
Out Monitor	⬜	⬜
Driving Tuner	⬜	⬜
Tuner Control OK	🟩	⬜
Tuner Position Control	⬜	⬜

Mask Status1	0
Mask Status2	63
Mask Status3	0
Mask Status4	0
Mask Status5	0
Mask Status6	0
Mask Status7	0

	IN TEMP	OUT TEMP
Circulator	27.8	28.0
Dummy Road	28.0	27.6

	TUNER1	TUNER2
Position	38.60	53.65
DSP	-0.48	-0.41
Senstive	200.00	0.00
Cold POS	28.96	54.03
Hot POS	35.68	54.03
Origin	90.00	45.00
cPCI Req. POS	38.59	54.03

	FBM Tank
Vc1	3997
Phs1	59.9
Vc2	4001
Phs2	59.9

Slow No.	0
RF Off Time	685
Trombone POS	0.1
ADC ERR Count	0
ADC ERR Count(t=0)	0

	Tk1	Tk2
Tk	990	1000

	Pf	Pr
V1	1180	0
V2	550	30
V3	510	20

	TANK1	TANK2
FreqShift DF	0.00	0.00
Td	18.62	18.59
QL	18.96	18.93
Delta-F	-0.08	-0.07
Delta-Phy	-0.59	-0.49

	CAV1		CAV2	
VAC	1.79	5	0.02	8

	AMP	Phase
ADC1	3999	59.9
ADC2	4005	59.9
ADC3	4004	60.1
ADC4	3994	60.2
DAC	4152	167.2
ADC1(t=0)	0	0.0
ADC1(SP)	0	0.0
ADC2(t=0)	0	0.0
ADC2(SP)	0	0.0

	ILK	Pri
PPS RF OK COLLECT	⬜	
MPS RF OK COLLECT	⬜	
TUNNEL NG	⬜	
KLYPS COLLECT	⬜	
MPS RF OK	⬜	⬜
Gate Alarm	⬜	⬜
KLY PS OK	⬜	⬜
TANK1 AND Contact OK	⬜	⬜
TANK2 AND Contact OK	⬜	⬜
TANK1 VAC Contact	⬜	⬜
TANK2 VAC Contact	⬜	⬜
Circulator Flow	⬜	⬜
Dummy Load Flow	⬜	⬜
FastI/L OK	⬜	⬜
50W Amp Power Error	⬜	⬜
50W Amp Temp. Error	⬜	⬜
50W Amp Fun Error	⬜	⬜
MCCB Status	⬜	⬜
50W Amp Out Upper Limit	⬜	⬜
50W Amp Out Lower Limit	⬜	⬜
Analog VAC No-Good 1-1	⬜	⬜
Analog VAC No-Good 1-2	⬜	⬜

	ILK	Pri
KLY Arc Sensor	⬜	⬜
Cir Arc Sensor	⬜	⬜
TANK1 Arc Sensor	⬜	⬜
TANK2 Arc Sensor	⬜	⬜
Pf Level Alarm V1	⬜	⬜
Pf Level Alarm V2	⬜	⬜
Pf Level Alarm V3	⬜	⬜
Pb Level Alarm V1	⬜	⬜
Pb Level Alarm V2	⬜	⬜
Pb Level Alarm V3	⬜	⬜
VSWR V1	⬜	⬜
VSWR V2	⬜	⬜
VSWR V3	⬜	⬜
cPCI Ok	⬜	⬜
ADC3 Limit	⬜	⬜
ADC4 Limit	⬜	⬜
DAC Limit	⬜	⬜
FPGA Limit	⬜	⬜
PLL OK	⬜	⬜
FB Temp. Error	⬜	⬜
Cir. Temp.Dif Error	⬜	⬜
Dummy Temp.Dif Error	⬜	⬜
Trombone Error	⬜	⬜
Drive Error 1-1	⬜	⬜
IN LIMIT 1-1	⬜	⬜
OUT LIMIT 1-1	⬜	⬜
MOTOR OVERHEAT1-1	⬜	⬜
Drive Error 1-2	⬜	⬜
IN LIMIT 1-2	⬜	⬜
OUT LIMIT 1-2	⬜	⬜
MOTOR OVERHEAT1-2	⬜	⬜
TUNER EMERGENCY	⬜	⬜

3) Consideration for future

- **Organize and refine each job and process for automation,** for example, RF calibration and beam compensation with environment changing (drifted HVDC, variated beam, …)

- LLRF is one of the most interesting jobs. Never stop in approaching **a simple-and-perfect control system**.

- Upgrade the LLRF system by using MTCA.4.

4) Spare information

Update: 2018/01/09

LLRF	Units for operation	Units for spare						
		CPU	IO	DSP-FPGA	Mix-IQ	RF	VS-Meter	Pre-amp
324MHz	24(+1)	6	4	4	4	12	3	1
972MHz	25				9	7	2	2

Klystron	Units for operation	Units for spare
324MHz	20	6
972MHz	25	5 (+2, next month)

Thank you very much

for your attention !