RF System
(other than RF cavities) for RAON

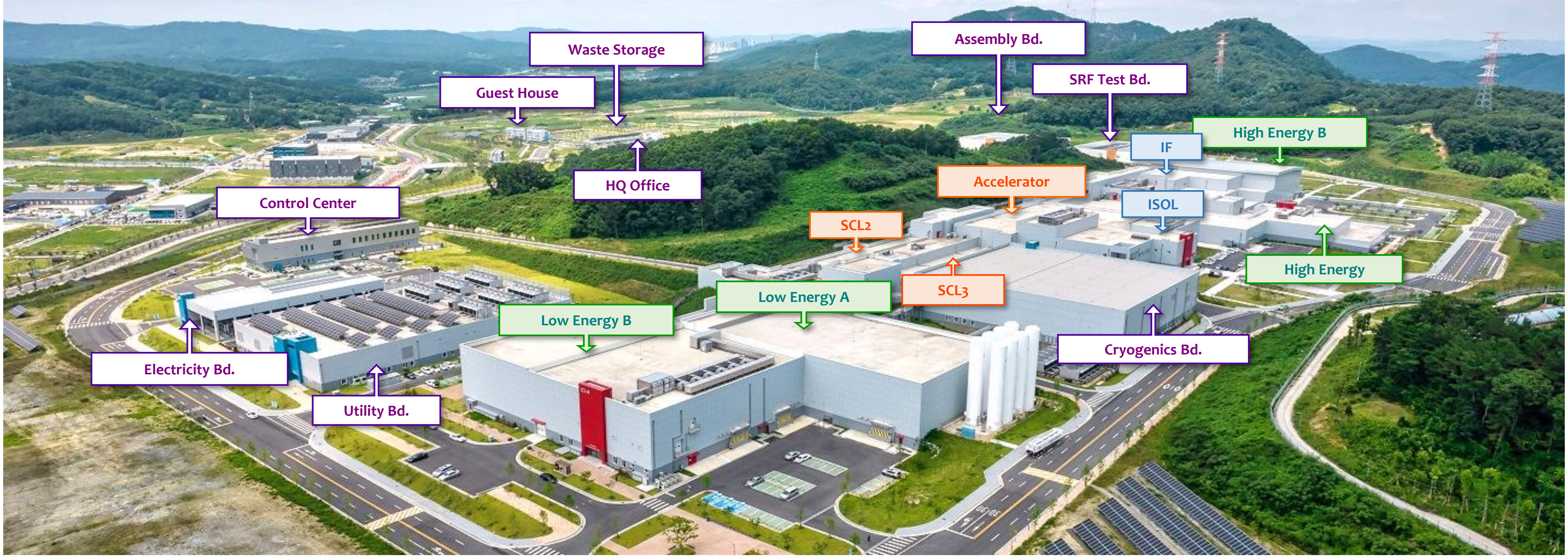
2026.07.09
고려대 가속기여름학교
설경태
Institute for Rare Isotope Science, IBS

Contents

RAON Rare Isotope Accelerator Complex

Campus Area: 952,066 m^2

- Accelerator System
- RI production System
- Conventional Utilities
- Experimental System



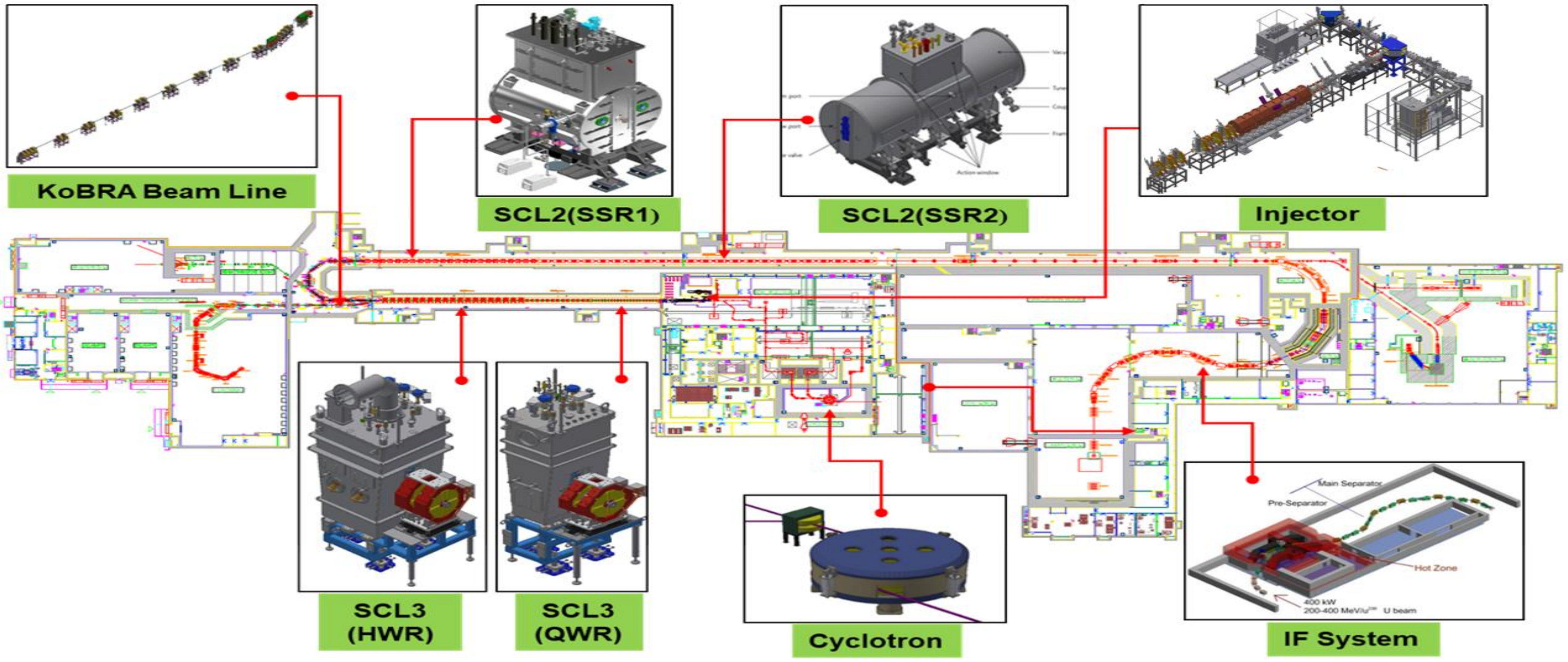
Accelerator Systems

Injector | SC Linac | IF

SCL3 | SCL2

0.5 MeV/u — 18 MeV/u — 200 MeV/u

ISOL/ECR	LEBT	RFQ	MEBT	SCL3-1	SCL3-2	CSS	SCL2-1	SCL2-2	HEBT	IF
				β=0.047	β=0.12		β=0.32	β=0.51		



Part 01.

RF System 개요

Institute for Rare Isotope Science

RF (Radio Frequency)

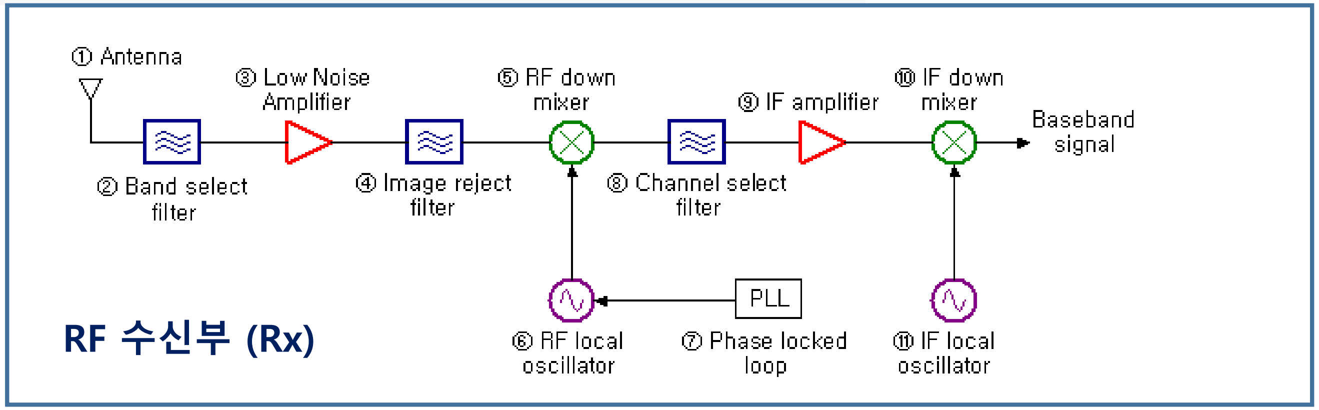
www.rfdh.com

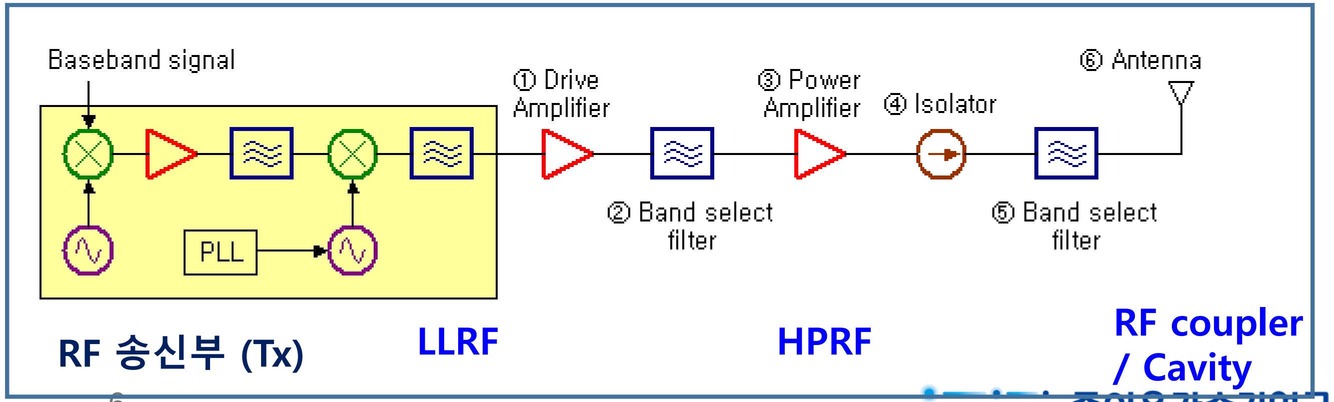
RF는 **Radio Frequency**의 약자로, 일반적으로 무선 통신에 사용되는 주파수 신호 및 관련 기술 분야를 의미합니다. 여기서 Radio는 단순히 라디오 방송만을 의미하는 것이 아니라, 본래 **무선(Wireless)** 전체를 포함하는 개념이며, Frequency는 신호가 일정 시간 동안 반복되는 횟수를 나타내는 **주파수**를 뜻합니다.

즉 RF는 단순한 장비명이나 특정 부품을 지칭하는 용어가 아니라, **무선으로 신호를 전달하기 위해 사용되는 고주파 신호와 이를 다루는 기술 전반**을 의미합니다.

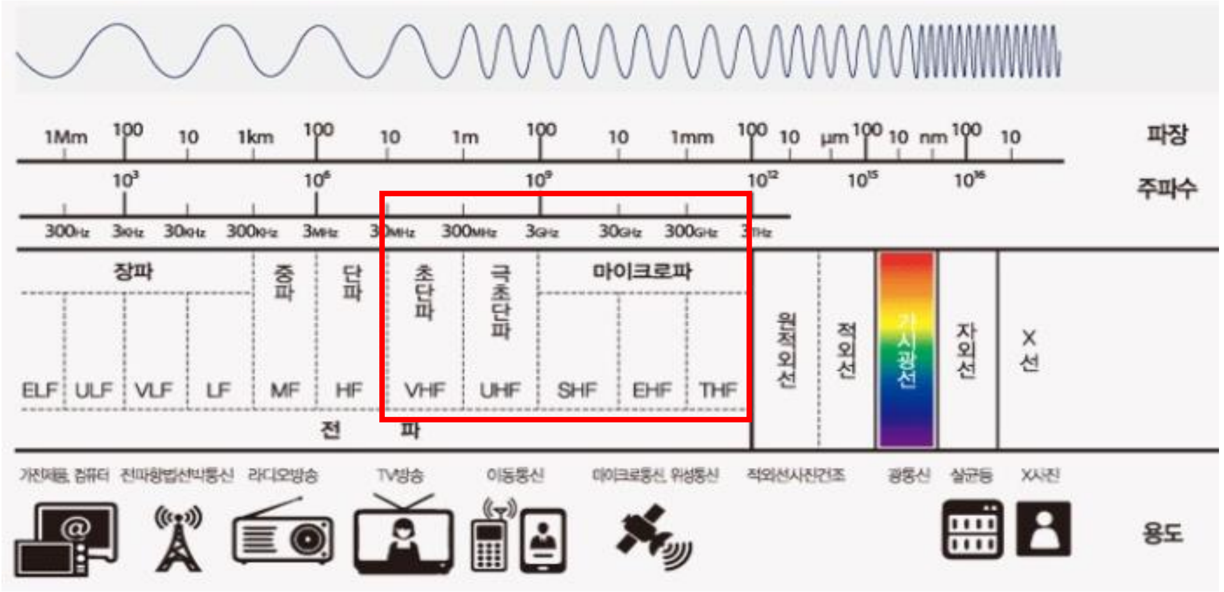
사용 분야

- **이동통신:** LTE, 5G, 향후 6G 시스템
- **무선 네트워크:** Wi-Fi, Bluetooth, IoT 디바이스
- **위성 통신:** 장거리 데이터 전송 및 글로벌 커버리지
- **자동차 전장:** 차량용 레이더, ADAS, 자율주행 센서
- **방송 및 위치 시스템:** TV/라디오 방송, GPS





RF (주파수 대역)



대역 기호	대역명	대역 번호	주파수대역	파장	비고
ELF	초저주파		20 ~ 300 Hz		
VF	음성		300 ~ 3000 Hz		음성대역
VLF	초장파	4	3 ~ 30 kHz	100 ~ 10 km	선박
LF	장파	5	30 ~ 300 kHz	10 ~ 1 km	항해용
MF	중파	6	300 ~ 3,000 kHz	1,000 ~ 100 m	항공,AM방송
HF	단파	7	3 ~ 30 MHz	100 ~ 10 m	단파방송,HAM
VHF	초단파	8	30 ~ 300 MHz	10 ~ 1 m	TV,FM방송
UHF	극초단파	9	300 ~ 3,000 MHz	1 ~ 0.1 m	마이크로파 (TV방송,이동전화,레이더)
SHF	센티미터파	10	3 ~ 30 GHz	10 ~ 1 cm	마이크로파 (위성통신,레이더)
EHF	밀리파	11	30 ~ 300 GHz	10 ~ 1 mm	미사일,우주통신
THF	서브밀리파	12	300 ~ 3,000 GHz	1 ~ 0.1 mm	

- 무선통신/레이더 (2차 세계대전때 군사용도를 위해 대역별 문자로 표기함에 유래)

구분	2차 세계대전 군사용	IEEE 분류 (레이더 분야)	기타 관용적 구분
HF (단파)		3 ~ 30 MHz	
VHF (초단파)		30 ~ 300 MHz	
UHF (극초단파)		300 ~ 1000 MHz	
L Band	390 ~ 1550 MHz	1 ~ 2 GHz	
S Band	1550 ~ 3900 MHz	2 ~ 4 GHz	
C Band	3.9 ~ 6.2 GHz	4 ~ 8 GHz	3 ~ 8 GHz
X Band	6.2 ~ 12.9 GHz	8 ~ 12 GHz	8 ~ 10 GHz
Ku Band	12.9 ~ 18 GHz	12 ~ 18 GHz	10 ~ 18 GHz
K Band	18 ~ 26.5 GHz	18 ~ 27 GHz	
Ka Band	26.5 ~ 40 GHz	27 ~ 40 GHz	
V Band		40 ~ 75 GHz	
W Band		75 ~ 110 GHz	
밀리미터파		110 ~ 300 GHz	

스마트폰 :

Wifi : 2.4 GHz, 5 GHz

Mircrowave oven :

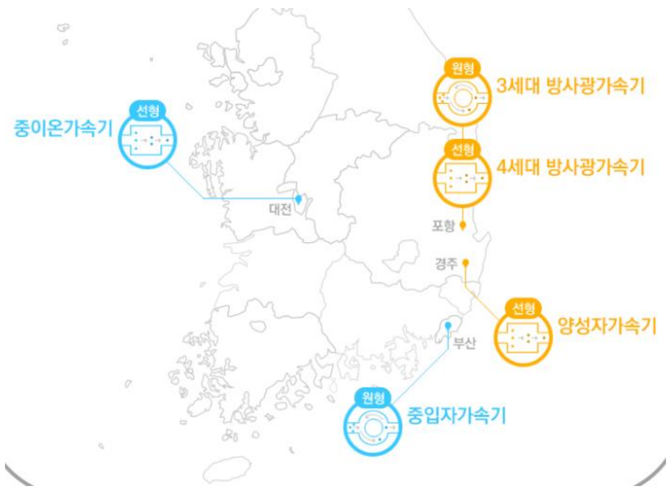
스타링크 :

구분	SKT	KT	LGU+
800 ~ 900MHz	20	20	20
1.8GHz	35	55	-
2.1GHz	40	40	40
2.6GHz	60	-	40
3.5GHz	100	100	100

가속기의 RF 주파수

국내

RAON (중이온)	QWR (81.25 MHz)
	HWR (162.5 MHz)
	SSR (325 MHz)
KOMAC (양성자)	RFQ, DTL (350 MHz)
	확장 (700 MHz)
PAL (전자)	선형 (S-band 2.856 GHz)
	저장링 (499.973 MHz)
	XFEL (S-band 2.856 GHz)
4GSR (전자)	선형 (S-band 2.997 GHz)
	저장링 (499.593 MHz)
중입자 치료	Injector (RFQ, DTL) (200 MHz)
(서울대, 연세대 ..)	



국외

가속기 / 시설	사용하는 RF 주파수	주로 쓰이는 구간 / 장치
CERN LHC	400 MHz, 설계값 400.8 MHz	초전도 RF 공동
CERN SPS	200.2 MHz	주 RF travelling-wave cavity
CERN PS Booster	1–18 MHz	wideband RF system
ESS, European Spallation Source	352.21 MHz, 704.42 MHz	proton linac, normal/superconducting structures
SNS, Oak Ridge Spallation Neutron Source	402.5 MHz, 805 MHz	RFQ/DTL, CCL, SRF linac
J-PARC Linac	324 MHz, 972 MHz	RFQ/DTL/SDTL, ACS
Fermilab PIP-II	162.5 MHz, 325 MHz, 650 MHz	HWR, SSR, elliptical SRF cavity
FRIB, Michigan State University	80.5 MHz, 322 MHz	heavy-ion SRF linac
European XFEL	1300 MHz (1.3 GHz), 3900 MHz (3.9 GHz)	TESLA형 SRF linac, 3rd-harmonic linearizer
SLAC LCLS-II	1300 MHz (1.3 GHz), 3900 MHz (3.9 GHz)	CW SRF linac, harmonic linearizer
SwissFEL	2998.8 MHz, 5712 MHz, 11,995.2 MHz	S-band gun/booster, C-band linac, X-band station
SACLA, SPring-8 Angstrom Compact FEL	5712 MHz (5.712 GHz)	C-band main linac
SuperKEKB	508.9 MHz	main ring / damping ring RF
BEPCII, Beijing Electron–Positron Collider II	500 MHz	SRF cavity
ESRF-EBS	3000 MHz, 352.2 MHz	linac, booster/storage ring
Jefferson Lab CEBAF	1497 MHz	CW SRF electron linac

- ✓ 입자 질량 -> 속도 -> 셀 길이
- ✓ Aperture, RF breakdown, 열, 오차..
- ✓ <u>고출력 RF source의 주파수도 고려</u>

입자 가속기의 RF 시스템

ChatGPT

입자 가속기의 RF 시스템에 대해 알려주고, 관련 자료 찾아줄래

먼저 RF 시스템의 역할과 주요 구성, 제어·설계 쟁점을 간단히 정리한 뒤 CERN, SLAC, USPAS 등 신뢰도 높은 공개 자료를 입문에서 심화 순서로 묶어보겠습니다.

5m 14s 동안 생각함 ›

입자 가속기의 **RF 시스템**은 전자기파, 즉 radio-frequency 전기장을 이용해 하전 입자 빔에 에너지를 전달하고, 입자들을 **번치(bunch)** 형태로 묶어 정해진 시간·위상에 맞게 지나가도록 제어하는 시스템입니다. 핵심 장치는 **RF 공동(cavity)** 인데, 금속 또는 초전도 금속으로 만든 공진기 안에 빔 진행방향 전기장을 만들고, 입자 번치가 적절한 위상으로 지나갈 때 에너지를 얻도록 합니다. CERN 설명에 따르면, RF 공동은 입자 가속기 내부에서 전자기장을 만들어 통과하는 하전입자에 전기적 임펄스를 주는 장치입니다. CERN +1

1. 왜 RF를 쓰나?

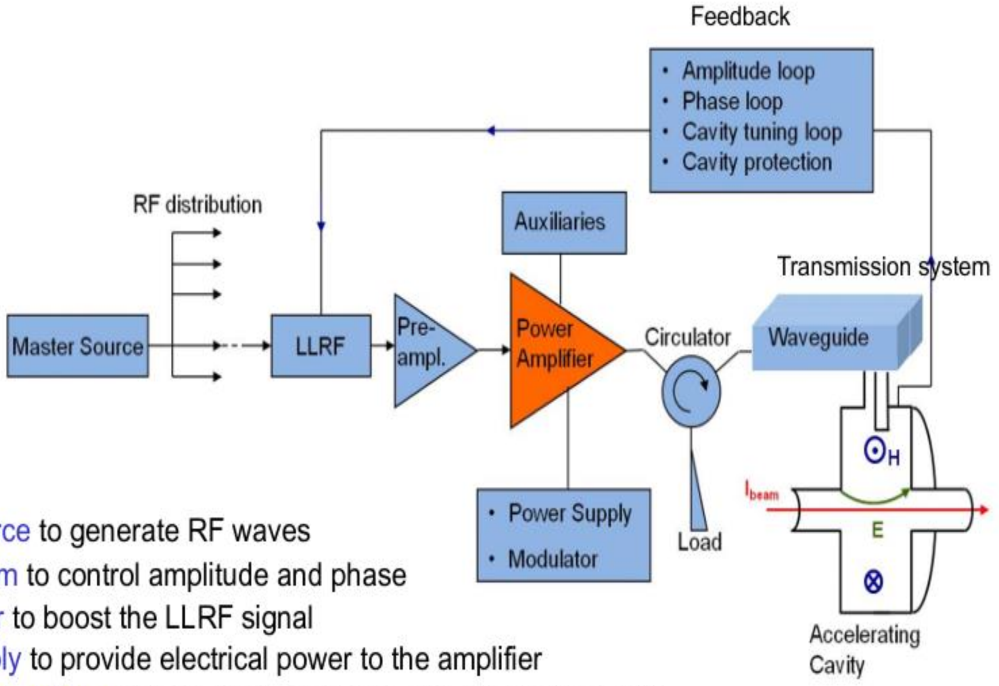
정전압 DC 가속기는 높은 전압을 한 번 걸어 입자를 가속하지만, 전압 절연·방전 한계 때문에 에너지를 계속 높이는 데 제약이 큽니다. RF 가속은 전기장을 시간적으로 진동시키고, 입자들을 연속류가 아니라 번치로 만들어 여러 번 같은 RF 구조를 통과하게 하거나 여러 RF 셀을 지나게 해서 높은 에너지까지 올립니다. CERN RF 그룹도 수 MeV 이상의 에너지에 도달하려면 높은 주파수의 시간변화 전기장과 번치 빔이 필요하므로 RF가 가속기에서 표준 기술이 된다고 설명합니다. CERN Accelerat...

2. 기본 구성

가속기 RF 시스템은 보통 다음 흐름으로 이해하면 됩니다.

기준 클록·동기 시스템 → LLRF 제어기 → 고전력 RF 증폭기 → 전송선/도파관 → 입력 커플러 → RF 공동 → 빔

Sakhorn Rimjaem, RF System, ISBA23, August 6, 2023



- Master source to generate RF waves
- LLRF system to control amplitude and phase
- RF amplifier to boost the LLRF signal
- Power supply to provide electrical power to the amplifier
- Transmission system to take power from the amplifier to the cavity
- Cavity to transfer the RF power to the beam
- Feedback from the cavity to the LLRF system to correct errors

전자장 (Maxwell's eq., Wave eq.)

$$\nabla \cdot \vec{D} = \rho \quad \text{or} \quad \nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla^2 \vec{E} = \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2}$$

$$\nabla^2 \vec{H} = \mu\epsilon \frac{\partial^2 \vec{H}}{\partial t^2}$$

Wave equation (=Helmholtz' eq.)!

$$\nabla^2 \vec{E} + \omega^2 \mu\epsilon \vec{E} = 0$$

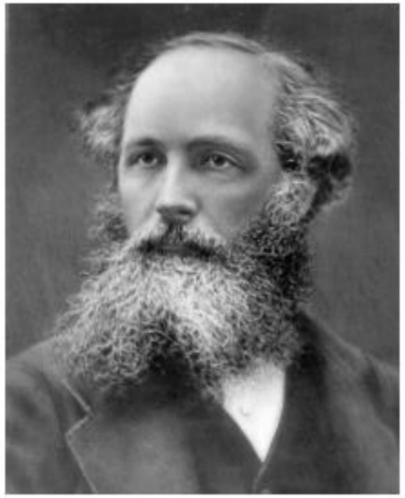
$$\nabla^2 \vec{H} + \omega^2 \mu\epsilon \vec{H} = 0$$

define

Propagation constant k

(or: phase constant, or wave number, or separation constant), with unit 1/m

$$k = \omega\sqrt{\mu\epsilon}$$



James Clerk Maxwell

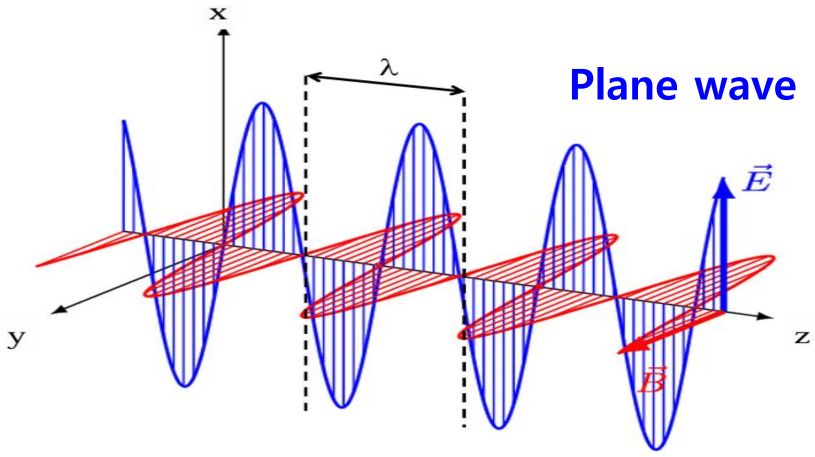
1831 – 1879

$$E(x,y,z,t) = E(x,y)e^{j(\omega t - \beta z)}$$

$$H(x,y,z,t) = H(x,y)e^{j(\omega t - \beta z)}$$

β is the propagation wavenumber along the guide direction.

$$\lambda_g = 2\pi/\beta$$



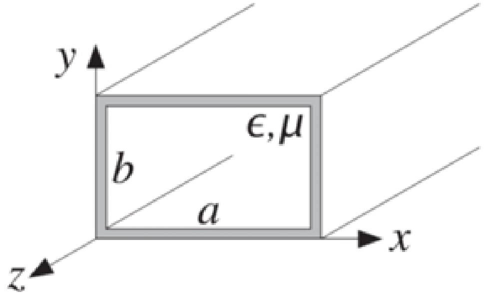
Note that E and B fields oscillate with the same phase.

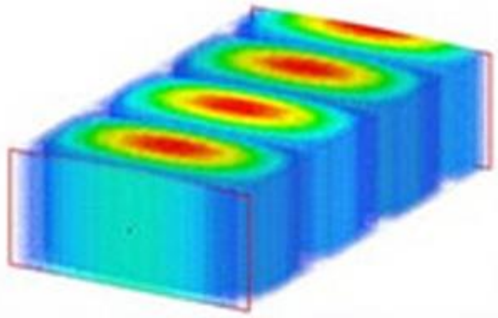
Rectangular waveguide

Magnetic and electric fields of transverse electric (TE_{nm}) modes

$$E_z(x, y) = 0$$

$$H_z(x, y) = H_0 \cos(k_x x)\cos(k_y y)$$



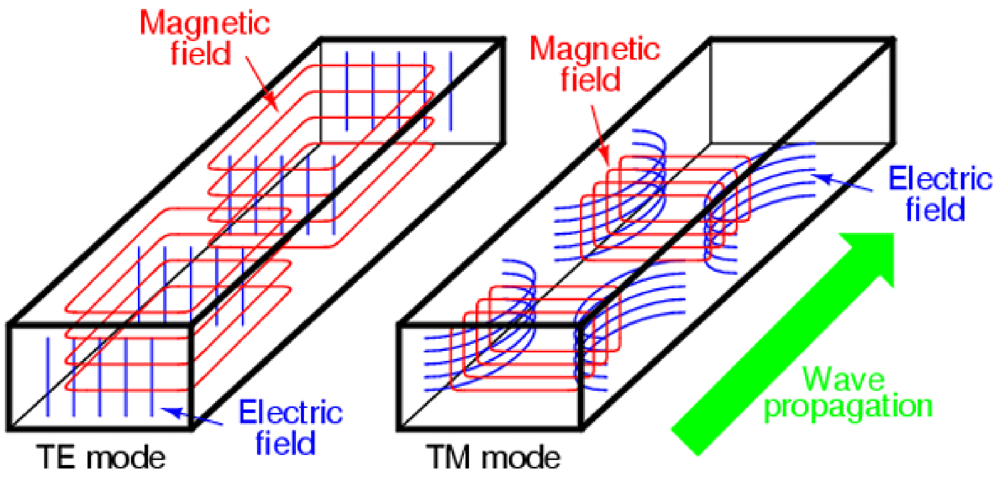


The boundary conditions require

$$k_x = \frac{n\pi}{a} \quad ; \quad k_y = \frac{m\pi}{b}$$

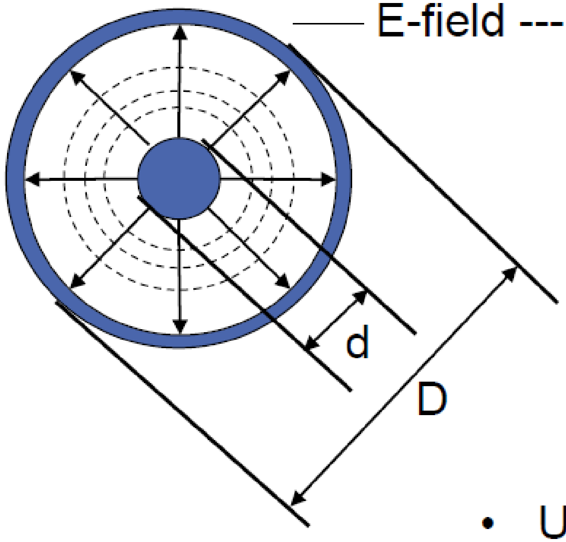
The frequency is

$$f_{c,mn} = \frac{1}{2\sqrt{\mu\epsilon}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$



$E_z = 0$; $H_z = 0$	TEM modes
$E_z = 0$; $H_z \neq 0$	TE modes
$E_z \neq 0$; $H_z = 0$	TM modes
$E_z \neq 0$; $H_z \neq 0$	hybrid modes

Coaxial line in TEM mode



- Characteristic impedance for a lossless line: $Z_0 = \sqrt{\frac{L'}{C'}}$

- From textbook, we look up *(calculated from electrostatic equations…)*:

$$L' = \frac{\mu}{2\pi} \ln\left(\frac{D}{d}\right) \qquad C' = \frac{2\pi\epsilon}{\ln\left(\frac{D}{d}\right)}$$

$$\Rightarrow \quad Z_0 = \sqrt{\frac{\mu}{\epsilon}} \frac{\ln\left(\frac{D}{d}\right)}{2\pi}$$

- Usually, there is low-loss dielectric between inner and outer conductor.

$$\epsilon = \epsilon_0\epsilon_r$$
$$\mu = \mu_0\mu_r \qquad \mu_r \approx 1$$

$$Z_0 = \frac{60\Omega}{\sqrt{\epsilon_r}} \ln\left(\frac{D}{d}\right)$$

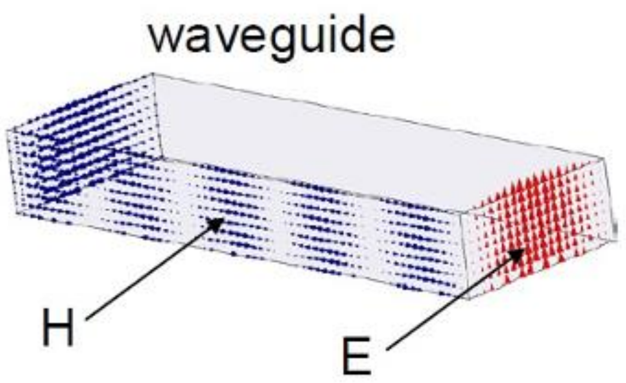
Coax characteristic impedance with low-loss dielectric

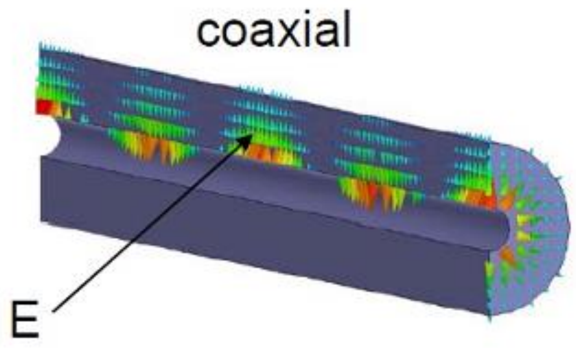
$$v_p = \frac{c_0}{\sqrt{\mu_r\epsilon_r}} = \frac{c_0}{\sqrt{\epsilon_r}}$$

- Full shielding properties is making the coaxial line very popular for RF measurement equipment.

RF transmission line (Coupler)

D. Alesini, Power Coupling, CAS, Ebeltoft, Denmark, June 2010



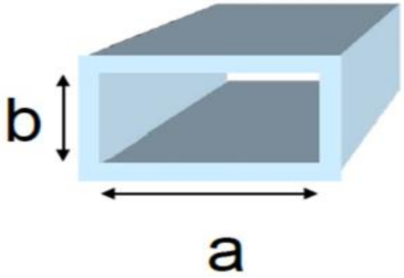


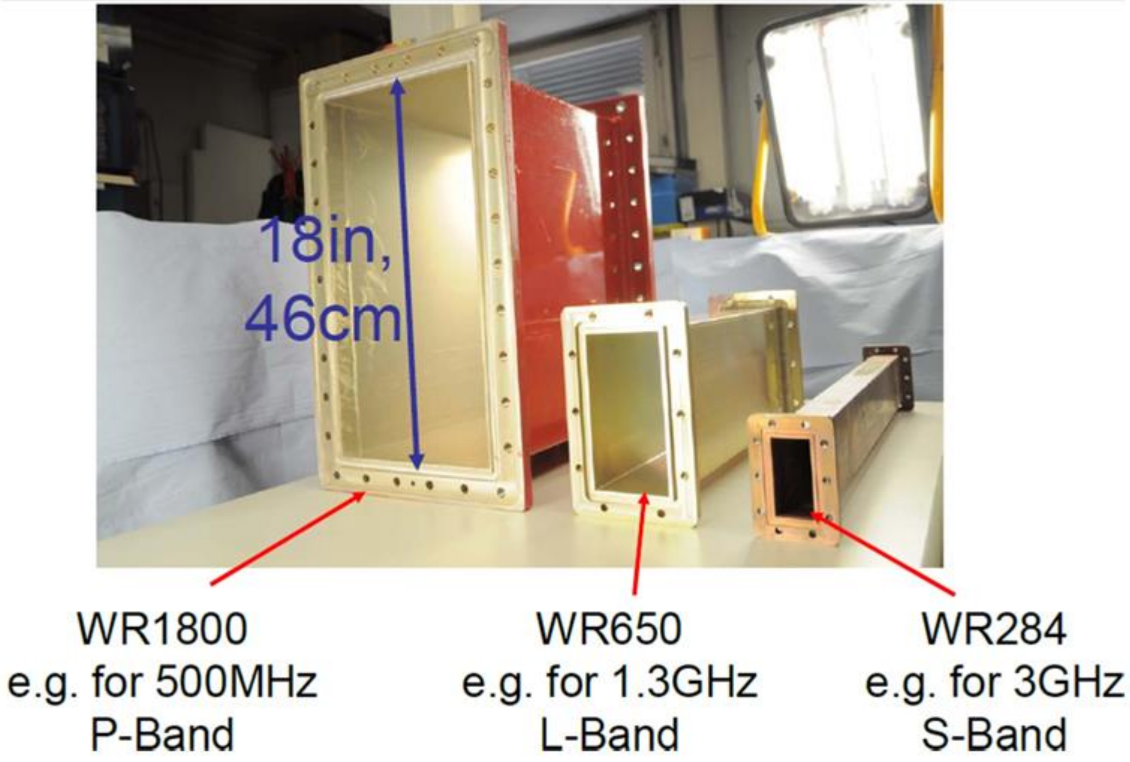
Parameter	Waveguide	Coaxial
Dimensions	larger	smaller
Power handling capacity	higher	lower
Attenuation	lower	higher
Vacuum / pumping speed	better	worst
Variable coupling	difficult	easier
Cooling	better	worst

Notes:
- Waveguide type is preferred at high frequencies & high gradient structures.
- Coaxial type is preferred at low frequencies.

Waveguide dimensions

Waveguide type	a (in)	b (in)	f_{c10} (GHz)	frequency range (GHz)
WR 2300	23.000	11.500	.256	.32–.49
WR 2100	21.000	10.500	.281	.35 –.53
WR 1800	18.000	9.000	.328	.41 –.62
WR975	9.750	4.875	.605	.75 – 1.12
WR770	7.700	3.850	.767	.96 – 1.45
WR650	6.500	3.250	.908	1.12 – 1.70
WR430	4.300	2.150	1.375	1.70 – 2.60
WR284	2.84	1.34	2.08	2.60 – 3.95
WR187	1.872	.872	3.16	3.95 – 5.85
WR137	1.372	.622	4.29	5.85 – 8.20
WR90	.900	.450	6.56	8.2 – 12.4
WR62	.622	.311	9.49	12.4 - 18





RF 측정 (dBm, dB)

dB 와 dBm 의 차이 ??

$$dBm = 10\ log(mW) = 10\ log(W) + 30$$

$$mW = 10^{(dBm/10)}$$

Spectrum Analyzer

Vector Network Analyzer

RF signal generator

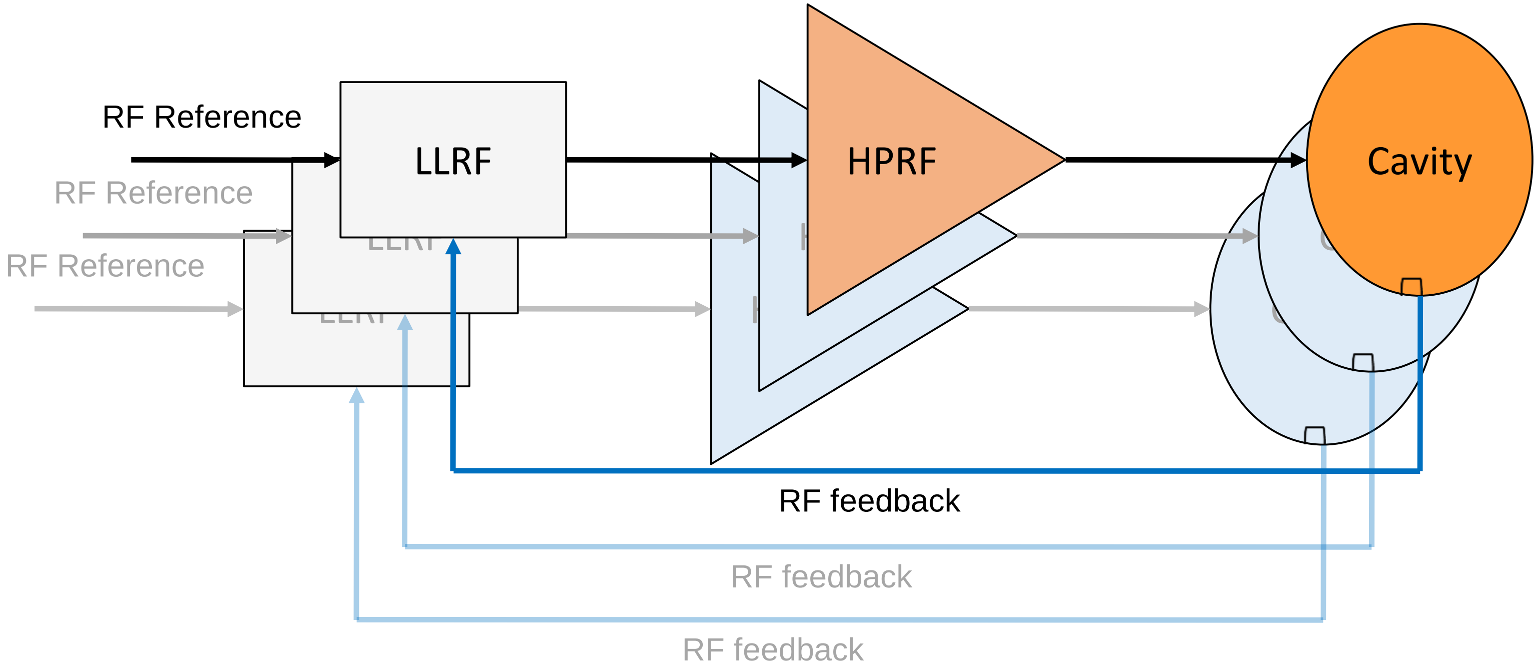
Power meter

Oscilloscope

가속기의 RF system

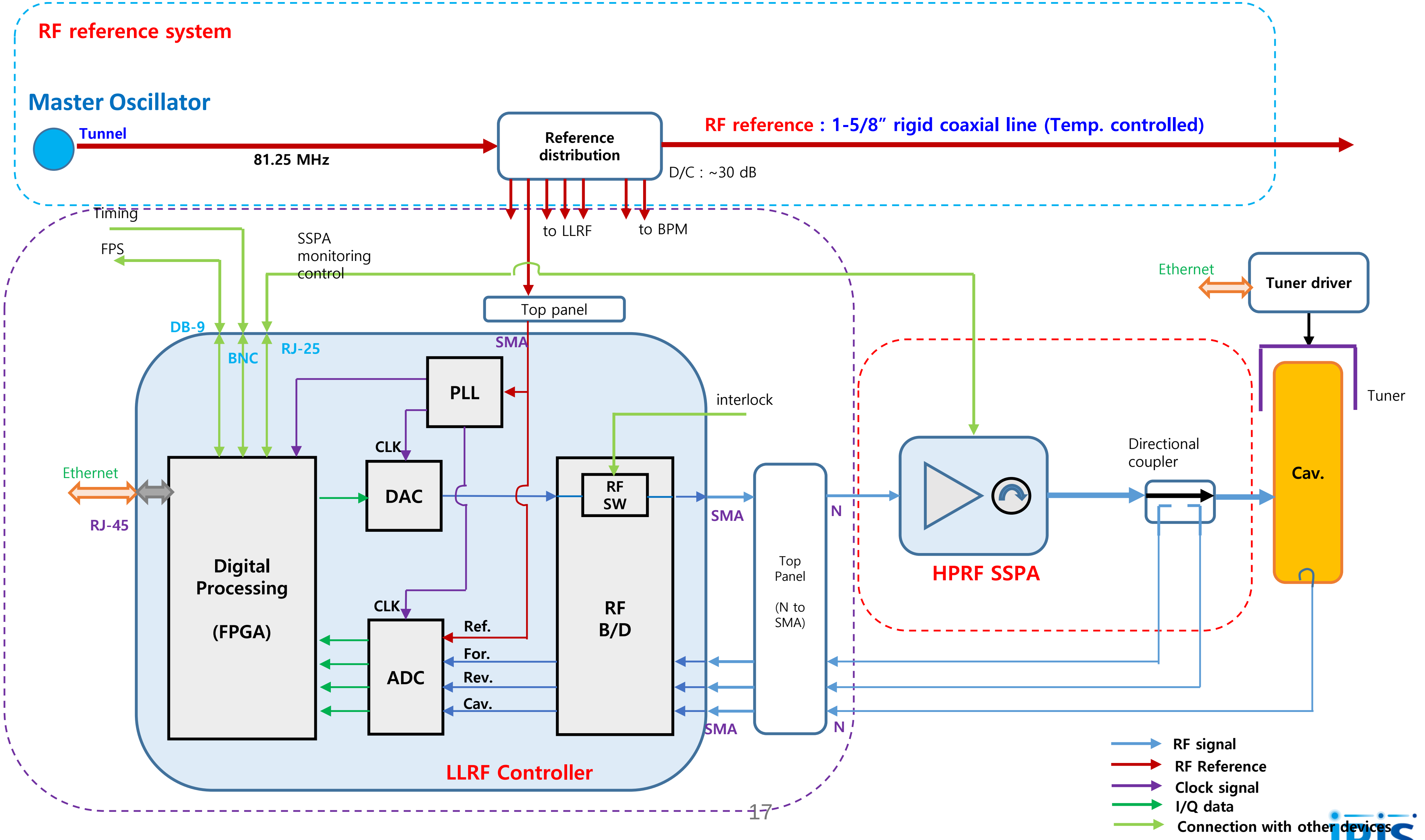
$$RF(x) = A\cos(2\pi f x + \phi)$$

Amplitude　　Frequency　　Phase



- **LLRF (Low-level RF) control** : RF generation, Feedback control (Amplitude, phase), Resonance control -> (A, P, F)
- **HPRF (High power RF)** : RF amplifier (SSPA, Klystron, Tetrode …), HPRF power transmission -> (A)
- **RF Reference** : RF reference signal distribution (LLRF, BPM ..) -> (F, P)

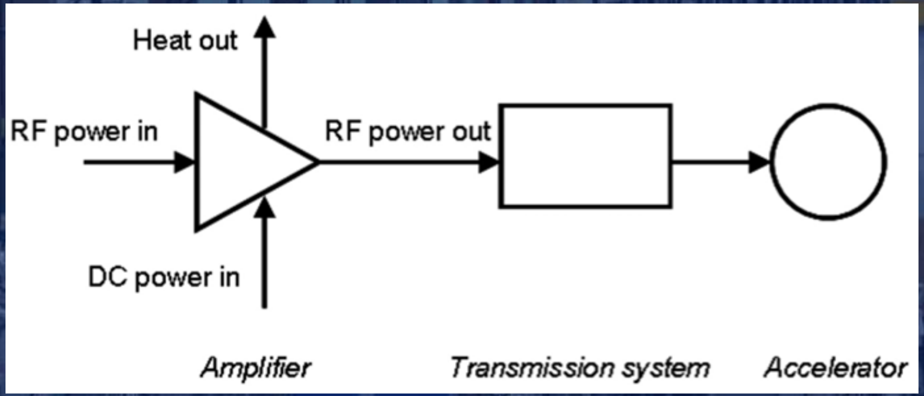
Block diagram of RF system (RAON)



iRIS 중이온가속기연구소 Institute for Rare Isotope Science

Part 02.

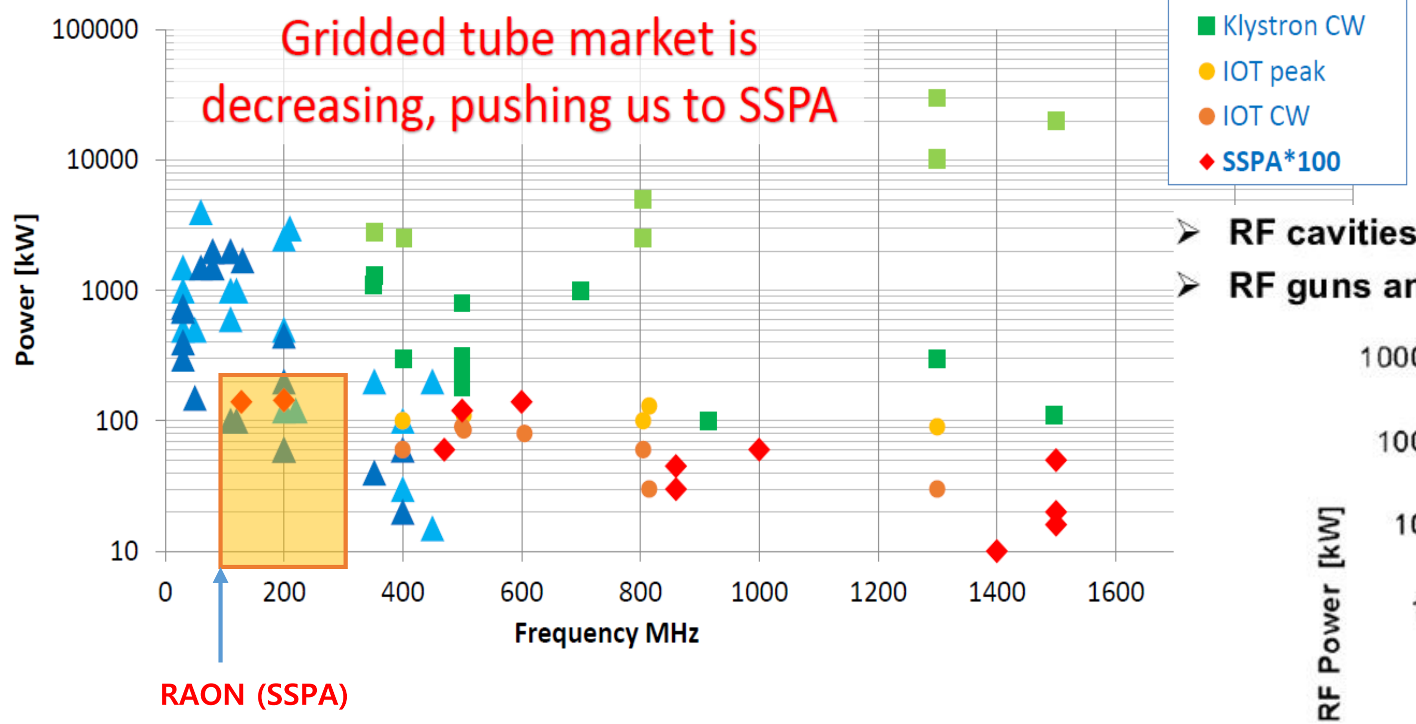
High-power RF system



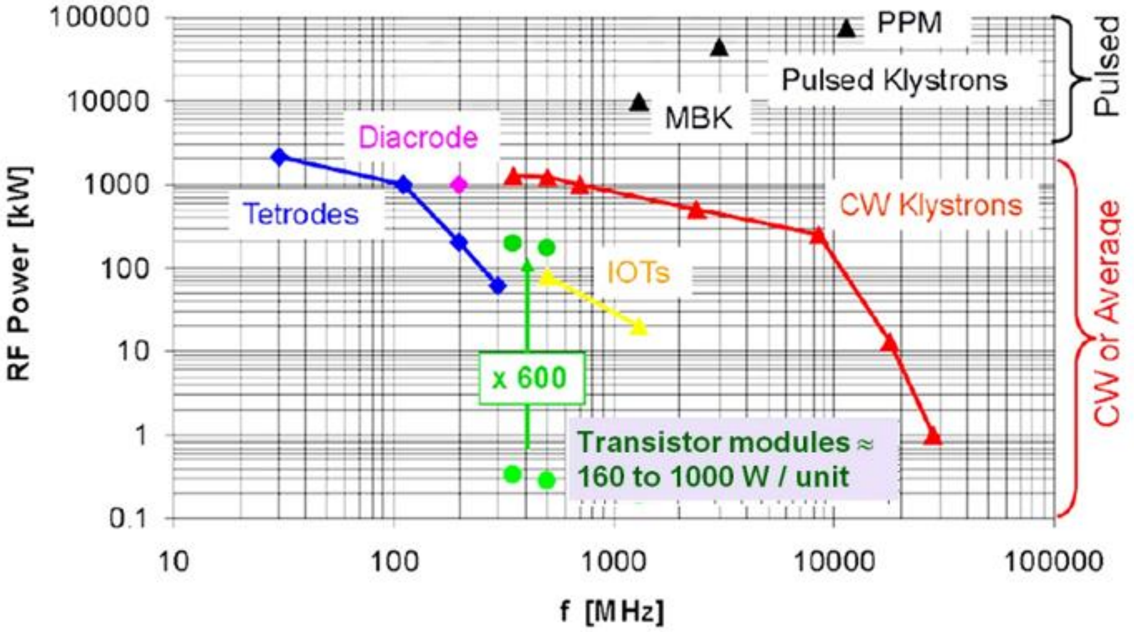
Institute for Rare Isotope Science

RF amplifier (Choices of frequency & power)

Available RF sources at a glance



- **RF cavities:** 200, 267, 352, 400, 508, 650, 704 MHz
- **RF guns and RF linacs:** 1.3, 2.856, 3, 3.7, 3.9, 5.6, 9.3, 11.424, 11.994 GHz



iRIS 중이온가속기연구소 Institute for Rare Isotope Science

RF amplifier (Vacuum tubes and SSPA)

Vacuum Tubes

Grid Tubes

- Triodes
- *Tetrodes*
- Pentodes
- Diacrodes

Linear Beam Tubes

- *Klystrons*
- Travelling Wave Tubes (TWT)
- Gyrotrons
- *Inductive Output Tube (IOT)*

Crossed-field Tubes

- Magnetrons

Transistor-based RF Amplifiers

Bipolar Junction Transistor (BJT)

Field Effect Transistor (FET)

- Junction Gate FET (JFET)
- Metal Oxide Semiconductor FET (MOSFET)

Gallium Nitride (GaN)

High Electron Mobility Transistor (HEMT)

Solid-state RF Amplifiers

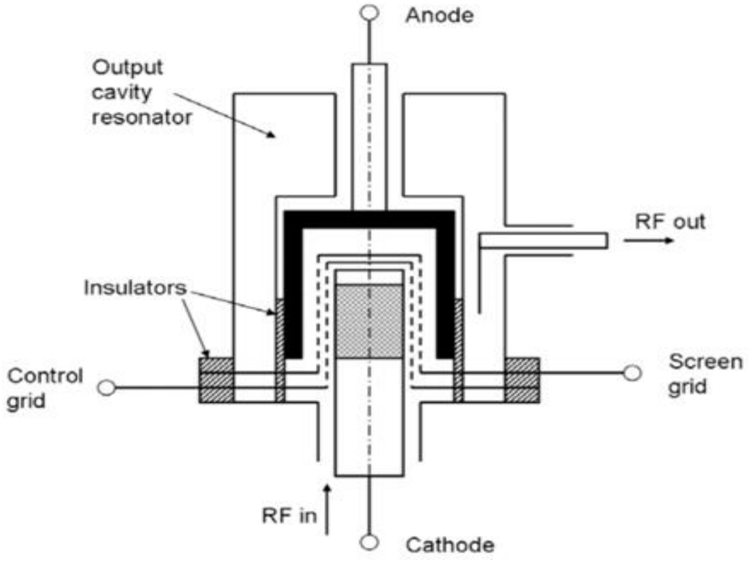
RF source 비교

항목	Tetrode	Klystron	Magnetron	SSPA
작동원리	- 진공관 증폭기 - 전류 제어 (grid) - 고전압 전원	- 전자빔 가속 - 변조 (Velocity, density) - 고전압 전원	- Crossed-field self oscillation - **전자 회전**, LC **공진** - **고전압 전원**	- 반도체 소자 증폭 - pallet (~1kW) - Combining
구성	Cathode, Control grid, Screen grid, Anode	Electron gun, Cavity resonator, Focusing magnet Collector	Cathode Anode cavity Magnet Antenna	PDU 전원(~60V) Driver (Splitter) Tr. (LDMOS, GaN..) Combiner
주파수 대역	중저주파 (대략 300MHz까지)	대략 300MHz 이상	**수** GHz ~ 30GHz	대략 1GHz 까지 (power에 따라 수 GHz 까지)
출력 RF 전력	중간 (~수백 kW)	고출력 (수백kW~MW이상)	**수** kW ~ **수** MW	수십~ 수백kW
비용	낮음	높음	**낮음 (고효율, 저비용)**	초기 비용 높음 (유지보수 비용 낮음)
유지보수	복잡 (진공관, 고전압)	매우 복잡	**단순 (주파수/위상 안정도 낮음)**	쉬움
유틸리티	고전압, 냉각수	고전압, modulator, 냉각수	**고전압, 냉각**	냉각수

Triode / Tetrode (1)

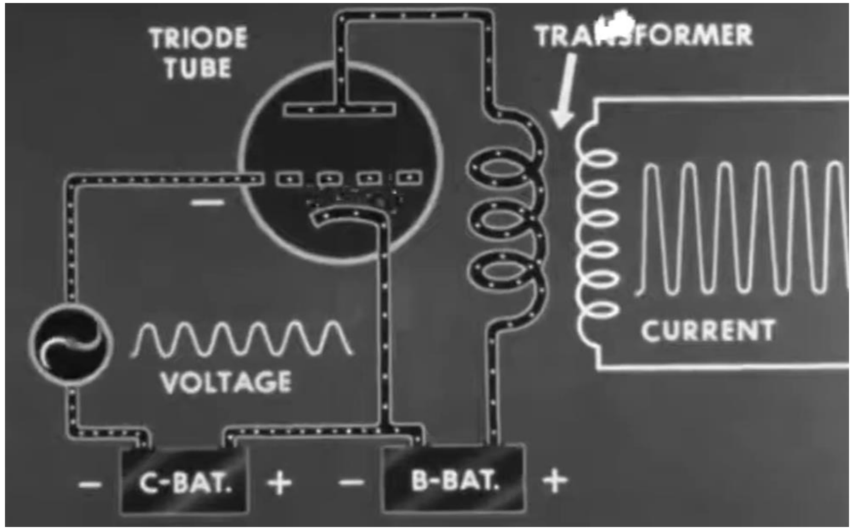
Tetrode electron guns

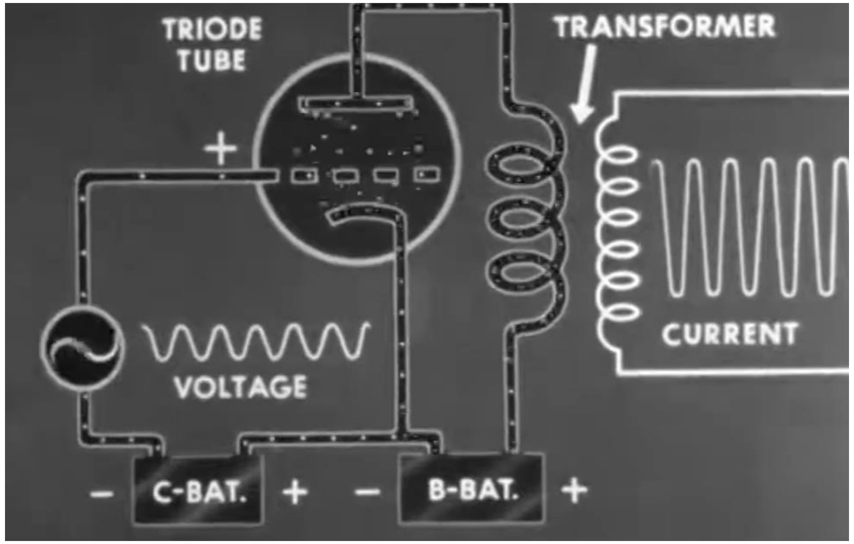
- It has a second grid to screen the control grid from the anode for avoiding feedback.
- It produces bunched beam.
- The beam is collected at the anode, where the potential fluctuates with the beam and hence providing an AC voltage.
- Gridded tubes are used at frequencies below a few hundred MHz.
- Low gain and low efficiency.



control grid와 anode를 RF적으로 차폐

Gain 상승, 안정적인 고출력 운전





Tetrode (KBSI – 165MHz, 100kW)

High power RF amplifier system for KBSI RFQ (IPAC2017)

- **TH781 (Thales)**

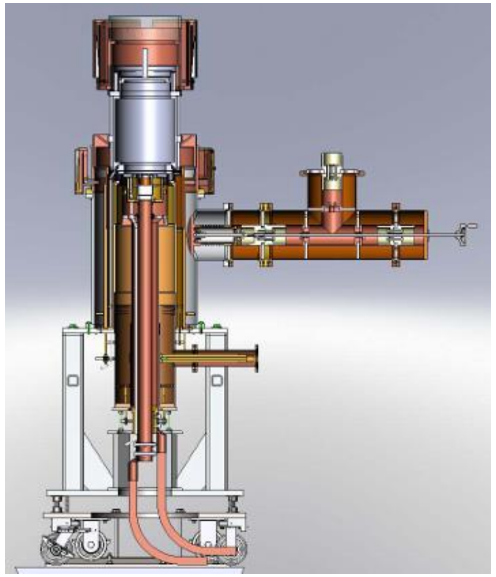
- Frequency : ~110 MHz

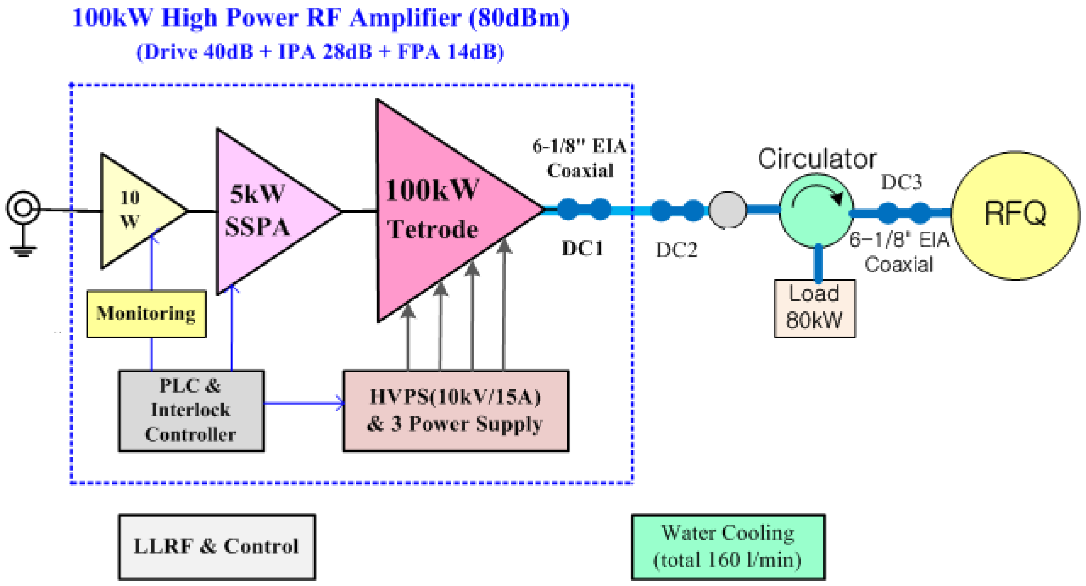
- RF power : ~250 kW

- Efficiency : ~65 %

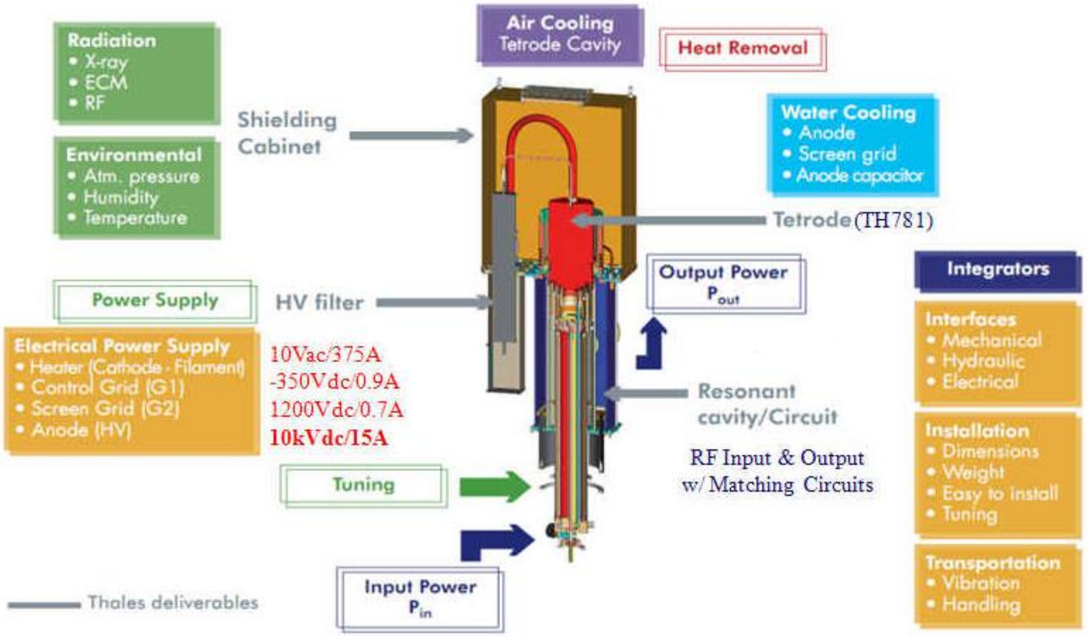
- Water cooling

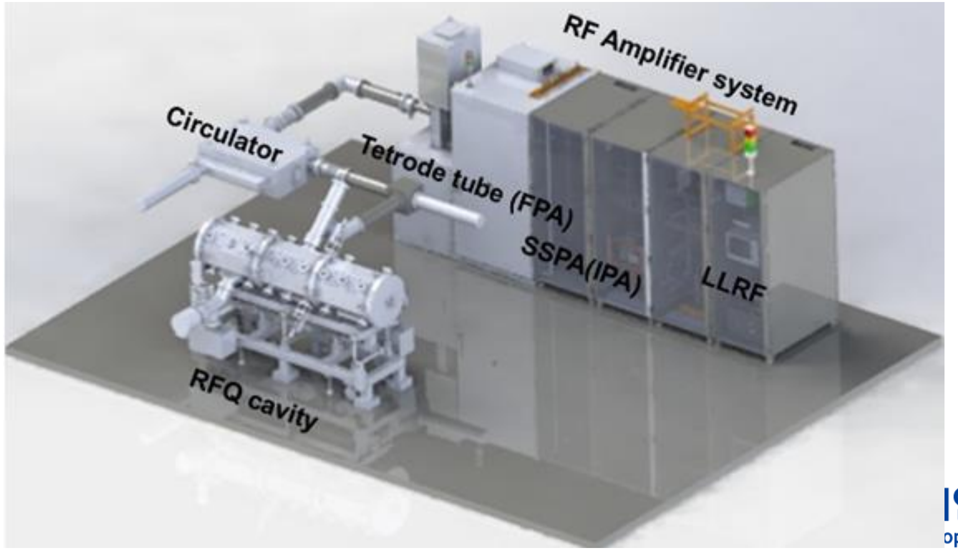
- High voltage : >15 kV





Integration parameters

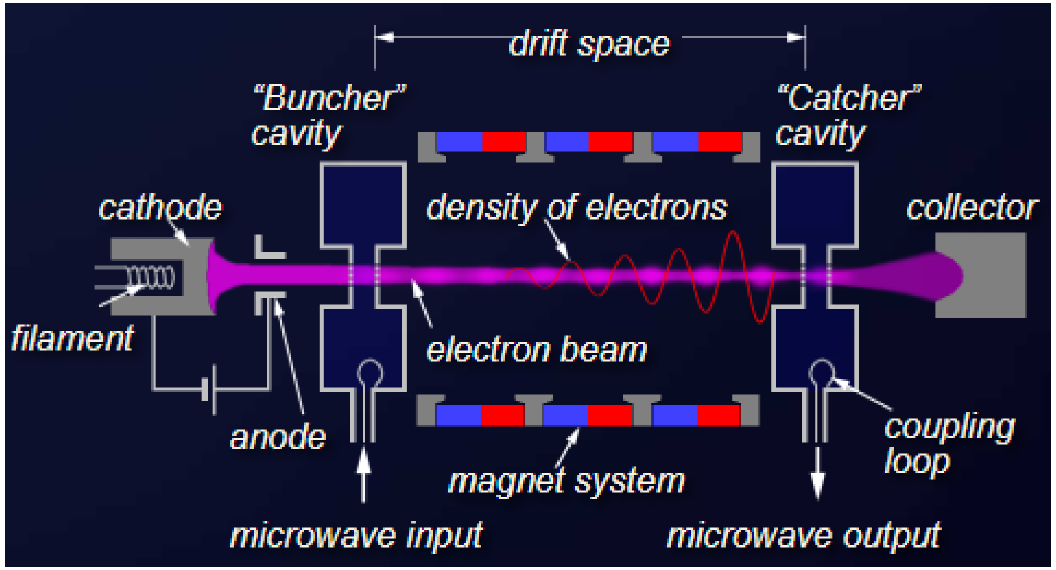




Klystron (1)

Klystrons

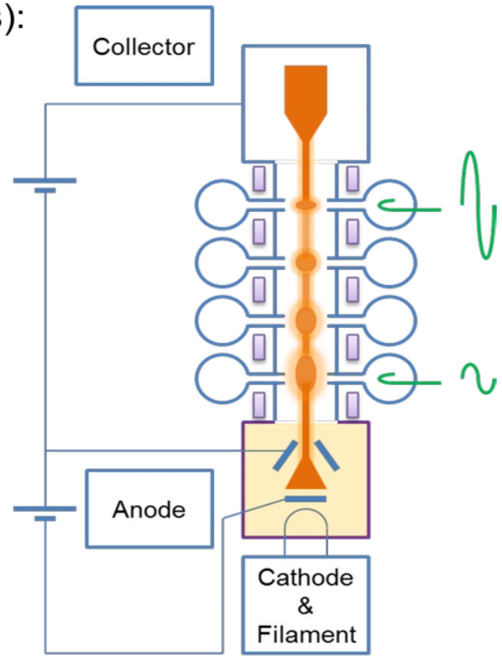
Klystron was invented at Stanford in 1937. The klystron severed as an oscillator in radar receivers during WWII. After the war, however, very high-power klystrons were built at Stanford for use in the first linear accelerators. This opened the way for the use of klystron not only in accelerators and radar, but also in UHF-TV, satellite communications, and industrial heating.

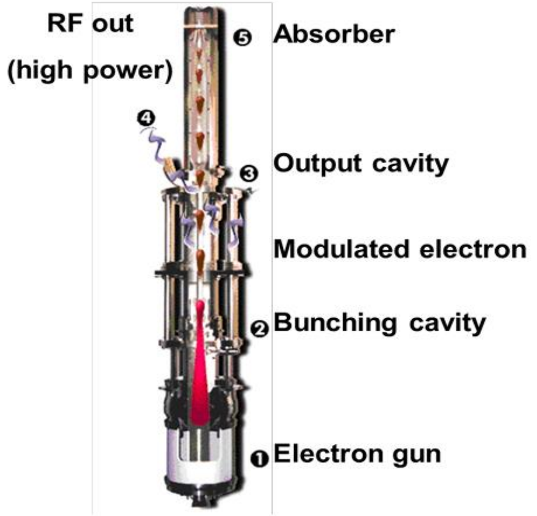


Pulsed Klystron (multiple resonant cavities):

Operating Principle: Velocity modulation of electrons in a vacuum tube. The RF signal is amplified as the electron beam passes through these cavities.

- Additional bunching cavities
  - Resonate with the pre-bunched electrons beam
  - Generate an additional accelerating/decelerating field
  - Better bunching
- Focusing magnets
  - To maintain the e-beam as expected and where expected





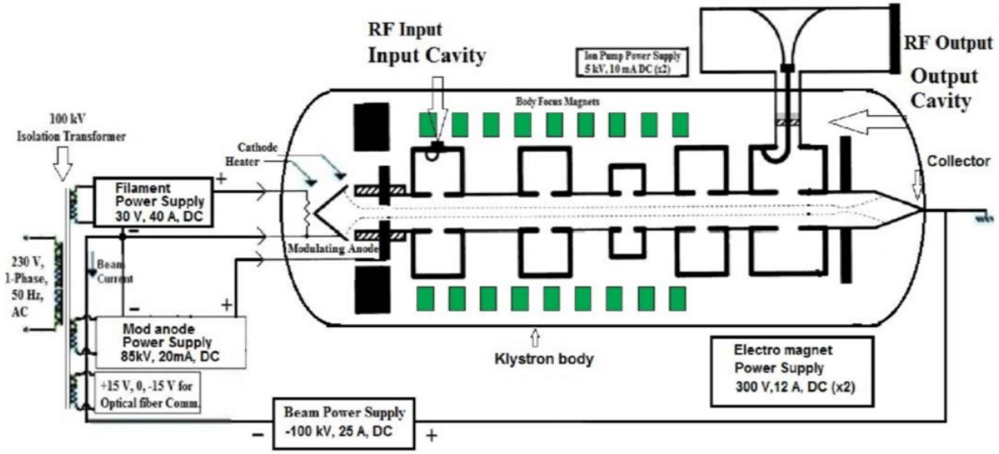
www2.slac.stanford.edu/vvc/accelerators/klystron.html

CERN LHC, TH 2167 klystron
330 kW @ 400 MHz

Klystron (KOMAC, PAL)

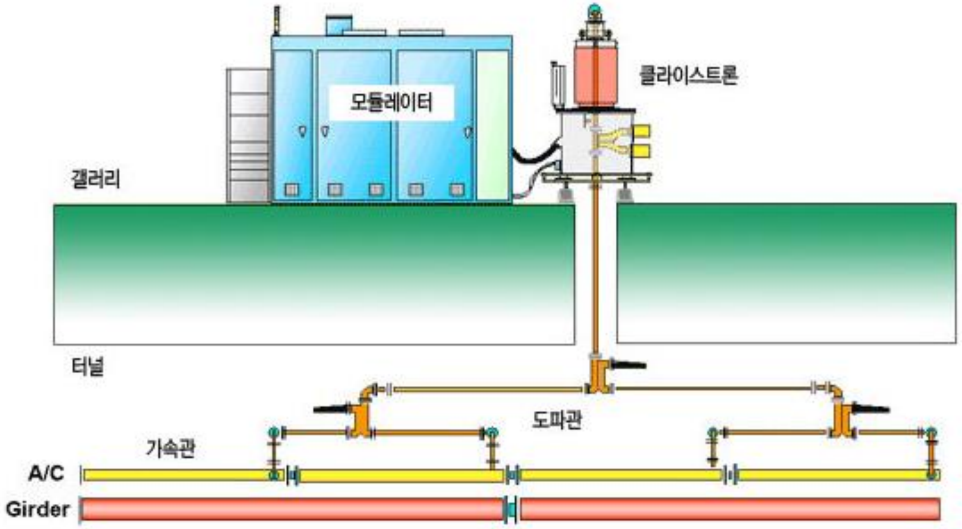
- **Klystron for KOMAC (RFQ, DTL)**

  : 350 MHz, 1MW CW Klystron (TH2089) -> Canon



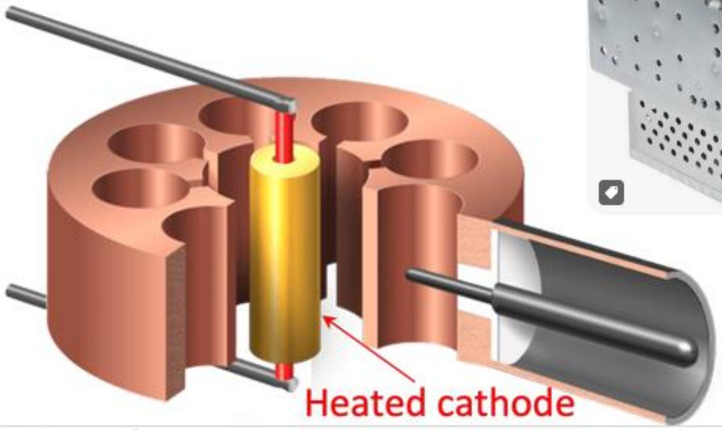
- **Klystron for PAL**

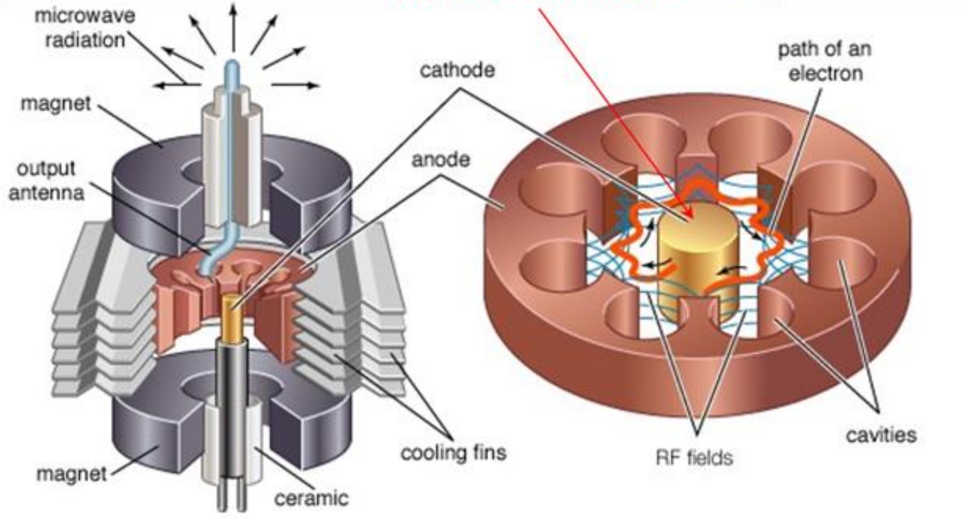
  : S-band (2.856 GHz), 80 MW pulsed (4us) Klystron

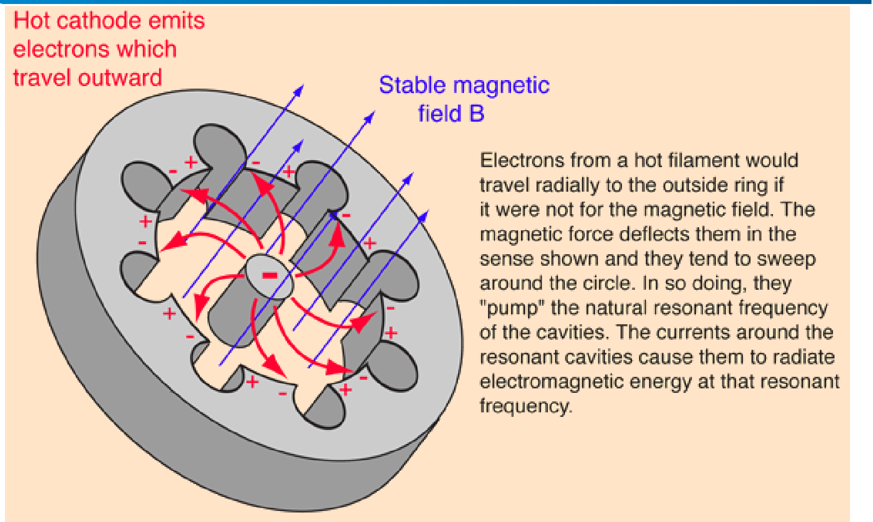


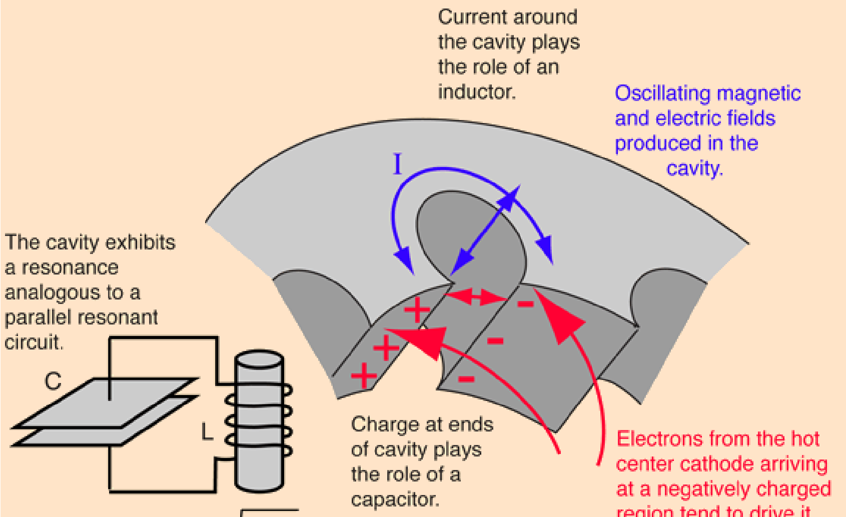
Magnetron (Oscillator)

- Magnetrons work by having an electron cloud rotate around a coaxial cathode due to interaction of electrons in crossed electric and magnetic fields.
- Cheap and fairly efficient for RF powers of below 5 MW pulsed or 30 kW CW at 3 GHz (100 kW at lower frequencies).
- Phase stability is not good enough for large accelerators.
- It is normally used for small industrial or hospital linacs.







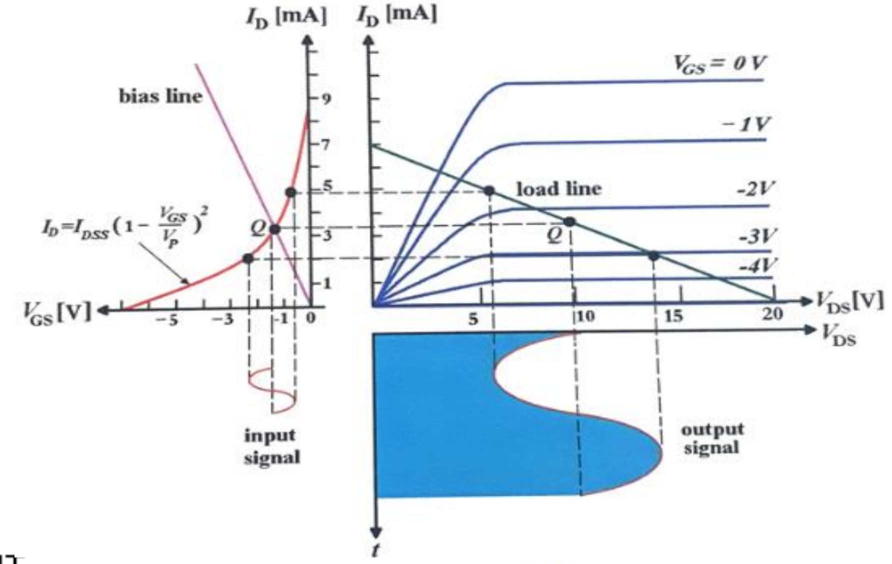


$$f_{resonance} \approx \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

Courtesy: I. Konoplev, Available RF power sources for reliable and robust medical accelerators

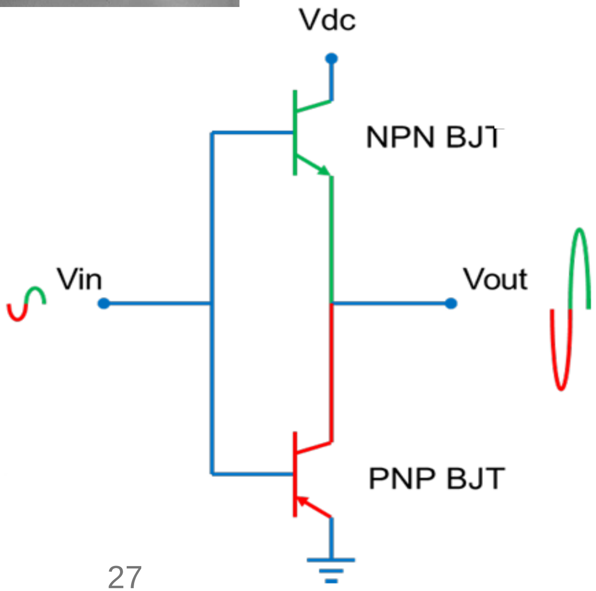
High-power RF SSPA (1)

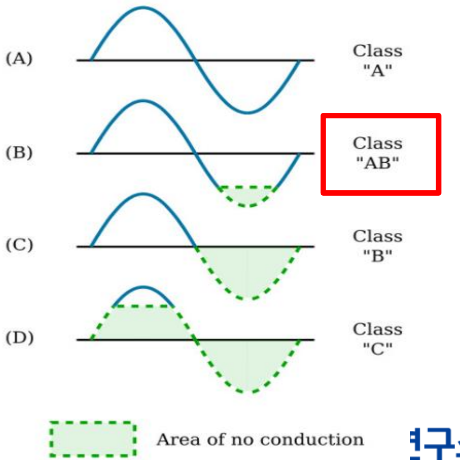
- 진공관이 아니라, LDMOS, GaN 같은 transistor를 사용해 RF 전력을 키우는 증폭기
- RF combining를 통해 kW~수백 kW, MW (<1GHz) 급으로 vacuum tube를 일부 대체하는 추세



In a push-pull circuit, the RF signal is applied to two devices

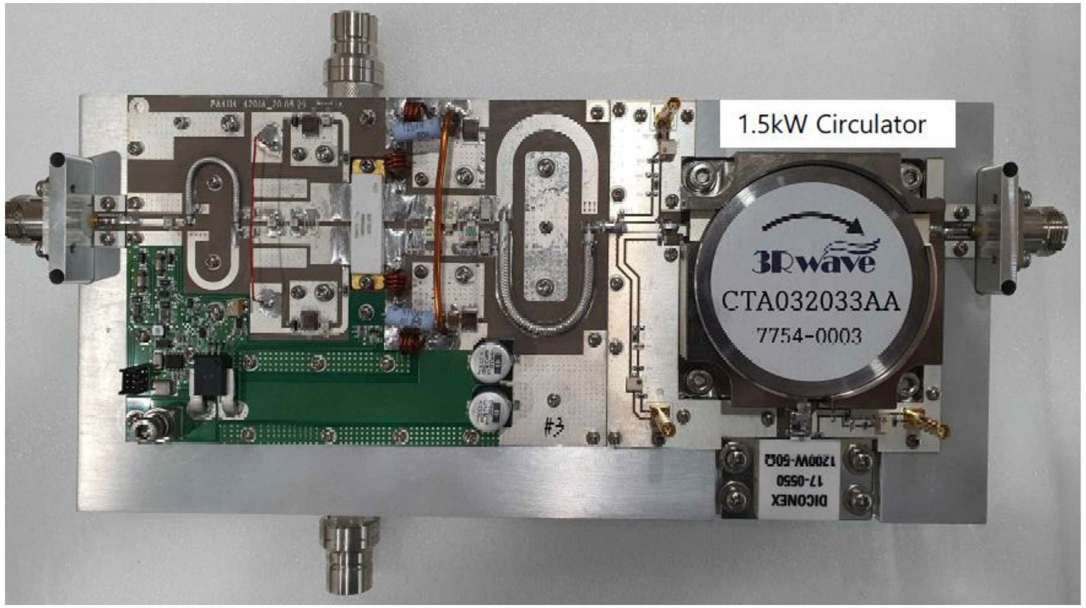
- One devices is active on the positive voltage and off during the negative voltage.
- The other device works in the opposite manner.
- So that the two devices conduct half the time, the full RF signal is then amplified.

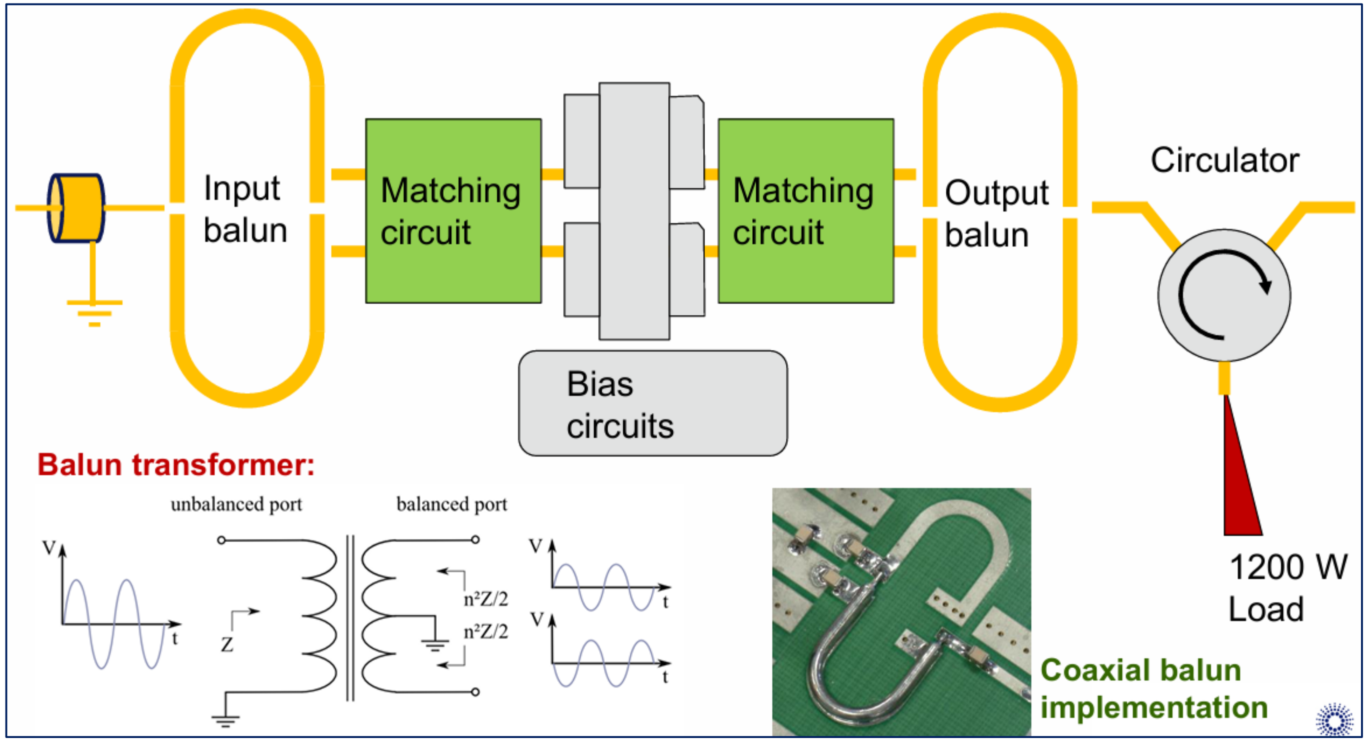


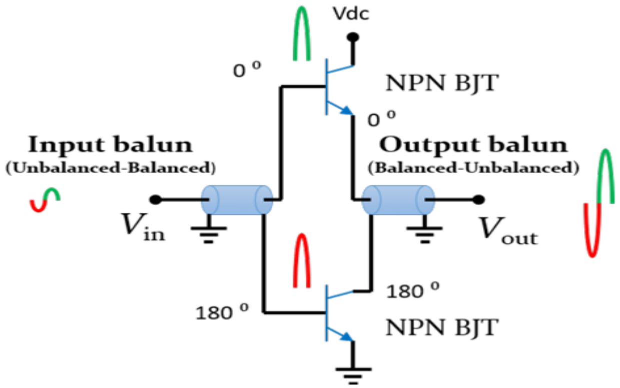


High-power RF SSPA (Pallet ~ 1.5kW)

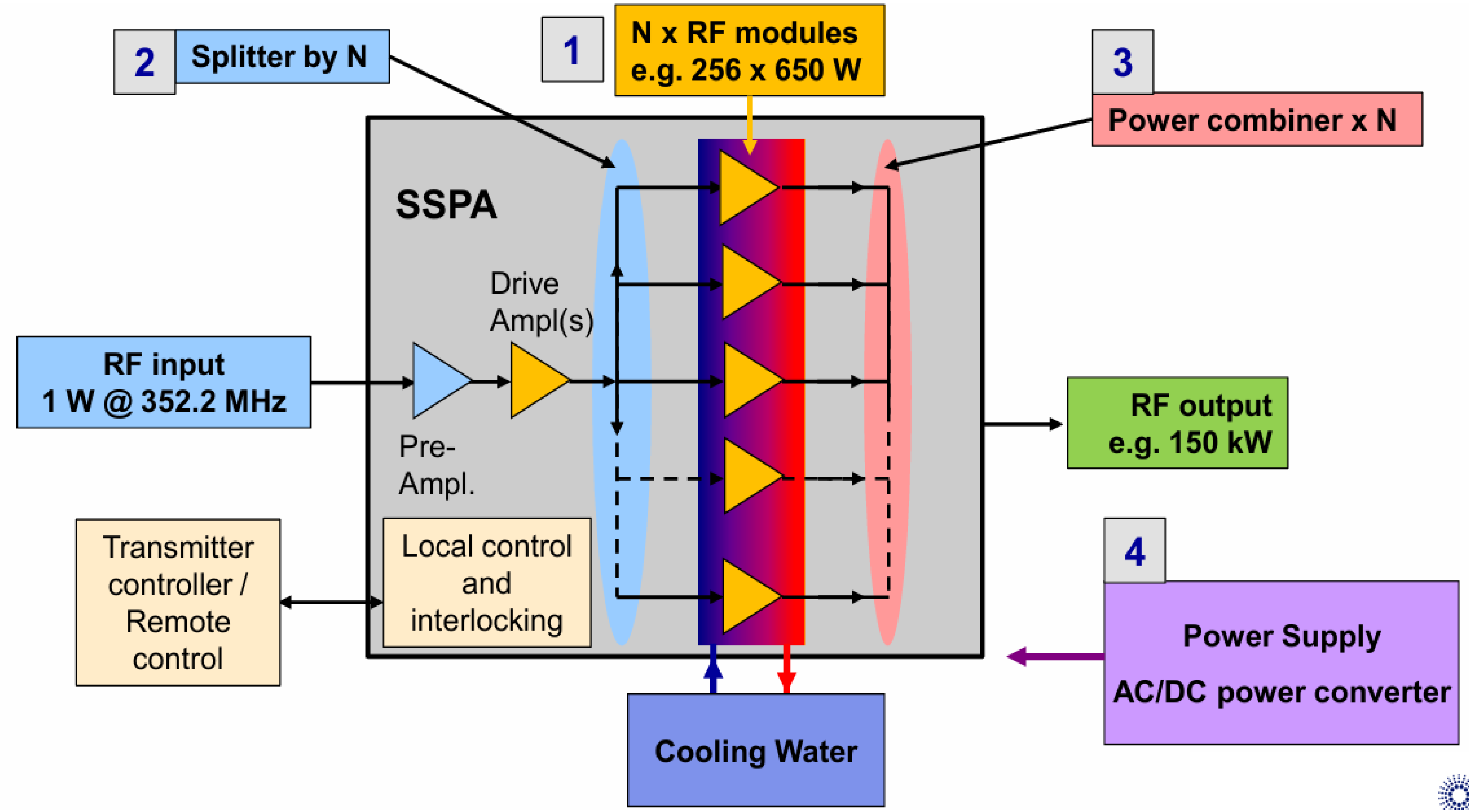
325 MHz, 1.5 kW pallet (for SSR1)







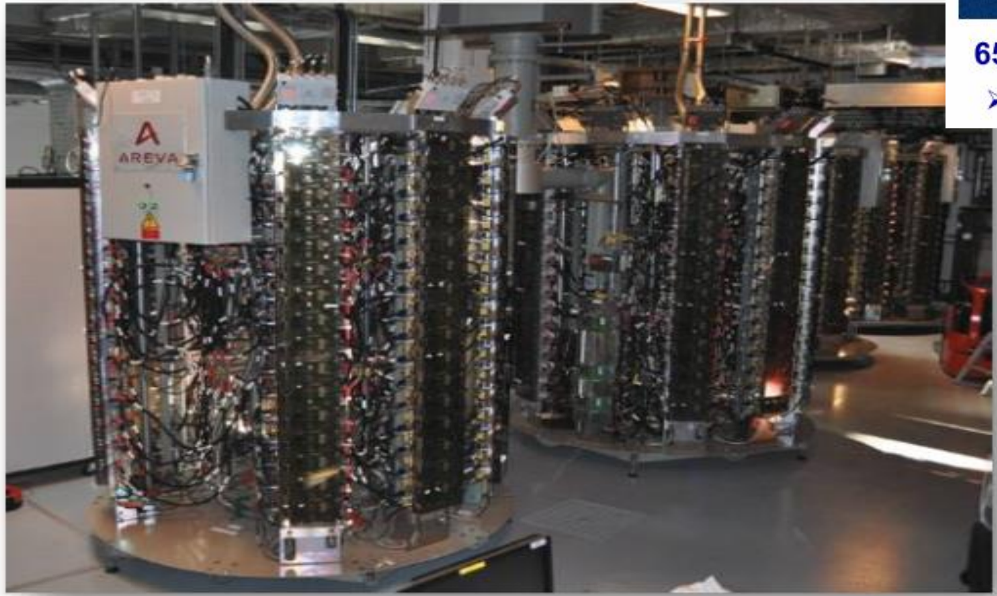
High-power RF SSPA 구성



High Power RF Solid State Amplifiers for Accelerators and Storage Rings (Jorn Jacob, 2018)

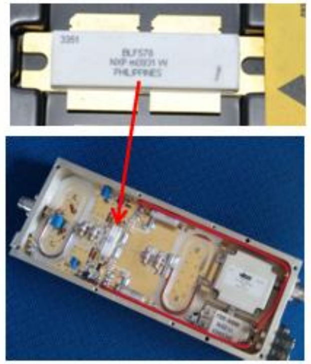
High-power SSPA 개발 초기

SOLEIL 45 kW @ 352 MHz tov
solid state amplifiers (2004 & 2



ESRF 75 kW @ 352 MHz tower
solid state amplifiers (2012)

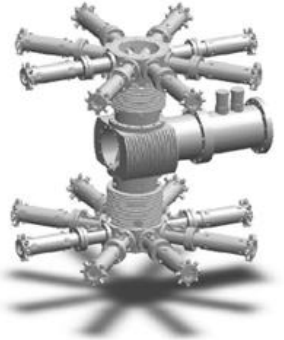
Pair of transistors in push-pull



x 128

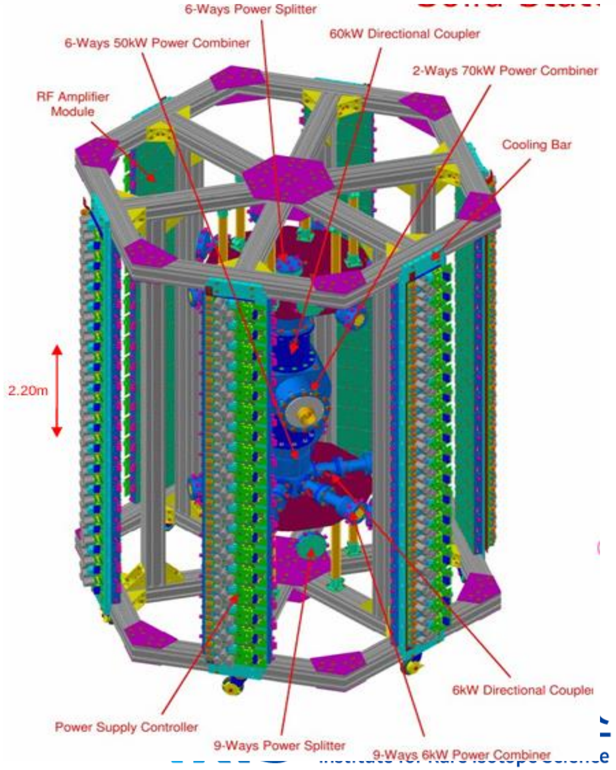
650 W RF module

- DC to RF: η = 68 to 70 %



x 2

75 kW coaxial power combiner tree



High Power RF Solid State Amplifiers for Accelerators and Storage Rings (Jorn Jacob, 2018)

High-power SSPA 개발 사례 (CERN SPS)

CERN LIU-SPS 200MHz RF SSPA (ESSRI 2022)

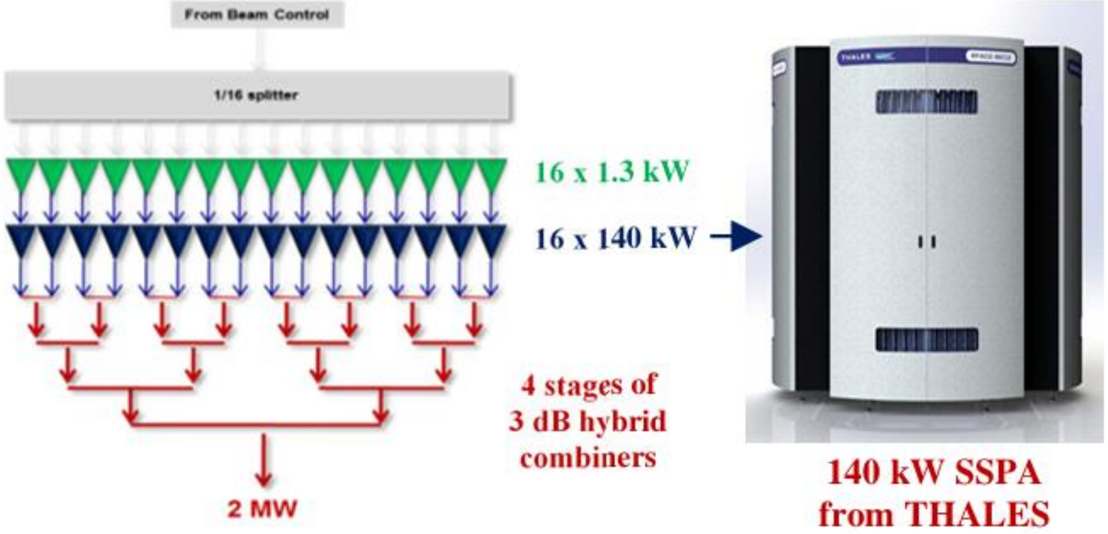
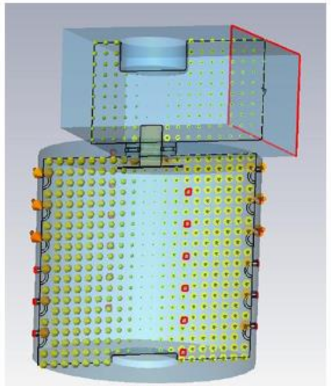
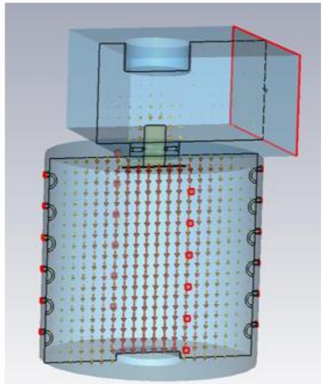


Figure 13: 2 MW 200 MHz CERN-SPS SSPA.



H field

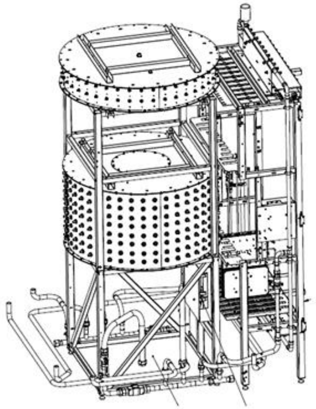
Homogenous magnetic coupling of all **input loops**



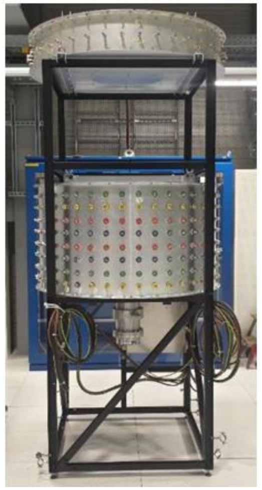
E field

Strong capacitive coupling to the **output waveguide**

TOWER



A tower is composed of
- One frame
- Four bays
- One cavity splitter
- One cavity combiner
- Electrical distribution
- Water distribution



A color code has been defined not to mix the RF connections

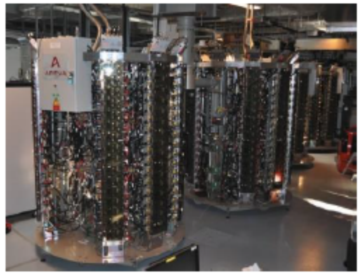
Indeed, modules are all the same, but mounted top and bottom affect the RF connections

In addition, the frame has been made such that all cable lengths are identical, needed for the cavity combiner

High-power SSPA (power density)

Power density

SOLEIL 45 kW @ 352 MHz
2004
Power density
3.5 kW m^{-3}



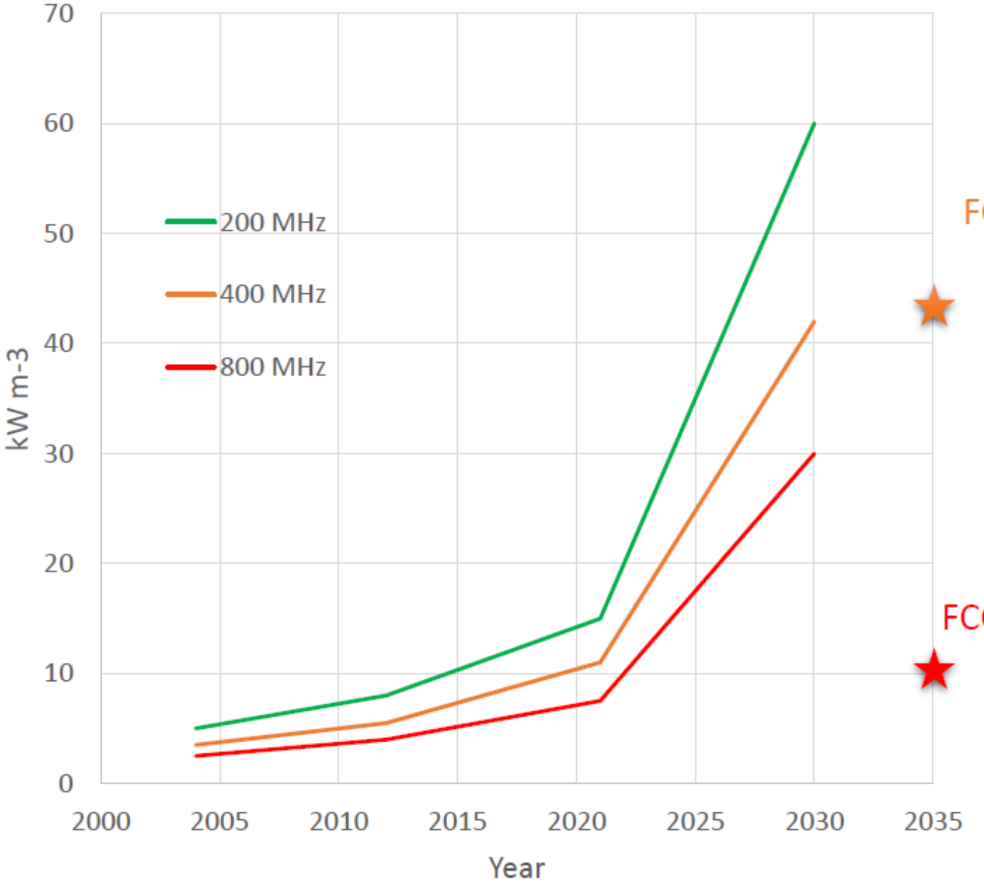
ESRF 150 kW @ 352 MHz
2012
Power density
6.5 kW m^{-3}

CERN 160 kW @ 200 MHz
2021
Power density
15 kW m^{-3}

$$\textit{Power density}\,(f) = \textit{Power density}_{200\,MHz}\sqrt{200/f}$$

Approximation, given the fact that transistors deliver less with respect to frequency, and taking into account a smaller combining system size

including power supplies and combining systems AND granularity providing **100 % availability !**



FCC 1 MW @ 400 MHz
Power density
43 kW m^{-3}

FCC 200 kW @ 800 MHz
Power density
10 kW m^{-3}

CERN LIU-SPS 200MHz RF SSPA (ESSRI 2022)

SSPA Developments in the world

Where	Supplier	Freq.	Power	Combiner
SOLEIL	In house	352 MHz	35 kW (booster) 160 kW (SR)	Several stage coaxial combiner (40 kW towers)
ESRF	SOLEIL/ELTA	352 MHz	150 kW	Several stage coaxial combiner (75 kW towers)
LNLS & SIRIUS, ThomX, SESAME	In house + transfer to Sigmaphi Electronics	476 MHz 500 MHz	160 kW	Several stage coaxial combiner
BESSY II	Cryoelectra GmbH	500 MHz	40 kW (booster) 75 kW (SR)	Waveguide combiner for last stage
SLS	In house, based on SOLEIL design	500 MHz	60 kW	Several stage coaxial combiner
ESRF	In house, pioneering cavity combiner	352 MHz	85 kW Tested at 90 kW	Cavity Combiner (single stage)
APS R&D	In house	352 MHz	200 kW	Cavity Combiner
SPring8	In house	509 MHz	110 kW	2 Cavity Combiners + waveguide comb x2
CERN SPS	THALES	200 MHz	16 x 144 kW = 2 MW, pulsed	1st Stage:80 x 2 kW cavity combiner 2^{nd} stage: 16 x 144 kW 3 dB coaxial hybrid network
GANIL-SPIRAL2	Bruker, now Sigmaphi Electronics	88 MHz	2.5 kW, 5 kW, 10 kW and 19 kW units	3 dB hybrids [Single power circulator → Phase shifters adjusted to tolerate cavity reflections]
MAX IV, SOLARIS	Rhode & Schwarz, FM transmitters	100 MHz	2 x 30 kW cabinets	3 dB hybrid

High Power RF Solid State Amplifiers for Accelerators and Storage Rings (Jorn Jacob, 2018)

RAON HPRF System (1)

- RF amp. : SSPA(Solid-State Power Amplifier), RF trans. : Rigid Coaxial Transmission Line

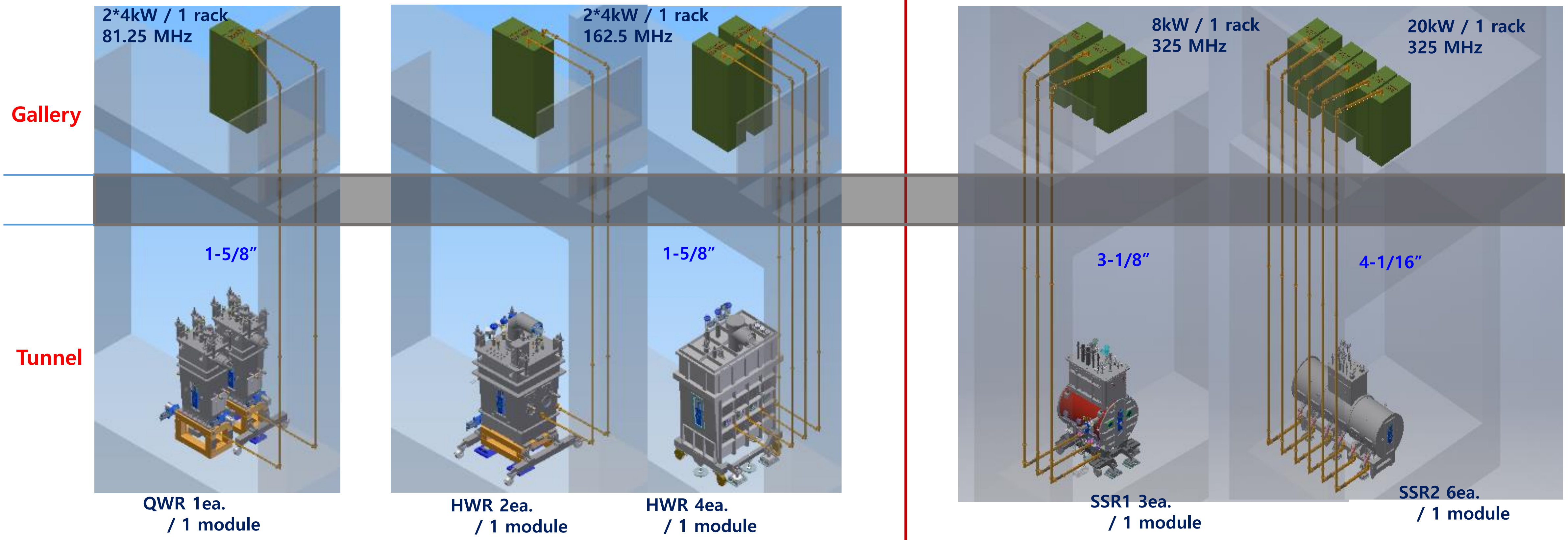
	Cavity	Quantity (EA)	Frequency (MHz)	RF Power (kW)	RF Transmission Line
SCL1 (Pended)	RFQ	2	81.25	80	6 1/8 inch EIA
	Rebuncher	4	81.25	20,15,4	3 1/8 inch EIA
	QWR	22	81.25	4	1 5/8 inch EIA
	HWR	102	162.5	4	1 5/8 inch EIA
SCL2 (high-energy)	**SSR1**	**69**	**325**	**8**	**3 1/8 inch EIA**
	SSR2	**144**	**325**	**20**	**4 1/16 inch EIA**
SCL3 (low-energy)	**RFQ (NC)**	**1**	**81.25**	**160 (80*2)**	**6 1/8 inch EIA**
	Rebuncher (NC)	**4**	**81.25**	**20,15,4*2**	**3 1/8 inch EIA**
	QWR	**22**	**81.25**	**4**	**1 5/8 inch EIA**
	HWR	**102**	**162.5**	**4**	**1 5/8 inch EIA**
P2DT & CSS	**HWR**	**4** +2	**162.5**	**4**	**1 5/8 inch EIA**

RAON HPRF System (2)

Superconducting linac #3 (SCL3)

Superconducting linac #2 (SCL2)

QWR (22 sets) | **HWR-A** (26 sets) | **HWR-B** (76 sets) | **SSR1** (69 sets) | **SSR2** (144 sets)



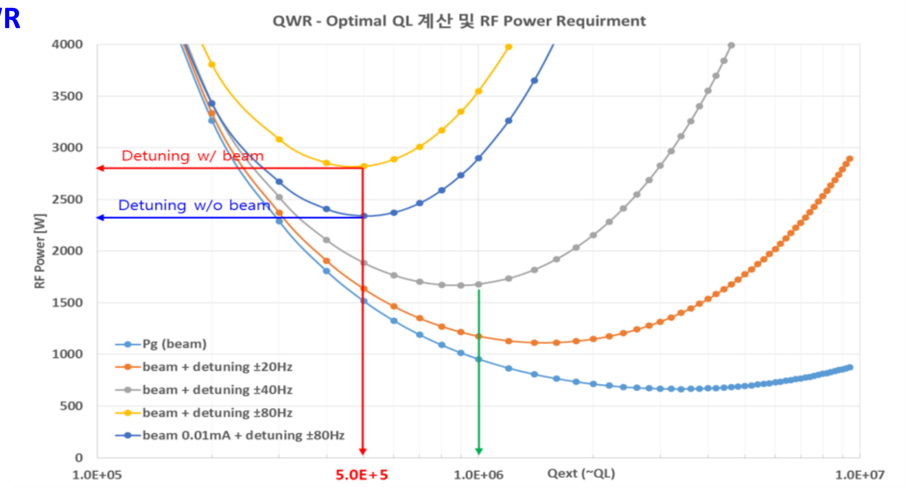
RF power requirements (Optimal loaded-Q)

$$P_g = \frac{1+\beta}{4\beta}\frac{V_{acc}^2}{\frac{R_{sh}}{Q}Q_L}\left\{\left(1+\frac{R_{sh}}{Q}Q_L\frac{I_b}{V_{acc}}\cos\phi_b\right)^2+\left(2Q_L\frac{\omega-\omega_0}{\omega_0}+\frac{R_{sh}}{Q}Q_L\frac{I_b}{V_{acc}}\sin\phi_b\right)^2\right\}$$

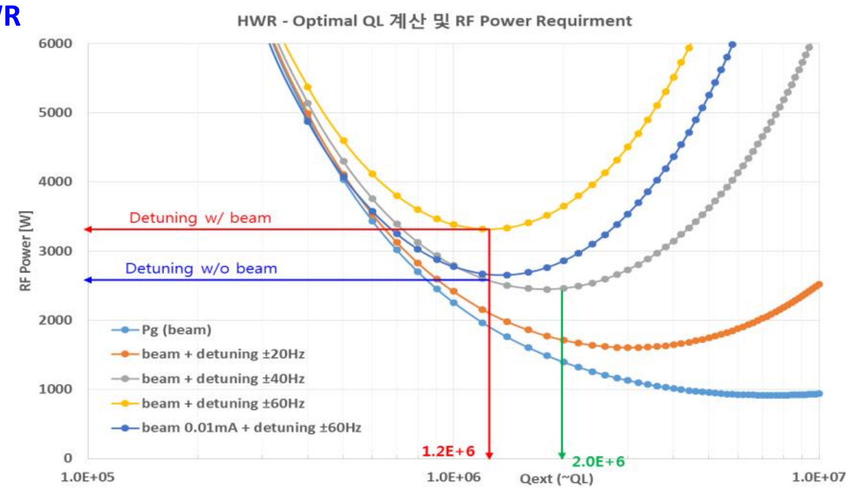
In our case, the RF system will operate in almost full reflection.

- low beam current
- Cavity detuning (df/dp, LFD, pressure fluctuation at LHe …)
- cavity’s bandwidth (±60 ~ 80 Hz)

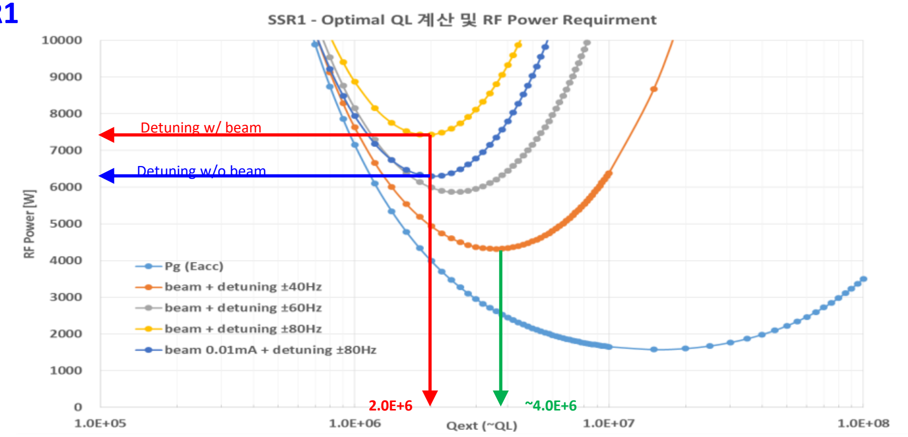
QWR



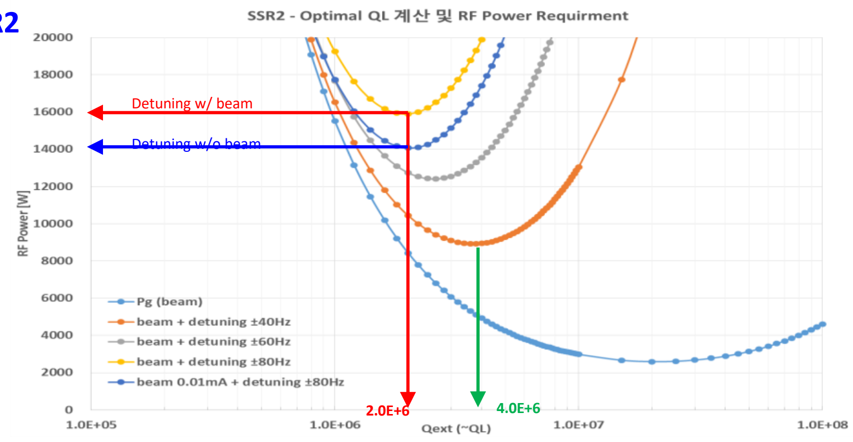
HWR



SSR1



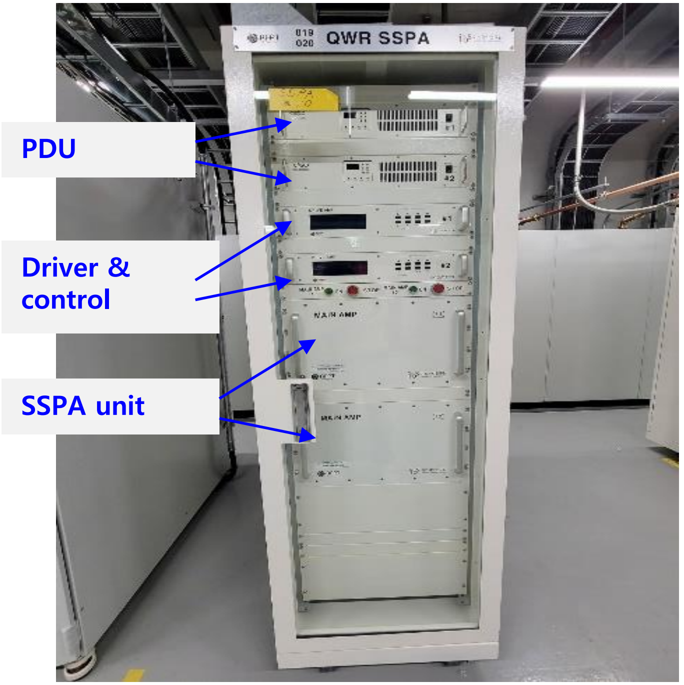
SSR2



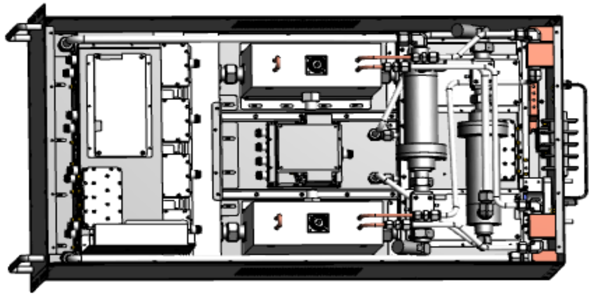
4 kW SSPA for SCL3 (QWR, HWR) - 운영중

- **QWR (81.25MHz 4kW) 22 sets, HWR (162.5MHz 4kW) 102 sets**
- **SSPA specifications**
  - two sets of 4kW SSPA / 1 rack
  - Gain : > 66 dB (Gain linearity : <6dB (-20dB range), <3dB (-10dB range)
  - Harmonics < -30dB,   Spurious < -60dB
  - Phase/Power stability : < 1 deg. <1% (within ±1 degree C of cooling water temp.)
  - Efficiency : > 50% (AC to RF, -3dB from max. RF)
  - Cooling (1 line / 1 rack) : Deionized. (operating temp. 22 degree C), flow < 3 m3/h (per 1 rack), Pressur

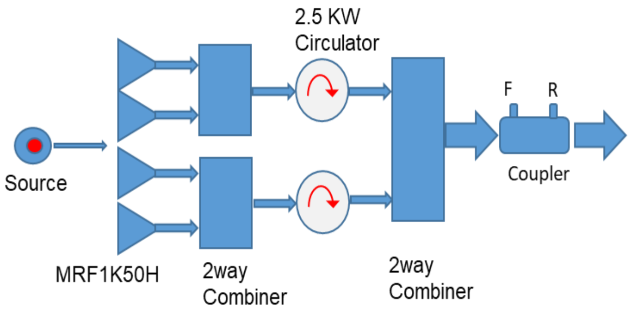
SSPA for SCL3 (128 sets)

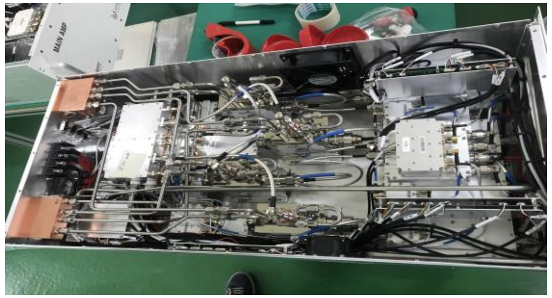


Two sets of 4kW SSPA / 1 rack

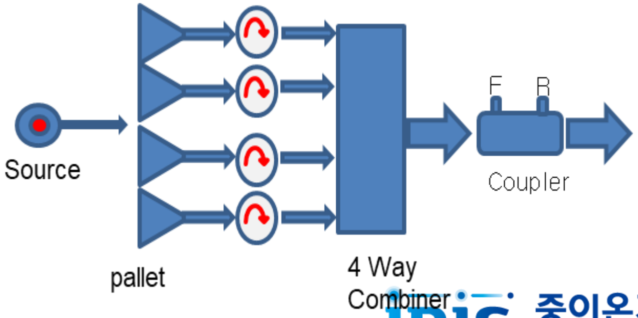


81.25MHz 4kW PA unit



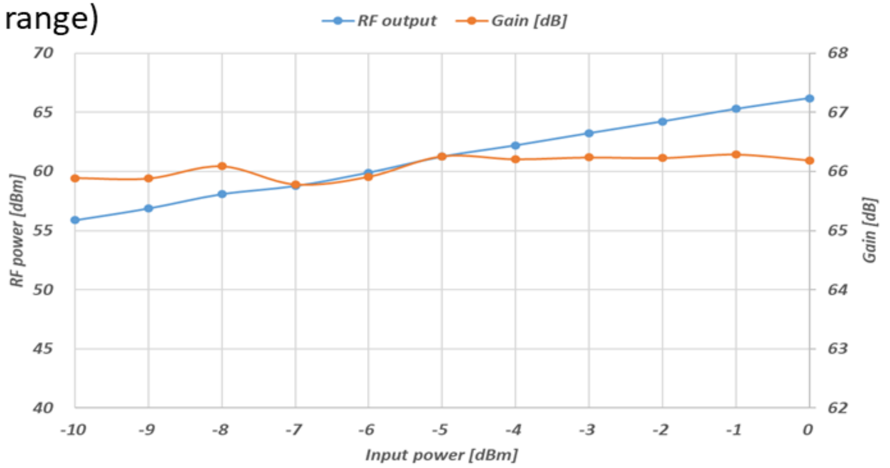


162.5MHz 4kW PA unit

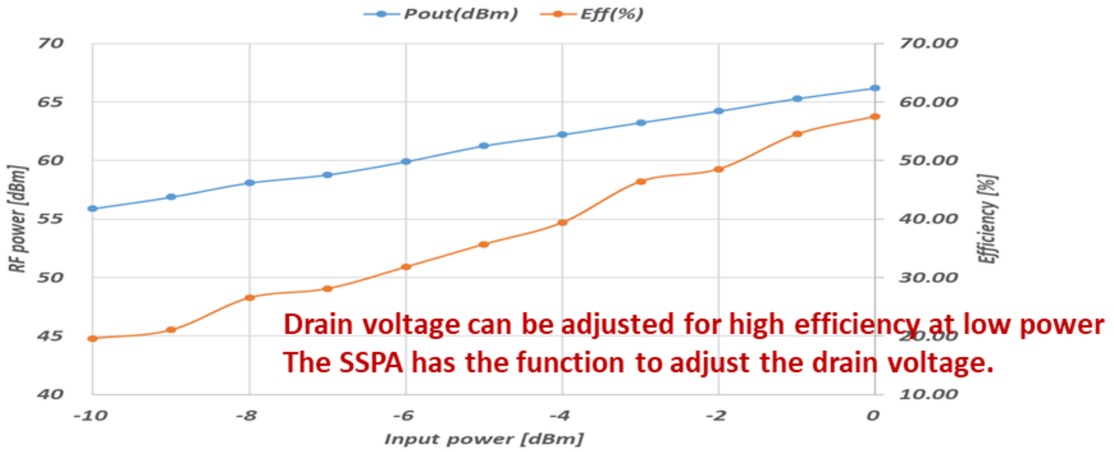


4 kW SSPA for SCL3 (QWR, HWR)

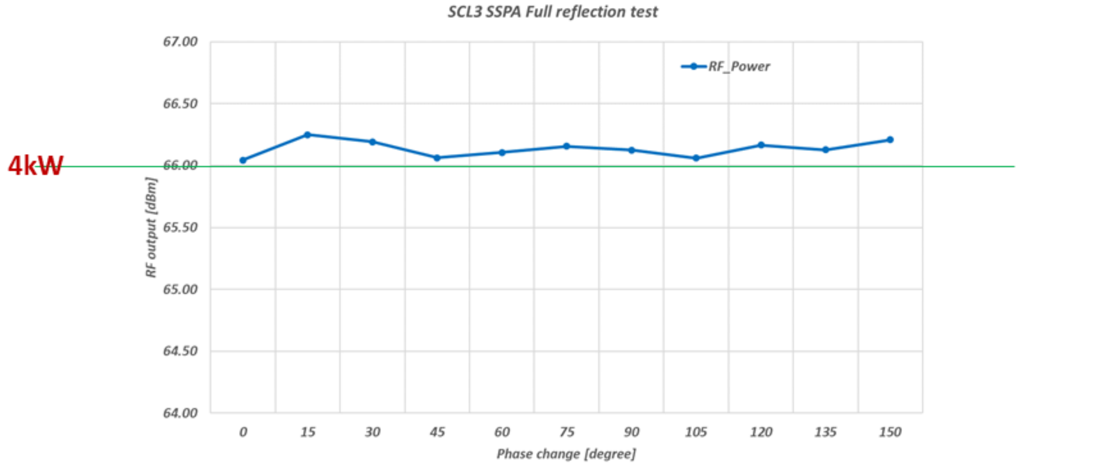
1) RF output (4kW), **Gain** (>66dB), **Gain linearity** (<6dB (-20dB range), <3dB (-10dB range)



2) Efficiency (> 50% (AC to RF, -3dB from max. RF))

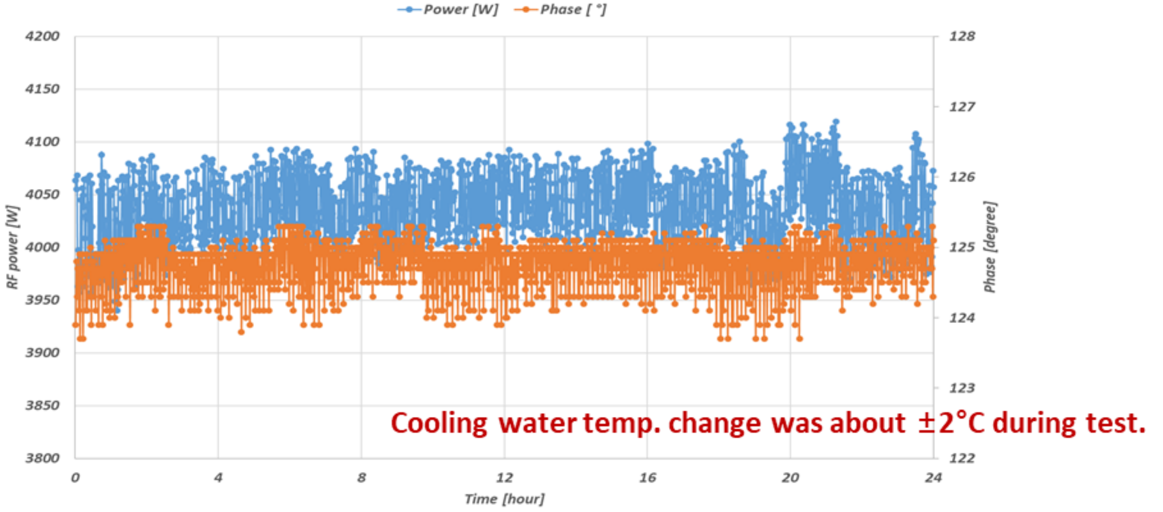


3) Full reflection test (stable output at any phase)



Measure RF power while changing reflection phase with a movable short

4) Long-term power test < 1 deg. <1% (within ±1 degree C of water temp.)

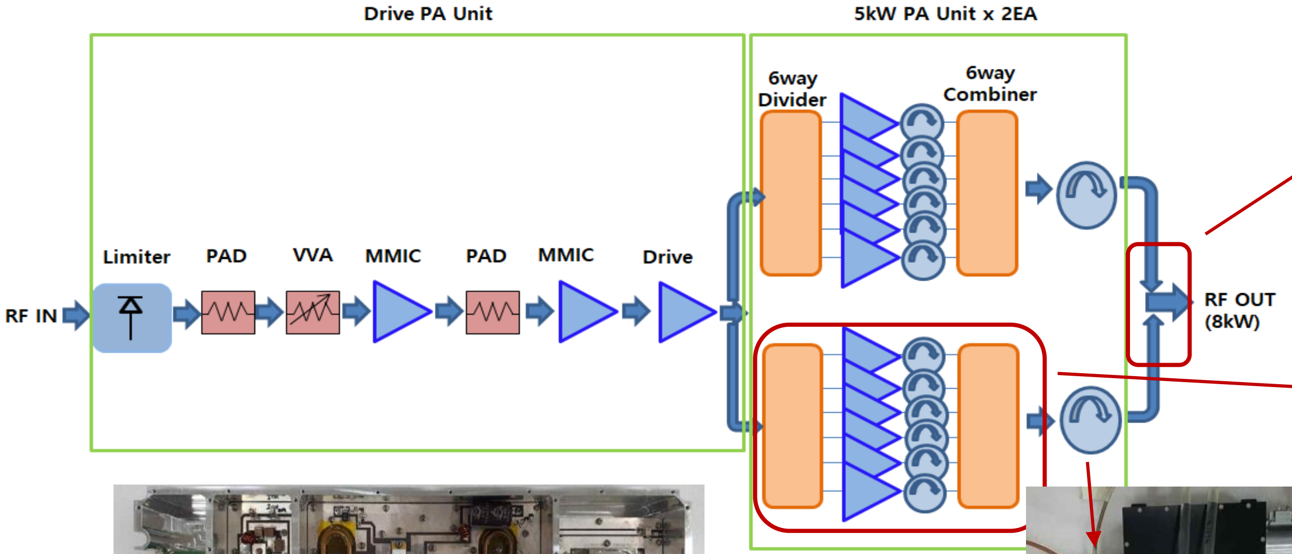


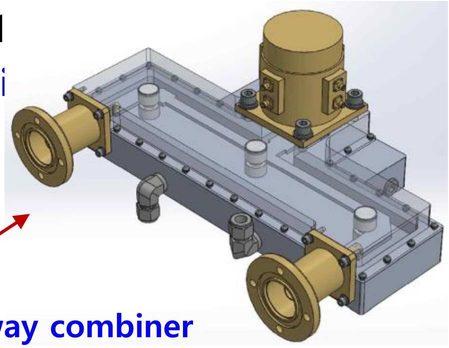
iRIS 중이온가속기연구소 Institute for Rare Isotope Science

8 kW SSPA for SSR1

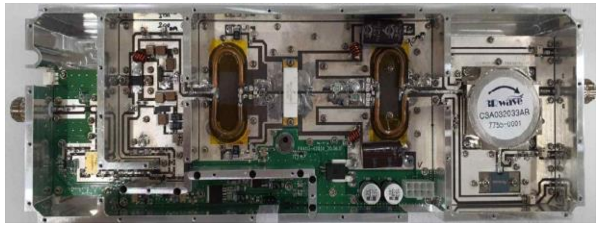

SSPA for SSR1 (69 sets)

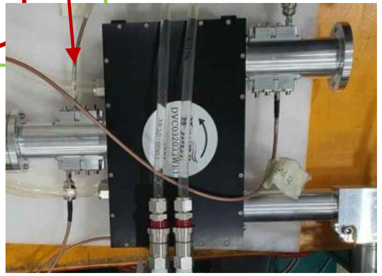
- **SSR1 (325MHz 8kW) 69 sets (2020.04 ~ 2021.11)**
- **SSPA specifications**
  - RF power : > 8kW at 0 dBm input (Gain linearity : <6dB (-20dB range), <3dB (-10dB range))
  - Harmonics < -30dB, Spurious < -70dB
  - Phase/Power stability : < 3 deg. < 5% (within ±1 degree C of cooling water temp.)
  - Efficiency : > 45% (AC to RF, -3dB from max. RF)
  - Cooling (1 line / 1 rack) : Deionized, flow < 6 m3/h (per 1 rack), Pressure 5~1
- **RF performance test , Full reflection test (Movable shorter), long-term stabi**

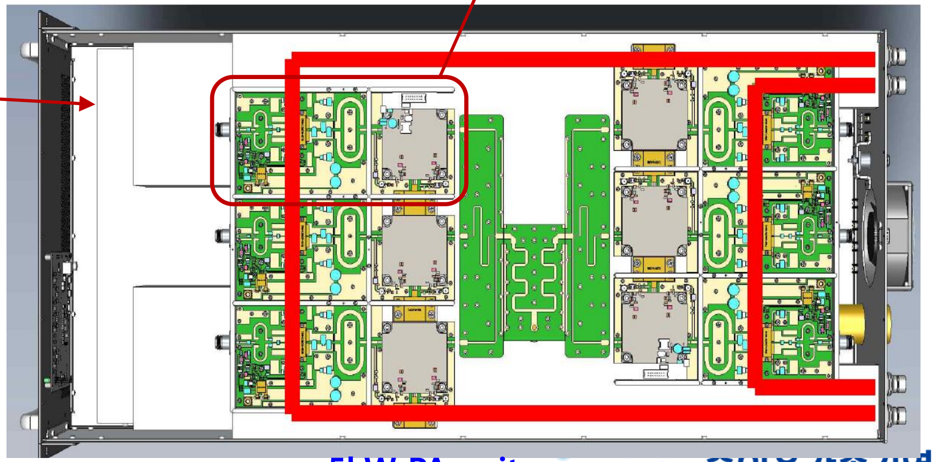



2-way combiner

1kW pallet (BLF188XR)

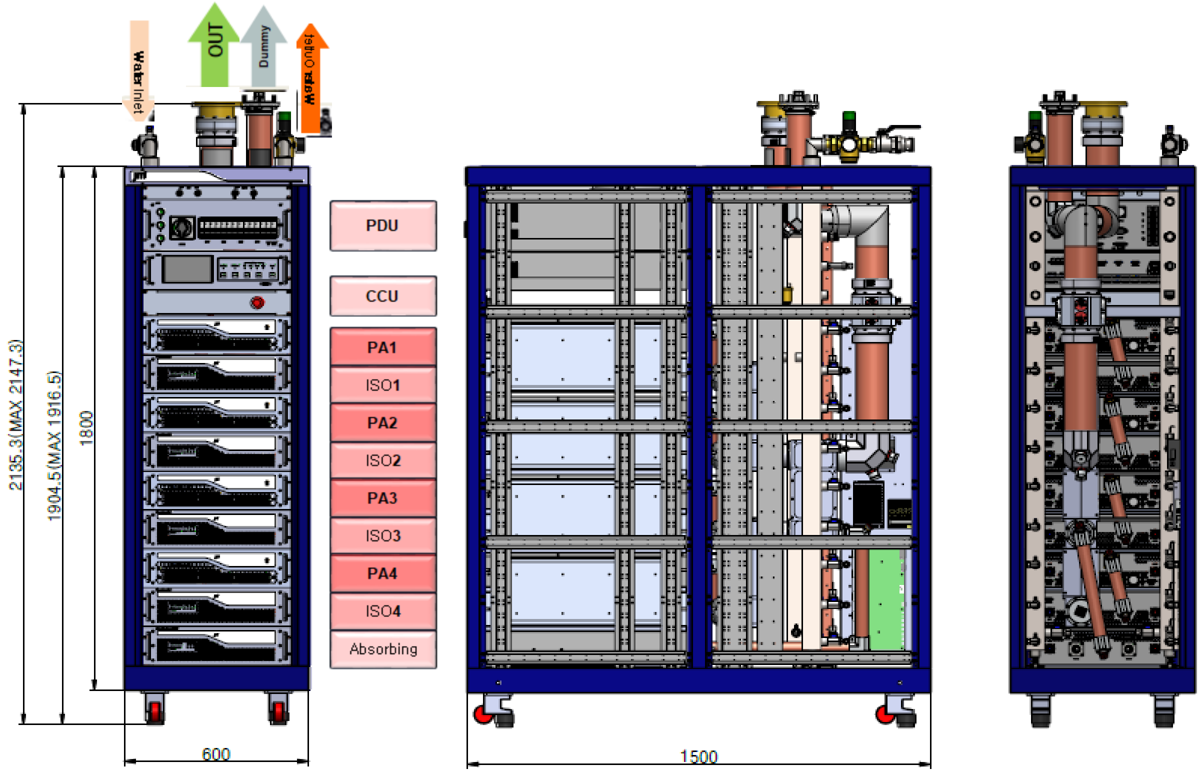

Drive amp. unit


5kW circulator

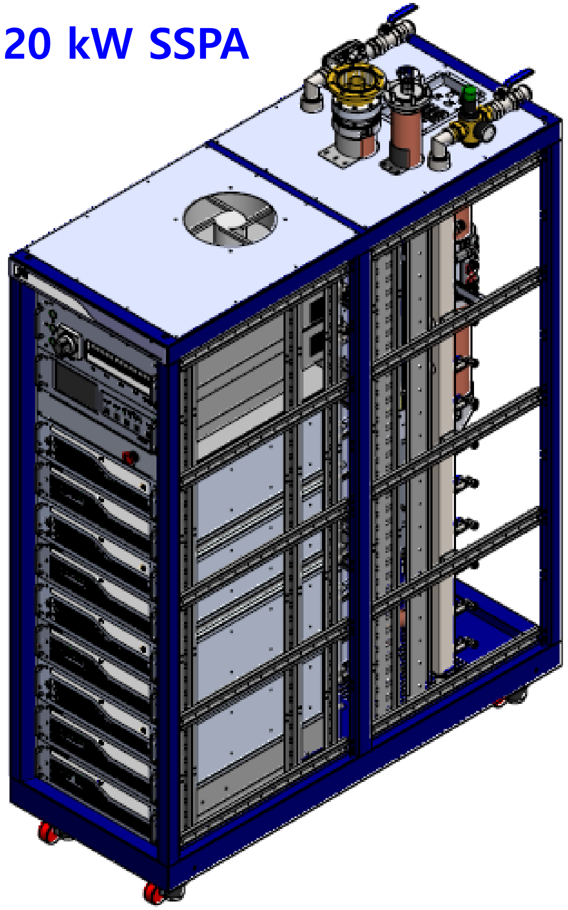

5kW PA unit

325 MHz, 20 kW SSPA for SSR2 (1)

- **SSR2 (325MHz 20kW) 144 sets -> 6 SSPAs for a CM (6 cavities) prototype were fabricated before mass production.**
- **SSPA specification**
  - RF power : > 20kW at 0 dBm input (Gain linearity : <6dB (-20dB range), <3dB (-10dB range))
  - Harmonics < -30dB, Spurious < -70dB
  - Phase/Power stability : < 3 deg. < 5% (within ±1 degree C of cooling water temp.)
  - Efficiency : > 50% (AC to RF, -3dB from max. RF)
  - Cooling (1 line / 1 rack) : Deionized, flow < 8 m3/h (per 1 rack), Pressure 5~10 bar
- **RF performance test , Full reflection test (Movable shorter), long-term stability test**



20 kW SSPA

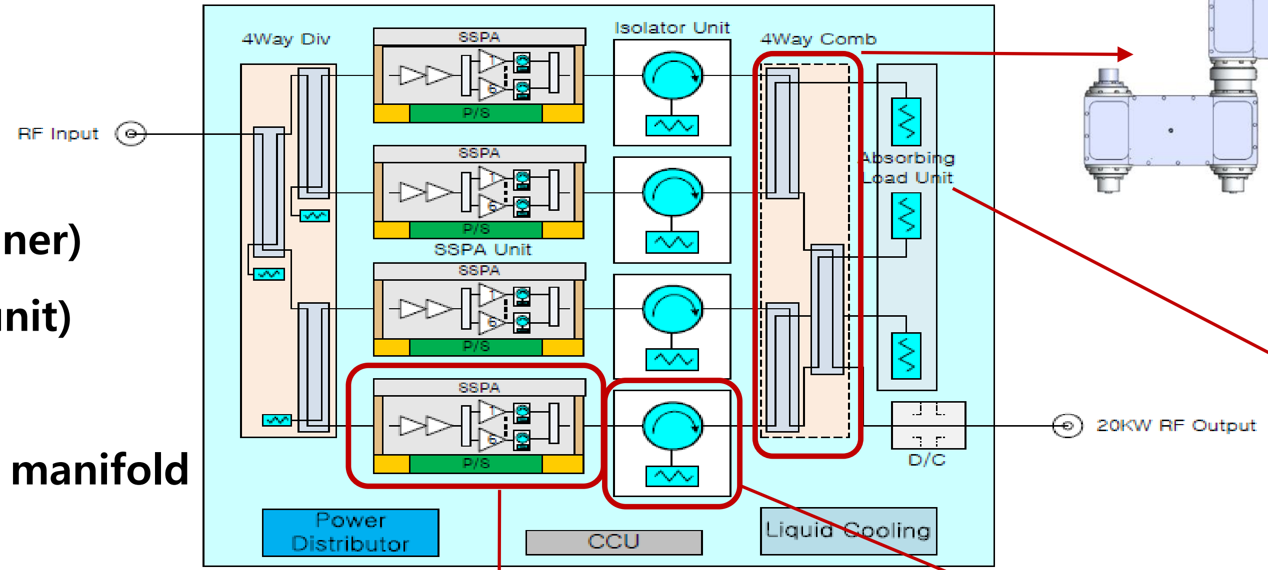


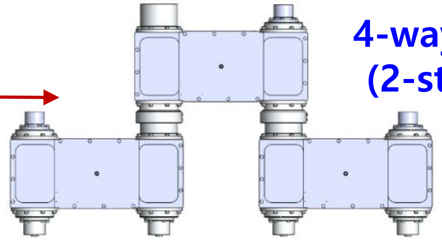
IRIS Institute for Rare Isotope Science

325 MHz, 20 kW SSPA for SSR2 (2)

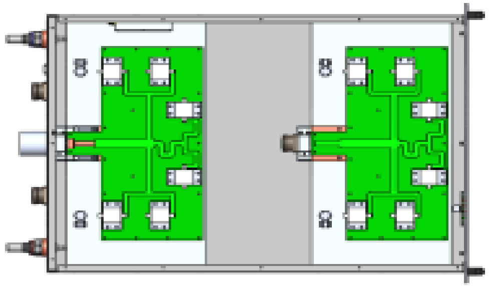
- 4 x 5kW PA unit
- 4 x 5kW Circulator unit
- 4-way combiner
- Absorbing unit (for combiner)
- PDU (Power distribution unit)
- CCU (control unit)
- inlet/outlet Cooling water manifold

20 kW SSPA



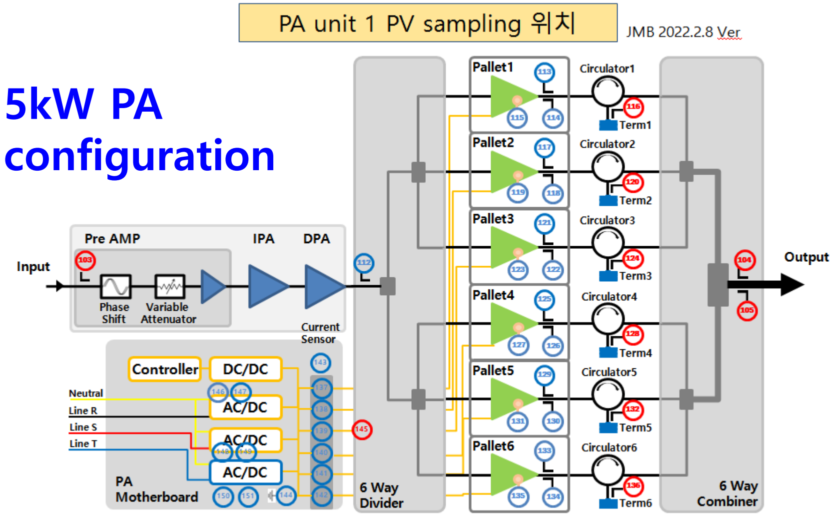


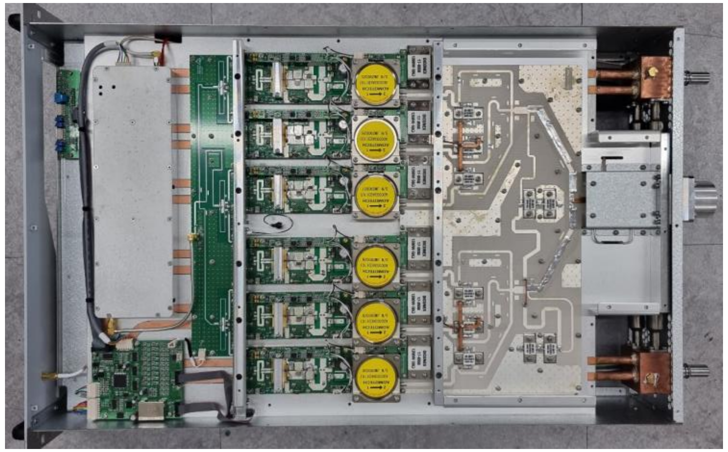
4-way combiner (2-stage hybrid combiner)



Absorbing load unit

5kW PA configuration



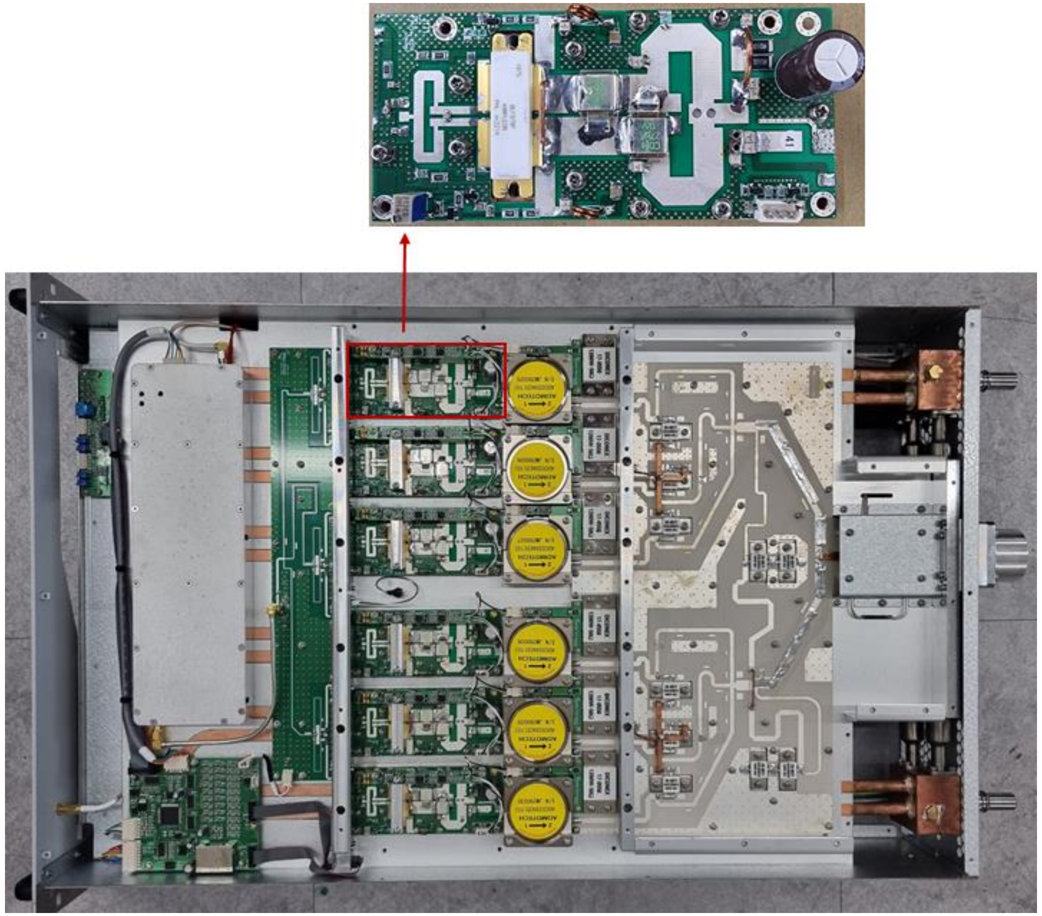


5kW PA unit

5kW Circulator unit

325 MHz, 20 kW SSPA for SSR2 (3)

- **Drive amplifier**
- **6-way divider**
- **6 x 1kW pallet (circulator)**
- **6-way combiner**
- **3 x commercial AC/DC power supply pack**



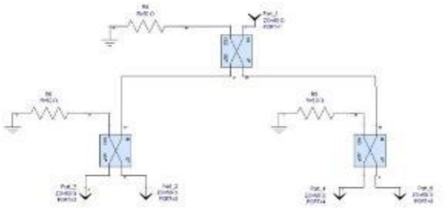
Frequency range	**325MHz ± 1MHz**
Class operation	AB
Transistor	LDMOS FET (BLF978)
Operation mode	CW & Pulse
Input/output Impedance	50 Ohms
Input return loss	≥ 20 dB
Input power	0 dBm (Max. 2 dBm)
Output power	≥ 5 kW
Harmonics	< -30 dBc
Spurious	< -60 dBc (carrier offset : > 100 kHz)
RF input connector	N-type
RF output connector	1-5/8” un-flanged
Gain linearity	< 2 dB (-10 dB range)
	< 6 dB (-20 dB range)

325 MHz, 20 kW SSPA for SSR2 (4)

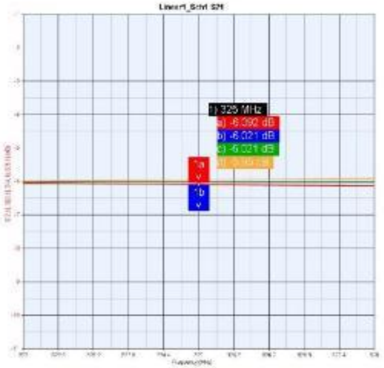
COM-TECH

- **2-stage hybrid combiner**
- **Circuit, Electrical and Thermal simulation was performed.**

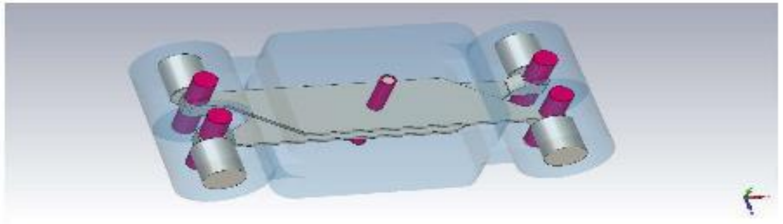
Schematic



Results



The overall frequency responses for the 4 ways are simulated based on the 3D EM model of the single Hybrid Coupler. The deviations from the ideal value will be < 0.1 dB (Typ. < 0.05 dB)



4-Ways Multicoupler 325MHz: Electrical and Thermal Simulations

Breakdown Margins

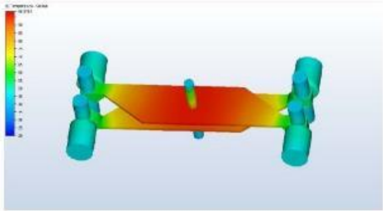
The E-Filed distribution is simulated for 1 Watt Peak Power; the maximum E-Field is worth 1778.12 V/m.
The Arc Resistance for air has been conservatively assumed = 1.6 MV/m.

$P_{Peak} = \left(\frac{E_{Breakdown}}{E_{EM@1W_{Peak}}}\right)^2 = \left(\frac{1.6MV/m}{1778.12V/m}\right)^2 = 809.7\ kW$ $\quad P_{RMS} = 0.5 \cdot P_{Peak} = 404.8kW$

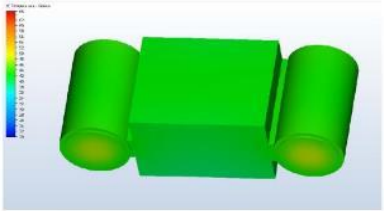
The estimated Breakdown Power is > 400 kW, which is >> 20 kW operating Power
=> The safety margins are widely met.

Thermal simulation (output Hybrid Coupler)

Input Power = 20 kW
Environment Temperature = 20 °C



Max internal temperature: 99 °C



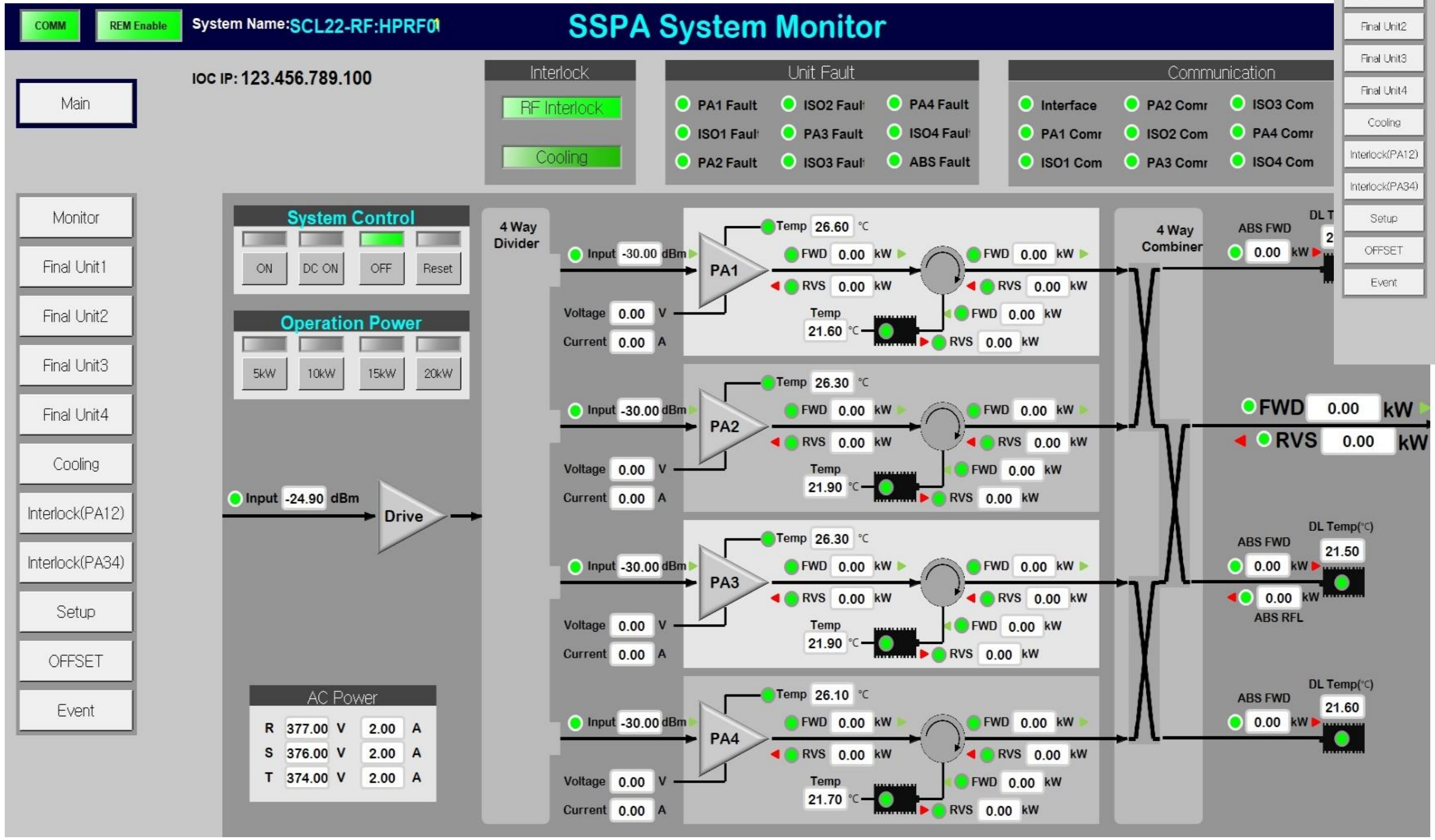
Max external body Temperature: 45 °C

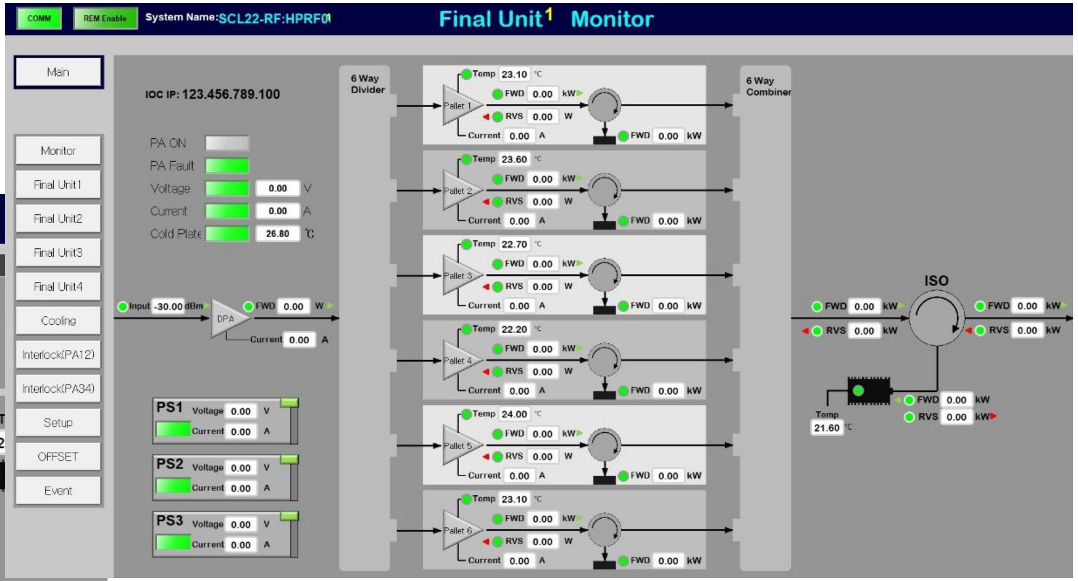
The over temperature of 25° C is compliant with the standard specific:
Max Operating Temperature (Body) = 65°C

ㅏ속기연구소
are Isotope Science

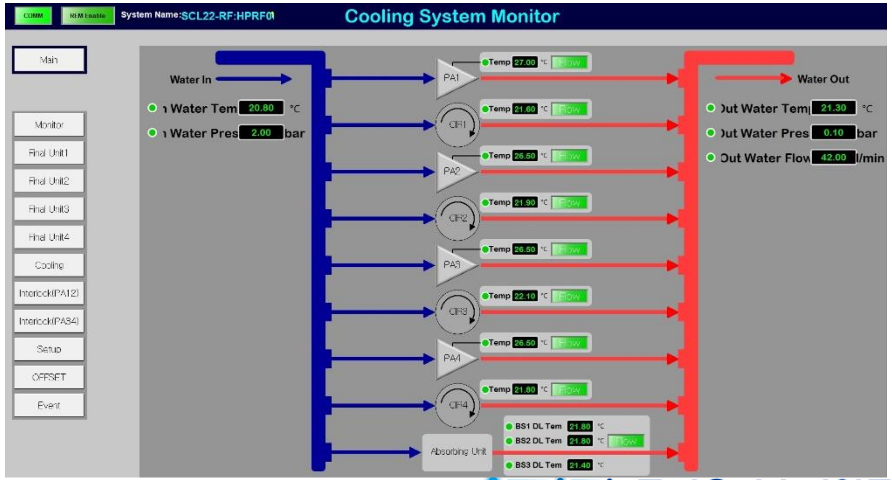
325 MHz, 20 kW SSPA for SSR2 (5)

EPICS OPI for 20kW SSPA





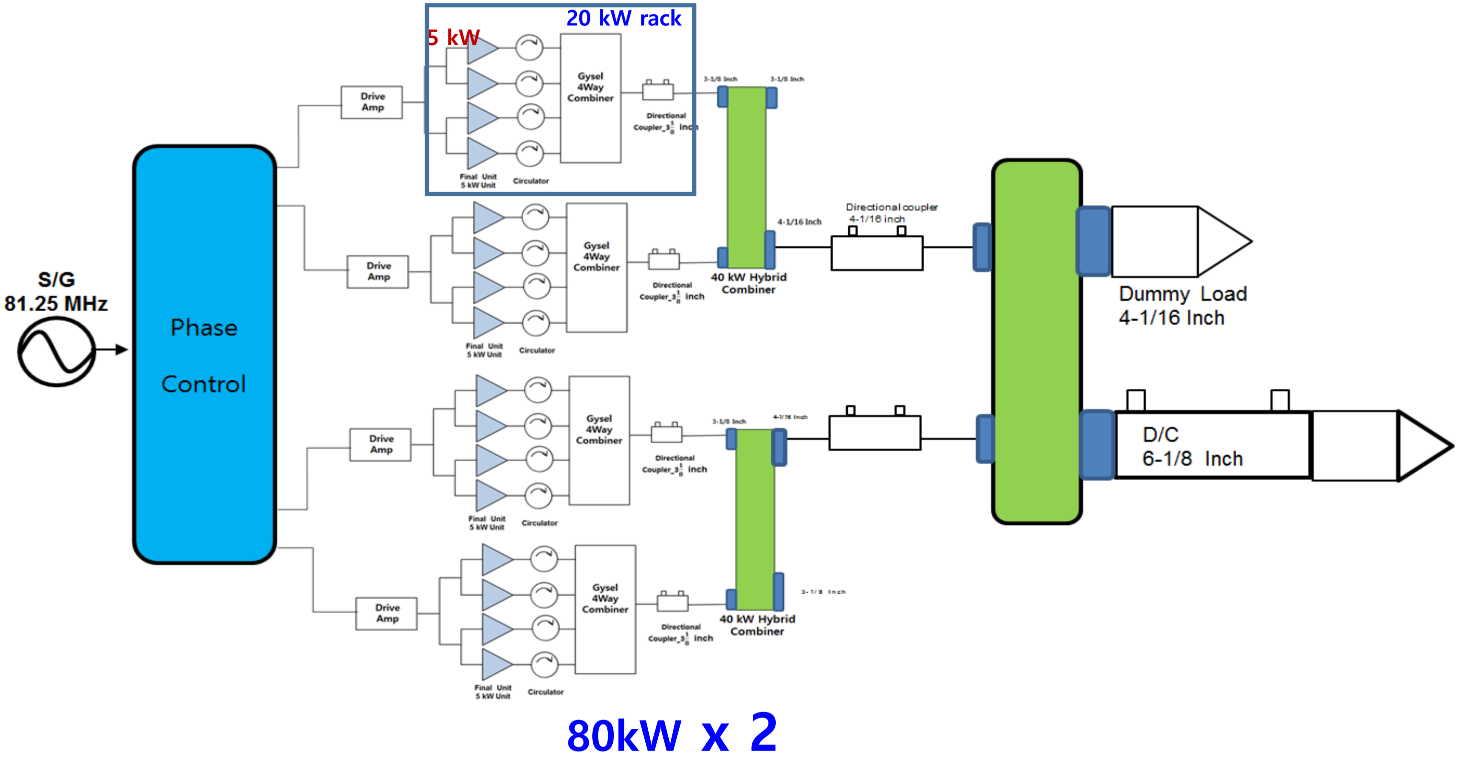
EPICS OPI for each 5kW PA

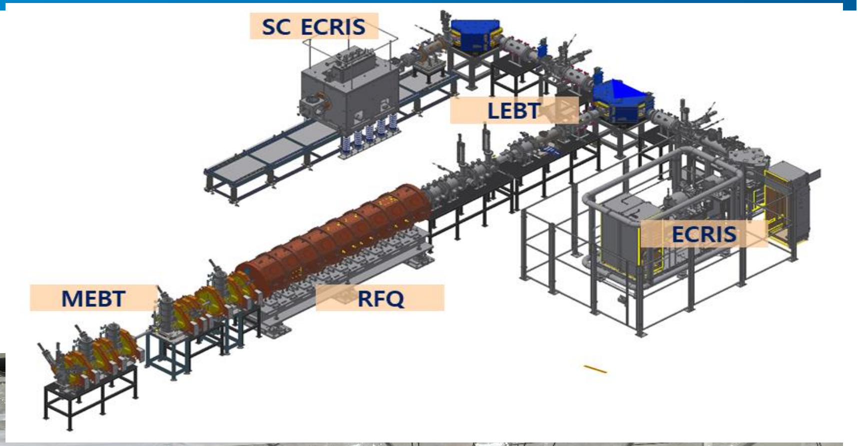


EPICS OPI for cooling water

160 kW SSPA for RFQ - 운영

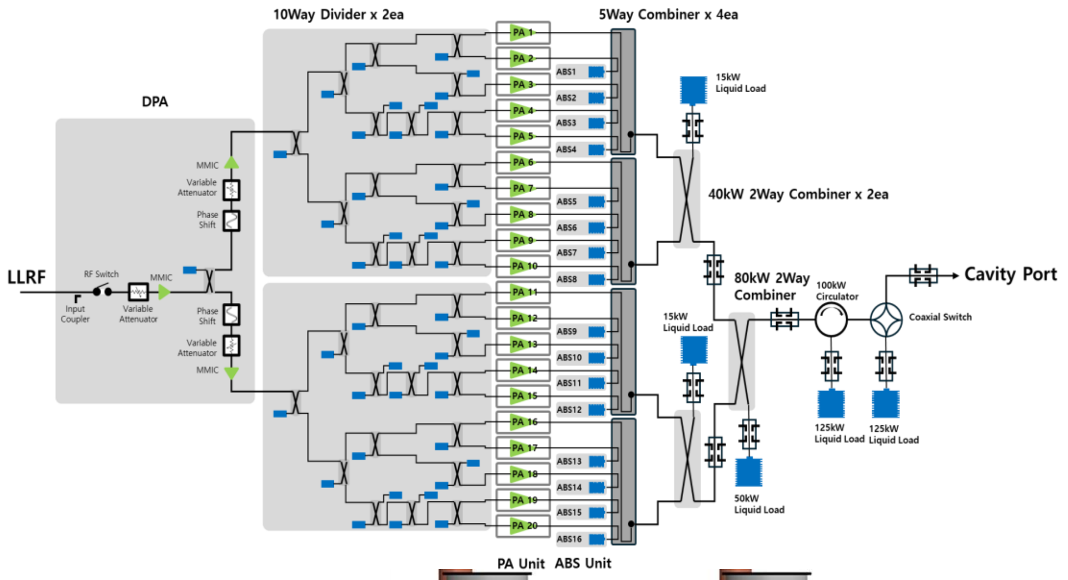
- SSPA Prototype (2015) : 81.25MHz, 160kW (80kW * 2)
- 80kW SSPA : four 20kW SSPA rack, 2-stage hybrid combiner
- 20kW (1 rack) : four 5kW PA unit, four 5kW circulator, 4-way combiner

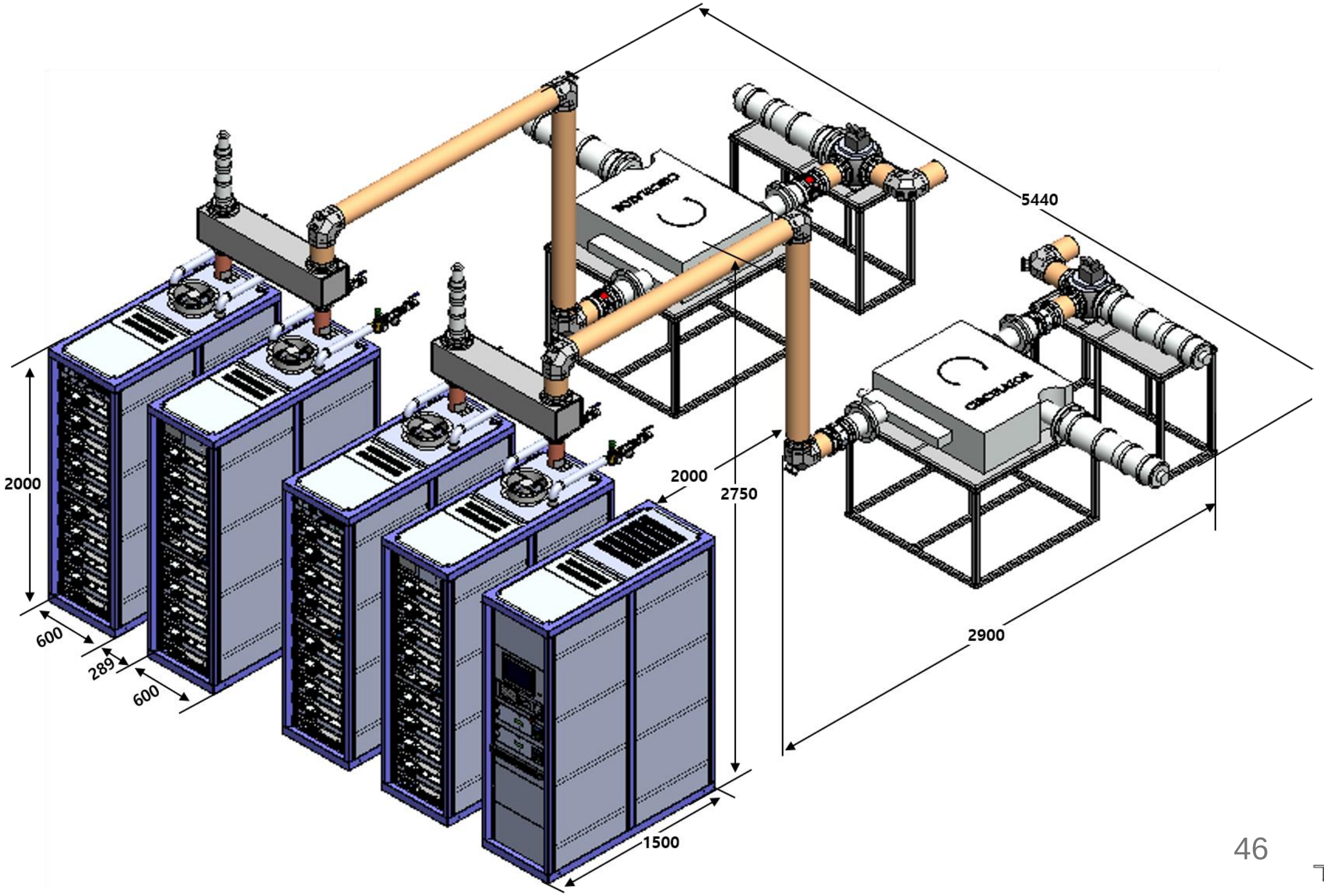


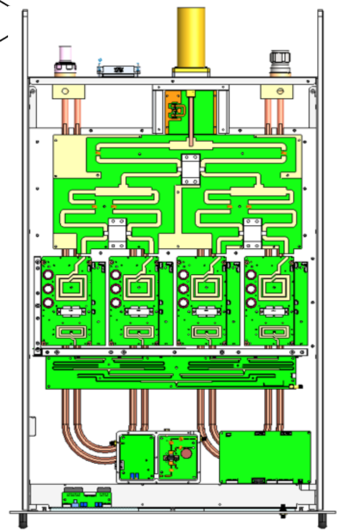


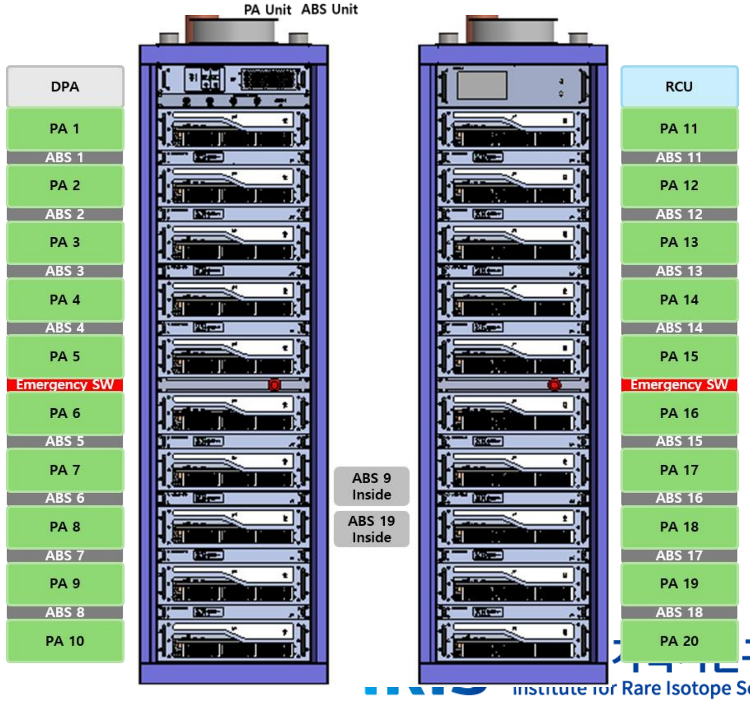
(new) 160 kW SSPA for RFQ - 제작중

- (new) SSPA 제작 (2026) : 81.25MHz, 160kW (80kW * 2)
- 80kW SSPA : two 40kW SSPA rack, hybrid combiner
- 40kW (1 rack) : ten 5kW PA unit, 10-way combiner
- High power circulator (final output)









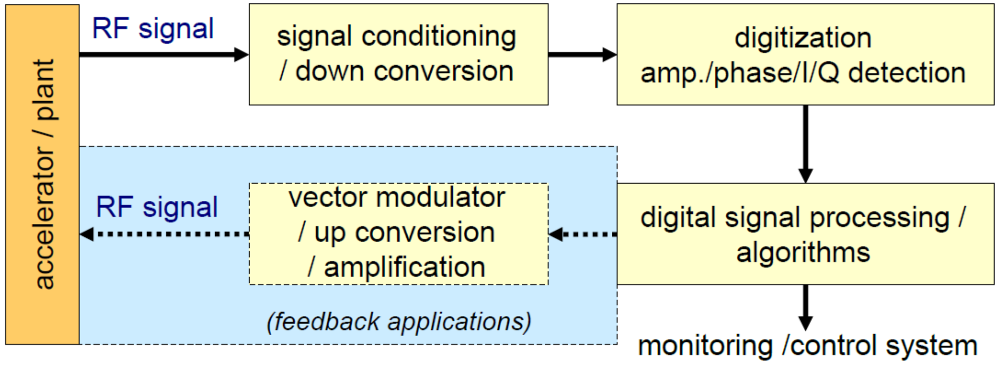
Part 03.

LLRF control system

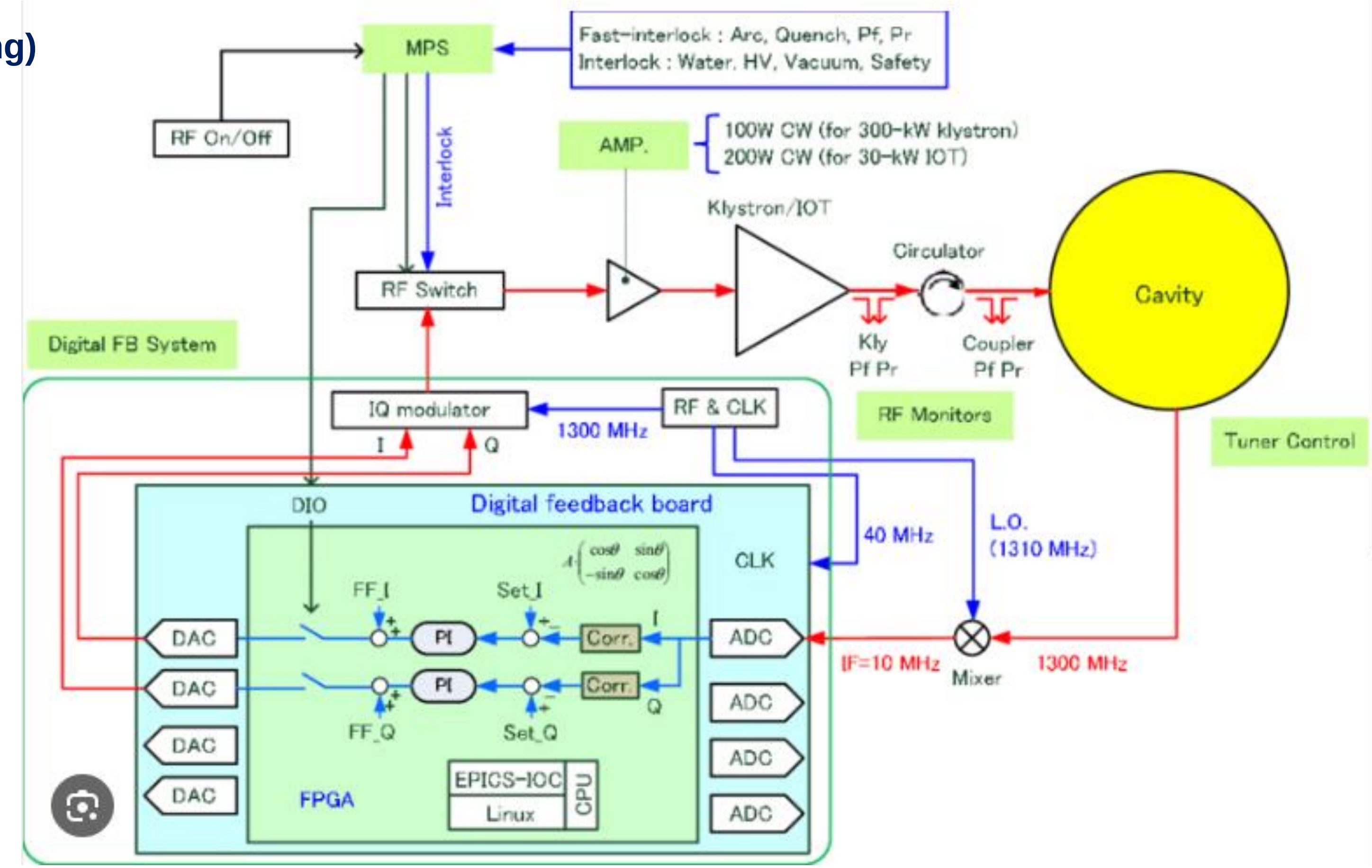
Institute for Rare Isotope Science

LLRF control system

- Low-level RF control system
  - ✓ RF generation, RF processing
  - ✓ Feedback control (amplitude, phase)
  - ✓ Resonance control (tuner control or water cooling)
  - ✓ RF interlock (Machine Protection)



LLRF looks very similar to many other applications,
e.g. diagnostics (bunch-by-bunch feedback, position monitoring, …)

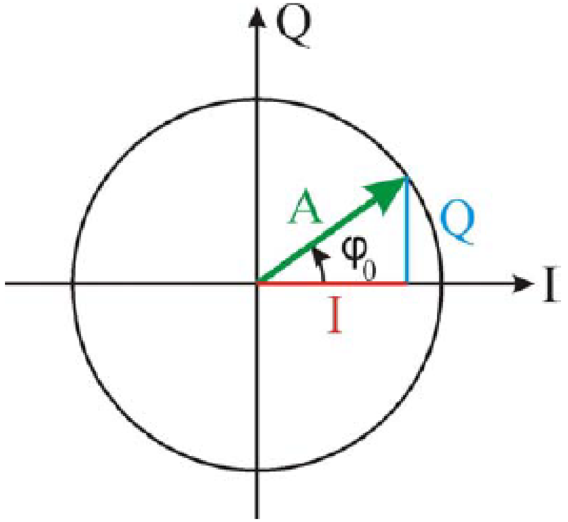


IQ sampling (1)

CAS 2007 (LLRF DSP by schilcher)

representation of any sinusoidal RF signal: phasor

(assumption: we measure the vertical component with ADC)



$$y(t) = A \cdot \sin(\omega t + \varphi_0)$$

$$y(t) = \underbrace{A\cos\varphi_0}_{=:I}\sin\omega t + \underbrace{A\sin\varphi_0}_{=:Q}\cos\omega t$$

I: in-phase component

Q: quadrature-phase component

$$y(t) = I \cdot \sin\omega t + Q \cdot \cos\omega t$$

$$I = A \cdot \cos\varphi_0 \qquad A = \sqrt{I^2 + Q^2}$$

$$Q = A \cdot \sin\varphi_0 \qquad \varphi_0 = \operatorname{atan}\left(\frac{Q}{I}\right)$$

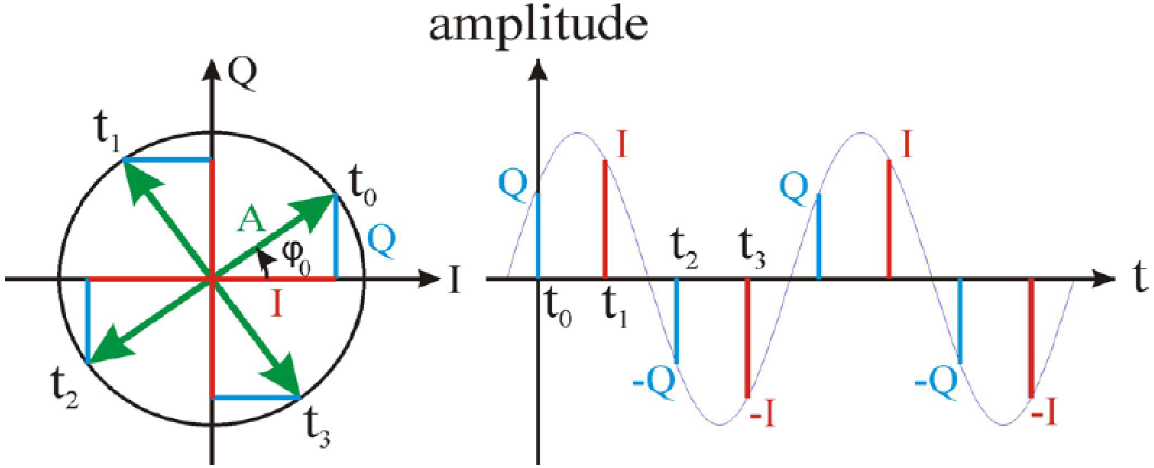
(sometimes I/Q are defined vice versa!)

definition:
positive frequencies
↔ counterclockwise rotating phasor

IQ sampling (2)

CAS 2007 (LLRF DSP by schilcher)

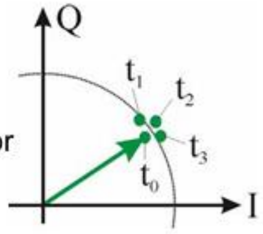
sampling of RF/IF freq.: $f_s = 4 \cdot f$ (i.e. 90° phase advance between two samples)

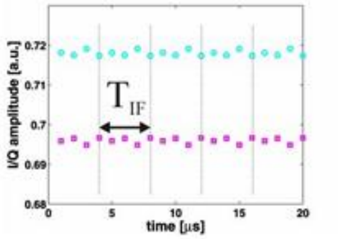


$$
\begin{aligned}
y(t) &= I \cdot \sin \omega t + Q \cdot \cos \omega t \\
I &= A \cdot \cos \varphi_0 \\
Q &= A \cdot \sin \varphi_0
\end{aligned}
\quad
\begin{aligned}
\omega t_0 = 0 : &\quad y(t_0) = Q \\
\omega t_1 = \pi/2 : &\quad y(t_1) = I \\
\omega t_2 = \pi : &\quad y(t_2) = -Q \\
\omega t_3 = 3\pi/2 : &\quad y(t_3) = -I
\end{aligned}
$$

- DC offsets of carrier frequency
- samples are not exactly 90° apart (e.g. due to ADC clock jitter)
  ➡ ripple on I/Q values with freq. of carrier (e.g. f_{IF})

rotated vector





IQ sampling (3) (Non-IQ)

CAS 2007 (LLRF DSP by schilcher)

choose sampling frequency f_S and IF frequency f_{IF} such that:

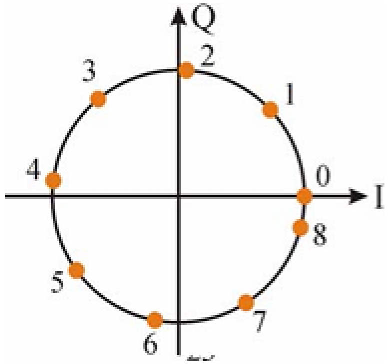
$$N \cdot T_s = M \cdot T_{IF} \qquad f_s = \frac{N}{M} \cdot f_{IF}$$

N, M: integers
N samples in M IF periods

➡ phase advance between two samples: $\Delta\varphi = \omega_{IF} T_s = 2\pi \frac{T_s}{T_{IF}} = 2\pi \frac{M}{N}$

➡ sampling "whole" IF sinusoidal signal if M, N are properly chosen

example: M=3 (IF periods), N=25



$$\begin{aligned}
y_0 &= I \cdot \sin\varphi_0 + Q \cdot \cos\varphi_0 \\
y_1 &= I \cdot \sin\varphi_1 + Q \cdot \cos\varphi_1 \\
y_2 &= I \cdot \sin\varphi_2 + Q \cdot \cos\varphi_2 \\
&\dots \\
y_{(N-1)} &= I \cdot \sin\varphi_{(N-1)} + Q \cdot \cos\varphi_{(N-1)}
\end{aligned}$$

where $\varphi_i = i \cdot \Delta\varphi = i \cdot 2\pi \frac{M}{N}$

➡ overestimated system of linear equations

➡ can be solved by least mean square algorithm

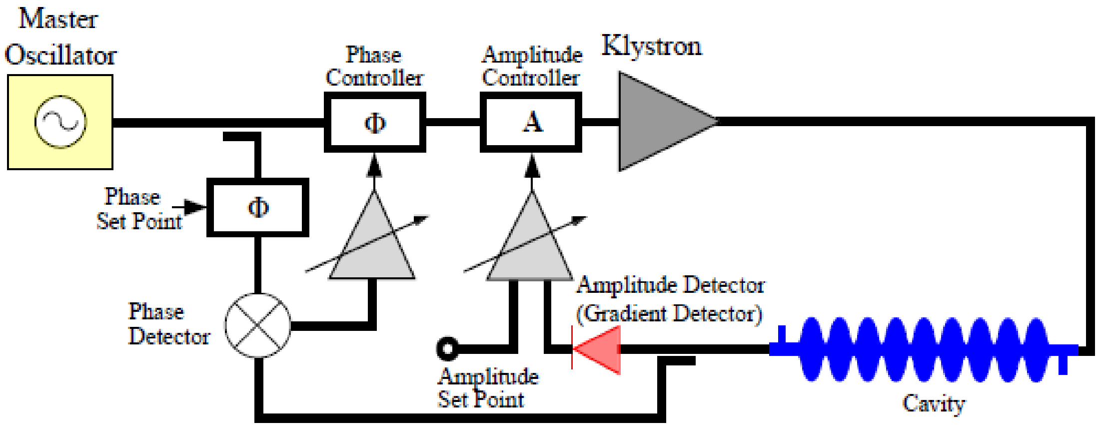
➡
$$I = \frac{2}{N} \cdot \sum_{i=0}^{N-1} y_i \cdot \sin(i \cdot \Delta\varphi)$$
$$Q = \frac{2}{N} \cdot \sum_{i=0}^{N-1} y_i \cdot \cos(i \cdot \Delta\varphi)$$

if $N \cdot T_s = M \cdot T_{IF}$
(sin and cos can be pre-calculated and stored in look-up tables)

$$\varphi_i = i \cdot \Delta\varphi = i \cdot 2\pi \frac{M}{N}$$

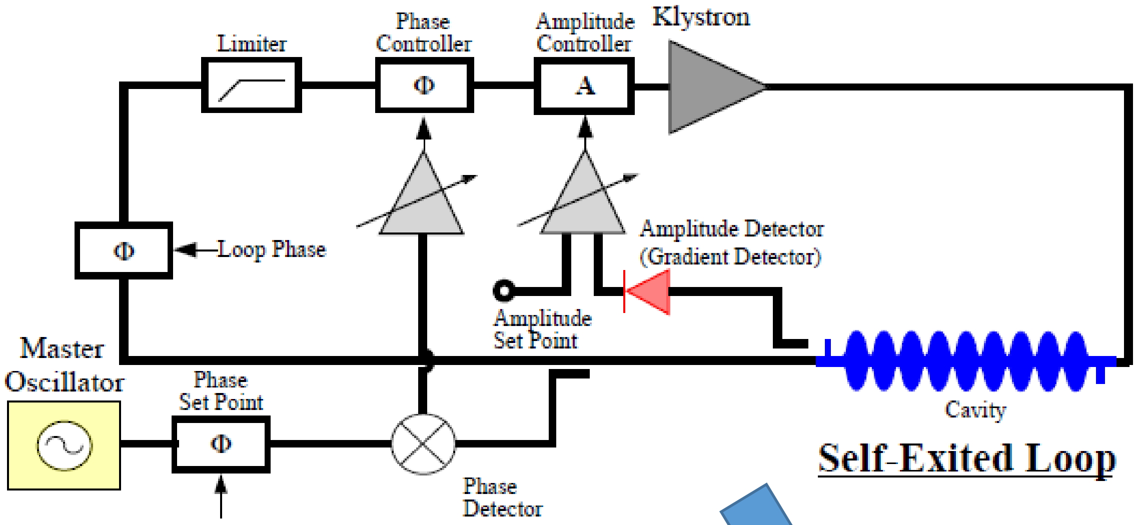
SEL (Self-excited loop)

- suitable for High QL cavities
- Resonant frequency can be found easily
- Automatic turn-on process with a lot of SRF cavities
- Good for Large Lorentz detuning, high microphonics



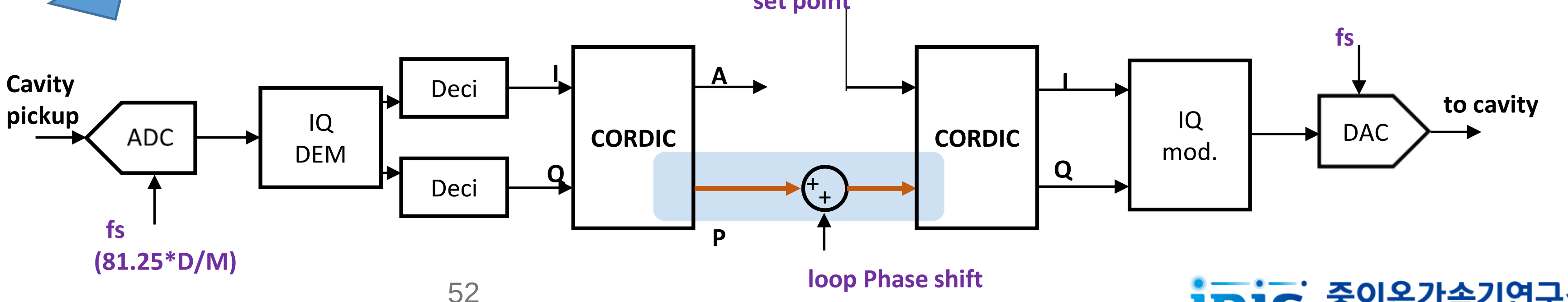
"Driven" Feedback

GDR (Generator-driven resonator)

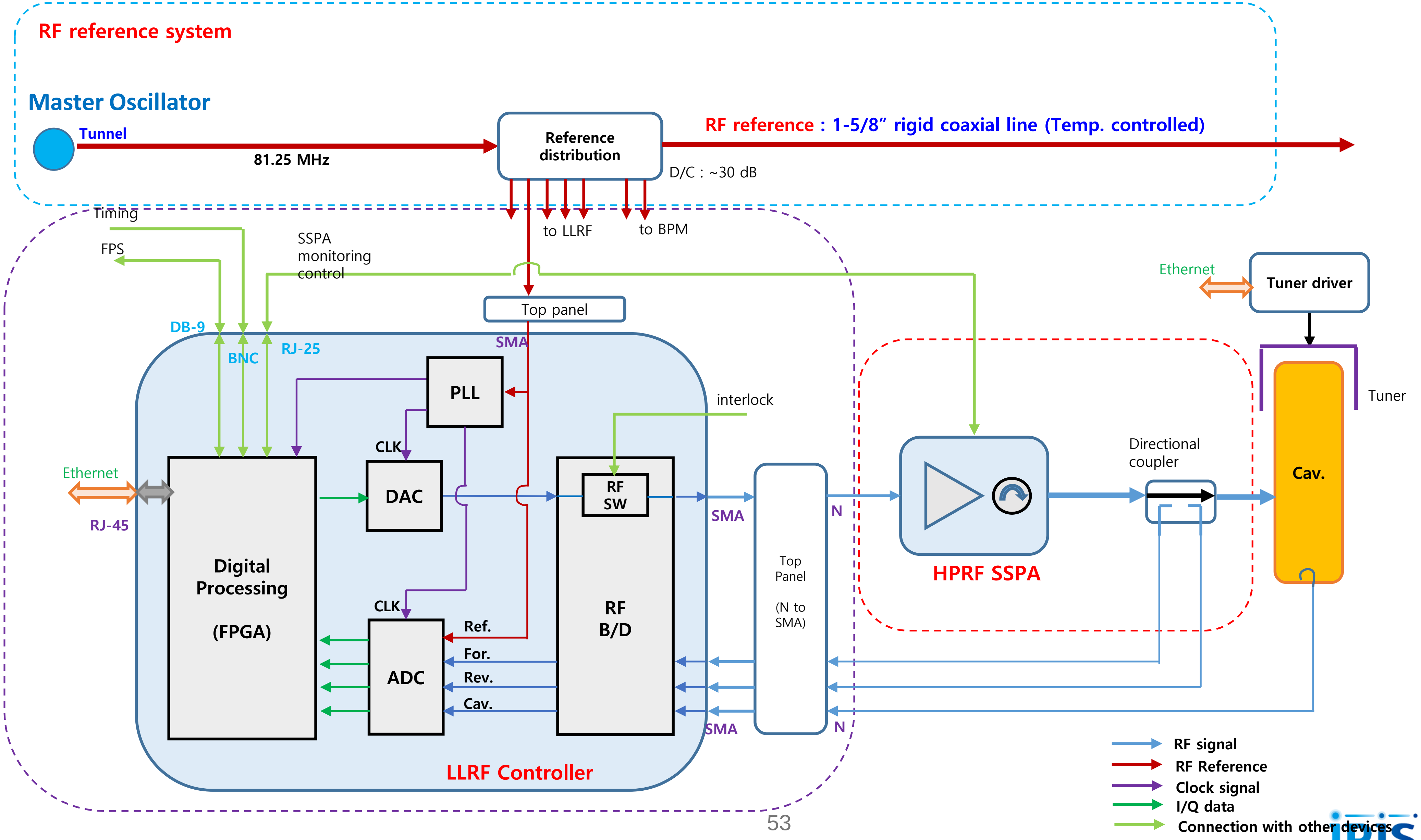


Self-Exited Loop

Digital SEL 구현



Block diagram for RAON RF system

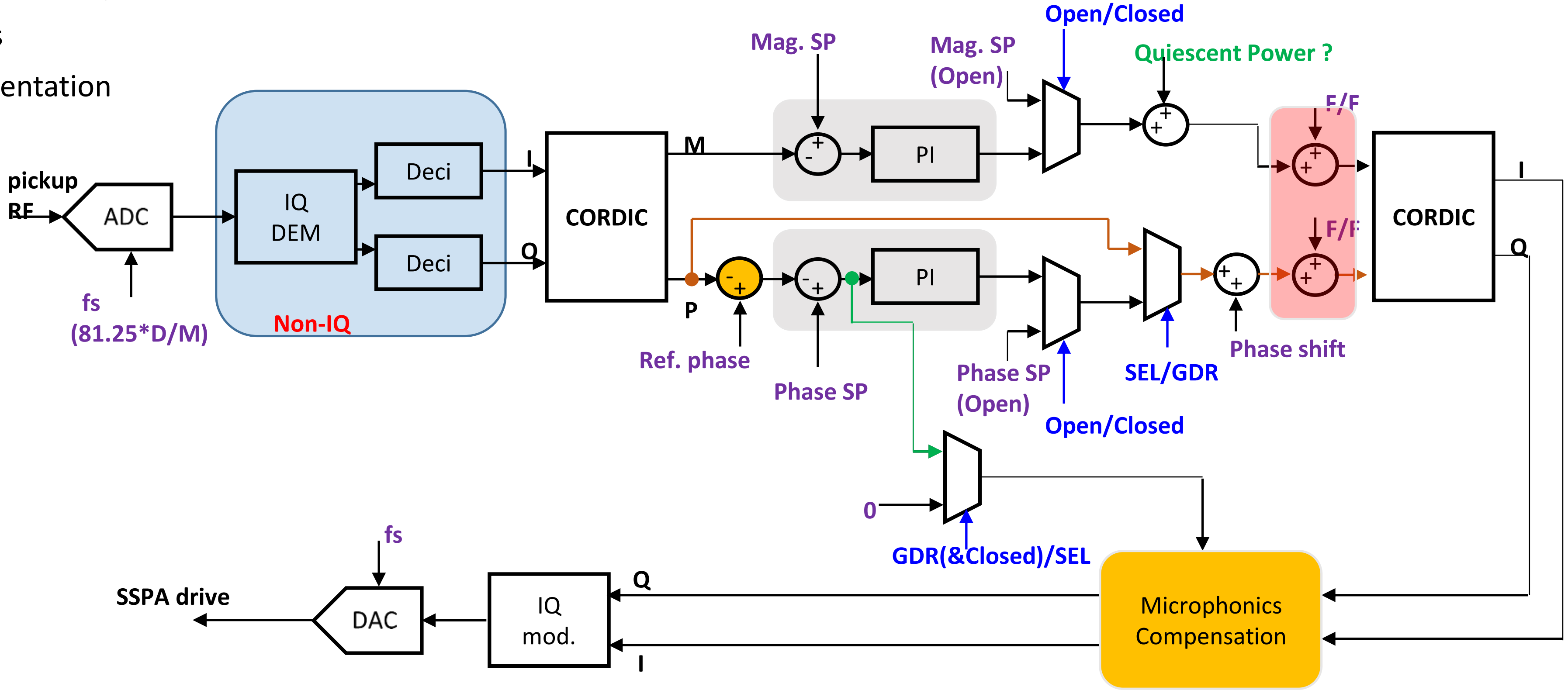


iRIS 중이온가속기연구소 Institute for Rare Isotope Science

LLRF control system for RAON

- **Stability requirement : 1%, 1° (peak to peak)**
- **LLRF features**

  - RF direct sampling (81.25 / 162.5 / 325 MHz)
  - Non-IQ sampling (Fs)
    : shifts aliases from fundamental (digitally filtered)
    : CIC filter : 31 (rejects harmonics <-30 dBc)
  - Digital SEL : Automatic turn-on process
    : Start-up algorithm implementation
  - PI control (Amplitude / Phase)
  - Latency



Feedback control (amplitude, phase)

- Requirements
  - Amplitude: <± 1 %
  - Phase: <± 1 °

Resonance control

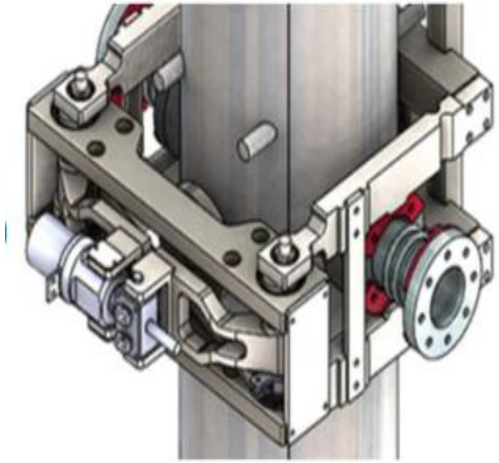
Cavity 공진주파수 에러 (위상 변화 측정)

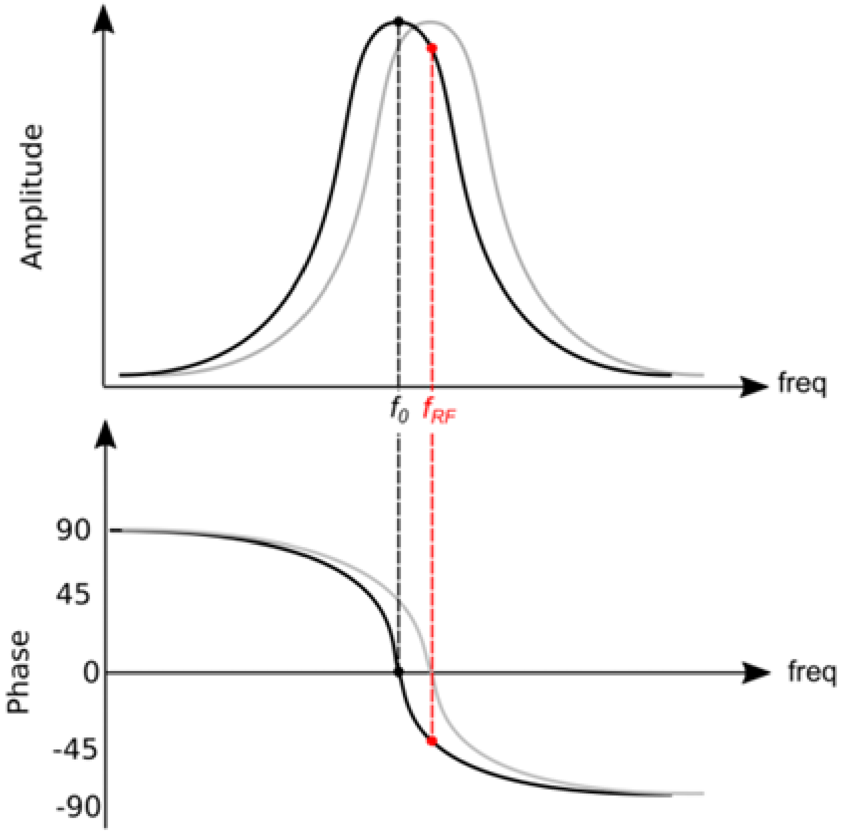
$$H(j\omega) = \frac{1}{1 + j2Q_L \frac{\omega - \omega_0}{\omega_0}} \qquad H(j\omega) = \frac{1}{1 + j2Q_L \frac{\Delta f}{f_0}}$$

$$\angle H = -\tan^{-1}\left(2Q_L \frac{\Delta f}{f_0}\right) \qquad \phi = -\tan^{-1}\left(2Q_L \frac{\Delta f}{f_0}\right)$$

$$\Delta f = -\frac{f_0}{2Q_L}\tan\phi \approx -\frac{f_0}{2Q_L}\phi \quad \text{(for small deviations)}$$

➡ **Tuner control (or cooling water temp. in NC (RFQ))**



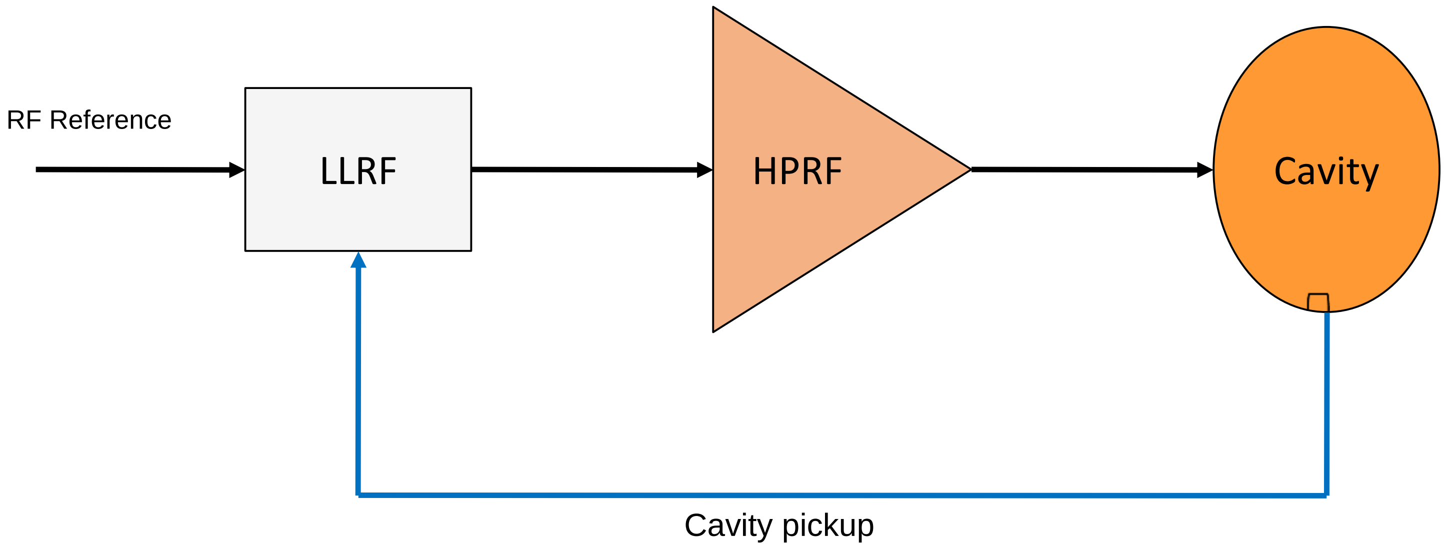


Cavity Detuning	➡ 가속전장 크기, 위상 변화	➡ Feedback 제어 (fast loop)
	➡ 위상변화 (△f)	➡ Tuner 제어 (Cooling water temp.)

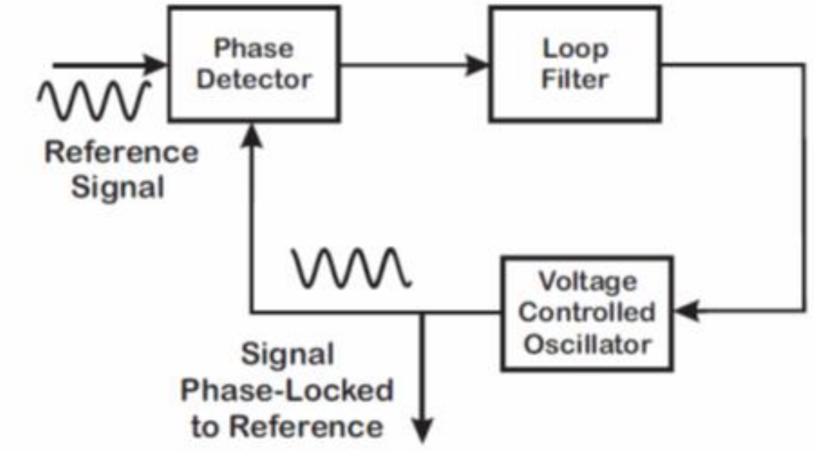
Vertical Test (VT)용 RF system (1)

$$RF(x) = A\cos(2\pi f x + \phi)$$

Amplitude — Frequency — Phase



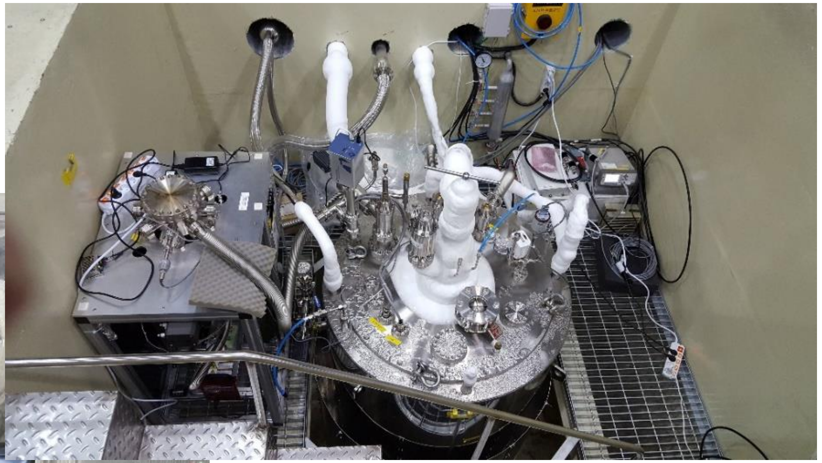
General VCO-PLL

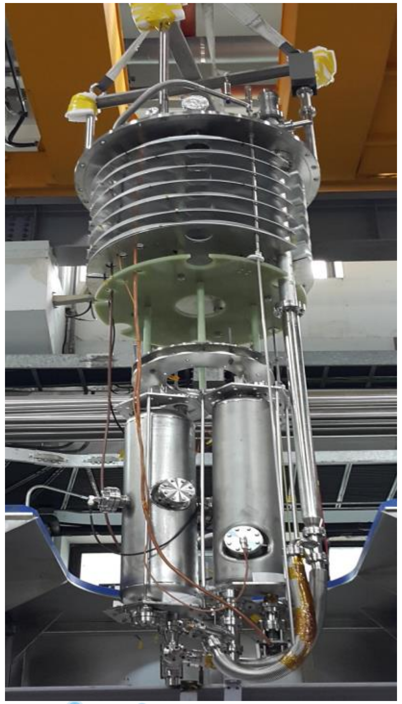


- **LLRF (Low-level RF)** : **Frequency tracking (VCO-PLL / SEL)**
- **HPRF ?** : **RF amplifier (SSPA: 200-500W)**
- **RF Reference : 10MHz generator (Signal generator)**

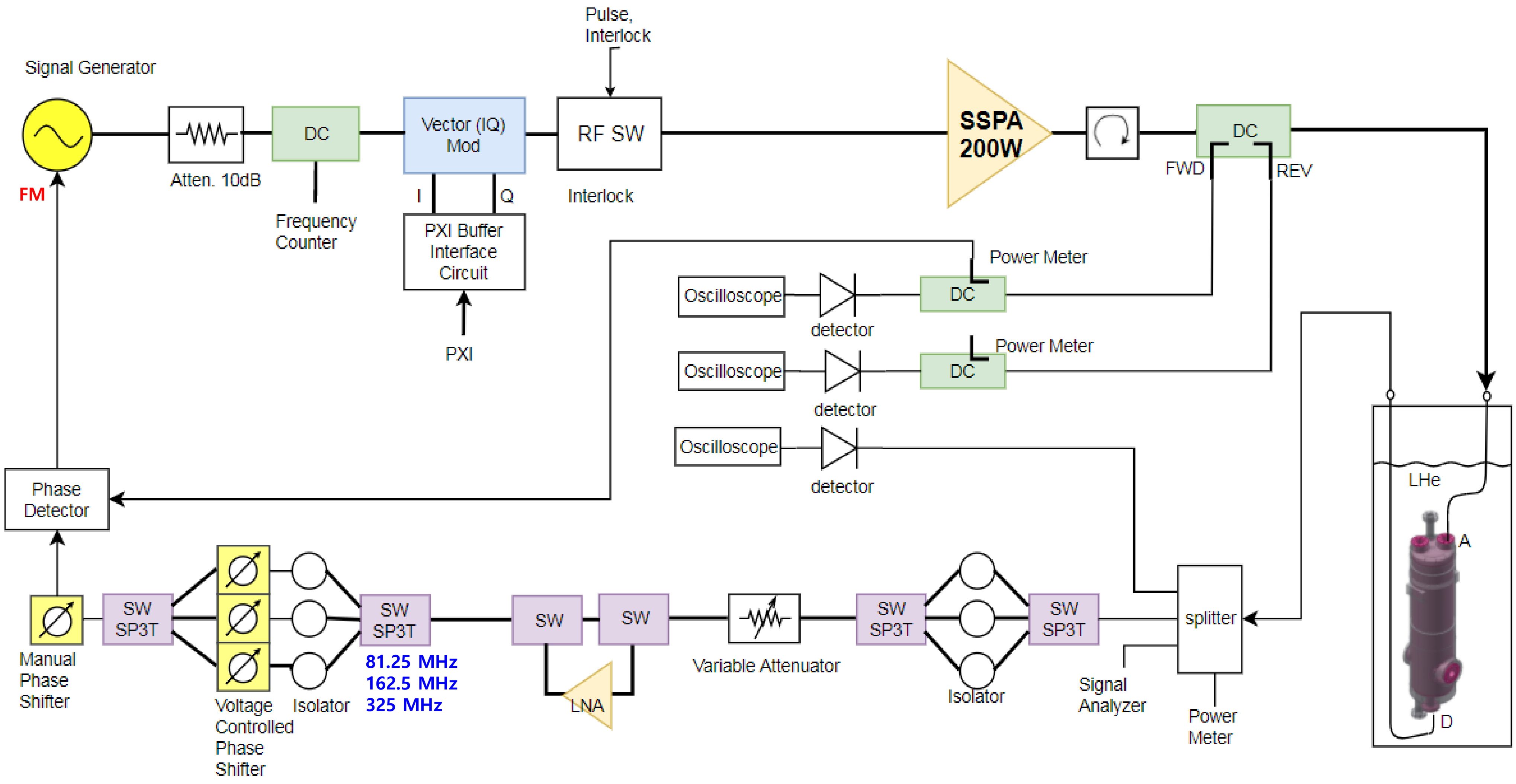
VT용 RF system (2) 문지캠퍼스

- LLRF : VCO-PLL type
- Monitoring and DAQ : LabVieW

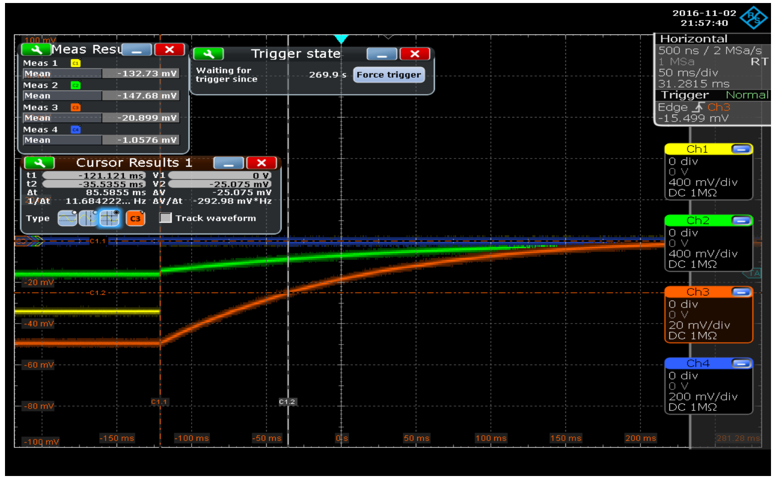


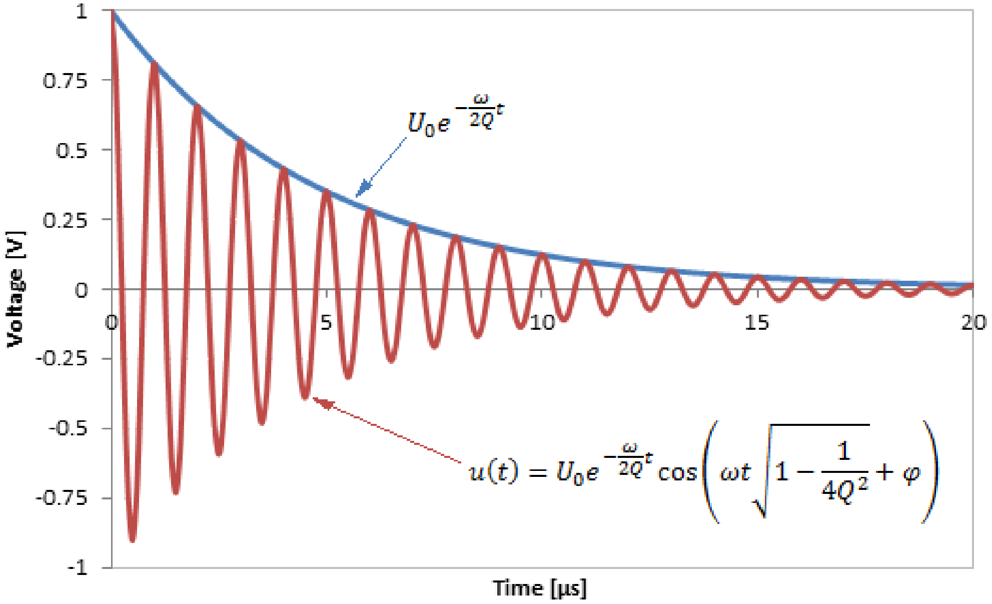


VT용 RF system (3) VCO-PLL 방식



VT용 RF system (4)





$$Q_L = 2\pi f(-\Delta t) / \left[\ln\left(10^{-\frac{\Delta a}{10}}\right)\right]$$

$$\therefore Q_{cavity} = Q_0 = Q_L(1+\beta_{in}+\beta_{out})$$

$$Q_0 = Q_t * \beta_t = Q_t * P_t / P_{loss}$$

$$(\beta_t = P_t/P_{loss}, \quad Q_t = Q_0/\beta_t)$$

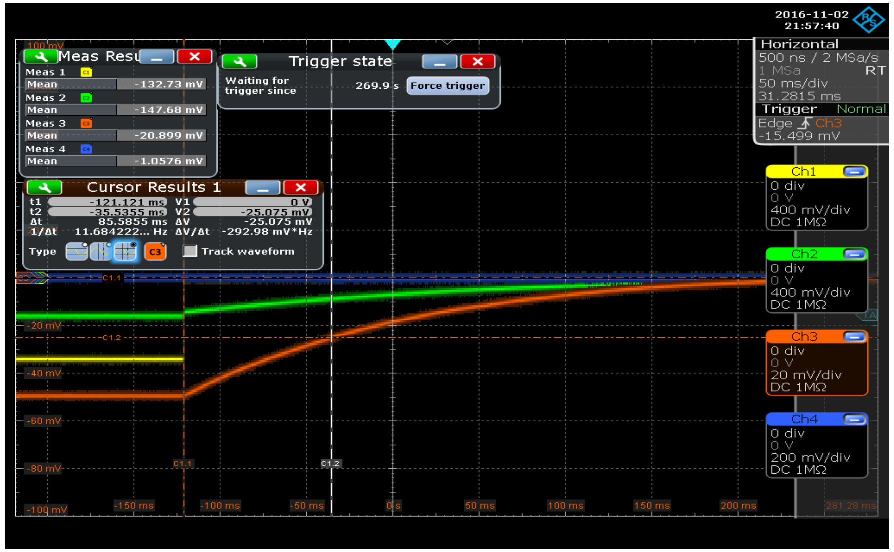
- envelope $V_0 e^{-\frac{\omega_0}{2Q_0}t} \rightarrow V_0 e^{-\frac{\omega_0}{2Q_0}t_1}$ at t_1 and $V_0 e^{-\frac{\omega_0}{2Q_0}t_2}$ at t_2
- $\dfrac{V_0 e^{-\frac{\omega_0}{2Q_0}t_2}}{V_0 e^{-\frac{\omega_0}{2Q_0}t_1}} = \dfrac{A_2}{A_1} \Leftrightarrow e^{-\frac{\omega_0}{2Q_0}(t_2-t_1)} = \dfrac{A_2}{A_1}$

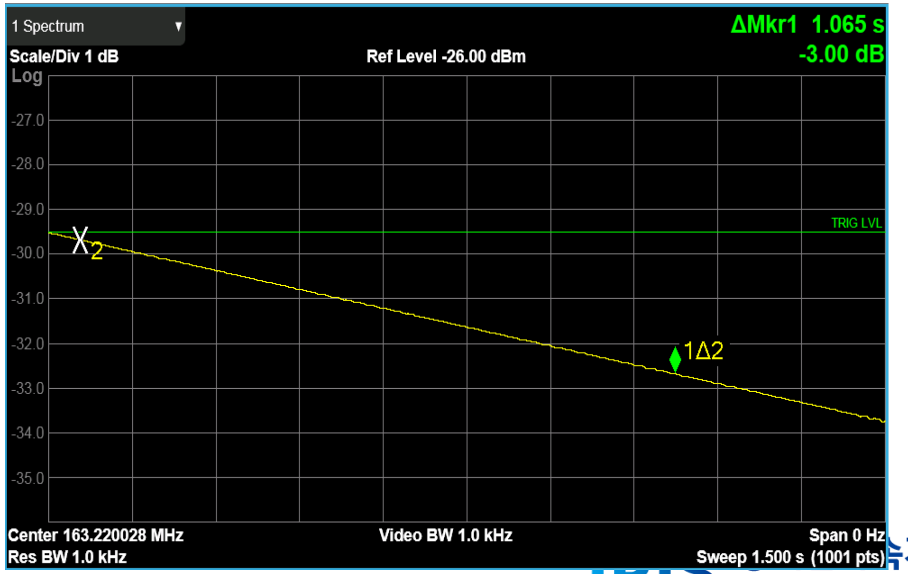
$$\Leftrightarrow -\frac{\omega_0}{2Q_0}(t_2-t_1) = \ln\left(\frac{A_2}{A_1}\right) \Leftrightarrow Q_0 = \frac{\omega_0(t_2-t_1)}{2\ln\left(\frac{A_1}{A_2}\right)}$$

- if $t_1 = 0$ and $t_2 = t$, and $\dfrac{A_2}{A_1} = 2$, $Q_0 = \dfrac{\omega_0 t}{2\ln 2}$

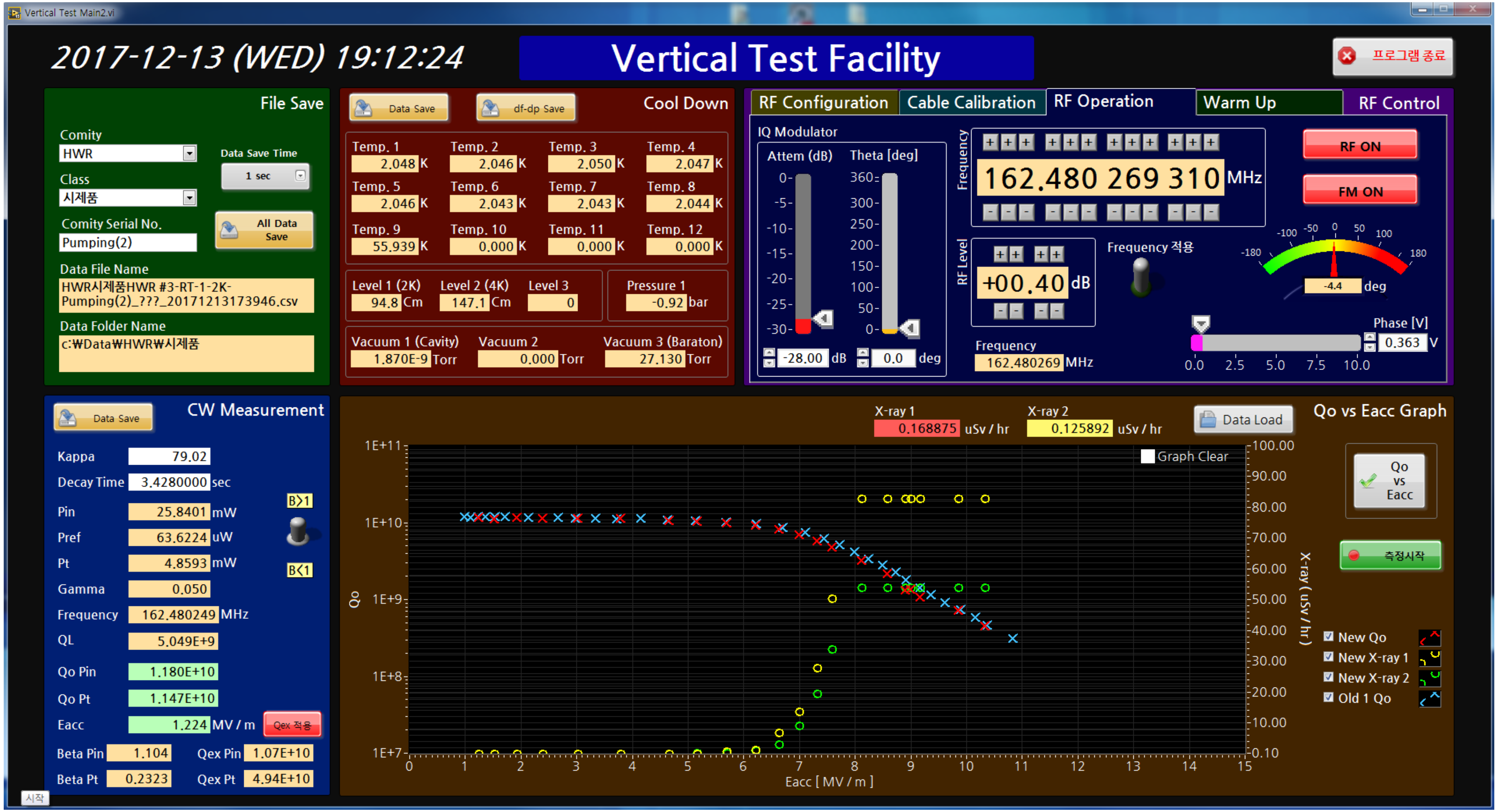
VT용 RF system (5)

- Frequency sweep(<- resonant frequency (VNA)) and tracking (FM)
- Decay time measurement (approximately 1~2MV/m, avoiding MP)
- Measuring Eacc vs Q slope





VT용 RF system (6)



iRIS 중이온가속기연구소 Institute for Rare Isotope Science

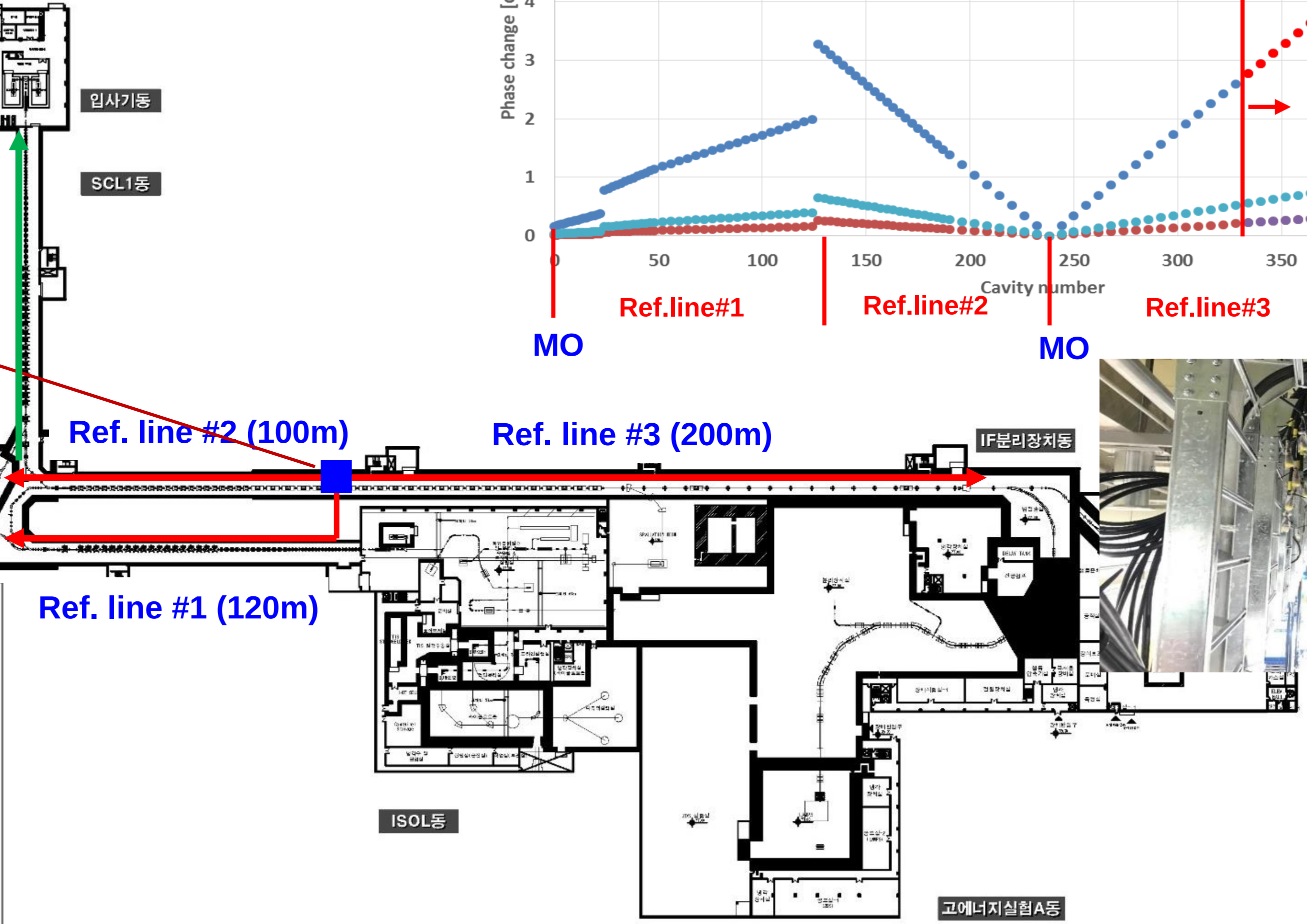
Part 04.

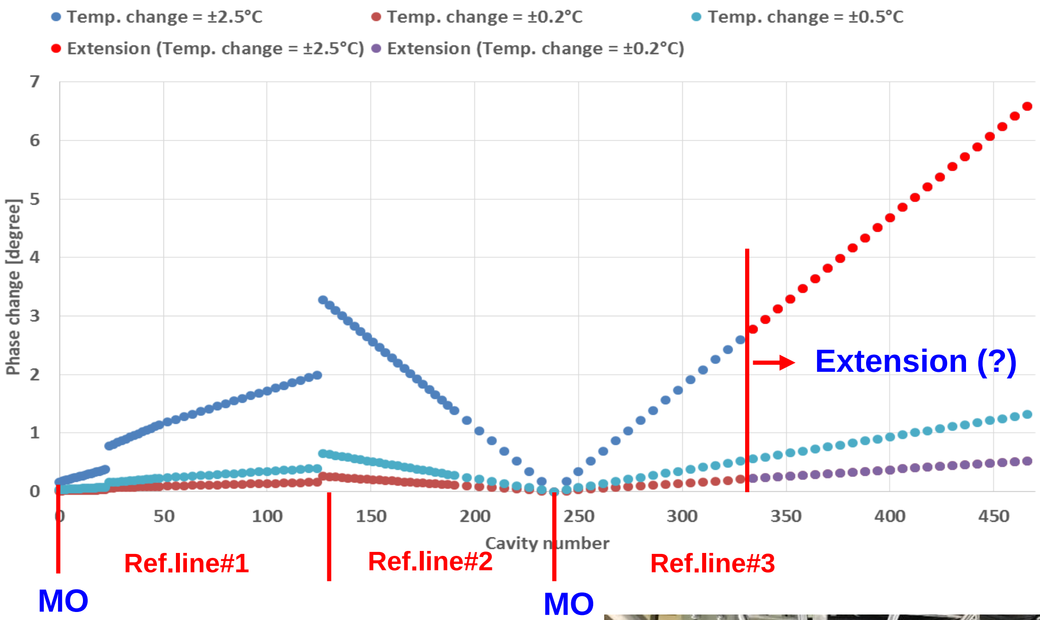
RF reference distribution system

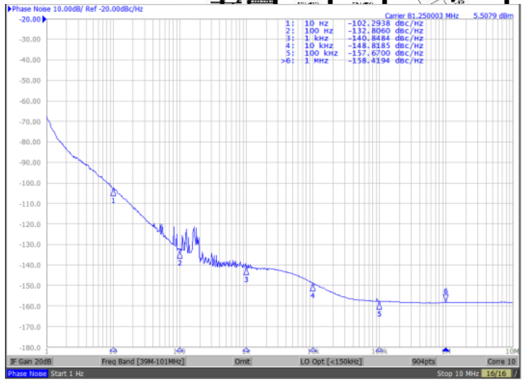
Institute for Rare Isotope Science

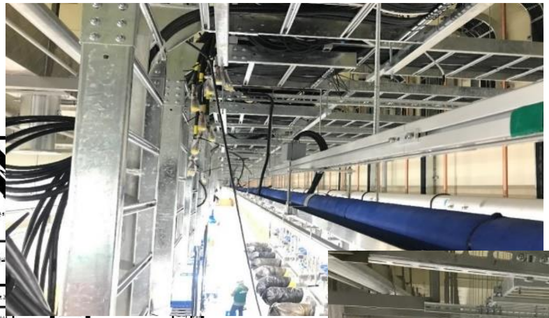
RF reference system for RAON

- Reference freq. : 81.25MHz
- 1-5/8″ rigid coaxial line
- temperature control with heater







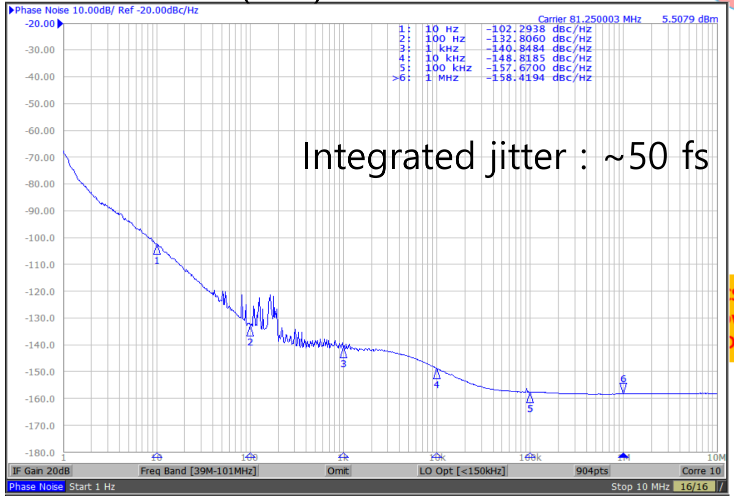


중이온가속기연구소
Institute for Rare Isotope Science

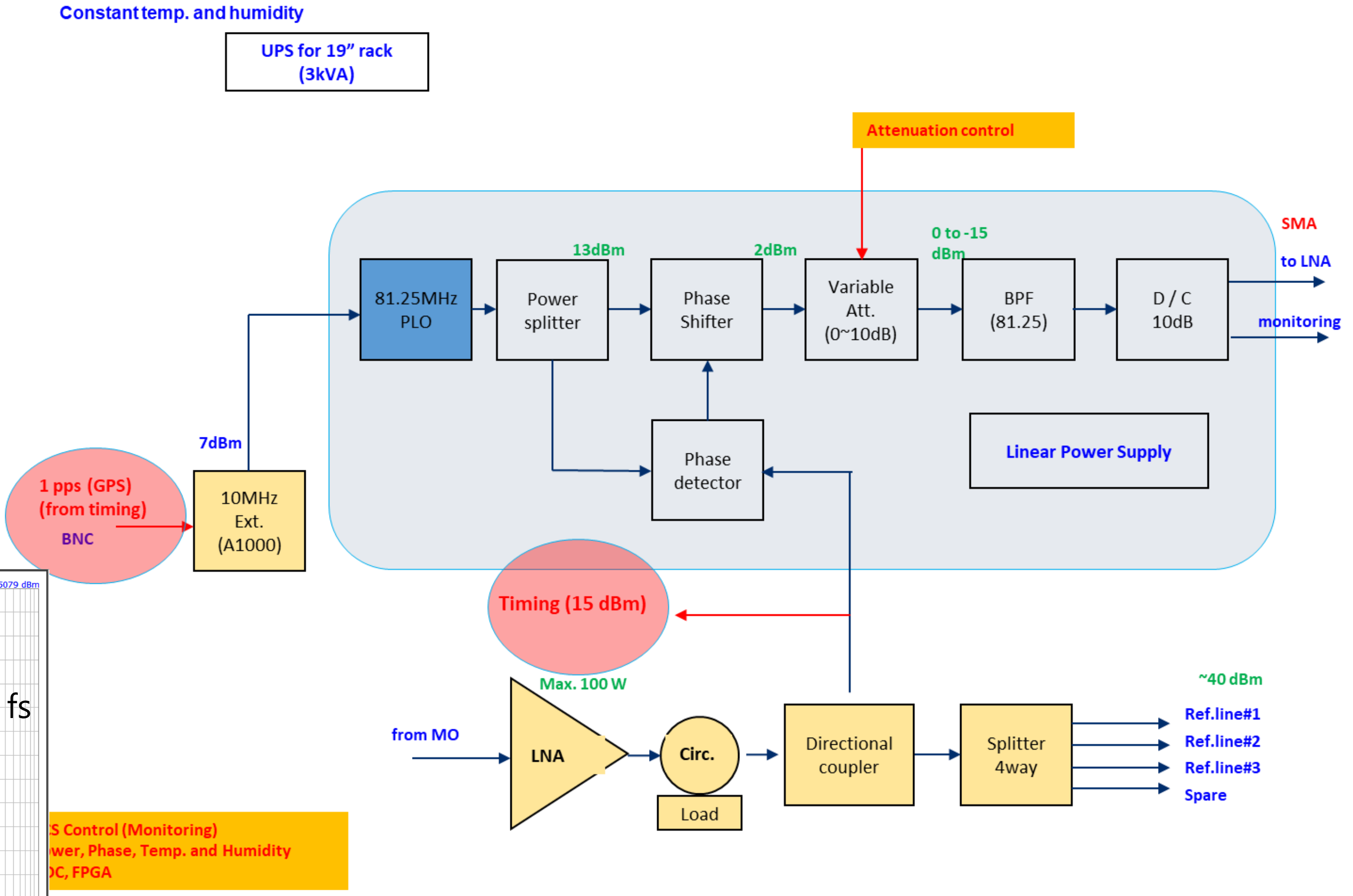
Master Oscillator

Master Oscillator

Phase noise (MO)



Phase error 0.0015 °



iRIS 중이온가속기연구소 Institute for Rare Isotope Science

OPI for RF reference

SCL3 RF Reference

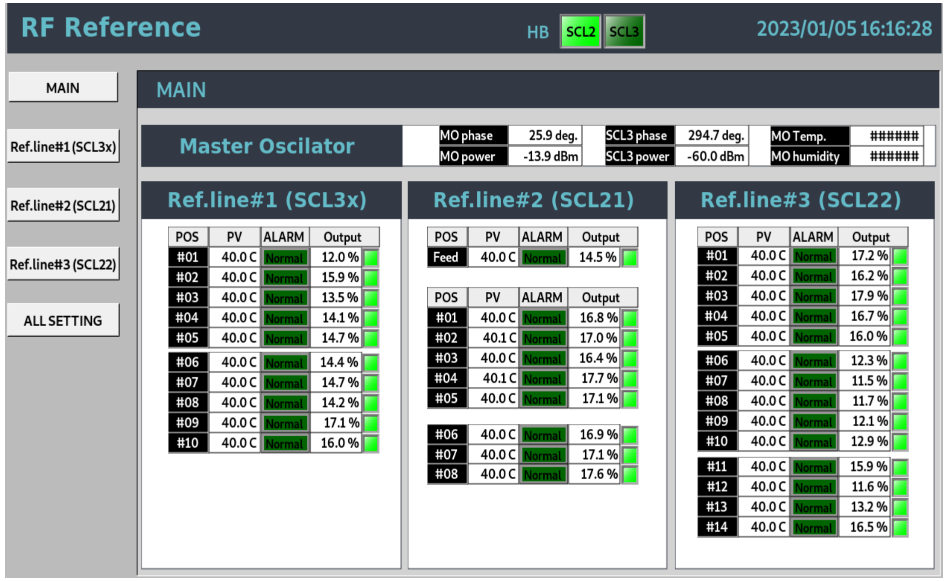
2022/12/13 16:21:05

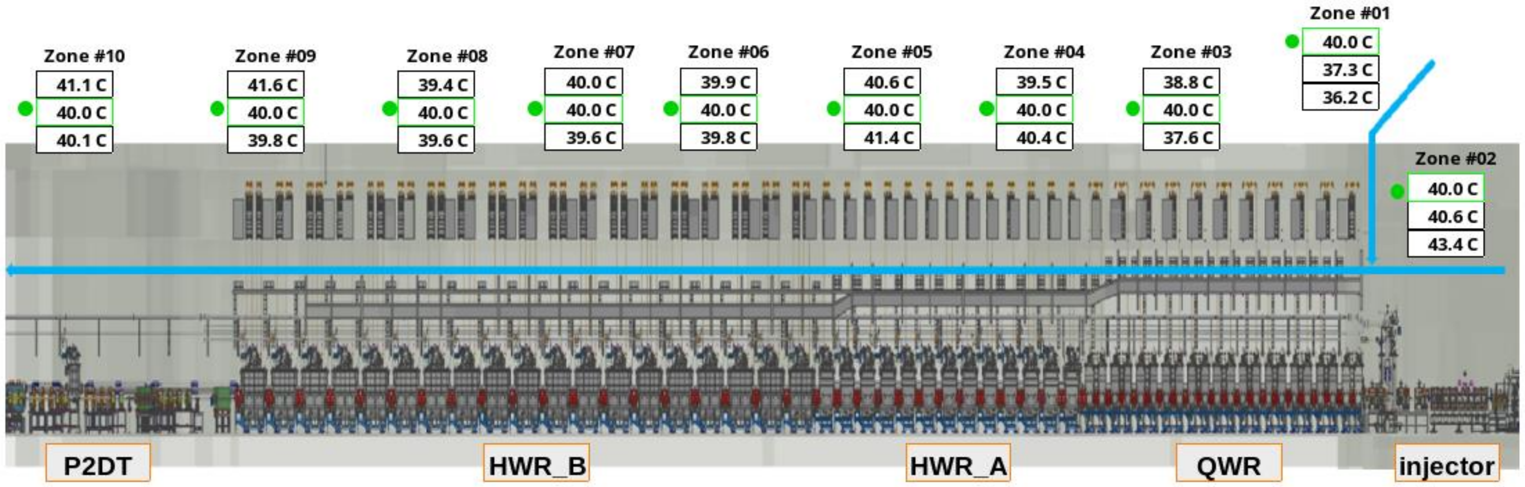
COMM

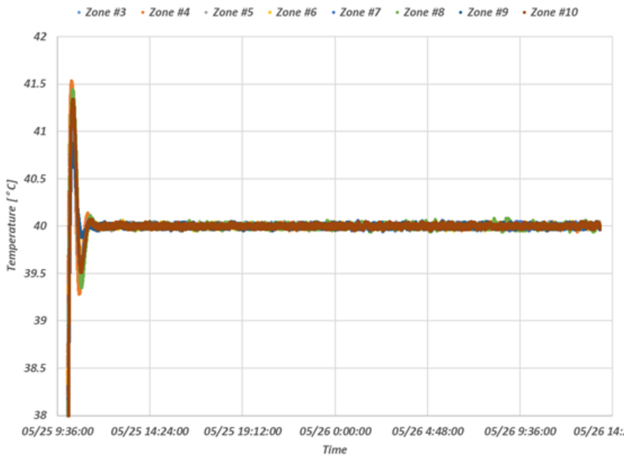
	현재 온도	온도 설정값		ALARM	HI 알람 설정	LO 알람 설정		Output
#01	40.00 C	40.0 C	0.0 C	Normal	45.0 C	30.0 C	CONFIG	11.6 %
#02	40.00 C	40.0 C	0.0 C	Normal	50.0 C	30.0 C	CONFIG	15.3 %
#03	40.00 C	40.0 C	0.0 C	Normal	45.0 C	30.0 C	CONFIG	13.0 %
#04	39.99 C	40.0 C	0.0 C	Normal	45.0 C	30.0 C	CONFIG	14.0 %
#05	40.01 C	40.0 C	0.0 C	Normal	45.0 C	30.0 C	CONFIG	14.3 %
#06	40.01 C	40.0 C	0.0 C	Normal	45.0 C	30.0 C	CONFIG	14.2 %
#07	40.02 C	40.0 C	0.0 C	Normal	45.0 C	30.0 C	CONFIG	14.1 %
#08	40.00 C	40.0 C	40.0 C	Normal	45.0 C	30.0 C	CONFIG	14.1 %
#09	40.00 C	40.0 C	40.0 C	Normal	45.0 C	30.0 C	CONFIG	16.7 %
#10	40.01 C	40.0 C	40.0 C	Normal	45.0 C	30.0 C	CONFIG	15.1 %
	ALL SET			SET				
	ALL HIALARM			SET				
	ALL LOALARM			SET				

Master oscillator 모니터링

MO phase	25.88 deg.
MO power	-13.88 dBm
SCL3 phase	295.78 deg.
SCL3 power	-60.00 dBm
MO랙 온도	22.33 deg.C
MO랙 습도	32.06 %



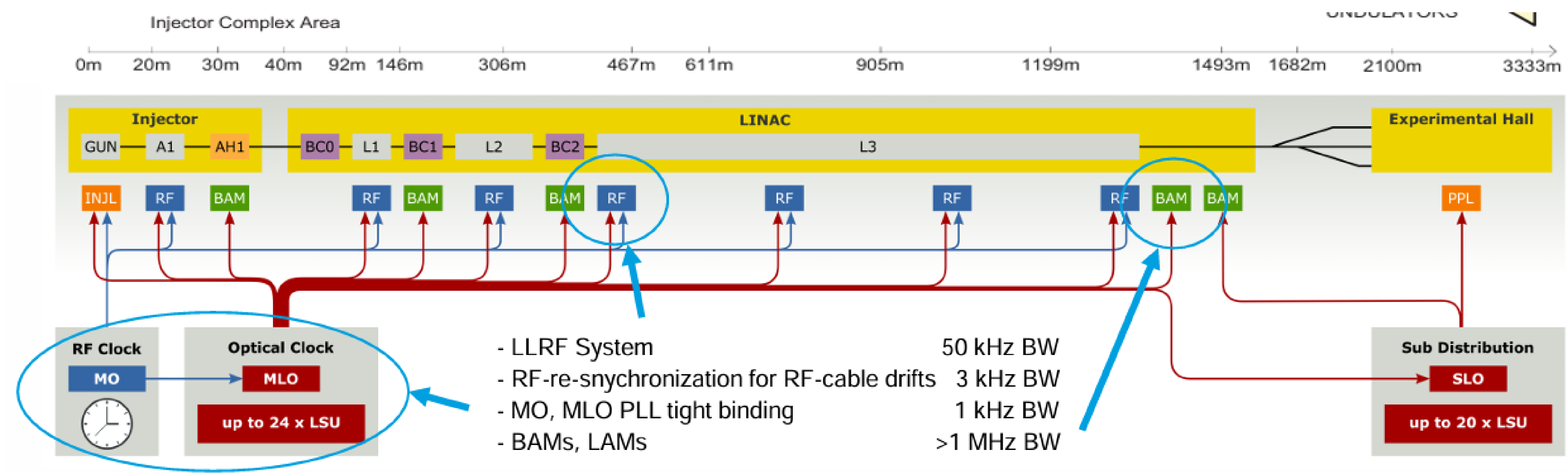




Temp. control (for 48 hours) : < 40±0.2 °C

iRIS 중이온가속기연구소 Institute for Rare Isotope Science

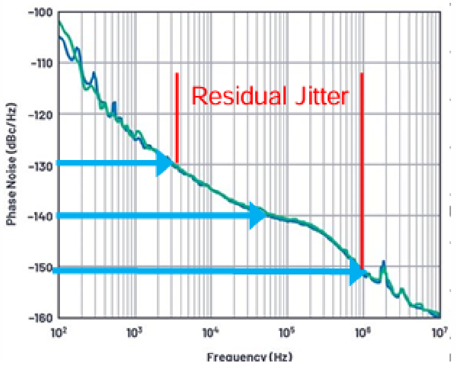
RF reference 예시 (European XFEL)



- LLRF System 50 kHz BW
- RF-re-synchronization for RF-cable drifts 3 kHz BW
- MO, MLO PLL tight binding 1 kHz BW
- BAMs, LAMs >1 MHz BW

se BWs :

MO, MLO PLL
REFM-OPT
LLRF-System
BAMs

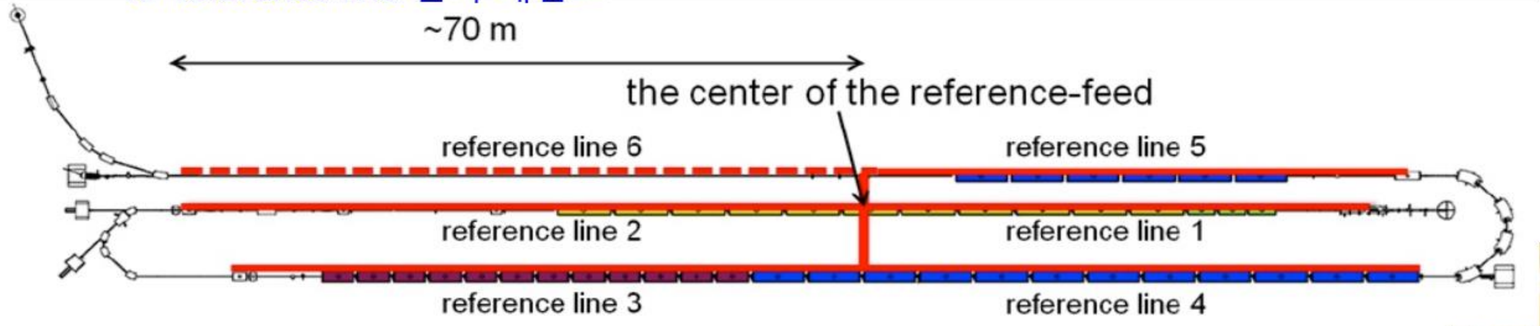


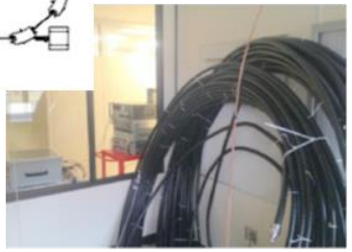
- Low 1/f-noise Main-Oscillator
- Low noise MLO
- Noise modelling, optimal BWs

RF reference 예시 (FRIB)

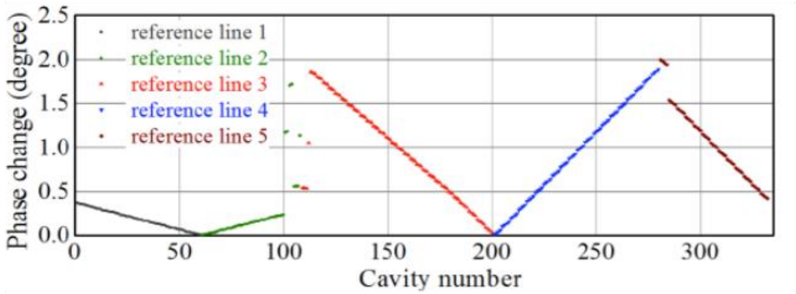
- Operating frequency : 80.5 / 322 MHz
- RF reference : 10.0625 MHz (1/8*80.5 MHz)
- Reference line 터널 설치 (w/o temp. control) / 터널 온도 조건 : 72 ± 6 degree F (22.2±3.3 °C)
- Reference line : RFS 7/8" LCF78-50J

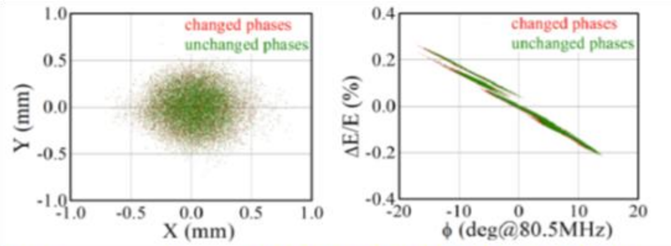
- RF reference line 설치 개념도





- 터널온도변화에 따른 각 reference 라인에서의 위상변화

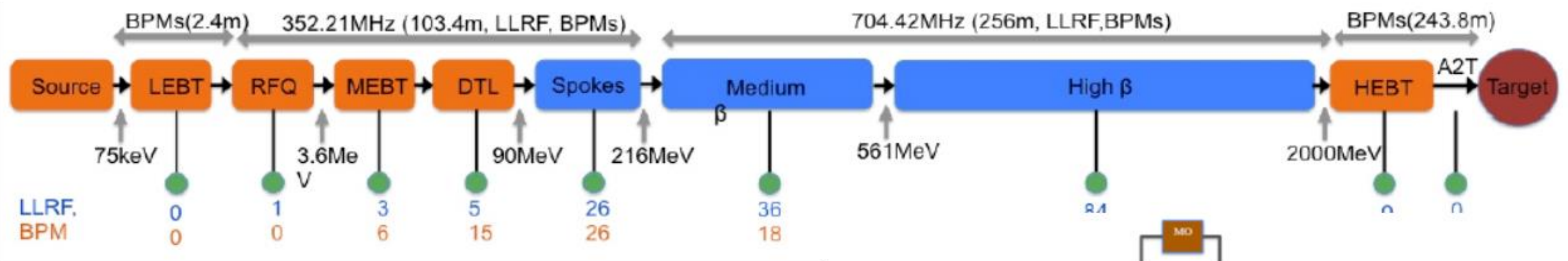


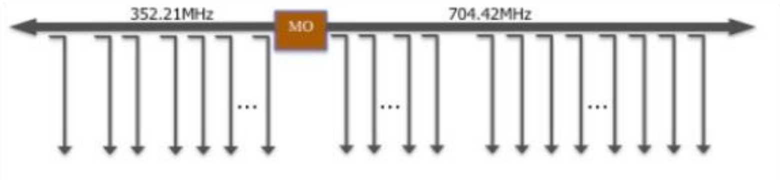


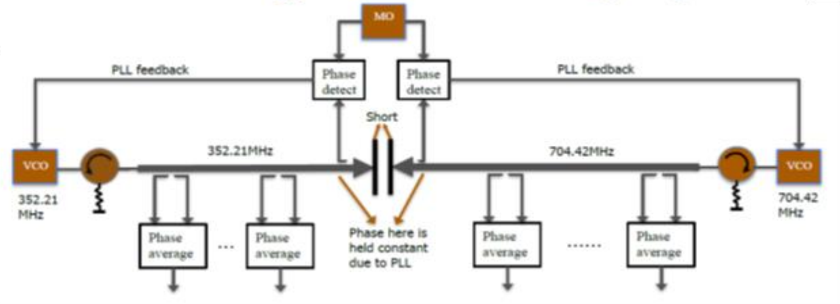
- Reference line 위상변화에 대한 빔 계산

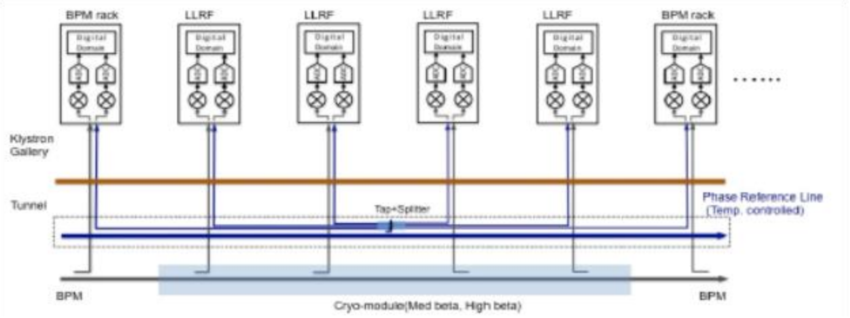
RF reference 예시 (ESS)

- Operating frequency : 352.21MHz / 704.42MHz
- Reference 요구조건 : 0.1도 (short term: during pulse) / 1도 (long term: days to months)
- RF reference : 352.21 / 704.42 MHz
- Reference line 터널 설치 (w/ temp. control)
- Reference line : 3-1/8 rigid copper coaxial
- SNS 시스템과 유사



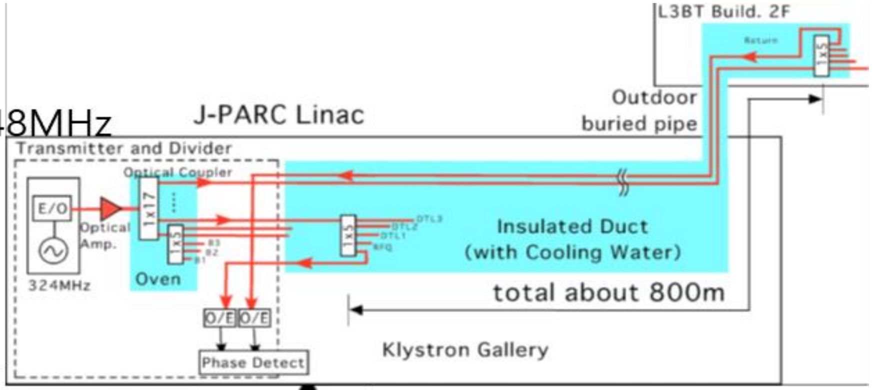


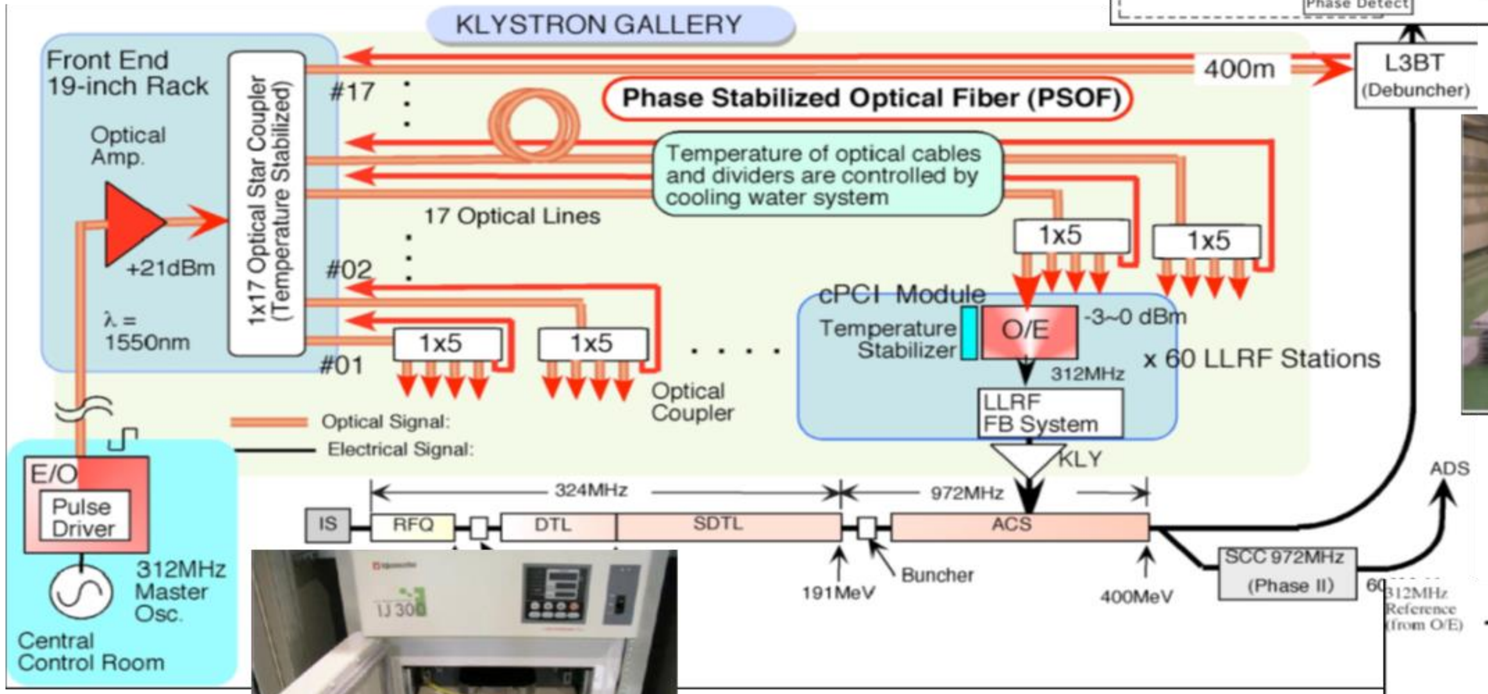


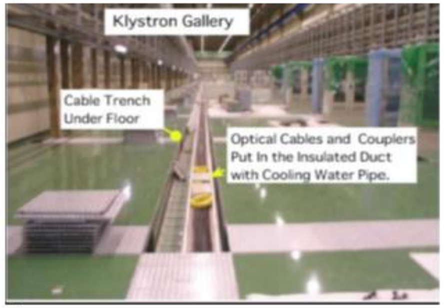


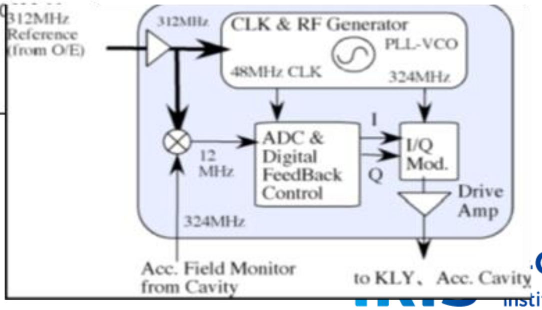
RF reference 예시 (J-PARC)

- LLRF reference : ±0.3 도
- Frequency : RF 324MHz, LO 312MHz, IF 12MHz, Clock 48MHz
- RF reference : 312 MHz LO
- Reference line : Optical cable (E/O, O/E)
- Reference line 갤러리 설치 (w/ . water temp. control)









Thank you ~~~

감사합니다.