Design of PLS-II Superconducting RF System

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On behalf of PLS-II RF group

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1. Introduction
2. Physics design
3. Cryomodules
4. Cryogenic system
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PLS-II Project

Parameters	PLS	PLS-II
Energy [GeV]	2.5	3.0
Current [mA]	200	400
Emittance [nm-rad]	18.9	5.9
Circumference [m]	280.56	281.82
Revolution frequency [MHz]	1.068	1.0638
Harmonic number	468	470
Electron energy loss / turn from dipoles [KeV]	548.4	1042
and insertion devices [KeV]	160	616
Beam loss power by synchrotron radiation [kW]	142	663.3
RF frequency [MHz]	500.082	499.973
Cavity type	NC	SC
No. of RF cavities	4	3 (2)
Accelerating Voltage [MV]	1.6	4.5 (3.3)
No. Insertion devices	10	20

Design Parameters

Parameters	Values	Unit
Required RF Power (Rad. + HOM)	670	kW
Number of SRF Cryomodules	**3** (2)	set
RF Voltage	**4.5** (3.3)	MV
RF Voltage per cavity	**1.5** (1.65)	MV
RF Frequency	499.973	MHz
RF acceptance	2.8	%
Number of power amplifiers, 300kW-class	**3** (2)	set
Required RF power per Cavity	223	kW
Cryogenic Cooling Capacity @4.5 K	700	W

- Baseline design: Three Cryomodules
- Two Cryomodules will be installed due to budget limitation.

Role of RF system

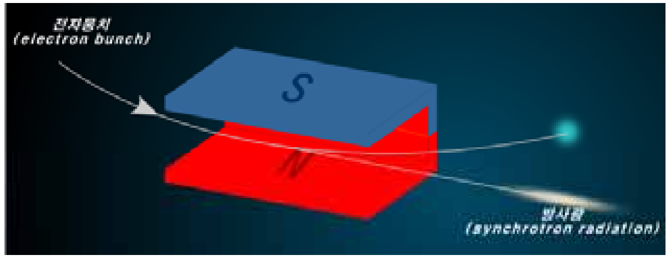
- supply sufficient energy to the electron beam to make up for power losses to synchrotron light in the dipoles and insertion devices

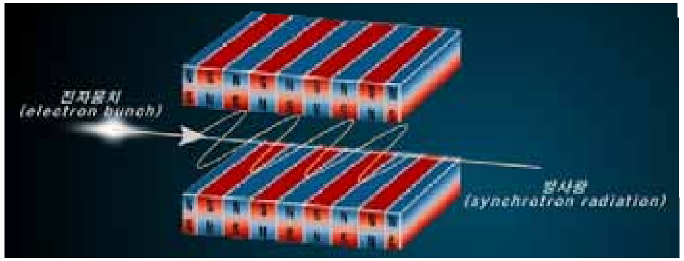
  PLS: 2.5 GeV/ 200mA → 150 kW

  PLS-II: 3 GeV / 400 mA → 670 kW

- Suppress Instability to store high current beam up to 400 mA

- The control errors of RF gap voltage, phase and frequency from the low-level RF system must not affect the orbit stability of electron beam.





Major Devices

1. RF Cavity

- Super-conducting or normal conducting
- Factors considered in choosing the cavity type
  - Beam stability
  - System reliability
  - Availability of ID space in SR tunnel
  - Budget & installation space
  - Vision for future

2. Power Source

- Klystron, IOT, or solid state amplifier

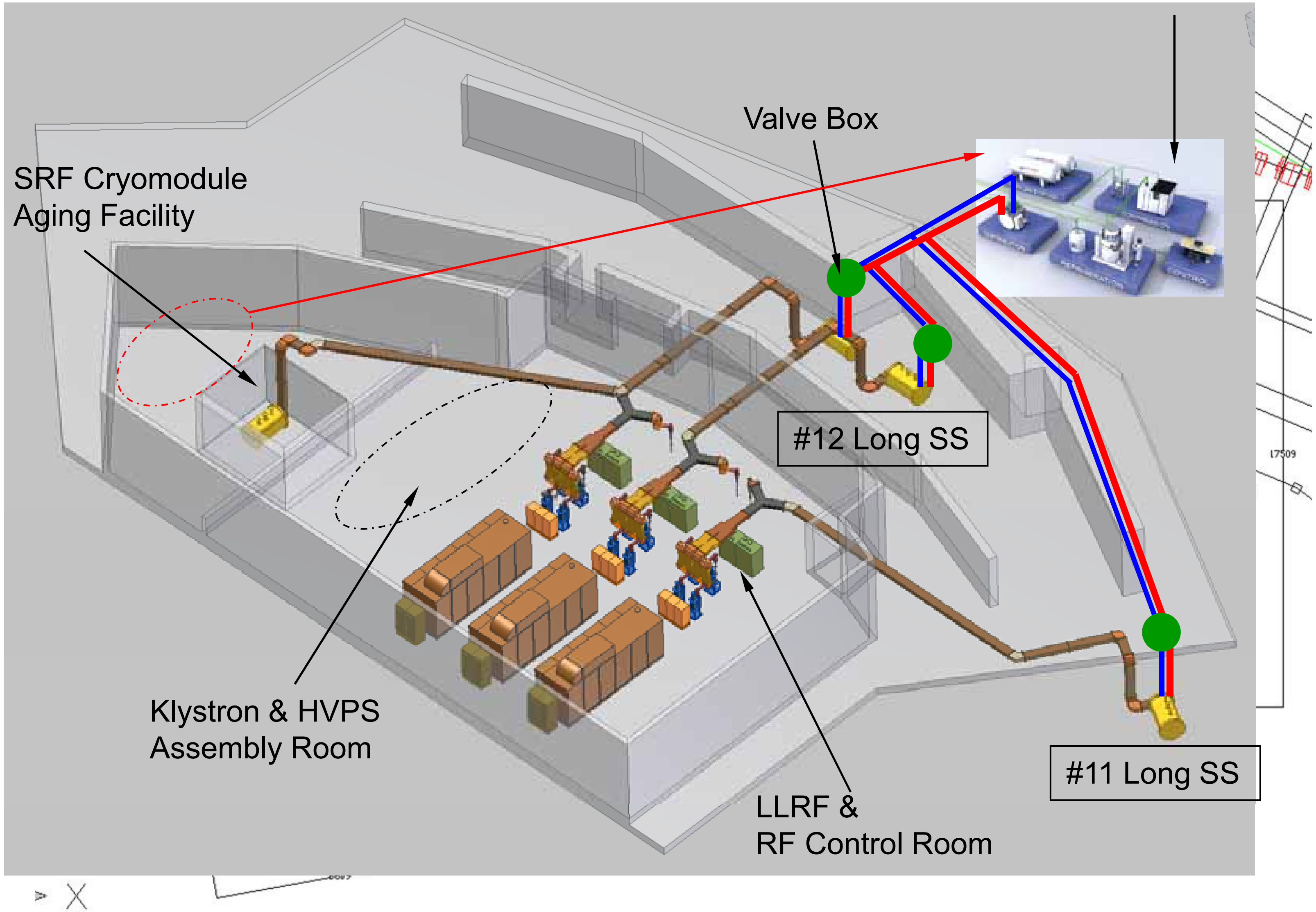
3. Low-Level RF System

- Digital or analog

Layout of SRF System

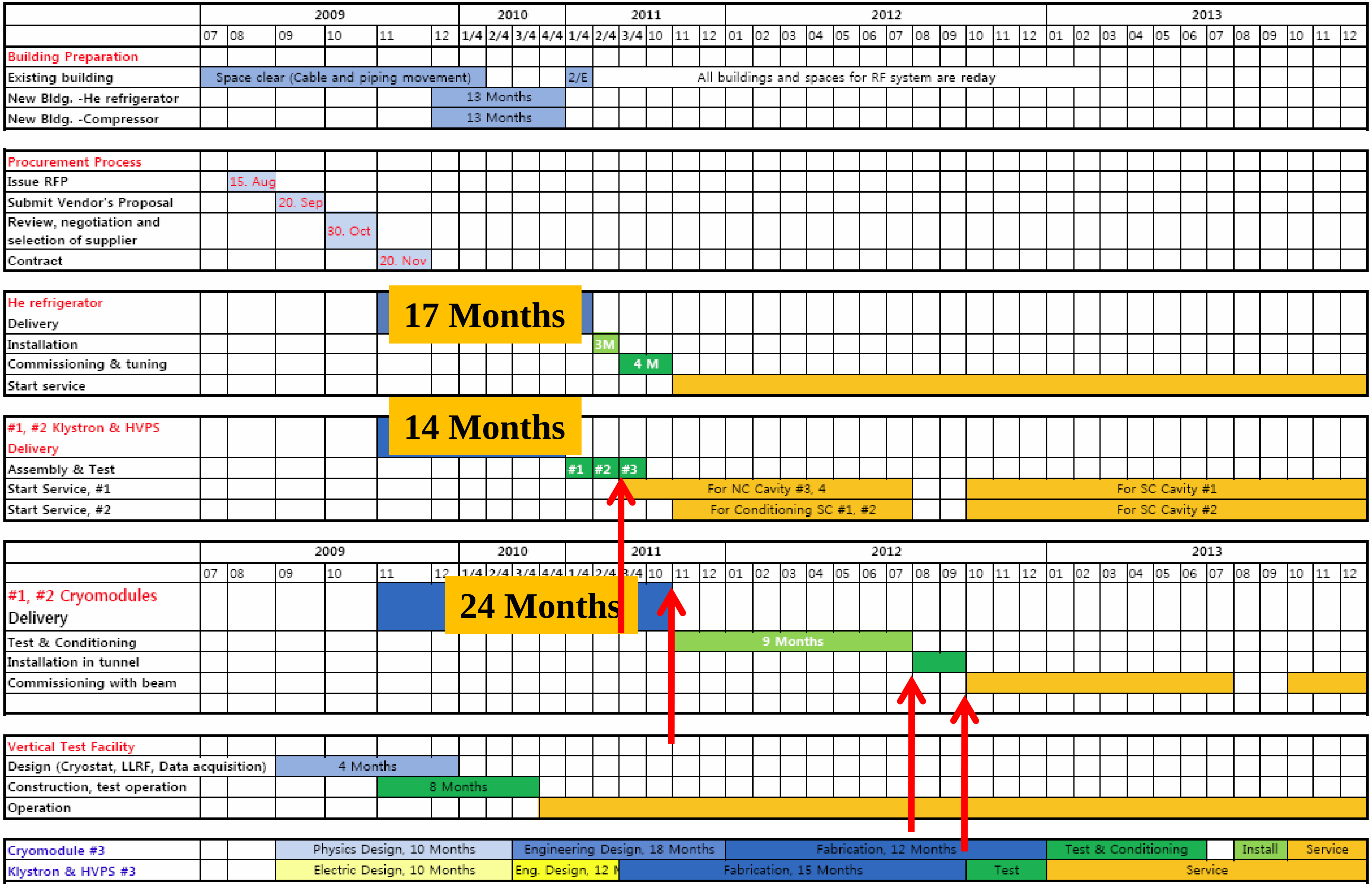
Compressor ~100 m away from SR

- He Refrigerator system in RF building (cold box, main dewar)



Schedule

PLS-II



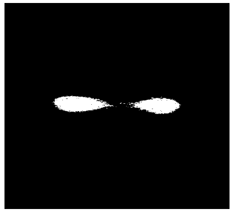
PHYSICS DESIGN

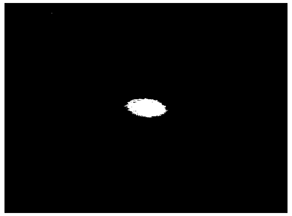
SRF cavity in synchrotron radiation facilities

Light Source	E (GeV)	I_b (mA)	Vc (MV)	P_b (kW)	Cavity type	Numbers of Cavity	Cavity design power (kW)	Cavity operating power (kW)
BEPC-II	2.1	250	4		SRF	2		
Diamond	3	300	4	536	SRF	2	300	110~190
CLS	2.9	250~320	2.4	245	SRF	1	300	250~320
SSRF	3.5	300	6	566	SRF	3	250	120
TLS	1.9	300			SRF			
TPS	3	400	4.8	720	SRF	4	180	
PLS-II	3	400	4.5	670	SRF	3	223	
NSLS-II	3	400			SRF	3		

Requirements of RF System

1. No coupled bunch Instabilities → SC RF
   – Instabilities become a big issue in high current operation (400mA)





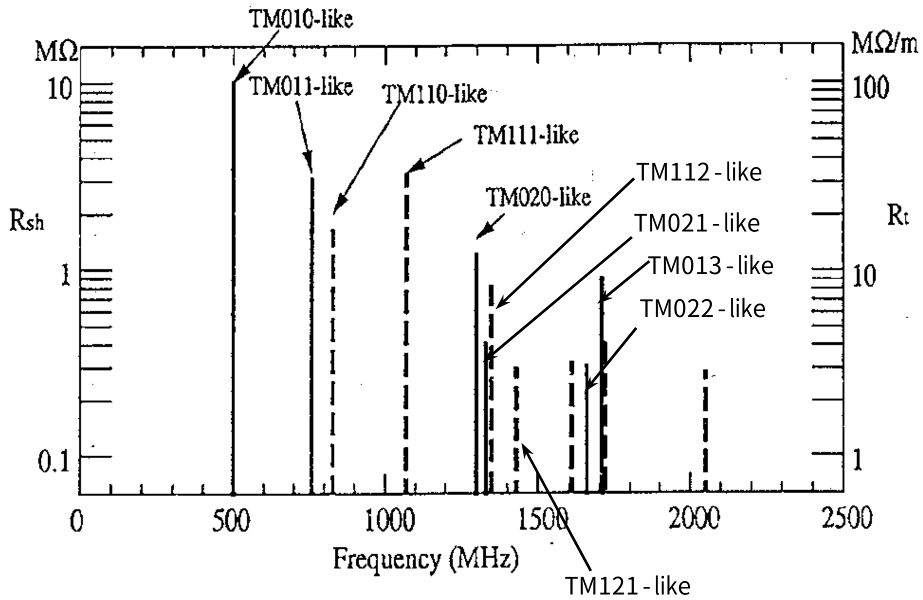
Synchrotron Light Sources using SC RF : TLS, CLS, SSRF, DLS
TPS and NSLS-II decided to use SC RF.

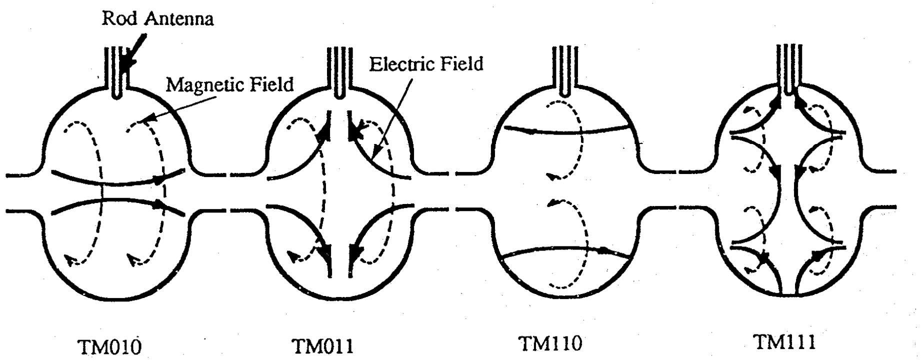
2. Stable operation → 300 kW Klystron
   – MTBF of RF system: > 6 days

3. Low RF amplitude and phase jitter → Digital LLRF
   – PLS-II lattice has a big dispersion at the straight section
   – Orbit variation due to RF jitter could be a problem
   – phase: 0.35 deg, amplitude: 0.75%

Higher-order modes in RF cavity

PLS RF cavity: NC





Rsh : 300 kΩ ~ 1 M Ω

PLS-II RF cavity: SC

HOM freq [MHz]	R/Q	Q_{load}	Rsh [Ohm]
1081.3	2.42	201	486
2932.3	0.75	471	353
4127.9	0.69	1267	874

CBI growth rate of PLS-II SC cavity

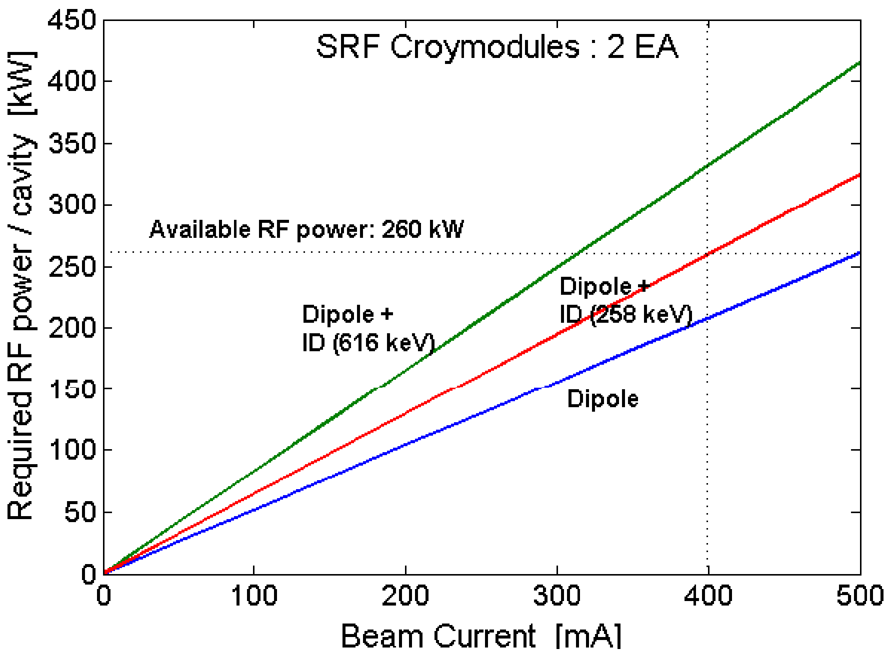
- To get an instability-free state, the instability growth rate should be smaller than the damping rate

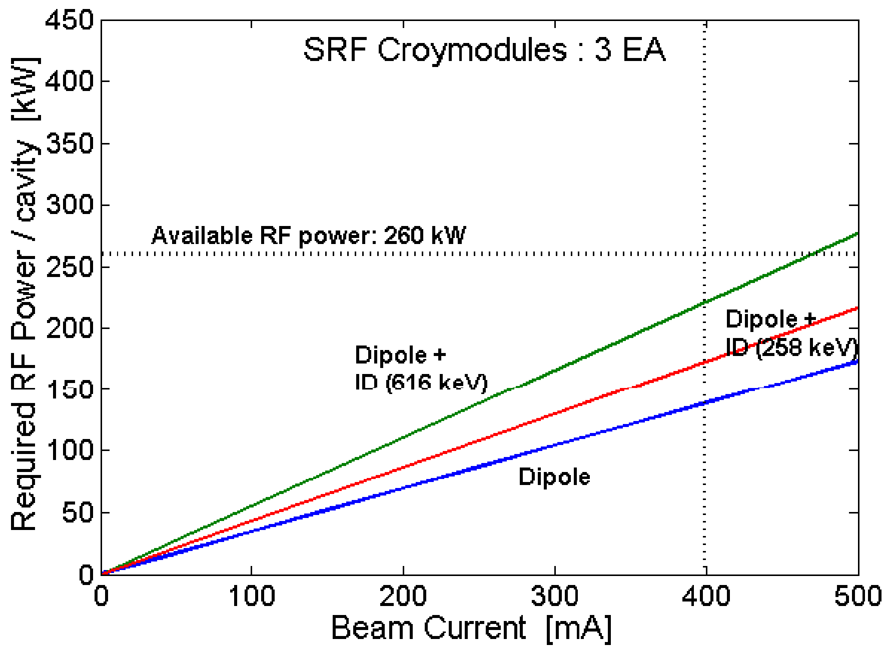
	Damping time	Damping rate [/sec]
Horizontal	2.062 ms	- 485
Vertical	2.707 ms	- 370
Longitudinal	1.604 ms	- 623

HOM frequency [MHz]	Direction	R/Q	Q_{load}	Mode number	Growth rate [sec^{-1}]
1081.3	Long.	2.42	201	75	4.5
4127.9	Long	0.69	1267	115	6.6
679.4	Trans.	165.2	78	299	1.6
1138.5	Trans.	38.7	22	333	0.22

RF Power Budget of PLS-II

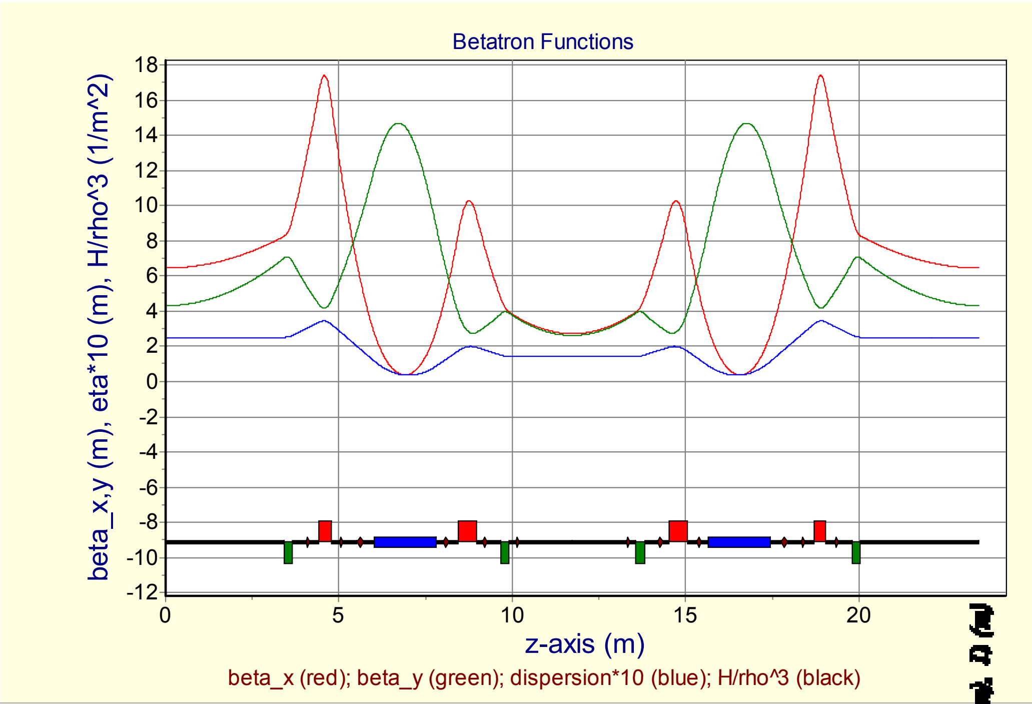
HOM loss: 5 kW, waveguide loss: 10 kW, Safety margin: 25 kW,
Available maximum power delivered to beam from 300 kW klystron is 26**0 kW.**





With two cryomodules, 210 kW is required to compensate dipole radiation loss at 400 mA current

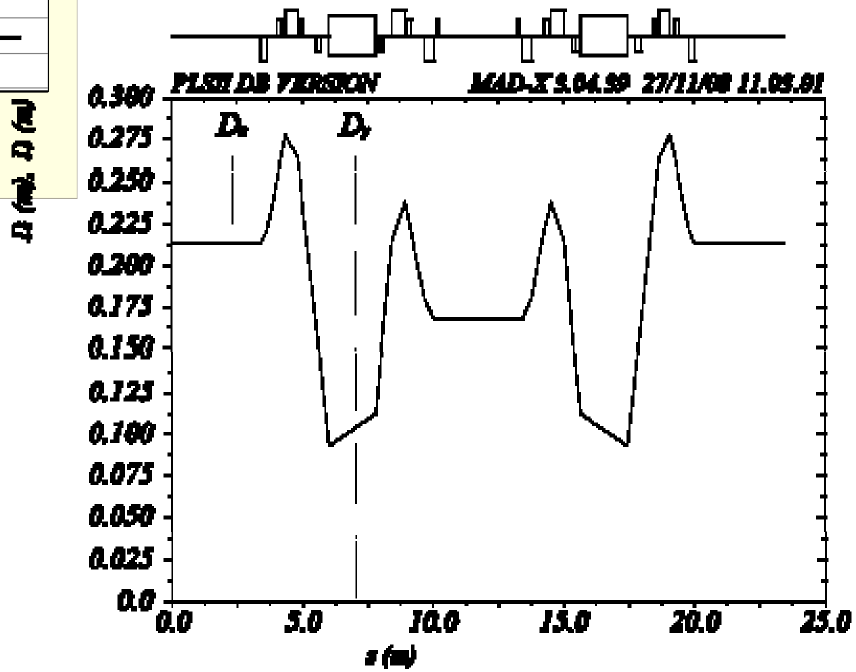
RF system amplitude and phase requirements



$$\Delta_{x,y} = \frac{\Delta p}{p}\,\eta_{x,y}$$

Dispersion function

Dispersion at long straight section : 210 mm



RF system amplitude and phase requirements

The obit variation induced by the momentum jitter is $\Delta_{x,y} = \frac{\Delta p}{p} \eta_{x,y}$

$$\frac{\Delta p}{p} = \frac{\nu_s}{h\alpha} \Delta\varphi$$

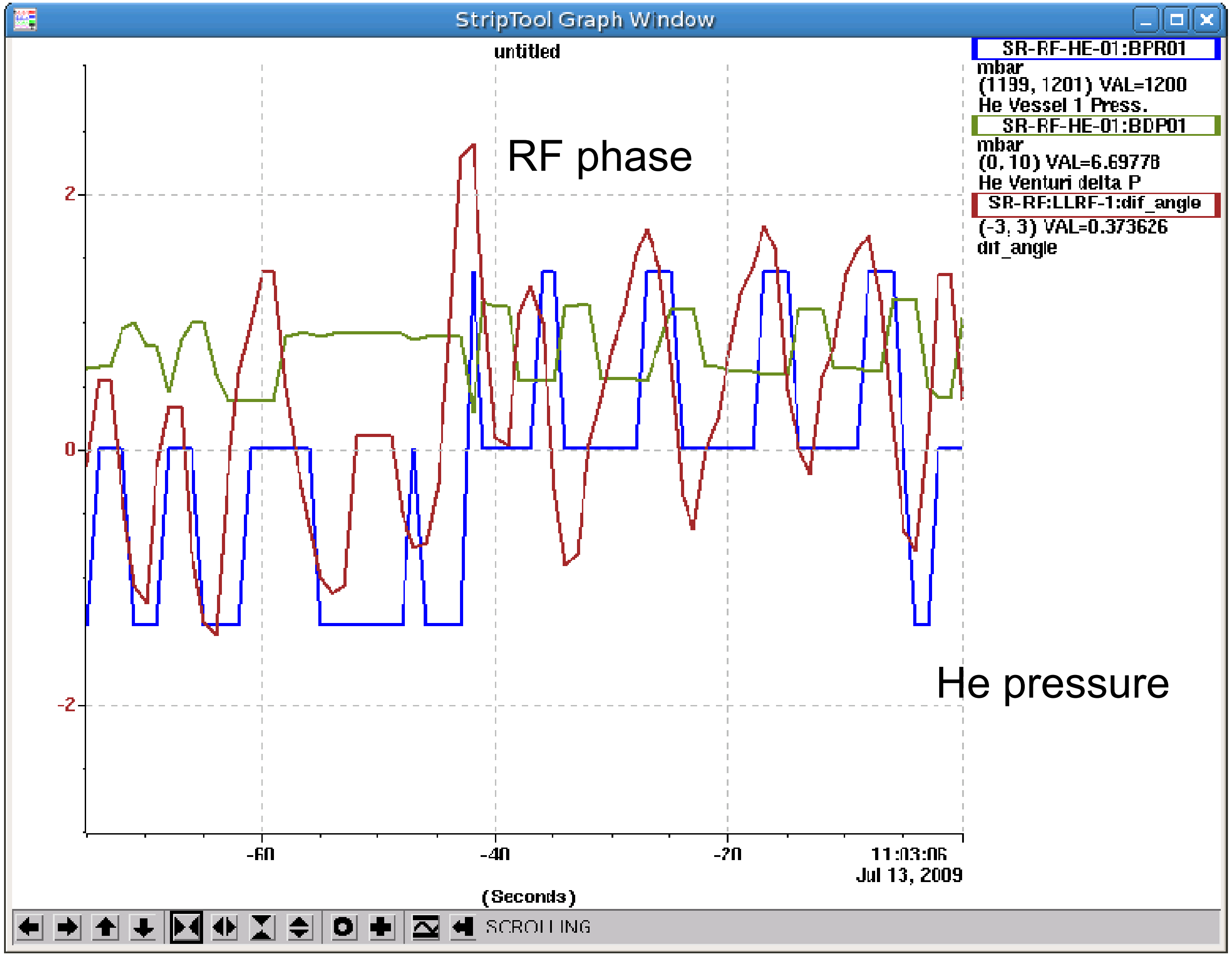
$$\frac{\Delta V}{V} = -\frac{\cos\varphi_s}{\sin\varphi_s} \Delta\varphi$$

Synchrotron tune, ν_s	0.00993
Harmonic number, h	470
Momentum compaction factor, α	0.001307

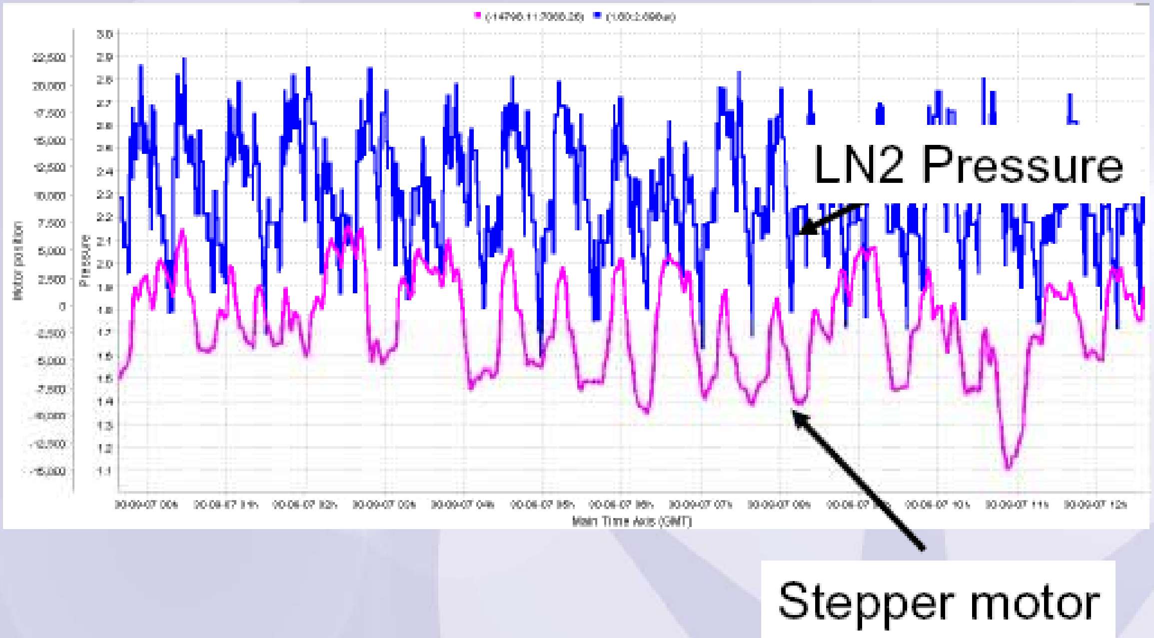
Orbit variation should be smaller than 10% of the horizontal and vertical beam size

	PLS-II		PLS	
	Vertical	Horizontal	Vertical	Horizontal
beam size	11 μm	248 μm	35	455 μm
10 % beam size	1.1 μm	25 μm	3.5	45.5 μm
Dispersion	5 mm	250 mm	5 mm	20 mm
Δp/p limit	1.1 μm /5 mm = 2.2×10^{-4}	1.0×10^{-4}	7.0×10^{-4}	
Δφ limit	0.78°	0.35°	5.9°	10°
ΔV/V limit	0.029	0.0075		

Performance of cryogenic system in SSRF



Superconducting Cavities



1 bar LN2 supply pressure variation leads to significant tuner motion

Issues in SRF System

- System Reliability of SRF is not so good as NC RF System
- Power handing capability of Input power coupler
  - CESR (500 MHz) was tested up to 450 kW CW, operated at 300 kW
  - CLS cryomodule recorded up to 320 kW, operated around 220-230 kW
  - KEKB (508 MHz) tested up to 800 kW CW, operated at 400 kW
- Multipacting
  - There is a multipacting zone between **130 - 160 kW in** DLS Cryomodules.
  - DLS is operating two cryomodules at **110 kW** and **200 kW,** respectively to escape the multipacting zone.

SRF System Reliability

PLS RF System Reliability

	2007	2008
User service beam time	4680 hrs	4680 hrs
RF fault time	48 hrs	5.8 hrs
RF fault number	41	12
MTBF	4.7 days →	**16.2 days**

- achieved by preventive & good maintenance of KSU
- the same in 2009

SRF System Reliability

Light Source	MTBF
SSRF	2.5 days
Diamond Light Source	4.2 days
KEKB	> 10 days

Specifications of SRF Cryomodule

Main Spec.

- **Q_0 > 1E9 @ Vacc ≤ 2.5 MV for Vertical test**
- **Q_0 > 0.5E9 @ Vacc ≤ 2.0 MV for Horizontal test**.
- **Qext = 1.7E5 +/- 0.2E5**
- Frequency tuning range > ±200 kHz with resolution of 10 Hz

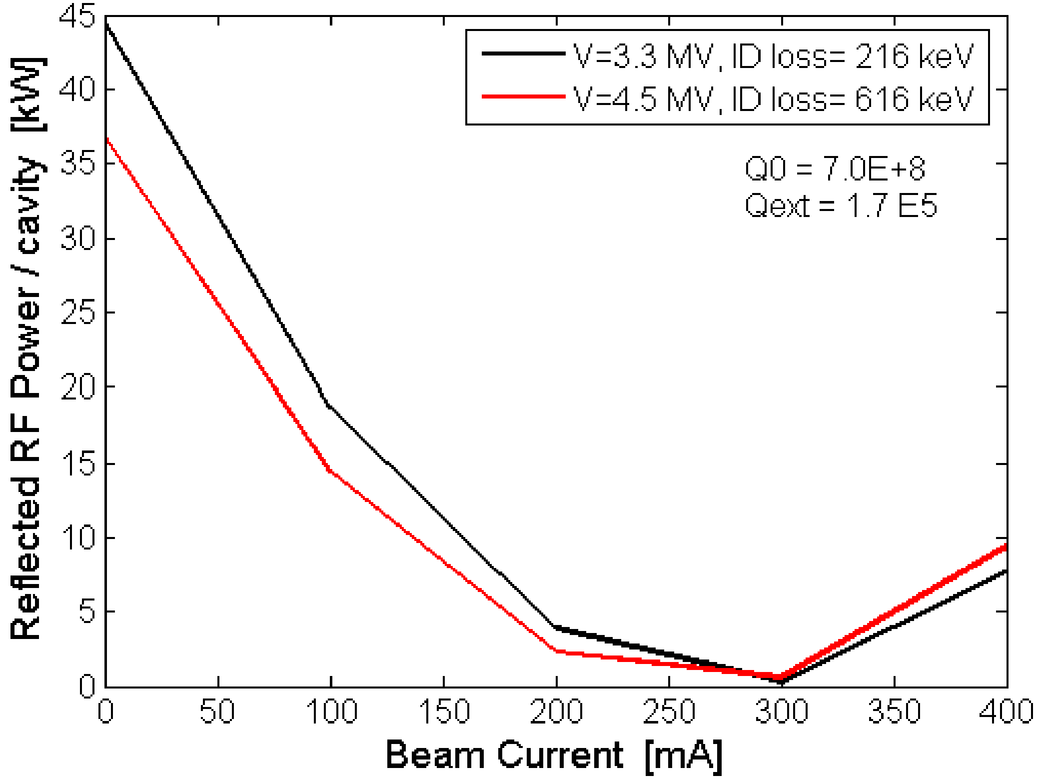
Window:

- **350 kW in traveling wave cw .**
- **125 kW standing wave cw at full reflection,**
- **500 kW in traveling wave at >20% duty cycle.**

65 kW → 2.0 MV
44.5 kW → 1.65 MV

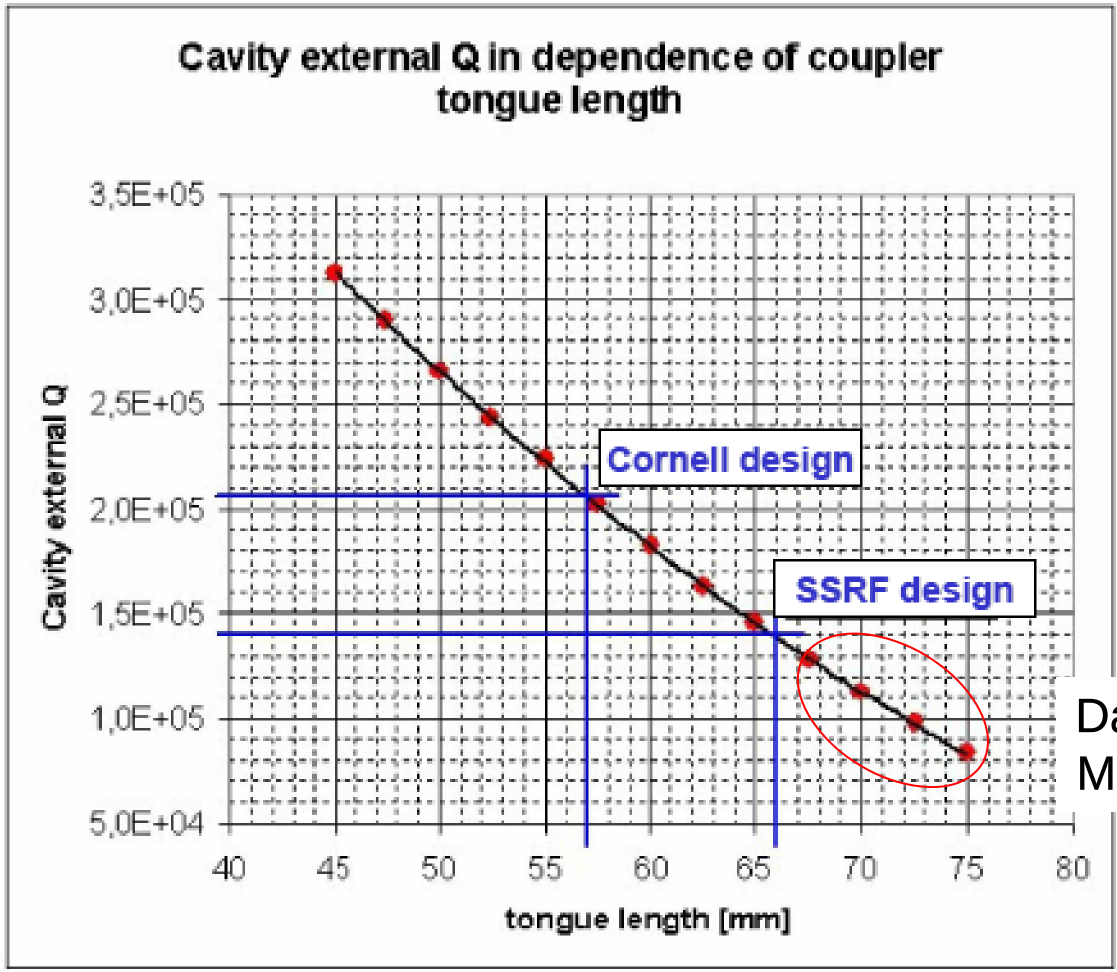
The straight section for SRF Cryomodules is **6289** meter long.

Reflected RF Power



NSLS-II: Qext = 65,000 for better Robinson damping
KEKB: Qext = 70,000

Cavity Coupling vs. tongue length



CSER cavity

Danger of Multipacting?

3-stub Tuner is required to tune for all beam loading conditions

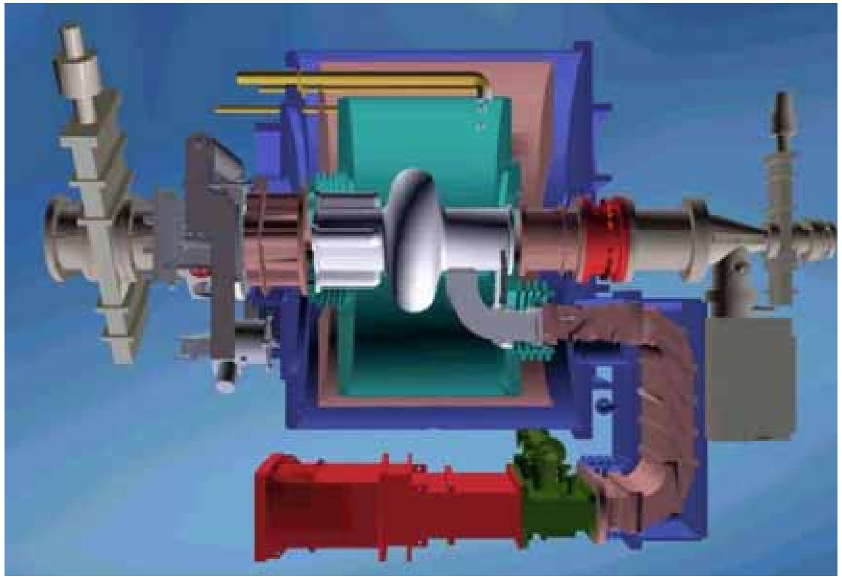
CRYOMODULES

Specifications of Available SRF Cavities

Specification	CESR-III	KEK-B
Resonant frequency [MHz]	499.765	499.8
R/Q [Ω]	89	95.3
Q_0	$>7\times10^8$	10^9
Operating Temperature [K]	4.5	4.5
Accelerating Voltage / Cavity [MV]	>2.5	>2 .0
Max. RF Power / Cavity [kW]	320	400
HOM Removal	Absorber	Absorber
Input power coupler	Waveguide	Coaxial

SC Cryomodule

CESR-B Type

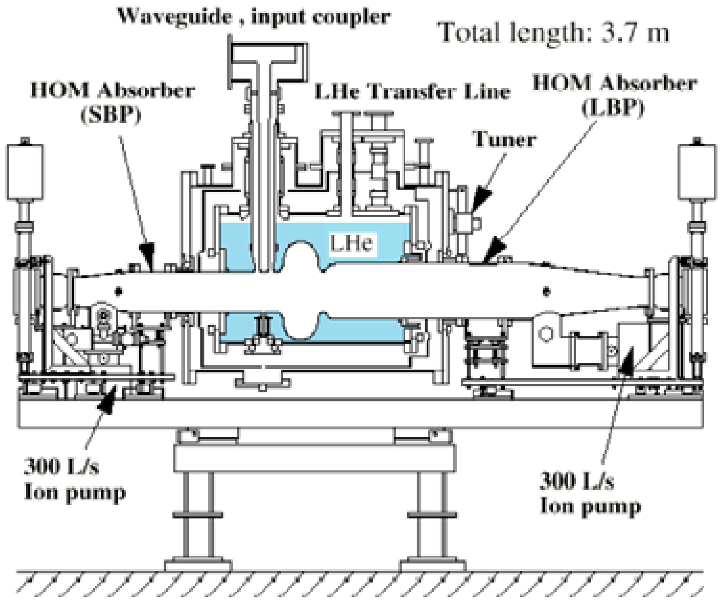


Cryomodule length: ~2.86 m

Input power coupler: Waveguide type

TLS, CLS, DLS, SSRF

KEK-B Type

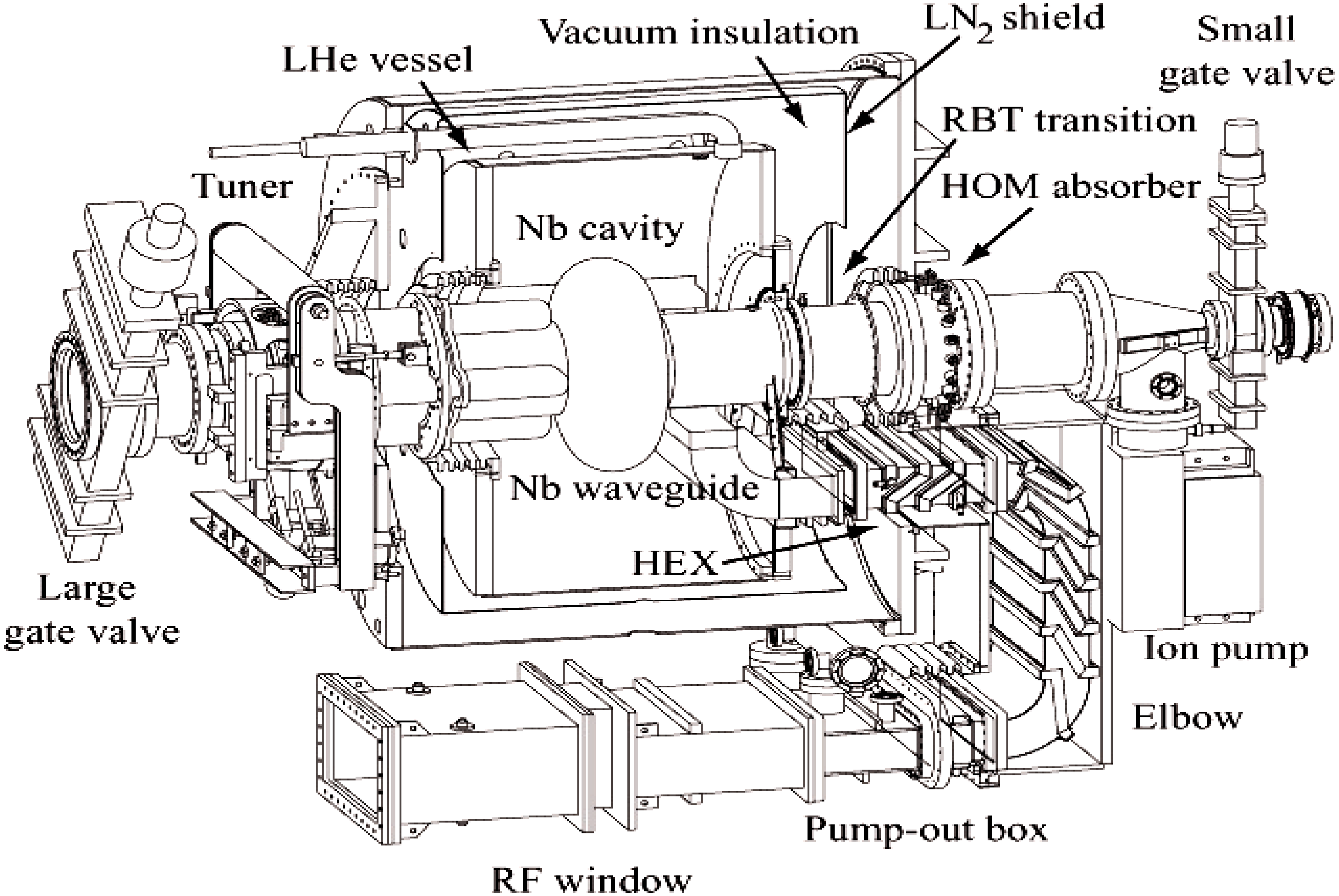


Cryomodule length: ~3.7 m

Coaxial type

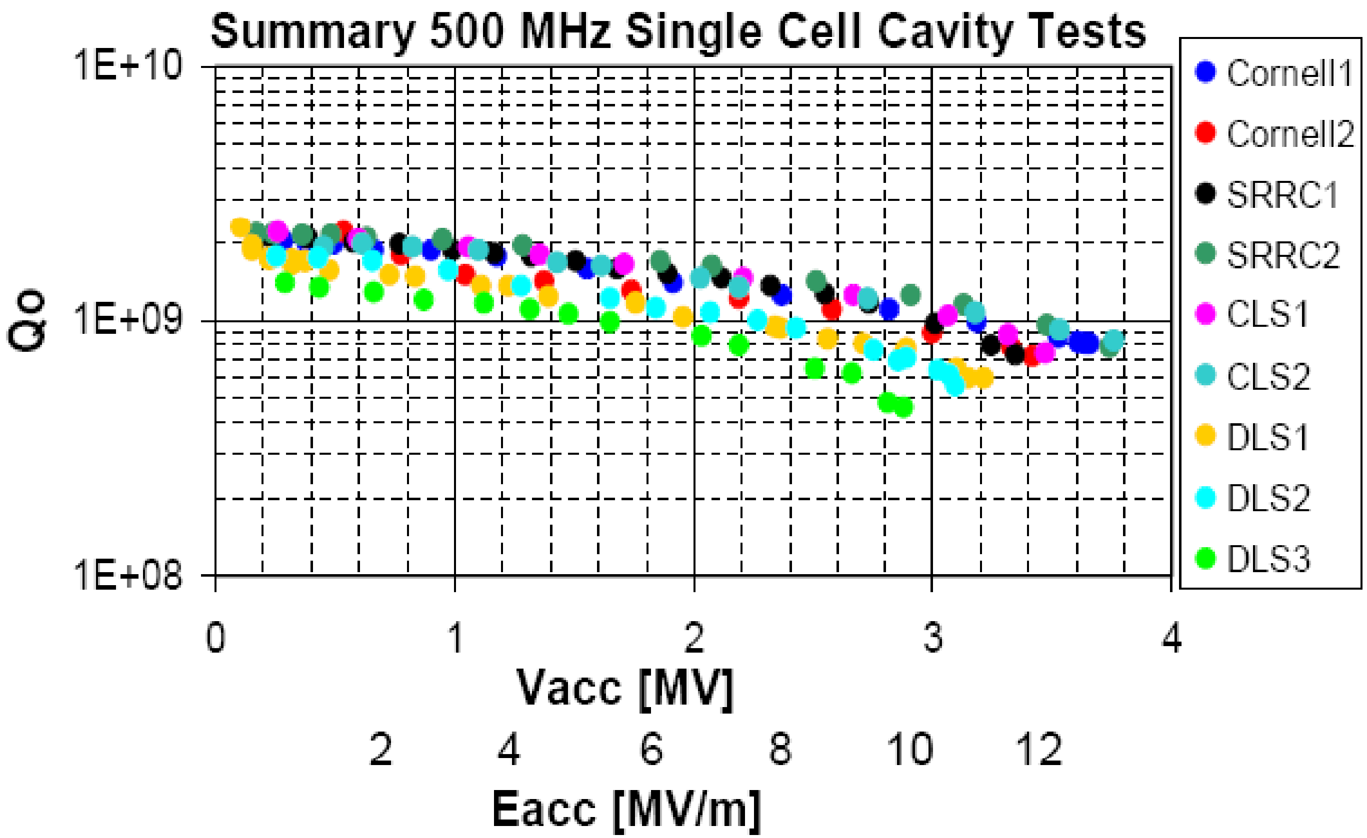
BEPC-II, KEKB

CSER-B type



Vacuum insulation
LN_2 shield
Small gate valve
LHe vessel
RBT transition
Tuner
HOM absorber
Nb cavity
Nb waveguide
HEX
Large gate valve
Ion pump
Elbow
Pump-out box
RF window

Vertical Tests of CESR-B Cavities



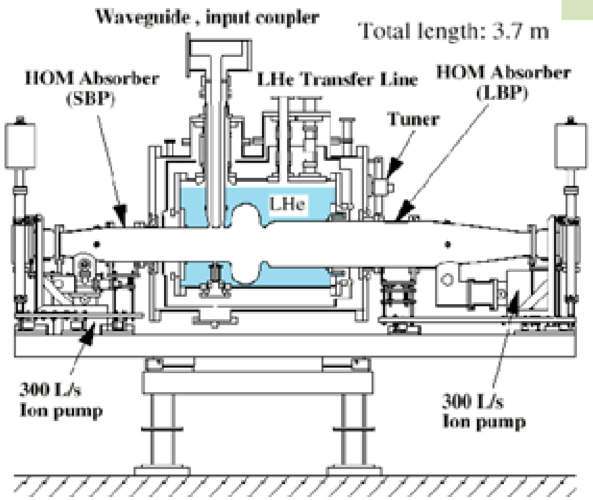
Q = w U / P

KEK-B Type SC Cryomodule

- Characteristics
  - Coaxial input power coupler, 350-400 kW
  - Frequency: 508 MHz
  - Beam tube diameter L/S: 300/220 mm
  - TM011 HOM damping with LBP
  - Cryomodule length: ~3.1 m

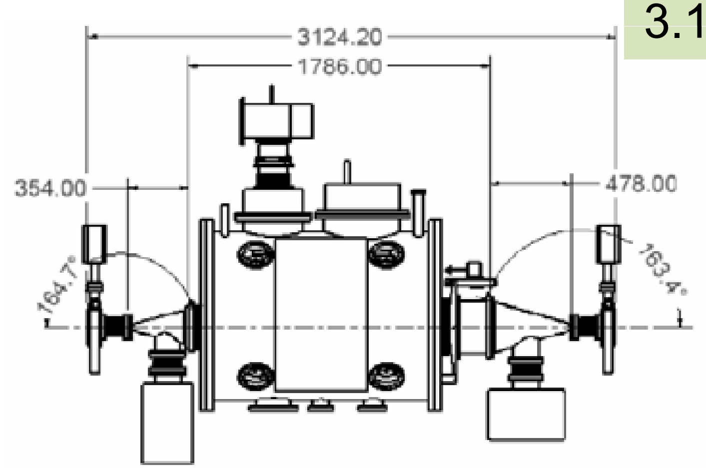
- Characteristics of coaxial power coupler
  - More compact, but more complicated
  - Smaller heat leak
  - Variable coupling possible
  - Biasing to suppress MP possible
  - Gas He and water cooling

3.7 m



BEPC-II Version

3.12 m

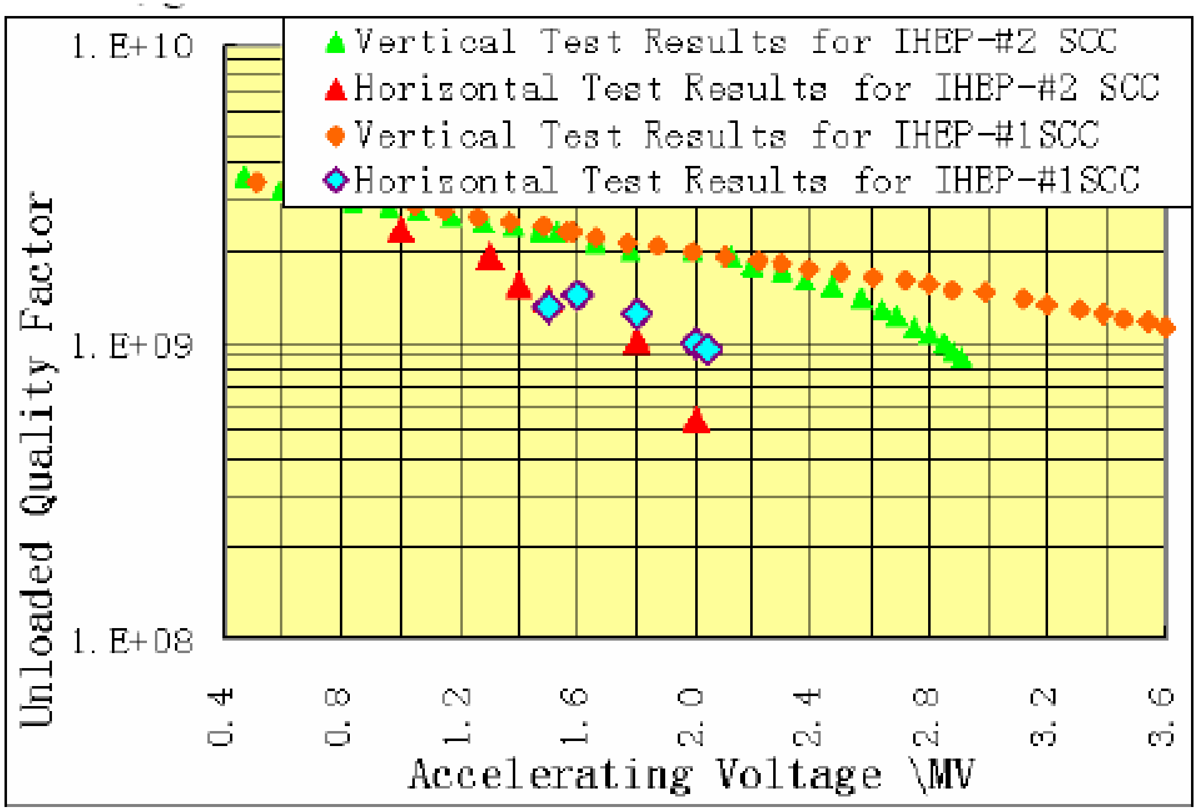


Proposed Version for PLS-II

KEKB cryomodule for BEPCII

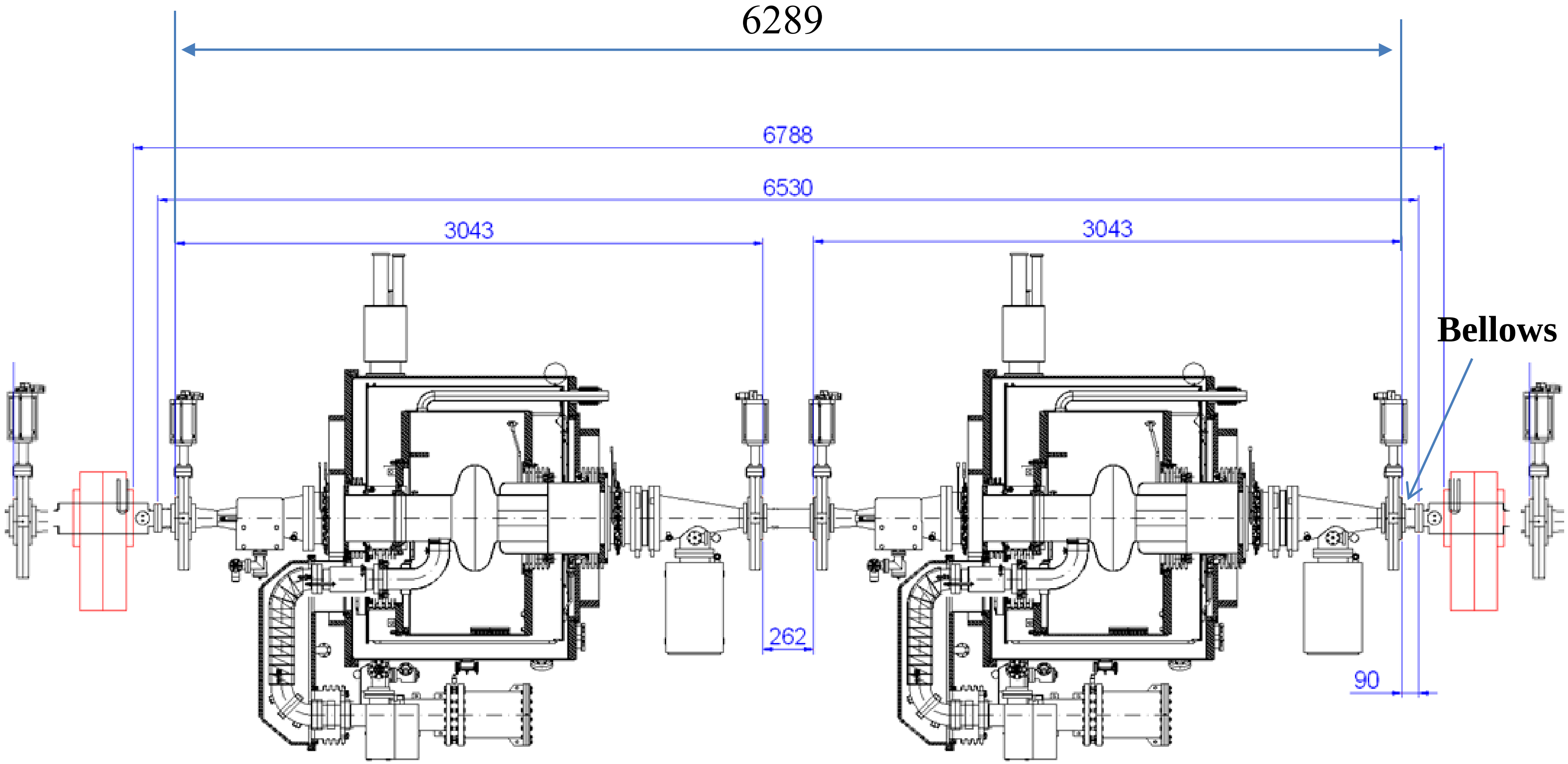
built by Mitsubishi Electric Corporation.

Vertical Tests of BEPC-II Version



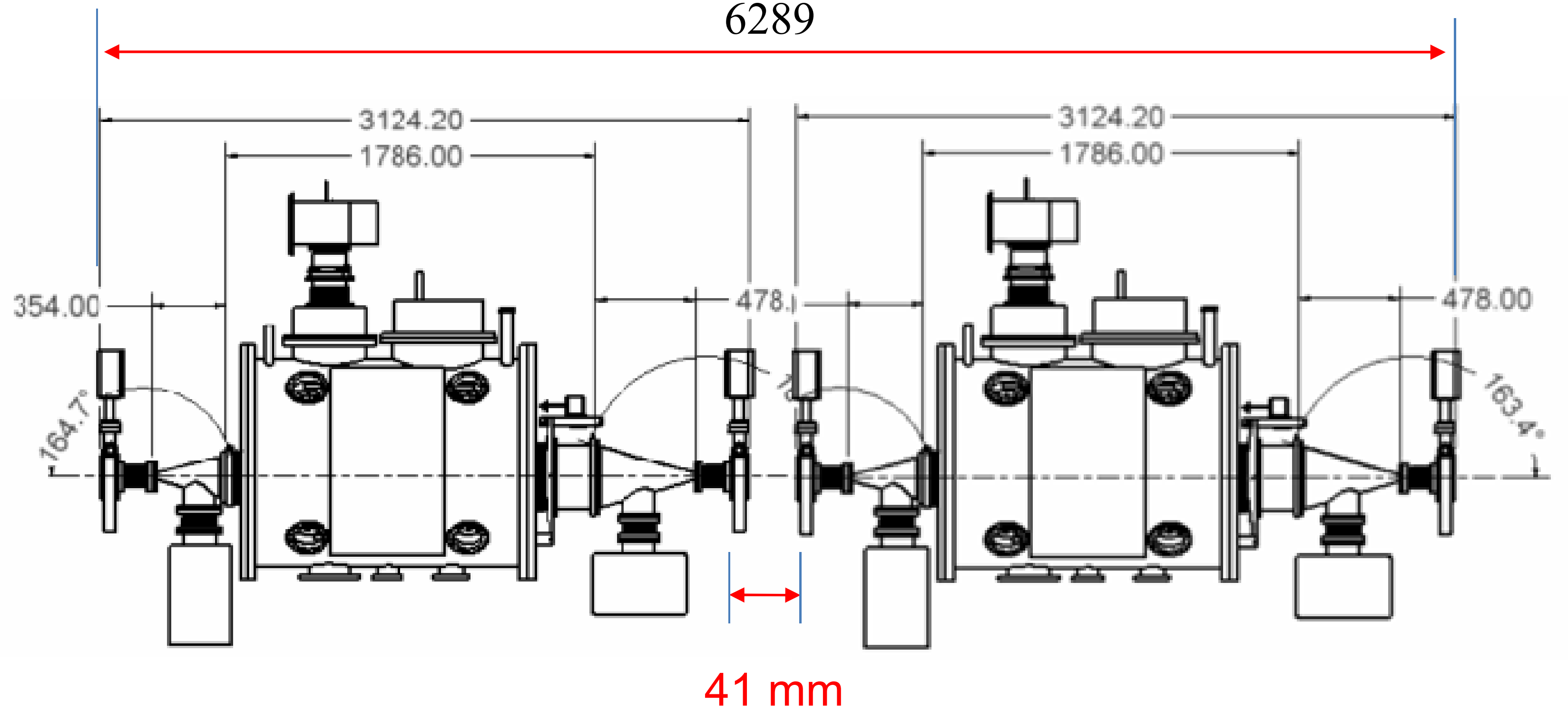
T. Furuya, et al, SRF2007, Beijing

Cryomodule arrangement (CSER-type)



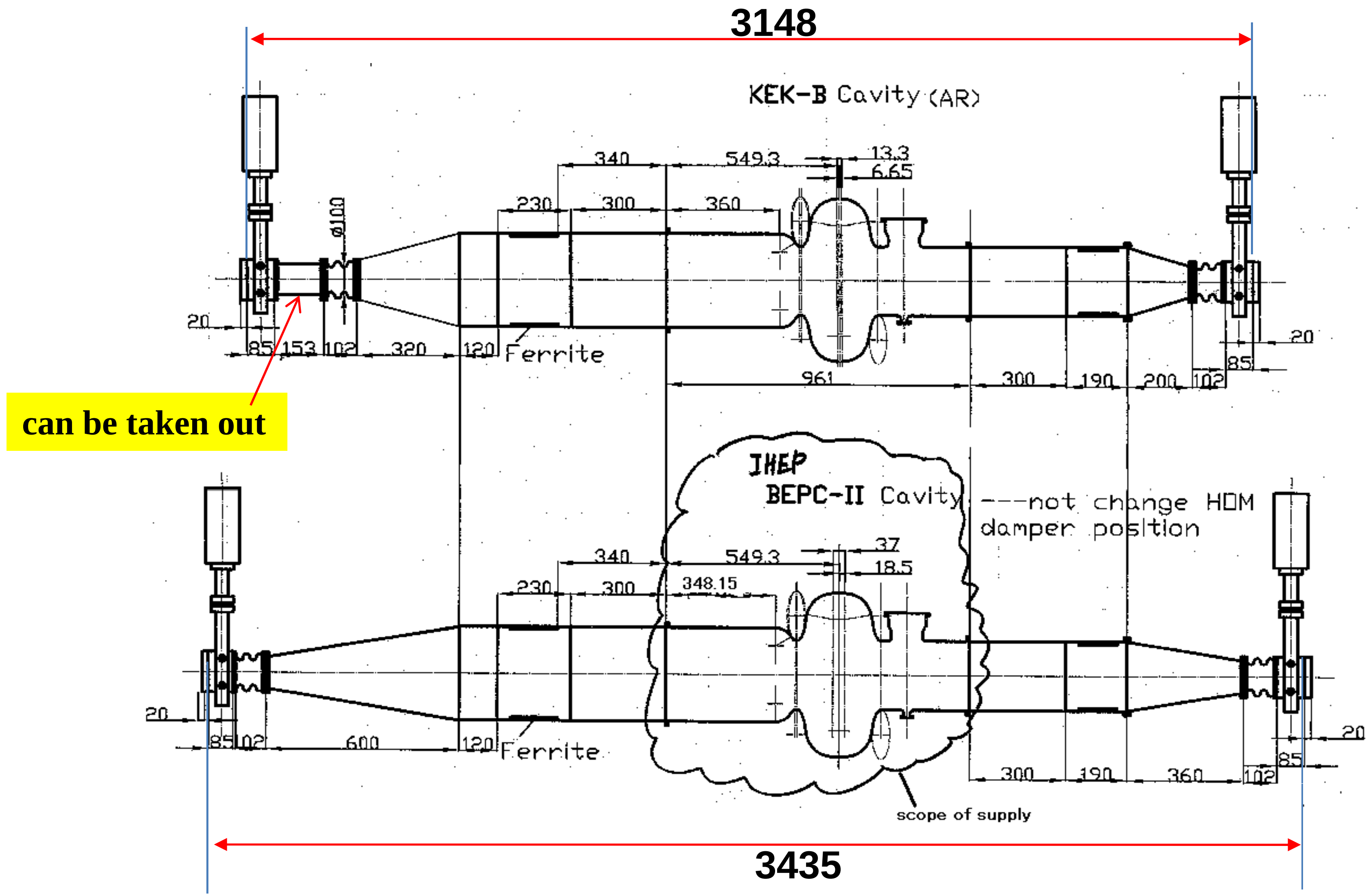
Two CESR-type cryomodules in a long-straight section.

Cryomodule Arrangement (KEKB-type)



Using the TPS design of KEK-B cryomodule

Length of KEKB Crromodule



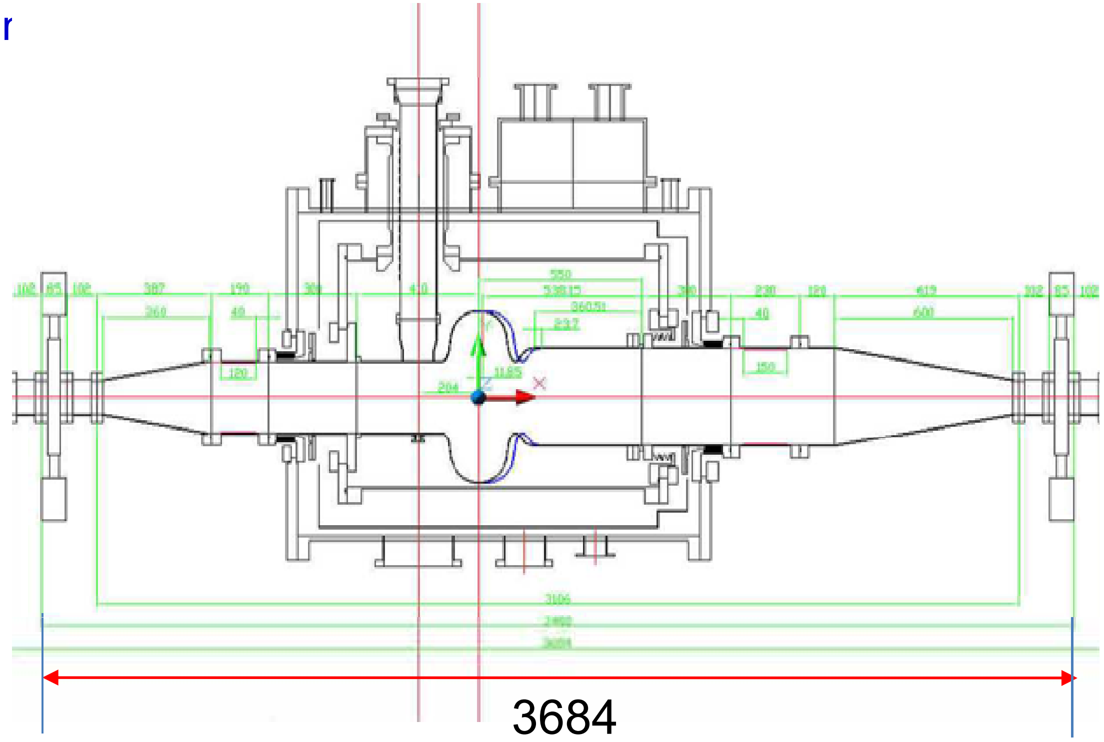
Collaboration with IHEP in Beijing

◆ BEPC-II of IHEP: SC module of 500 MHz

- Upgrading of BEPC (Beijing Electron Positron Collider).
  collision mode: 1.89 GeV, 910 mA + 910 mA
  SR mode: 2.5 GeV, 250 mA
- Use of SC cavities based on KEKB cavity.
- Because of a difference of RF frequency, a slight modification was given to the equator straight. (13.3 r

Parameters of Cavity Shape

•Frequency	(MHz)	499.8
•Accelerating gap	(mm)	267
• beam pipe diameter	(mm)	220
•Large beam tube diameter	(mm)	300
•*R*/*Q*	(Ohm/cavity)	95.3
•Loss factor	(V/pC)	0.075
•*Esp*/*Eacc*		1.87
•*Hsp*/*Eacc*	Gauss/(MV/m)	41.1



CRYOGENIC SYSTEM

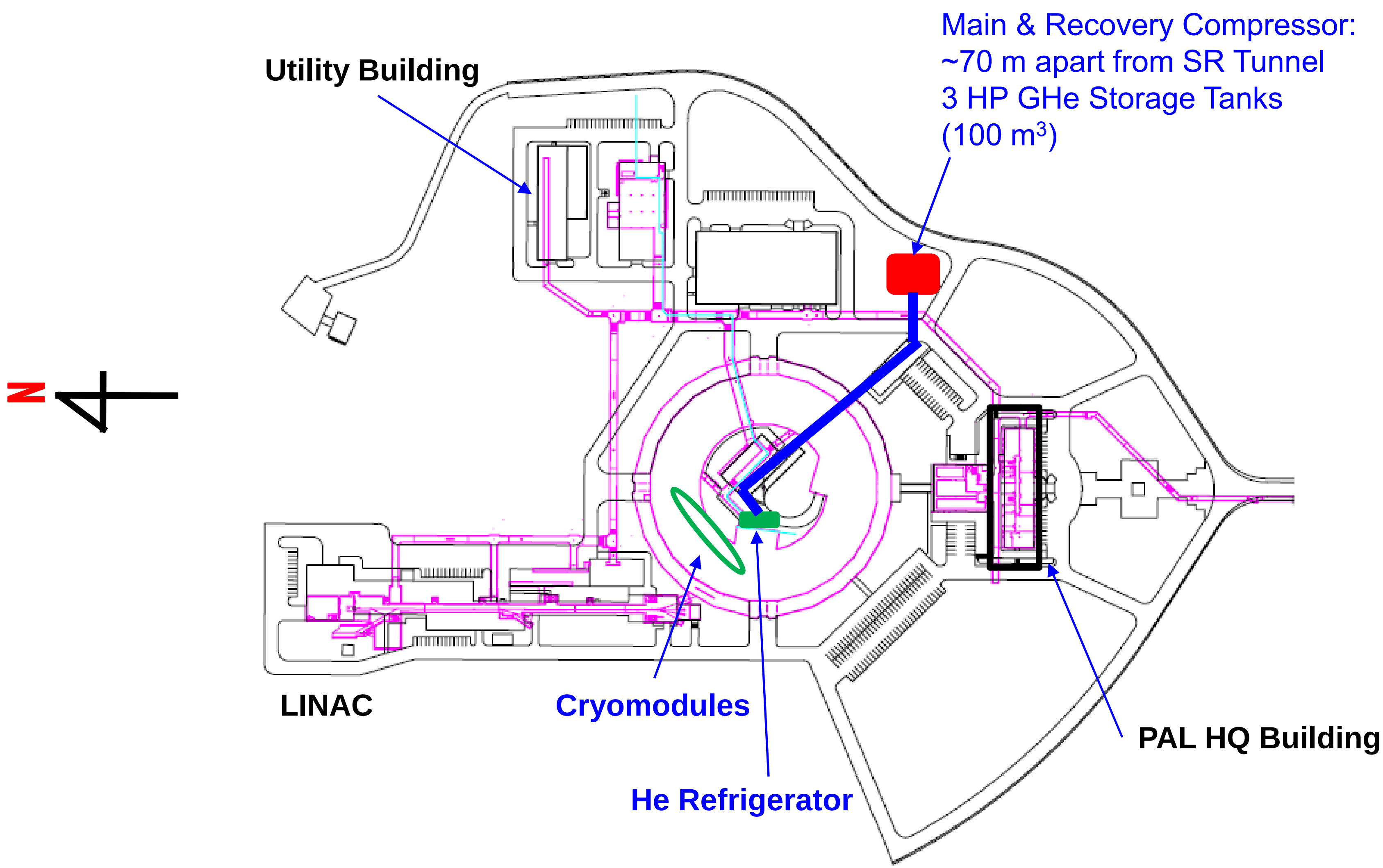
Cryogenic Heat Loads

Sources and parameters	Value	Unit
Number of SRF Cryomodule	3	-
SRF Cavity Static Heat Load	30 ✕ 3	W
SRF Cavity Dynamic Heat Load @1.7 MV	65 ✕ 3	W
Cooling Input Power Coupler (require LHe flow)	6 x 3	Liter/hour
Distribution Valve Box	30	W
L He Transfer Line (Length: 35 m +15 m x 3)	80	W
L He Dewar (2000 liter)	30	W
Estimated Heat Load from main SRF modules	425	W
Total Heat Loads	**425** **18**	**W** **Liter/hour**
Machine capacity Margin	50	%
Required Capacity of He Refrigerator	700	W

Parameters of a PLS-II cryomodule cooling system

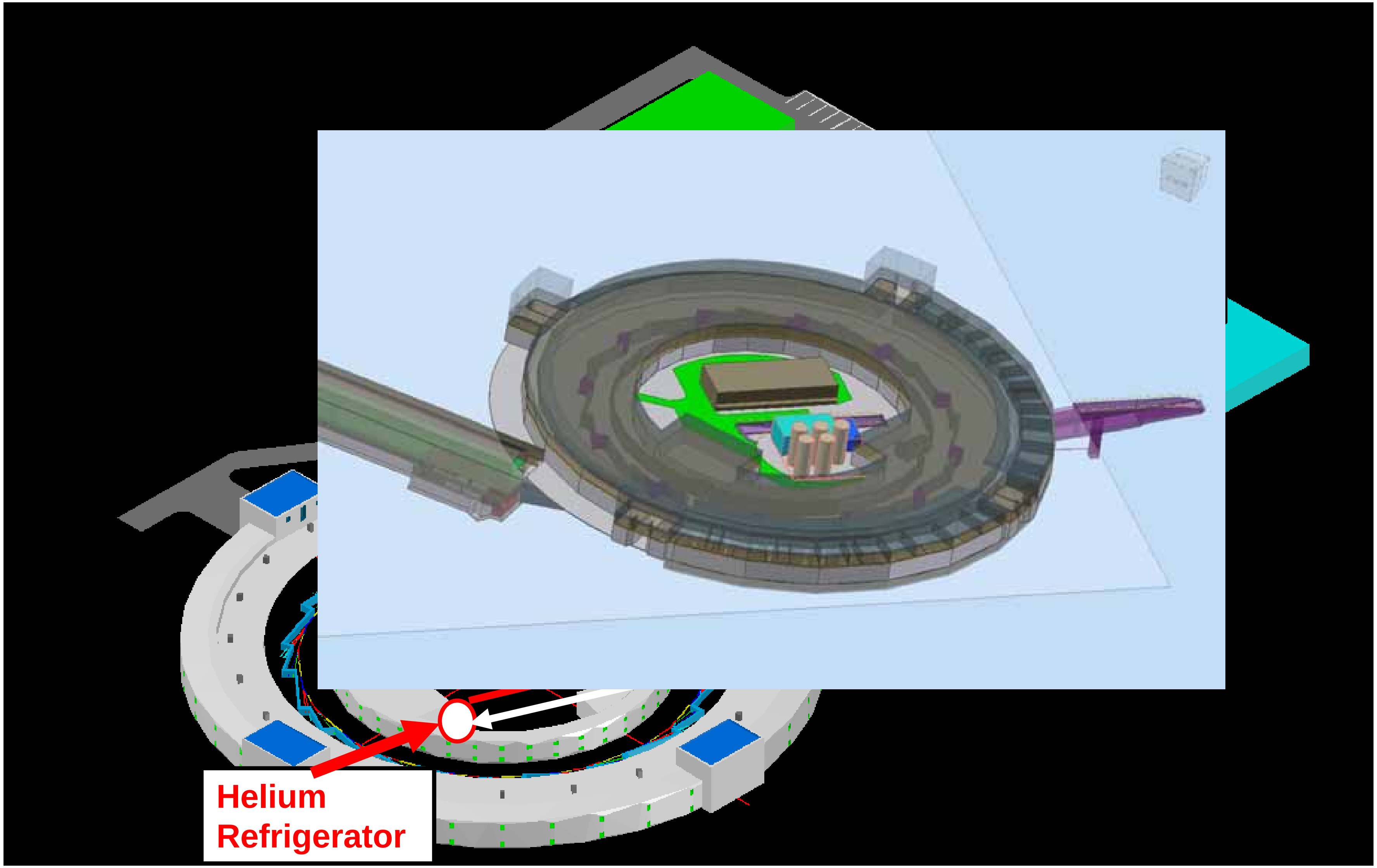
Parameter name	**Value**
Cavities per cryomodule	1
Helium circuit static heat load	~30 W
Helium circuit dynamic heat load	< 70 W
Pressure in helium vessel	1220 ± 3.0 mBar
Temperature in helium vessel	4.5 K
Helium liquid level tolerance in helium vessel	1.0 %
Pressure of the helium liquid circuit supply	~1.28 Bar
Maximum allowable pressure in helium vessel	1.49 Bar
Relief pressure in helium vessel	1.35 Bar
Temperature of the nitrogen circuit gas supply	77 K supply
Nitrogen input	< 2 g/s (100 l/min.)
Pressure of the cooling water supply	8.0 Bar
Temperature of the cooling water	25 ^{o}C ~ 35 ^{o}C
Pressure of the cooling water return	4.0 Bar
Water flow at HOM dampers	> 3 l/min
Water flow at RF window	> 11.5 l/min
Water flow at tapers	> 3.0 l/min
Water velocity	2 m/s

Arrangement of Cryogenic System



※ Pink Line: Underground Tunnel for utility like piping, wires

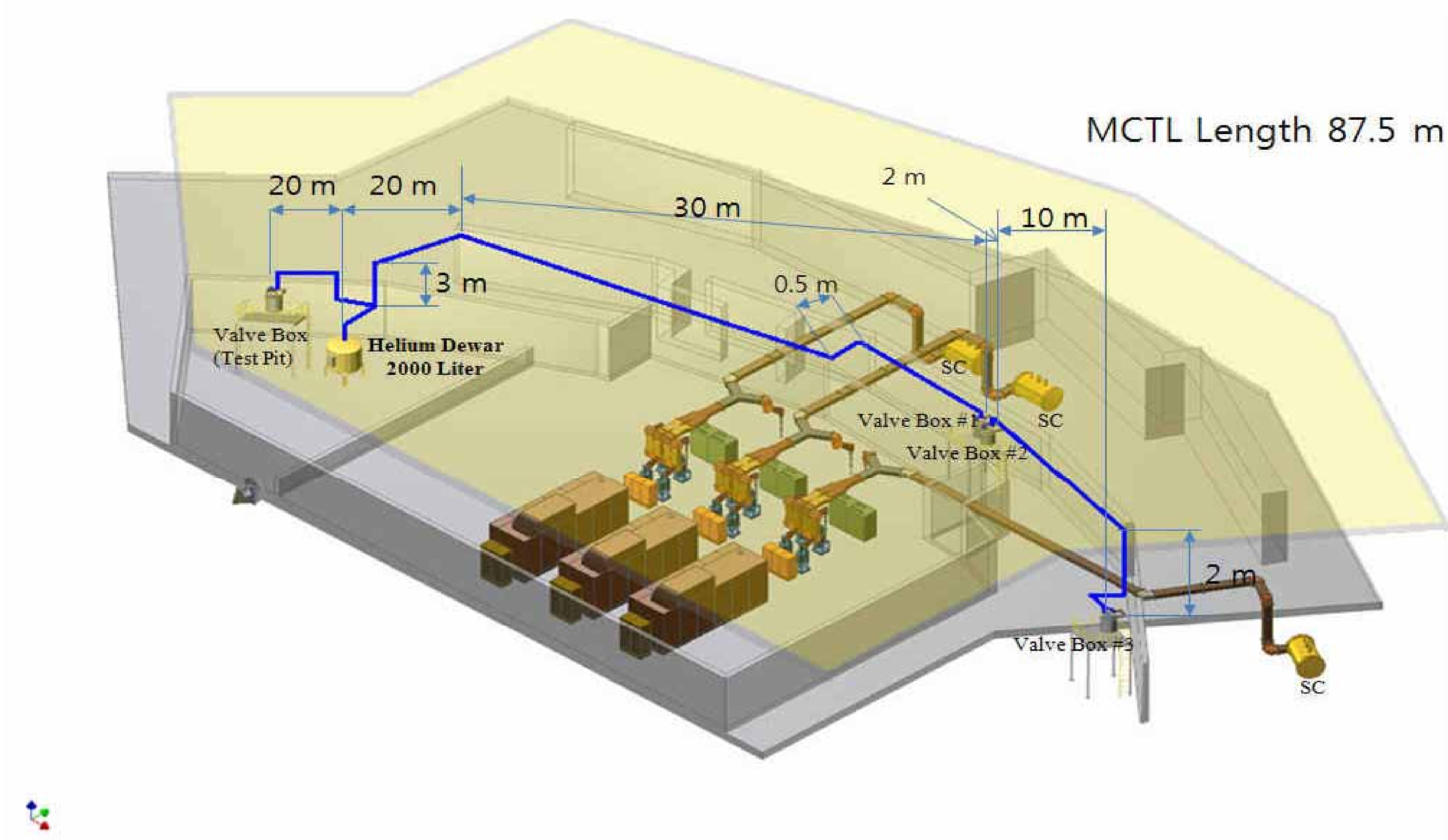
Proposed Layout of He Facility



Capacity of 700 W Cryogenic System

- Minimum of **450 W** Refrigerating capacity at **4.5K** without LN2 Pre-cooling.
- Minimum of **18 L/h** liquefying capacity at **4.5K** with LN2 Pre-cooling
- Minimum of **715 W** Refrigerating capacity at **4.5K** with LN2 Pre-cooling

MCTL Design

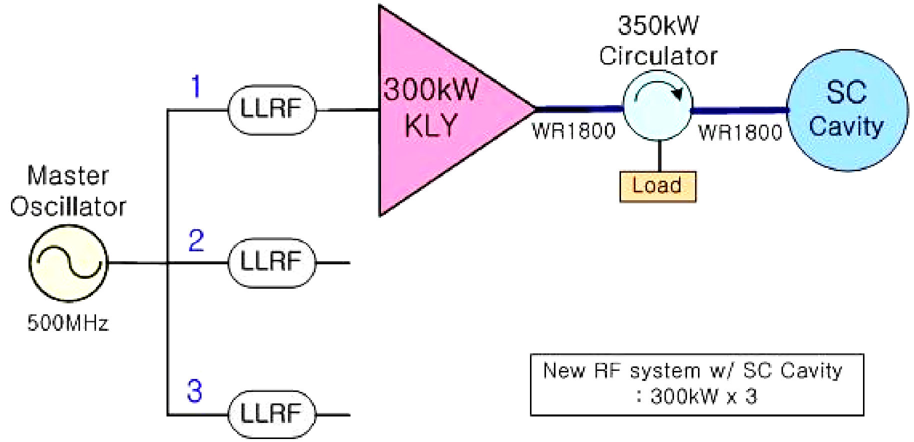


MCTL Length 87.5 m
20 m
20 m
30 m
2 m
10 m
3 m
0.5 m
Valve Box
(Test Pit)
Helium Dewar
2000 Liter
SC
SC
Valve Box #1
Valve Box #2
2 m
Valve Box #3
SC

HIGH POWER RF & LLRF

High Power System

- Scheme of power transmission

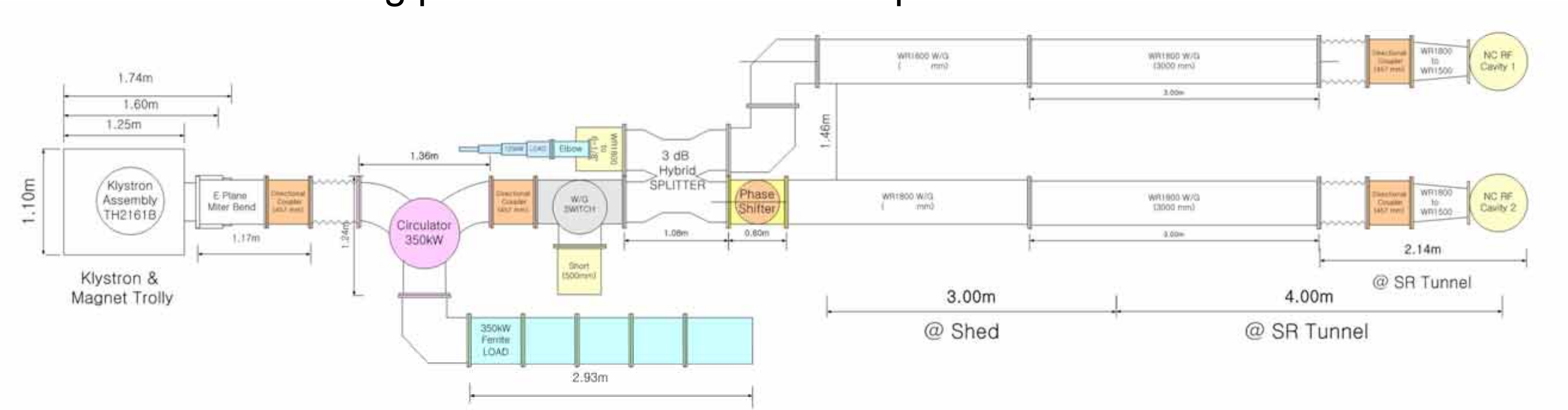


- <u>Baseline design: Klystron</u>
- Specification of power transmission

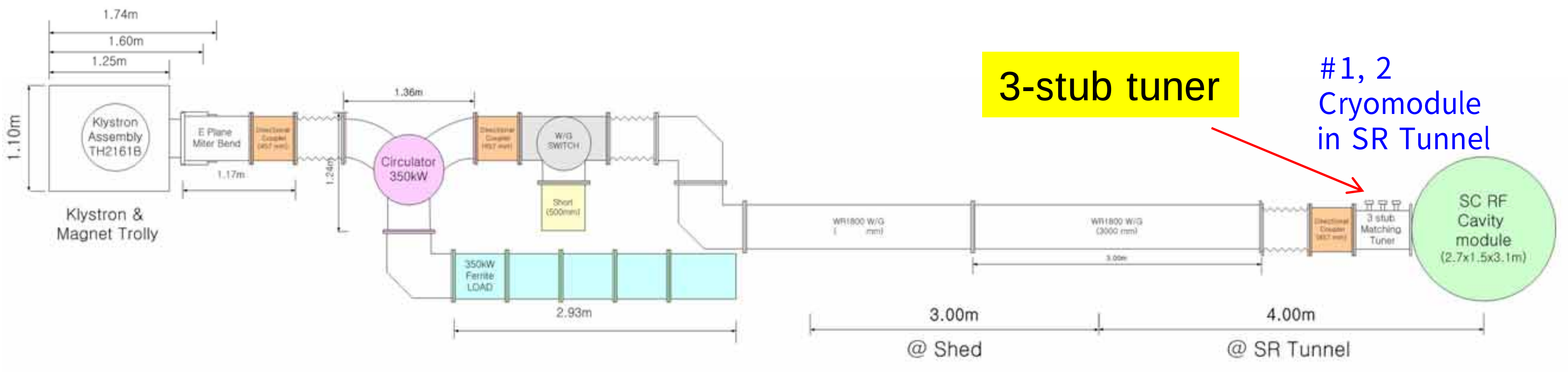
# of Amplifier/HVPS	3
Waveguide	WR1800
Circulator	~350kW
Amplifier	300kW klystron
HVPS	55kV/10A

Configuration of Power Transmission

1. Commissioning phase: New 2x300 kW amplifiers and 4 NC cavities



2. Design with 3 SC RF system: New 3x300 kW amplifiers and 3 SC cavities



300kW High Power System of SSRF

COMMISSIONING SCHEME & MILESTONE

Commissioning Plan

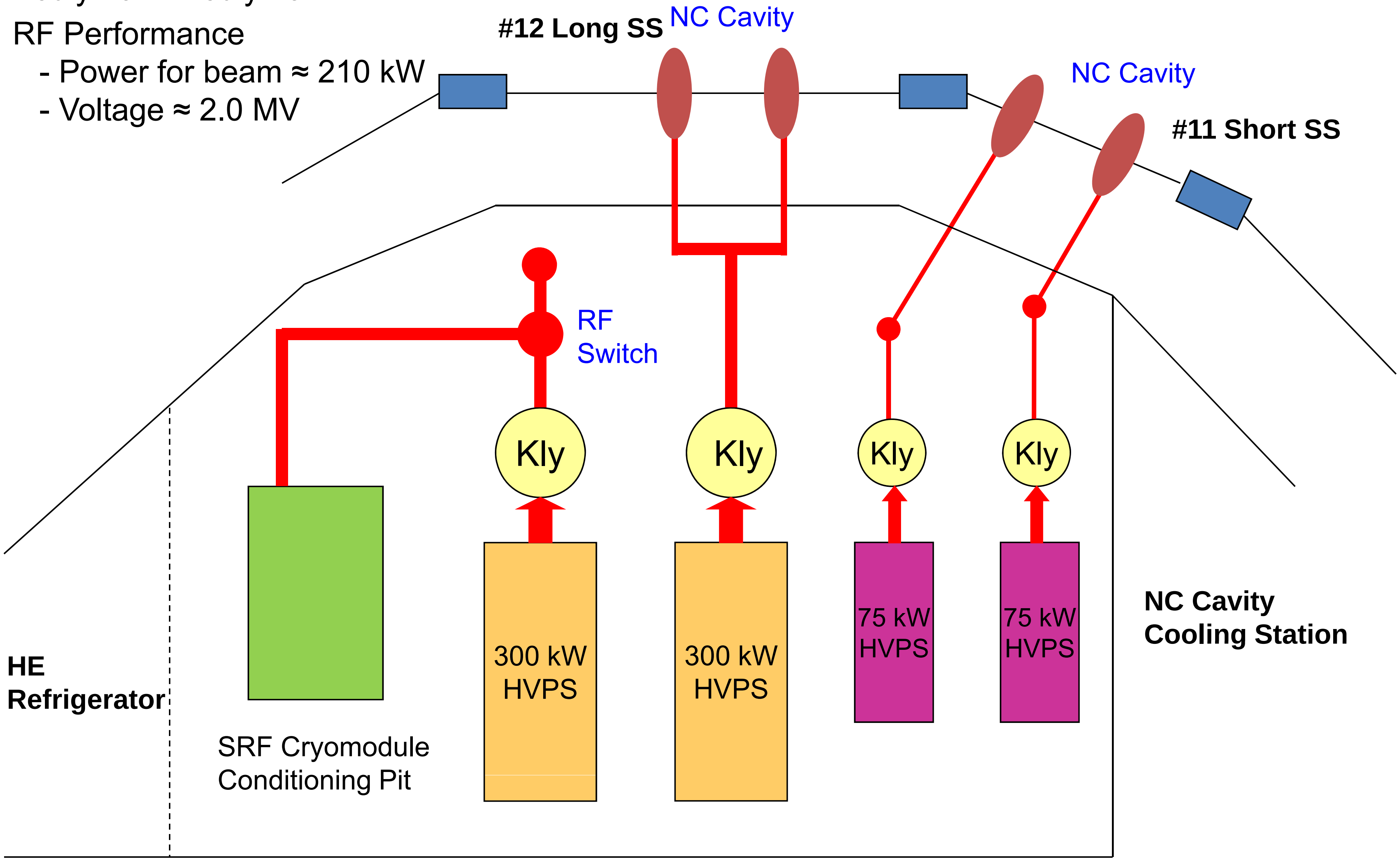
Period	Cavity	RF power source	RF voltage	Available RF Power for beam	Beam Current류 [mA]	Touschek lifetime [hrs]
2011. 7 – 2012. 7	NC: 4 ea	300 kW: 1ea 75 kW: 2 ea	0.55 x 2 = 1.1 0.45 x 2 = 0.9 Total = 2 MV	70 x 2= 140 35 x 2 = 70 Total = 210 kW	200 mA (without ID)	> 7 hrs
2012. 8 – 9	• Two SC Install • Dismantlement of Two NC					
2012. 10 – 2013. 7	SC: 2 ea NC: 2 ea	300 kW: 2ea 75 kW: 2 ea	1.65 x 2 = 3.3 0.45 x 2 = 0.9 Total= 4.2 MV	260 x 2= 520 35 x 2 = 70 Total=590 kW	400 mA (without ID)	> 25 hrs
2013. 8 - 9	• Third SC Install • Dismantlement of Two NC					
2013. 10 ~	SC: 3 ea	300 kW: 3ea	1.5 x 3 = 4.5 Total= 4.5 MV	260 x 3= 780 Total=780 kW	400 mA (with ID)	> 20 hrs

Commissioning Phase

July 2011 – July 2012

RF Performance

- Power for beam ≈ 210 kW
- Voltage ≈ 2.0 MV

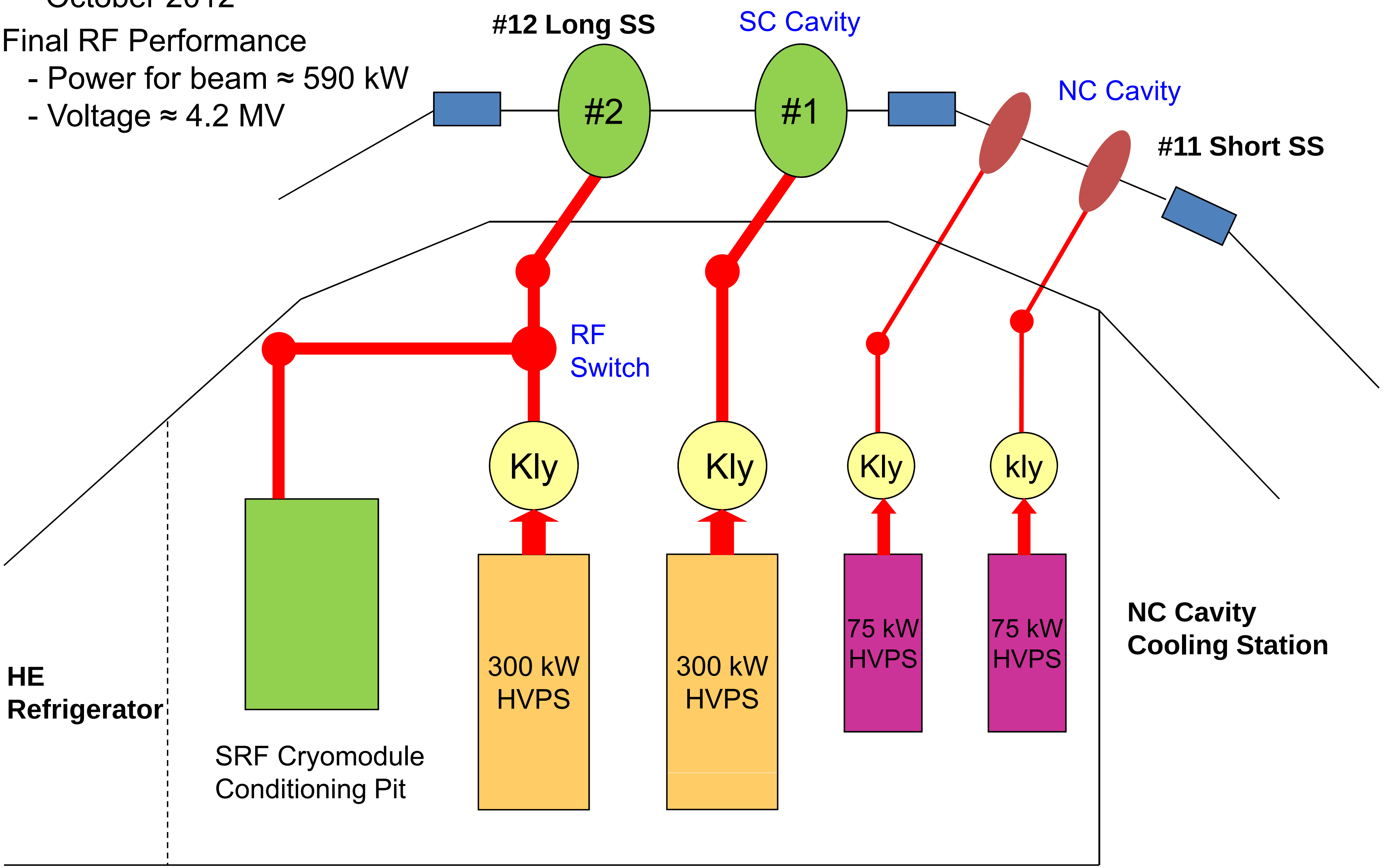


Hybrid RF System Phase

October 2012

Final RF Performance

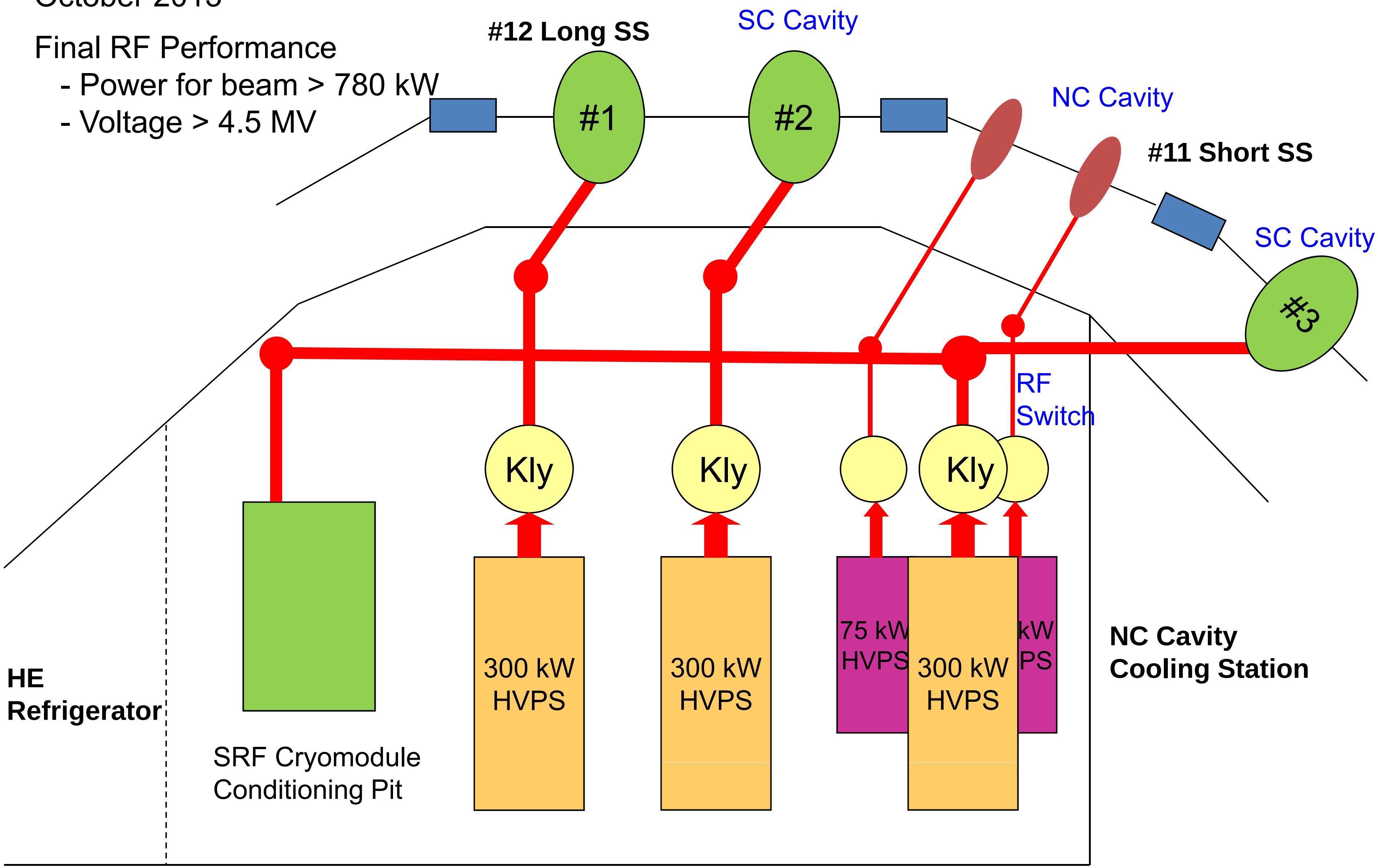
- Power for beam ≈ 590 kW
- Voltage ≈ 4.2 MV



Final SC Phase

October 2013

Final RF Performance
- Power for beam > 780 kW
- Voltage > 4.5 MV



Thank you for Listening