DRFS Development

KEK S. Fukuda

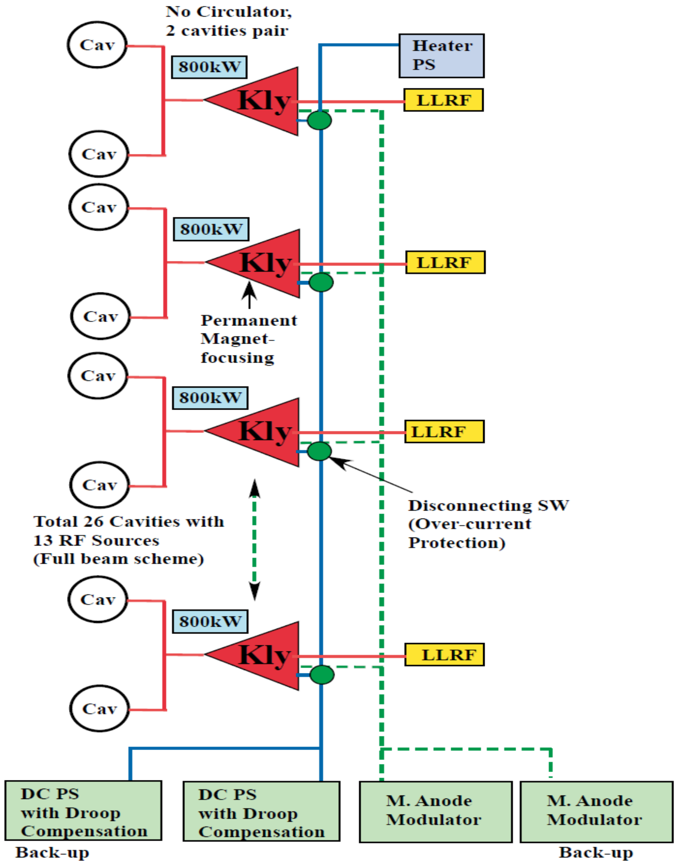
- Concept of DRFS
- New DRFS Layout
- Radiation Issue
- R&D Plan for DRFS in KEK
- Summary

Concept of DRFS

Concept of DRFS

- The Distributed RF System (DRFS) is another possibility for a cost-effective solution in support of a single Main Linac tunnel design.

- Base line of proposed DRFS
  - **one unit of 800kW Modulating Anode (MA) klystron would drive two cavities (in basic configuration scheme –RDR).**
  - **totally about 8000 MA klystrons would be used.**
  - **It is based on much simpler and more compact HLRF and LLRF units than the RDR baseline or KCS.**
  - **It offers a good operational flexibility in coupling with performance variations of individual cavities.**
  - **By employing suitable back-up modules for key component, high availability would be expected.**
  - **Complete single tunnel model, no facility in the surface**



Parameters in DRFS

In the RDR scheme, three units of ILC cryomodules, containing 26 cavities in total, are driven by the RF power from one unit of 10MW L-band klystron.

In the proposed new scheme of DRFS, 2 cavities are driven by one unit of **800kW L-band MA klystron allowing the cavity gradient variation of 31.5MV/m +-20%.**
Therefore, one would see that three cryomodules with 26 cavities will be driven by thirteen units of MA klystrons.

Specification

Klystron	Frequency	1.3	GHz
	Peak Power	800	kW
	Average Power Output	8.00	kW
	RF pulse width	1.5	ms
	Repitition Rate	5	Hz
	Efficiency	60	%
	Saturated Gain		
	Cathode voltage	65.8	kV
	Cathode current	20.3	A
	Perveance(Beam@65.8k\	1.2	micro Perv
	(Gun@54.4 kV)	1.56	micro Perv
	Life Time	120,000	hours
	# in 3 cryomodule	13	
	Focusing	Permanent magnet	
	Type of Klystron	Modulated Anode Type	
DC Power supply per 3 cryomodules			
	# of klystron (3 cryomodu	13	
	Max Voltage	71.5	kV
	Peak Pulse Current	264	A
	Average Current	2.67	A
	Output Power	177	kW
	Pulse width	2.2	ms
	Repitition Rate	5	Hz
	Voltage Sag	<1	%
	Capacitor	26	mF
Bouncer Circuit			
	Capacitance	260	mF
	Inductance	4.9	mH
M. Anode Modulator			
	Anode Voltage	54.4	kV
	Anode Bias Voltage	-2	kV

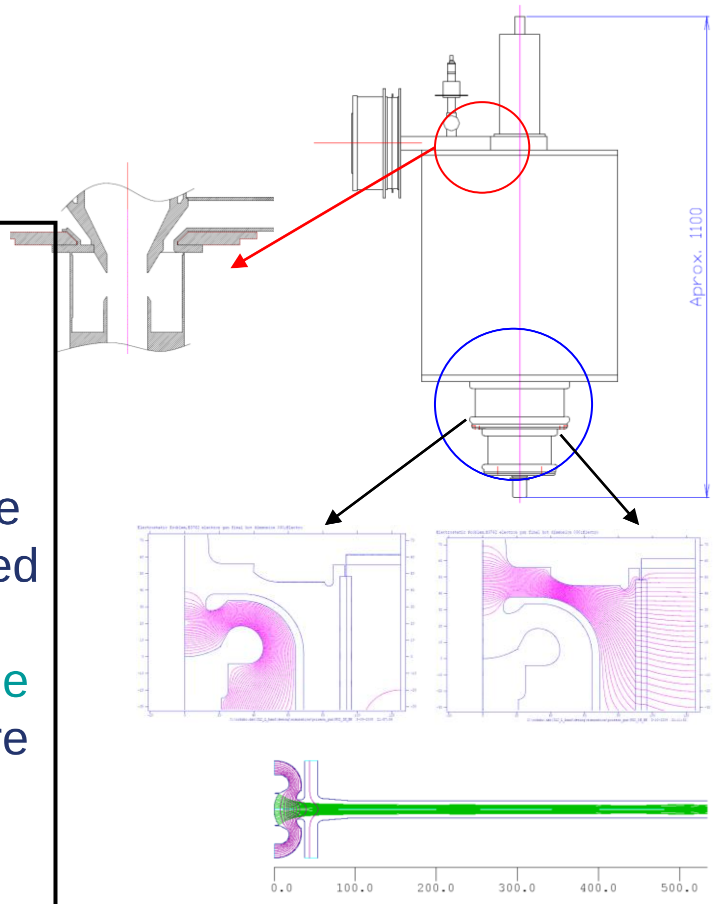
Klystron for DRFS

Parameters of MA klystron is summarized
In the previous table.

Features of DRFS klystron

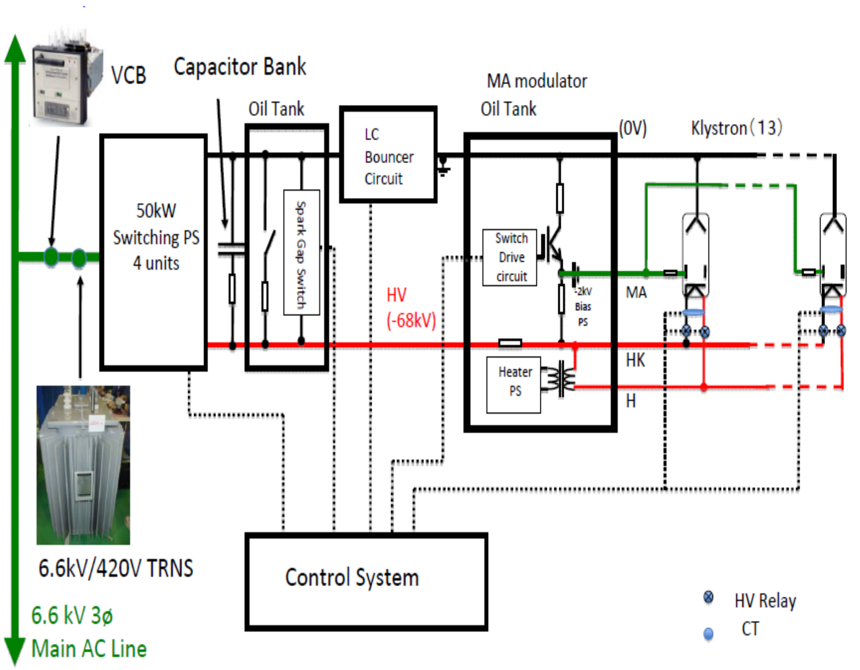
Applied voltage of less than 65kV
60% efficiency with 1.2 micro-perveance
Low field gradient in klystron gun —few arcing
Low cathode loading--- long cathode life
Low output power--- free from output window failure
→ Long life of klystron would be expected

Permanent magnet focusing---from availability issue
free from magnet and power supply failure
Common heater power supply with back-up
--- contribute to high availability



Modulator Scheme/Base Line DRFS

- The DC power and anode modulation for a group of 13 units of klystrons are provided by **one common DC power supply and one common anode modulator** (MA modulator).
- **In order to realize high reliability, each two-RF unit of the DC power supplies and MA Modulators has an backup units, which will be designed and implemented to be "hot-swappable".**

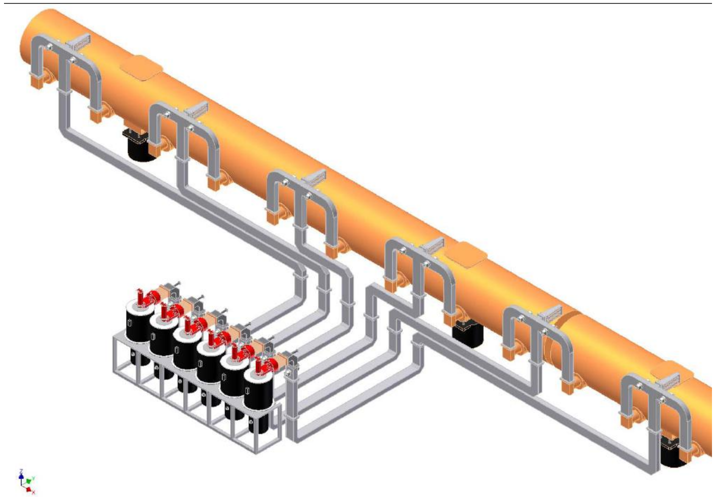


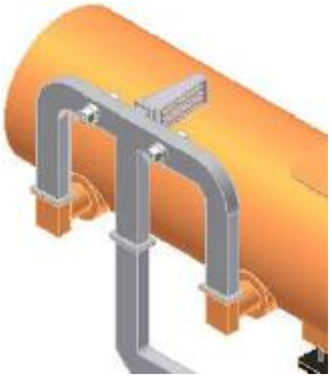
- Each of the power and voltage distribution circuits will have **a high-voltage SW or relay**, which switches off the line when over curren failures are detected.
- A DC power supplies has a **bouncer circuit for compensation of the pulse flat droop**.
  (This leads to a relatively small condenser bank)
- The charger of a DC power supply comprises of a bundle of several units of identical switching PS. This allows us to increase its electrical power with ease, simply by adding more switching PS. So it is possible to expand the system more than RDR unit.
- Common heater power supply and permanent magnet focusing to eliminating magnet power supply.

Power Distribution System (PDS) in Base line DRFS

Simpler power distribution system than RDR. PDS feeding configuration is shown in right figure.

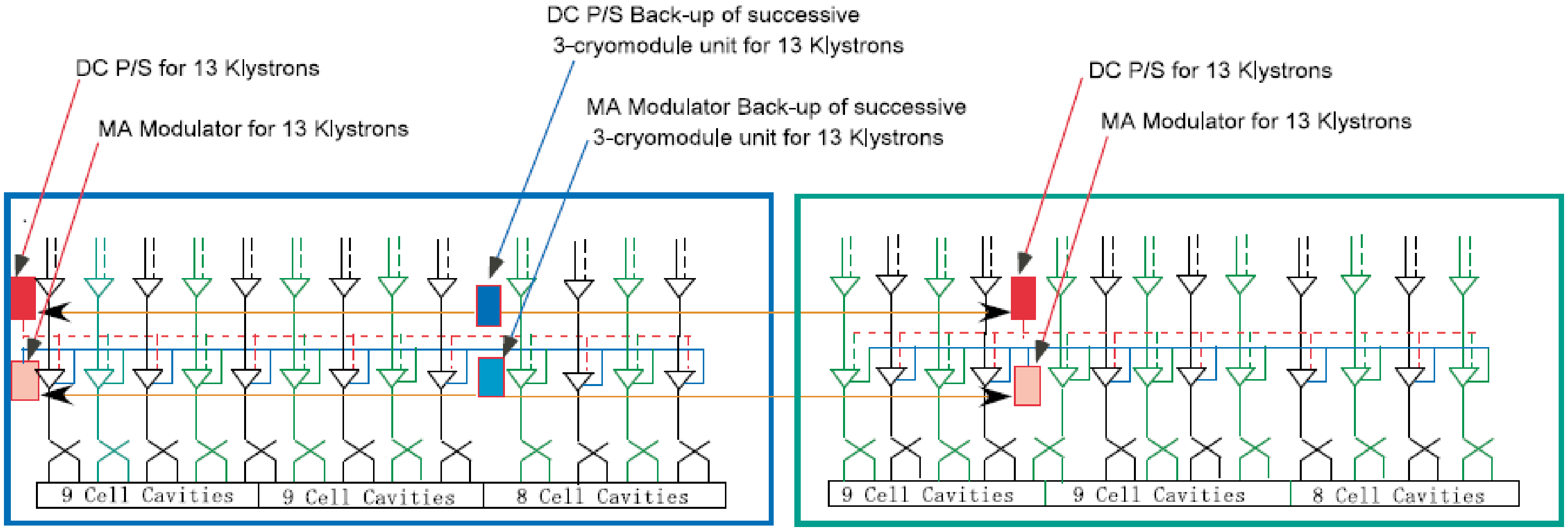
- **No circulator**
- **Power divider employs magic tee with high isolation for space saving.**
- **One phase-fixed waveguide for cost saving which assures the cancellation of reflection and phasing of beam among the successive cavities.**
- **Design of eliminating flange as possible leads to the cost reduction.**
- **800kW RF is propagated in the dry air without any extra ceramic window**





Redundancy Scheme

Availability Consideration Revised



Full Power Option@ 26-Cavities
(1 klystron feeds 2 cavities)
= 1 DC P/S +0.5 Back-up
1 MA Pulser +0.5 Back-up
13 Klystrons
26 Cavities
13 Magic-tee(Hybrid)

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Cavity Pairing Scheme in DRFS

- We permit that SCRF Cavity Property varies 31.5 MV/m+-20%. This means from 25MV/m to 38MV/m.
- In DRFS, baseline doesn't use circulator and in order to accept above variety, cavity pairing scheme of having almost the same gradient is required.

  (25MV/m&25MV/m ………..38MV/m&38MV/m)
- From the HLRF viewpoint, most severe condition is come from the pair of 38MV/m cavities, while 800kW output from the DRFS klystron can drive the pair of 38MV/m cavities if 9% overhead of rf is allowed. For less than 38MV/m cavities, more overhead is allowable.
- Considering the klystron yield rate, proper combination of klystron variation and cavity variation result in efficient application of resources.

Overhead of LLRF and DRFS Klystron Output

Cavity sorting accepting up to 38MV/m
Pairs requires power of 728kW for 4
Cavities in beam current of 4.5mA case.
(waveguide loss of 2.5% is included).

LLRF overhead is about 9%.
(Minimum overhead)

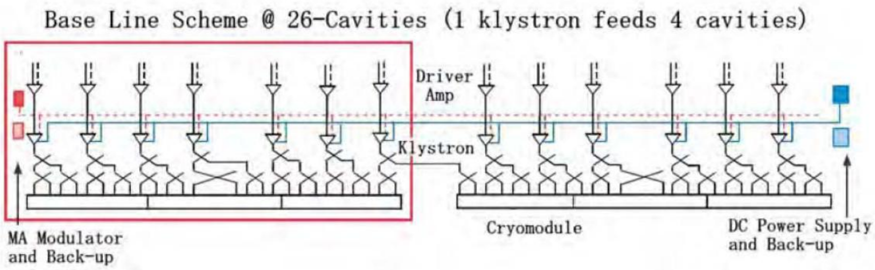
For more than 38MV/m, DRFS klystron
Feeds power of 800kW.

There are various sorting ways.
All same gradients cavity group

Mixture of different gradients
-> To optimize the performance,
P&Q adjustment may be reqired

Half-Power Option		4.5mA	
Applied Voltage		65820	V
μP		0.0000012	
Kly Po		800	kW
38MV/m Cavity			
	Required P	177.4	kW
	x 4Cavities	709.6	kW
	WG Loss	728	kW
	Overhead	9.1	%
31.5MV/m Cavity			
	Required P	147.1	kW
	x 4Cavities	588.4	kW
	WG Loss	603.5	kW
	Overhead	24.6	%
25MV/m Cavity			
	Required P	116.7	kW
	x 4Cavities	466.8	kW
	WG Loss	478.8	kW
	Overhead	40.2	%

DRFS upgrade pass



System configuration of DRFS in the baseline case.

Low Power OPtion

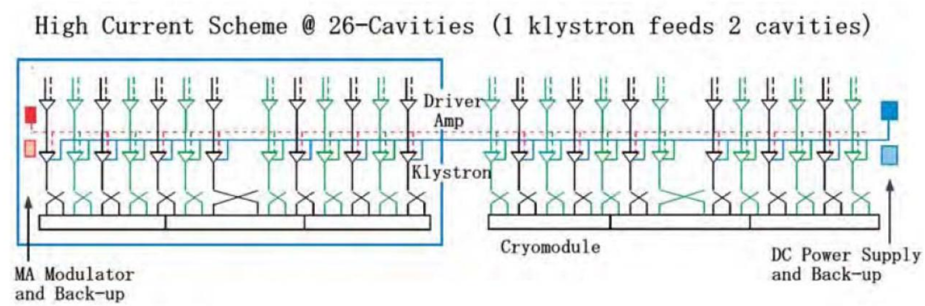
Base Line Scheme (@ 3 Cryomodules)

Cavity	26
DC	26
Magic T	19.5
750kW Kly.	6.5
PM Focusing	6.5
Coil PS	0 PM focusing
Heater PS	0.5 (0.5 back-up)
Preamp	6.5
MA Pulser	0.5 (0.5 back-up)
LLRF&Intlk	6.5
DC P/S	0.5 (0.5 back-up)

The component count for the DRFS in the baseline case. For comparison with the RDR. The numbers are quoted for a group of three cryomodules.

Klystrons are increased.
PDS are changed.
Charger of a DC power supplies are reinforced.

High Current Scheme



High Current Scheme (@ 3 Cryomodules)

Cavity	26
DC	26
Magic T	13
750kW Kly.	13
PM Focusing	13
Coil PS	0 PM focusing
Heater PS	1 common (1 back-up)
Preamp	13
MA Pulser	1 (1 back-up)
LLRF&Intlk	13
DC P/S	1(1 back-up)

The component count for the DRFS in the high-current case. For comparison with the RDR, the numbers are quoted for a group of three cryomodules.

Operability

- Only 4 cavities are driven by a klystron, and LLRF control is very easy. 4-vector sum enables us to have an easy Ql and distribution control, fast loop delay, and high FB gain.

  Cf. RDR baseline: 26 cavities are one set of vector sum

  For KCS, about 700 cavities are one set of vector sum.
- Each cavity field flatness is easy with suitable sorting of the cavity.
- With relatively unsophisticated sorting of the cavities, a high efficient operation is expected to achieve a high average accelerating gradient.
- In case of failures of cavities, the affected number of cavity units is limited and we can minimize the effect to the operation.
- High operation flexibility will be achieved.

MTBF of Important components in DRFS

Items	No	MTBF (hrs)
DC Power Supply	1	50,000
possibly having redundancy (Failure free/y)	+1(Back-up)	>100,000
Modulating Anode Modulator	1	70,000
possibly having redundancy (Failure free/y)	+1(Back-up)	>100,000
MA Klystron	6.5	110,000-120,000 (KEK's recent 10 years data)
Focusing Coil— Permanent Magnet	6.5	Degaussing by gamma ray???
Coil PS	0	-
Heater Power Supply	1+1(Back-up)	70,000 (Fan)
IP PS	0	-
Preamplifier (radiation?)	6.5	>100,000
Interlock module	6.5	
Bin module/PS	6.5	
Rack System with cooling	2	
Water flow SW	15	

Klystron: MTBF=110,000hr, ILC Op/year=5000hr, then 325 tubes are failured. Fraction=4.5%.

Two scheduled long maintenance covers the 2,5% failures, and if overhead is more than 2.5%, klystron failures don't affect to the ILC operation.

DC Power supply: MTBF of 70000hr is assumed. Fraction=7.1%.

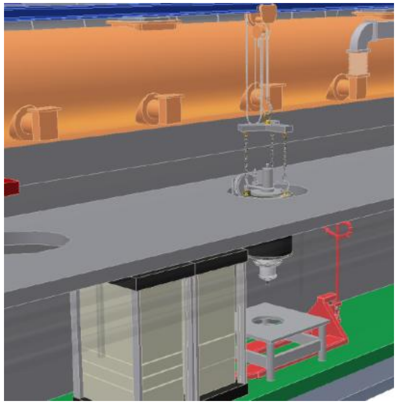
This fraction exceeds the allowable overhead. It is possible to introduce backup DC power supply as the redundancy as MA modulator. Then DC PS failures don't affect to the ILC operation. Cost impact is not large in DRFS.

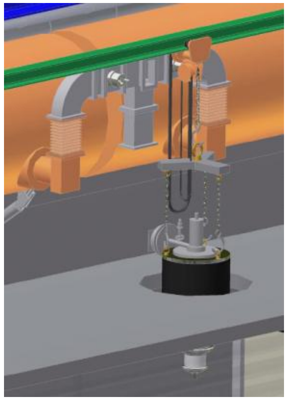
MA Modulator: Assume MTBF=from 50,000 to 70,000 hr.

Back-up modulator covers the another modulator's failure. Since two modulators failures at the same time are very rare, we can expect no failure in a year operation. Failured MA modulator are repaired or exchanged in the scheduled shutdown.

DRFS Exchanging Working In Scheduled Shut down (in Baseline)

- **Maintenance model: 24 hours maintenance in every 2-weeks of continuous operation (312hrs)**
- **Numbers of replacement required**





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Component	# of units requiring replacement or repair	MTBF assumed	Total # of units deployed at the ILC
DC power supply	2	50,000 hours	325
MA modulator	1.5	70,000 hours	325
MA klystron	12	110,000 hours	4225

Action	Time for unit piece of work	Rationale
Transportation of klystron	0.5 person-hours / tube	2 persons in 2 hours could bring 8 tubes on one carrier.
Removal of a failed klystron and installation of a replacement klystron	4 person-hours / tube	2 hours with 2 persons
Time for personnel to move from one point of repair to another	2/3 person-hours / tube	20 minutes with 2 persons
Replacement of a MA modulator	6.67 person-hours / modulator	
Replacement of a DC power supply	27 person-hours / DC power supply	

•Then 62 person-hour for 12 MA klystron replacement.
•10 person-h for 1.5 MA Mod.
•54 person-h for 2 DC PS.
•→16 person-days
•→43 person for 9 hours/shift

•Backup for Mod. and DC PS enables us to employ less person.

This is likely to be manageable!

New DRFS Layout

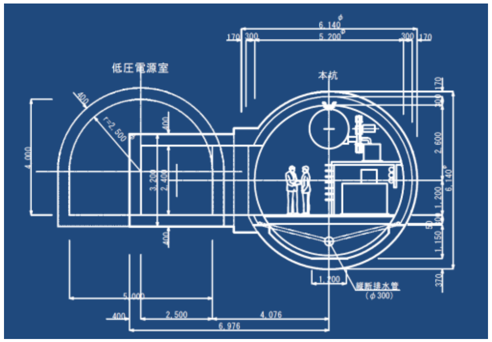
AC Power Supply Line

- For Power Supply Line,
  - **In each 152m position, low voltage power facility (LVPF) is introduced and 6.6kV line is reduced to 420V and then power of 420V is delivered to four sections (3-cryomodule unit).**
    - 420 V cable line is large and long: Special room of LVPF results in more cost.

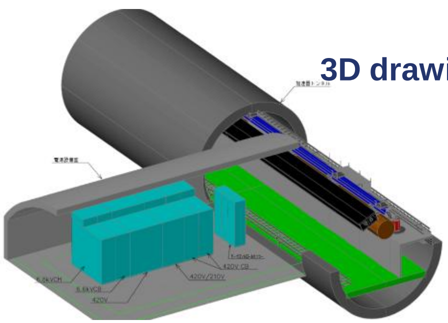
↓

  - **6.6 kV is delivered directly to each DRFS station (3-cryomodule unit) and reduced to 420V and power is fed via VCB.**

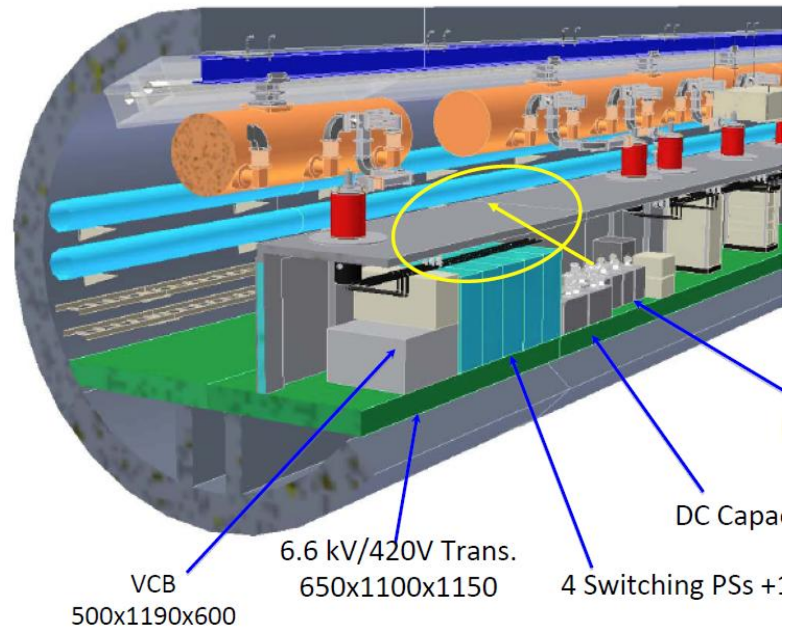
Low Voltage Power

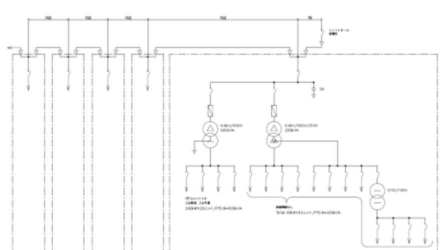


In each 152m, low voltage power facility (LVPF) is introduced and 6.6kV power is reduced to 420 V to deliver power to 4 stations.



3D drawing of low voltage power facility





Circuit Diagram

New DRFS Layout (1)

- Cryomodule is on the floor due to the objection from another area
  - **Vibration problem for beam line**
  - **Tunnel inner strength when cryomodule is hanged from ceiling**
  - **Air duct and ventilation space on the ceiling is desirable**
- PDS is under the floor to make a free space beneath the ceiling
- Radiation shield structure is changed from inverse-L shape to wall-like shape. This allows us to use wider and higher space in the HLRF components area
- Cooling water system also locates under the floor.

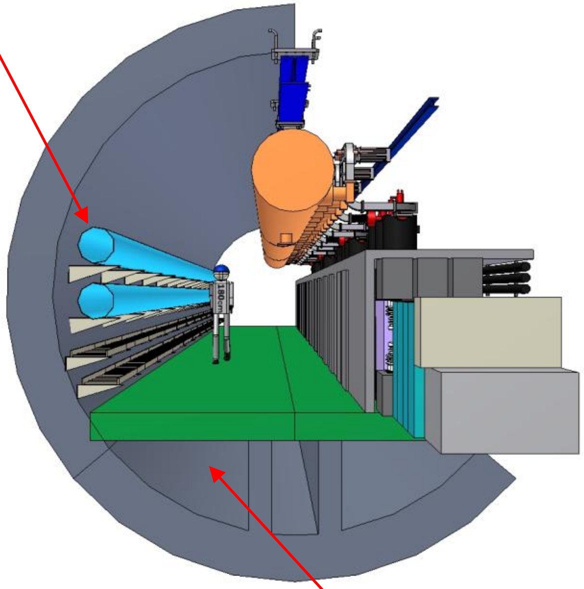
Cryomodule from ceiling to floor

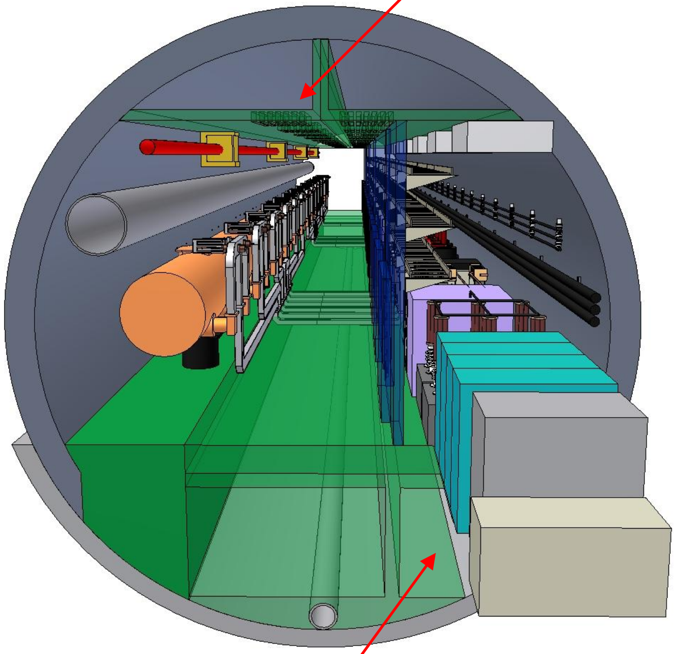
A Method of
<u>Hanging from a Ceiling</u>

A Method of
<u>Installing on Floor</u>

Cooling Water

Air Ventilation





Air Ventilation

Cooling Water

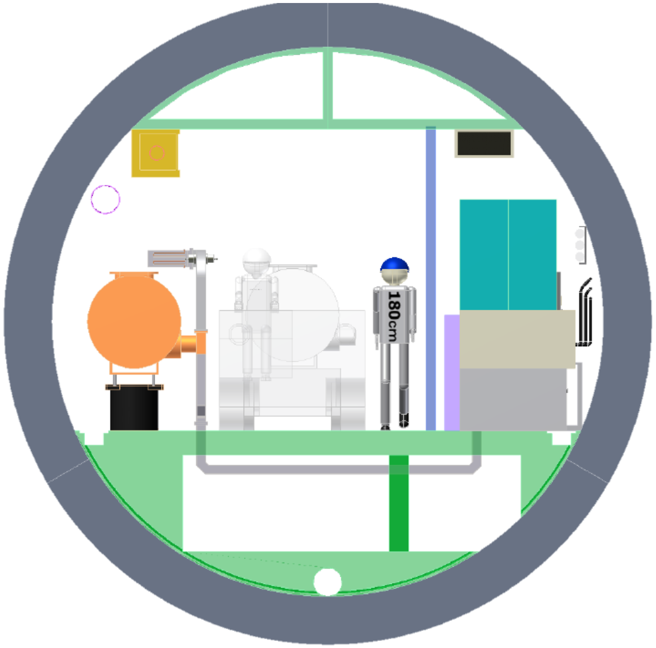
φ5.2m Section

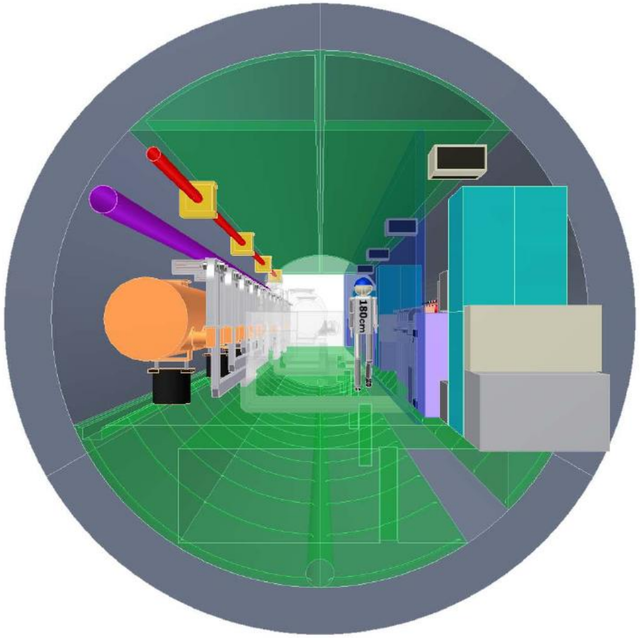
φ5.7m Section

New DRFS Layout (2)

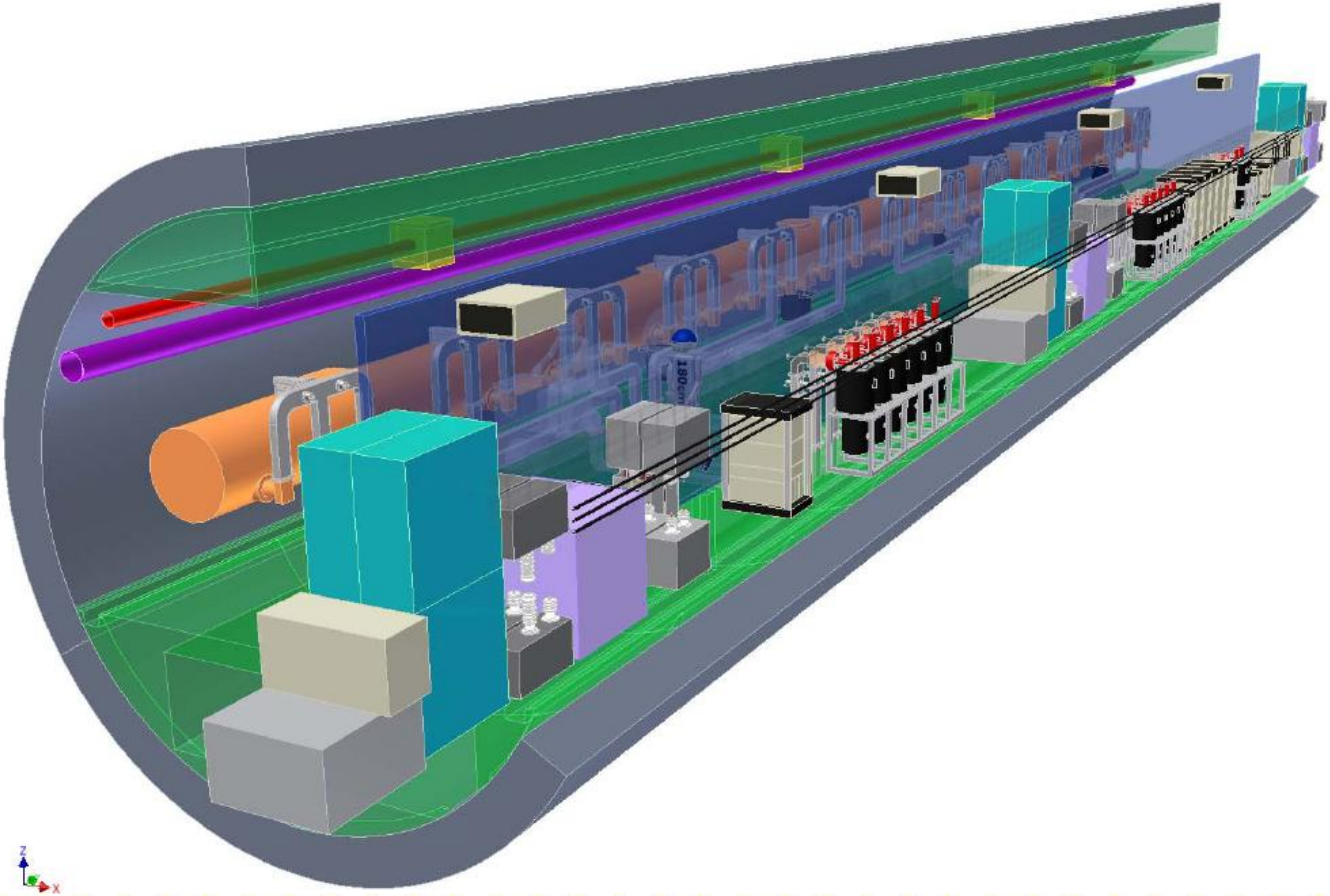
- Tunnel diameter is chosen to be 5.7m
  - **Egress space during the component transfer is kept as 0.5m passage.**
  - **Central passage is used to move the components replacement**
- In the HLRF components area, all DRFS klystrons are put on the floor and 5 or 6 of them are bunched up for the efficient line-up of PDS. Control racks are also bunched up for the efficient cooling pass.
- For the view point of redundancy, a spare DC power supply is introduced in every two RDR units (6 cryomodules) instead of every one RDR unit. Back-up modulation-anode modulator is also introduced with the same manner.
  - **This change is introduced by cost consideration.**

Cross-sectional View

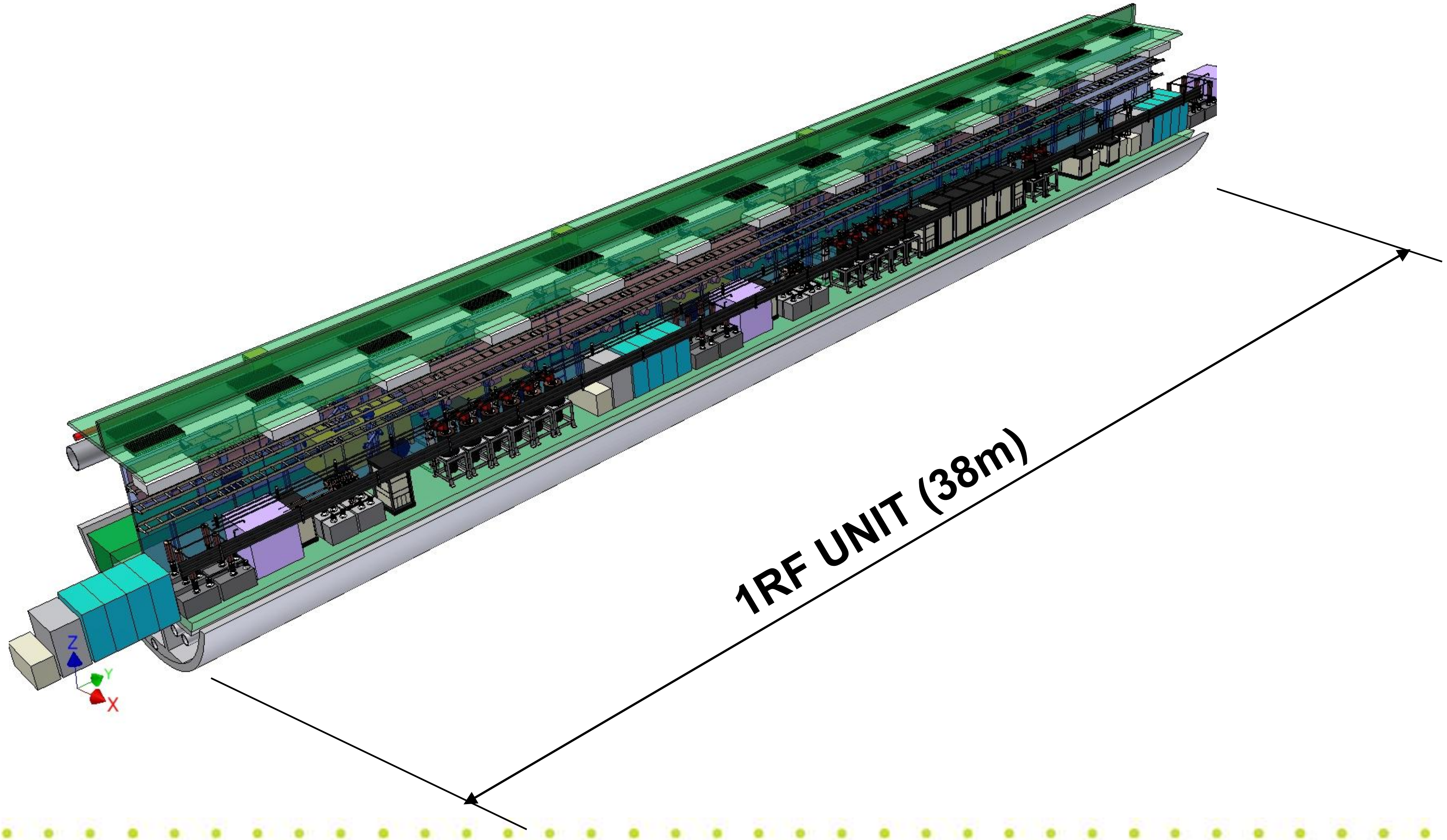




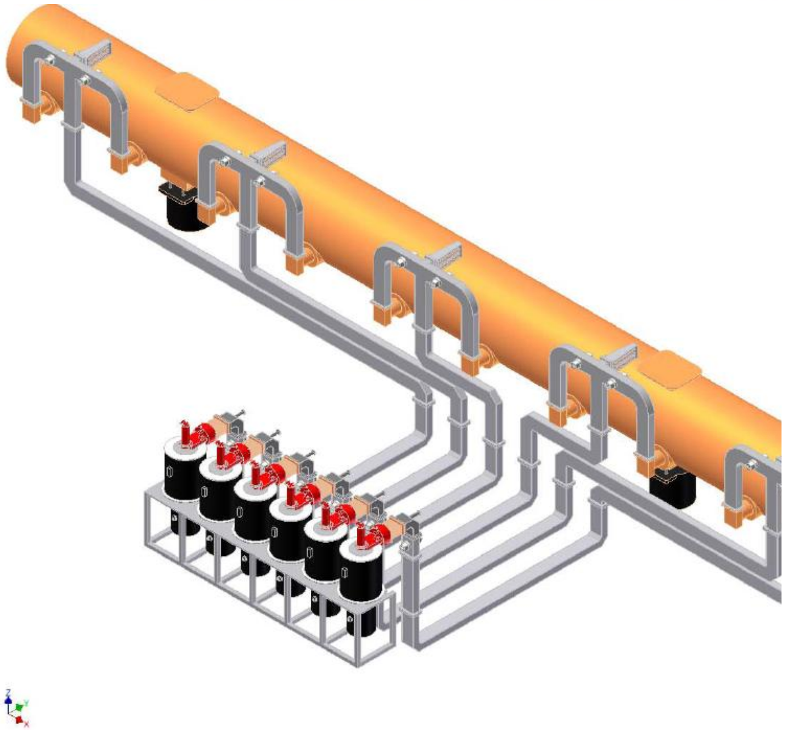
Bird's Eye View of New DRFS Configuration

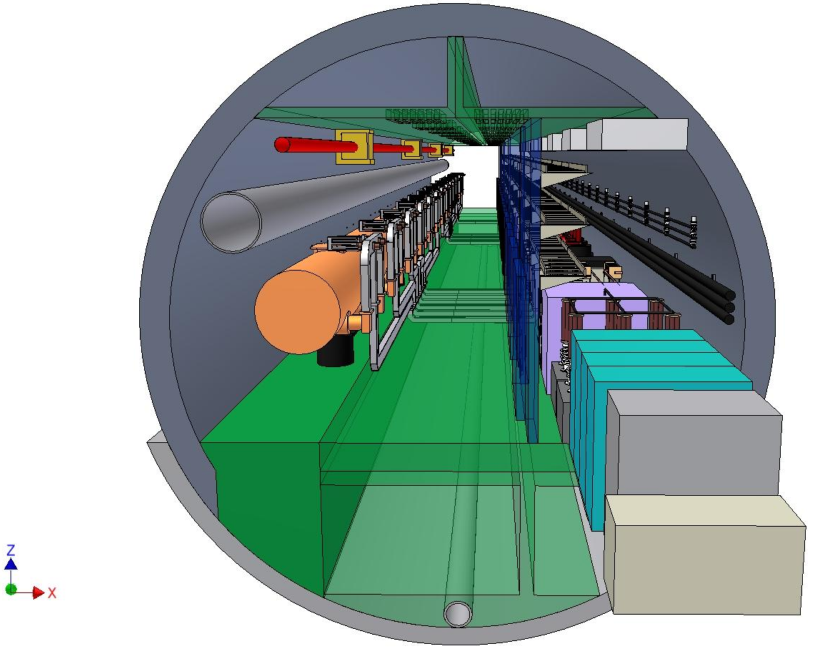


φ5.7m-Version Perspective



PDS in New DRFS Configuration





DRFS Layout New Feature

- **Layout consideration**
  - **Radiation Shield is changed to be wall-like structure**
  - **Height limitation disappears and better space factor for the HLRF and LLRF components might be possible.**
  - **Floor height considering the drainage groove for cooling water**
  - **Maintenance space consideration for cryomodule and HLRL/LLRF components**
  - **Reconsideration of HLRF/LLRF components to make the maintenance space**
  - **Space for cable rack, space for cryogenic pipe**
  - **Better Configuration for power distribution system in the floor**

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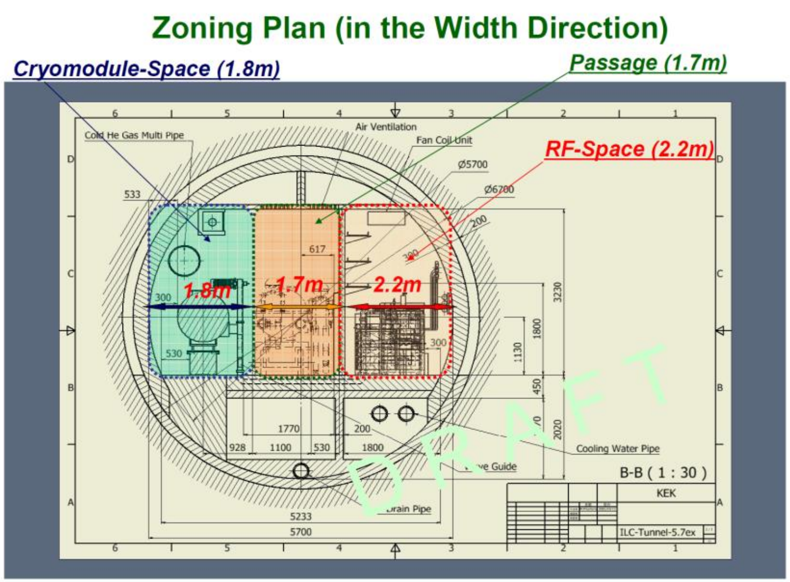
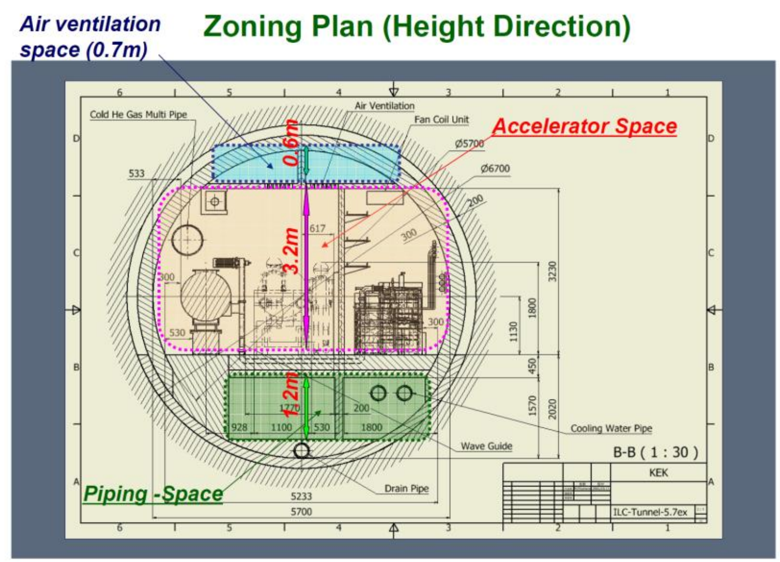
DRFS Configuration with CFS Collaboration (seeking more better configuration)

- **3D CAD data of DRFS Configuration are merged to the 3D CAD of CFS. More realistic layout including electricity plants, cooling system and cryogenics are started to discuss. Base line: 5.7m dia. Cryomodule on the floor.**
- **Zoning concept is introduced to develop more flexible configuration.**





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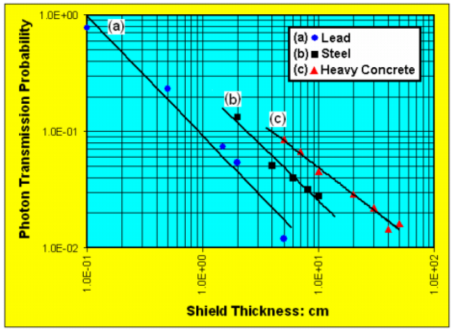
Radiation Issue

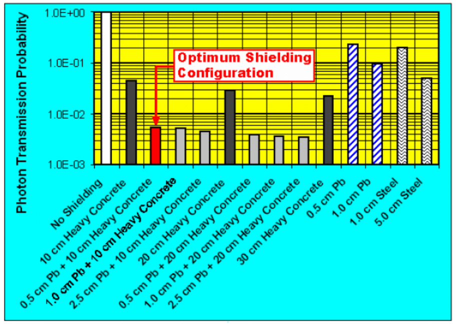
Concerns about the radiation effects against the electrical component in the tunnel

- Since DRFS is a complete single tunnel plan, great concern of the radiation effect against the electrical components in the tunnel.
- Front ends of LLRF are required to be near to the cavities, RDR base line and KCS would face to the same problems.
- DRFS has a shielding structure which is assumed to be similar with FLASH and XFEL. All electronics would be installed in this shield.
- First study for the radiation effect is studied by FLASH facility in advance to construct XFEL. DRFS first insight for this problems is come from their study.

Efficacy testing of shielding materials for XFEL using the radiation fields produced at FLASH

TESLA-FEL 2008-06





In SB2009 document, we assume the shied of 10 cm heavy concrete and 1cm lead.

More Study about Radiation Effect or Restructuring of DRFS

- Radiation Damage Experiment

  Durability test of key components with various radiation shield in the KEK's tunnel.

- Redesign of reinforced radiation shield (double shield: additional shield in the HLRF component area)
  - **Reinforced shield for IGBTs in the CD P/S supply, MA Modulator and LLRF unit.**

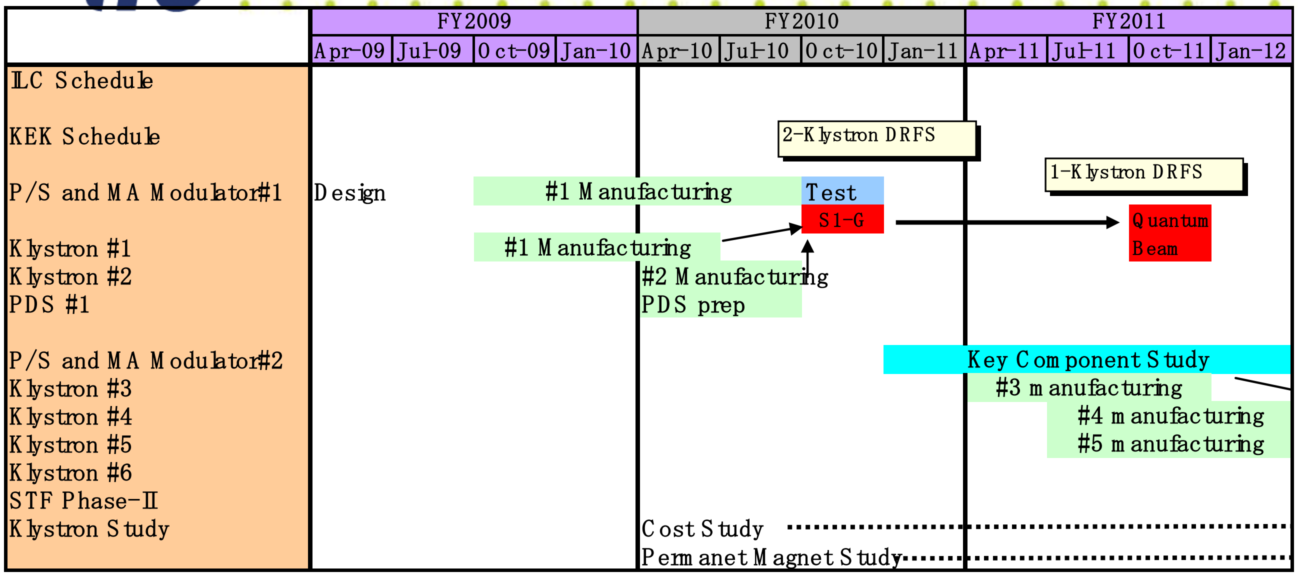
- Restructuring or repositioning of HLRF components
  - **DC P/Ss and MA modulators are buched up in the alcove**

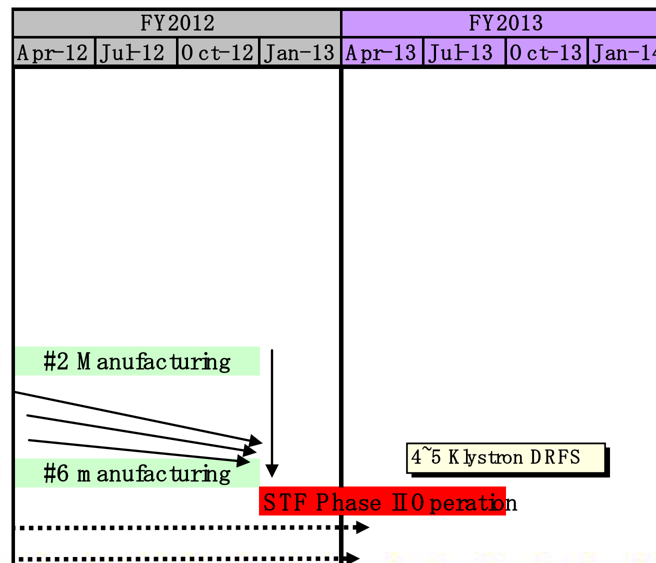
R&D Plan for DRFS in KEK

Introduction : DRFS R&D Plan in KEK

- DRFS Plan is supported in ASIAN ILC project, especially it is matched with Japan site condition.
- For S1 global in end of 2010, budget of 2-klystron DRFS system are approved or will be approved).
- For STF phase-II project in 2013, DRFS system for 1 full cryomodule, i.e., 4-5 klystron DRFS system, is strongly supported.
- For these periods, study of DRFS basic configuration are performed.
- Critical issues such as the reliability of the over-current protection HV relay or switch and crowbar protection are intensively studied.
- Cost related study of klystron are now under consideration.

Milestone of KEK DRFS R&D





2 big events in KEK employ the DRFS system

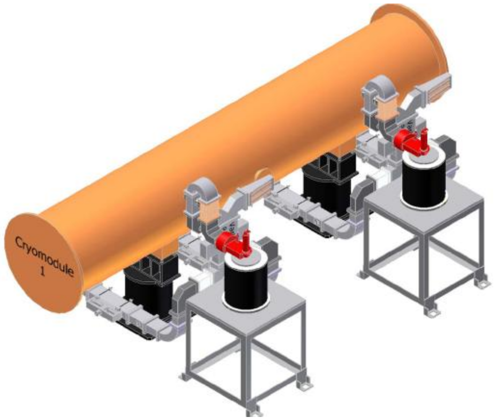
S1 global : 2 Klystron DRFS

STF-II : 4~5 Klystron DRFS

(1 Cryomodule)

Task and R & D schedule of DRFS in KEK

- R&D study is easy since the DRFS system is not large.
- Task force team of DRFS starts and try to solve the problems of DRFS.
- Prototype RF unit is manufactured in FY09
- Further R&D required for the DRFS RF system is continued from FY09. Three year R&D budget was approved.
- Permanent magnet, high voltage SW and IGBT will be studied intensively.
- Prototype will be evaluated in the S1 global test (2 Klystron DRFS)
- And then installed in the buncher section of STF-II aiming for the realistic operation.
- More large scale of DRFS (4~5 Klystron DRFS) is planed for STF-II in KEK.



S1-Global Plan

DRFS R&D : Current program

- 2 units DRFS for S1 global project(2010)
  - **RF source of DRFS comprises of a prototype DC power supply, a modulating-anode (MA) modulator and 2 proto-type MA klystrons.**
  - **Power distribution system (PDS) employs the circulator-less system to show the feasibility of proposed DRFS PDS.**
  - **Power supply system has a simple crowbar circuit using a gap switch, available HV relays, but does not include the bouncer circuit.**
  - **LLRF feedback is also introduced to test the DRFS LLRF system.**

- Prototype DRFS klystron outputting medium power of 750kW was designed and manufactured in 2009 and completed in 2010.

  Second tube is manufactured in 2010.

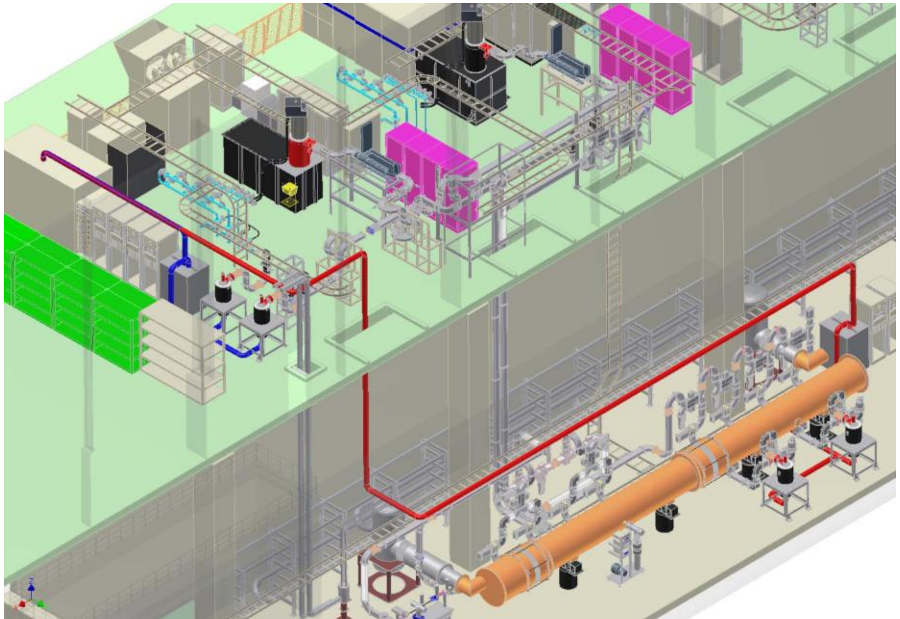
  Various evaluations will be performed after the S1-Global HLRF test.

- PDS performance using high isolation magic-tee without a circulator is investigated for 2-cavity system under the LLRF feedback.

  Crosstalk and diagnoses of cavity parameters at the pulsed tail are studied in S1-Global test.

DRFS R&D

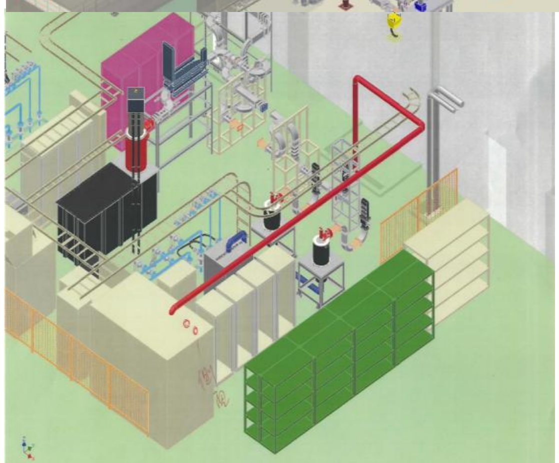
DRFS Demo in S1-Global



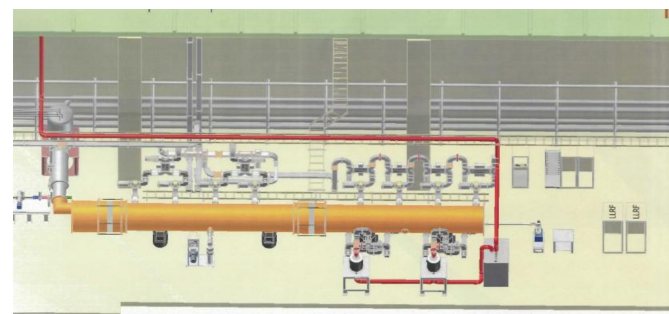
DRFS demonstration will be Prepared in the end of S1-global: December of 2010.

2 units DRFS

Birds eye view of STF site



First evaluation test is done in klystron gallery



Then 2 DRFS units are connected to the four cavities in the cryomodule.

DRFS R&D

- S1-Global Demonstration
- Change of the DRFS Klystron Specification
  - Output Power of DRFS
  - Should be changed from 750kW to 800kW Considering the Margin of the SC Cavity performance Distribution such as 31.5MV/m +-20%
    - Even for the case of pair of 38MV/m cavities, 10% overhead for LLRF requires about 800kW output from Klystron.
    - Further discussion is necessary from HLRF and LLRF
- Klystron for 10 Hz Operation are newly proposed and we can expect almost the same efficiency in 10 Hz operation scheme.
- R&D for HV relay SW are proposed by US company and prototype will be expected to be tested in S1 global.

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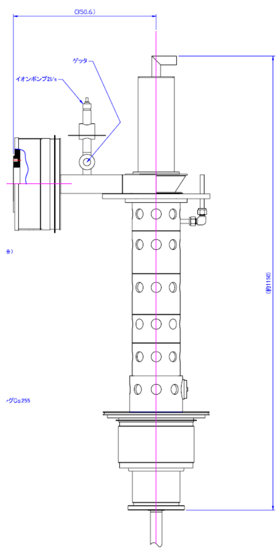
Prototype DRFS Klystron (S1-G)

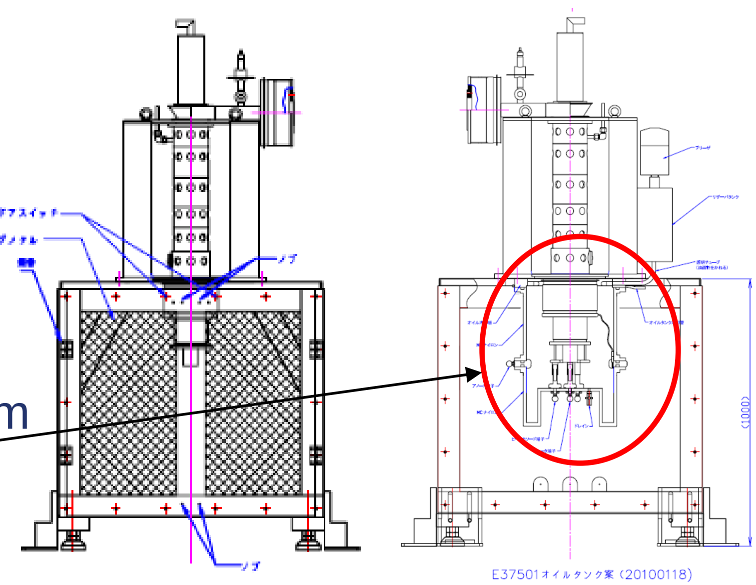
- For S1-global demonstration, KEK will order 2 DRFS klystrons.
- A prototype klystron was ordered in FY09 and will be delivered in around August of 2010. Another klystron will be ordered in April of 2010 and we expect to finish basic performance test till middle of November. Two klystrons and a MA modulator are installed S1-global bench on December and tested.



DRFS klystron

Proto-type employs
Electro-magnet focusing.

HV Ceramic is immersed
In a small oil tank.
Design is now modified from
right figure.



Socket Assembly of DRFS klystron

DRFS Power Supply/Modulator

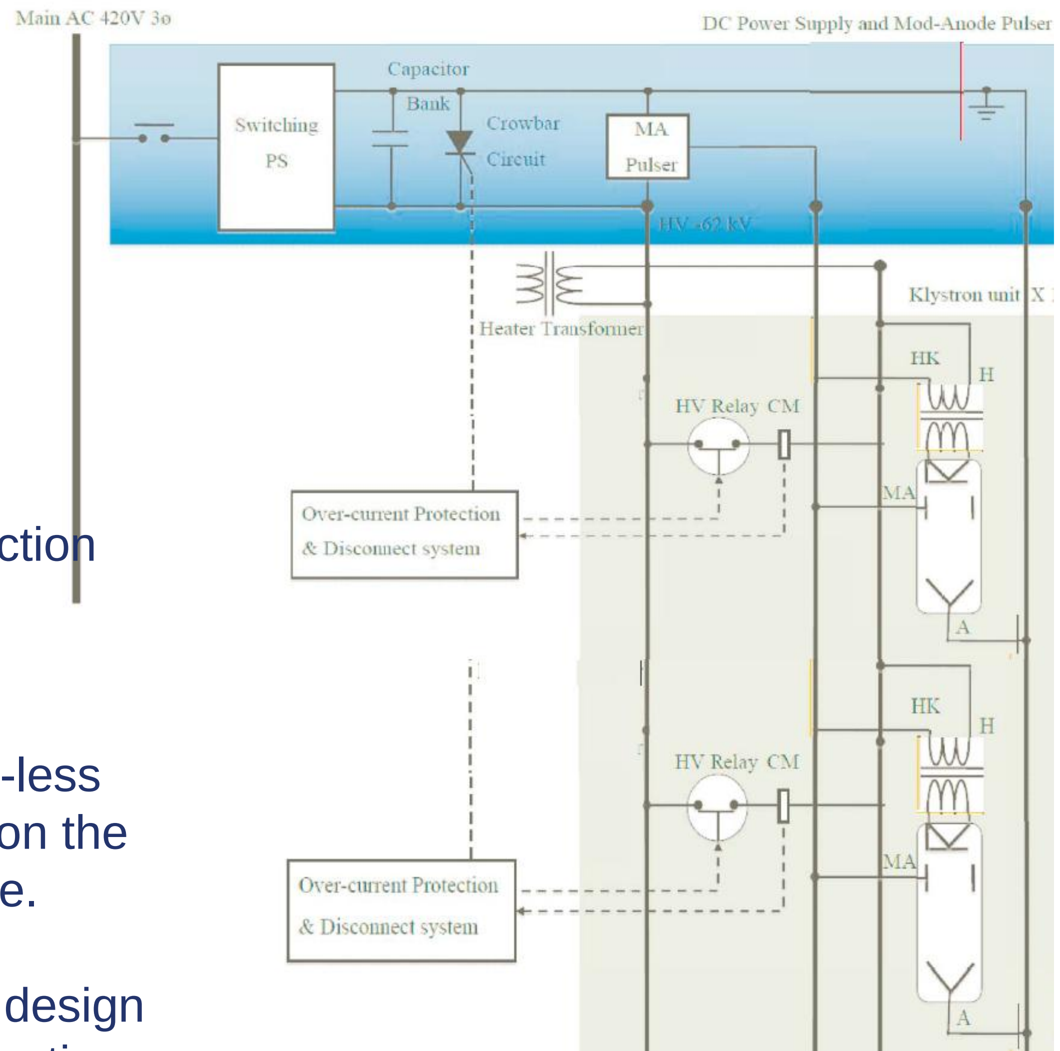
In FY09, prototype DC modulator And MA modulator are ordered.

Capability for 2 klystron loads

Due to small budget, bouncer circuit are not used in S1-G. Compensation of sag for RF is covered by LLRF feedback. (If this attempt is successful, reduction of capacitors are benefit for cost).

Crowbar circuit using thyratron is introduced. Possibility for crowbar-less is tested. This is strongly depend on the klystron durability for HV discharge.

MA modulator is based on J-Parc design and studied the shunt resistor reduction. (strong effect for cost)



Basic Diagram of P/S& modulator of S1-G

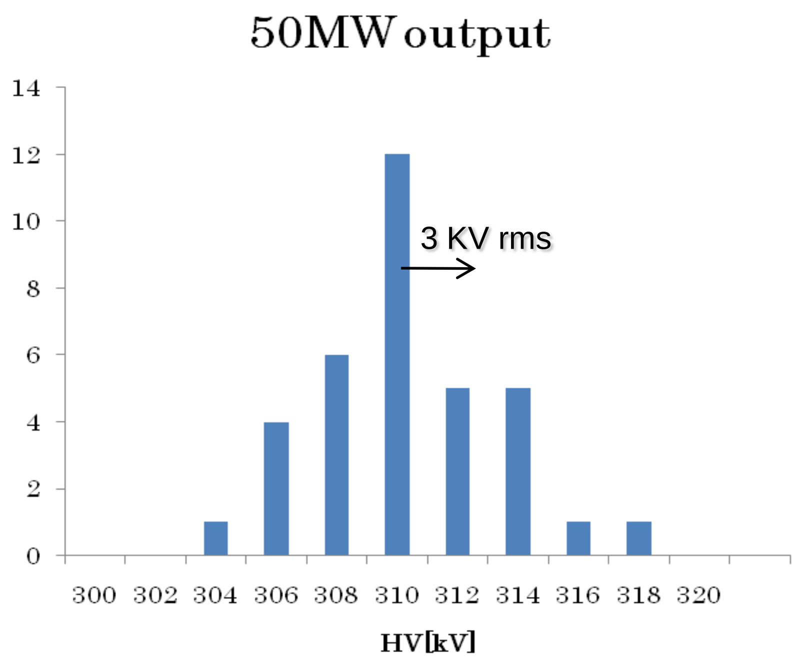
Summary

- R&D plan of Distributed RF Scheme (DRFS) is presented.
- 2-klystron DRFS is almost approved and is demonstrated in S1- global test.
- 4 (5)- klystron DRFS is strongly supported for STF-phase II in 2013 and R&D plan is under establishing.
- A prototype DRFS klystron is now manufacturing.
- A prototype power supply is also under manufacturing.
- Several R&D key issues are descried.

Operation Mode in ILC

Mode	Energy(GeV)	Current(mA)	Rep. Rate (Hz)	Relative Power
RDR	500	9	5	1
Low Power Option	500	4.5	5	0.5
	250	4.5	5	0.25
Low Energy Option	250	4.5	10	0.5

HLRF requirements



- KEKB injector klystrons (40 MW and 50 MW) are statistically analysed.
- Klystrons have 1.2% (40 MW) and 1% (50 MW) rms HV distribution to reach 40 or 50 MW.
- These correspond to ~3% power distribution with same HV. (P~V^2.5)

- Suppose the cavity distribution is 3 MV/m rms (~10%), 770kW klystrons can drive 38 MV/m cavities with 15% rf overhead.

				10%sigma cavities			
				31.5	0.5		4000
35				32	0.563059	0.063059	504.4741
	3%sigma Klystron			33	0.683031	0.119971	959.7712
34	0.158655254			34	0.786301	0.10327	826.1597
35	0.5		4000	35	0.86674	0.080439	643.5129
36	0.841344746	0.341345	2730.758	36	0.923436	0.056697	453.5723
37	0.977249868	0.135905	1087.241	37	0.959597	0.036161	289.2881
38	0.998650102	0.0214	171.2019	38	0.980467	0.02087	166.9581

BAW1.DRFS (S. Fukuda)