DRFS in SB2009

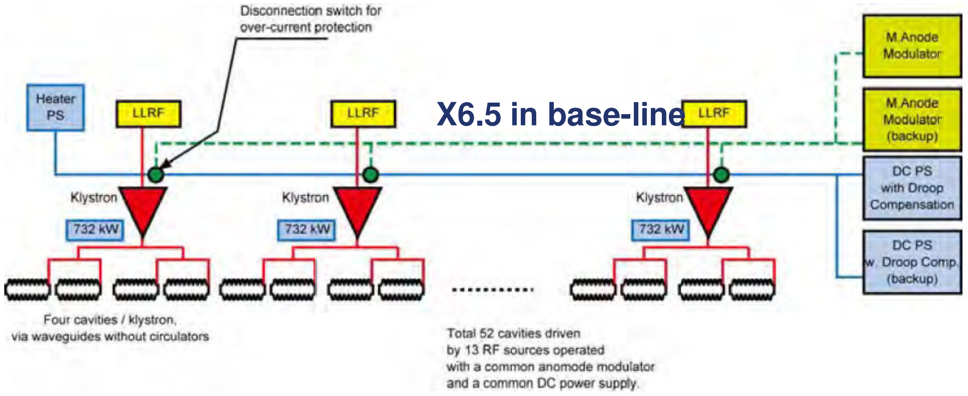
KEK S. Fukuda

- Concept of DRFS
- System Description
  - Modulator
  - Klystron
  - PDS
  - Baseline and upgrade pass
  - Tunnel layout
- Heat Dissipation
- Radiation in the tunnel
- Operability
- Availability and maintainability
- Cost of DRFS
- R&D
- Pros and cons of DRFS
- Summary

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 750kW Modulating Anode (MA) klystron would drive four cavities (in high current scheme (HCS), two cavities) .**
  - **totally about 4000 (8000 in HCS) MA klystrons would be used.**
  - **It is based on much simpler and more compact HLRF and LLRF units than the RDR baseline or KCS.**



RF unit for 3 cryomodules

  - **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, four cavities are driven by one unit of 750kW L-band MA klystron. Therefore, one would see that three cryomodules with 26 cavities will be driven by six and a half units of MA klystrons.

In a practical implementation, the proposed scheme of DRFS is to use 13 units of MA klystrons to drive six cryomodules, containing 52 cavities.

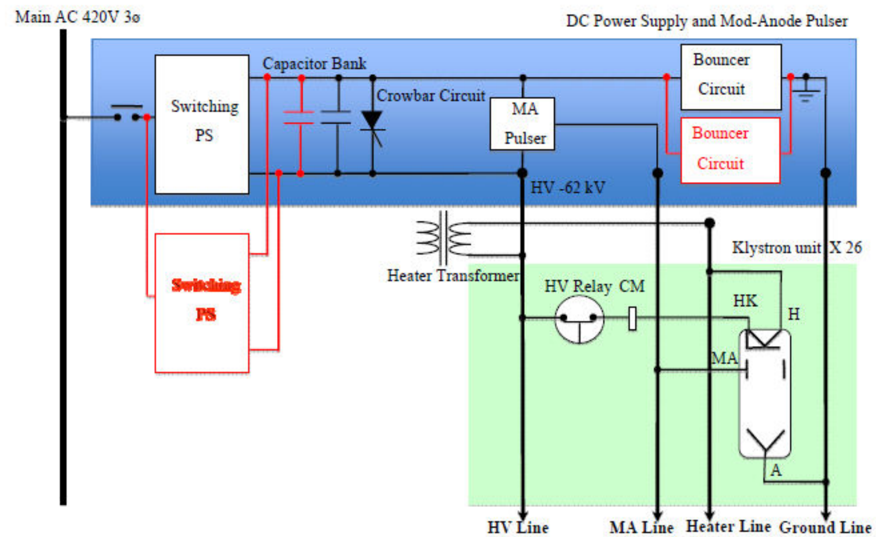
Klystron		
	Frequency	1.3 GHz
	Peak Power	750 kW
	Average Power Output	7.50 kW
	RF pulse width	2 ms
	Repitition Rate	5 Hz
	Efficiency	60 %
	Saturated Gain	
	Cathode voltage	62.7 kV
	Cathode current	18.8 A
	Perveance(Beam@62.5kV)	1.2 μPerv
	(Gun@53kV)	1.53 μPerv
	Life Time	110,000 hours
	# in 3 cryomodule	6.5
	Focusing	Permanent magnet focusing
	Type of Klystron	Modulated Anode Type
DC Power supply per 6 cryomodules		
	# of klystron (6 cryomodule)	13
	Max Voltage	71.5 kV
	Peak Pulse Current	244 A
	Average Current	2.47 A
	Output Power	177 kW
	Pulse width	2.2 ms
	Repitition Rate	5 Hz
	Voltage Sag	<1 %
Bouncer Circuit		
	Capacitor	26 μF
	Capacitance	260 μF
	Inductance	4.9 mH
M. Anode Modulator		
	Anode Voltage	53 kV
	Anode Bias Voltage	−2 kV

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 of the DC power supplies and MA modulators is associated with **one 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**, which switches off the line when over current 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.

• Common heater power supply and permanent magnet focusing to eliminating magnet power supply.

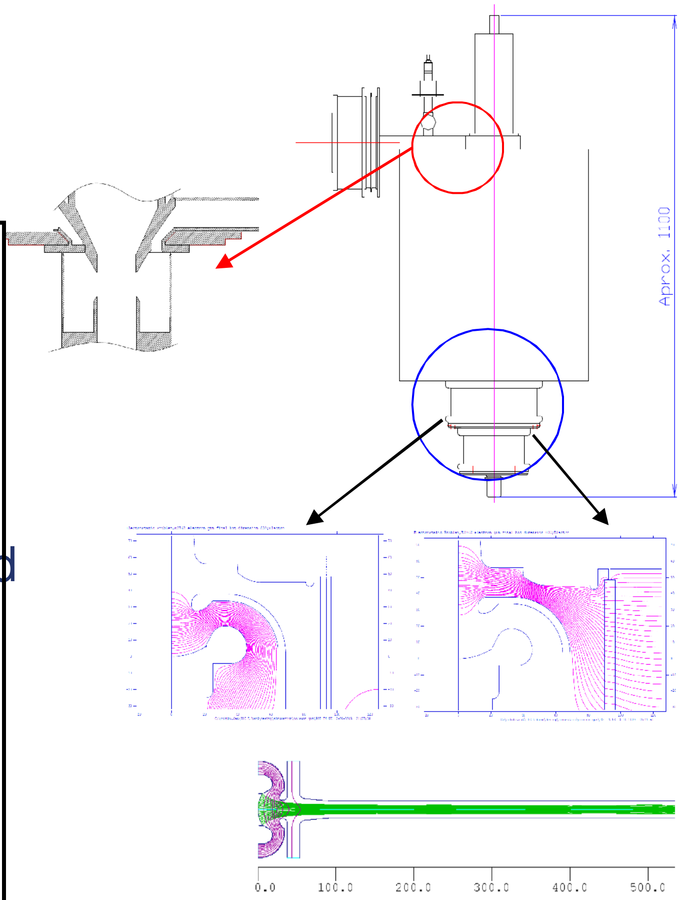
Klystron for DRFS

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



Power Distribution System (PDS) in Base line DRFS

Very simple power distribution system

- No circulator
- Power divider employs magic tee with high isolation for space saving.
- One Phase-shifter with symmetric PDS between couplers or asymmetric PDS with a phase-fixed waveguide for cost saving

•Design of eliminating flange as possible

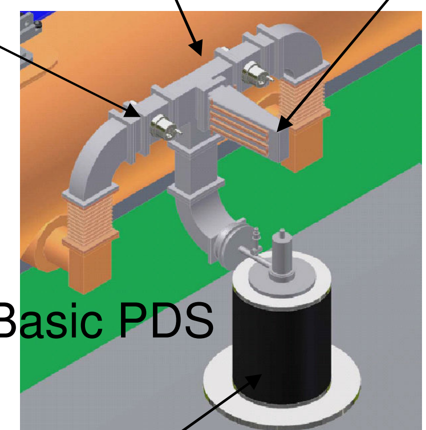
- 750kW RF is propagated in the dry air without any extra ceramic window

- In base line, an MA klystron feeds power to 4 cavities and additional PDS is required.

Magic Tee

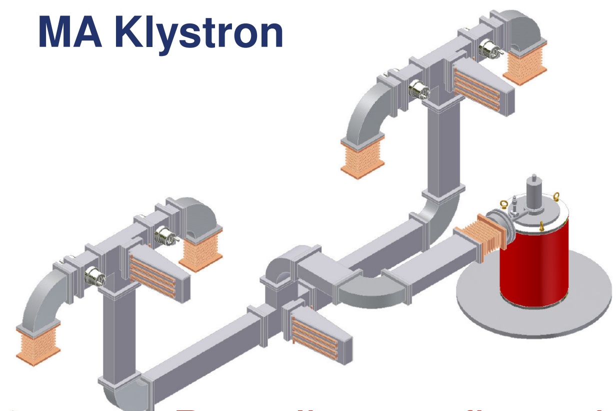
Dummy Load

Directional Coupler



DRFS Basic PDS (HCS)

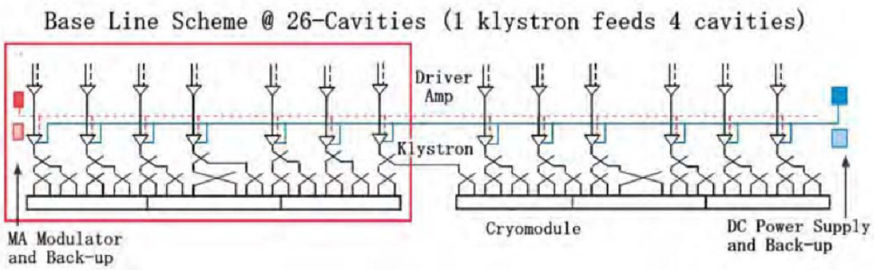
MA Klystron



Base line configuration

Base line DRFS and upgrade pass

Base Line Configuration



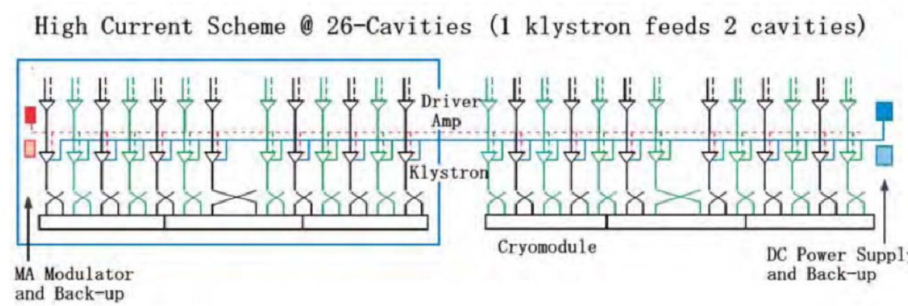
System configuration of DRFS in the baseline case.

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.

High Current Scheme



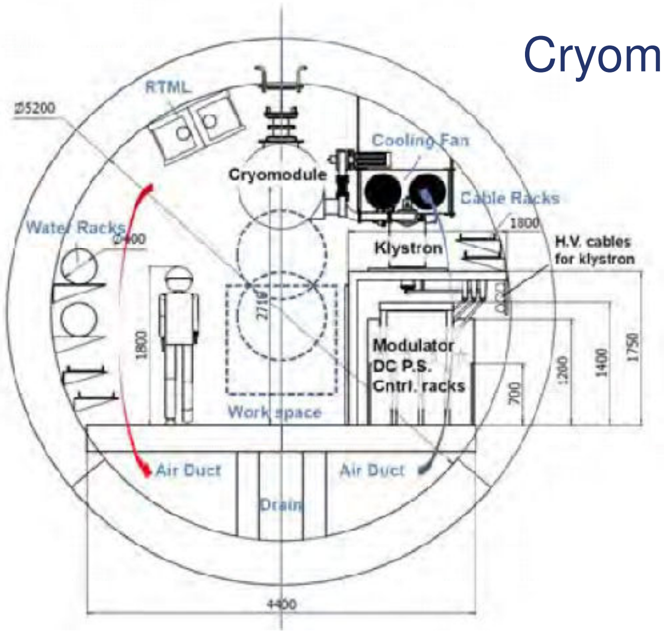
High Current Scheme (@ 3 Cryomodules)

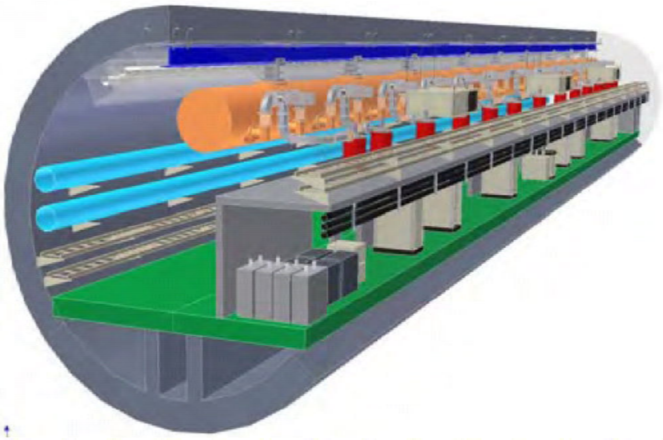
Cavity	26
DC	26
Magic T	13
750kW Kly.	13
PM Focusing	13
Coil PS	0 PM focusing
Heater PS	1 common (1 back-up)
Preamp	13
MA Pulser	1 (1 back-up)
LLRF&Intlk	13
DC P/S	1(1 back-up)

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.

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

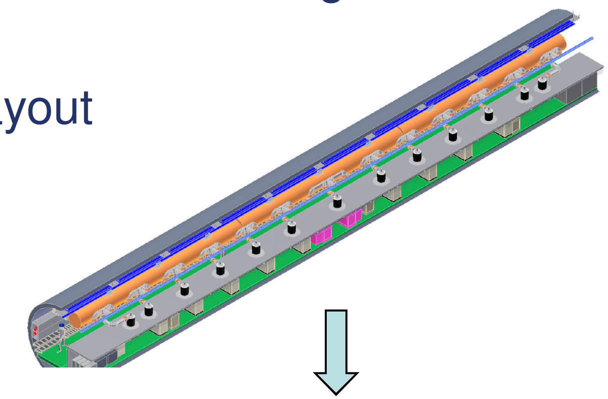
DRFS Tunnel Layout



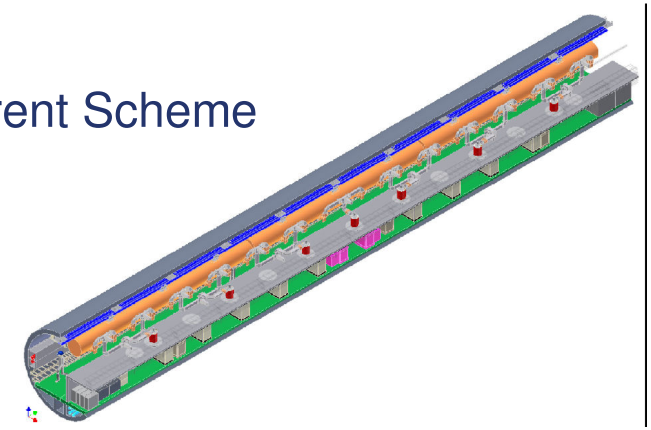


Cryomodule is hanged down from ceiling

Base line layout

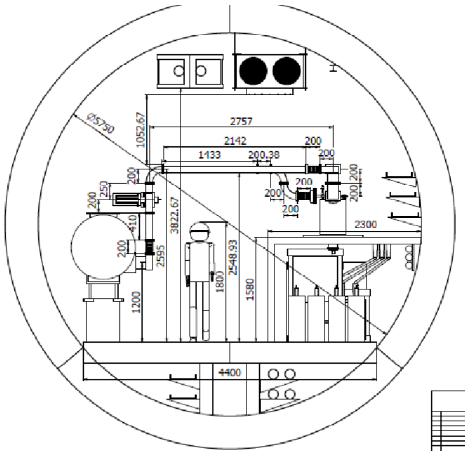


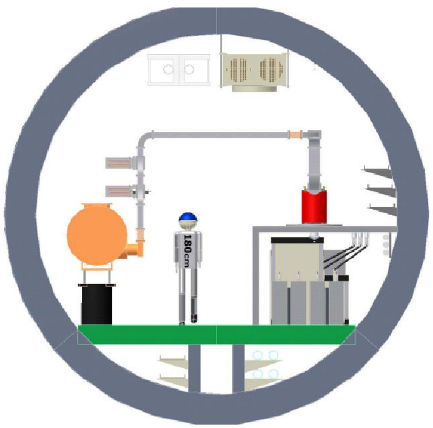
High Current Scheme

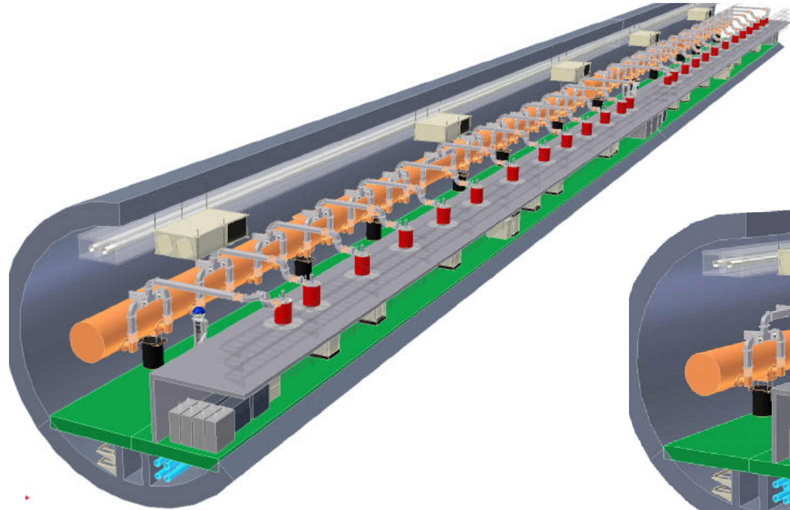


Example of LowP PDS Layout

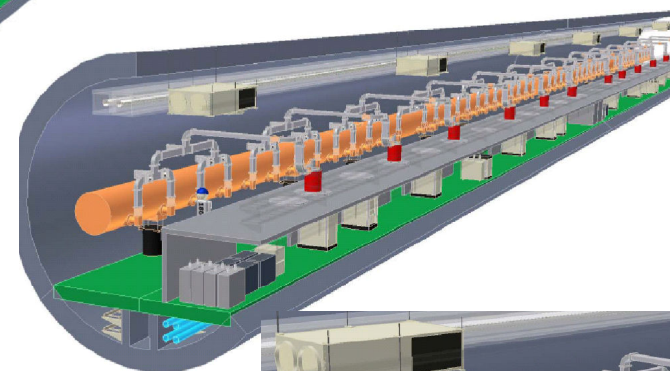
Another Layout of DRFS
Cryomodule on the ground



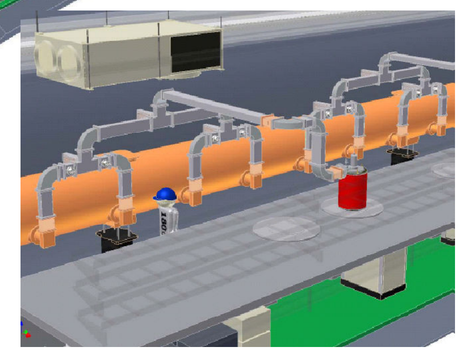




High Current Scheme



Baseline



If tunnel diameter is chosen to be 5.75m, it is possible to
Have an enough maintenance/installing space in the center.

Heat Dissipation

One of the potential issues in hardware implementation of the DRFS is the heat dissipation by components in the single main linac tunnels.
Heat dissipation table is shown below.

WATER AND AIR HEAT LOAD for SB2009 DRFS Base Line Scheme

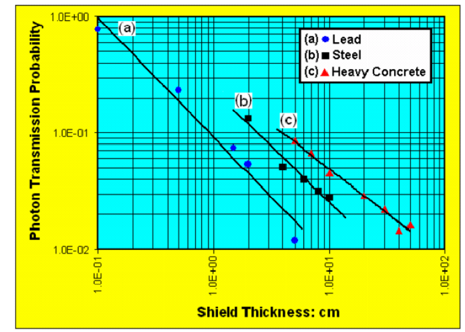
MAIN LINAC - ELECTRON & POSITRON					To Low Conductivity Water	to Chilled Water	keith Jobe load to air Nov 22 06		To Fan Coil Chilled
Components		Quantity Per 36m	Total Heat Load (KW)	Average Heat Load (KW)	Heat Load to LCWater (KW)	Heat Load to Rack Chilled Water (KW)	Power fraction to Tunnel Air (0-1)	Power to Tunnel Air (KW)	Heat Load to Fan Coil Chilled Water (KW)
RF Components									
--- High Voltage Circuit Breaker (6.6 kV) ---		1/76 m							
DC Power Supply, 6.6 kV (I), 60 kV, 2 A (O), 125 kW, 90% eff.	Rack 1	1/76 m		12.50	7.50	0.00	0.40	5.00	5.00
Modulating Anode Modulator, 6.6 kV (Shunt 0.5A, then 3 kW heat load)	Rack 3	1/76 m		3.00	1.80	0.00	0.40	1.20	1.20
Heater P/S, 200V,18A, 4kW	Rack 3	1/76 m		0.50		0.50	0.00	0.00	0.00
Klystron Socket Tank / Gun 0.3 kW X 13		13/76 m		3.90	3.12	0.00	0.20	0.78	0.78
4.5 kW X 13		13/76 m		58.50	56.75	0.00	0.03	1.76	1.76
Klystron Body & Windows		13/76 m		3.76	3.76	0			
--- LLRF Racks ---		3Units/76m		0.91		0/91	0.00	0.00	0.00
--- Other Racks ---		8Units/76m		19.30		19.30	0.00	0.00	0.00
Waveguides in beam tunnel		13/76 m		0.80	0.00	0.00	1.00	0.80	0.80
RF Loads		13/76 m		22.80	22.12		0.03	0.68	0.68
Pulse motor for input coupler/tuner		(26+26)/76 m	1.79	0.00			1.00	0.00	0.00
Vacuum Pumps		(2+2)/76 m		1.26			1.00	1.26	1.26
Subtotal RF unit Only				127.23	95.04	20.71			11.48

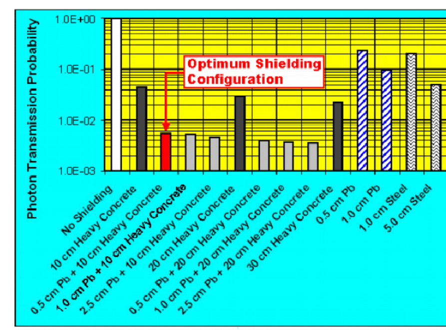
Concerns about the radiation effects against the electrical component in the tunnel

- 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.

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.

Remarks : High Availability for Cavity Variation

- For the purpose to use the variation of cavity accelerating field in the range of 31.5MV/m+-20% (25MV/m to 38 MV/m → 116kW to 147kW of RF power), DRFS accepts this variation by suitable sorting of cavity field.
- For example in extreme case of a pair of 38MV/m cavities (maximum) and a pair of 25MV/m cavities to be driven by a single MA klystron, the required power would be 588kW, and actual power would be 710 kW including the LLRF feedback overhead.

(For pulse flatness, coupler tuner is assumed)

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.

Klystron Data in KEK

Contribution to long MTBF

Fiscal year of product	Total No. of tubes	Unused No. of tubes	Living No. of tubes	Living STB	Living Working	Living Av.Op.time (hours)	Failed No. of tubes	Failed causes emission	Failed causes window	Failed causes others	Failed Mean age	Cumulative operation (hours)	MTBF (hours)
1993	14	1	4	3	1	27,618	9	1	6	2	30,275	382,948	42,550
1994	13	0	4	4	0	31,783	9	2	4	3	18,215	291,068	32,341
1995	23	0	7	1	6	71,158	16	11	2	3	16,737	765,893	47,868
1996	15	0	8	1	7	70,989	7	5	2	0	25,420	745,849	106,550
1998	20	0	12	4	8	52,752	8	2	3	3	35,654	918,258	114,782
1999	15	0	10	1	9	52,630	5	2	3	0	12,568	589,144	117,829
2000	12	0	7	0	7	45,801	5	3	0	2	26,402	452,618	90,524
2001	12	0	12	3	9	26,994	0	0	0	0	----	323,924	----
2002	12	1	10	1	9	15,994	1	1	0	0	29,668	189,604	189,604
2003	6	3	3	0	3	16,952	0	0	0	0	----	50,855	----
2004	5	4	1	0	1	10,876	0	0	0	0	----	10,876	----
2005	4	4	0	0	0	----	0	0	0	0	----	0	
2006	4	4	0	0	0	----	0	0	0	0	----	0	
2007	0	0	0	0	0	----	0	0	0	0	----	0	
2008	0	0	0	0	0	----	0	0	0	0	----	0	
Total	155	17	78	18	60	42,681	60	27	20	13	23,198	4,721,035	78,684

Cathode Crisis

Due to the 1996-product failure of cathode, life was short.

We stop buying of new klystrons due to the long life

Recent cumulative MTBF data from 19xx to 2004

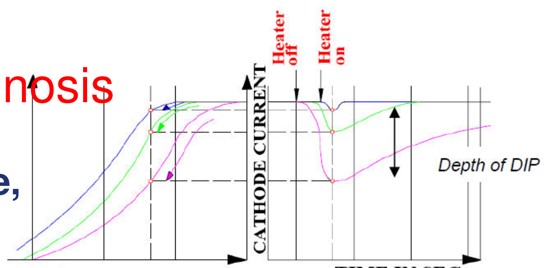
93-'04	147	9	78	18	60	42,681	60	27	20	13	23,198	4,659,305	77,655
94-'04	133	8	74	15	59	43,496	51	26	14	11	21,949	4,327,212	84,847
95-'04	120	8	70	11	59	44,165	42	24	10	8	22,750	4,047,020	96,358
96-'04	97	8	63	10	53	41,166	26	13	8	5	26,450	3,281,127	126,197
97-'04	82	8	55	9	46	36,828	19	8	6	5	26,829	2,535,278	133,436
98-'04	62	8	43	5	38	32,384	11	6	3	2	20,411	1,617,020	147,002

KEK Klystron's MTBF Data (Since 1993 for KEKB operation)

- **Averaged run time for a year; about 7000 hours.**
- **Scheduled maintenance; 3 months (summer) and 2 weeks (winter) in a year and one day for every 2 to 3 weeks.**
- **Klystron replacements are done mainly in long shut down.**
- **Sudden failure of klystron itself was only one case for these 5 years.**

Importance of cathode diagnosis

- **7 emission degradation failures are replaced in long maintenance, and these are predicted by dip-test checking, so these are examples of preventive maintenance.**



Measurement of Miram plot takes 2-3 hours.

Dip test takes about 10 min.

Miram plot and dip test

Candidate of replacement
If necessary go to Miram plot

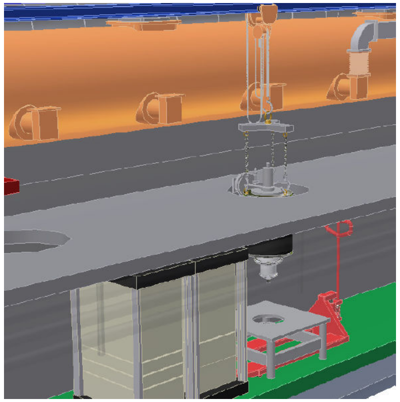
Consideration and Justification of Long MTBF for DRFS Klystron

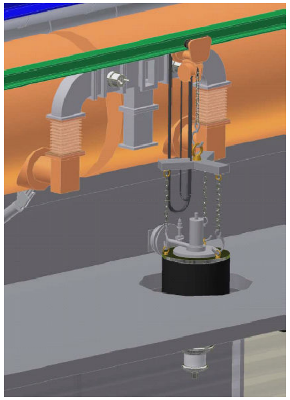
- Potential sources of klystron failure
  - **Arcing in gun region**
    - DRFS tube's field gradient in the gun electrode is lower than KEKB tube and SLAC tube. Though operation is near to DC, gradient is lower than usual CW tube design.
  - **Arcing in output cavity gap**
    - Much lower comparing even in 10 MW MBK since output power is only 750kW.
  - **Crack or puncture in the output cavity**
    - Low probability due to the low output power
  - **Emission degradation**
    - Lower probability due to the lower cathode loading
  - **Mechanical failure**
  - **Parasitic oscillation**

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**

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





- **Estimated times of the repair work of DRFS**

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!

Cost study of DRFS

- DRFS requires a large number of DC power supplies, MA modulator and MA klystrons. Reduction of cost is a key issues.

- **MA Klystrons**

  Total of 4200 MA klystrons need to be manufactured (850/year * 5year)
  - **Vendor response the process up to baking tubes. Processing will be performed in ILC site.**
  - **Deploying hydro-forming of the part, auto-tuning of cavities, elimination of ion pump (use getter), elimination of lead shield and elimination of electromagnet focusing.**
- **DC power supplies and MA modulator**
  - **Modulation anode method is cost effective. Employing bouncer circuit enables us to use smaller capacitors in DC PS.**
- **Power Distribution System (PDS)**
  - **Use very simple PDS. Elimination of circulator. Employing the small numbers of component and trying to eliminate flange as possible.**

- **Taking into account of above consideration, the cost of the RF system of DRFS is approximately 2/3 of that of RDR. More study and R&D, further cost reduction may be expected.**

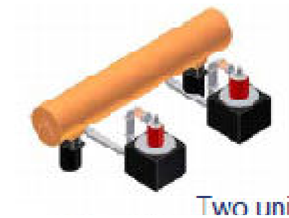
DRFS COST

Switching Regulator P/S

DRFS	HCS		Baseline		Cost Impact
	No@26 Cav	Cost	No@26 Cav	Cost	%
DC PS w Backup	1	325	1	195	
MA Modulator	1	80	1	80	
MA Klystron	13	845	6.5	423	
Magic Tee	13	91	20	137	
		1341		834	62.2
BCD	**Standard**		**Low Power Option**		**Cost Impact**
	No@26 Cav	Cost	No@26 Cav	Cost	%
Mod	1	515	0.5	297	
Kly	1	300	0.5	150	
PDS	1	345	0.5	173	
		1160		620	53.4
	Cost impact DRFS Base line/RDR Standard				71.9

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**
- **And then installed in the buncher section of STF-II aiming for the realistic operation.**
- **More large scale of DRFS is planed for STF-II in KEK.**



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	FY2009				FY2010				FY2011			
	Apr-09	Jul-09	Oct-09	Jan-10	Apr-10	Jul-10	Oct-10	Jan-11	Apr-11	Jul-11	Oct-11	Jan-12
ILC Schedule												
KEK Schedule						S1 Global	DRFS Install					
MA Klystron #1	Design	#1 MA Kly Manufacturing			Test							
MA Modulator #1		Design	#1 Manufacture									
DC Power supply #1		Design	#1 Manufacture									
PDS of #1			Manufacture									
MA Klystron #2			Design		#2 MA Kly Manufacturing							

2 Klystron or 4 klystron DRFS for STF-II(1)

Pros and Cons for DRFS Comparing with RDR

	Pros	Cons	Comment
Configuration	*Complete single tunnel; Very simple	*All heat dissipation in a tunnel *Concern about radiation effect against the components	*Need more study *Check XFEL data
Operability	*Very good *RF Vector sum of only 4 cavities *Flexible to cavity quench etc.		
Availability		*Concern about failures of components *Maintenance	*Check for MTBF *Introduce Redundancy *Reasonable plan
Cost	*70% cost reduction for SB2009		
R&D	*Easy demonstration		

Summary

- Proposal of Distributed RF Scheme (DRFS) is presented.
- This is one of the possible HLRF system for a cost-effective solution in support of a single Main tunnel design.
- Pros and cons of DRFS comparing to RDR is shown.
- Reasonable solutions for some concerns for heat dissipation, radiation effect for instrument, maintainability and cost are presented.
- DRFS has a high operability and flexibility in operation and is acceptable for the cavity field variation.
- Similar system is employed in many projects, such as SNS, J-Parc, J-lab and so on.
- Since DRFS is system comprised of small units, it is easy to perform a R&D and feasibility will be easily shown.