Introduction to L-band Klystrons for the ILC

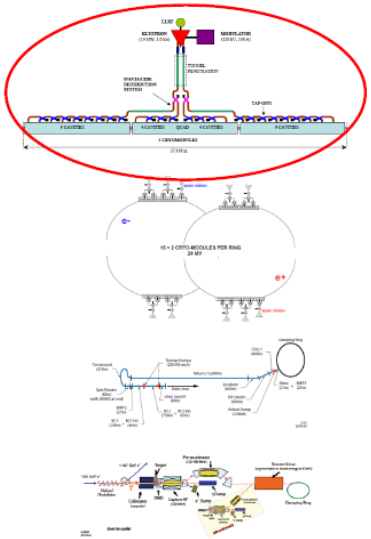
L-Band Klystron in ILC & Other Project
(For Hints of CLIC RF Source)

Shigeki Fukuda

(KEK)

SB2009 and HLRF

Construction Cost Profile



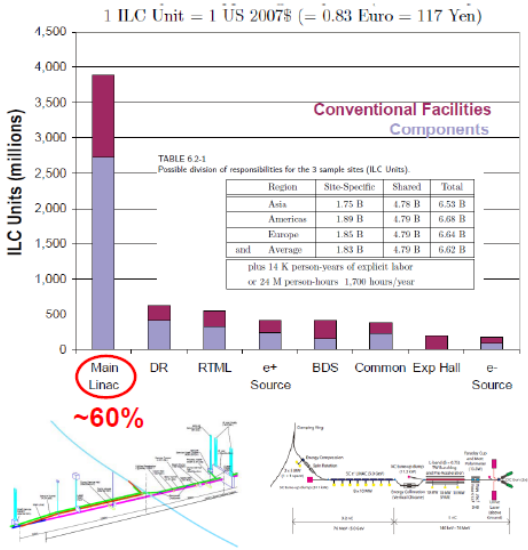


TABLE 6.2-1
Possible division of responsibilities for the 3 sample sites (ILC Units).

Region	Site-Specific	Shared	Total
Asia	1.75 B	4.78 B	6.53 B
Americas	1.89 B	4.79 B	6.68 B
Europe	1.85 B	4.79 B	6.64 B
and Average	1.83 B	4.79 B	6.62 B
plus 14 K person-years of explicit labor or 24 M person-hours 1,700 hours/year			

RDR(2007) to TDR(2012)

- Cost Containment -

- RDR: 6.62 BILCU (4.80 Shared + 1.82 Site Specific) + 14.1 kPerson
- SB2009: 7 working assumptions with ~13% cost reduction
- One of the most cost-effective assumptions is:

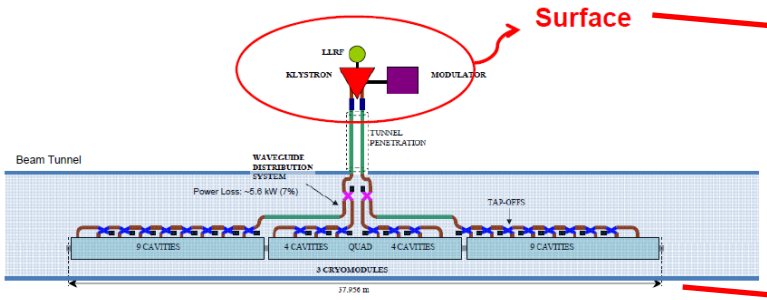
2. **A single-tunnel solution for the Main Linacs and RTML, with two possible variants for the High-Level RF (HLRF):**
   - Klystron cluster scheme (KCS);
   - Distributed RF Source scheme (DRFS).

RF Source
Klystron: 10 MW MBK
Modulator: IGBT Pulse Modulator with Bouncer

Single tunnel configuration 1 (KCS)

ML Single-Tunnel Configuration

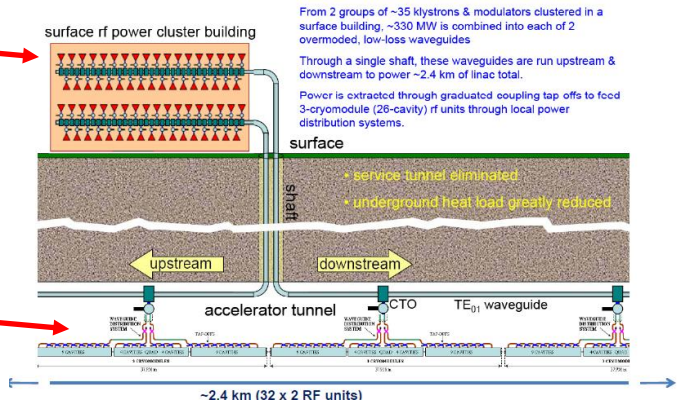
- Klystron Cluster System (KCS)-



e- ML	282 RF units	Field gradient	31.5 MV/m
e+ ML	278 RF units	Energy gain per RF unit	850 MeV
Total	560 RF units	(with 22% tuning overhead)	

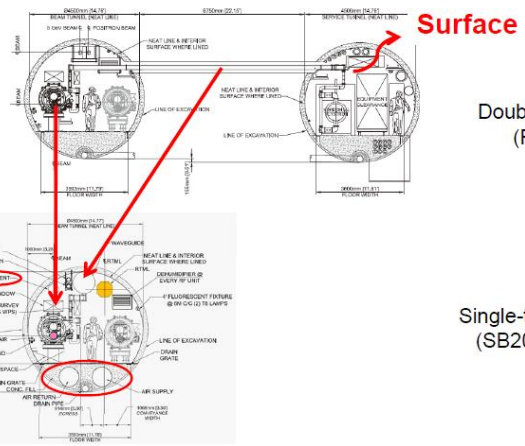
ML RF Units

- Klystron Cluster System (KCS) -



ML Civil Engineering

- Klystron Cluster System (KCS) -



Double-tunnel (RDR)

Single-tunnel (SB2009)

RF Source

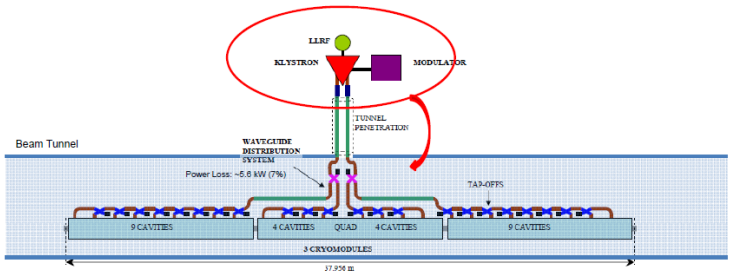
Klystron: Bunch of 10 MW Klystron on the Surface

Modulator; Bunch of RDR Modulator or Marx Modulator

Single Tunnel Configuration 2 (DRFS)

ML Single-Tunnel Configuration

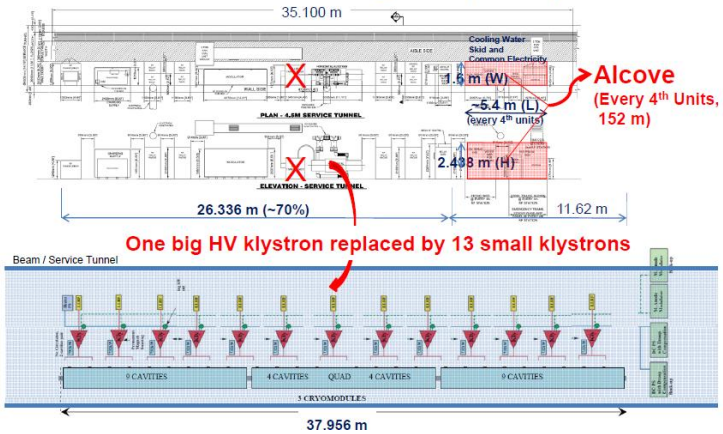
- Distribute RF System (DRFS) -



e- ML	282 RF units	Field gradient	31.5 MV/m
e+ ML	278 RF units	Energy gain per RF unit	850 MeV
Total	560 RF units	(with 22% tuning overhead)	

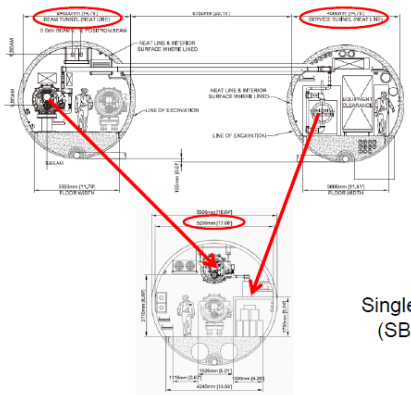
ML RF Unit

- Distributed RF System (DRFS) -



ML Civil Engineering

(DRFS)



Double-tunnel (RDR)

Single-tunnel (SB2009)

RF Source

Klystron: 8000 800kW-MA Klystrons

(MA: Modulation Anode)

Modulator; DC Power Supply

MA Modulator

RDR Klystron in ILC
10 MW MBK

Accelerator Laboratory, KEK

Klystron Requirement for ILC

- Long Pulse (1.5ms), High Power (10MW) and High Efficiency (>60%)
- In order to achieve above requirements, M B K (Multi-beam Klystron) was developed as the first case of high power application.
- So far three companies (Thales, CPI and Toshiba) developed MBKs independently.
- Alternative:

  SBK (Sheet Beam Klystron)

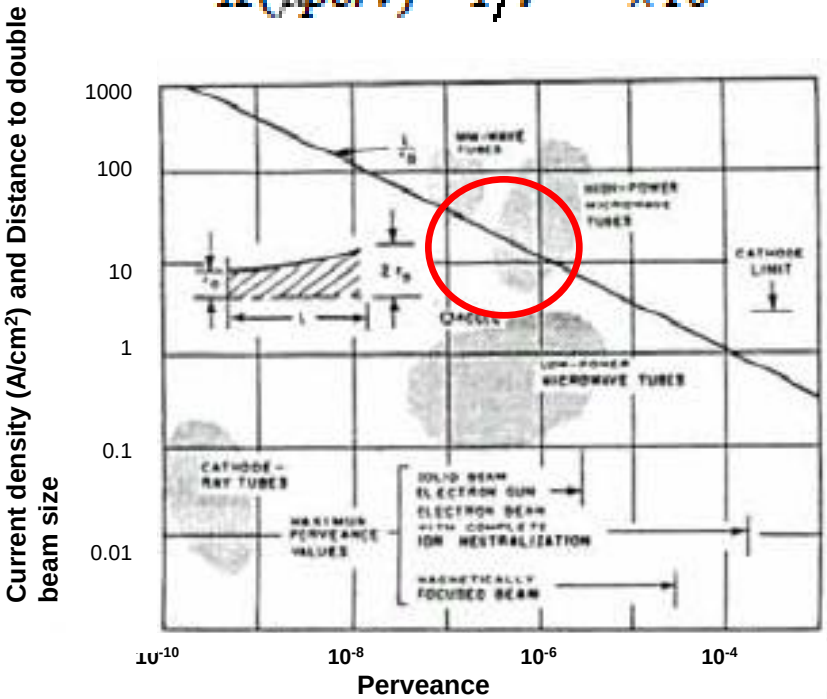
  <36-beam Klystron>

Why M B K ?

->Relation between perveance and efficiency

Definition of perveance

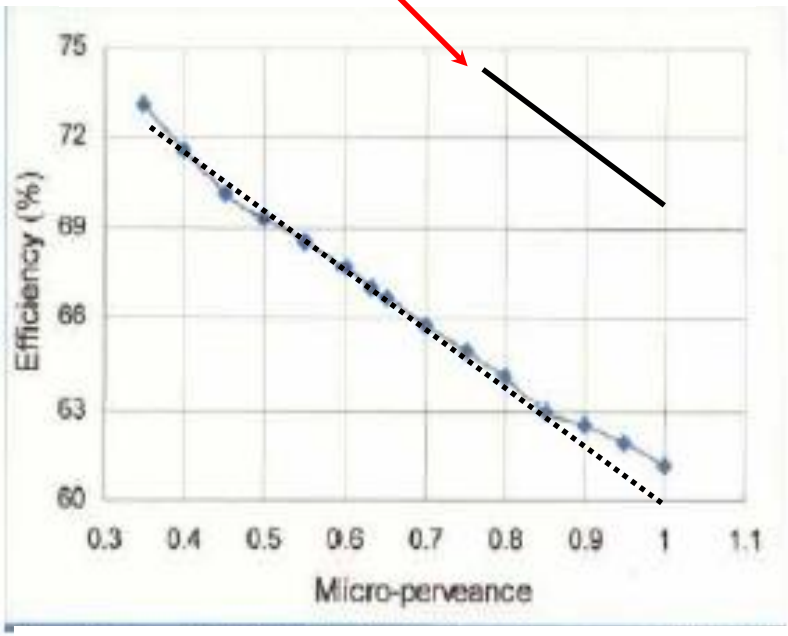
$$K(\mu perv) = I/V^{3/2} \times 10^6$$



Relation between perveance and beam current density

Symons Equation

$$\eta(\%) = 90 - 20 \times K(\mu perv)$$



Empirical relation for efficiency and micro-perveance

More lower perveance beam, more higher efficiency

Accelerator Laboratory, KEK

Pass to MBK

- Lower perveance for a single beam in order to get the higher efficiency

  ->lower current, but higher applied voltage (discharge possibility)

- Keeping to allowable low applied voltage, and increase the number of beam-lets

  -> Complicated gun

  Possible oscillation due to the electric gun

  3D design

  Contribution from the axial-asymmetric part

  (Thermal expansion for non-axial symmetry)

- Complicated cavity design

  ->Mode stabilization, Free from Oscillation

Thales

CPI

Toshiba

MBK of three companies

MBK Comparison with three companies

Item	Unit	TH1801 Thales	E3736 Toshiba	VKL-8301 CPI
Frequency	MHz	1300	1300	1300
Output Peak Power (max)	MW	10	10	10
Output Average Power (ma	kW	150	150	150
Beam Voltage	kV	110	115	114
Beam Current	A	130	132	131
Pulse width	ms	1.5	1.5	1.5
Efficiency	%	65	>65	65-67
Gain	dB	48	47	47
Number of beam		7	6	6
Beam micro-perveance	uA/V^3/2	3.5	3.38	3.4
Single beam micro-perv.	uA/V^3/2	0.50	0.56	0.57
Cavity numbers		6	6	6
Cathode loading	A/cm^2	<2	<2.1	<2.1

Interaction between cavity and beam

TH2108(Thales) **One cylindrical cavity interacts to 7 beamlets. 7 beams couple to FM(fundamental mode) -TM010.**

VKL8301(CPI) **Input and output cavities are annular cavity which M010. Intermediate cavity is cylindrical of TM010.**

E3736(Toshiba) **All are annular cavities and TM010 couples to 6 beamlets. Third cavities are harmonic cavity.**

10-MW MBK Manufacturing Data

Toshiba has manufactured 4 10MW-MBK for DESY and ILC(KEK/SLAC)
And historical data are as follows.

No	ITEM	Output Powe	Input Power	Efficiency	Banc Width	Delivery Date
	Unit	MW	W	%	MHz	
1	DESY-Vertical	10.6	120	70	4.1	2006/March
2	DESY-Horizontal	10.3	120	67	3.6	2007/September
3	KEK/SLAC-Vertical	10.1	134	68	3.8	2008/January
4	KEK-Horizontal	10.3	100	67	3.5	2010/March

* Operating condition: beam pulse width of 1.7ms, rf pulse width of 1.5ms and pulse rep. rate of 10Hz

•Vertical MBK in SLAC are running to accumulate the long-term running data.

Full energy and Low-energy running (KCS)

- KCS (Chris Adolphson)

  MBK: Toshiba MBK Klystron Data

  – 125GeV case
    - NBK

    P0=10MW -> 5MW

    V=117kV -> 94kV

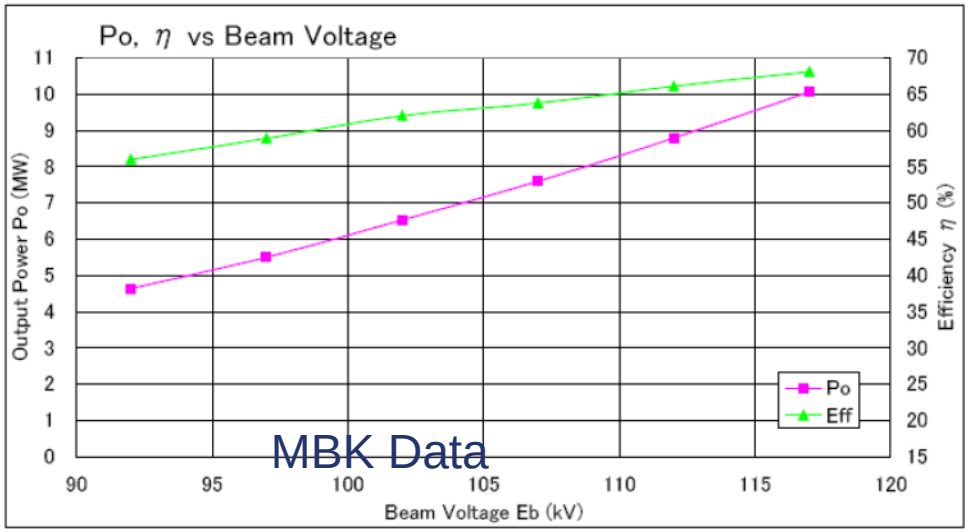
    Eff. 67% - > 59-60%

  – Modulator

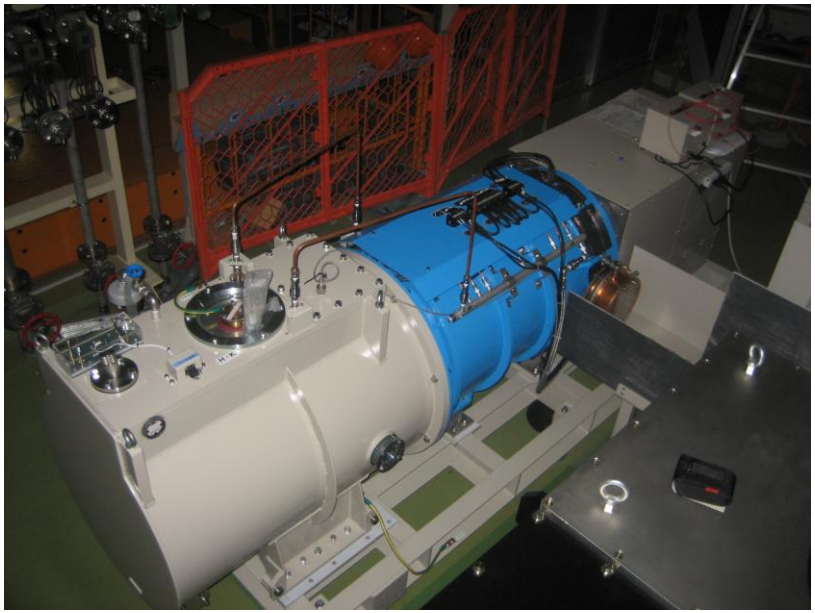
    Power=100% -> 58%

    Pulse Width = 100% -> 47%

    Near to the 50%



KEK 10MW Horizontal MBK



In FY2009 at KEK, a 10MW horizontal klystron is procured but due to the poor resource, it has not yet operated.

Thales and CPI MBK in DESY

Thales MBK, TH1802, horizontal klystron

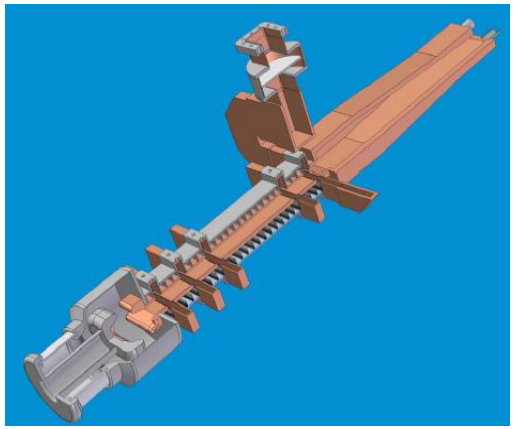
CPI MBK, VKL8301B, horizontal klystron

Accelerator Laboratory, KEK

Alternative 1.3GHz RF Source

10 MW Sheet Beam Klystron (SBK)

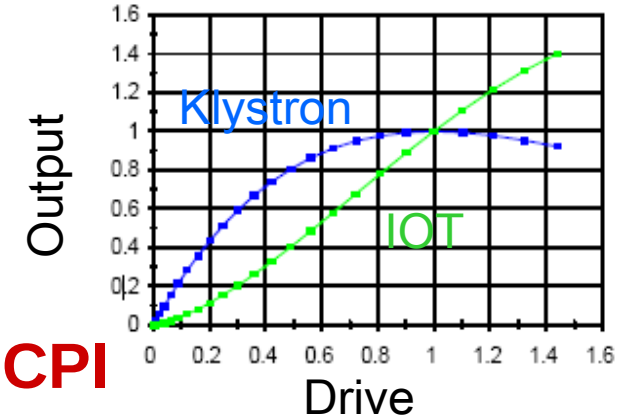
Parameters are similar to 10 MW MBK



SLAC

5 MW Inductive Output Tube (IOT)

Peak Output Power	5	MW (min)
Average Output Power	75	kW (min)
Beam Voltage	115	kV (nom)
Beam Current	62	A (nom)
Current per Beam	5.17	A (nom)
Number of Beams	12	---
Frequency	1300	MHz
1dB Bandwidth	4	MHz (min)
Gain	22	dB (min)
Efficiency	70	% (nom)



CPI

Low-voltage 10 MW MBK

voltage 65 kV
Current 238A
Many beamlet such as 30-40

No pulse transformer

KEK

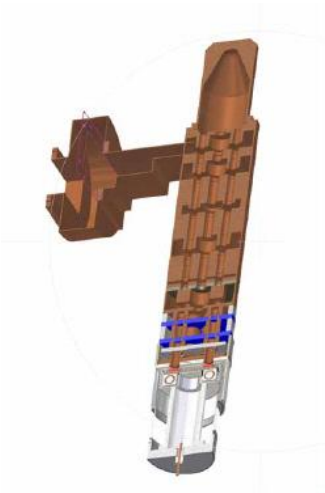
Accelerator Laboratory, KEK

10 MW 36-beam Klystron (design only)

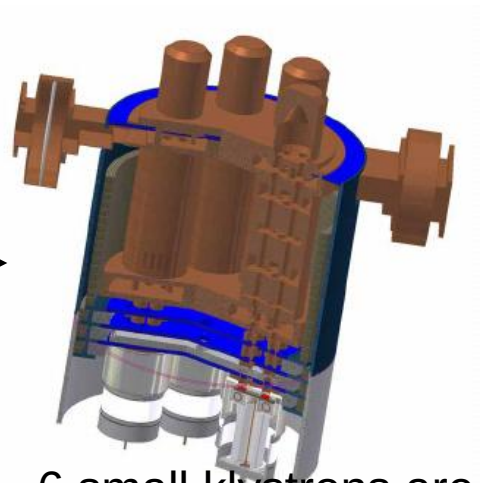
10 MW Output Condition for MBK

No. of Beam	1	7	18	24	30	36	42	48
Current	106.8	17.1	11.8	10.59	11.08	8.6	7.07	6.02
Beamlet power	19.2	2	0.83	0.64	0.55	0.43	0.35	0.3
Perveance	1.4	0.43	0.64	0.72	0.99	0.77	0.63	0.54
Efficiency	52	71.5	67.3	65.6	60.2	64.6	67.4	69.2
Cathode Voltag	180	117	70	60	50	50	50	50
Total Perv.	1.4	2.99	11.47	17.29	29.72	27.68	26.56	25.84

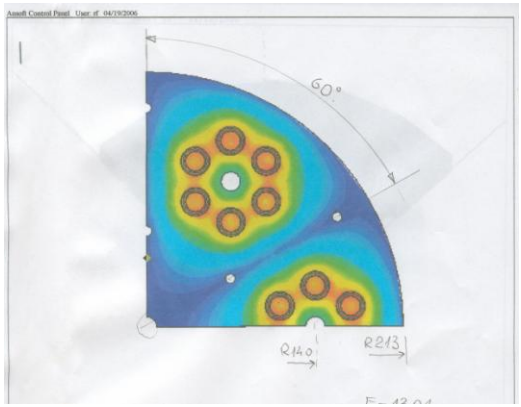
(1) Small klystron of 6 beamlets positioned annually.
(2) 6 klystrons are positioned annually.
(3) Common input and output cavities for 36 beamlets



Small klystron with 6 beams



6 small klystrons are combined



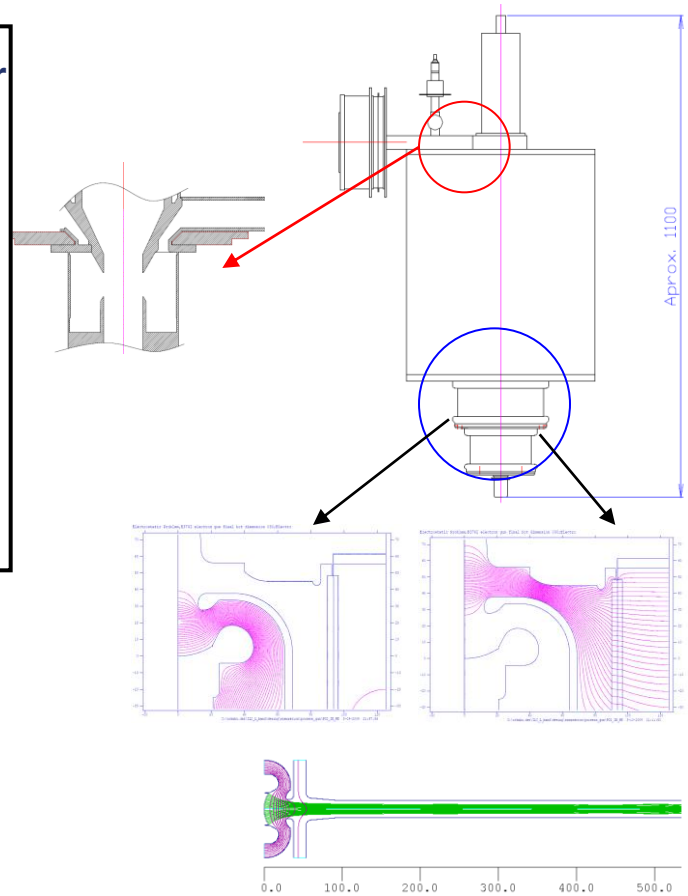
Beam and rf mode

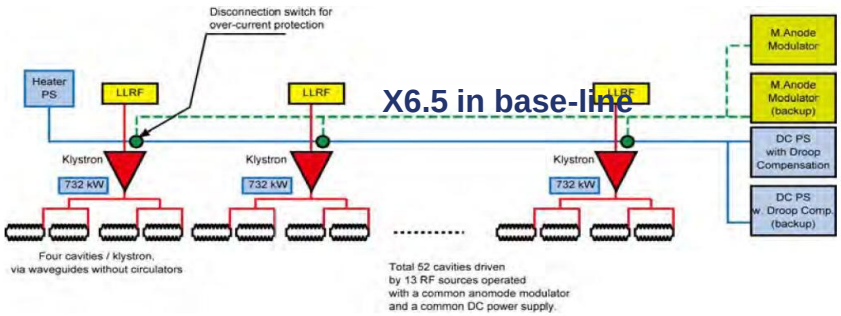
Klystron for DRFS

DRFS Klystron is a Modulated-anode type klystron or triode type klystron,

By changing the voltage of modulated anode electrode relative to cathode, it is possible to change the beam perveance.

Beam perveance is strongly related to the RF efficiency. Lower the beam perveance, higher the efficiency is.

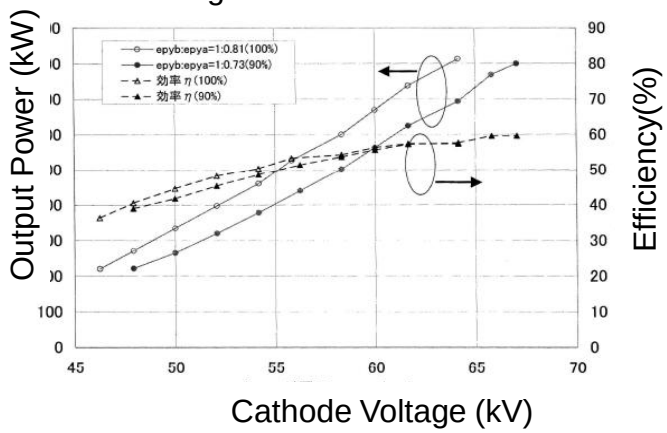




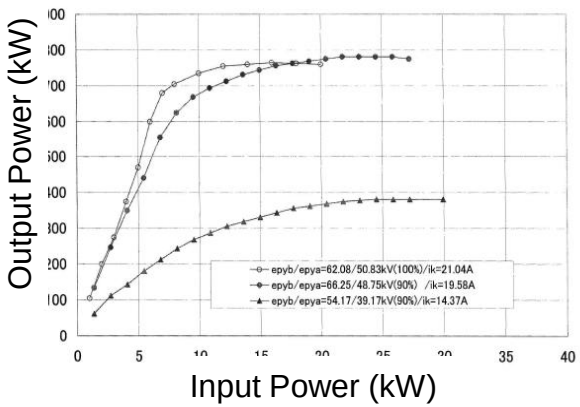
RF unit for 3 cryomodules

Data of prototype DRFS Klystrons

E37501 #1 Saturation power vs applied voltage



E37501 #1 Input-output characteristics



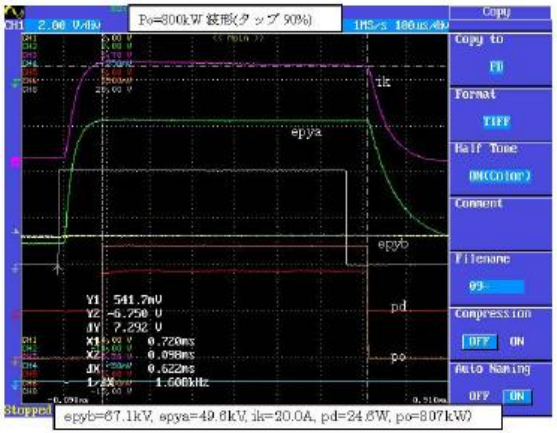
Achieving data

Original design was 750kW but same Design achieved More than 800kW.

No. 1 DRFS klystron:
806.7kW at 67.1kV
(Micro-perveance=1.15),
Eff.=**60.1**%

813.0kW at 64.2kV
(Micro-perveance=1.36),
Eff.=57.4%

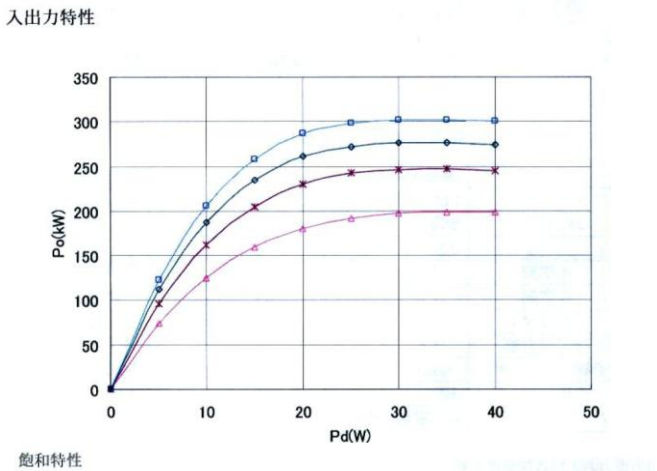
Two prototype DRFS klystrons
Are waiting for test.

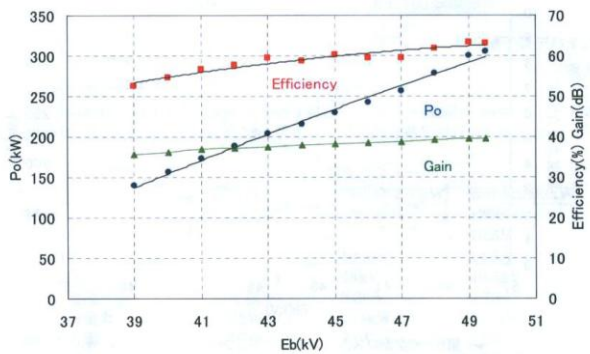


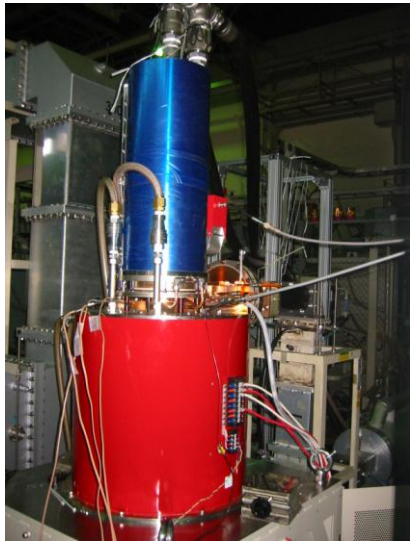
Waveform

1.3 GHz 300kW CW Klystron for ERL Project

	Unit	Design	Achieved
Frequency	MHz	1300	1300
Beam Voltage	kV	<52	49.5
Beam Current	A	<11	9.74
P Out at Saturation	kW	>270	305
Perveance	uA/V^1.5	0.89	0.89
Efficiency	%	>50	63.2
Gain	dB	>38	39.5







At Toshiba Test

Very stable performance. We can expect more higher efficiency from the data of Po vs Frequency.

So far 63.2% at microperveance of 0.89

Mitsubishi PV-1040 Klystron for SKEKB Injector

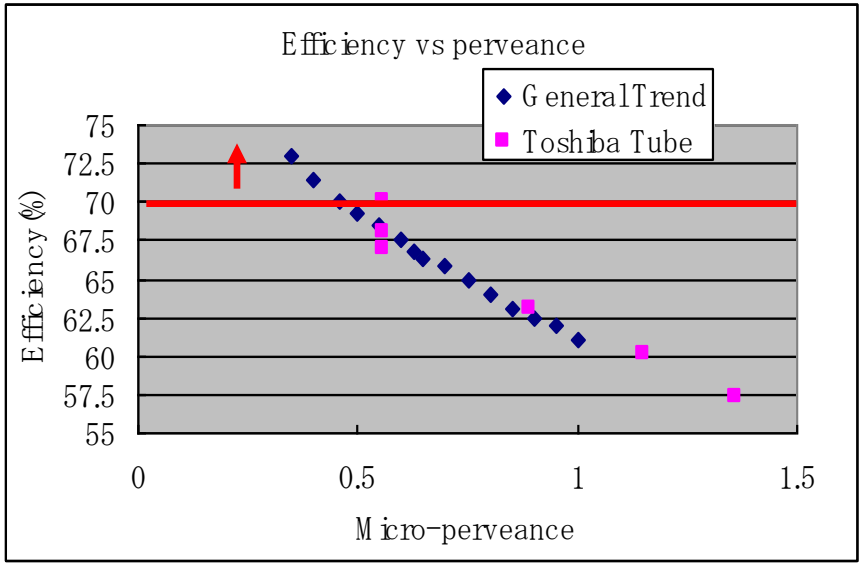
Parameter	PV-1040
Frequency (MHz)	1300
Output Power (MW)	40
Beam Voltage (kV)	295
Beam Current (A)	335
Efficiency (%)	40
Perveance (μP)	2.1

Simple Consideration for CLIC L-band RF Source of Driving Beam

Requirements for the CLIC L-band Tube

From Toshiba Quotation,

- High Efficiency of More than 70%
- High Power of more than 40MW
- Long pulse width around 150 us
- Frequency near to ILC Frequency, but need to change a bit (1.3->1.0 GHz))
- Reliability



Technical Difficulty

- High Power and High Efficiency

  High Efficiency → Low perveance, and High applied voltage

  In order to avoid difficulty, approach MBK like ILC.

  High Power → More many –beam MBK, or Distributed MBK System

  Still need study about, cathode loading, minimize gun arching, RF window study

Simple survey of CLIC-L

- Constraint: Output power of 40MW, efficiency of 70%, and cathode loading of 2A/cm^2. Search of MBK direction.

  Pulse width of about 150us is not short, and cares to cathode loading, allowable field gradient and window capability are necessary.

No. of Beam		1	6	8	12	16	24	36
P0 Total	MW	40	40	40	40	40	40	40
Power/beam	MW	40	6.67	5.00	3.33	2.50	1.67	1.11
Voltage	kV	438.0	213.9	190.7	162.1	144.5	122.9	104.5
Current	A	130.5	44.5	37.5	29.4	24.7	19.4	15.2
Beamlet power/bea	MW	57.14	9.52	7.14	4.76	3.57	2.38	1.59
Perveance	uP	4.5E-07	4.5E-07	4.5E-07	4.5E-07	4.5E-07	4.5E-07	4.5E-07
Efficiency	%	70	70	70	70	70	70	70
Cathode loading	A/cm^2	2	2	2	2	2	2	2
Cathode Diametr	cm	9.1	5.3	4.9	4.3	4.0	3.5	3.1

Another Example (Eff. of 70% and 75%)

Eff. of 70% needs uP=0.45. Cathode loading of 3A/cm^2 in this case.

No. of Beam		1	6	8	12	16	24	36
P0 Total	MW	40	40	40	40	40	40	40
Power/beam	MW	40	6.67	5.00	3.33	2.50	1.67	1.11
Voltage	kV	438.0	213.9	190.7	162.1	144.5	122.9	104.5
Current	A	130.5	44.5	37.5	29.4	24.7	19.4	15.2
Beamlet power/beai	MW	57.14	9.52	7.14	4.76	3.57	2.38	1.59
Perveance	uP	4.5E-07	4.5E-07	4.5E-07	4.5E-07	4.5E-07	4.5E-07	4.5E-07
Efficiency	%	70	70	70	70	70	70	70
Cathode loading	A/cm^2	3	3	3	3	3	3	3
Cathode Diametr	cm	7.4	4.3	4.0	3.5	3.2	2.9	2.5

Eff. of 75% needs uP=0.3. Cathode loading of 3A/cm^2 in this case.

No. of Beam		1	6	8	12	16	24	36
P0 Total	MW	40	40	40	40	40	40	40
Power/beam	MW	40	6.67	5.00	3.33	2.50	1.67	1.11
Voltage	kV	501.1	244.7	218.1	185.5	165.3	140.6	119.5
Current	A	106.4	36.3	30.6	24.0	20.2	15.8	12.4
Beamlet power/beai	MW	53.33	8.89	6.67	4.44	3.33	2.22	1.48
Perveance	uP	3E-07	3E-07	3E-07	3E-07	3E-07	3E-07	3E-07
Efficiency	%	75	75	75	75	75	75	75
Cathode loading	A/cm^2	3	3	3	3	3	3	3
Cathode Diametr	cm	6.7	3.9	3.6	3.2	2.9	2.6	2.3

Summary

- HLRF configuration of ILC is shown.
- 10 MW MBK status including basic idea is shown.
- Other alternative RF sources in ILC and some recent L-band tubes developed in KEK are presented.
- Basic simple numerical consideration for the CLIC L-band klystron for driving beam system, and key issues are also listed up.