RF System in Accelerator

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Introduction

RF Source Importance

- Modern Accelerator is so called "RF accelerator", and **RF is the key technology.**
- Accelerator frequency is ruled by the existence of the rf source of matched frequency.
- RF system is expensive and large fraction of total cost is shared in RF source. Therefore choice of RF is very important.
- RF source is the source of failure (arcing etc.) and careful availability consideration and constant effort of maintenance are required.

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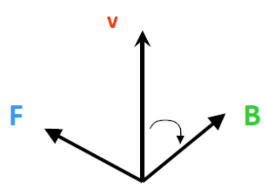
Early Accelerator and RF

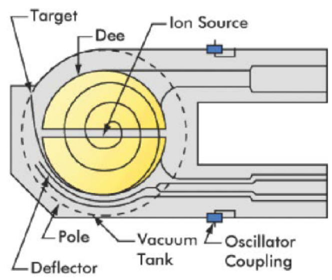
Introduction(1)
Circular Accelerator

Lorentz Force Equation

F=e･E+e･v x B

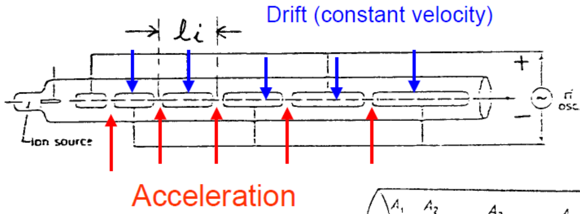


Cyclotron

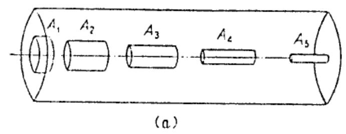


Electron has a circular orbit
In the magnetic field.
Revolution time is constant if B=const.
RF field is repeadedly used.

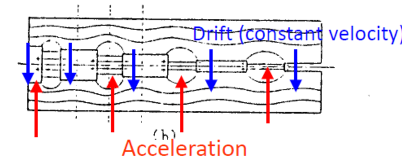
History of the Linac(1)



Ising(1924)
Wiedroe's Linac
(1928)



Alvarez Linac
(1946)



Cyclotron

Simple Application of low frequency RF

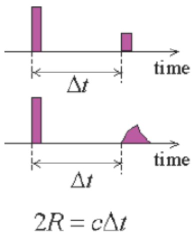
Idea of linear Accelerator

RF source is required. For efficient use, powerful RF Source was needed.

RF Source Development

History of the Linac(1)

- Linac was developed after the World War II.
  → Due to the **Radar Technology for military purpose**



World War II forced to develop RF technology.

Short pulse high power microwave source.

Klystron was invented by Varian Brothers, in 1939.
(a few microsecond, 10 MW 10cm microwave)
Related high-power power supply
(300kV,300A pulsed source)

RF Technology is the key technology for linear accelerator

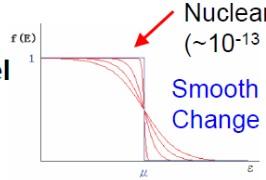
History of Linac(2)

- **Stanford University Electron Linac(1950-)**

Linac=Very big electron microscope

R. Hofstadter studied nuclear structure by electron scattering(1954-57) and was awarded a Nobel prize (1961).

Comparing with Dr. R. L. Moessbauer, Nobel Winner In 1961, he was called the son of Big Science.



Nuclear surface ($\sim 10^{-13}$ cm)

Smooth Density Change

- **2 mile accelerator was constructed in SLAC (Stanford Linear Accelerator Center, CA, USA) (1966-)**
- **SLC(SLAC linear Collider) was constructed (1983-)**
- **Both cases, RF source (Klystron) was developed in SLAC**

Stanford Mark III Linac made the klystron
Power of 3-order higher in 1950's..

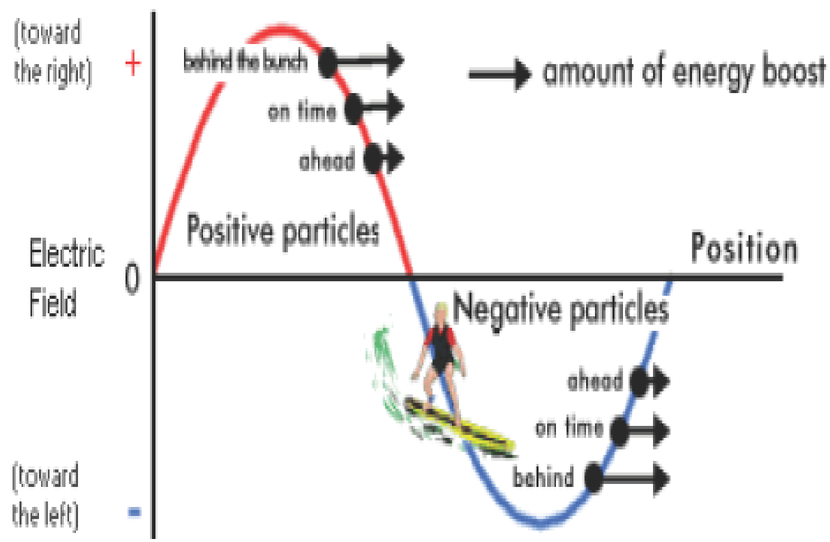
Phase of RF is important

Linear Accelerator (Linac)

Charged particles are accelerated linearly.

High frequency electromagnetic wave (micro-Wave) is used for the acceleration.

Principle:

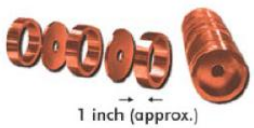


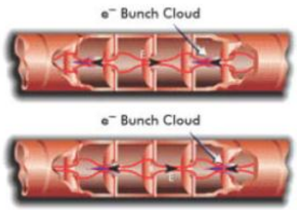
In the linac, the wave is electromagnetic. That means it is made up of changing magnetic and electric fields

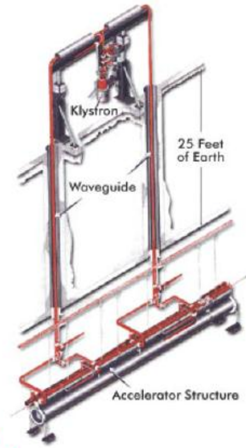
Variant of Linac

- Since the electron mass is light, it is easy to be accelerated up to the **light velocity** (velocity is **constant**).

→***overall structures are the same***







- Longest Linac is SLAC 2-mile Linac (3.2km and 20GeV)
- Second longest linac is KEK linac (500m and 8 GeV)
- Small linac was developed for medical use (2-3m and 30 MeV)
- Short pulse linac of which pulse duration of a few to 20 microsec.

-----wavelength of 10cm (S-band), 5cm (C-band) and X-band (2.5cm)

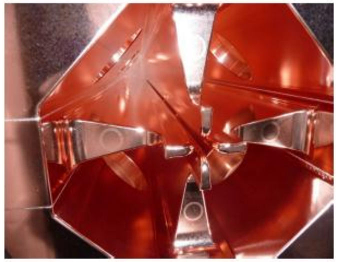
- Long pulse linac of which pulse duration of a millisecc

------wavelength of 20cm class (L-band, ex., 1.3GHz)

Electron Linac

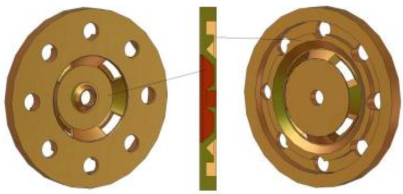
- Since the proton mass is 2000 times heavier than electron, it is hard to be accelerated up to the **light velocity** and depending on the β(=v/c), several structures are used in proton linac and each structure has a suitable frequency.
  - RFQ structures-----VHF band such as 201MHz-432MHz
  - Alvarez structures/DTL(Drift Tube Linac)-----same as RFQ
  - ACS(Anular Coupled Structure), SCS(Single Coupled-cell Structure) etc-------Harmonics of low β section (0.8-1GHz)

Proton Linac



RFQ Structure

DTL Structure



Element of ACS

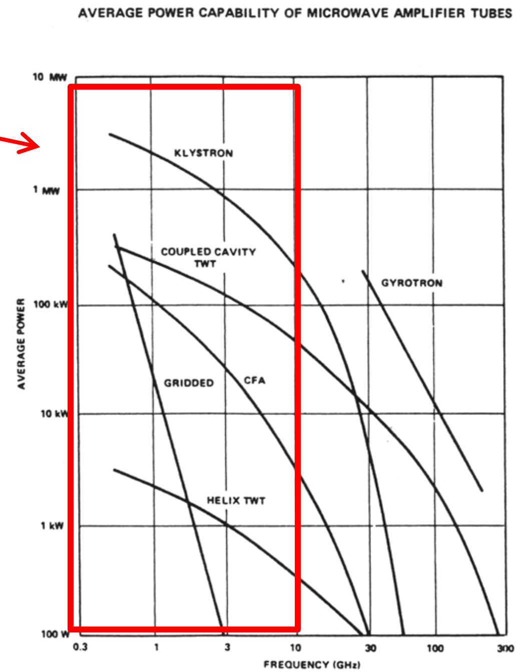
RF Sources suitable for accelerator

- Factors required to accelerator rf source
  1. **Frequency range** - higher than 0.3 GHz, klystron is best rf source. Less than 0.3 GHz, Solid state amplifier, IOT and Tetrode are used.
  2. **Peak power capability** -related with energy gain, short linac, and cost benefit. How to minimize the discharge rate in tube and structures.
  3. **Average power capability** – related with duty cycle or repetition rate. Cw accelerator.
  4. **Gain** – relate with driver amplifier. High gain is preferable; Generally klystron is high gain such as 50 dB. IOT is around 20 dB. Power tetrode is poor gain.
  5. **Phase stability** – klystron is voltage driven device and if applied voltage is stable, phase property is excellent.
  6. **Simplicity, Availability and Long life** – klystron is much matured device and satisfy these requirements.

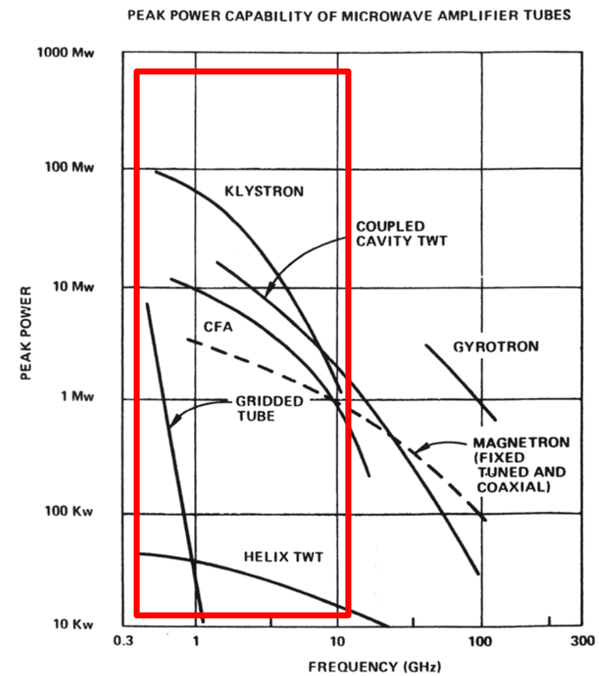
Available RF Sources –states of art now

Frequency range
Suitable for accelerator

Most available rf source for accelerator use, klystron is a best device for average and peak power capability.



Average power vs frequency plot

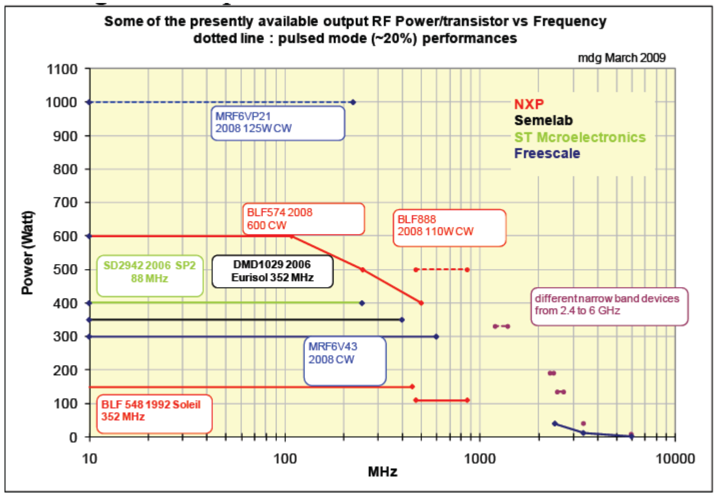


Peak power vs frequency plot

Comparison of various RF sources

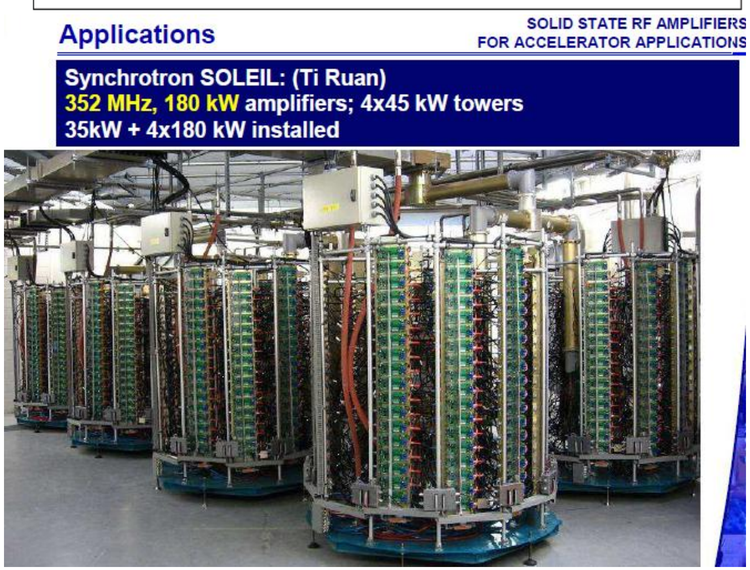
	Efficiency (%)	Bandwidth (%)	Gain (dB)	Relative Operating Voltage	Relative Complexity of Operation
Gridded Tube/Diacrode	10-50	1-10	6-15	Low	3
Klystron	30-70	1-5	40-60	High	2
Magnetron	40-80			High	3
Helix TWT	20-40	30-120	30-50	High	3
Coupled Cavity TWT	20-40	5-40	30-50	High	3
Gyrotron	10-40	1	30-40	High	5
IOT	10—70	1—5	20—25	High	3

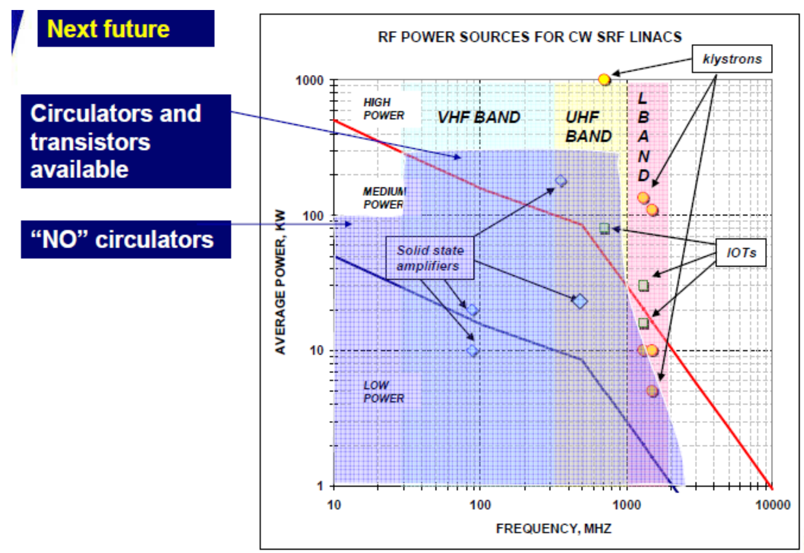
Progress of Recent Solid State Amplifier



For CW use, solid-state amplifiers replace to Klystron. High efficiency is achievable.

In KEK, 20-30 kW cw solid-sate amplifier (1.3GHz)is more likely candidate than IOT or Klystron for cERL.





Original diagram by S. Belomestnykh: RF systems for CW SRF linacs, Linac08

RF Technology

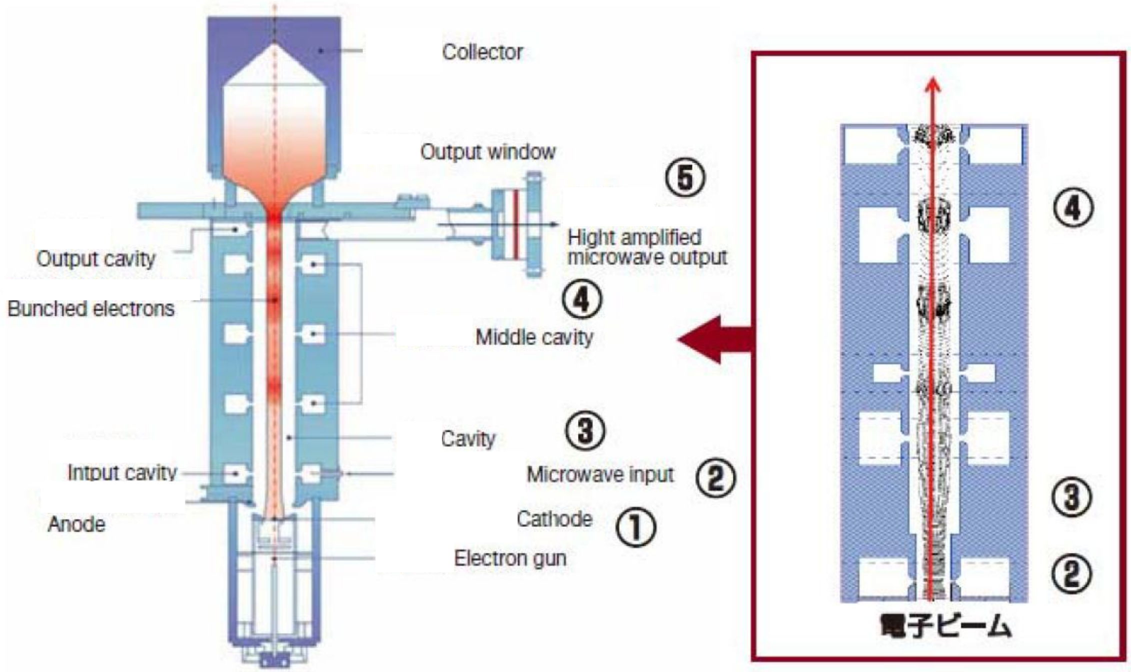
1. ***RF Source (Klystron)***
2. ***PS/Mpdulator***
3. ***Waveguide***
4. ***LLRF***

Klystron

Klystron Structure and Mechanism

☐ Key Component of Klystron

- Electron Gun
- RF Cavity
- Drift Tube
- RF Window
- Beam Collector
- Focusing Magnet
- Cooing System



☐ Basic Mechanism of Klystron

- Electron is <u>**velocity-modulated**</u> in an input cavity.
- Then, electrons form bunch; density modulation
- Bunches are de-accelerated in an output cavity
  ---> beam energy to rf power

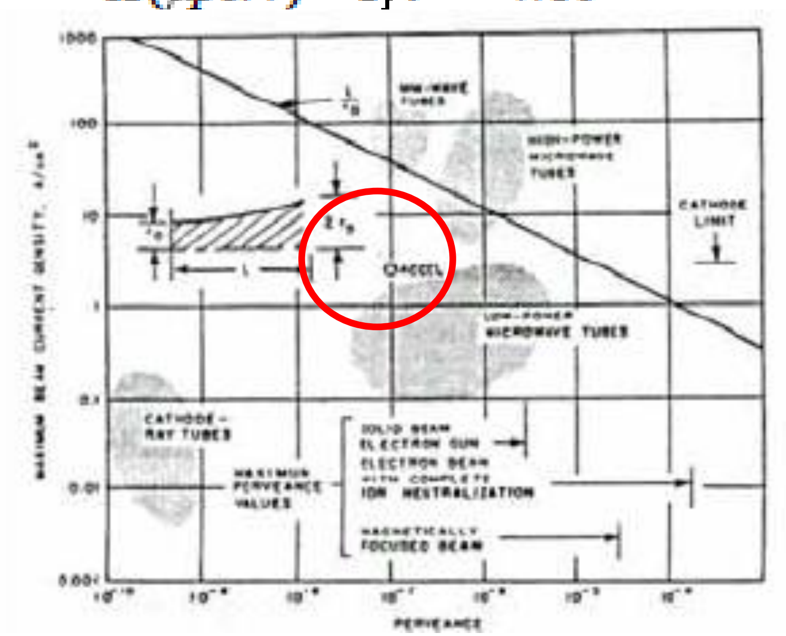
See: Inverse process of accelerator
  Accelerator ----> rf power to beam energy

Accelerator Laboratory, KEK

Important parameter; Perveance

Definition of Perveance

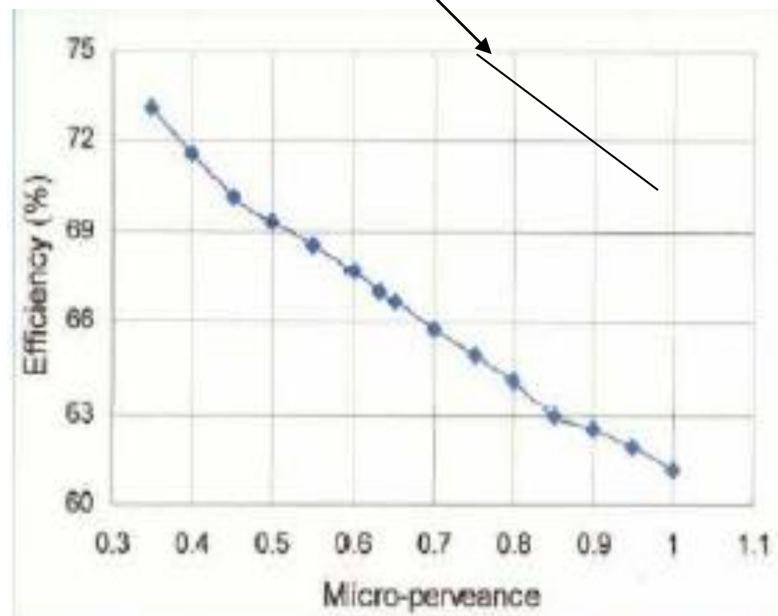
$$K(\mu perv) = I / V^{3/2} \times 10^{6}$$



It characterize the space charge force and deeply related with the bunching formation and therefore with efficiency.

Simon's formula

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



Low perveance klystron has high efficiency but applied voltage is high.

Beam Bunching Theory

☐ Basic Mechanism of Klystron(Linear theory)

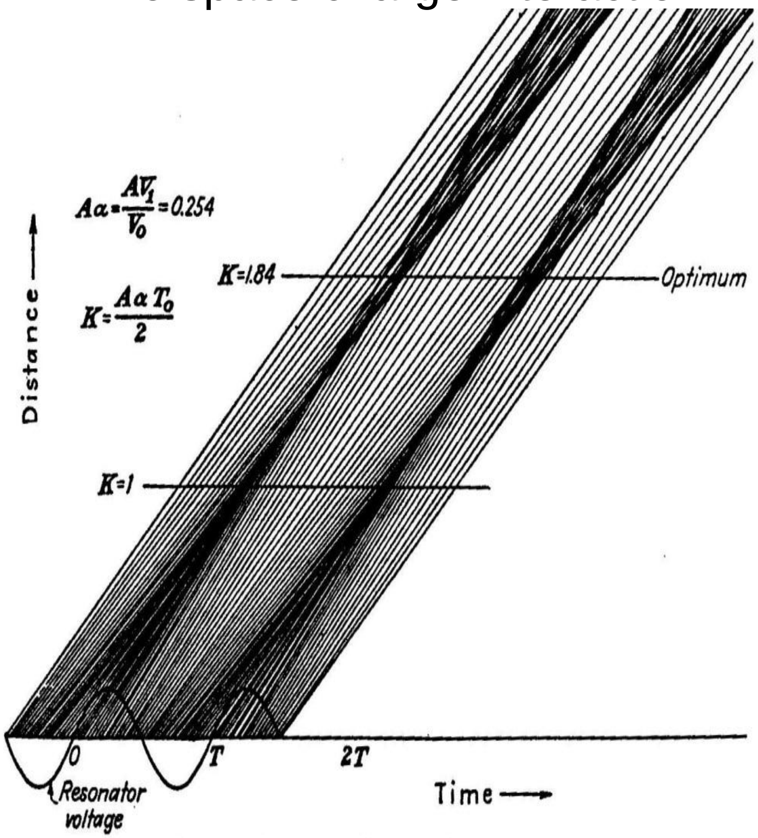
- Electron is **velocity-modulated** in an input cavity.
- Then, electrons form bunch; density modulation
- For this bunching mechanism, a simple linear theory is educative. There are two approaches:
  - Ballistic theory: electron which has a modulated velocity propagate without any interaction with other electrons.
  - Space-charge wave theory: entire electrons behave like a wave which is ruled by space charge force, and automatically it contains the space charge force effect.

☐ More Realistic Analysis (large Signal Analysis)

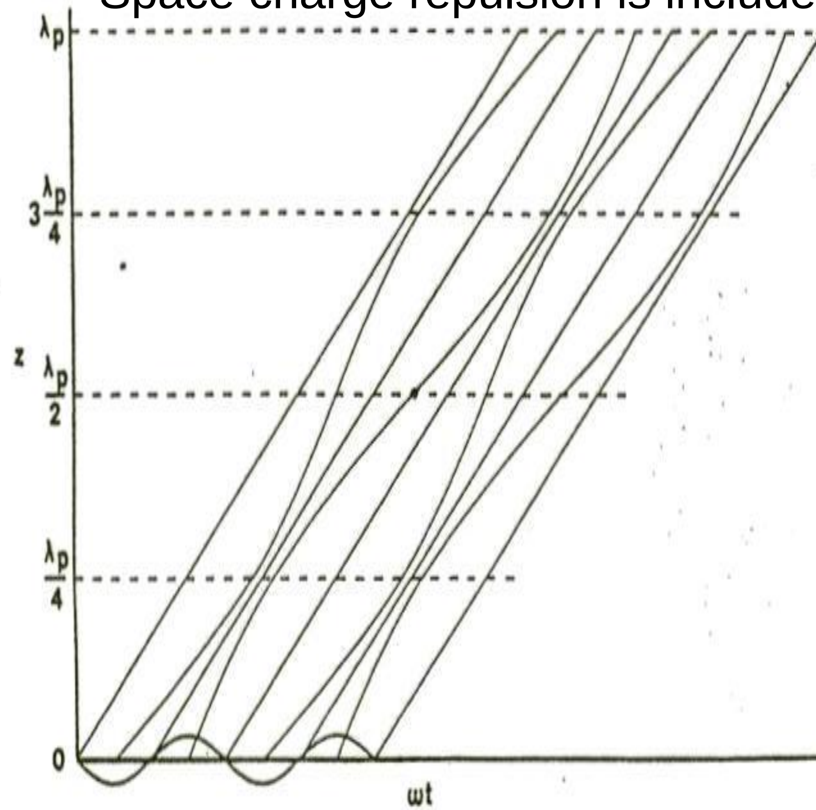
- For the interaction region near to output cavity, linear theory is not applicable and non linear large signal analysis are required.
- One dimensional analysis: Disc model
- 2.5 dimensional analysis: Particle in cell Analysis including magnetic interaction
- 3 dimensional analysis: MAFIA / MAGIC code

Comparison of the beam trace among two approach

Ballistic Analysis Approach
No space charge interaction



Space-charge wave approach
Space charge repulsion is included



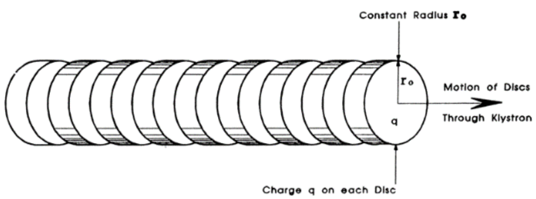
More Realistic Analysis of Klystron

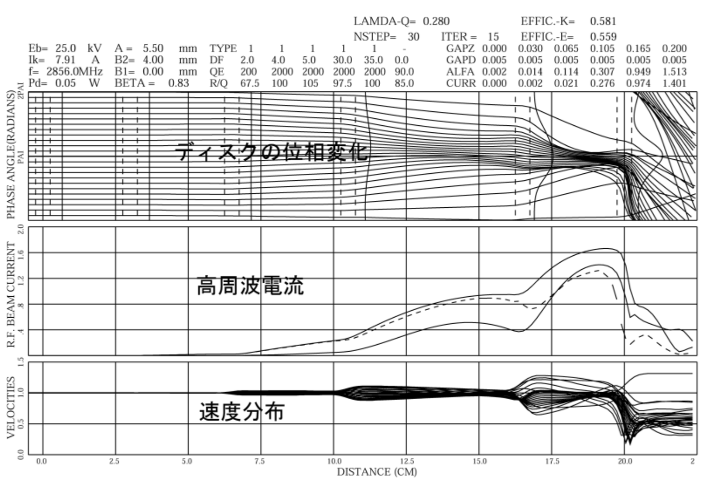
One dimensional disc model

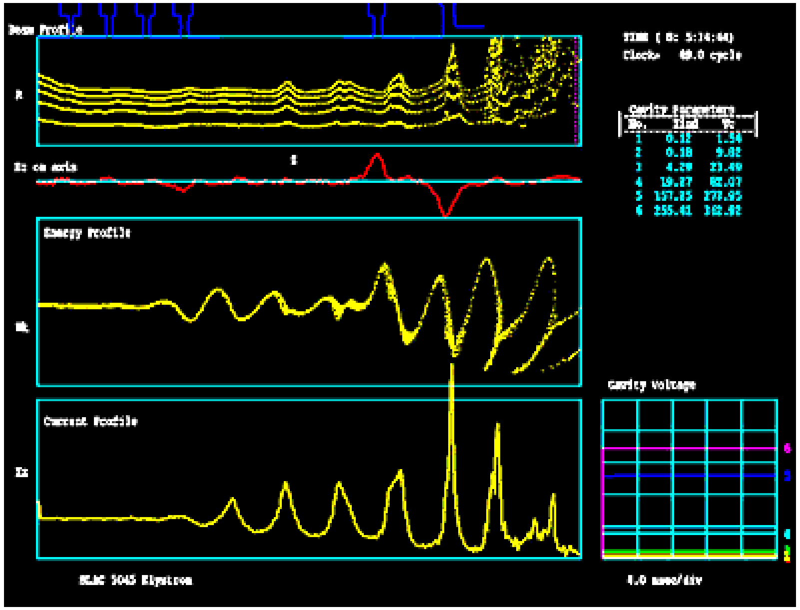
- Constant diameter beam is expressed as series of disc and moving as ballistic manner.
- Space charge among discs is considered
- Cavity-beam interaction is properly considered.

2.5 dimensional PIC program

- Electron particle in 3D
- Solving under axial symmetric condition
- Space-charge and magnetic field effect are included.
- Realistic approach and fairly good agreement between simulation and test







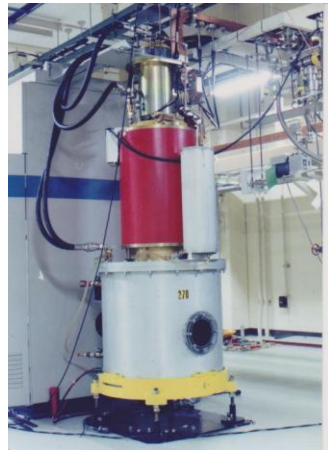
Comment for IUAC Klystron

- IUAC needs the S-band klystron whose frequency is 2860 MHz. So far no commercial klystron coincides to the frequency.
- Due to the recent development of computer simulation, it is easy to do the special design, but quite independent design results in expensive cost.
- Miner change from existing 2856 MHz is easy and with minimum cost rise.

Klystron Handling

Klystron Window Shop



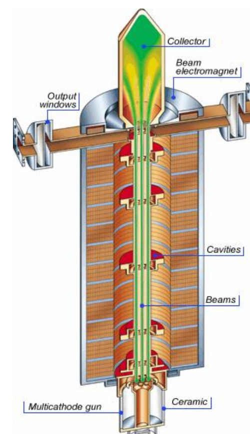


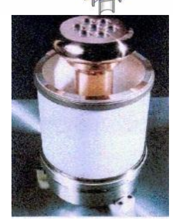

S-band pule klystron: 50MW

324MHz: J-Parc

Measured performance of MBK: TH1801

Operation Frequency:	1.3GHz
Cathode Voltage:	117kV
Beam Current:	131A
μperveance:	3.27
Number of Beams:	7
Cathode loading:	5.5A/cm^2
Max. RF Peak Power:	10MW
RF Pulse Duration:	1.5ms
Repetition Rate:	10Hz
RF Average Power:	150kW
Efficiency:	65%
Gain:	48.2dB
Solenoid Power:	6kW
Length:	2.5m
Lifetime (goal):	~40000h



L-Band MBK:THALES TH1801

Klystron Characteristics

- Child's Law- In space charge limit current, emission current is as follows. $$I = P_\mu V^{3/2}$$

  where P_μ is perveance, and *I* is current, and *V* is applied voltage.

- Then, power is $$P = I \bullet V = P_\mu V^{5/2}$$

  Power's variation $$\frac{\delta P}{P} = \frac{2.5 P_\mu V^{3/2} \delta V}{P_\mu V^{5/2}} = \frac{5}{2} \frac{\delta V}{V}$$

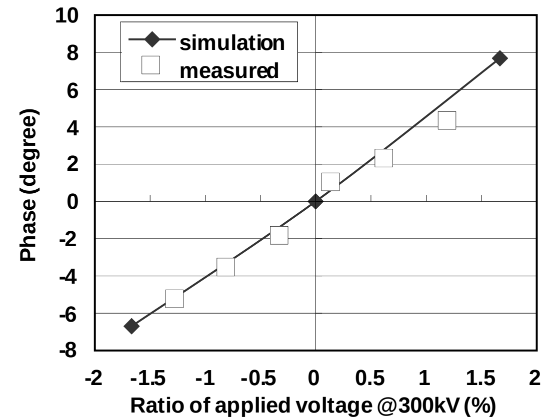
- Klystron's Impedance $$Z = \frac{V}{I} = \frac{V}{P_\mu V^{3/2}} = \frac{1}{P_\mu \sqrt{V}}$$

  Therefore, klystron's impedance varies with applied voltage.

Phase Variation of RF from Klystron

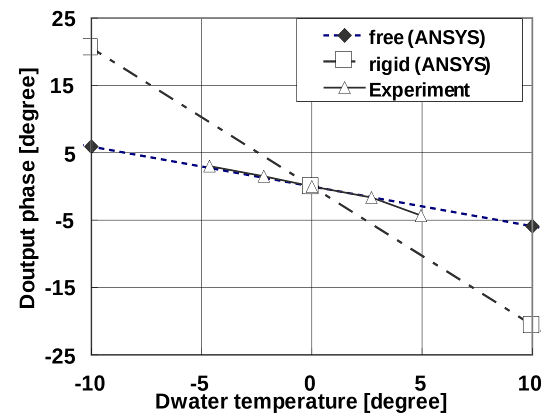
- For linac, phase stability of RF is extreamly important because variation dirctly reduces to energy variaion DE
- Since klystron is voltage driven device and votage determine the electron velocity, rf phase strongly depends on the voltage variation.

$$\Delta\theta = \frac{2\pi L_0}{u_0} = \frac{2\pi L_0}{c\sqrt{1-\frac{1}{(1+\frac{eV_0}{mc^2})^2}}}$$ and $$\frac{\Delta\theta}{(\Delta V/V)} = 6-8 \quad ({}^{\text{deg}}/_{\%\Delta V})$$

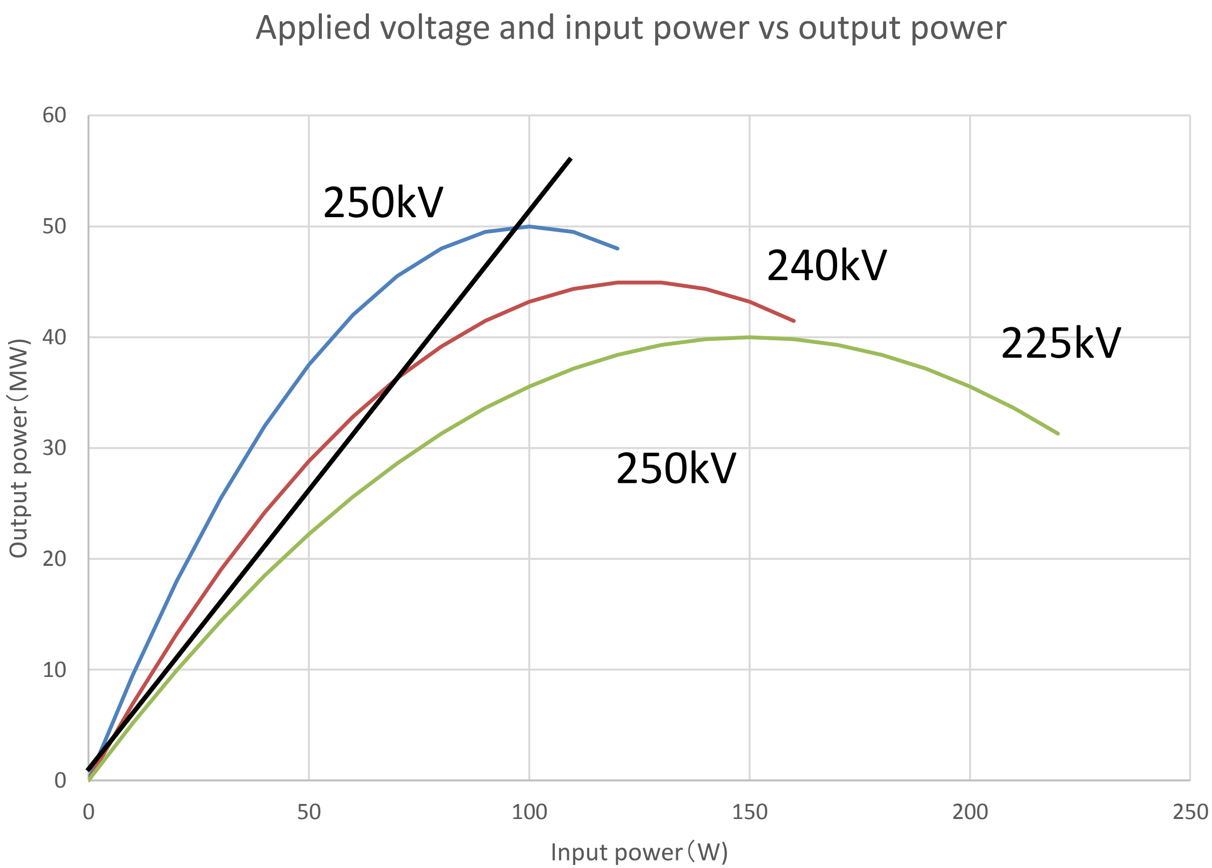


  – Usual S-band tube operating at 300kV range, this phase variation Is roughly 6-8 deg./(dV/V%).
    If you want to get ΔE /E=0.1%, then 0.025% of voltage flatness is required.

- Water cooling variation of tube body also causes rf phase variation.
  This happens since water temeperature changes the gain cavitiy's detuning frequency and bunch center changes from original position.
  – this phase variation Is roughly
    0.5-1 deg.phase/1 deg water temp.



Applied Voltage and power-gain relationship



Generally higher the applied voltage, lower the saturated point is and Higher the gain is.

Electron gun and beam generation

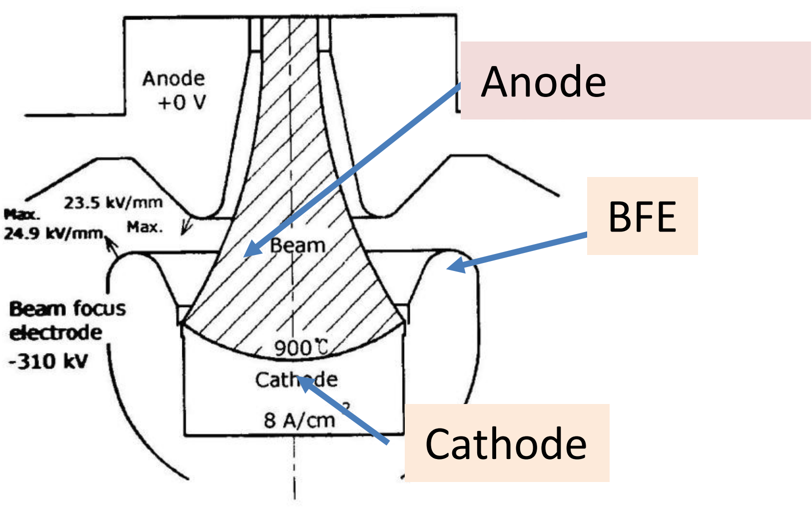
Structure of electron gun in the klystron

From the requirement of large current, electrons generated from the large aperture cathode are focused and emitted to the drift tube.

Cathode: 900-1100 deg. Thermal electrons are emitted

Beam forming electrode (BFE) form the laminar flow beam.

Anode: entrance to drift tube



Generally cathode is negative and anode is o volt.

Temperature limited (TL) flow and space-charge (SC) limited flow

As cathode surface temperature getting higher due to the heater power up, thermal electrons are start to emit from the cathode surface.

- Current is described by the Richardson-Dushman's formula.

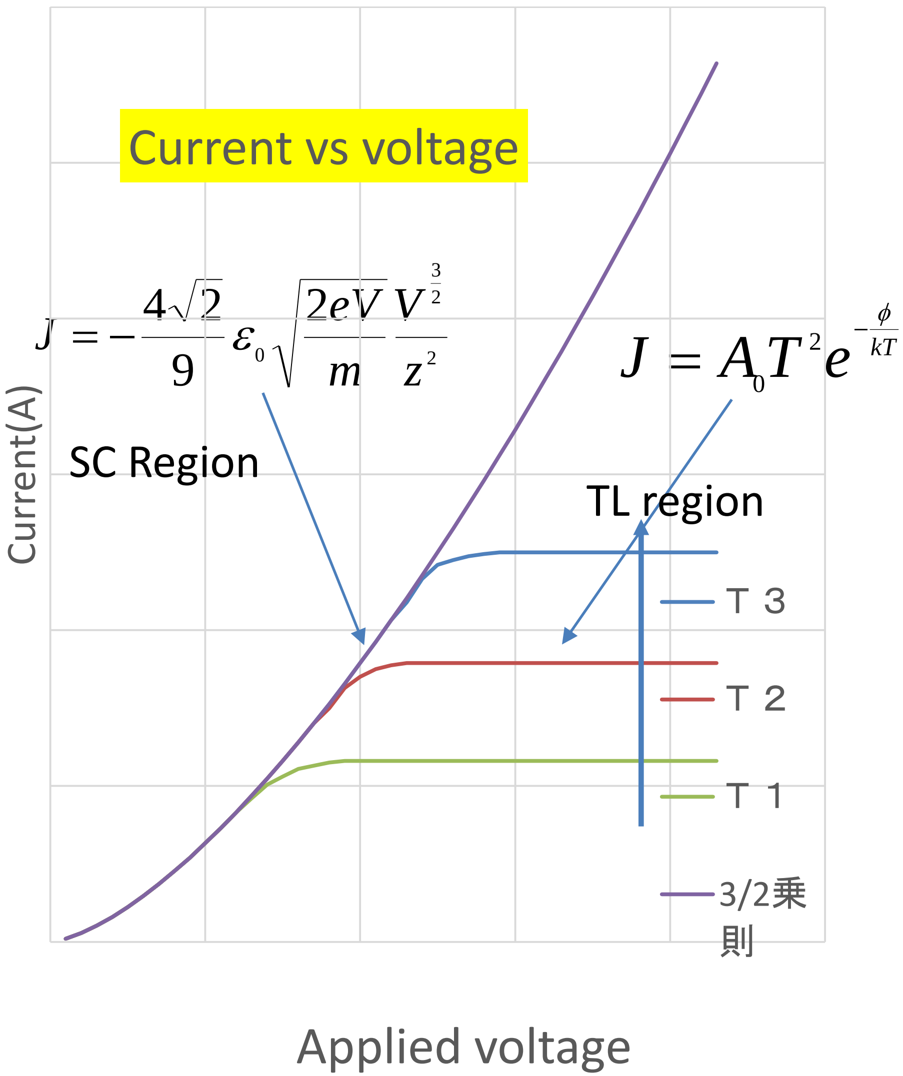
$$J = A_0 T^2 e^{-\frac{\phi}{kT}}$$

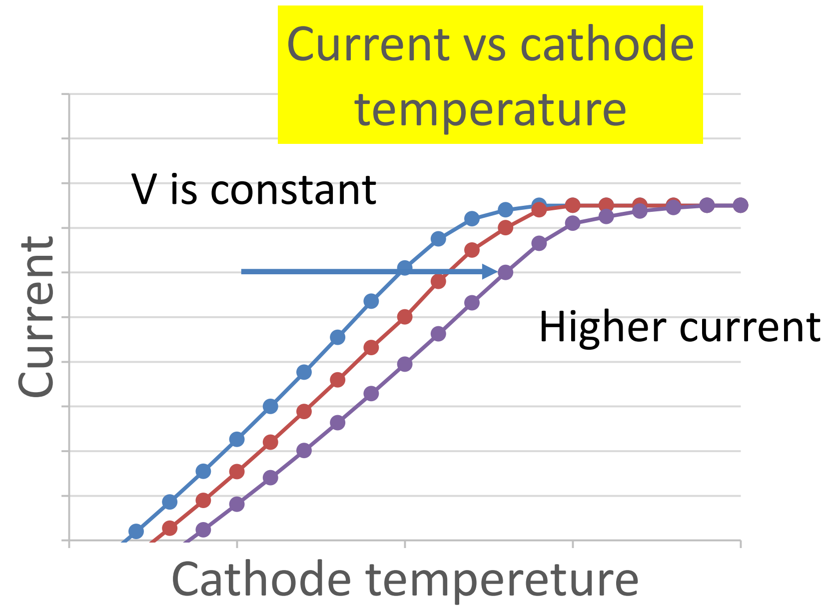
T is absolute temperature, ϕ is work function of the cathode and k is the Boltzmann constant. This current emission range is called as temperature limited region(TL).

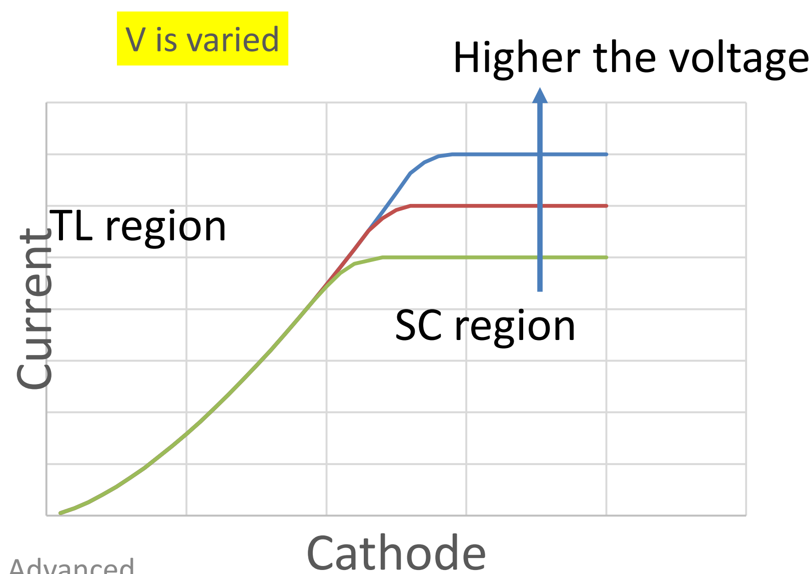
- More higher the cathode temperature is, cathode surface is filled with space charge and current does not increase as temperature is getting high.
- Emission of this range is called space charge limited region (SC).
- Emitted current is determined by the geometry of the gun and applied voltage.
- Current is proportional to power of 3/2 of the voltage. Ideal SC flow is called as FSCL: Full Space Charge Limit. Real cathode deviates slightly from FSCL.
- FSCL Emission from the parallel electrode is follows.

$$J = \frac{4\sqrt{2}}{9} \varepsilon_0 \sqrt{\frac{2eV}{m}} \frac{V^{\frac{3}{2}}}{z^2}$$

TL flow and SC flow

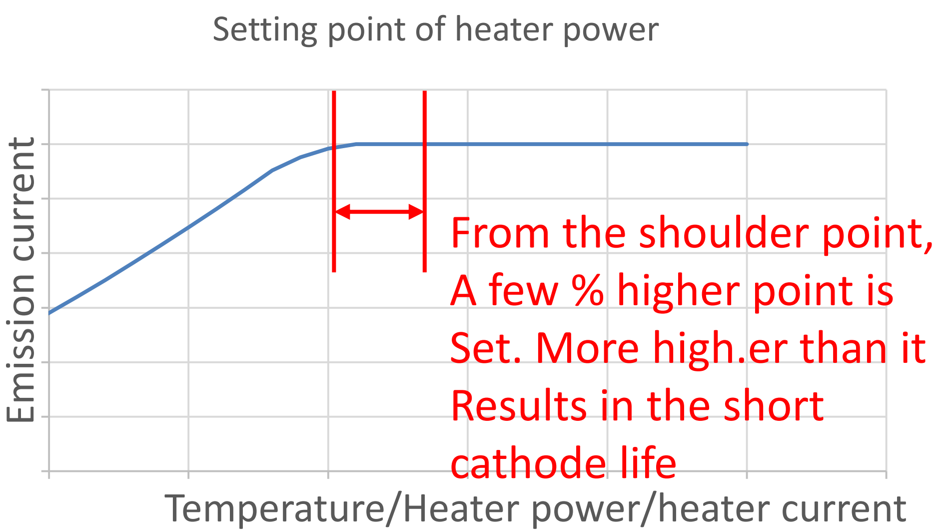


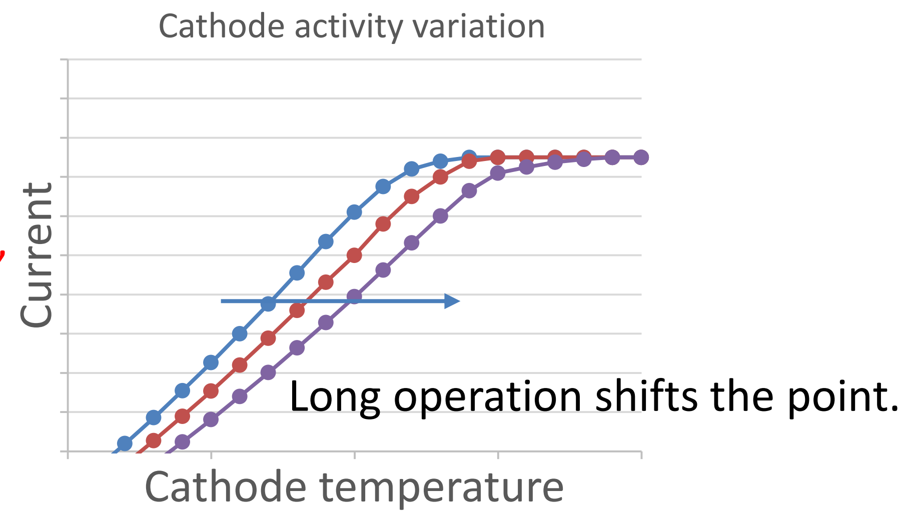




Heater adjustment and the klystron life

- Usually operation point is the saturated point because the current fluctuation is minimum for other parameter's fluctuation
- Heater power setting point is important because it affects the stabilities and klystron life. From Miram plot, following way is recommended.

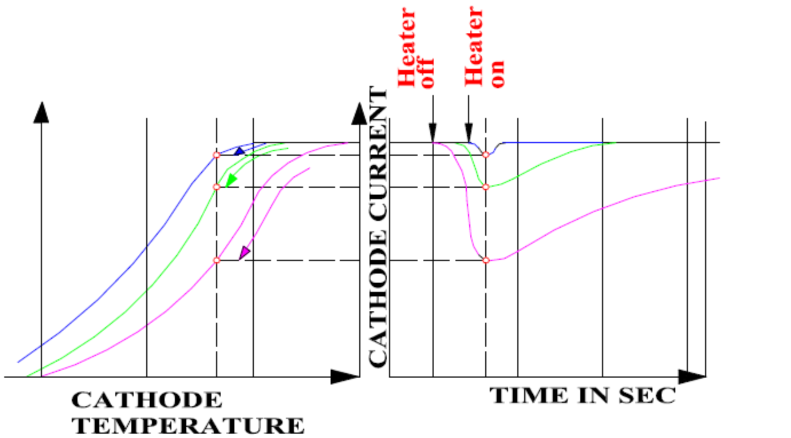




- Measuring 1 point on the Miram plot takes about 30 min. to reach to the stable current.
- After the long usage, due to the degradiation of thecathode, emission decrease gradually and you must readjust the operating point.

Convenient method to measure Miram plot DIP testing

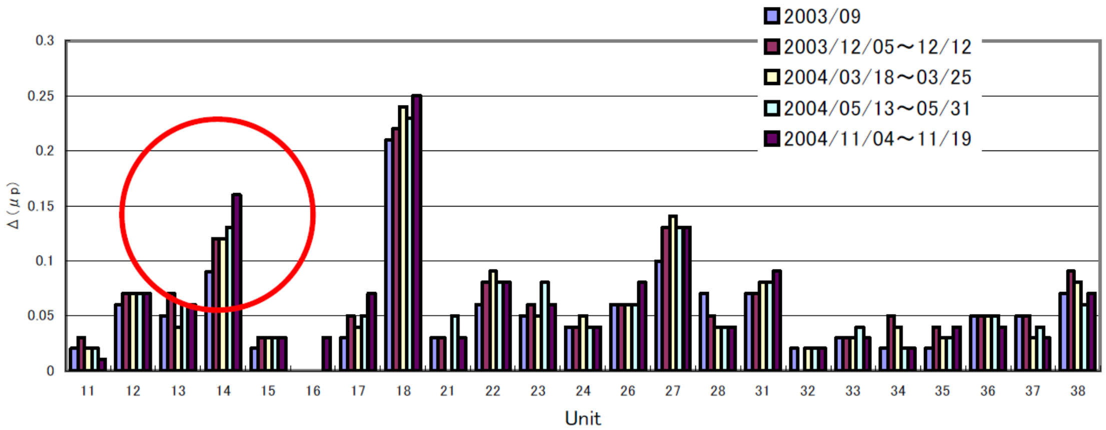
Usually it takes a long time to complete the measurement of Miram plot because at each point you must wait for the heat equilibrium. Half day per one klystron is required, and the institute having many klystrons has a difficult to have a measurement frequently.



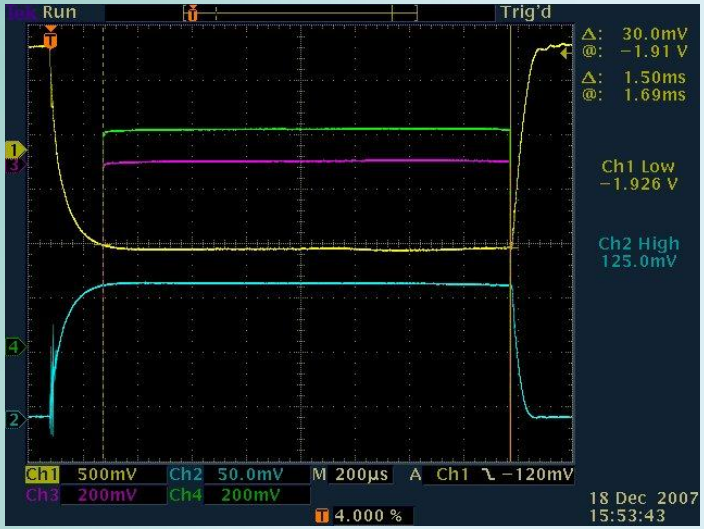
Dip testing is a convenient way to evaluate the operation point of the cathode.

During the operation, quick heater off is done and the dip (decreasing amount of current) is measured.

Special care is for abnormal HV in Line type modulator.
Interlock off sequence is needed.



Multi-beam klystron for ILC



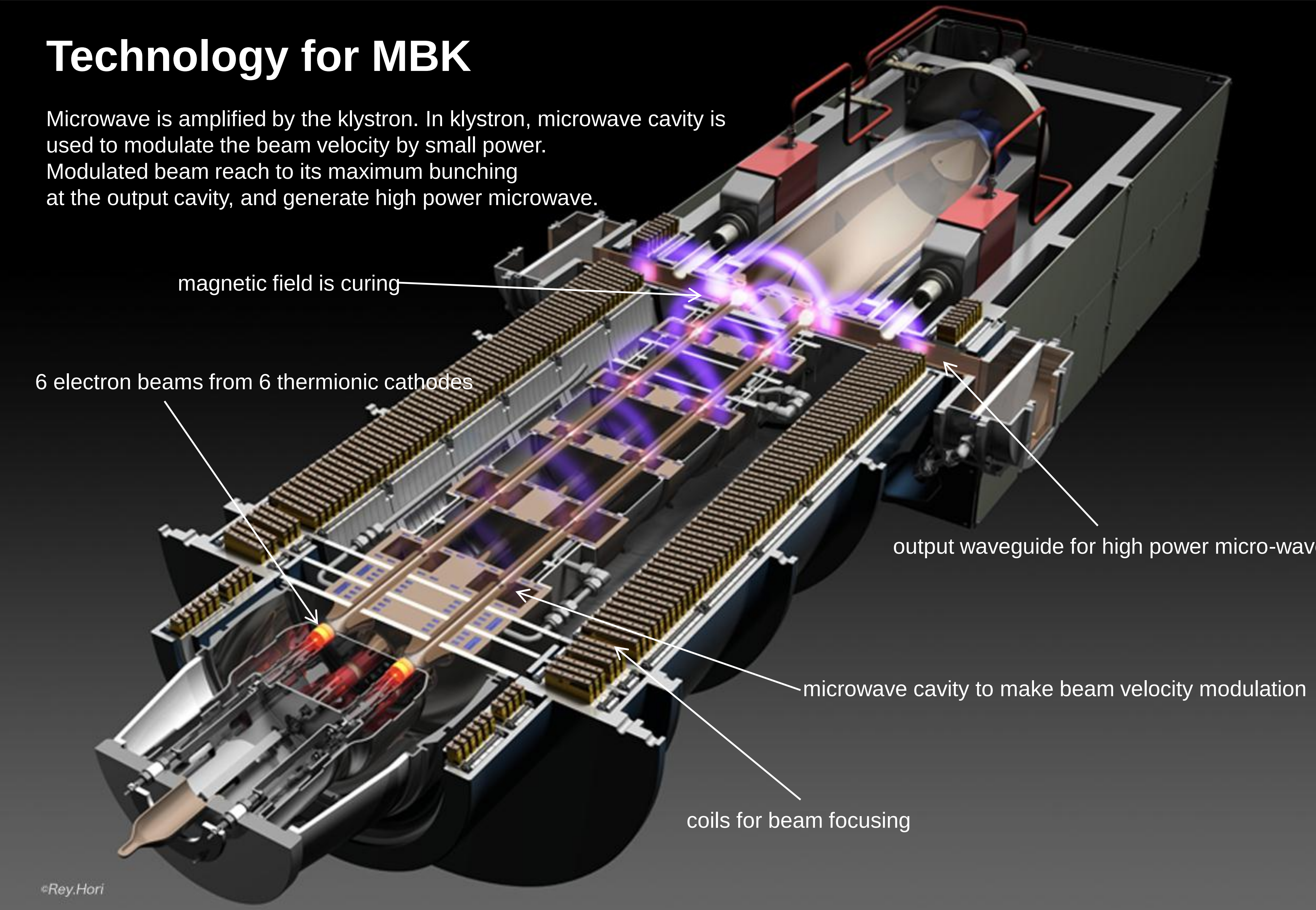
10MW 1.5ms
67% efficiency

Scope picture of the klystron test. The lines show the klystron voltage (116 kV) in yellow, the current (128 A) in blue and RF output (5 MW each) in magenta and green.

Toshiba E3736H

Technology for MBK

Microwave is amplified by the klystron. In klystron, microwave cavity is used to modulate the beam velocity by small power.
Modulated beam reach to its maximum bunching
at the output cavity, and generate high power microwave.



Accelerator Laboratory, KEK

Important parameter; Perveance

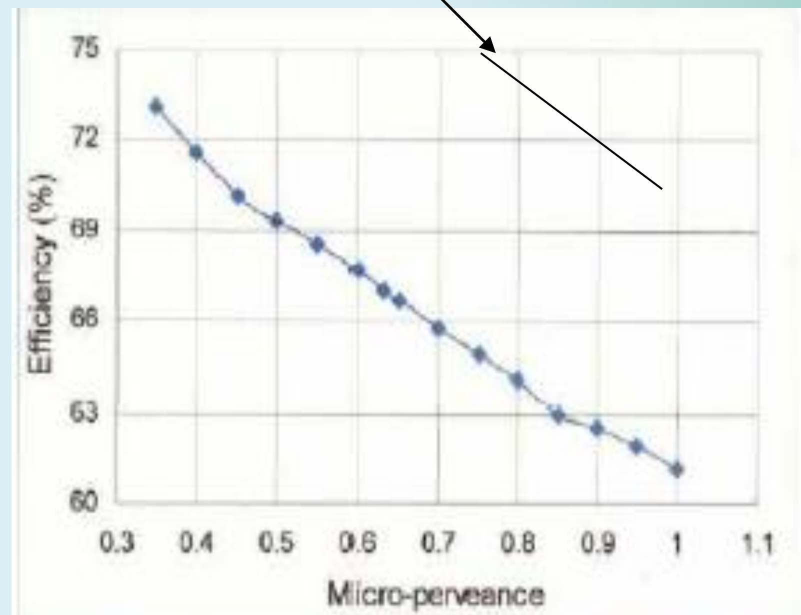
Definition of Perveance

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

It characterize the space charge force and deeply related with the bunching formation and therefore with efficiency.

Simon's formula

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



Low perveance klystron has high efficiency but applied voltage is high.

Modulator

Requirement to RF source from accelerator specification

- Energy Gain *E*
  - » It depends on the accelerator final energy, and it is the SQRT of P (proportional to electric field)
- Energy width $\delta E/E$ should be as small as possible
  - » this corresponds to minimize $\Delta P/P$ and $\Delta\theta/\theta$.

- In order to achieve these requirements, good quality of modulator (good stability of output pulse) is required.

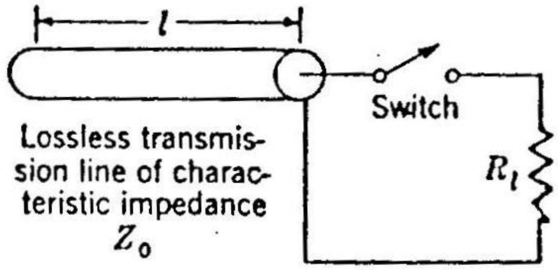
Various Modulator

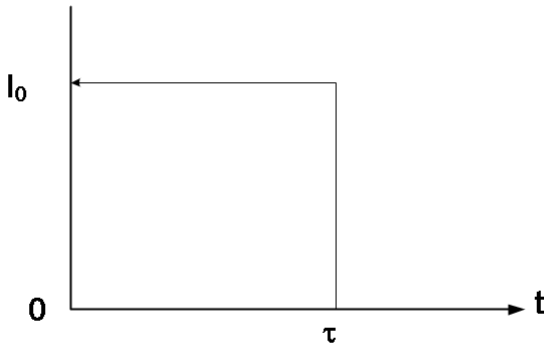
- Modulator for short pulse (~ microsecond order) – electron linac
  - Line type modulator: most popular, low cost, simple
    - Pulse forming
      - PFN (pulse forming network)
      - Blum Line
  - Hard tube pulser (Solid state amplifier)
    - Pulse amplifier
    - Pulse generation by IGBT
  - Magnetic compressor modulator
  - Marx Generator
- Modulator for long pulse(~ a few hundred microseconds to a few milliseconds) – proton linac
  - IGBT modulator with bouncer circuits
  - ≈
  - Marx generator

Modulator(1)
Line-type Modulator

Principle of Line Type Modulator (Most popular modulator)

- Basic Circuit





- Pulse width is determined by the traveling time of the line

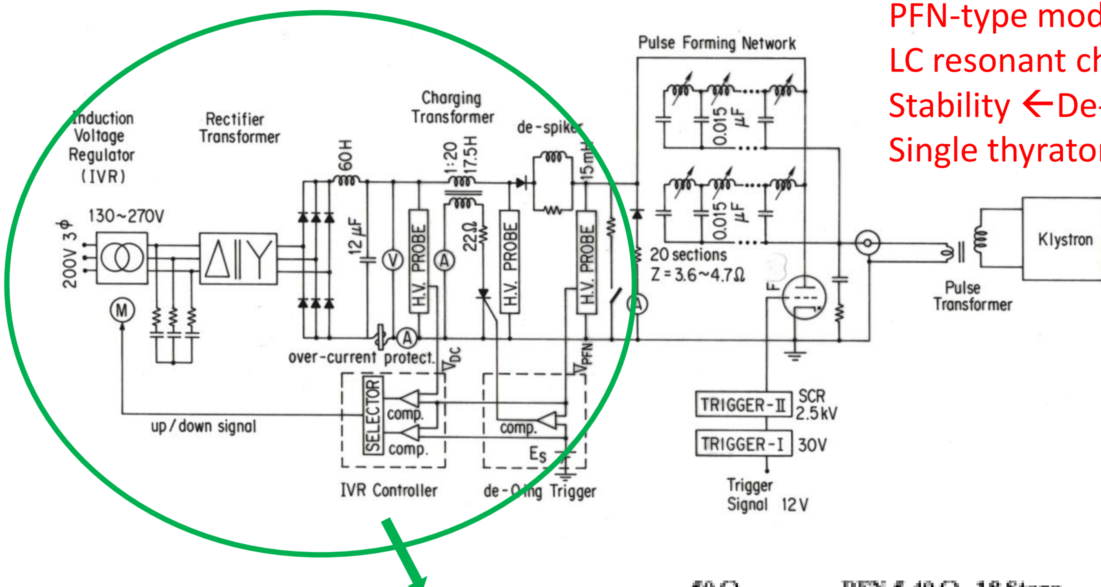
$$\tau = \frac{2\ell}{u} . \cdots where\, \ell\, is\ the\ length\ of\ \ line$$

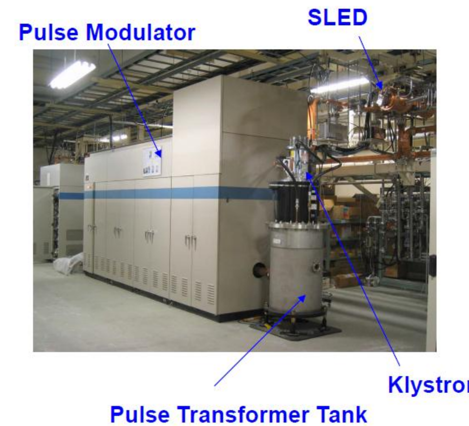
- Matching condition (Z0 is characteristic impedance of co-axial line)

$$Z_0 = R_\ell$$

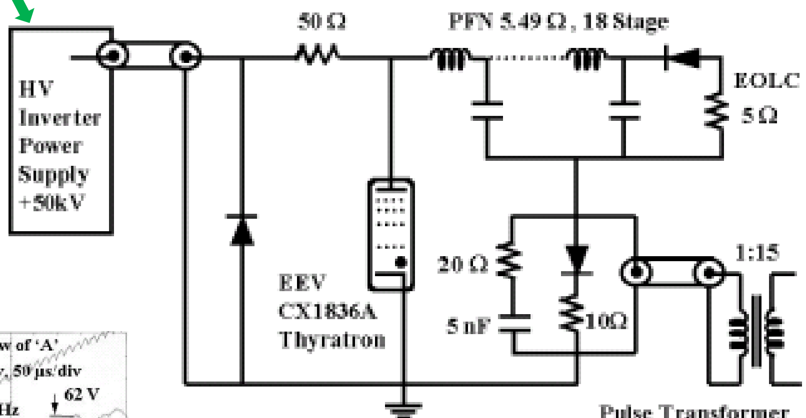
Line-type Pulser

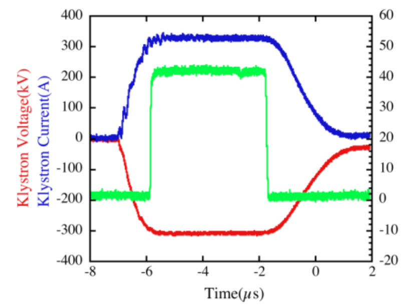
PFN-type modulator
LC resonant charging
Stability ←De-Qing
Single thyratorn switch

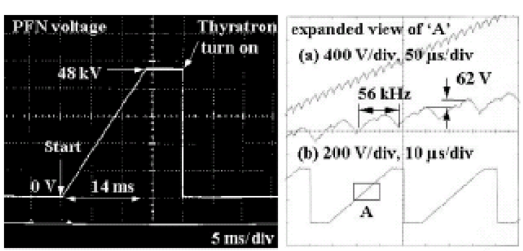




Charging Circuit can be replaced by rather small inverter P/S.



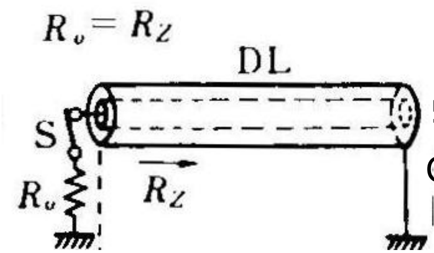




Stability ←determined by charger

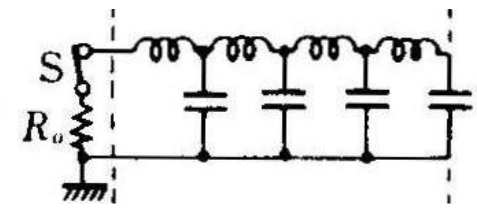
Discharging Circuit

- Cable



nt circuit

Open end



- Analysis of N stage pulse forming network (PFN)

1st stage

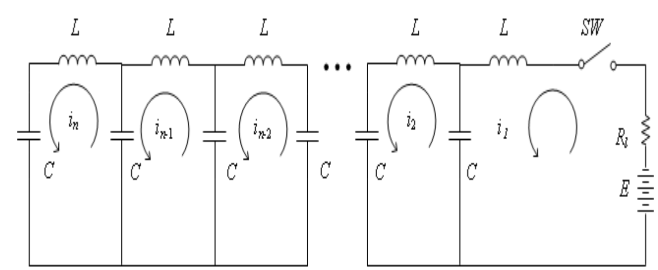
$$L\frac{di_1(t)}{dt}+R_\ell i_1(t)+\frac{1}{C}\int_0^t (i_1(\tau)-i_2(\tau))d\tau = E$$

r-th stage

$$L\frac{di_r(t)}{dt}+\frac{1}{C}\int_0^t (i_r(\tau)-i_{r-1}(\tau))d\tau+\frac{1}{C}\int_0^t (i_r(\tau)-i_{r+1}(\tau))d\tau = 0$$

n-th stage

$$L\frac{di_n(t)}{dt}+\frac{1}{C}\int_0^t (i_n(\tau)-i_{n-1}(\tau))d\tau+\frac{1}{C}\int_0^t i_n(\tau)d\tau = 0$$



Solving this exactly is difficult and using Laplace transformation with suitable approximation or computer simulation is frequently used.

Characteristics of PFN

- For n-stage PFN

  pulse width

$$\tau = 2\sqrt{L_N C_N} \approx 2n\sqrt{LC}$$

$$where \quad L_N = \sum L_i = nL, \quad C_N = \sum C_i = nC$$

Characteristic impedance of PFN

$$Z_{PFN} = \sqrt{\frac{L_N}{C_N}} = \sqrt{\frac{L}{C}}$$

Requirement of PFN-Parameter

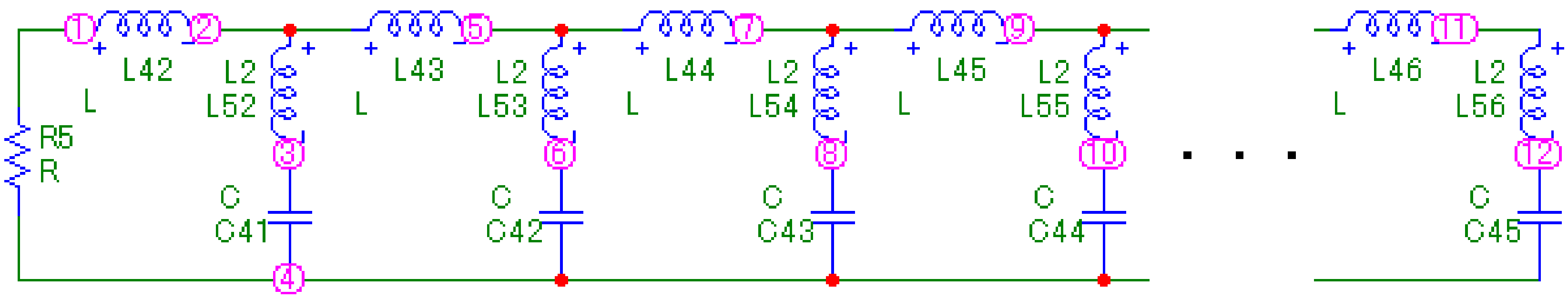
- Klystron's operation point V_s, I_s then $Z_s = V_s / I_s$
- Step up ratio of pulse transformer n, then primary impedance is $Z_S = Z_S / n^2$
- From matching condition, PFN characteristic impedance $Z_{PFN} = Z_S$
- Pulse width τ is come from Klystron's requirement or system design.
- Total capacitance of PFN is derived
  by energy equation: energy stored in
  PFN=energy supplied to the load

$$\frac{1}{2} C_T V_C^2 = \int_0^\tau V_p I_p dt$$

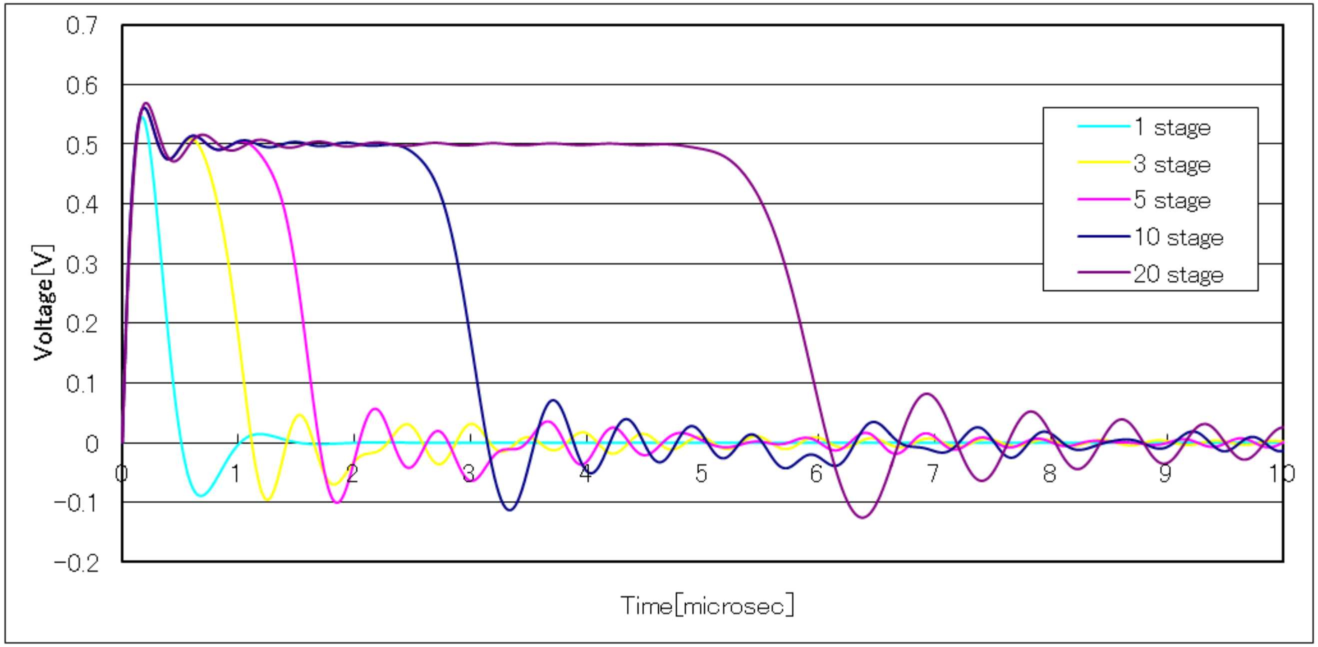
$$or \quad C_T = \frac{2 V_p I_p \tau}{V_C^2}$$

- stage number is determined by flat top condition

PFN Simulation Example



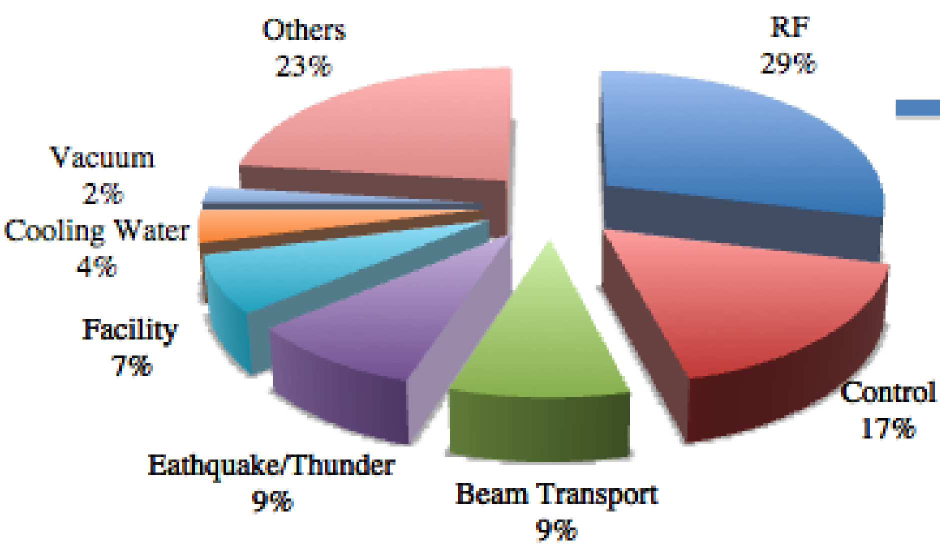
L=1.3[μH]
L2=0[H]
C=0.015[μF]
Stage number of PFN
1,3,5,10,20



Operation Statistics in FY2007

- **Linac failure distribution**

Total operation time : 6322 Hours
Machine failure time : 114 Hours

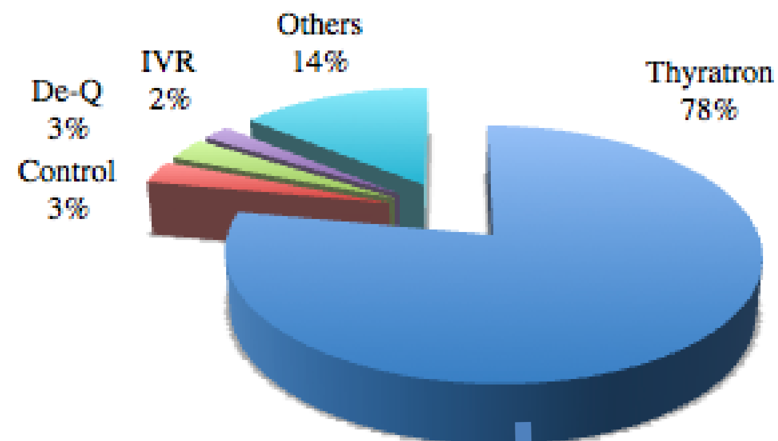


Reliabilty of an RF system is directly linked to the linac availability.

- **Modulator failure distribution**

Modulator failure time = 17.6 Hours

53% of RF failure

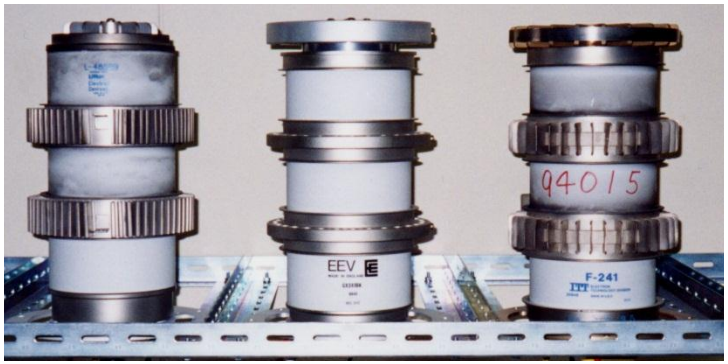


- Keep-alive current tuning
- Thyratron failure
- Air cooling fan

Modulator availability=0.997

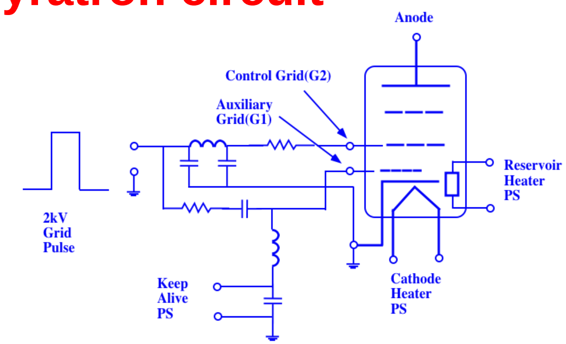
Status of Thyratron

- 45 kV, 5 kA, 6 µs, 50 Hz Switching



Litton L4888B | EEV CX2410K | ITT F-241

- Thyratron circuit

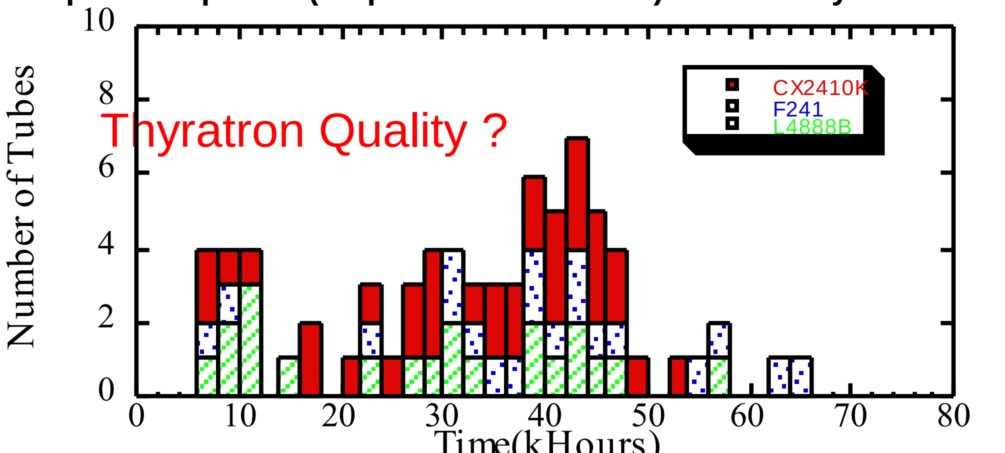


Driver circuit

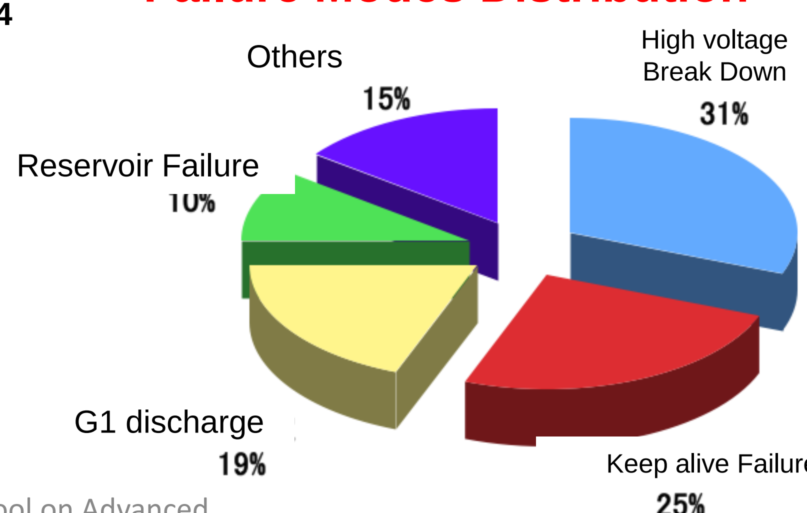
- Keep alive has ~250 mA dc current at 100 V

- Lifetime Profile

Operation period (Sep. 1998～ Feb.2008) : No. of Thyratrons=74



- Failure Modes Distribution



Matching and mismatching

- For lossless transmission line, current transformation is

$$i(p)=\frac{V_g}{p(R_\ell+Z_0\coth p\delta)}=\frac{V_g}{p(Z_0+R_\ell)}\cdot\frac{1-e^{-2p\delta}}{1+\dfrac{Z_0-R_\ell}{Z_0+R_\ell}e^{-2p\delta}}$$

$$=\frac{V_g(1-e^{-2p\delta})}{p(Z_0+R_\ell)}\left[1-\frac{Z_0-R_\ell}{Z_0+R_\ell}e^{-2p\delta}+(\frac{Z_0-R_\ell}{Z_0+R_\ell})^2e^{-4p\delta}\dots\right]$$

- And its inverse transformation,

$$i(t)=\frac{V_0}{Z_0+R_\ell}\left\{1-U(t-2\delta)-\frac{Z_0-R_\ell}{Z_0+R_\ell}\left[U(t-2\delta)-U(t-4\delta)\right]-\frac{Z_0-R_\ell}{Z_0+R_\ell}\left[U(t-2\delta)-U(t-4\delta)\right]+(\frac{Z_0-R_\ell}{Z_0+R_\ell})^2\left[U(t-4\delta)-U(t-6\delta)\right]+\cdots\right\}$$

$$\textit{where}\quad U(\Delta t)=1\quad \textit{for}\ \Delta t>0\quad \textit{and}\ U(\Delta t)=0\quad \textit{for}\ \Delta t<0$$

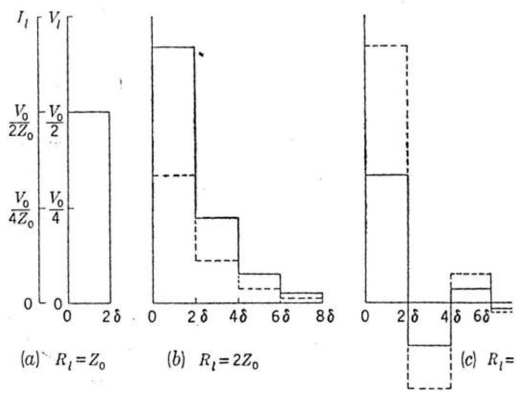
$$\Delta t=(t-n\delta),\quad n=2,4,6\cdots$$

- Therefore, depending on R_ℓ , waveform is different after t=2δ.
- $R_\ell=Z_0$ matching condition and no reflection
- $R_\ell>Z_0$ mismatch (positive mismatch)

  extreme case :open end

  lower operation point than normal
- $R_\ell<Z_0$ mismatch (negative mismatch)

  extreme case :short end



Protection Circuit for load discharge etc.

- If discharge occurred in klystron or pulse transformer circuit, pulse reflection occurs due to the mismatching effects. Serious case, undesirable inverse voltage causes the failure of various devices. Therefore, protection circuit is employed in the system and it force to stop operation with a pulse or a few pulses later.
- Fast protection: End of line clipper (within a pulse response)

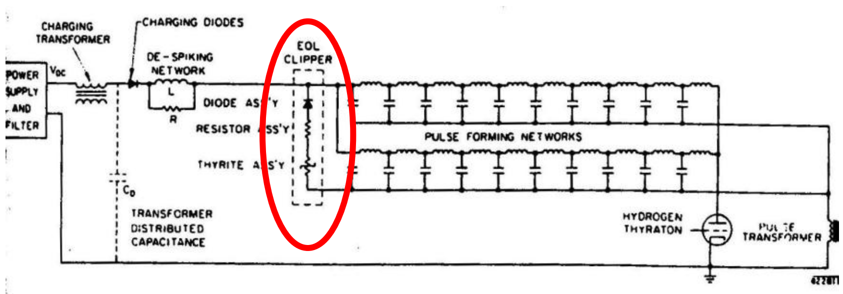
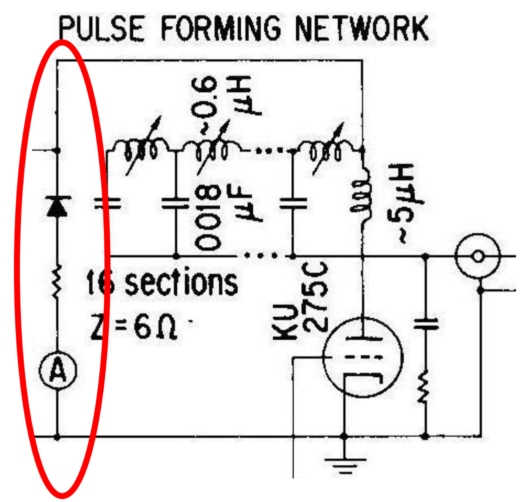


Fig. 17. The pulse voltage (upper, peak 12 kV) and the EOL clipper current (lower, peak 300 A). Load 3.5 Ω, 2 µs/div.

- Rather slow protection: reversed shunt circuit
  Average of inversed current due to the load discharge is sensed and stop operation by meter relay etc.



Commercial Solid-state Amplifier (Scandinova)

Parameters	K2-3	Unit
RF Peak Power	30- 60	[MW]
Pulse Voltage	280 - 450	[kV]
Pulse Current	230 - 450	[A]
Modulator Peak Power	160	[MW]
Modulator Average Power	0,5 - 100	[kW]
Mains: 1-phase / 3-phase	3	
Cooling	Water	

RF POWER UP TO 60 MW MODULATOR PEAK POWER UP TO 160 MW

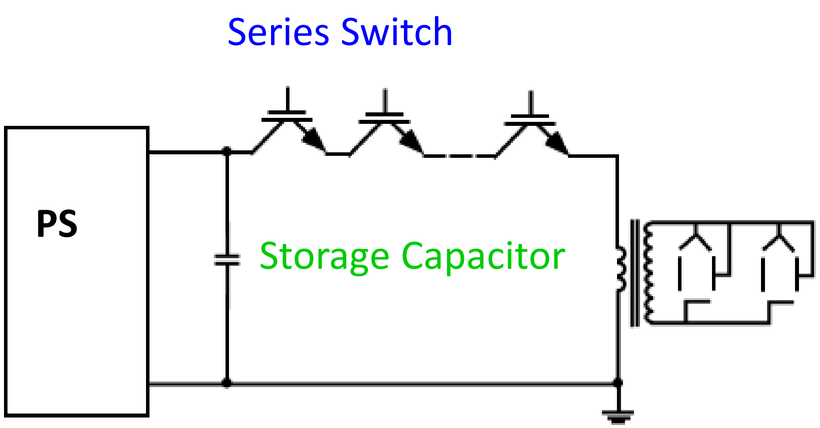
Pulse transformer is used to step up the voltage

IUAC is planning to introduce this type of modulator.

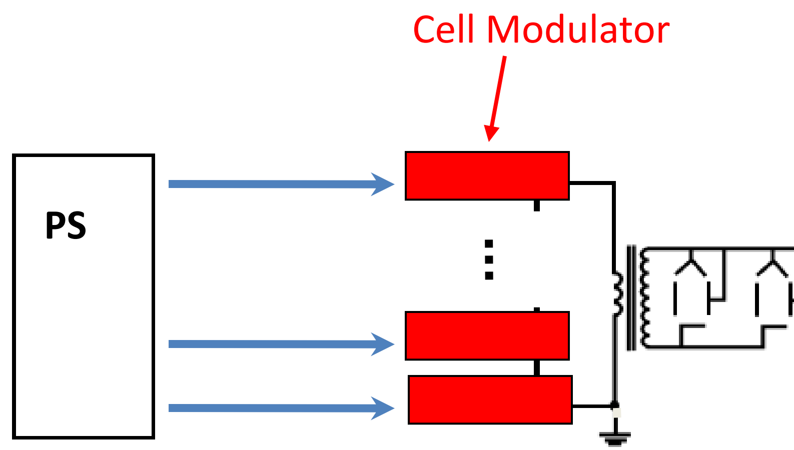
Modulator other than Line-Type

Pulse Modulator Using Multi-Series Switch(1)

- **Series Switch Modularor**



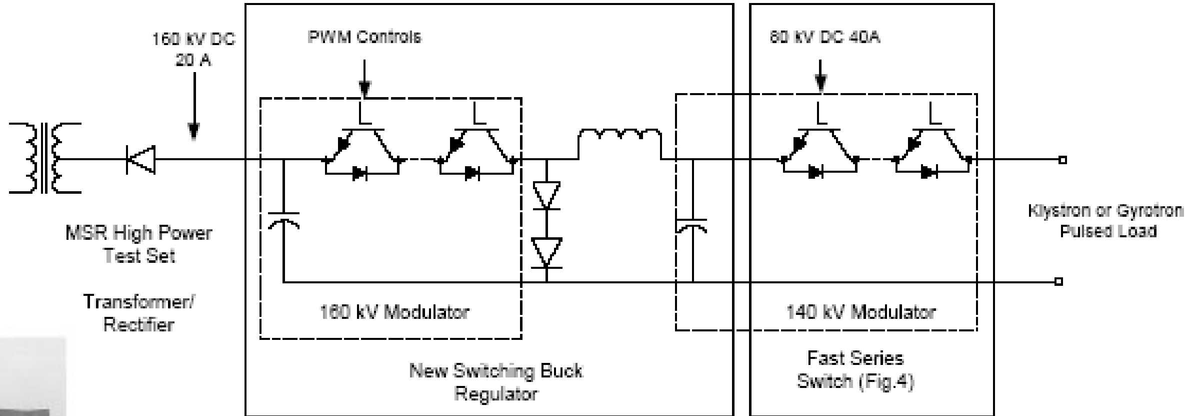
- **Marx Type Modulator**



- **Flexible**

  Active waveform control
  - Pulse waveform
  - Pulse flatness

Series Switch Modulator (Diversified Technologies, Inc.)



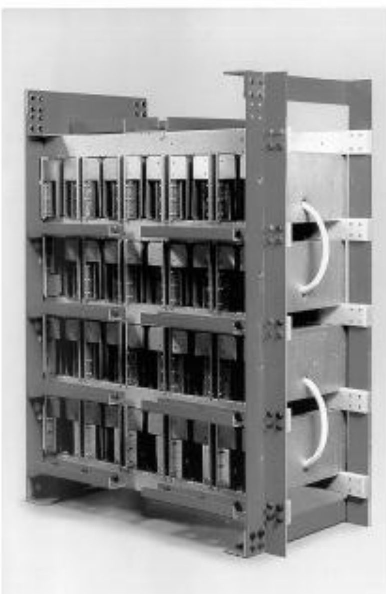


Figure 2. 140kV, 500A solid-state switch

IGBT Series Switch

140kV, 500A switch shown at left in use at CPI

As a Phase II SBIR, DTI is building a 120 kV, 130 A version with a bouncer to be delivered to SLAC at the end of 2006

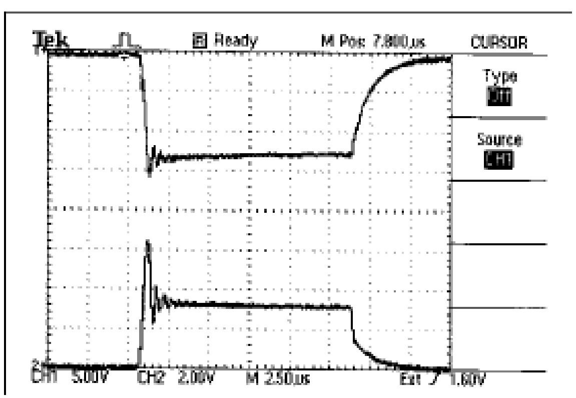
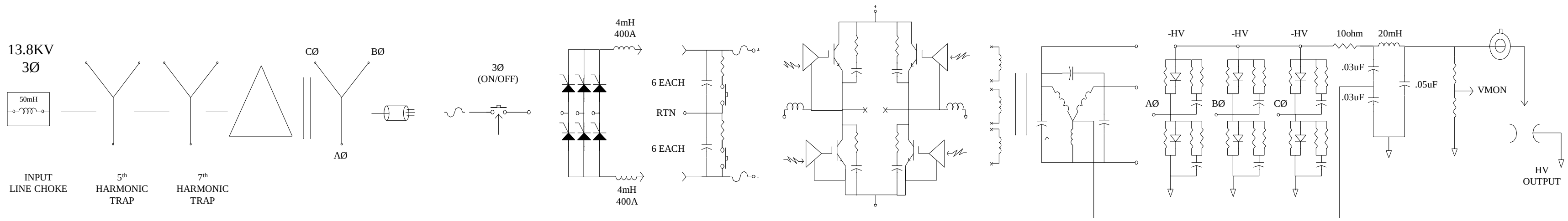


Figure 3: Test pulse (140 kV, 160 A, 13 μsec) of solid-state modulator. Upper trace is voltage at 63 kV/division. Lower trace is current at 100 A/division

Other Alternative Modulators

SNS High Voltage Converter Modulator (Unit installed at SLAC)

RECTIFIER TRANSFORMER AND FILTERS | SCR REGULATOR | ENERGY STORAGE | SWITCHING | BOOST TRANS-FORMER | HV RECTIFIER AND FILTER NETWORK



RECTIFIER TRANSFORMER AND FILTERS

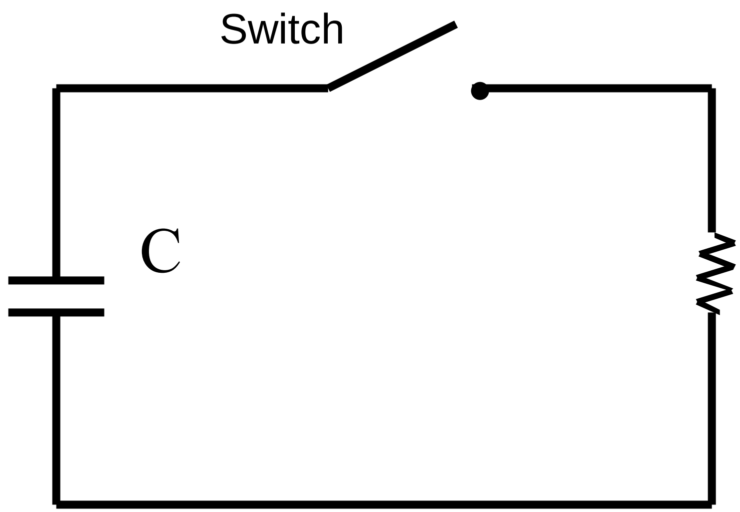
SCR REGULATOR

HVCM

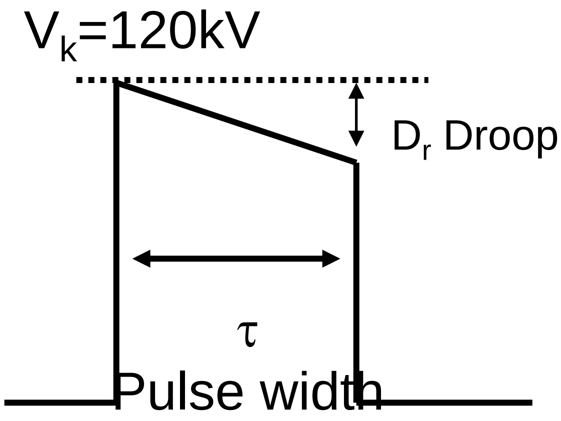
EQUIPMENT CONTROL RACK

Longer Pulse Modulator with sag compensation with RC circuit

Long Pulse Modulator with Bouncer Circuit(1)



Klystron Impedance
R=120kV/140A
=857Ω



$$V = V_0 \cdot e^{-\frac{t}{CR}}$$

$$C = \frac{\tau}{R \cdot D_r}$$

$$E = \frac{1}{2} C V_k^2$$

τ=1.7ms
Dr=1%
R=857Ω

Secondary Capacitance
C=198μF

E=1.4MJ

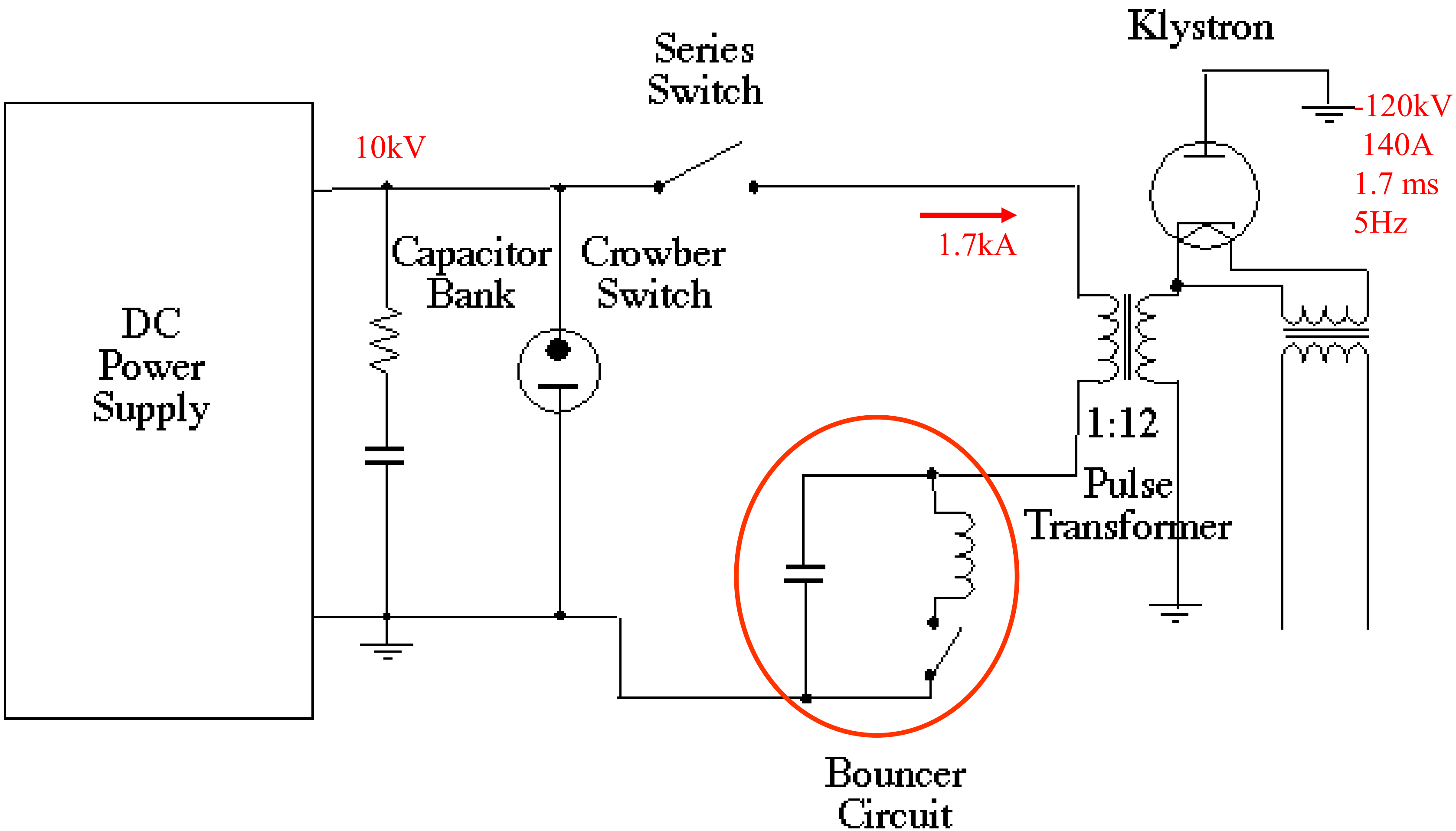
24min run of 1kW heater

If droop of 20% is allowed, then C and E are 1/20

Save Capacitor bank and space to1/20

C=9.9μF (Secondary)
C=1426μF(Primary)

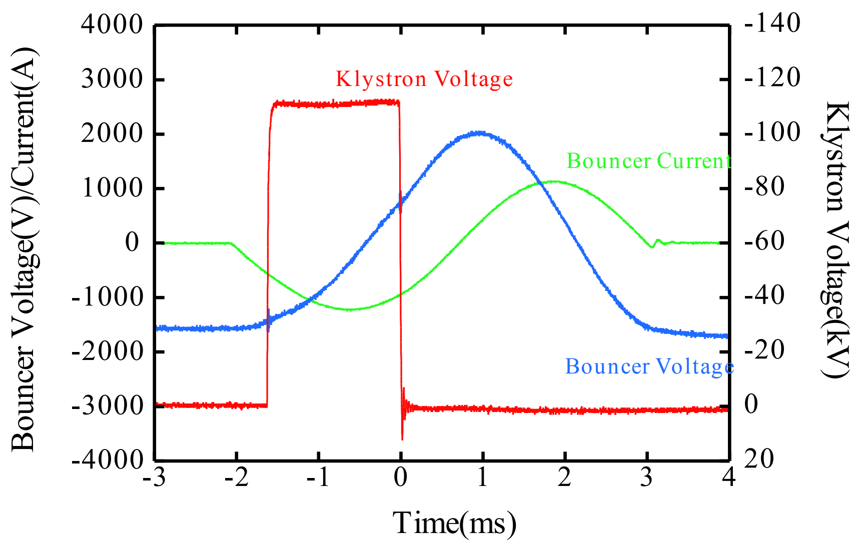
Long Pulse Modulator with Bouncer Circuit(2)

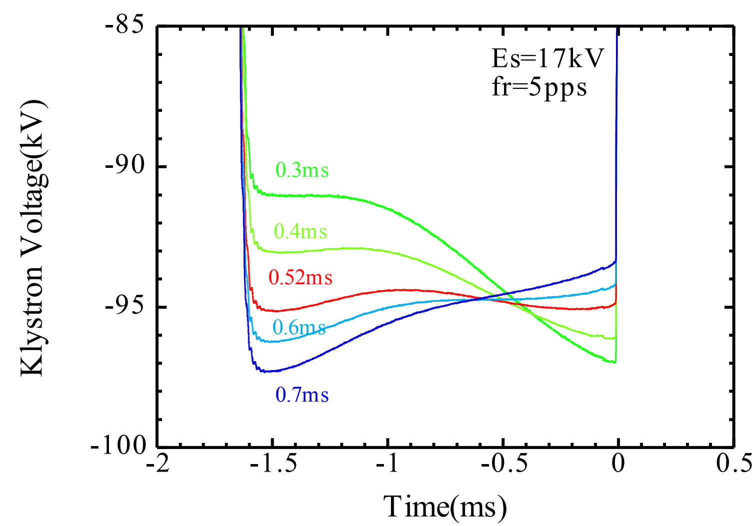


Actual Waveform by Bouncer Circuit

Accelerator Laboratory

- **With Bouncer Circuit**





Es=20kV, Pw=1.7ms, fr=5pps
Rise-time(10-90%)=33μs

Es=17kV, Pw=1.7ms, fr=5pps
Flatness=0.8%(p-p)

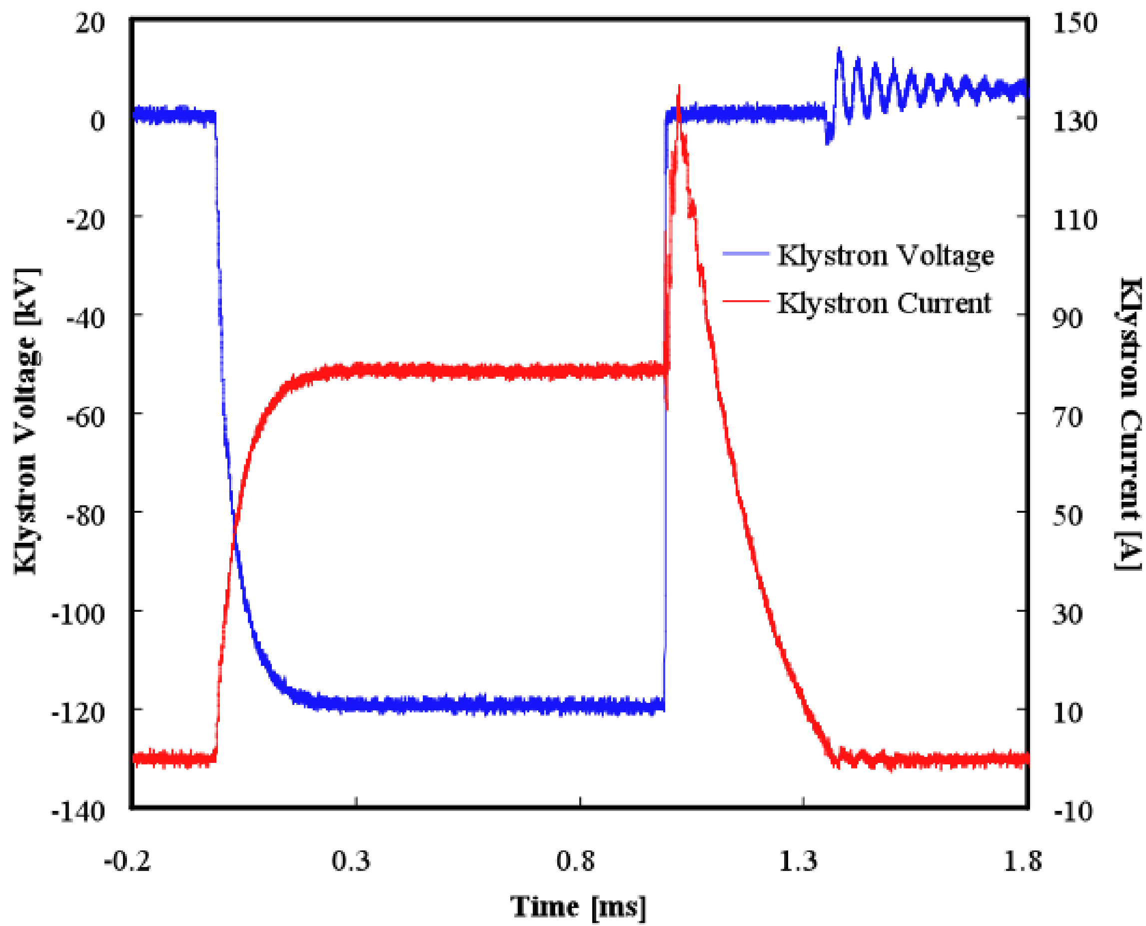
Protection of Klystron at Breakdown

Energy deposit in klystron
from gun spark

Arc voltage＝100 V

$$W = 100V \cdot \int I_k dt$$

W=2.0 J < design value **20 J**

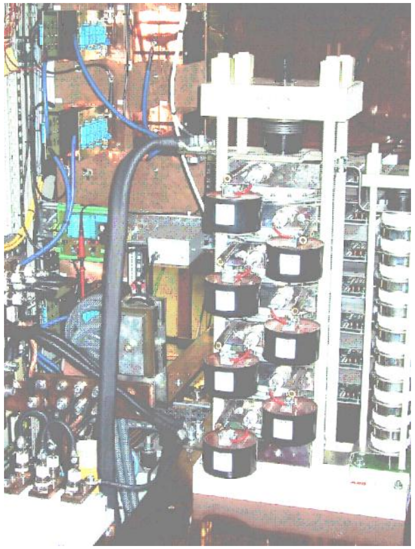


Es=9.0 kV, Pw=1.7 ms, fr= 5 pps

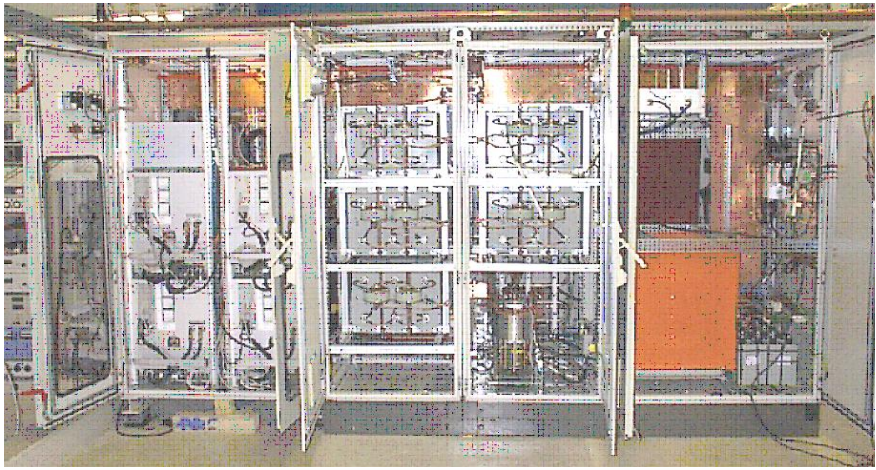
Pulse Transformer Modulator Status

- 10 units have been built, 3 by FNAL and 7 by industry (PPT with components from ABB, FUG, Poynting).
- 8 modulators are in operation.
- 10 years operation experience.
- Working towards a more cost efficient and compact design.
- FNAL building two more, one each for ILC and HINS programs – SLAC has bulit switching circuits.

IGCT Stack

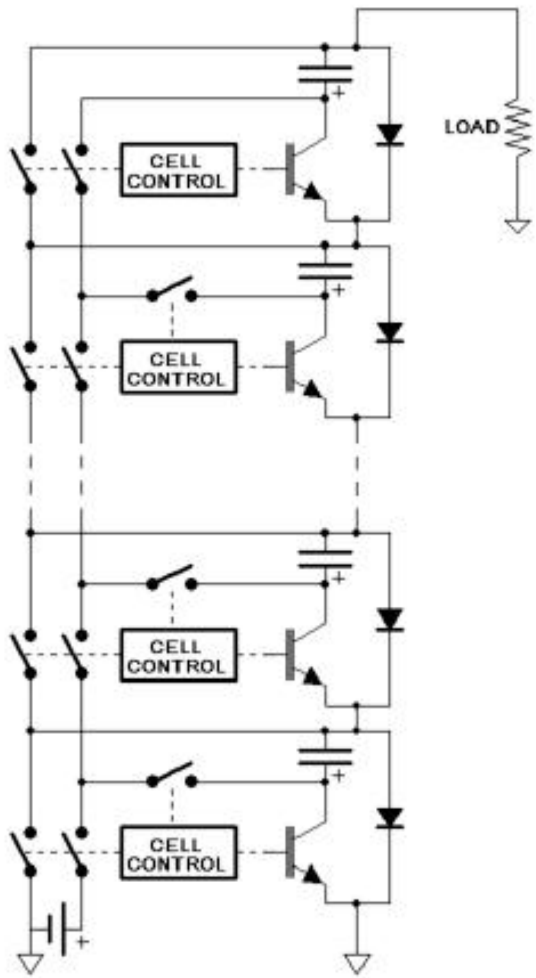


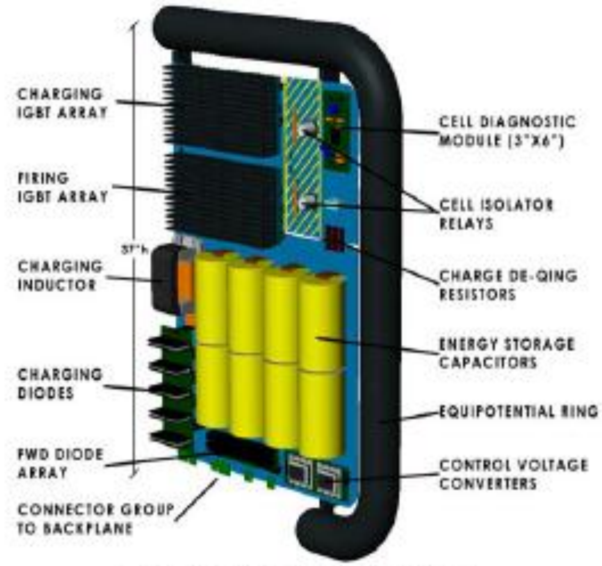
HVPS and Pulse Forming Unit



Marx Modulator for ILC

Marx Generator Modulator





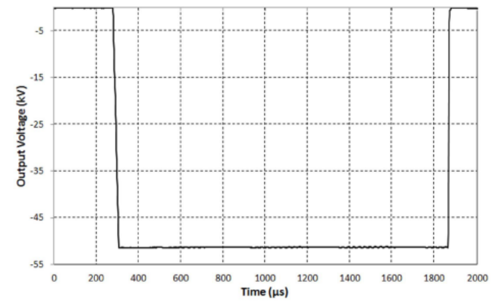
12kV MARX CELL, FRONT VIEW

12 kV Marx Cell (1 of 16)

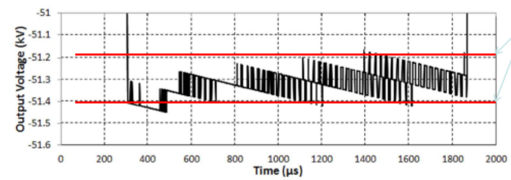
- IGBT switched
- No magnetic core
- Air cooled (no oil)

SLAC's New Type Marx Modulator : P2

P2 Nearly Assembled



Shown are initial results with 17 cells at 3kV each. Full voltage anticipated by January 20.



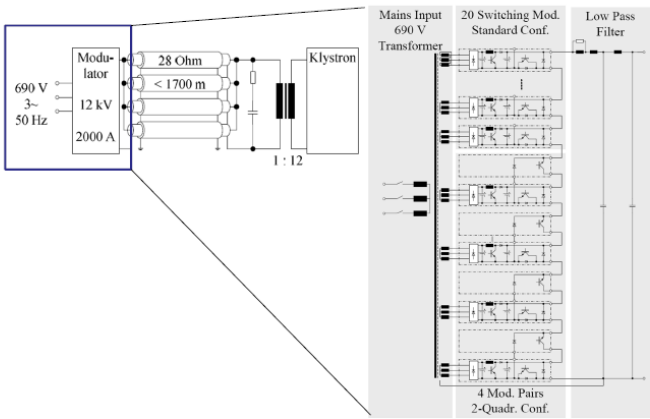
+/- 0.2% bands

- Eventually, flat top anticipated to be <0.1%
- ADC resolution is ~100V

Parameters

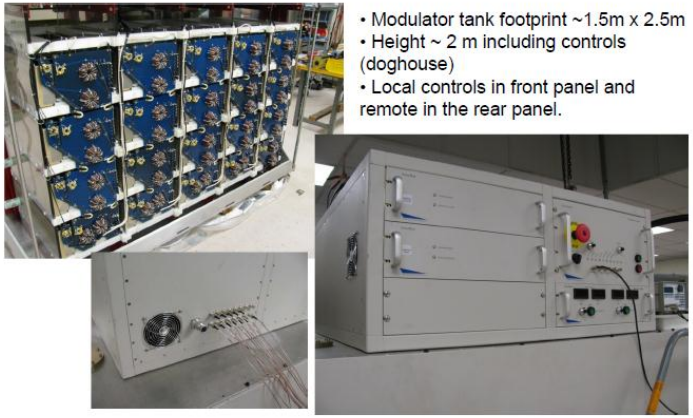
Parameter	Value	Note
AC to DC bus efficiency	~85%	*Commercial power supply*
DC bus to pulse output efficiency	>95%	*Calculated*
Modulator flattop	+/-0.2%	*Achieved, 17/32 cells*
	+/-0.1%	*Anticipated*
Voltage output repeatability	<+/-0.1%	*Anticipated*

Vendor Design Marx Modulator for ILC

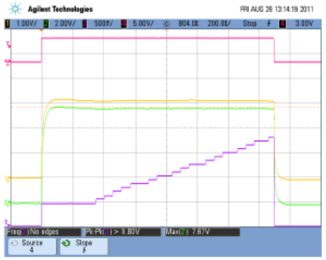


Thomson Marx Modulator: Low voltage Marx and Pulse Transformers

ASSEMBLY



Full Voltage/Current/PW Spec



Voltage:	**120kV**
Current:	**130A**
Pulse width:	**1.5ms**

Ch4: Command
Ch1: Pulse current 40A/V
Ch2: Voltage 15kV/V
Ch3: Feedback integrated control

- Modulator has demonstrated full spec single pulsing into a resistive load.
- Due to source and load limitations, full spec pulsing has been demonstrated at 5Hz with a double full PW pulse, three 1ms pulses and ten 150 us pulses.

DTI's Marx Modulator: 120kV Direct Pulse Generation

Marx Modulator's Feature

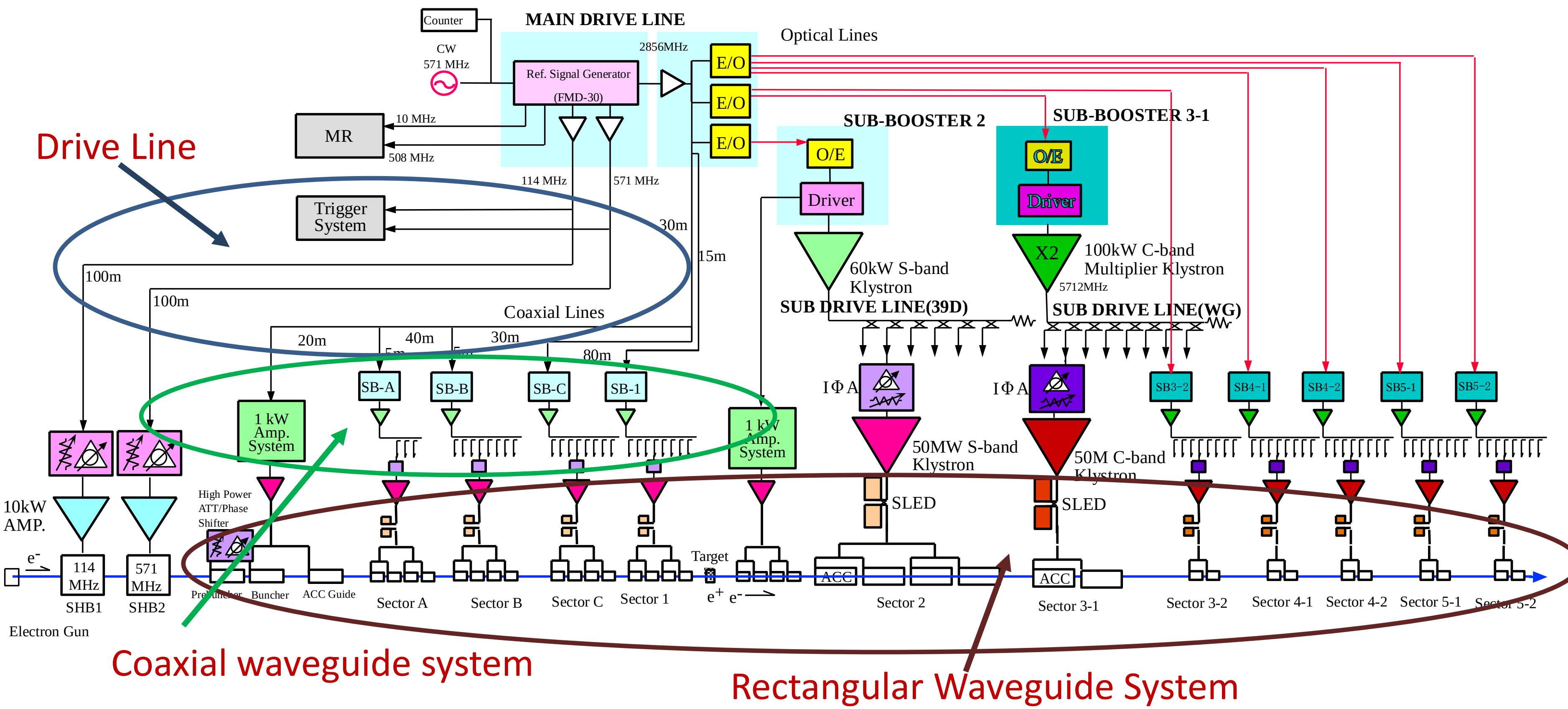
- Good flat top pulse when pulse duration is long such as a few millisecond.

  (timing adjustment of individual Marx cell
      enable to make a good flat top)
- Even a direct output pulse case, acring probability in the modulater is small due to comprise of the low voltage cell’s assembly
- Fast shutoff of the output when klystron fails.

Power Distribution System (Waveguide System)

Layout of RF System in KEK

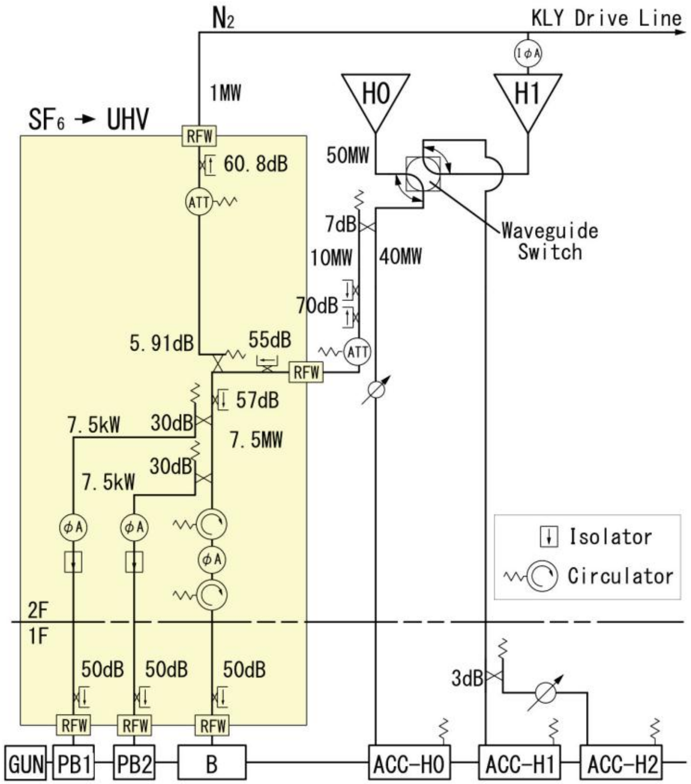
RF System Diagram C-band Plan(example)

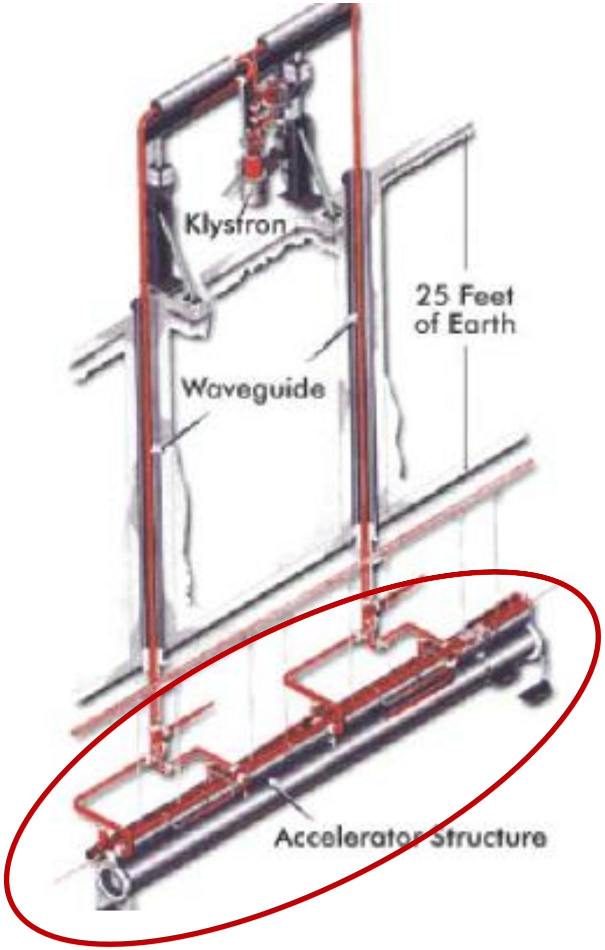


Importance of Power Distribution System

- Cost of RF system is expensive, and about 1/3 of cost is PDS cost.
- Sometimes RF efficiency and capability are determined by PDS. For example, SLED (energy doubler) specifies the peak power capability.
- Fractions of the failures of linac are come from poor design of PDS.
- PDS variants
  - Coaxial waveguide PDS: low peak power, low frequency
  - Rectangular waveguide PDS of air, nitrogen and SF6 w/o pressurizing.
  - Rectangular waveguide PDS in vacuum
  - PDS with circulator for cw/longer pulse operation, feeding to standing wave cavity structure
  - Vacuum window or waveguide valve to keep structure low pressure when klystron is replaced.
  - Power divider system w/o changing the delivering power
  - Phase shifter system or fixed length of waveguide considering the phase at cavity and beam

Layout of Waveguide in Electron Linac





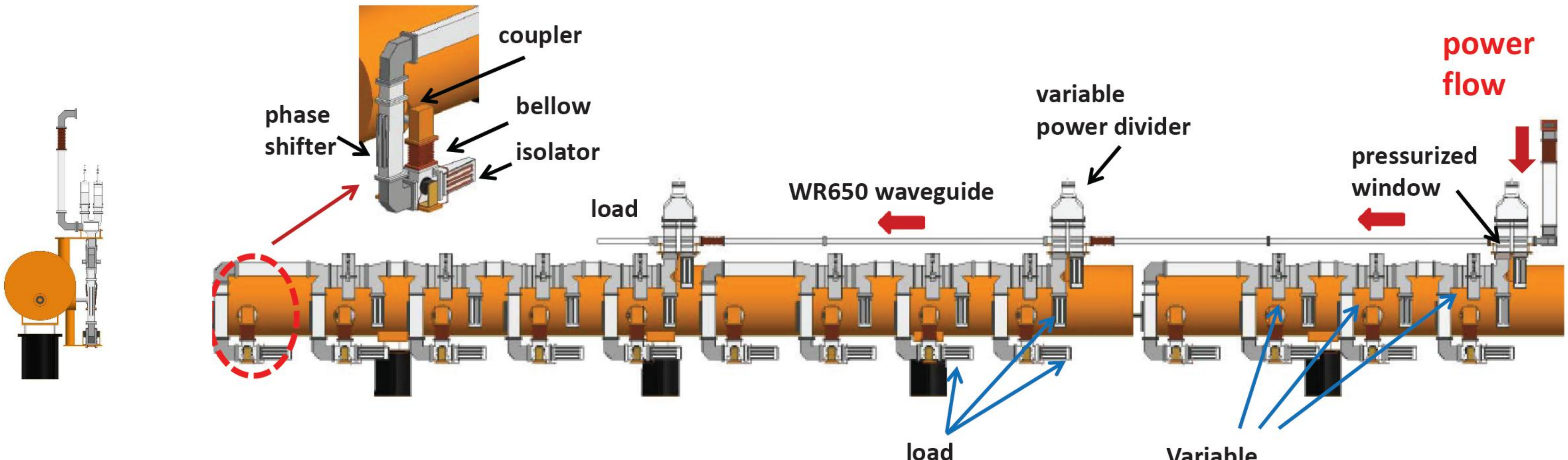
Exact phase adjustment between the acc. structures is required.

For the phasing of prebuncher, buncher, Phase shifter and variable power dividers are required. For easy manufacturing, pressurizing system is employed.

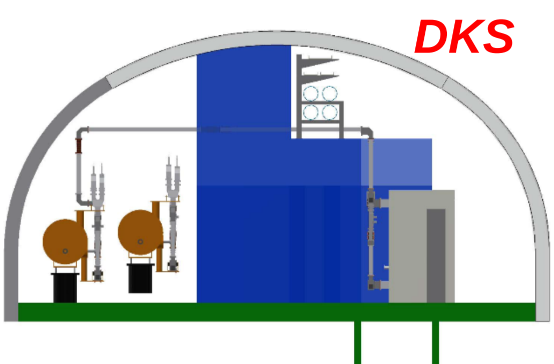
Waveguide phase-shifters are eliminated because of saving the money.

Example of waveguide system in ILC

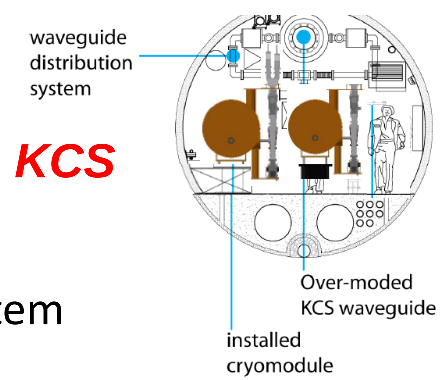
Local PDS Layout of KCS / DKS



Many waveguide components including isolators are installed
In atmosphere or pressurizing system.

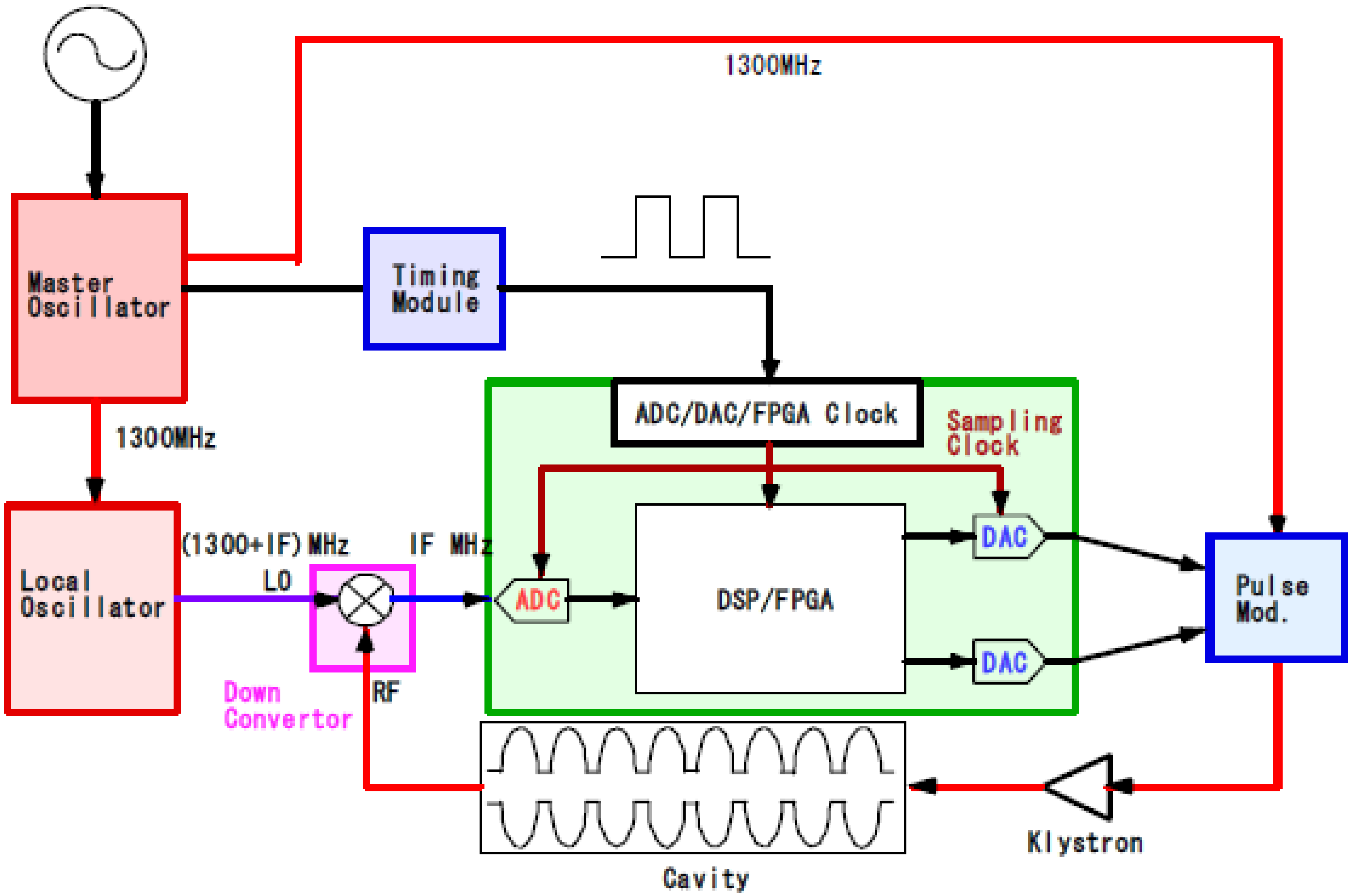


Cross section view of tunnel
and installation concept of
local power distribution system



LLRF (Low Level RF)

Low level RF System



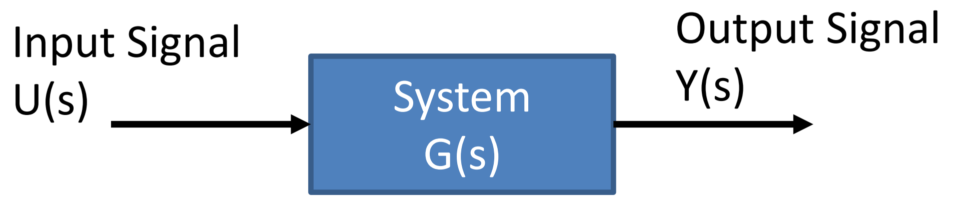
System includes master oscillator(MO), local oscillator(LO), timing module, down converter and digital RF controller. Pulse modulator and driver amplifier Is also included. RF protection system including slow starter of RF is in this area.

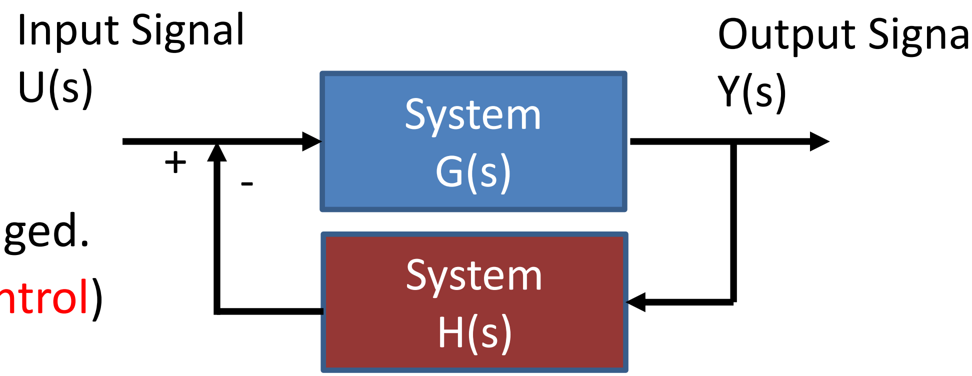
Function of LLRF

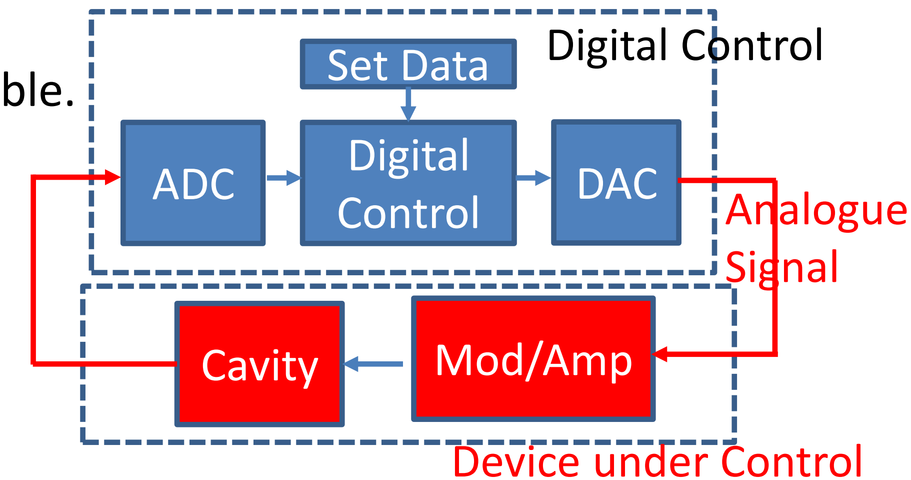
- Low level RF system is the system from master oscillator to the input rf for main klystron.
- Stable rf (frequency, power and phase) is required.
- Beam loading compensation is sometimes requested.
- Most important function of LLRF for the accelerator is a stable phase. Phasing is also important when the electron energy is changed.
- Feed forward/feed back for the output power and phase is required. Recently digital feed back is becoming more popular.

Feed forward or feed back control

- Upper System
  - Its output does not change the input signal (Feed forward control)
- Lower System
  - Parts of output signal goes back to the input signal and input is changed. (Closed loop control or Feedback control)
  - Digital Feedback
    ADC changes digital signal and then digitally controlled. Delay time is inevitable. Usually expensive. Easy to change.
  - Analogue Feedback
    No delay. Not easy to change. Inexpensive.

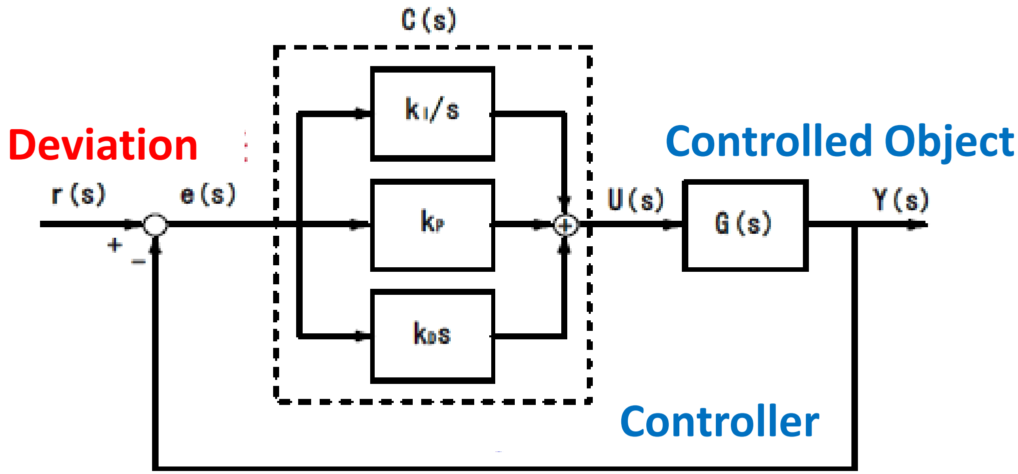






PID Control

- PID Control is one of popular control method.
- P=proportional, I=Integral, D=derivative



- P-control feedbacks the deviation to control signal U(s), and current information is reflected.
- I-control feedbacks the integration of the deviation to U(s) and past information is reflected.
- D-control feedbacks the derivative of the deviation to U(s) and future information is reflected.

Digital RF Controller

Digital controller comprises of ADC, DAC and DSP/FPGA.

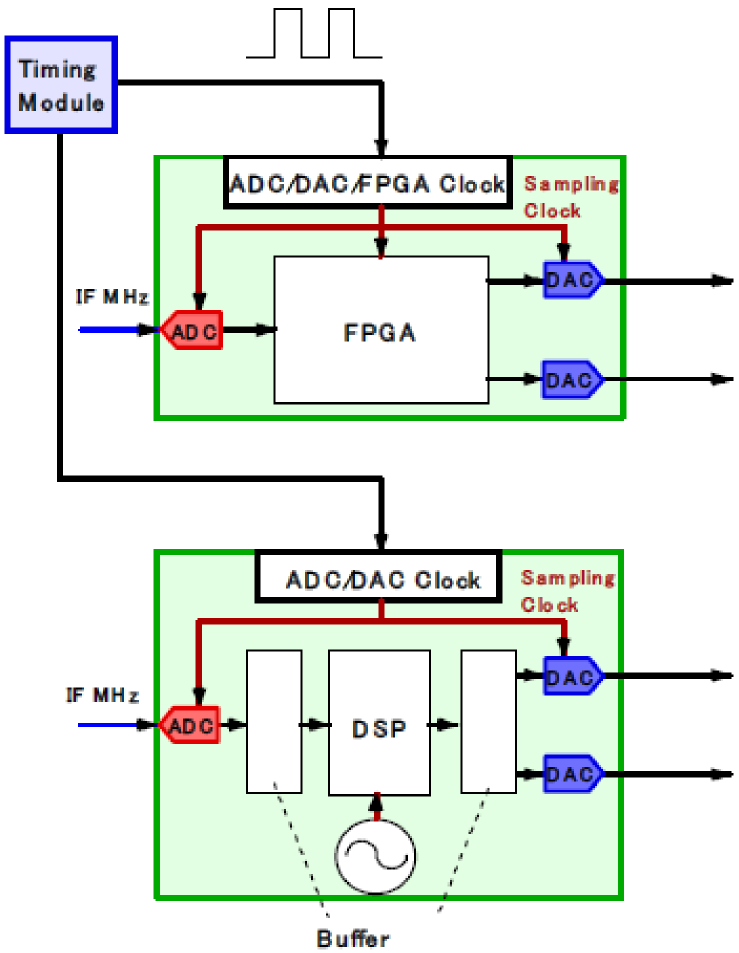
DSP (Digital Signal Processor):

This has a signal processor in the device and its calculation ability is powerful.
Between ADC/DAC and DSP, there required the buffer device and buffer device is not synchronized with sampling signal.
A few microsecond delay time is inevitable.

FPGA(Field Programmable Gate Array):

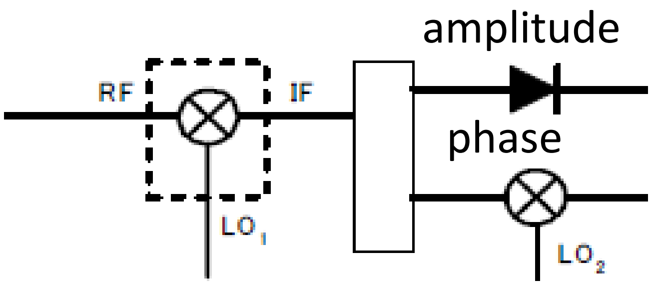
Algorism of signal process is generated of numerical formula written by the hardware language.
Synchronized operation with the clock signal of ADC/DAC and FPGA. Faster than DSP.

Recently FPGA is becoming more popular.

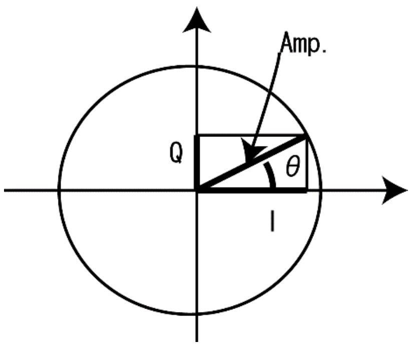


Amplitude-phase and IQ control

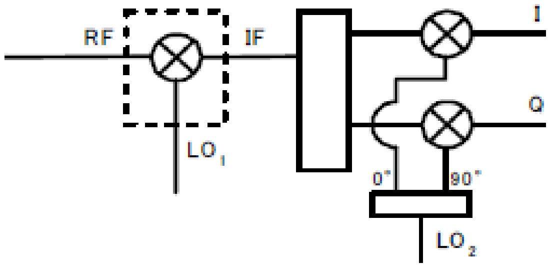
Important parameter in RF is signal’s amplitude and phase. Signal from cavity is also amplitude and phase, and this means the measurement of I-component and Q-component of RF signal



Amplitude and phase measurement

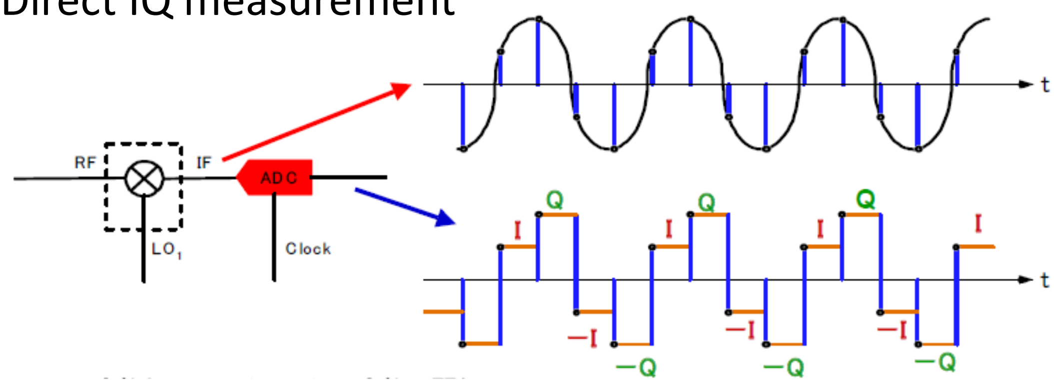


IQ and polar coordinate Relationship



IQ measurement

Direct IQ measurement



Using the sampling signal of IF (Intermediate Frequency), direct I and Q signals are possible to be Measured.

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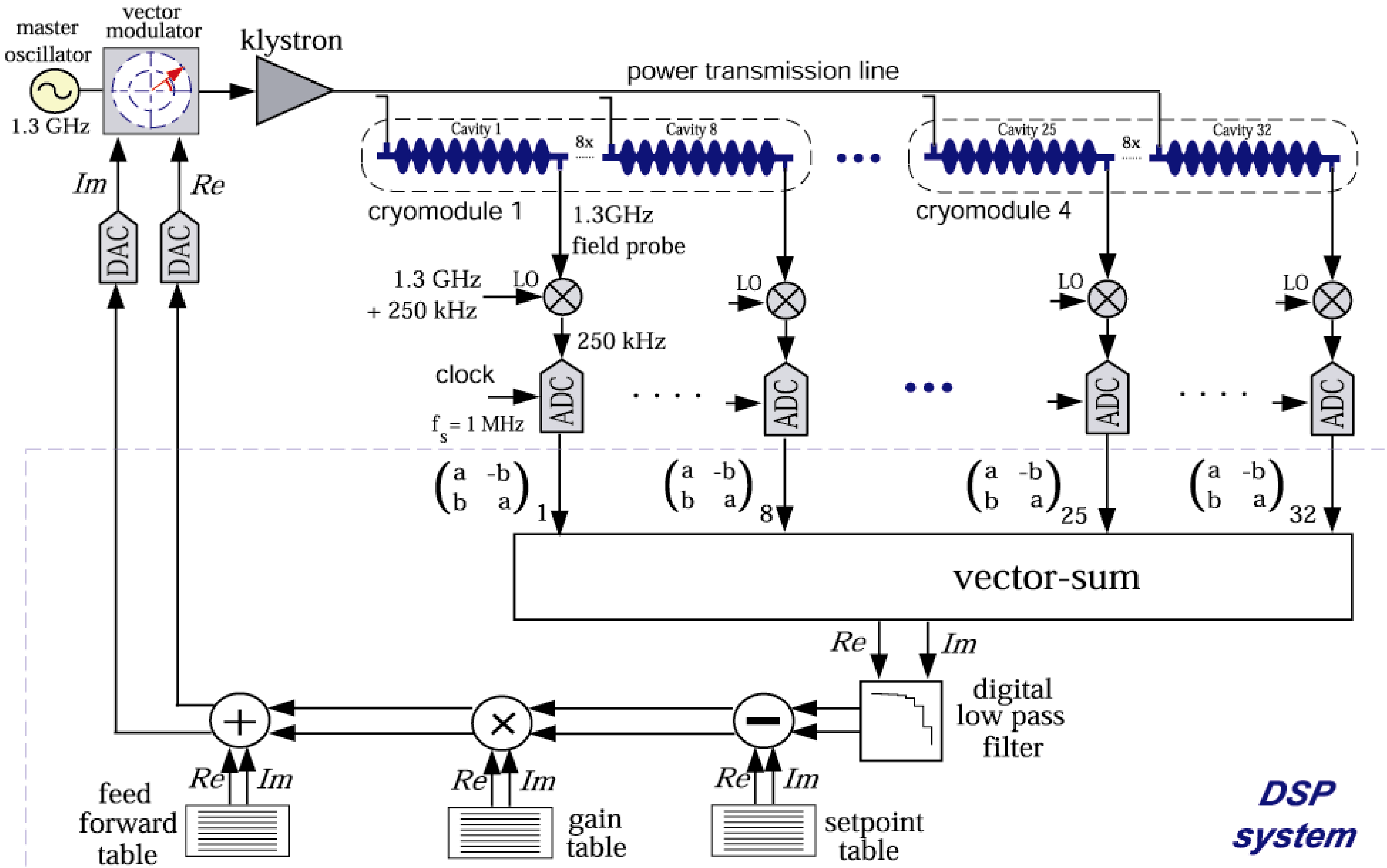
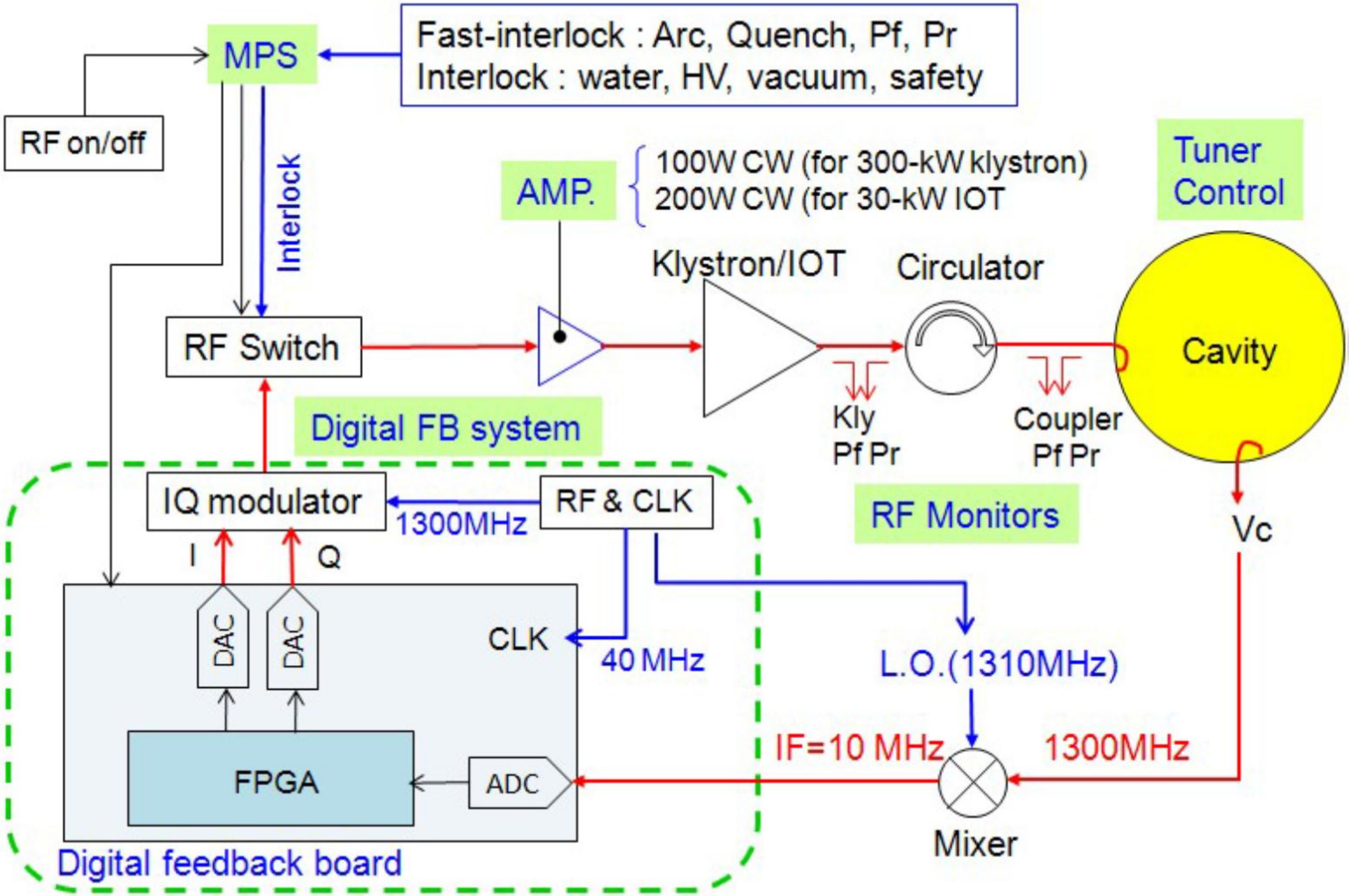
Example of LLRF in KEK STF



Example of LLRF in KEK cERL



Thanks for listening my lecture