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National Synchrotron Radiation Research Center

RF Linacs and Pulsed High Power Microwave Technologies

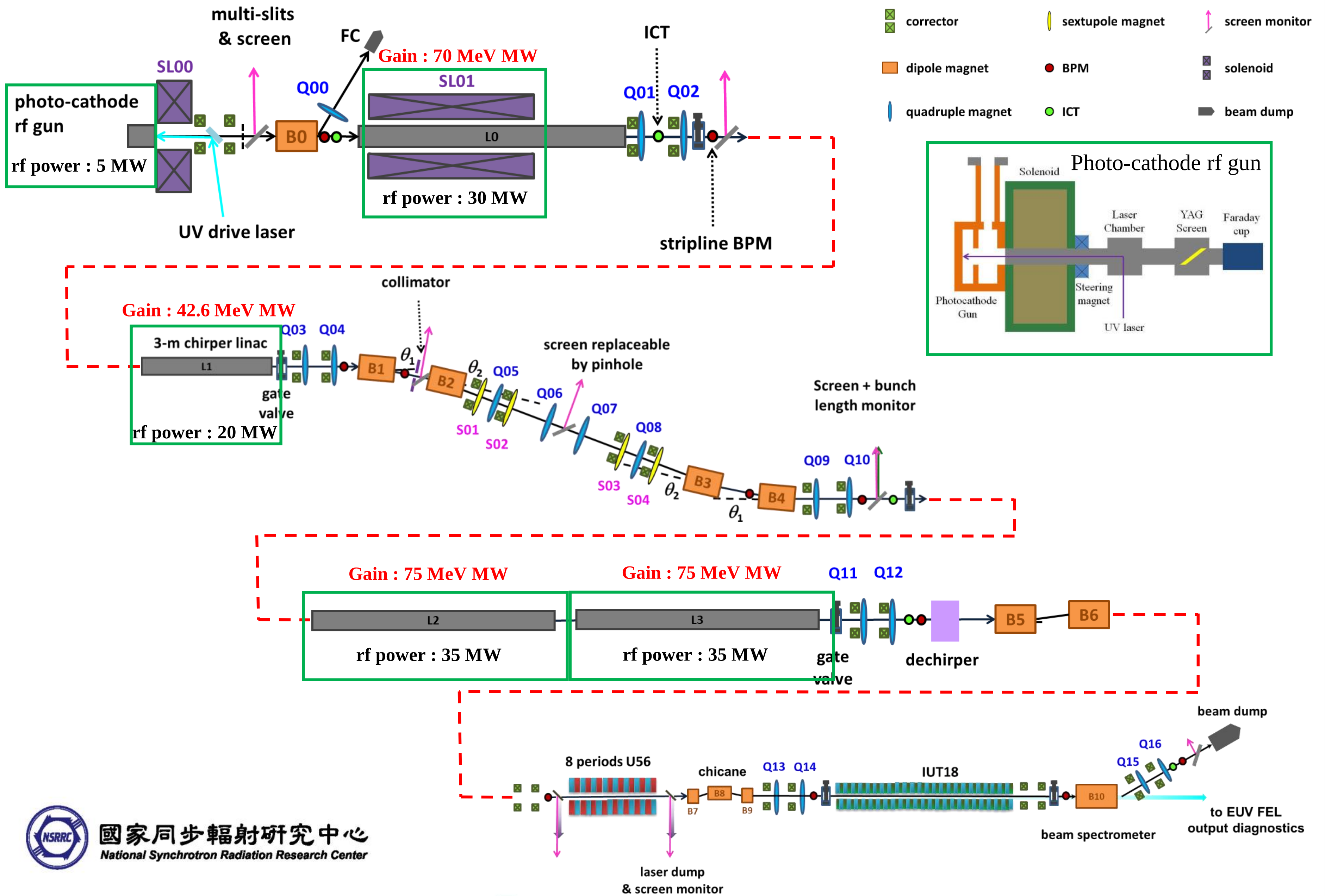
W. Y. Chiang

2022 FEL Winter School

Outline

- The NSRRC EUV/THz FEL Test Facility Layout
- Introduction of Microwave Tubes
- Microwave Tube R&D
- Klystrons
- Waves in Periodic Structures
- Linear Accelerators
- Future Work

The NSRRC EUV/THz FEL Test Facility Layout



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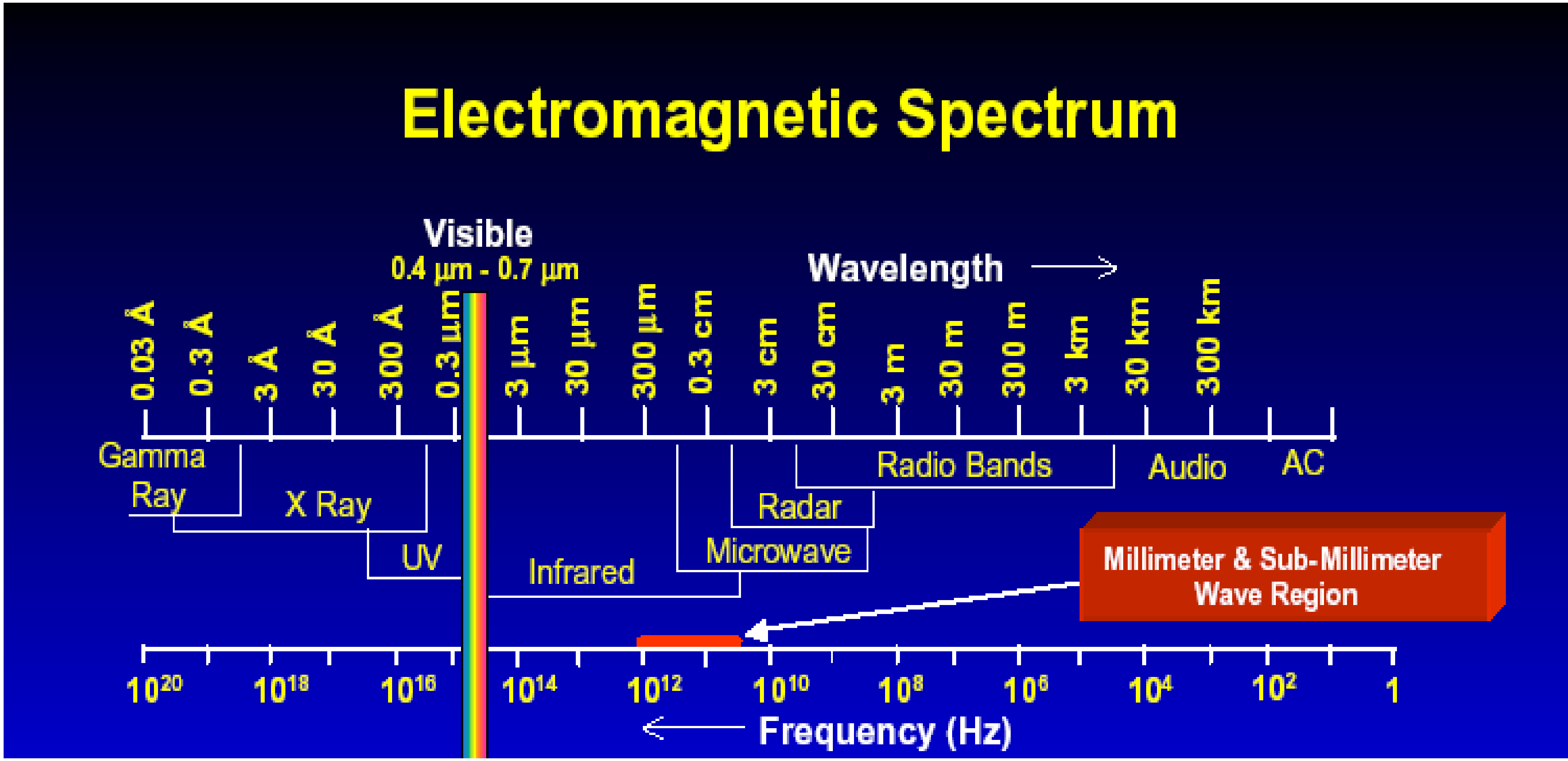
New Trend : Terahertz Waves



THz region

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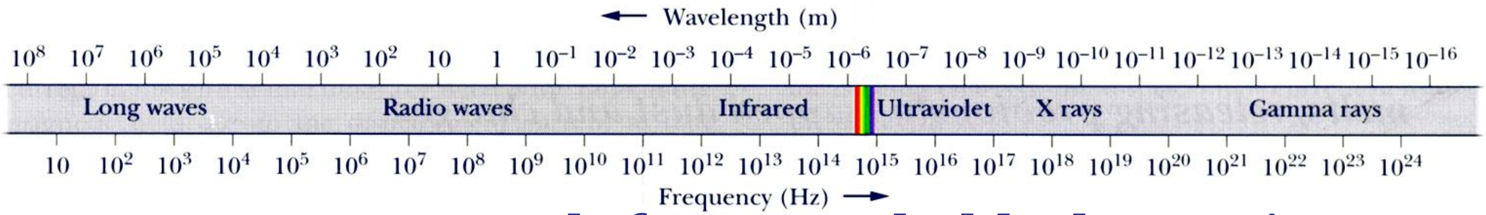


Frequency Bands for Household Electronics

AM broadcast band: 535-1605 kHz

Shortwave radio: 3-30 MHz

FM broadcast band: 88-108 MHz

VHF TV (channel 2-4): 54-72 MHz

VHF TV (channel 5-6): 76-88 MHz

UHF TV (channel 7-13): 174-216 MHz

UHF TV (channel 14-83): 470-890 MHz

Microwave Bands

L-band: 1 - 2 GHz

S-band: 2 - 4 GHz

C-band: 4 - 8 GHz

X-band: 8 - 12 GHz

Ku-band: 12 - 18 GHz

K-band: 18 - 26.5 GHz

Ka-band: 26.5 - 40 GHz

U-band: 40 - 60 GHz

V-band: 60 - 80 GHz

W-band (IEEE): 80 - 100 GHz

Vacuum Electronics

Vacuum electronics addresses electron-wave interactions in a vacuum, usually for radiation generation. It involves a much broader frequency range than the microwave band (e.g. X-ray free electron laser, FEL). This chapter covers only the microwave regime.

	Conventional Microwave Electronics	Relativistic Electronics
Examples ,	TWT, Klystron, Magnetron	ECM, FEL
Frequency	$< 10^{11}$ Hz	10^{10} Hz – X-ray
Power	$< 10^{6}$ W	10^{4} W – 10^{10} W
Electron Energy	$< 10^{5}$ V	10^{3} V – 10^{10} V
Beam Current	$< 10^{2}$ A	1 A – 10^{6} A
Basic Equations	Circuit equations + Fluid equations	Maxwell equations + Relativistic particle eqs.

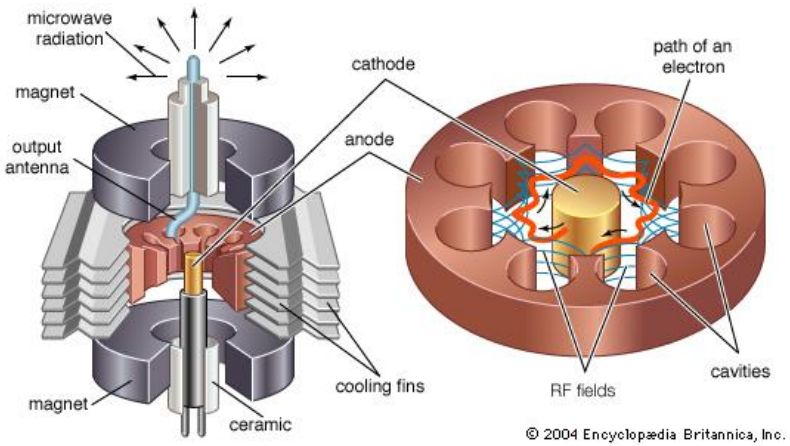
Introduction of Microwave Tubes

Amplifier	Oscillator	Interaction Process
Gridded Tube	Gridded Tube	Grid control of the beam current
Klystron	1.Two Cavity Oscillator 2.Extended Interaction Oscillator 3.Reflex Klystron	Velocity Modulation with resonant cavities
1.Helix TWT 2.Coupled Cavity TWT	Backward wave Oscillator	Velocity Modulation with traveling wave structure
Crossed Field Amplifier	1.Carcinotron(M-type BWO) 2.Fixed Frequency Magnetron 3.Coaxial Magnetron 4.Voltage Tuned Magnetron	Crossed Field
Gyrotron	Gyrotron	Spiraling beam

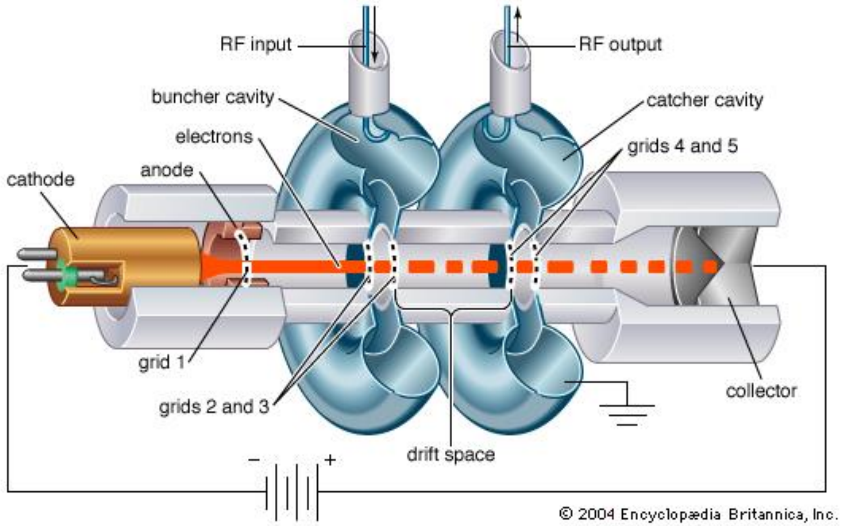
※Linear beam tubes are called O-type devices.

※Crossed-field tubes are called M-type devices.

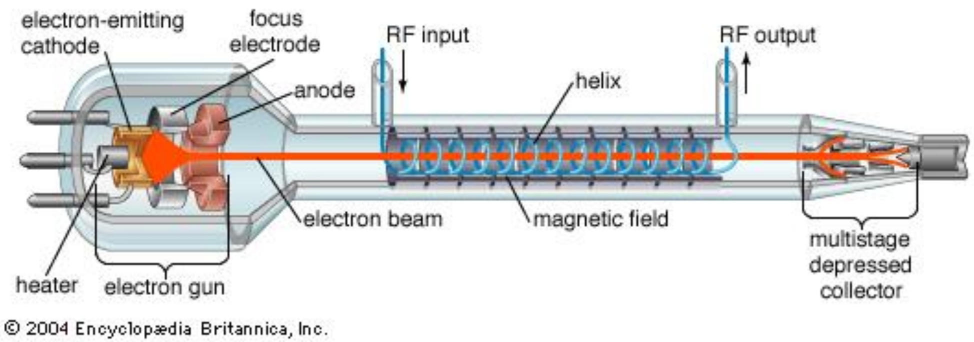
Conventional Microwave Electronics



Magnetron



Klystron



Helix TWT

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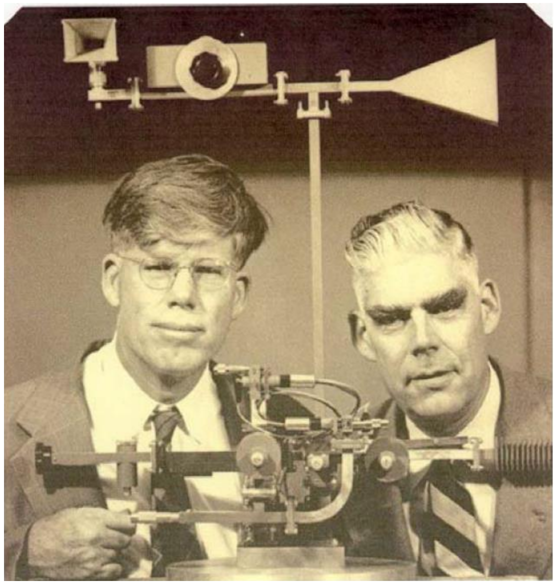
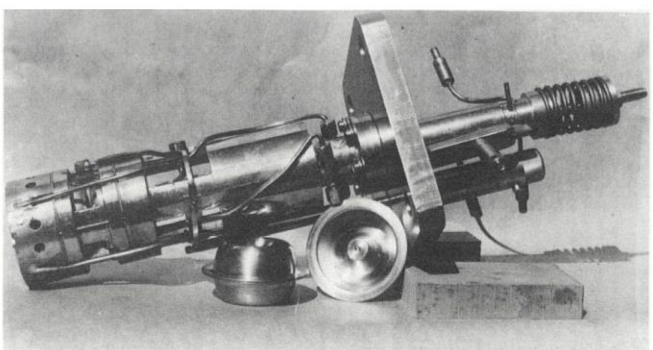
Klystrons



The first klystron invented by the Varian brothers at Stanford



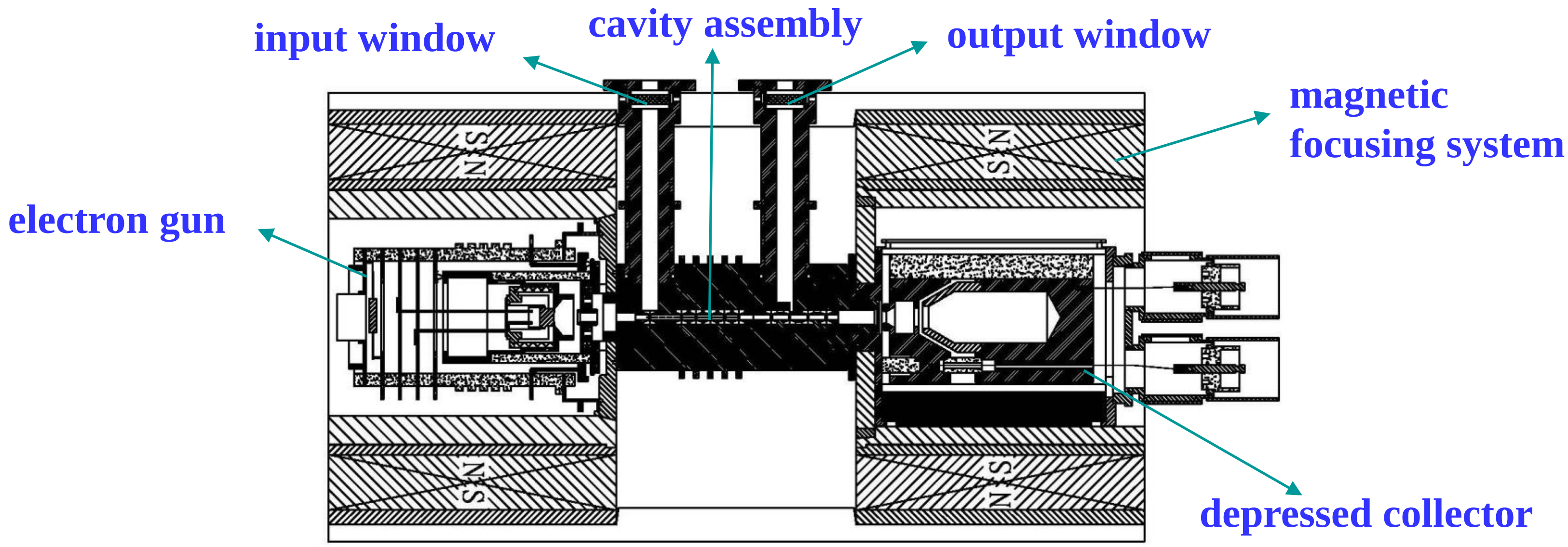
The Stanford "Model A" klystron

Table 1: Typical 5045 Operating Parameters

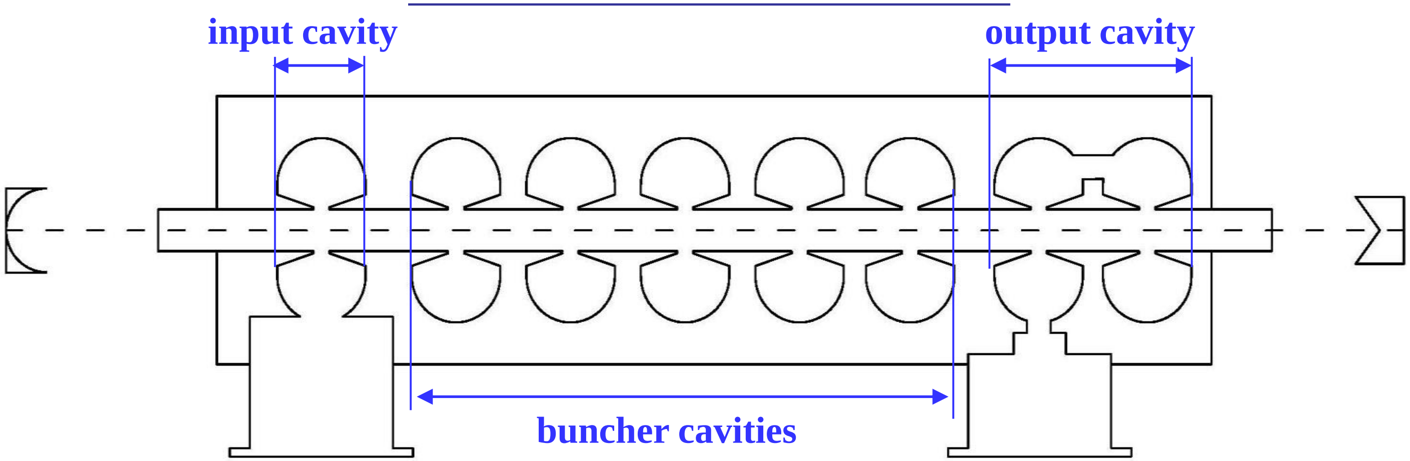
Operating Parameter	Value
Frequency	2.856 GHz
Beam Voltage	350 kV
Perveance	2.0 $\mu A/V^{1.5}$
Peak Output Power	65 MW
Average Output Power	41 kW
RF Pulse Width	3.5 μs
Pulse Rep. Rate	180 Hz
Gain	50 dB
3 dB Bandwidth	20 MHz
Saturated Efficiency	45%
Cathode Current Density	8 A/cm^2

The SLAC S-band klystron

Klystron Assembly



Interaction Circuit



Conditions Required for the Generation of Coherent Radiation - Common to All Types of Microwave Tubes

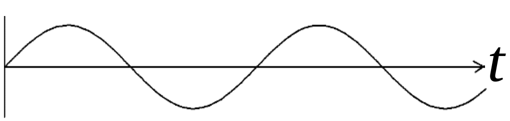
1. A mechanism for the RF fields to *bunch* a DC electron beam into an AC electron beam (Microwave tubes are distinguished by their bunching mechanisms).
2. *Synchronism* between the bunched electrons and the RF fields.

$$\text{Let}\ \begin{cases} J\ \text{(electron current)} = \begin{cases} J_0 & \text{[DC]} \\ J_0 \sin\omega t & \text{[AC]} \end{cases} \\ E\ \text{(wave electric field)} = E_0 \sin\omega t \end{cases}$$

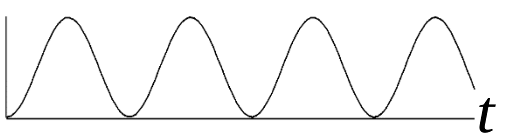
$$\text{Then, } P\ \text{(power)} = JE = \begin{cases} J_0 E_0 \sin\omega t & \text{[DC]} \\ J_0 E_0 \sin^2\omega t & \text{[AC]} \end{cases}$$

$$\Rightarrow\quad \langle P \rangle_t \begin{cases} = 0 & \text{[DC], no energy exchange} \\ \neq 0 & \text{[AC], energy exchange} \end{cases}$$

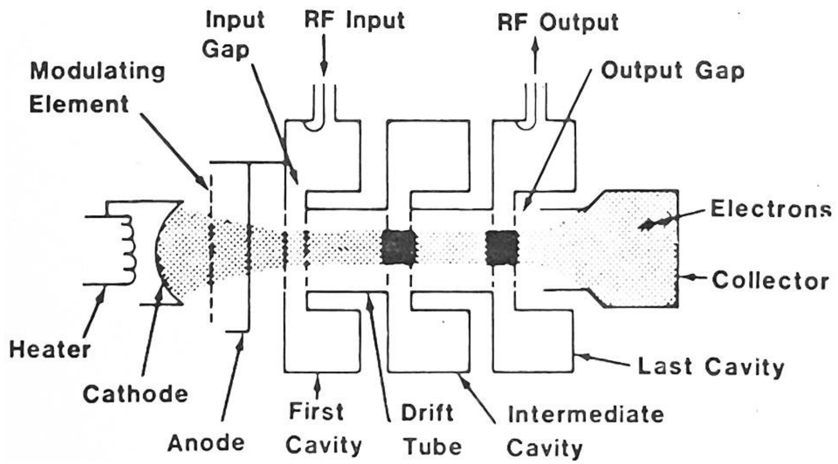
$\sin\omega t$



$\sin^2\omega t$



The design principle of the klystron



Elements of a Three-Cavity Klystron Amplifier

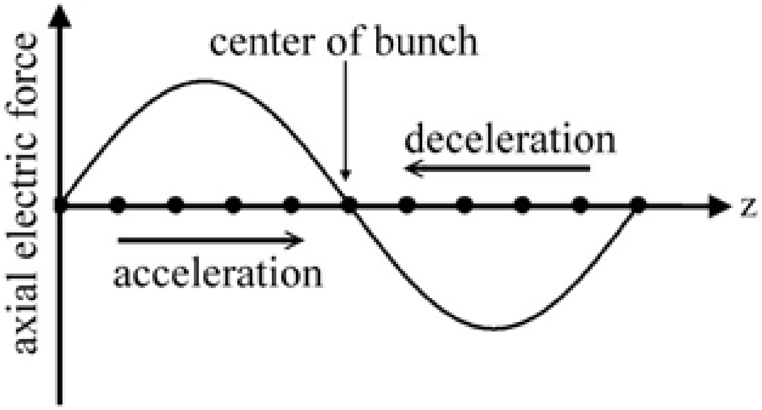
Plasma Frequency

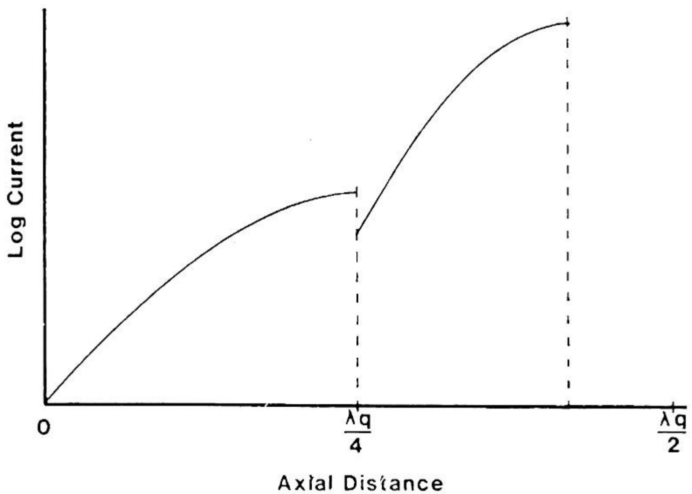
$$\begin{cases} \omega_{pe} \equiv \sqrt{\dfrac{4\pi n_0 e^2}{m_e}} \; [= 5.64\times10^4 \sqrt{n_0(\mathrm{cm}^{-3})} \; \dfrac{\mathrm{rad}}{\mathrm{sec}}] \\ \omega_{pi} \equiv \sqrt{\dfrac{4\pi n_0 e^2}{m_i}} \; [= \sqrt{\dfrac{m_e}{m_i}}\omega_{pe} \ll \omega_{pe}] \end{cases}$$

For (18) to have a non-trivial solution ($E_{1k} \neq 0$), ω can only have a single frequency given by $\omega^2 = \omega_{pe}^2 + \omega_{pi}^2 = \omega_p^2$ (19)

where $\omega_p^2 \equiv \omega_{pe}^2 + \omega_{pi}^2$ (20)

ω_p is called the plasma frequency. It is a characteristic frequency of the plasma most frequently encountered in plasma studies.





RF Current Growth in Beam in a Three-Cavity Klystron Amplifier

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Tuning of the multi-cavity klystron

(1)同步調諧(synchronously tuned)

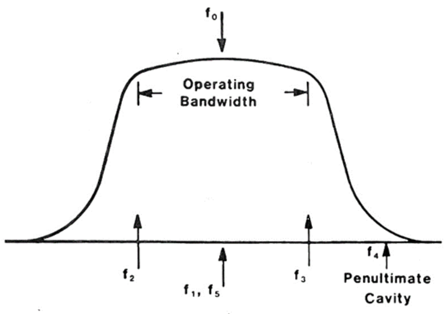
以多腔速調管為例，若將各段諧振腔頻率設計成一致，電子束經過腔體所造成的群聚效果會逐級增加，因此速調管增益最高，又稱為增益調諧(gain tuned)。一般而言，每級的增益大約15-20 dB，故4個諧振腔的速調管放大器，預期可提供共50 dB以上的增益。

(2)效率調諧(efficiency tuned)

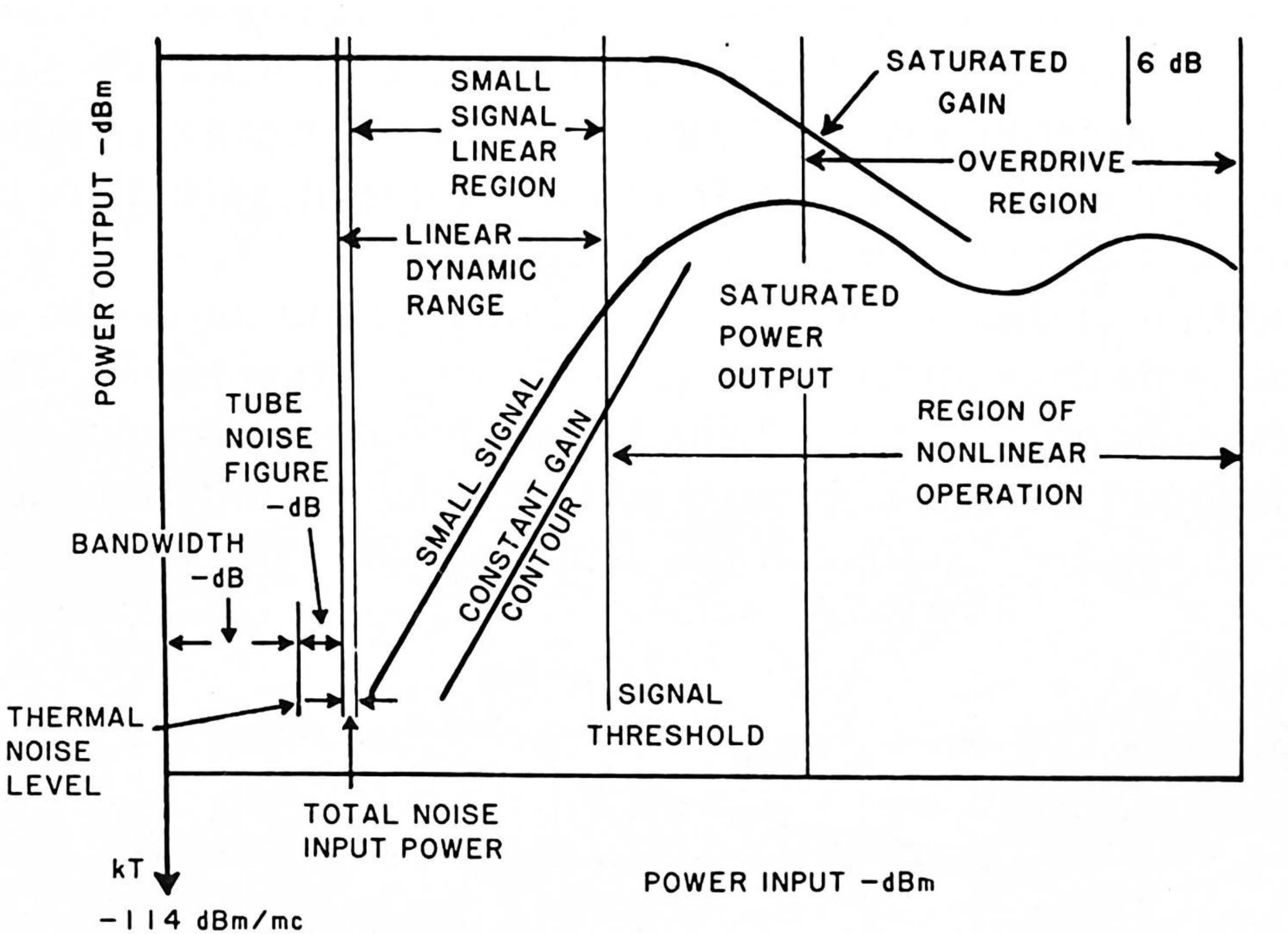
將倒數第二腔(penultimate cavity)的諧振頻率調高至通帶(pass band)以外，腔體呈現電感性，則間隙電壓將落後由電子束在腔體表面所感應的電流，所以當一個群聚的電子團到達腔體間隙時，間隙電壓會使群聚的電子團前面的電子減速，將這些電子被掃進前一個群聚電子團；當群聚電子團離開腔體的瞬間，間隙電壓將群聚和群聚之間的電子加速至下一個群聚電子團，於是群聚效率再次提昇，進入輸出腔後便會激起更強的感應電流，進而使輸出功率增加。若將倒數第二腔的諧振頻率調高至通帶的高頻端外，頻寬變寬了，雖然增益會下降約10 dB左右，但是效率調諧會使電子束的群聚效率提昇，結果會多出15~20 %的功率輸出。

(3)寬頻調諧(broadband tuned)

速調管在一般情況下是窄頻寬的器件，其頻寬包含了群聚頻寬及輸出迴路頻寬兩部分。群聚頻寬的任務是提供一個速度零散小的高度群聚的電子束，通常利用參差調諧的方法(stagger tuning)，犧牲高增益的特性來換取群聚頻寬。參差調諧是將不同諧振腔的諧振頻率調高或調低於中心頻率，以增加其頻寬。



The design principle of the klystron



Transfer Curve of rf amplifier

Small-Signal Analysis

Ka-Band Klystron

P3 := PPmax − 3   P1 := PPmax − 1

Vo ≡ 14000	Beam Voltage (V)
Io ≡ 0.5	Beam Current (A)
f0 ≡ 35	Center Freqency (GHz)
a ≡ 0.000375	Tunnel Radius (m)
b ≡ 0.000225	Beam Radius (m)

Number of Data Points   npoints ≡ 256

Calculation Bandwidth (GHz)   BW ≡ 0.30

Plot Markers   fl = 34.886   fh = 35.088   PPmax = 52.633 dB

Gain at center frequency   PPf0 = 52.002 dB

1dB Bandwidth (GHz)   Bndwthdb = 0.179   % BW(1dB)   fbw1 = 0.512

3dB Bandwidth (GHz)   Bndwth = 0.202   % BW(3dB)   fbw3 = 0.576

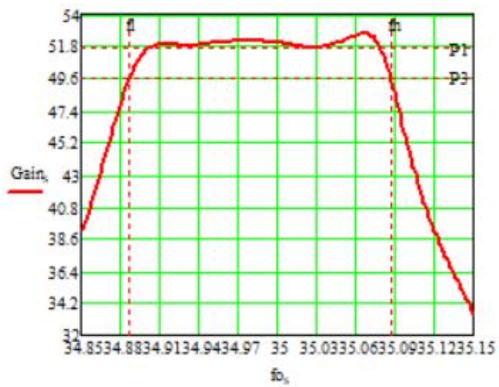
Remember to update the shape factor d2 if the fill-factor changes.

$\beta e = 3.212 \times 10^{3}$ $\beta q = 169.200$ $\gamma \cdot a = 1.173$

Empirical expression for Qe of the output cavity - not used in the gain calculation: Irf ≡ 1.5

$$Qe_N := \frac{\frac{Vo}{Io}}{RQ_N\left[\frac{2}{\sigma\cdot(\sigma+1)}\cdot(M_N)^2\cdot Irf\right]} \qquad (11)$$

$Qe_N = 176.205$



Number of Klystron Cavities: N ≡ 6

Gun Microperveance (uA/V^1.5)   K = 0.302

Brillouin Field (gauss) $Bbr = 2.397 \times 10^{3}$

Beam current density (A/cm²)   Jbeam = 314.380   Cathode current density (A/cm²)   Jcathode := 5

Gun convergence $\frac{Jbeam}{Jcathode} = 63$

Cavity Rs/Q (Ohms)	External Q and Qo		Cavity Frequency (GHz)	Gap-Gap L (m)	Gap Length (m)	Coupling coefficient at r=a
$RQ_1 \equiv 128$	$Qe_1 \equiv 350$	$Qo_1 \equiv 2000$	$f_1 \equiv 34.98$	$L_1 \equiv 0$	$d_1 \equiv 0.0004$	$Ma_1 \equiv 0.919$
$RQ_2 \equiv 128$	$Qe_2 \equiv \infty$	$Qo_2 \equiv 2000$	$f_2 \equiv 34.9$	$L_2 \equiv 0.005$	$d_2 \equiv 0.0004$	$Ma_2 \equiv 0.919$
$RQ_3 \equiv 128$	$Qe_3 \equiv \infty$	$Qo_3 \equiv 2000$	$f_3 \equiv 35.09$	$L_3 \equiv 0.005$	$d_3 \equiv 0.0004$	$Ma_3 \equiv 0.919$
$RQ_4 \equiv 128$	$Qe_4 \equiv \infty$	$Qo_4 \equiv 2000$	$f_4 \equiv 35.09$	$L_4 \equiv 0.005$	$d_4 \equiv 0.0004$	$Ma_4 \equiv 0.919$
$RQ_5 \equiv 128$	$Qe_5 \equiv \infty$	$Qo_5 \equiv 2000$	$f_5 \equiv 35.17$	$L_5 \equiv 0.005$	$d_5 \equiv 0.0004$	$Ma_5 \equiv 0.919$
$RQ_6 \equiv 218$	$Qe_6 \equiv 350$	$Qo_6 \equiv 2000$	$f_6 \equiv 35.00$	$L_6 \equiv 0.0047$	$d_6 \equiv 0.0004$	$Ma_6 \equiv 0.919$

Total coupling coefficient

$$M = \begin{pmatrix} 0.711 \\ 0.711 \\ 0.711 \\ 0.711 \\ 0.711 \\ 0.711 \end{pmatrix}$$

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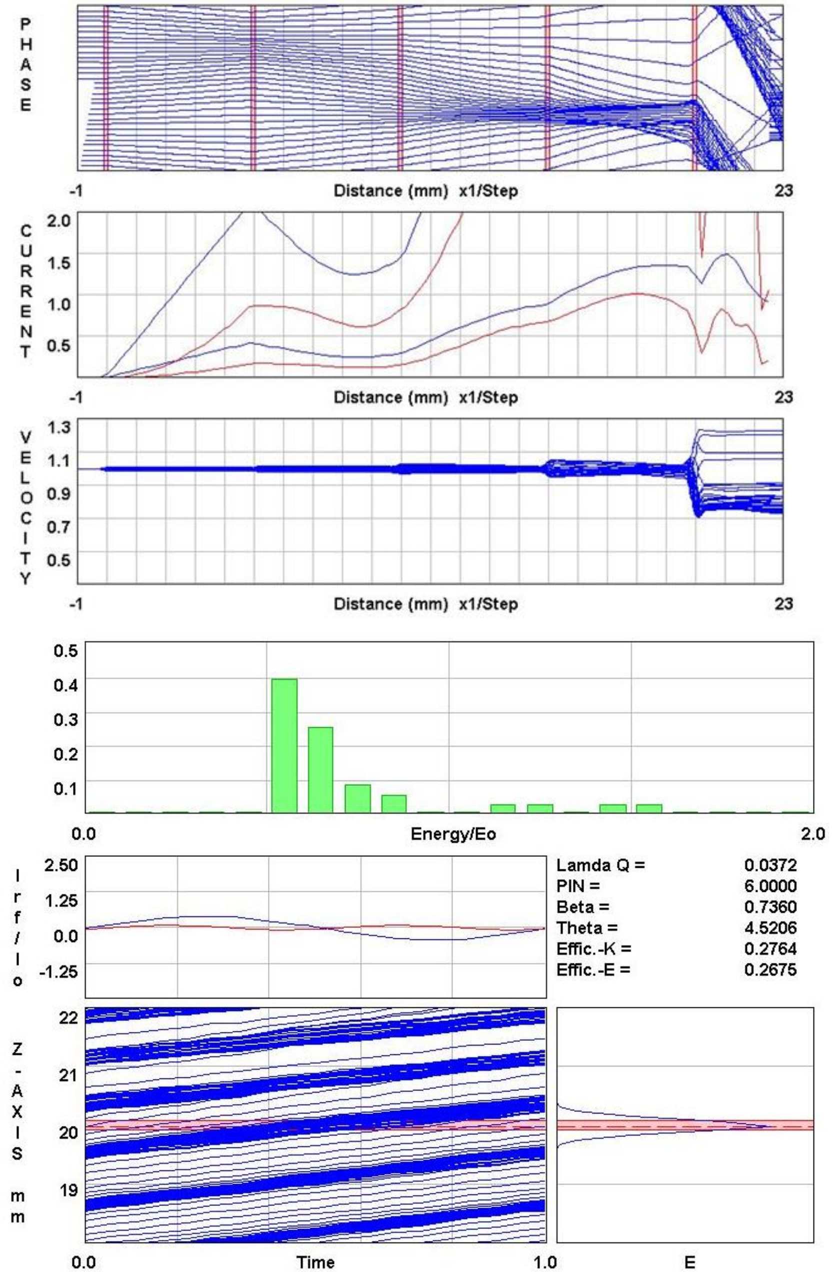
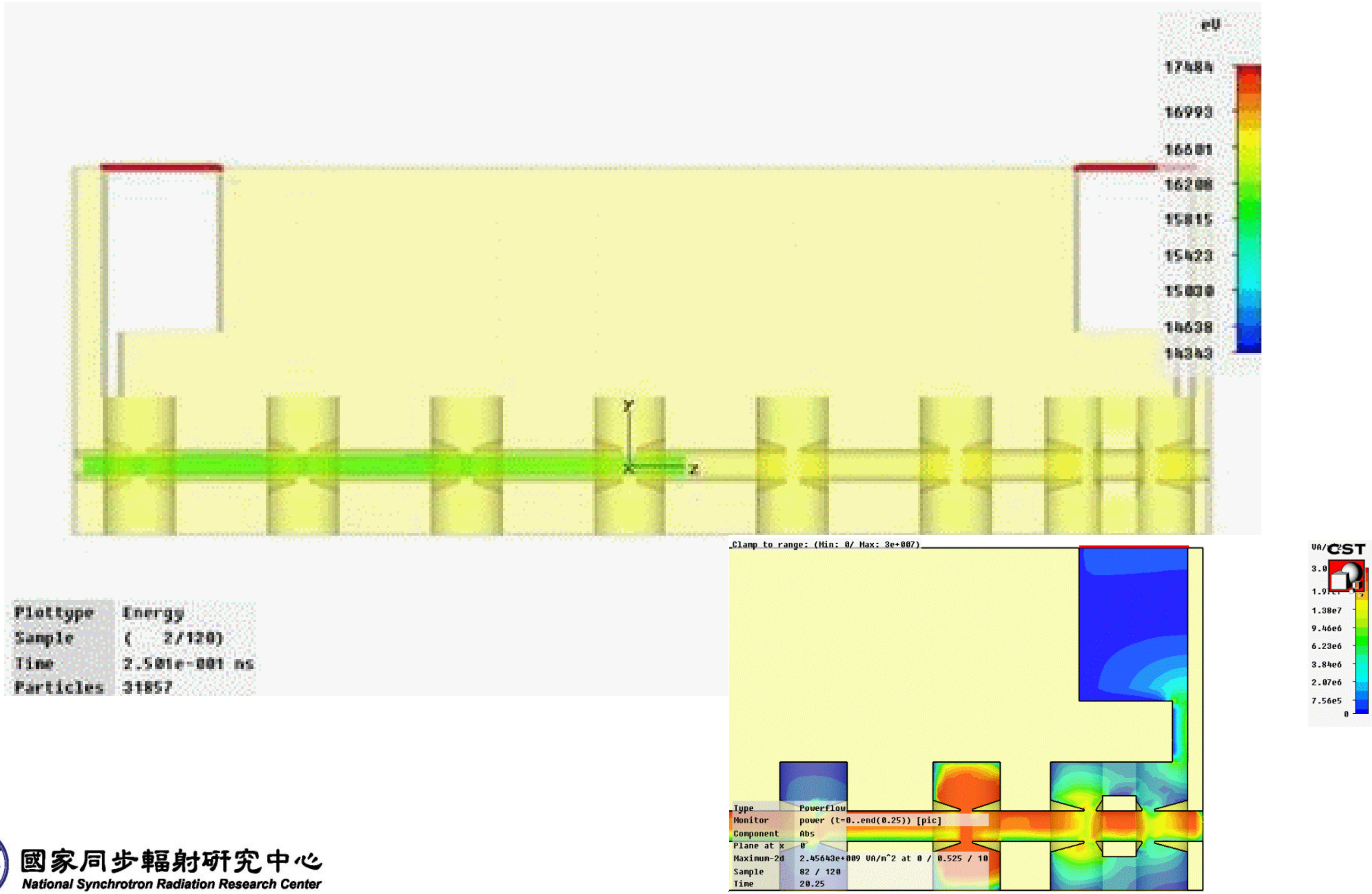
Big-Signal Analysis



Principle of beam-wave interaction



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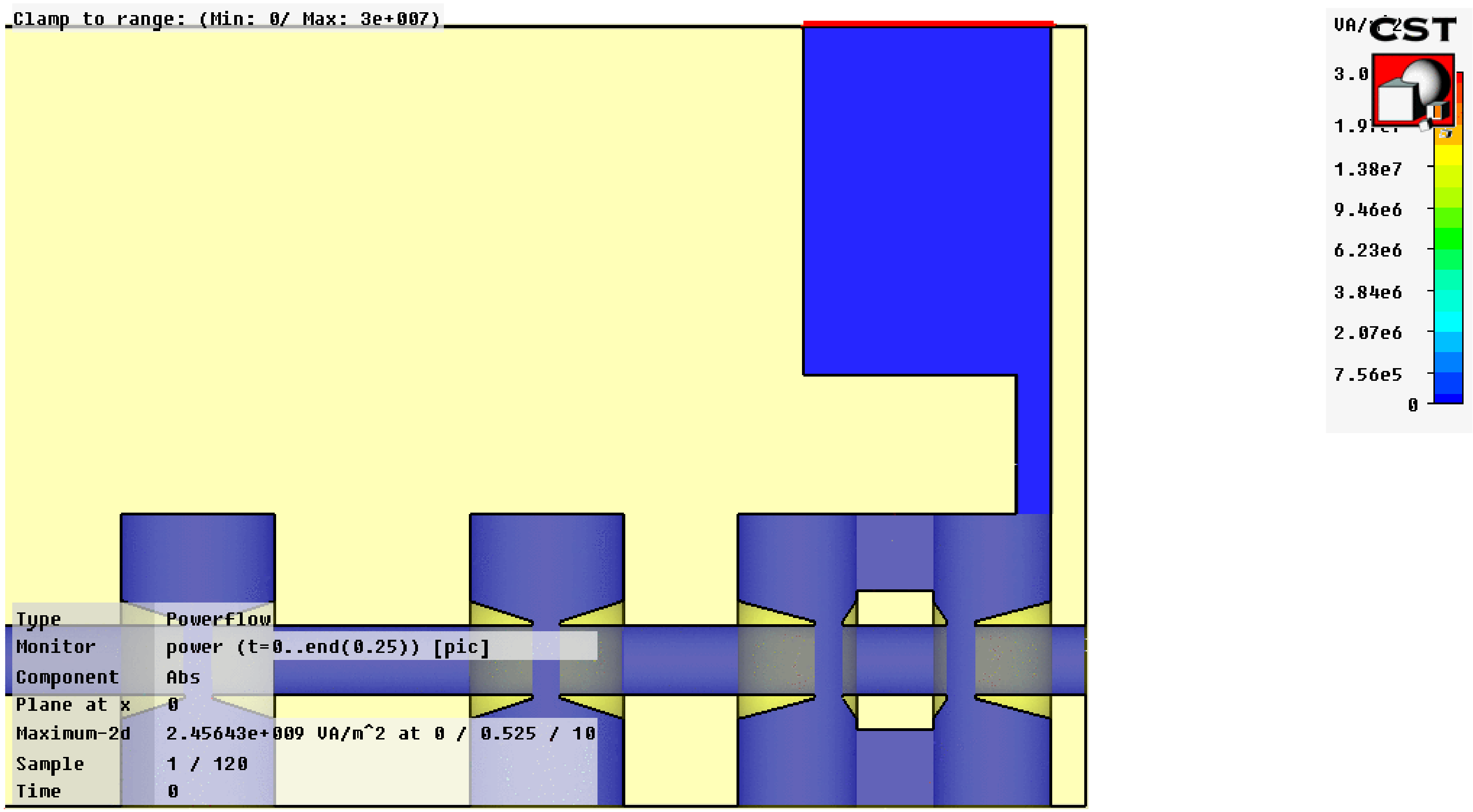
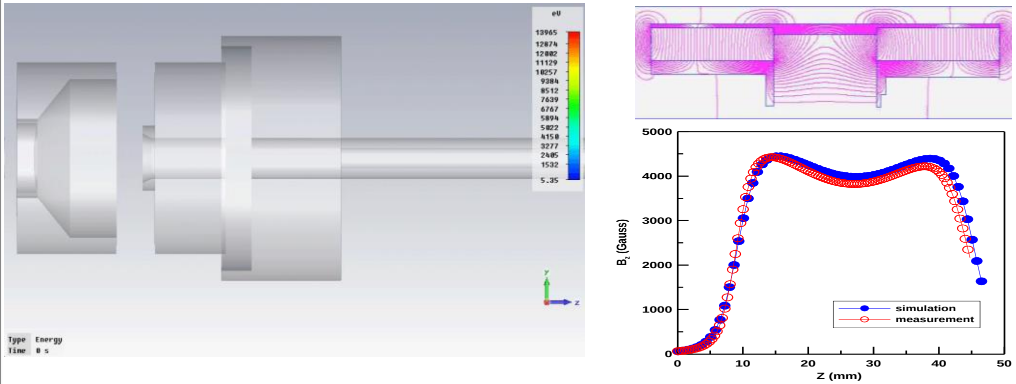
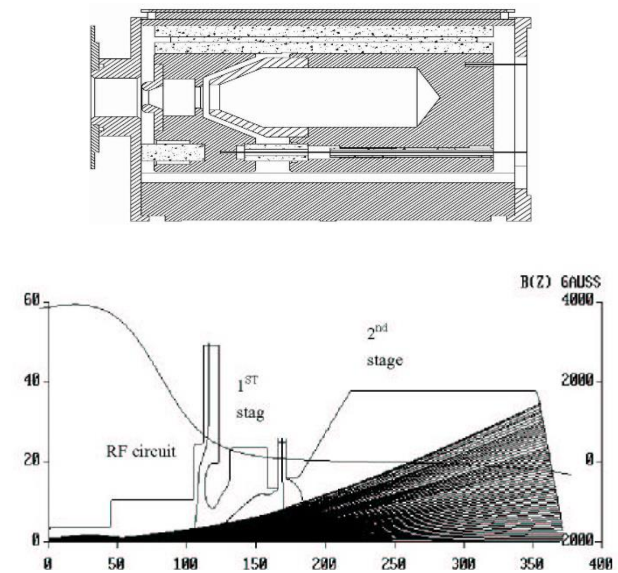
Principle of beam-wave interaction



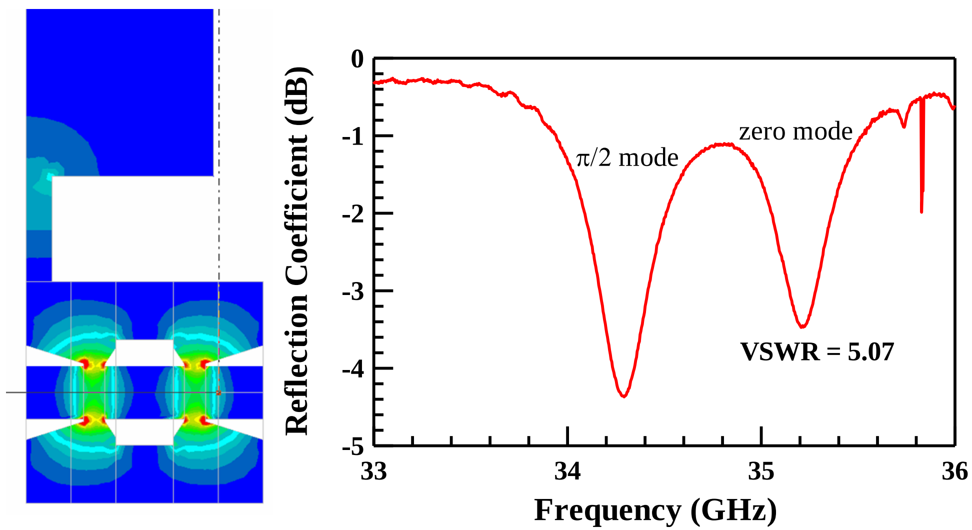
Simulation of the Klystron



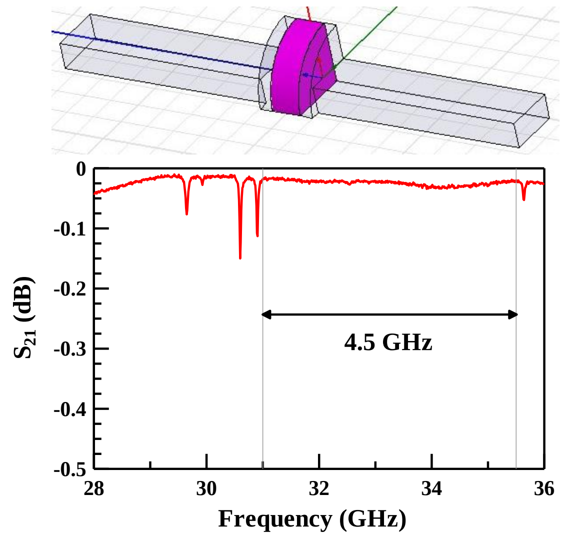
E-Gun and Magnetic Focusing System



Collector Simulation



Interaction Structure



Pillbox Window

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Thales TH2100 klystron

RF performance

Frequency	2 998.5	2 998.5	MHz	
RF output power				
• peak	37	45.1	MW	
• average	17	20	kW	
Peak RF drive power	200	200	W	max.
- 1 dB bandwidth	10	10	MHz	min.
RF pulse duration	4.5	4.5	µs	max.
Saturated gain	53.5	55	dB	typ.
Efficiency	45	43	%	typ.

Electrical characteristics

Anode voltage	279	307	kV	typ.
Beam current	295	340	A	typ.
Heater voltage	30	30	V	max.
Heater current	28	28	A	max.

Toshiba E37310A pulsed klystron

Typical Operation

Frequency	2998 MHz
Peak beam voltage	293 kV
Peak beam current	320 A
Beam pulse width	6.2 µs
RF pulse duration	4.0 µs
Drive power	374W
Peak output power	35.5MW
Efficiency	38.8%
Gain	49.7dB
Filament voltage	18.3Vac
Filament current	18.4Aac

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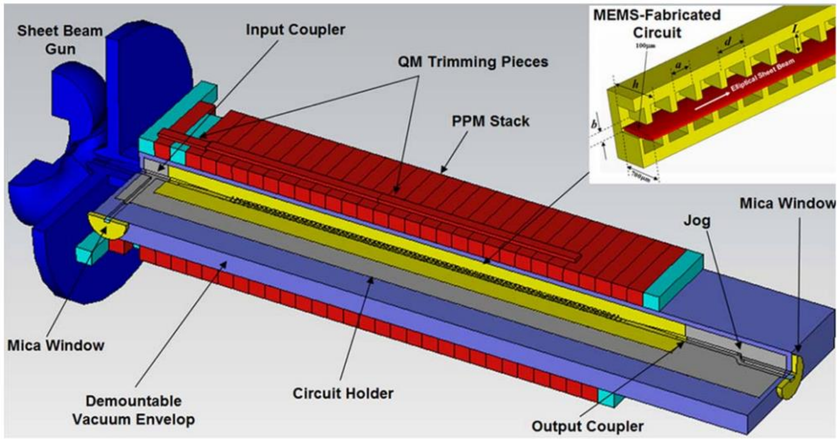
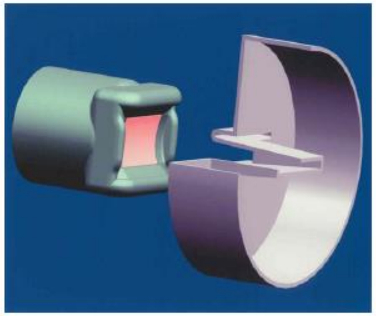
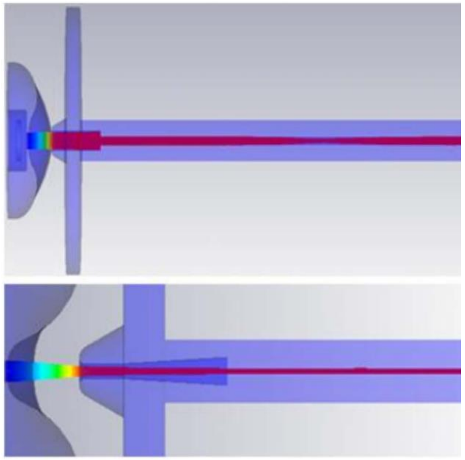
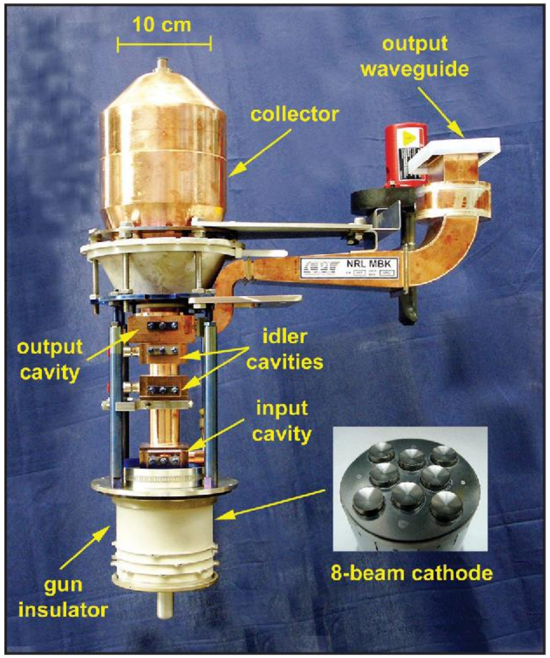
Advanced Klystron Configurations

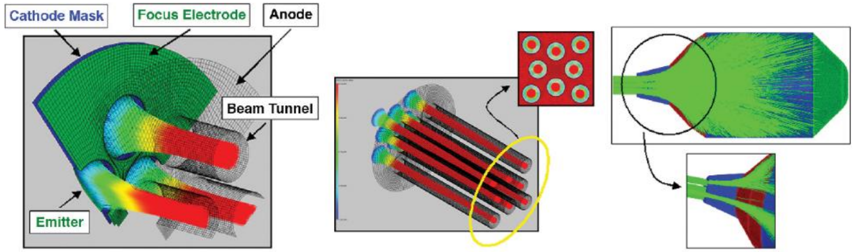






Sheet-Beam Klystrons (SBKs)





Multiple Beam Klystrons (MBKs)

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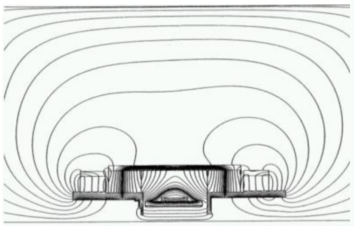
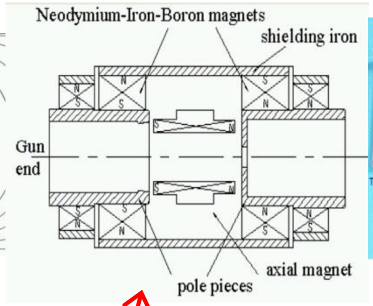
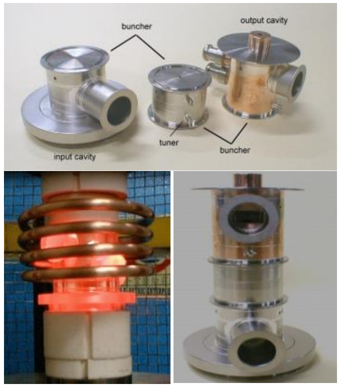
Microwave Source R&D







CAD

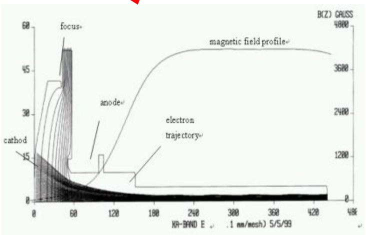
Engineering Drawing

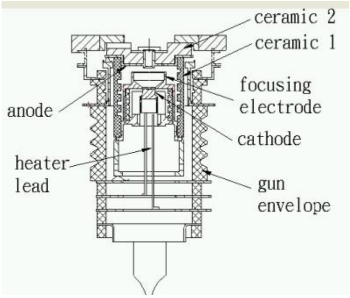
Precision Machining

Brazing

EIKA Assembly

Hot Test





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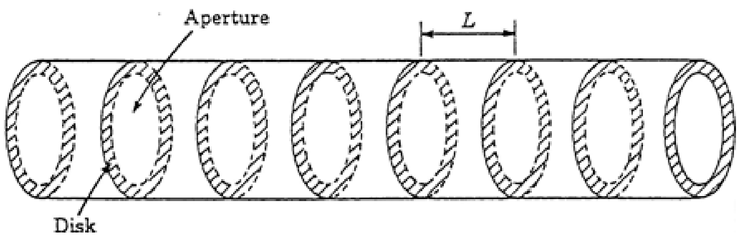
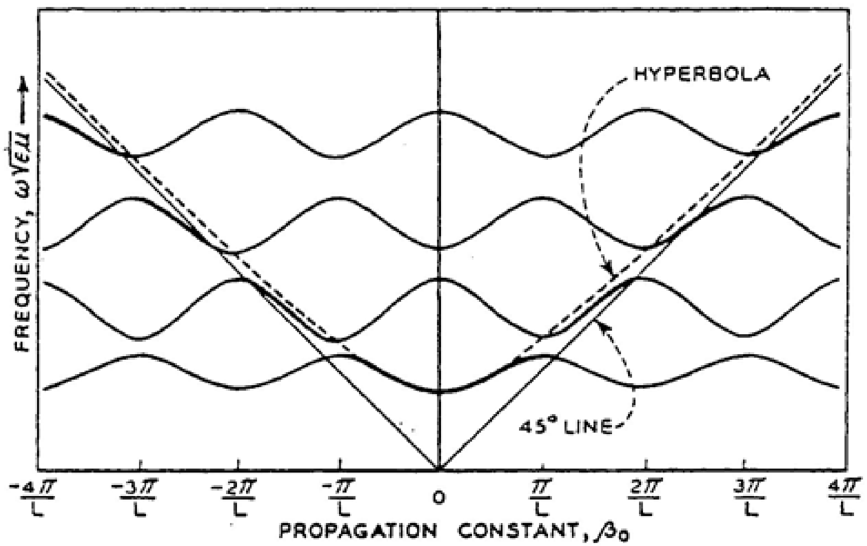
Waves in Periodic Structures

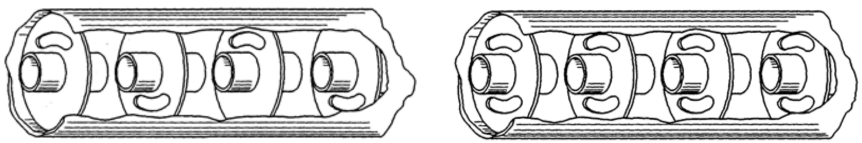
weak periodic loading

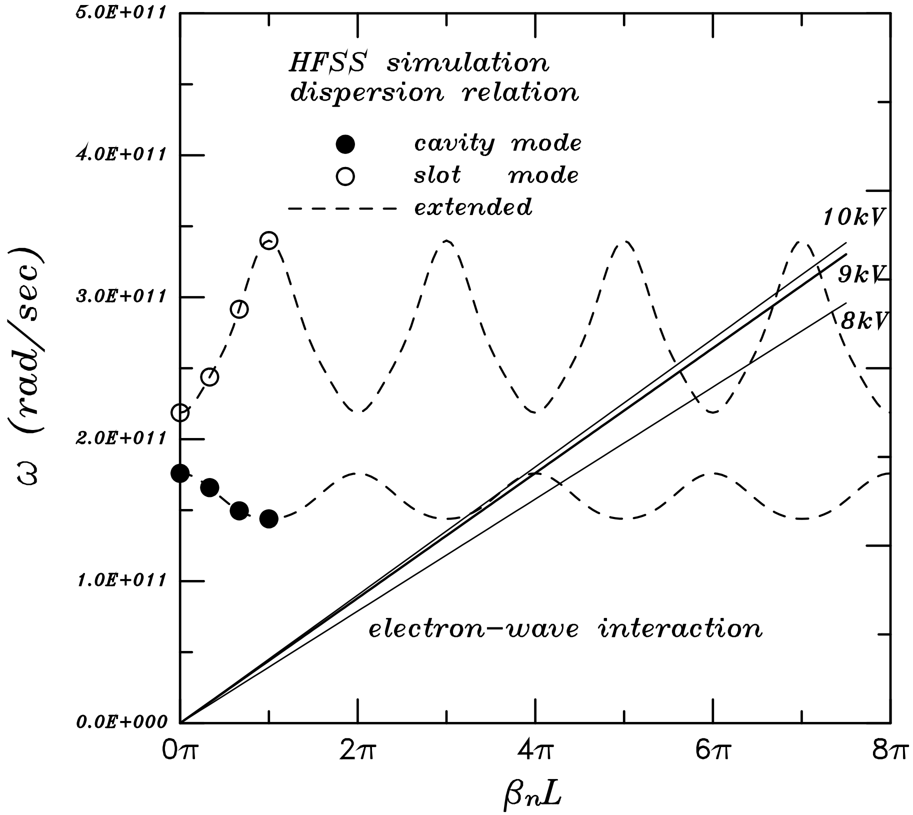




ω-β Diagram of slow wave structure

strong periodic loading





ω-β Diagram of slow wave structure

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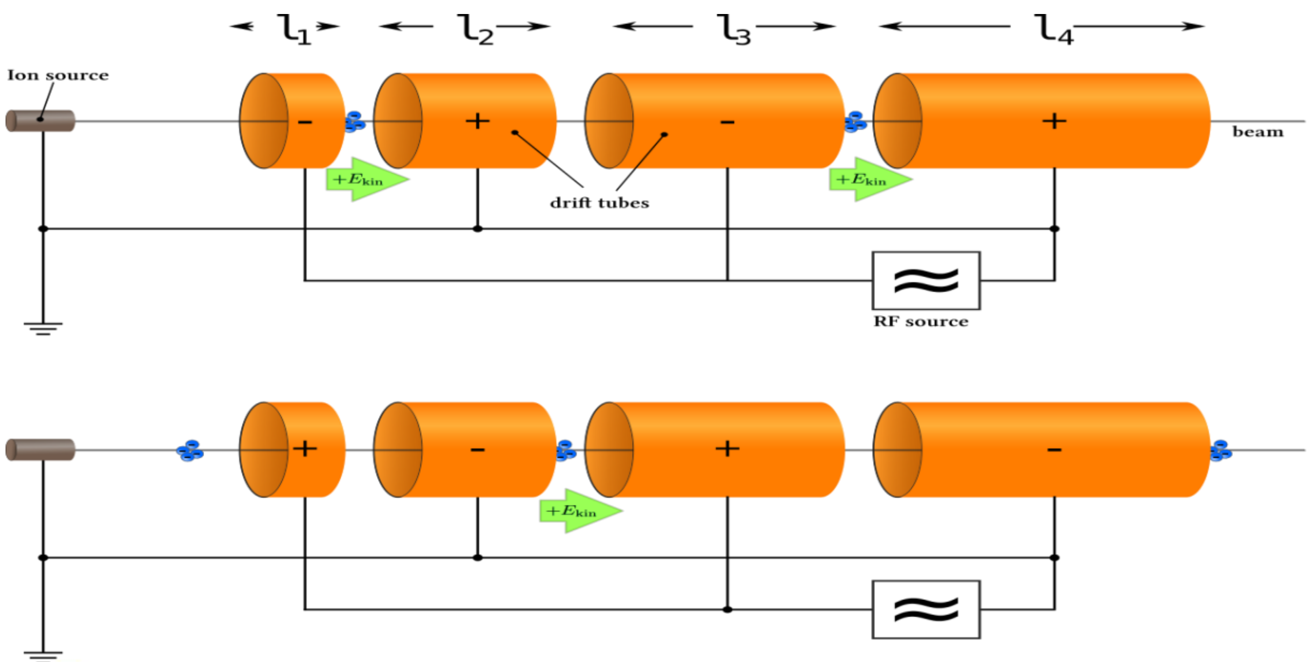
Early History of Linear Accelerators

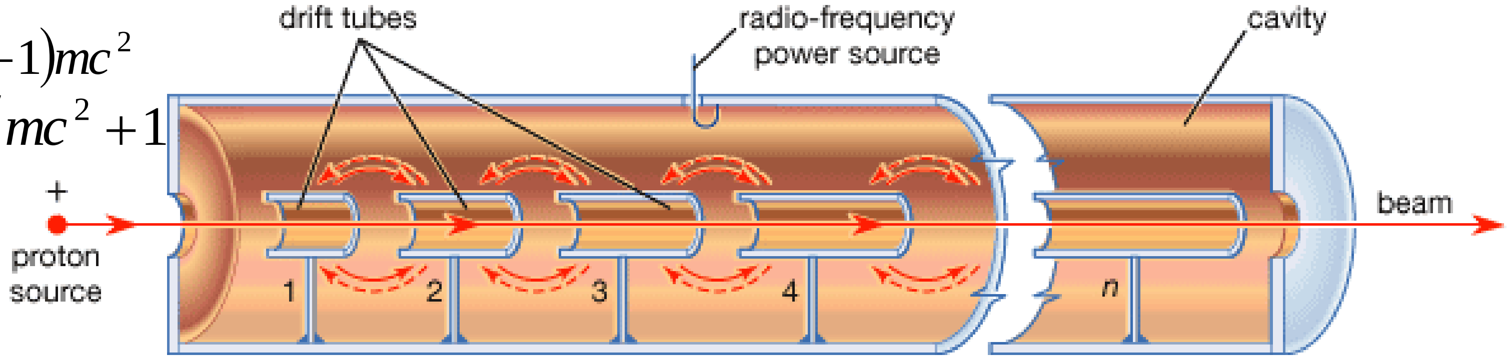
- In 1924, **Gustav Ising** proposed the concept of an accelerator using **time-dependent fields**. It consists of a straight vacuum tube and a sequence of metallic drift tubes with beam holes.
- In 1927, the first rf linear accleerator was demonstrated experimentally by a Norwegian student, **Rolf WiderØe** at RWTH Aachen University in Germany.



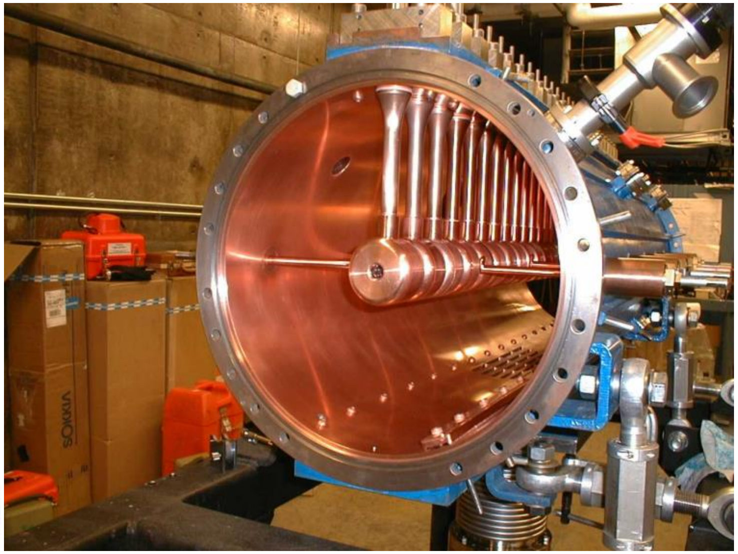
Rolf WiderØe
(1902 – 1996)

Drift Tube Linac

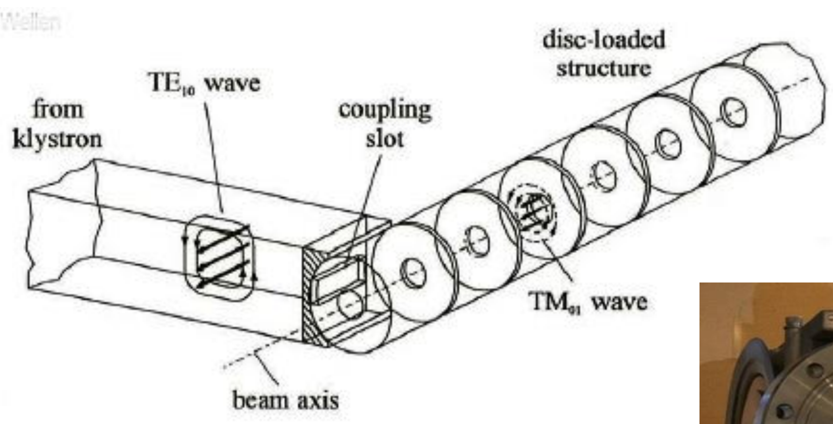
$$qV = (\gamma - 1)mc^2$$
$$\gamma = qV/mc^2 + 1$$

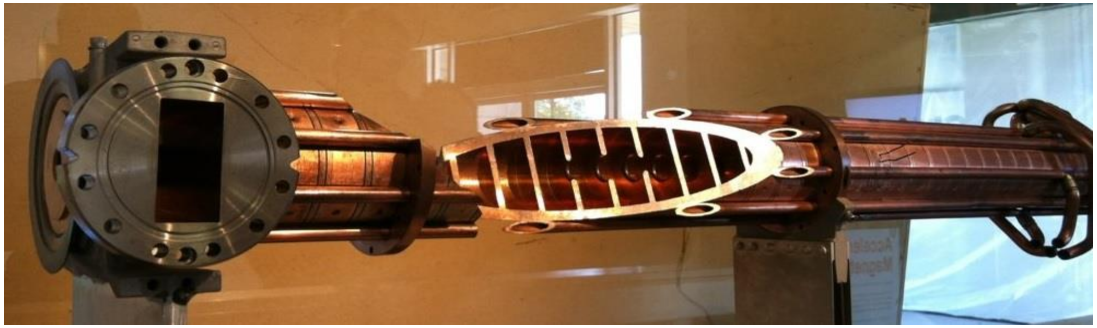


Unlike the Wilderoe structure, in the DTL the fields in adjacent gaps are in phase. Good for proton and ion acceleration from ~0.04 – 0.4 c. Acceleration of ions at even lower velocity can be done by RFQ.

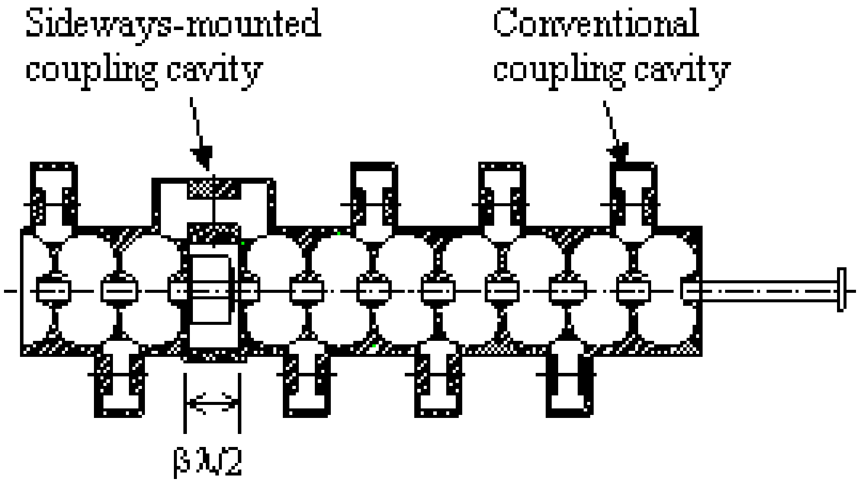


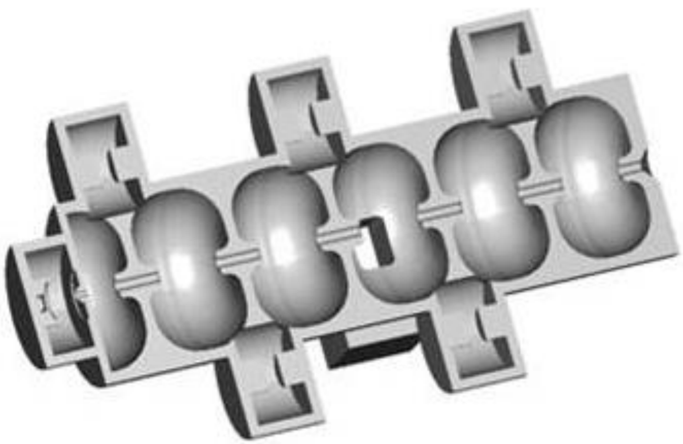
The SLAC Linac Structure



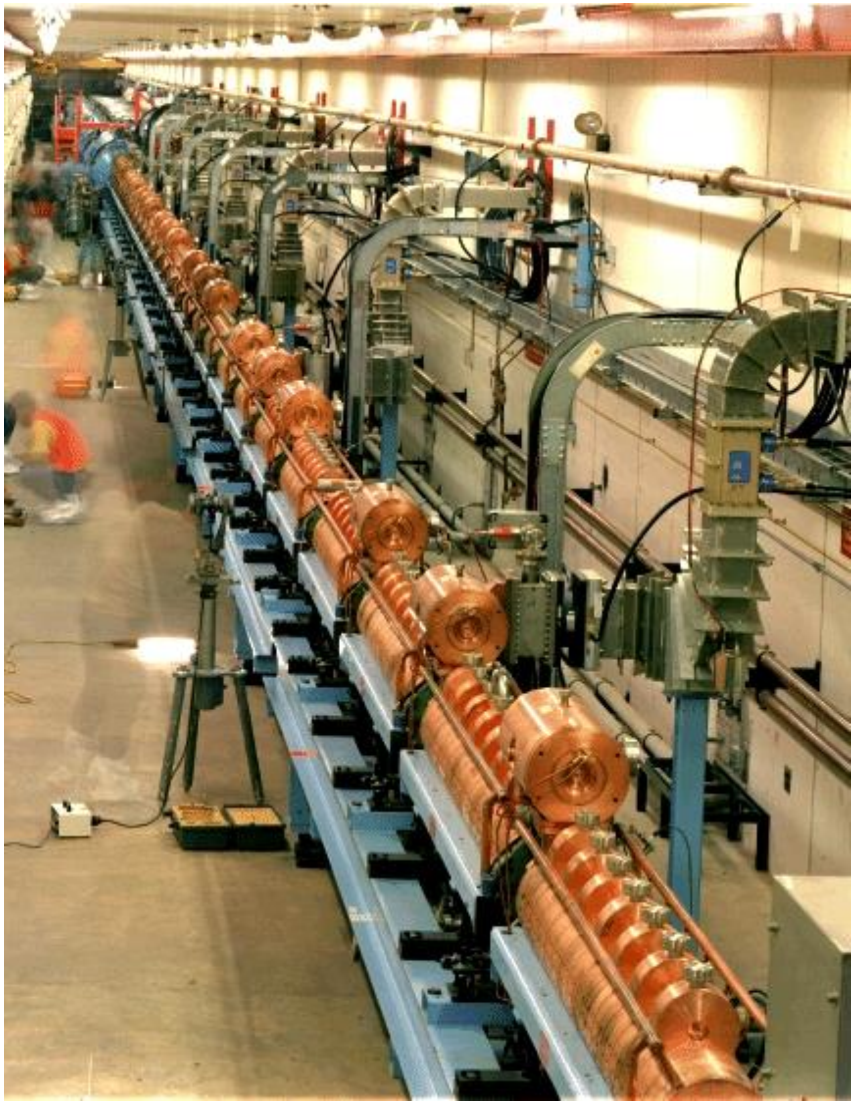


Coupled-cavity Linac



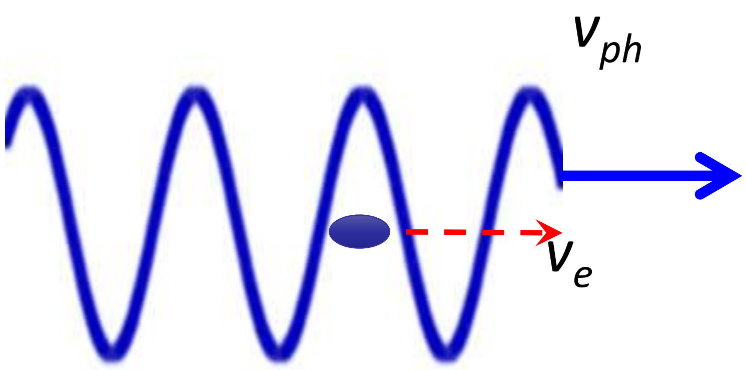


A side-coupled cavity linac with e-gun (for medical and industrial applications).



A side-coupled cavity linac system for ion acceleration.

Particle Acceleration in RF Fields

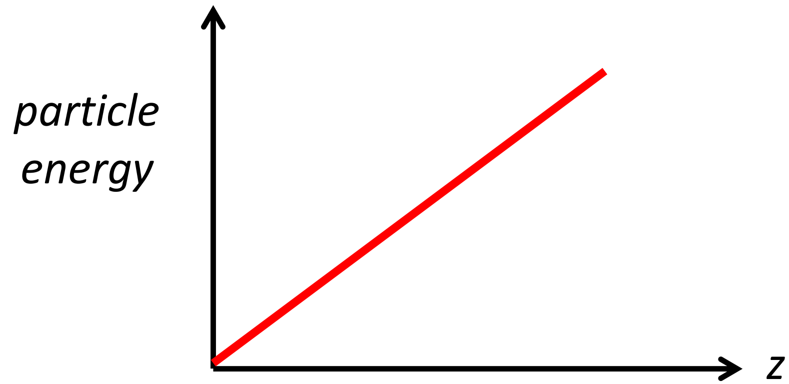


$$E_z(z,t) = E(z)\cos\left[\omega t - \int_0^z dz k(z) + \phi\right]$$

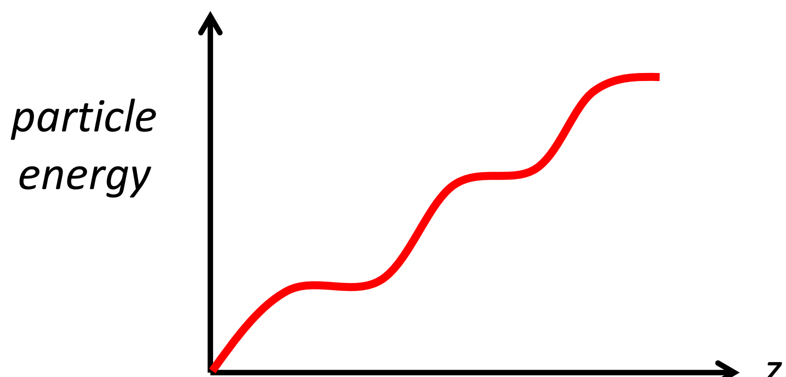
with $\quad k(z) = \omega / v_p(z)$

For a traveling wave propagating along +z axis in a waveguide (for efficient acceleration , the phase velocity must equals to the particle velocity at any time)

For standing wave $\quad E_z(z,t) = E(z)\cos(\omega t + \phi)$



energy gain of a “synchronous particle” along z during acceleration by a traveling wave



particle energy gain vs. z during acceleration by SW linac

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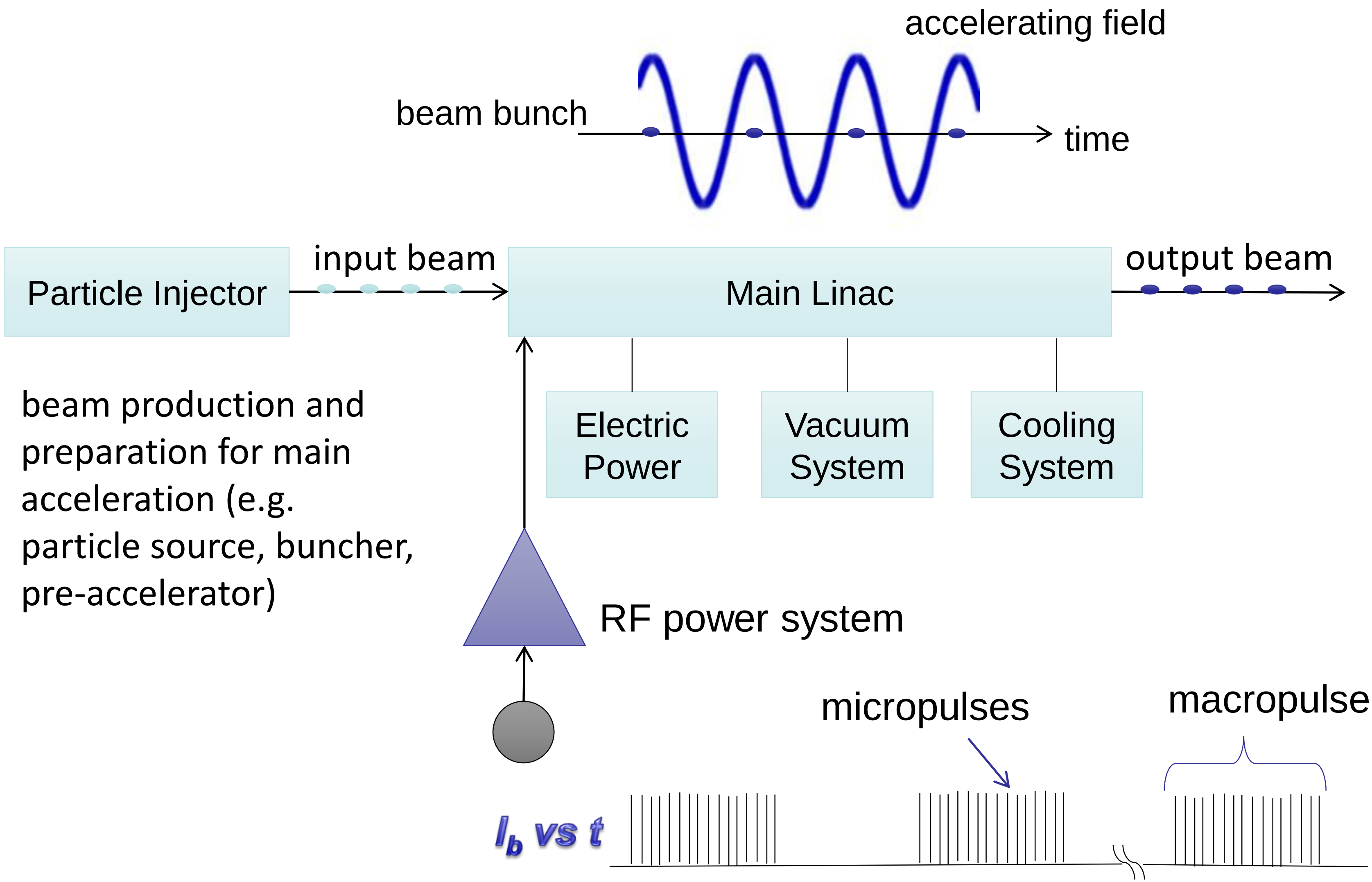
A Typical Electron Linac System



TIME STRUCTURE OF e-BEAM IN LINAC

Longitudinal Dynamics of Low-Energy Beams Injected into a v=c Traveling-wave Structure

The equation of motion of a particle accelerated by a traveling-wave

$$\frac{d}{dt} mc\beta\gamma = mc\gamma^3 \frac{d\beta}{d\phi}\frac{d\phi}{dt} = qE_0 \cos\phi(z,t)$$

where the phase of the traveling-wave is

$$\phi(z,t) = \omega t - \frac{2\pi z}{\lambda}$$

the phase motion is

$$\frac{d\phi}{dt} = \frac{2\pi c}{\lambda}(1-\beta)$$

Since β<1, ϕ increases with time. The particle falls behind the initial phase on the wave

expressing γ in the equation of motion in β, we have

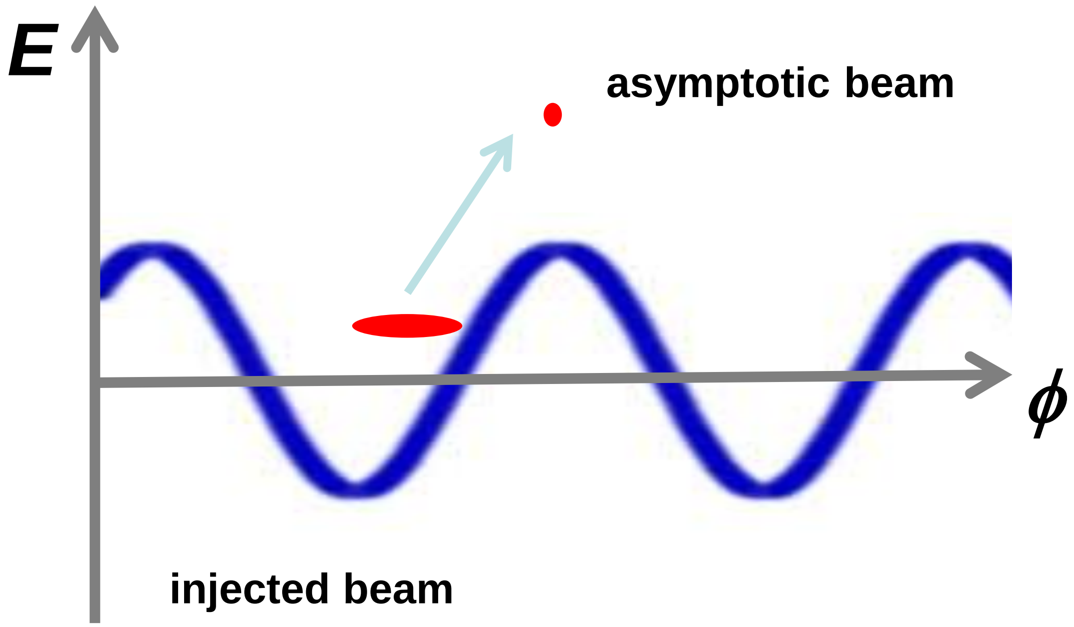
$$\frac{1}{(1+\beta)\sqrt{1-\beta^2}}\frac{d\beta}{d\phi} = \frac{qE_0\lambda}{2\pi mc^2}\cos\phi \quad \xrightarrow{\text{integration}} \quad \sin\phi = \sin\phi_i + \frac{2\pi mc^2}{qE_0\lambda}\left(\sqrt{\frac{1-\beta_i}{1+\beta_i}} - \sqrt{\frac{1-\beta}{1+\beta}}\right)$$

at asymptotic phase ($\beta \rightarrow 1$),

$$\sin\phi_\infty = \sin\phi_i + \frac{2\pi mc^2}{qE_0\lambda}\sqrt{\frac{1-\beta_i}{1+\beta_i}}$$

if we want to set ϕ_∞ at the rf crest for efficient acceleration, the condition is

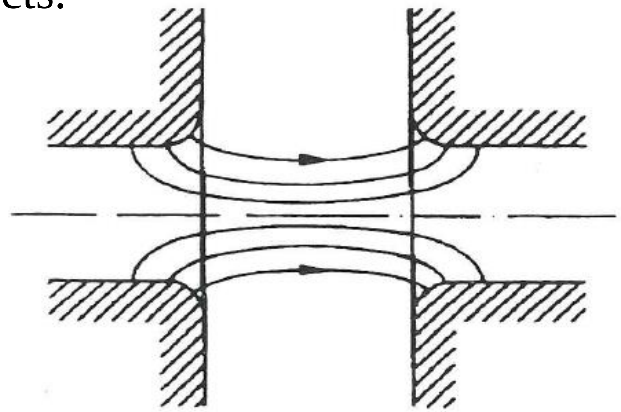
$$\sin\phi_i = -\frac{2\pi mc^2}{qE_0\lambda}\sqrt{\frac{1-\beta_i}{1+\beta_i}}$$



Transverse Dynamics of a Beam in a Traveling-wave Structure

- Off-axis particles experience radial electric and magnetic forces
- The oppositely directed radial electric forces in the two halves of the gap will not cancelled out because:

✓ the fields vary in time as the particle crosses the gap.
✓ the particle velocity increases while passing the gap ➔ the particle does not spend equal times in each half of the gap.
✓ the fields acting on the particle depend on the radial particle displacement, which varies across the gap. This is very likely affected by space charge and finite emittance effects.



The rf field components of the synchronous space harmonic (principle wave) experienced by a particle of phase ϕ are

$$E_z = E_0 T I_0(Kr)\cos\phi$$
$$E_r = -\gamma E_0 T I_1(Kr)\sin\phi$$
$$B_\theta = -\frac{\gamma_s\beta_s}{c} E_0 T I_1(Kr)\sin\phi$$

where $K = 2\pi / \gamma_s\beta_s\lambda$ and E_0T is the axial electric field of the traveling wave

The radial Lorentz force component is

$$\frac{dp_r}{dt} = mc\frac{d(\gamma\beta r')}{dt} = q(E_r - \beta c B_\theta) = -q\gamma_s(1-\beta\beta_s)I_1(Kr)E_0T\sin\phi$$

The radial momentum impulse on the particle over a length L is

$$\Delta(\gamma\beta r') = \frac{1}{mc}\int_0^L -q\gamma_s(1-\beta\beta_s)E_0TI_1(Kr)\sin\phi\frac{dz}{\beta c}$$
$$= -q\frac{\gamma_s(1-\beta\beta_s)}{mc^2\beta}E_0TI_1(Kr)\sin\phi$$

If we assume that $\beta = \beta_s$, then

$$\Delta(\gamma\beta r') = -\frac{qE_0TLI_1(Kr)\sin\phi}{mc^2\gamma_s\beta_s}$$

For Kr <<1, we have $I_1(Kr) \approx Kr/2$, and

$$\Delta(\gamma\beta r') = -\frac{\pi qE_0TL\sin\phi}{mc^2\gamma_s^2\beta_s^2\lambda}r$$

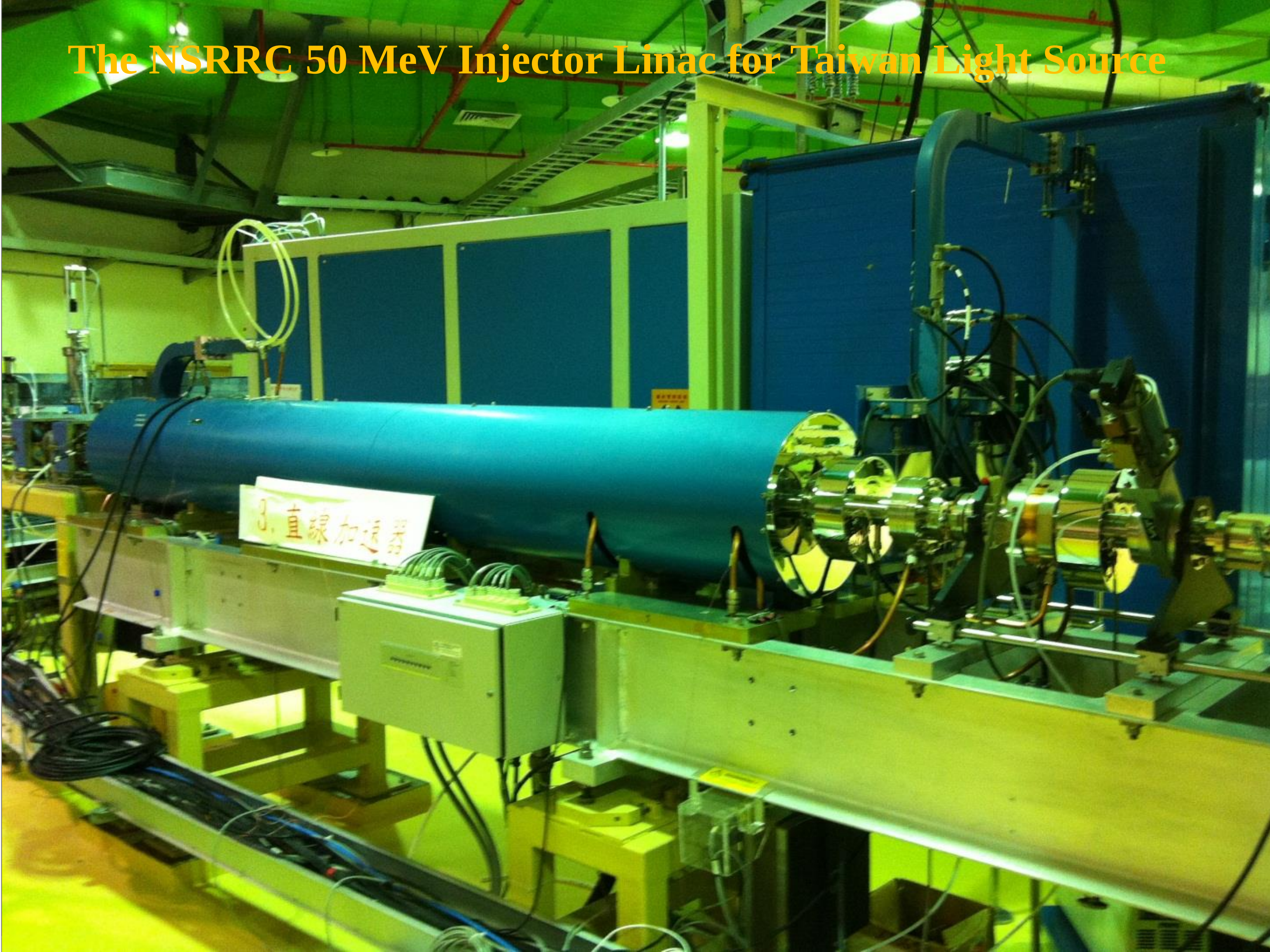
For longitudinal stability the sign of ϕ_s is –ve (consider phase slippage), the radial impulse is +ve and is a defocusing impulse!! Focusing lenses are required after an acceleration tank.

the quadrupole triplet for beam focusing after a linac structure

The 5.2m Constant Gradient Traveling-wave Linac Structure Manufactured by RI Research Instruments GmbH

It is an array of 156 cavity cells. The first cell is for microwave coupling and the last 6-cell are design to absorb microwave energy.

The NSRRC 50 MeV Injector Linac for Taiwan Light Source



The NSRRC 150 MeV Injector Linac for Taiwan Photon Source

(Courtesy of NSRRC Linac Group)

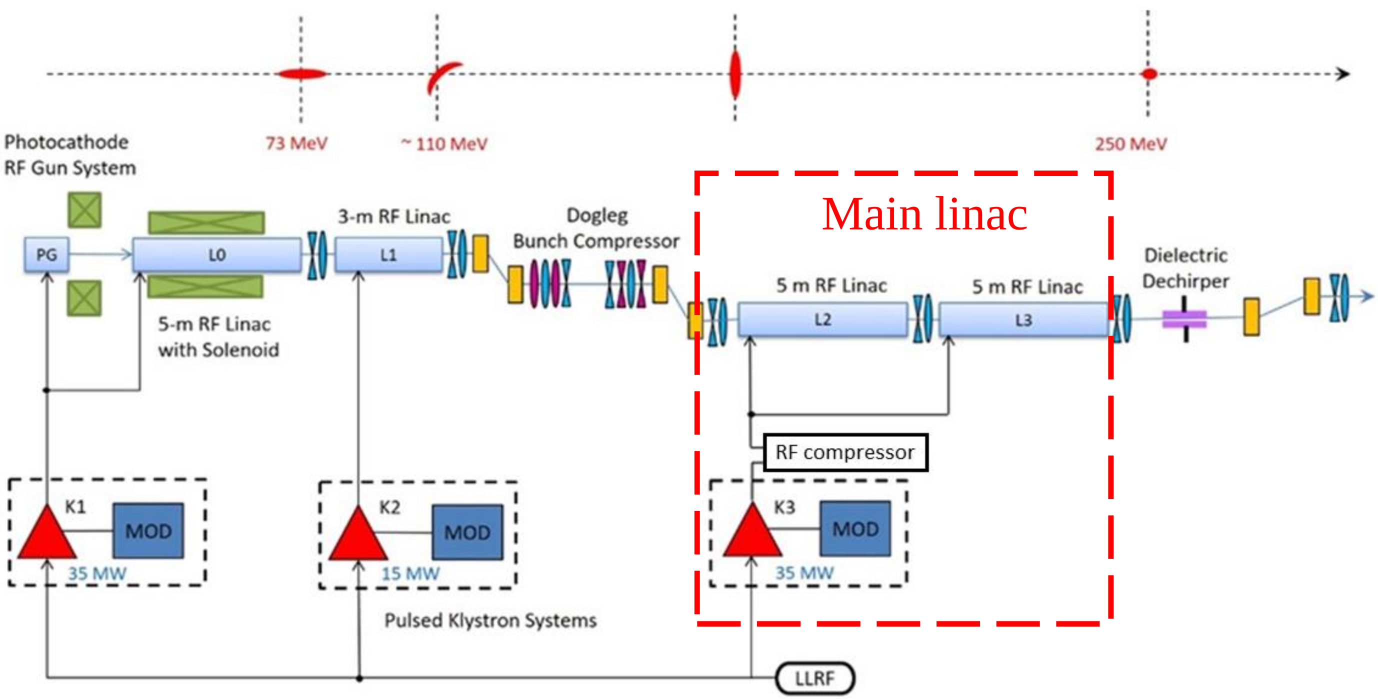
Applications of Modern RF Linacs

- Electron linacs
  - e^-e^+ colliders for high energy physics research
  - **High quality electron for free electron lasers (FELs)**
  - Pulse neutron sources for nuclear and material science research
  - **Pre-injectors for electron synchrotron**
  - **X-ray sources for radiotherapy, non-destructive testing**
  - **Food preservation and sterilization of medical devices**
- Proton linacs
  - Injectors of high-energy synchrotrons for HEP and proton therapy
  - High energy linacs for CW spallation neutron sources used for condensed matter and materials research, production of nuclear fuel, transmutation of nuclear wastes and accelerator-driven fission-reactor concepts
  - CW neutron sources for materials irradiation studies related to fusion reactors
  - **Low energy neutron sources for medical applications such as boron neutron-capture therapy (BNCT)**
- Heavy ion linacs
  - Linacs for nuclear physics reseach
  - Multi-GeV linacs for heavy-ion driven inertial confinement fusion
  - **Ion implantation for semiconductor fabrication**

Future Work - RF Power Compressor for Main Linac

To deliver enough RF power to two linacs :

1. Use two 35 MW klystrons to deliver rf power respectively.
2. Use one high power klystron(>70MW) and one 3dB divider.
3. Use one 35MW klystron and one rf compressor.



RF Pulse Compression Methods for Linear Accelerators

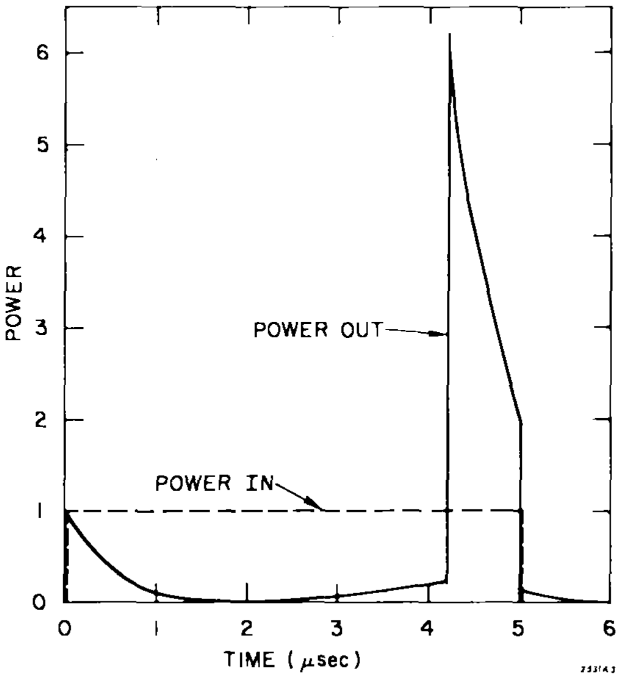
- SLED (SLAC energy doubler) : developed by SLAC in 1974
- SLEDII (Resonant Delay Line Pulse Compressor) : presented in 1988 then developed by SLAC in 1990
- BOC (Barrel Open Cavity): developed in1994 for the VLEPP project
- SLED 3 (Spherical Cavity and dual-mode circular polarizer): developed by SLAC in 2016
- Correction Cavity Chain : developed in 2016 for CLIC

SLED Cavity

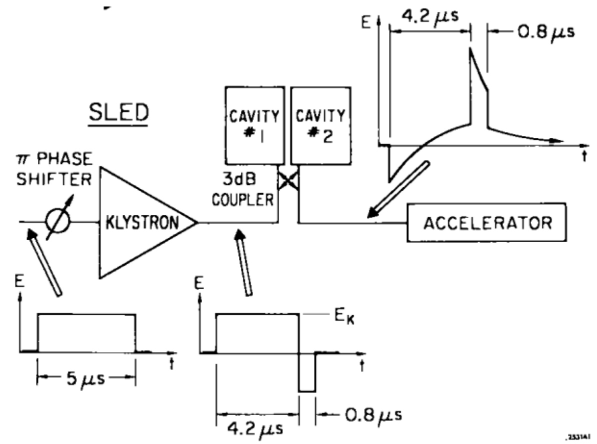
SLED = SLAC Energy Doubler

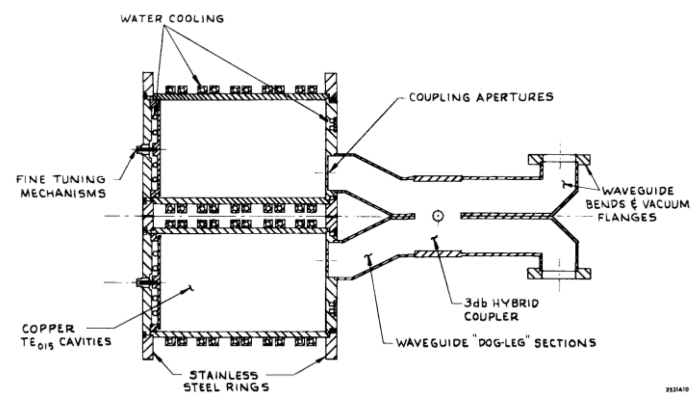
•A method of achieving RF pulse-compression through the use of high-Q resonant cavities.

•The cavities store klystron energy during a large fraction of each pulse and then discharge this energy rapidly into the accelerator during the remainder of the pulse.



SLED output power waveform





SACLA XFEL C-band SLED

- An rf mode converter is attached to convert the waveguide mode from rectangular TE_{10} to circular TE_{01}.
- The converter uses a four-hole coupling, which symmetrically excites TE_{0x} modes and reduces TE_{1x} mode coupling and lower rf field at coupling hole.

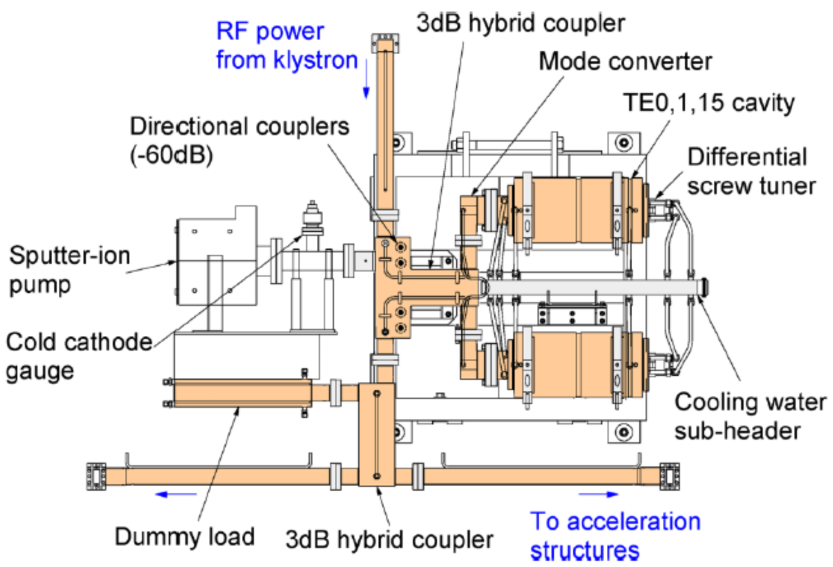
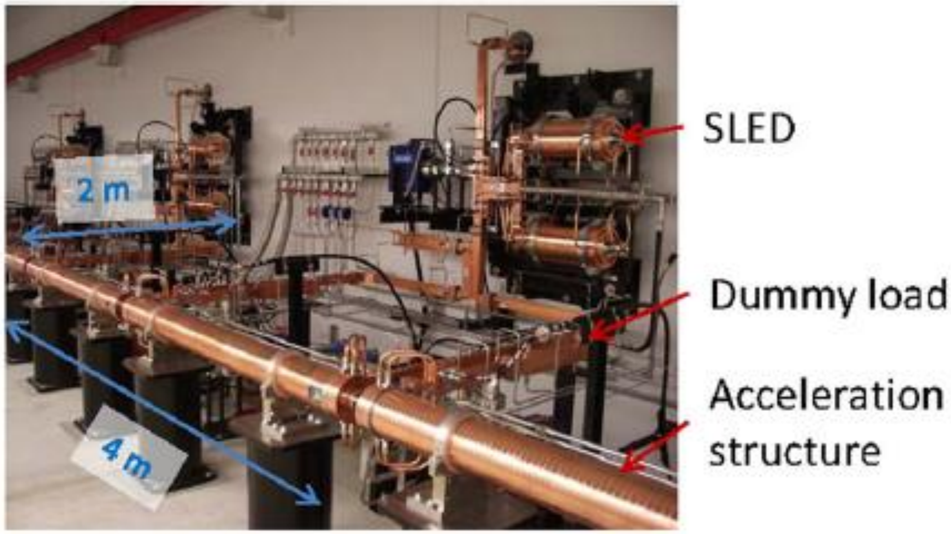


TABLE II. SLED parameters.

Resonant frequency	5712 ± 0.02 MHz
Resonant mode	TE0,1,15 (cylindrical)
Unloaded Q-factor	185 000
Coupling constant β	9.0
VSWR	< 1.1
Power gain (average over 300 ns)	4

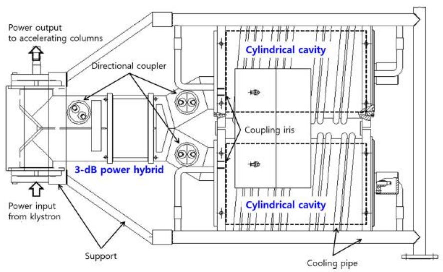


PAL-XFEL S-band SLED

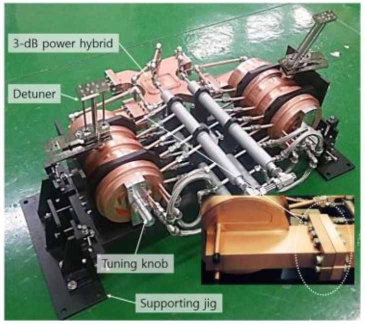
- The peak output power of the PLS-II klystron increased up to 60 MW ,the unacceptably high radiation dose rates due to the RF breakdown.
- The S-band RF station of the PAL-XFEL Linac requires a klystron RF output peak power of 80 MW, a pulse length of 4 μs and a repetition rate of 60 Hz.

PAL-XFEL Linac SLED Specifications.

Description	Value
Operation frequency	2856 MHz
Operation bandwidth	± 5 MHz
Operation temperature (cooling water temperature)	30 ± 1 °C
Coupling coefficient	5 ± 0.3
Cavity quality factor	> 100,000
Cavity resonance frequency error (at 2856 MHz)	< 1 kHz
SLED energy gain	> 1.6
Operation mode	TE_{015} cylindrical cavity mode
Max. klystron peak power	80 MW
Pulse length	4 μs
Repetition rate	60 Hz
Detune (remote control)	Enable



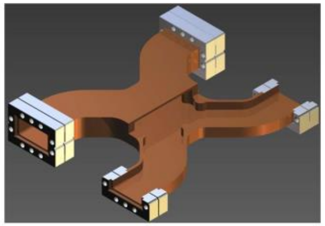
The original SLED used in PLS-II.

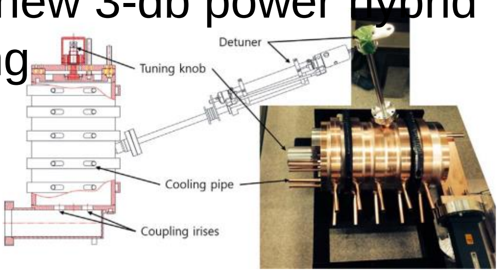


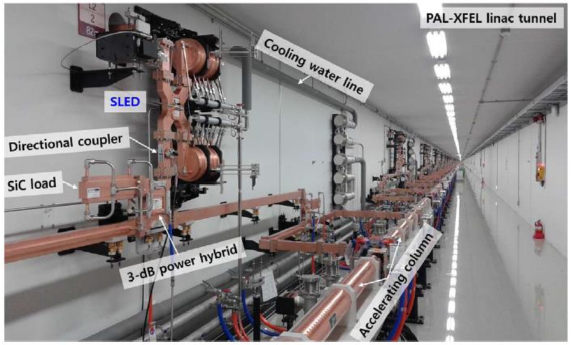
New SLED

SLED cavity with new 3-db power hybrid

ling







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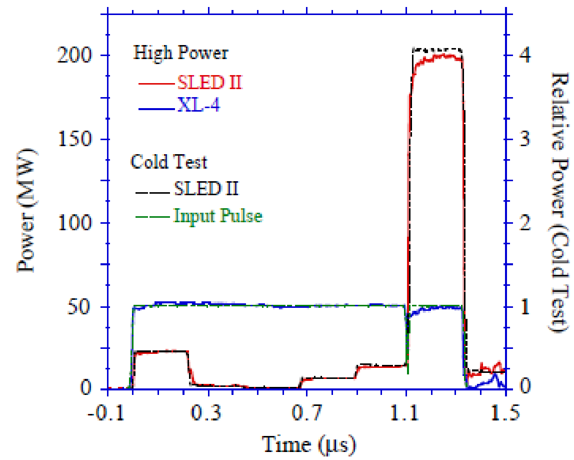
SLEDII

- The improvement is the replacement of the pair of resonant cavities by a pair of long resonant delay lines.
- The emitted field changes only at discrete time intervals given by the round-trip delay time, a flat output pulse of -that duration is obtainable.



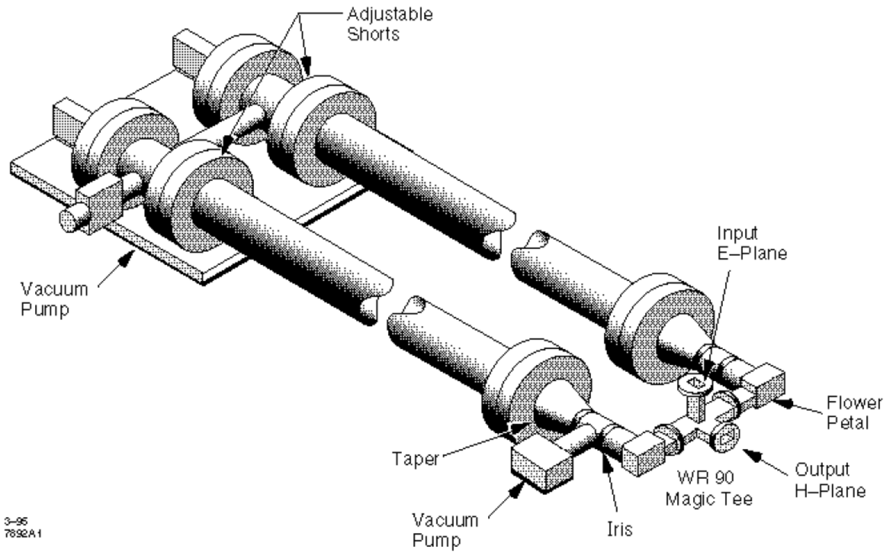
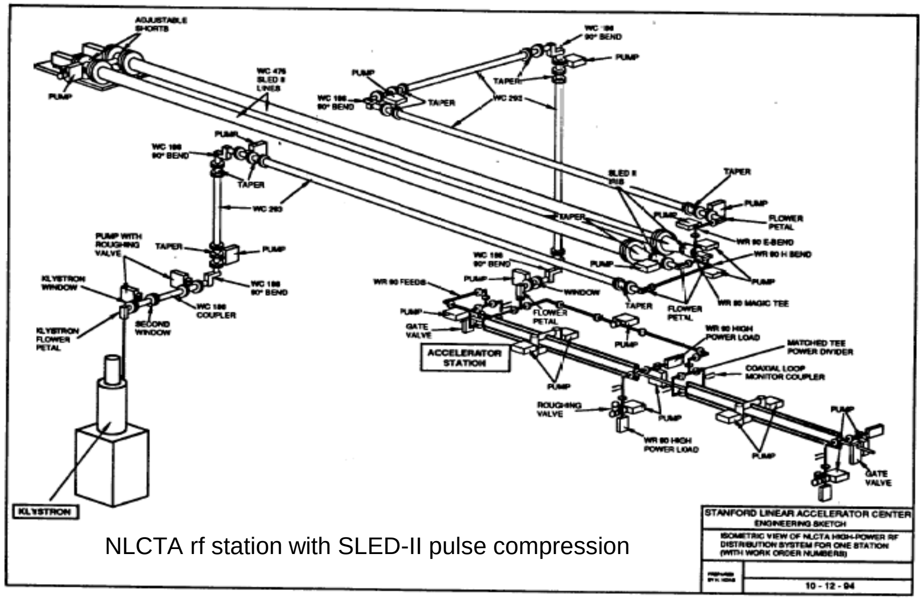


Figure 1. SLED-II Layout. It has two 12.065 cm diameter waveguides, 35.35 m in length (223 nS round-trip time.)



NLCTA rf station with SLED-II pulse compression

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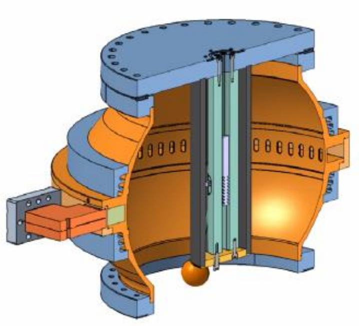
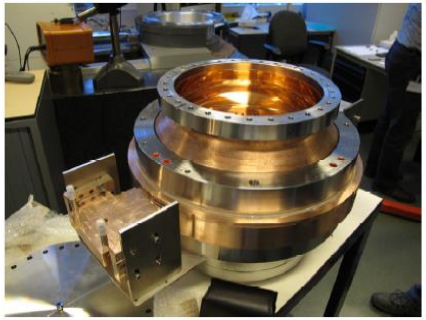
Barrel Open Cavity (BOC)

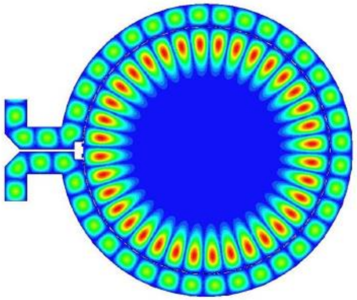
- The BOC makes use of a "whispering gallery" mode which has an intrinsically high quality factor and operates in a resonant rotating wave regime
- A single cavity is sufficient to define the pulse compressor, without the need for two cavities and a 3-dB hybrid.

Table 1: Main Parameters of BOC

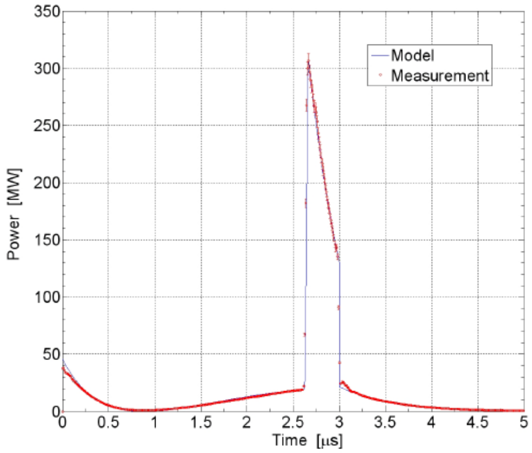
Pulse compressor	**Design parameter**
Type	Barrel Open cavity
Frequency	5.712 GHz
Resonant mode	$TM_{18,1,1}$
Diameter	492 mm
Number of coupling slots	70
Q	216000
Coupling factor (β)	10
Max. input power	50 MW
RF input pulse length	3 μs
RF compressed pulse length	330 ns
Energy multiplication factor (M)	2.13
Repetition rate	100 Hz







$TM_{18,1,1}$ mode



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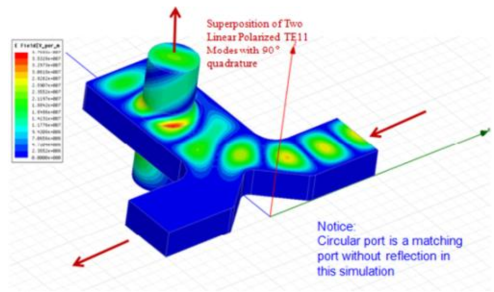
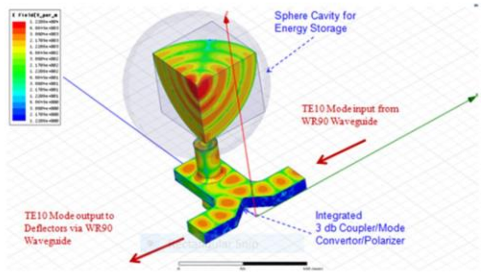
SLED 3 - Super Compact X-band pulse compression system

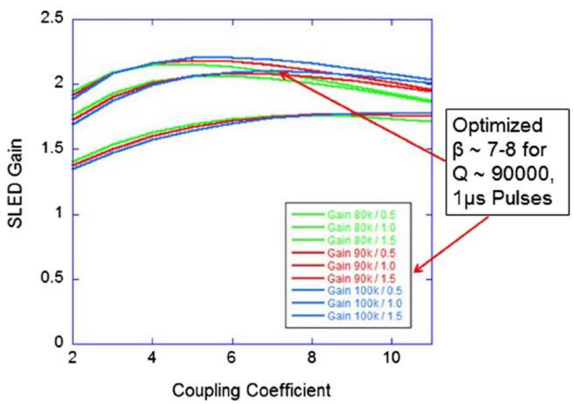
- The traditional 3 dB coupler will be replaced by a more compact dual-mode circular polarizer.
- Two cylindrical energy storage cavities will be replace by a high-Q spherical cavity with two polarized modes.

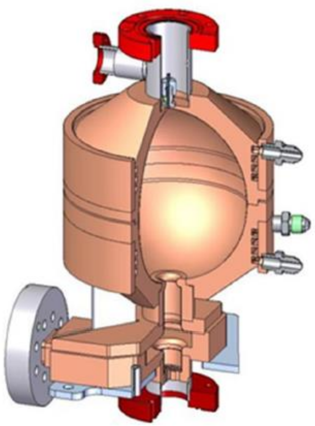




Dual-mode circular polarizer

Optimized design	
peak gain	>2
Q0	~90000
Pulse width	1us
β	7~8





SLED gain as a function of the coupling coefficient for
various pulse widths and storage cavity Q0 values.

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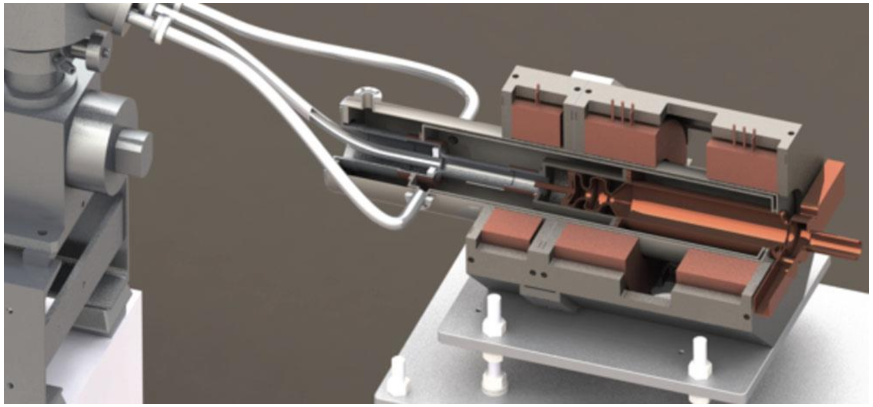
Future Work - Superconducting RF Linac

- π-mode multi-cell standing-wave structures
- High average power, high-repetition-rate, and high gain operation
- Energy recovery is possible
- Liquid He cryogenic system required
- 500, 1300 and 1500 MHz multi-cell structures have been developed (structures at high frequencies are rare)

Future Work –
Ultrahigh field cryogenic rf photocathode sources

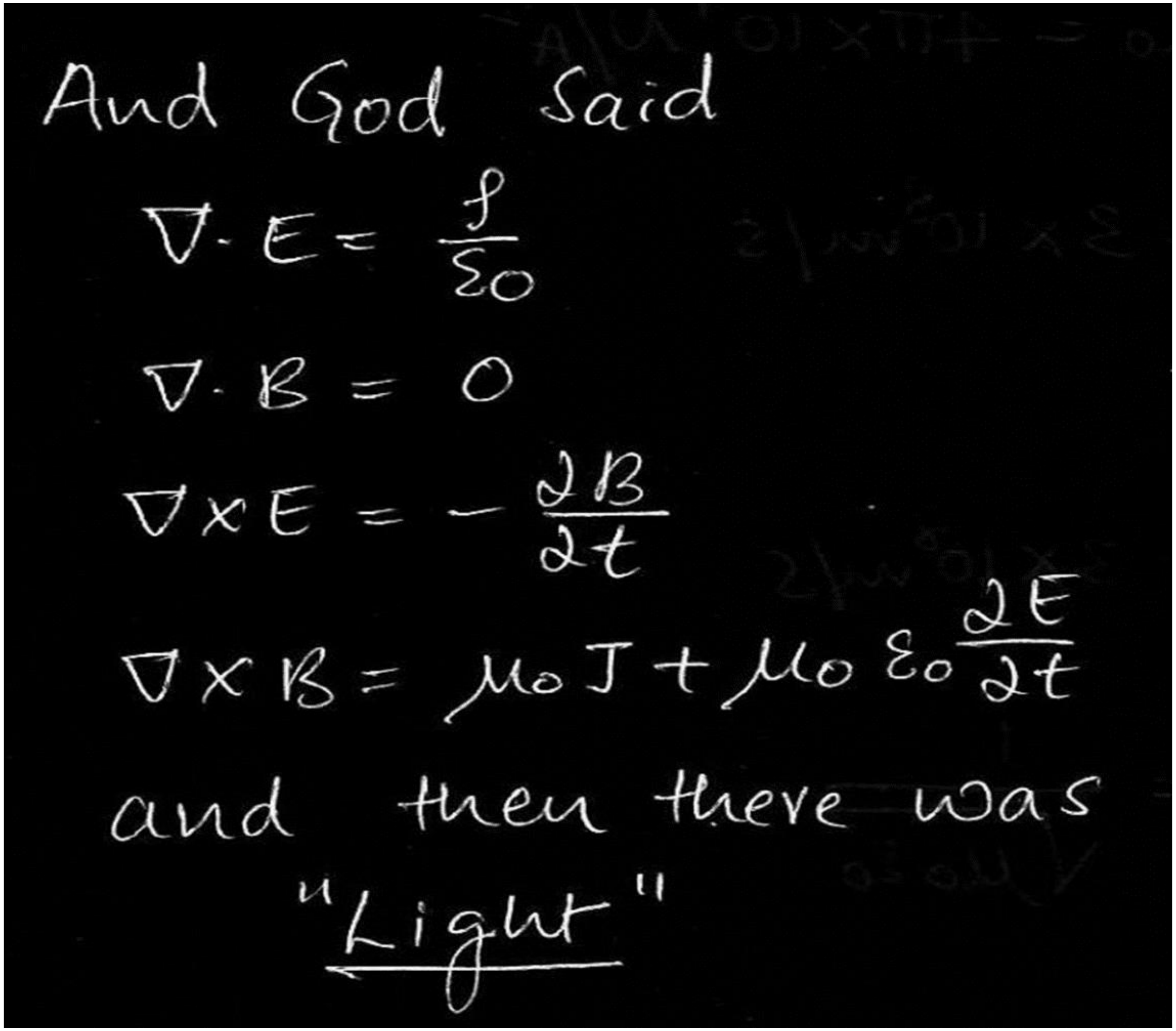


Cryogenic, very high field S-band photoinjector, with 1.45 cell Cu gun structure (center) externally coupled to waveguide through a mode-launcher scheme (far right).

Parameters of rf gun and feed system

Internal quality factor Q_0 (300 °K)	13 483
Internal quality factor Q_0 (27 °K)	62 425
Input power	50 MW
Normalized shunt impedance R/Q	136 Ω
Peak field at end of rf fill	250 MV/m
Fill time ($\beta_c = 9$)	0.9 μ sec
Energy dissipated/pulse ($\tau = 0.9$ μs)	3.04 (365 W at 120 Hz)

Thank You !


And God Said
$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$
$\nabla \cdot B = 0$
$\nabla \times E = -\frac{\partial B}{\partial t}$
$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$
and then there was
"Light"