Electron Accelerators –

Challenges & Opportunities

Vaishali Naik
Variable Energy Cyclotron Centre (VECC), Kolkata India

Electron Accelerators

- 30 thousand particle accelerators around the world

  More than half of these are electron accelerators
  - ➢ 44% are radiation therapy machines
  - ➢ 14% used for industrial processing & research
  - ➢ 41% are ion accelerators for semiconductor industry
  - ➢ 1% are > 1 GeV machines used for particle physics

- 1 % push the limits of technology ⇒ **Challenges**

rest are spinoffs based on technology developed over the years

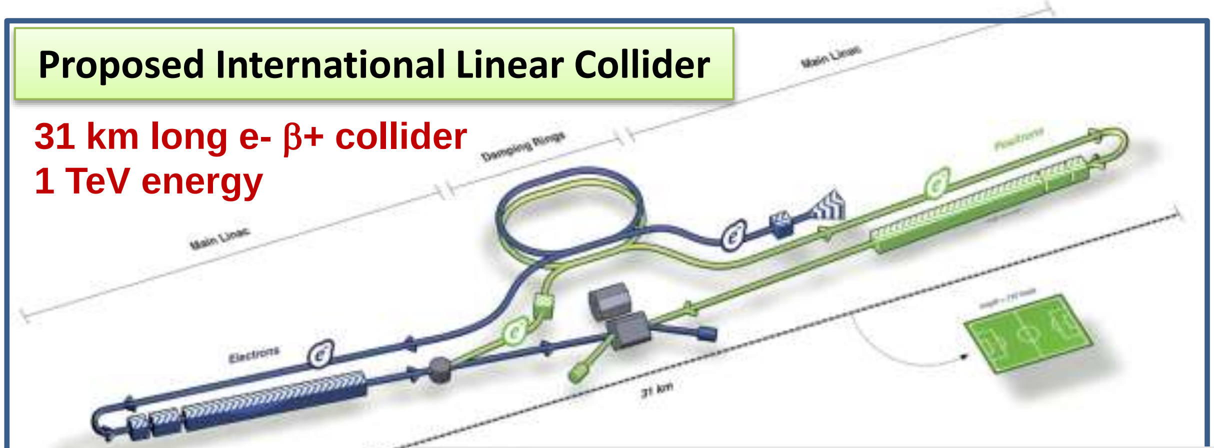
- **Opportunities** both in meeting the challenges (R&D) & in expanding the spinoffs (applications)

Large Electron Accelerators for particle physics

Bridging the technology frontier to break the energy frontier

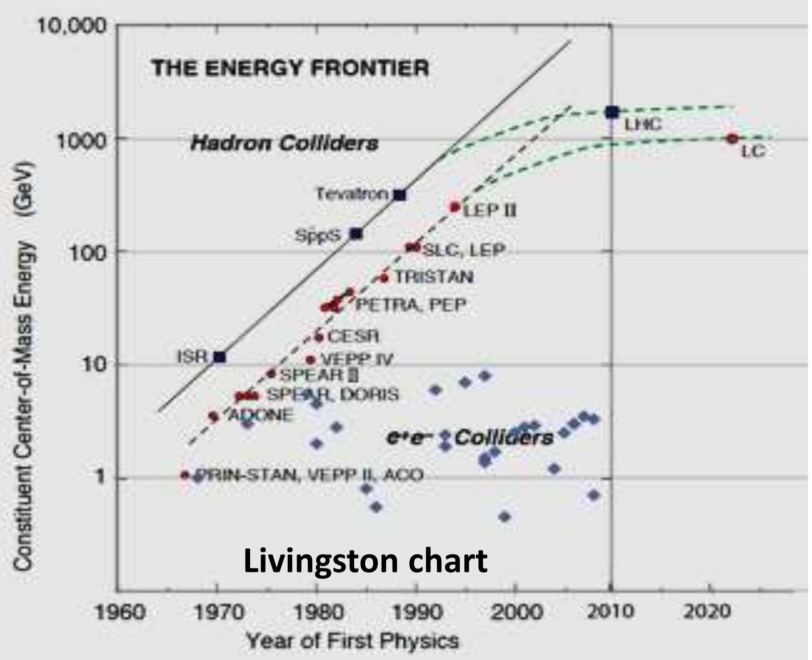
Proposed International Linear Collider

31 km long e- β+ collider
1 TeV energy



Possible site: Japan

Collider	Location	Shape	Length	Energy	Particles
SLAC	Stanford, CA	Linear	3.2 km	100 GeV	electron/positron
Tevatron	Fermilab, IL	Circular	6.3 km	1,960 GeV	proton/anti-proton
LEP	CERN, Geneva	Circular	26.6 km	209 GeV	electron/positron
LHC	CERN, Geneva	Circular	26.6 km	14,000 GeV	proton/proton



Livingston chart

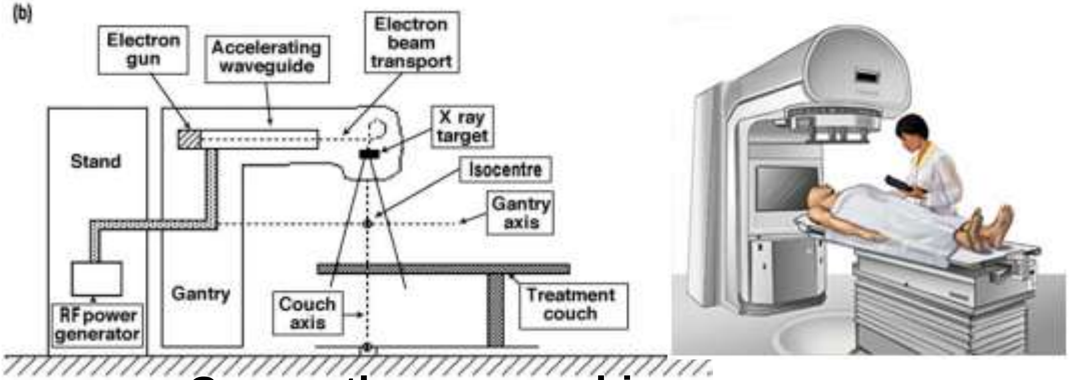
Source: Jordan Nash, Current and Future Developments in Accelerator Facilities, 2010 IOP Meeting

Large Electron Accelerators for multidisciplinary science

Diamond SR Light source, UK

Spring8 XFEL SCALA at RIKEN, Japan

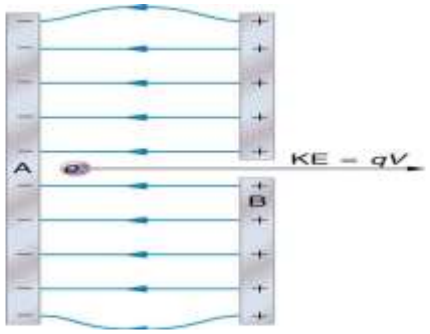
Medical and Industrial Linacs

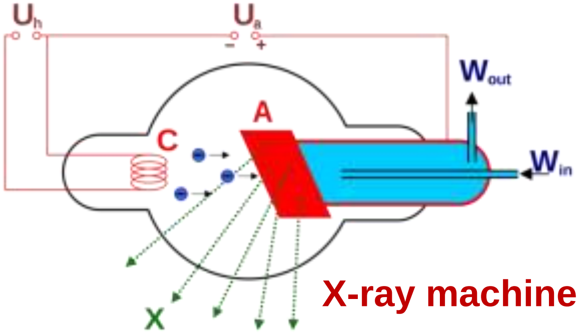


Cancer therapy machines

Irradiation of cables

Simplest acceleration is by applying a dc potential



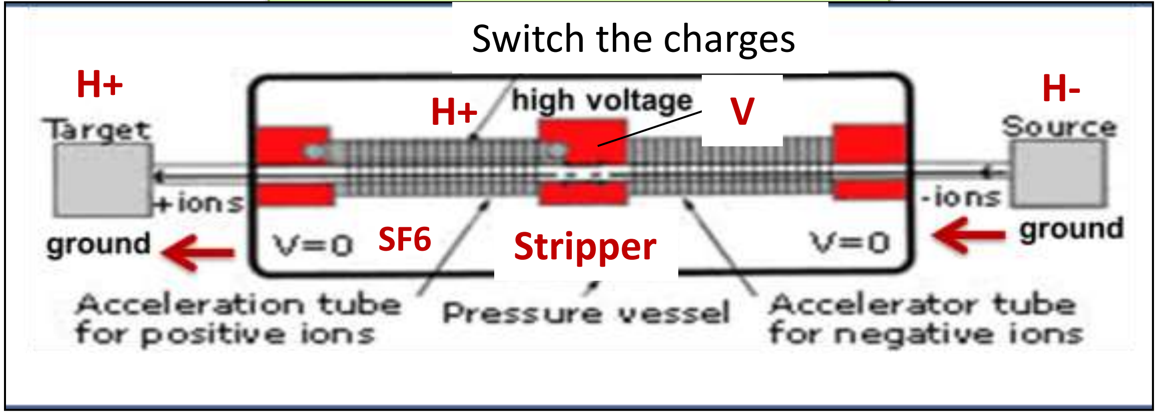


V

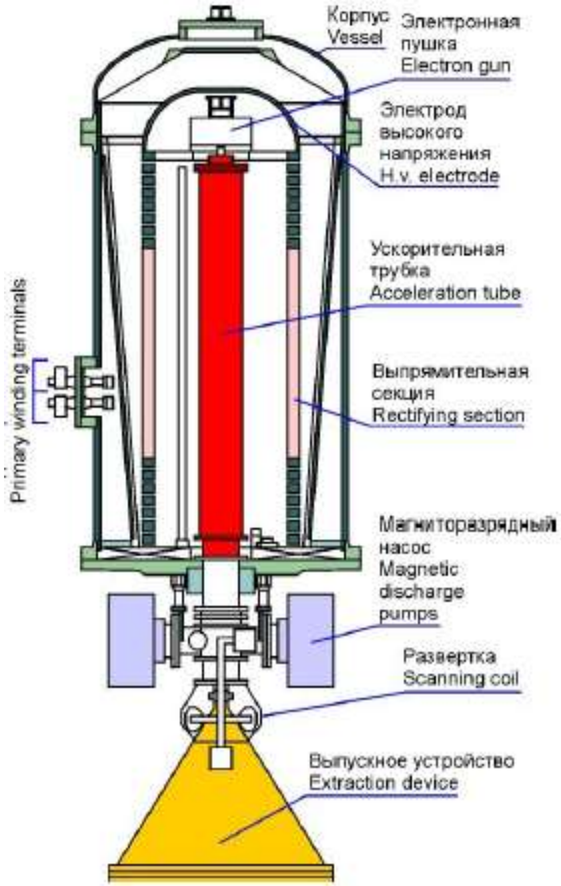
Air
breakdown
at 3 MV/m

Tandem electrostatic accelerator

Switch the charges



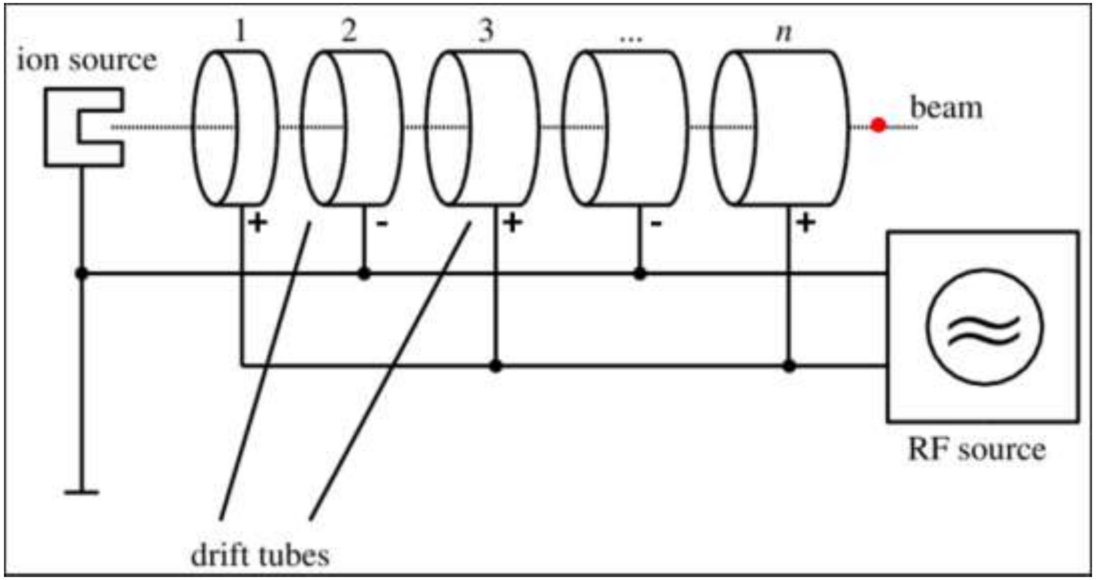
Energy = 2V MeV



2.5 MV ELV accelerator
by BINP Russia

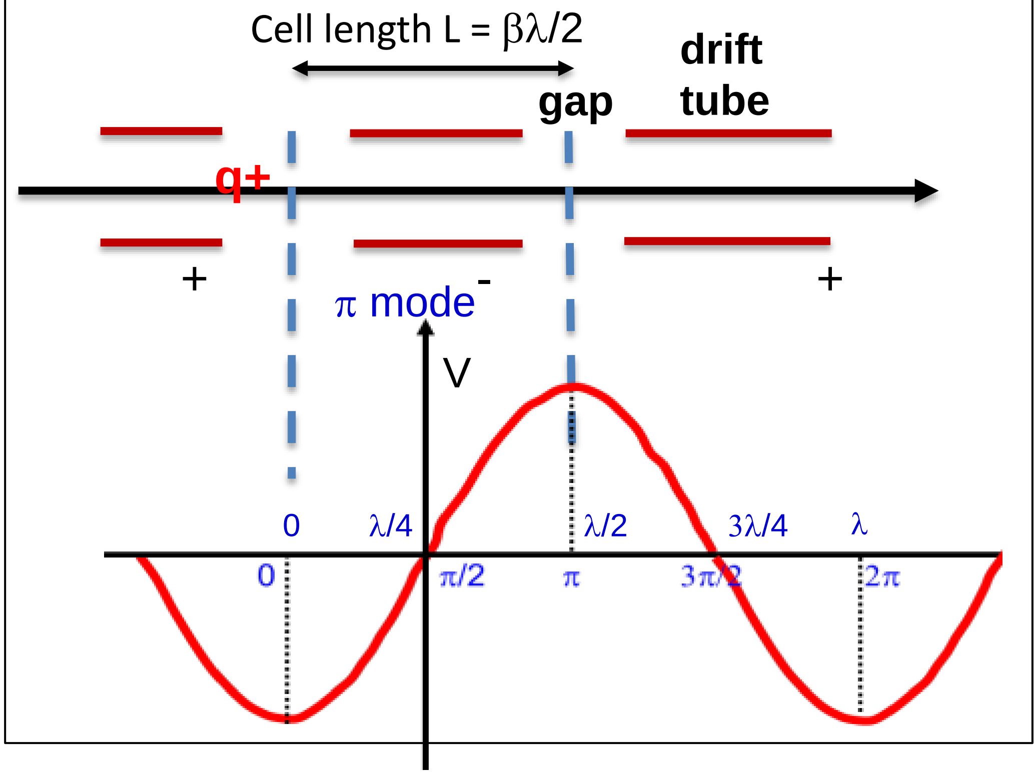
RF linear accelerator

Switch the voltage and continuously accelerate the charged particle



RF linac : choice of frequency

Acceleration in each gap ; drift tube longer as particle gains energy so that it arrives in next gap in exact time to the see the accelerating voltage ; constant gap to keep amount of acceleration same



Geometry depends on velocity of the incoming particle

- e.g. β=v/c=0.03 ; say L=15 cm (from practical considerations) ;

then $\beta\lambda/2$=15 cm,

gives λ= 15x2/0.03 = 1000 cm (10 m) ;

and freq. f = c/λ= $3\text{x}10^{10}$ /1000 = 30 MHz

- for β=0.3 ; L becomes 1.5m for 30 MHz ; linac will be too long with very low acceleration rate ; solution ⇒ increase the freq and accelerate over much smaller length

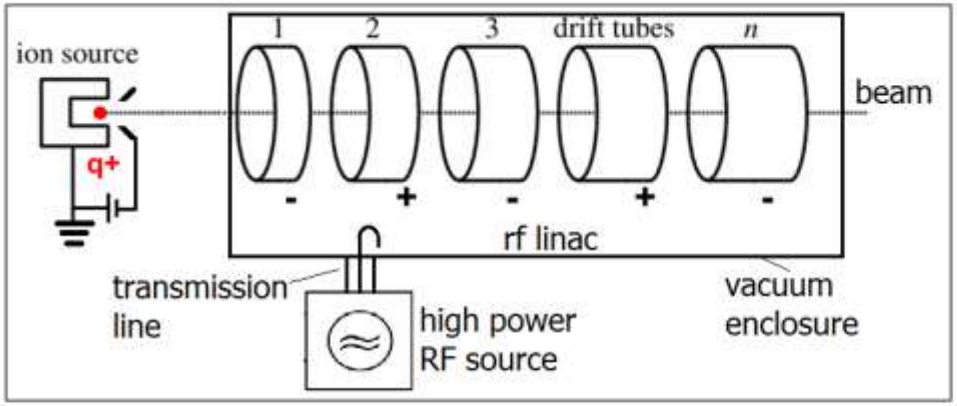
- say for $\beta\approx1$, if we again choose L=15 cm

now $\beta\lambda/2$=15 cm gives $\lambda\approx$ 15x2/1 = 30 cm

and freq. f = $3\text{x}10^{10}$ /30 = 1 GHz ;

i.e. for relativistic particles, freq. of rf source will be in GHz range

RF linac : figures of merit



$$Q = \frac{stored\ energy}{energy\ loss\ per\ cycle} = \frac{\omega U}{P}$$

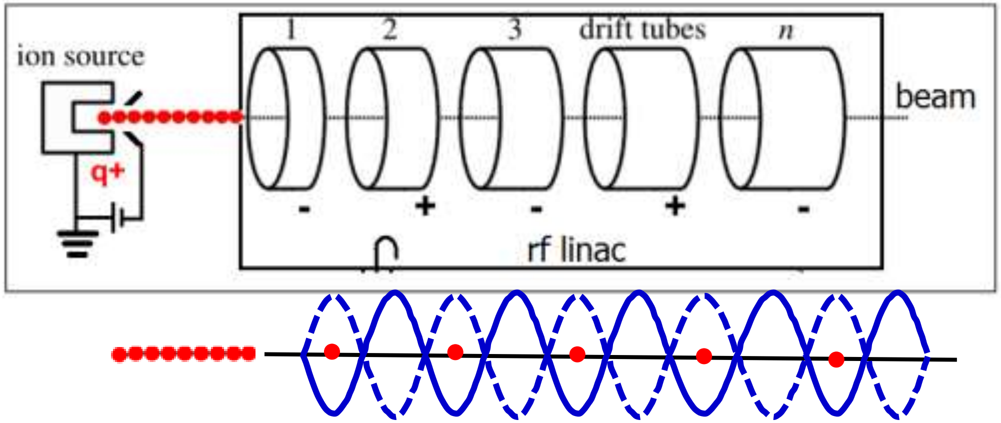
$$r_s = \frac{V_0}{2P}$$ *; shunt impedance*

where, V_0 *=axial accelerating voltage*

Shunt impedance r_s *is the measure of effectiveness of the structure to produce desired accelerating voltage* V_0 *with minimum dissipated power* P

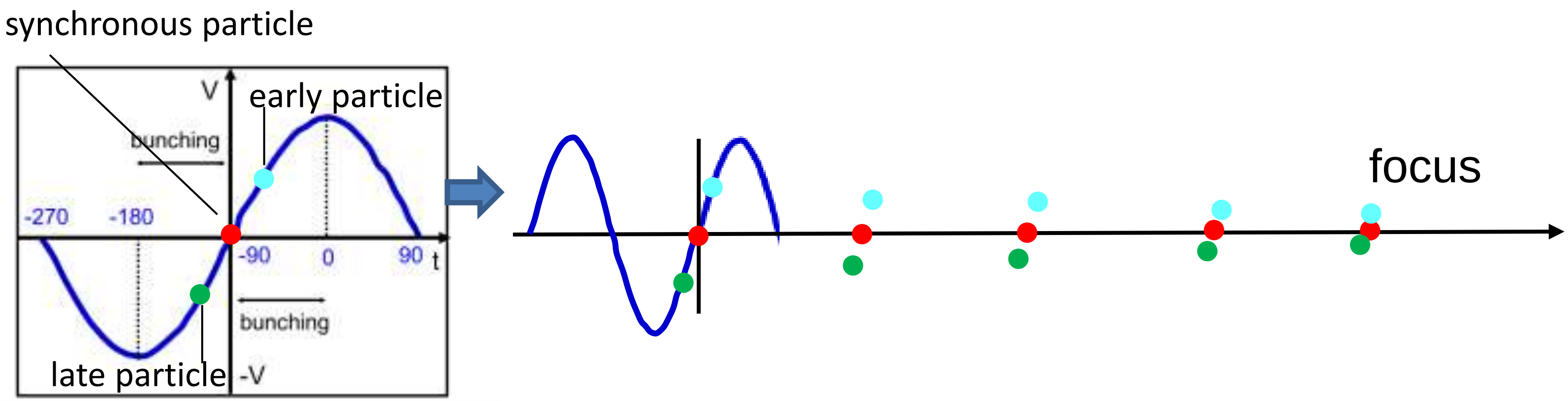
- Linac is basically a set of specially designed high Q resonant structure excited by electromagnetic energy fed from a matched rf power source
- EM energy is transported to the Linac via conventional transmission line or waveguide
- There is a resonant build-up of fields in the high Q structure of the linac. This transforms low field levels of the input waveguide into high fields within the structure. The result is a large ratio of stored input energy to the ohmic energy dissipated per cycle
- Internal structure designed so as to concentrate electric field along the trajectory of the beam & electric field between the drift tubes is much higher than incoming EM field in the waveguide

Bunching of beam particles

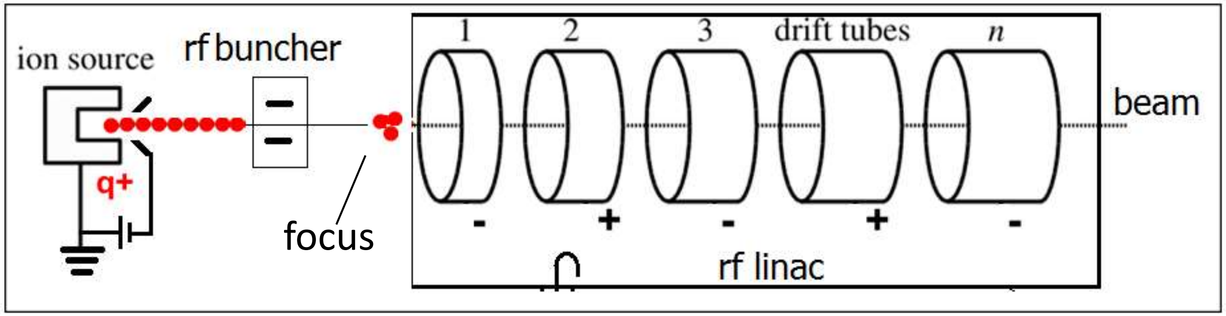


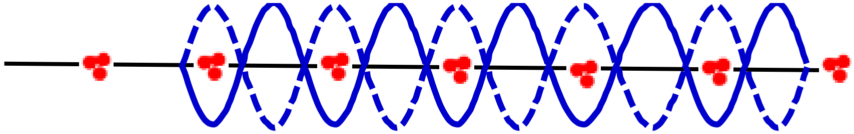
- Continuous stream of particles arrive from the dc ion-source
- But only the particle seeing the right voltage in the gap is accelerated because only that one keeps time synchronizations within each gap ; this particle is called the **Synchronous** particle
- To accelerate other particles, they have to be brought closer to the Synchronous particle . This is done by accelerating slower particles and slowing down the faster ones. This is called **Bunching**.

Bunching of beam particles



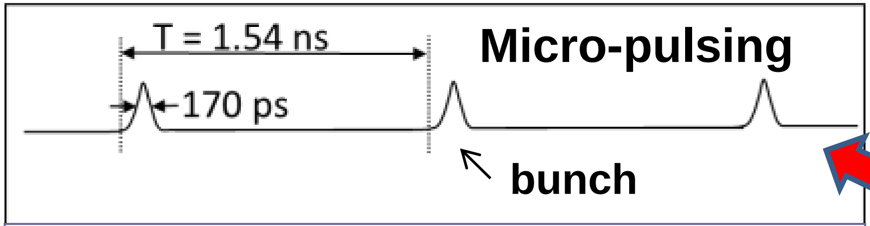
rf voltage in the buncher





Micro-pulsing, CW and pulsed beam

The rf source feeding the Linac may be pulsed or operated continuously



Bunch width:

f = 650 MHz

∴ T = 1.54 ns

Now, 1.54 ns ≡ 360 degree

∴ $170 \text{ ps} = 360/1.54 * 170 * 10^{-3}$

≈ 40 degree i.e ±20 degree

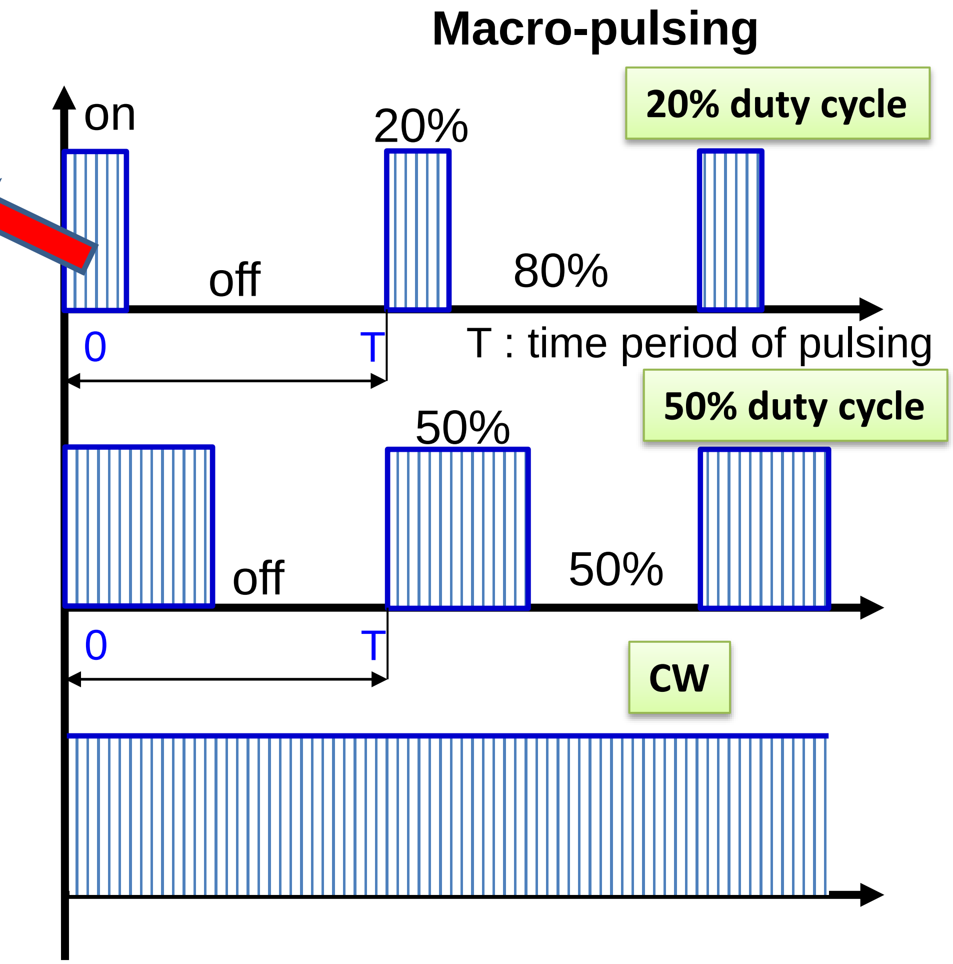
Charge per bunch:

T = 1.54 ns

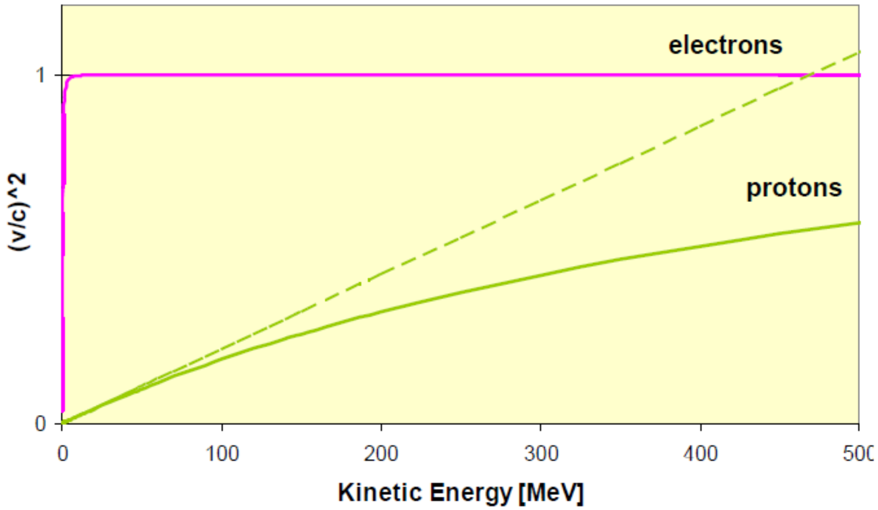
Now, say beam current = 10 mA

i.e 10 mC per sec ∴ in 1.54 ns ~ 15 pC

i.e. bunch charge = 15 pC/pulse



Relativistic relations



When particle's velocity approaches c, its mass increases with the velocity

$$m = \frac{m_0}{\sqrt{1-({}^{v}/_{c})^2}} = \frac{m_0}{\sqrt{1-(\beta)^2}} = m_0\gamma$$

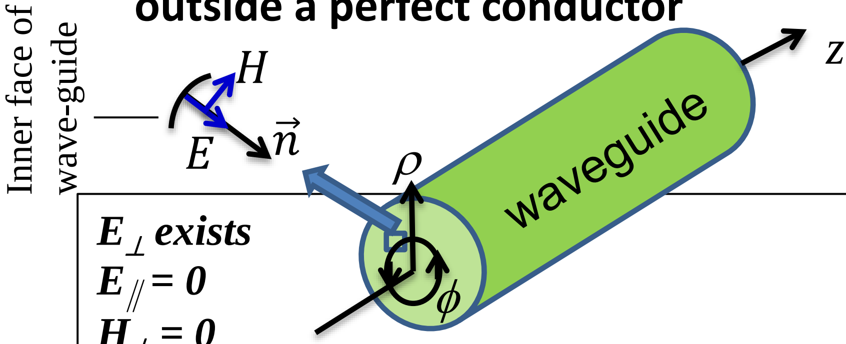
$$E = mc^2 = m_0\gamma c^2 = m_0c^2 + KE$$

$$KE = m_0c^2(\gamma - 1)$$

- **Electron becomes relativistic very fast**
- **Even at 1 MeV, $\boldsymbol{\beta = {}^{v}/_{c} \approx 0.94}$**
- **As it is accelerated further, its velocity *v* almost remains constant, slowly approaching ~ c, but its relativistic mass increases**
- **Thus for electrons the drift tubes can be identical i.e the linac cell length L can be kept constant**
- **Relativistic electron has ~ same velocity as the electromagnetic wave. Hence, the EM wave can deliver continuous energy to the electron if it has a electric field component along the direction of electron motion.**

EM modes in circular wave-guide

From Maxwell's eqn consider E & M field outside a perfect conductor



$E_\perp$ exists

$E_\parallel = 0$

$H_\perp = 0$

$H_\parallel$ exists

- ***Above boundary conditions are satisfied by two sets of modes : Transverse magnetic TM_{mnp} (magnetic field $\perp$ to direction of propagation, E_z exists) & transverse electric TE_{mnp} modes (electric field $\perp$ to direction of propagation, H_z exists)***
- ***TM_{mnp} : integer indices m,n,p indicate number of changes E_z undergoes in z, ρ & ϕ direction***
- ***TM_{010} : E_z exists on axis & this mode has the lowest frequency $\therefore$ used for acceleration***
- ***TM_{110} : Higher order modes***

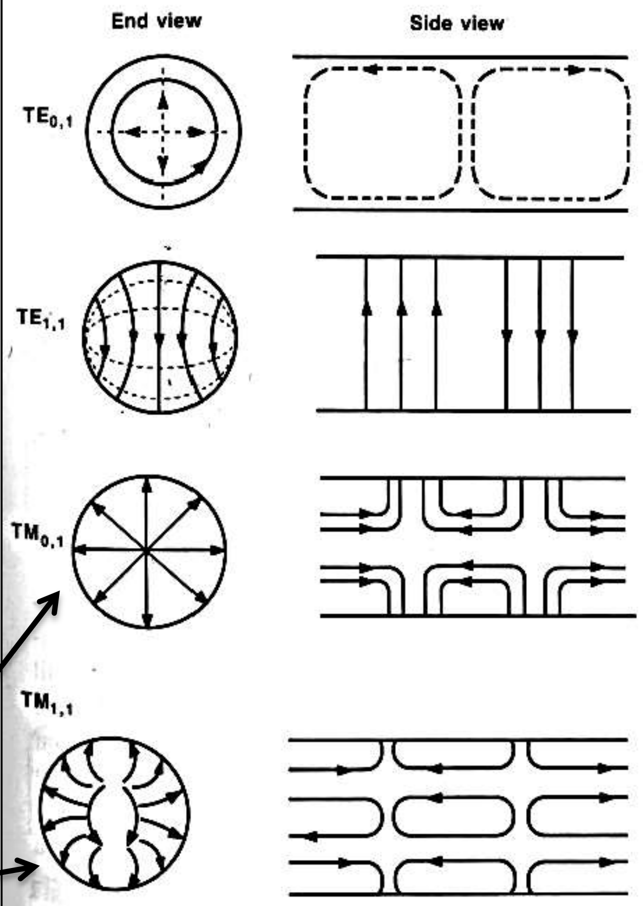
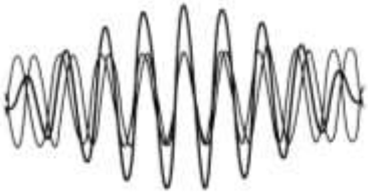


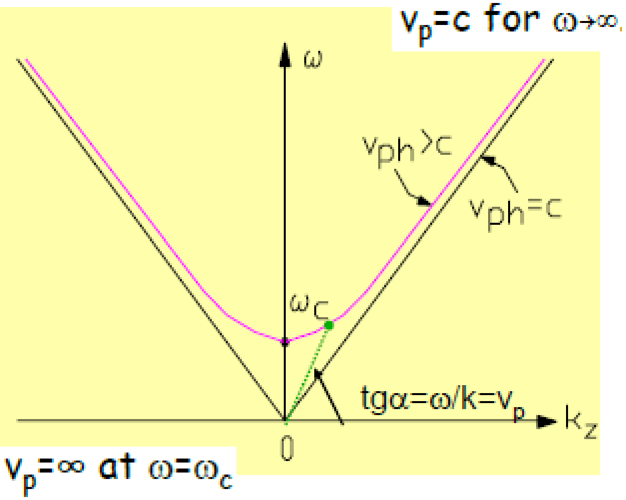
Fig. 4-22 Typical TE and TM modes for circular waveguide.

Propagation of EM wave in circular wave-guide :

Travelling wave structure

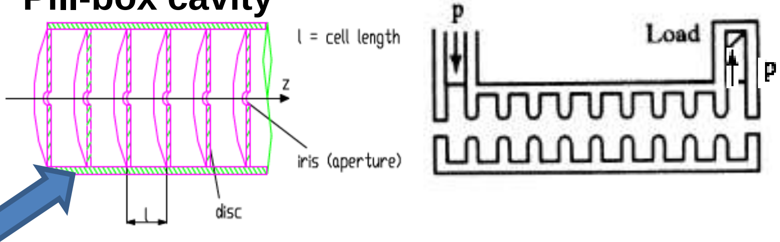


- *Ideal EM waves are monochromatic, real waves are not*
- *Real waves are a superposition of waves of different freq and wave no. The combined wave group propagates in the wave guide with group velocity v_g while individual waves move with phase velocity v_p. Each harmonic wave moves with different v_p ; only the wave with v_p=c can be used for acceleration of the β~1 particle*
- *Only the waves with freq > cut-off freq w_c will propagate in the waveguide*
- *But the dispersion relation shows that for waves with freq>w_c ; v_p is >c*
- *Periodic discs added to the wave-guide to slow down v_p to = c (disk loaded cavities)*



$$v_p = \frac{c}{\sqrt{1-(\,\omega_c/\omega\,)}}$$

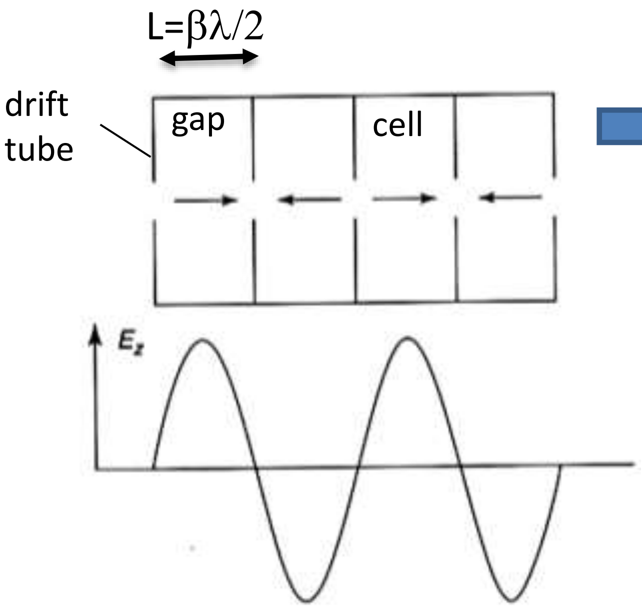
Pill-box cavity

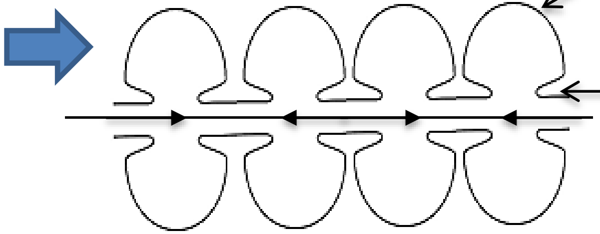


Travelling Wave structure ; used for electrons with β~1 and for accelerating short beam pulses

Standing wave structure

Standing waves generated when forward and reflected travelling waves in the cell combine

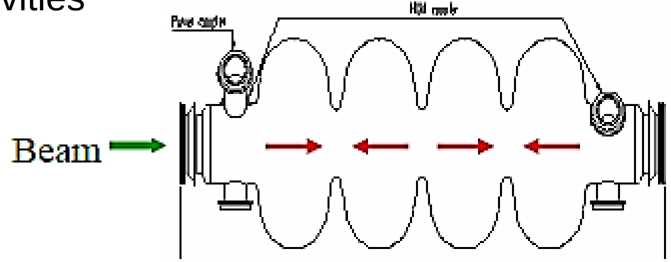




Chain of coupled cavities

Circular shape minimizes surface area for a given volume, thereby reducing energy loss

Nose cone added to concentrate axial electric field



SC cavities have larger aperture, no nose cone and elliptical shape

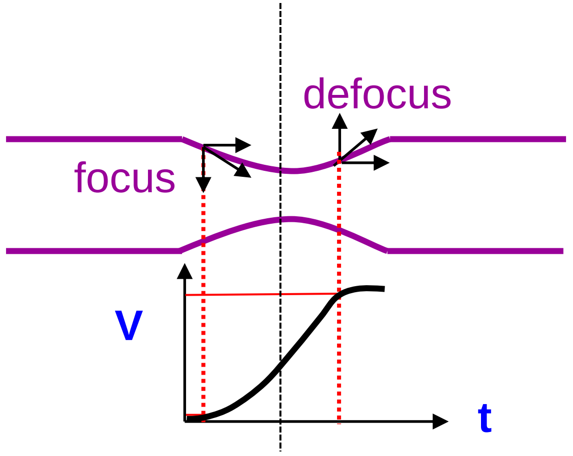
Accelerating voltage → $V_{acc} = \int_0^L E_z dZ$

Peak accelerating field → $= E_0 T L$

Average accelerating field → $E_{acc} = V_{acc}/L$

T : transit time factor → $T = \dfrac{energy\ gained\ in\ time\ varying\ electric\ field\ in\ the\ gap}{energy\ gained\ in\ dc\ field\ of\ voltage\ V_{acc}}$

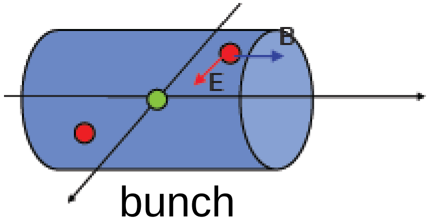
Transverse defocusing disappears as v~c



- Off-axis particles experience radial rf electric & mag. fields as they pass the accelerating gap
- although these forces are in opposite directions in the two halves of the gap, because of higher net voltage in the second half, there is net transverse rf defocusing (general low velocity case)
- For particles with v~c, Lorentz transformations and calculation of radial momentum impulse per period gives : $\Delta p_r \propto \frac{1}{\gamma^2}$
- $\therefore$ for relativistic particles $(\gamma \gg 1)$ transverse rf defocusing goes to 0

Consequence : no focusing elements needed inside cryomodules of electron SC linacs

Space charge repulsion disappears as v~c



bunch

- Particles in the bunch experience a radial repulsive Coulomb force
- But there is also an azimuthal magnetic force due to motion of the charged particles in the beam
- The net Lorentz force is :

$$F = e(E_r - vB_\varphi) = eE_r(1 - \frac{v^2}{c^2}) = eE_r(1 - \beta^2) = \frac{eE_r}{\gamma^2}$$

- $\therefore$ for relativistic particles ($\gamma \gg 1$) the net force goes to 0 i.e. repulsive electric force is cancelled by attractive magnetic force

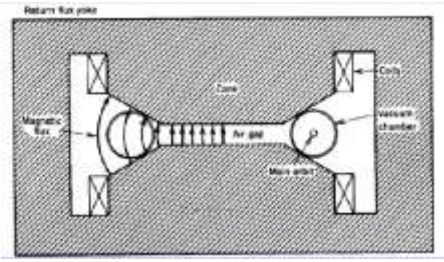
Note charge per bunch and emittance from electron-gun decides the final beam quality. Light sources need ultra-short high brightness beams that can only be delivered by photo cathode electron guns.

Next : acceleration of electrons in Circular rf accelerators

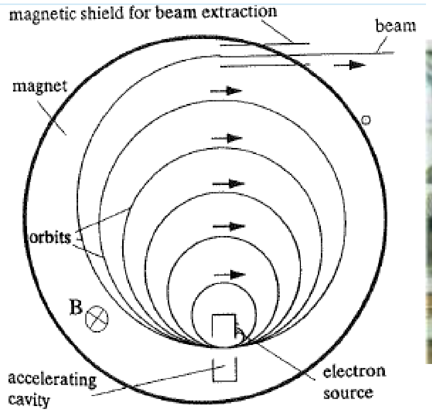
Circular electron accelerators

Betatron

Microtron



A 45 MeV Betatron for particle therapy

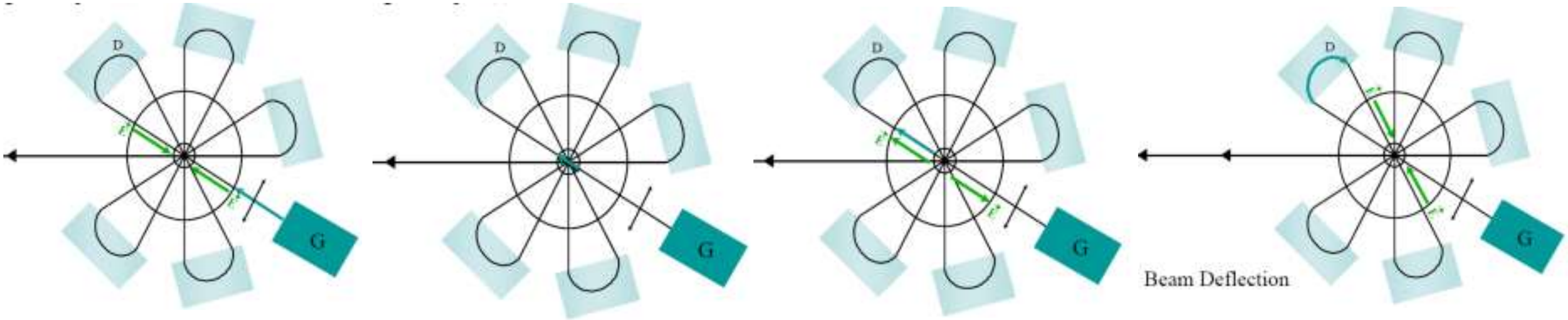


20 MeV Microtron at RRCAT

- Magnetic field produced by pulsed coils
- Time varying magnetic field creates an induced emf potential in the vacuum chamber that accelerates the electron
- Beam energy up to ~ 50 MeV
- Limitation is that the magnet need to be very homogeneous – difficult for large magnets

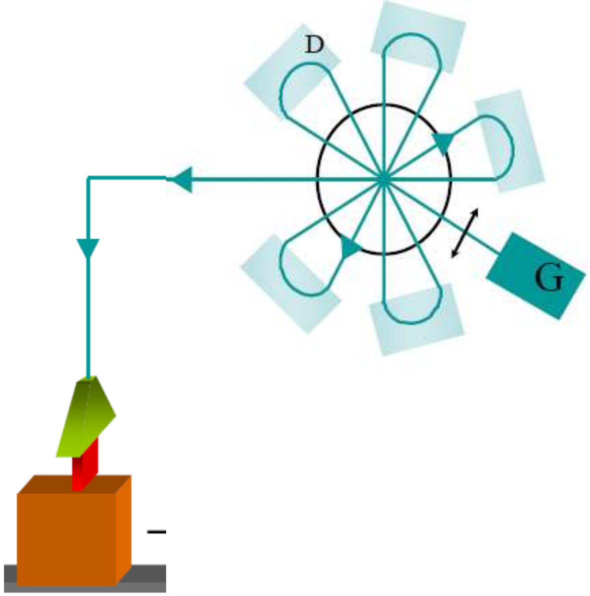
- A Cyclotron for electrons
- Fixed rf frequency and well separated orbits
- Beam energy up to ~ 30 MeV
- Limitation is that magnet weight $\propto$ $beam\ energy^3$

Rhodotron



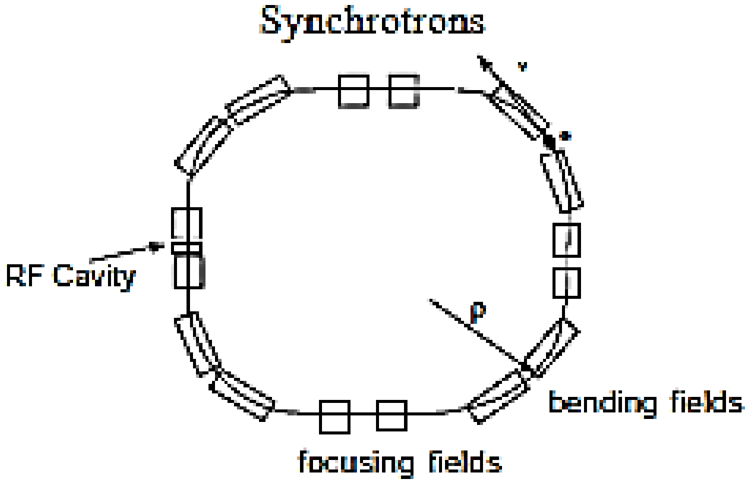
Commercial Rhodotron for electron beam processing applications

- Central rf cavity for acceleration of electrons and magnets placed on the circumference to bend the beam to the rf cavity
- Beam accelerated in successive passes through the rf cavity
- Radiation loss ↑ as energy ↑
- Beam energy up to 13 MeV



Synchrotron for electrons

- Electron moves at fixed radius ρ
- Dipole magnets along the electron path bend it in circular orbit
- Beam accelerated through successive passes through the rf cavity
- As the electron momentum increases, magnetic field B is increased to keep the radius ρ constant
- At high energies there is loss due to Synchrotron radiation (SR) as the beam is bent in the magnets
- **Energy loss by SR** $\propto \quad E^3/m^2\rho$



450 MeV Indus-1 synchrotron at RRCAT

Radiation loss ↑ as energy ↑ ; to limit loss by SR large circumference needed e.g. LEP@CERN (200 GeV) has 27 km long ring

Superconducting rf (SRF) based Linacs can achieve high energy, high current acceleration with high efficiencies

- **Rf surface resistance for Niobium is 10^5 times smaller than that for normal conducting (NC) Cu at the same frequency**

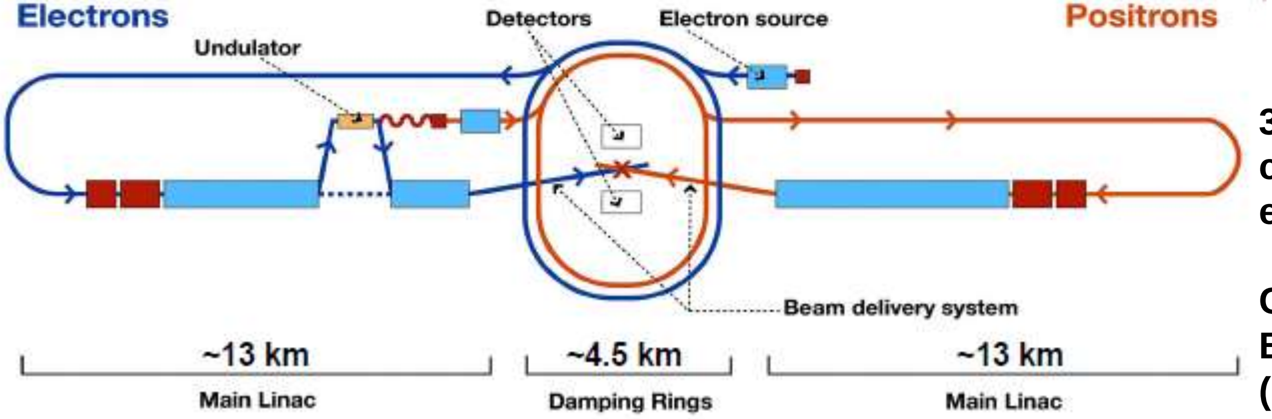
- **Q of SC resonant cavities is very high typically ~ $10^{10} – 10^{11}$ & power dissipated to achieve the given acceleration gradient is several orders of magnitude lower**

- **For high freq (≥ 500 MHz) CW case, dissipated rf power in Cu cavity will be enormously high ~ 100 kW for accel. gradient of 1 MV/m – limits of water cooling reached. For high acceleration gradient CW operation (or high duty cycle) , SC is the only choice**

- **AC wall plug power for SC case will be at least 100 times lower than NC Cu considering the same freq cw operation and power requirement for cryogenic cooling to 2K as well as klystron power for NC cavities**

Next generation TeV Colliders & FEL accelerators become possible with Superconducting rf (SRF) technology

International Linear Collider (ILC)



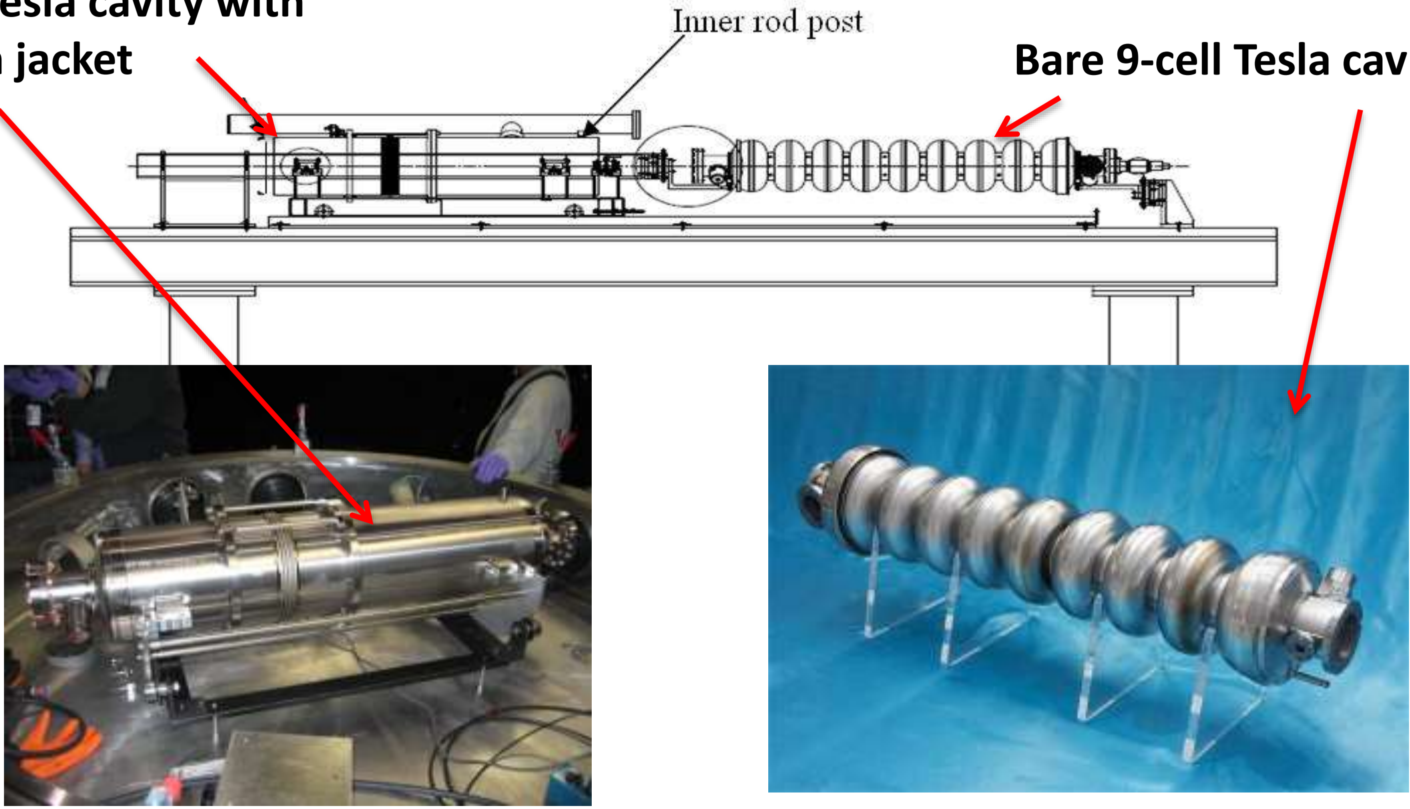
31 km long e- β+ collider 1 TeV energy

Cost ~ 7.8 Billion USD (2012)

- **1.3 GHz srf technology for ILC developed at Tesla (TeV Energy Superconducting Linear Accelerator) test facility at DESY, KeK, Fermilab , J-Lab, Cornell University, etc**
- **High acceleration gradient (> 37 MV/m) elliptical Niobium superconducting cavities developed via decades long intense R&D led by the above labs**

Superconducting Niobium Tesla cavities

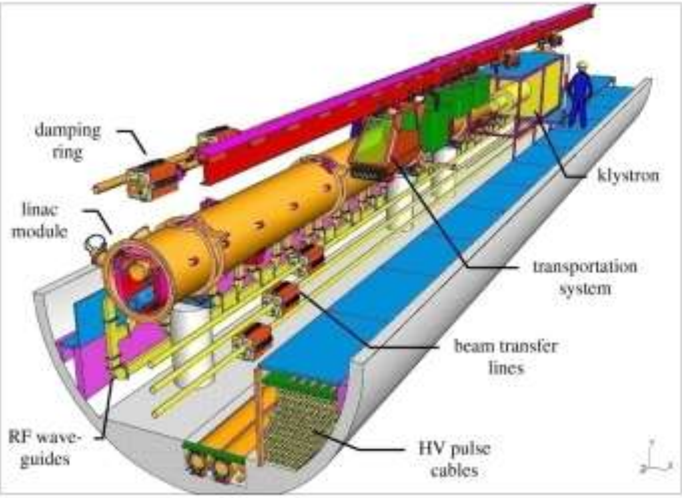
Operated at 1.3 GHz & 2K Liq. He temperature

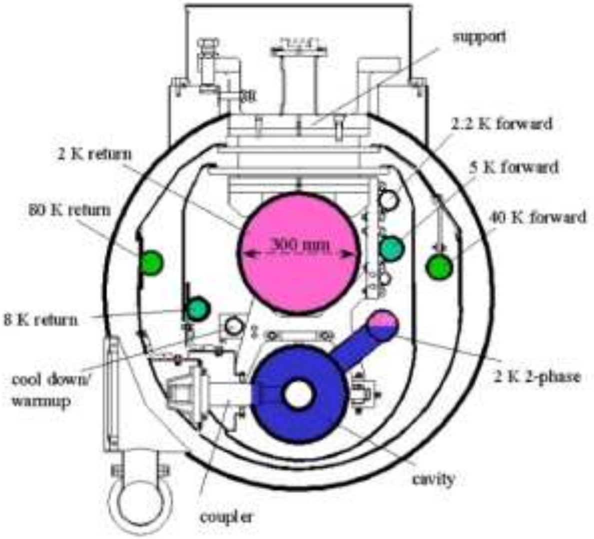


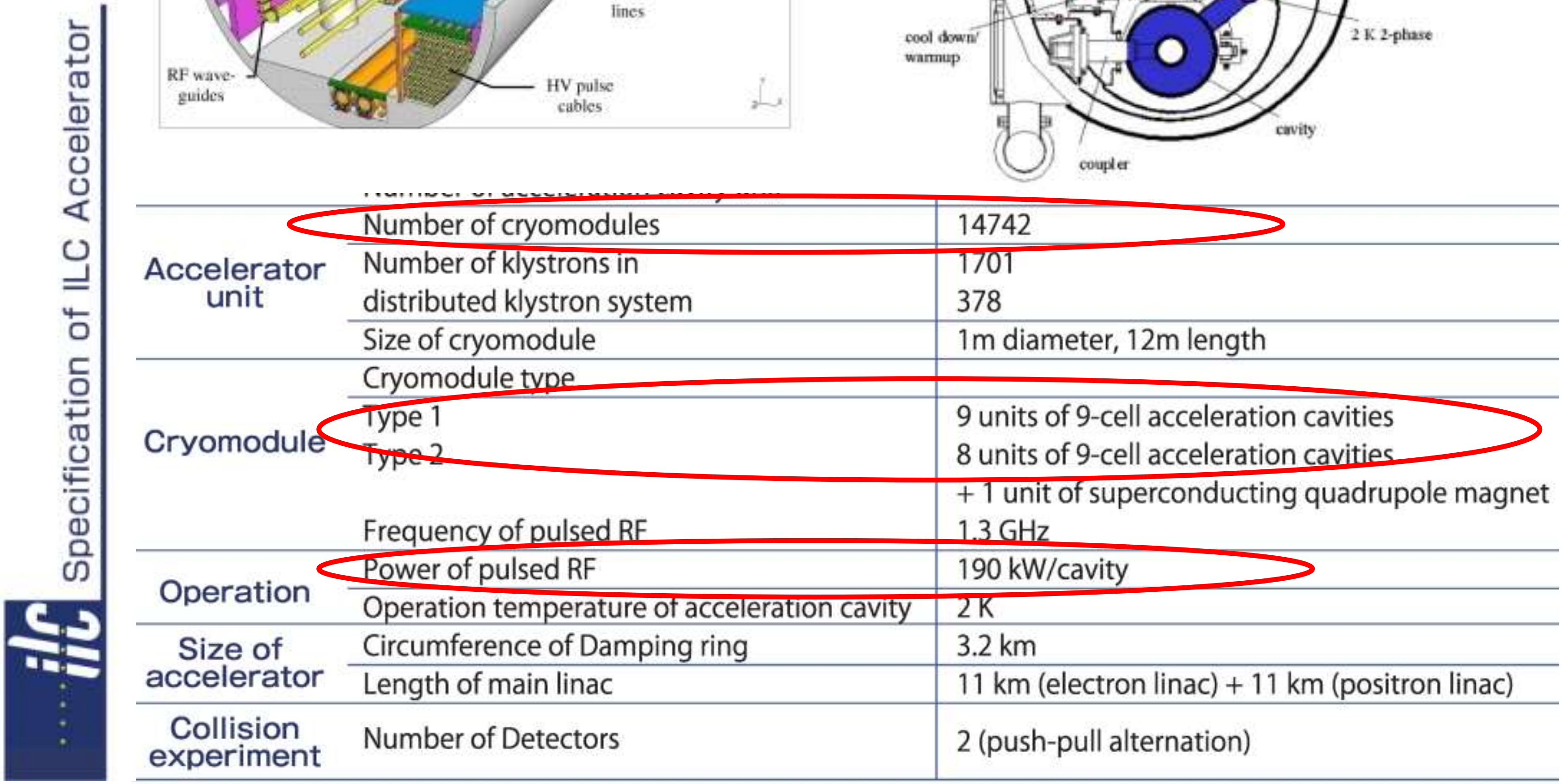
9-cell Tesla cavity with Helium jacket

Bare 9-cell Tesla cavity

Cryomodules






Specification of ILC Accelerator

Accelerator unit	Number of cryomodules	14742
	Number of klystrons in	1701
	distributed klystron system	378
	Size of cryomodule	1m diameter, 12m length
Cryomodule	Cryomodule type	
	Type 1	9 units of 9-cell acceleration cavities
	Type 2	8 units of 9-cell acceleration cavities + 1 unit of superconducting quadrupole magnet
	Frequency of pulsed RF	1.3 GHz
Operation	Power of pulsed RF	190 kW/cavity
	Operation temperature of acceleration cavity	2 K
Size of accelerator	Circumference of Damping ring	3.2 km
	Length of main linac	11 km (electron linac) + 11 km (positron linac)
Collision experiment	Number of Detectors	2 (push-pull alternation)

High frequency rf behaviour for normal conductors e.g Copper and superconductors e.g. Niobium

For normal conductors high frequency (f) rf current flows only though the surface : *Skin Effect*

One defines rf surface resistance R_s as :

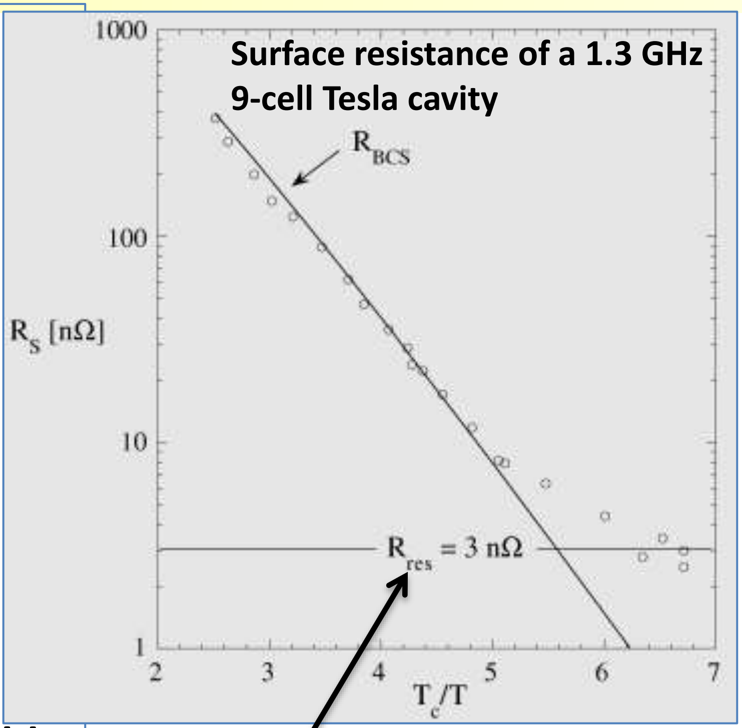
$$R_s = \frac{1}{\sigma\delta} \propto \sqrt{\frac{const.f}{\sigma}}; \quad \sigma : ele.conductivity$$

$$\delta : skin\ depth$$

As temperature $T \downarrow$ $\sigma \uparrow$ but eventually saturates

For superconductors current density and magnetic fields exist only within a layer of thickness known as *London penetration depth* λ_L and the rf surface resistance is

$$R_s \text{ i.e. } R_{BCS} \propto \text{const.} \frac{f^2}{T} exp\left[-1.76T_c/T\right]$$



Surface resistance of a 1.3 GHz 9-cell Tesla cavity

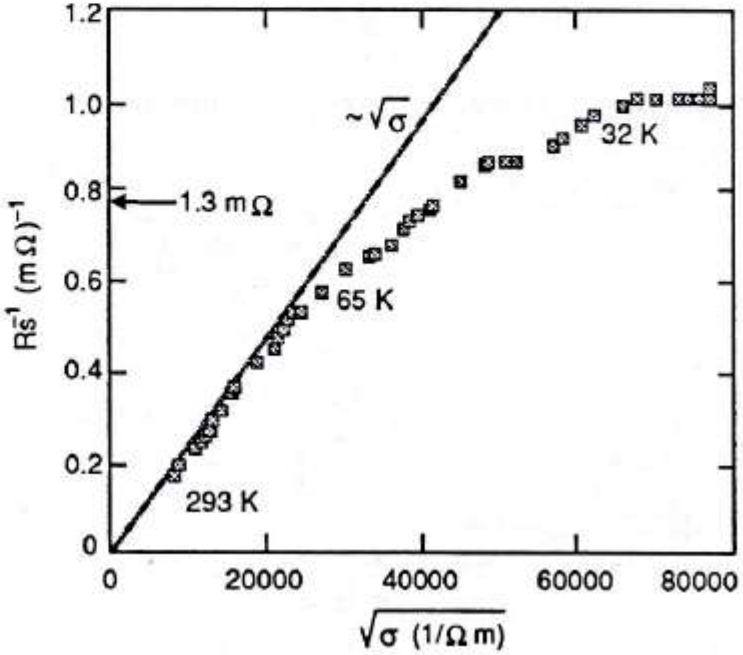
Additional residual resistance, due to impurities, lattice distortions, frozen-in magnetic fields. It is temperature independent .

Why not just use Copper at cryogenic temperature

- Due to the anomalous skin effect, the rf surface resistance R_s for Cu at 4.5 K is only ~ 10 times lower than that at Room temp.

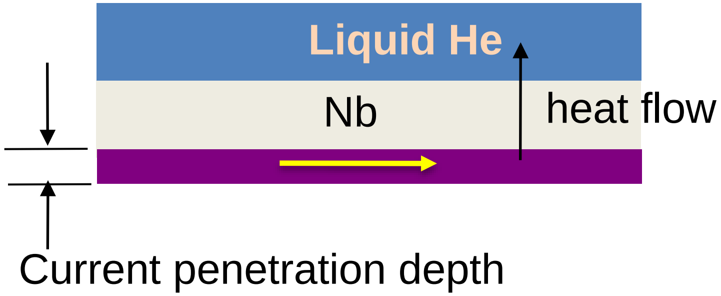
$$R_s = \frac{1}{\sigma\delta} \propto \sqrt{\frac{const.f}{\sigma}}$$

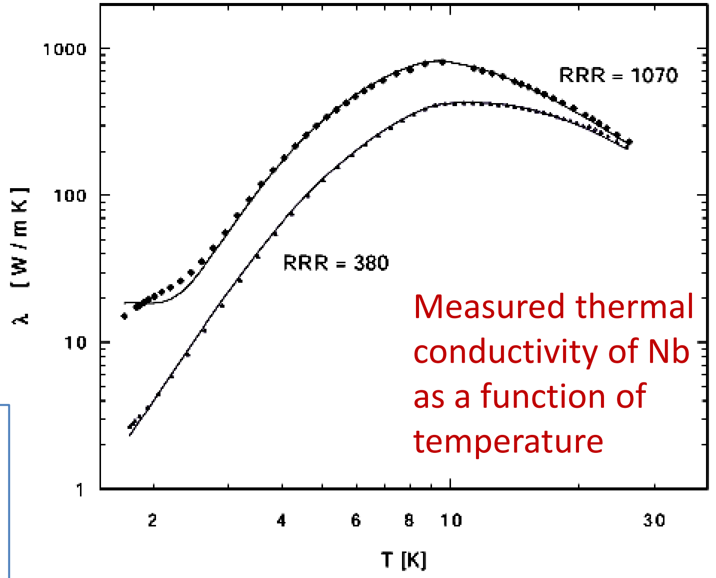
- Cryogenic cooling will need power that is much higher than this gain.



Anomalous Skin effect in a 500 MHz Copper cavity

Thermal conductivity is also important for efficient heat removal from Niobium at cryogenic temperature





Measured thermal conductivity of Nb as a function of temperature

- **Heat produced at the inner wall of the Nb cavity due to rf power dissipation has to reach the Liquid He bath through the thickness of the wall.**

- **Thermal conductivity λ of Nb at cryogenic temp scales approx with RRR Residual Resistivity Ratio (thumb-rule)**

$$\lambda\,(4.2K) \;\approx 0.25\;RRR\;\left(\frac{W}{mK}\right)$$

Starting Nb sheet RRR ~ 300
Improved further by cavity processing

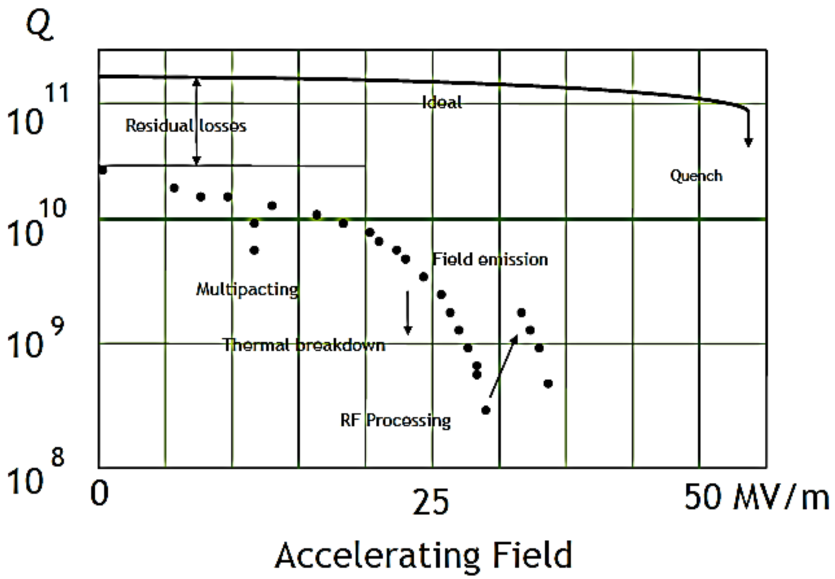
$$RRR \equiv \frac{\textit{resistivity at room temp}}{\textit{resistivity at } 4.2\ K}$$

SRF cavity performance

One is aiming at accelerating field (gradient) > 35 MV/m at Q-value > 10^{10}

Three factors effect the cavity performance

- **Multi-pacting**
- **Thermal break-down due to localized heating of surface defects**
- **Field emission from sharp points on the surface**

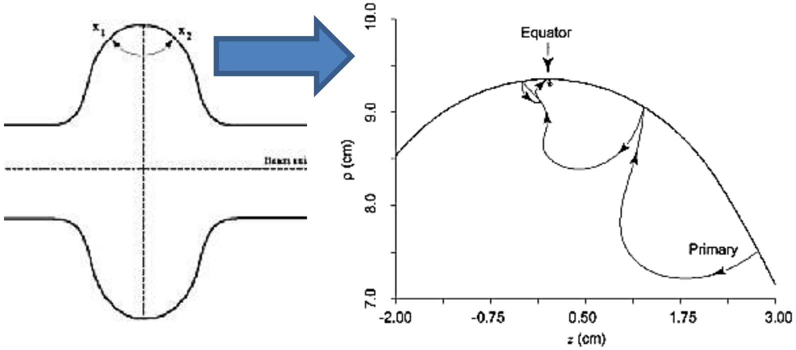


Tackling the problem

- **One starts with high quality Nb sheets and the cavities are fabricated under strict quality control**
- **Extensive step-wise cavity processing is done to achieve the required gradient**
- **Clean-room testing and assembly is must**

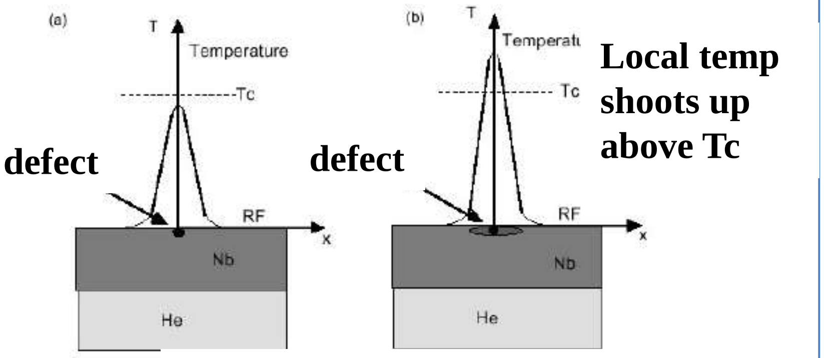
Factors limiting SRF cavity gradients

Multi-pacting : resonant process in which an electron avalanche builds up and starts absorbing rf power making it impossible to further raise cavity fields. These energetic electrons hit the cavity surface and cause damage of wall & thermal breakdown. *Controlled by choosing elliptical shape at the equator*

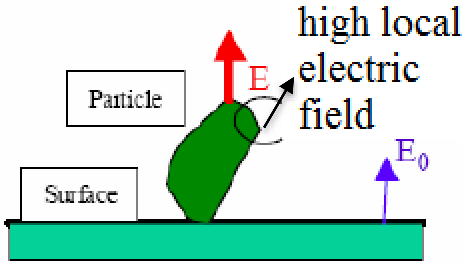


Elliptical shape causes electrons to drift to the equator. At equator electric field = 0, so electrons don't gain energy & no stable orbits are formed for resonant absorption of rf power

Thermal breakdown and Field emission: Caused by impurities, surface defects and contaminations. *Can be controlled by choosing high RRR defect free Nb sheet, QA during cavity fabrication and post-processing for smooth, clean surface e.g. chemical etching, high pressure cleansing, polishing etc*



Local temp shoots up above Tc

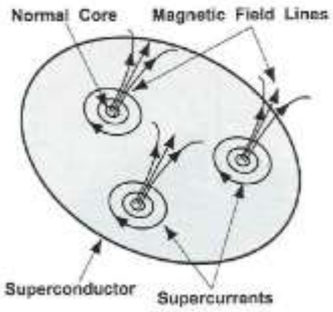


high local electric field

Other factors limiting SRF cavity gradients

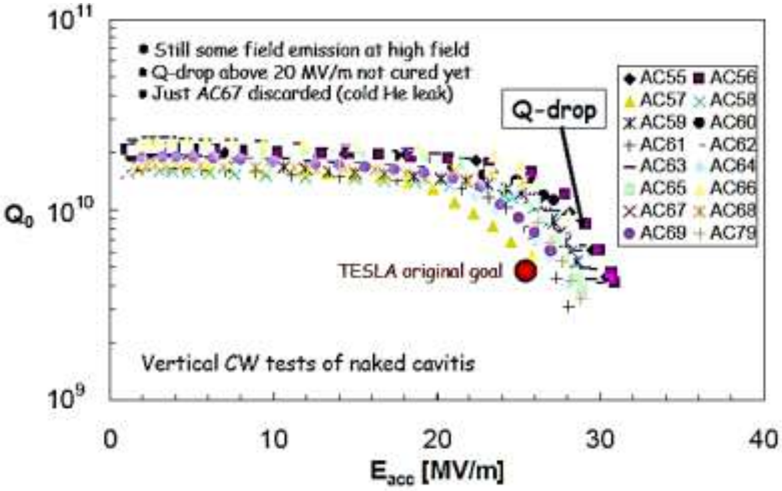
Influence of stray or earth's magnetic fields :

Niobium is soft type-2 superconductor without flux pinning (localized trapping of magnetic flux). But in practice, weak dc magnetic fluxes are not expelled upon cool down but remain trapped in the Nb. At 1.3 GHz, surface resistance caused by trapped flux is 3.5 nΩ per micro-Tesla. Thus *even earth's magnetic field of 50 micro-T is unacceptable, and Mu-metal shielding is needed for the cavities*.



Q-disease :

Sharply reduced Q-value to 10^9 which falls further at higher gradients. Seen in cavities after all the cleaning procedures have been done. Caused by increased surface resistance attributed to hydride formation on the surface of Nb.. *Can be controlled by baking at 800 °C in high temperature furnaces.*



Why Niobium?

- **Niobium is a soft type-II superconductor almost bordering on type-I . Available in pure, bulk quantity, easy to machine**

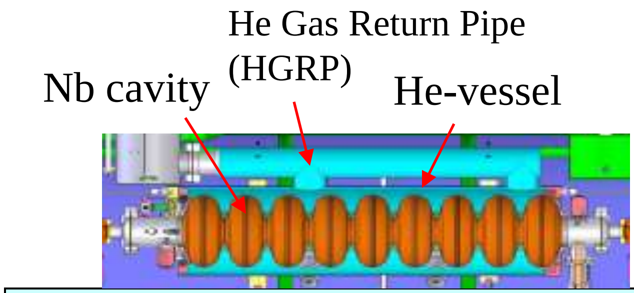
Tc = 9.2 K, critical mag field HC1 = 170 mTesla. DC magnetic field is not expelled above HC1 and a mixed mode exists till HC2 = 240 mTesla. Being a 'Soft' SC – it has very small flux pinning – desirable for reduced hysteretic losses

- **Niobium has a low rf surface resistance $R_s = 15\,n\Omega\;(at\;2K)$**

- **In accelerator cavities, unlike sc magnets external dc magnetic field is absent but high frequency rf current flows on the cavity surface. Above HC1 up to a rf critical field Hsh a metastable superconducting state is retained. Hsh = 240 mTesla for Nb. Hsh does not depend on HC2.**

Material	Tc (K)	Rs @ 2K (nΩ)	Hsh (mT)
Niobium	9.2	15	240
Lead	7.9	50	120
Nb_3Sn alloy	18	4	400

Niobium cavity fabrication & tests



Cavity Fabrication

Deep drawing of ½ cells from high purity Nb sheets

Intermittent frequency measurement and tuning

Surface Processing

Cleaning – ultrasonic degreasing, chemical etching, HPWR, baking

Cavity EBW

Surface Processing

Cleaning – ultrasonic degreasing, chemical etching, HPWR, baking

Q vs E_{acc} in VTC

Fail!

Pass!

Ti He Vessel & HGRP Welding

Surface Processing

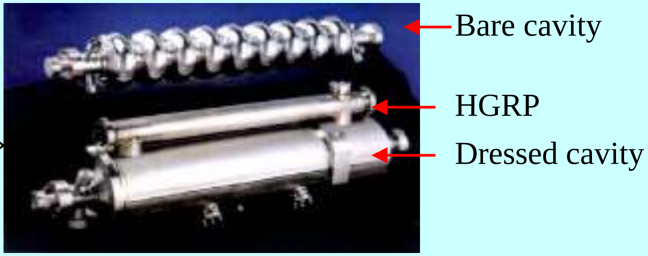
Cleaning – ultrasonic degreasing, chemical etching, HPWR, drying

Q vs E_{acc} in HTC or ICM

Fail!

Pass!

Cavity String : dressed Nb cavity with HGRP, cold part of coupler, bellows etc, ready for assembly



Basic surface processing steps

<u>Preparation step A</u>
Removal of damage layer / post purification / tuning

↓

<u>Preparation step B</u>
Final cleaning and assembly for vertical test

↓

<u>Preparation step C</u>
Welding of connection to H vessel / He vessel welding

↓

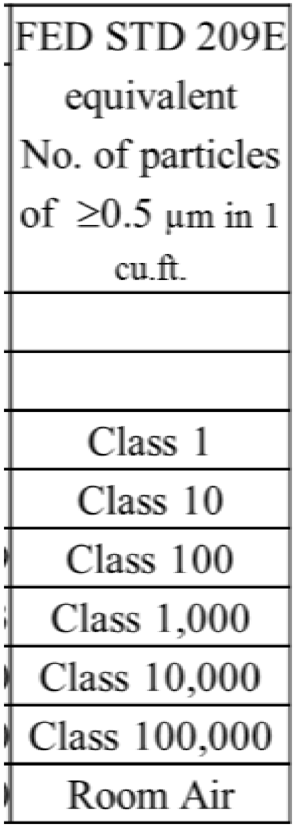
<u>Preparation step D</u>
Final cleaning and assembly for module / horizontal test

Source J. Delayen

Clean room assembly of cavities

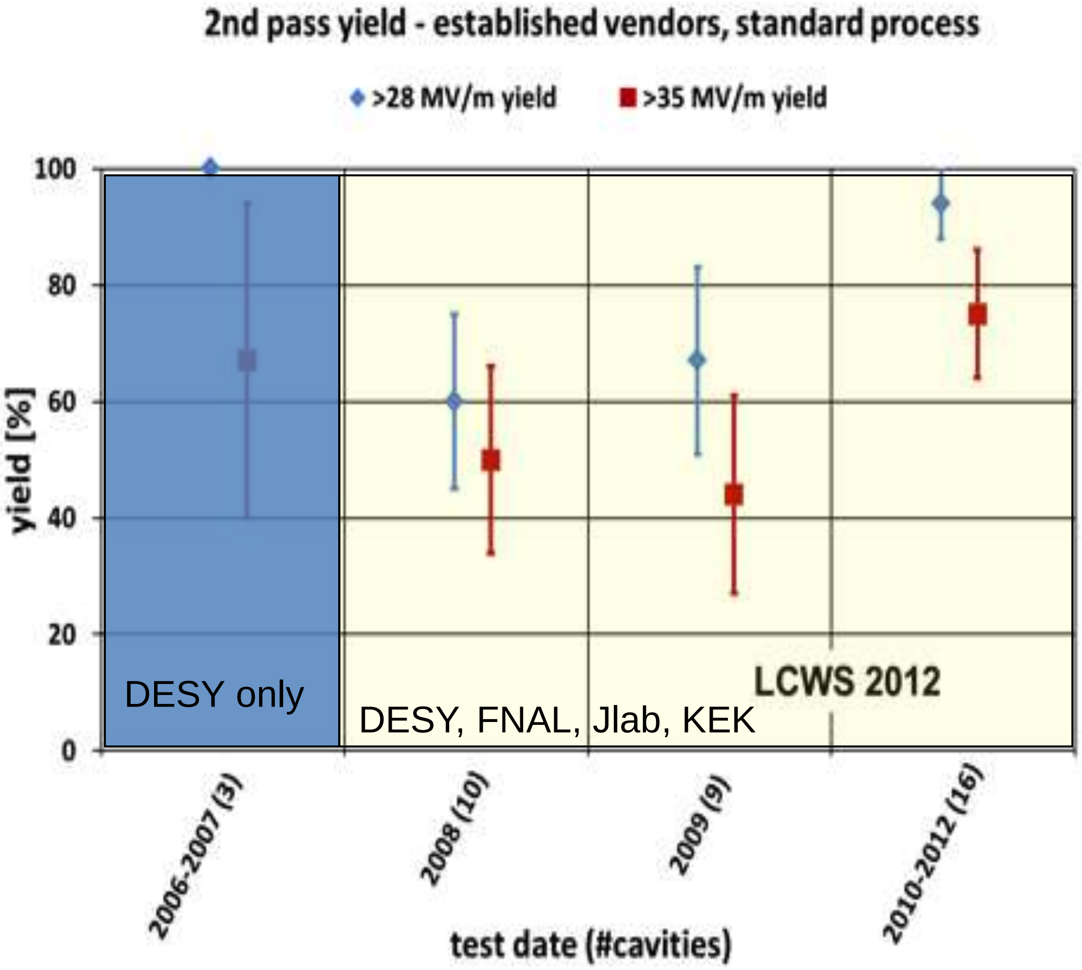
Clean room classification

Cavity assembly in Class 10 Clean room



FED STD 209E equivalent No. of particles of ≥ 0.5 µm in 1 cu.ft.
Class 1
Class 10
Class 100
Class 1,000
Class 10,000
Class 100,000
Room Air

SCRF Cavity Gradient status



- Production yield:
  94 % at > 28 MV/m
  at 35 MV/m +/- 20%)
- Average gradient:
  37.1 MV/m

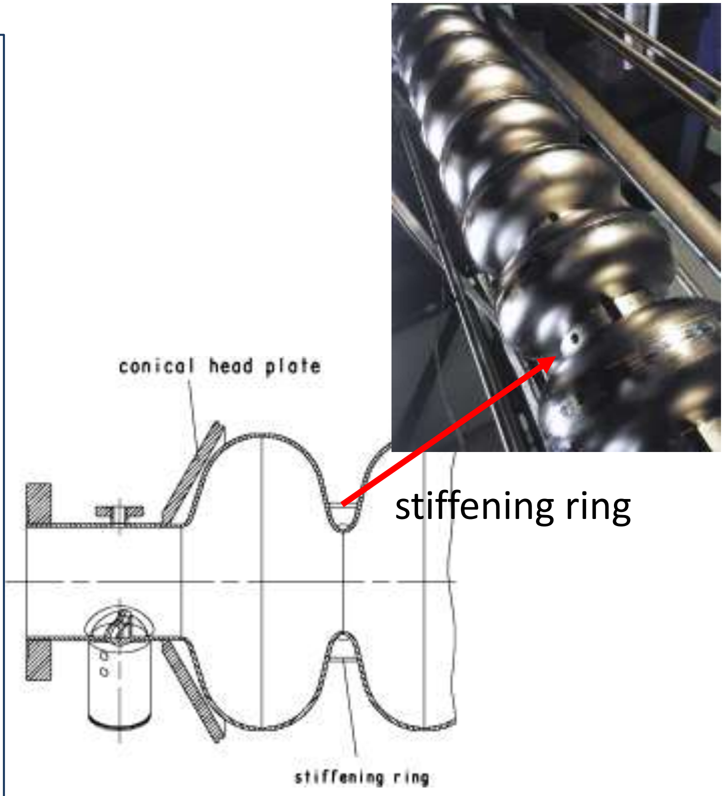
Achieved (2012)

Source Akira Yamamoto

Lorentz-Force Detuning

- Electromagnetic fields in the cavity will interact with the surface charge & currents. Tesla cavity wall is 2.8 mm thin (to get good thermal conductance for Liq. He) and these forces create outward and inward on the cavity wall. This will lead to detuning of cavity. This effect is mitigated by welding stiffening rings between cavity cells.

- Lorentz detuning is a static effect in CW linacs, but causes transient behaviour in pulsed Linacs – controlled by fast piezo tuners.



stiffening ring

Feeding power to a heavily beam loaded cavity

- **In the sc linac, say if we want to accelerate maximum beam current of 10 mA with acceleration gradient of 10 MV/m**

- **Power needed to reach this gradient in a 9-cell Tesla cavity is very small, only 10 watt whereas power in the beam = 10 MV x 10 mA = 100 kW**

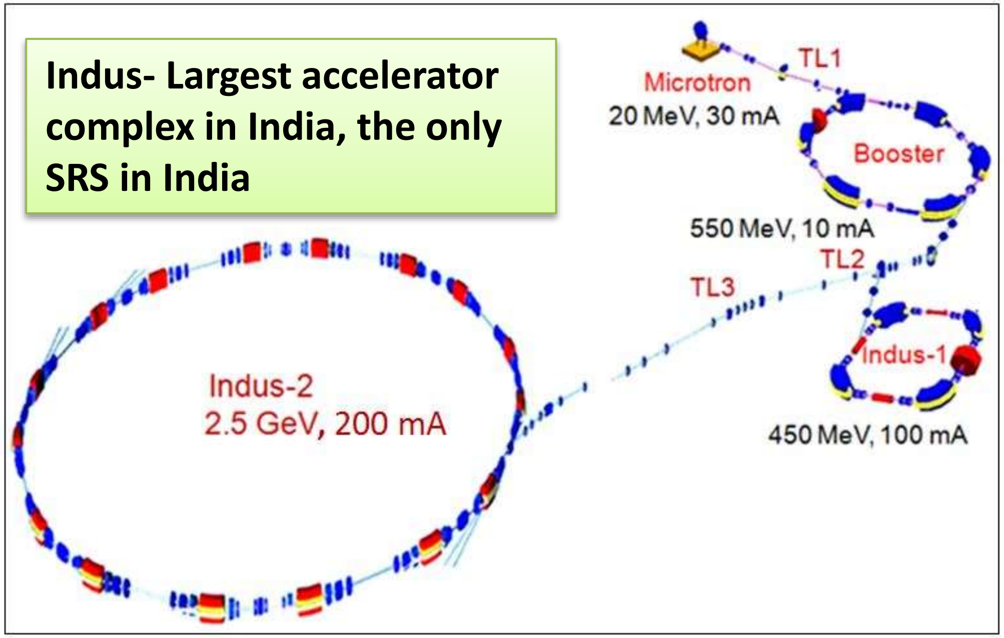
- **In such case where $P_{beam} \gg P_{cavity}$ the effect of beam on the cavity field cannot be ignored. As the beam bunch passes through the cavity it induces charges on the surface of the cavity which in turn oppose the beam. This effect is called *beam loading*. To compensate for beam loading, the generator current must be increased to counteract the voltage reduction caused by the beam**

- **The coupler is tuned to transfer power to the combined cavity + beam system. The intrinsic Q_0 of the cavity is $\sim 10^{10}$, but the Q for the combined system is $Q_{ext} = \frac{V_{acc}}{R/_{Q_0} \cdot I_0} \sim 10^6$**
- **The coupler's tuning range is limited (±5 mm) : tuning range compensates for factor of 10 i.e. if the system tuned for 2 mA for reflection less operation , tuning range is sufficient to operate at 0.2 mA without reflection. But at lower beam currents, coupler will be over-coupled : high reflected power i.e. high generator power .**

Next : Electron accelerators in India

Electron accelerators at RRCAT

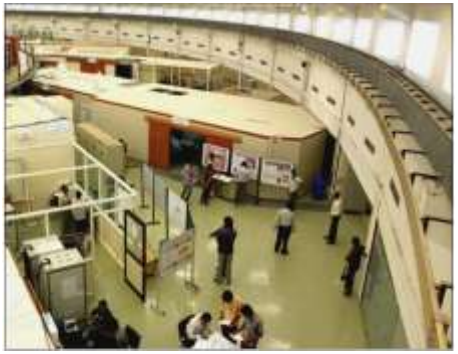
Indus- Largest accelerator complex in India, the only SRS in India



Indus-1 storage ring

Indus-2 tunnel

Indus-2 control room



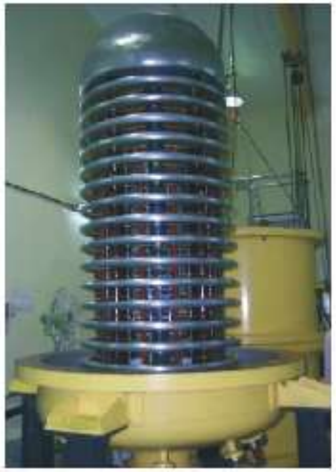
Indus-2 expt hall

Industrial accelerators at RRCAT

Two accelerators are operating:

- 5-10 MeV Linac (operating at 5 kW)
- 750 keV DC accelerator (operating at 5 kW)

10 MeV Electron Linac for radiation processing



Accelerator assembly

Accelerator assembly in pressure vessel

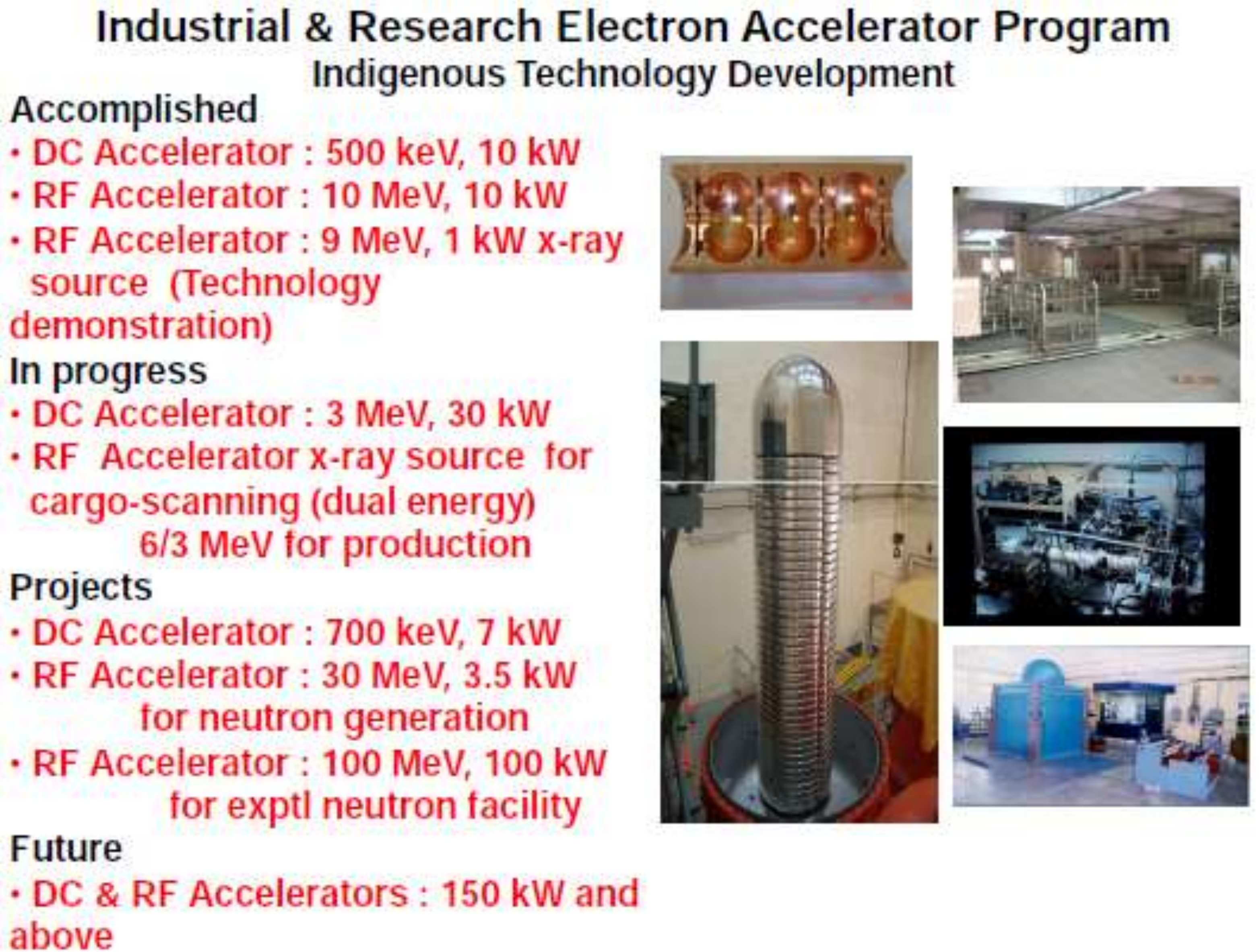
Conveyor system

Scanning system

750 keV D C INDUSTRIAL ACCELERATOR

Source Jishnu Dwivedi, RRCAT

Electron accelerators at BARC



Industrial & Research Electron Accelerator Program

Indigenous Technology Development

Accomplished

- DC Accelerator : 500 keV, 10 kW
- RF Accelerator : 10 MeV, 10 kW
- RF Accelerator : 9 MeV, 1 kW x-ray source (Technology demonstration)

In progress

- DC Accelerator : 3 MeV, 30 kW
- RF Accelerator x-ray source for cargo-scanning (dual energy) 6/3 MeV for production

Projects

- DC Accelerator : 700 keV, 7 kW
- RF Accelerator : 30 MeV, 3.5 kW for neutron generation
- RF Accelerator : 100 MeV, 100 kW for exptl neutron facility

Future

- DC & RF Accelerators : 150 kW and above

Source K.C. Mittal, BARC

Medical Linacs at SAMEER

2014 as "Made in India" Year for Electronics
MSIPS Applications worth ₹65,500 Crore

Indian Linac for Cancer Patient Care
7th Greenfield EMC Approved

Domestically Designed 6MV Linear Accelerator (Linac) to reduce price of medical care for Cancer patients

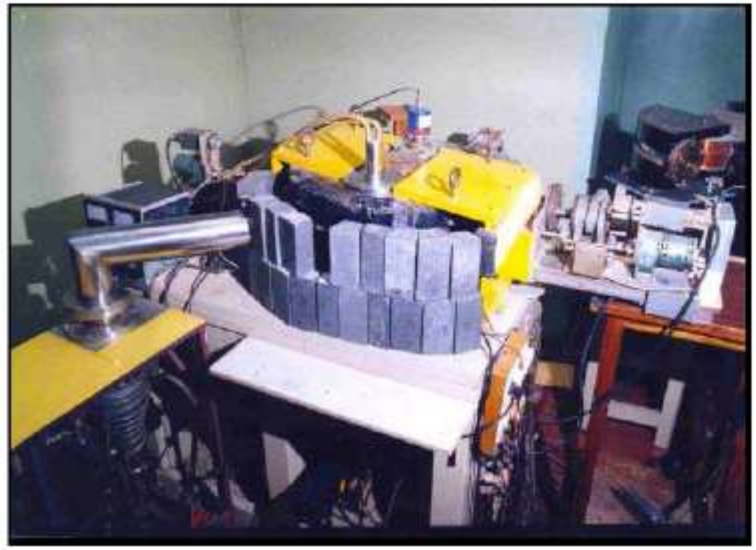
Secretary, DeitY, Shri J. Satyanarayna handing over the Transfer of Technology (TOT) Agreement & Certificate of Partnership for 6 MV Linac Technology in New Delhi on23rd Dec, 2013

A 6 MV Medical Linac has been developed by Society for Applied Microwave Electronics Engineering & Research (SAMEER), Mumbai and CSIO, Chandigarh. SAMEER is an R&D organisation under DeitY. The Medical Linac caters to 70-80% of Cancer treatment related radiotherapy applications. It conforms to IEC standards for radiological and non-radiological safety and is type approved by AERB, Mumbai.

The Linac developed by SAMEER and CSIO is expected to cost about ₹2.5-3 Crore as against ₹4-5 Crore for similar Linacs available in the market. This is expected to lead to reduce the cost of medical care for cancer patients.

Electron accelerators in Pune University

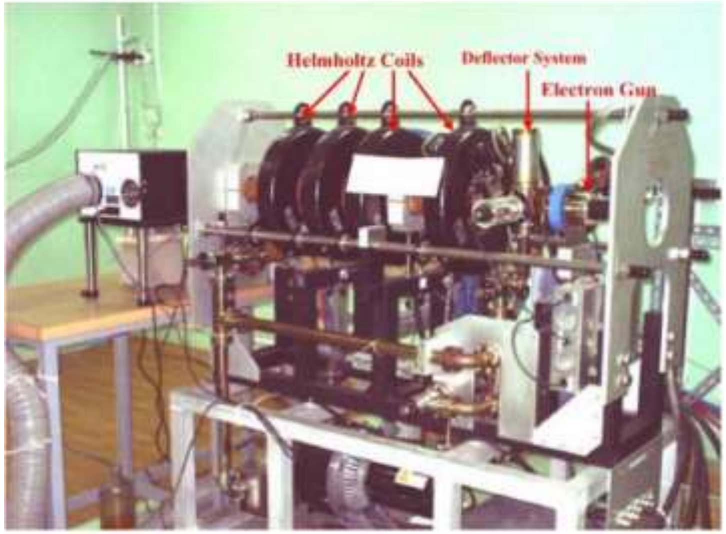
8 MeV Racetrack Microtron



Installed in Department of Physics

Pune University Linac Facility (PULAF)

7 MeV S-band (2998 MHz Linac)



Installed in Department of Chemistry under BRNS project for pulse radiolysis studies

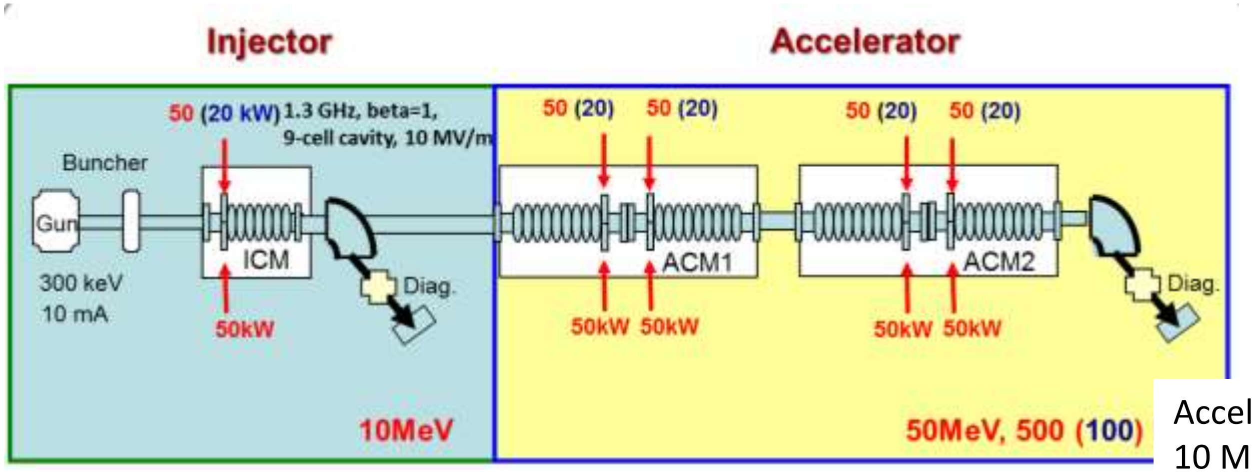
Microtron Centre at Mangalore University

8 MeV Microtron, developed at RRCAT for Mangalore University

Electron Energy	:	8 MeV
Electron Beam Current	:	50 mA (max)
No. of Electron Orbits	:	14
Pulse Repetition Rate	:	250 Hz (max)
Pulse Width	:	2.5 µs (max)
Beam Size	:	3 mm X 5 mm
Microwave Source	:	Magnetron
Magnetron Power	:	2 MW
Operation Frequency	:	2998 MHz
Dose rate at 30 cm	:	2 kGy/min (max)

Superconducting Electron Linac development at VECC

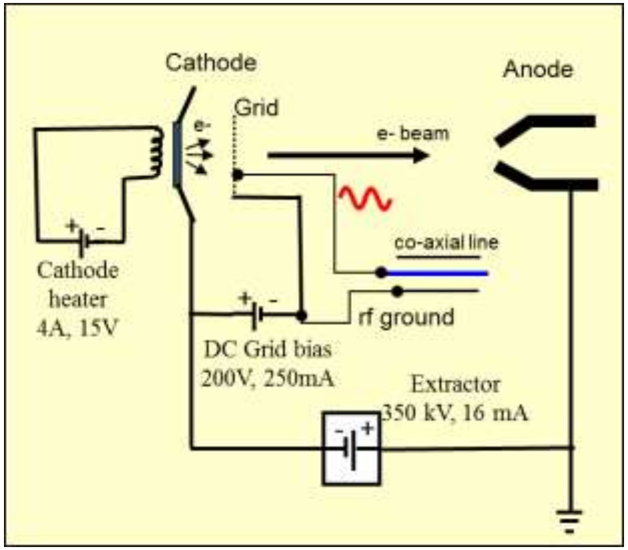
50 MeV, 100 kW cw SC Linac based on 1.3 GHz SRF technology is being developed in collaboration with TRIUMF Canada



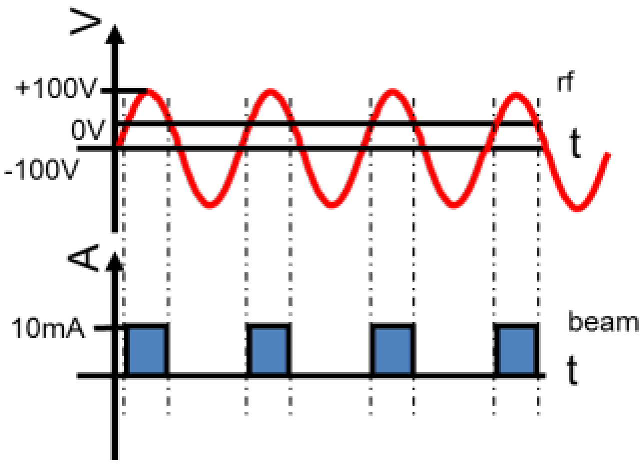
Acceleration gradient : 10 MV/m guided by power handling capacity of couplers ; cryogenics designed for 14 MV/m

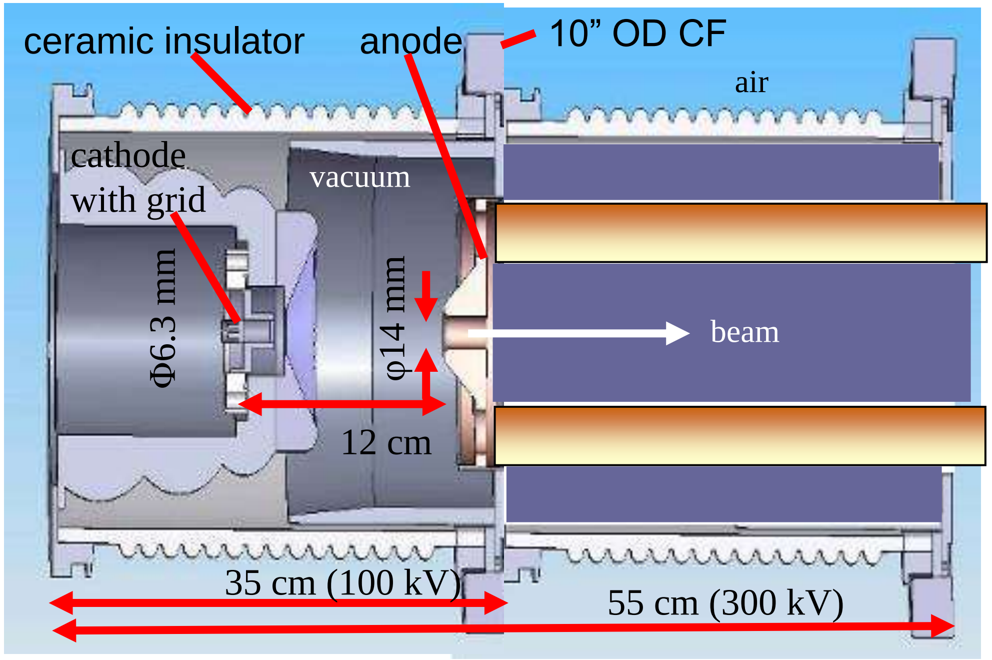
Will be used for production of Rare Isotope Beams

DC Thermionic Electron gun with gridded cathode



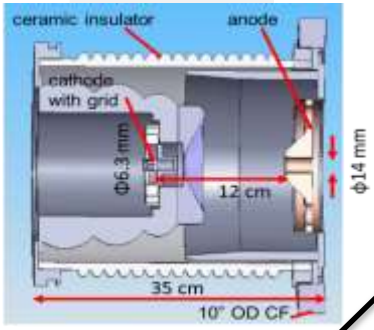
• Beam energy	300 keV (100kV)
• Beam current	10 mA (2mA)
• Bunch length	170 ps FWHM ± 16° @ 650 MHz
• Charge per bunch	16 pC
• Normalized emitt.	5 pi. mm. mrad FWHM
• Beam size	±3 mm





For initial tests a 100 keV electron gun & LEBT line is being fabricated in Indian industry

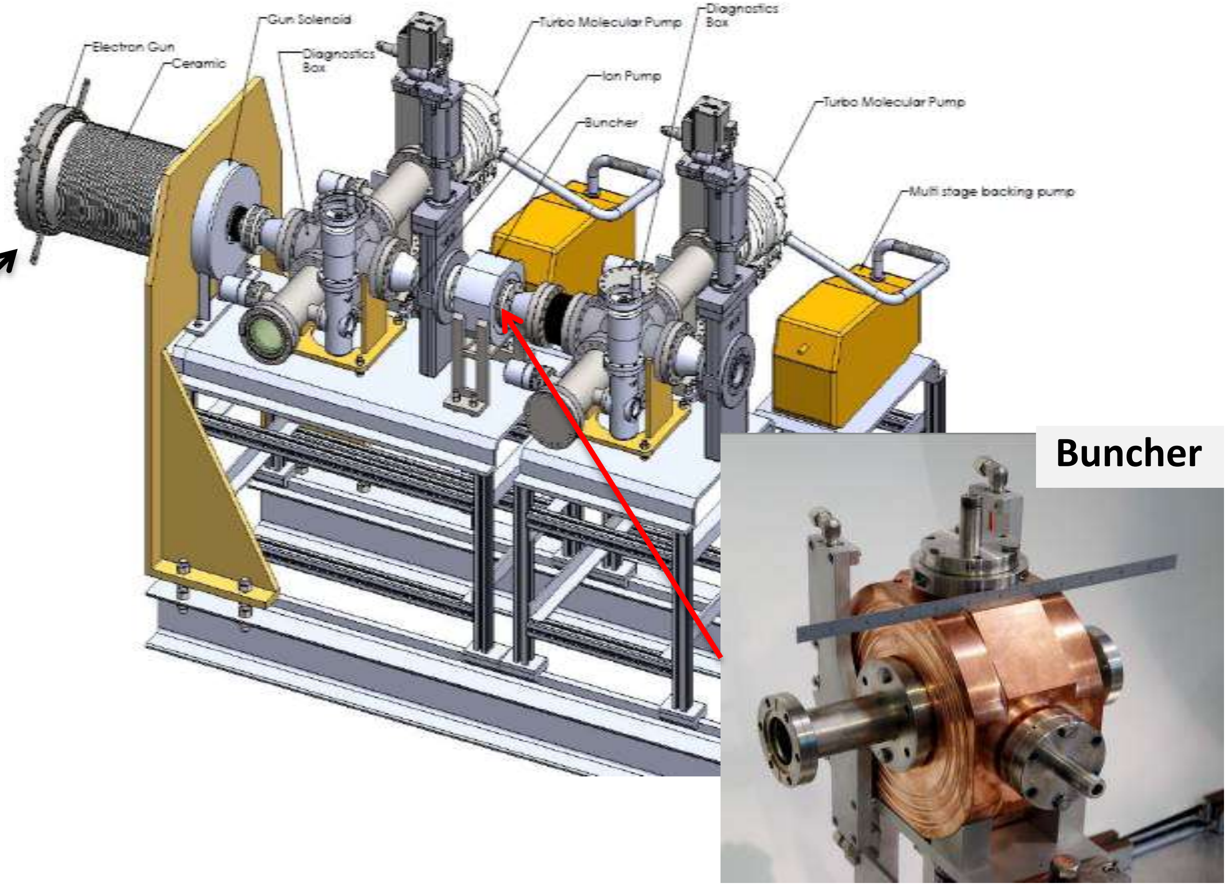
Electron gun



e-gun with 100 kV insulator

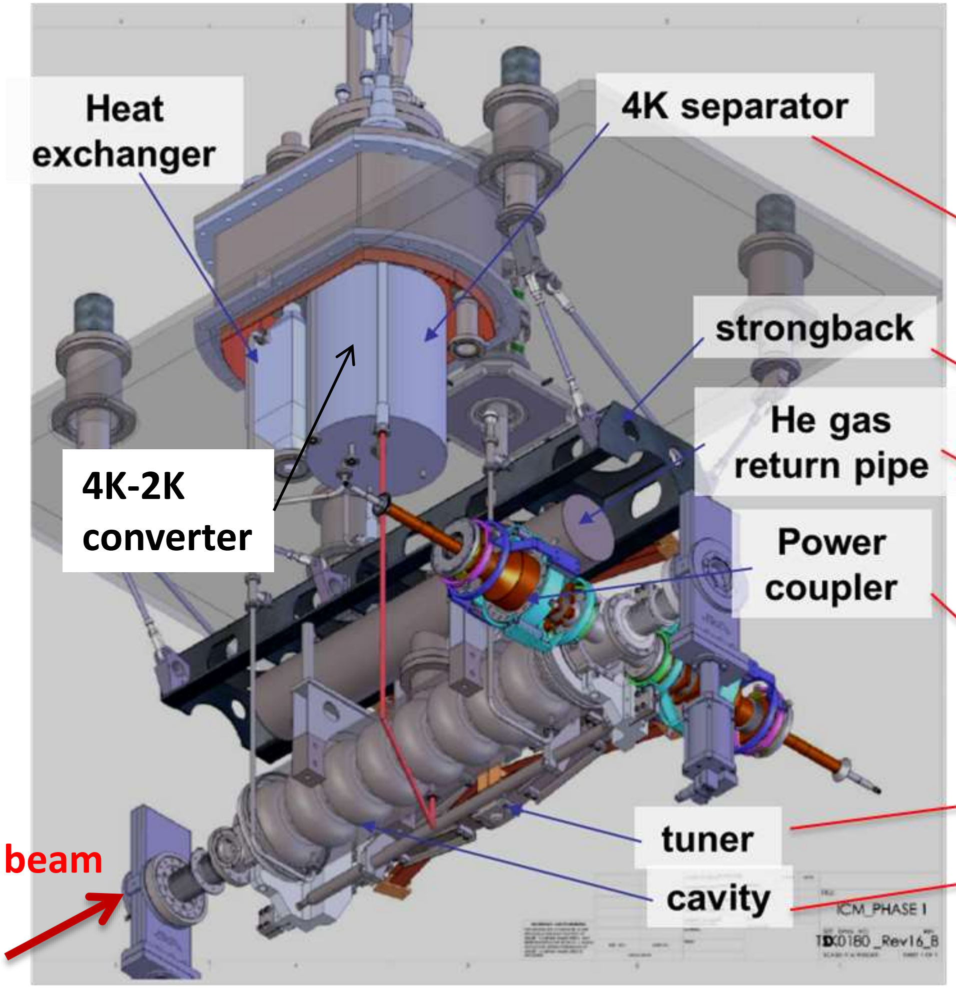
Gun

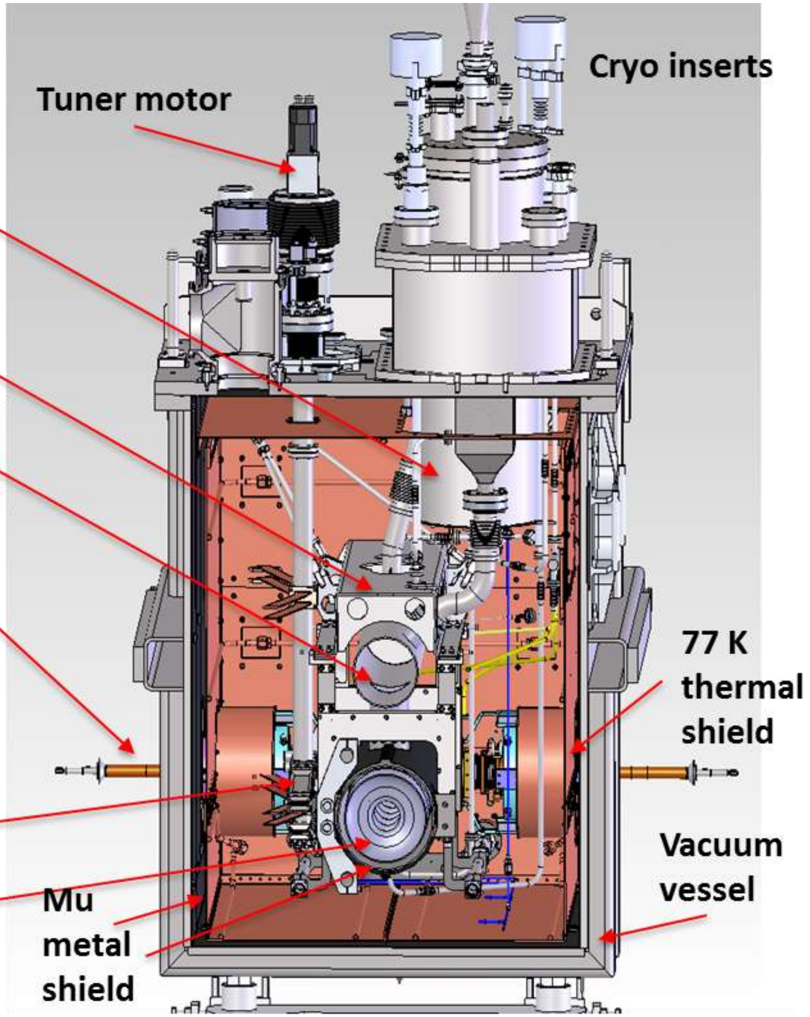
Cathode



Buncher

Injector Cryo Module (ICM)

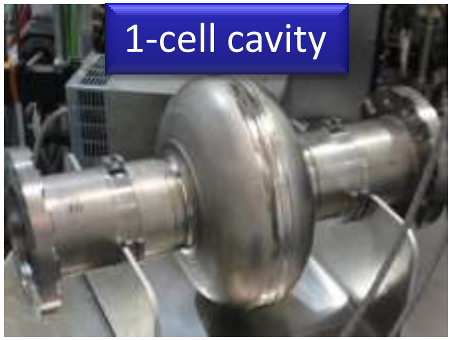




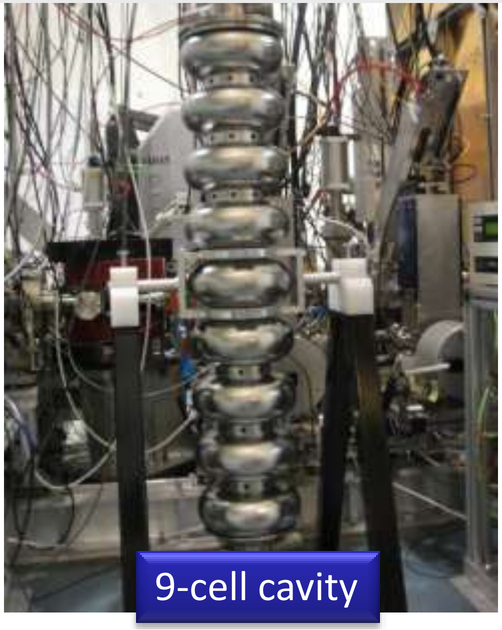
Being developed at TRIUMF for both the institutes

Niobium Cavity development at TRIUMF

Dressed 9-cell cavity



1-cell cavity



9-cell cavity

1-cell cavity cold tests

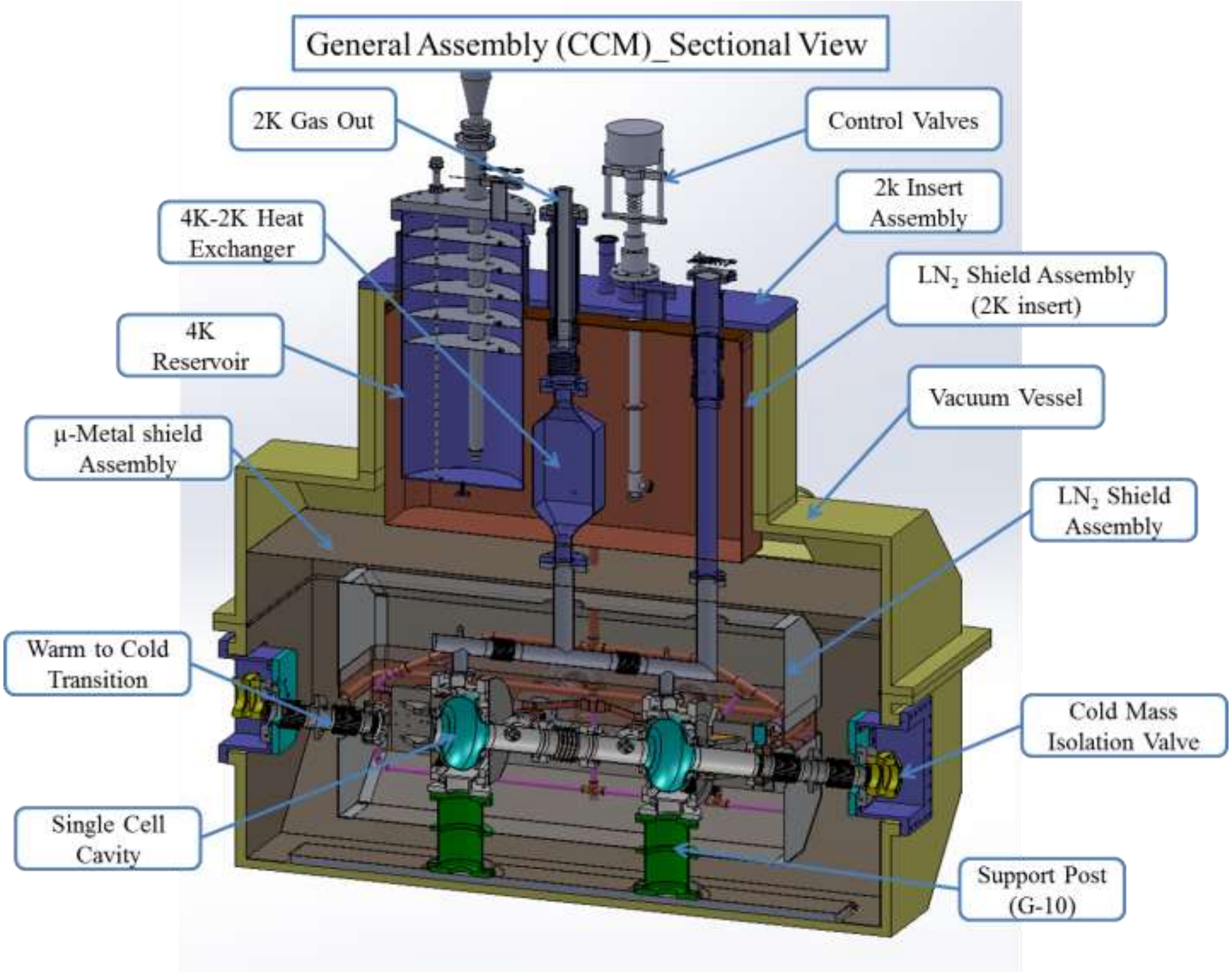
9-cell cavity alignment

9-cell cavity inspection

Cavities for VECC will come from from TRIUMF

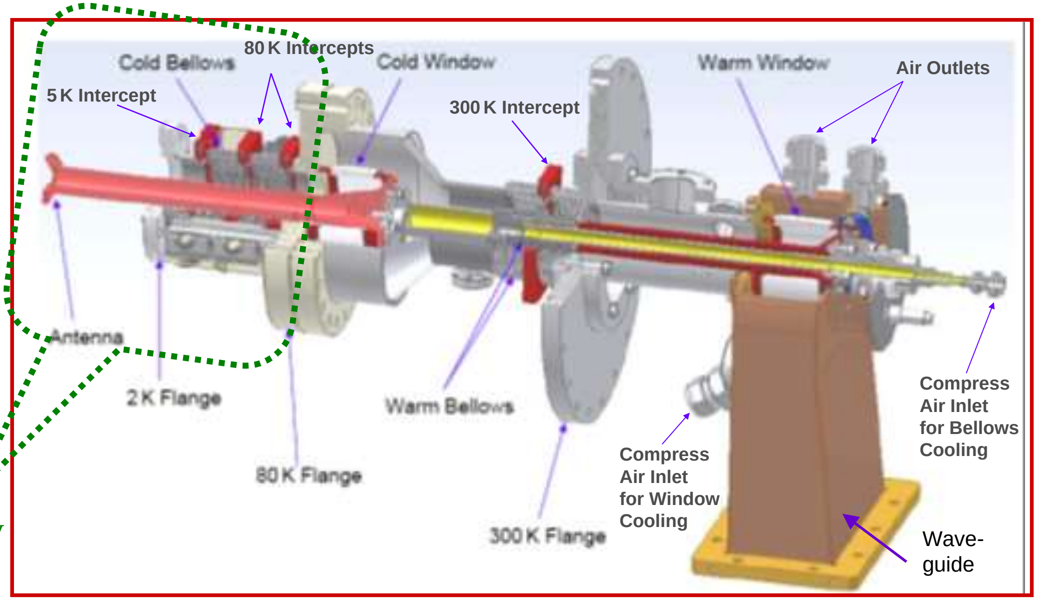
Capture Cryo Module (CCM) : to be fabricated in Indian industry

CCM will be used with 100 keV gun for e-Linac tests at Salt Lake campus



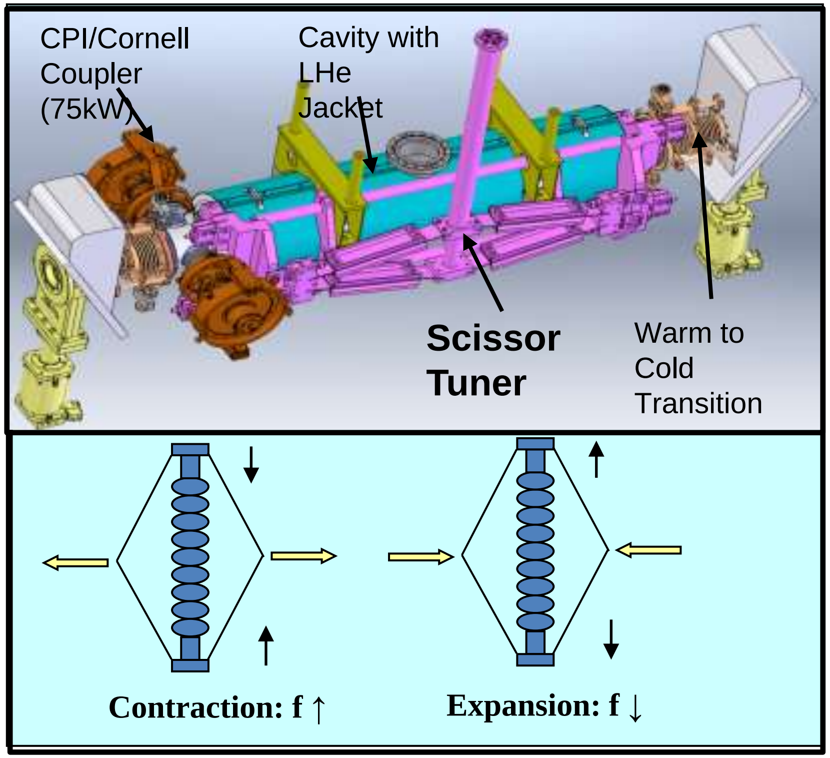
E-Linac power coupler

- CPI/Cornell 75kW coupler (0.02W @2K per kW input power)
- TTF-III 7 kW coupler (0.06W @2K per kW input power)
- Couplers mounted horizontally
- 4K/80K temperature intercept

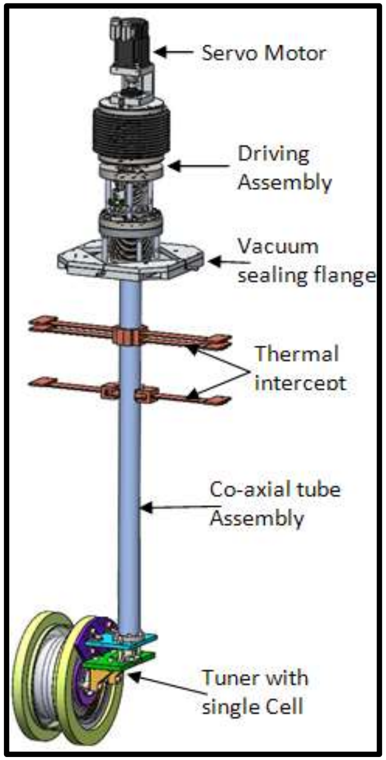


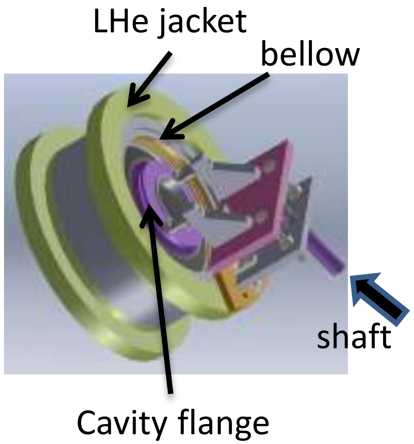
Coupler cold-part assembled on cavity

Scissor type Tuner for ICM



Rocker arm type Tuner for CCM



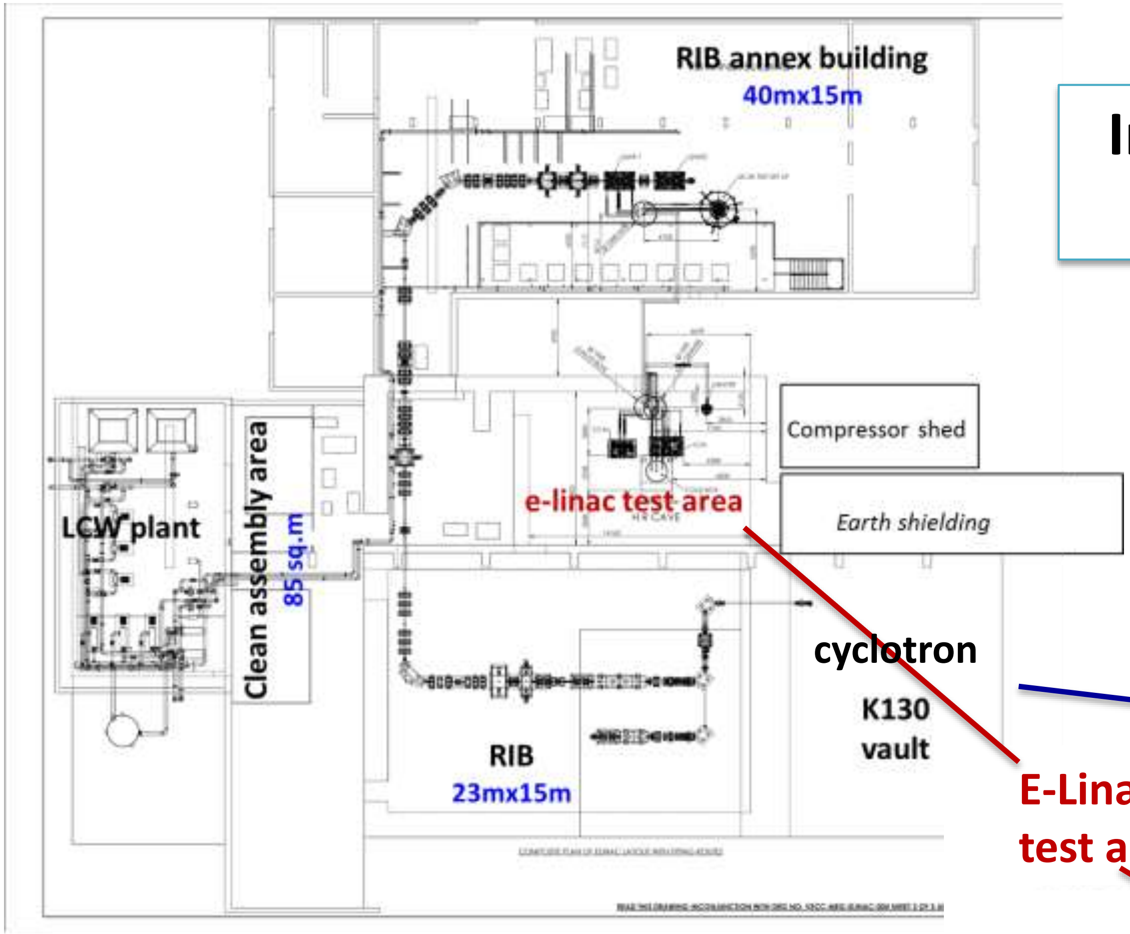


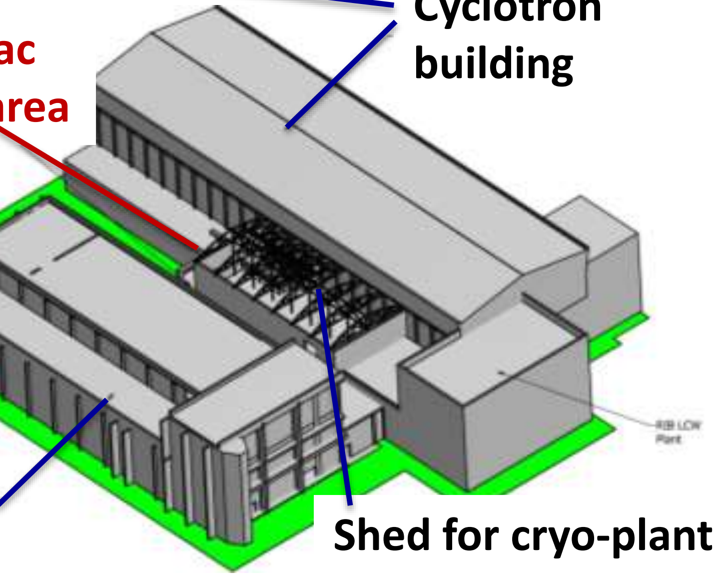
Parameter	Unit	Capture (1-Cell)	9-Cell
Frequency Goal (Fab.)	**kHz**	**±100**	**±100**
Tuning Range	**kHz**	**±250**	**±250**
Sensitivity (df/dz)	**kHz/mm**	**~6000**	**~400**
Range	**mm**	**±0.04 (required)** **±0.1 (tuner design)**	**±0.6**
Resolution	**Hz(nm)**	**±5(2.5)**	**±6 (10.0)**

E-Linac : heavily beam-loaded, cw machine

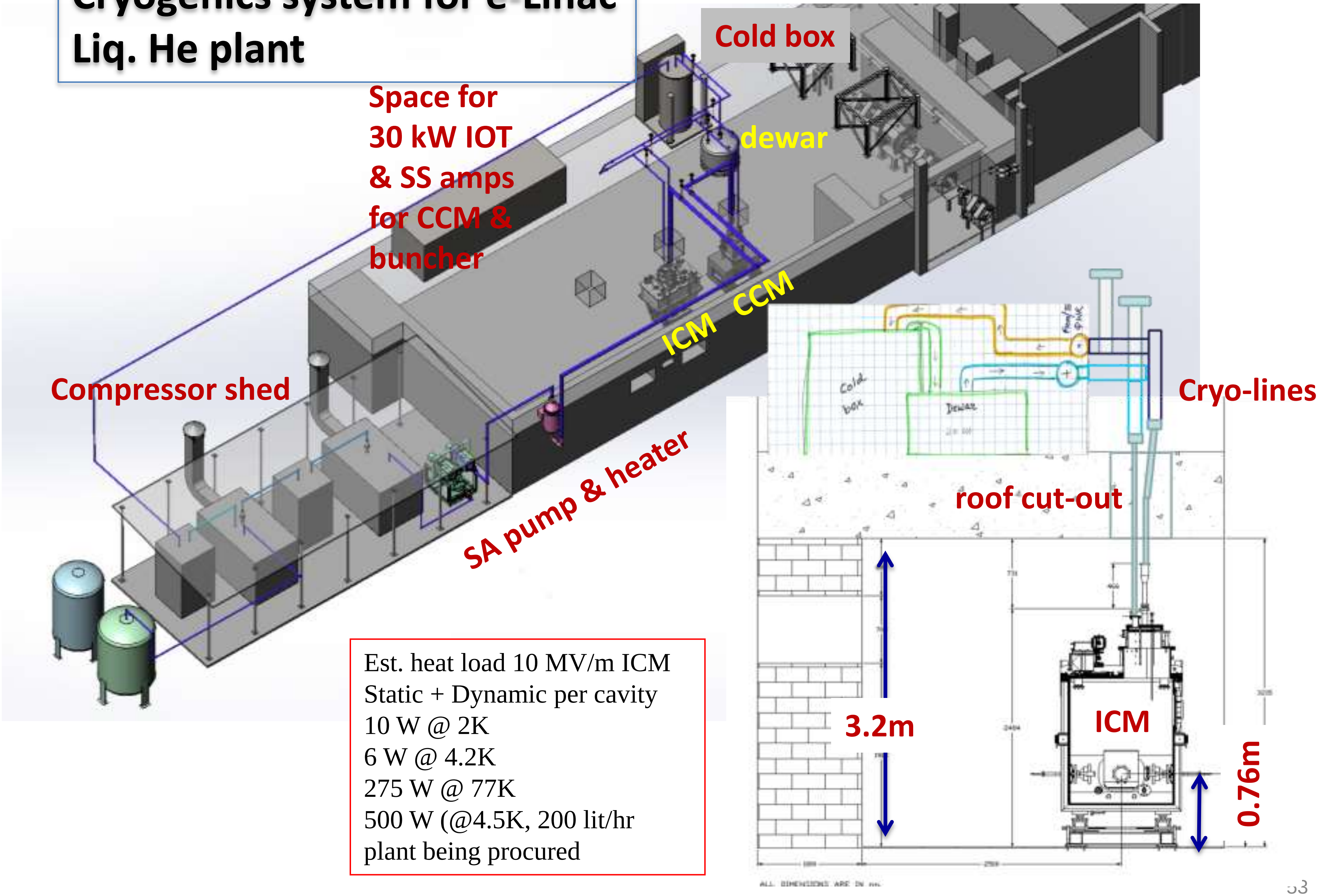
- Loaded bandwidth of cavity Δf ~ 100 Hz, microphonics de-tuning smaller than Δf
- no transient beam pulses, Lorentz detuning is static effect, peizo tuners not needed

Infrastructure for e-Linac at VECC





Cryogenics system for e-Linac Liq. He plant

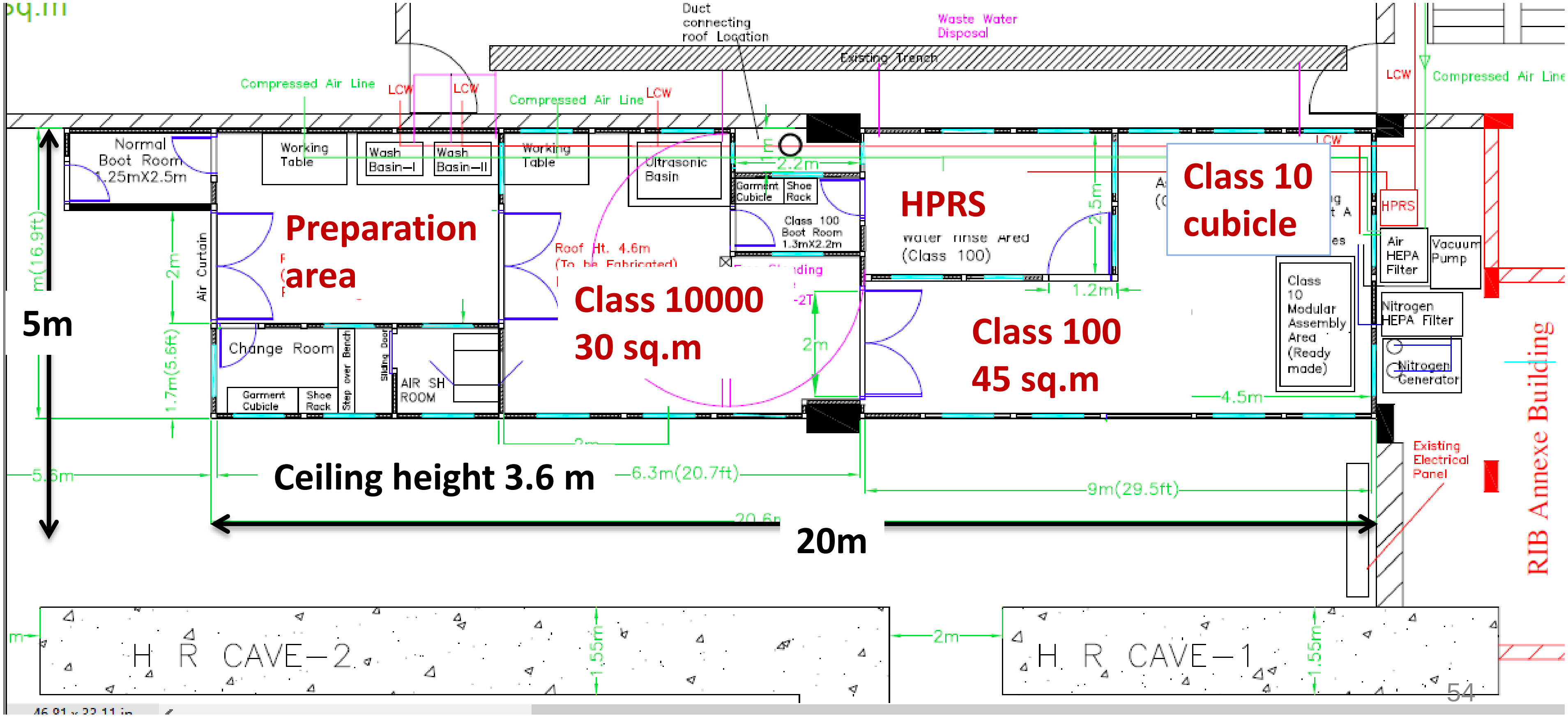


Est. heat load 10 MV/m ICM
Static + Dynamic per cavity
10 W @ 2K
6 W @ 4.2K
275 W @ 77K
500 W (@4.5K, 200 lit/hr
plant being procured

Layout of clean assembly area

Purpose:

To water rinse and assemble single cell cavities/cold mass for CCM ; 9-cell cavity cleaning in case of contamination & assembly of QWR resonators



Preparation area

Class 10000
30 sq.m

HPRS

Class 10 cubicle

Class 100
45 sq.m

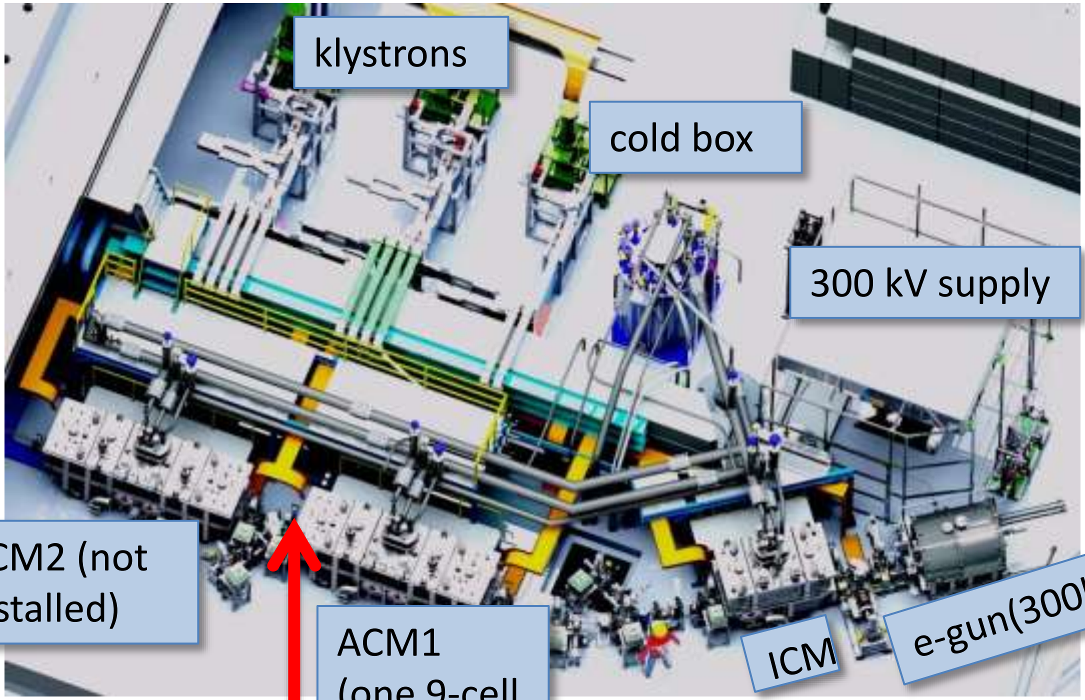
5m

Ceiling height 3.6 m

20m

E-Linac hall at TRIUMF (Sept 2014)

First beam accelerated to 23 MeV on 29th Sept 2014 at TRIUMF



klystrons

cold box

300 kV supply

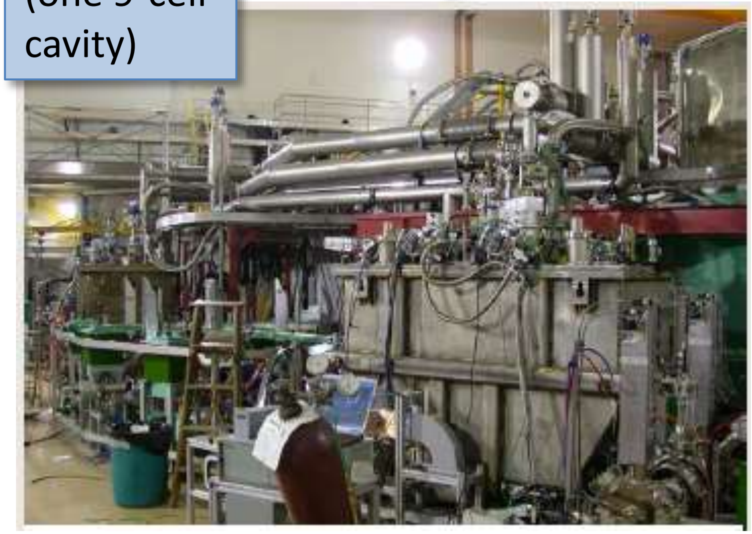
ACM2 (not installed)

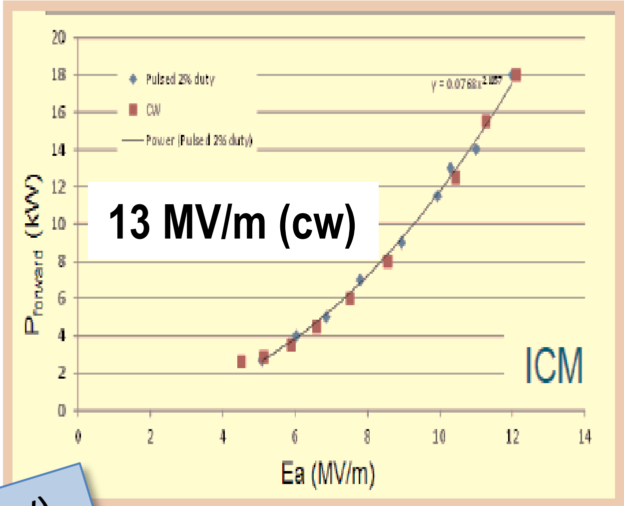
ACM1 (one 9-cell cavity)

ICM

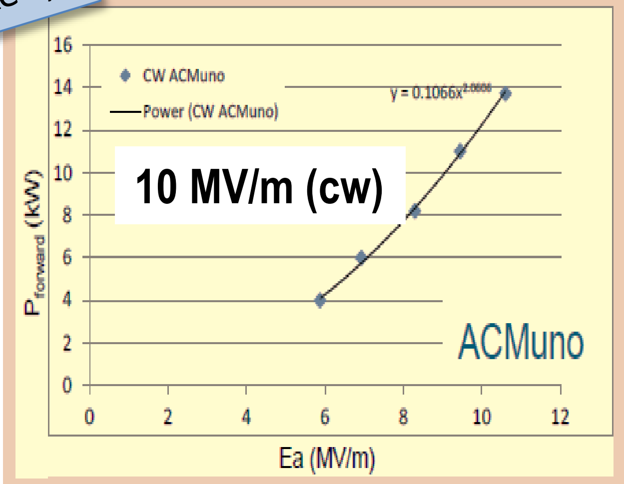
e-gun(300keV)

23 MeV, 10 microAmp





13 MV/m (cw)



10 MV/m (cw)

Conclusions :

- **An overview of various kinds of Electron Accelerators and accelerators in India has been presented.**
- **Superconducting rf (SRF) technology is the state of art in reaching higher accelerator gradients aimed at next generator high energy/ high power accelerators.**
- **VECC has started development of a 50 MeV 100 kW superconducting electron linear accelerator in collaboration with TRIUMF laboratory in Canada. First a 10 MeV injector is being developed which is expected to be installed in coming two years.**

Suggested further reading :

- Thomas P. Wrangler – RF Linear Accelerators
- Hasan Padamsee et. al. – RF superconductivity for accelerators
- B. Aune et.al. – Superconducting Tesla cavities
- US and CERN Particle Accelerator School publications available on the web

Thank you for your kind attention