ILC-doc-392-v4

A Cartoon Description of Linear Accelerators

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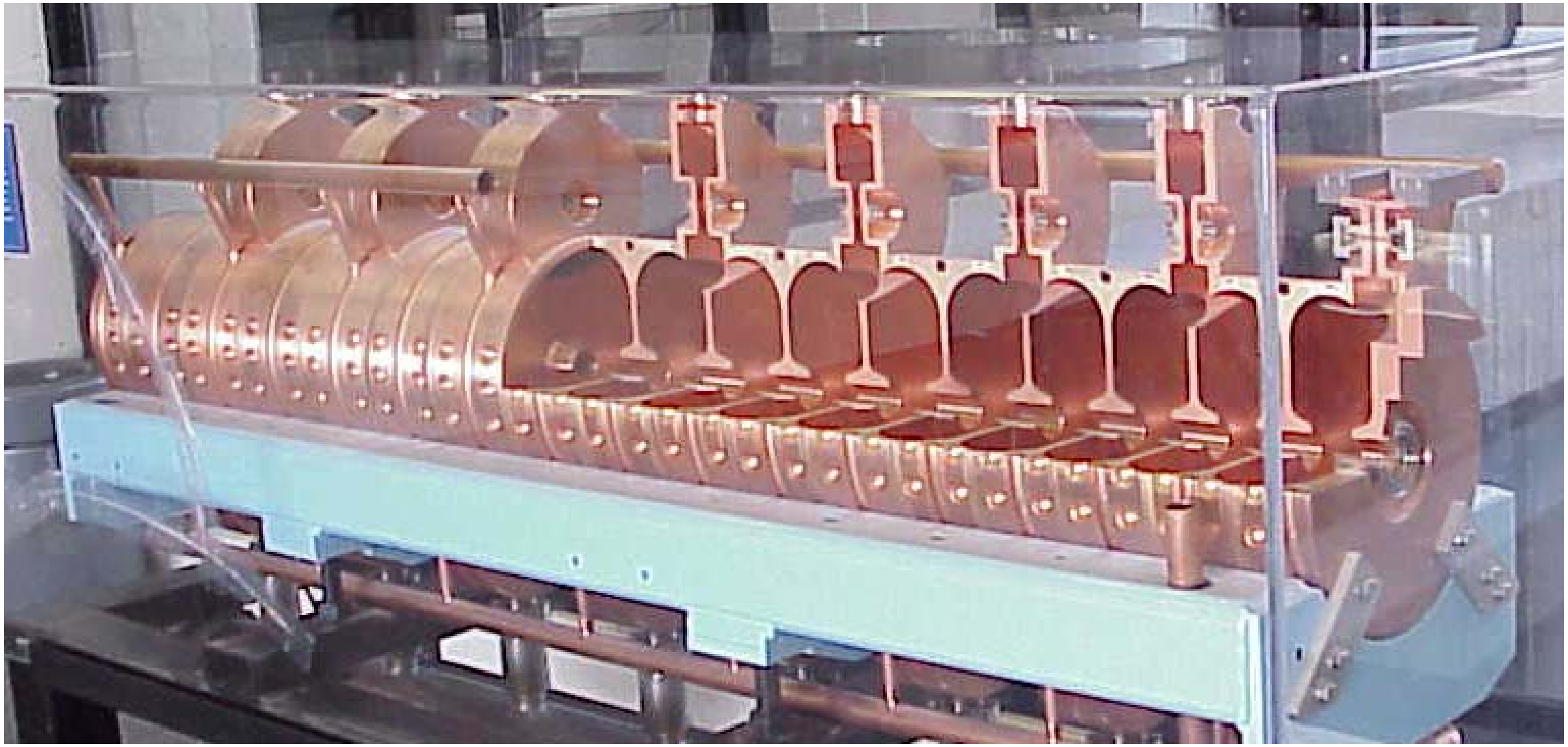
Caveat

- My background is detectors not accelerators.
- Many of you may know more than I do about some part or other. Please feel free to add comments and to correct any mistakes I have made.

A Few Numbers

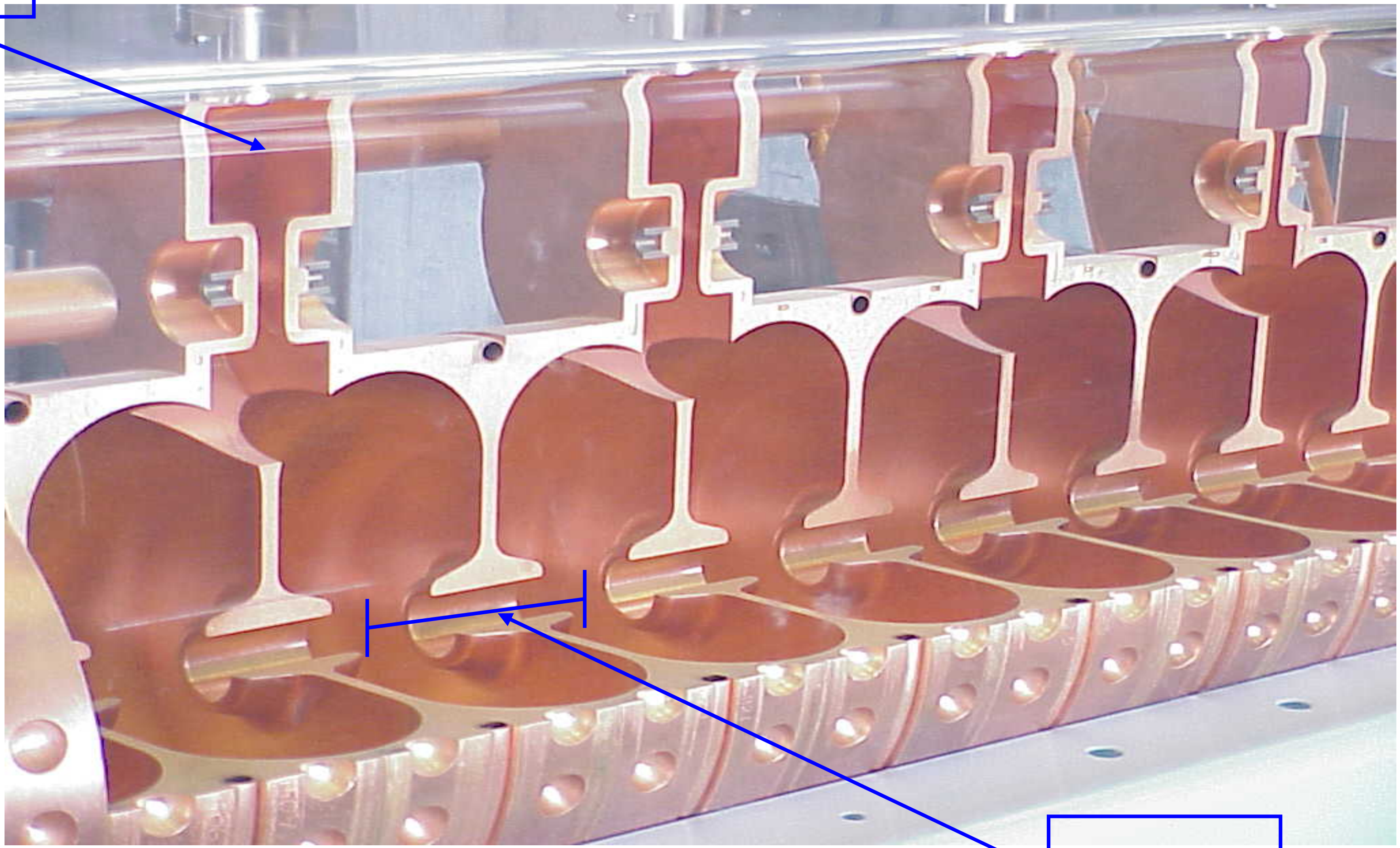
- Operating frequency: ν = 1.3 GHz
- Wavelength: $\lambda = c/\nu$ = 23.1 cm
  - Feature sizes are typically rational fractions of the wavelength: $\lambda, \lambda/2, \lambda/4$ ...
- For electrons:
  - E=100 MeV, 1-v/c=12.E-6
    - Difference of 12 microns over 1 m.
    - Bunch length is 300 microns.
  - So to a good approximation the electron speed is constant over long lengths of the linac.
    - Notable exception in first few meters.

RF Cavity Cutaway on 15th Floor



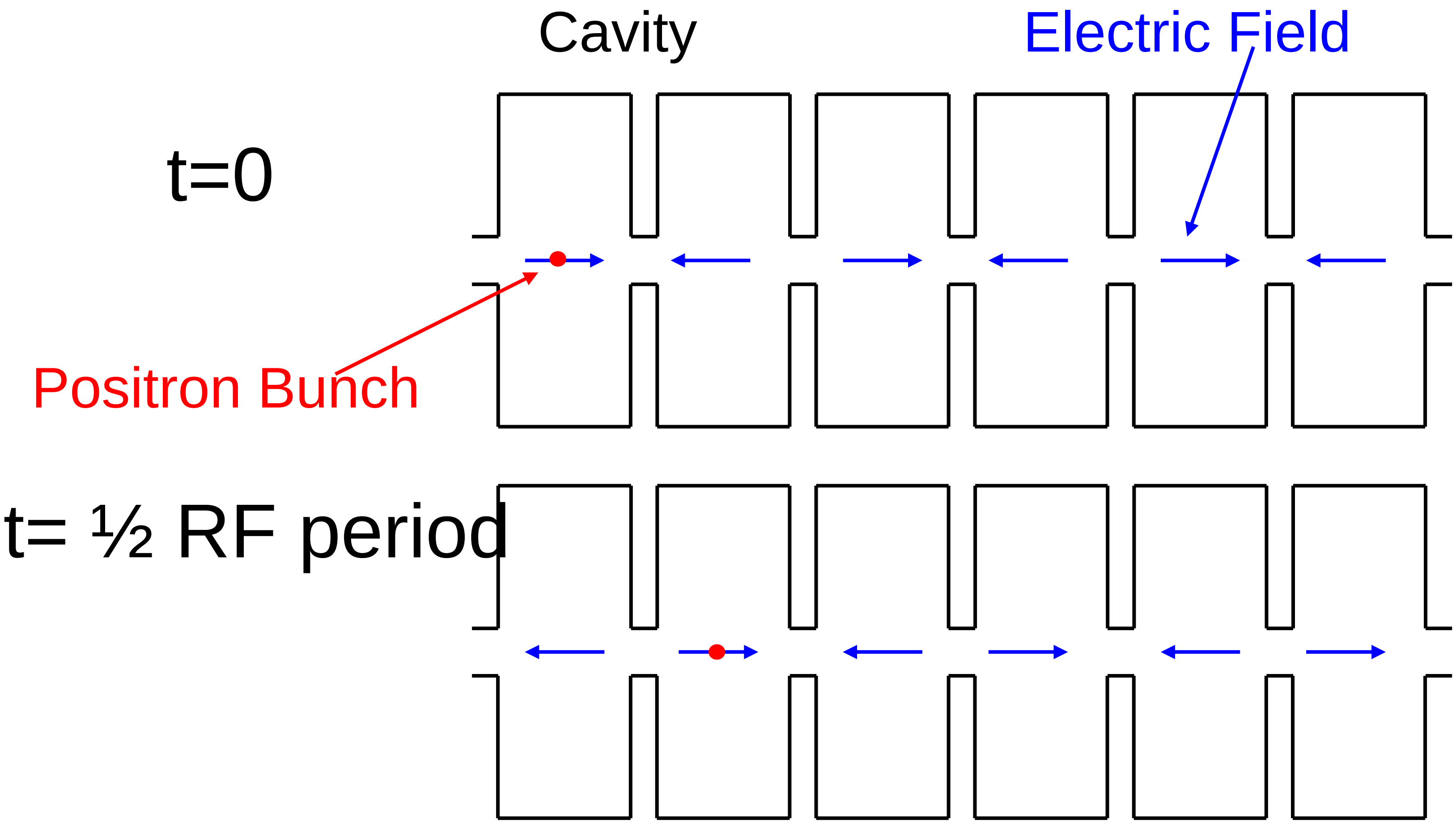
The RF Cavities are the heart of the ILC

Detail of the 15th Floor Cavity



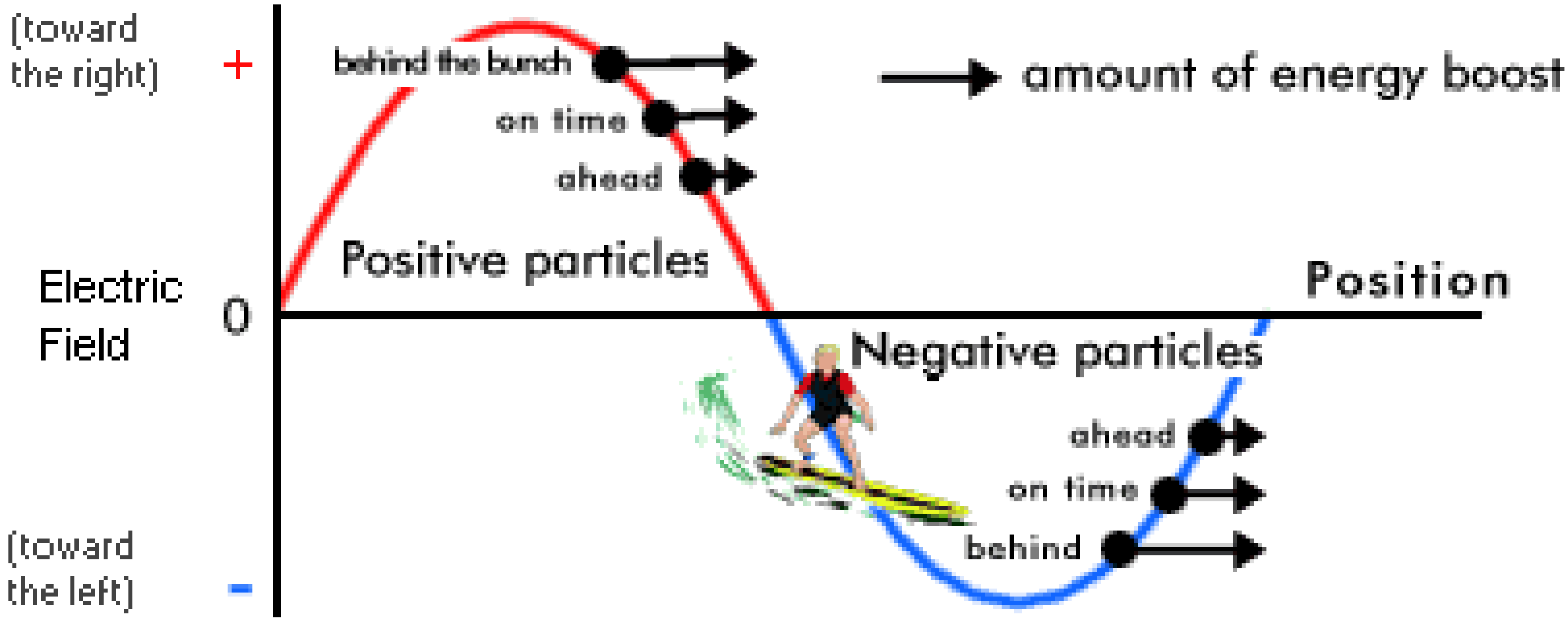
- RF energy enters via ports
  - ILC has only one port per 9 cell cavity (?).
- Energy bounces around inside the cavity cells. Bouncing waves interfere with each other.
- Shape designed to get standing wave interference pattern with the property that the on axis electric field is:
  - Parallel to the axis.
  - Oscillates in strength (+ and -).
- I forget what the field is off from axis.
  - Close to axis the transverse components are small.
- Q = quality factor of resonantor.
- Q of unloaded ILC cavity needs to be $10^{10.}$ High Q implies:
  - Higher on-axis field for a given input power at correct frequency.
  - Tighter demands on accuracy and stability of the input frequency.
  - Tight mechanical and material tolerances.
- Cavities can be tuned to respond to the correct frequency (within small tolerances).

Basic Idea for Acceleration



- Positrons accelerate in the direction of the electric field.
- Electrons accelerate in the direction opposite to the electric field.
- Node in the standing wave between cells.
- Detailed shape of cavity and choice of the RF frequency ensures that the electric field has the correct phase (timing) with respect to the arrival of each bunch.
- Electrons/positrons extract energy from the standing wave.

Snapshot of Electric Field Strength



"Phase Focusing" keeps bunches bunched.

- Operate close to max field strength:
  - Gives maximum acceleration
- But not too close:
  - No phase focusing exactly at max.
  - Actually defocuses if bunch straddles max.
- High frequency, short bunch length and long accelerator length make it harder to precisely control the timing of the RF relative to the arrival of the bunch at every cell.
- Q increases with falling temperature
  - Cost optimum around 2K.
- Bunch extracts energy from the standing wave.

- ILC 9 cell cavity in its vertical orientation.
- Only one input port per 9-cell cavity.
- 2 other ports discussed later.

Why 9 Cells per Cavity?

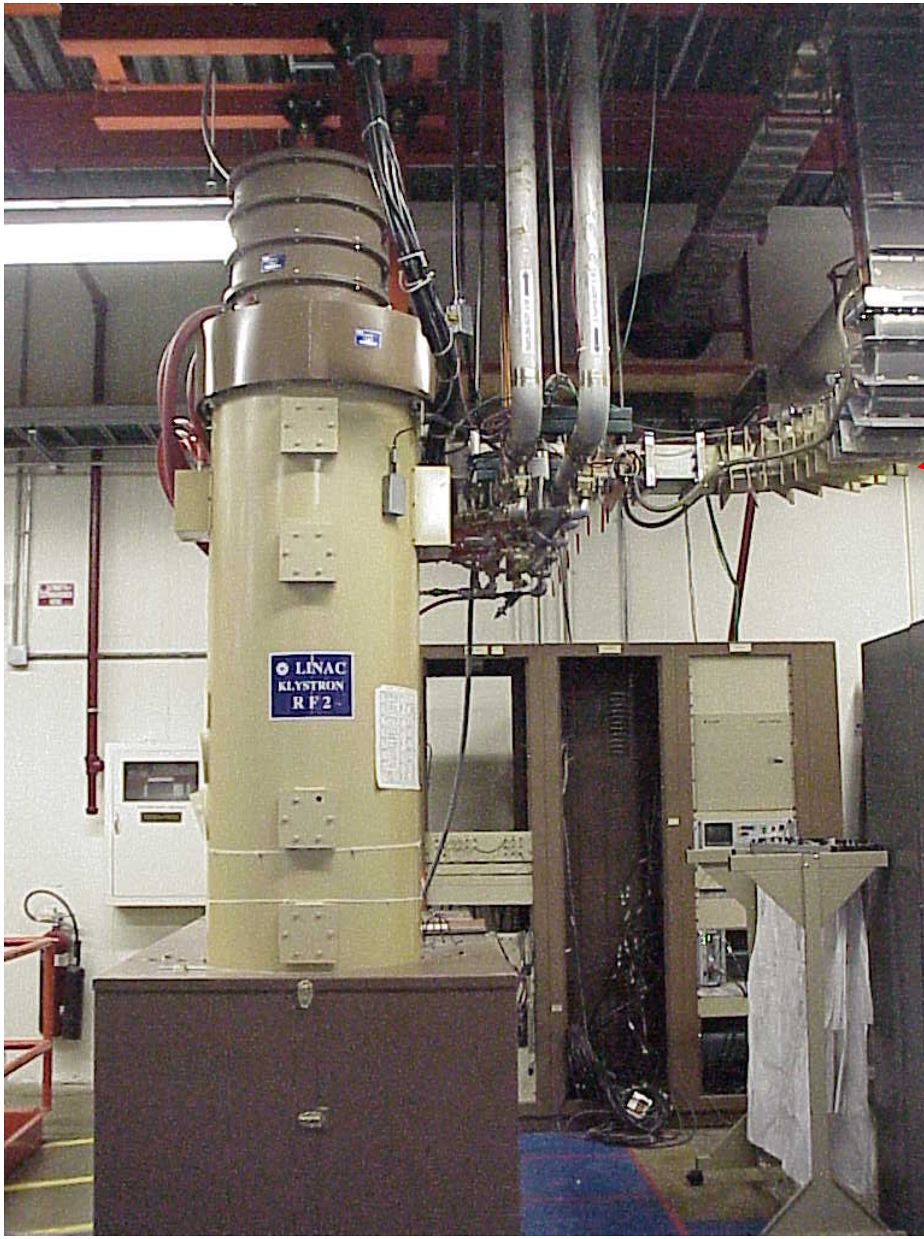
- If too few cells/cavity the packing fraction is too small.
  - Need things like bellows between cavities to allow for thermal expansion.
  - Other reasons?
- If too many cells/cavity:
  - Production yield issues.
  - Peak accelerating field drops with number of cells (really another sort of yield issue).
  - Other reasons? Approximation of constant speed fails????

What Are the Other Parts For?

- Delivering power to RF cavities.
- Corrections for imperfections.
  - Includes focusing of off-axis particles.
- Feedback and monitoring.

Klystron

- A narrow band RF amplifier.
- Phase of output waveform controlled by a reference wave (from low level RF).
- Amplitude of output frequency governed by power delivered by the RF Modulator (think of it as a power supply for the klystron).
- More info:
  - http://en.wikipedia.org/wiki/Klystron
  - http://www2.slac.stanford.edu/vvc/accelerator.html



- Klystron in the linac gallery (well, the housing of a klystron …)

Waveguide

- Like a very low loss cable for RF energy.
- Evacuated rectangular structures.
- Transverse dimensions fractions of a wavelength of RF (½, ¼ I forget which).

- Amount of power from klystron that gets into the cavity is called the transmitted power or forward power.
- What happens if you put power into a cavity but no bunch comes through?
  - Energy bounces around the cavity and comes back out the wave guide.
    - Reflected power.
    - Time scale for discharge is a few ms (O(Q periods)).
      - Loaded cavity has a Q of O(3 x 10^6).
  - Need to protect klystron from reflected power
    - Circulator directs reflected energy to a load.
- Bunch does not remove 100% of the energy so some always bounces back. (Check this?).
  - Modulator should be programmed to supply less energy if a small bunch is expected.
    - Or else input energy is just transported to dump. Wasteful.
  - Is this controlled by low level RF?
- If klystron frequency does not match cavity's, almost all power is reflected and only a little is stored in the cavity.

- What happens if you send an on axis beam down an unpowered cavity?
  - It creates a standing wave in the cavity (which runs out the waveguide if one attached).
- What about an off axis beam?
  - Creates higher order modes (HOM) in the cavity.
    - Excites other patterns of standing waves at different frequencies.
    - Need to get rid of this energy by putting a second port on the cavity (at a location that does not disturb the primary standing wave much).
    - Connect a waveguide to the HOM port and send the higher order mode energy to a load.
    - Drum head example?
- Offaxis beam in powered cavity is the same.

- Could use the HOM port for diagnostics?
- ILC design has three ports:
  - Main power input port
  - 2 HOM ports.
- Can also check cavity performance with and without beam by measuring the reflected power.
- For the first few meters of the linac the electron speed is much less than c and special treatment is needed.

Dewars, Cryostats, Cryomodules

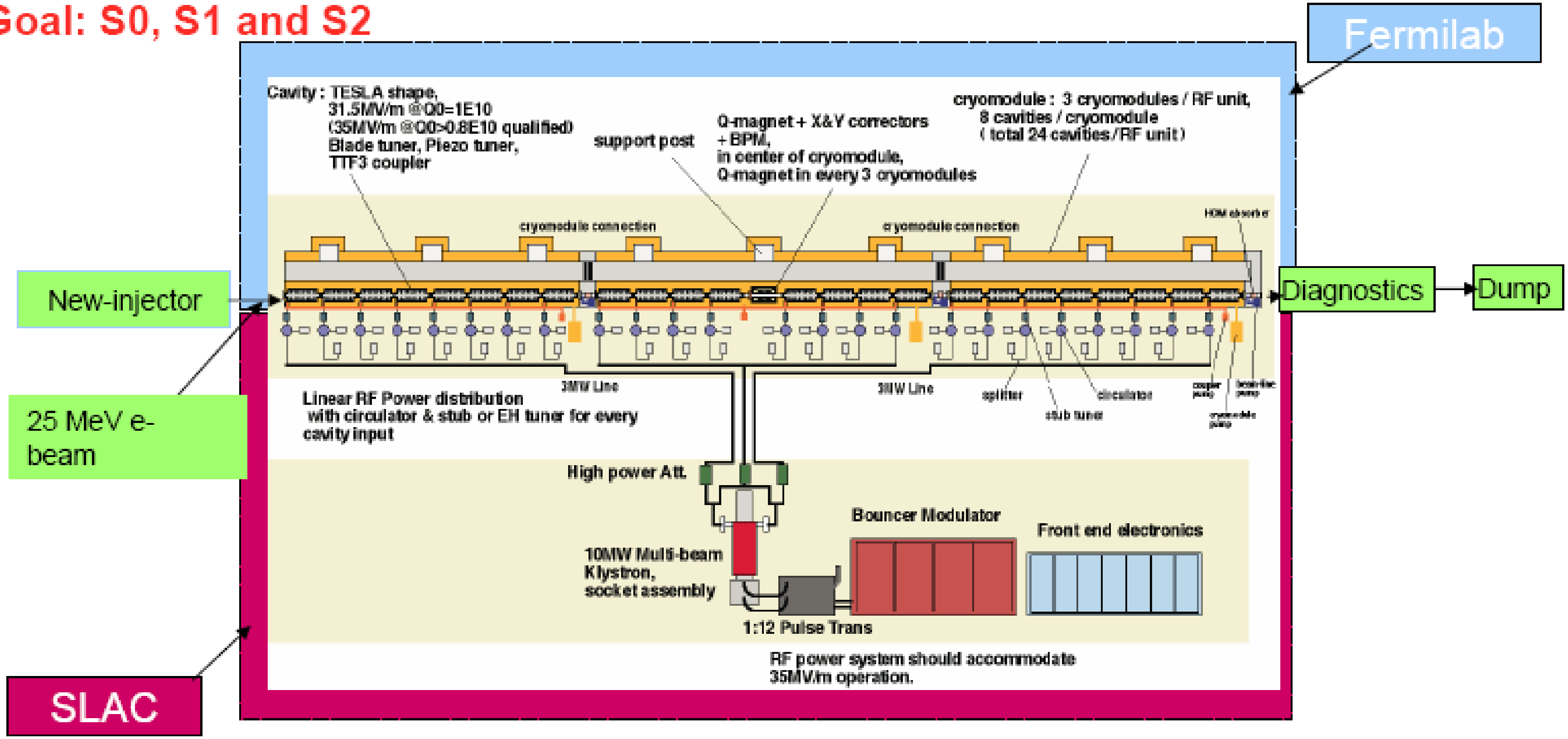
- Dewar:
  - Vessel with vacuum insulation (thermos bottle).
  - Contents is not under vacuum; vacuum is in the walls.
- Cryostat:
  - A device used to maintain constant low temperature.
  - Usually two layers of dewars: liquid nitrogen layer outside and liquid helium layer inside.
    - I guess ILC ones are like this (don't really know).
- Cryomodule:
  - 3 cavities (9+9+8) cells enclosed in a single cryostat.
  - 8 cell cavity also holds some magnets
    - Focusing, correcting??? Not sure.

RF Unit

- In ILC design 3 cryomodules are powered by a single klystron (plus its modulator and associated low level RF).
- Powered distributed via waveguides.
- Transition from waveguide to cavity is made by an RF power coupler.
  - Has controls to adjust phase of RF to ensure that all cavities have correct relative phase.
- Why 3 cryomodules per RF Unit?
  - Power limit of spec'd klystrons.
  - Commercial klystrons do not (yet) reach the specs for lifetime. One of the R&D projects.

ILCTA @ Fermilab Phase 1: 1 RF Unit

Goal: S0, S1 and S2



Components provided by US and International Collaborators

1st RF Unit Integrated by US Laboratories and Universities

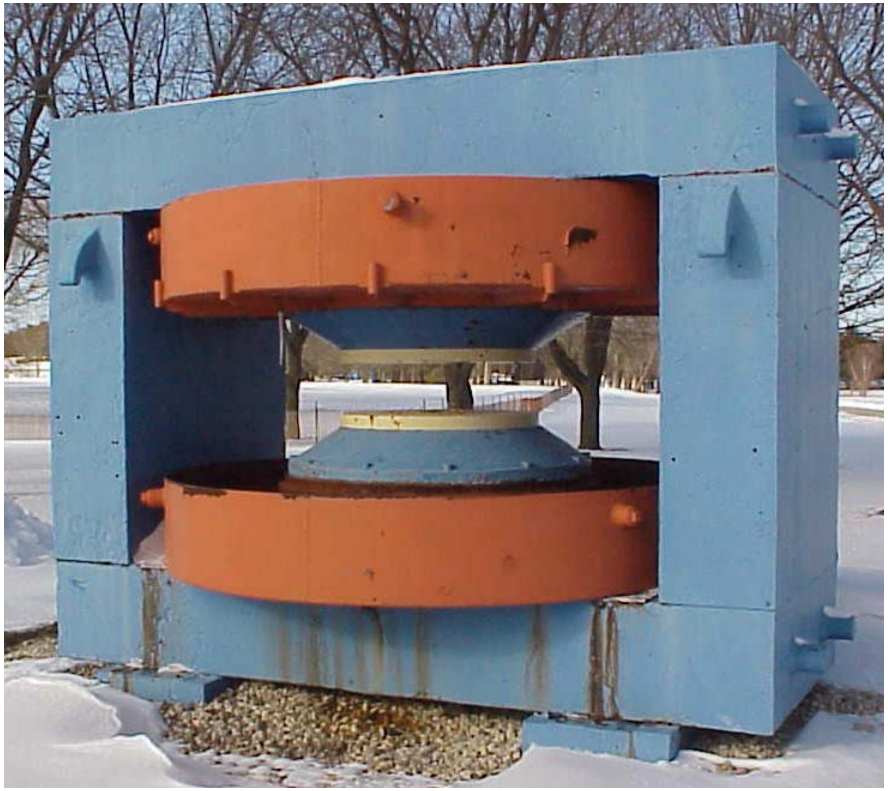
2nd RF Unit Produced and Integrated by ILC laboratories, Universities and Industries

ILC LLRF, Control, Instrumentation, Feedback etc. ILC Institutions

Multipole expansion

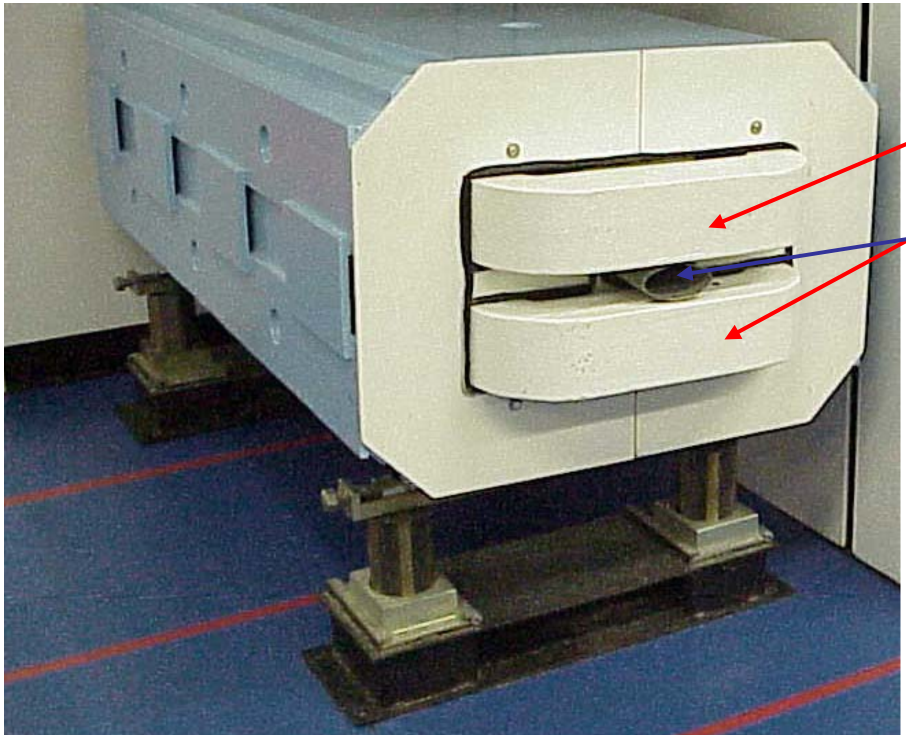
- One can write an arbitrary magnetic field as a power series expansion with powers of $1/2^n$.
  - Dipole – two lobes in field pattern.
  - Quadrupole – 4 lobes in field pattern.
  - Octopole – 8 lobes
  - Hexdecapole – 16 lobes
  - …
- Why no n=0 term or other odd terms?
  - Magnetic monopoles (magnetic analog of electric charges) have not been observed, even though we have looked very hard.

Dipole Magnet – Old Style



- Current carrying circular coils go into the orange housings.
- Current runs in same sense in upper and lower coil packages.
- This magnetizes the iron.
- Magnetic field is constant and vertical between the pole pieces.
  - Trajectory for a horizontal particle is (arc of) a circle.
- For TeV dipoles, distort pole shape to a racetrack.

Mockup of a TeV Dipole



Coils: "racetrack" shape.

Beam Pipe

- On axis field is constant and vertical.
  - Edge effects – see later.
- Without iron pole tip, field is still constant and vertical but changes more rapidly off axis.
- Iron is useful up to about 1 T (check value).

Dipole Magnets

- When iron is present:
  - The shape of the field between the pole tips is governed by the shape of the iron.
  - Can be sloppier about coil construction.
- For fields over about 1 Tesla, iron saturates.
- To get stronger fields, just use coils without iron.
  - Tougher construction tolerances for coils.
  - To get really strong fields you need very high currents: use superconducting coils to keep losses low.

Quadrupole Magnets

- What happens if a particle is not traveling exactly along the cavity axis, or if the axes of all cavities are not perfectly lined up.
  - Particle starts to drift transversely.
- Focused back to the beam axis by quads.
  - Four current loops.
- Quads focus (FO) in x and defocus (DO) in y (or vise versa).
  - Or pick any pair of orthogonal transverse coords.
- If a FODO pair have the correct separation there is net focusing in both planes.
- During acceleration, the beam is only focused enough to keep it in the “sweet spot” of the machine.
  - At IP the beam is tightly focused.
- (Spot size times divergence) is conserved.

Corrector Magnets.

- Dipoles and quads have end effects, construction tolerances, materials defects …
- These produce higher order multi-pole components.
- Need to have higher order magnets to correct for the errors induced by these effects:
  - Sextupole
  - Octopole
  - Hexadecapole
  - …
- Positions of these magnets are fixed. To make the corrections, one varies the currents in them.

Kicker Magnet

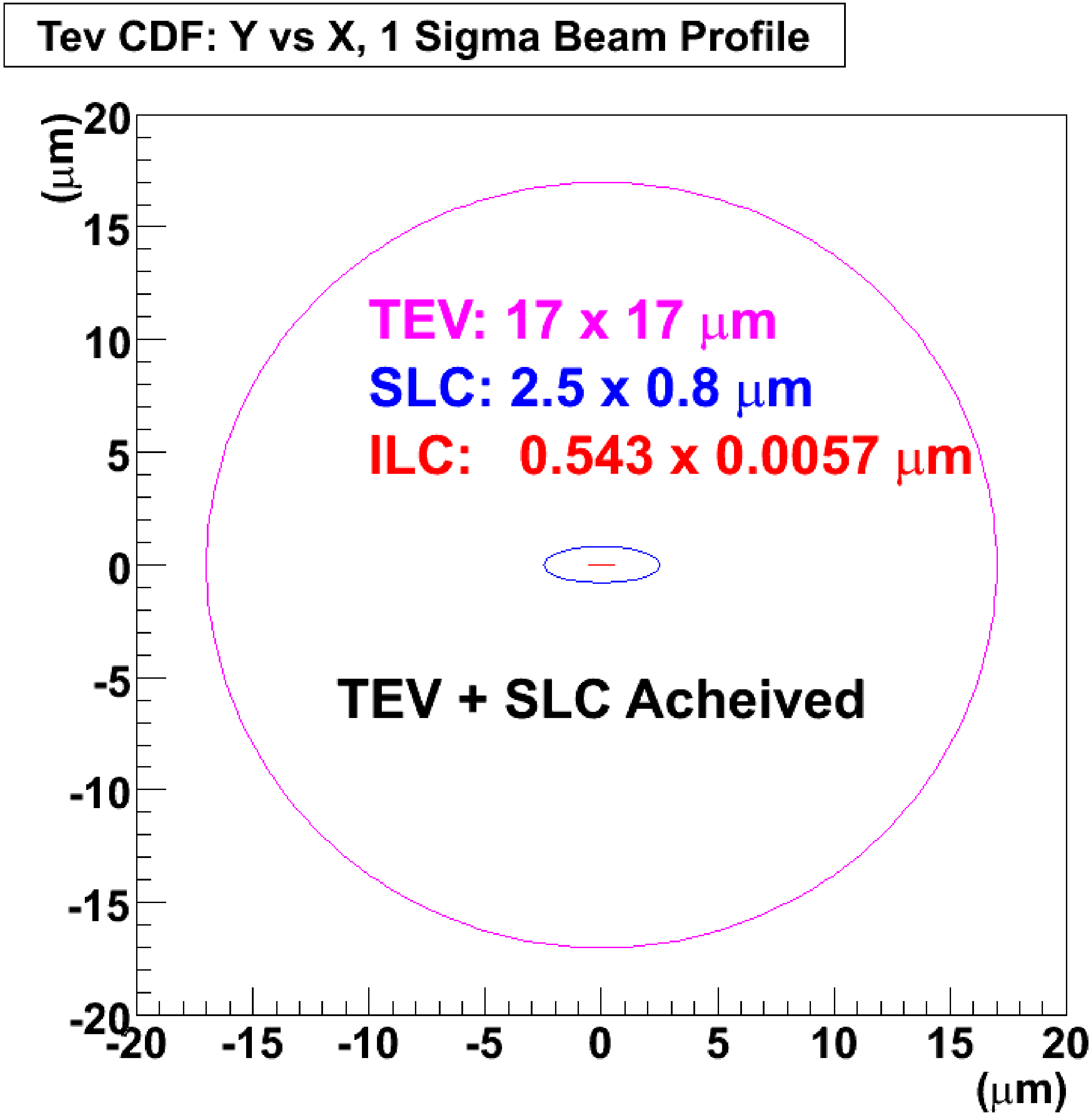
- Magnet used to move particles from one trajectory to another. Example: injection or extraction into MI, TeV, Booster …
  - All the ones I know of are dipoles.
- Magnet and associated power supply must have fast rise and fall times.
  - Do not want to disrupt leading and trailing bunches, just the one you want.
  - For ILC some very fast kickers are needed.
- Often the bore needs to be wider than a typical magnet to accommodate the two trajectories.

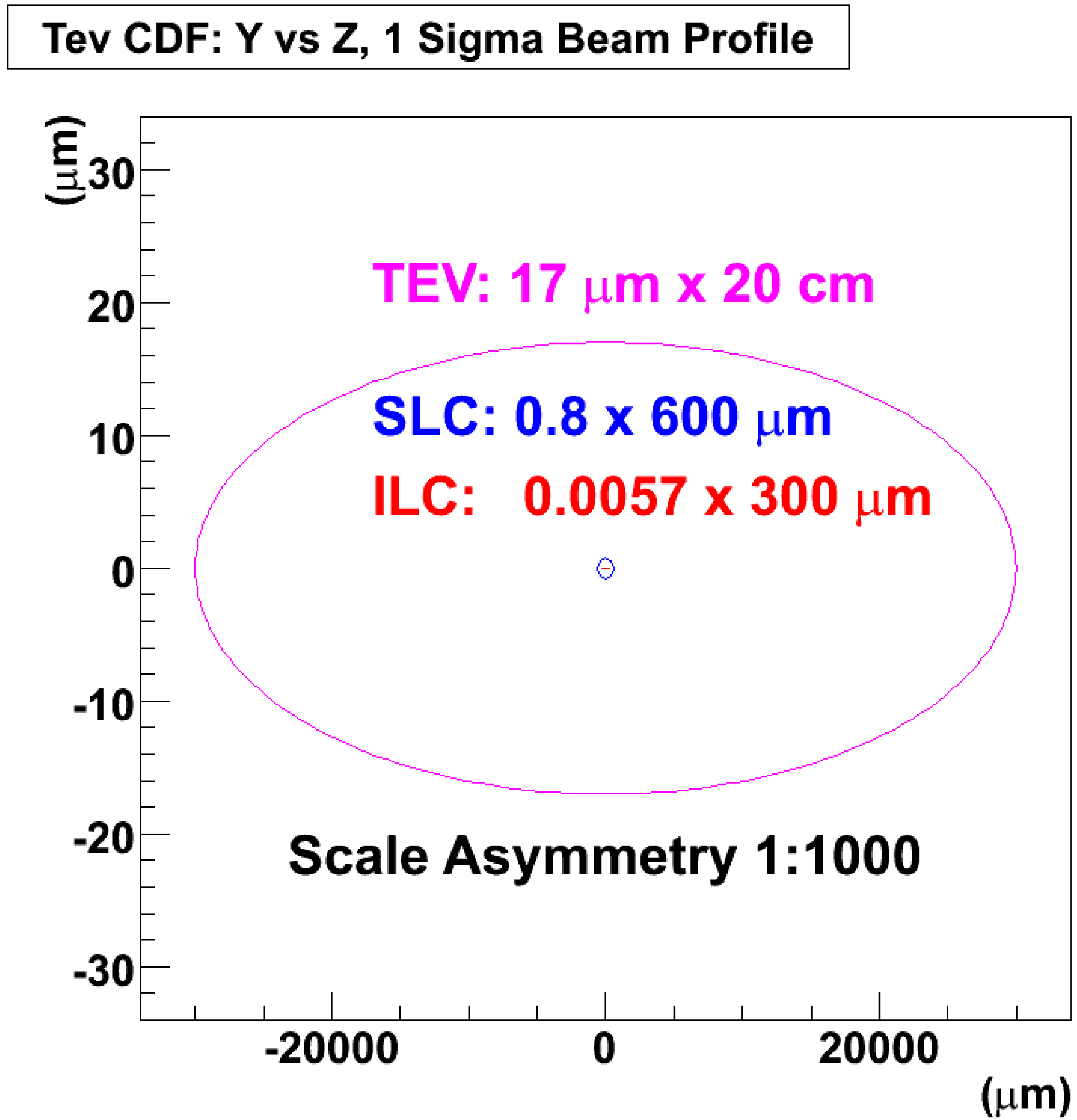
Magnet Summary

- Dipole: bends beam
- Quad: focuses beam in one plane.
- FODO pair of quads: focuses beam in both planes.
- Higher order poles:
  - Correct for end effects, manufacturing tolerances ….

Spot Sizes at IP

- Along linac focusing is just enough to keep beams in the linac.
  - Spot size is relatively large.
- Just before IP the beams pass through very strong quads to tightly focus the beam and make a small spot size at the IP.
- Spot size is much, much smaller than anything previously achieved.
  - See figures on next two pages.
  - SLC refers to the Stanford Linear Collider, a previous “linear” collider than ran in the 1990’s.

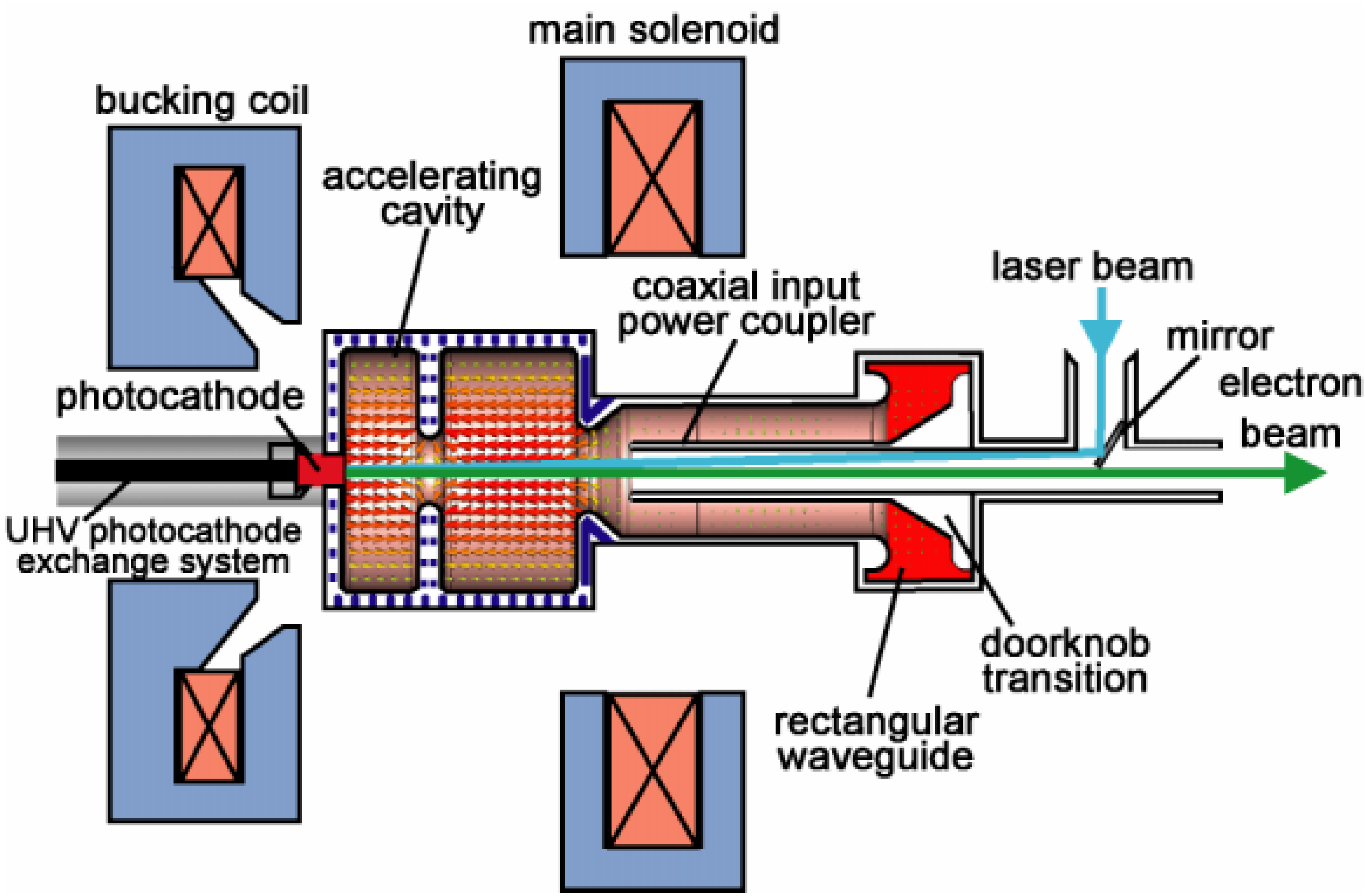

Tev CDF: Y vs X, 1 Sigma Beam Profile
TEV: 17 x 17 μm
SLC: 2.5 x 0.8 μm
ILC: 0.543 x 0.0057 μm
TEV + SLC Acheived
(μm)
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0
5
10
15
20
(μm)


Tev CDF: Y vs Z, 1 Sigma Beam Profile
(μm)
30
20
10
0
-10
-20
-30
TEV: 17 μm x 20 cm
SLC: 0.8 x 600 μm
ILC: 0.0057 x 300 μm
Scale Asymmetry 1:1000
-20000
0
20000
(μm)

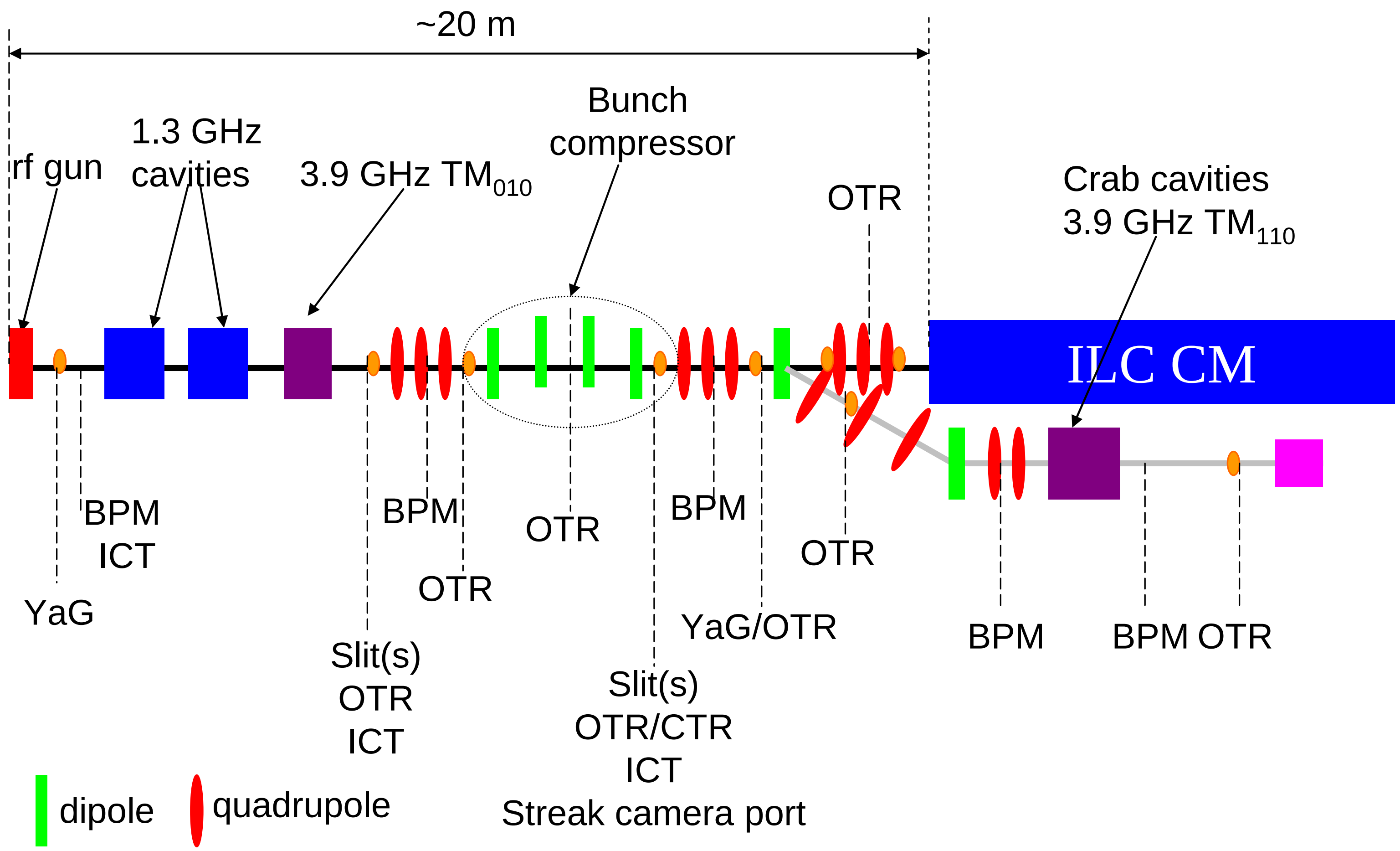
Making Positrons

- The ILC will accelerate bunch trains of about 1 ms in length, 5 times a second.
  - Duty cycle is about 1/200.
- During the off-cycle, electrons will be accelerated partway down the main linac and diverted to an undulator.
  - Static, period magnetic structure with very high magnetic field gradients.
  - This wiggles the beam to radiate forward going photons.
  - Then you steer the electrons out of the way.
- Put a sheet of high-Z material (Pb?) in the path of the photons: produces electron-positron pairs (plus junk).
- Keep the positrons and throw the rest away.
  - Do this with magnetic and electric fields.
  - Then focus and cool the positrons.

RF Gun


main solenoid
bucking coil
accelerating cavity
coaxial input power coupler
laser beam
mirror
electron beam
photocathode
UHV photocathode exchange system
doorknob transition
rectangular waveguide

NML Test Accelerator Schematic



Still to come

- Faraday Cup
  - Metal, cup-shaped electrode.
  - Used to measure ion currents. Think of a closed electric circuit in which part of the path is not a wire but a stream of ions or electrons traveling in vacuum. The rest of the path is a more traditional electric circuit.
  - Not sure how it is used here. I guess it is used to measure the electron current somewhere in the RF gun.
- Dark Current.
- Magnetic Chicane bunch compressor.
- Superconducting.

The 3.9 GHz Cavities

- 3.9 GHz. The NML test accelerator contains some 3.9 GHz cavities that are used to bunch the beam more tightly.
  - Being developed as part of A0 project.
- We will make one set for us and another set to send to DESY who will use it in the same way at TTF.

Not Ready for Prime Time

IQ Plot

- Could mean a few things. This is my guess.
- Many observable things can be represented as a complex number.
  - An RF signal at a fixed frequency has a magnitude and phase.
- I and Q are just the real and imaginary parts of the complex number. (Sometimes the polar representation might be more useful).
- Language comes from the idea that you are measuring the amounts of some signal that are “In phase” and “in Quadrature” with a reference signal.
- Or it could refer to something totally different.
- I need to know the context in which you saw this to be sure.

More Trivia

- When a pulse of energy comes down wave guide from klystron, it induces currents in the walls of the cavity.
- These currents repel and attract each other (known as Lorentz forces).
- These forces distort the cavity and change its resonant frequencies (tune).
- Piezoelectric actuators are present to pre-distort the cavity in the opposite direction so that the Lorentz force distorts the cavity back to the correct shape.