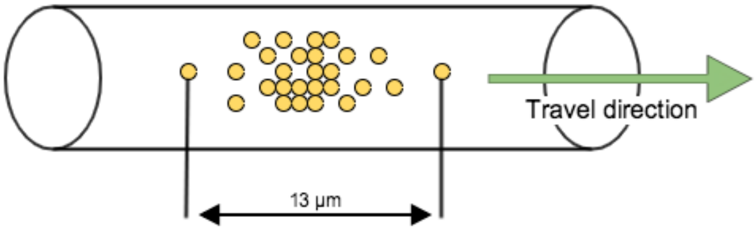
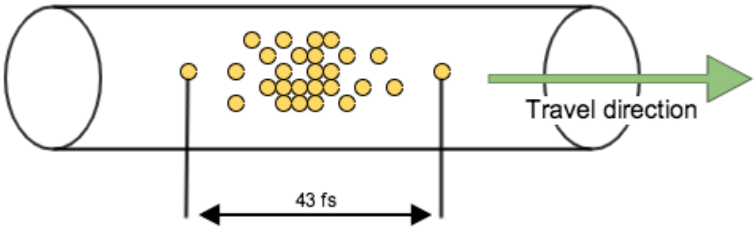
How the Length of the Bunch is Measured

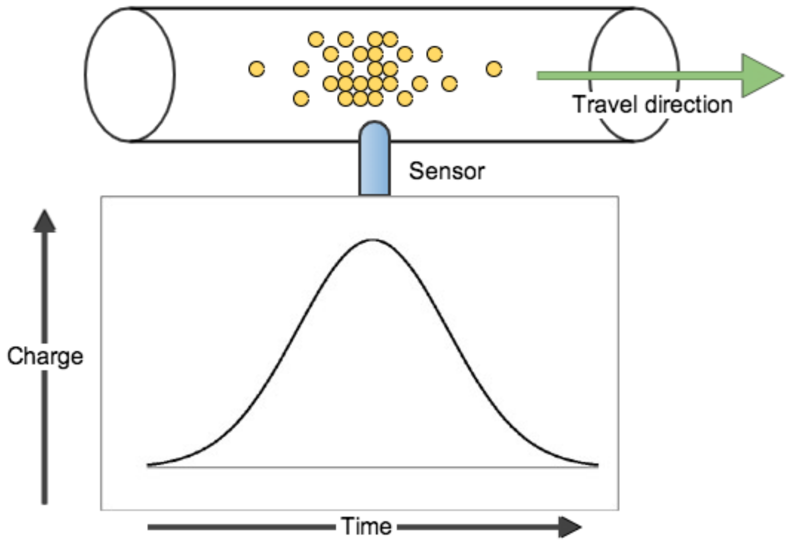
So, you have a bunch of electrons running inside a pipe "full of vacuum" and one of the parameters you want to measure is its length:



One way to represent the length is by using space units. But, as the electrons are running near the speed of light, we can think by means of the time that they travel in such a small distance (13 µm in our example). Doing 13 µm (13 x 10^{-9} km) divided by 300,000 km/s, we get 43 fs (femtoseconds).



In order to measure this tiny distance in this really small time, the first solution we can think is to place a sensor in the pipe and digitize the intensity of the electrons as they pass near the sensor. As the electrons distribute themselves close to a Gaussian, we would get a reading similar to the one below. The more electrons we have, the bigger will be the area below the bell curve. Ok, the physicists will run to me to complain that, sometimes, the distribution has two peaks, like two Gaussians summed up and that's why you will not show this document to them, deal? 🙂



So, in order to have enough sampling data, we could measure, let's say, 20 samples during the time the bunch passes. For doing so, we need a digitizer that can measure one sample each 2.15 femtosecond, in other words, 465 tera-samples per second. Easy peasy, despite the fact that the fastest digitizer nowadays can measure a few hundreds of giga-samples per second in an experimental way. One thousand less than what we need!

I know, I know... You are reading this in 2050, laughing at my face, because your cell phone has a peta-samples-per-second digitizer. In fact, now you are laughing even more because only your grandfather remembers what a cell phone is.

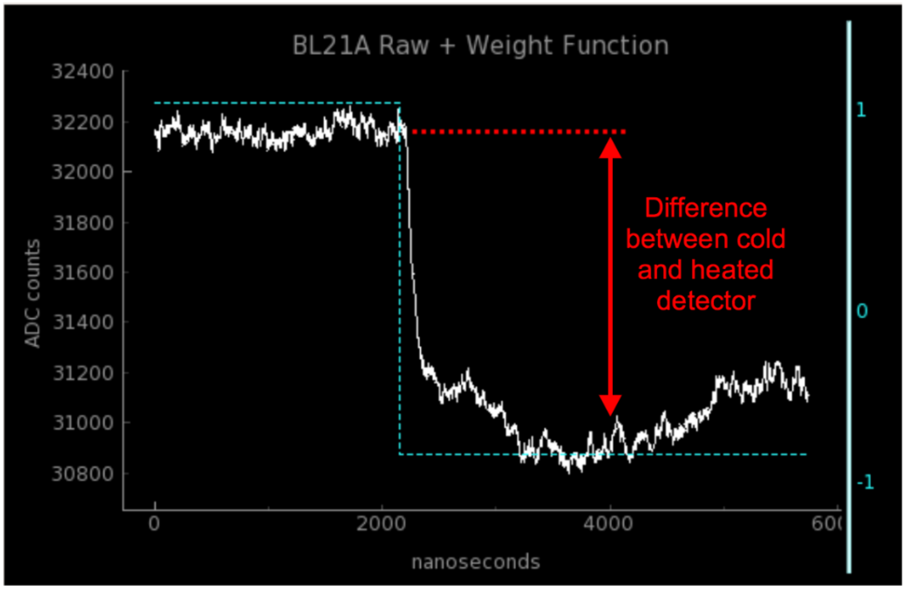
Martin Cooper, Motorola Engineer, holds the first cellphone in 1973, weighing 1.1 kg.

Well, we need to measure the length now, and not in 2050, so, we need to think of another method.

One of the solutions developed at SLAC involves a pyroelectric detector, which converts the infrared emitted by the electron bunch into voltage by measuring fast changes in the temperature of the detecting crystal. At the end of this document, there is an explanation about how this infrared is generated by the bunch and how it arrives at the pyrodetector. Take a look at here.

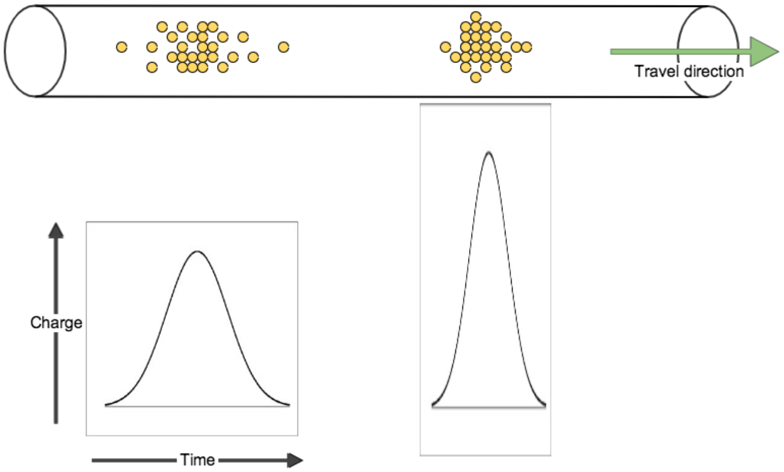
This pyrodetector takes some time to cool off after this pulse of heat, and so we can measure its signal using an MSPS (mega sample per second) digitizer. Imagine the pyrodetector as a sensor that can measure the area under the Gaussian and this area corresponds to the total charge of the bunch (there are still some complications, but keep going with this in mind).

And how do we see the output of this sensor?



The idea here is to measure the signal when the pyrodetector is cold and compare with the signal when it is heated. This difference is proportional to the total charge of the bunch (the area under the Gaussian). This digitizer outputs an inverted waveform, with the cold moment being shown higher than the heated moment. But that doesn't matter as we need only the difference between them.

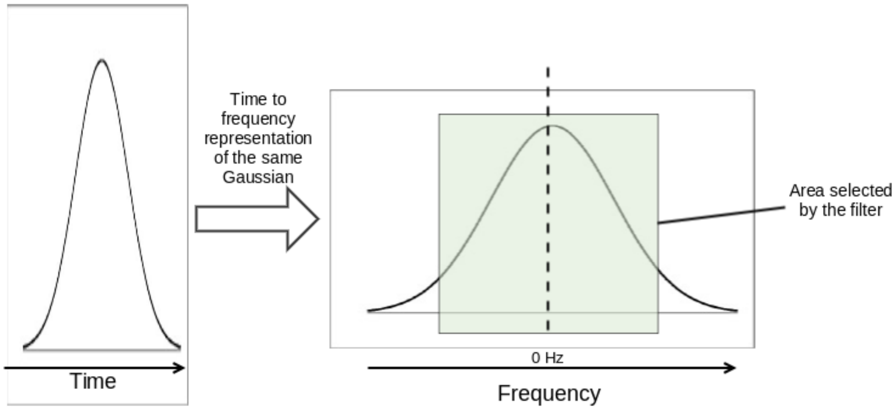
Now, let's take a look at two different electron bunches. Imagine that we have two bunches with 100 million electrons each. Let's keep with the example with bunches having the same number of electrons for now. You will see later what to do when this is not the case. One of the bunches is wider than the other. See how the charge is distributed in time:



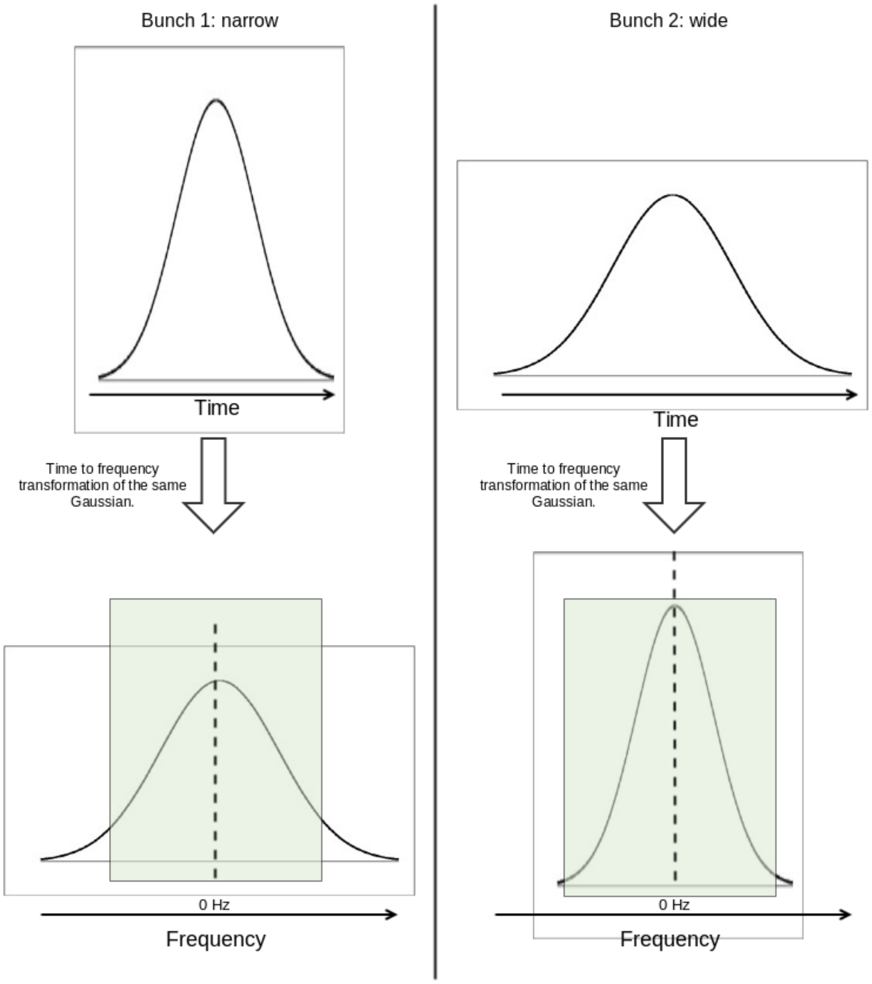
The wider bunch has few electrons in the center than the shorter one. This is due to a property of the Gaussian: the area below the curve is proportional to the number of electrons. So, in the figure above where we have the same number of electrons, if we short it in the X-axis, we must grow it in the Y-axis in order to maintain the same area. As the area is the same, and we are interested exactly in the area, we need to help our pyrodetectors to differentiate one from the other. Let's check how this is done.

Sinusoidal waves are our bricks in the construction of any kind of waveform we need. When we see a high-speed rise of a curve, that means we need a bunch of high-frequency sinusoidal waves to build it, while low-speed rise can be built with low-frequency waves. Take a look at the 8:30 minutes video What is a Fourier Series? (Explained by drawing circles) to get an easy intuition about it. The way we see our building bricks is not in a traditional time-domain chart, with time in the x-axis. For this, we need a chart in the frequency domain, with the many different frequencies that build up our waveform in the y-axis.

With all of this in mind, we can see that a narrow Gaussian in the time domain is a wider Gaussian in the frequency domain and vice-versa. The bunch-length system uses an optical low-pass filter that removes some of the high-frequencies. It is like we are removing the bricks from the right side of the wall. We can draw the effect of the filter in the frequency domain Gaussian (note that both charts represent the same Gaussian, the first one in the time domain, the second one in the frequency domain):

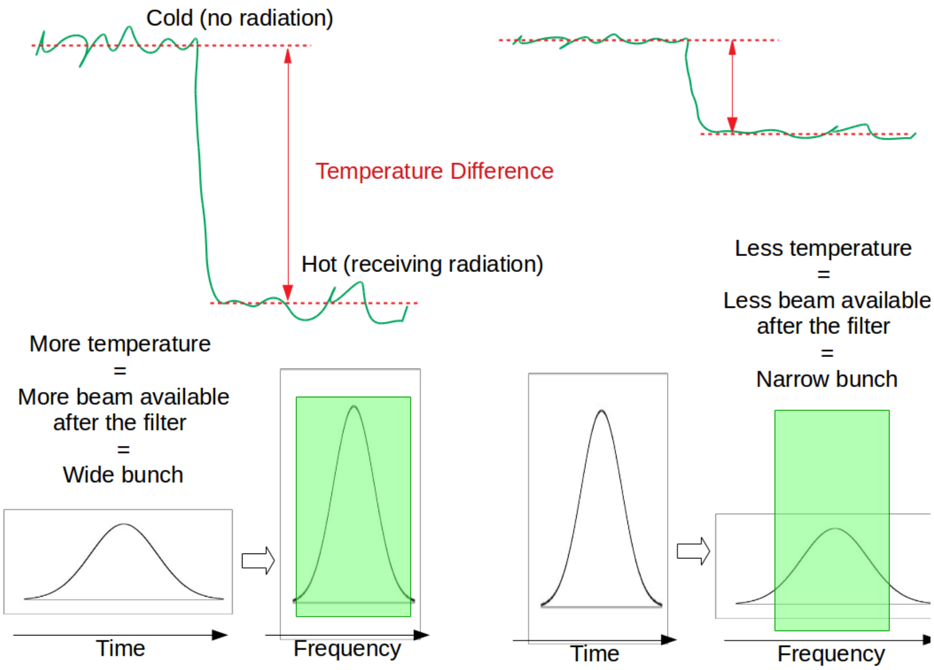


Using the same filter for 2 bunches with different lengths:



See that, in the first chart, part of the Gaussian is filtered out while, in the second chart, almost everything passes through the filter. So, for the narrow bunch, part of the power is absorbed by the filter and less radiation arrives at the pyrodetector. For the wide bunch, we have more radiation arriving.

So, when we see a small difference when comparing the sensor reading hot or cold, that means the length is **smaller** when compared to a big temperature difference:



Now, given a Gaussian, all we need to calculate the length is to know the peak of the charge. For this, we need a formula that converts the difference of the temperature (cold compared to hot) into this value (more details below):

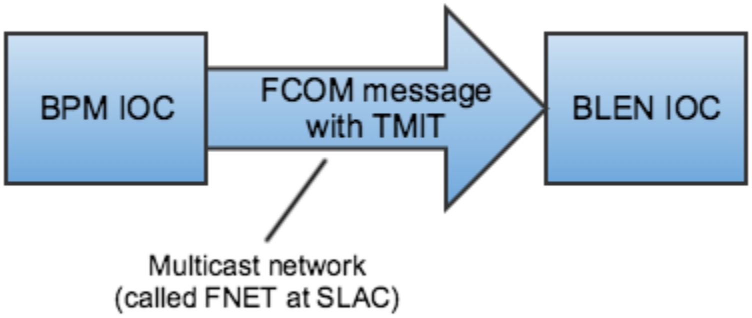
$$IMAX = B \cdot TMIT^{C} \cdot ARAW^{D} + E \cdot TMIT^{F} \cdot ARAW^{G}$$

ARAW is exactly the difference between temperatures when the pyrodetector is receiving radiation or not. B, C, D, E, F, and G are numbers configured by physicists during the calibration process to convert the difference in temperature measured by the pyrodetector into the peak current.

We could be happy right now that we understand how the length of the bunch is measured, but there is still an important concept missing: imagine that we have two bunches with the same length, but with a different number of electrons. For example, one bunch with 100 million electrons and another one with 200 million. Despite the fact that they have the same length, the doubled number of electrons will transfer more infrared to the sensor, making the temperature reading greater. Remembering that we are using a Gaussian to calculate everything, more temperature means that the calculation results in a bigger peak charge, what tells us that the bunch should be wider than the bunch with fewer electrons. This is a wrong result!

The way we deal with it is by applying a normalization. We need the charge of each bunch to compare the number of electrons in order to make the area below the Gaussian always equal for all bunches. If the area is equal, a bigger peak will always mean a wider bunch, no matter how many electrons are traveling in that bunch.

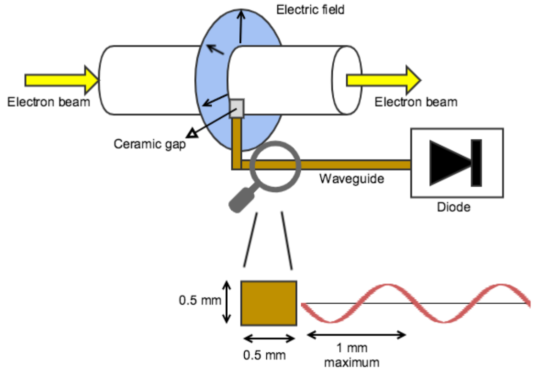
This charge is called TMIT (TransMitted IntensiTy) and we get the value from the BPM that is placed right before the bunch length system infrared mirror. The value is sent by the BPM IOC to the BLEN IOC using the production multicast network (called FNET). The language they speak is the protocol FCOM, created at SLAC.



This charge is exactly the parameter TMIT we see in the formula.

The gap diode

The pyrodetectors are not the only technique used at SLAC to measure the length of the bunch. The gap diode is another way to do this. Take a look at this image an read the text from Alan S. Fisher below:



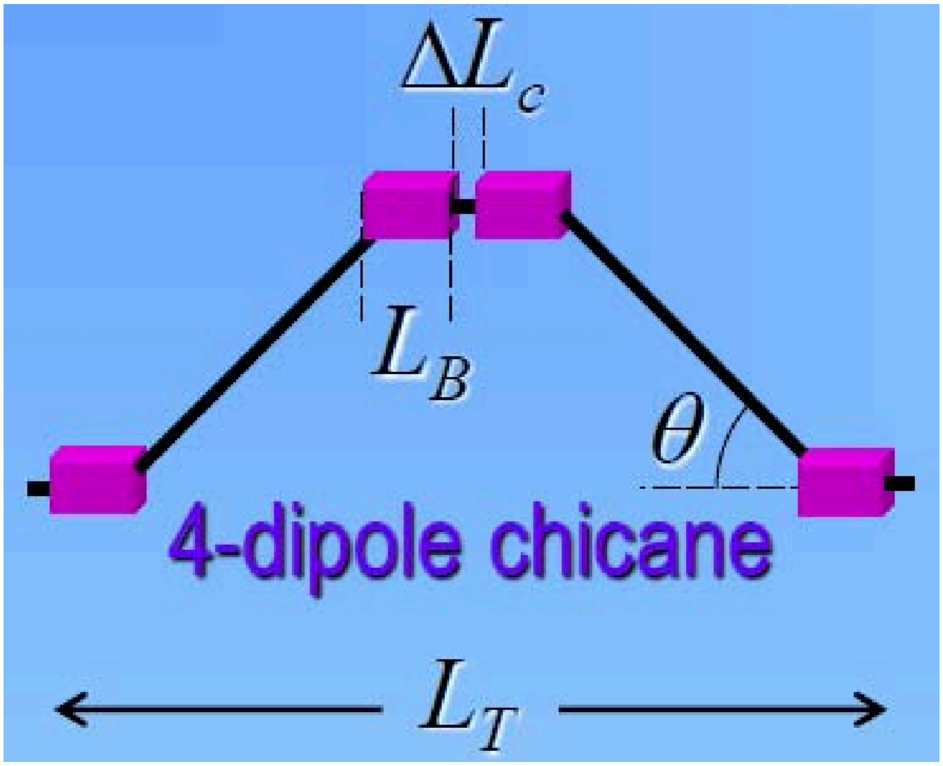
The electric field from the passing bunch forms a flat "pancake" in the radial direction. This field leaks through a ceramic gap in the metal beampipe and is collected as millimeter wave radiation in small waveguides. Waveguides do not transmit wavelengths that are too big to fit; the cutoff is when the wavelength is twice the width of the narrow dimension of the guide. So the waveguide itself is a filter passing only shorter wavelengths (higher frequencies). The special RF diode measures the power after the waveguide filters the radiation.

Consider two bunches, one short and one long, with equal charge. The field of the short bunch containing more high frequencies than the field of the long bunch. The waveguide passes only the wavelengths below cutoff—the higher frequencies—to the RF diode, and so the diode gives more signal for the shorter bunch.

We still have to ensure that we are not fooled by two bunches with the same length but different charge. This is again done by normalizing with a TMIT signal.

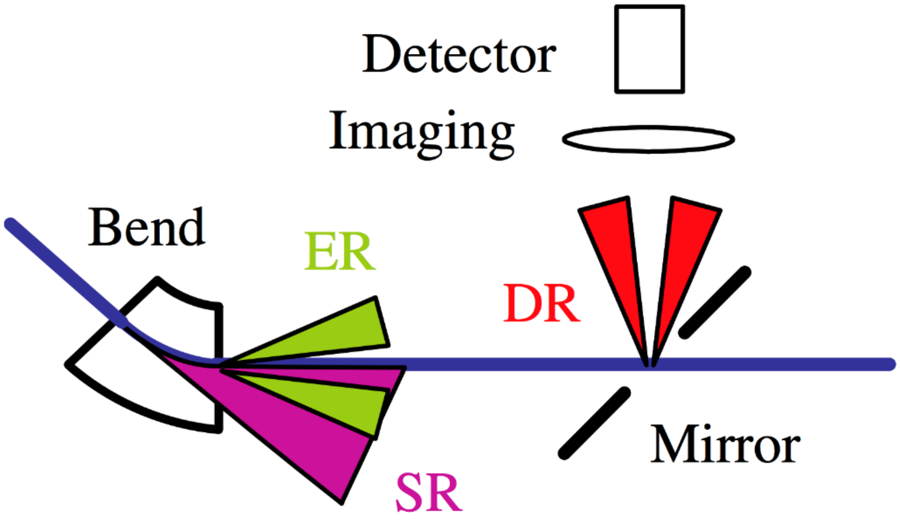
How the electron bunch generates infrared

The bunch length systems that use pyrodetectors are located just after the bunch compressors. The bunch compressor is a set of 4 electromagnets, called dipoles, that change the direction of the electrons.



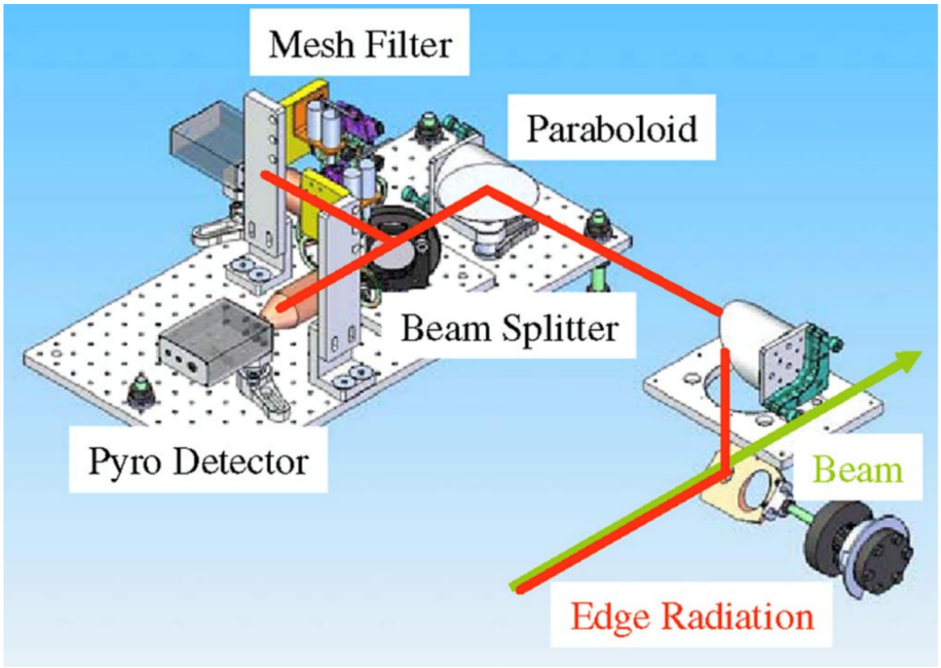
Think about the bunch compressor as a device where electrons with higher energy run in a longer path than the ones with lower energy. Then the slower electrons pass through in a shorter time than the faster ones. Just before the compressor we use a clever trick: an accelerating microwave cavity is timed to give the electrons that arrive earlier more energy than those that arrive toward the end of the bunch. Then the late electrons catch up with the early ones, making the bunch smaller from head to tail.

One side effect of each change in direction is that the electrons lose energy in the form of synchrotron radiation. Take a look at the last dipole of the bunch compressor:



SR stands for synchrotron radiation. ER stands for edge radiation. DR stands for diffraction radiation. The set draw as Mirror, Imaging, and Detector is our Bunch Length system. The mirror is positioned at 45 degrees from the beam direction and has a hole in the middle that allows the electron bunch to pass through. The mirror gets primarily edge radiation, mostly in the infrared, which reflects from a parabolic focusing mirror to the pyrodetector.

Here is a 3-D drawing showing how a set of mirrors conducts the infrared to a beam splitter and optical filters before hitting the pyrodetectors.



But why we get infrared at the mirror and not other wavelengths? Well, due to a physics property (there is a text from Alan Fisher below if you are in a mood for good adventures), the power of the radiation drops off at wavelengths shorter than the bunch length. The bunch has some microns in length, so anything with a shorter wavelength than some microns would be attenuated until being irrelevant. The infrared radiation goes from 700 nm to 1 mm, what puts microns just inside this range. That is why infrared is the most useful radiation at this point of the accelerator.

Text from Alan S. Fisher explaining the physics properties:

"The pyro (optical) BLEN system uses light emitted in the fourth and last dipole of the chicane of the compressor. When the beam goes around a bend, it emits synchrotron light in the uniform field. At the start or end of this curved path, it emits edge radiation. Both arise from accelerating a charge. The radiation from one electron is broadband, going up to x rays for our typical beam energies, but we have lots (N) of electrons. If they were all in the same place, the fields would be precisely in phase, and so would add. Then the power, which goes with the square of the field, would go up by N^2. But fields are complex, with phases as well as magnitudes. If the electrons are spread out over a wavelength or more, all values phases would be present and so the phases from different electrons—the cross terms—would cancel when we take the squared complex magnitude. Only the powers from individual electrons can add, and the power goes up like N. This fact causes the power to drop off at wavelengths shorter than the bunch length and explains why we see only far infrared. That is the reason that the light has a spectrum that goes to higher frequencies (shorter wavelengths) as the bunch gets shorter in time."