Northwestern University Plans

Topic: RF-pickup for **bunch length measurement**

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CTF3 Collaboration Meeting
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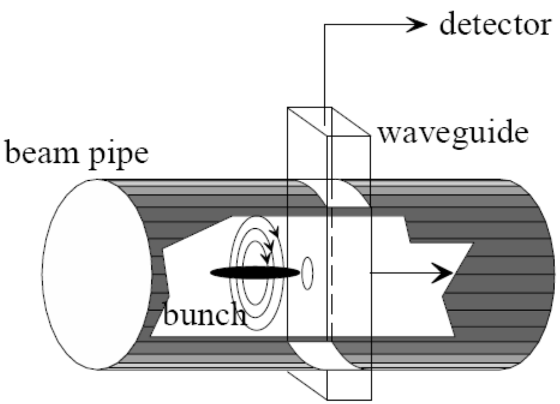
RF-Pickup for bunch length measurement

- Principle of the measurement
- Why do we need this type of bunch length measurement?
- Status of the hardware purchased and installed
- Design improvements envisage for the pickup and analysis setup

Principle of the measurement I

The RF-pickup **detector** measures the spectrum of the electromagnetic field of the bunch collected by a rectangular RF-pickup connected to a waveguide.



The frequency spectrum of the bunch contains all the information about the bunch shape and length.

The field induced in the waveguide has a temporal evolution directly related to that of the electron bunch

Hence it is possible to derive the spatial charge distribution from the frequency spectrum of the field excited in the waveguide

In this measurement, one takes advantage of the power spectrum in the frequency domain. For a given beam current, the larger the power spectrum amplitude, the shorter the bunch length.

Principle of the measurement II

Consider an electron bunch of N particles with longitudinal charge distribution Λ(z), following a straight line trajectory in free space.

The transverse fields in the laboratory moving frame, with a Gaussian bunch shape.

$$E_r(r,z) = \frac{eN}{2\pi\varepsilon_0 r}\left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)\Lambda(z) \quad \text{and} \quad H_\theta(r,z) = \frac{eNv}{2\pi r}\left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)\Lambda(z)$$

From the above equations we can derive the fields at the beam pipe wall at z= 0 for a beam traveling coaxially

$$E_r(r,t) = \frac{eN}{2\pi\varepsilon_0 R}\Lambda(t) \qquad \text{and} \qquad H_\theta(r,t) = \frac{eNv}{2\pi R}\Lambda(t)$$

The bunch is very often Gaussian

$$\Lambda(t) = \frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{t^2}{2\sigma_t^2}}$$

Fourier transform of a Gaussian→ a Gaussian

$$\mathcal{F}_x\left[e^{-a x^2}\right](k) = \sqrt{\frac{\pi}{a}}\, e^{-\pi^2 k^2/a},$$

Principle of the measurement III

$$\Lambda(t) = \frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{t^2}{2\sigma_t^2}}$$

,Where σ_t is the bunch length in time units $\sigma_z = v\,\sigma_t$

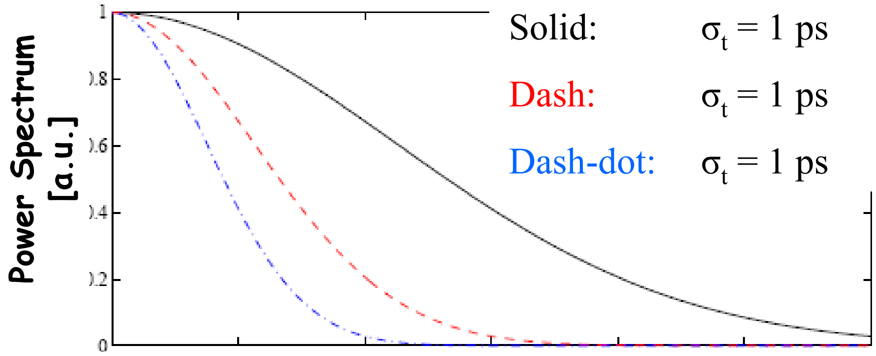
The frequency spectrum is found by Fourier transformation the fields, e.g.

$$\Lambda(\omega) \approx e^{-\sigma^2\omega^2}$$

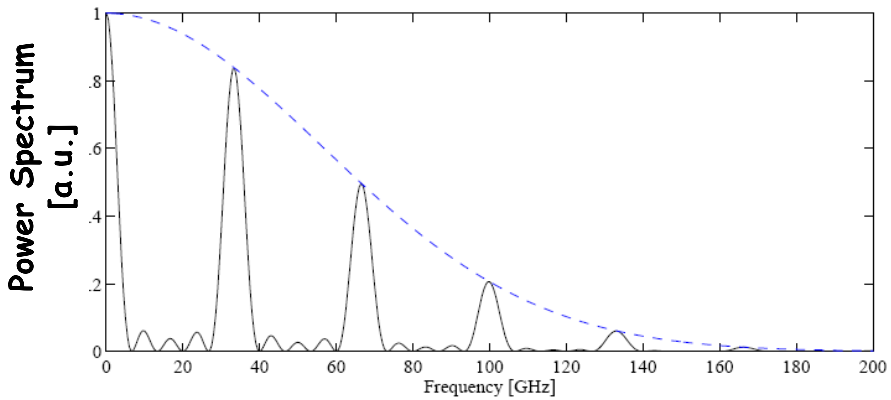
→The smaller the bunch length the larger the signal at a given frequency

→The smaller the bunch length the larger measured power

→To reach the < ps sensitivity, need to have reach of high frequencies

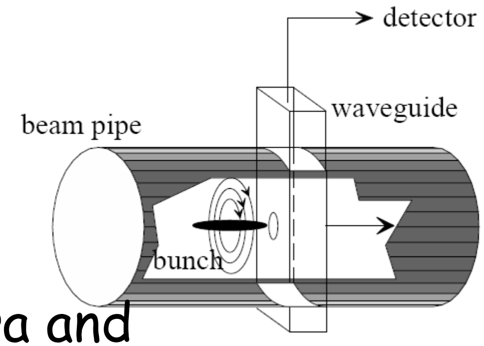


Power spectrum for Gaussian bunches of different length.



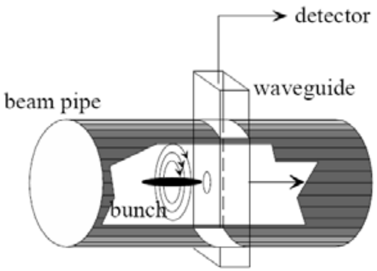
Frequency spectrum of a train of 5 bunches.

Advantages of the RF-Pickup



- Advantages
  - Non-intercepting / Non destructive
  - Easy to implement in the beam line
  - Relatively low cost (compared to streak camera and RF deflector)
  - Relatively good time resolution (ns) → follow bunch length within the pulse duration
  - Measure a single bunch or a train of bunches
  - Relative calibration within measurements
- Short comings in the calibration
  - Beam position sensitive
  - Sensitive to changes in beam current
- If used with the RF deflector (method of measuring bunch length at CTF3)
  - Can provide an excellent cross calibration of device

RF-pickup device installed in CTF2



- An RF pickup was installed in CTF2
  - Rectangular waveguide coupled to a rectangular hole made on the beam pipe surface
  - Using the mixing technique it measured bunches as short as 0.7ps. It was limited by a maximum mixing frequency of 90 GHz.

C. Martinez et al, **CLIC note 2000-020**

- This device was dismantled in 2002, and is no longer being used at CTF3.

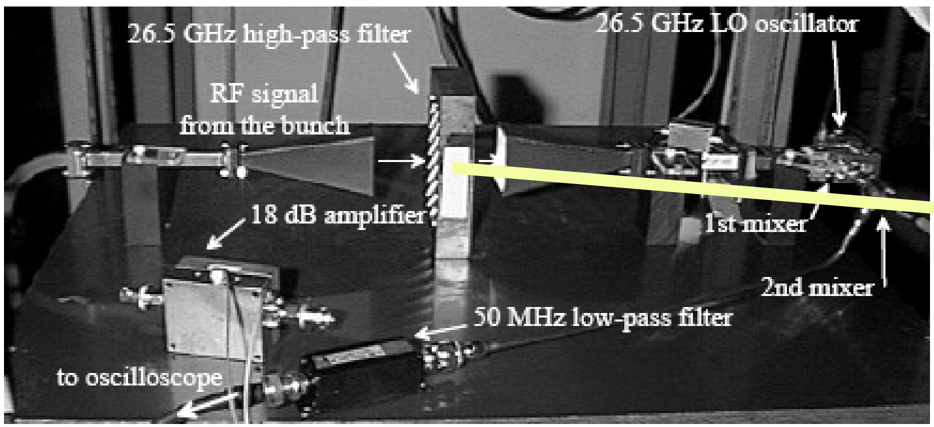
- Goal is to re-install the device with an improved design
  - Increase maximum frequency reach to max mixing at 170 GHz, to reach bunch length measurements of 0.3ps
  - Design a ceramic/diamond RF window for good vacuum and transmission at high frequency
  - Spectral analysis by single shot FFT analysis from a large bandwidth waveform digitizer

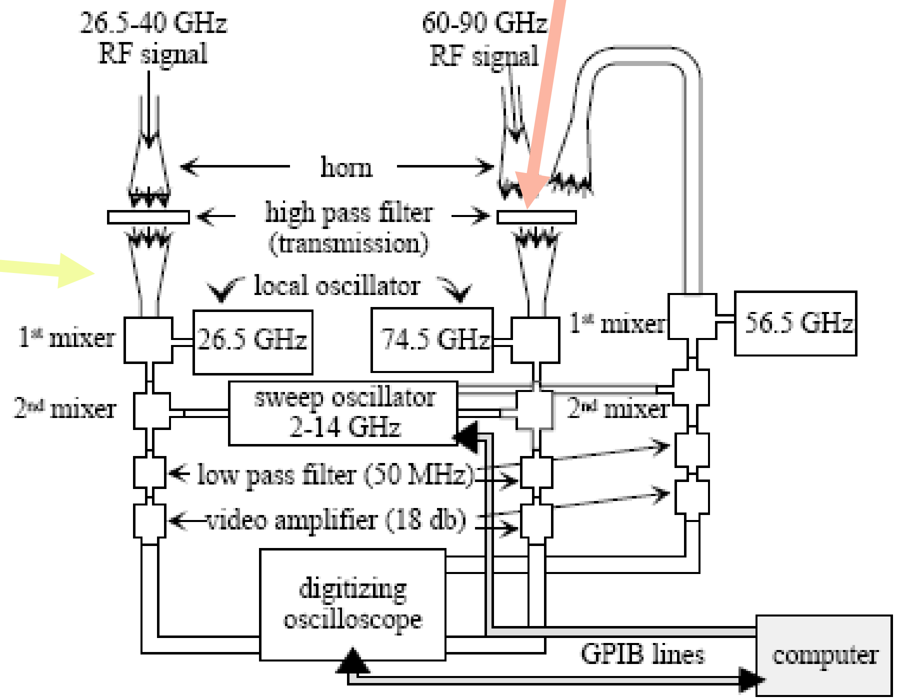
At CTF2, had 2 pickups in the machine with two different waveguides

WR-28 Ka band (26.5-40GHz) and

WR-12 E band (60-90 GHz)

In E band, use high pass filter at 74.5 GHz to separate the 60 – 74.5 GHz signal, and the 74.5-90 GHz signal





Complete measuring time for a spectrum at CTF2, including sweeping with the synthesizer and averaging ~ 20 min

mixing technique in CTF3

Install **one WR-28 pickup**, with **WR-28 waveguide** to transport the signal to the gallery

use a series of filters, and waveguide pieces on the same mounting board in the gallery to separate the signal in the following frequency ranges:

Frequency range	Components
(26.5 - 40) GHz	WR-28 Waveguide components, and mixer at 26.5 GHz
(60.0 - 74.5) GHz (74.5 - 90) GHz	WR-12 Waveguide components and mixer at 56.5 and 74.5 GHz
(143 - 157) GHz (157 - 170) GHz	WR-6 Waveguide components with mixer at 157 GHz

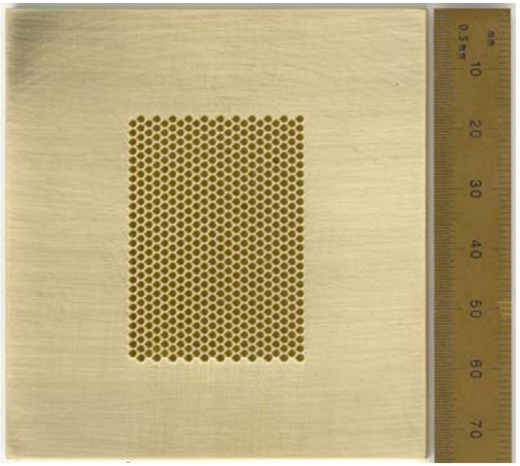
Investment in new hardware

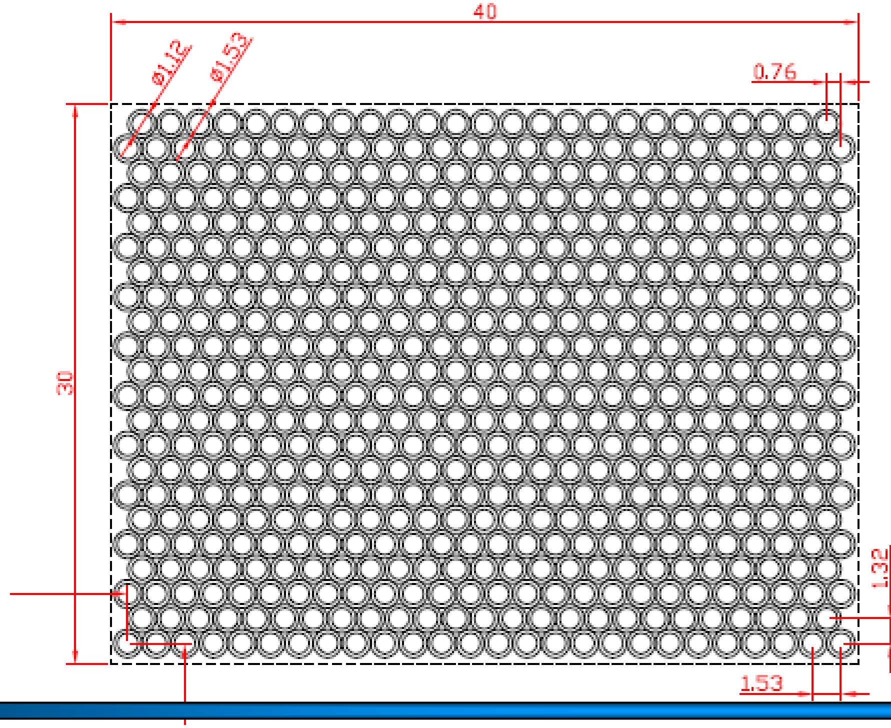
Components purchased by Northwestern

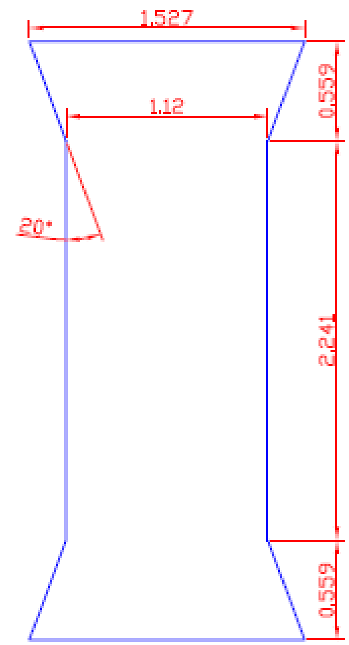
- Local oscillator (Down converter)
  - LO 157 GHz
  - RF 142-177 GHz
- D-band waveguide components (110-170 GHz, waveguide WR-6 1.65 mm x 0.83 mm)
  - D-band Horn (gain 20dB)
  - D-band fixed attenuator (10 dB)
  - D-band waveguide 5cm

Investment in new hardware - Filters

- Fabrication of Brass filter at 157 GHz
  - Conical edge at angle of 20 degrees, thickness 3 x diameter of hole
- Used as a high/low pass filter to study frequency band:
  - 157 GHz-14 GHz
  - 157 GHz+14 GHz
- Other filters to be used from CTF2 setup: 26.5 GHz, 40 GHz, 56.5 GHz, 74.5 GHz

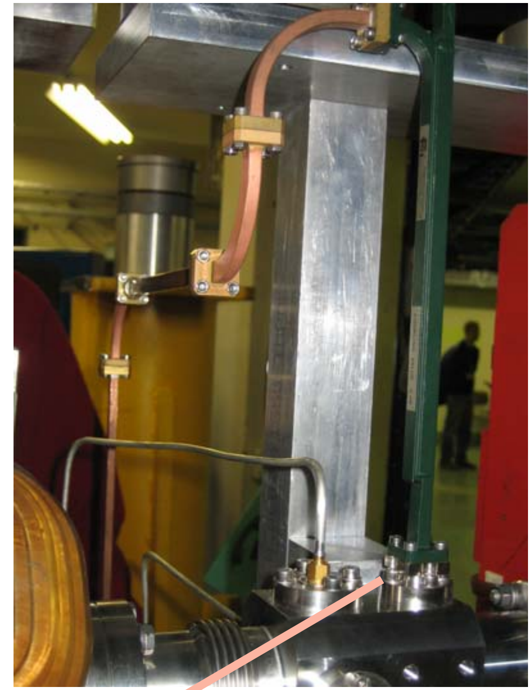


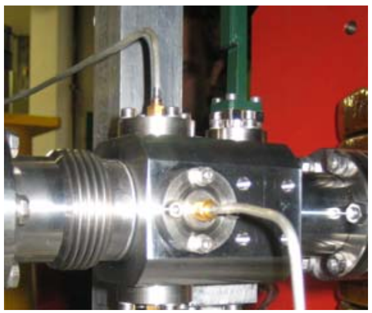


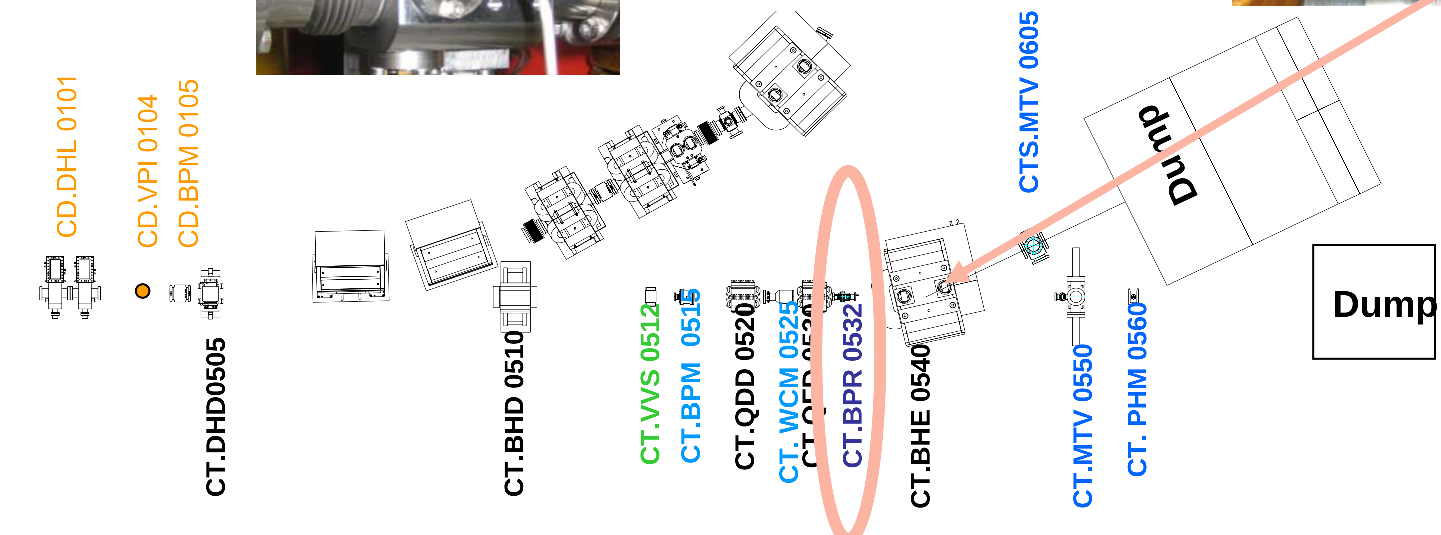


Scale (mm)

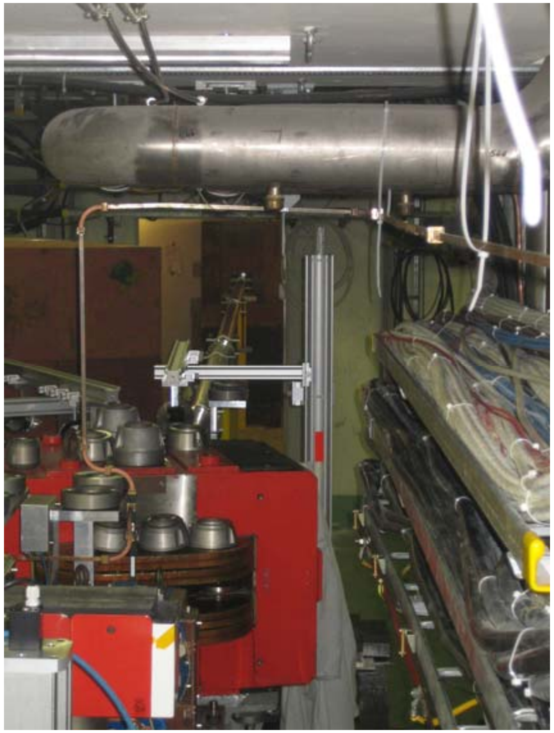
- Most recent Shutdown
- Pickup with Al_2O_3 window (3.35 mm thickness) installed in the CT line
- Signal from BPR0523 split, and ½ taken to the gallery along ~ 15m of WR-28 waveguide



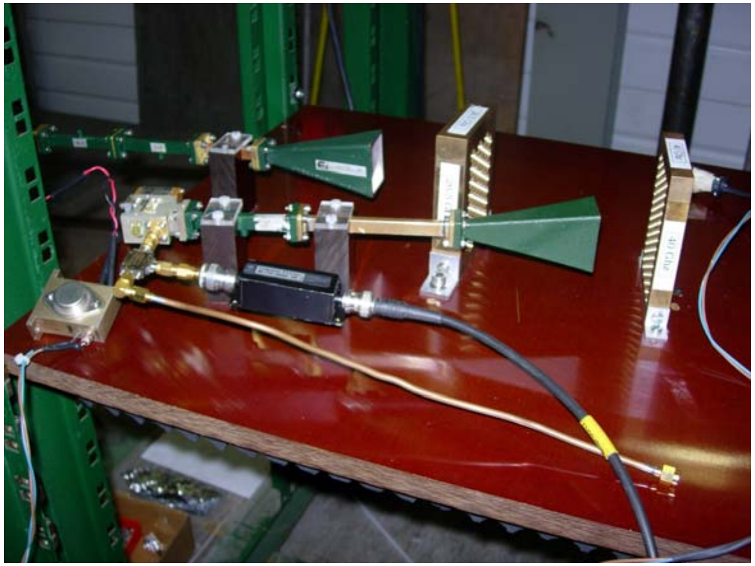




Status of installed hardware



The gallery →



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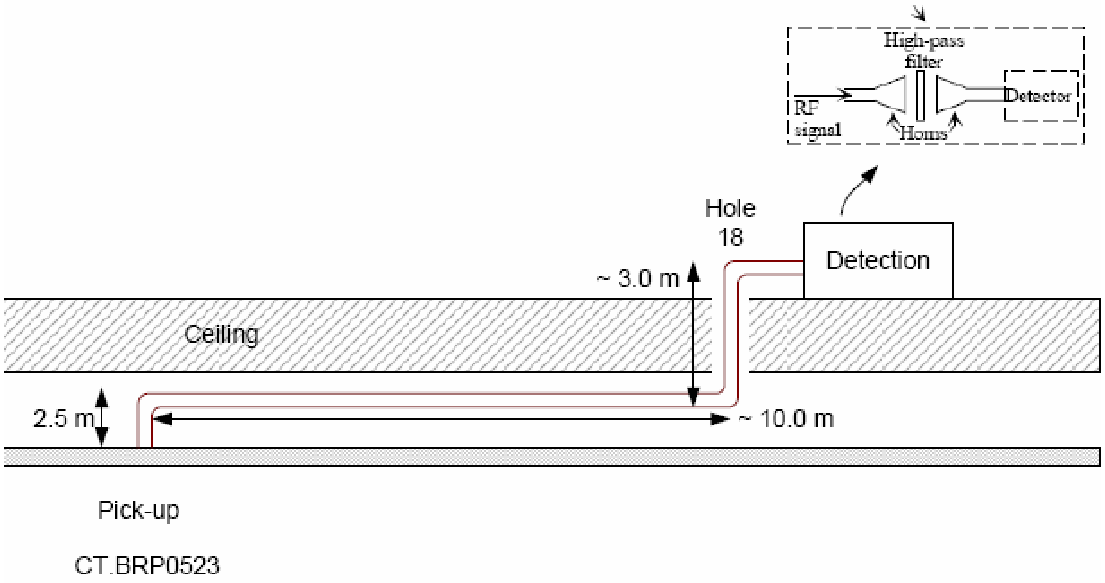
The machine



Al_2O_3 window in current setup

Current window in Pickup is a 3.35 ± 0.07 mm thick, with size roughly the size of WR-28 waveguide

Relative permeability ε_r of Al_2O_3 ~ 8.8

A wavelength in vacuum of 3.35 mm corresponds to a frequency of ~ 90 GHz

But at 90 GHz though Al_2O_3 with ε_r 8.8, λ is effectively ~ 1 mm

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r}}$$

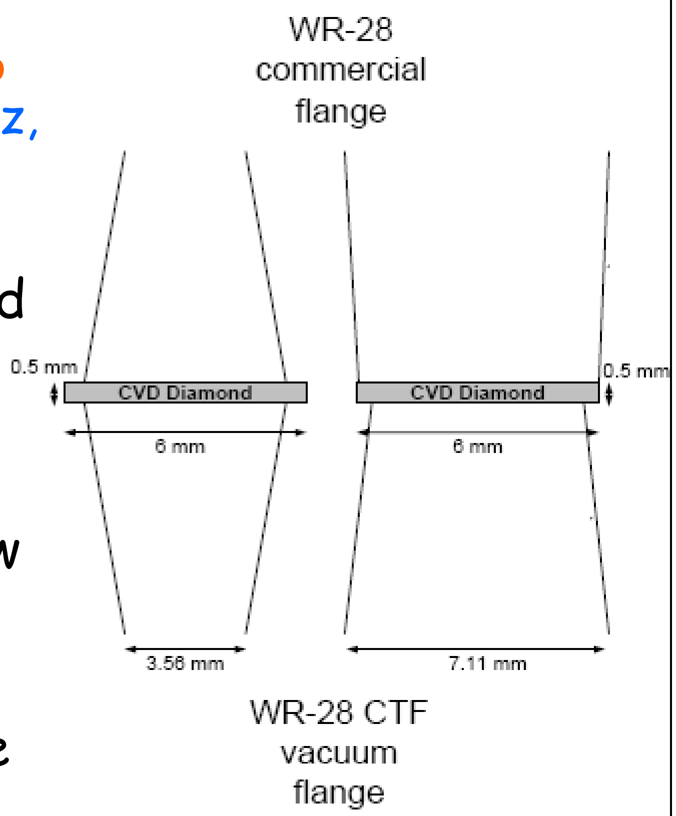
So reflections using an Al_2O_3 of this thickness at high frequencies is not optimized for good transmission

improvements:

- Make the window thinner
- Choose a material with lower ε_r
- Or both

Possible improvements on window design

- Given the limitation using Al_2O_3 at high frequencies (reflections)
  - Considering diamond as alternate material
  - CVD diamond Sample donated by Element 6 (manufacturing standard ε_r 5.68 at 175 GHz, tanδ (x 10-6) 20-50)
- RF properties of diamond sample measured at CERN (Raquel Fandos)
  - Relative permeability, ε_r ~ 6 at 30 GHz
- A diamond window is being designed, with flanges just like the current Al203 window (WR-28 flanges)
- Piece machined Molybdenum / Titanium
- Brazing test with the CVD diamond sample in early 2006 (perhaps before)
- Hope to install diamond window in machine before March 2006 run



Simulation of S-parameters HFSS

Envisioned final design

- Experience with the new RF-pickup setup will allow us to learn much about possible improvements in the setup
  - Window
  - Mixing and filter setup of the detector, and power transmitted at high frequencies
- Final RF-pickup design will probably be based on a thin diamond window → wait for result of brazing / vacuum test for final design parameters
- Improved control software to facilitate measurements in regular operation
- Possible investment in a large bandwidth waveform digitizer for single shot FFT analysis

Conclusion

- An RF-pickup has been installed in the CT line in CTF3
- The setup should provide a **bunch length measurement up to 0.3ps**
- Should make a measurement within the next few days
- Design work is on-going on an improved RF window for high frequencies.
- Window using a diamond is proposed, and a design and brazing test should occur within the next 6 weeks, in order to be installed in the March 2006 run for a test.
- The final Pickup will be installed close to the RF deflector for a good cross calibration of bunch length.
- The Pickup device is flexible, and can be installed in various locations once calibrated

Thank you's

- Much support has been received from Raquel Fandos and Alexej Grudiev in using Network Analyser and Simulation software and design.
- Also BDI and TIC team with special technical advise and help from Thibaut Lefevre and Hans Braun.

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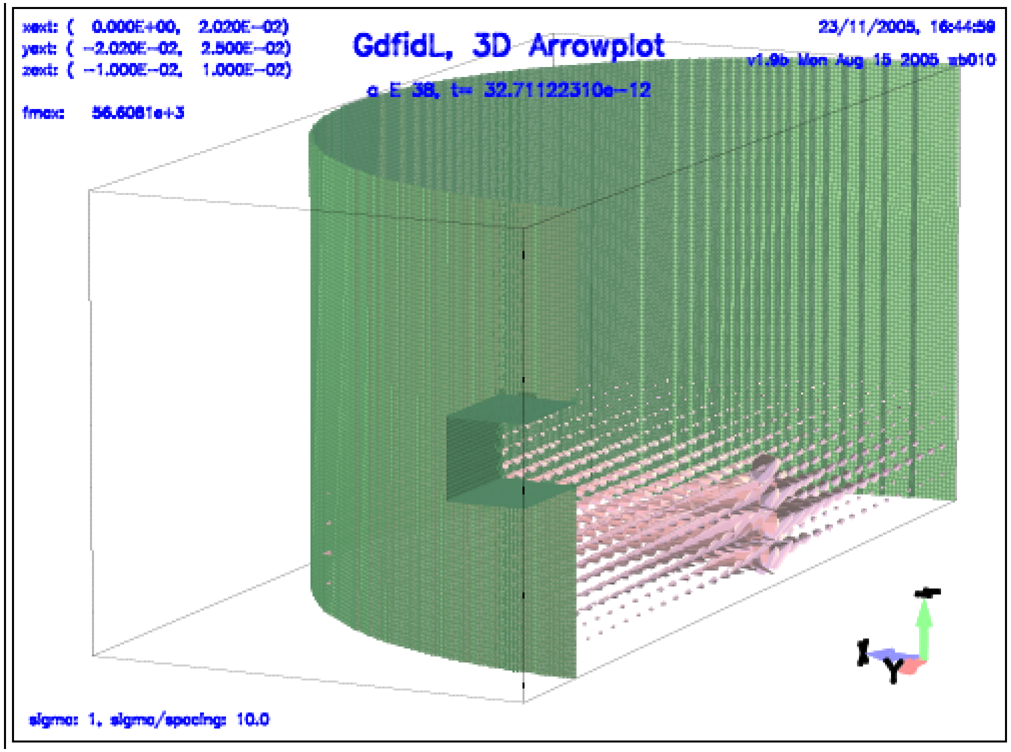
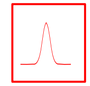
Simulation of the response of the pickup to an incoming bunch simulated using Gdfidl

Here you can see the evolution of the bunch along the beam, after simulation time of 32 x 10^{-12} seconds, exciting a field in the waveguide



Why is this measurement needed?

Performances of Bunch Length detectors (table thanks to Thibaut)

	 	 σ	1 n!	Limitations
• Optical radiation				
• Streak camera --------------------		xxxxxxx	xxxxxxx	> 200fs
• Non linear mixing -----------------		xxxxxxx	xxxxxxx	Laser to RF jitter : 500fs
• Shot noise frequency spectrum --		xxxxxxx	xxxxxxx	Single bunch detector
• Coherent radiation				
• Interferometry -------------------		xxxxxxx	xxxxxxx	
• Polychromator ---------------------		xxxxxxx	xxxxxxx	
• RF Pick-Up -------------------------------	xxxxxxx	xxxxxxx	xxxxxxx	> 500fs
• **RF Deflector** ----------------------------	xxxxxxx	xxxxxxx	xxxxxxx	
• RF accelerating phase scan -------------	xxxxxxx	xxxxxxx	xxxxxxx	High charge beam
• Electro Optic Method				
• Short laser pulse ------------------	xxxxxxx	xxxxxxx	xxxxxxx	Laser to RF jitter : 500fs
• **Chirped pulse** ----------------------	xxxxxxx	xxxxxxx	xxxxxxx	> 70fs
• Laser Wire Scanner ---------------------	xxxxxxx	xxxxxxx	xxxxxxx	Laser to RF jitter : 500fs