Intense Broadband Terahertz from FACET at SLAC

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SLAC National Accelerator Laboratory

Workshop on Terahertz Sources
Argonne National Laboratory
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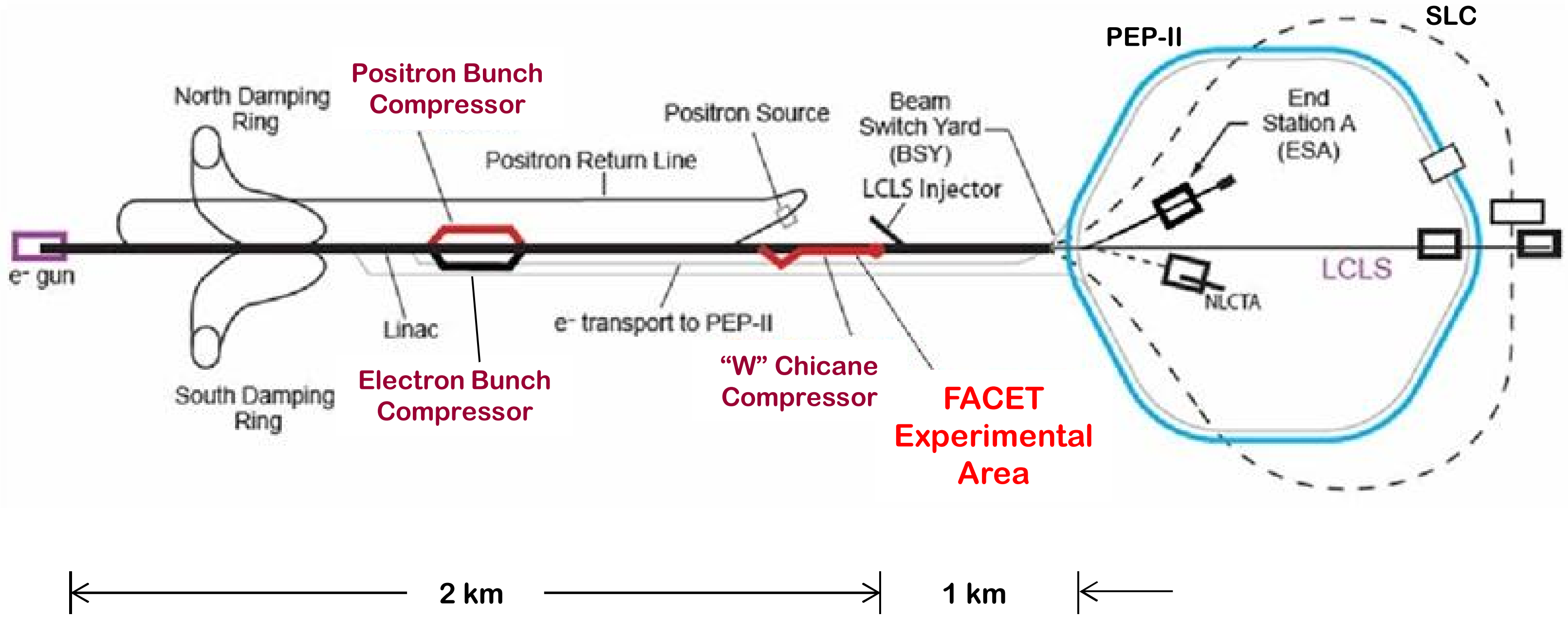
Purpose

- Longitudinal diagnostics of compressed electron bunches
- High peak fields for THz science

The FACET User Facility at SLAC

- Facility for Advanced Accelerator Experimental Tests
  - Provides highly compressed e^- (and soon e^+) bunches at high energy and with high charge
  - Uses the first 2 km of the SLAC linac
- Experiments include:
  - Plasma wakefield acceleration
  - Dielectric wakefield acceleration
  - Ultrafast magnetic switching
  - Smith-Purcell radiation
  - Terahertz radiation

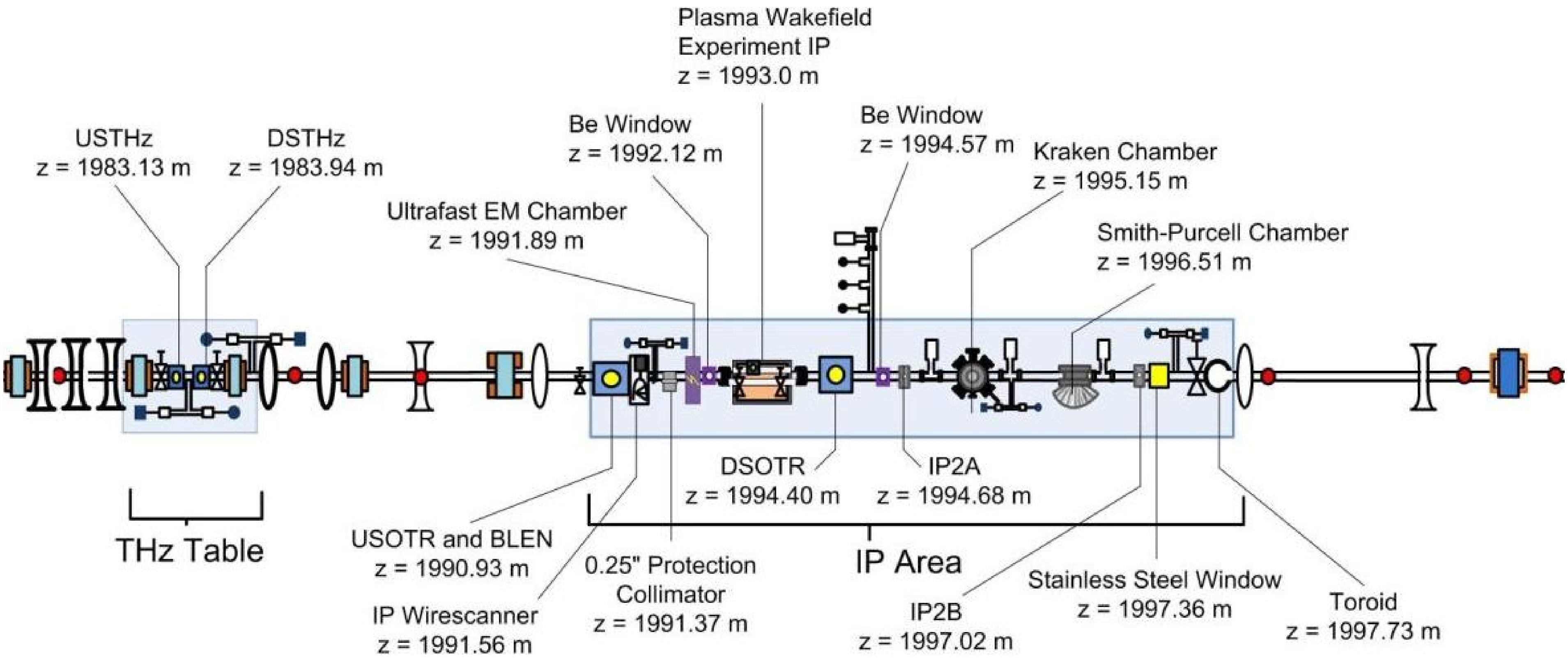
FACET and the SLAC Linac



FACET Beam Parameters

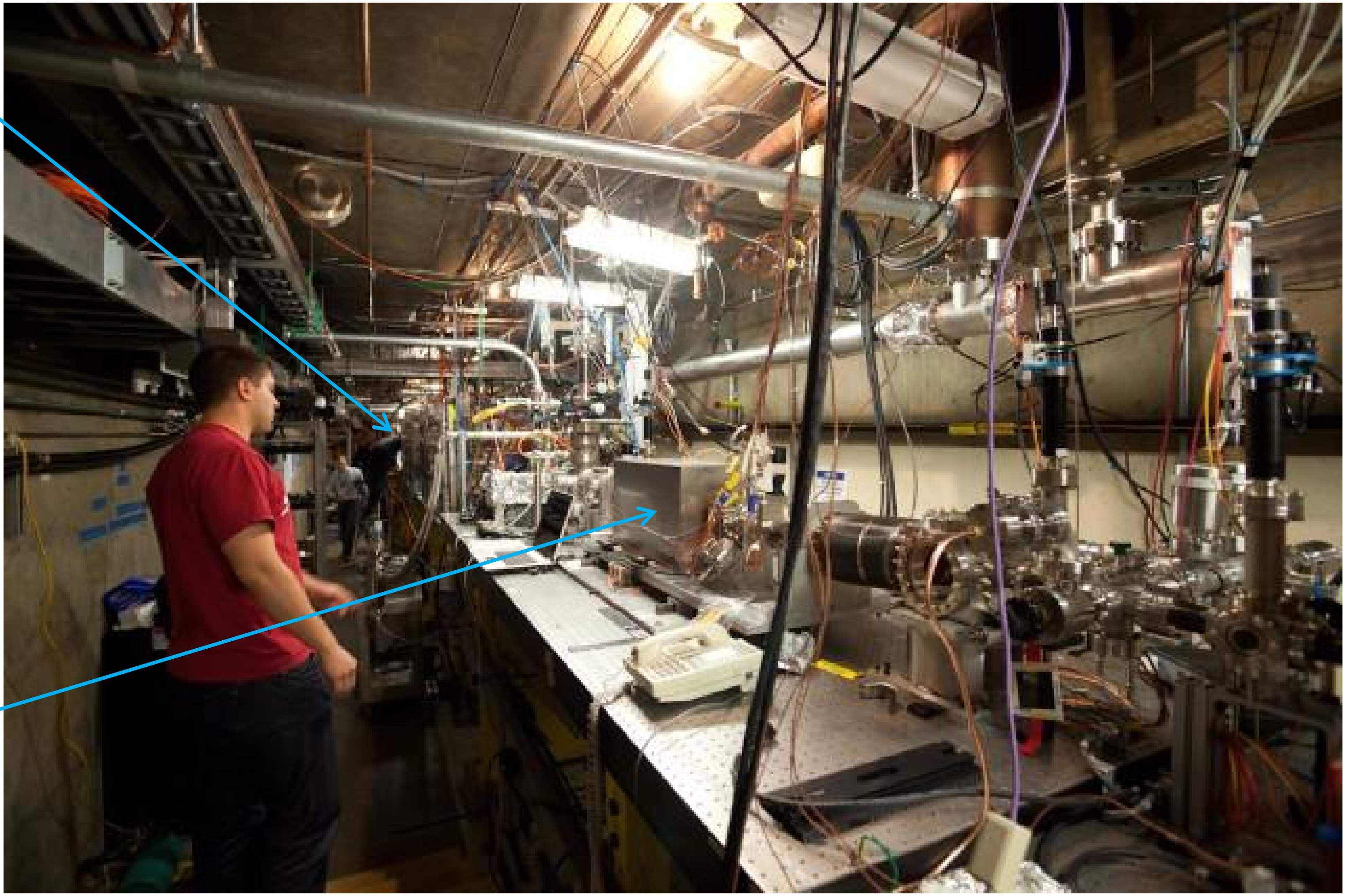
	2012 Run		Design	
	Typical	Best		
Energy	20.35	21.1	23	GeV
Charge	2.5–2.9	3.2	3.2	nC
Size at focus (σ_x)	35	20	20	µm
(σ_y)	35	23	20	µm
Bunch length (σ_z)	25–30	<25	<20	µm
(σ_t)	83–100	<83	<67	fs
Repetition rate	10	10	30	Hz

THz Table and the FACET IP



- THz source: Coherent transition radiation from two 1-μm-thick Ti foils
  - 10–14 m before main focus at experiments on the IP Table
  - Allows parasitic operation and use of THz for beam diagnostics
  - But *e*-beam at THz foil is larger than at IP

Upstream IP Table



THz table

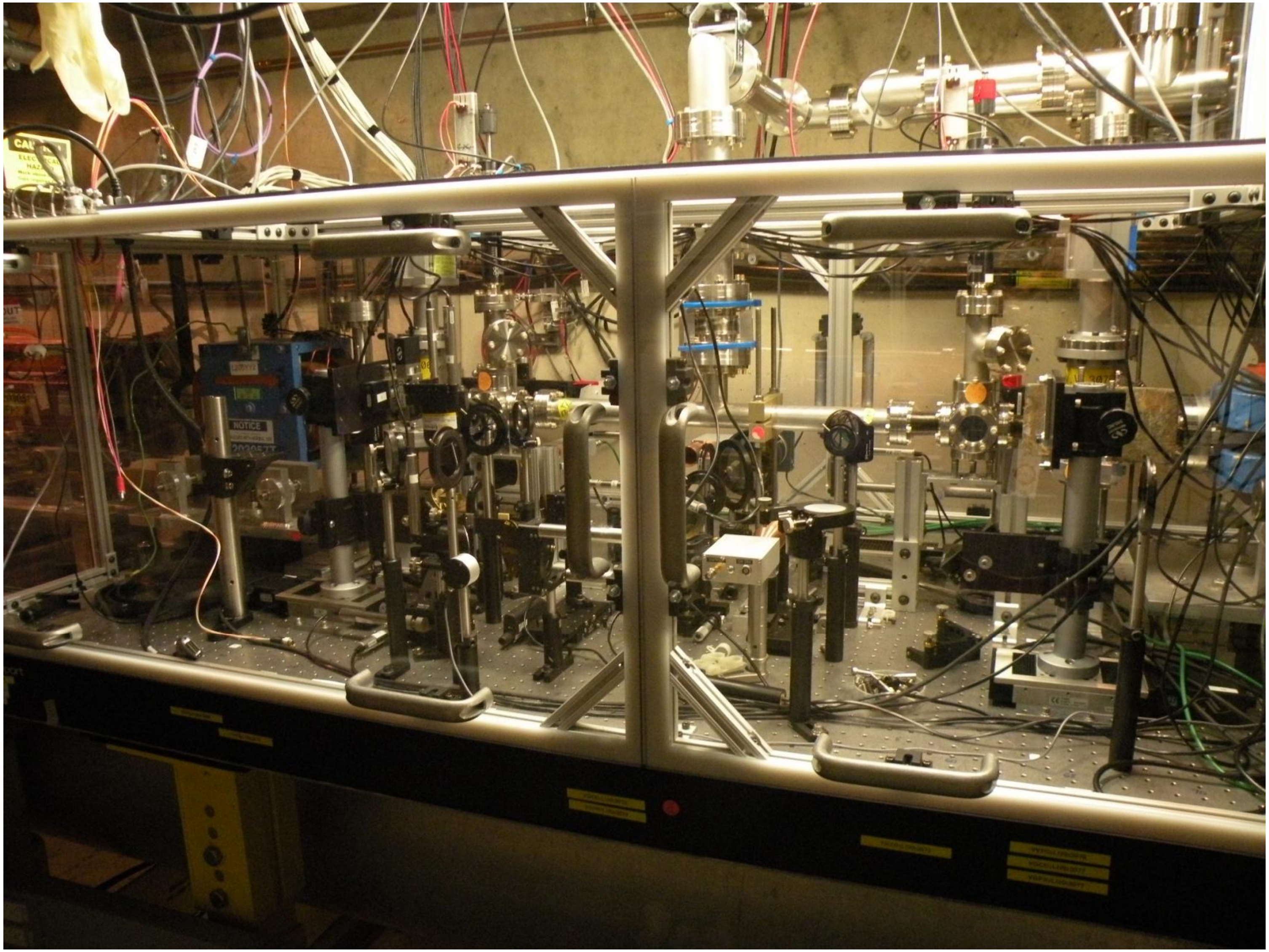
Plasma oven

Upstream IP table

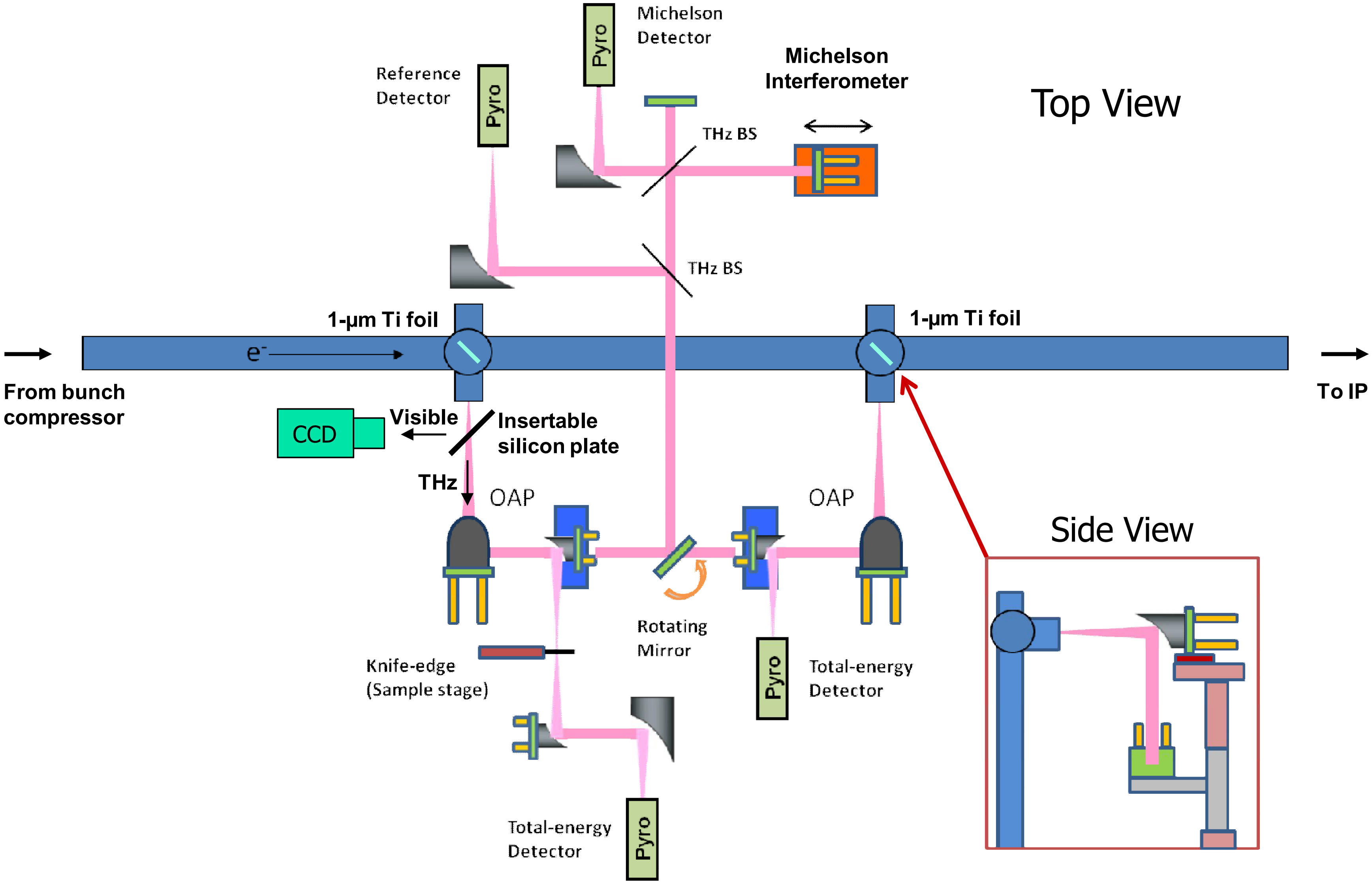
Downstream IP table

IP Tables

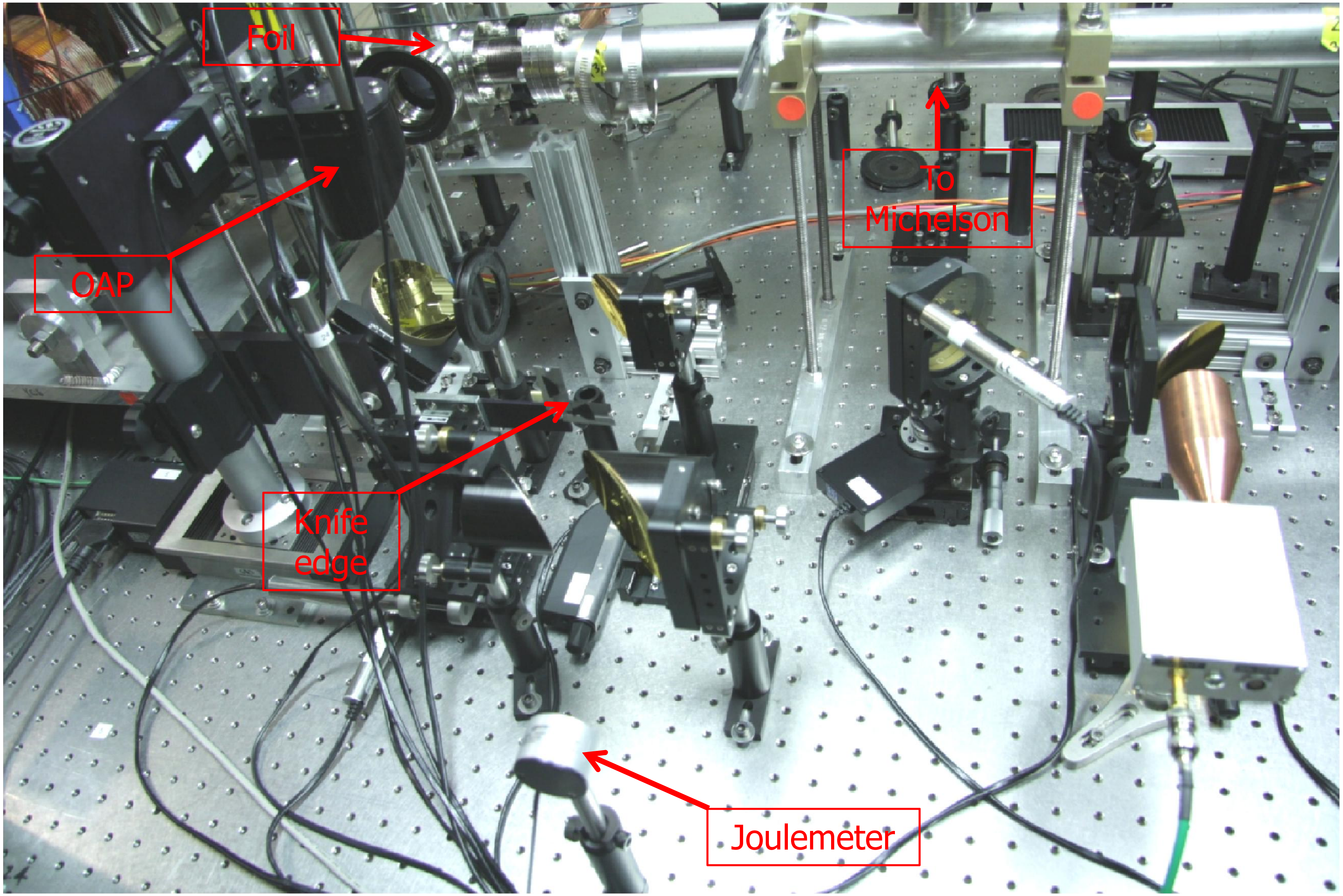
THz Table with Dry-Air Enclosure



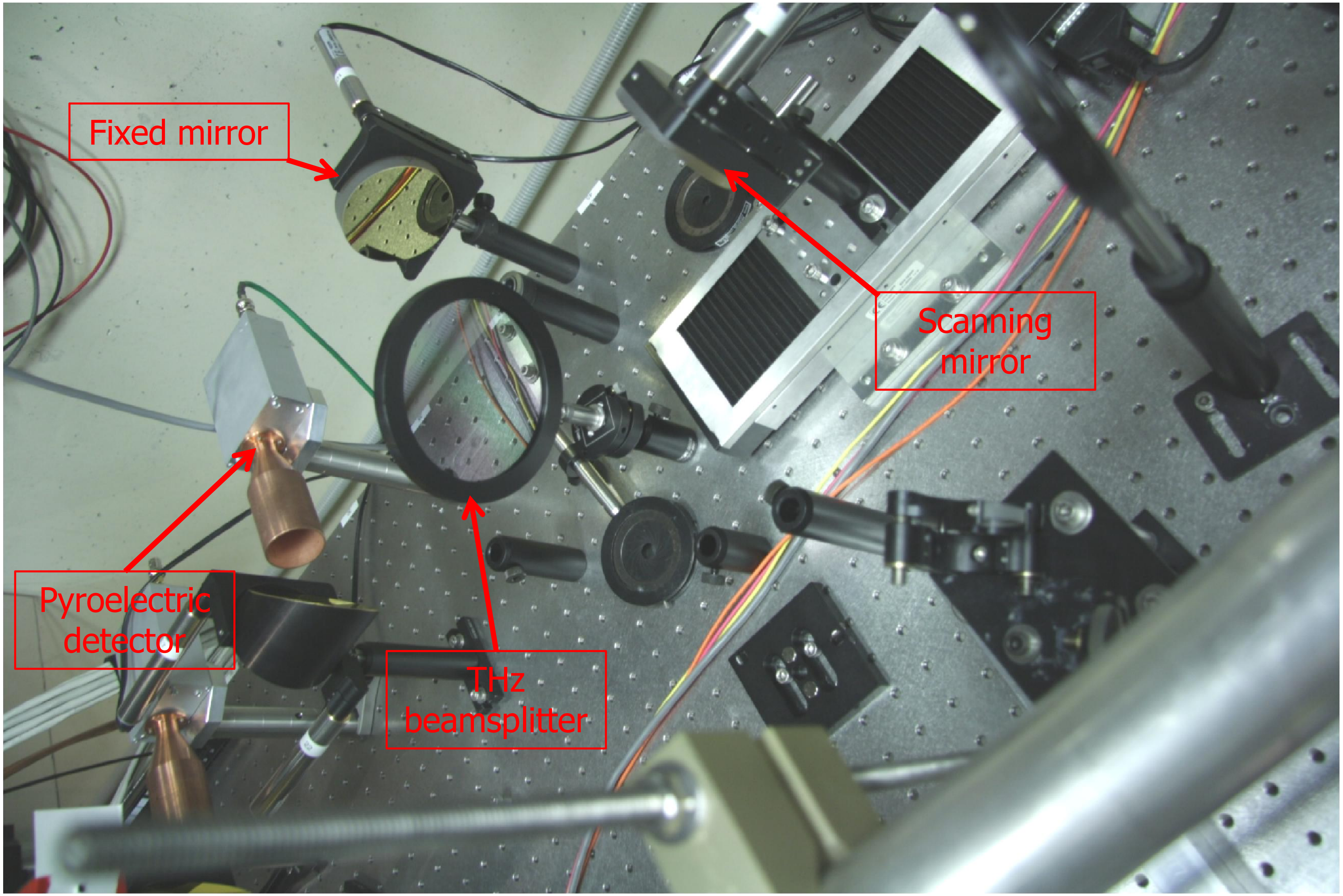
Layout of the THz Table



Optics for Upstream Foil



Michelson Interferometer



Finding the Peak Electric Field

- Electric field at the focus modeled as a Gaussian

$$E = E_0 \exp\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}+\frac{z^2}{\sigma_z^2}\right)\right]$$

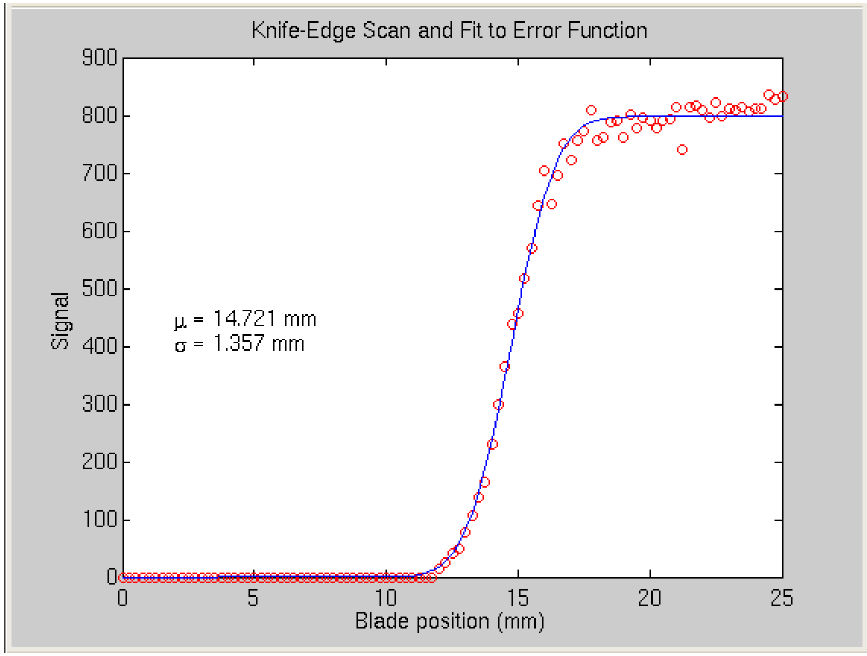
- Energy in the pulse

$$W = \iiint \frac{1}{2}\varepsilon_0 E^2\,dx\,dy\,dz = \frac{1}{2}\pi^{3/2}\varepsilon_0 E_0^2 \sigma_x \sigma_y \sigma_z$$

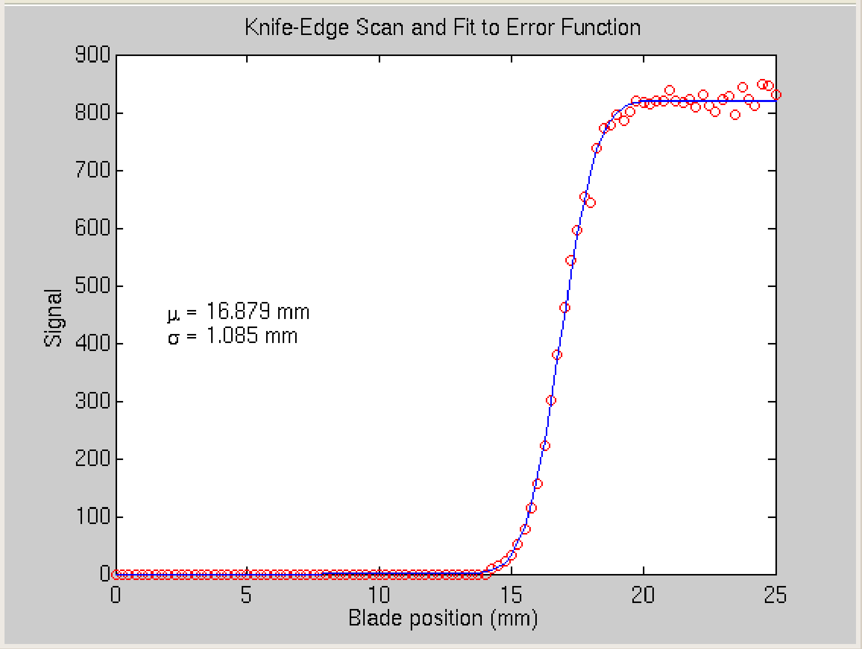
- Dependence on bunch charge q, bunch compression σ_z:
  - Field $E_0 \sim q/\sigma_z$
  - Energy $W \sim E_0{}^2\sigma_z \sim q^2/\sigma_z$
- Coherence
  - Less energy, due to incoherent emission, for wavelengths $\lambda \leq \sigma_{x,y,z}$
- Measurements needed:
  - Knife-edge scans, for widths of focus $\sigma_{x,y}$
  - Michelson interferometer, for pulse duration $\sigma_t = \sigma_z/c$
  - Pyroelectric joulemeter, for pulse energy W

Knife-Edge Scans at a THz Focus

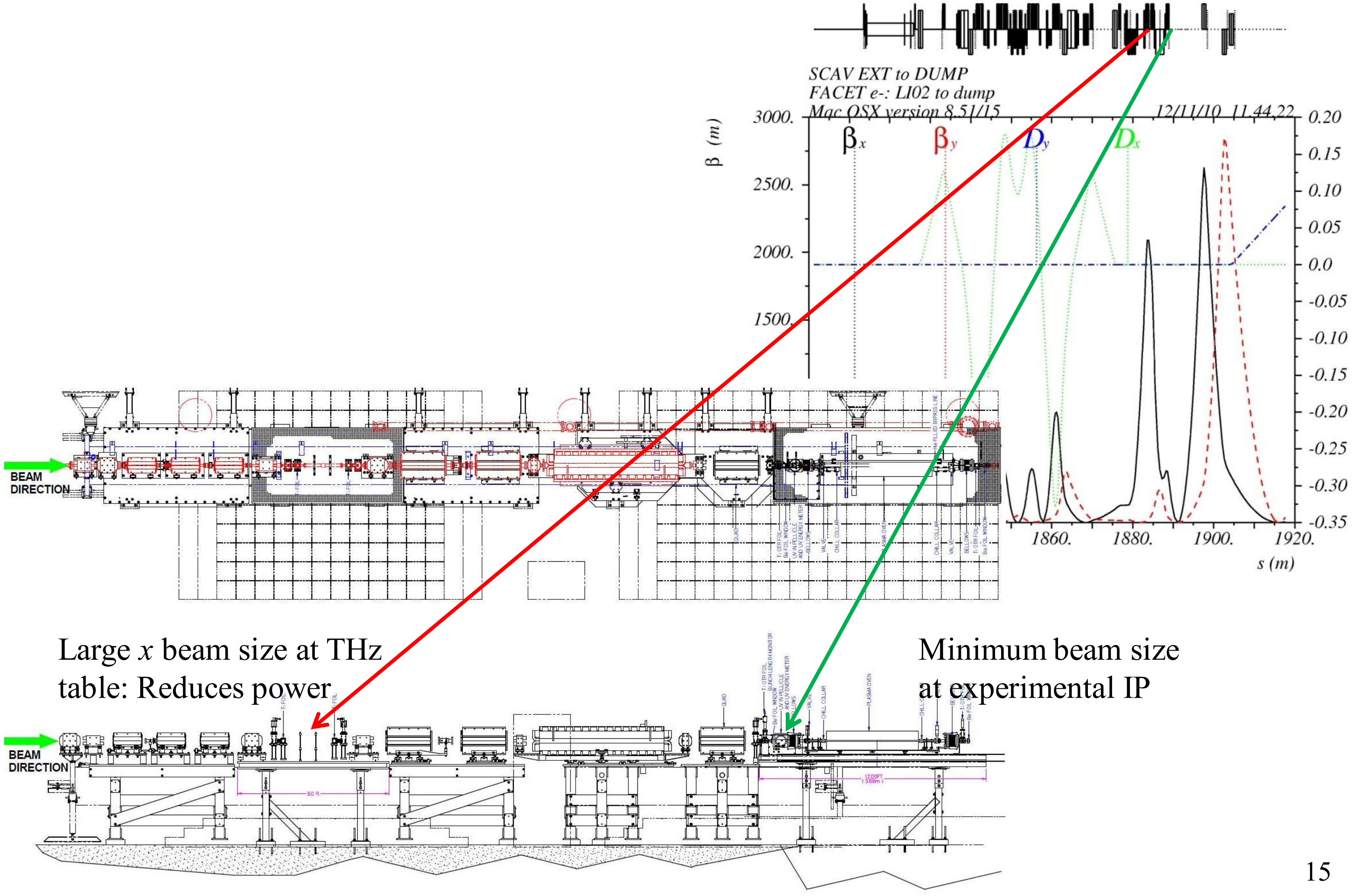
Horizontal Profile



Vertical Profile



Standard Electron Optics near the THz Table

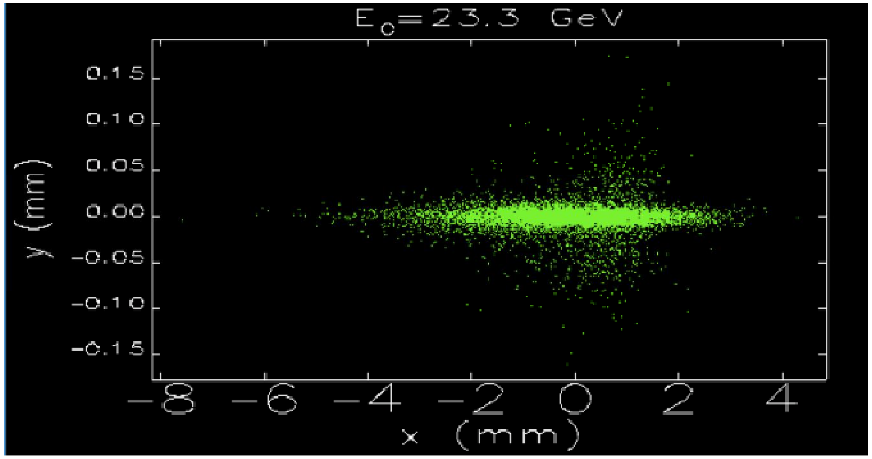


Large *x* beam size at THz table: Reduces power

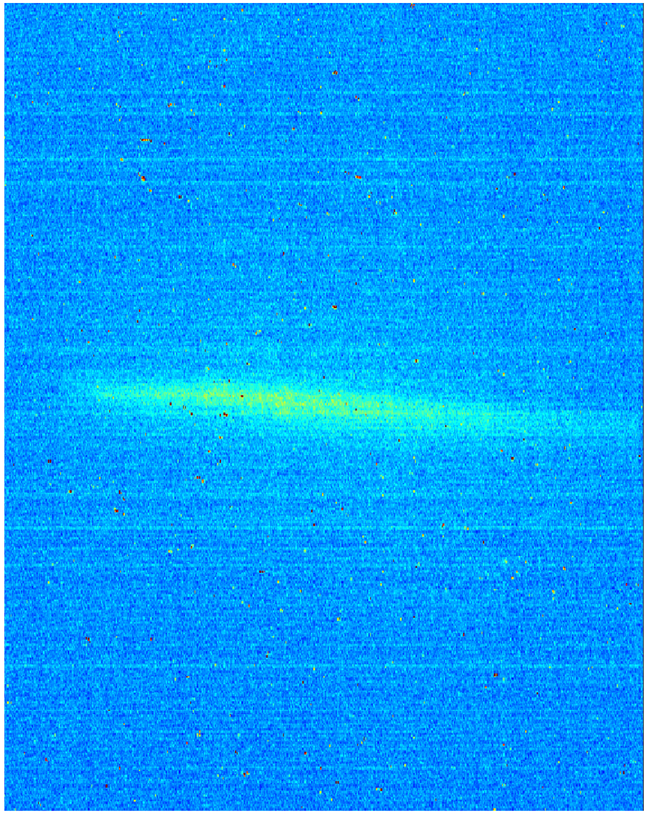
Minimum beam size at experimental IP

Transverse *e*-Beam Size

Simulated beam with standard optics:
$\sigma_x = 1.2$ mm, $\sigma_y = 6$ µm

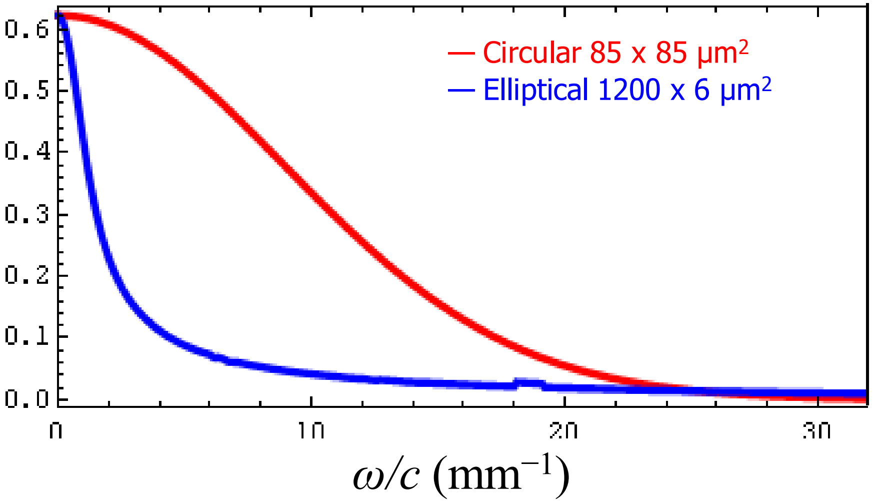


Measured with optical
transition radiation

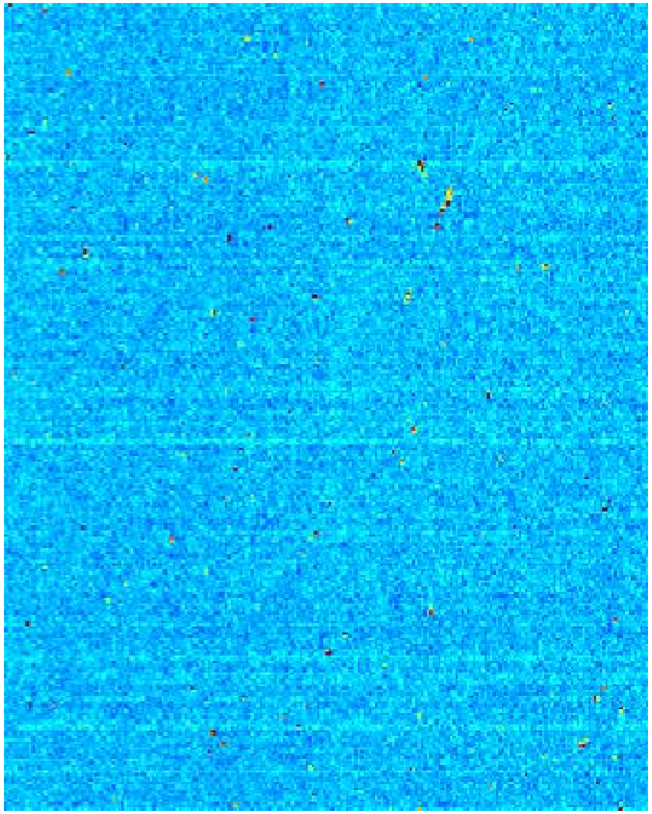


Refocus to Reduce Transverse *e*-Beam Size

Simulation comparing standard optics to a circular 85-μm beam

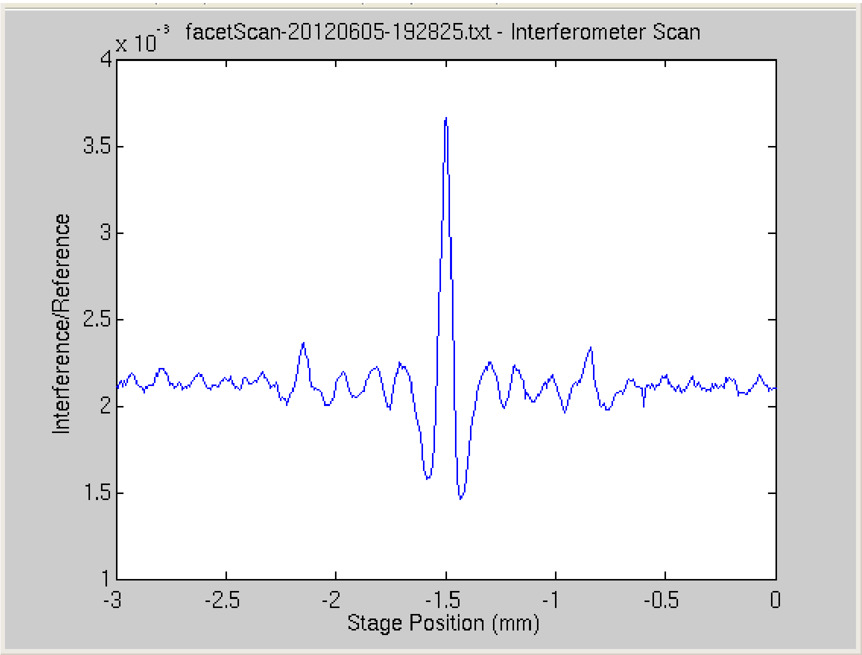


"Double Waist": Focus remains at IP, but x size at foil is reduced: $\sigma_x = 317$ μm, $\sigma_y = 36$ μm

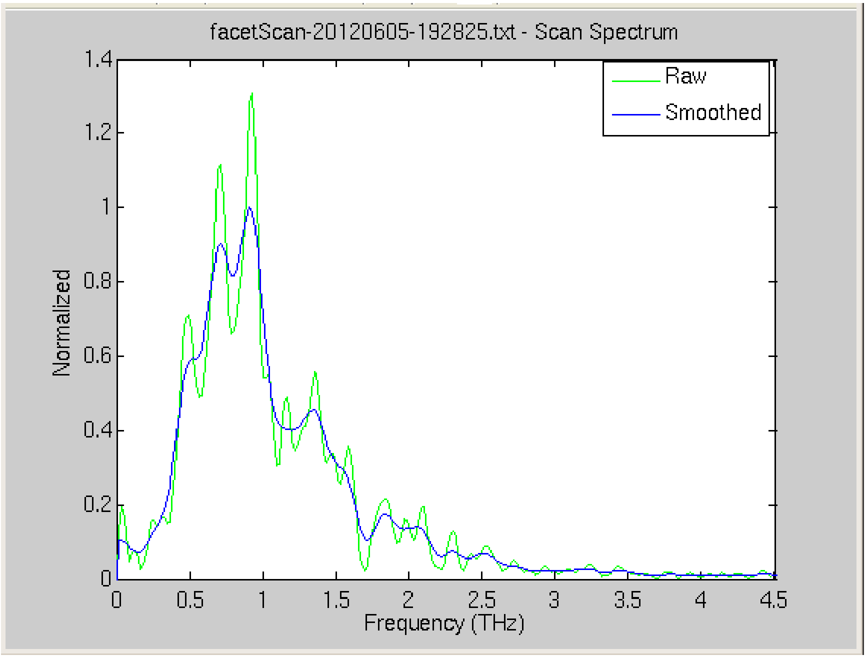


Scan of the Michelson Interferometer

Interferogram



Spectrum

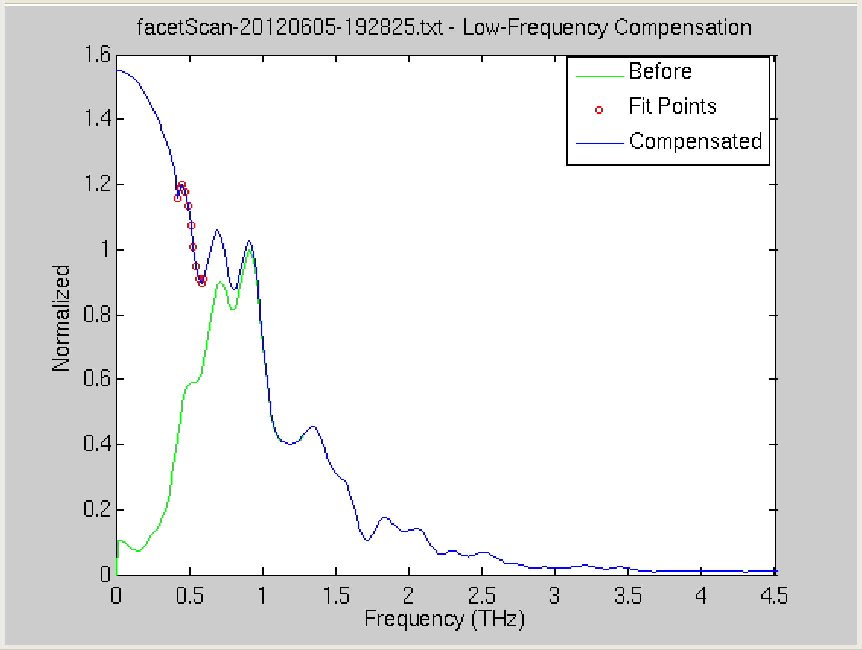


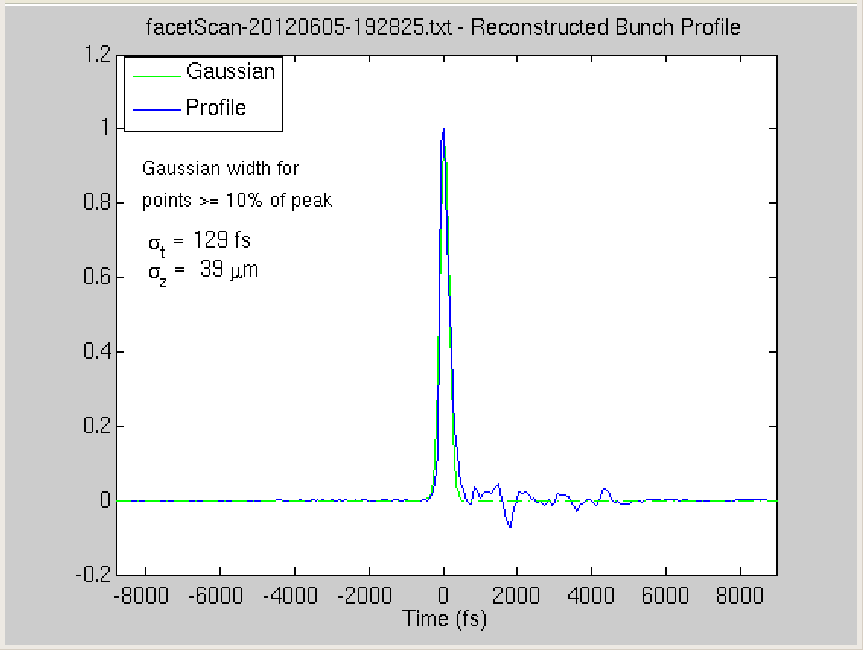
Reflections from detector layers lead to spectral modulation.

Restoring Low Frequencies and Phase

Spectrum after
Low-Frequency Compensation

Temporal Profile using
Kramers-Kronig Phase Restoration





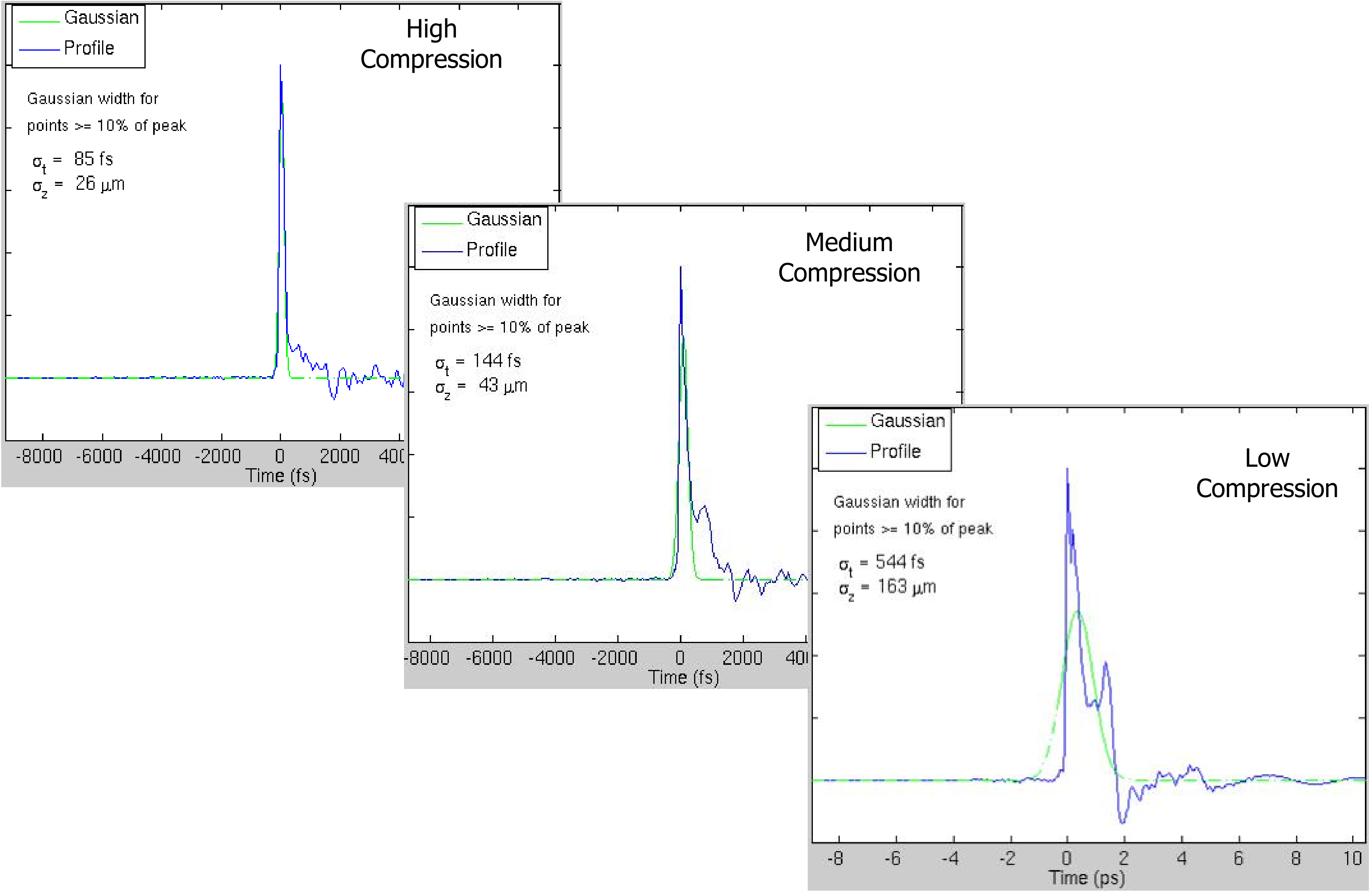
- Model low-frequency loss as a filter:

$$1-\exp\left(-f^2/f_0^2\right)$$

- Divide by filter, except very near $f = 0$
  - Just fit a parabola near $f = 0$
    - Result is not very sensitive to fit

- Kramers-Kronig relations give phase from magnitude of form factor $f(\omega)$
- Inverse transform gives distribution $f(t)$

Profiles at Three Bunch Compressions



Peak Electric Field

- In the case just shown:
  - Charge of 3 nC
  - Energy in the pulse $W = 0.46$ mJ
    - The large σ_x of standard electron optics gives 0.35 mJ
  - $\sigma_x = 1.36$ mm, $\sigma_y = 1.08$ mm
  - $\sigma_z = 39$ µm
  - $E = 5.7$ MV/cm
- Measured under other conditions (but not at one time):
  - Energy = 0.7 mJ
  - Bunch length = 25 µm
  - These would give 8.8 MV/cm (= 0.088 V/Å)
- Higher fields should be possible with a smaller beam at the foil
  - But not too small: The beam has drilled holes through 1-µm Ti foils at the IP focus

Transporting THz up to the Klystron Gallery

- First stage: Transport THz from the downstream foil to a small table in the Klystron Gallery
    - Now beginning detailed engineering
    - 19-m path, including an 8-m vertical section up through a penetration
    - Characterize pulse before and after transport: energy, focus, spectrum
- Severe diffraction of these long wavelengths
    - Large-diameter mirrors and tubing: 200 mm (8 inches)
    - Frequent refocusing with a lattice of off-axis parabolic (OAP) mirrors
        - Alternately collimating and focusing to a waist
        - Toroidal mirrors may be better for the long focal lengths at bottom and top of penetration
    - Evacuate to remove water vapor and convection (UHV unnecessary)
- Next stage: Another 20 m to the Sector-20 laser building
    - User experiments, including THz pump and laser probe

Summary

- We have characterized intense THz from CTR at FACET
    - Energy ~ 0.5 mJ
    - Focus size ~ 1 mm
    - Spectrum ~ 1 THz
    - Bunch length ~ 25 fs
    - Electric fields ~ 6 MV/cm
- Higher fields should be possible with more bunch compression and charge, and a smaller transverse beam size
    - But foil breakage could be a problem
- Upgrades in planning
    - Tests of other foil materials
    - Tests of other detectors
    - THz transport line to a user area above the tunnel

Finding the Form Factor of the Bunch

- Electric field E of a bunch of N electrons at positions t_j:

$$E(t) = \sum_{j=1}^{N} E_1(t - t_j) \qquad E(\omega) = E_1(\omega) \sum_j e^{-i\omega t_j}$$

  - Here E_1 is the field of one electron
- Energy in the pulse is related to the longitudinal "form factor" $f(\omega)$:

$$U_0 = \int dt\, E^2(t) = \int \frac{d\omega}{2\pi} \left|E_1(\omega)\right|^2 \left|\sum_j e^{-i\omega t_j}\right|^2 = N^2 \int \frac{d\omega}{2\pi} \left|E_1(\omega)\right|^2 \left|f(\omega)\right|^2$$

- Interferometer gives the pulse energy in an autocorrelation with a delay τ:

$$U(\tau) = U_0 + \mathrm{Re} \int \frac{d\omega}{2\pi} \left|E_1(\omega)\right|^2 \left|f(\omega)\right|^2 e^{i\omega\tau}$$

- The power spectrum $U(\omega)$ is then (neglecting the DC component):

$$U(\omega) = \left|E_1(\omega)\right|^2 \left|f(\omega)\right|^2$$

- E_1 is essentially constant at THz frequencies, and so $U(\omega)$ gives us $|f(\omega)|^2$

Retrieving the Phase with Kramers-Kronig

- If we express $f(\omega)$ in terms of its magnitude $\rho(\omega)$ and phase $\psi(\omega)$, then:

$$\ln f(\omega) = \ln \rho(\omega) + i\psi(\omega)$$

- Since $\ln f(t)$ is causal, and since ρ and ψ are real, they obey the Kramers-Kronig relations, which give:

$$\psi(\omega) = -\frac{2\omega}{\pi} P\int_0^\infty d\omega' \frac{\ln\left[\rho(\omega')/\rho(\omega)\right]}{\omega'^2 - \omega^2}$$

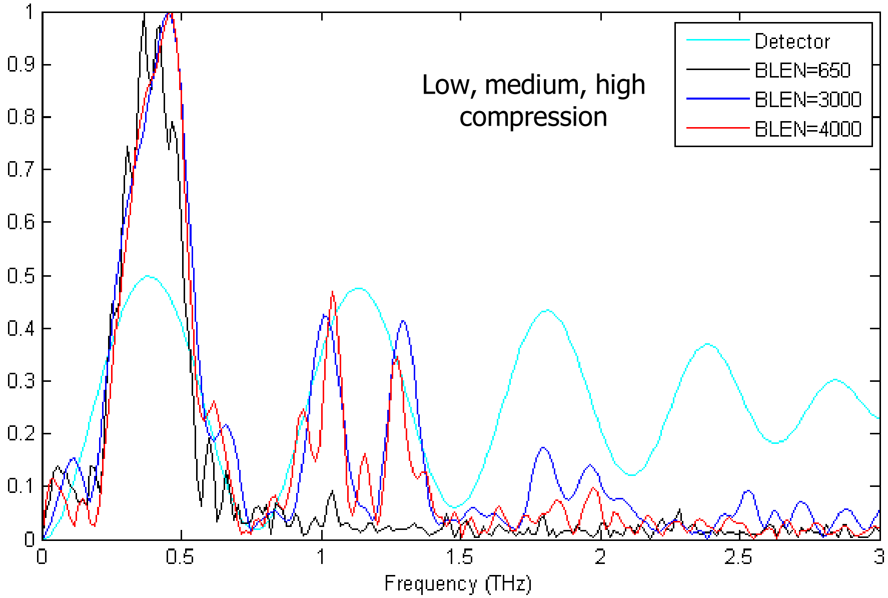
- The magnitude and phase then let us find $f(t)$

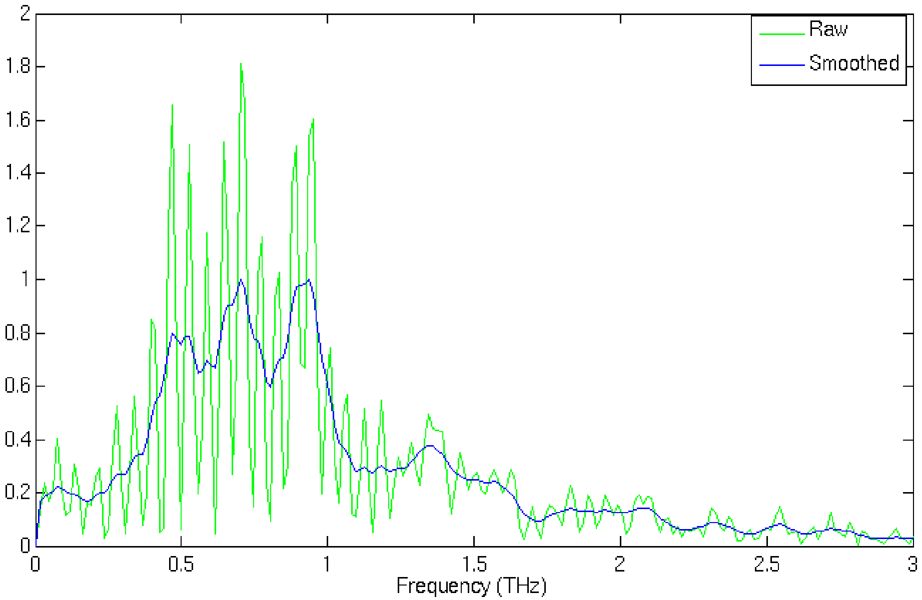
Detector Response

- THz detectors are poorly calibrated and are not spectrally flat
  - Significant etalon effects (reflections from detector layers)

- Infratec has strong modulation
  - Dip in response near 0.8 THz cuts out part of spectrum
    - Not suitable for interferometer
  - Compare to model (Henrik Loos)

- Gentec has thinner layers
  - 60-GHz modulation
  - When 60 GHz is filtered, 240 GHz becomes visible
    - Better, but not ideal



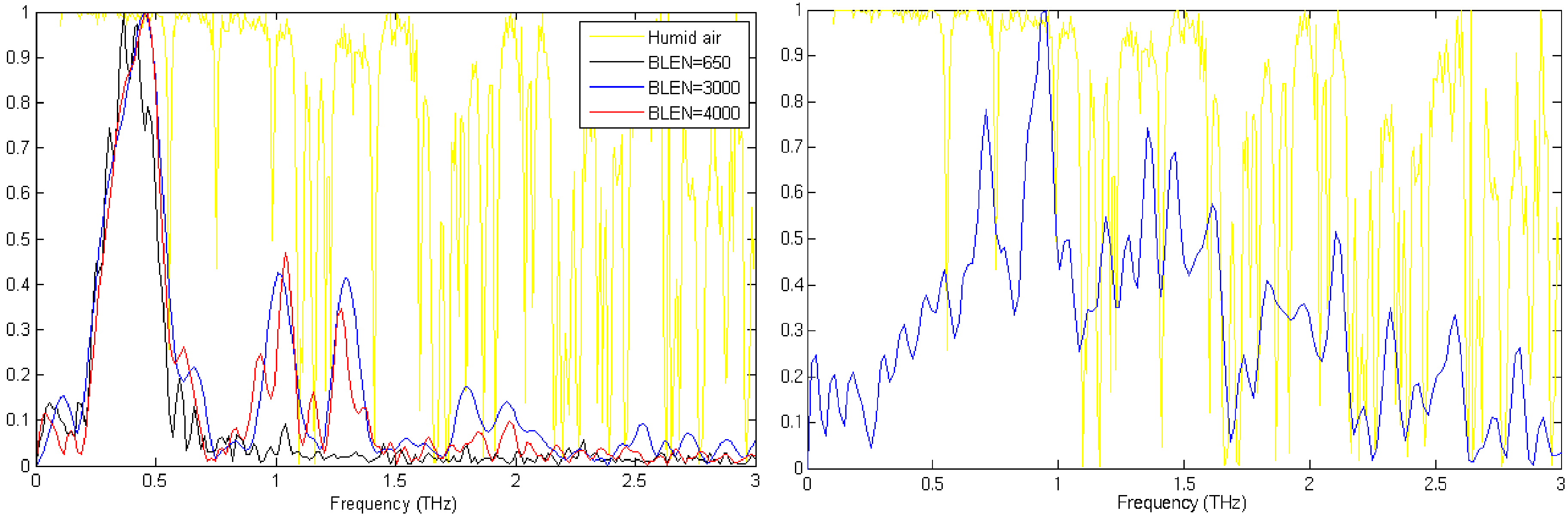


Water Vapor

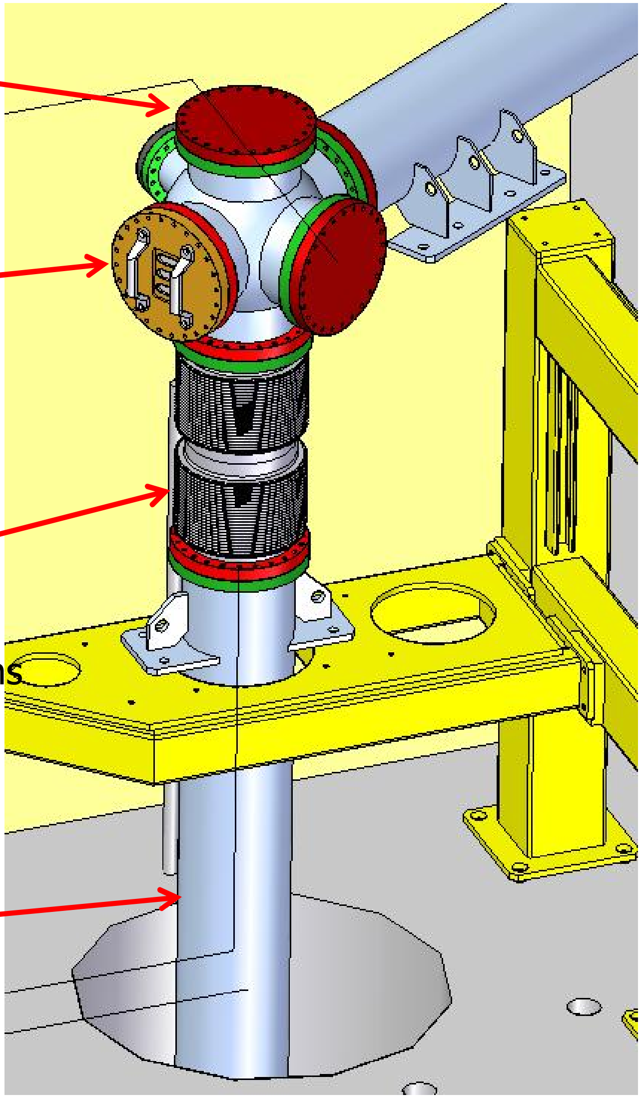
- Before and after adding the dry-air enclosure
  - Compare to transmission through 1-m of humid air

- Without dry-air enclosure
  - Dips near 0.75 and 1.2 THz
  - 3 bunch compressor settings

- With dry-air enclosure
  - Much improved, but there may still be some absorption
  - Will increase flow of dry air



Transport Line



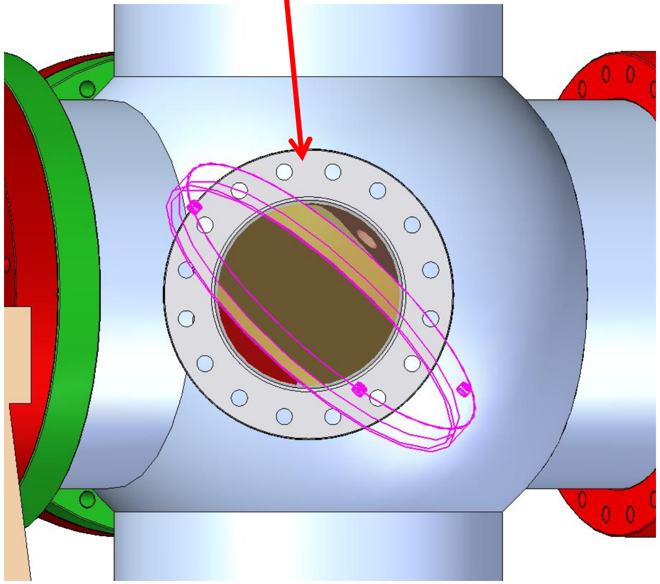
Pumping flange

Flange with mirror mount

Bellows
- Flexibility
- Breaks up reflections from pipe wall

200-mm (8-inch) tubing

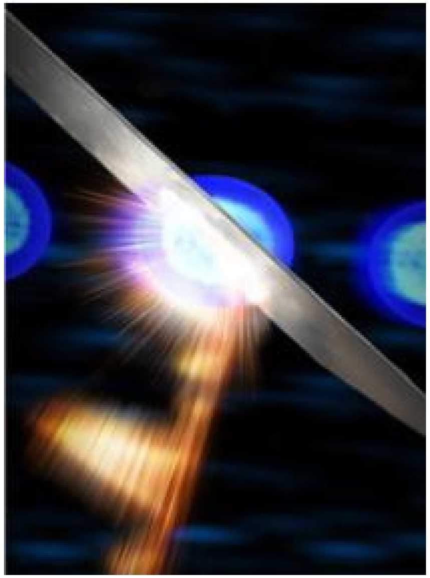
Alignment viewport
- View HeNe alignment beam directly or with a camera



SLAC THz Workshop

Frontiers of THz Science

5-6 September, 2012,
SLAC National Accelerator Laboratory



This workshop is focused on exploring and defining scientific opportunities associated with THz radiation in a wide range of scientific fields.

https://slacportal.slac.stanford.edu/sites/conf_public/THz_2012_09/Pages/default.aspx