# Diagnostics for Plasma Accelerators

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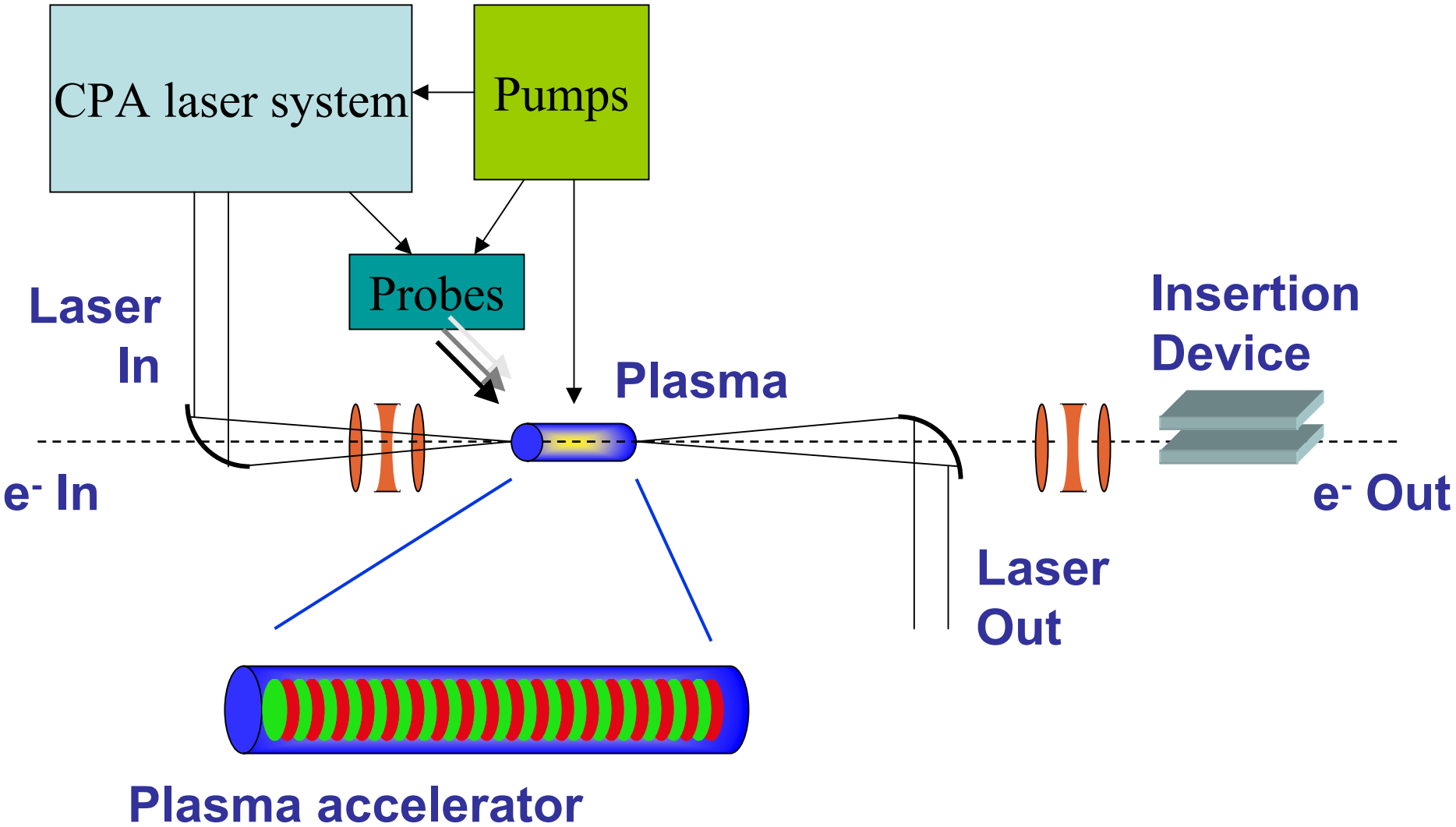
**Collaborators**
Entire Advanced Accelerator Community
Past and Present

# Typical Plasma Accelerator Laboratory



# Laser In and Out

**Quality of drive and probe laser beams (and green pump beams!)**

- $\Delta\lambda$ central frequency, bandwidth, spatial/**temporal phase**
- $\tau$ **pulse shape**, pre- and post-pulse
- Energy
- Wavefront amplitude and phase distortion
- $M^2$, focal quality, intensity
- Pointing, pointing jitter
- Contrast, ASE

**Quantify output beams**

- **Phase modulations**
- $\Delta\omega$ **spectral changes**
- $\Delta\tau$ **pulse distortion**
- Absorbed power
- **Scattering**
- **Guiding**

# Laser In and Out

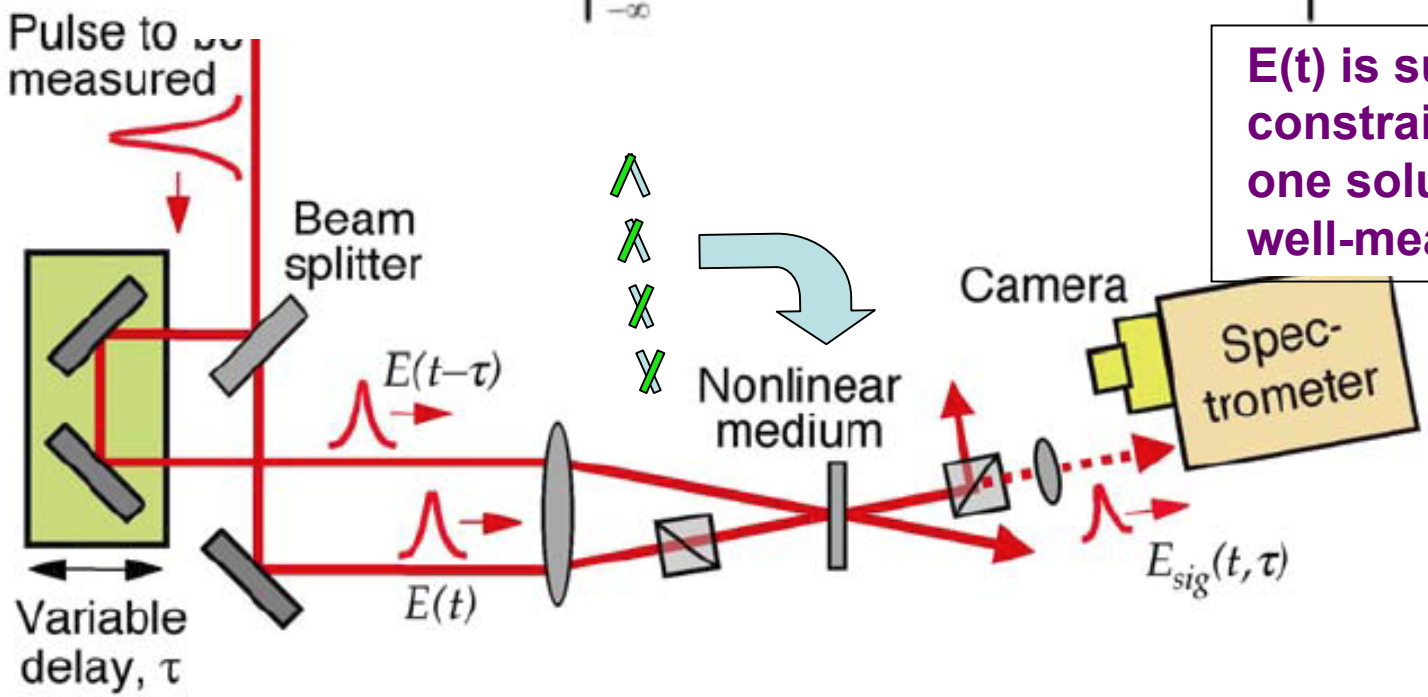
## Pulse shape and temporal phase

### FROG = Frequency Resolved Optical Gating

$$E_{sig}(t,\tau) = \underbrace{E(t)\ |E(t-\tau)|^2}$$

$$I_{FROG}^{PG}(\omega,\tau) = \left| \int_{-\infty}^{\infty} E(t)|E(t-\tau)|^2 \exp(-i\omega t)\, dt \right|^2$$

**E(t) is sufficiently constrained; only one solution per well-measured $I_{FROG}$.**




**FROG apparatus using the polarization-gate geometry**

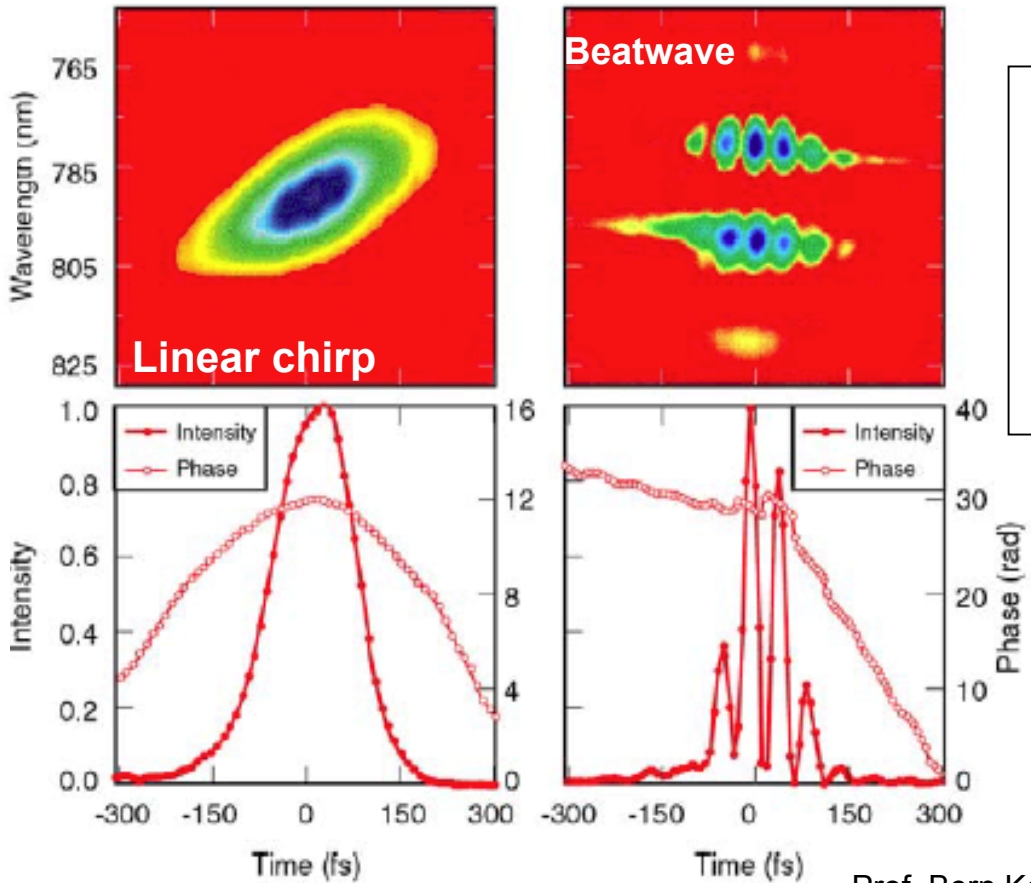
# Laser In and Out (cont.)

## Pulse shape and temporal phase

$$I_{FROG}^{PG}(\omega,\tau) = \left| \int_{-\infty}^{\infty} E(t)\,|E(t-\tau)|^2 \exp(-i\omega t)\, dt \right|^2$$

**FROG traces (Experimental)**

**FROG-derived Electric fields Amp & Phase!**




**E(t) 'recovered' through 2-D 'phase retrieval' algorithm (analogous to sharpening blurred images)**

Prof. Bern Kohler, Ohio State University.

# The "Target" & the Plasma

**Characterization of accelerator's local environment**

- **Profile of gas**/clusters in a "gas jet"
- Gas uniformity in capillaries
- Lithium vapor profile in a heat-pipe oven
- Edge effects
- Vibrations of target
- Vacuum quality

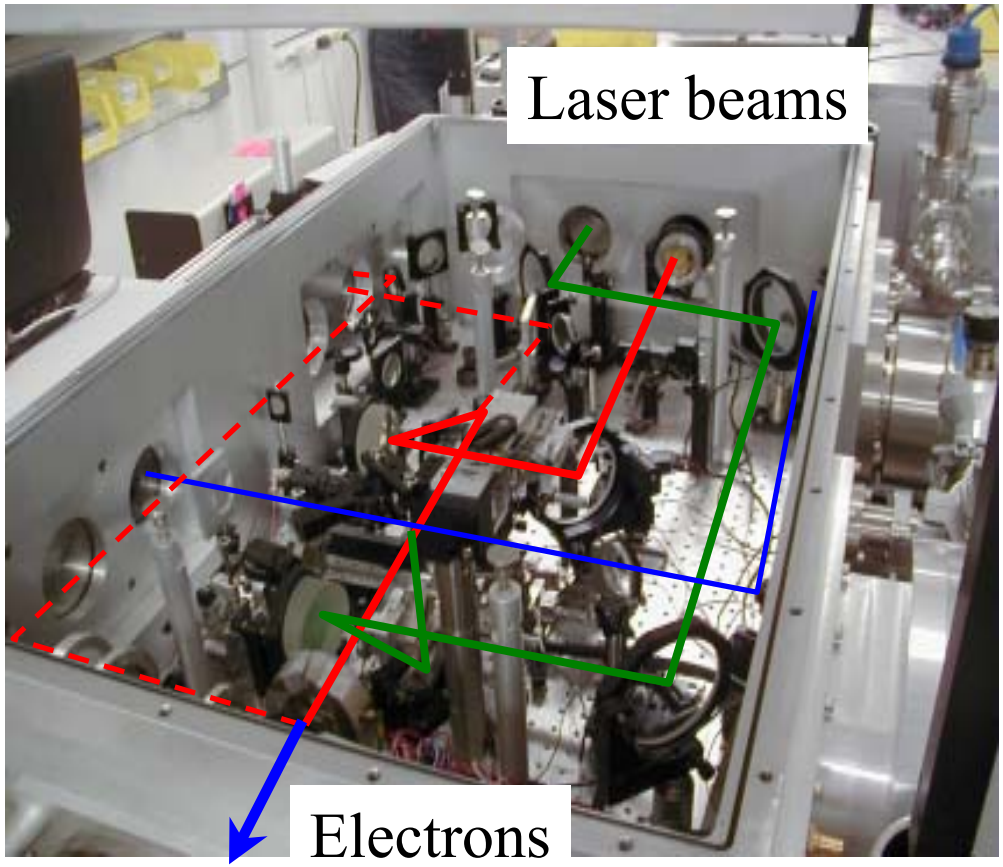
**Parameters of plasma itself**

- Ionization state
- **Density profiles**, longitudinal and transverse
- **Optical properties of plasma fiber**
- Plasma parameters in a capillary discharge
- Hydrodynamic evolution both pre- and post-acceleration
- Laser- Beam-Plasma instabilities with Driver present
- X-Rays, fast ions

# Laser pointing and jet profile

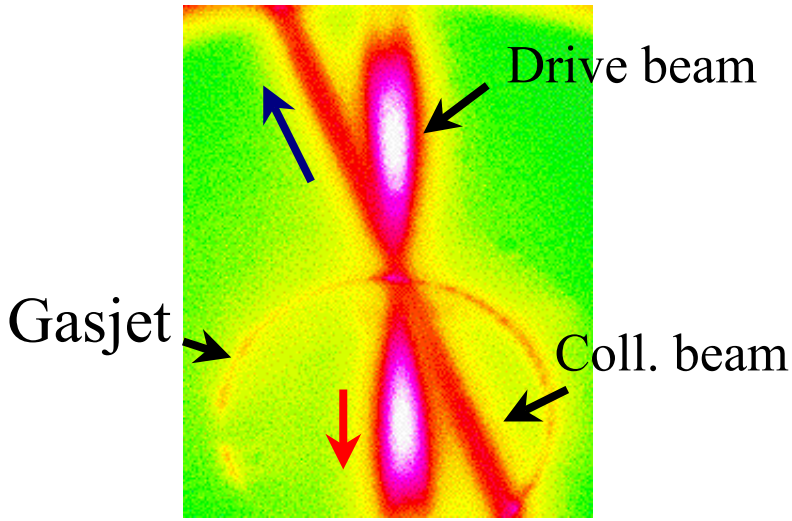
## Plasma afterglow and interferometry

- ✓ Focusing + spatial overlapping of beams: dumb-bell+interferometer
- ✓ Femtosecond synchronization

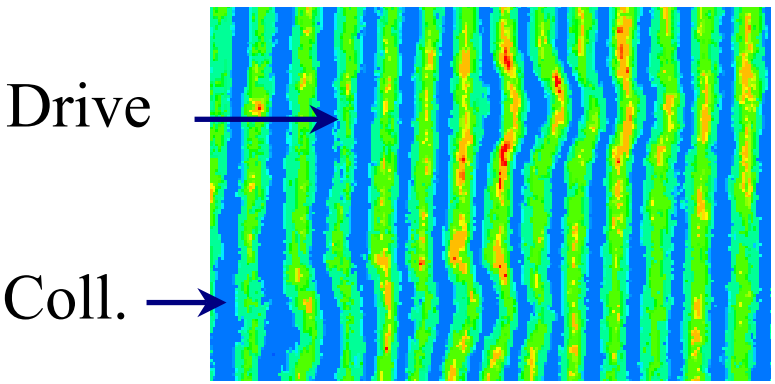



LBNL

Top view




Side view



# Parameters of Plasma Itself
## Optical probing of plasma–Theory

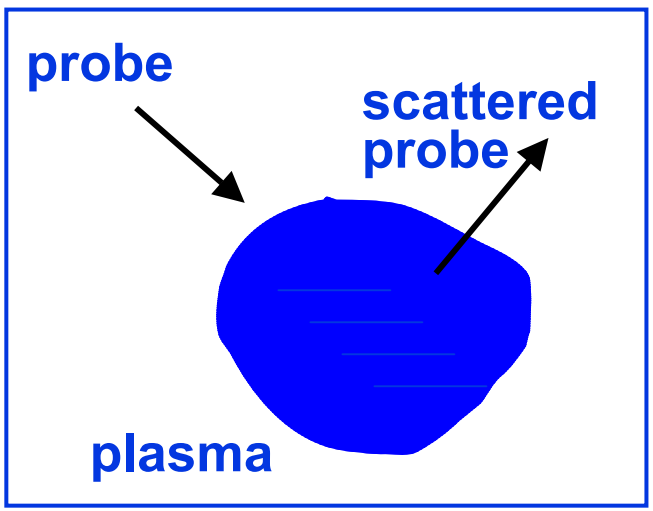
### Spatio-temporal geometry determines best 'theory'

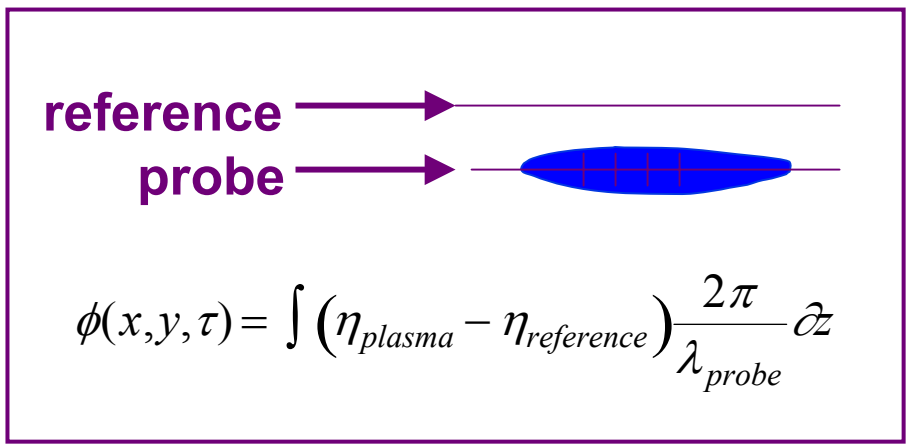
**Probe crosses many crests/valleys of 'wave' & $\tau_{integr} >> \omega_{wave}^{-1}$**

- Ensemble-average of scattered field from each electron in scattering volume (thermal Thompson scattering)
- **OR** Fluid description of $\tilde{n}(\mathbf{r},t)$ + Maxwell's equations

**Probe sees slowly-varying or ~ static** $\tilde{n}(\mathbf{r},t)$

- Refractive index description of density perturbation -> Interferometry, "Photon acceleration", etc.



# Optical probing of plasma–Theory

## Probe crosses many crests/valleys of 'wave'

### Incident probe

$$E_{i0}\cos(\vec{k}_i\cdot\vec{r}-\omega_i t)\hat{i}$$

### Radiated field ~ acceleration

$$\vec{\beta}' = \frac{-e}{mc}E_{i0}\cos(\vec{k}_i\cdot\vec{r}-\omega_i t)\hat{i}$$

### Scattered wave…

$$\vec{E}_s(\vec{R},t) \approx \frac{e}{Rc}\left[\hat{s}\times(\hat{s}\times\vec{\beta}'(t')\right]$$

### …at t' = retarded time

$$t' = \frac{\left|\vec{R}-\hat{s}\cdot\vec{r}\right|}{c} \approx t - \frac{R}{c} + \frac{\hat{s}\cdot\vec{r}}{c}$$

### Total scattered field

$$\vec{E}_s^T = \int_V d\vec{r}\;\; n_e(\vec{r},t')\vec{E}_s$$

$$= \int_V d\vec{r}\;\; \left\{\int \frac{d\vec{k}}{(2\pi)^2}\int\frac{d\omega}{2\pi}n_e(\vec{k},\omega)e^{-i(\vec{k}\cdot\vec{r}-\omega t)}\right\}\vec{E}_s$$

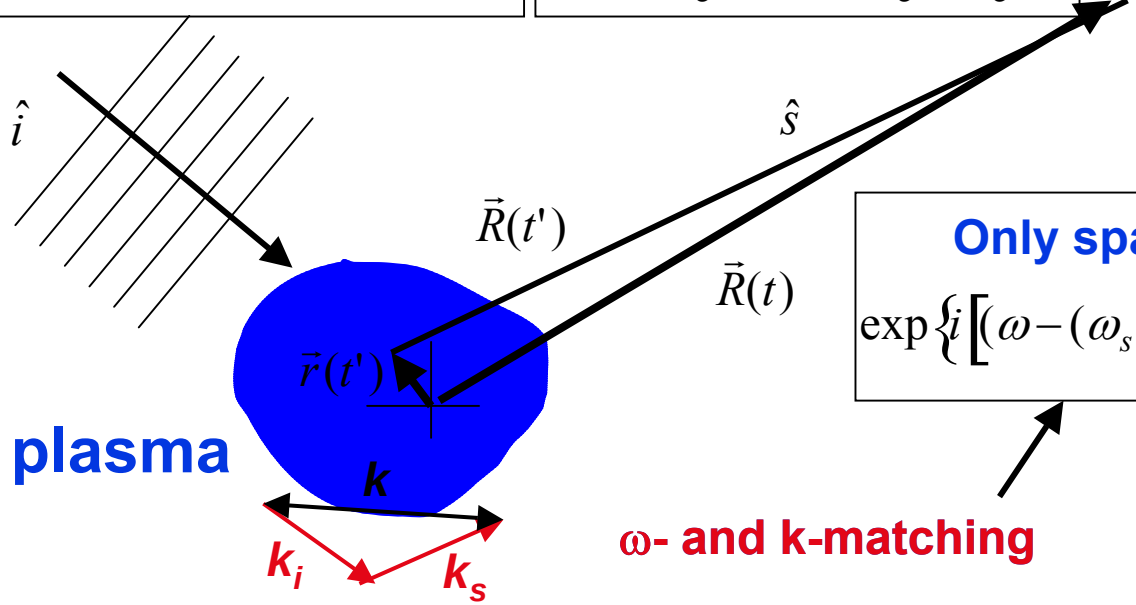
### Detected power

$$P_S(\vec{R},\omega_s)d\Omega d\omega_s =$$

$$\frac{cR^2}{4\pi}d\Omega d\omega_s\left|\int_{-\infty}^{+\infty}dt E_s^T(t)e^{-i\omega_s t}\right|^2$$

### Only space and time dependence…

$$\exp\left\{i\left[(\omega-(\omega_s\pm\omega_i)t-(\vec{k}-(\vec{k}_s\pm\vec{k}_i))\cdot\vec{r}\right]\right\},\quad \frac{\hat{i}\,\omega_s}{c}\equiv\vec{k}_s$$




**ω- and k-matching**

$$\alpha \equiv \frac{1}{k\lambda_{De}}\begin{cases}\Rightarrow & > 1\text{, collective TS}\\ \Rightarrow & << 1\text{, incoherent TS}\end{cases}$$

# Probe crosses many crests/valleys of 'wave'

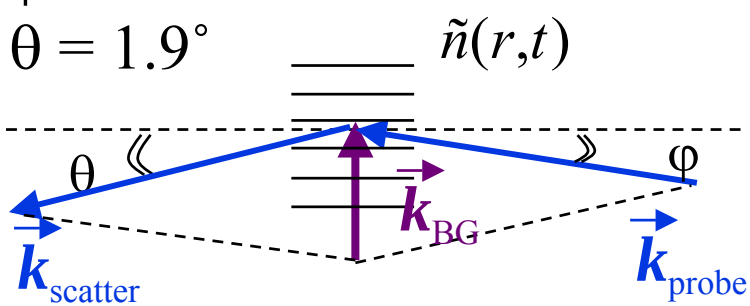
## Importance of k-matching

### Wave-wave coupling

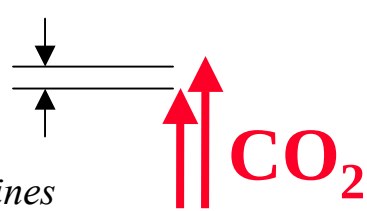
$$n_e(\omega,k) = \tilde{n}_{fast}(\omega_p, k_{fast}) + \tilde{n}_{slow}(\omega_{BG}, 2k_0)$$

$\varphi = 3.7^\circ$

$\theta = 1.9^\circ$



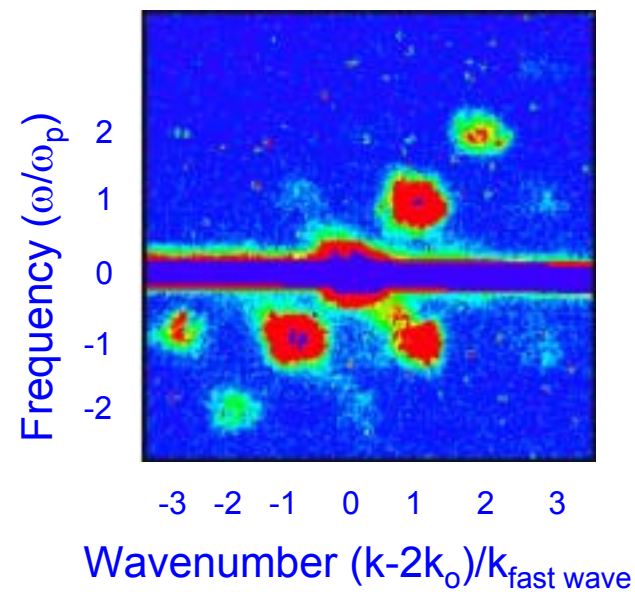

$k_{fast} \approx \Delta k_{CO_2 Lines}$




### $\omega$- and $k$-matching

$$\exp\left\{i\left[(\omega - (\omega_s \pm \omega_i)t - (\vec{k} - (\vec{k}_s \pm \vec{k}_i)) \cdot \vec{r}\right]\right\}$$

$$k \rightarrow k_{fast} \pm n k_{slow} \quad \omega \rightarrow \omega_{fast} \pm n\omega_{BG}$$



# Optical probing of plasma–Theory

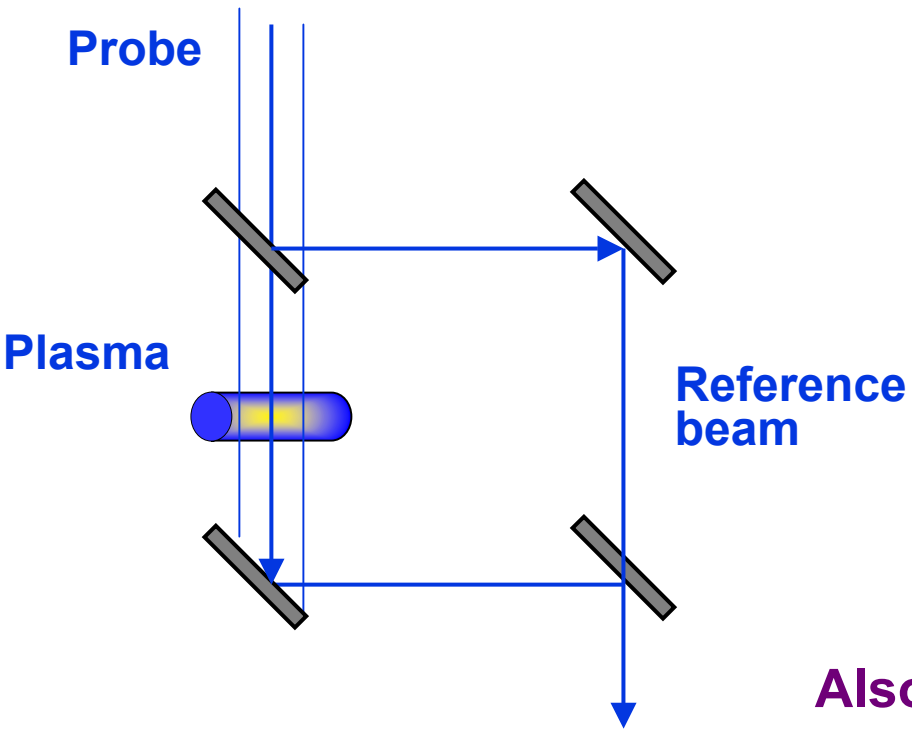
## Probe sees slowly-varying or ~ static ñ(r,t)

$$\eta \equiv \frac{k_i c}{\omega_i} = \left(1 - \frac{\omega_p^2}{\omega_i^2}\right)^{1/2} \approx 1 - \frac{1}{2}\frac{\omega_p^2}{\omega_i^2 \gamma_i}$$

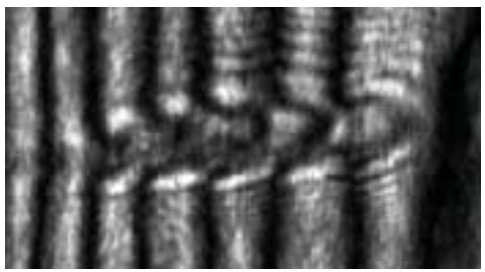
$$\left(\omega_i^2 = \omega_p^2 + c^2 k_i^2\right)$$

$$\approx 1 - \frac{1}{2}\frac{\omega_p^2}{\omega_i^2}\left(1 + \frac{\tilde{n}(r,z)}{n_0} + \frac{\Delta n(r,z)}{n_0} - \frac{a_i^2(r,z)}{2}\right)$$

**Mach-Zehnder interferometer; Spatial phase $\eta(x,y)$ imprinted onto one arm.**




Ignitor + Heater



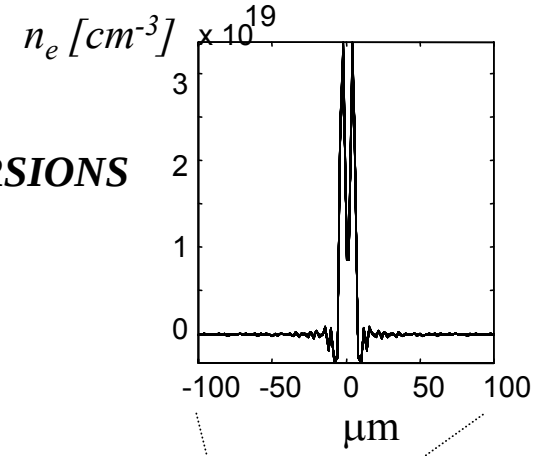
LBNL result

**Also, 'freq.-domain interferometry' (later).**

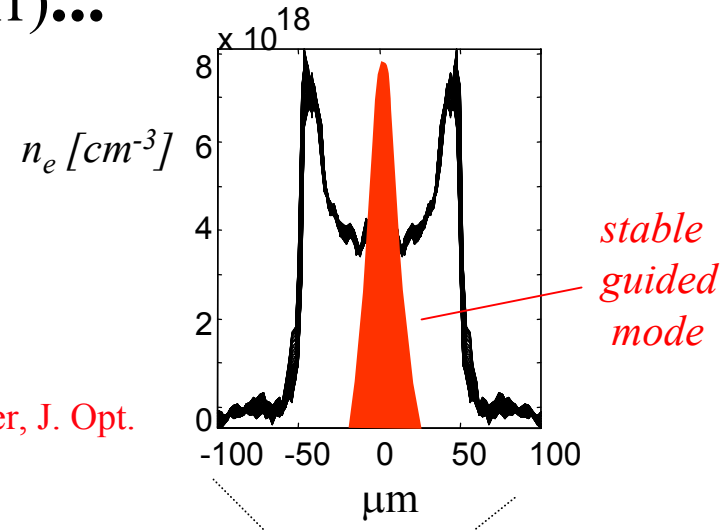
# Longitudinal & transverse profiles
## And optical properties of plasma fiber (@2 $10^{17}$ W/cm$^2$)

**Fully-ionized He channel** (400 Torr)**...**

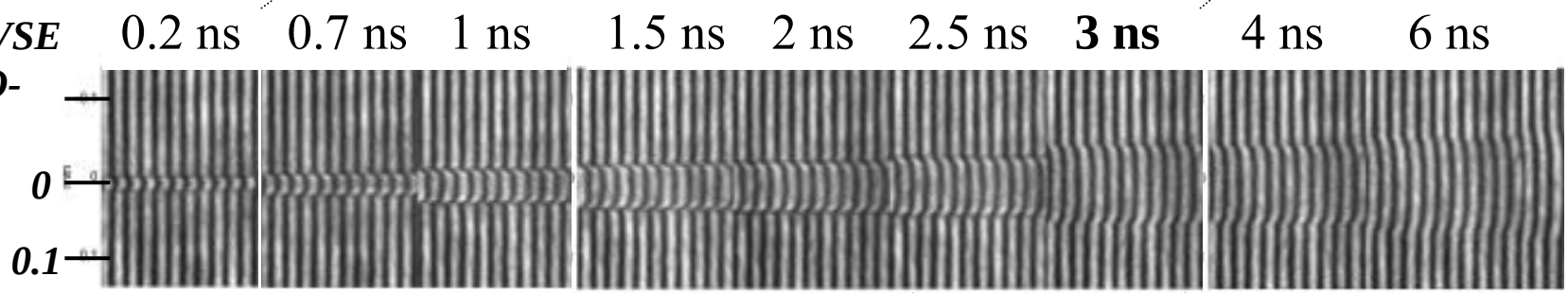
***ABEL INVERSIONS***



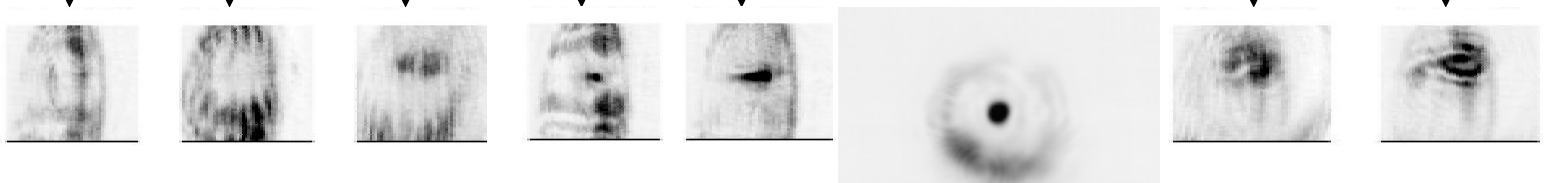

Zgadzaj, Gaul, Downer, J. Opt. Soc. Am. B (2003)




***TRANSVERVSE INTERFERO-GRAMS***




***EXIT MODE IMAGES***



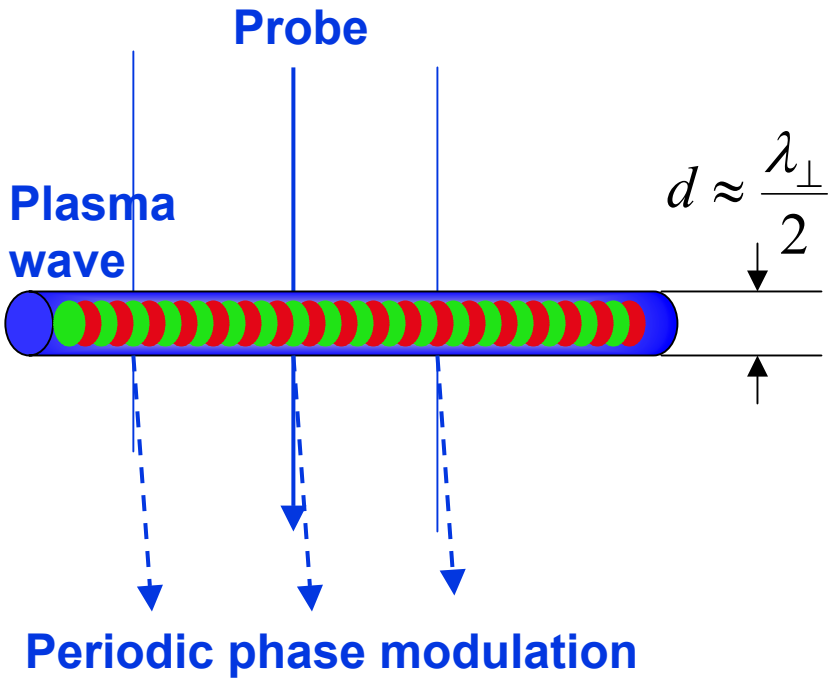
# Plasma Wave/Accelerating Structure

**Characterization of accelerating wave structure**

- **Amplitude of density perturbation** along z.
- Magnitude of longitudinal/radial fields
- Spatial/temporal scale of fields, “acceptance”
- Phase velocity
- Self-trapping
- Beam loading

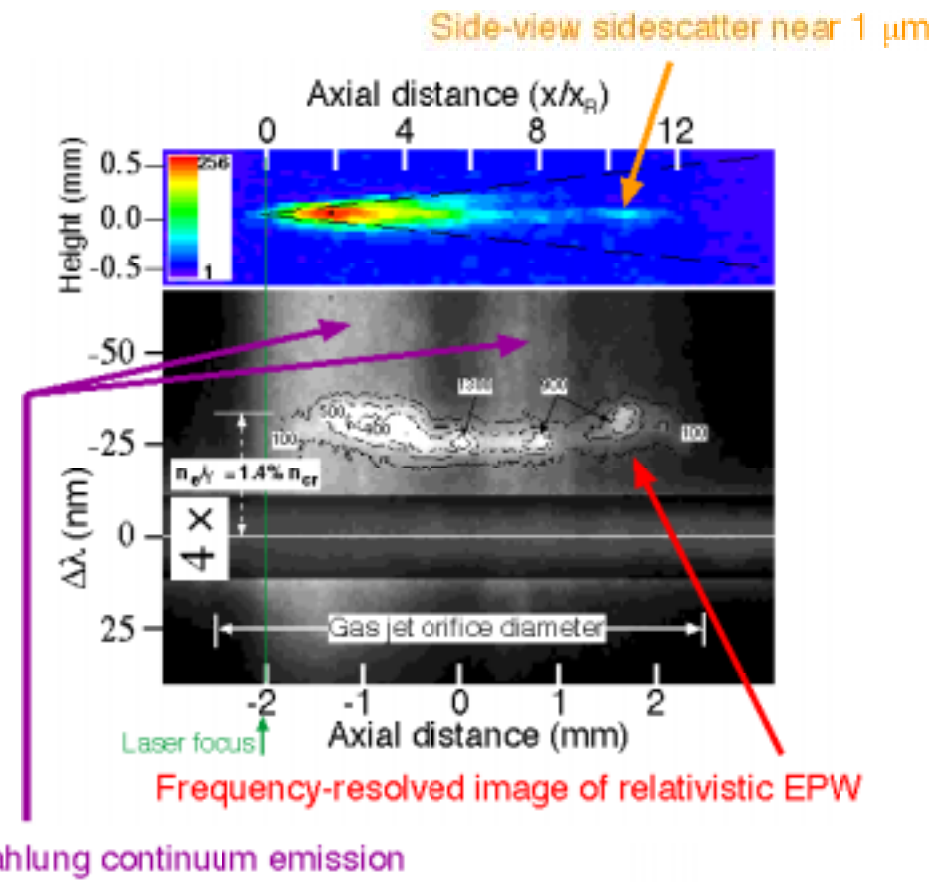
# Characterization of accelerating wave structure

## Probe sees quasi-static structure




$$\tau_{transit} = \frac{d}{c} \approx \frac{\pi}{ck_\perp} < \frac{\tau_p}{2}$$

$$\Rightarrow \quad k_\perp > k_\parallel$$



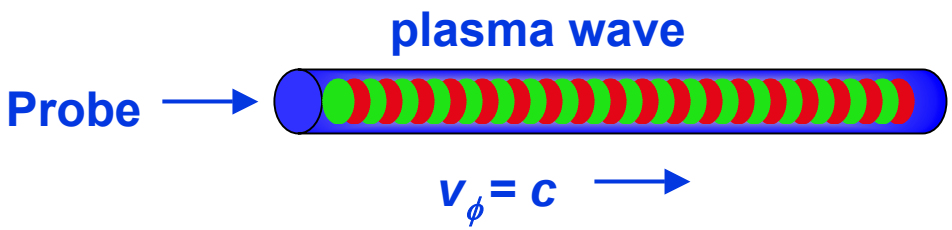

**Correlations seen in EPW, sidescatter, Bremsstrahlung**

**RAL, UCLA, IC, LULI**

# Characterization of accelerating wave structure

## Probe sees quasi-static structure

### Refractive index probe




$$E_s(t,L) \approx E_{i0}\cos\left(\omega_i t + k_{i0}\int_0^L \Delta\eta(z,t)dz\right)$$

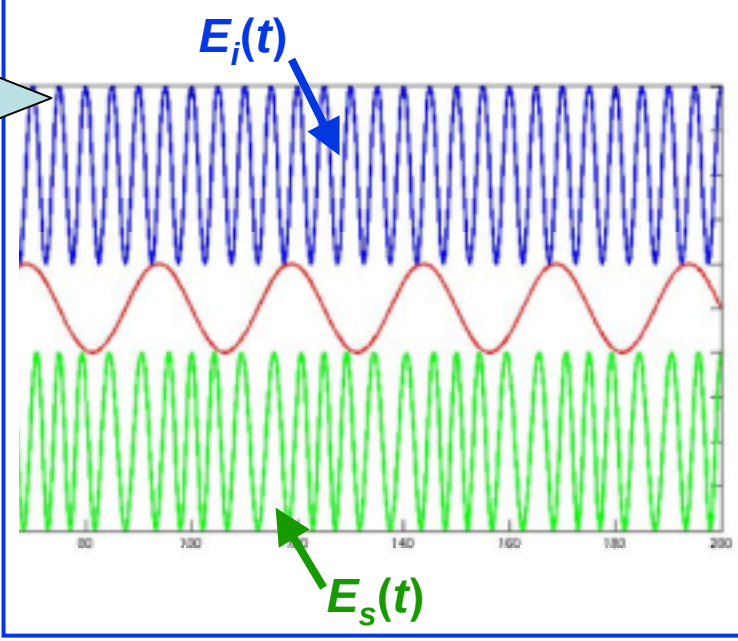
### Amplitude of "Refractive Index" wave…

$$\Delta\eta(z,t) \approx \left[1-\frac{1}{2n_0}\frac{\omega_p^2}{\omega_i^2}(n_0-\tilde{n})\right]-\left[1-\frac{1}{2n_0}\frac{\omega_p^2}{\omega_i^2}(n_0+0)\right]$$

$$\int_0^L \Delta\eta(z,t) \approx \pi\frac{\tilde{n}}{n_{crit}}\frac{L}{\lambda_i}\sin(\omega_p t)$$

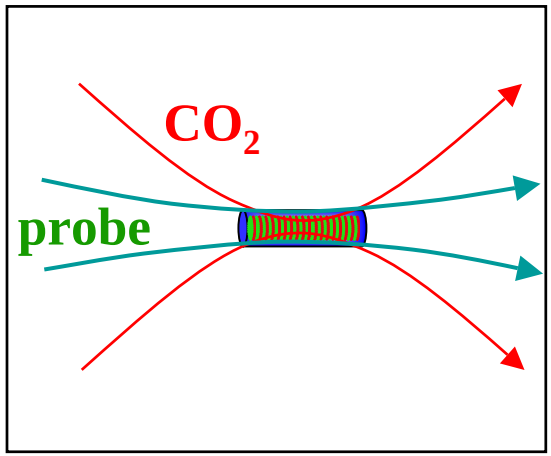
### Pure phase-modulation (FM)

$$\cos\left(\omega_i t + \varepsilon\sin(\omega_p t)\right)$$
$$\approx J_0(\varepsilon)\cos(\omega_i t) + \sum_{n=\pm1,\pm2,\ldots}\frac{J_n(\varepsilon)}{n!(-1)^n_{n<0}}\cos(\omega_i t + n\omega_p t)$$




**Photon acceleration!**

# Characterization of accelerating wave structure
## Collinear Thomson Scattering



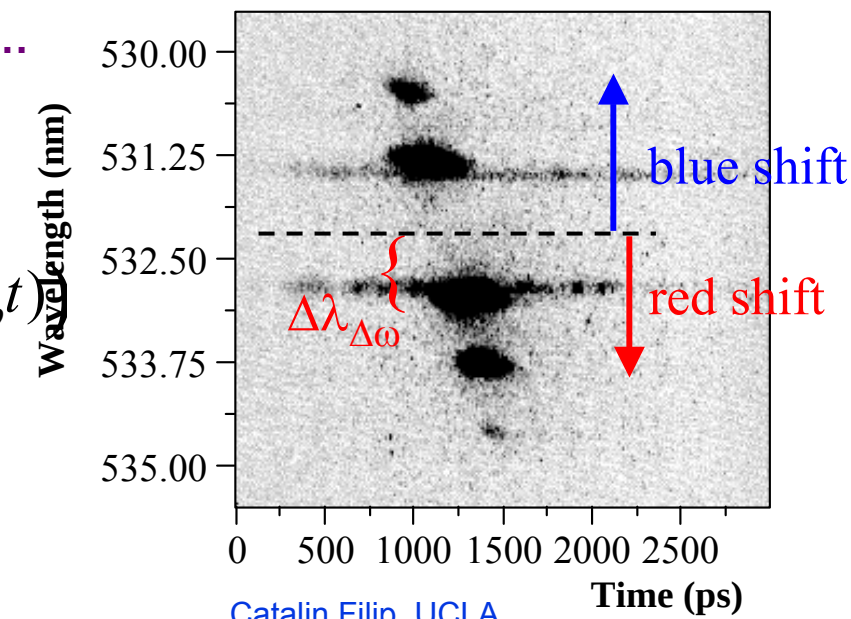

$$E_s(t,L) \approx E_{i0}\cos\left(\omega_i t + k_{i0}\int_0^L \Delta\eta(z,t)dz\right)$$

**Longitudinal phase modulation;**

**Experimental result…**

$$E_s(t,L) \approx E_{i0}\cos(\omega_i t) + \underbrace{E_{i0}\left(\frac{\pi}{2}\frac{\tilde{n}}{n_{crit}}\frac{L}{\lambda_i}\right)}\left(\cos(\omega_i t + \omega_p t) - \cos(\omega_i t - \omega_p t)\right)$$

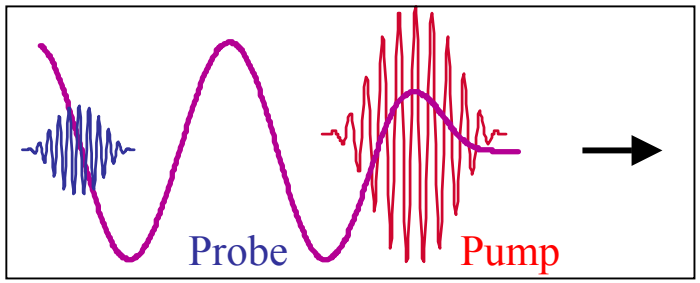
**Looks like "ordinary" Thomson scattering scattered amplitude.**

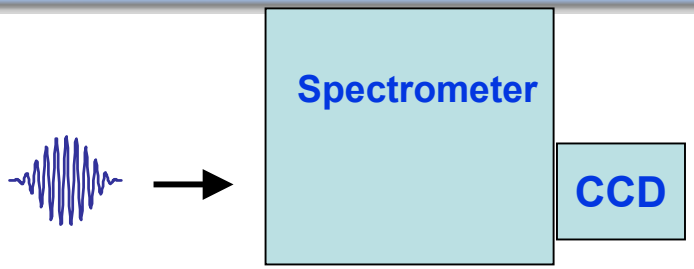



Catalin Filip, UCLA

# Characterization of accelerating wave structure

## Photon Acceleration




$$\phi(t) = \eta(t) k_i L$$
$$\approx \phi_0 + \phi_1 t$$

$$I(\omega) = \frac{1}{2\pi}\left|\int_{-\infty}^{\infty} e^{-i\omega t} E_i(t) e^{i\phi(t)} dt\right|^2$$

$$I(\omega) = \frac{1}{2\pi}\left|e^{i\phi_0}\int_{-\infty}^{\infty} e^{-i(\omega-\phi_1)t} E_i(t) dt\right|^2$$
$$= I(\omega - \phi_1)$$

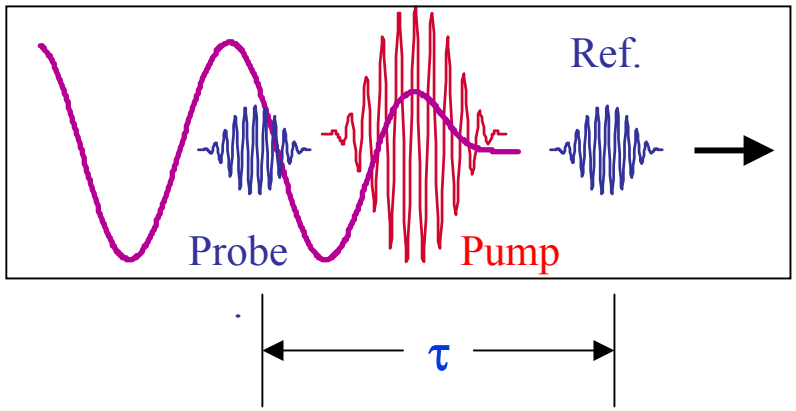
**First derivative of $\phi(t)$**

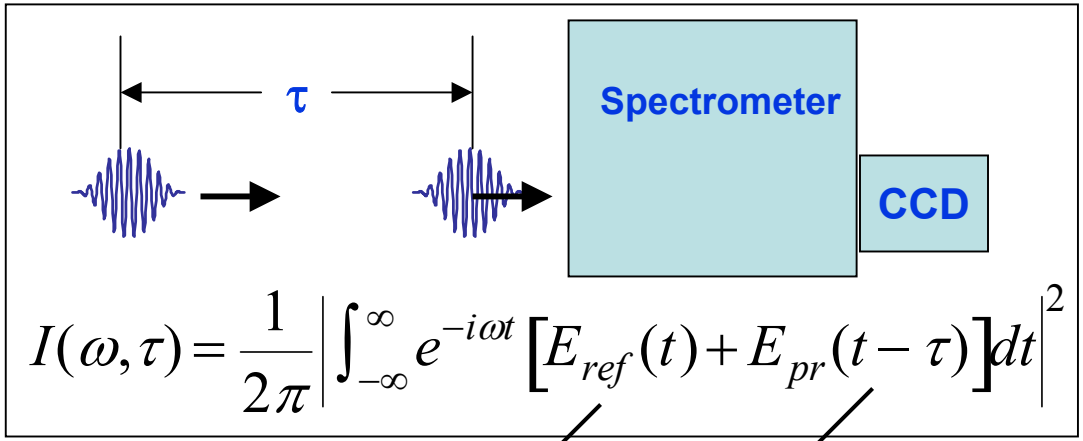
$$\phi_1(\zeta) = k_i L \frac{d\eta(\zeta)}{d\zeta}$$

**Frequency shift**

$$\Delta\omega = \omega_i - \phi_1 \approx \omega_i \frac{\tilde{n}}{n_0}\frac{n_0}{n_{Crit}} k_p L \cos(k_p \zeta)$$

# Characterization of accelerating wave structure
## Frequency-domain interferometry




$$I(\omega,\tau)=\frac{1}{2\pi}\left|\int_{-\infty}^{\infty}e^{-i\omega t}\left[E_{ref}(t)+E_{pr}(t-\tau)\right]dt\right|^2$$

$$\tilde{E}_{ref}(\omega)e^{i\varphi_{ref}(\omega)}+\tilde{E}_{pr}(\omega)e^{i\varphi_{pr}(\omega)-\omega\tau}$$

$$I(\omega,\tau)=\left|\tilde{E}_{ref}(\omega)\right|^2+\left|\tilde{E}_{pr}(\omega)\right|^2+\left|\tilde{E}_{ref}(\omega)\right|\left|\tilde{E}_{pr}(\omega)\right|\cos\underbrace{\left[\varphi_{ref}(\omega)-\varphi_{pr}(\omega)+\omega\tau\right]}_{\arg\{\Im[I(\omega,\tau)]\}}$$

**Recall that $\varphi_{ref}(\omega)$ in known from FROG**

$$I_{FROG}^{PG}(\omega,\tau)=\left|\int_{-\infty}^{\infty}E(t)\left|E(t-\tau)\right|^2\exp(-i\omega t)\,dt\right|^2$$

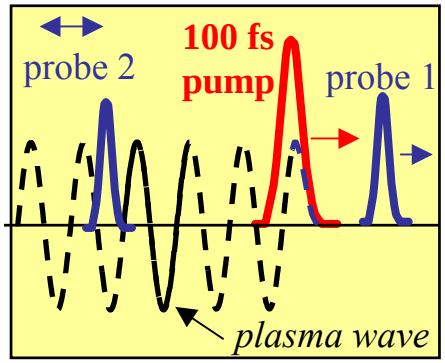
**$\varphi_{pr}(\omega)$ can be extracted!**

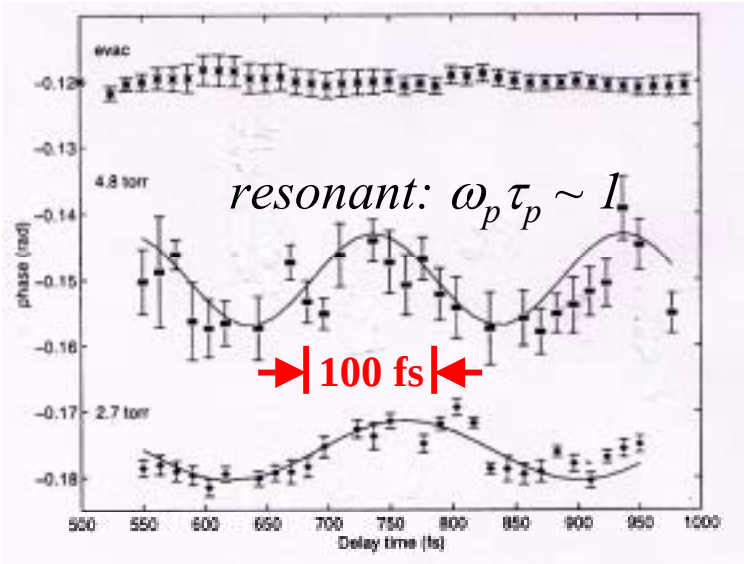
# fs-time-resolved measurement of Resonant LWFA

$\omega_p^{-1} = \tau_p$

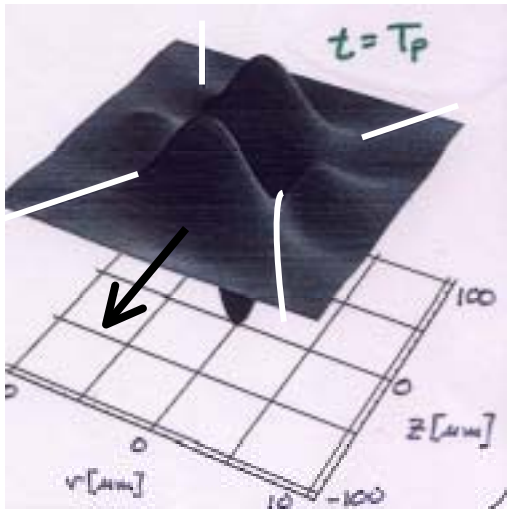
Siders *et al.*, PRL **76**, 3570 (1996). Marquès *et al.*, PRL **78**, 3463 (1997).

$n_e \sim 10^{17}\ cm^{-3}$, $\partial n/n \sim 1$, $E_z \sim 10\ GV/m$, $E_r \sim 5\ E_z$



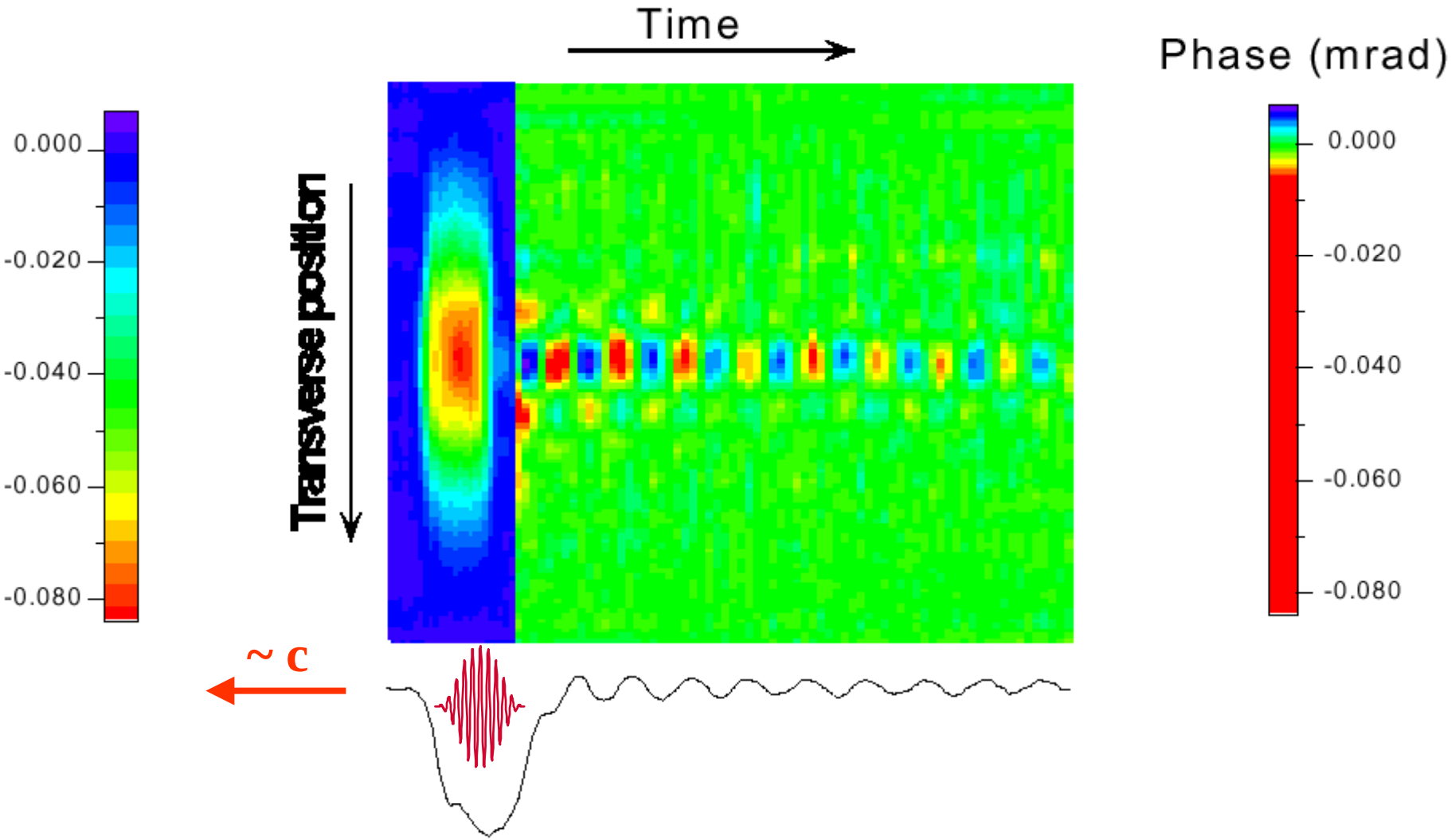

- sub- $\lambda_p$ characterization of fast plasma waves




2D wakefield structure

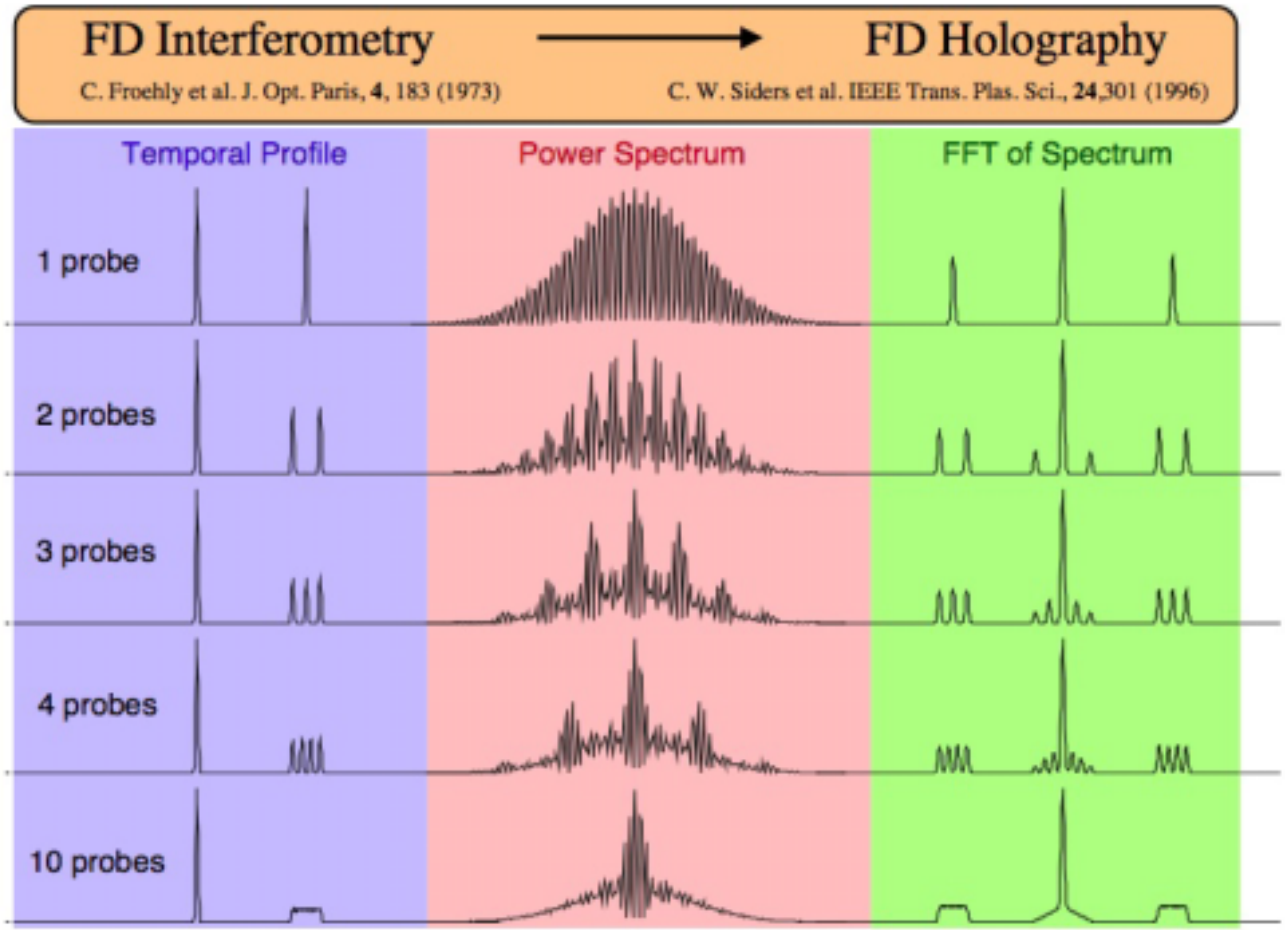
# Characterization of accelerating wave structure
## Frequency-domain interferometry w/ radial info

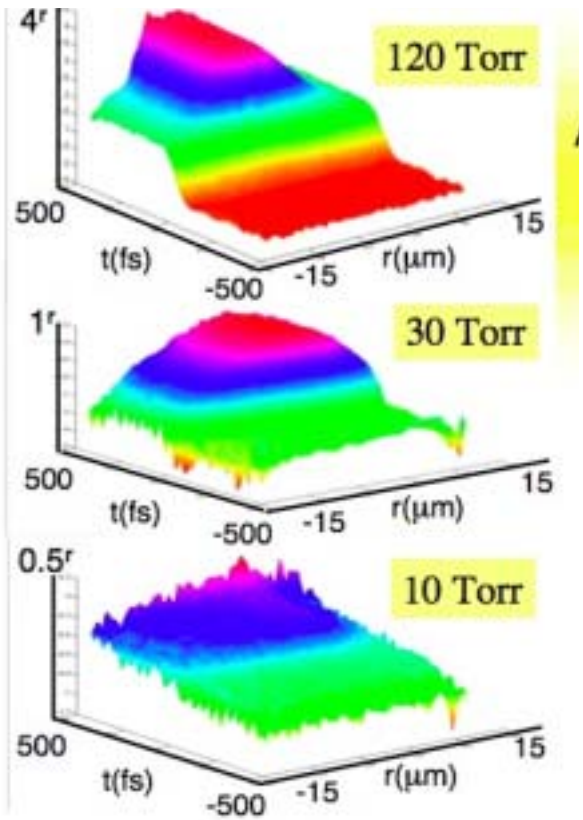





J.R. Marques et al. PRL **76**, 3566 (1996) & PRL **78**, 3463 (1997)

# Characterization of accelerating wave structure
## Single-shot, 2D longitudinal "holography"




C.W. Siders *et al.*, IEEE Trans. Plas. Sci.. **24**, 301 (1996)

LeBlanc *et al.*, Opt. Lett. **25**, 764 (2000)

# Electrons In and Out

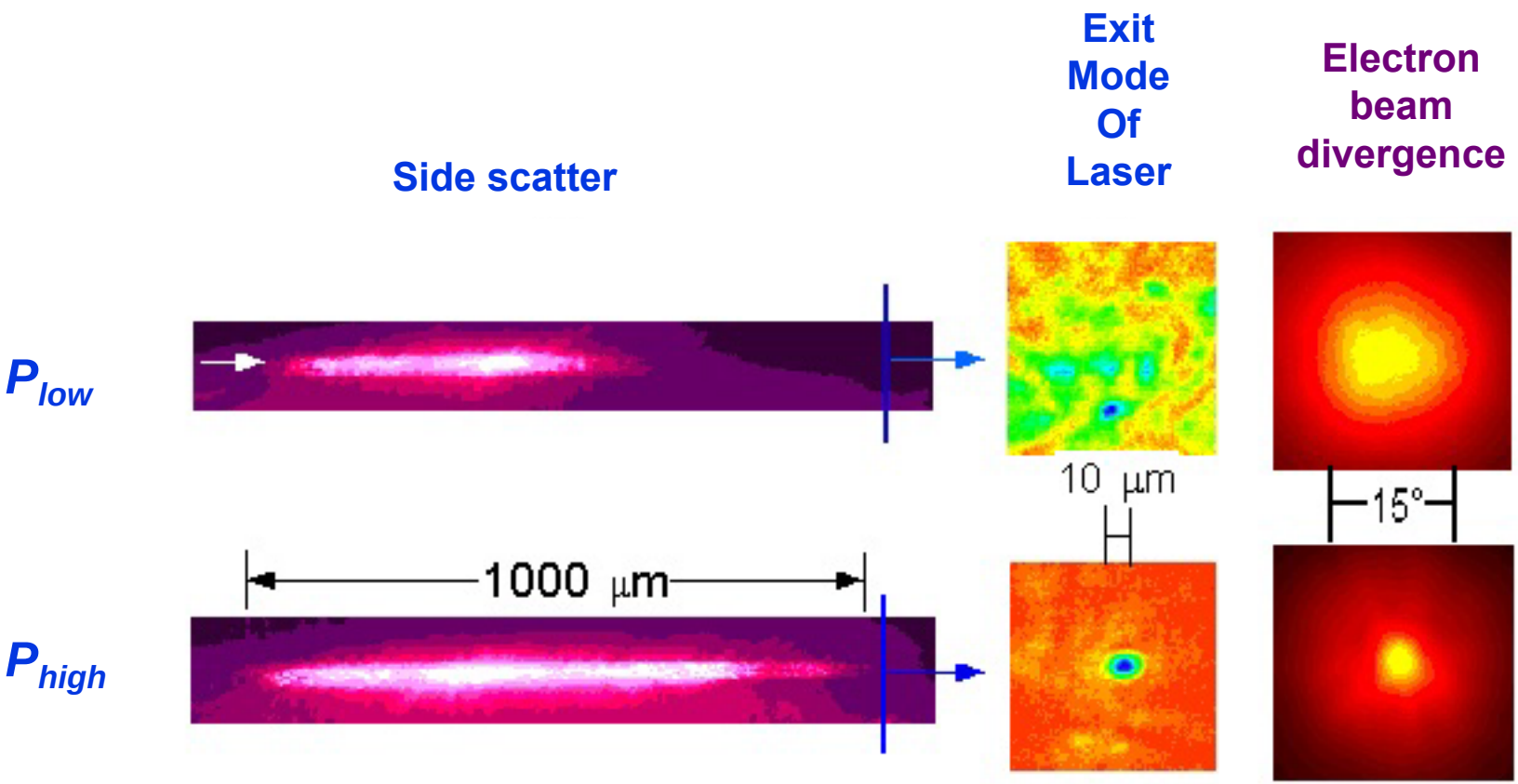
**Quality of injected electrons**

- Central energy, energy spread, temporal chirp
- $\tau$ pulse shape, pre- and post-pulse
- Total charge
- Emittance, focal quality, brightness
- Pointing jitter
- Dark current

**Quantify output electrons**

- Energy spectrum, charge
- Number of buckets
- Bunch length within single bucket
- Source size, beam density
- Betatron phase, amplitude

# Characterization of electrons out
## Correlations with sidescatter and Laser Out

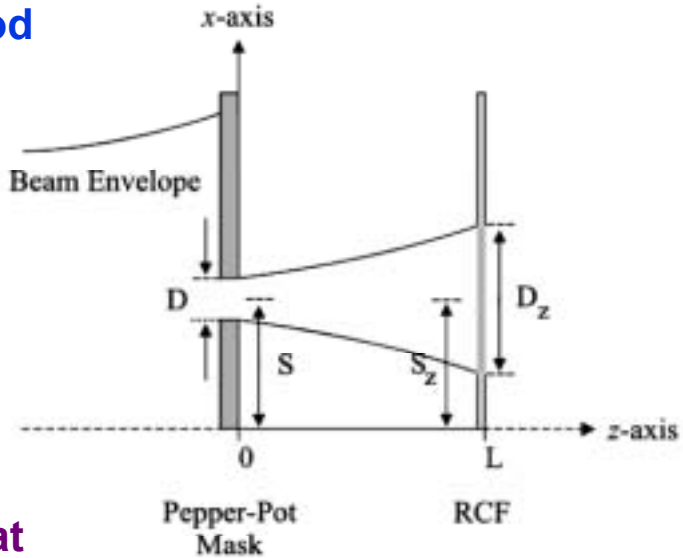



Don Umstadter, U of Michigan

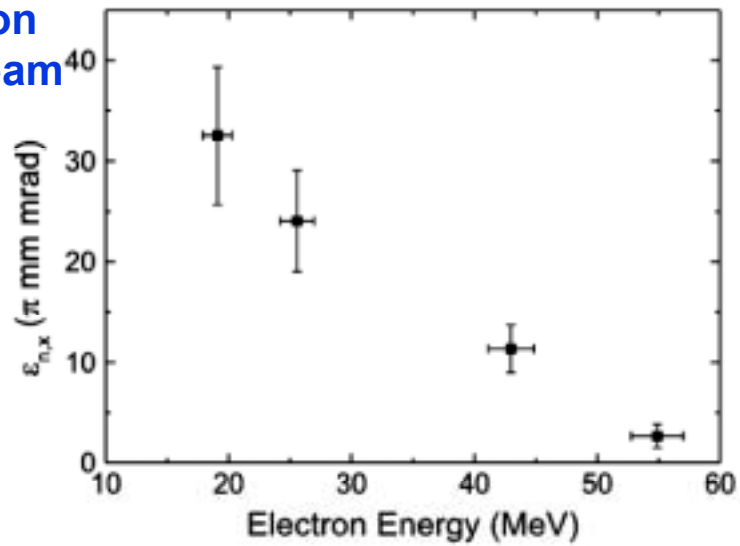
# Characterization of electrons out

## Transverse emittance via scanned "pepper pot"

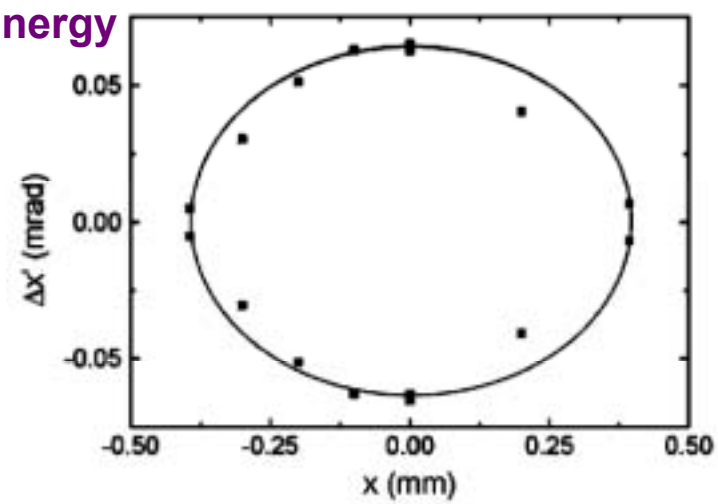
**Method**




**Variation with beam energy**

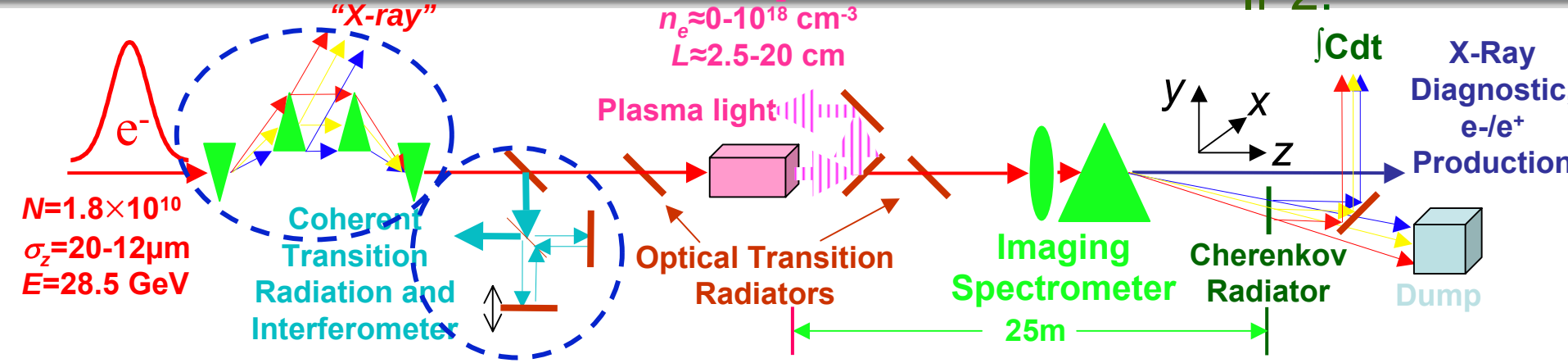



**Data at 'single' energy**

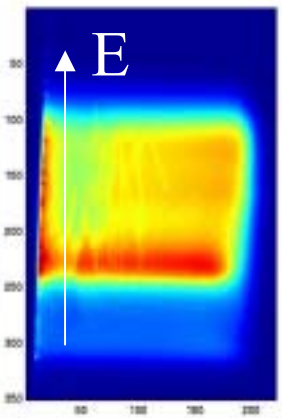


# Characterization of electrons in & out

## Transverse & longitudinal size, energy

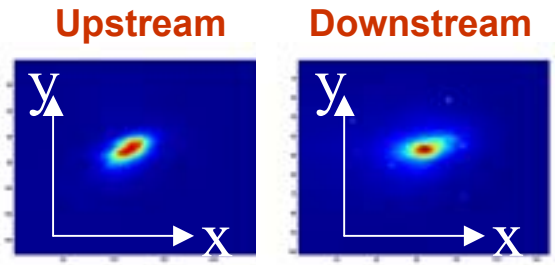



- X-ray Chicane



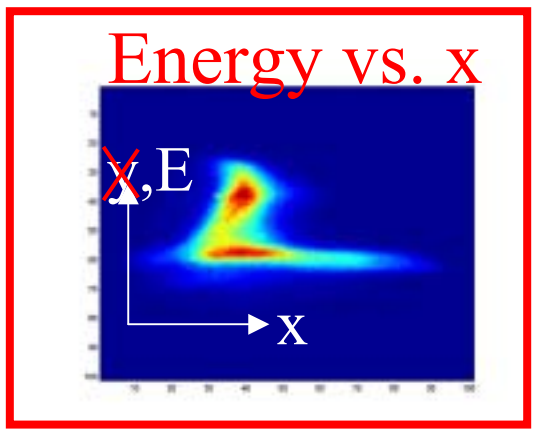

-Energy resolution ≈60 MeV

- Optical Transition Radiation (OTR)



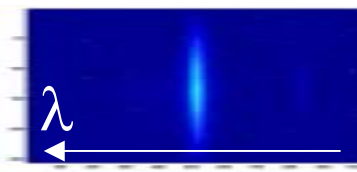

-1:1 imaging, spatial resolution ≈9 μm

- Cherenkov (aerogel)

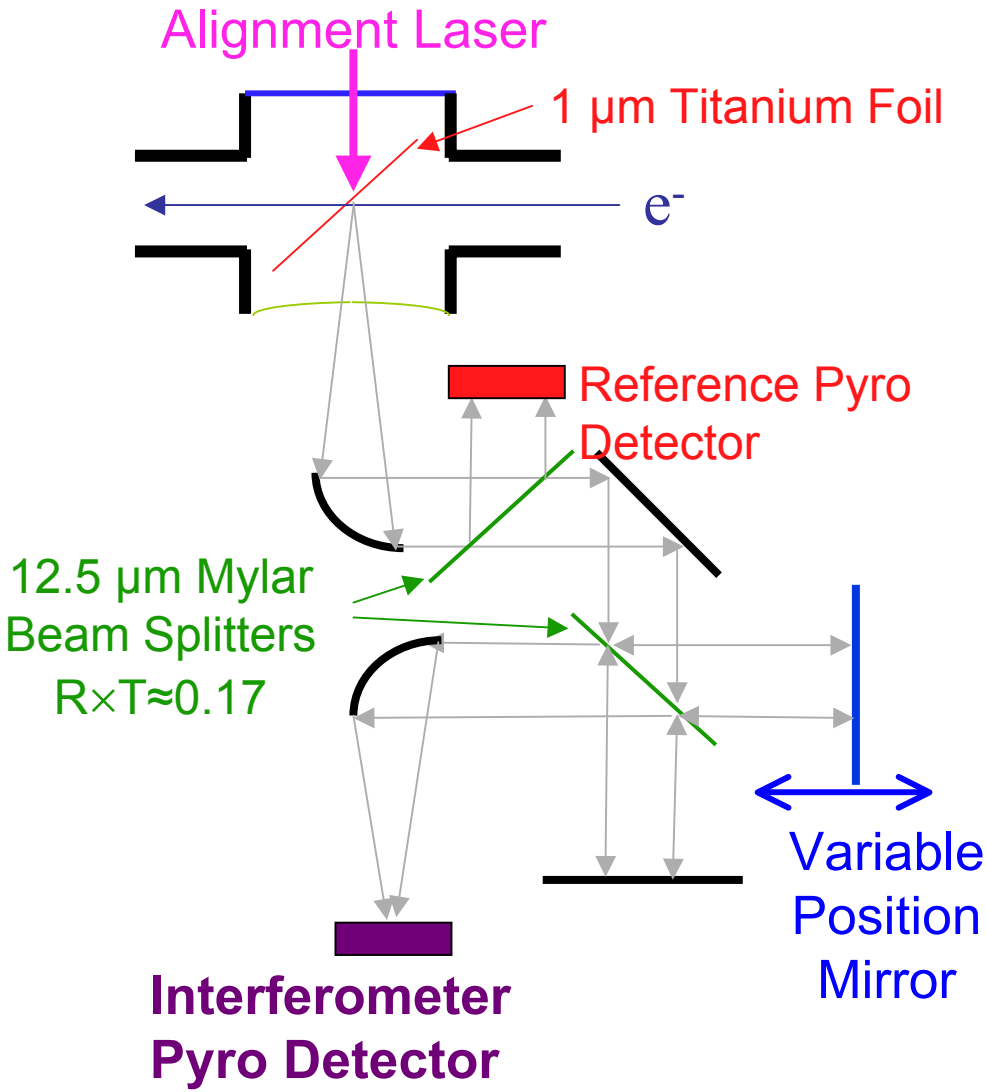



- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV

- Plasma Light

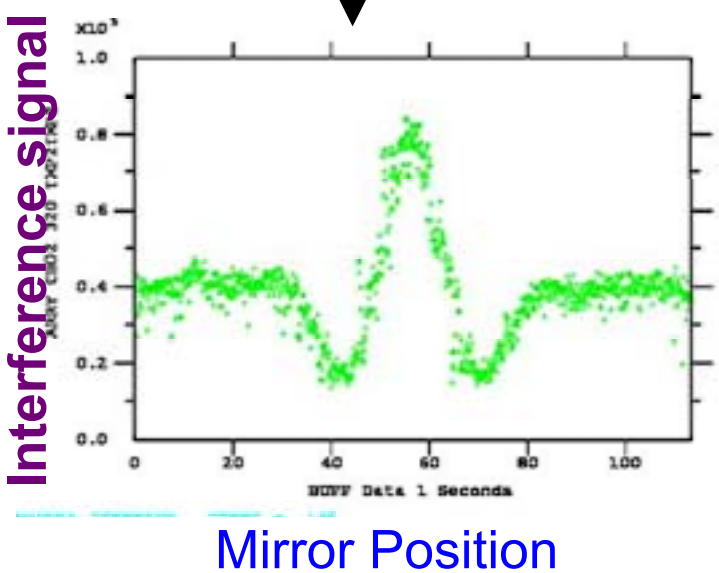


# Characterization of electrons in
## Time-domain interferometry (many shots)



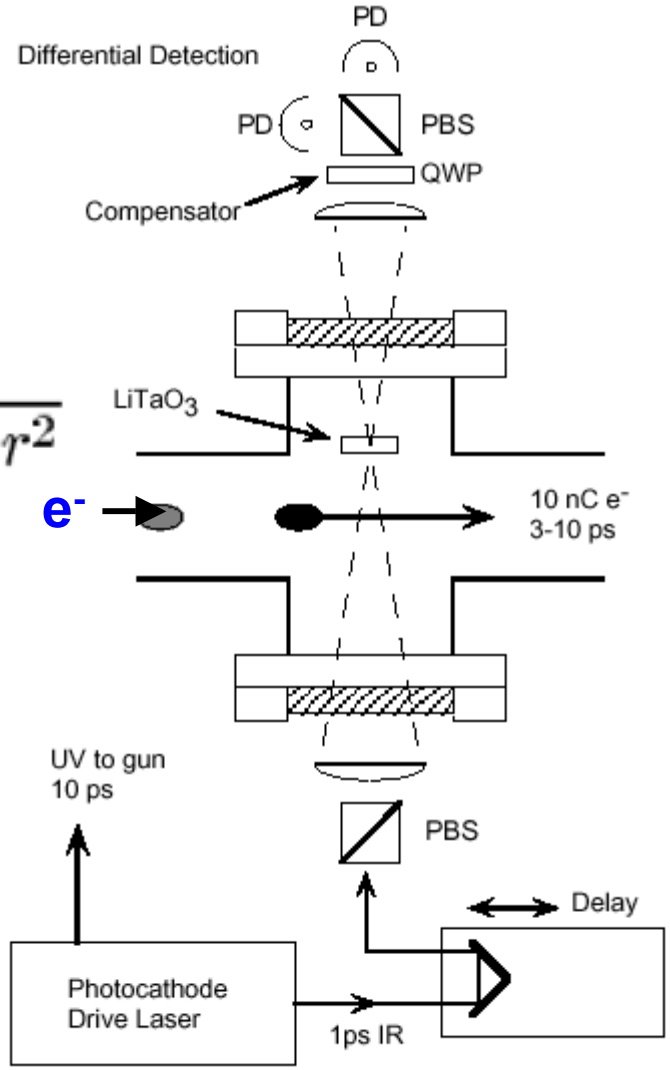

Transition Radiation coherent

for $\lambda > (2\pi)^{1/2}\sigma_{z,\ Gaussian}$ (CTR)

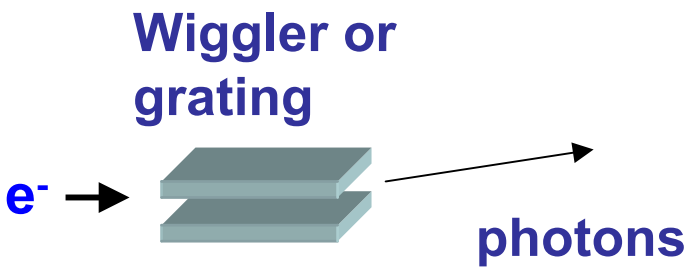


# Characterization of electrons in or out
## Electrooptic effect, wiggler radiation

$$E = \gamma N_e \frac{q}{4\pi\epsilon_0 r^2}$$




Fitch et al.




Catravas et al.

# Summary

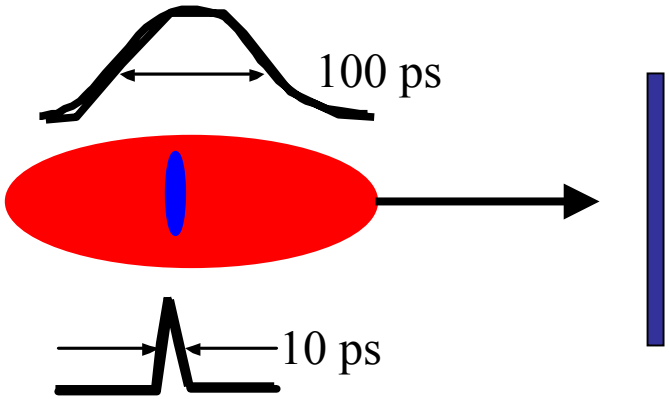
**“Measurement is King”**

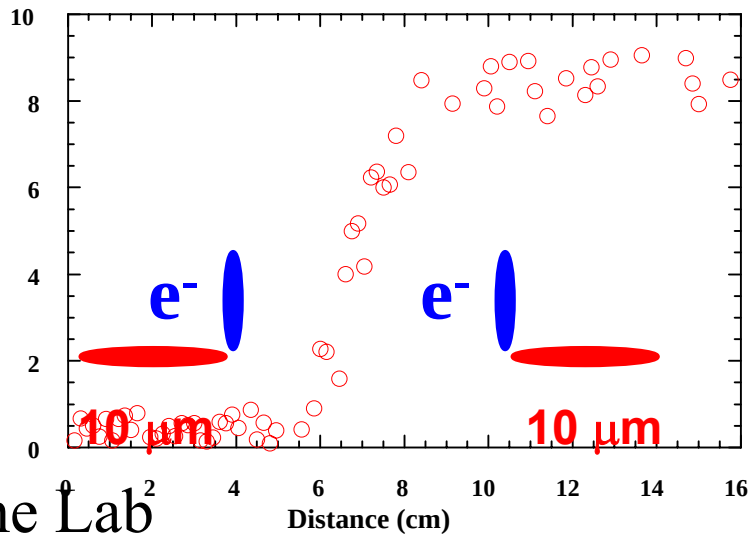
- Quantify
- Correlate
- Improve input parameters
- Improve output parameters
- Understand physics
- Advanced Accelerator community is pioneering in many advanced diagnostic techniques.

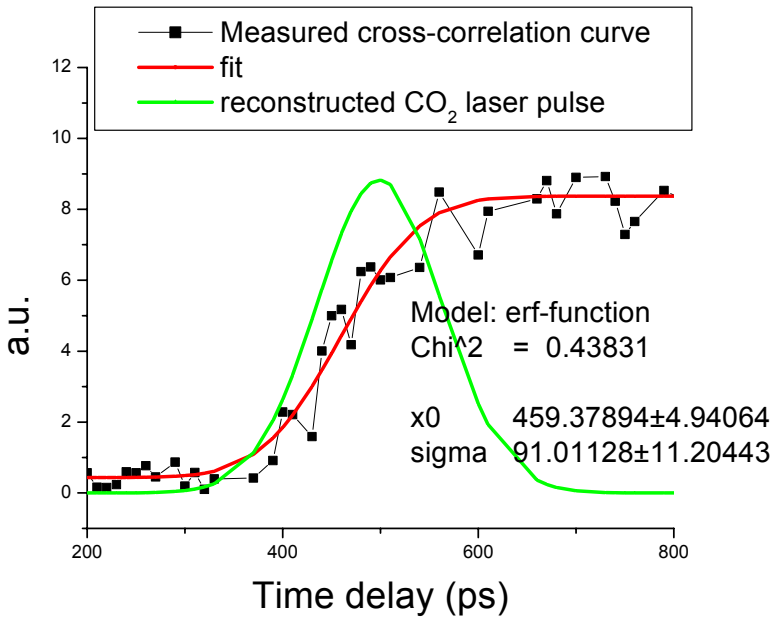
# Sub-100 ps synchronization between $CO_2$ laser and e-bunch

10-μm $CO_2$ laser pulse

e-bunch

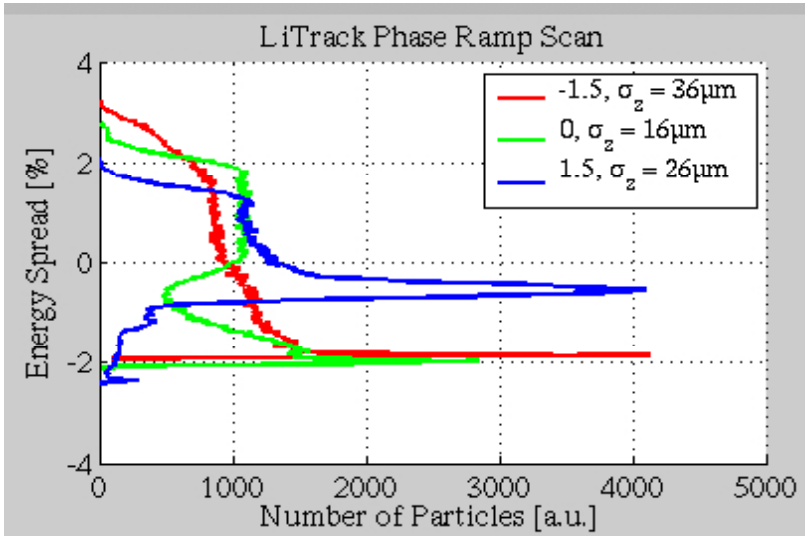


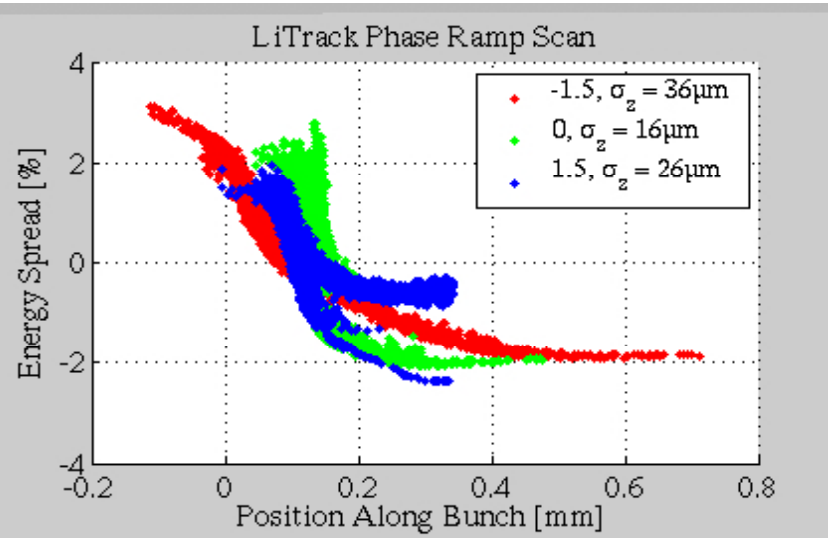




Neptune Lab

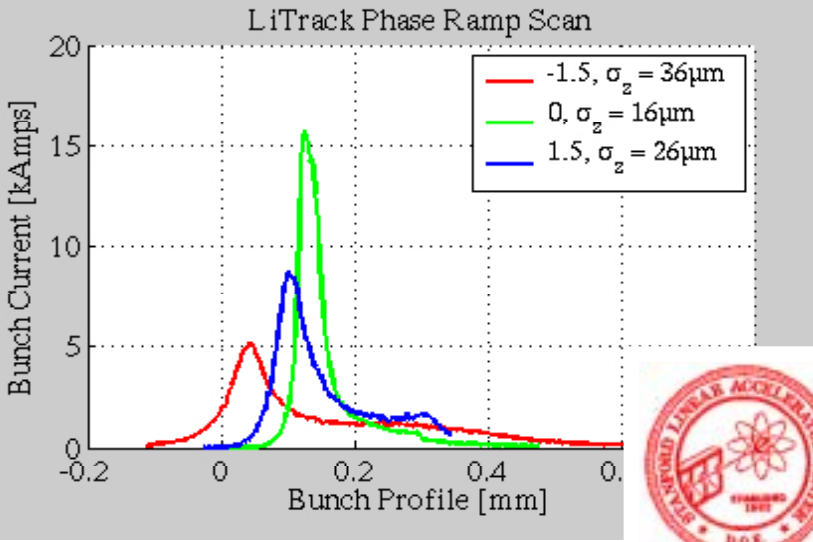
# Characterization of electrons in Simulation of longitudinal phase space



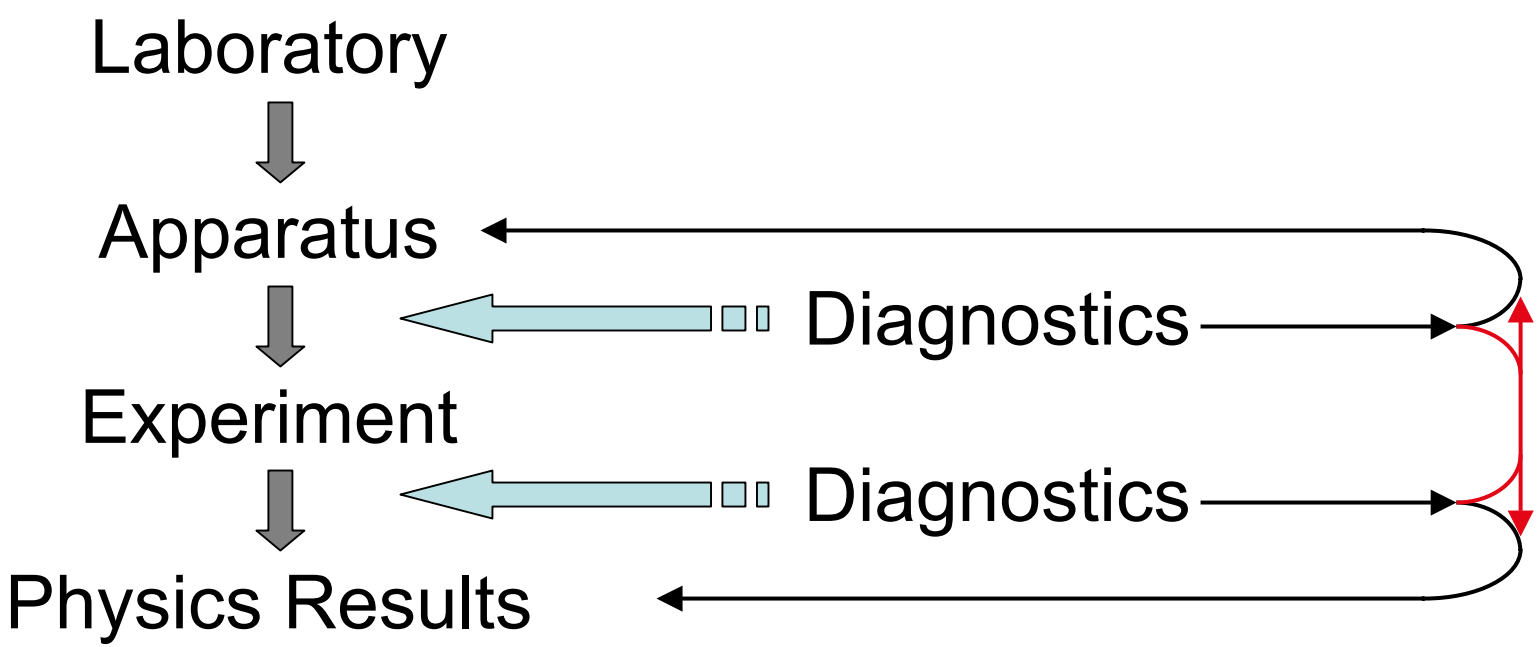




Charge : 1.9E+10
Compressor : 0.042375
Li02-06 Phase : -19.25

RTL R56 : 0.59
FFTB R56 : 0.002
NR into NRTL Timing Jitter : 0



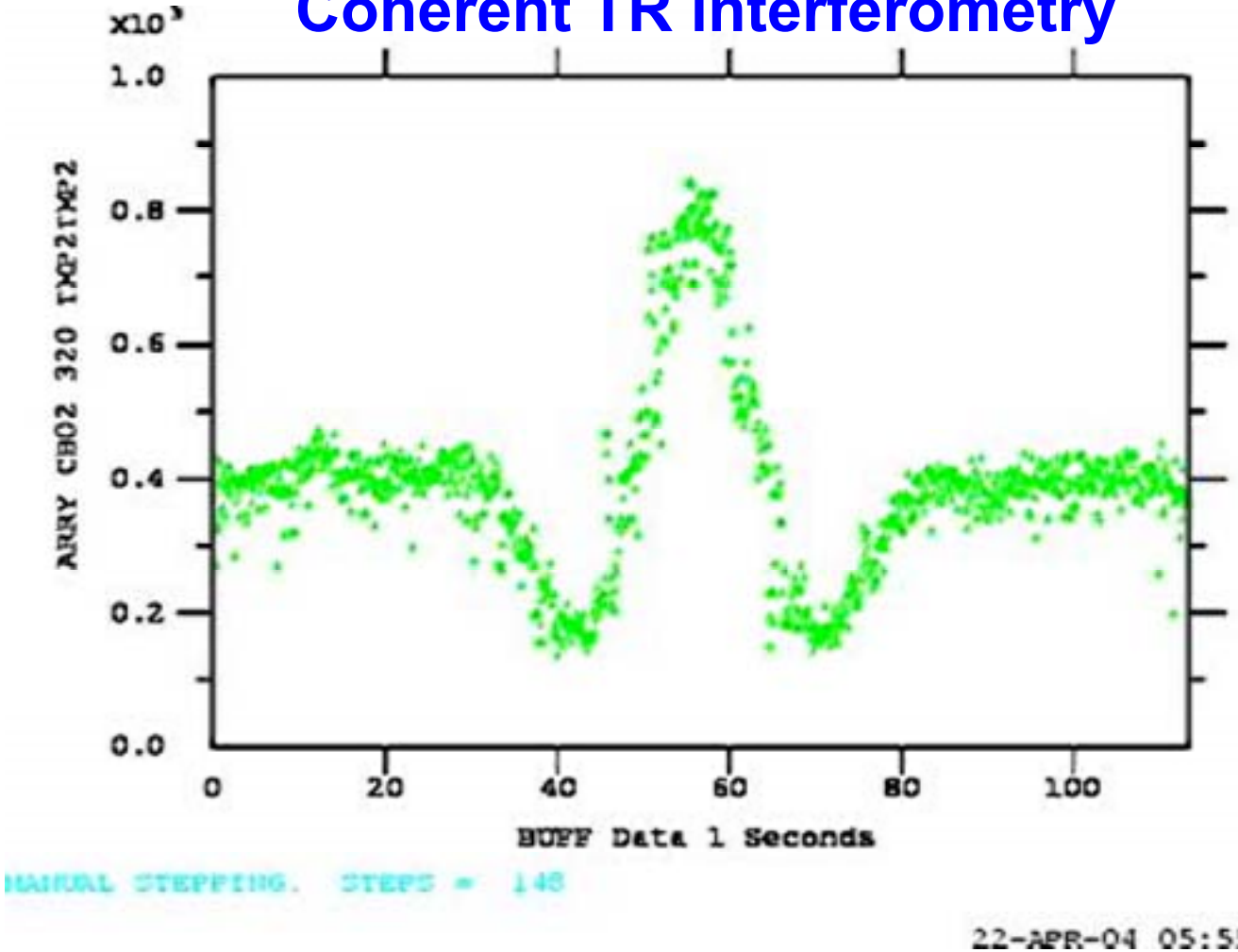
# "Measurement is King!"

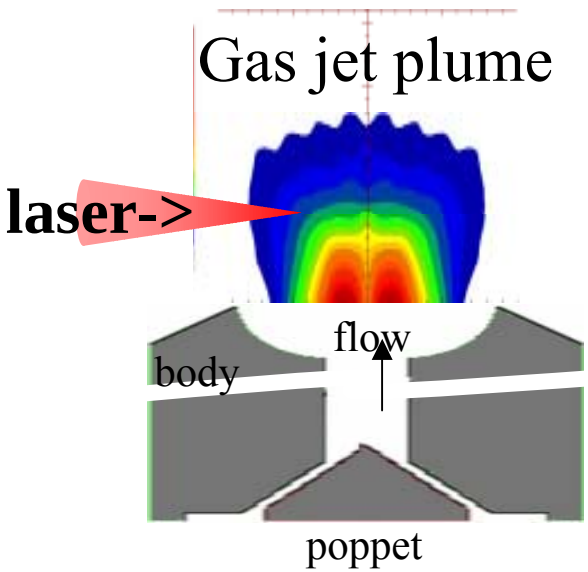



Correlations
Parametric dependencies
-> Improved understanding

# Characterization of electrons in
## (Partial) bunch length measurement

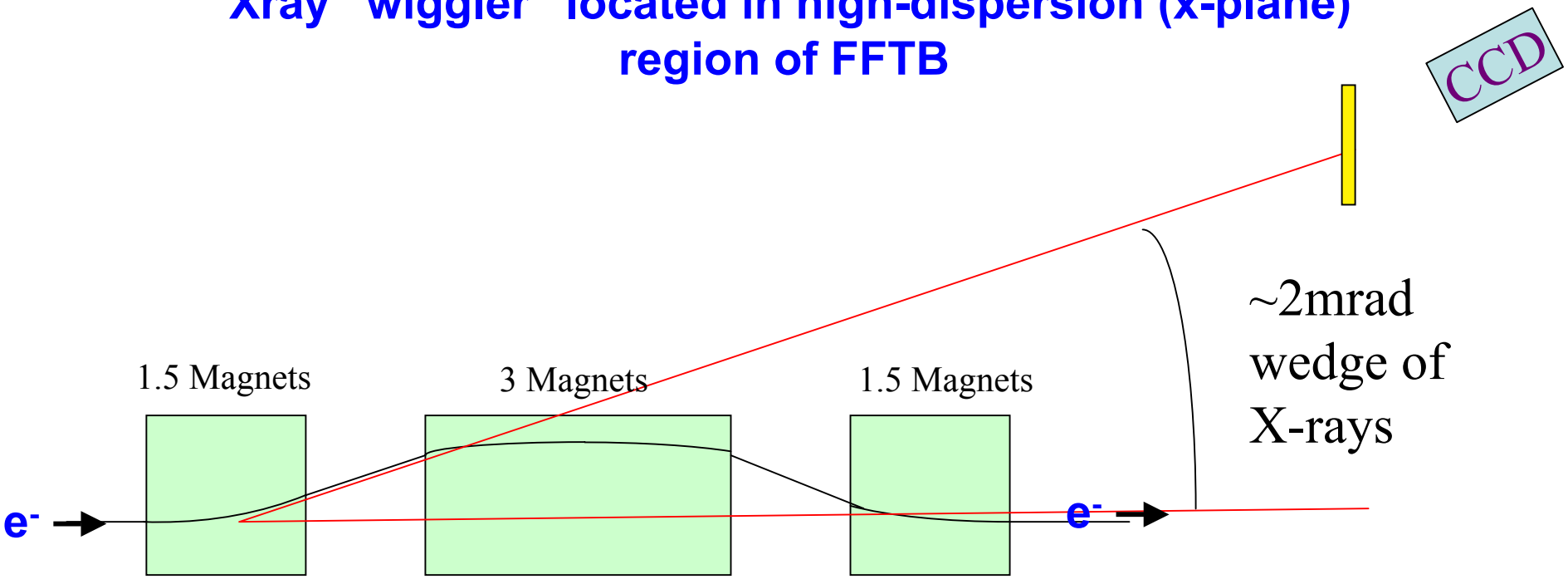
### Coherent TR interferometry




Gas jet plume
laser->
flow
body
poppet

# Characterization of electrons in
## Non-invasive energy spectrum measurem

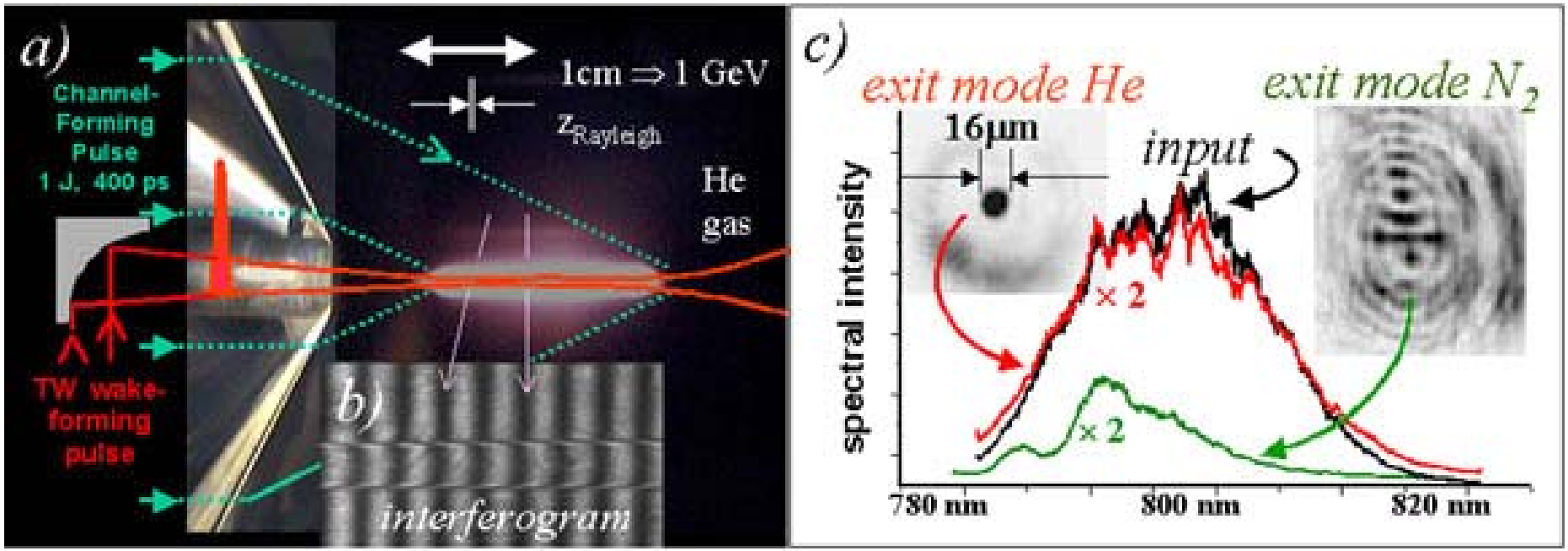
**Xray "wiggler" located in high-dispersion (x-plane) region of FFTB**




**Observe bending-radiation from a small kick in y-direction**

# A DISTORTION-FREE Propagation of 1 TW Pulses through FULLY-IONIZED He CHANNEL

Gaul *et al*., Appl. Phys. Lett. **77**, 4112 (2000)




*~ 50% throughput*

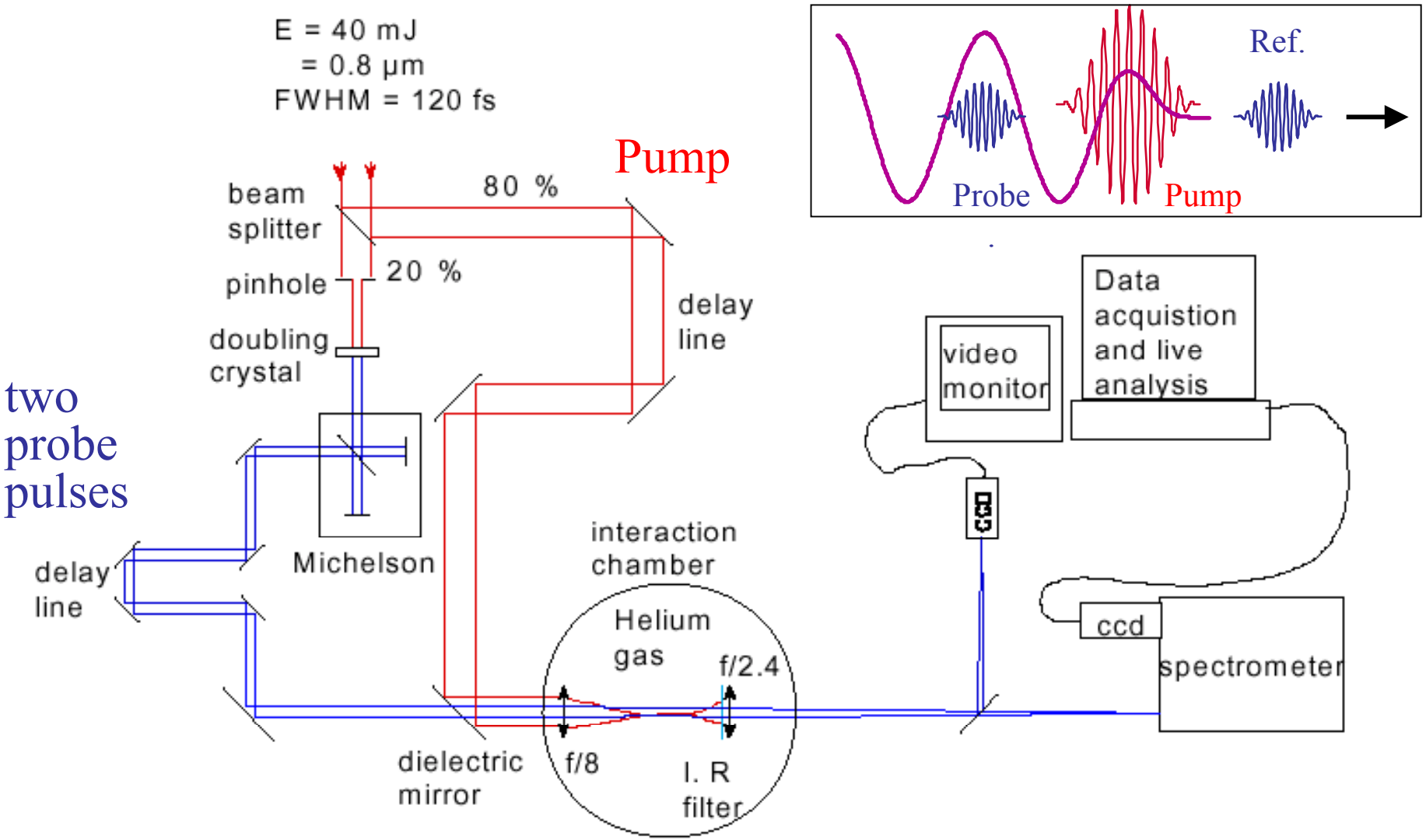
Highest **intensity-length** product demonstrated:

**$0.2 \times 10^{18}$ W/cm$^2$ × 1.5 cm**

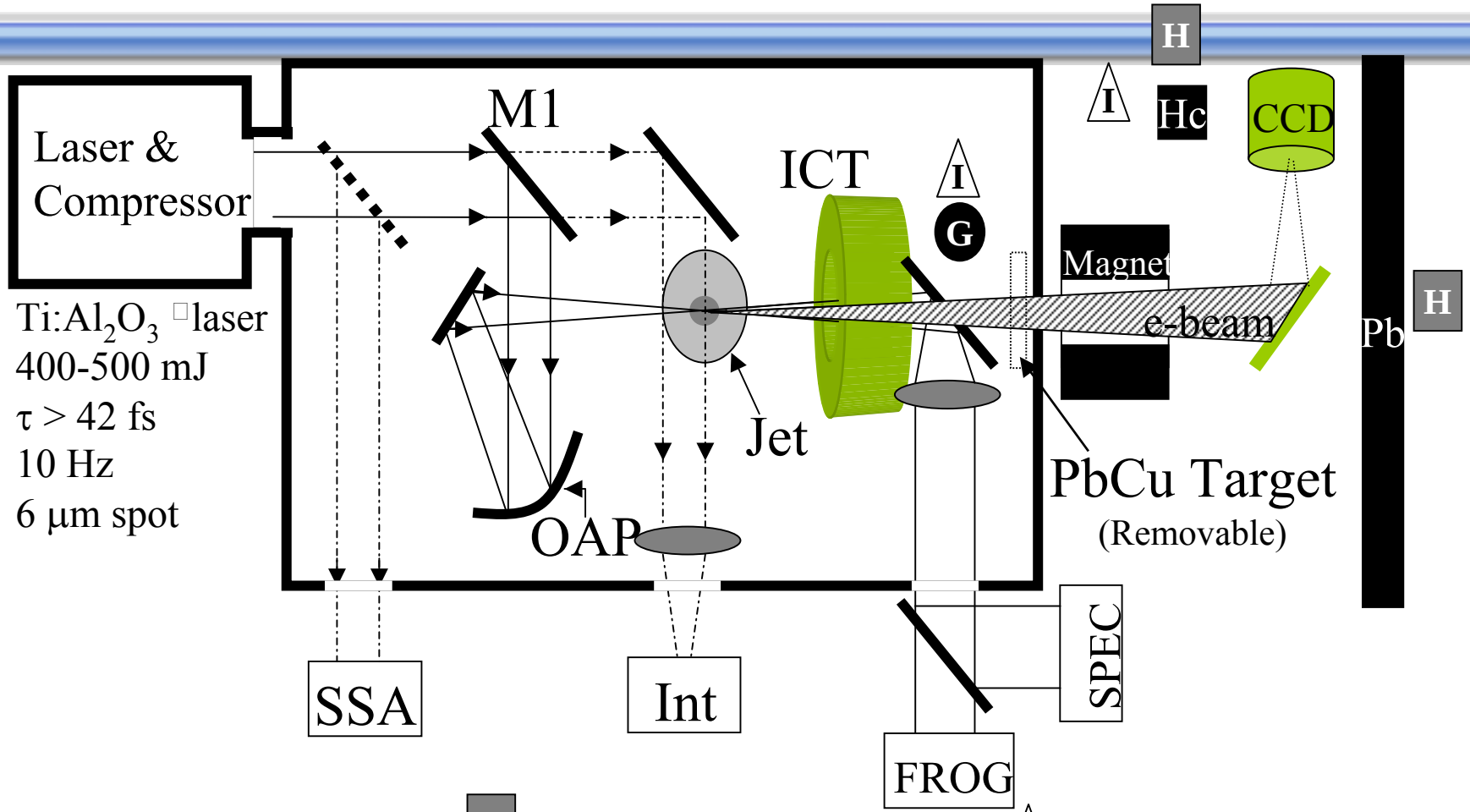
Suitable for **stable** LWFA up to **GeV energy**

Ecole Polytechnique

# Setup for Laser Wakefield and Frequency-domain interferometry



# Self Modulated Laser Wakefield Accelerator Setup




Mirror or Splitter

Flip-in Mirror

Phosphor

H He3 Detector

Hc Cd Lined He3 Detector

G GM Counter

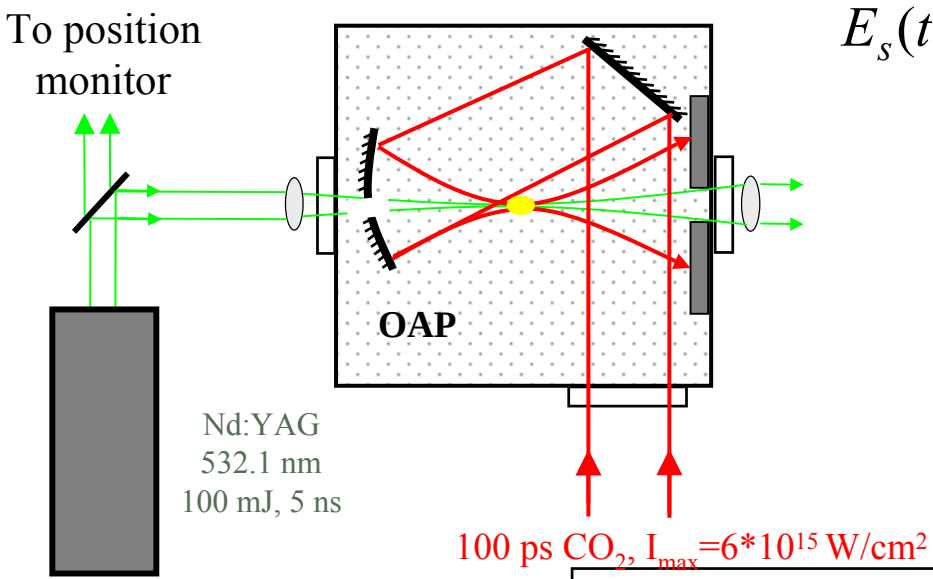
I Ion Chamber

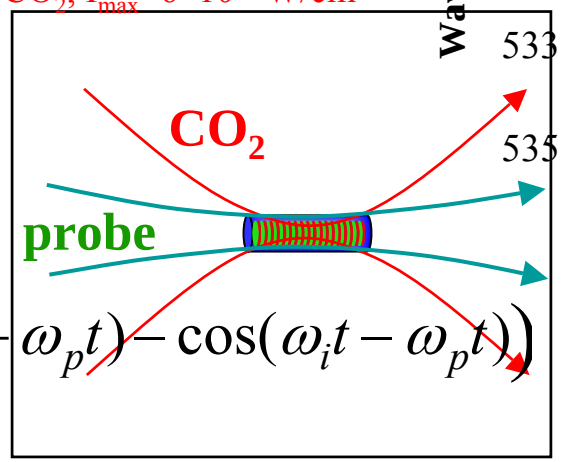
Not shown:
Side/front/back scatter
Mode image

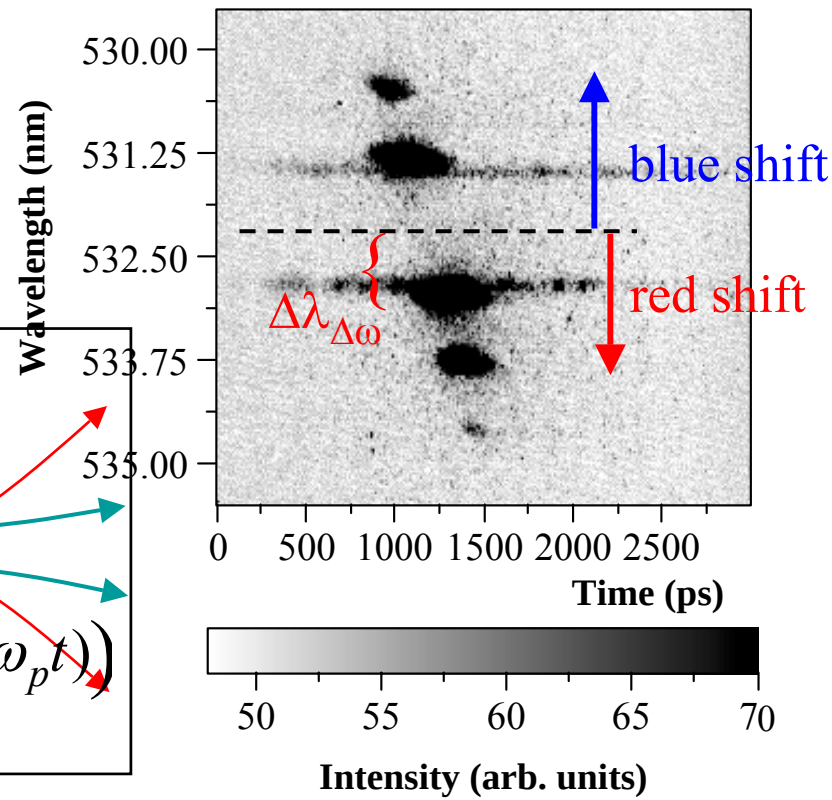
# Characterization of accelerating wave structure

## Collinear Thomson Scattering ~ cross ϕ modulation

$$E_s(t,L) \approx E_{i0}\cos\left(\omega_i t + k_{i0}\int_0^L \Delta\eta(z,t)dz\right)$$




$$E_s(t,L) \approx E_{i0}\cos(\omega_i t) + E_{i0}\left(\frac{\pi}{2}\frac{\tilde{n}}{n_{crit}}\frac{L}{\lambda_i}\right)\left(\cos(\omega_i t + \omega_p t) - \cos(\omega_i t - \omega_p t)\right)$$