Laser Based Beam Diagnostics

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BIW08, Lake Tahoe

6th May 2008

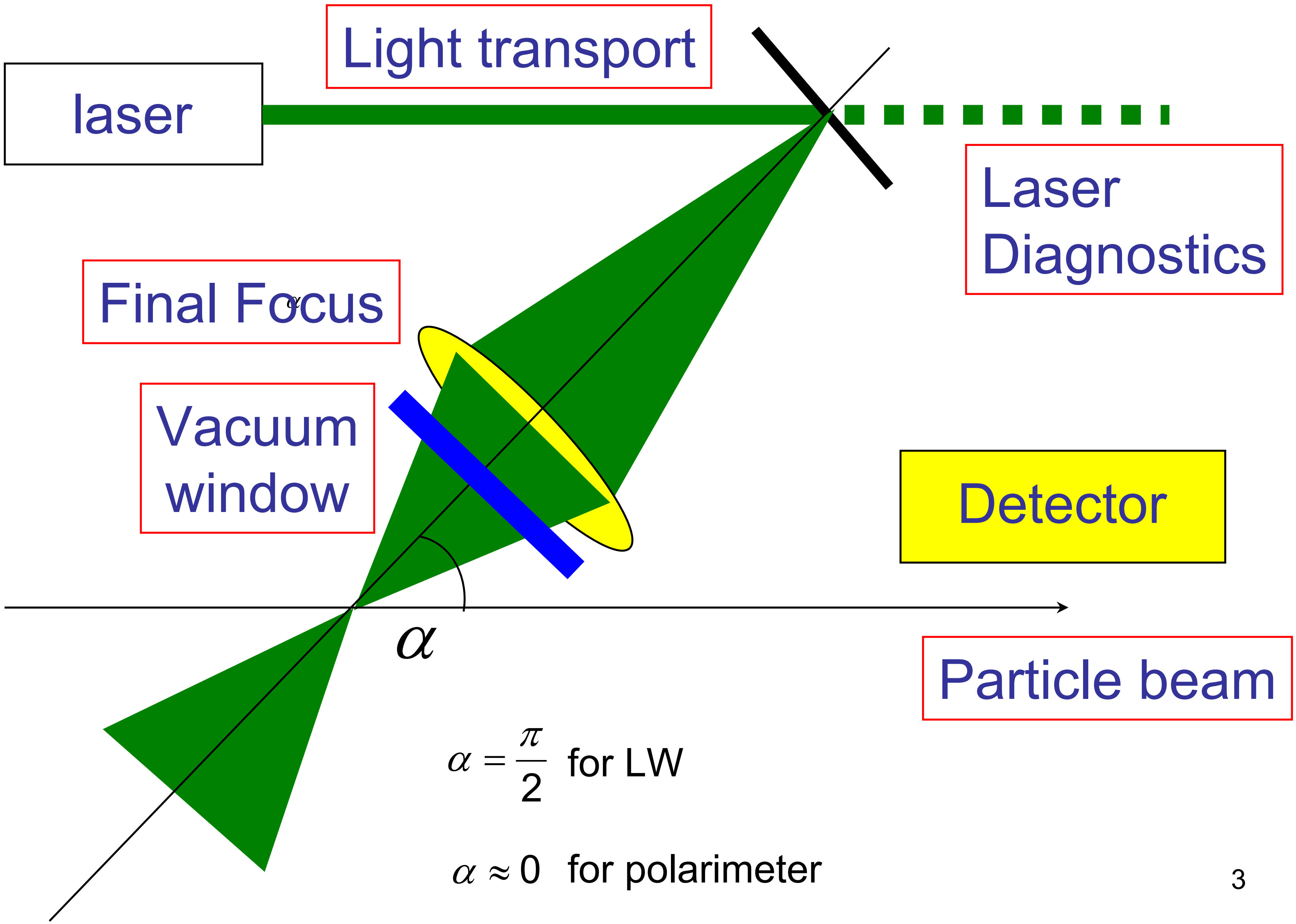
- Introduction
- Emittance measurement
- Laser optics; Gaussian beams
- Laser-wire principle
- Interferometric techniques
- PETRA and ATF laserwire projects
- Signal extraction
- Use in H- machines
- Summary

Lasers in Beam Diagnostics

- Transverse emittance (LW)
- Polarimetry
- Energy Spectrometry (Compton end-point)
- Longitudinal emittance (LW + EO)
- H^- measurements (LW, stripping)
- Isotope selection (excitation)
- Others?

See talk by
J.Van Tilborg

General Scheme



$\alpha = \frac{\pi}{2}$ for LW

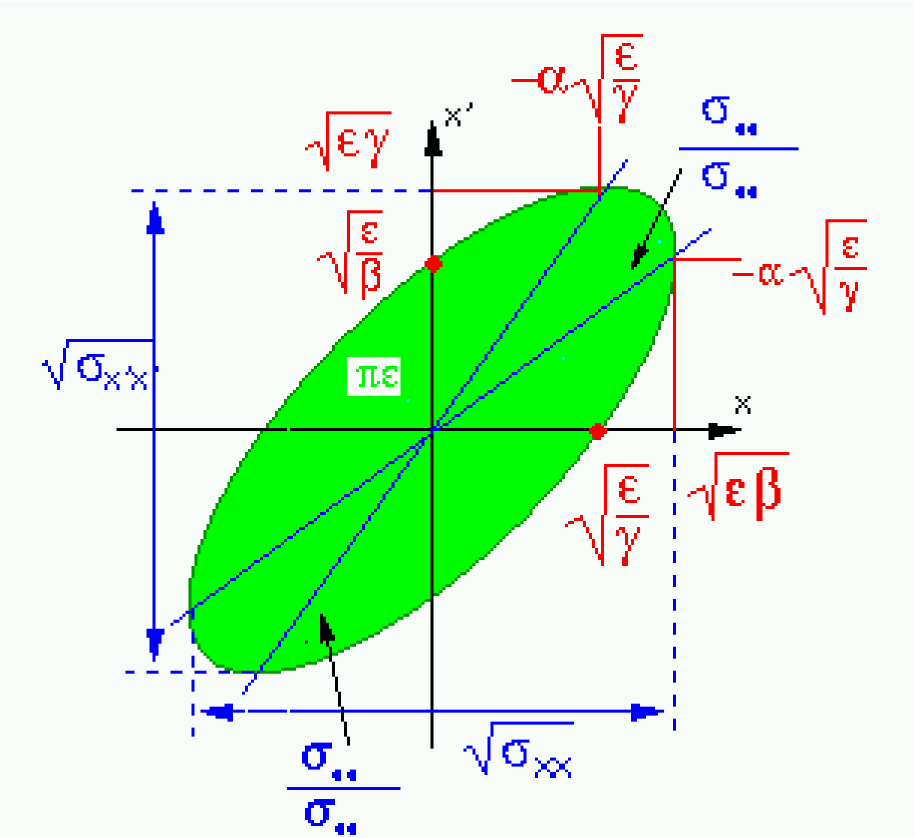
$\alpha \approx 0$ for polarimeter

Luminosity

$$L = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

Big L $\Rightarrow$ small ε

$$\varepsilon = \frac{\pi\sigma^2}{\beta}$$



Need ≥4 scanners per BDS arm

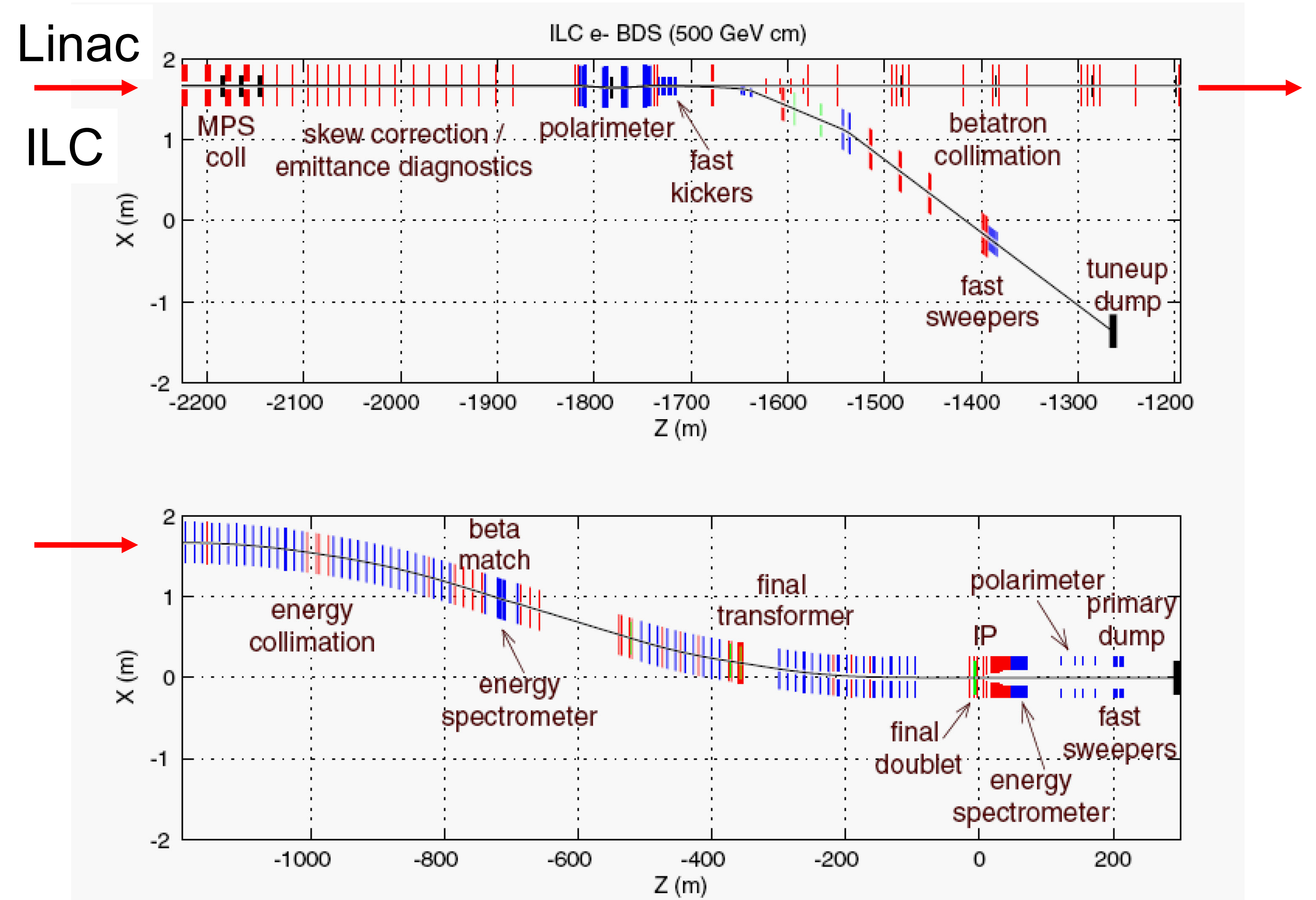
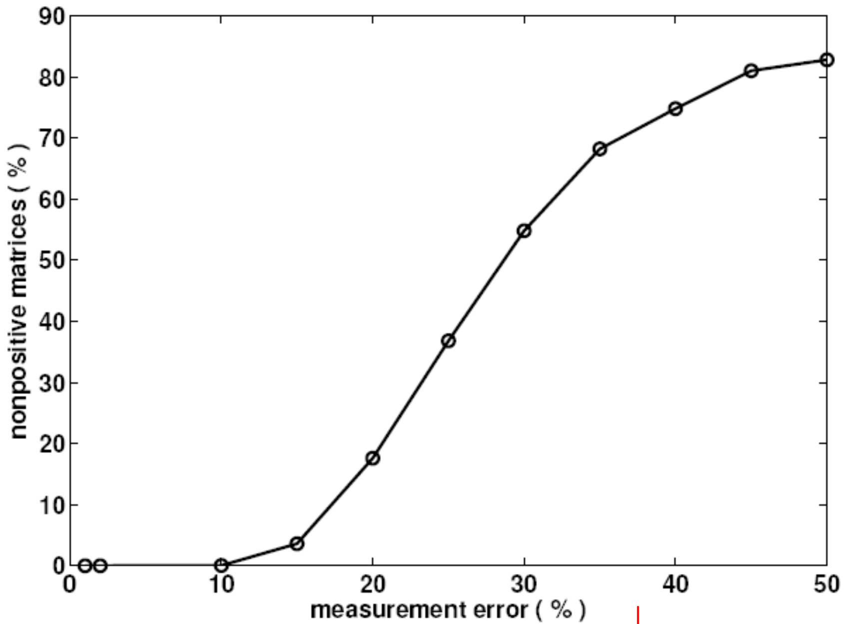


FIGURE 2.7-2. BDS layout showing functional subsystems, starting from the linac exit; X – horizontal position of elements, Z – distance measured from the IP.

Laser wire : Measurement precision

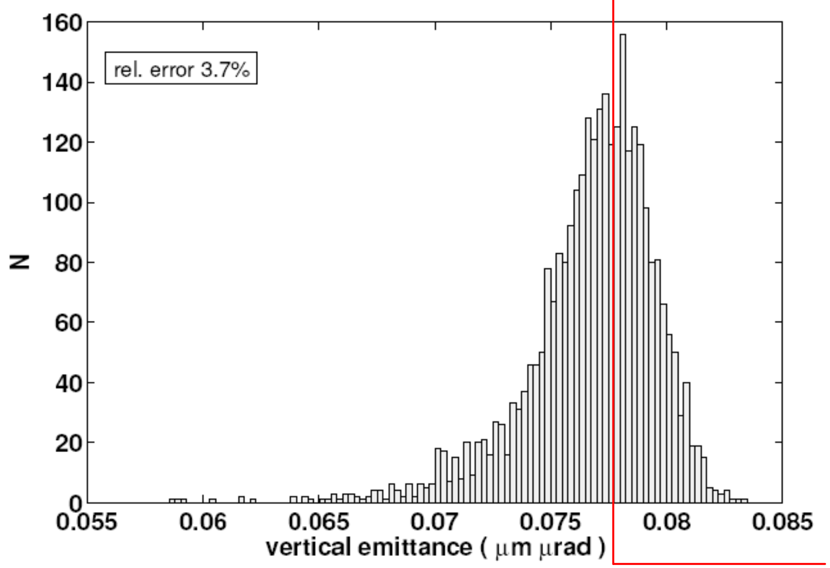
Phys. Rev. ST Accel. Beams 10, 112801 (2007)

I. Agapov, G. B., M. Woodley



The Goal: Beam Matrix Reconstruction

NOTE: Rapid improvement with better σ_y resolution

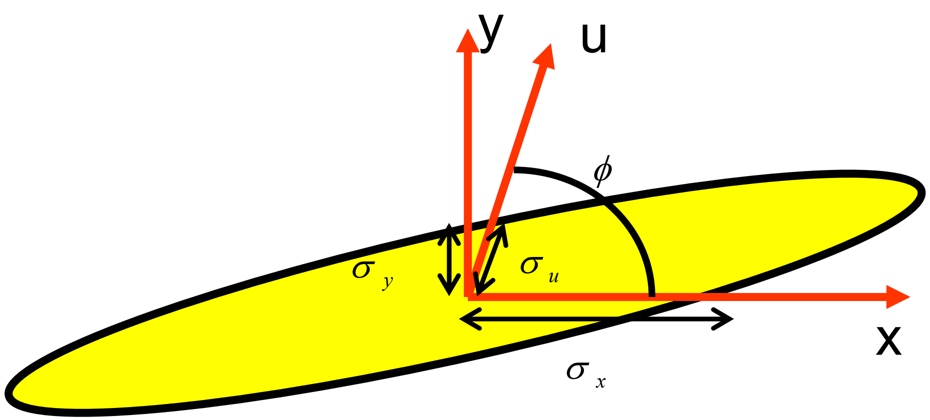


Reconstructed emittance of <u>one ILC train</u> using 5% error on σ_y

Assumes a 4d diagnostics section With 50% random mismatch of initial optical functions

The true emittance is 0.079 μm μrad

Skew Correction



$$\phi_{\text{optimal}} = \tan^{-1}\left(\frac{\sigma_x}{\sigma_y}\right)$$

$$\approx 68^\circ - 88^\circ \text{ at ILC}$$

Error on coupling term:

$$\delta\langle xy\rangle = \sigma_x\sigma_y\left[4\left(\frac{\delta\sigma_u}{\sigma_u}\right)^2 + \left(\frac{\delta\sigma_x}{\sigma_x}\right)^2 + \left(\frac{\delta\sigma_y}{\sigma_y}\right)^2\right]^{\frac{1}{2}}$$

ILC LW Locations E_b = 250 GeV

σ_x(μm)	σ_y (μm)	ϕ_{opt}(°)	σ_u (μm)
39.9	2.83	86	3.99
17.0	1.66	84	2.34
17.0	2.83	81	3.95
39.2	1.69	88	2.39
7.90	3.14	68	4.13
44.7	2.87	86	4.05

Maxwell Wave Equation

Maxwell: $$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)E(x,y,z,t) = 0$$

Write: $$E(x,y,z,t) = u(r,x)\,e^{ik(x-ct)}$$

where: $r = \sqrt{y^2 + z^2}$ (assume axial symmetry)

$$2ik\frac{\partial u}{\partial x} - \frac{\partial^2 u}{\partial x^2} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)$$

Paraxial Wave Equation

$$2ik\frac{\partial u}{\partial x} \boxed{-\frac{\partial^2 u}{\partial x^2}} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)$$

Drop this term; valid provided divergence of any ray is less than about 1 radian.

$$\boxed{2ik\frac{\partial u}{\partial x} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)}$$

Gaussian Solution

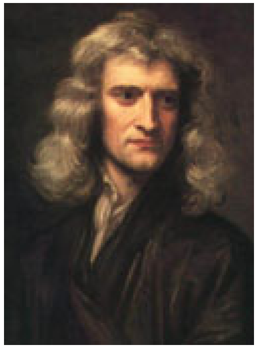
Attempt to find a solution of the form:

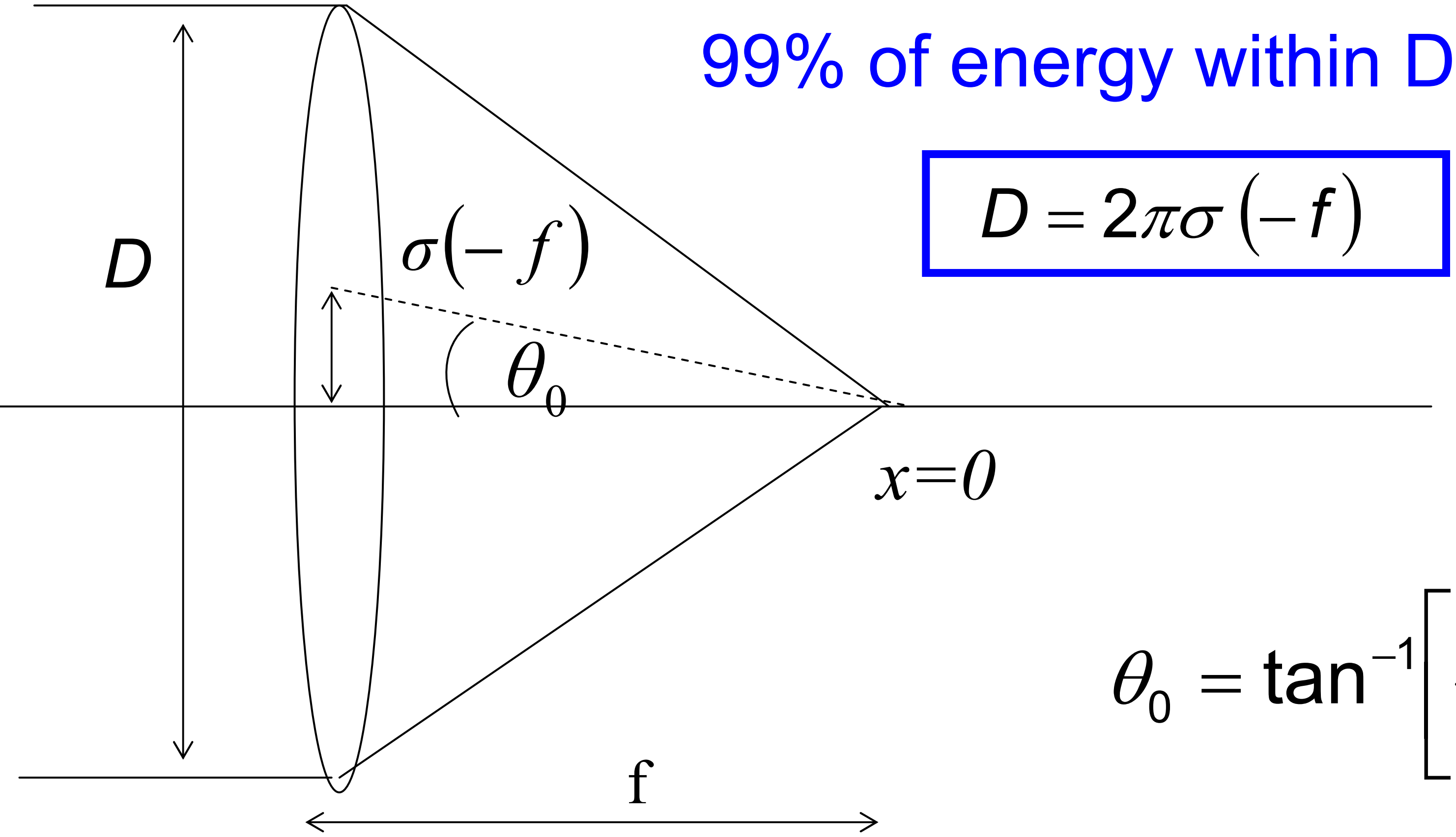
$$|u(x,r)|^2 = \frac{I_0}{2\pi\sigma(x)^2}\exp\left(-\frac{r^2}{2\sigma(x)^2}\right) \quad \text{so: } u(x,r) = \sqrt{\frac{I_0}{2\pi}}\frac{1}{\sigma(x)}\exp\left(-\frac{r^2}{4\sigma(x)^2}\right)e^{i\phi(x,r)}$$

Needed to conserve energy

$\sigma(x) = \sigma_0\left[1+\left(\frac{x}{x_R}\right)^2\right]$	$x_R = 4\pi\frac{\sigma_0^2}{\lambda}$ Rayleigh range
$\phi(x,r) = \tan^{-1}\left(\frac{x}{x_R}\right) - \frac{\pi}{\lambda}\frac{r^2}{R(x)}$	$R(x) = x + \frac{x_R^2}{x}$

Classical approximation

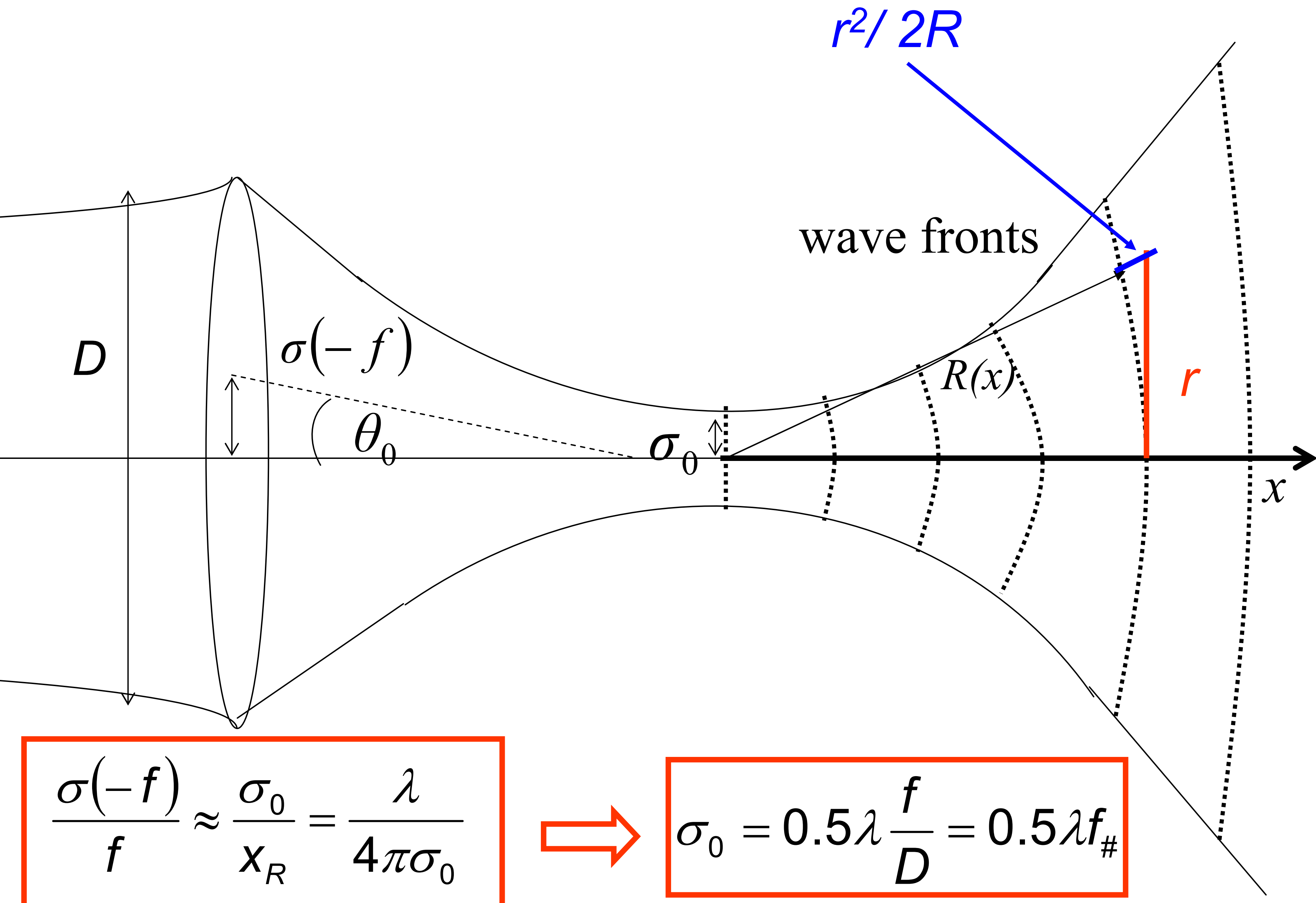




99% of energy within D →

$$\boxed{D = 2\pi\sigma\left(-f\right)}$$

$$\theta_0 = \tan^{-1}\left[\frac{\sigma\left(-f\right)}{f}\right]$$



$$\boxed{\frac{\sigma(-f)}{f} \approx \frac{\sigma_0}{x_R} = \frac{\lambda}{4\pi\sigma_0}}$$

$$\Rightarrow$$

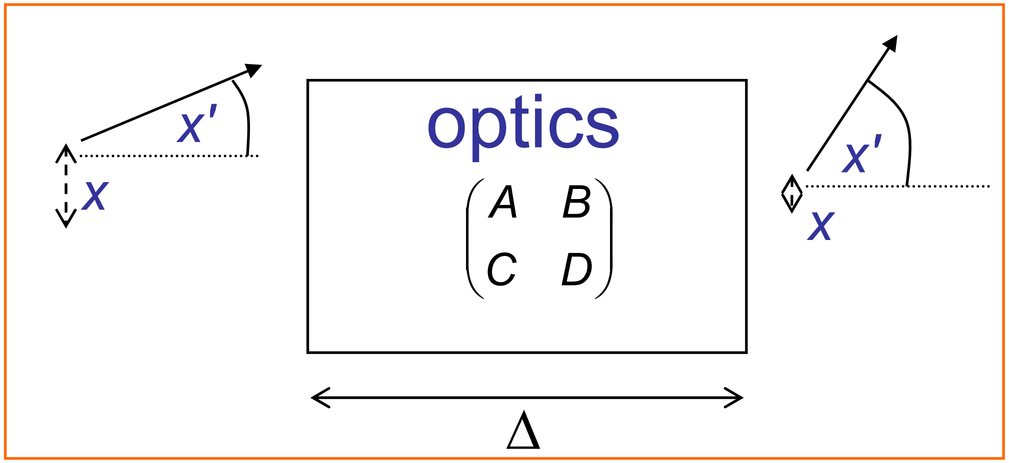
$$\boxed{\sigma_0 = 0.5\lambda\frac{f}{D} = 0.5\lambda f_{\#}}$$

General Spherical Gaussian Waves

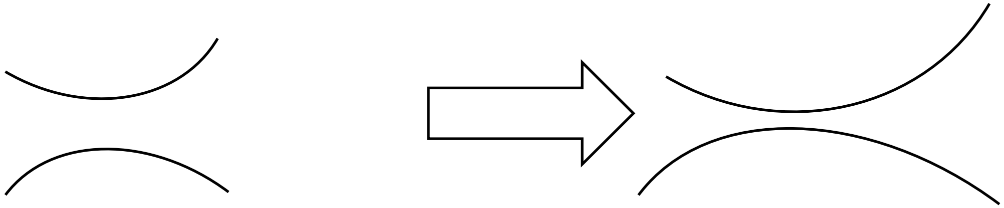
Complex radius:

$$\frac{1}{q(s)} = \frac{1}{R(s)} + iM^2 \frac{\lambda}{4\pi\sigma(s)^2}$$

$$\begin{pmatrix} x(s+\Delta) \\ x'(s+\Delta) \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} x(s) \\ x'(s) \end{pmatrix}$$



$$q(s+\Delta s) = \frac{Aq(s)+B}{Cq(s)+D}$$

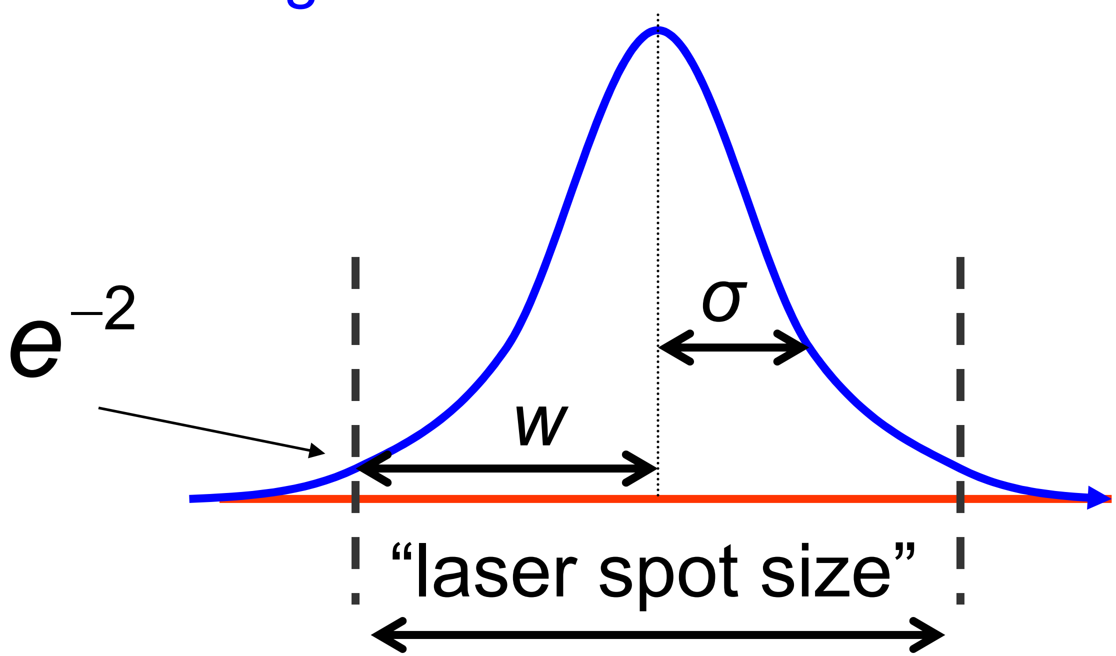


Practical Considerations

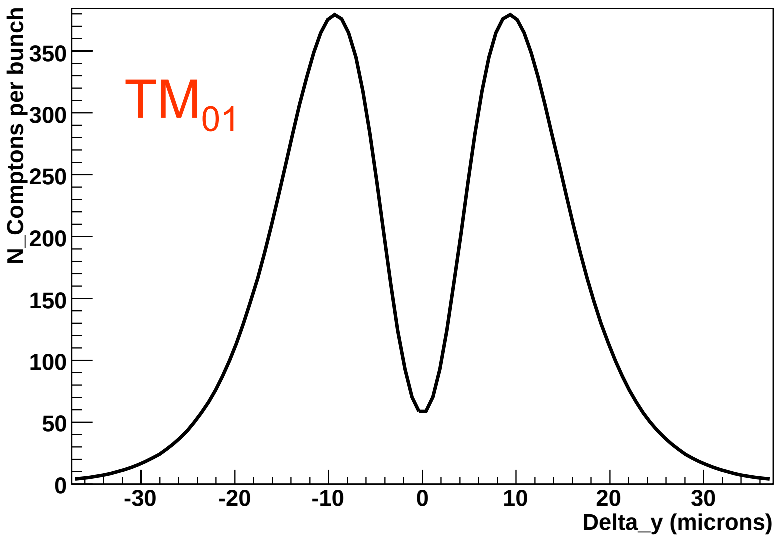
- Obtaining theoretical values of D for a given optical layout is hard (alignment, stability, …).
- In the following, assume a "practical" factor; to be conservative, k_p~2 is chosen in the following:

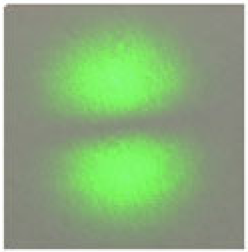
$$\sigma_\ell = k_p \sigma_0 \qquad\qquad \boxed{\sigma_\ell \approx \lambda f_\#}$$

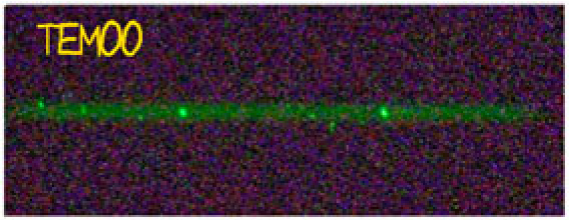
Beware of confusing conventions:

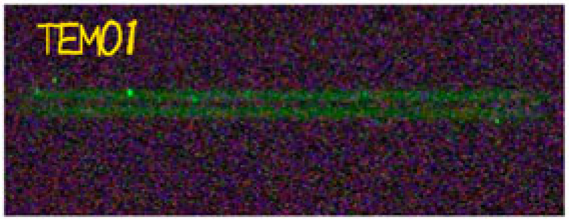


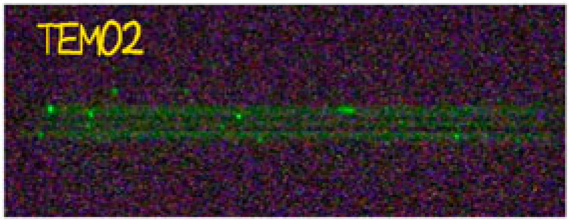
Higher Order Modes









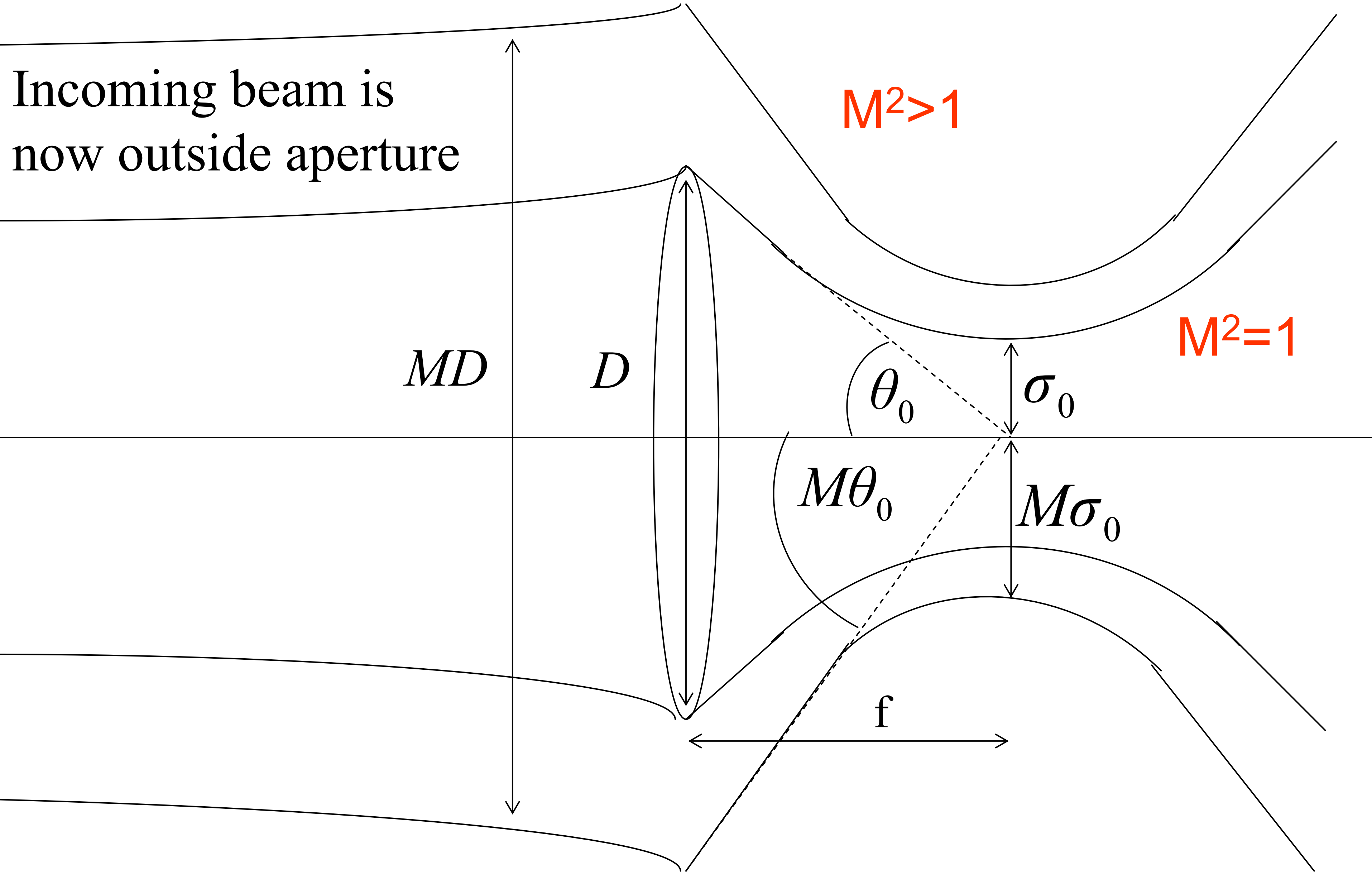


Their presence increases the effective "emittance" of the laser

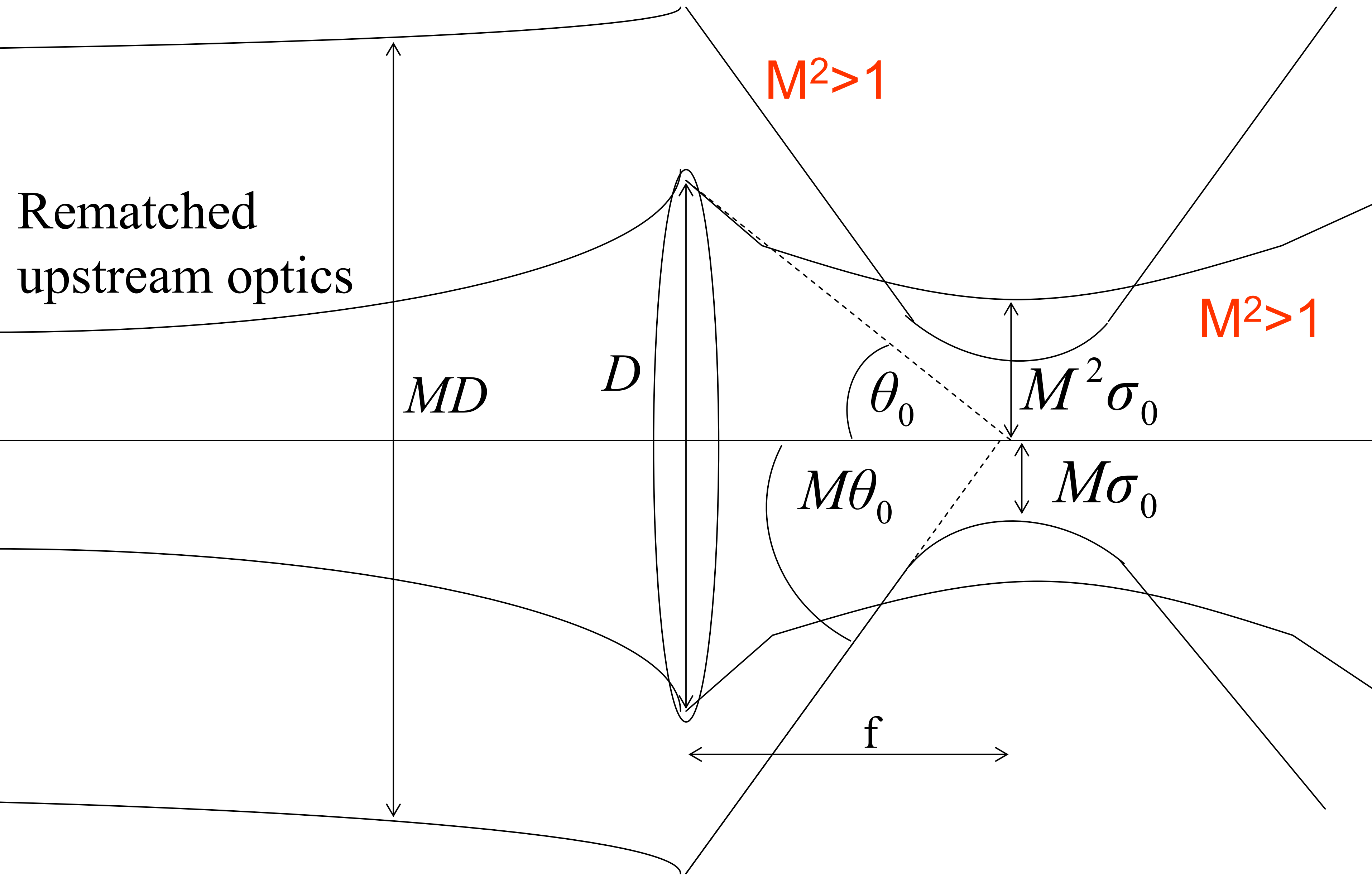
$$\sigma_x \sigma_{x'} = \frac{\lambda}{4\pi} \rightarrow M^2 \frac{\lambda}{4\pi} \qquad (M^2>1)$$

pure TM$_{00}$

property of a realistic laser



Incoming beam is
now outside aperture
M²>1
M²=1
MD
D
θ0
σ0
Mθ0
Mσ0
f

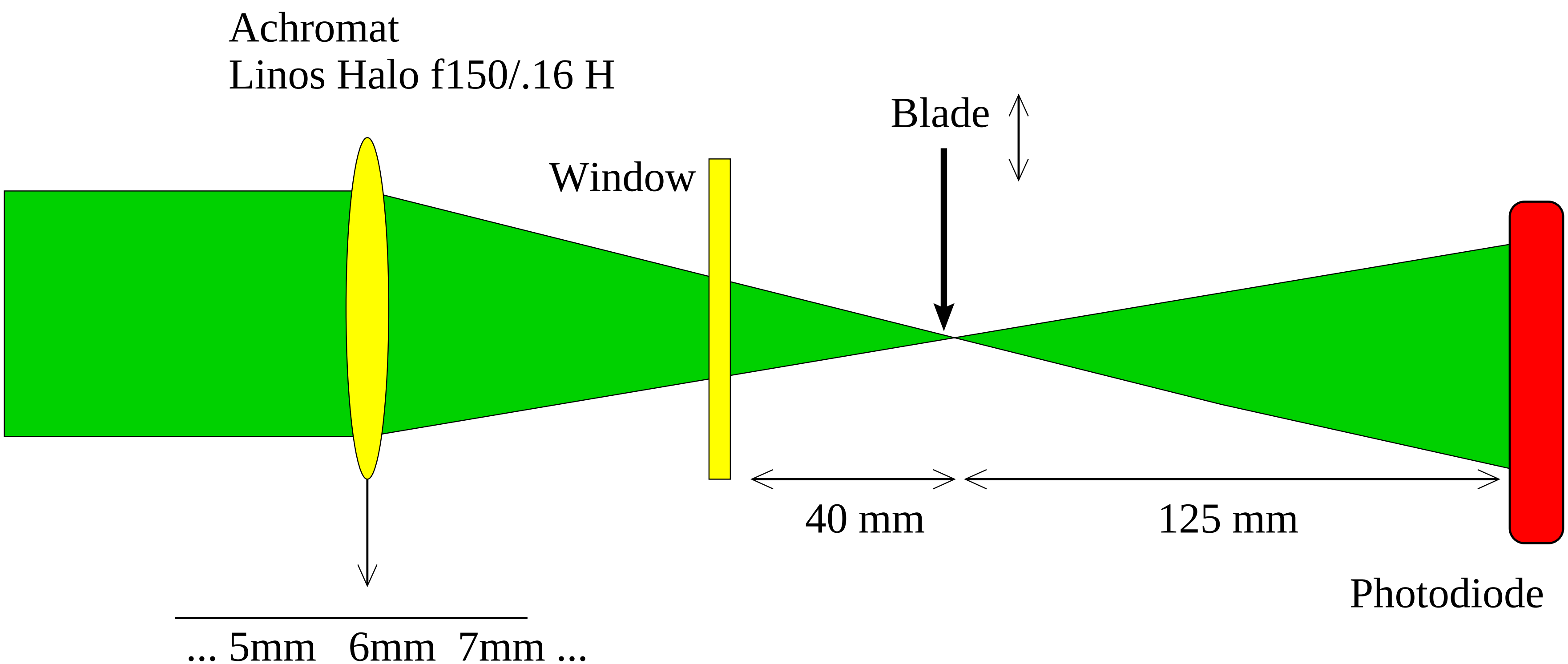


Rematched upstream optics
$M^2>1$
$M^2>1$
MD
D
θ_0
$M^2\sigma_0$
$M\theta_0$
$M\sigma_0$
f

Important Lesson

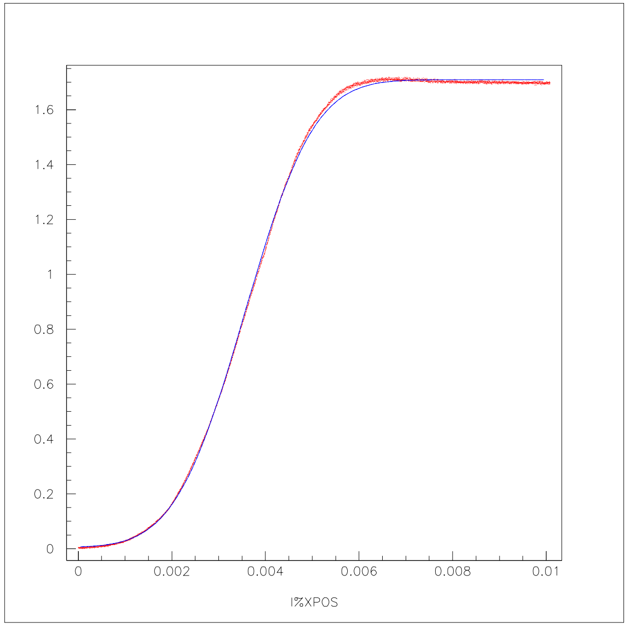
- In any practical environment, including light transport, alignment, finite aberrations etc., it would be unwise to trust the formulae.
- Measurement of the light distribution near the focus is essential.
- Absolute measurement with knife-edge scans (see below).
- Relative frequent measurements of an image-point with a CCD camera.

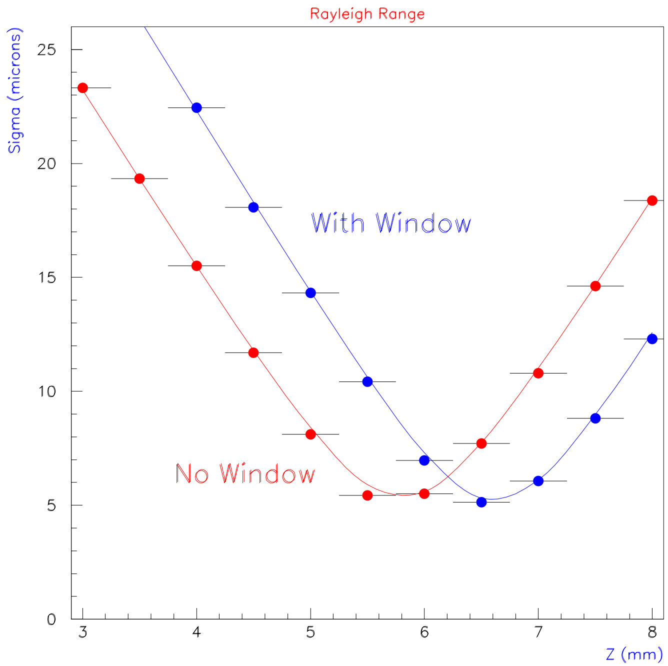
Spotsize measurement



Blade moved with stepping motor
Intensity measured as a function of position

Spotsize results for test laser



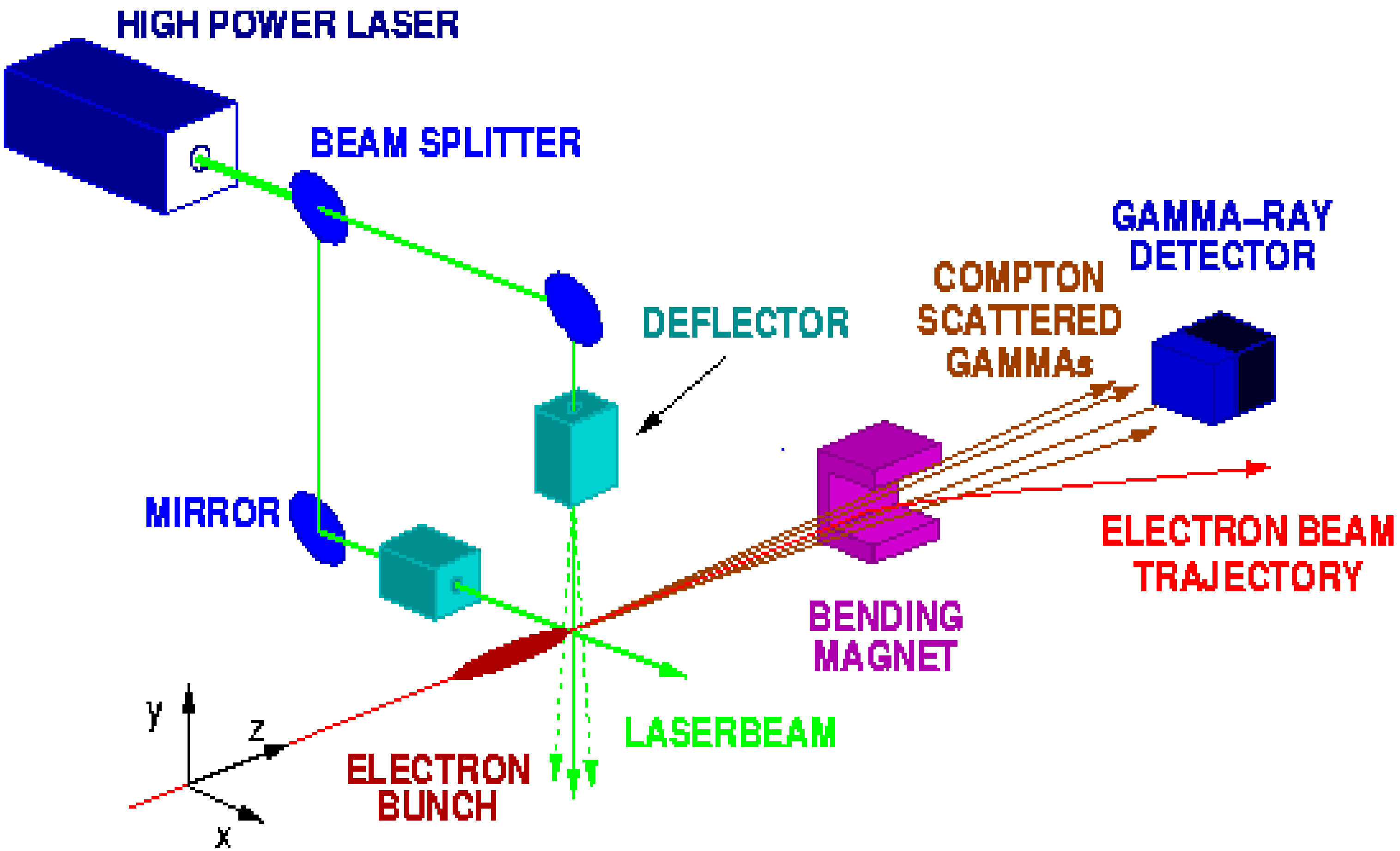


Single scan

Sigma vs z

$\Rightarrow$ Fit to function: $$\sigma(z)=\sigma_0\sqrt{1+\left(\frac{M^2\lambda(z-z_0)}{\pi(2\sigma_0)^2}\right)^2}$$

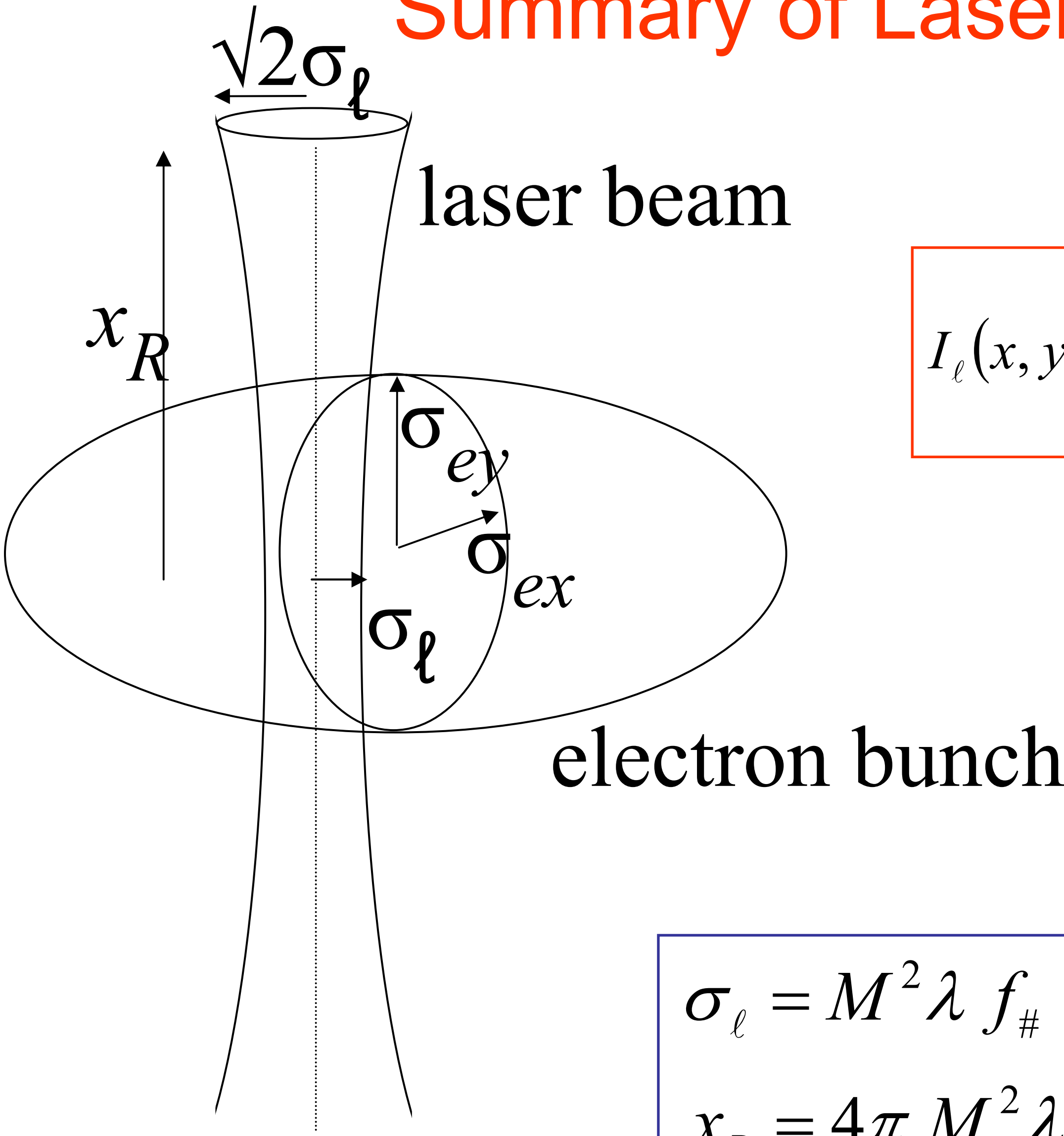
Laserwire


HIGH POWER LASER
BEAM SPLITTER
GAMMA–RAY
DETECTOR
COMPTON
SCATTERED
GAMMAs
DEFLECTOR
MIRROR
ELECTRON BEAM
TRAJECTORY
BENDING
MAGNET
LASERBEAM
ELECTRON
BUNCH
y
z
x

Measuring the Beam Profile

- Traditional method is to sweep a solid wire across the beam.
- Measure background vs relative position of wire and beam.
- Micron-scale precision required for LC
- Solid wires would not stand the intense beams of the LC
- Solid wires could ablate, harming SC surfaces nearby.
- So: replace wire with a laser beam.
- Count Comptons downstream.

Summary of Laser Conventions



For TM_{00} laser mode:

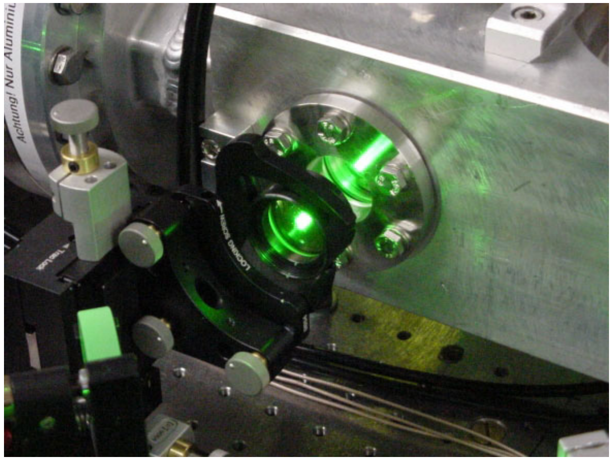
$$I_\ell(x,y,z) = \frac{I_0}{2\pi\sigma_\ell^2}\frac{1}{f_R(x)}\exp\left[-\frac{y^2+z^2}{2\sigma_\ell^2 f_R(x)}\right]$$

$$f_R(x) = 1 + \left(\frac{x}{x_R}\right)^2$$

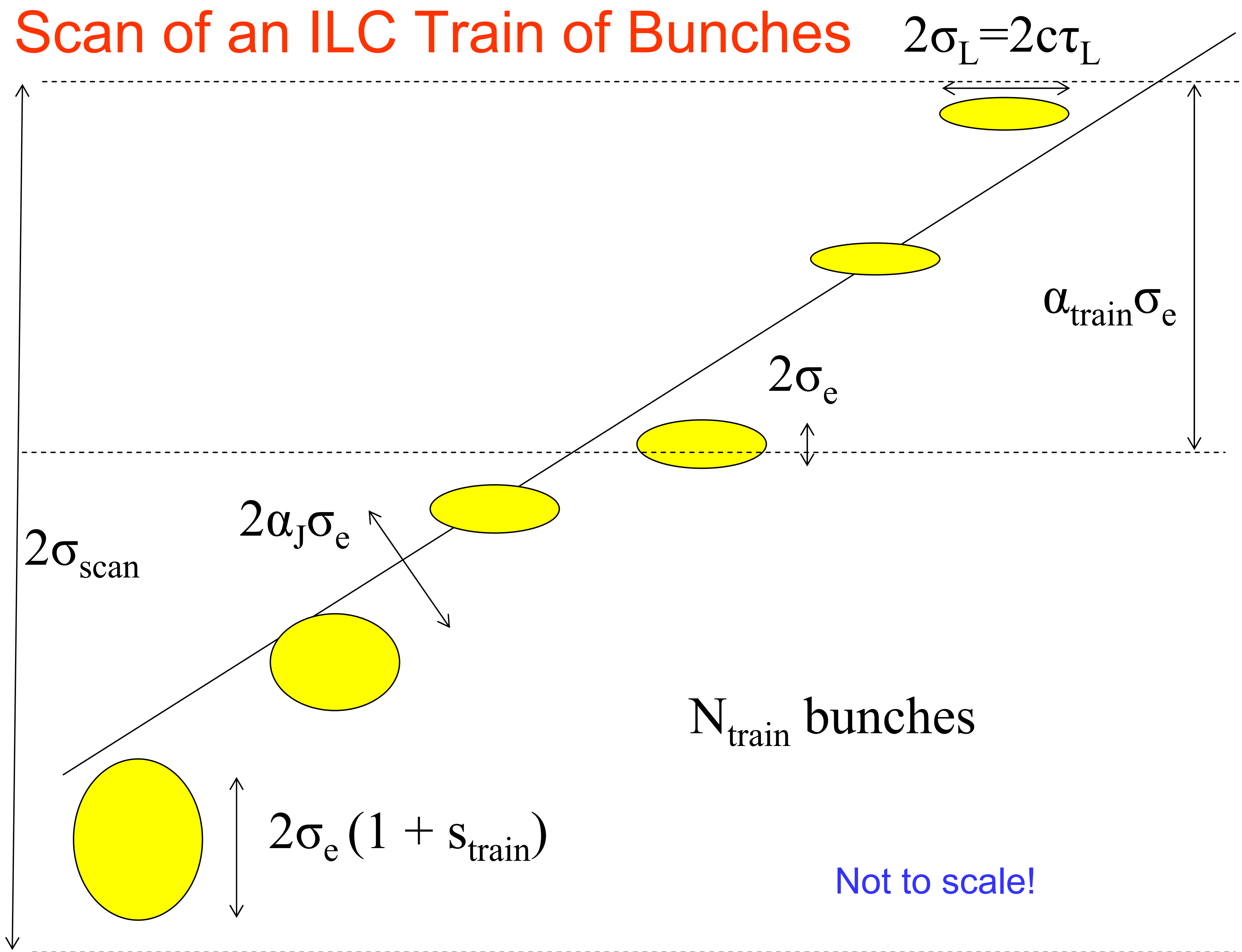
$$\sigma_\ell = M^2 \lambda\, f_\#$$

$$x_R = 4\pi\, M^2 \lambda\, f_\#^2$$

Note: here, $f_\#$ includes an M-factor



Scan of an ILC Train of Bunches



Machine Contributions to the Errors

$$\sigma_e = \left[\sigma_{\text{scan}}^2 - \boxed{\left(\alpha_J \sigma_e\right)^2} - \boxed{\left(\eta \delta_E\right)^2}\right]^{\frac{1}{2}}$$

Bunch Jitter

$$\boxed{\frac{\delta\sigma_e}{\sigma_e} \approx 5\times 10^{-2}\left(\frac{\alpha_J}{0.5}\right)^2\left(\frac{\sigma_{\text{BPM}}}{100\text{nm}}\right)}$$

BPM resolution of 20 nm may be required

Dispersion

$$\boxed{\frac{\delta\sigma_e}{\sigma_e} \approx 2.3\,[\eta/\text{mm}]^2\left(\frac{\langle\delta\eta\rangle}{\eta}\right)}$$

Assuming η can be measured to 0.1%,
then η must be kept < ~ 1mm

Compton Statistics

$$N_{\text{Detected}} = 1212\xi \boxed{\frac{1}{\sqrt{2\pi}\sigma_m} \exp\left(-\tfrac{1}{2}\left[\frac{\Delta_y}{\sigma_m}\right]^2\right)}$$

Approximate – should use full overlap integral (as done below…)

Where :

Compton xsec factor

e-bunch occupancy

$$\xi = \left(\frac{\eta_{\det}}{0.05}\right)\left(\frac{P_\ell}{10\text{ MW}}\right)\left(\frac{N_e}{2\times10^{10}}\right)\left(\frac{\lambda}{532\text{ nm}}\right)\left(\frac{f(\omega)}{0.2}\right)\mu\text{m}$$

Laser wavelength

Laser peak power

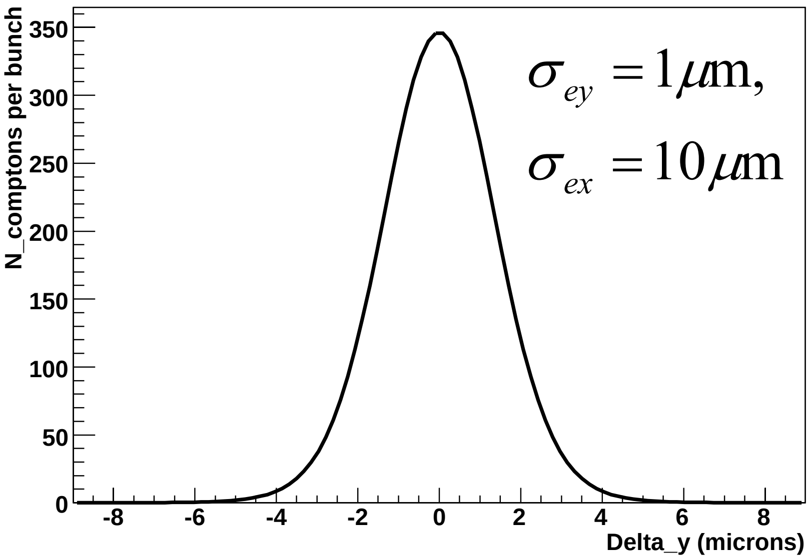
Detector efficiency (assume Cherenkov system)

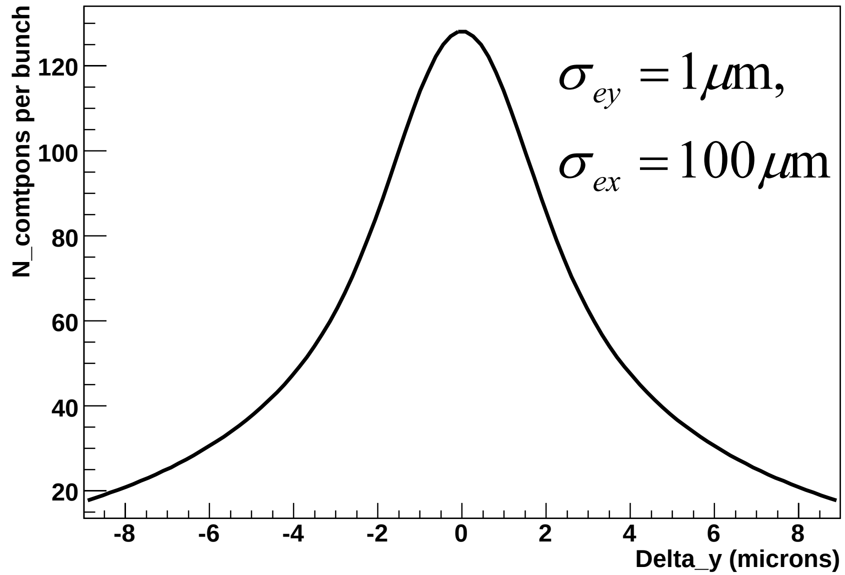
Laserwires at ILC/CLIC

Requiring a few thousand comptons per bunch sets the minimum pulsed power of laser beam to ∼ few × 10 MW.

e^- Energy (GeV)	Laser λ (nm)	Pulsed Laser Power (MW)	XSec (10^{-25}cm^2)	N_C
250	1064	100	2.73	19200
250	532	50	1.98	3510
250	355	25	1.60	950
250	266	10	1.36	242
1500	1064	100	1.06	7450
1500	532	50	0.668	1186
1500	355	25	0.500	297
1500	266	10	0.404	72

TM_{00} Mode Overlap Integrals





Rayleigh Effects obvious

Main Errors:

- Statistical error from fit ~ $\xi^{-1/2}$
- Normalisation error (instantaneous value of ξ) – assume ~1% for now.
- Fluctuations of laser M^2 – assume M^2 known to ~1%
- Laser pointing jitter ψ

$$\frac{\delta\sigma_e}{\sigma_e} \approx 2.2\times10^{-3}\left(\frac{\psi}{10\mu\text{rad}}\right)^2\left(\frac{\delta\psi}{\psi}/10\%\right)$$

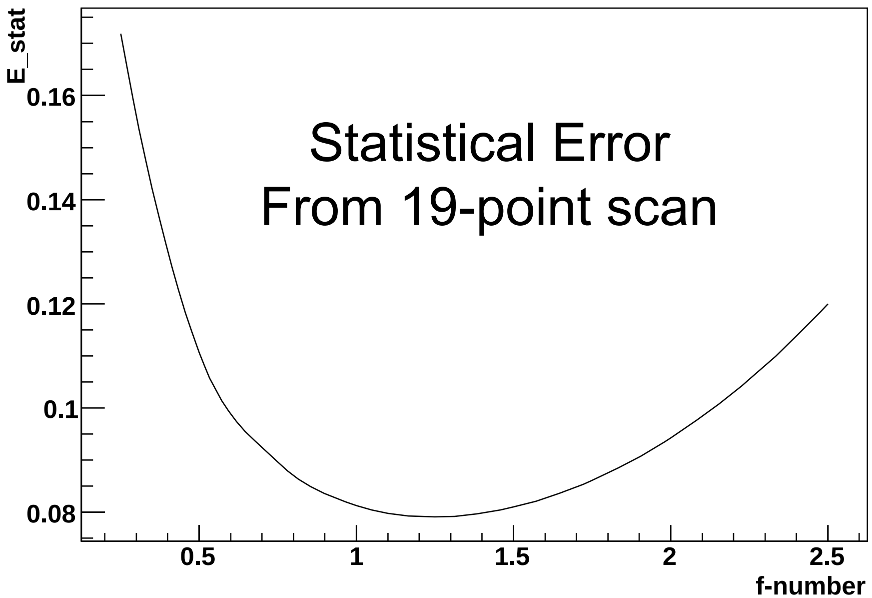
$$\frac{\delta\sigma_e}{\sigma_e} \approx \left(\frac{\lambda f_\#}{\sigma_e}\right)^2 M^2\left(\frac{\delta M^2}{M^2}\right)$$

Laser Requirements

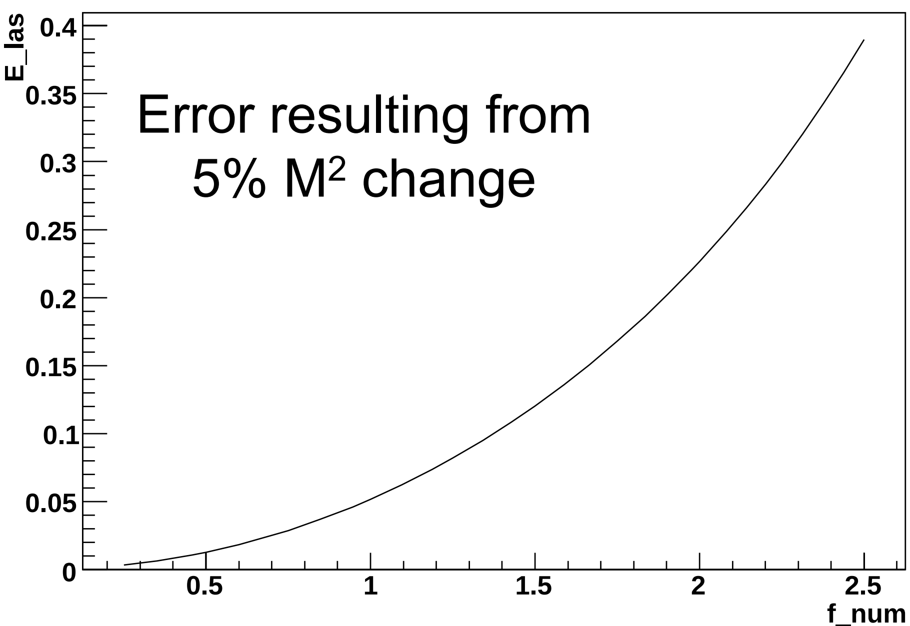
Wavelength	$\leq$ 532 nm
Mode Quality	$\leq$ 1.3
Peak Power	$\geq$ 20 MW
Average power	$\geq$ 0.6 W
Pulse length	$\geq$ 2 ps
Synchronisation	$\leq$ 0.3 ps
Pointing stability	$\leq$ 10 μ rad

ILC-spec laser is being developed at JAI@Oxford
based on fiber amplification. L. Corner et al

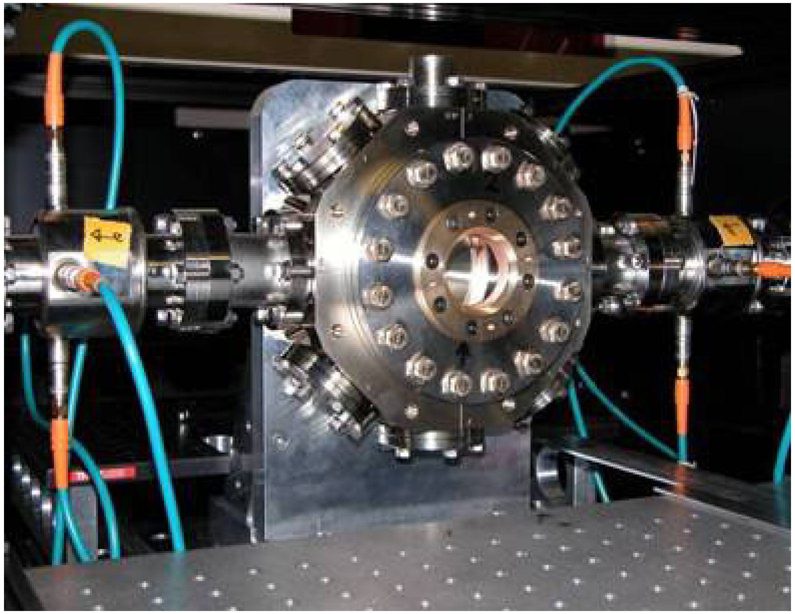
TM_{00} mode



Relative Errors



- Optimal f-num≈1-1.5 for λ= 532nm
- Then improve M^2 determination
- f-2 lens about to be installed at ATF



ATF2 LW; aiming initially at f_2; eventually f_1?

Towards a 1 μm LW

preliminary Resultant errors/10^{-3}

E_ξ	2.5
E_{point}	2.2
E_{jitter}	5.0
E_{stat}	4.5
E_{M^2}	2.8
Total Error	8.0

Final fit, including dispersion

Goals/assumptions

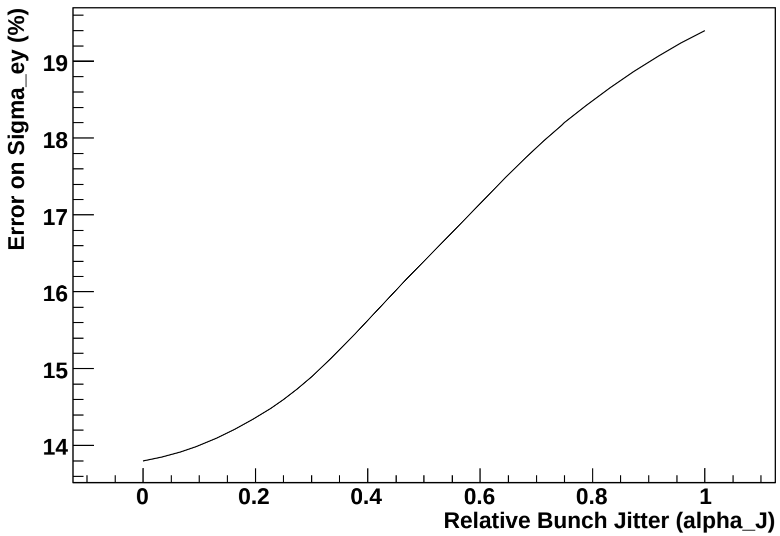
Wavelength	266 nm
Mode Quality	1.3
Peak Power	20 MW
FF f-number	1.5
Pointing stability	10 μrad
M^2 resolution	1%
Normalisation (ξ)	2%
Beam Jitter	0.25σ
BPM Resolution	20 nm
Energy spec. res	10^{-4}

Could be used for η measurement $\rightarrow E_\eta$

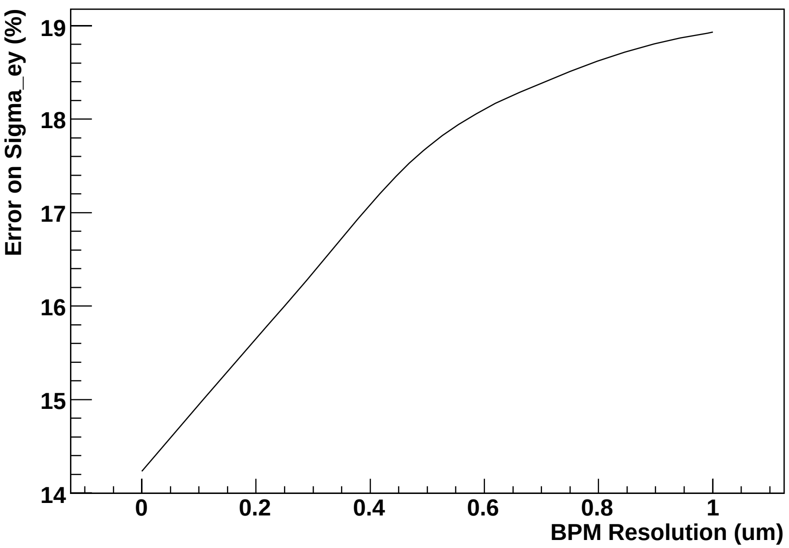
Alternative Scan Mode

- R&D currently investigating ultra-fast scanning (~100 kHz) using Electro-optic techniques
- Alternative: Keep laser beam fixed and use natural beam jitter plus accurate BPM measurements bunch-by-bunch.
  Needs the assumption that bunches are pure-gaussian
- For one train, a statistical resolution of order 0.3% may be possible

Single-bunch fit errors for $\sigma_{ey} = 1\mu\text{m}, \sigma_{ex} = 10\mu\text{m}$

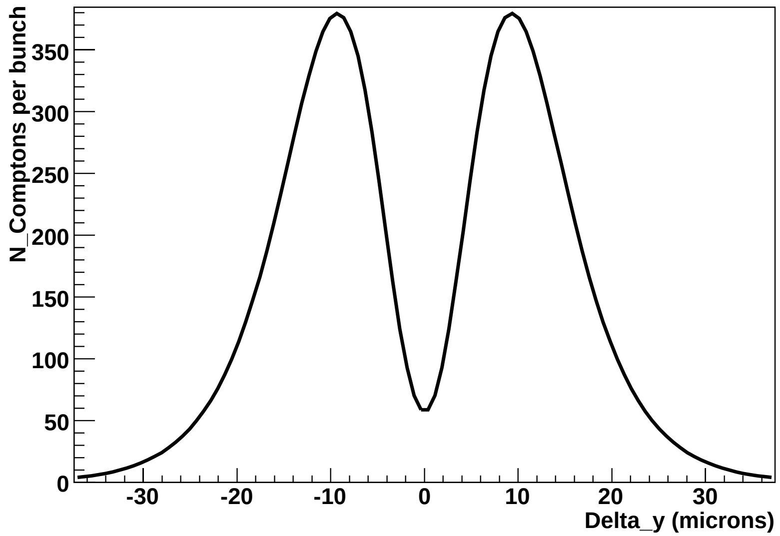


Beam jitter fixed at 0.25σ

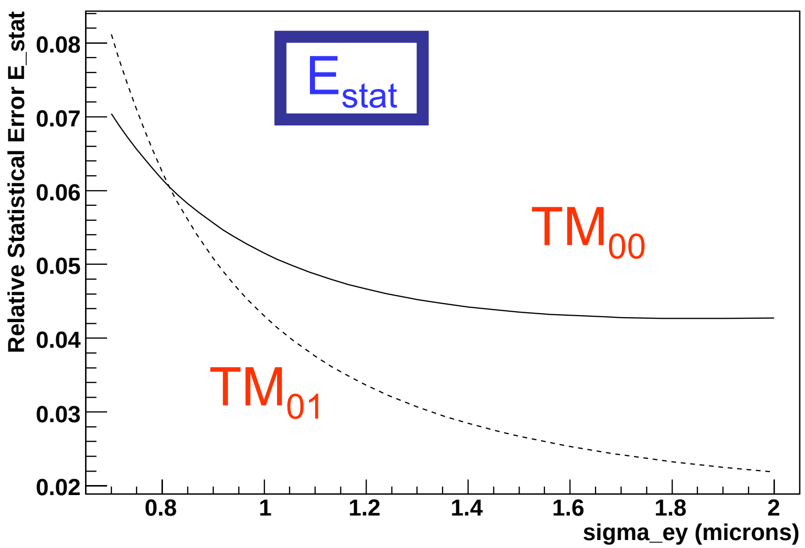


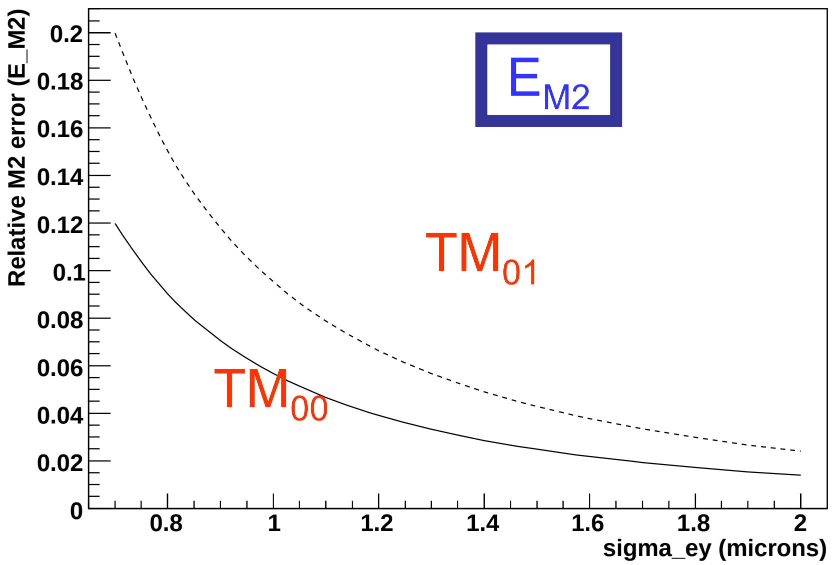
BPM resolution fixed at 100 nm

TM_{01} Mode used for scans

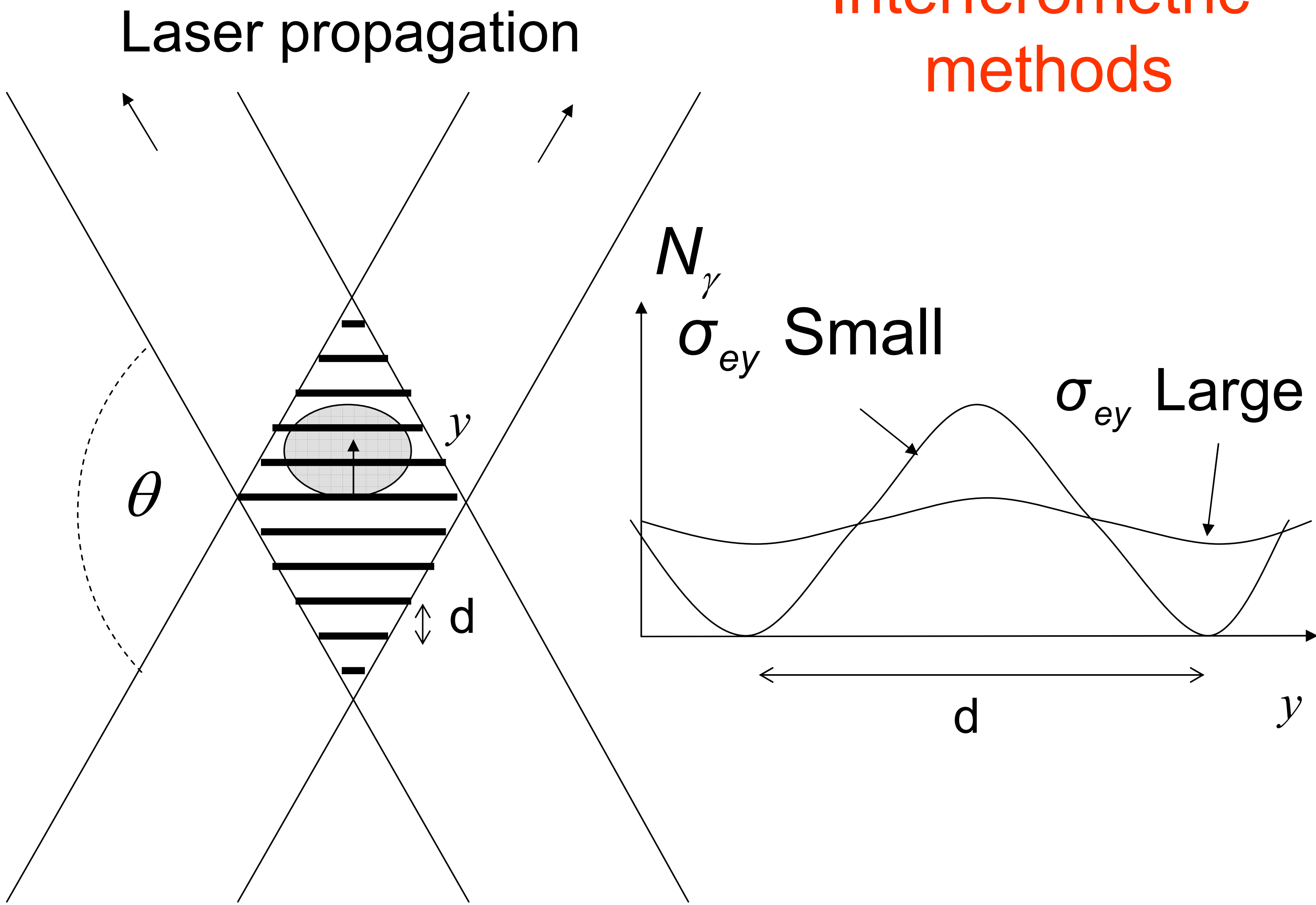


TM01 gives some advantage for larger spot-sizes



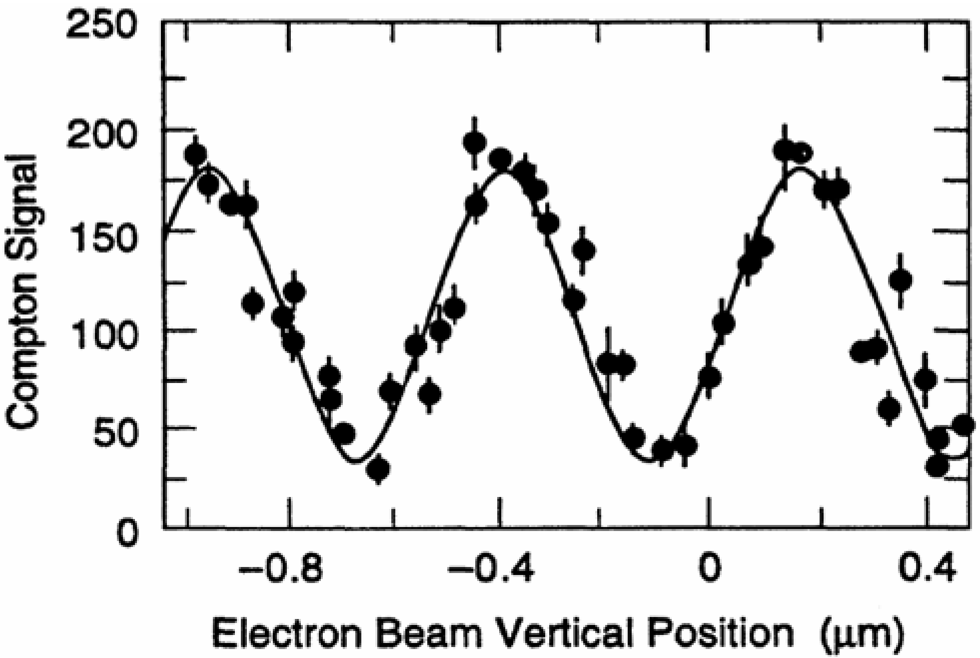


Interferometric methods



Shintake Monitor

$$N_\gamma \propto 1 + \cos(2k_y y)\cos\theta \exp\left[-2\left(k_y \sigma_y^2\right)\right]$$



$$k_y = \frac{2\pi}{\lambda}\sin\left(\frac{\theta}{2}\right)$$

Balakin et al
PRL 74, 2479 (1995)

FFTB measured σ_y=37 nm

LW Experimental Programme:

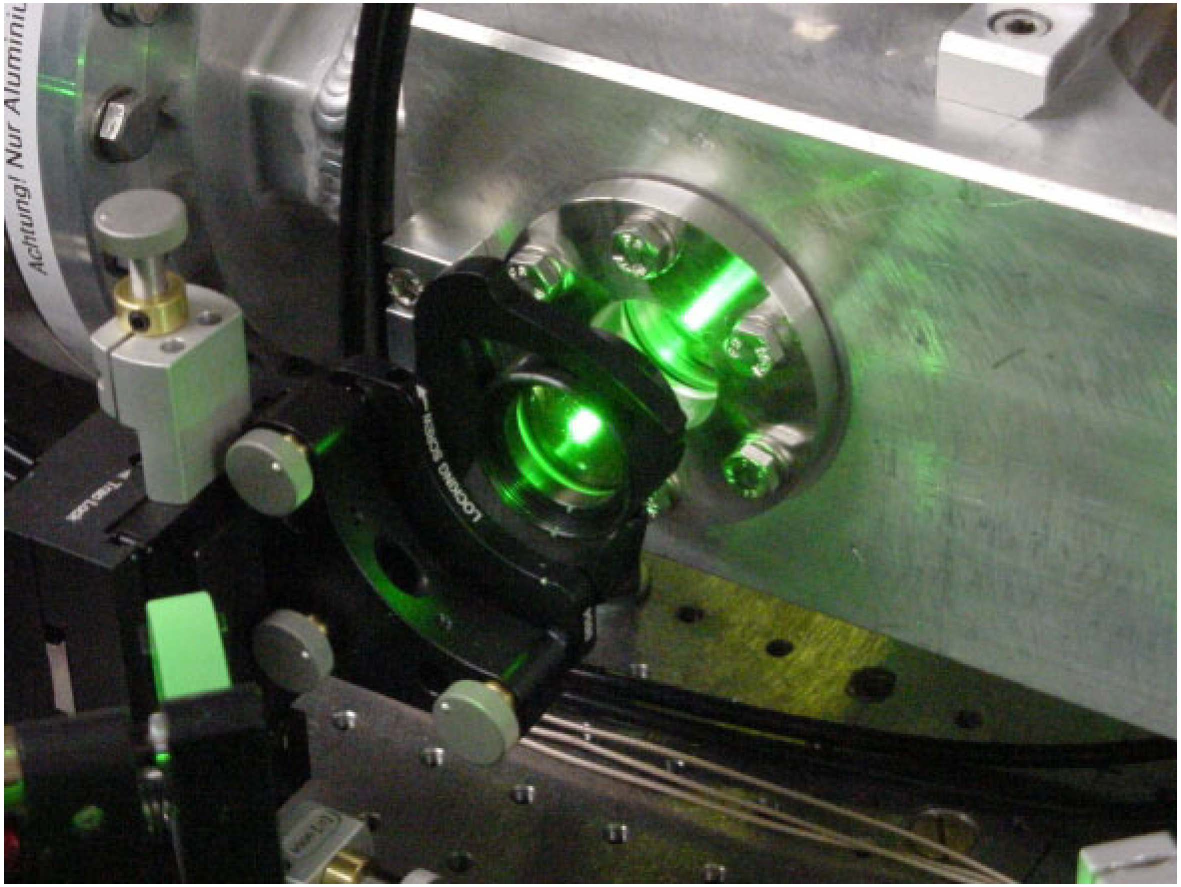
Started at CTF2

PETRAII

ATF2

SNS

FETS



Laser-wire People

BESSY: T. Kamps

CERN: I. Agapov

DESY : E. Elsen, V. Gharibyan, H. C. Lewin, F. Poirier, S. Schreiber, K. Wittenburg, K. Balewski

JAI@Oxford: B. Foster, N. Delerue, L. Corner, D. Howell, L. Nevay, M. Newman, R. Senanayake, R. Walczak

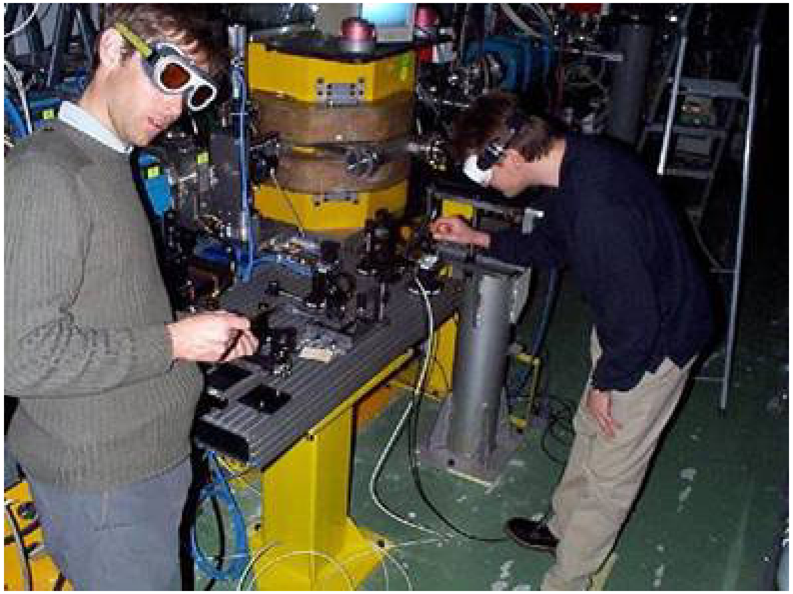
JAI@RHUL: A. Aryshev, G. Blair, S. Boogert, G. Boorman, A. Bosco, L. Deacon, P. Karataev, S. Malton , M. Price,

KEK:, H. Hayano, K. Kubo, N. Terunuma, J. Urakawa

SLAC: A. Brachmann, J. Frisch, M. Woodley

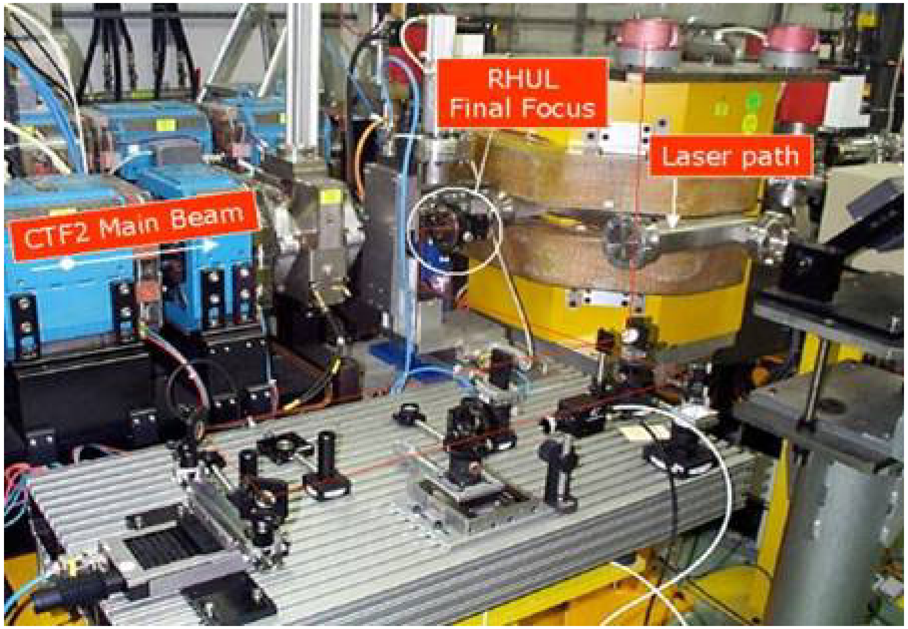
FNAL: M. Ross

Took part in CTF2 laser-wire:



Problems with backgrounds (CTF2 energy 45 MeV)

But we learnt a lot!

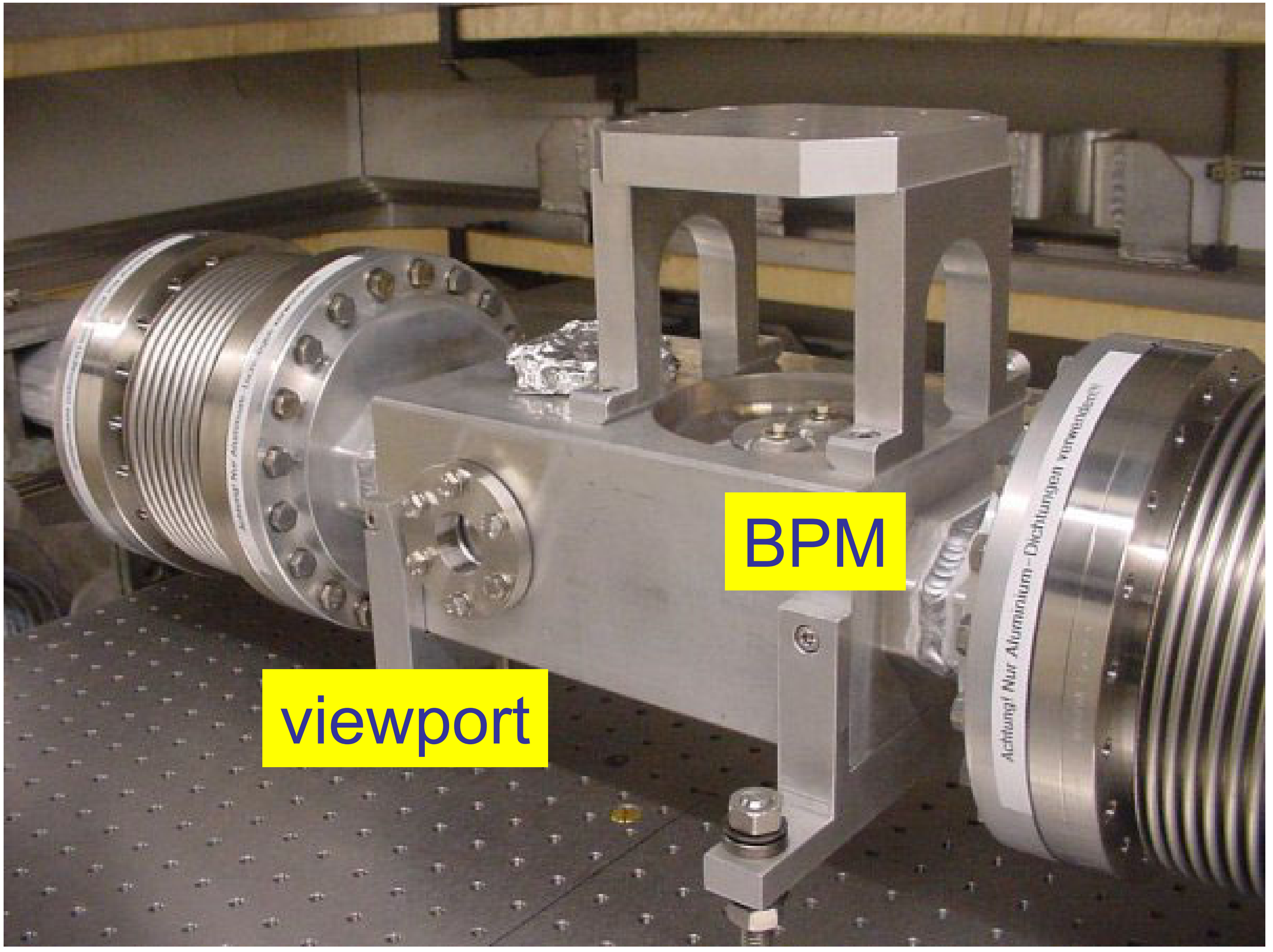


PETRA LW

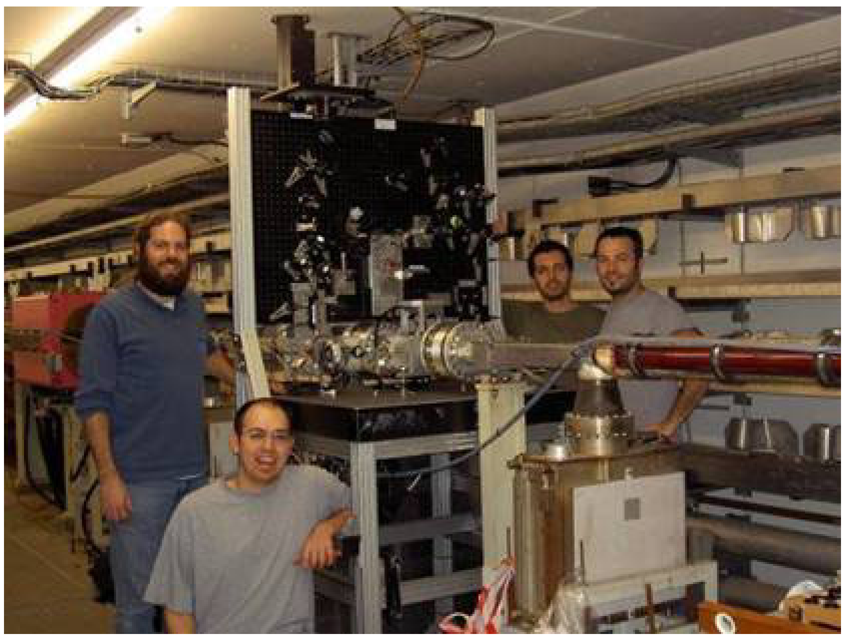
Routine scans of two-dimensions were achieved
PETRAII programme now finished; preparing for PETRAIII
Fast scanning system with 130kHz laser at RHUL planned
Collaborating with DESY on fast DAQ
Look forward to installation in new location for PETRAIII this year

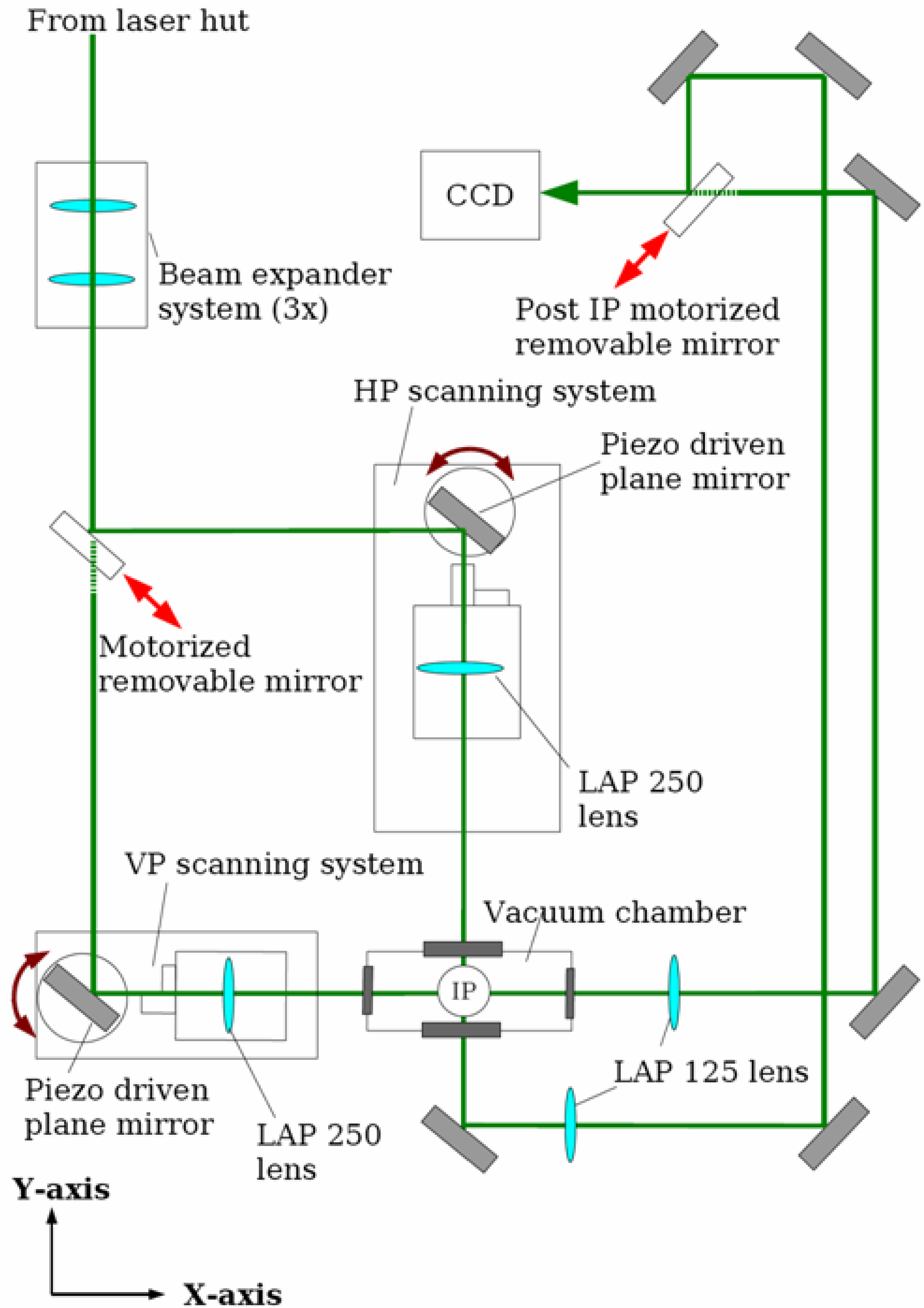
Optics built and tested at RHUL

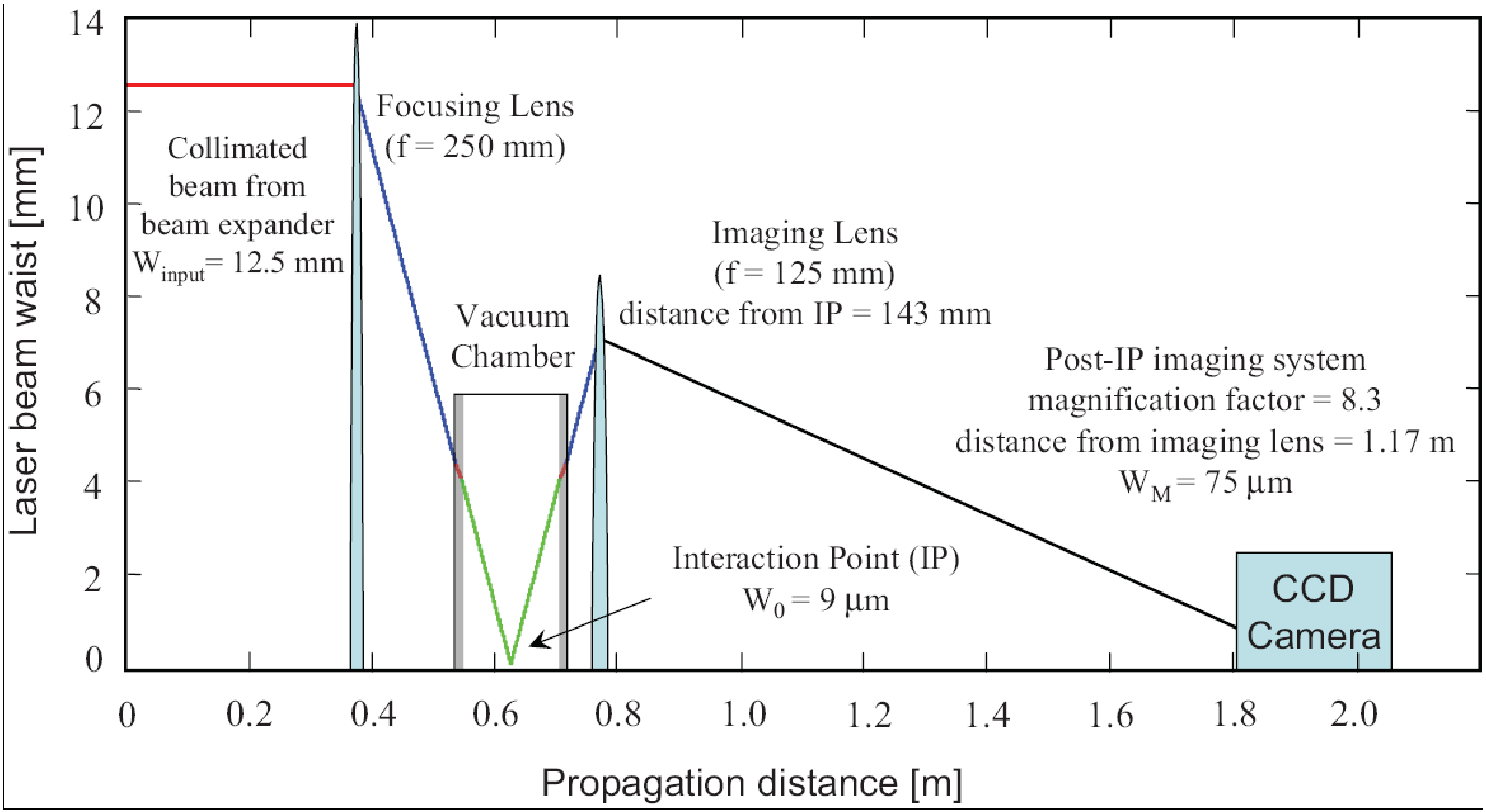
PETRA interaction chamber



Vertical bread-board design; 2D scanning:

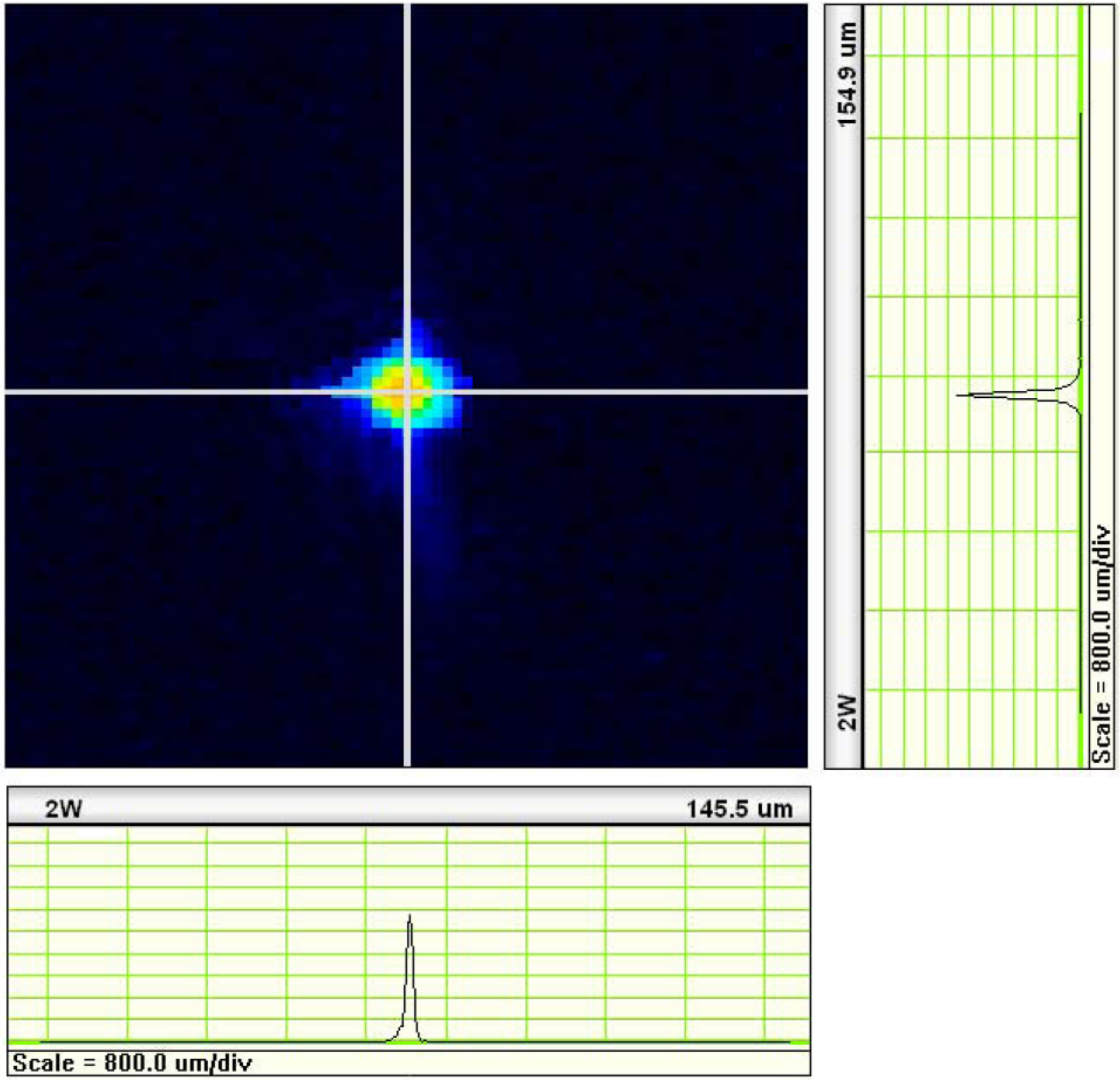






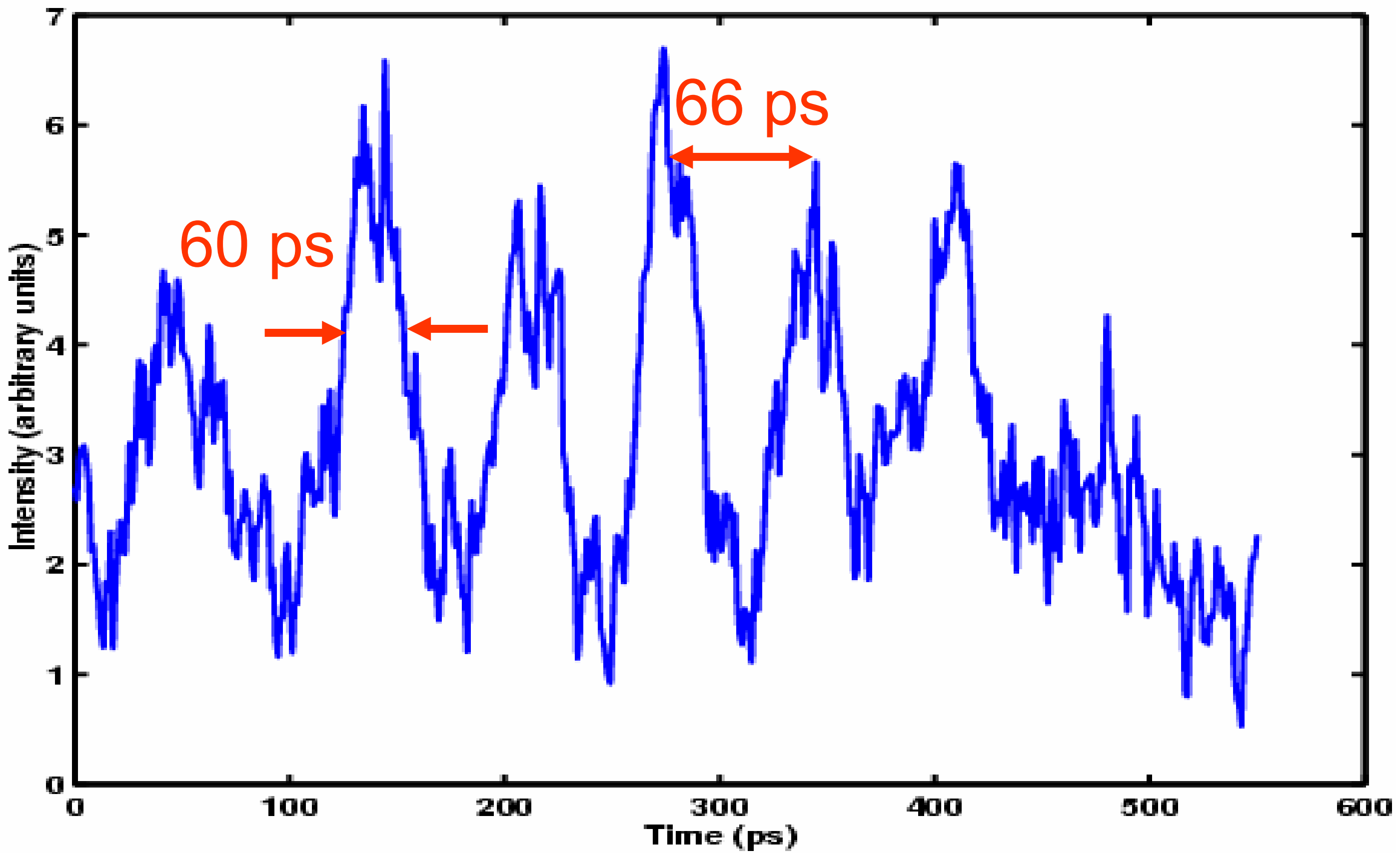
Laser beam waist [mm]
14
12
10
8
6
4
2
0
Collimated beam from beam expander
W_{input} = 12.5 mm
Focusing Lens (f = 250 mm)
Vacuum Chamber
Imaging Lens (f = 125 mm)
distance from IP = 143 mm
Post-IP imaging system
magnification factor = 8.3
distance from imaging lens = 1.17 m
W_M = 75 µm
Interaction Point (IP)
W_0 = 9 µm
CCD Camera
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Propagation distance [m]

Laser Transverse Profile

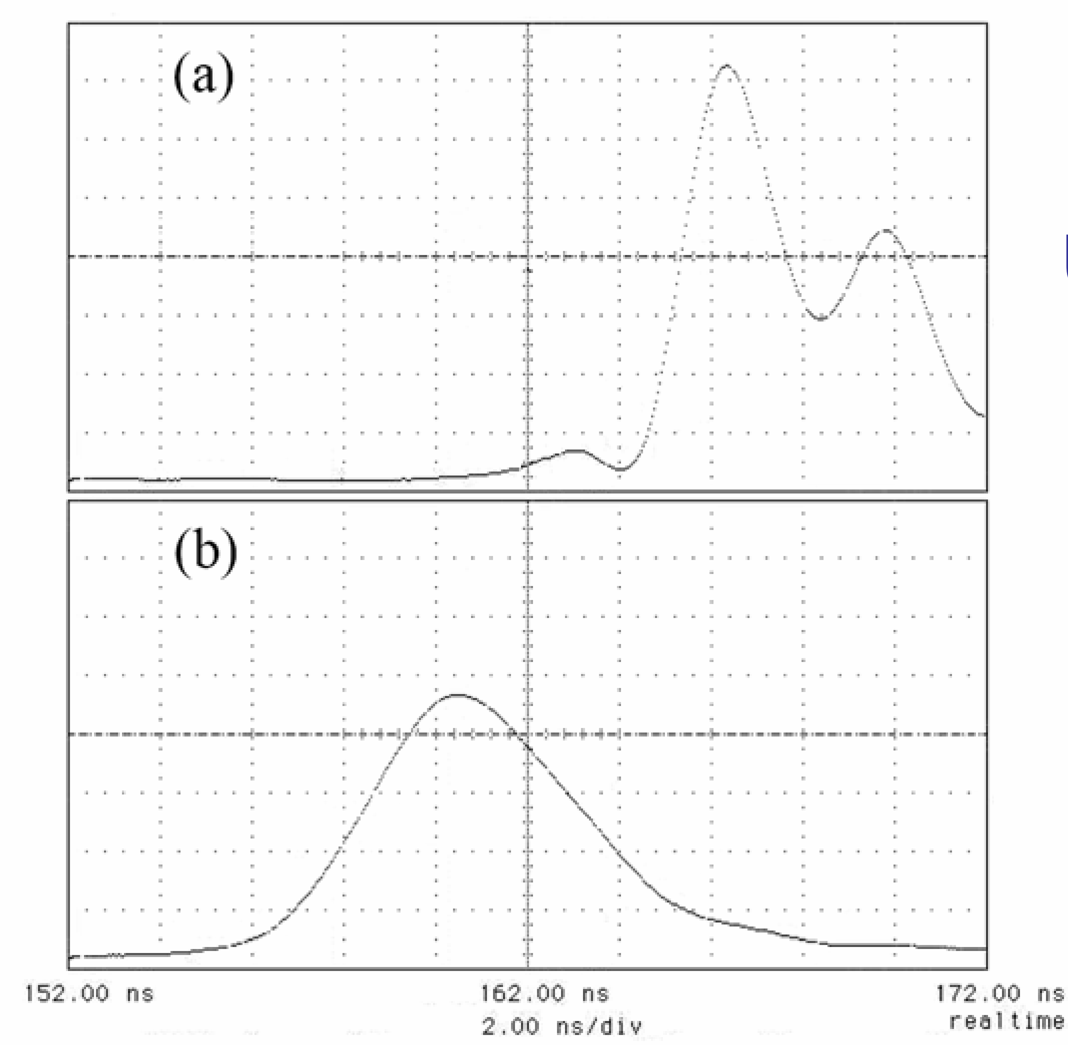


Q-switched, unseeded Laser Longitudinal Profile

- Example of a single shot measurement of the profile
  500 ps window, resolution 5 ps



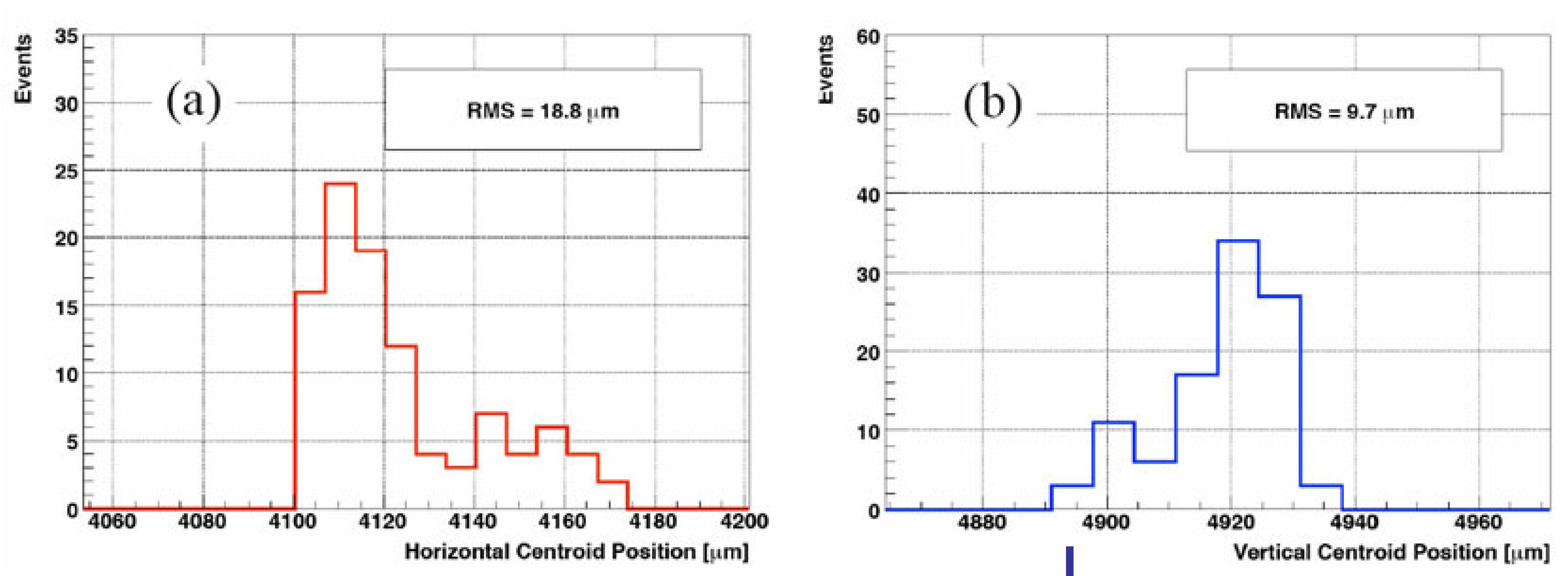
Laser Temporal Profile



Unseeded

Seeded

Laser Pointing Jitter

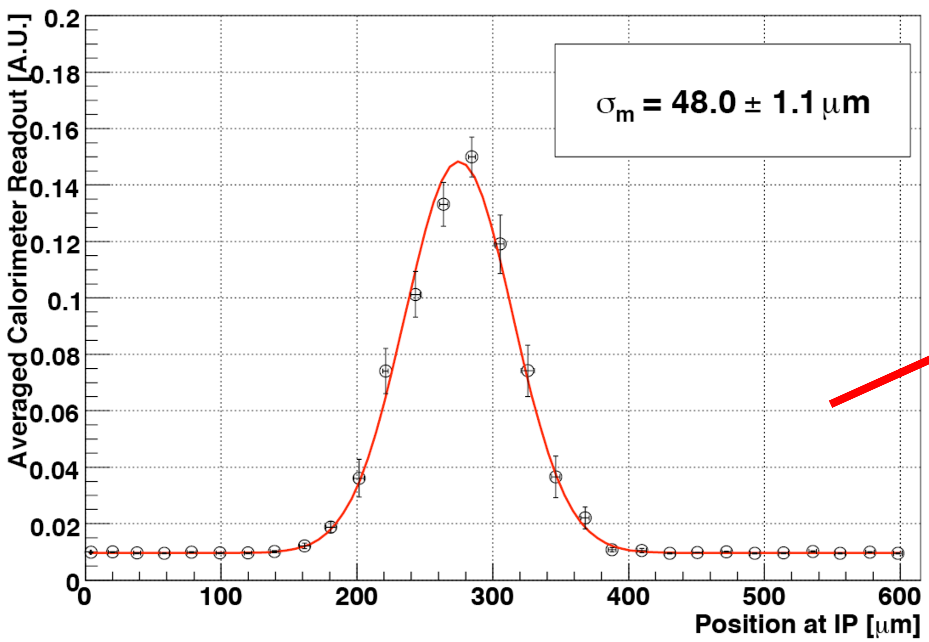


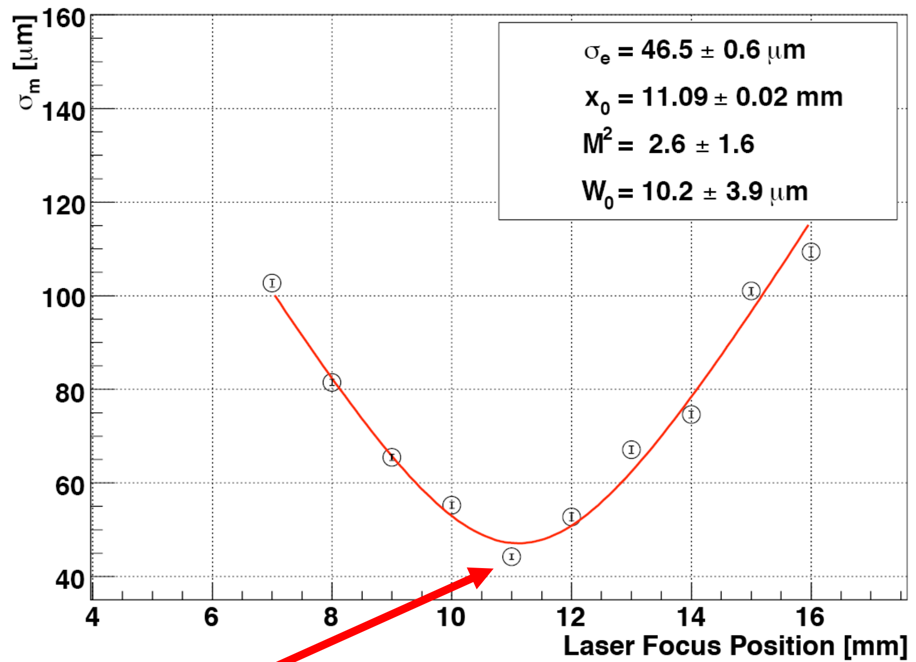
Translates to longitudinal so not relevant

Translates into a 1.6 μm jitter at the LW IP for Both horizontal and vertical scans

PETRAII Results: Vertical

Convoluted profile
(takes<50s)

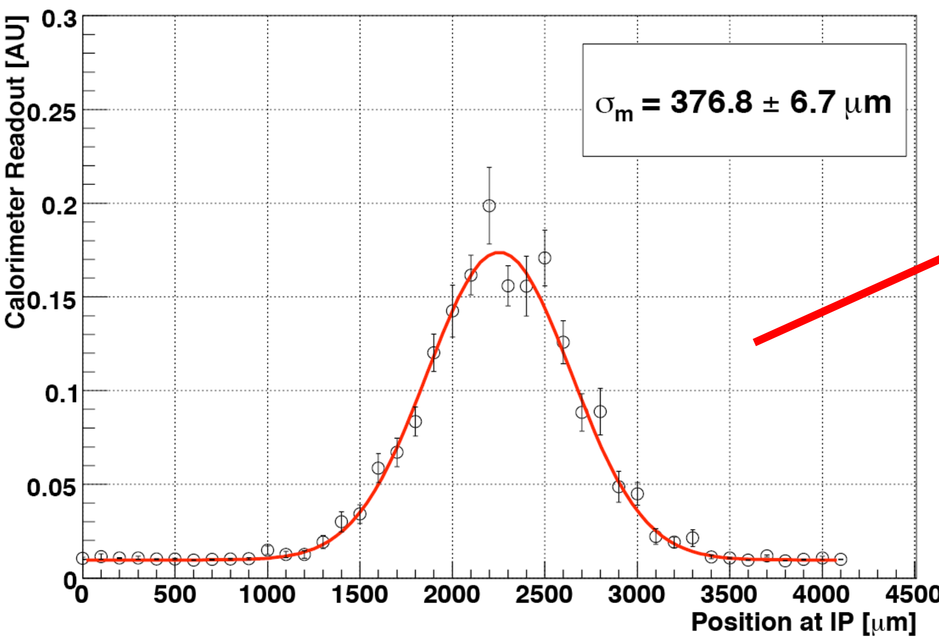


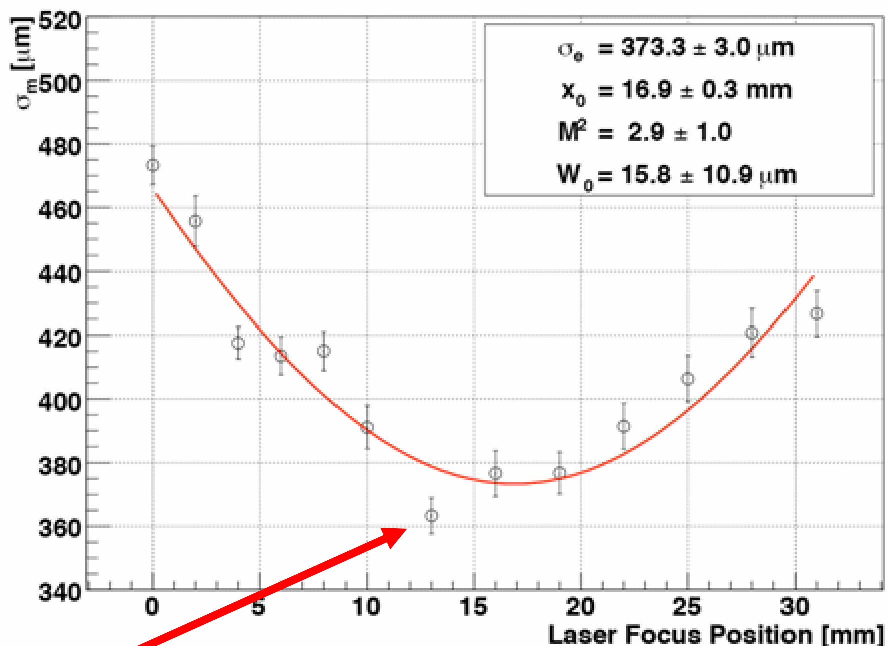


Fit to Rayleigh formula

PETRAII Results: Horizontal

Convoluted profile



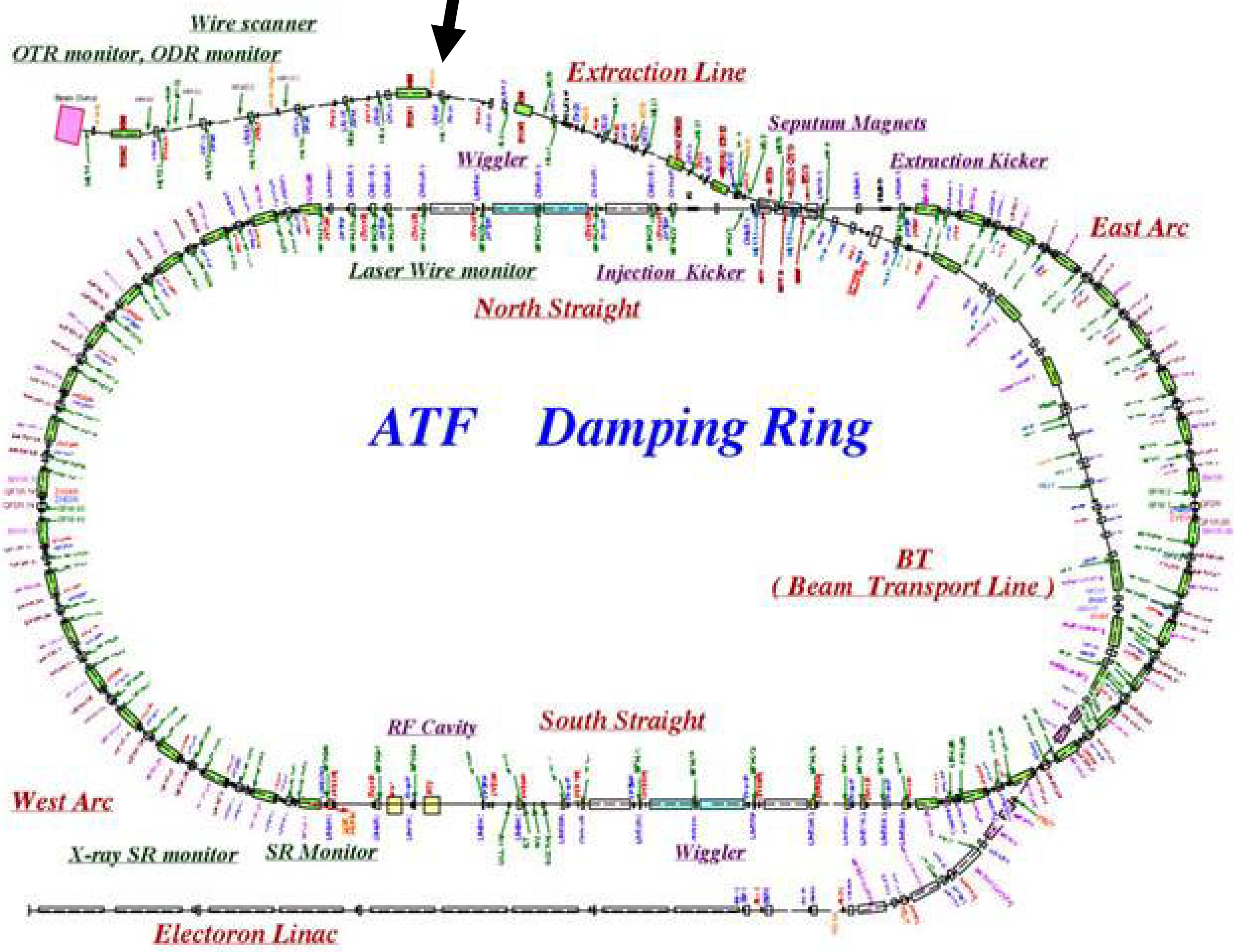


Fit to Rayleigh formula

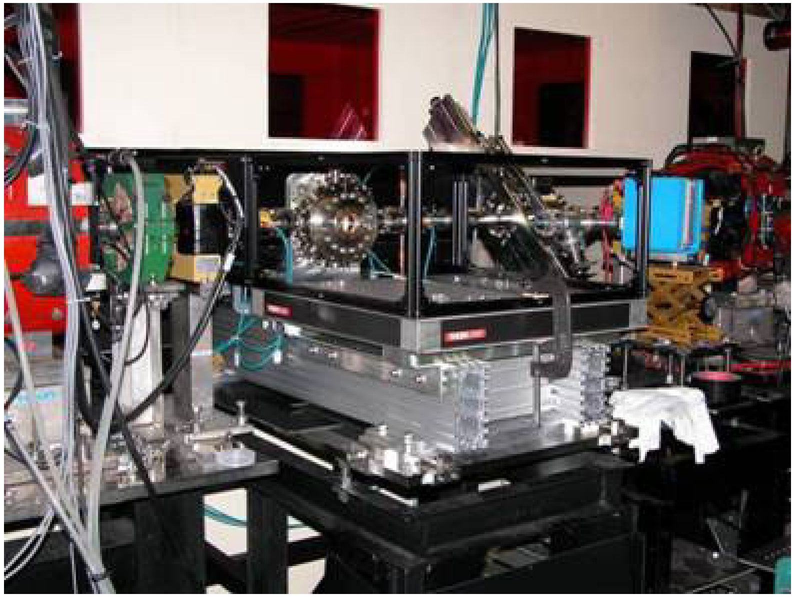
NIM A accepted

LW in the ATF Extraction Line

pulsed laser-wire location



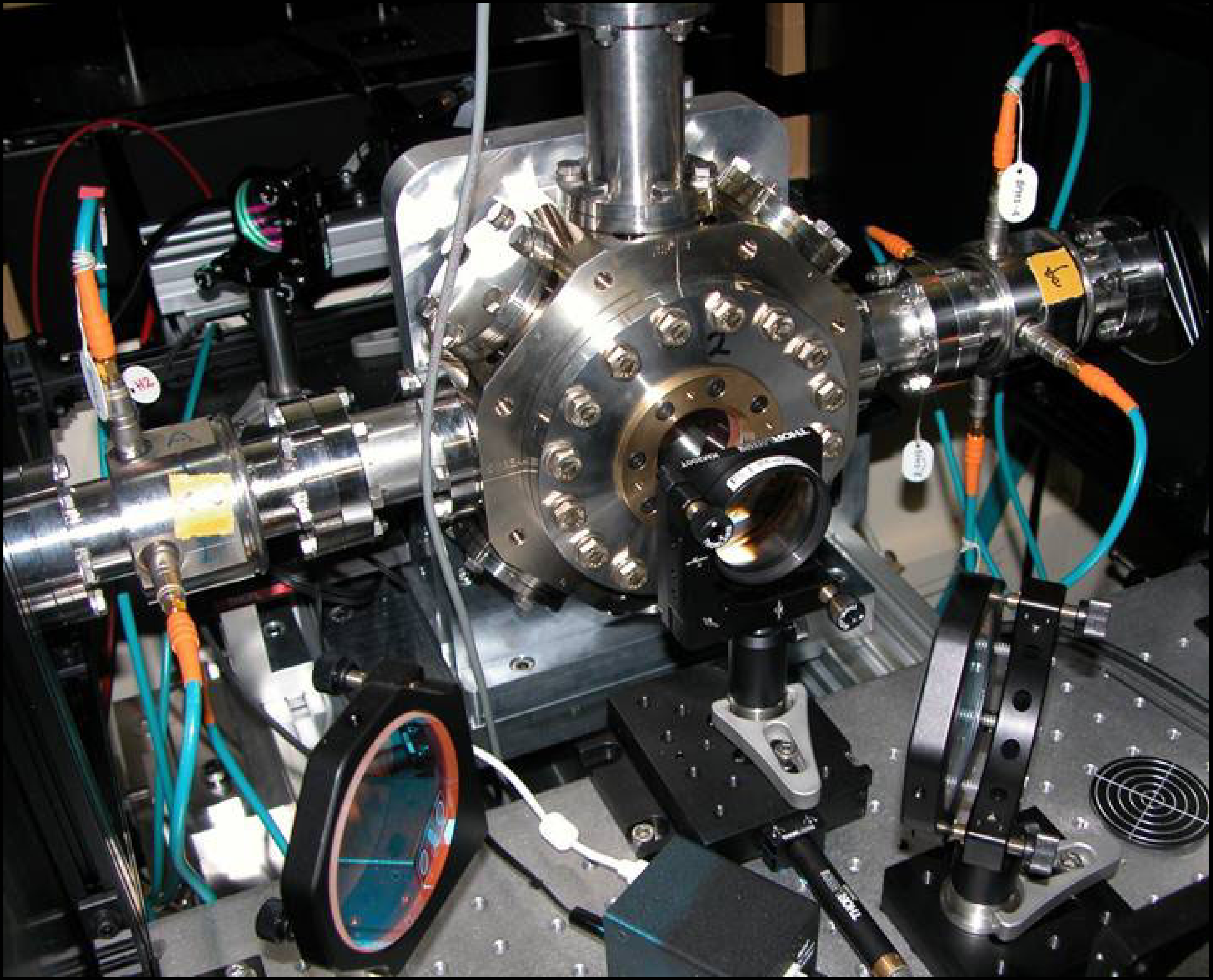
ATF Parameters



Beam energy :	1.28 GeV
Beam intensity single bunch operation :	1.0×10^{10} electrons/bunch
multi bunch operation :	0.7×10^{10} electrons/bunch x 20 bunch
Beam reputation :	0.7 - 6.4 Hz
X emittance (extrapolated to 0 intensity) :	1.0×10^{-9}rad.m (at 1.28GeV)
Y emittance (extrapolated to 0 intensity) :	1.0×10^{-11} rad.m (at 1.28GeV)
Typical beam size :	70µm x 7µm (rms horizontal x rms vertical)

ATF Laser-Wire

Aiming at micron-scale vertical scans



ATF/ATF2 Laser-wire

- At ATF2, we will aim to measure micron-scale electron spot-sizes with green (532 nm) light.
- Two locations identified for first stage (more stages later)
  1) 0.75m upstream of QD18X magnet
  2) 1m downstream of QF19X magnet

Nominal ATF2 optics

LW-IP (1)	LW-IP (2)
$\sigma_x = 38.92\ \mu m$	$\sigma_x = 142.77\ \mu m$
$\sigma_y = 7.74\ \mu m$	$\sigma_y = 7.94\ \mu m$

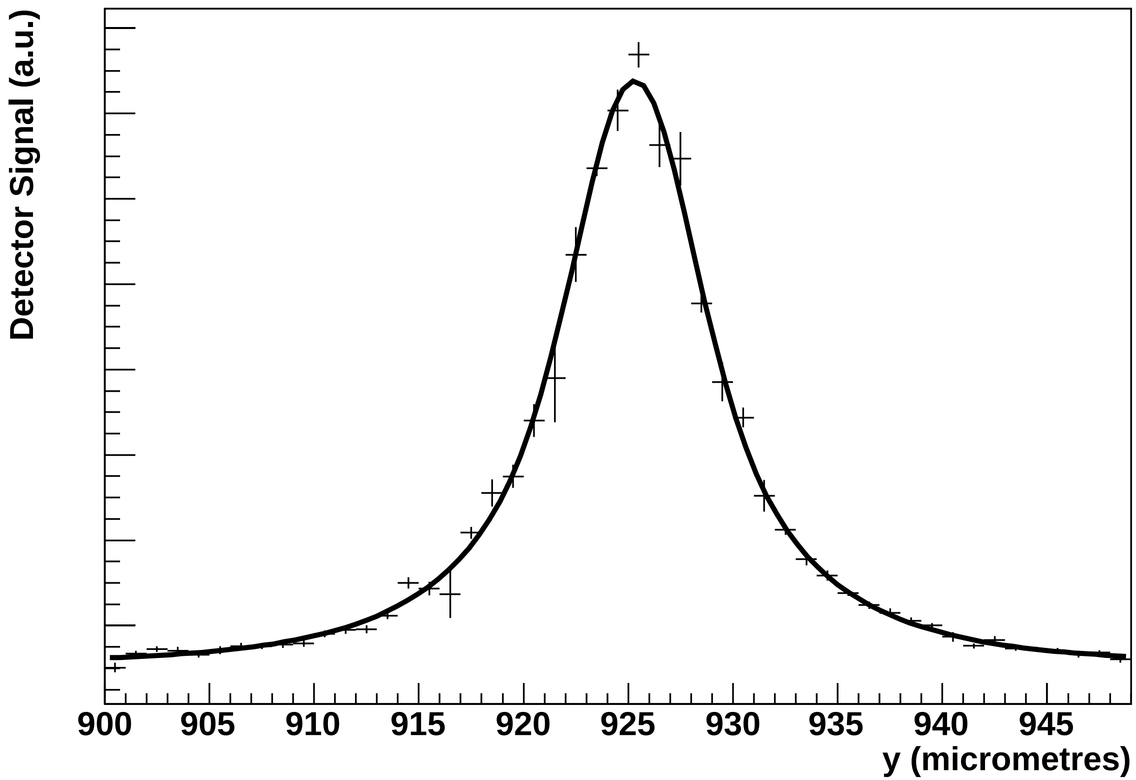
ATF2 LW-test optics

P. Karataev

LW-IP (1)	LW-IP (2)
$\sigma_x = 20.43\ \mu m$	$\sigma_x = 20\ \mu m$
$\sigma_y = 0.9\ \mu m$	$\sigma_y = 1.14\ \mu m$

$\Rightarrow$ Ideal testing ground for ILC BDS Laser-wire system

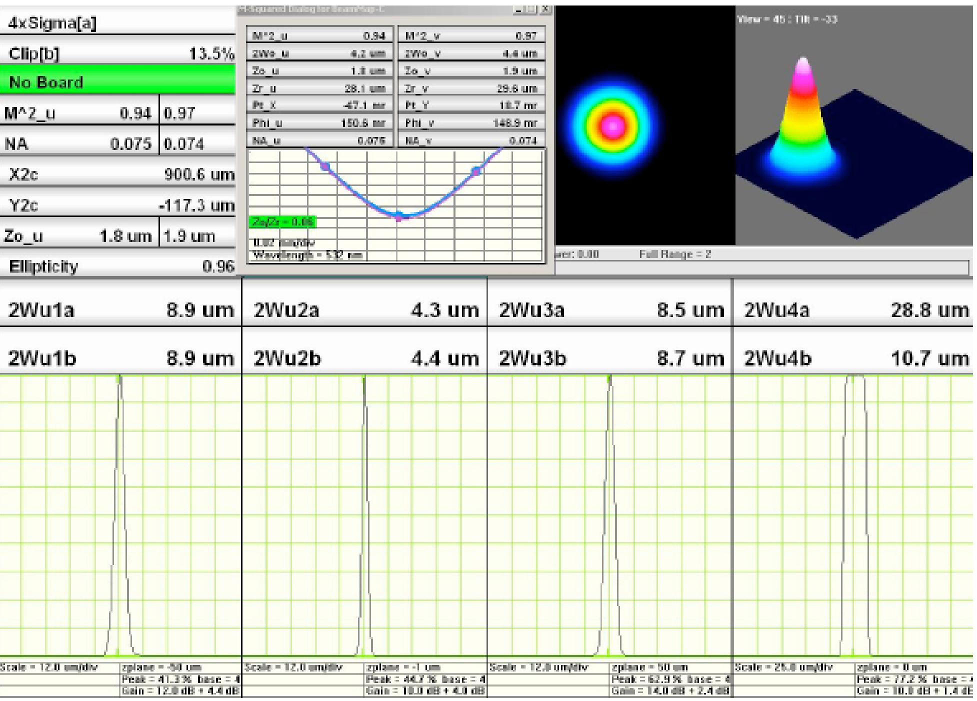
Prelminary ATF LW Results



Laser M^2 not yet optimised

Laser astigmatism not yet corrected

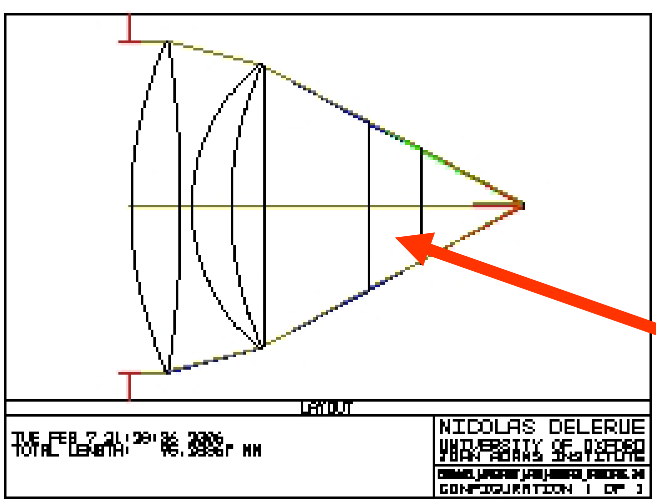
Rayleigh Range effects well described by fit



M. Newman, D. Howell et al.

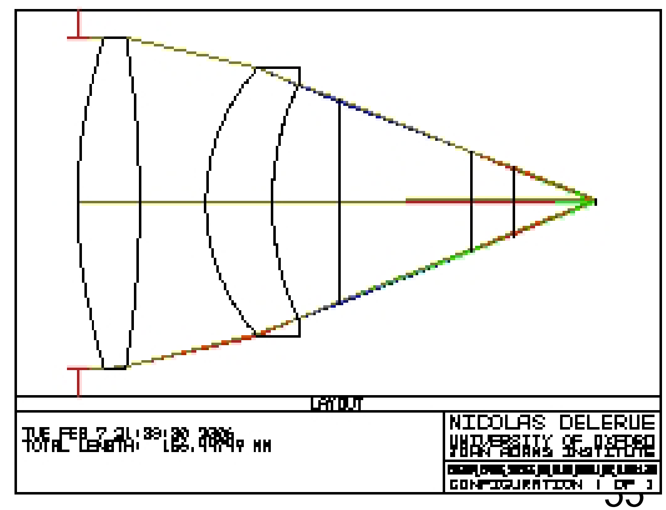
- Low f-number
- Radiation hard
- Spectral width?

Designs for f-1 optics are currently being studied, including:



Aspheric doublet

Vacuum window

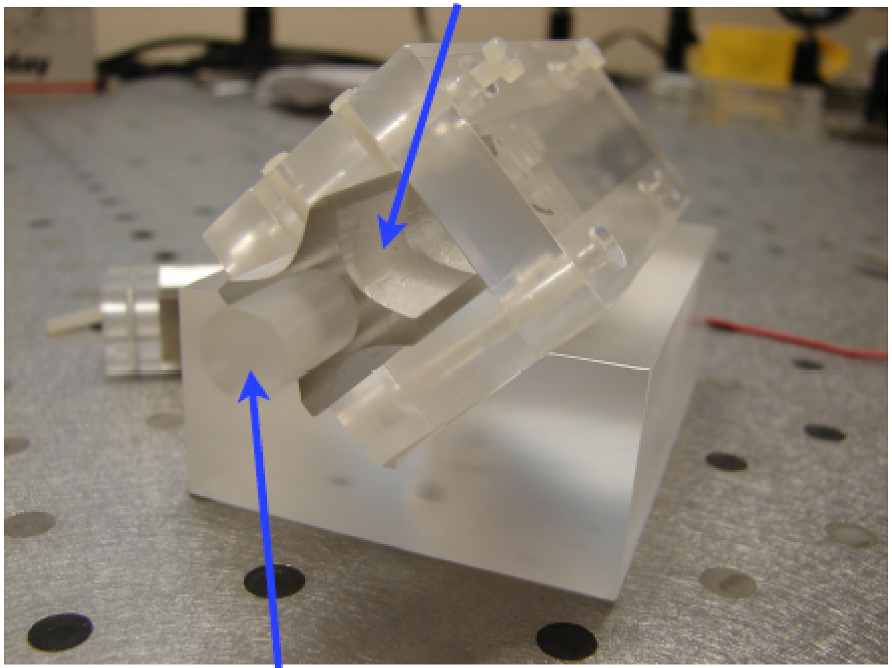


N. Delerue et al.

Prototype scanner

- First stage of high power scanner prototype
  - Simple EO crystal geometry
- Currently using
  - Lithium Niobate
  - Diameter 8.5 mm
  - Length 45 mm
- Different crystals
  - Damage thresholds
  - Electro-optic coefficient

Quadrupole electrodes on outer surface

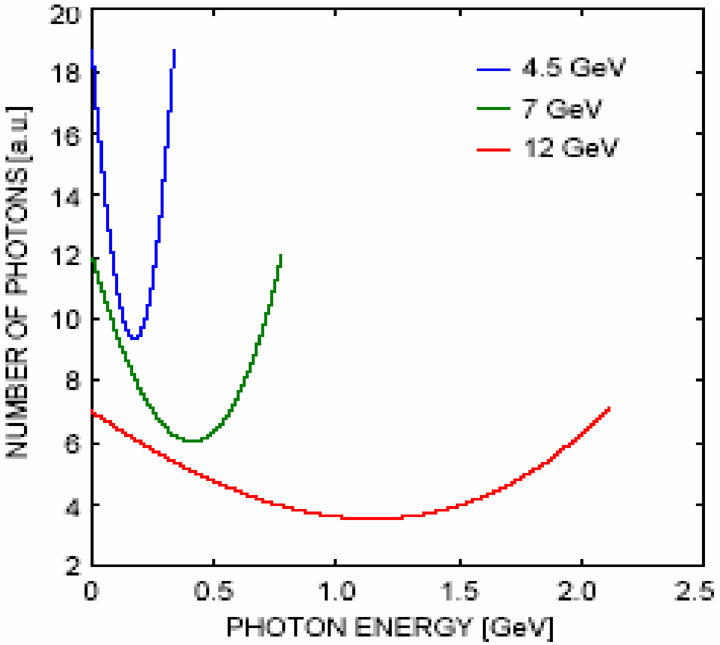


Cylindrical crystal hole

Signal Extraction

PETRA

Compton Spectrum

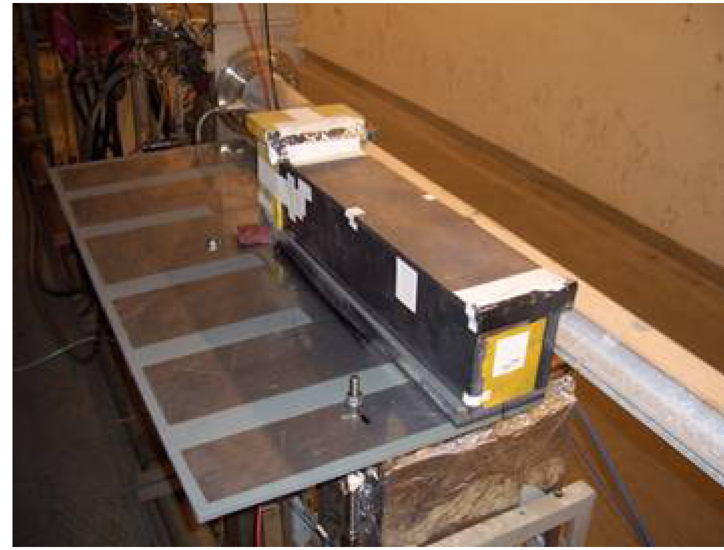


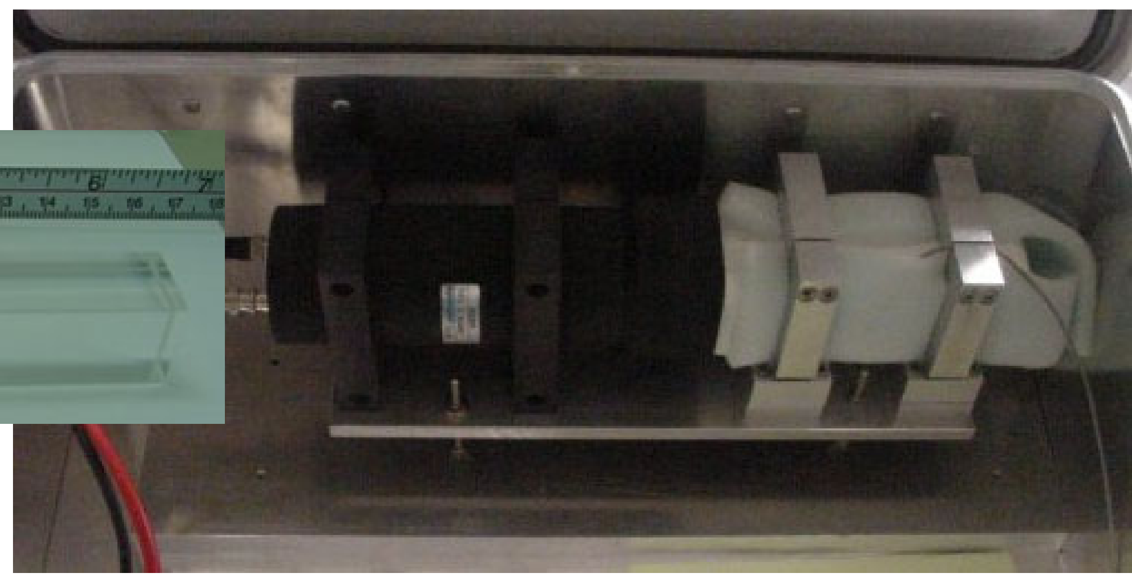
At peak, ~1000 photons
For 7 GeV Petra;
Mean E = 0.5 GeV per photon

Downstream of Laser-wire

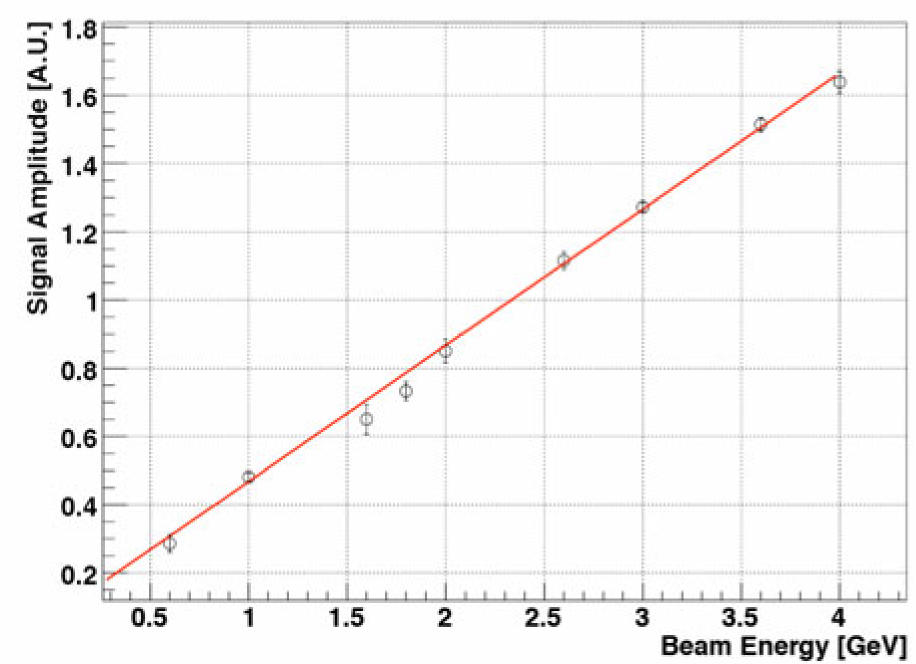
PETRA Detector

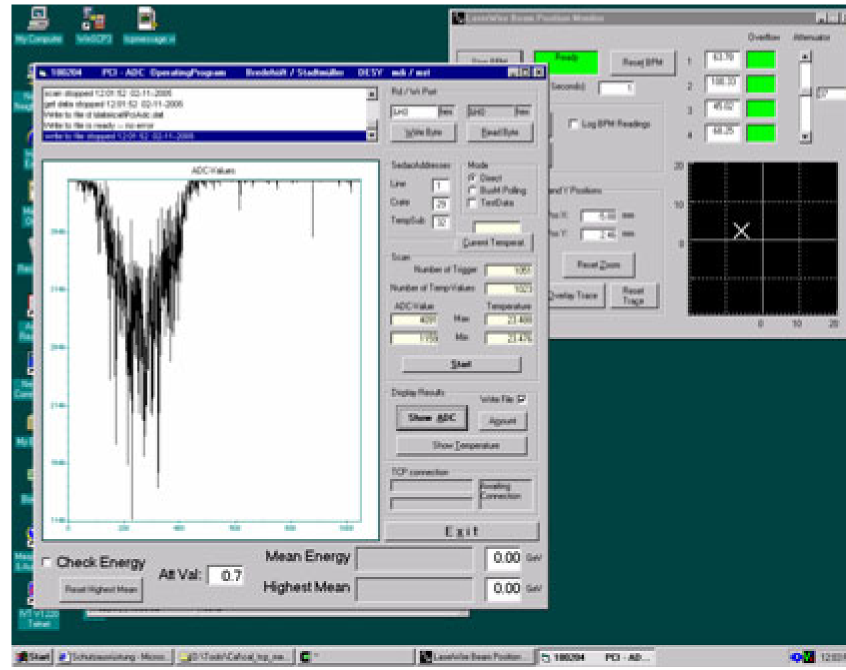
- Requirements for detector material
  - short decay time (avoid pile up)
  - short radiation length
  - small Moliere radius
- Cuboid detector crystals made of $PbWO_4$
- 3x3 matrix of 18x18x150 mm crystals
- Energy resolution better than 5%





PETRA Detector Response





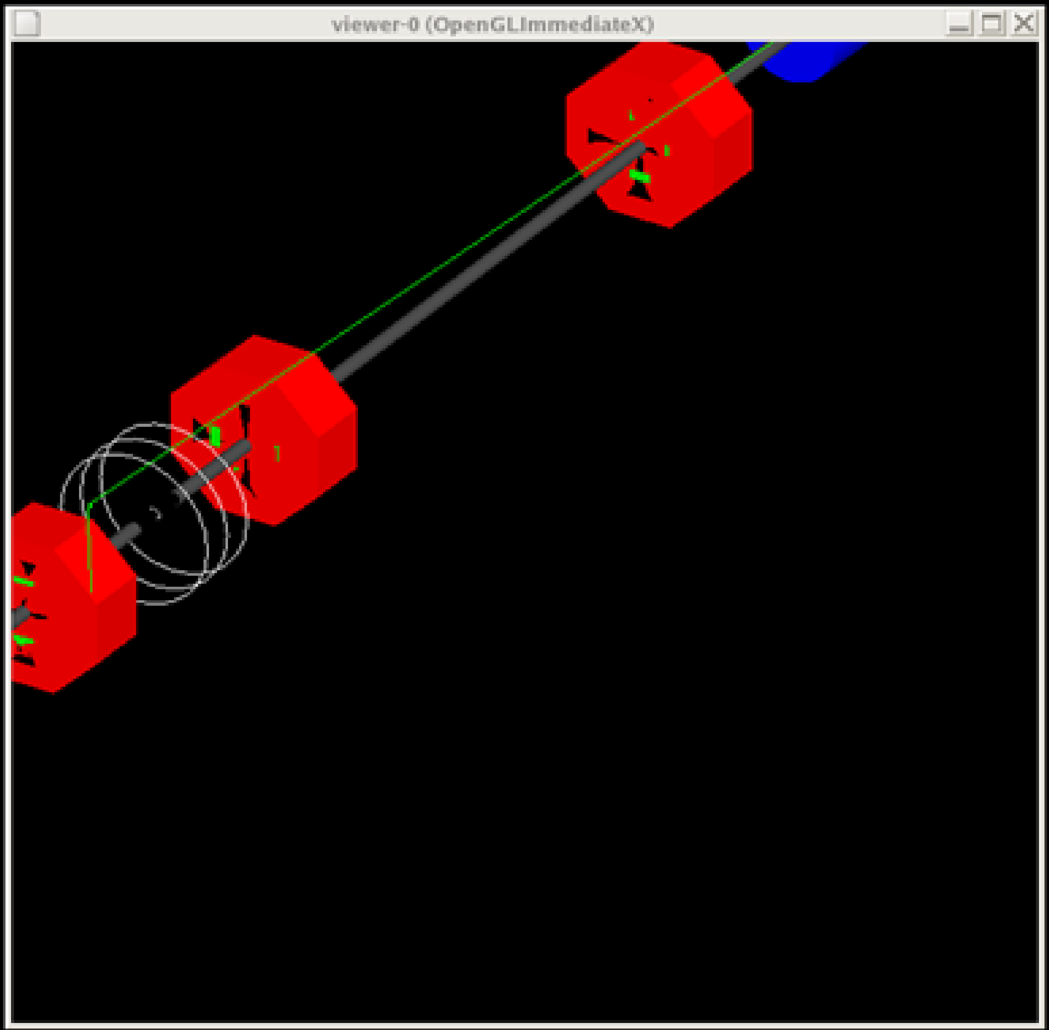
Calorimeter BPM

DESY test beam

Online system

ATF2 Detector

Geant4 Simulation of Beamlines

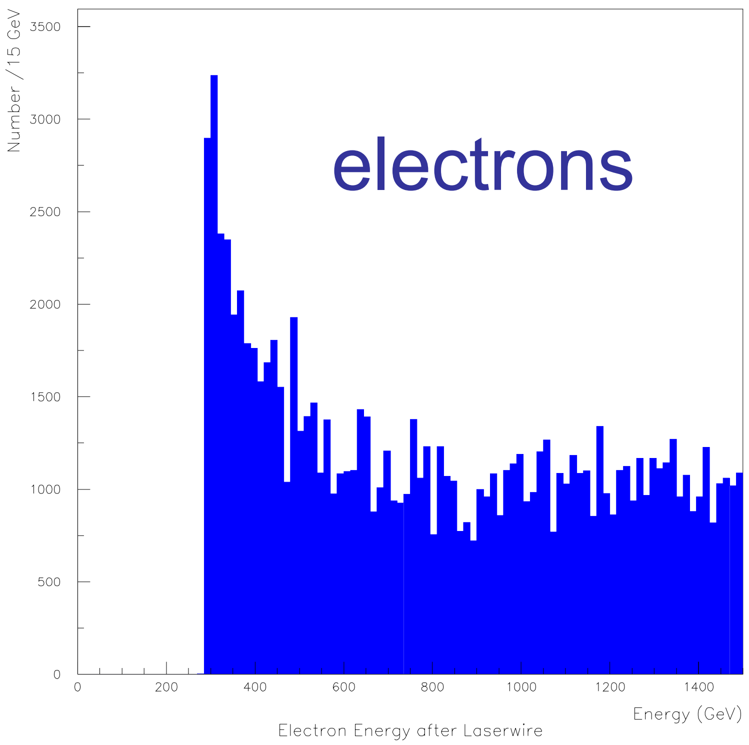


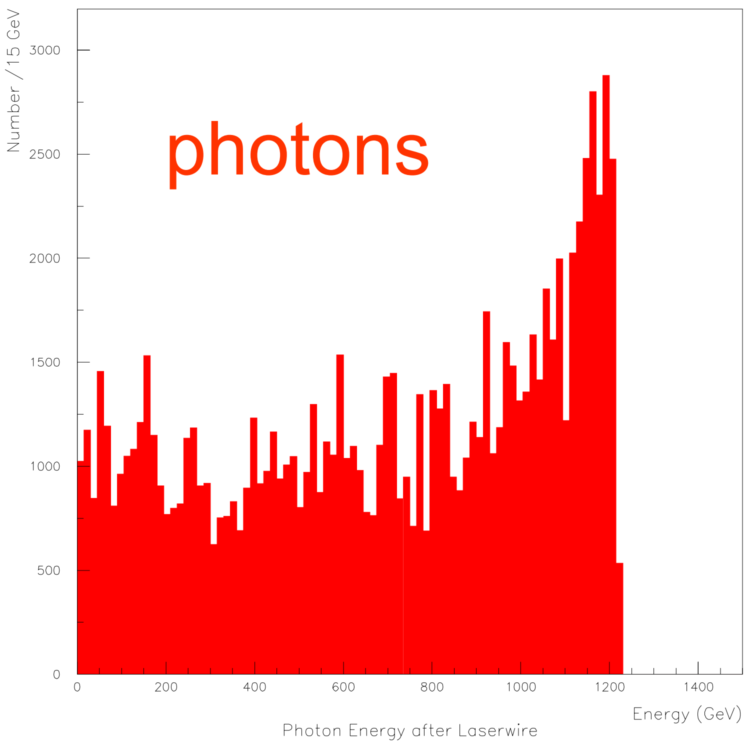
BDSIM

- BDSIM is a geant4 based programme for detailed simulation of BDS.
- Fast machine-style tracking combined with full shower simulation and physics processes.
- Original BDSIM: CLIC-Note-509 (2002)
- Backgrounds from Halo loss along BDS, especially in collimation region.
- Laserwire process included (among many others)
- https://twiki.pp.rhul.ac.uk/twiki/bin/view/JAI/Simulation

Compton Spectrum at CLIC

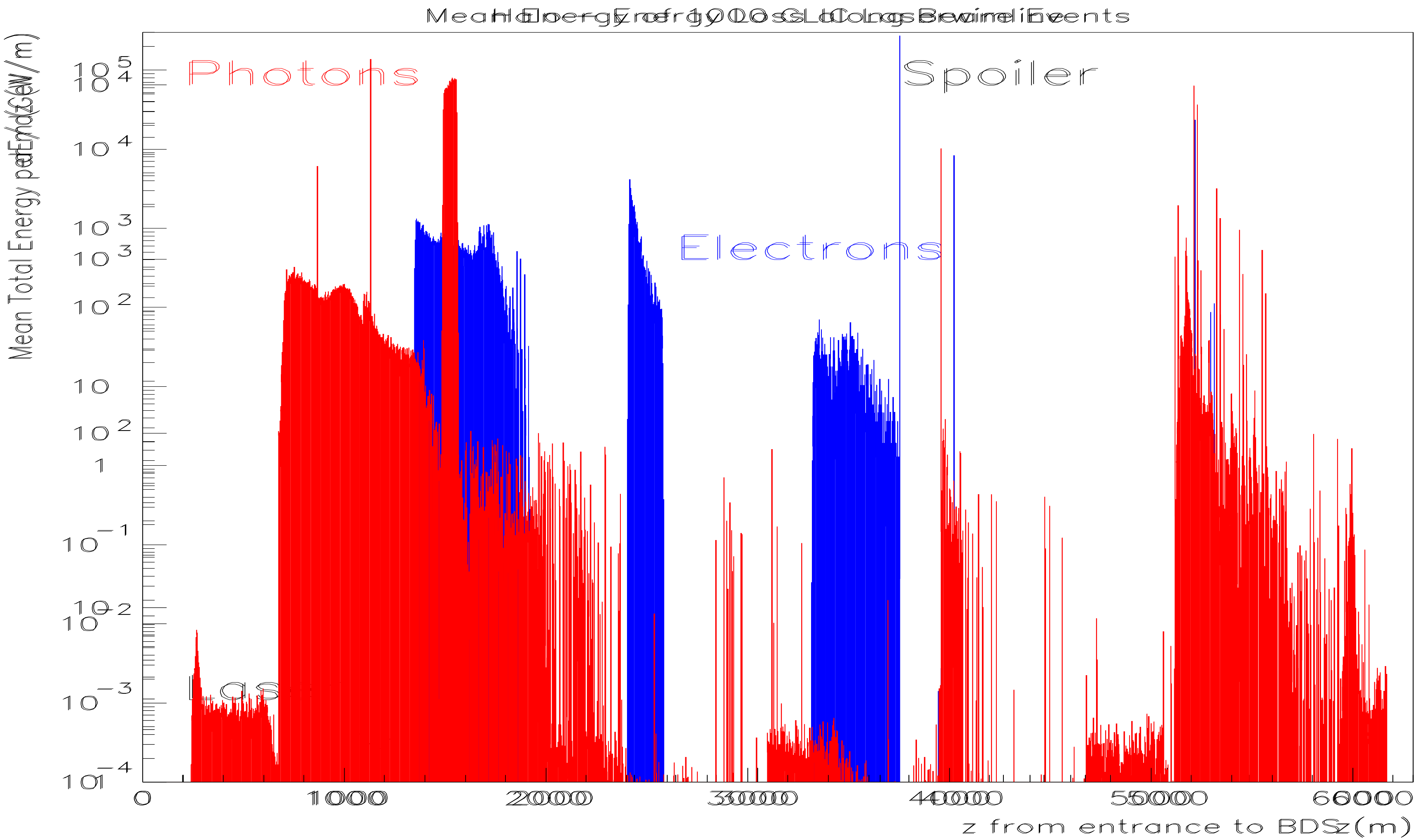
Energy Spectrum at 1.5 TeV:

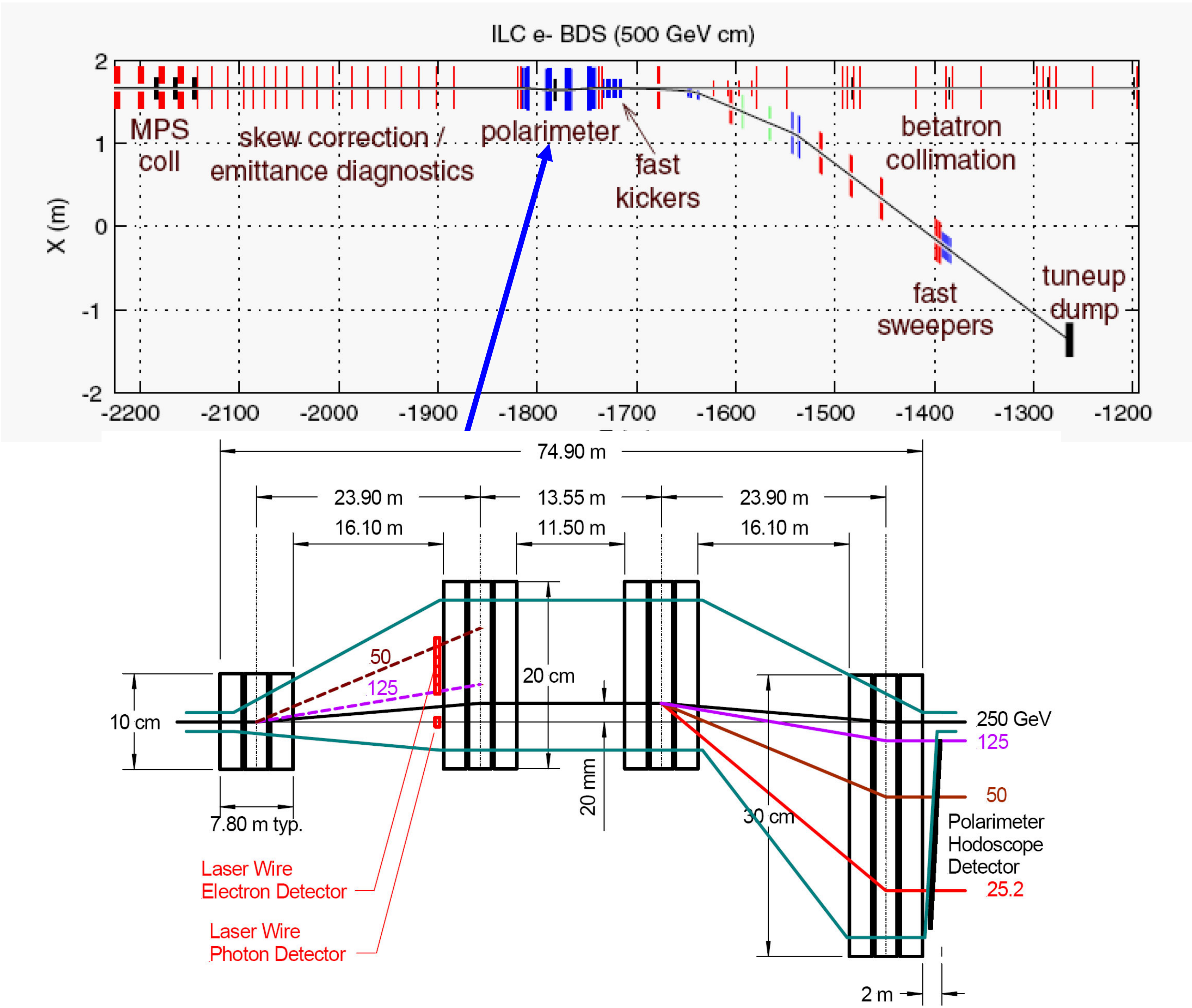




Both electrons and photons need to be tracked downstream.

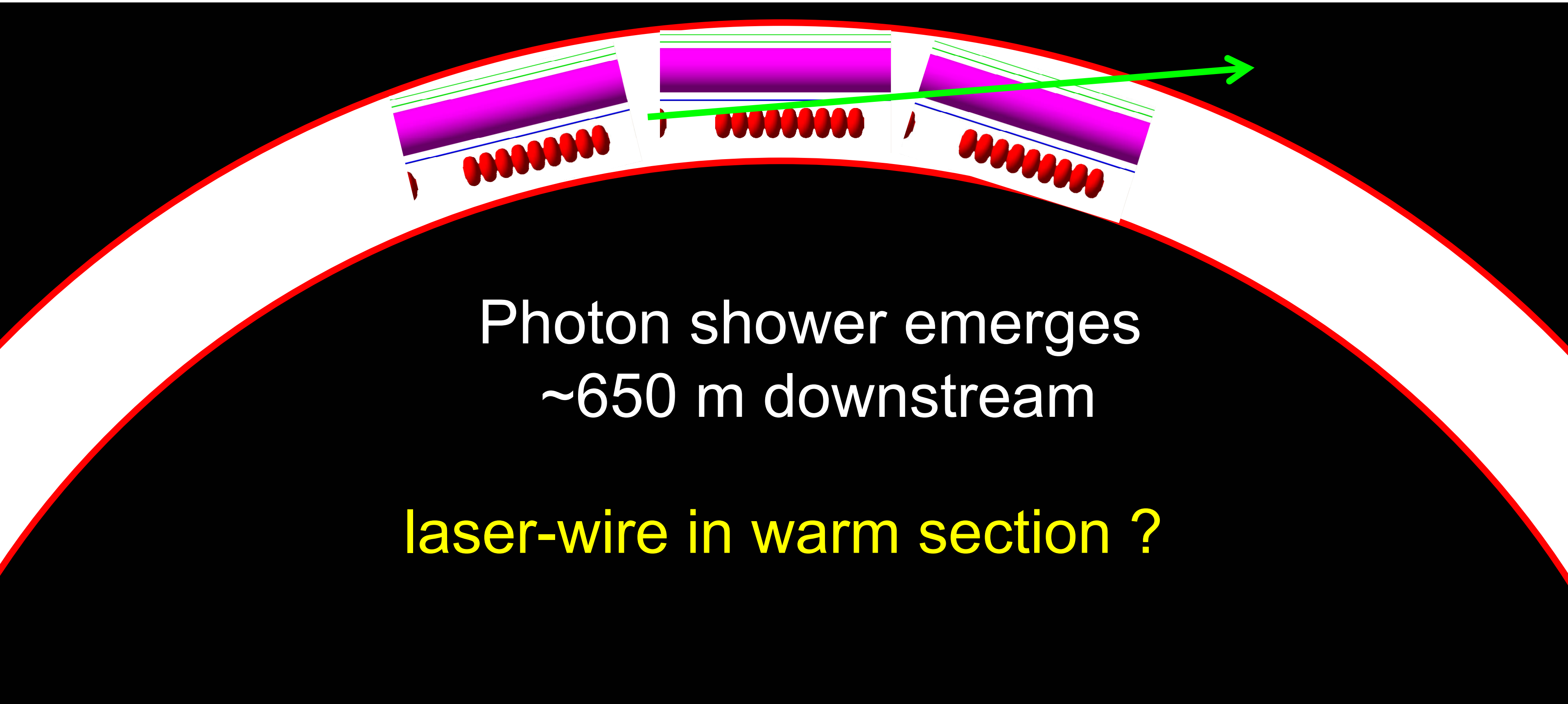
Laserwire Simulation (CLIC)



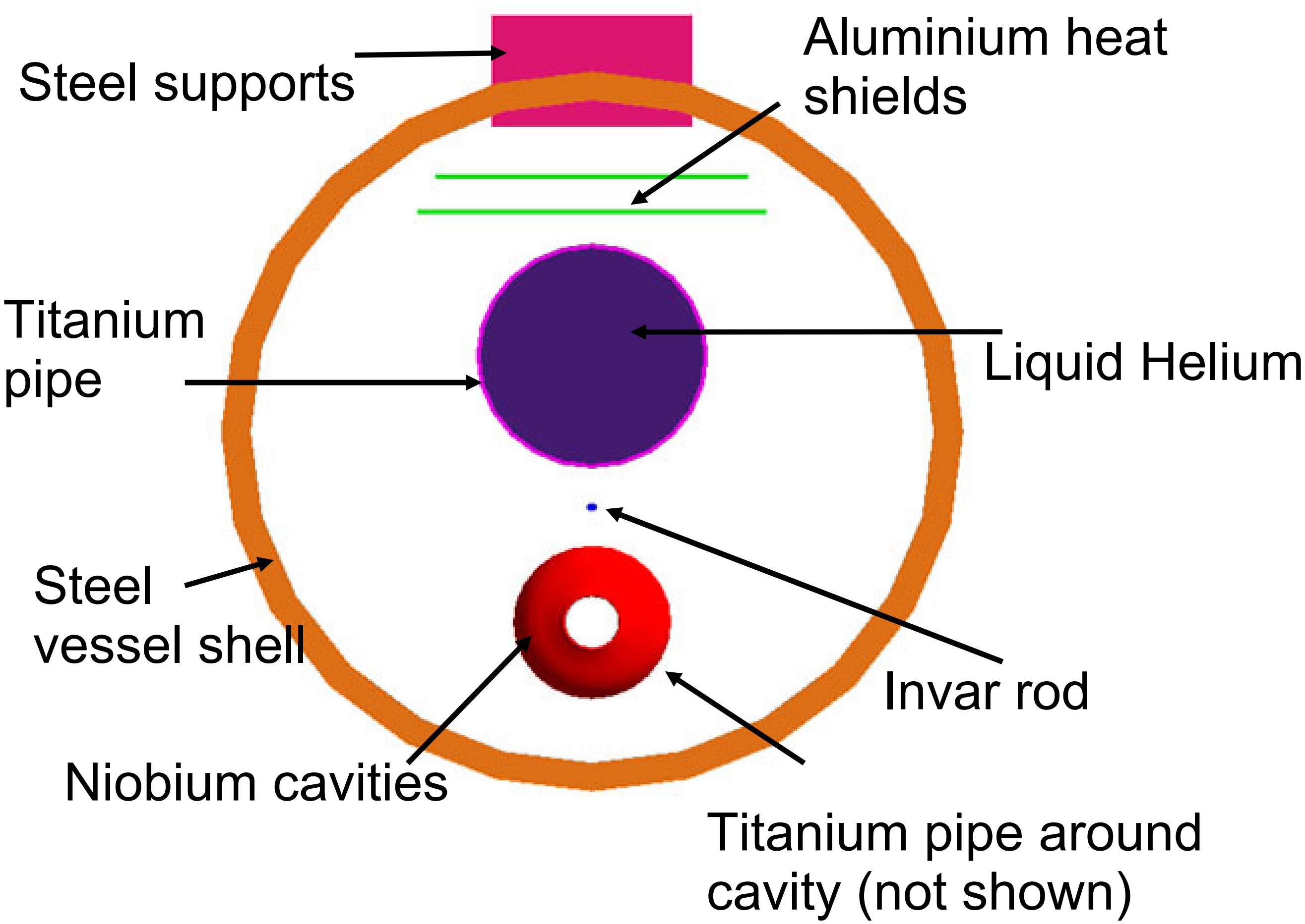

ILC e- BDS (500 GeV cm)
X (m)
2
1
0
-1
-2
-2200
-2100
-2000
-1900
-1800
-1700
-1600
-1500
-1400
-1300
-1200
MPS coll
skew correction / emittance diagnostics
polarimeter
fast kickers
betatron collimation
fast sweepers
tuneup dump
74.90 m
23.90 m
13.55 m
23.90 m
16.10 m
11.50 m
16.10 m
50
125
20 cm
10 cm
250 GeV
125
50
25.2
20 mm
30 cm
7.80 m typ.
Polarimeter Hodoscope Detector
Laser Wire Electron Detector
Laser Wire Photon Detector
2 m

Laser-wires in the ILC LINAC?

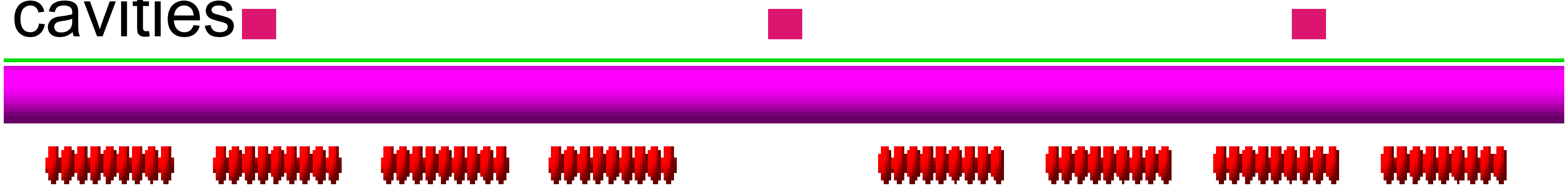
To extract signal:
- Quadrupole fields with scattered electrons.
- Earth's curvature for photons?



Linac Module



- Length 12.5m
- 8 sets of 9 cavities



L. Deacon

H^- Neutralisation

The process $H^- + \gamma \rightarrow H^0 + e^-$

has threshold energy ~0.75 eV

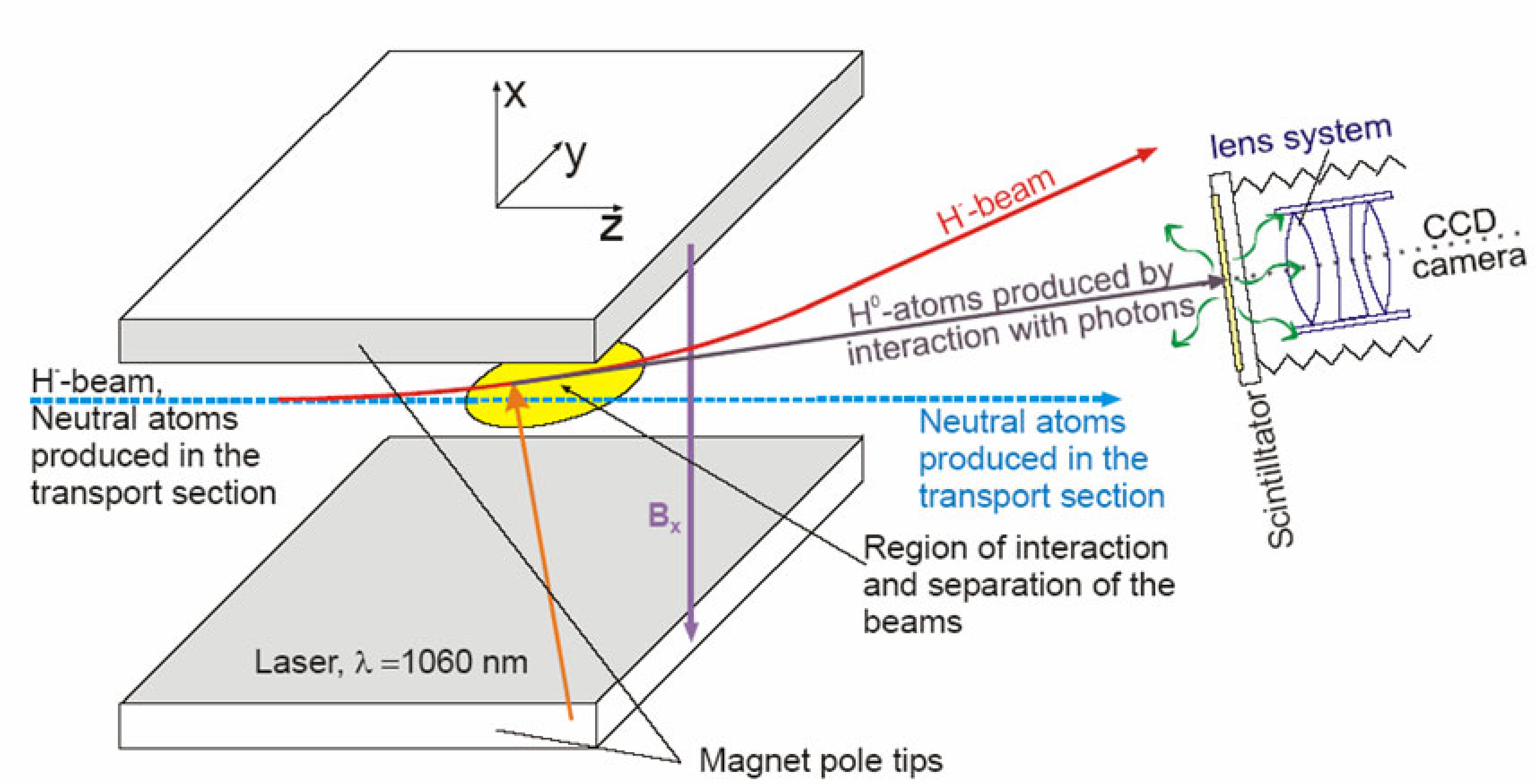
so it can be driven by a Nd:YAG laser operating at 1060 nm.

A focussed laser beam can thus be used to

- Measure emittance of H- beam
- Enable proton production by laser-induced stripping.

All the previous technical issues apply…

Schematic Operation

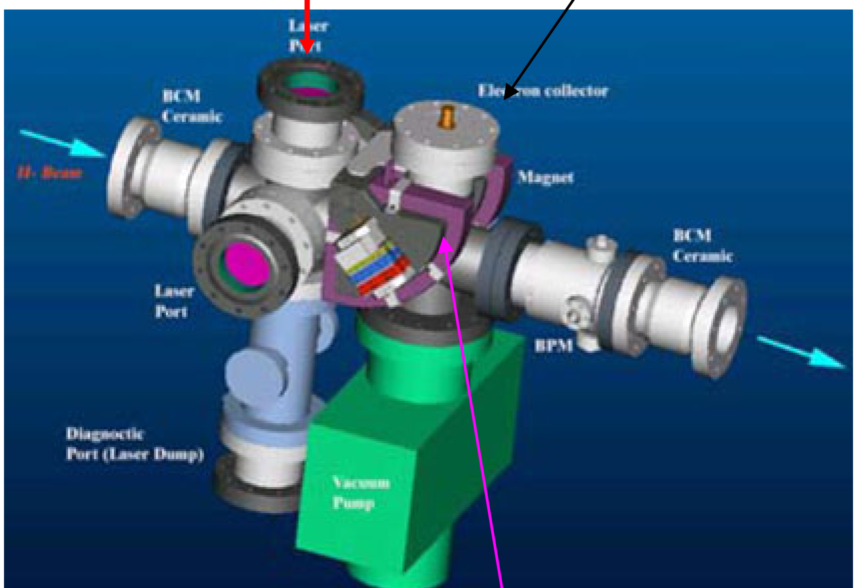


Front End Test Stand (RAL) – electrons + neutrals
SNS (detect electrons)

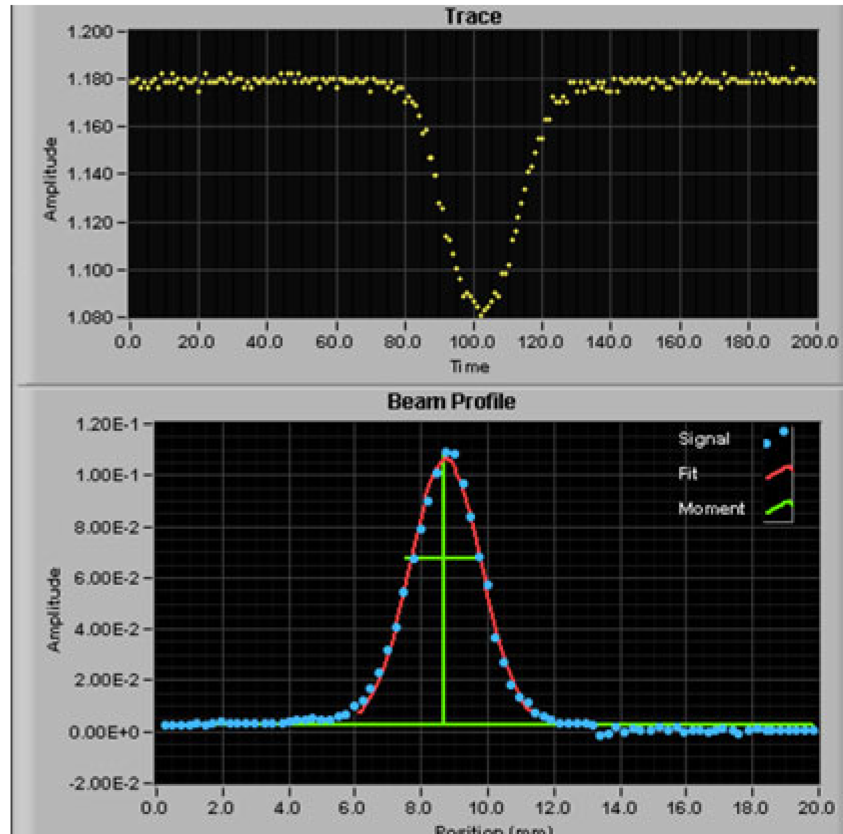
SNS laser-wire system

Laser

e$^-$ detector



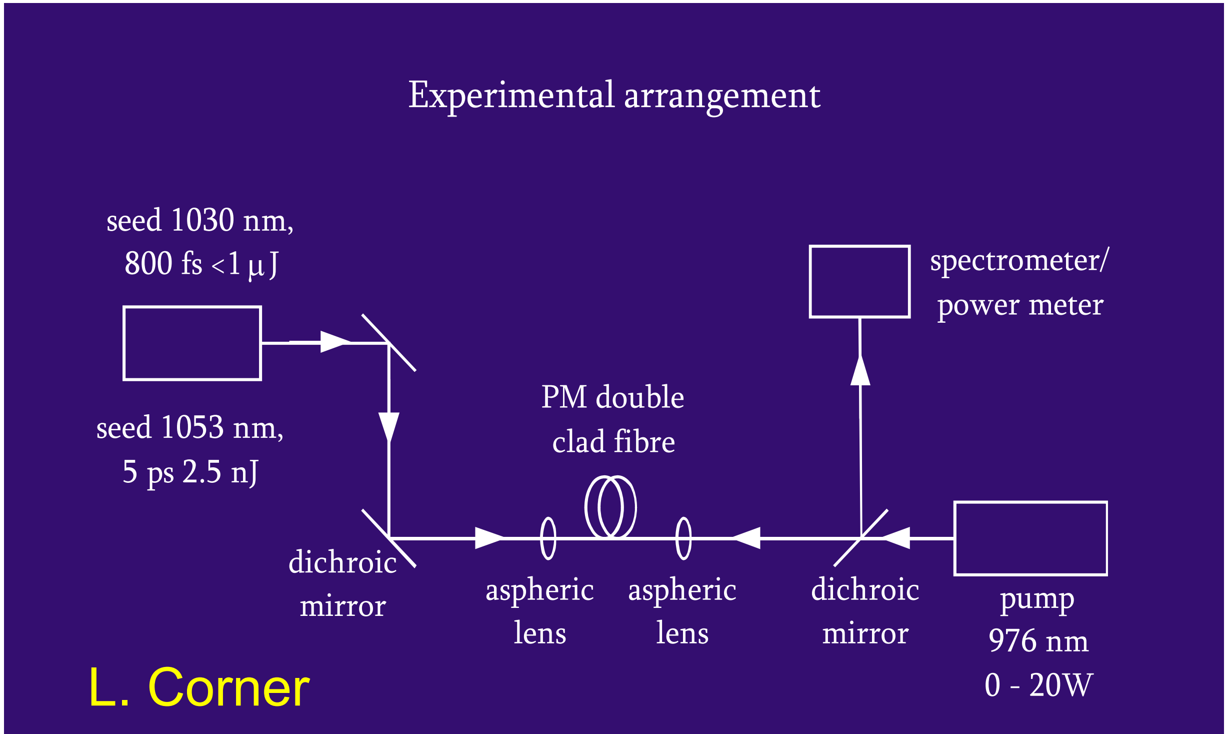
dipole to extract e$^-$



Fiber Laser R&D

- Excellent pointing stability
- Reliability
- Spectral width? (important for final focus optics)

A mini-workshop on this topic would be timely…



Summary

- Very active + international programme in laser-based diagnostics:
  - Hardware
  - Optics design
  - Advanced lasers
  - Emittance extraction techniques
  - Proton machines
  - Data taking + analysis
  - Simulation
- Important effects:
  - Laser pointing
  - M^2 monitoring
  - Low-f optics
  - Fast scanning
  - High precision BPMs
- Signal extraction is not trivial
  - Full simulations in progress.