Beam diagnostics using lasers – Laser-wire beam profile monitor

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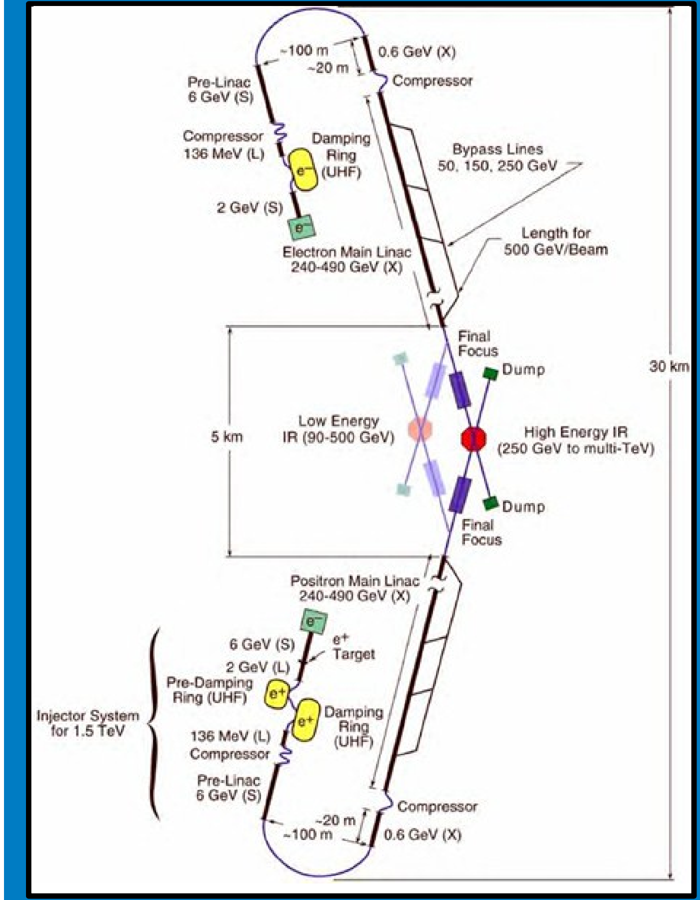
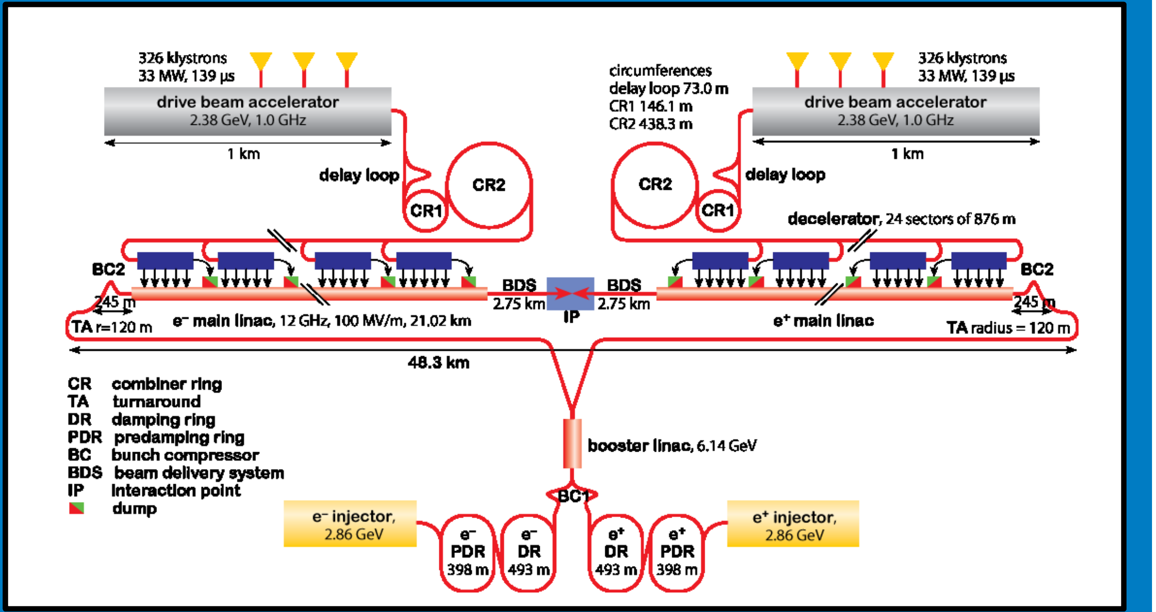
Outline

- Colliders and diagnostic requirements
- Beam size profile monitors
- Principle of laser-wire
- Laser-wire experiments
- Case study: ATF2 laser-wire
- Design considerations for future laser-wires

Linear colliders – ILC/CLIC



- New colliders e^-/e^+ high precision machines.
- Two main current designs - International Linear Collider (ILC) and Compact Linear Collider (CLIC).
- Extreme focusing/charge/luminosity requirements.
- Making focussed beams of 1 – 5 nm!
- Need high quality measurements of beam size, position, charge, duration……….



Ref. 1

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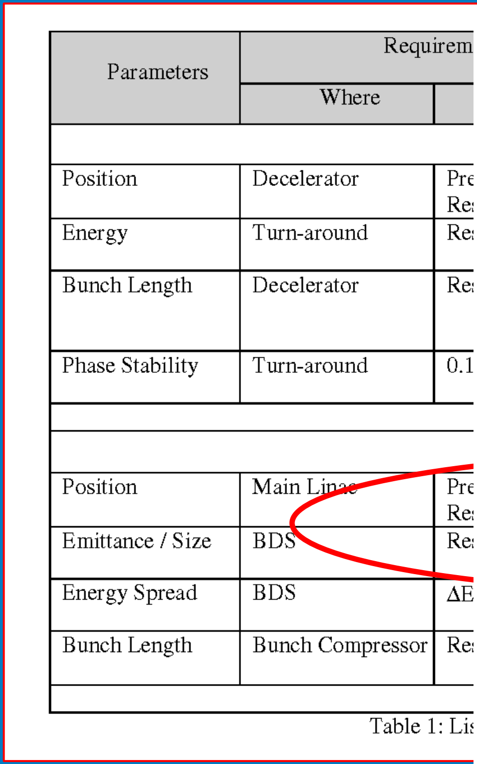
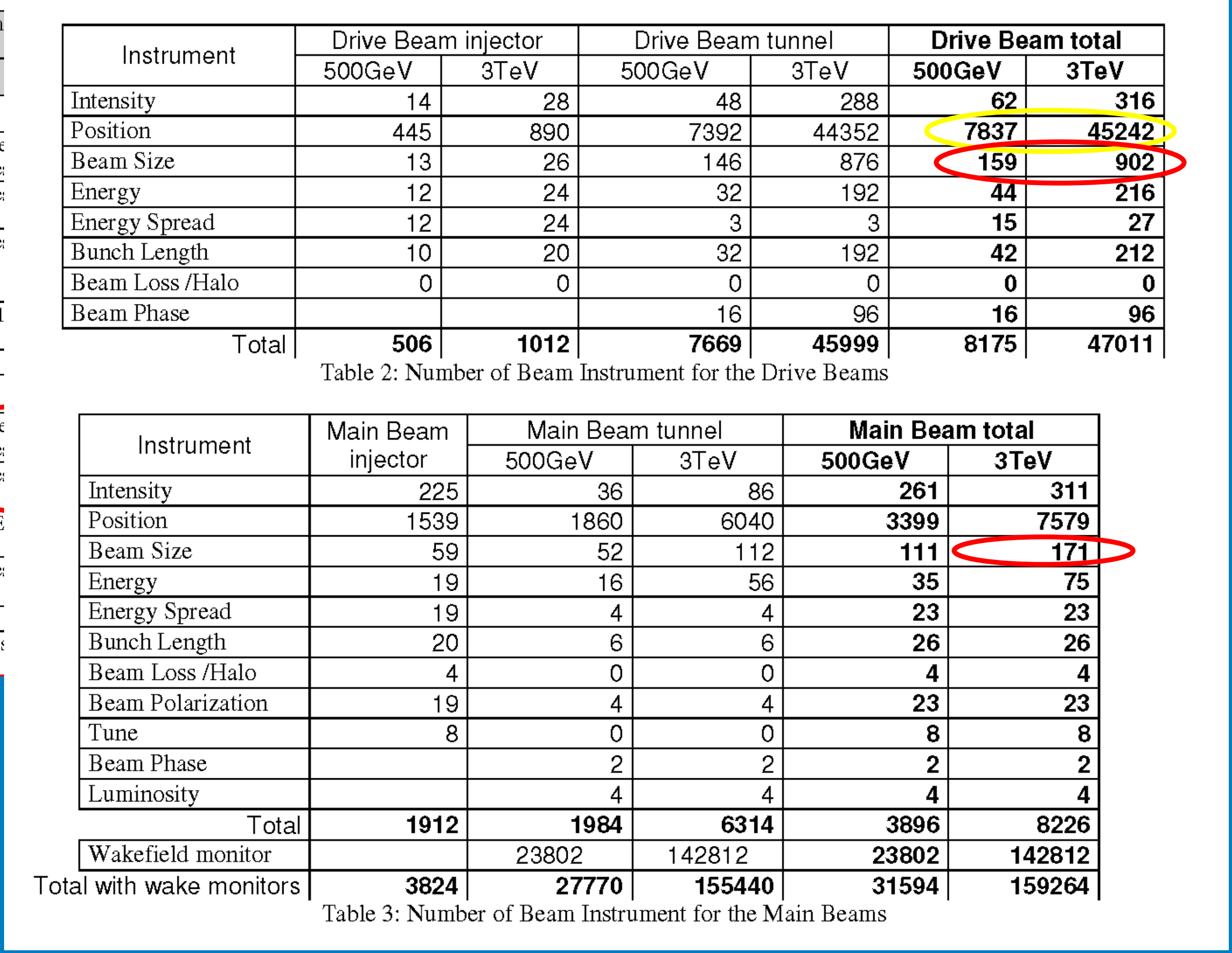
Beam instrumentation requirements



Parameters	Requirem	
	Where	
Position	Decelerator	Pre Re
Energy	Turn-around	Re
Bunch Length	Decelerator	Re
Phase Stability	Turn-around	0.1
Position	Main Linac	Pre Re
Emittance / Size	BDS	Re
Energy Spread	BDS	ΔE
Bunch Length	Bunch Compressor	Re

Table 1: Lis



Instrument	Drive Beam injector		Drive Beam tunnel		**Drive Beam total**	
	500GeV	3TeV	500GeV	3TeV	**500GeV**	**3TeV**
Intensity	14	28	48	288	**62**	**316**
Position	445	890	7392	44352	**7837**	**45242**
Beam Size	13	26	146	876	**159**	**902**
Energy	12	24	32	192	**44**	**216**
Energy Spread	12	24	3	3	**15**	**27**
Bunch Length	10	20	32	192	**42**	**212**
Beam Loss /Halo	0	0	0	0	**0**	**0**
Beam Phase			16	96	**16**	**96**
Total	**506**	**1012**	**7669**	**45999**	**8175**	**47011**

Table 2: Number of Beam Instrument for the Drive Beams

Instrument	Main Beam injector	Main Beam tunnel		**Main Beam total**	
		500GeV	3TeV	**500GeV**	**3TeV**
Intensity	225	36	86	**261**	**311**
Position	1539	1860	6040	**3399**	**7579**
Beam Size	59	52	112	**111**	**171**
Energy	19	16	56	**35**	**75**
Energy Spread	19	4	4	**23**	**23**
Bunch Length	20	6	6	**26**	**26**
Beam Loss /Halo	4	0	0	**4**	**4**
Beam Polarization	19	4	4	**23**	**23**
Tune	8	0	0	**8**	**8**
Beam Phase		2	2	**2**	**2**
Luminosity		4	4	**4**	**4**
Total	**1912**	**1984**	**6314**	**3896**	**8226**
Wakefield monitor		23802	142812	**23802**	**142812**
Total with wake monitors	**3824**	**27770**	**155440**	**31594**	**159264**

Table 3: Number of Beam Instrument for the Main Beams

CLIC parameters:
T. Lefevre et.al.

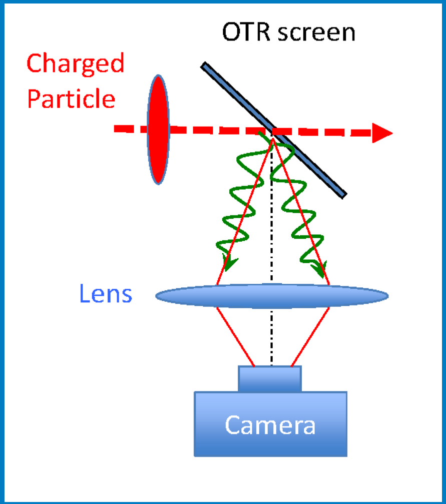
Ref. 1

All these systems are research devices themselves!

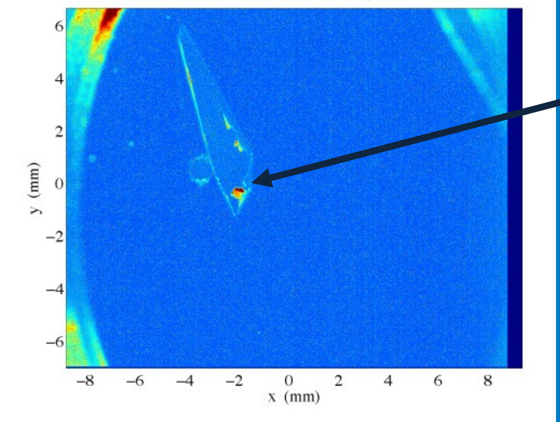
Beam profile monitors – emittance measurements

- Need to monitor beam size/emittance throughout machine to maintain luminosity.

- Standard options – wire scanners or optical transition radiation (OTR) screens.



- Wire scanners – simple, cheap, resolution > few µm, easily damaged in high charge beams, invasive.
- OTR – relatively simple, destructive, resolution (although being addressed), damage to screen, radiation damage to optics/camera.

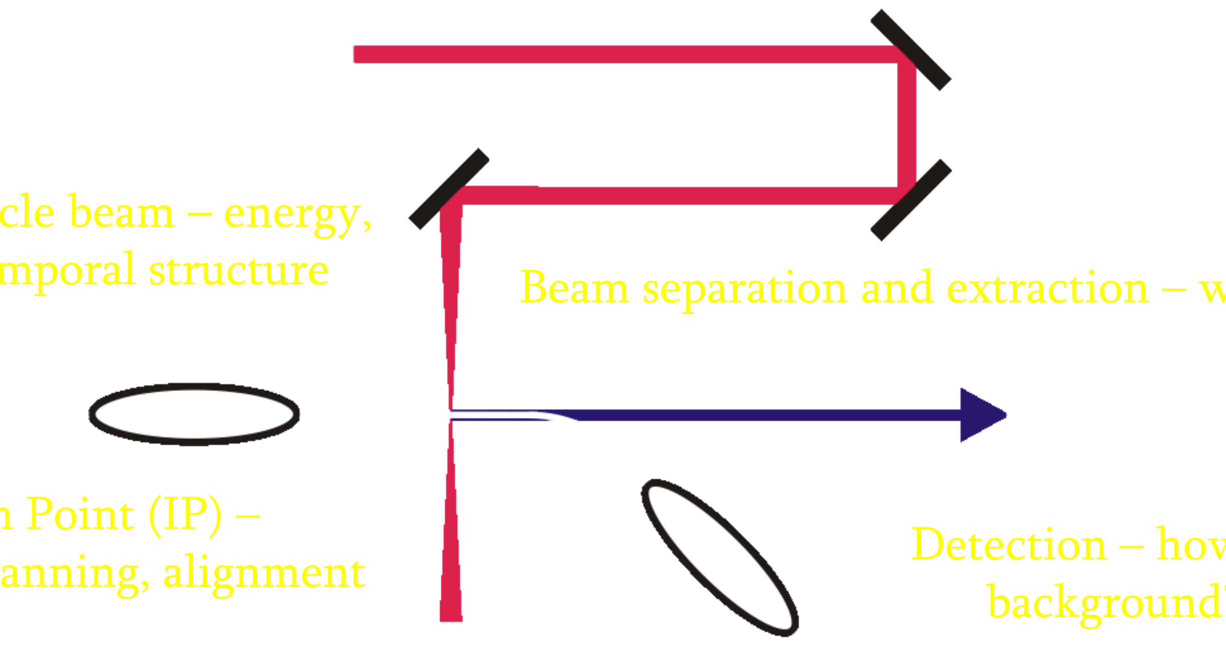


FACET OTR screen bunch damage

ATF2 OTR screen Laser damage

Ref. 11

Laser-wire principle



Laser system – choice of parameters

Beam transport –
how far? how many stations?

Particle beam – energy,
temporal structure

Beam separation and extraction – where?

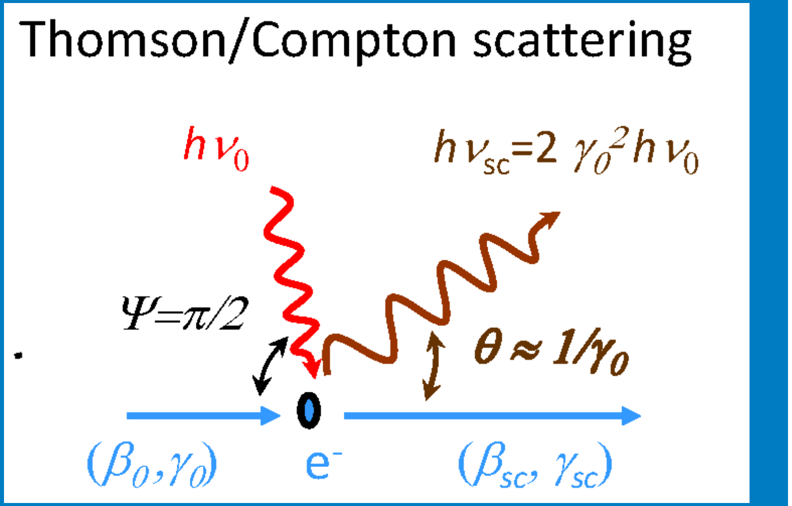
Interaction Point (IP) –
focusing and scanning, alignment

Detection – how? where?
background? S/N?

Post – IP – diagnostics,
energy, beam dumping

(inverse) Compton scattering

- Inelastic scattering of photon and electron – photon upshifted and scattered.
- Scattering angle – predominantly in 1/γ cone .
- For relativistic e⁻ photon scattered close to beam.



$$\frac{\sigma_C}{\sigma_T}=\frac{3}{4}\left\{\frac{1+\epsilon_1}{\epsilon_1^3}\left[\frac{2\epsilon_1(1+\epsilon_1)}{1+2\epsilon_1}-\ln(1+2\epsilon_1)\right]+\frac{1}{2\epsilon_1}\ln(1+2\epsilon_1)-\frac{1+3\epsilon_1}{(1+2\epsilon_1)^2}\right\}$$

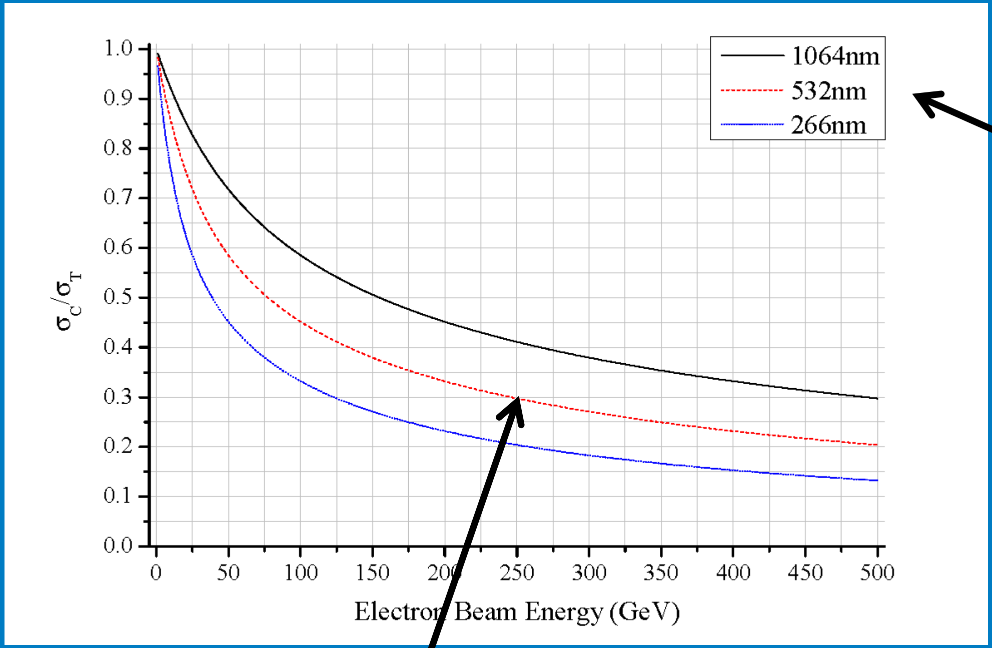
$$\sigma_T=\frac{8\pi}{3}\left(\frac{q^2}{4\pi\epsilon_0 mc^2}\right)^2$$

$$\epsilon_1\equiv\gamma h\nu_0/m_e c^2$$

•Cross section σ_C related to low energy elastic Thomson scattering cross section σ_T.

Ref. 2

Compton scattering cross section



What does this equation look like?

3 typical laser wavelengths

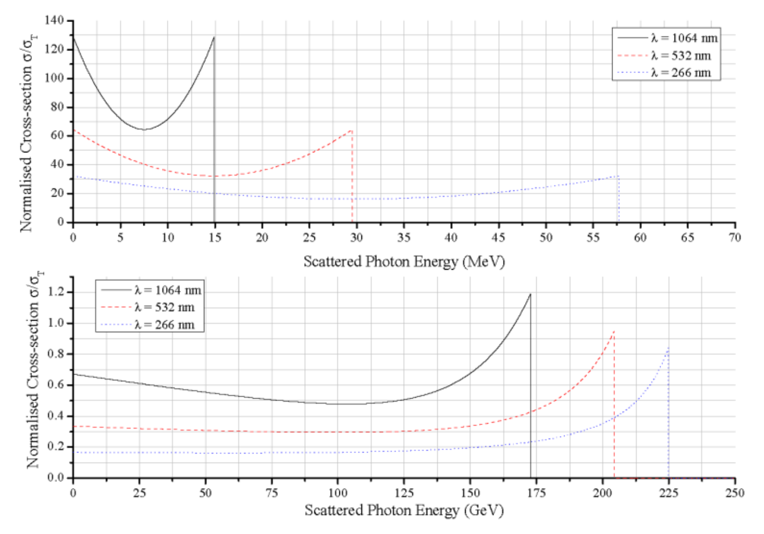
Cross section drops off with beam energy.

Need more photons (power) for same signal at higher energy.

For ILC (e^- 250GeV) σ_C for 532nm only 30% $\sigma_T \sim 0.3 \times 0.66 \times 10^{-24}$ cm^{-2} – pretty small.

Big impact on laser requirements!

Scattered photon signal



Photon energy for 1.3GeV e^- (ATF2)
Detect scattered photons

Photon energy for 250GeV e^- (ILC)
Detect electrons?

No. scattered photons given by:
constant laser power

$$\langle N_\gamma \rangle = N_e \frac{P_L \lambda}{hc} \sigma_C \int\int\int_{-\infty}^{+\infty} \rho_e(x,y,z)\rho_L(x,y,z)\; dx\; dy\; dz$$

For Gaussian beams this reduces to:

$$\langle N_\gamma \rangle = N_e \frac{P_L \lambda}{hc} \sigma_C \frac{1}{\sqrt{2\pi}\sigma_s} exp\left(-\frac{\delta y^2}{2\sigma_s^2}\right)$$

$$\sigma_s = \sqrt{(\sigma_L^2 + \sigma_e^2)}$$

$$\delta y = y_L - y_e$$

Want lots of photons and small beam sizes

Ref. 2

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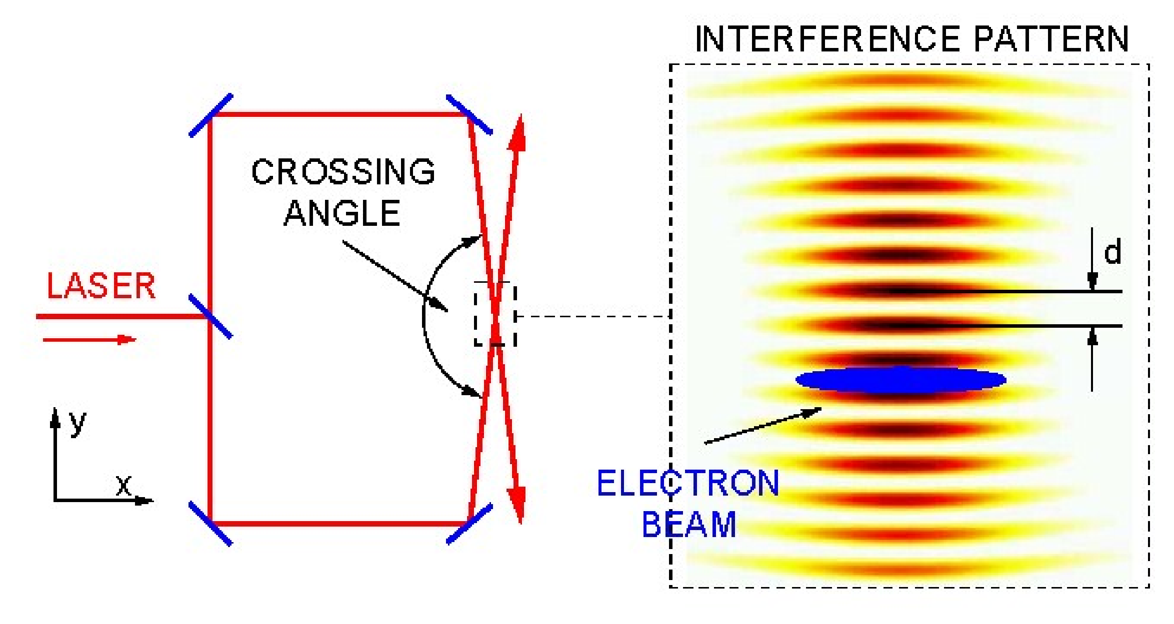
Measuring really small beams – interference fringe monitor



For < 1μm beams need something different – scan interference fringes across beam and look for modulation in Compton signal.
This monitor is *really* hard to align and make work well………

Ref. 6

Laser-wire experiments

- Stanford Linear Collider – beam scanned across laser spot
  reflective focusing optics
  no astigmatism (laser beam stationary)
  350nm THG Nd:YLF, 1mJ, 10MW, prototype (ref. 4).

- KEK ATF2 damping ring – cw (quasicontinuous DR bunches)
  cavity (enhance power)
  cavity on moveable table scanned through beam
  vertical design e^- beam size $\sigma = 8.8\mu m$
  laser waist (determined by cavity) $w_o = 14.8\mu m$,
  532nm, 25mW input to cavity, stored power 1 – 3W
  measured e^- beam size $\sigma = 9.8 \pm 1.5\mu m$
  low signal counts, S/N ratio (ref. 14).

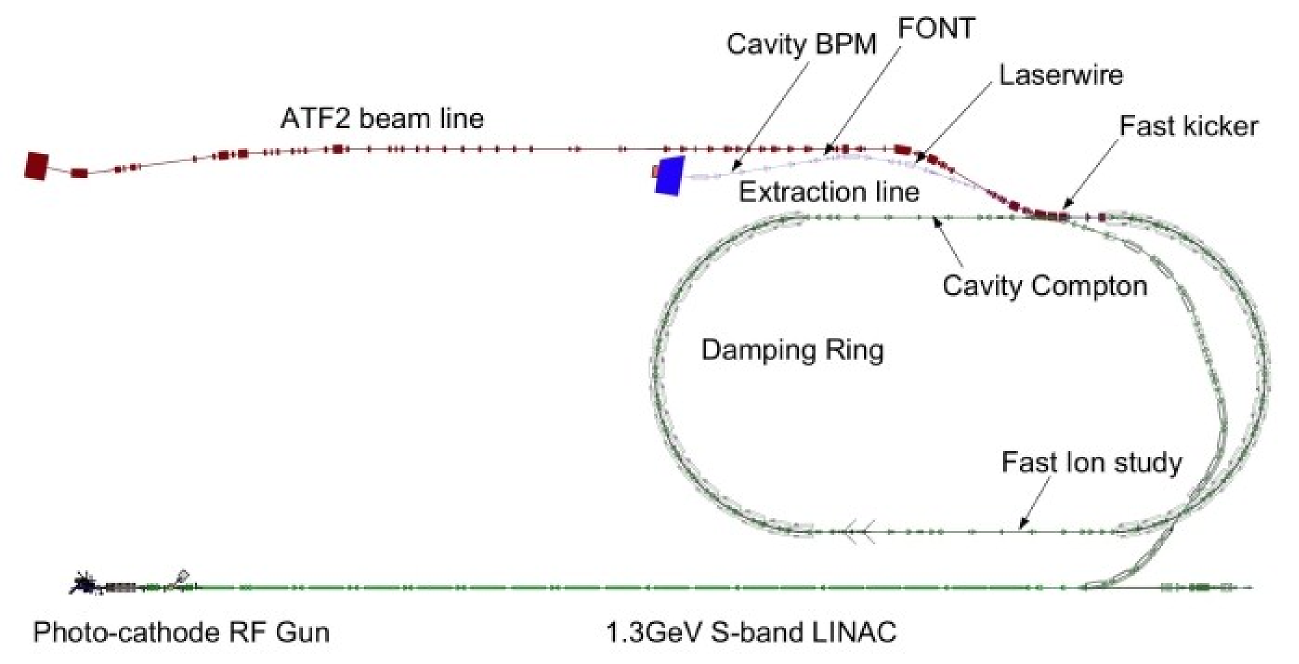
- Oakridge SNS – H^- ion laser-wire, measure e^-, ion bunch 50ps
  Nd:YAG, 1064nm, 30 Hz, 7ns
  active stabilisation of beam transport (> 200m),
  2D scans over beam - translate final turning mirror
  9 stations, 1 laser, beam sizes $\sigma \sim 2 - 3mm$ (ref. 13).

JAI laser-wire experiments – PETRA and ATF2

- PETRA – emphasis on usable system, 2D scanning (not simultaneous)
  6 GeV e^+, 130kHz, 40ps
  laser focus scanned by piezo mirrors, 2.5mrad, 1.25mm (V), 3.75mm (H)
  designed for larger beam sizes, runs remotely
  Q switched 6ns Nd:YAG, 532nm, 20Hz
  (upgrade: mode locked oscillator/amplifier, 200ps, 130kHz)
  knife edge scan to measure laser spot size $w_o = 9\mu m$
  convoluted beam sizes $\sigma = 30\mu m$ (V), $294\mu m$ (H), scans from $10\mu m$ to 10mm
  automated beam finding and scanning (ref. 12).

ATF2 – case study (ref. 8)

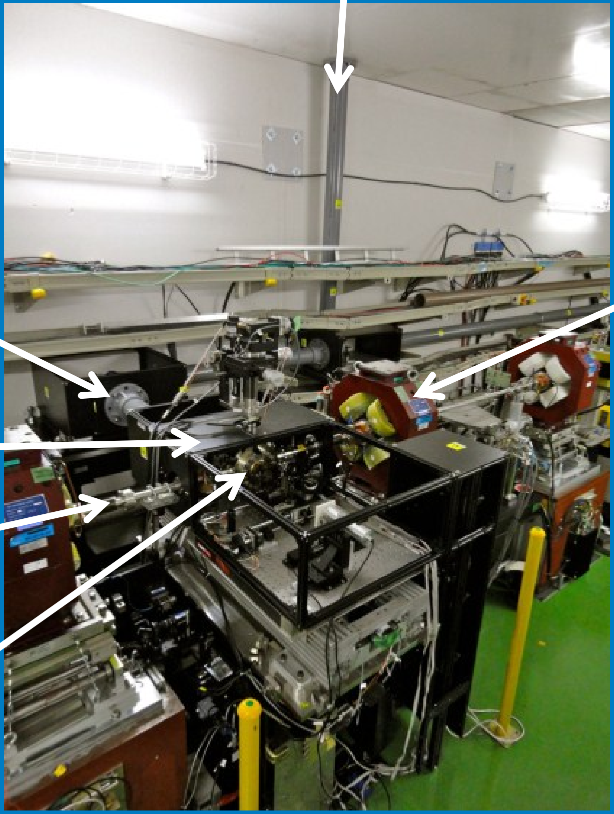
ATF2 laser-wire



- ATF2 major international collaboration – scaled test of ILC optics.
- Aim – electron beam size < 40nm.
- Major test of new diagnostics – high resolution (< 5nm) bpms, fast feedback etc.
- Laser-wire designed for highest resolution – measurement ~ 1μm.

Laser-wire specifications

- Laser-wire IP on extraction line of ATF2 .
- 1D vertical scanning system.
- Joint set up with OTR high resolution experiment.
- Beam energy 1.3 GeV.
- Pulse duration σ = 30ps.
- Single bunch, single train, 1.56Hz.
- Can run multibunch – spacing ~ 154ns.
- Vertical beam size at IP 1 – 10μm.



Beam from laser hut

Quadrupole magnet

Beam delivery to final focus

Vacuum chamber

Electron beam line

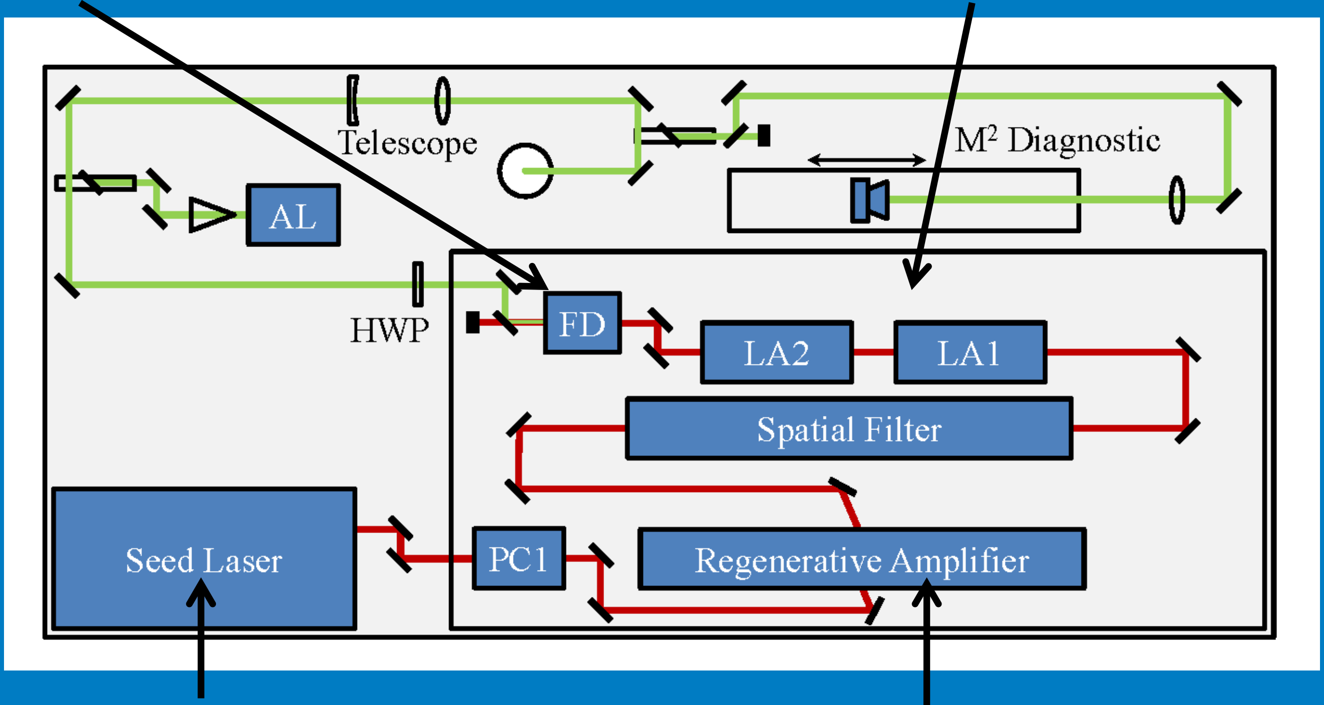
Laser exit window

Ref. 8

ATF2 laser system

SHG – 532nm, 100mJ

Linear amps up to 500mJ



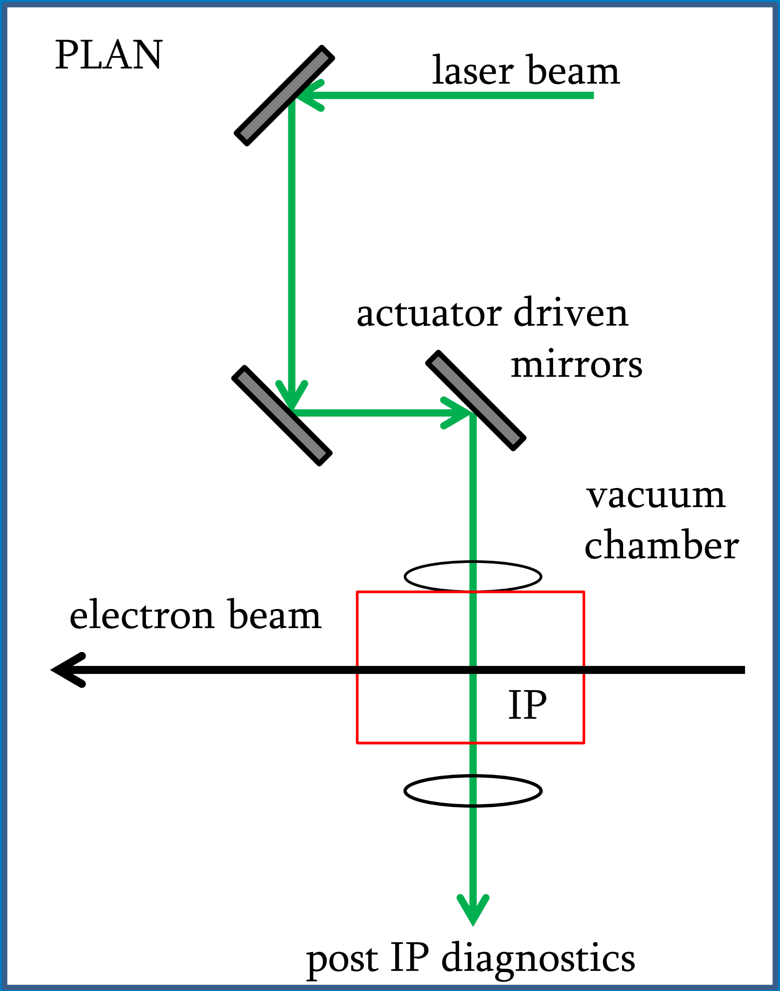
Seed laser @ 357MHz locked to sub-multiple of accelerator frequency

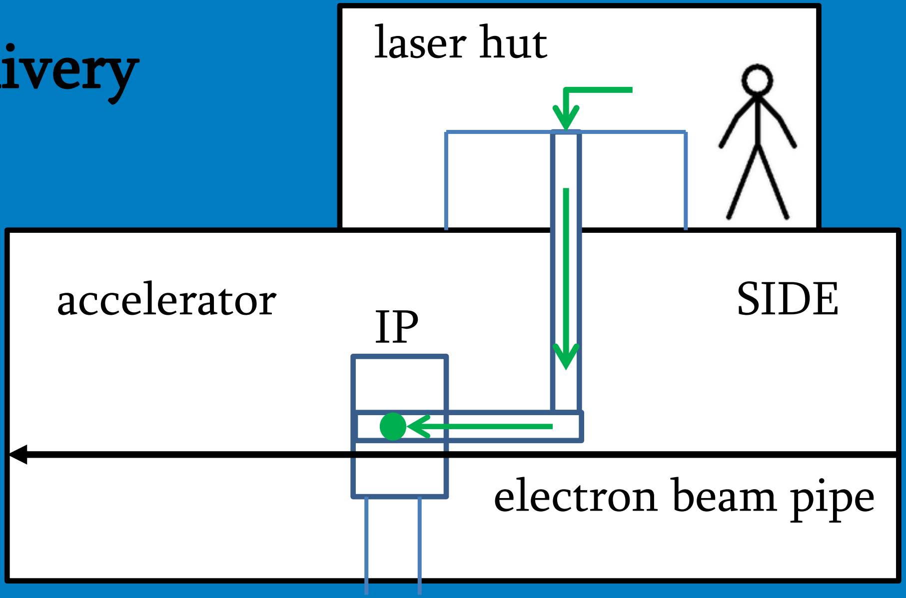
Seed pulse injected into Nd:YAG flashlamp pumped regenerative amplifier – 1.56Hz, 200ps, 10mJ

Issues – beam quality, pulse duration, reliability

Ref. 2

Beam delivery





IP ~ 17m from laser hut, on top of accelerator.

Beam transported down to accelerator level.

Multiple reflections – lossy.

Plan to automate alignment – cameras behind mirrors, steer with actuators on mirror axes.

Optics all fused silica – radiation hard.

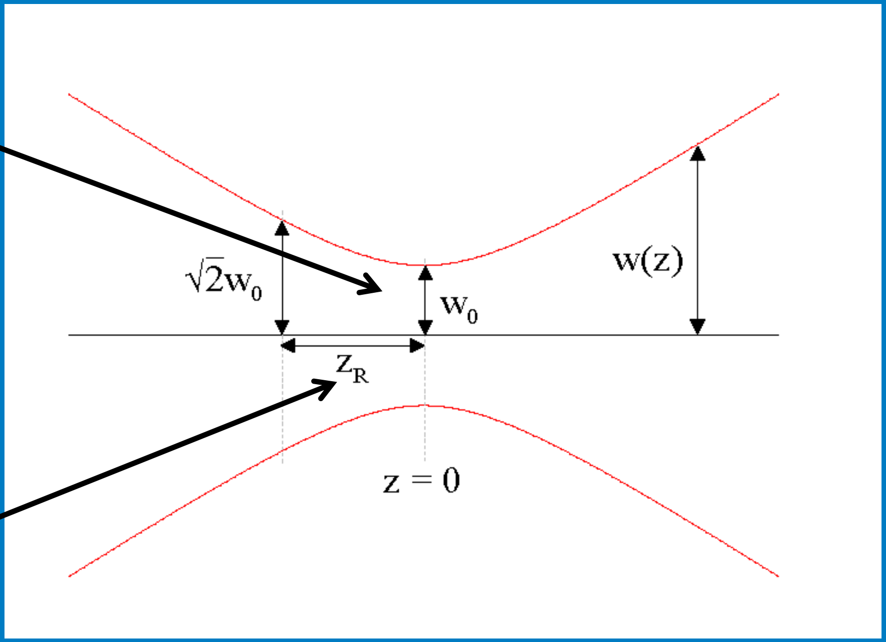
Perfect Gaussian beam focusing

Spot size w_o

$$w_o = \frac{\lambda f}{\pi w_{in}}$$

$$z_R = \frac{\pi w_o^2}{\lambda}$$

Rayleigh range z_R



Spot size (resolution) limited to ~ λ ('diffraction limited')

Want:

- short λ
- short f
- large w_{in}

High f/# optics – hard to achieve.

But small spots diffract more quickly – smaller z_R.

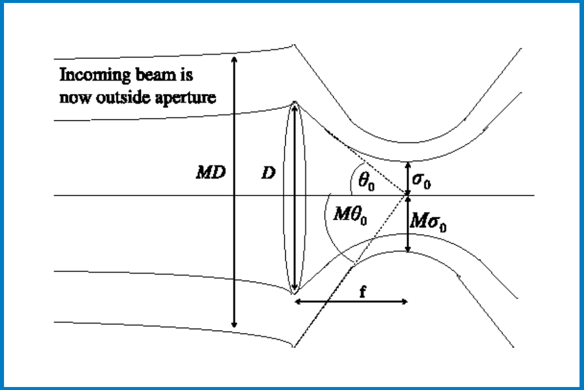
Caution! $w = 2\sigma$ for Gaussian beams – endless possibilities for confusion……

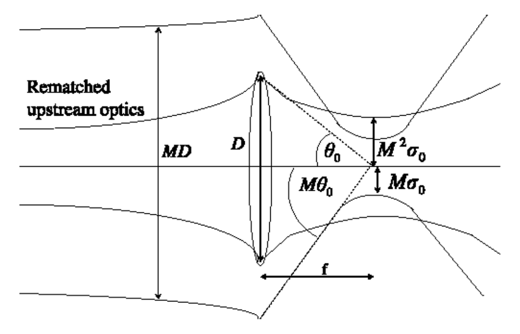
Not quite that simple………

No laser beam perfect – can be quantified by beam quality factor ‘M^2’.
$M^2 = 1$ – perfect Gaussian beam.

New beam size $W = Mw$ – need to consider effect on lens aperture.
If aperture D fixed have to reduce w by factor M to fit ($D > \pi w$) so at final focus:

$$W_o = \frac{M^2 \lambda f}{\pi W_{in}}$$

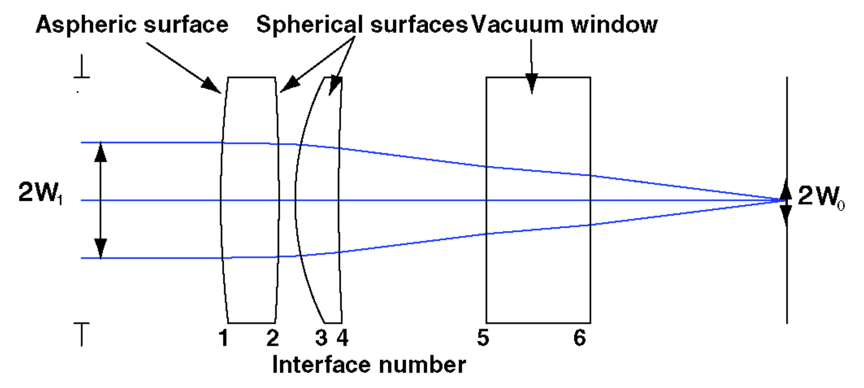


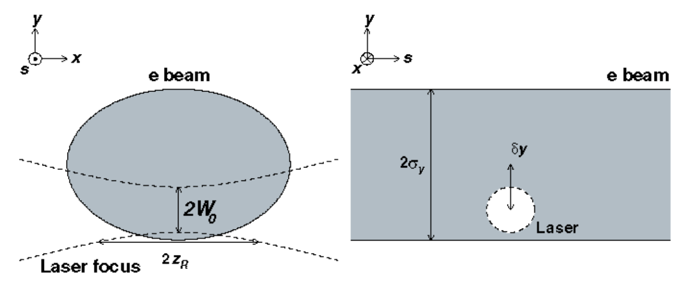


Large diameter, short f, corrected lenses very expensive! Want $M^2 \sim 1$.

ATF2 Focusing

- Special lens designed – no spherical aberrations for smallest focus.
- Complex and expensive – only fused silica for radiation hardness.
- Bolted to vacuum chamber – whole lens + chamber system scanned vertically over electron beam.

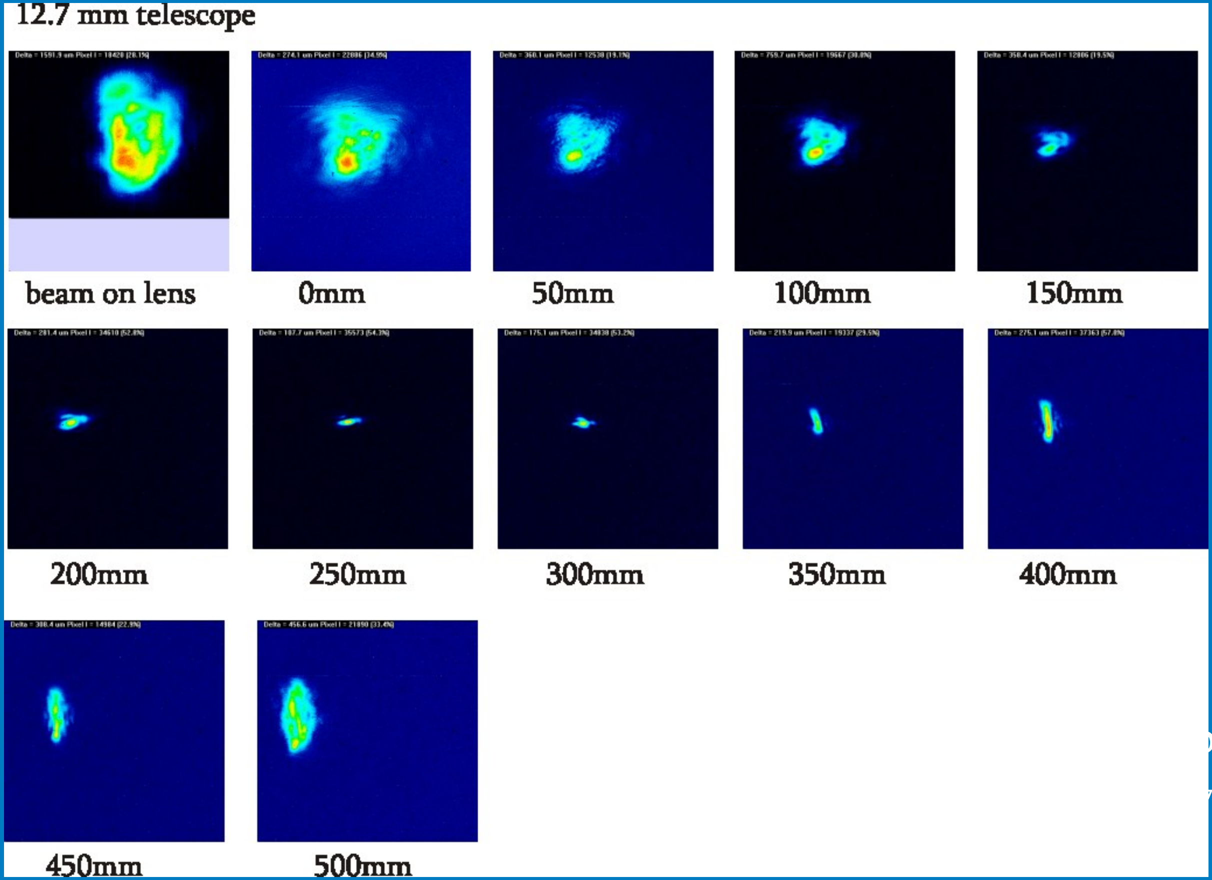




Refs. 2, 8

Laser propagation through focus

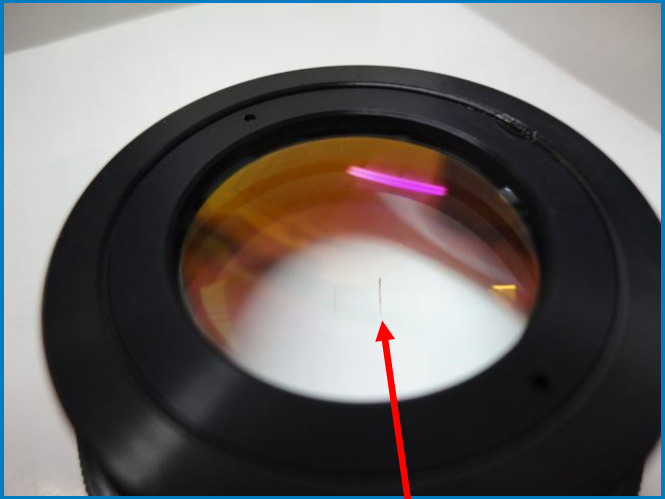
Can’t measure beam at focus – too small. Can do similar measurement with longer lens to study laser propagation through focus. Not ideal…………..



rofile
tically

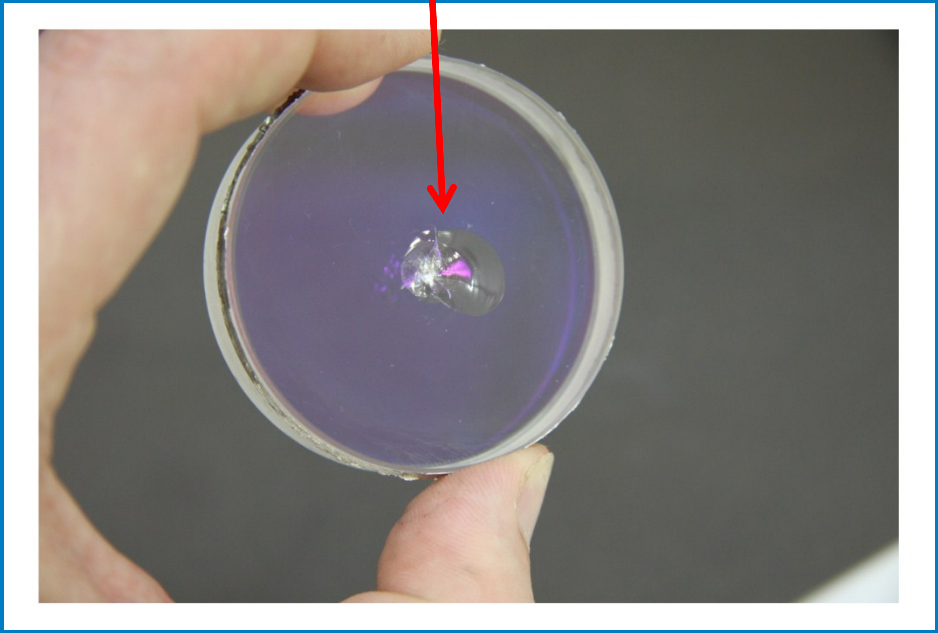
Focusing problems

Odd laser propagation makes it difficult to correctly predict beam size and intensity in beam transport and focusing – damage to lens and vacuum window despite careful design and high performance AR coatings.

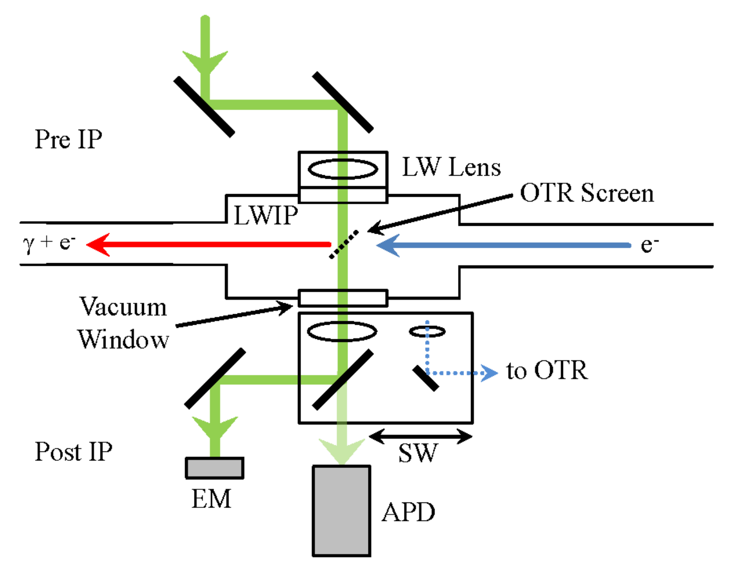


Back reflection through IP focus
on lens – small damage spot

Large damage spot on vacuum window



Interaction point and overlap



Need to overlap laser/electrons beams in space and time (~ 10µm, 30ps).

Use signals from OTR near to electron beam and obscuring laser beam to achieve this.

Spatial: repeatable unless laser alignment changes.
Temporal: every shift.

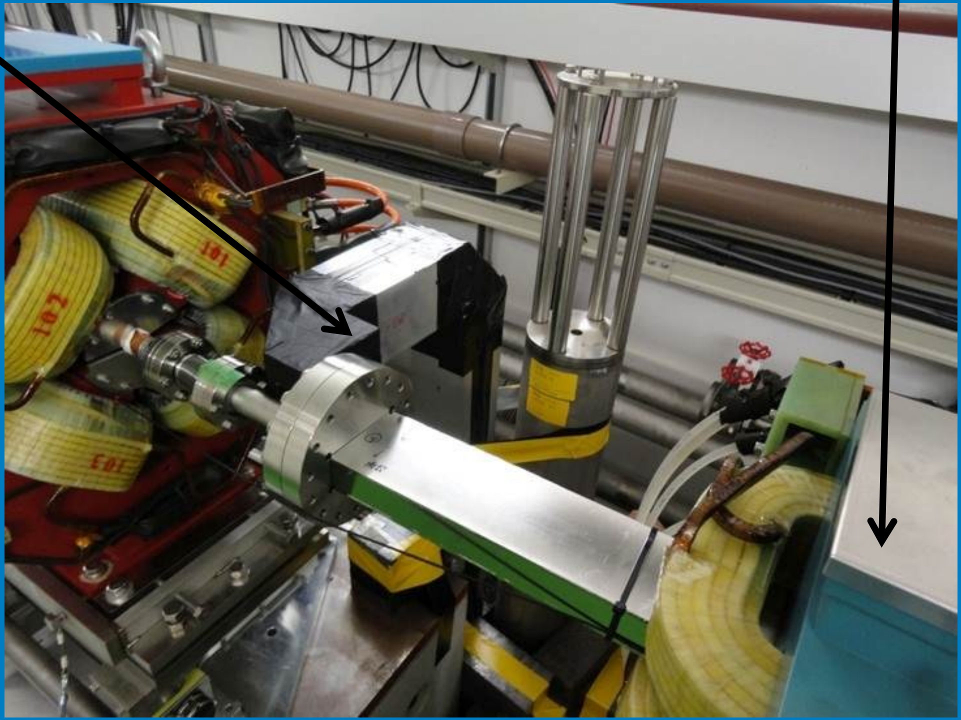
Hard – need to consider how this will be done as part of diagnostic design – automated?

Ref. 2

Detection

Photons extracted through 1mm Al window
Detector placed next to window

Dipole magnet separates
electrons and photons

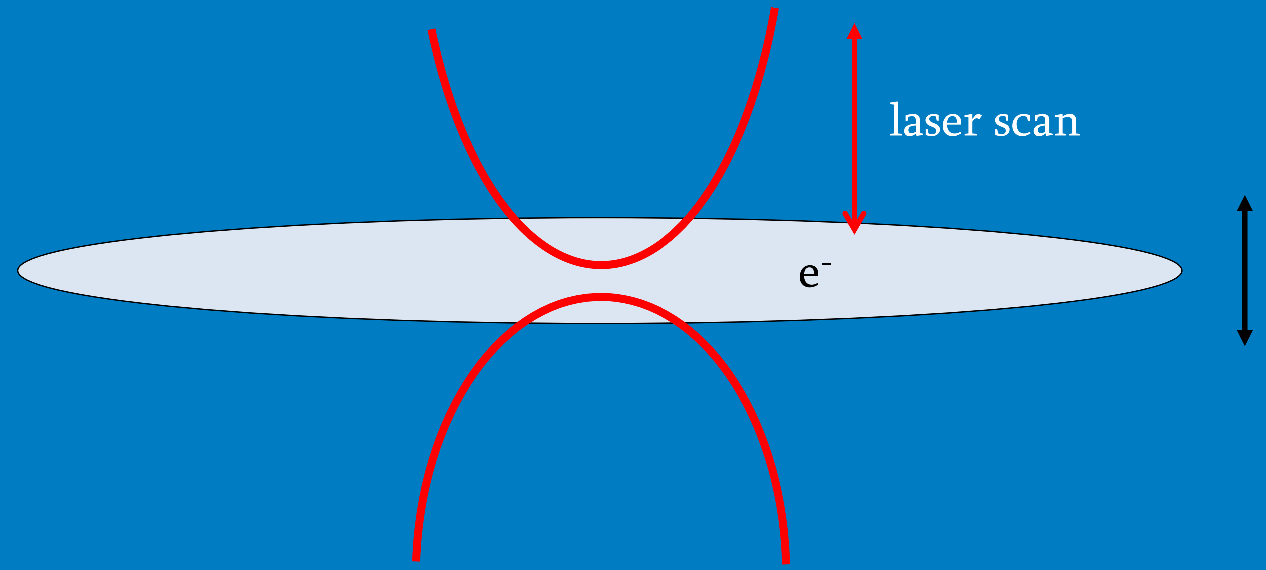


Cherenkov detector – γ converted to e^-/e^+ pairs in lead, generate Cherenkov radiation in aerogel, guided to PMT below beam line.

Results and analysis

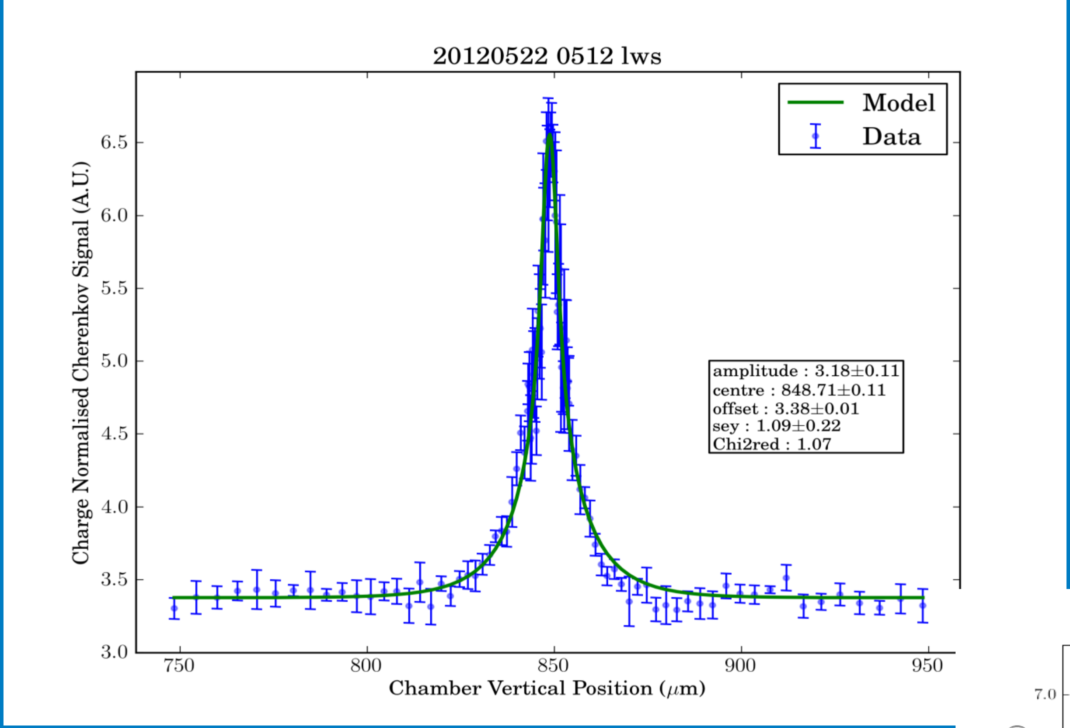
Electron beam aspect ratio very large – cannot assume laser same size across particle beam.

Try to model laser propagation and solve full overlap integral for particle and laser beam distributions – complex analysis because of electron beam size and laser properties – not just simple adding of beam sizes in quadrature.



~ few 100 μm

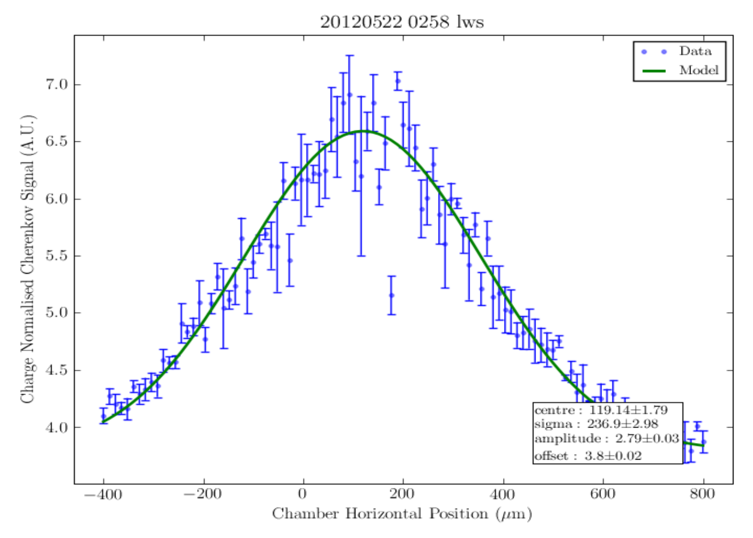
Preliminary scans and analysis



Vertical scan – $\sigma_{ey} = 1.09 \pm 0.22\ \mu m$

Demonstrated 1μm beam size measurement – scan ~ 2 min.

Horizontal scan –
$\sigma_{ex} = 236.9 \pm 2.98 \mu m$

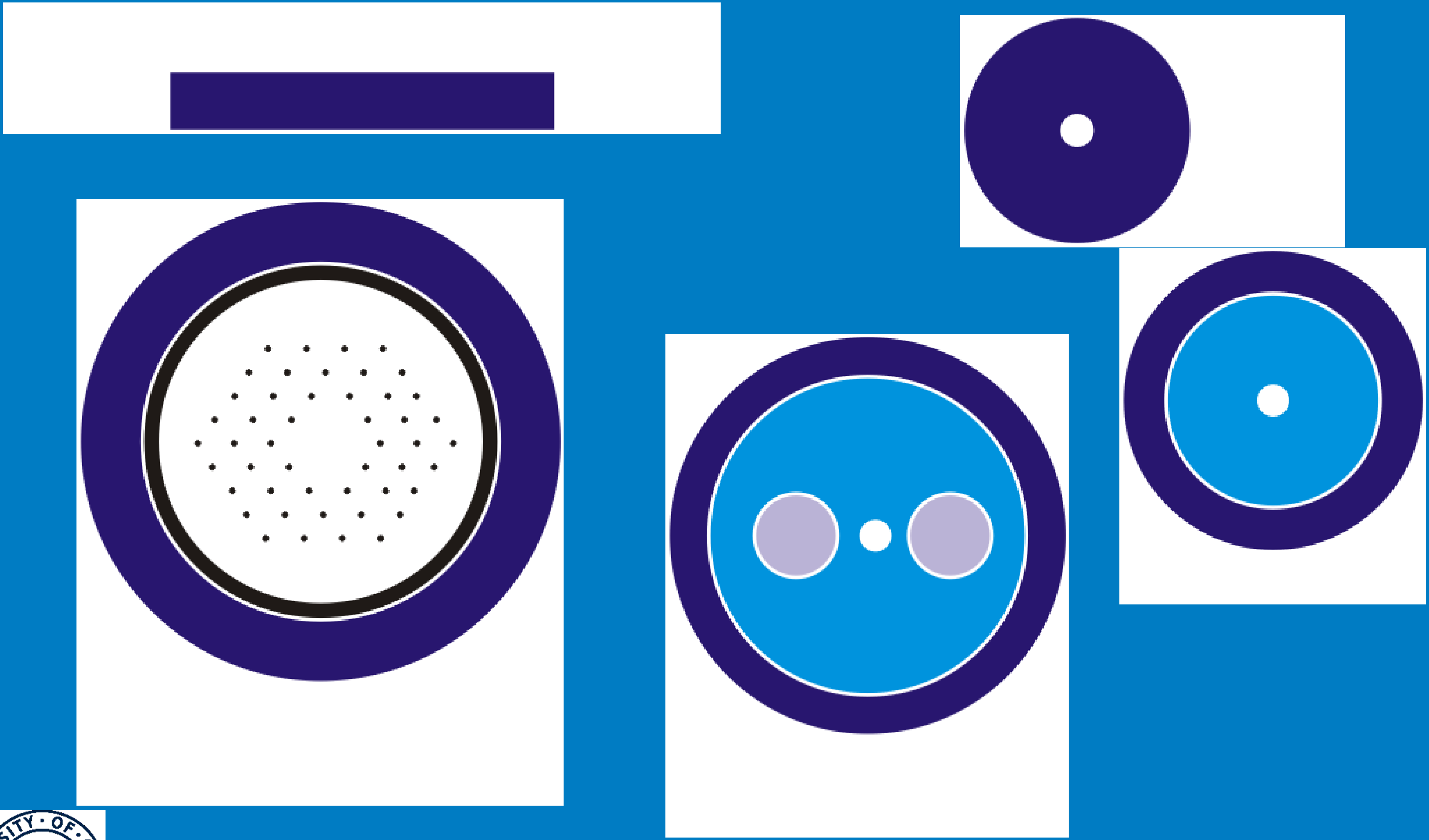


Data: L. Nevay, A. Aryshev, L. Corner

Improvements to ATF2 laser-wire

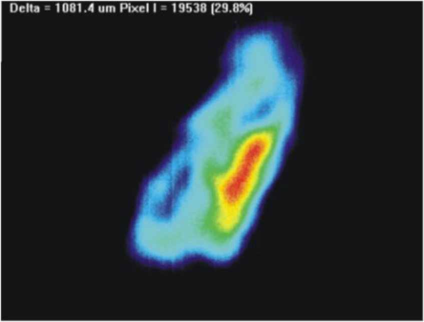
- Laser – new fibre laser system: higher rep rate (intra train scanning), excellent beam quality, efficient, stable.
- Subtraction of beam jitter – bpm data.
- Real time analysis and fitting of data.
- Automated laser propagation measurement and laser energy normalisation.
- Easy operation for non-specialist in control room.
- Reduction of background, improving S/N.
- Tests on larger/smaller electron beam sizes.

Fibre laser and amplifiers

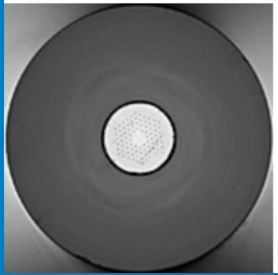


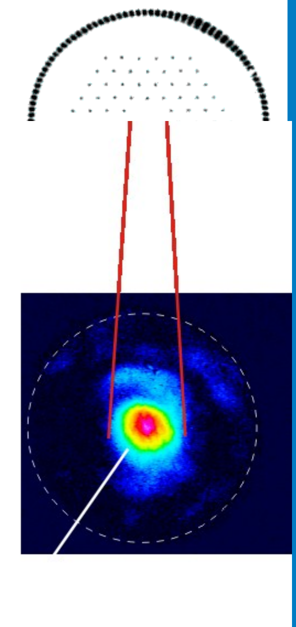
Fibre laser development

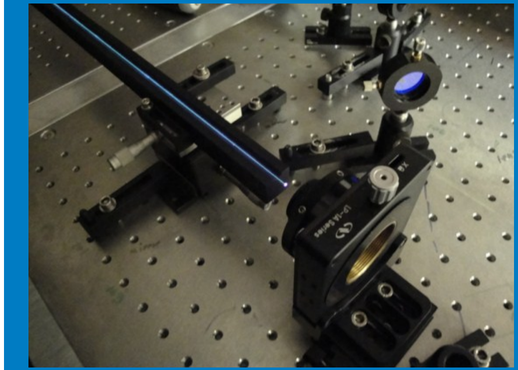
- Laser at KEK not completely suitable for laser-wire.
- Poor spatial quality – larger focus, worse resolution.
- Temporal profile (200ps) not well matched to electron bunch (30ps)
- Inefficient (flashlamp pumped), limited in repetition rate.



Project in Oxford to develop new fibre laser system for laser-wire.



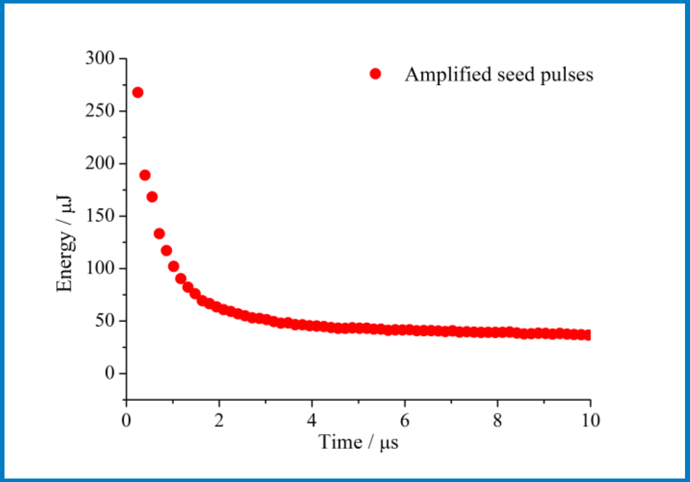




Fibres: efficient, waveguides, excellent spatial mode quality, high repetition rate, diode pumped, no active cooling.

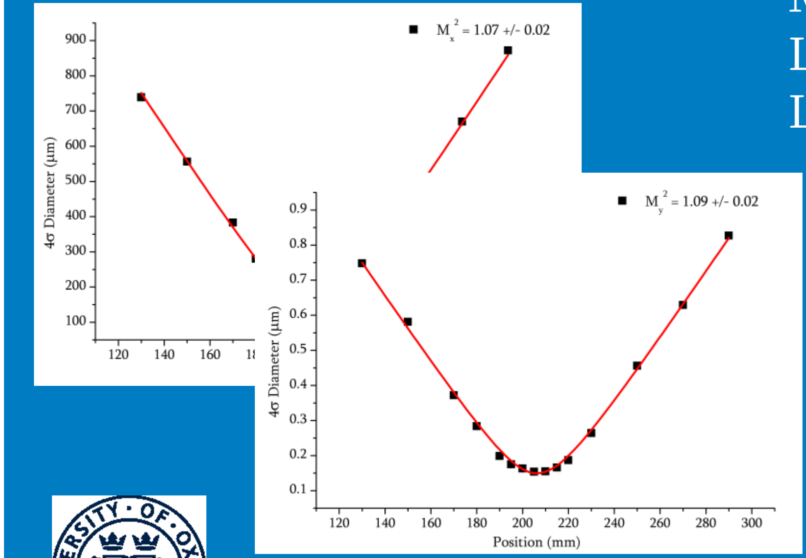
Standard SM fibre amplifiers – low energy. Solution – very large mode area photonic crystal fibre – still single mode, energy 100uJs/pulse.

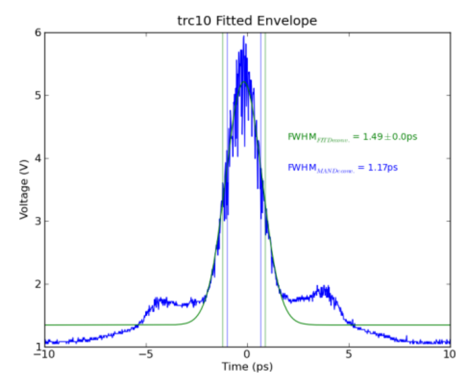
Fibre laser results

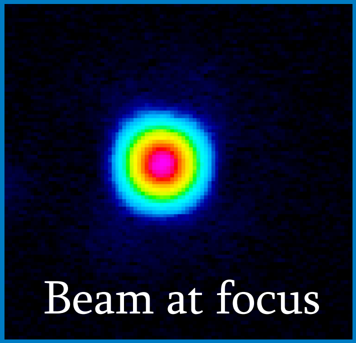


Aim – better laser source for laser-wire, smaller laser spot, multibunch scanning.
Spec – 100µJ @ 6.49MHz in ir, $M^2 < 1.1$, 1 – 10ps, $\Delta\lambda <$ 1nm in green.
Expt – amplify commercial fibre laser in photonic crystal fibre, burst mode.

Results – pulses amplified from 1.4µJ to 268µJ in 70cm of PCF (gain 32dB/m).
$M^2_x = 1.07 \pm 0.02$, $M^2_y = 1.09 \pm 0.02$.
Lower energy pulse in green $\Delta\lambda = 0.5$nm.
Lower energy pulse compressed to $\sigma < 1.5$ ps.





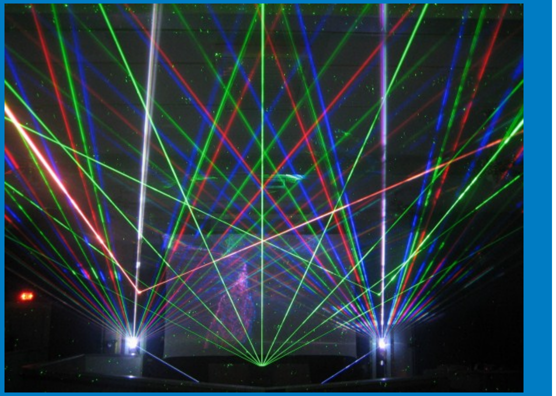

Beam at focus

Ref. 2

Laser-wire design considerations

- Particle beam – energy, size, duration, repetition rate.
    - Direct impact on laser choice: wavelength - spot size, cross section.
    - Power required – S/N, cross section, beam transport losses.
    - Repetition rate – intratrain scanning? Scanning speed.
    - Pulse duration – short for temporal profiling, too long wastes energy.
    - Focusing – more difficult for smaller spot size (higher resolution).
    - Detection – energy of scattered photons/electrons.
    - Accelerator design – position of laser-wires, separation of beams.

Choosing a laser – pick a nice colour?



- Laser properties – temporal, spectral, spatial
- Temporal – particle bunch length, repetition rate, scanning, CPA, bandwidth
- Spectral – wavelength, cross section, resolution, frequency conversion, availability, bandwidth.
- Spatial – resolution, focus size, focusing optics, mode quality, beam transport, damage

Total number of lasers – COST!

Summary

- New generation of accelerators require high performance diagnostics.
- Development of these diagnostics major science research projects.
- Laser-wires provide non-invasive, high resolution beam size/emittance measurement.
- Demonstrated in number of facilities world wide:
  - Electron/positron/H- machines.
  - Multiple stations, 2D scanning, moving beam or laser.
  - Usable in standard machine running.
  - High resolution (<1 μm).
- Improvements needed in laser technology, data analysis, cost.
- Need to be integrated in new accelerator designs.
- Plenty of research still to do!

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