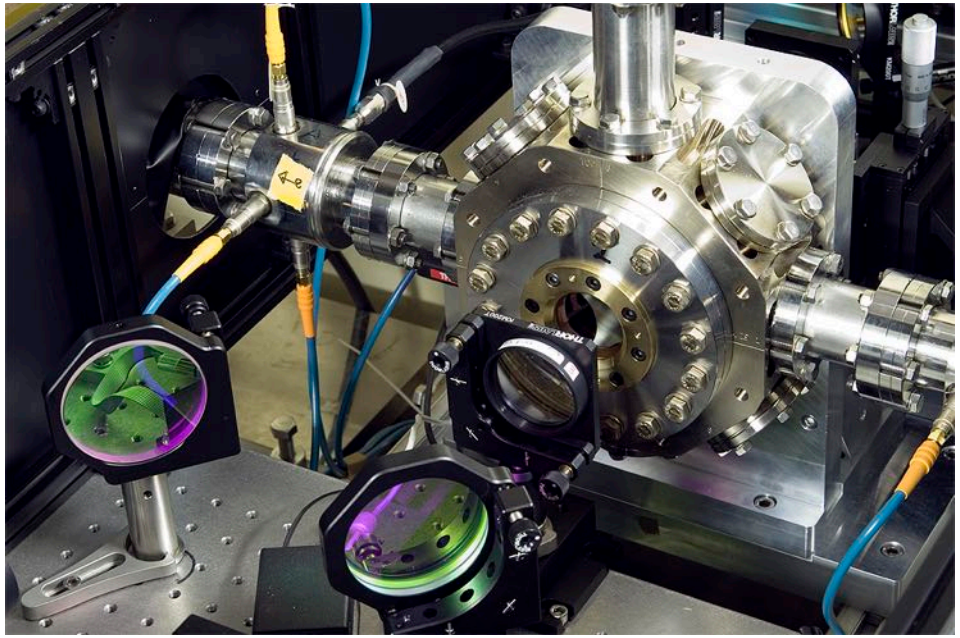
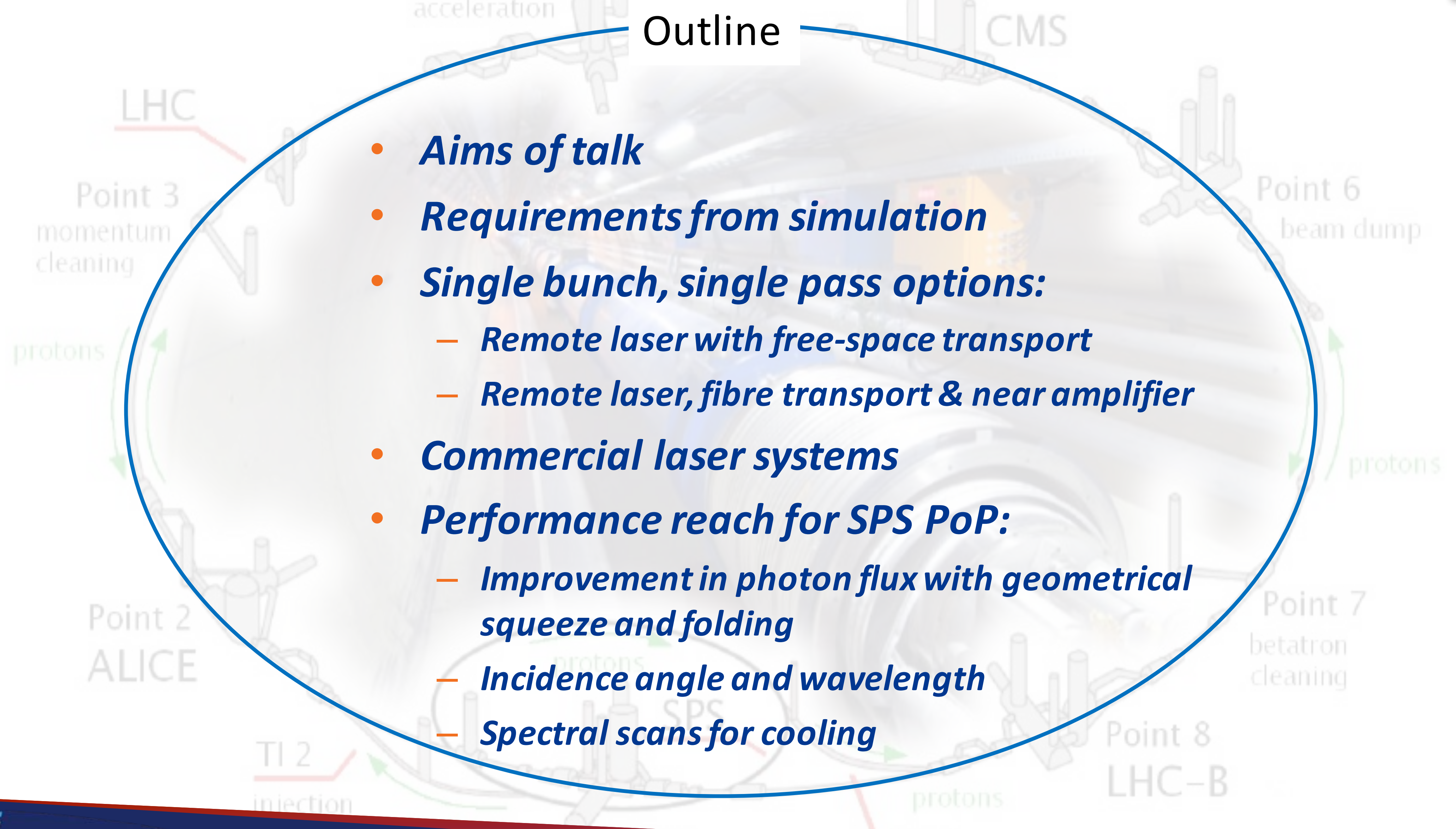
Laser system for single bunch, "photon production" option



Gamma Factory Meeting:
PoP Experiment
28 March 2019

Stephen Gibson, Siobhan Alden, Laurie Nevay
John Adams Institute for Accelerator Science
Royal Holloway, University of London, UK

Overview



Outline

- ***Aims of talk***
- ***Requirements from simulation***
- ***Single bunch, single pass options:***
  - ***Remote laser with free-space transport***
  - ***Remote laser, fibre transport & near amplifier***
- ***Commercial laser systems***
- ***Performance reach for SPS PoP:***
  - ***Improvement in photon flux with geometrical squeeze and folding***
  - ***Incidence angle and wavelength***
  - ***Spectral scans for cooling***

Aims of this talk

From Brennan's slides:

Main objectives

- Verify of simulations on rate of atomic excitation
- Demonstrate matching of characteristics of ion bunches to those of the laser bunches, match laser spectrum to width of the atomic excitation and achieve resonance for adequate fraction of ion population
- Measure of emitted X-rays, characterisation of flux and spectrum, and demonstration of photon extraction from the collision zone
- Demonstrate integration and operation of laser and Fabry-Perot cavity in a hadron storage ring

Ambition/complexity/cost cut-off

- Demonstrate laser cooling of relativistic beams and investigation of the different approaches
- Demonstrate feasibility of relativistic Atomic Physics measurements.

Aims of this talk

From Brennan's slides:

Single-pass or optical resonator option?

- An important concept to demonstrate is the FP cavity, since this is essential for an LHC application
- Highly desirable in the SPS PoP: **consider as baseline** since many aspects are contingent on this
- Adds extra complexity and potential R2E aspects for laser and cavity electronics
- Fallback solution of single pass to at least evaluate for performance and cost

Aims of this talk

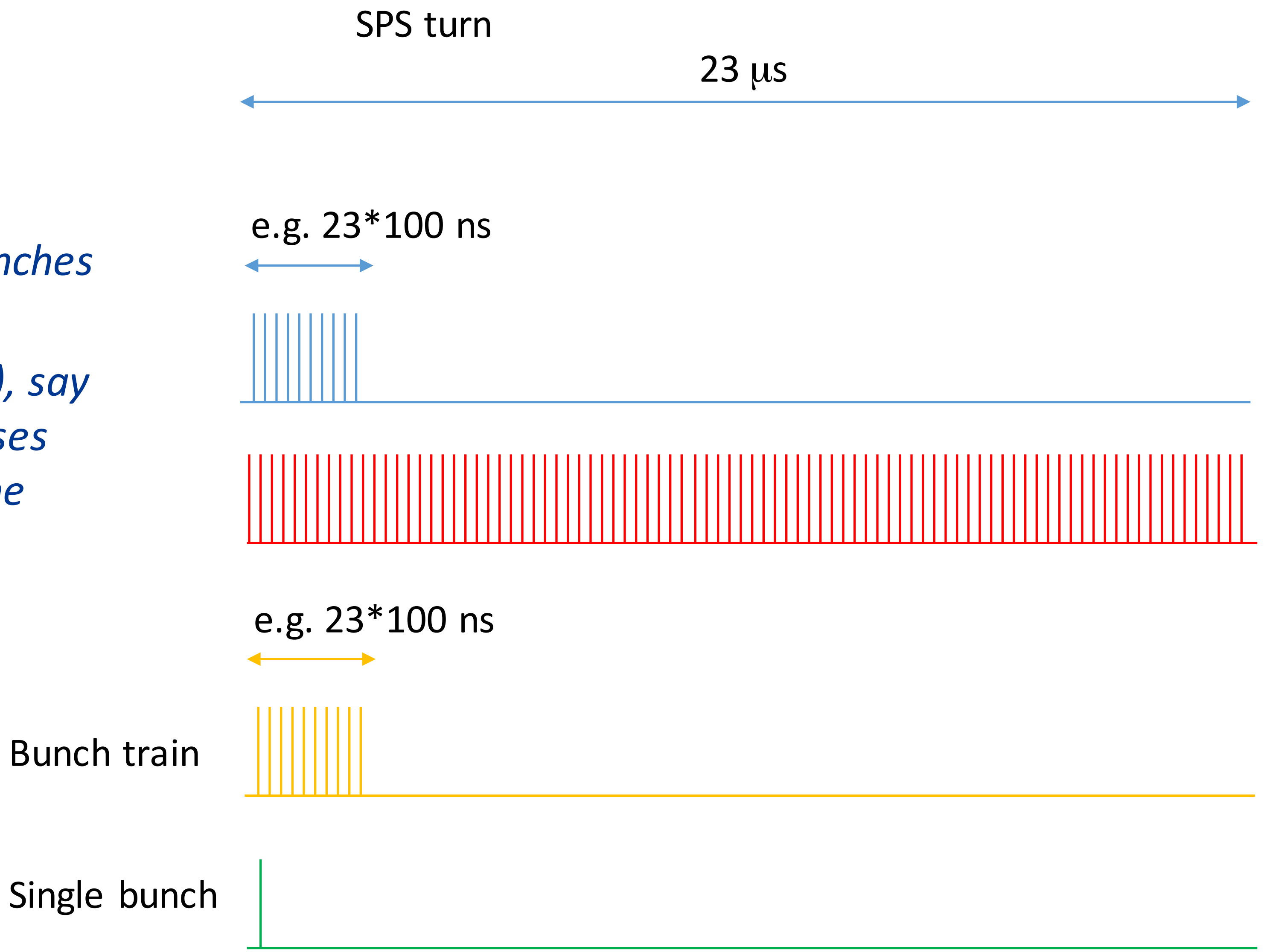
Laser design for SPS Proof of principle experiment:

- ***Baseline design*** is a pulsed 1030nm laser that is remote controlled and tolerant to SPS radiation levels so can be installed underground, with free-space transport to a Fabry Perot (FP) cavity [optical resonator] to amplify the pulse energy by a factor >5000 at interaction point, and a repetition rate matched to every bunch in the train: 40 (20) MHz.
- -> see talk by Kevin Cassou.

- This talk: asked to consider a "***fall back solution*** for a single pass laser in case the radiation issues for the laser + FP in the tunnel prove insurmountable."
- Aim to hit the same single bunch on each 23 μs turn:
  - SPS revolution frequency 43 kHz == repetition rate of laser.
  - Would like same laser pulse energy at IP, with much lower average energy.

SPS bunch timing

- *SPS bunch structure for Pb ions:*
  - *Krakow meeting: “up to 30 ion bunches in SPS”…*
  - *At SPS f_{rev} = 43 kHz (23μs per turn), say 24 bunches at 100ns the laser pulses need only be present for 10% of the turn?*



SPS turn

23 μs

e.g. 23*100 ns

e.g. 23*100 ns

Bunch train

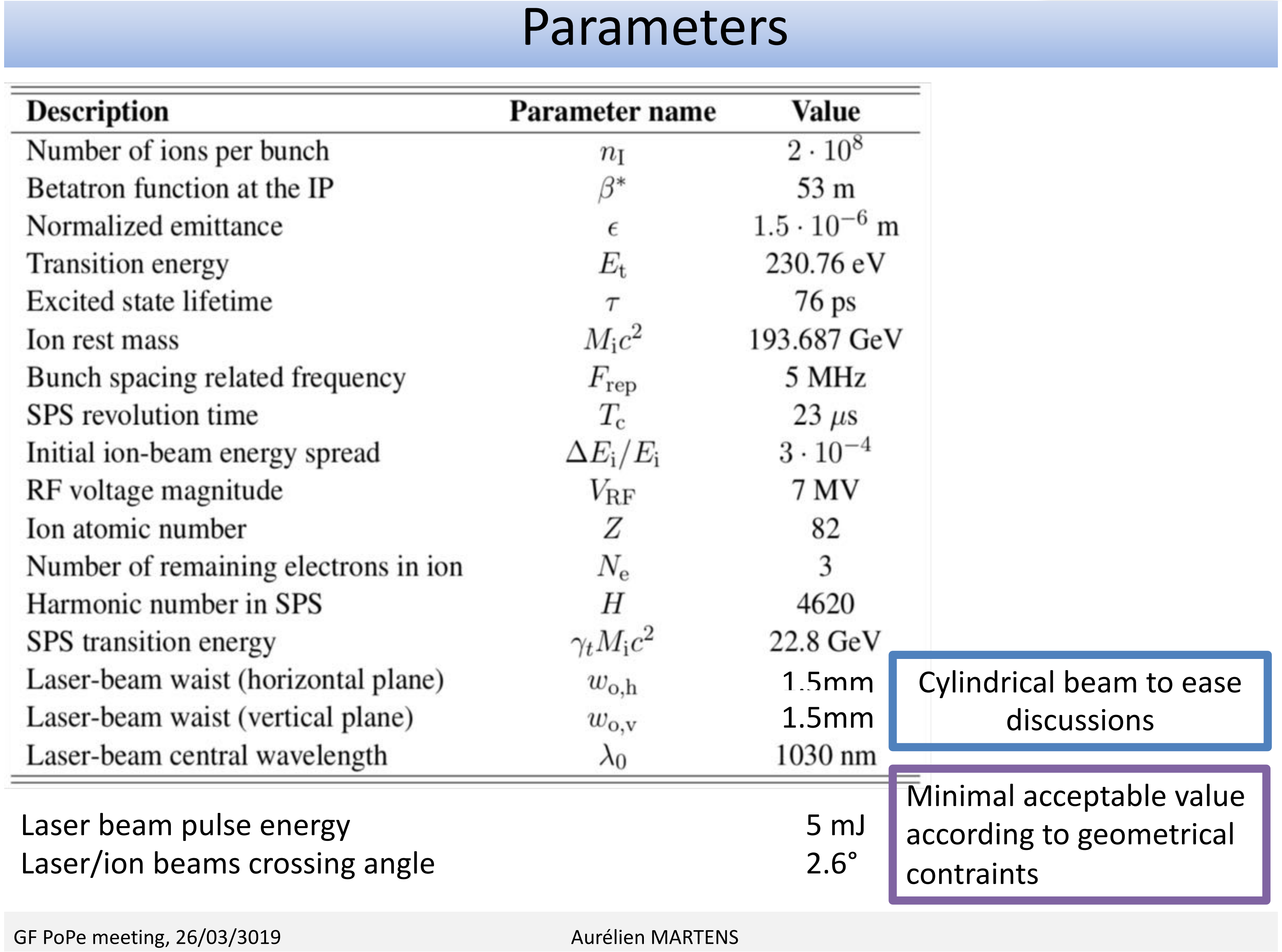
Single bunch

Summary of baseline laser + FP cavity

- Wavelength: 1030 nm
- Crossing angle: 2.6 deg

- **Optical resonator used to amplify low pulse energy of laser source:**

- Initial laser pulse energy: 1 μJ
- FP cavity **gain: 5000**
- Laser pulse energy at IP: **5 mJ**



Parameters

Description	Parameter name	Value
Number of ions per bunch	n_{I}	$2 \cdot 10^8$
Betatron function at the IP	β^*	53 m
Normalized emittance	ϵ	$1.5 \cdot 10^{-6}$ m
Transition energy	E_{t}	230.76 eV
Excited state lifetime	τ	76 ps
Ion rest mass	$M_{\mathrm{i}}c^2$	193.687 GeV
Bunch spacing related frequency	F_{rep}	5 MHz
SPS revolution time	T_{c}	23 μs
Initial ion-beam energy spread	$\Delta E_{\mathrm{i}}/E_{\mathrm{i}}$	$3 \cdot 10^{-4}$
RF voltage magnitude	V_{RF}	7 MV
Ion atomic number	Z	82
Number of remaining electrons in ion	N_{e}	3
Harmonic number in SPS	H	4620
SPS transition energy	$\gamma_t M_{\mathrm{i}}c^2$	22.8 GeV
Laser-beam waist (horizontal plane)	$w_{\mathrm{o,h}}$	1.5mm
Laser-beam waist (vertical plane)	$w_{\mathrm{o,v}}$	1.5mm
Laser-beam central wavelength	λ_0	1030 nm

Laser beam pulse energy	5 mJ
Laser/ion beams crossing angle	2.6°

Cylindrical beam to ease discussions

Minimal acceptable value according to geometrical contraints

GF PoPe meeting, 26/03/3019 Aurélien MARTENS

Summary of baseline laser + FP cavity

- Initial ion beam:
- Relativistic gamma: 96.3
- Energy spread: 3.10^{-4}
- Initial ion bunch length 400 ps

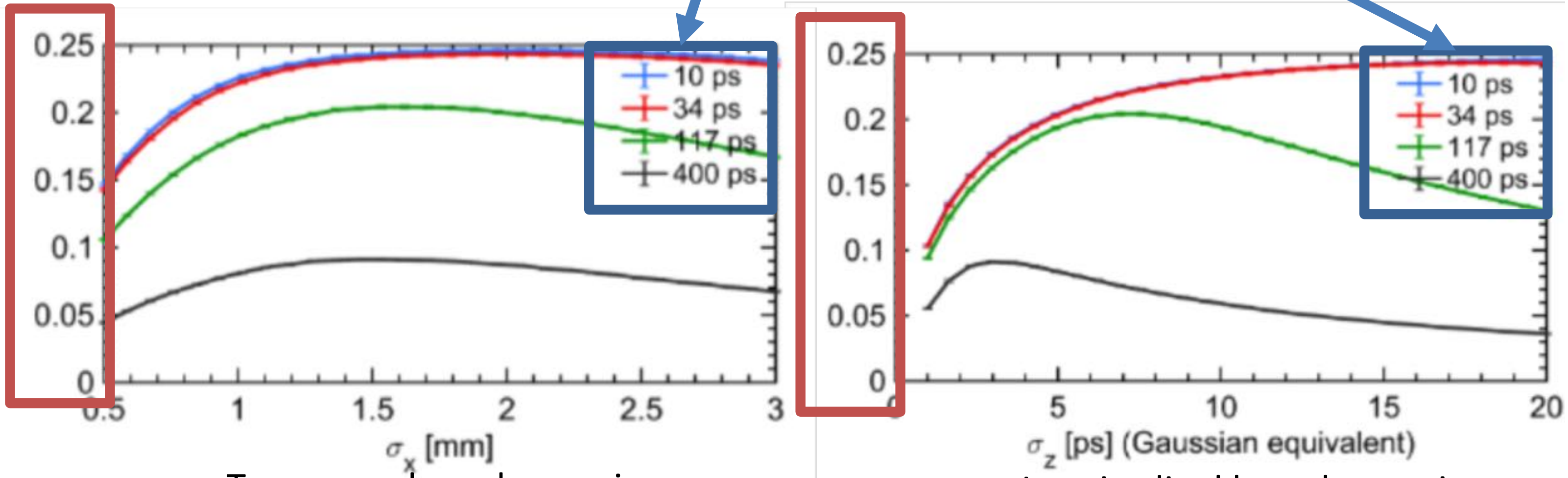
- Optimisation of excitation fraction implies constraints on laser pulse dimensions at IP:

Table on previous slide "waist":
$w_{o\ H,V}$ = 1.5 mm (0.361 σ)
$\sigma_{L\ x,y}$ = 0.54 mm ?

Δt FWHM = 10ps (2.355 σ)
$\sigma_{L\ z}$ = 1.275 mm == 4.25 ps ?

Ion bunch duration is varied (laong with energy spread) from 400ps to 10ps

Fraction of intercepted ions maximised over all other parameters



Transverse laser-beam size

Longitudinal laser-beam size

The fraction is maxised over the other parameter

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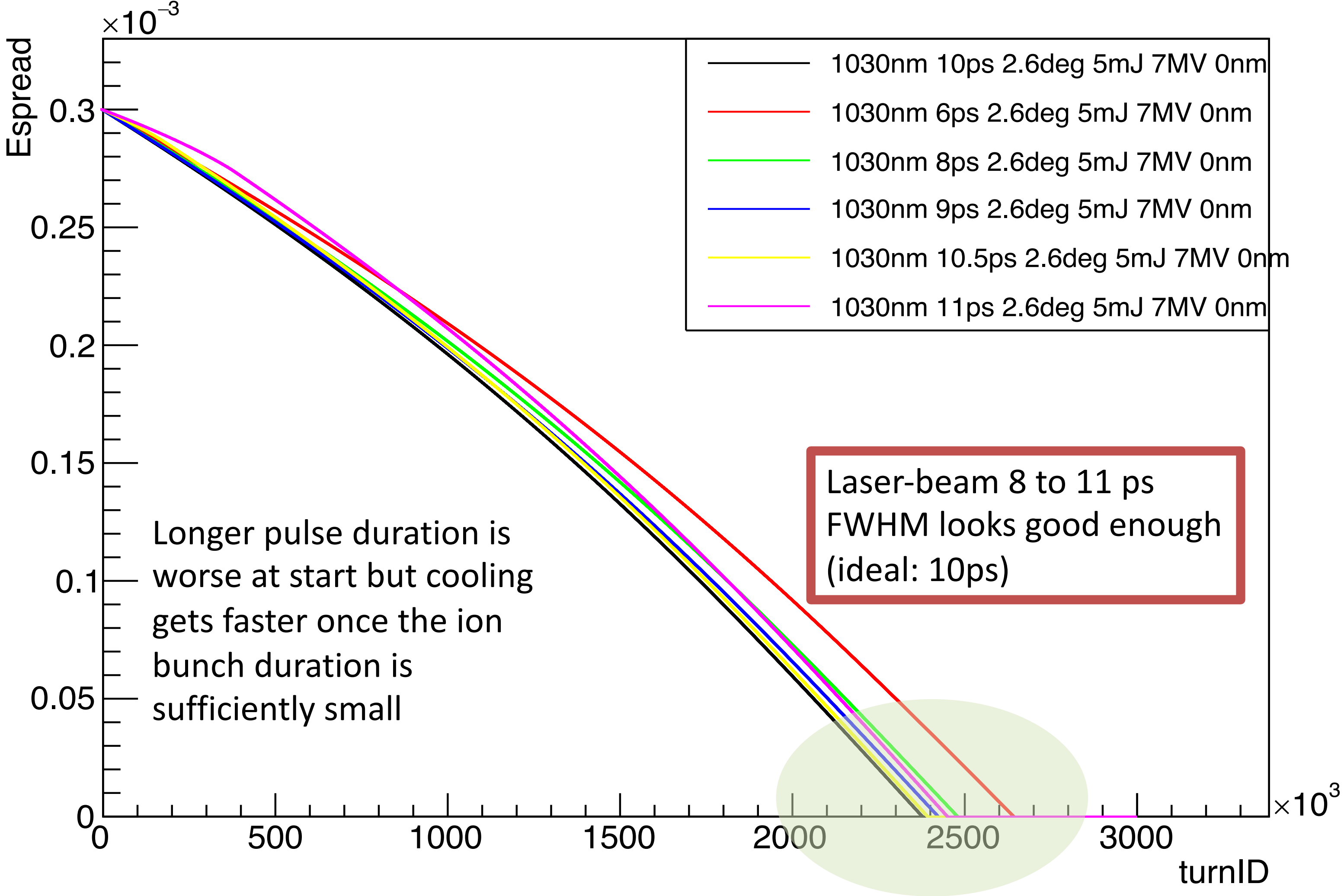

Longer pulse duration is worse at start but cooling gets faster once the ion bunch duration is sufficiently small

Laser-beam 8 to 11 ps FWHM looks good enough (ideal: 10ps)

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Single pass, single bunch laser requirements

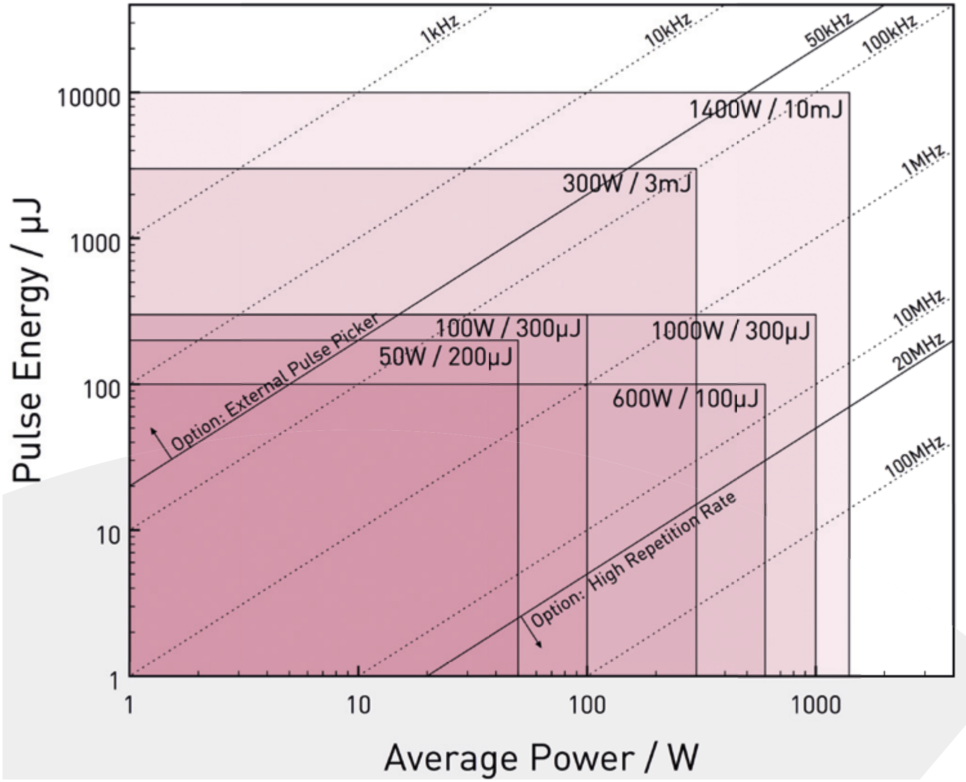
Requirements from simulations:

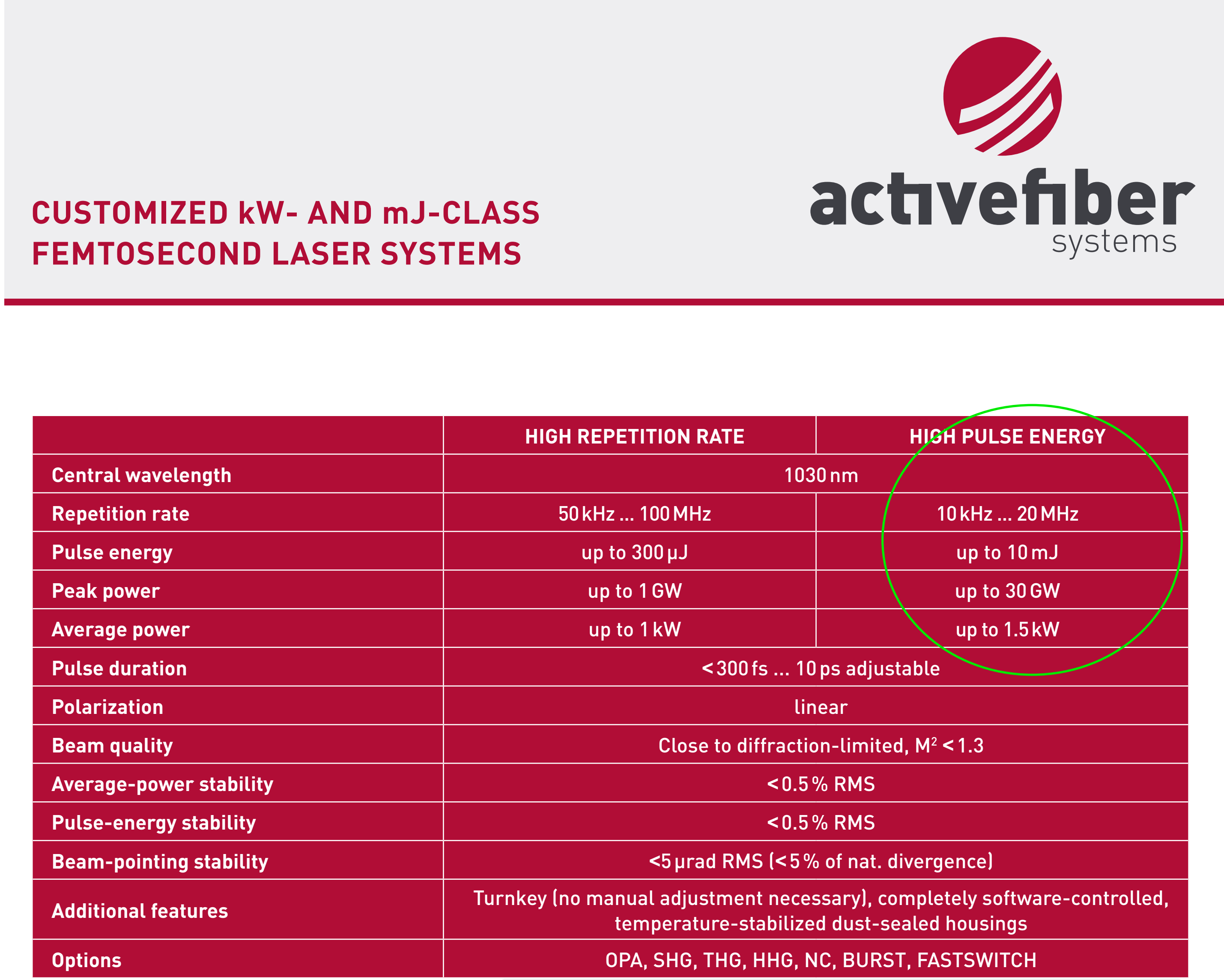
- **Repetition rate** matched to **SPS 43 kHz**
- **Pulse energy at IP: 5mJ**
  - Implies an average power of 215 W:
  - Far less than power stored in an FP cavity at 5 - 20 MHz, however, still too much optical power to transport by fibre (even in photonic crystal fibre)
  - Laser layout options:
    a) High pulse energy laser in tunnel near IP: would need same radiation tolerance as baseline.
    b) High pulse energy laser away from radiation, with >10 m free-space beam transport.
    c) Low pulse energy laser with fibre transport, with subsequent amplification in tunnel
- **Pulse duration: FWHM ~10 ps**
  - Short pulse implies peak pulse power of 500 MW [again, far too much for fibre transport without option (c); even then, consider streched pulse in fibre and pulse compression in tunnel]

Single pass, single bunch laser options: activefiber

As suggested by Valentin Fedosseev at Krakow workshop

Free space beam output, up to 10 mJ





CUSTOMIZED kW- AND mJ-CLASS FEMTOSECOND LASER SYSTEMS

activefiber systems

	HIGH REPETITION RATE	HIGH PULSE ENERGY
Central wavelength	1030 nm	
Repetition rate	50 kHz ... 100 MHz	10 kHz ... 20 MHz
Pulse energy	up to 300 µJ	up to 10 mJ
Peak power	up to 1 GW	up to 30 GW
Average power	up to 1 kW	up to 1.5 kW
Pulse duration	< 300 fs ... 10 ps adjustable	
Polarization	linear	
Beam quality	Close to diffraction-limited, $M^2 < 1.3$	
Average-power stability	< 0.5 % RMS	
Pulse-energy stability	< 0.5 % RMS	
Beam-pointing stability	<5 µrad RMS (< 5 % of nat. divergence)	
Additional features	Turnkey (no manual adjustment necessary), completely software-controlled, temperature-stabilized dust-sealed housings	
Options	OPA, SHG, THG, HHG, NC, BURST, FASTSWITCH	

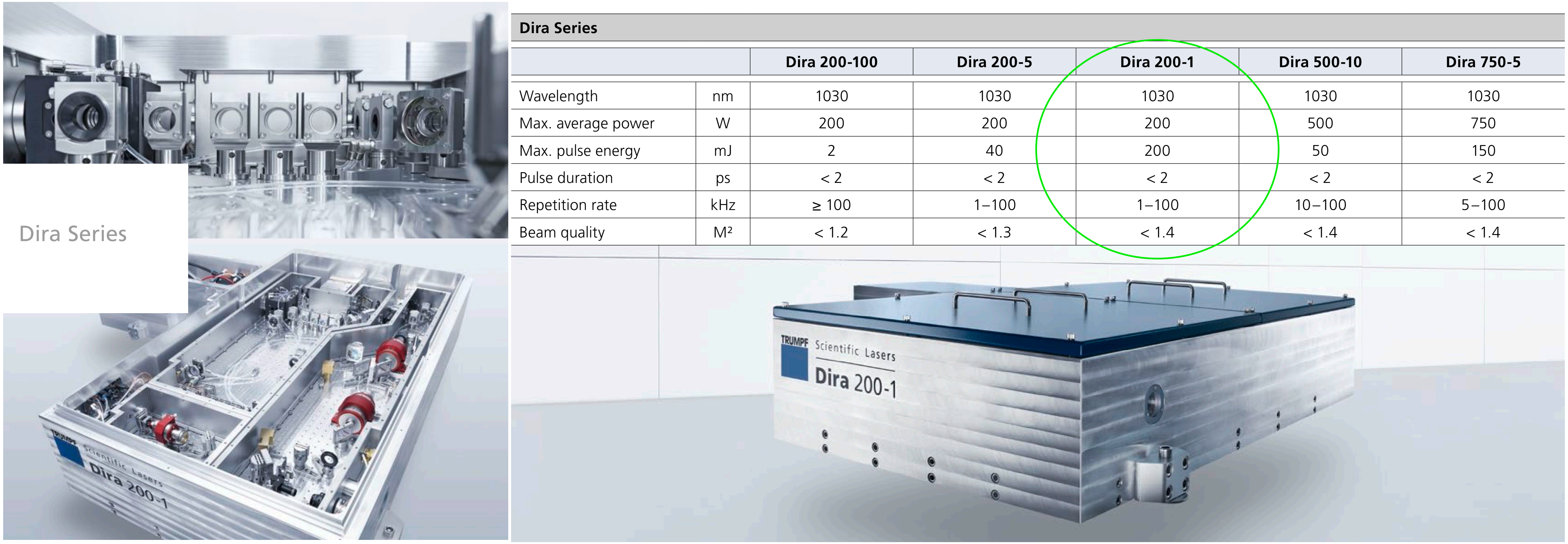
Single pass, single bunch laser options: Trumpf DIRA

TRUMPF

Extremely high pulse energy achievable, up to 200 mJ

Pulse duration < 2 ps (bandwidth? / stretch pulse?)

DIRA: Disk Regenerative Amplifier



Dira Series

Dira Series

		Dira 200-100	**Dira 200-5**	**Dira 200-1**	**Dira 500-10**	**Dira 750-5**
Wavelength	nm	1030	1030	1030	1030	1030
Max. average power	W	200	200	200	500	750
Max. pulse energy	mJ	2	40	200	50	150
Pulse duration	ps	< 2	< 2	< 2	< 2	< 2
Repetition rate	kHz	≥ 100	1–100	1–100	10–100	5–100
Beam quality	M^2	< 1.2	< 1.3	< 1.4	< 1.4	< 1.4

Single pass, single bunch laser options: Amplitude

High rep rate to 40 MHz:

Pulse duration to 10 ps

Pulse energy only 500 μJ

Factor ten less than required for cooling; good enough for photon production.

Tangor

Powerful, full-featured and versatile femtosecond laser

Tangor is a powerful femtosecond laser combining both high repetition rate (going up to 40 MHz and adjustable according to your needs) and high energy per pulse (going up to 500 μJ that can be splitted in several beams according to your production need).

Versatile and full-featured, Tangor femtosecond laser is equipped with: the customization function FemtoBurst™ (choose the number of pulses, their rhythms, time between each pulse between 25 to 100 ns, etc.), the trigger on demand for selecting individual pulses, SuperSync Control for getting more precise synchronization with a high speed scanning system. Tangor femtosecond laser is available with UV output going up to 30W.

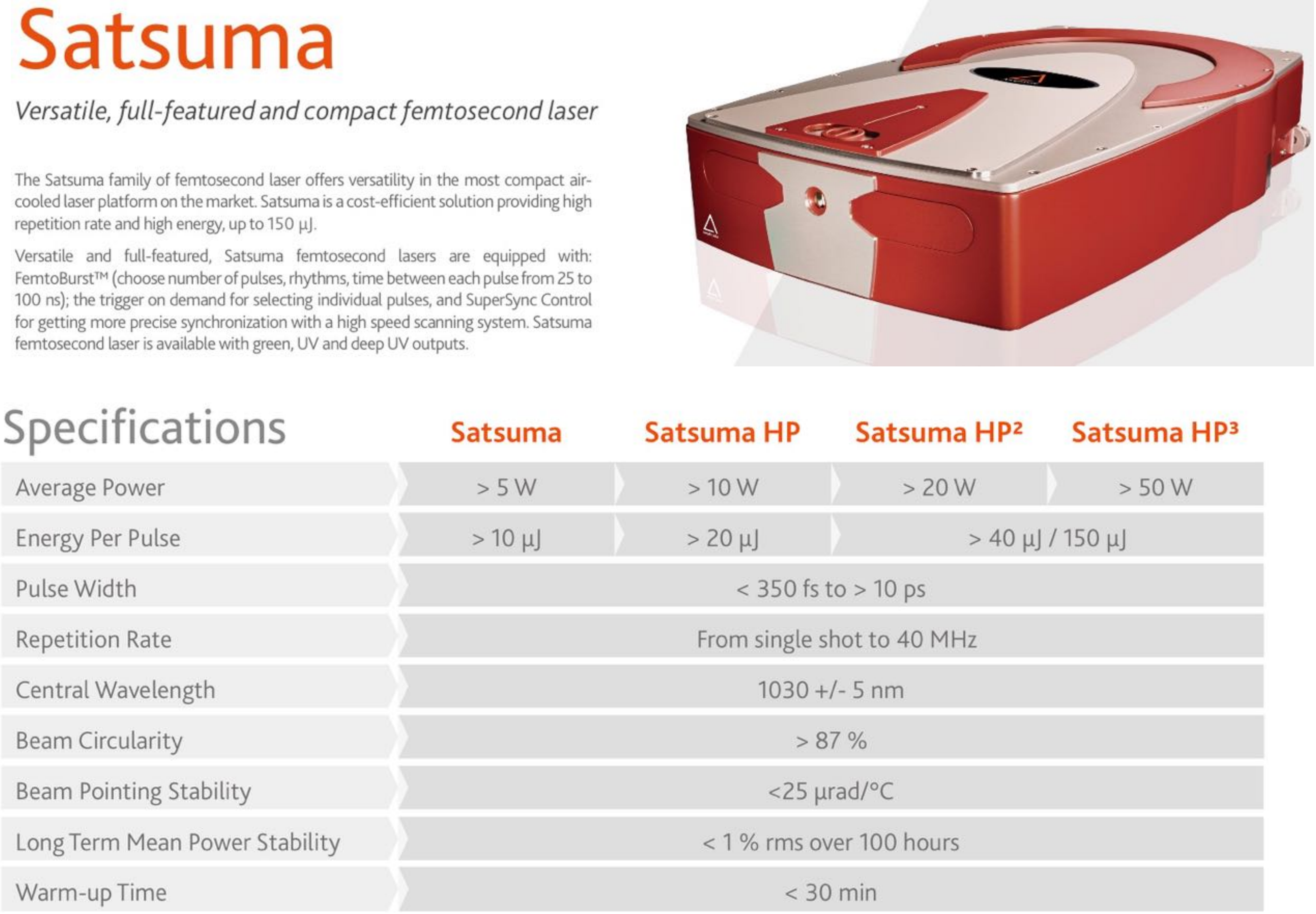
Specifications	Tangor	Tangor HP
Average Power	> 50 W	**> 100 W**
Energy Per Pulse	> 300 μJ	**> 500 μJ**
Pulse Width	< 500 fs to > 10 ps	
Repetition Rate	From single shot to **40 MHz**	
Central Wavelength	1030 +/- 5 nm	
Beam Circularity	> 87 %	
Beam Pointing Stability	<25 μrad/°C	
Long Term Mean Power Stability	< 1 % rms over 100 hours	
Warm-up Time	< 30 min	

Single pass, single bunch laser options: Amplitude

High rep rate to 40 MHz:

Pulse duration to 10 ps
Pulse energy only 150 μJ,

Compatible with fibre coupling option in hollow core fibre: e.g. used for industrial engraving.



Satsuma

Versatile, full-featured and compact femtosecond laser

The Satsuma family of femtosecond laser offers versatility in the most compact air-cooled laser platform on the market. Satsuma is a cost-efficient solution providing high repetition rate and high energy, up to 150 µJ.

Versatile and full-featured, Satsuma femtosecond lasers are equipped with: FemtoBurst™ (choose number of pulses, rhythms, time between each pulse from 25 to 100 ns); the trigger on demand for selecting individual pulses, and SuperSync Control for getting more precise synchronization with a high speed scanning system. Satsuma femtosecond laser is available with green, UV and deep UV outputs.

Specifications	Satsuma	Satsuma HP	Satsuma HP^2	Satsuma HP^3
Average Power	> 5 W	> 10 W	> 20 W	> 50 W
Energy Per Pulse	> 10 µJ	> 20 µJ	> 40 µJ / 150 µJ	
Pulse Width	< 350 fs to > 10 ps			
Repetition Rate	From single shot to 40 MHz			
Central Wavelength	1030 +/- 5 nm			
Beam Circularity	> 87 %			
Beam Pointing Stability	<25 µrad/°C			
Long Term Mean Power Stability	< 1 % rms over 100 hours			
Warm-up Time	< 30 min			

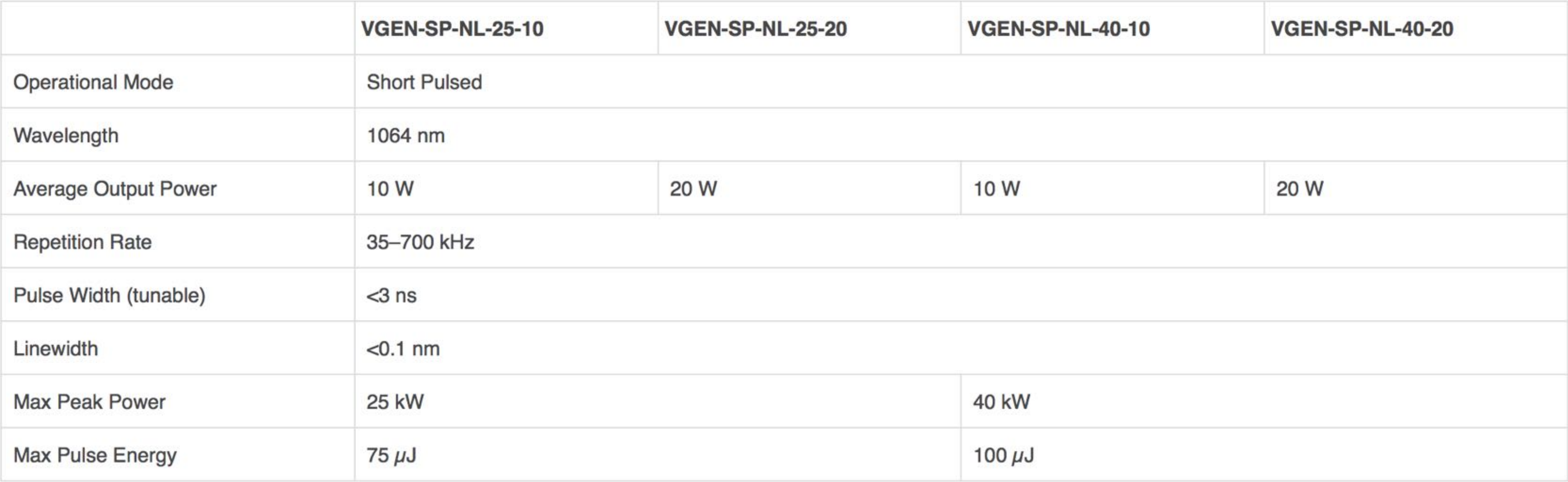
Single pass, single bunch laser options: V-gen

Fibre coupled: V-gen laser used for Linac4 laserwire

Wavelength 1064nm – bit too high for SPS ion energy?

Tuneable pulse duration: 3ns, linewidth < 0.1nm

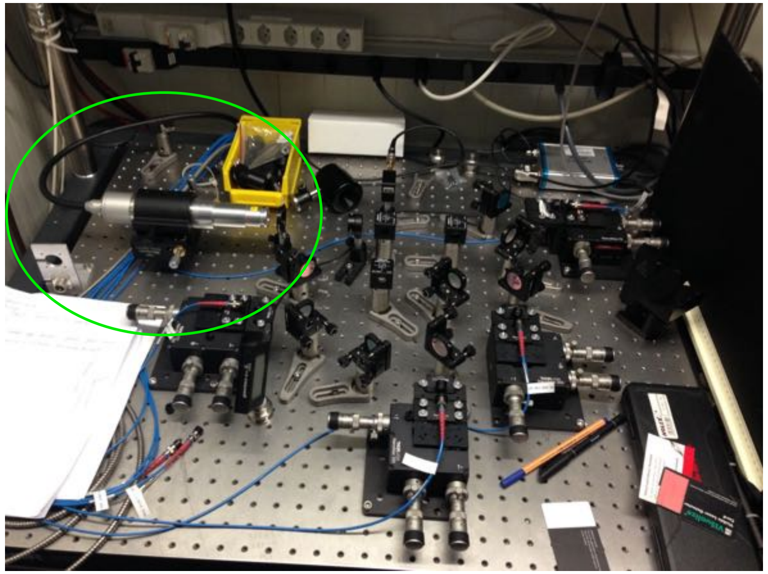
IR short pulse MOPA (master oscillator power amplifier fibre laser



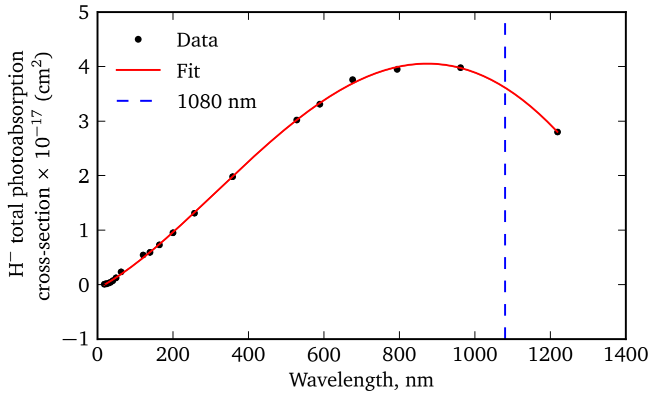
	VGEN-SP-NL-25-10	VGEN-SP-NL-25-20	VGEN-SP-NL-40-10	VGEN-SP-NL-40-20
Operational Mode	Short Pulsed			
Wavelength	1064 nm			
Average Output Power	10 W	20 W	10 W	20 W
Repetition Rate	35–700 kHz			
Pulse Width (tunable)	<3 ns			
Linewidth	<0.1 nm			
Max Peak Power	25 kW		40 kW	
Max Pulse Energy	75 μJ		100 μJ	

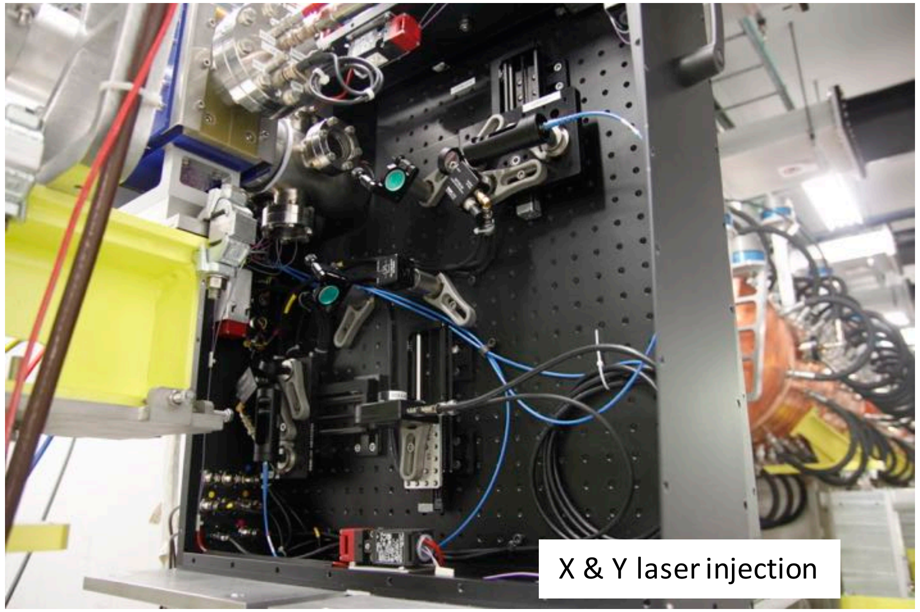
H^- **laserwire:** Linac4 profile & emittance scanners

- *Dual-station laserwire for operation at 160 MeV, measure stripped electrons and H^0*

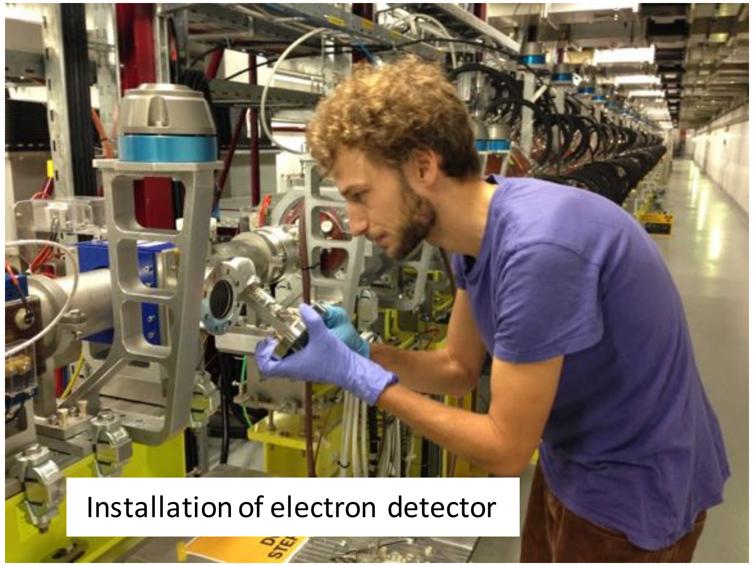


- *V-gen laser powers 4 laserwires in X and Y at two locations*
- *Up to **70 m transport fibres** in LMA fibre, with upto ~10 kW peak powers.*
- *Low duty cycle; amplification matched to accelerator*





X & Y laser injection

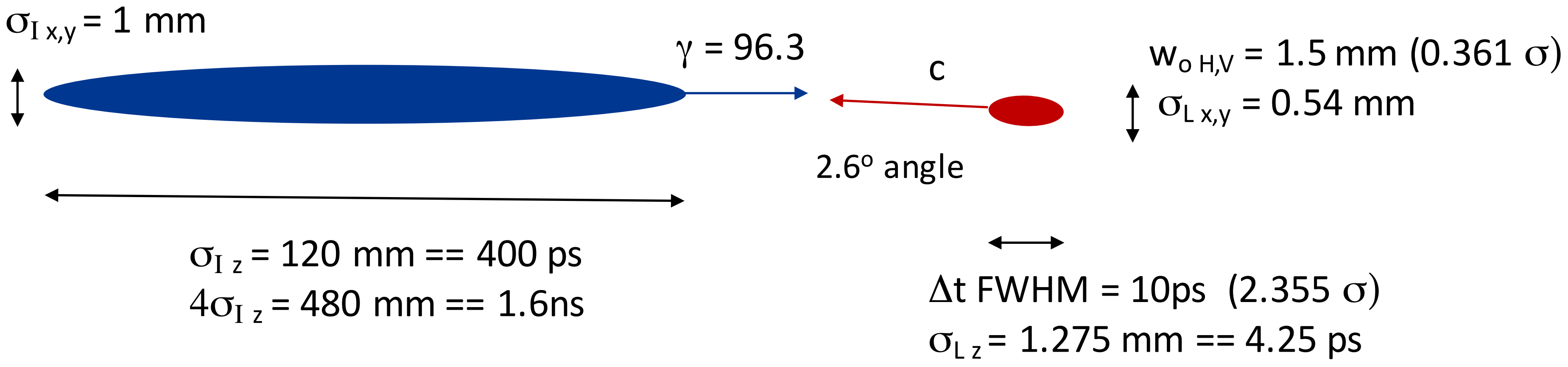


Installation of electron detector

PSI : photon pulse interaction region

Initial ion bunch

Laser pulse, λ = 1030 nm, 5 mJ



$\sigma_{I\ x,y}$ = 1 mm

γ = 96.3

c

2.6° angle

$\sigma_{I\ z}$ = 120 mm == 400 ps

$4\sigma_{I\ z}$ = 480 mm == 1.6ns

$w_{o\ H,V}$ = 1.5 mm (0.361 σ)

$\sigma_{L\ x,y}$ = 0.54 mm

Δt FWHM = 10ps (2.355 σ)

$\sigma_{L\ z}$ = 1.275 mm == 4.25 ps

- Note the ion bunch is rather circular in cross section, $\sigma_x \sim \sigma_y$ and the laser pulse has transverse dimension slightly smaller than the ion bunch: the laser pulse moves longitudinally *and transversely* through the ion bunch.
- Fraction of ions excited depends on **spatial-temporal overlap** of the two beams.
- Probability of excitation depends on **photon flux** and **time spent by ion in laser** field.

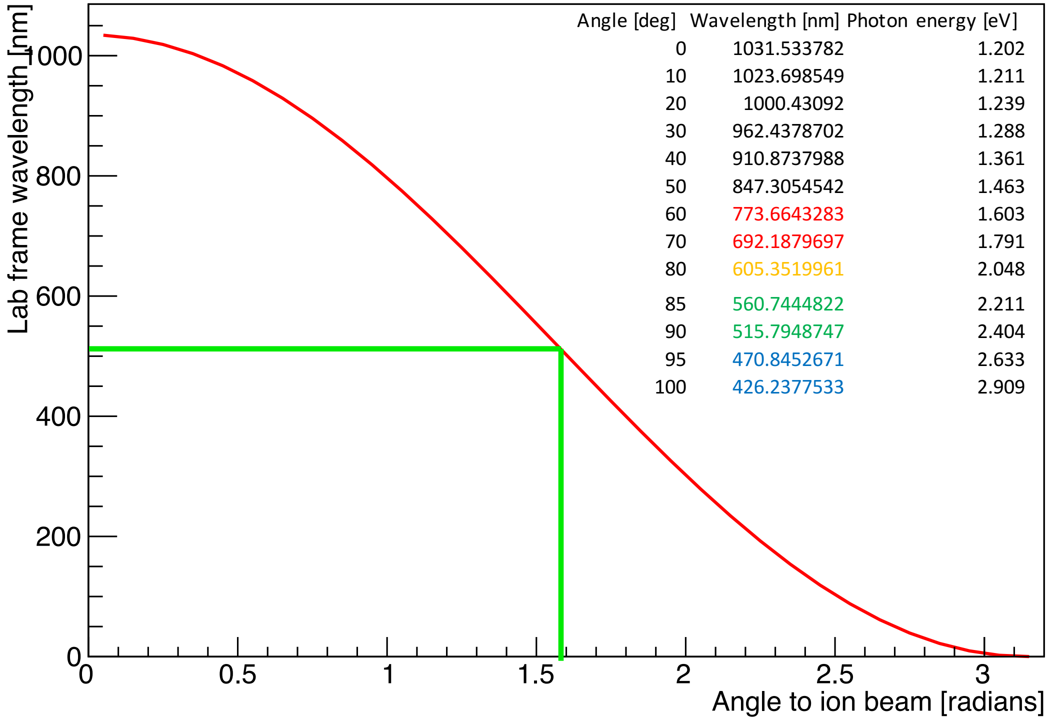
$$P_s = 1 - exp^{-\sigma(\lambda)\rho(x,y,z)t}$$

Consider an alternative wavelength and geometry:

Laser parameter

- Optimisations so far based on nearly head-on (2.6°) PSI-photons collisions using 1030nm (1.2 eV) laser, doppler shifted by γ =96.3 to the atomic transition energy (230.76 eV).
- ***Consider a radical change of wavelength and geometry:***

- A green laser was previously ruled out for FP cavity scenario mainly because a frequency doubled laser (532nm) is has an inherent loss of pulse energy, and wavelength increases absorption at mirrors.
- For single pass design however, absorption is not critical, and the orthogonal geometry enables photon flux to be enhanced by squeezing the beam with focusing optics (see next slide).



Angle [deg]	Wavelength [nm]	Photon energy [eV]
0	1031.533782	1.202
10	1023.698549	1.211
20	1000.43092	1.239
30	962.4378702	1.288
40	910.8737988	1.361
50	847.3054542	1.463
60	773.6643283	1.603
70	692.1879697	1.791
80	605.3519961	2.048
85	560.7444822	2.211
90	515.7948747	2.404
95	470.8452671	2.633
100	426.2377533	2.909

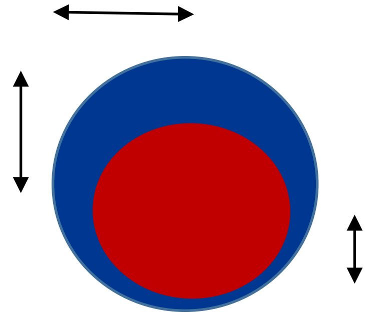
Photon flux enhancement: laserwire configuration

Reduce geometrical overlap

- Orthogonal geometry gives narrow beam of photons (laserwire): this reduces the interaction volume and increases the photon flux for the ions that pass through this region.

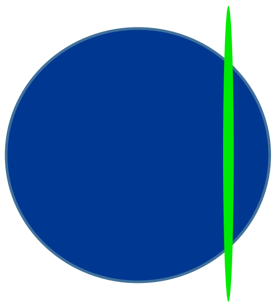
Transverse (XY) views of ion bunch in blue

$\sigma_{I\ x,y} = 1$ mm



$w_{o\ H,V} = 1.5$ mm $(0.361\ \sigma)$

$\sigma_{L\ x,y} = 0.54$ mm



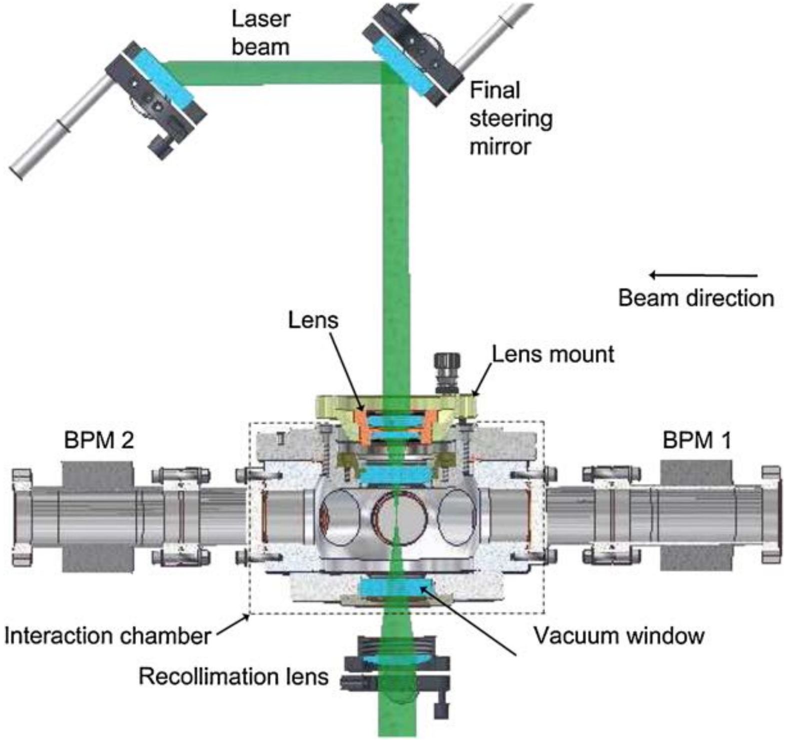
1030 nm head on (2.6°) pulse, spreads over most of bunch in transverse plane
Individual ions see less photon flux

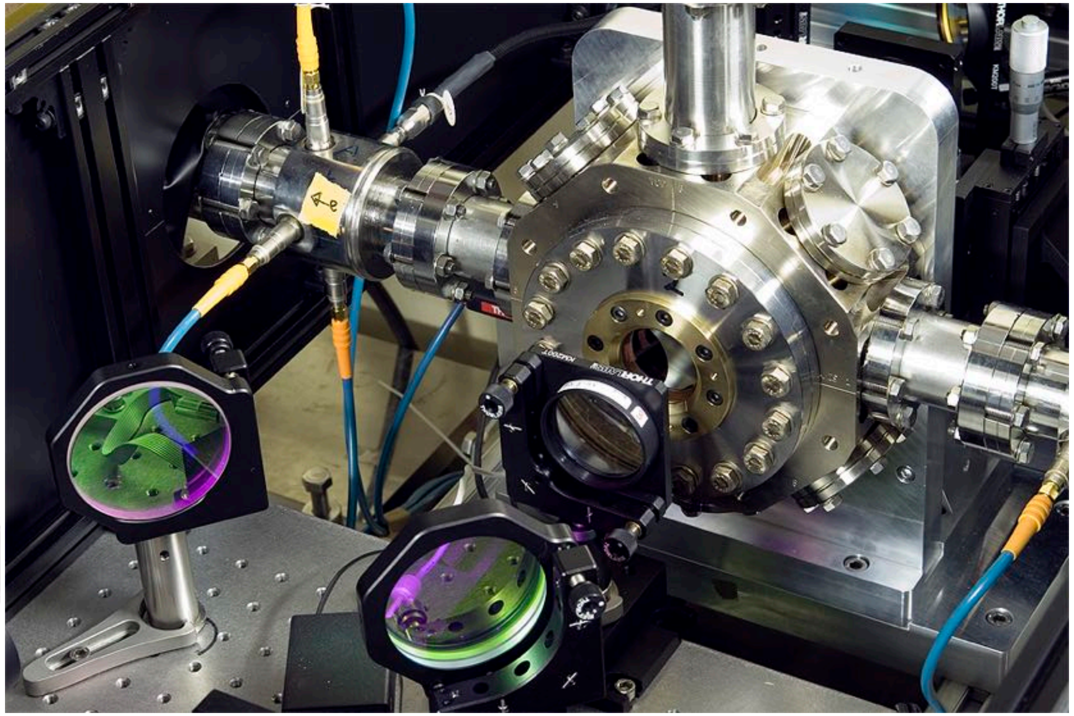
532nm orthogonal pulse, focus photons in specific slice of ion bunch.
Laserwire waist << 100um

Improves photon flux by factor ~100

e- laserwires: ATF setup

- Light focused into interaction chamber through vacuum window required careful optics design to deliver beam with minimal aberrations:





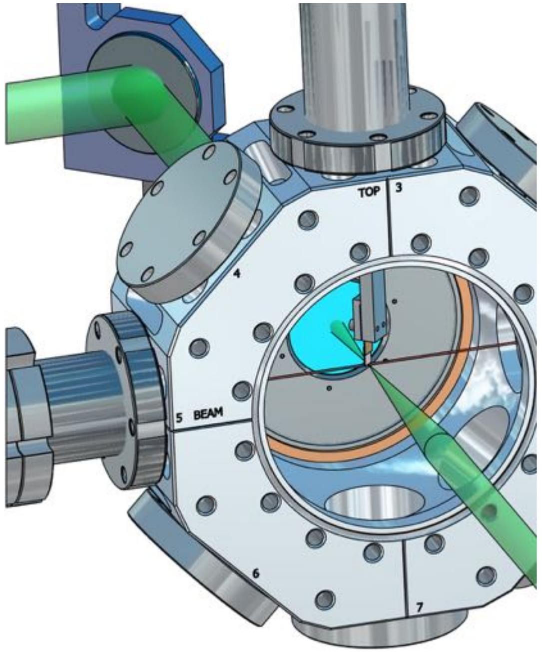
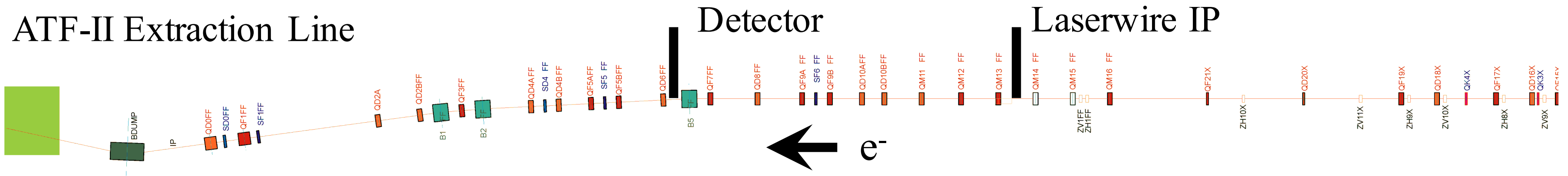


FIG. 10. View of the interaction chamber with the laser exit side flange removed, showing the 45° screen/knife edge.

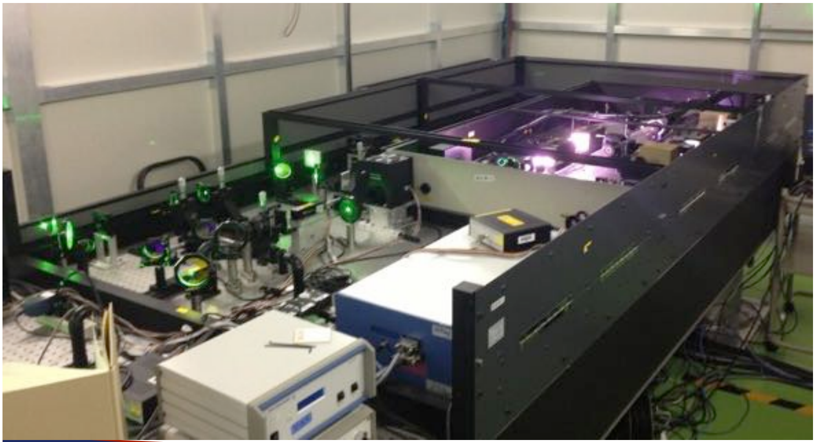
- S. Boogert et al: Micron-scale laser-wire scanner for the KEK Accelerator Test Facility extraction line Phys. Rev. Special Topics - Accel. Beams, 13, 122801 (2010)
- Beam emittance measurement with laser wire scanners in the International Linear Collider beam delivery system Phys. Rev. Special Topics - Accel. Beams, 10, 112801 (2007), Issue 11

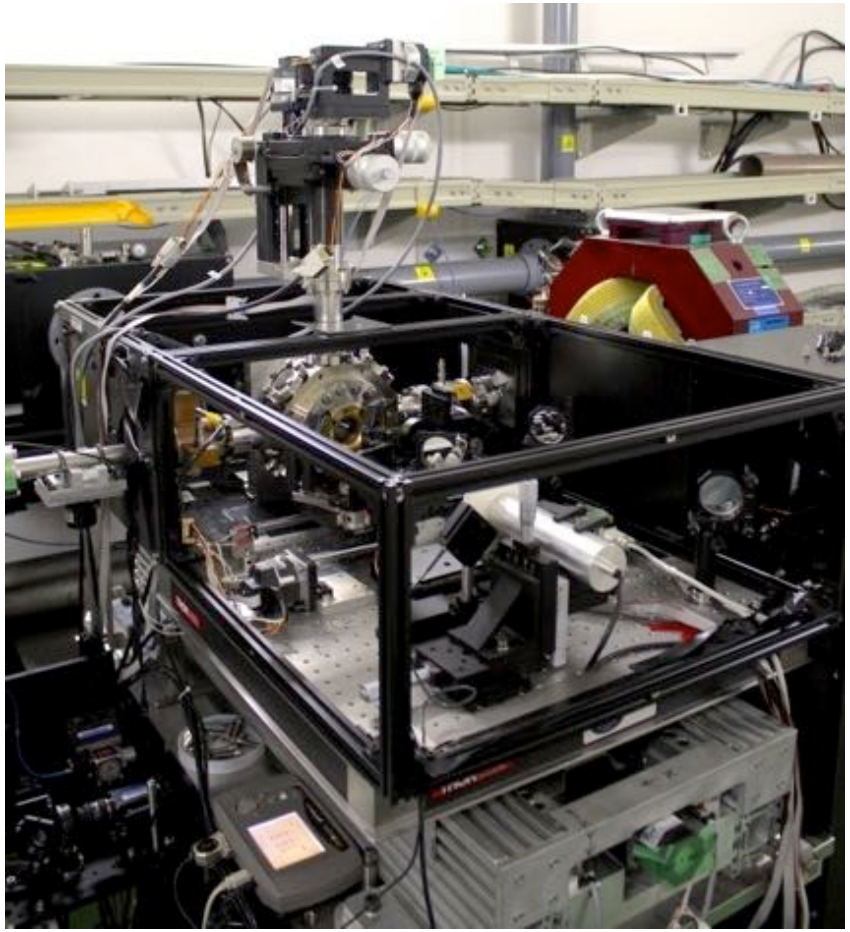
e- laserwires: ATF2 setup

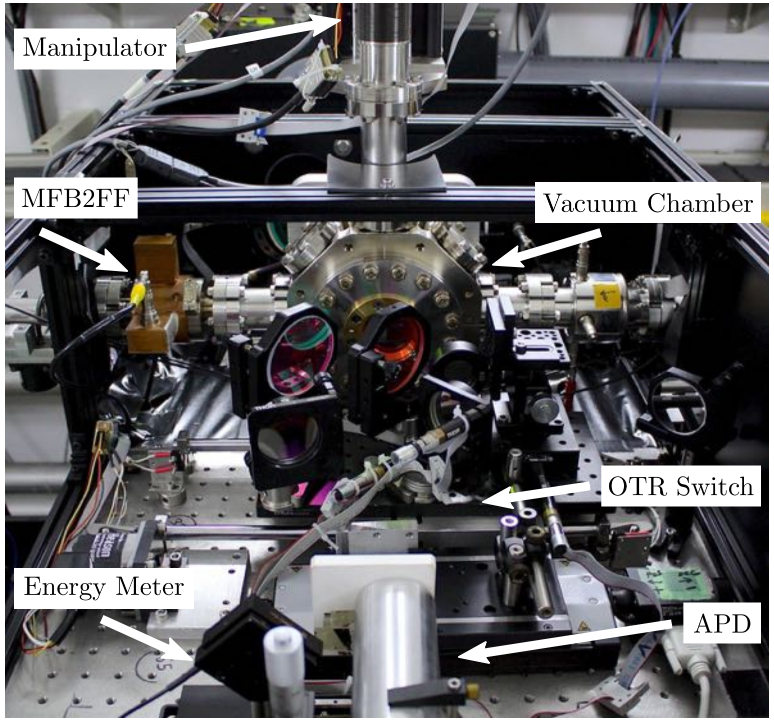


A. Aryshev, S. Boogert L. Corner, D. Howell, P. Karataev, K. Kruchinin, **L. Nevay**, N. Terunuma, J. Urakawa, R. Walczak

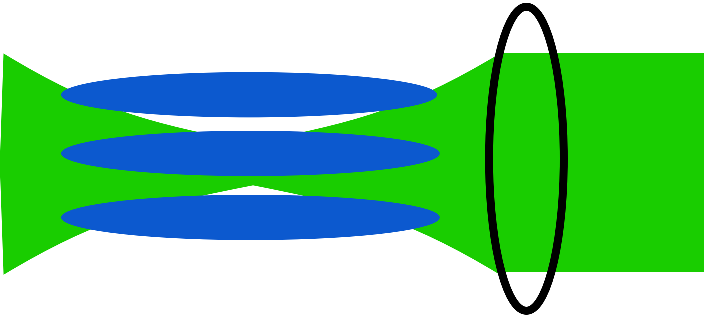
- Goal: Sub-micron resolution laserwire using transmissive optics
- Demonstrate 1μm vertical profile
- Use mode-locked Nd:YAG laser
- 1x10^{10} e^- and ~2GW peak power
- Cherenkov detector for γ-rays







e- laserwires: ATF2 laser beam characterisation



- Electron beam 1 x 250μm
- λ= 532nm laser, σ_0 = 1μm, M^2 (spatial quality) = 1.3
- Rayleigh range = 15μm
- laser σ ~ constant over 30μm << 250μm
- Vertical laserwire scan non-Gaussian
- Use measured laser propagation in overlap integral

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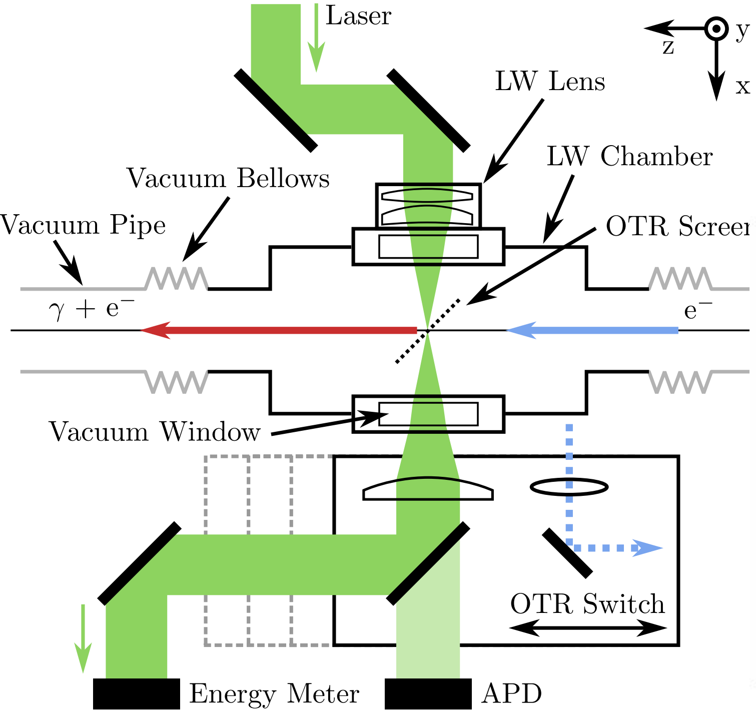
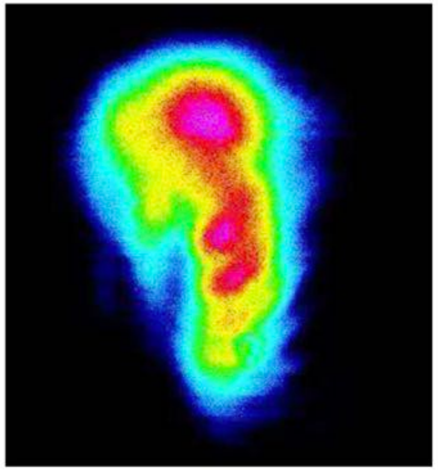
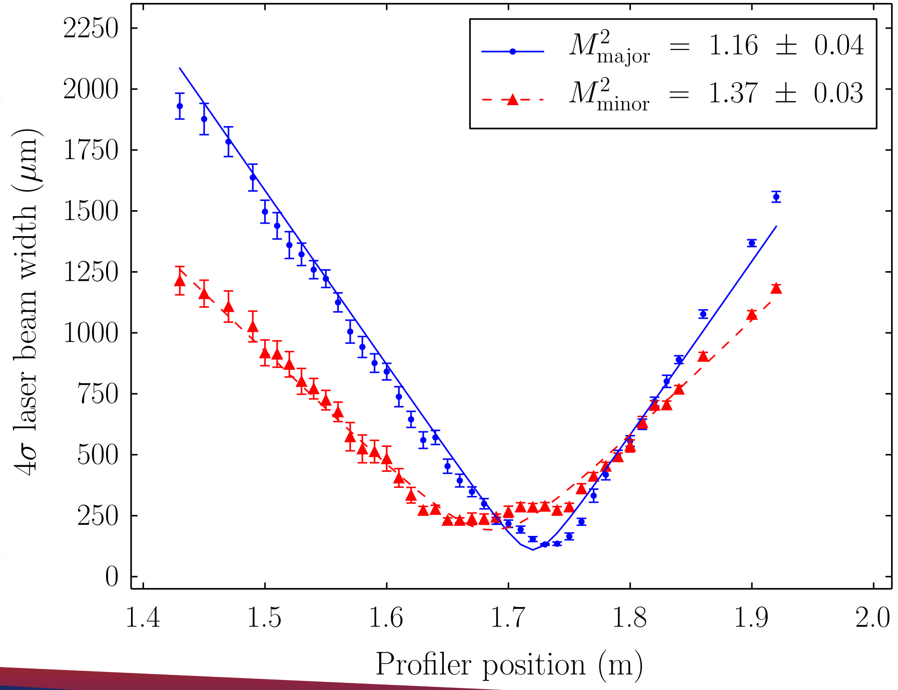
Laserwire at the Accelerator Test Facility 2 with submicrometer resolution Phys. Rev. Special Topics Accel. Beams, 17, 072802 (2014)

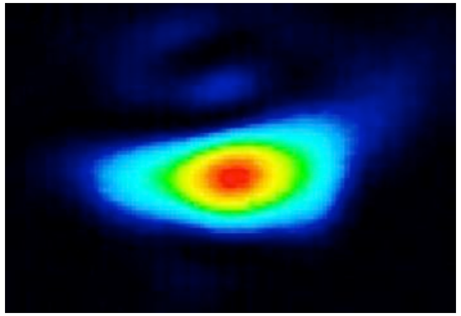


Input 4σ = 12mm



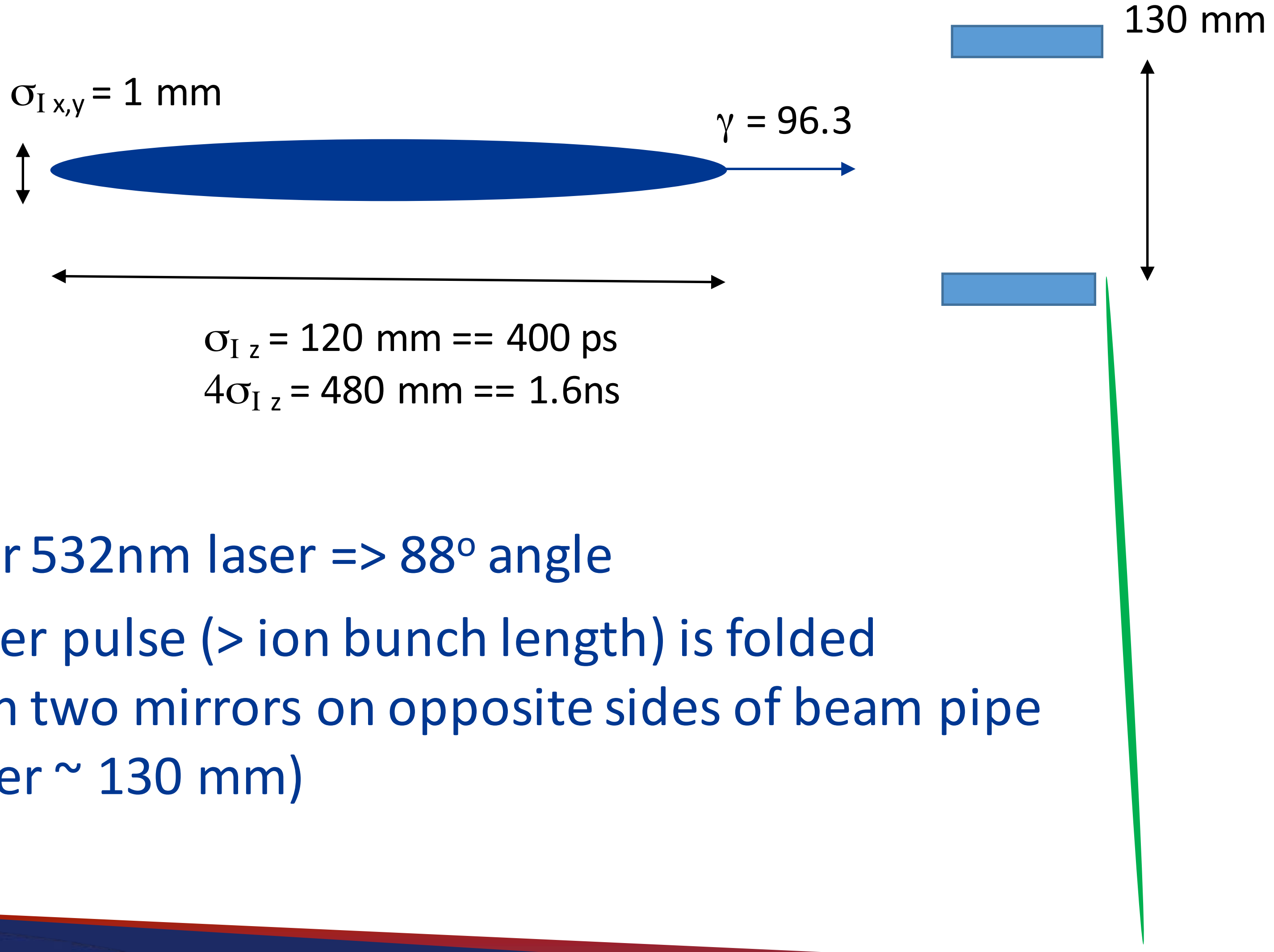


Scaled focus
4σ = 50μm



Green fibre laser, folded geometry:

Ion bunch interaction



130 mm

$\sigma_{I\ x,y}$ = 1 mm

γ = 96.3

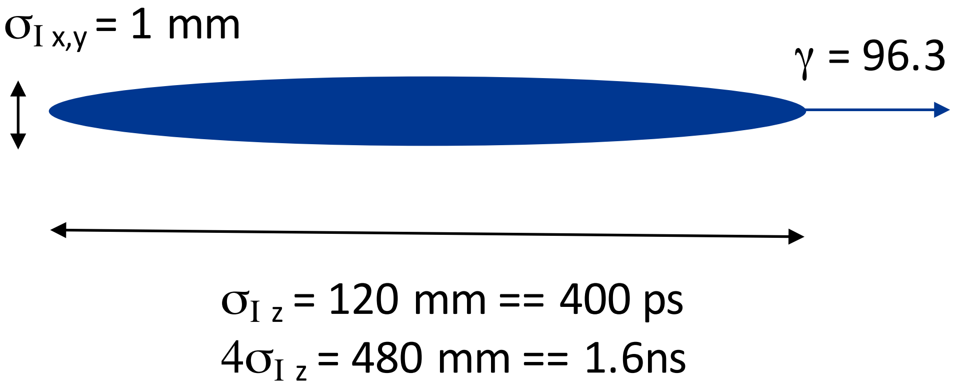
$\sigma_{I\ z}$ = 120 mm == 400 ps

$4\sigma_{I\ z}$ = 480 mm == 1.6ns

- Consider 532nm laser => 88^{o} angle
- Long laser pulse (> ion bunch length) is folded between two mirrors on opposite sides of beam pipe (diameter ~ 130 mm)

Green fibre laser, folded geometry:

Ion bunch interaction



$\sigma_{I\ x,y}$ = 1 mm

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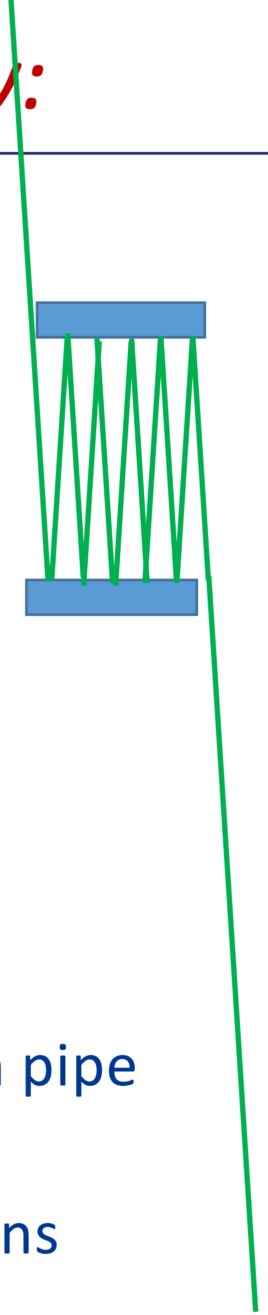
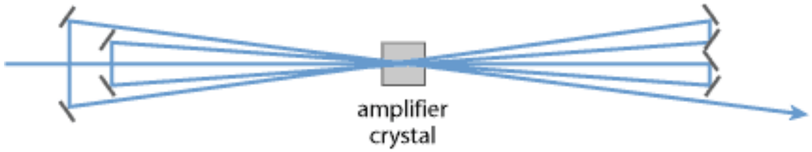
$4\sigma_{I\ z}$ = 480 mm == 1.6ns



Note vertical laserwire

Similar to multi pass amplifier



- Consider 532nm laser => 88° angle
- Long laser pulse (> ion bunch length) is folded between two mirrors on opposite sides of beam pipe (diameter ~ 130 mm)
- Fast moving ion bunch passes through all photons

Effectively amplifies by factor of number of reflections ~10
(minor mirror absorption)

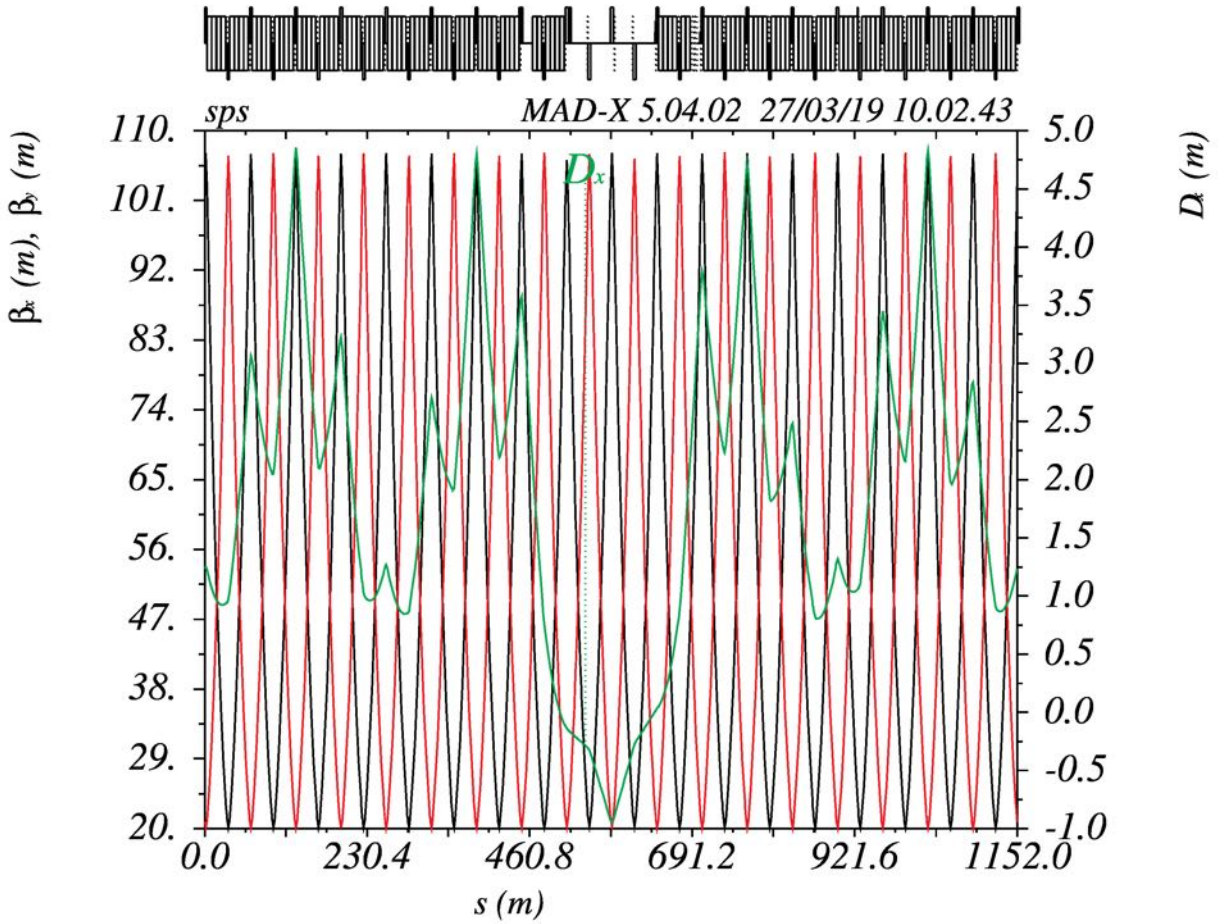
For ~130mm between mirrors, want laser pulse length of 1.3m ~ 4ns

Dispersion and spatial targeting of most energetic ions

Reduce energy and spatial overlaps

- Instead of 1030 nm, 10ps pulse, with broad line width, spread over the full momentum range and spatial extent of the ion bunch, consider a 532nm long pulse, and narrow line width, targeting only the high energy ions in the bunch

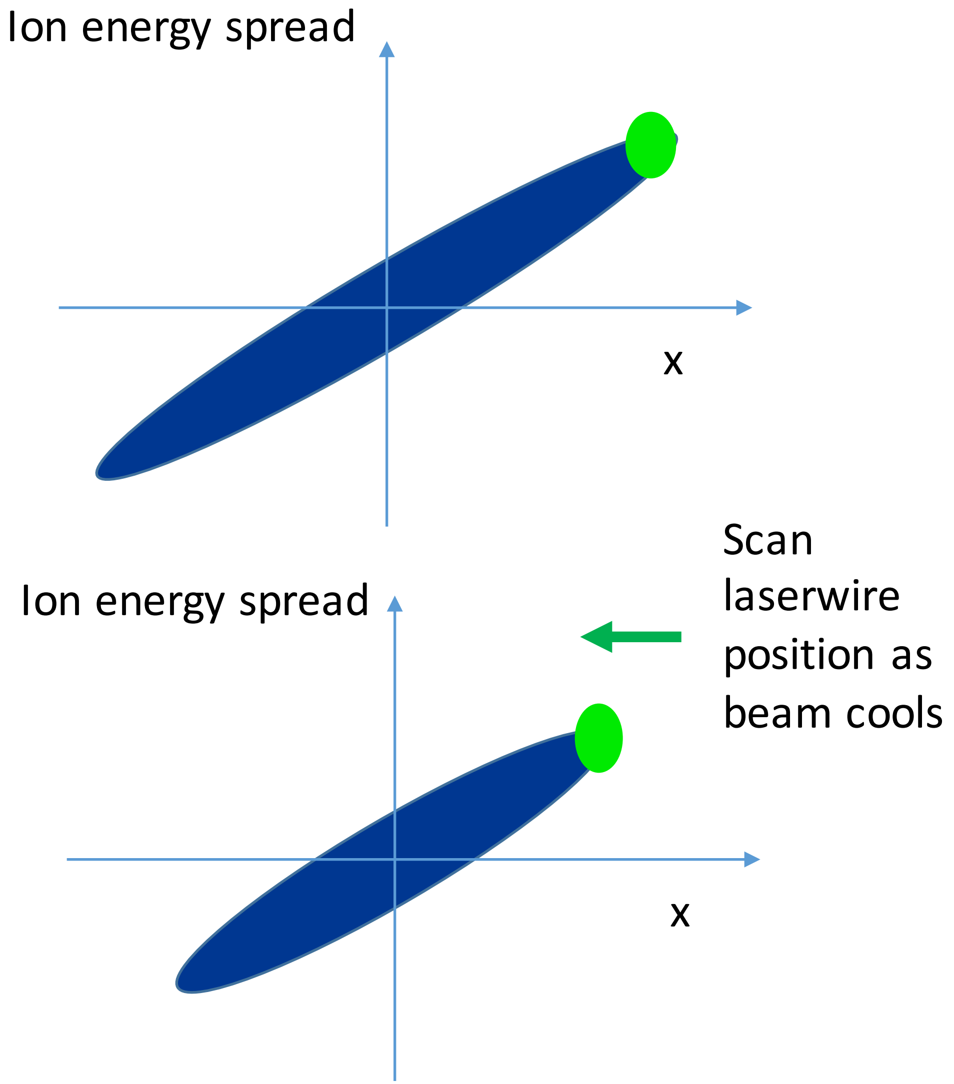
- If laser is in high dispersive region, the correlation with transverse beam position x, can be used to target high energy ions required to be cooled.



Dispersion and spatial targeting of most energetic ions

Energy scans

- Target spatially the ion energies required to be cooled, in a dispersive region of the accelerator.
- As the phase space is cooled, move the laserwire laterally in x to cool to lower energies.
- Or could use multiple vertical laserwires to cover x.
- Spectral scans could alternatively be achieved by varying the incident angle / mirror chirp (or tuning the laser wavelength).

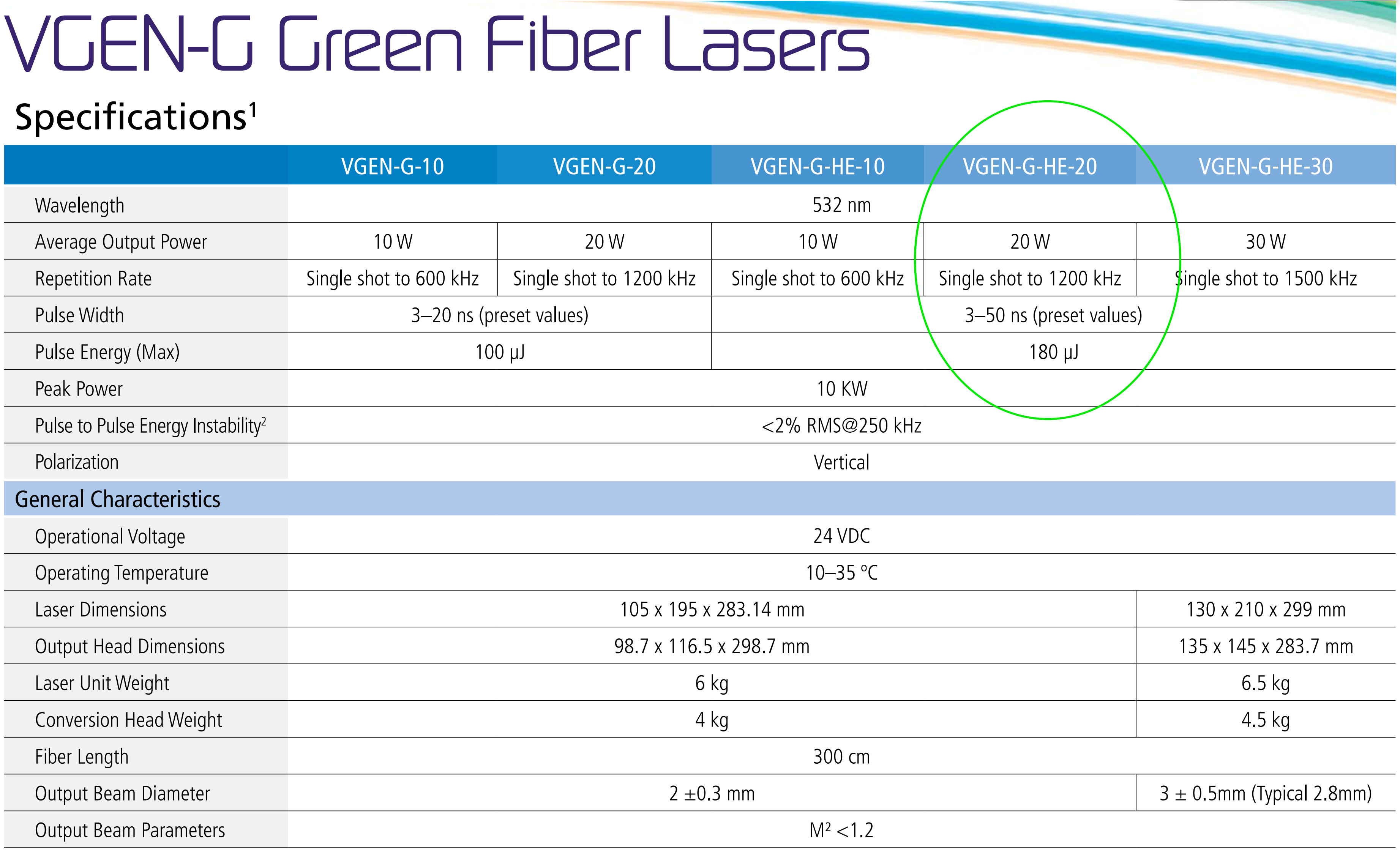


Scan laserwire position as beam cools

Multi pass, single bunch laser options: V-gen 532nm

The VGEN-G Advantage

- *Up to 30 W average output power*
- *3–50 ns (preset values) pulse width*
- *Single Shot – 1500 kHz (tunable) repetition rate*
- *Up to 180 µJ pulse energy*
- *High beam quality (M^2<1.2)*
- *Complies with the industry standard (RS232 and TTL interfaces)*
- *Air-cooled*



VGEN-G Green Fiber Lasers

Specifications[1]

	VGEN-G-10	VGEN-G-20	VGEN-G-HE-10	VGEN-G-HE-20	VGEN-G-HE-30
Wavelength	532 nm				
Average Output Power	10 W	20 W	10 W	20 W	30 W
Repetition Rate	Single shot to 600 kHz	Single shot to 1200 kHz	Single shot to 600 kHz	Single shot to 1200 kHz	Single shot to 1500 kHz
Pulse Width	3–20 ns (preset values)		3–50 ns (preset values)		
Pulse Energy (Max)	100 µJ		180 µJ		
Peak Power	10 KW				
Pulse to Pulse Energy Instability[2]	<2% RMS@250 kHz				
Polarization	Vertical				
General Characteristics					
Operational Voltage	24 VDC				
Operating Temperature	10–35 °C				
Laser Dimensions	105 x 195 x 283.14 mm				130 x 210 x 299 mm
Output Head Dimensions	98.7 x 116.5 x 298.7 mm				135 x 145 x 283.7 mm
Laser Unit Weight	6 kg				6.5 kg
Conversion Head Weight	4 kg				4.5 kg
Fiber Length	300 cm				
Output Beam Diameter	2 ±0.3 mm				3 ± 0.5mm (Typical 2.8mm)
Output Beam Parameters	M^2 <1.2				

Summary

- Single bunch option reduces repetition rate to 43kHz and eases average energy requirement to 215 W.
- Several commercial laser system identified with pulse energies, even up to 200mJ, suited for single pass option at 1030 nm at 43 kHz.
  - However such system would require free-space transport
- Commercial 1030nm systems with fibre based delivery appear limited to ~150uJ pulse energies. Maybe high enough for photon production, but not cooling.
- Rethinking geometry & wavelength for the single bunch option could enhance photon flux, if interested in demonstrating ‘photon production’. Smaller source for photon diagnostics
- For potential cooling, targeting higher energy ions in a dispersive region with spatial scans angular incidence, may be an option: to be investigated with simulation.

Back up

JAI @ Royal Holloway, University of London

John Adams Institute:

- A centre of excellence for Accelerator Science in the UK, formed between Royal Holloway, University of Oxford and Imperial College London.
- Strong research links with CERN, DESY, Diamond, KEK Japan, SLAC US, etc.

Academics:

Stewart Boogert

Stephen Gibson

Pavel Karataev

Senior research officers

Alexey Lyapin

Accel. Technology

Gary Boorman
RHUL-CERN PJAS

Accel. Engineering
(CERN based)

Mechanical workshop

Richard Elsom

Workshop manager

Paul Bamford

Technician

Post-doctoral researchers

Alessio Bosco
JAI

EO-BPM/laserwire

Laurie Nevay
(JAI)

BDSIM / Collimation
(CERN based)

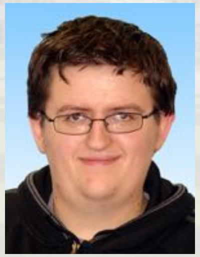
Hector Garcia
(JAI / HL-LHC-UK)

Sixtrack / Fluka
(CERN based)

Konstantin Lekomtsev

THz / Novel

William Shields

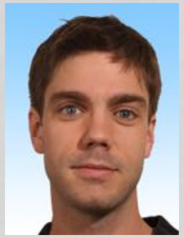


Medical accelerators

Alberto Arteche

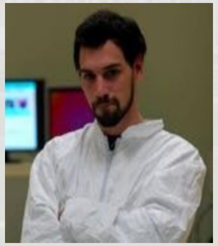
EO-BPMs

Marcus Palm
RHUL-CERN PJAS



HL-LHC Diagnostics
(CERN based)

Robert Kieffer
RHUL-CERN PJAS



HL-LHC Diagnostics
(CERN based)

JAI PhD students at Royal Holloway

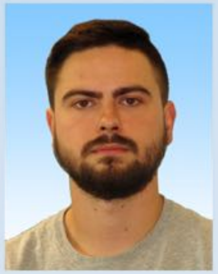
Helena Pikhartova

LHC backgrounds
(CERN based)

Stuart Walker

LHC / ATLAS Backgrounds

Andrey Abramov



HL-LHC / BDSIM
(CERN based)

GF: PSI simulations

Theo Christodoulou

Medical

GF: laser-ion

Siobhan Alden

FETS Laserwire

Gian Luigi D’Alessandro

Beyond Colliders

Daniel Harryman

Diagnostics

Michele Bergamaschi

OTR Diagnostics

Niki Vitarotou

Diamond BLMs

Sophie Bashforth

EO-BPMs
(CERN based)

Swann Levasseur

BGI at CERN
(CERN based)

Tom Vaughan

Diagnostics

Andrei Olenik

Pyroelectrics

Kirill Federov

Diagnostics

Advantages of remote laser system & beam transport

- *Lasers are sensitive and can be temperamental; best to keep in a safe laser cabin, away from the accelerator tunnel:*
  - *Laser room a thermally stabilised environment and vibration free – good for operation.*
  - *Personal can safely access the laser during beam operation, away from radiation.*
  - *Eliminates expensive commercial electronics from suffering irreparable radiation damage*
  - *Satisfies CERN safety: interlocked access control on laser cabin, shielding, googles, signs.*
  - *No need to wait for an accelerator shut down to alter laser settings; particularly important at SPS, with very limited technical stops per year.*
- *Must therefore transport the laser beam to the accelerator tunnel, two viable options:*
  - *Free space beam via series of mirrors, and tubes:*
    - *challenging beam pointing requirements, especially if tubes contain air, susceptible to refractive index change)*
    - *May be only option if very high power is required.*
  - *Transport in* optical fibres*:*
    - *Easy to install, limits on peak power / pulse duration due to non-linear effects in the fibre.*

e$^-$ **laserwires:** ATF2 results

Successful measurement of the 1.07 μm profile electron beam!

A. Aryshev, S. Boogert L. Corner, D. Howell, P. Karataev, K. Kruchinin, **L. Nevay**, N. Terunuma, J. Urakawa, R. Walczak

***L. Nevay** et al: Laserwire at the Accelerator Test Facility 2 with submicrometer resolution*
Phys. Rev. Special Topics - Accel. Beams, 17, 072802 (2014)

Projected laser dimension at interaction point

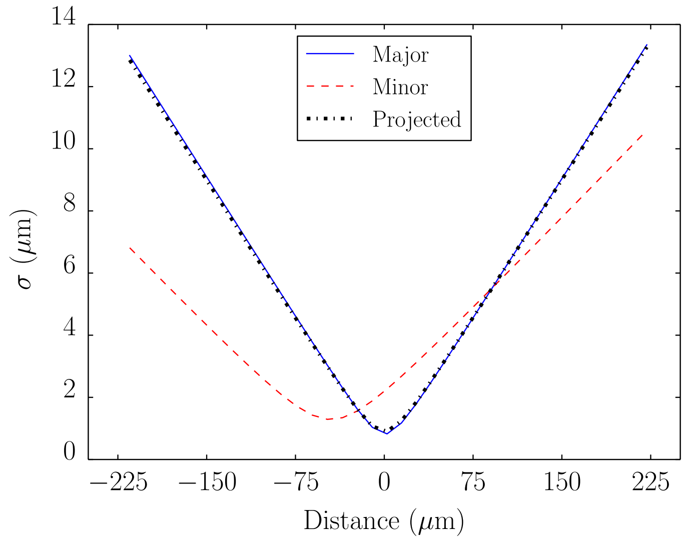


FIG. 12. Calculated projected vertical sigma for the laser as well as the two axes of propagation at the LWIP. The distance is

Measured vertical e- beam profile

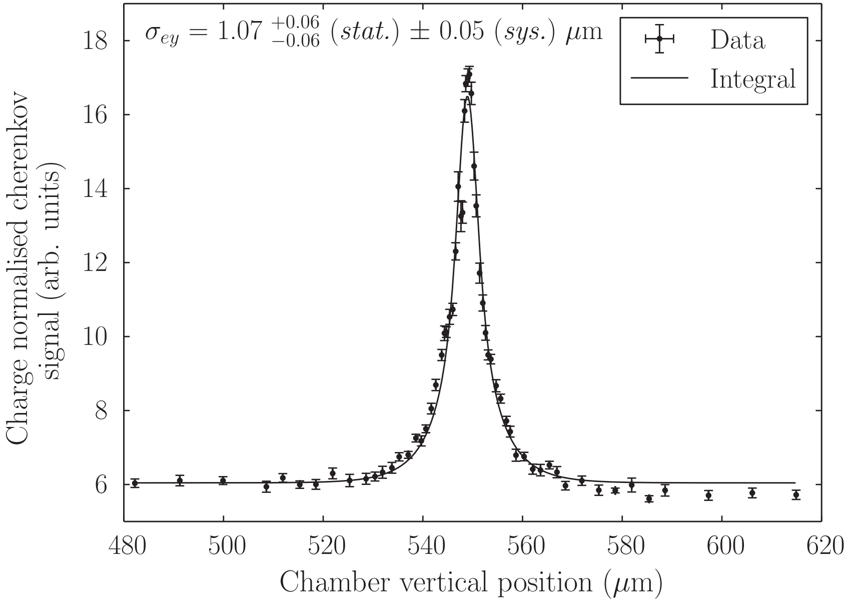


FIG. 19. Nonlinear step size laserwire scan with the smallest measured electron beam size.

Measured horizontal e- beam profile

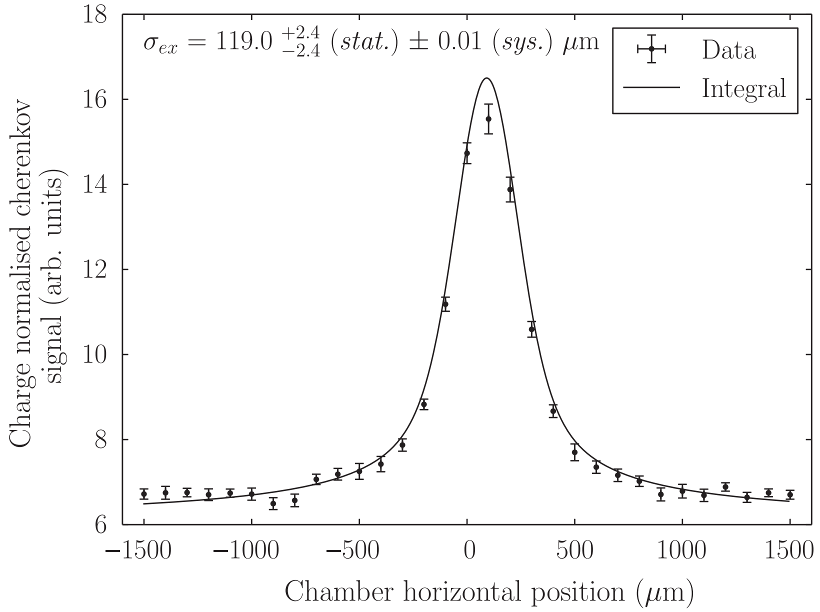
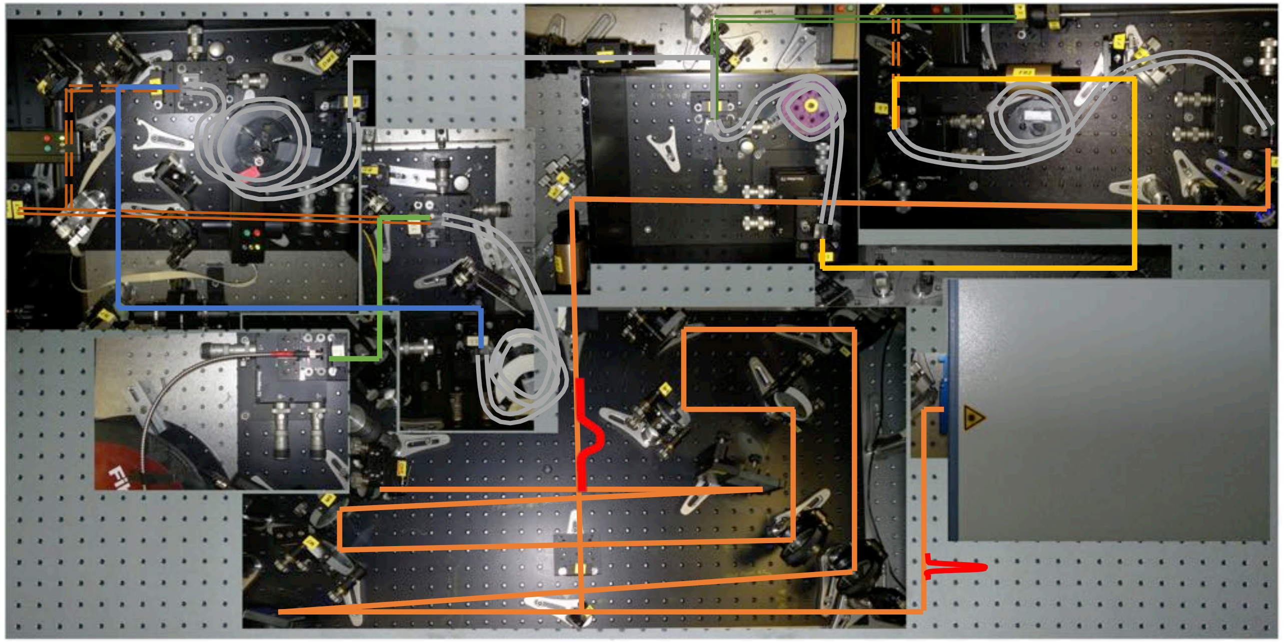


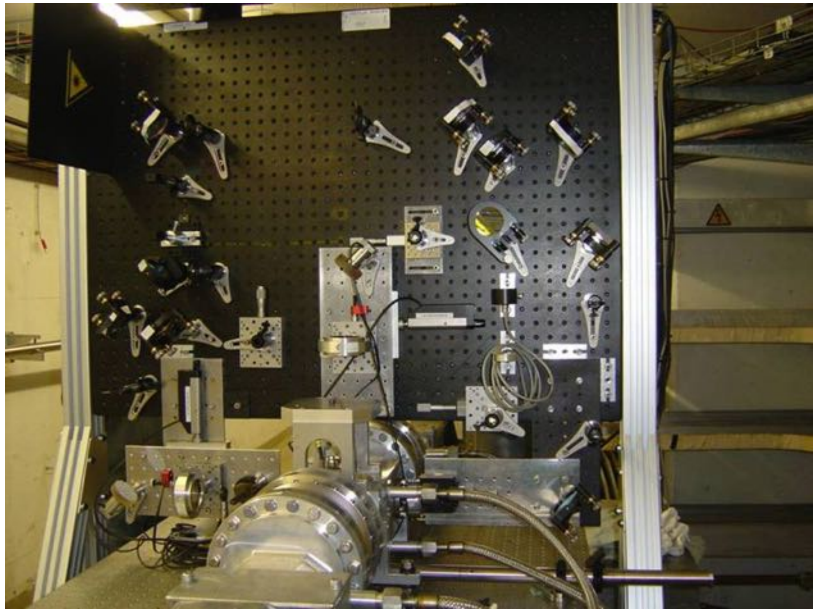
FIG. 20. The corresponding horizontal laserwire scan for the smallest vertical scan, which was required for the combined analysis.

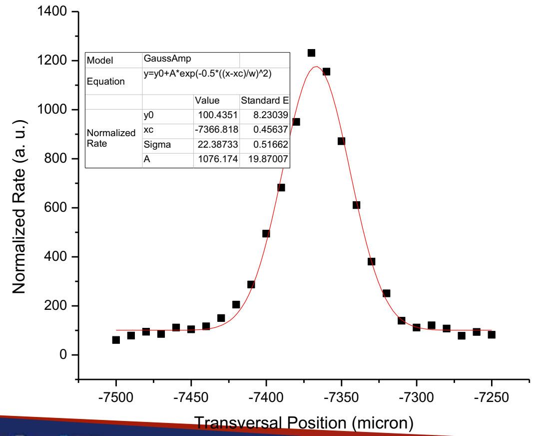
e^- laserwires: at PETRA-II & -III

Chirp pulse amplification scheme as previously described

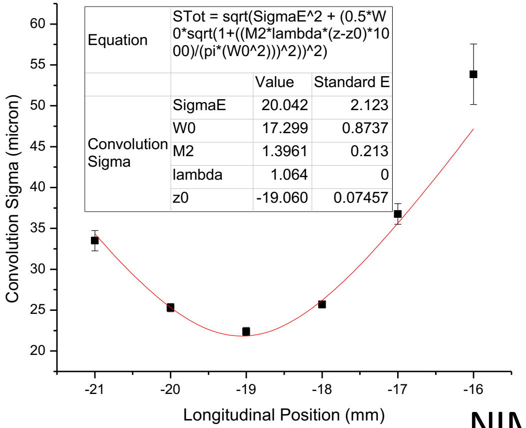


Vertical breadboard at beam pipe





Model	GaussAmp		
Equation	y=y0+A*exp(-0.5*((x-xc)/w)^2)		
		Value	Standard E
Normalized Rate	y0	100.4351	8.23039
	xc	-7366.818	0.45637
	Sigma	22.38733	0.51662
	A	1076.174	19.87007

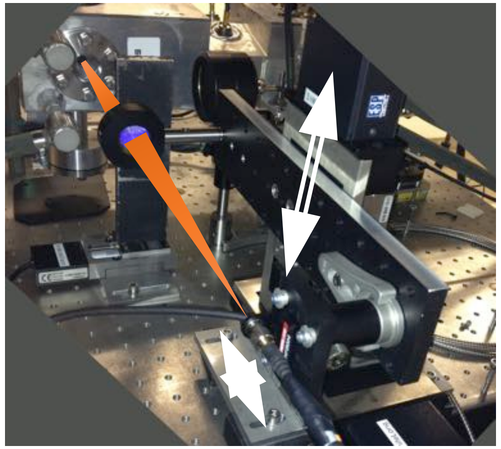


Equation	STot = sqrt(SigmaE^2 + (0.5*W0*sqrt(1+((M2*lambda*(z-z0)*1000)/(pi*(W0^2)))^2))^2)		
		Value	Standard E
Convolution Sigma	SigmaE	20.042	2.123
	W0	17.299	0.8737
	M2	1.3961	0.213
	lambda	1.064	0
	z0	-19.060	0.07457

Fibre amplified laser transport to tunnel in photonic crystal fibre – large area single spatial mode.

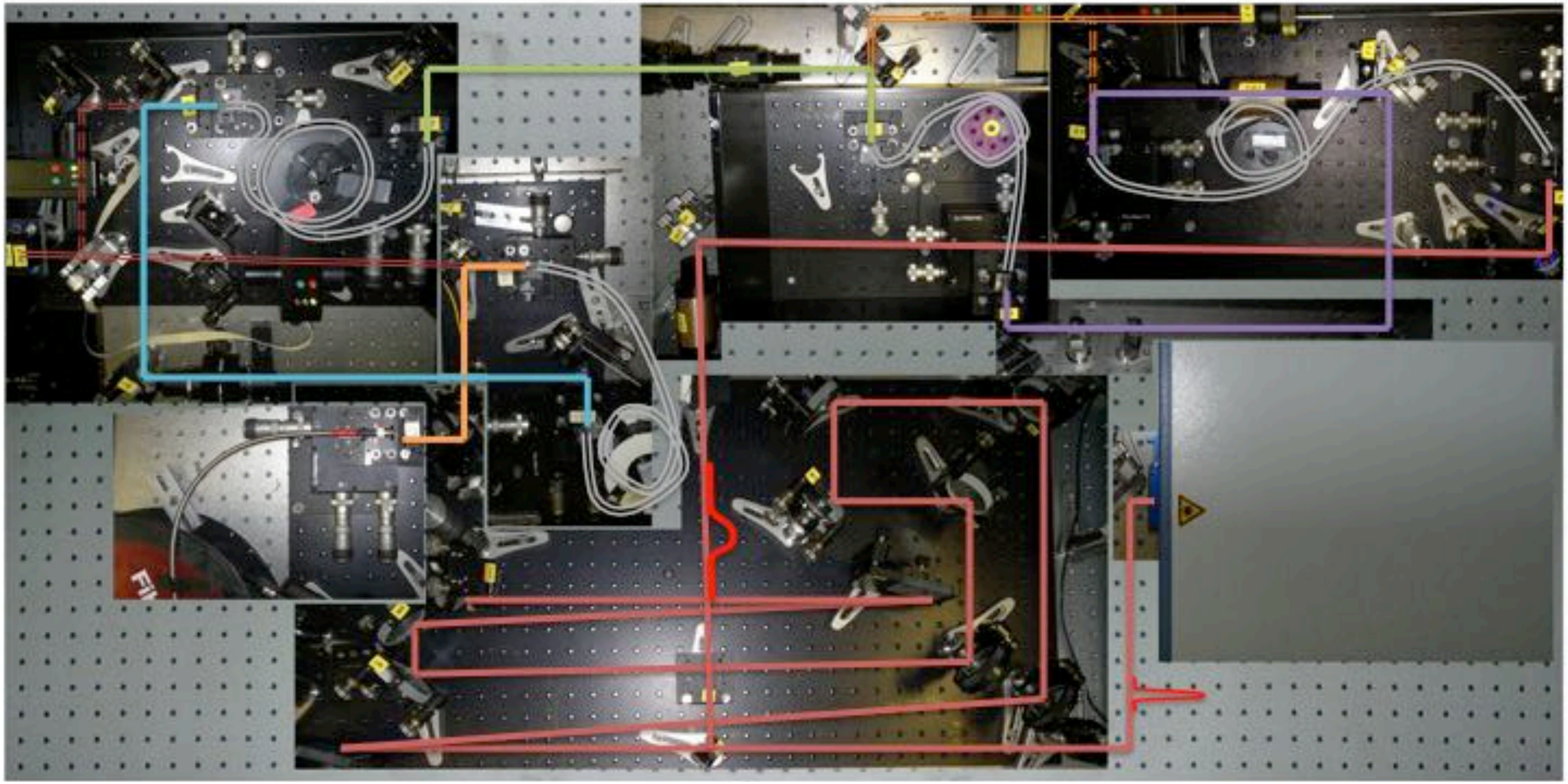
Beam delivery optics:

NIM in Phys. Res. A 592(3):162-170 · July 2008



Chirp pulse amplification at Petra-III laserwire

Laser oscillator is a Nd:YVO4 solid state mode-locked oscillator emitting laser light at 1064 nm



Master oscillator

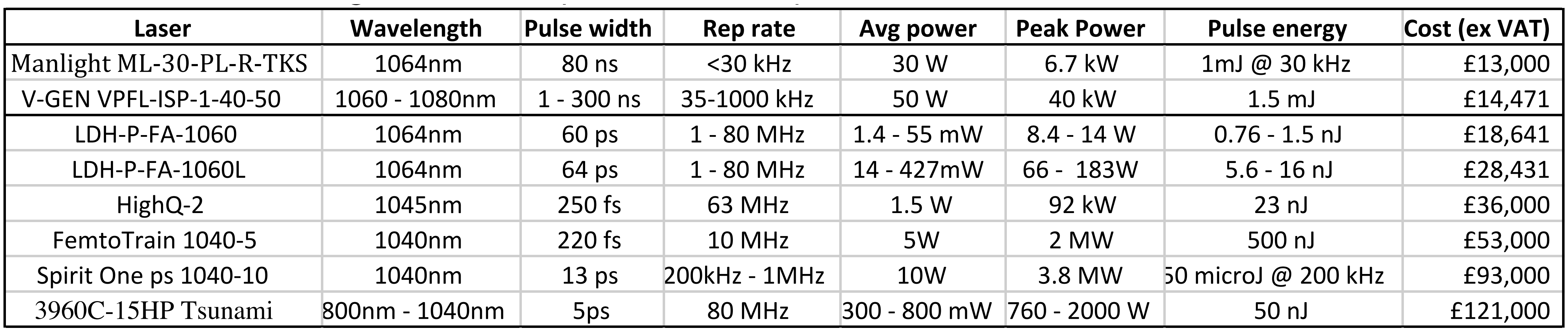
Parameter	Value
Wavelength	1064 nm
Pulse Duration (FWHM)	10 ps
Repetition Rate	62.45 MHz
Average Power	850 mW
Pulse Energy	13.5 nJ
Peak Power	1.3 kW

After ***pulse stretching*** and ***4 stage fibre amplification***

Parameter	Value
Wavelength	1064 nm
Pulse Duration (FWHM)	200 ps
Repetition Rate	520 kHz
Average Power	1.5 W
Pulse Energy	2.9 uJ
Peak Power	14 kW

A. Bosco et al, RHUL/DESY

Some examples of pulse laser systems



Laser	Wavelength	Pulse width	Rep rate	Avg power	Peak Power	Pulse energy	Cost (ex VAT)
Manlight ML-30-PL-R-TKS	1064nm	80 ns	<30 kHz	30 W	6.7 kW	1mJ @ 30 kHz	£13,000
V-GEN VPFL-ISP-1-40-50	1060 - 1080nm	1 - 300 ns	35-1000 kHz	50 W	40 kW	1.5 mJ	£14,471
LDH-P-FA-1060	1064nm	60 ps	1 - 80 MHz	1.4 - 55 mW	8.4 - 14 W	0.76 - 1.5 nJ	£18,641
LDH-P-FA-1060L	1064nm	64 ps	1 - 80 MHz	14 - 427mW	66 - 183W	5.6 - 16 nJ	£28,431
HighQ-2	1045nm	250 fs	63 MHz	1.5 W	92 kW	23 nJ	£36,000
FemtoTrain 1040-5	1040nm	220 fs	10 MHz	5W	2 MW	500 nJ	£53,000
Spirit One ps 1040-10	1040nm	13 ps	200kHz - 1MHz	10W	3.8 MW	50 microJ @ 200 kHz	£93,000
3960C-15HP Tsunami	800nm - 1040nm	5ps	80 MHz	300 - 800 mW	760 - 2000 W	50 nJ	£121,000

A. Bosco et al, RHUL/DESY