High repetition rate lasers and plasma sources for wakefield acceleration

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Applications for particle accelerators

LWFA is a promising technology for high gradient particle acceleration - source of compact, perhaps cheaper accelerators.

But only with high efficiency drive systems – rf klystrons 40 – 50%, prototypes up to 80 or 90%.

What's a perfect laser driver?

800 nm? 1 μm? CO_2 @ 10μm?

Wavelength?

kHz? 100s kHz? MHz?

How high rep rate?

Luminosity – collider running time

- High peak power
- High average power
- High rep rate
- Short pulse length
- High efficiency
- Excellent beam quality

One that works!!

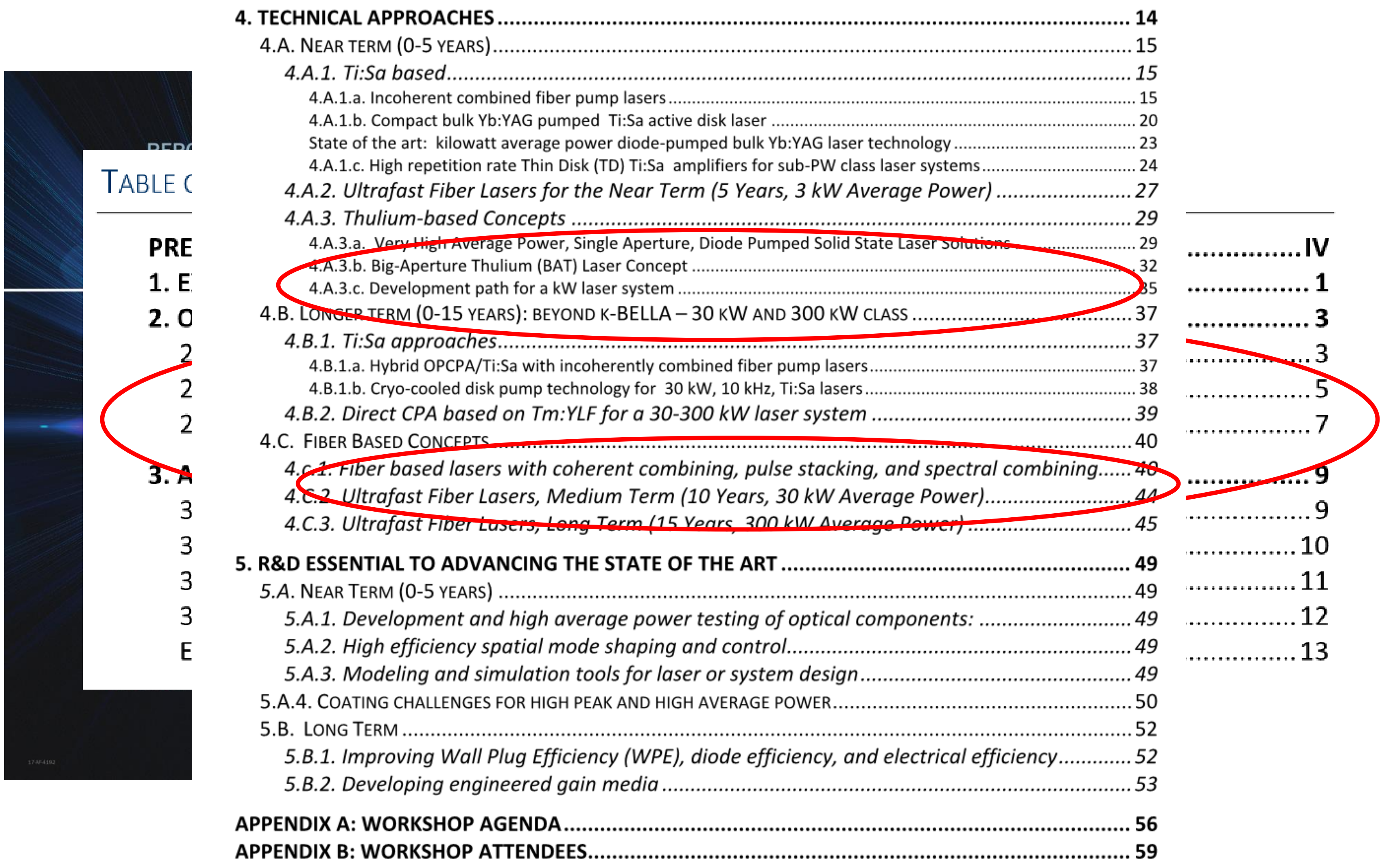
How short?

Multi-pulse? Modulation of ps pulses? External injection? MOPA? Different injection & acceleration stage lasers?

Lasing medium?

What's out there?

Technology Options



Laser requirements

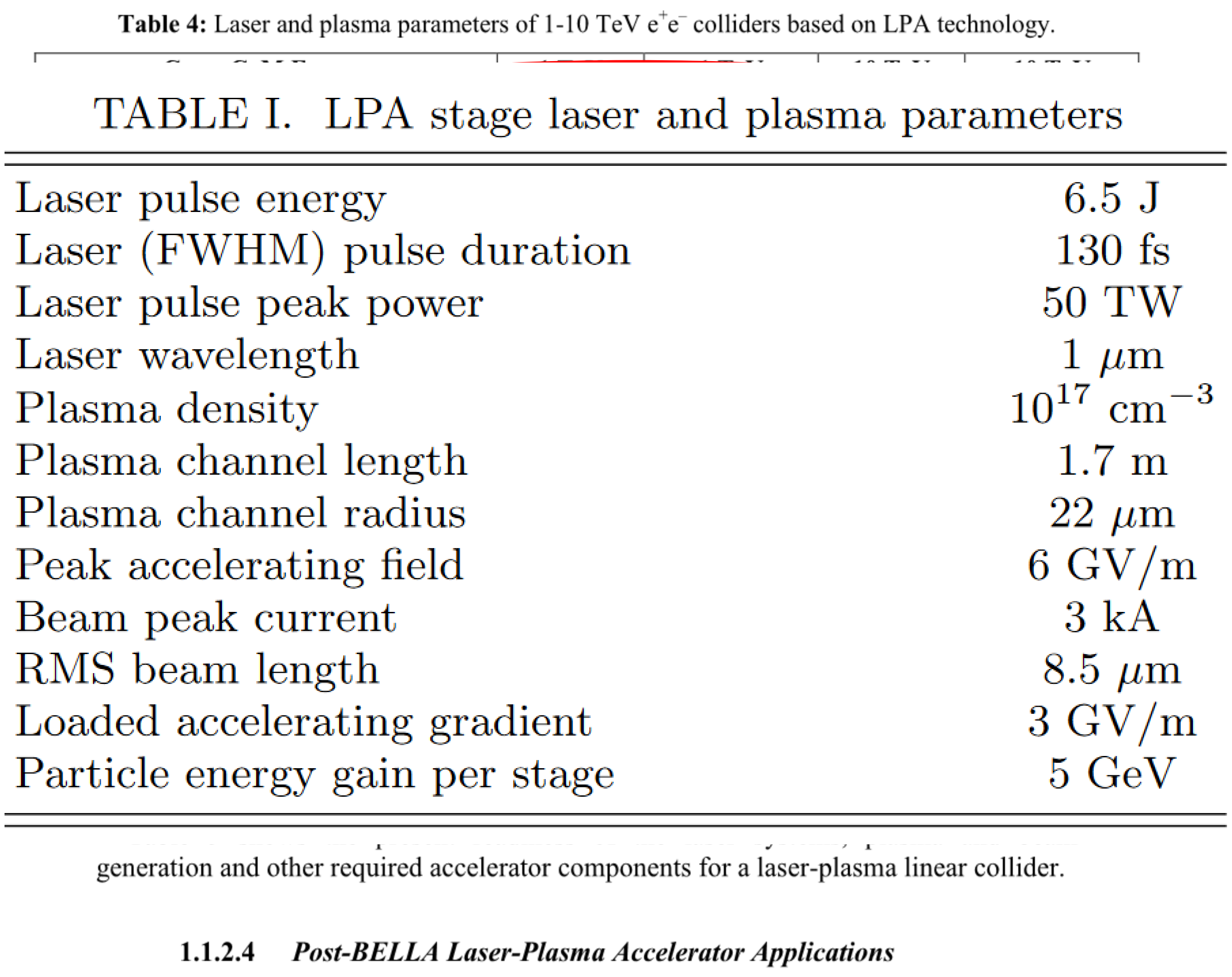


Table 4: Laser and plasma parameters of 1-10 TeV e^+e^- colliders based on LPA technology.

TABLE I. LPA stage laser and plasma parameters

Laser pulse energy	6.5 J
Laser (FWHM) pulse duration	130 fs
Laser pulse peak power	50 TW
Laser wavelength	1 μm
Plasma density	10^{17} cm^{-3}
Plasma channel length	1.7 m
Plasma channel radius	22 μm
Peak accelerating field	6 GV/m
Beam peak current	3 kA
RMS beam length	8.5 μm
Loaded accelerating gradient	3 GV/m
Particle energy gain per stage	5 GeV

generation and other required accelerator components for a laser-plasma linear collider.

1.1.2.4 ***Post-BELLA Laser-Plasma Accelerator Applications***

Benedetti et al.
arXiv:2203.08366

https://www-bd.fnal.gov/icfabd/WhitePaper_final.pdf

What can we improve right now?

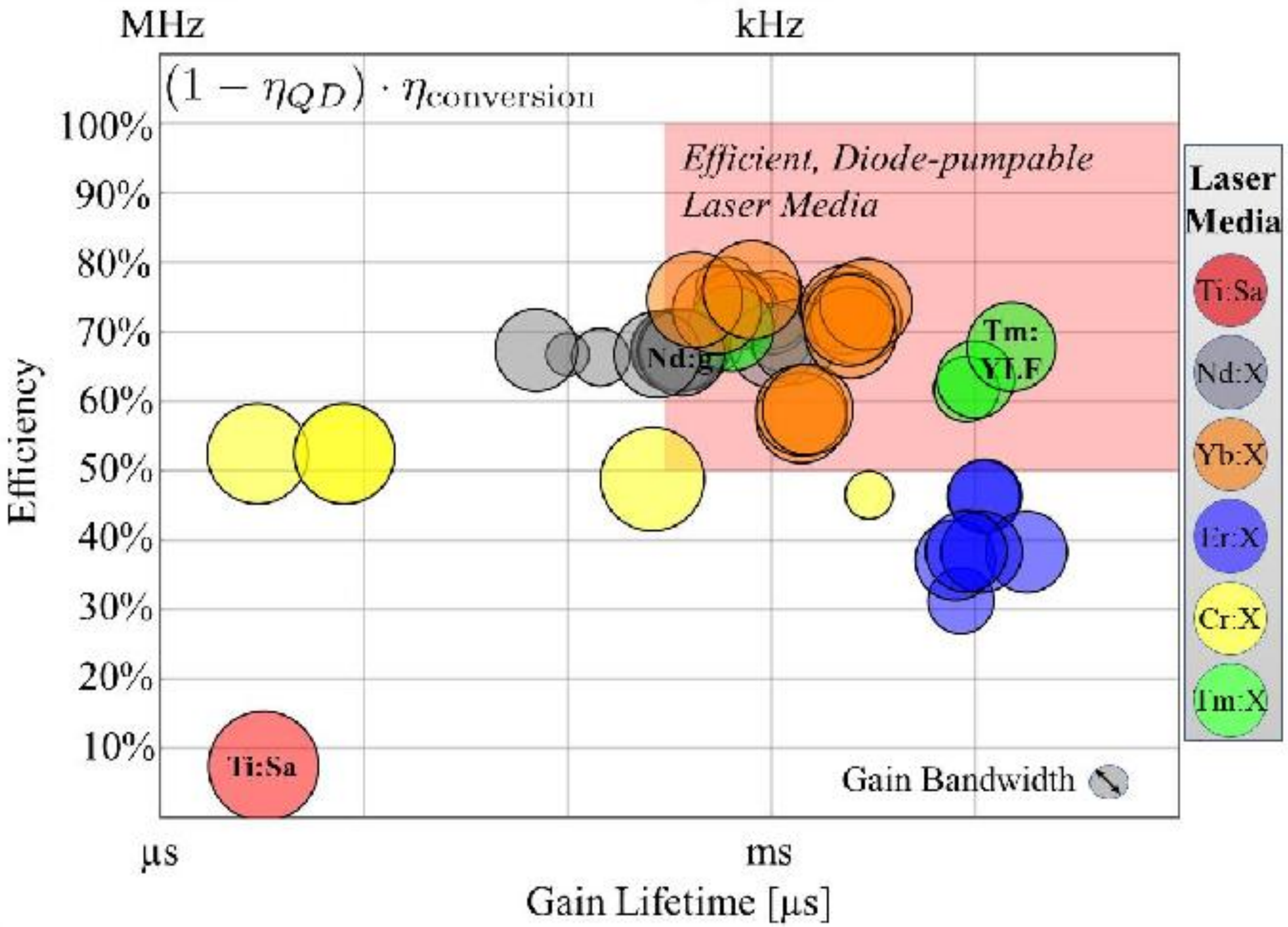
Ti:sapp lasers:

- Well known.
- Commercially available.
- Optics and experiments built around 800nm drive.

What can we improve on a longer timescale?

- New laser media
- New ways of using lasers we already have.

Laser Medium Options



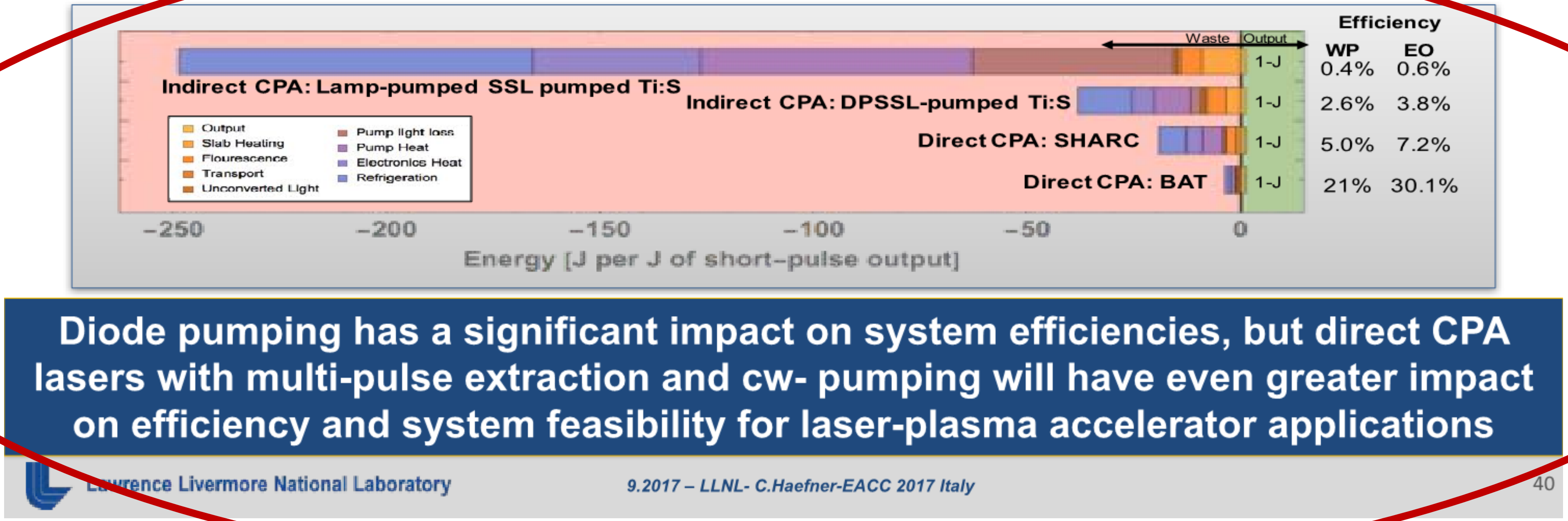
Slide Prof. C. Haefner

https://agenda.infn.it/event/12611/contributions/15316/attachments/11189/12585/2017_08_29_EACC_plenary_Haefner_final-_compressed_-_upload.pdf

Summary

- LLNL is exploring avenues to break the kW barrier for high peak power lasers to drive high flux x-ray, ɣ-ray, and particle beams

- Performed extensive architecture and material study. Crucially important for high average power lasers is high wall-plug efficiency: reduce heat (once heat is in it's expensive and hard to pull it out) and heat effects (heating-cooling gradients cause beam deterioration, break stuff and limit average power)
  - Direct CPA increases dramatically the efficiency; beam quality and temporal pulse contrast require additional attention
  - Long radiative lifetime gain media become available through multi-pulse extraction at safe energy extraction fluencies
  - CW-pumping reduces massively the capital cost for high average power DPSSL



Diode pumping has a significant impact on system efficiencies, but direct CPA lasers with multi-pulse extraction and cw- pumping will have even greater impact on efficiency and system feasibility for laser-plasma accelerator applications

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9.2017 – LLNL- C.Haefner-EACC 2017 Italy

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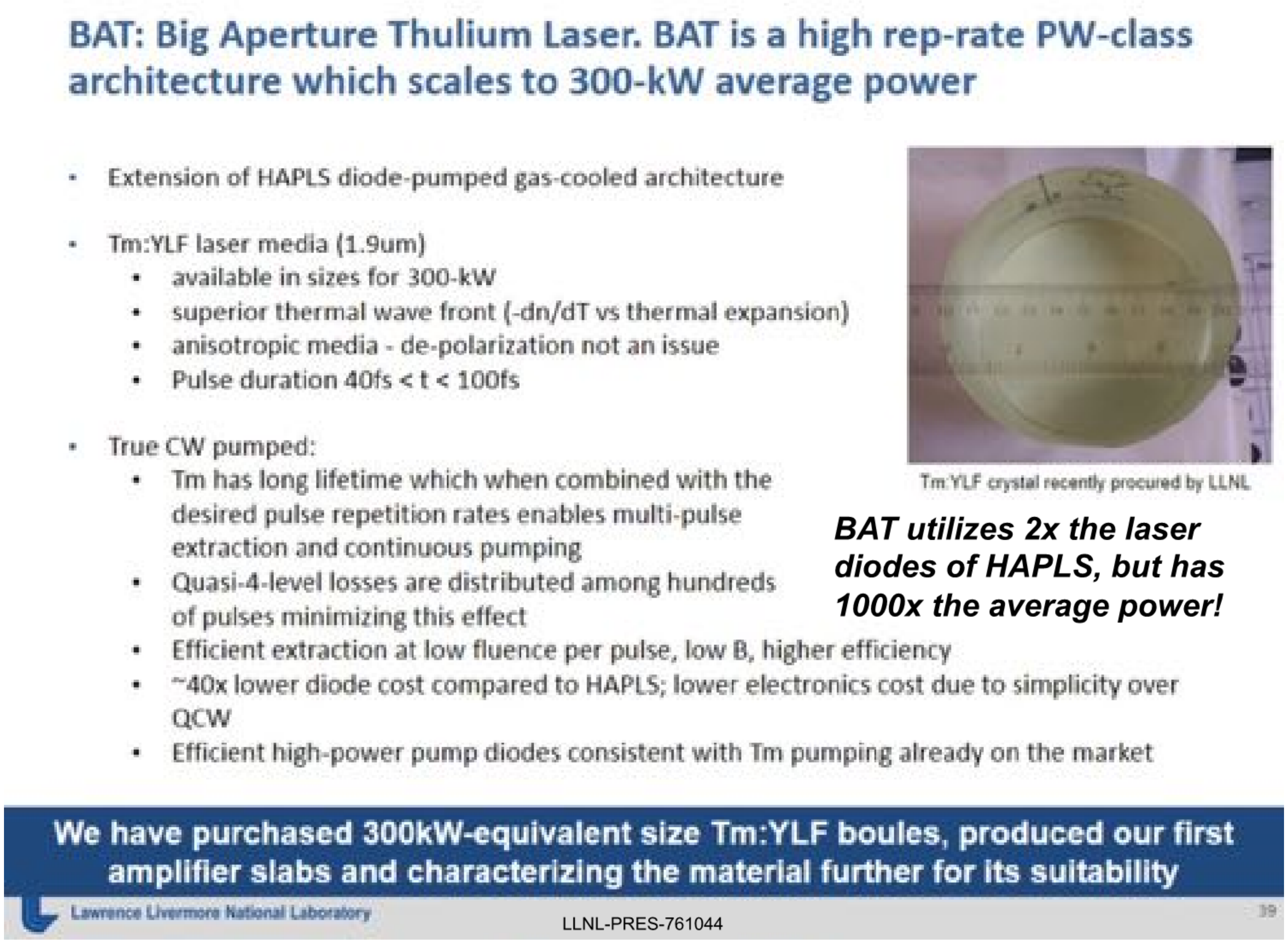
Thulium Lasers



BAT: Big Aperture Thulium Laser. BAT is a high rep-rate PW-class architecture which scales to 300-kW average power

- Extension of HAPLS diode-pumped gas-cooled architecture
- Tm:YLF laser media (1.9um)
  - available in sizes for 300-kW
  - superior thermal wave front (-dn/dT vs thermal expansion)
  - anisotropic media - de-polarization not an issue
  - Pulse duration 40fs < t < 100fs
- True CW pumped:
  - Tm has long lifetime which when combined with the desired pulse repetition rates enables multi-pulse extraction and continuous pumping
  - Quasi-4-level losses are distributed among hundreds of pulses minimizing this effect
  - Efficient extraction at low fluence per pulse, low B, higher efficiency
  - ~40x lower diode cost compared to HAPLS; lower electronics cost due to simplicity over QCW
  - Efficient high-power pump diodes consistent with Tm pumping already on the market

Tm:YLF crystal recently procured by LLNL

BAT utilizes 2x the laser diodes of HAPLS, but has 1000x the average power!

We have purchased 300kW-equivalent size Tm:YLF boules, produced our first amplifier slabs and characterizing the material further for its suitability

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LLNL-PRES-761044

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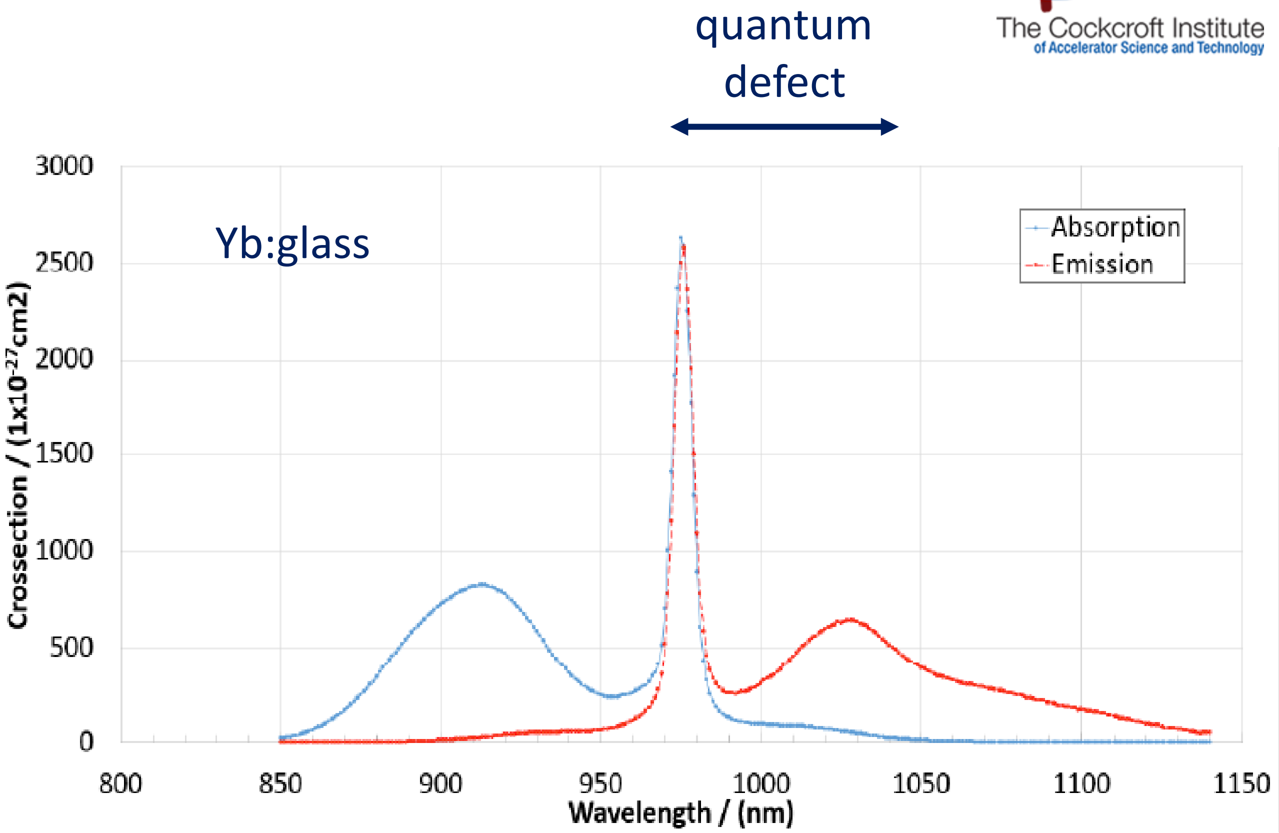
Prof. C. Haefner

Fibre lasers

- **Fibre lasers:**
  - Yb – low quantum defect.
  - Direct diode pumping nir (@976nm).
  - Optical-optical 80%.
  - WPE 40%.
  - Single mode – efficiency at focus (intensity!)
  - Air/water cooled.

- **Current laser drivers for LWFA:**
  - High peak power (100s TW/PW systems, J, <100 fs)
  - Low repetition rates ~ 1Hz (low average power)
  - Inefficient – expensive to run



Fibre lasers:

- High repetition rates (> kHz)
- Low pulse energy (~ mJ)
- Single fibres considered limited to < 10GW peak power (Schimpf et al. J. Opt. Soc. Am. B. 27 20151 (2010))

Can we use this technology to make both high **peak and average** power lasers?

Make many low energy pulses into one high energy pulse – coherent combination

Coherent combination

- Tiled aperture v. filled aperture

Tiled aperture:

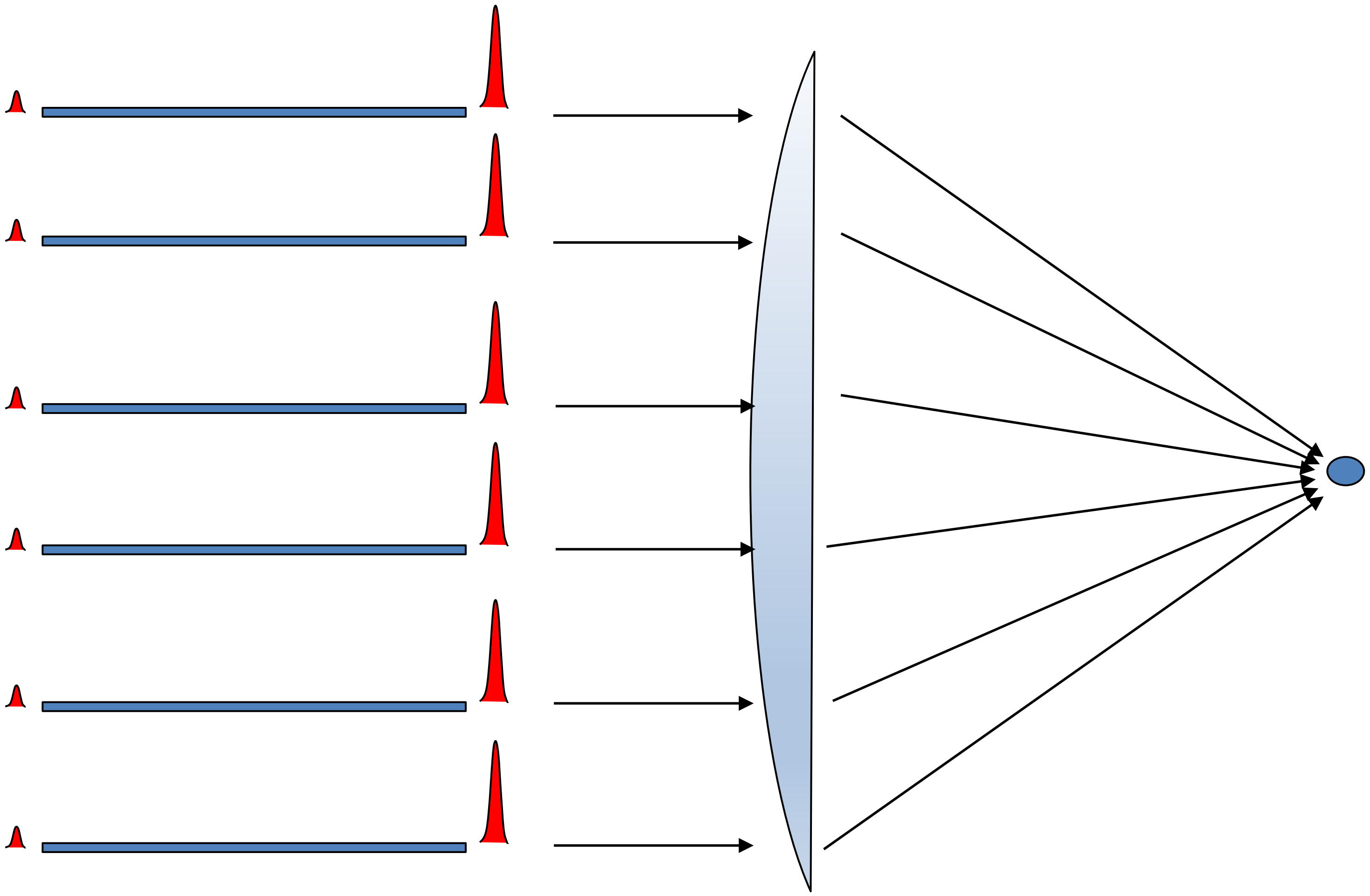
- Beams placed alongside each other.
- Combined in the far field.
- No beam combination element.
- Inherent < 100% combination.
- Energy in side lobes.
- Phase control.

Filled aperture:

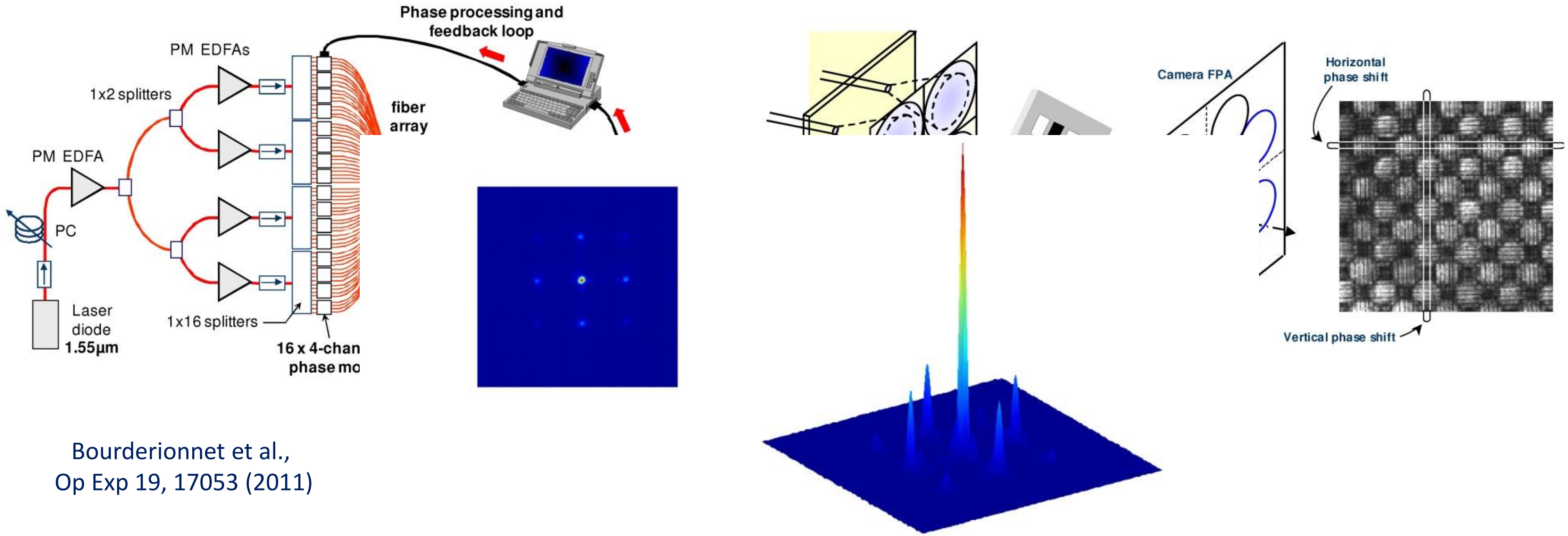
- Beams combined in near and far field.
- Beam combination element(s) required.
- Scaling with channel number?
- Phase control.

Review: Fathi et al., Photonics 8, 566 (2021)

Tiled aperture



Tiled aperture combination

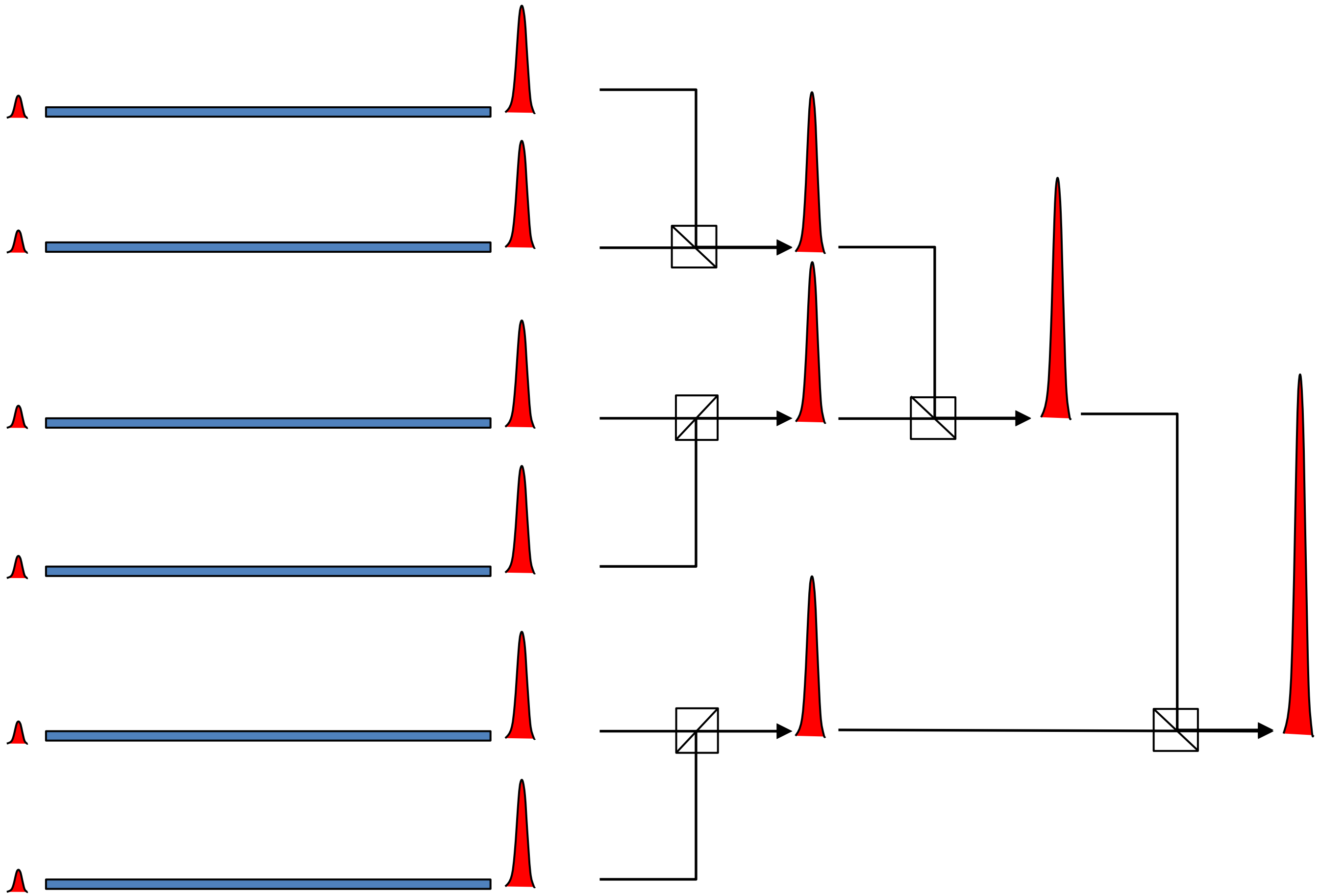


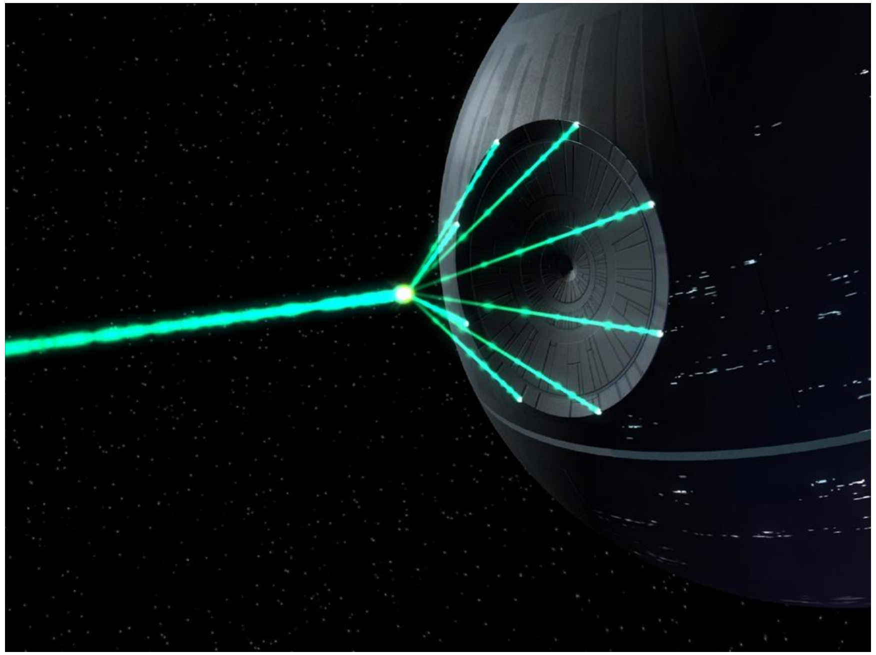
Bourderionnet et al.,
Op Exp 19, 17053 (2011)

- Signal split and amplified in 64 cw fibres with integrated phase modulators.
- Light collected in microlens array.
- Phase between adjacent fibres analysed in quadriwave lateral shearing interferometer.
- 34% beam in central lobe (cf 44% theoretical).

Filled aperture combination

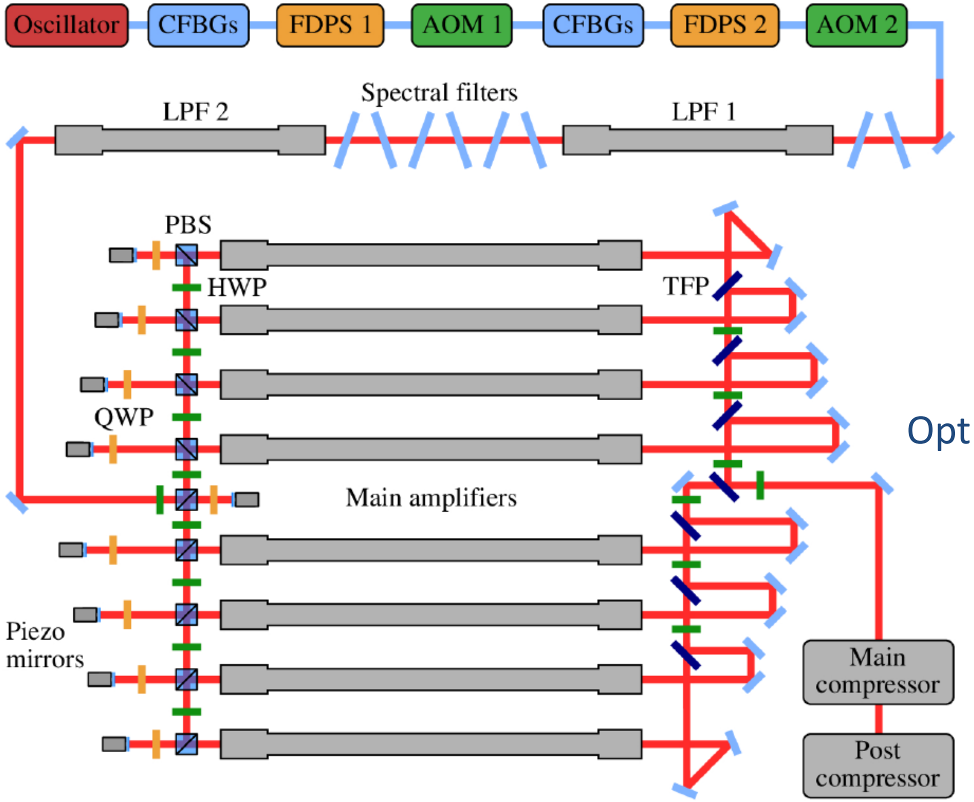
Binary tree example – polarisation combination and locking





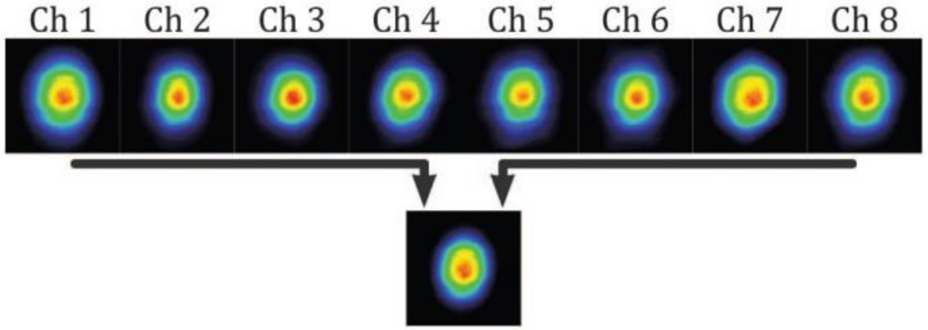
Limits of beam splitter based combining:
Müller et al., Opt. Exp. 29, 27900 (2021)

Polarisation combination

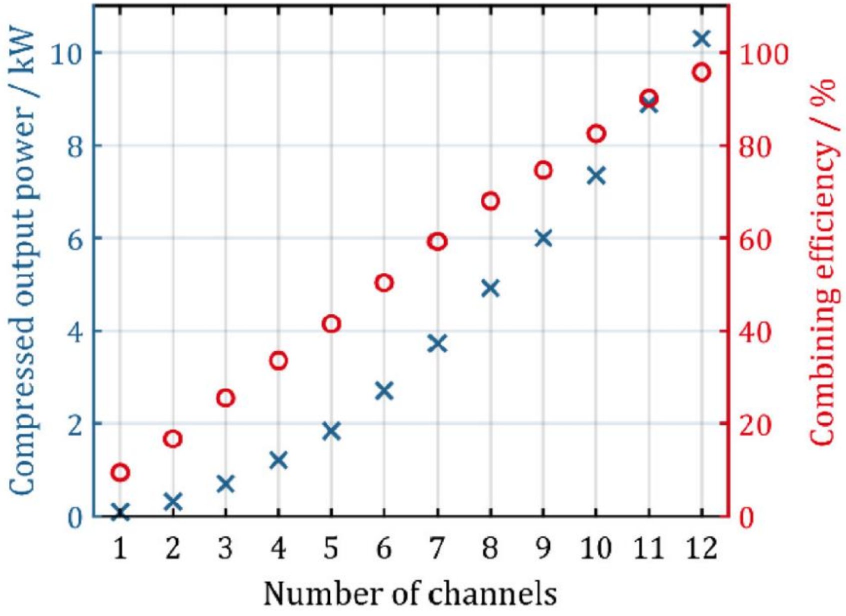


Stark et al.,
Opt. Letts. 46, 969 (2021)

Müller et al., Opt. Letts. 41, 3439 (2016)



Müller et al., Opt. Letts. 45, 3083 (2020)



- Seed split and amplified in large pitch photonic crystal fibres.
- Polarisation – piezo mirror phase control.
- 1 MHz, 1.1mJ, 1kW, 8 fibres (2016).
- 80MHz, **>10kW,** 254fs, 12 fibres (2020).
- 100kHz, **10mJ,** 1kW, **120fs,** 16 fibres (2021).
- Does not scale gracefully to > 1000 fibres.

Commercial systems

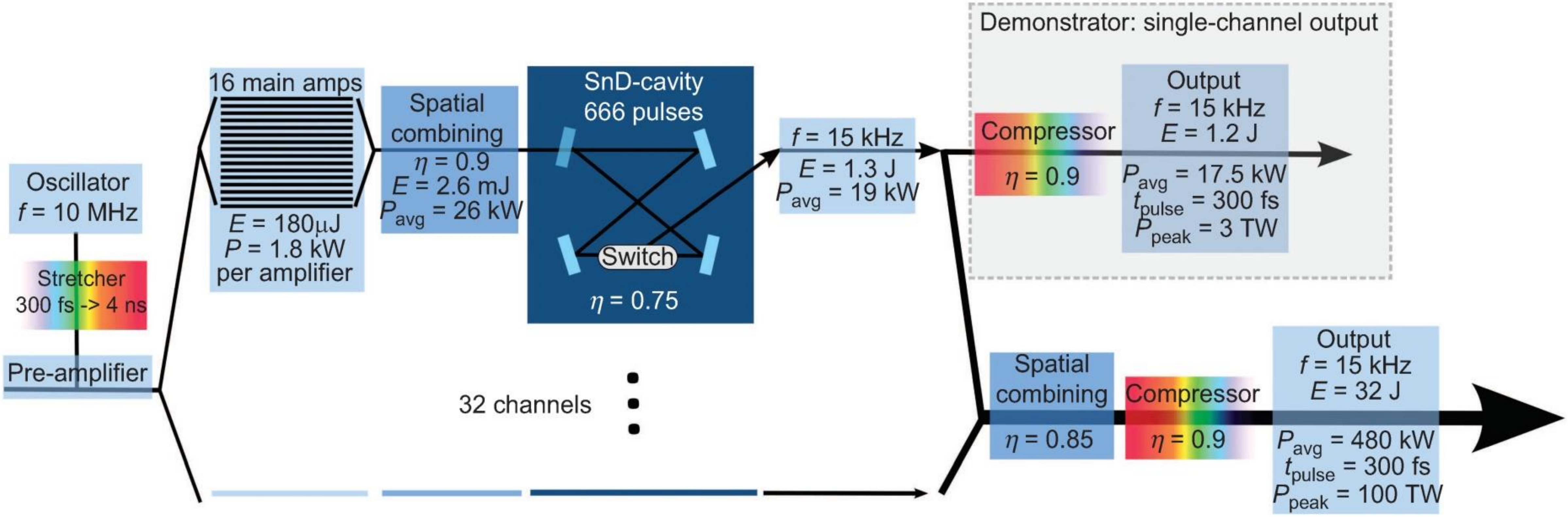
Main amplifier design

afs

Member of the TRUMPF Group

Active Fiber Systems GmbH I www.afs-jena.de I 22

Enhancement cavities

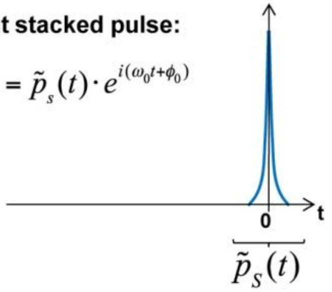


Breitkopf et al., Light Sci. Appl. 3, e211 (2014)
Breitkopf et al. Appl. Phys. B 122, 297 (2016)

Enhancement cavities

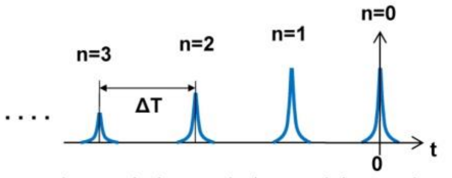
Output stacked pulse:

$${}^{out}\tilde{p}(t) = \tilde{p}_s(t)\cdot e^{i(\omega_0 t+\phi_0)}$$

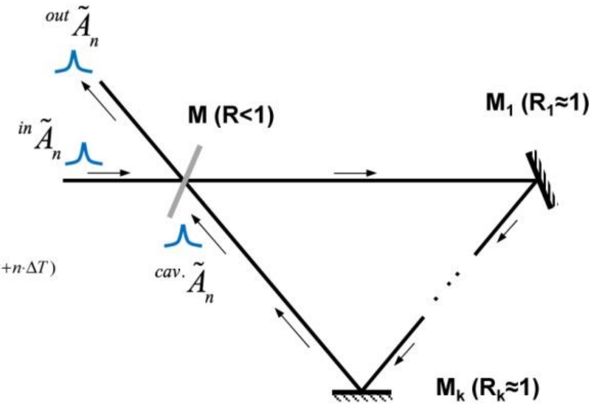


Input stacking pulse burst:

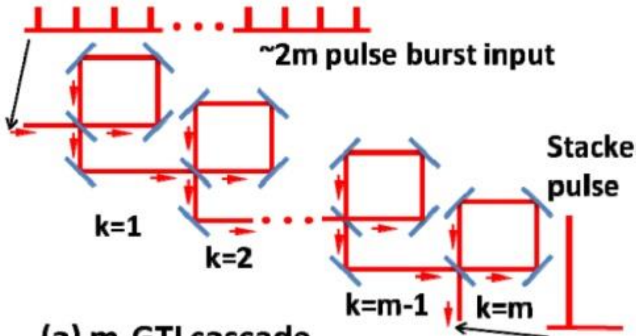
$${}^{in}\tilde{p}(t) = \sum_{n=0}^{\infty} {}^{in}\tilde{p}_n(t) = \sum_{n=0}^{\infty} {}^{in}\tilde{A}_n\cdot\tilde{p}_s(t+n\cdot\Delta T)\cdot e^{i\omega_0(t+n\cdot\Delta T)}$$



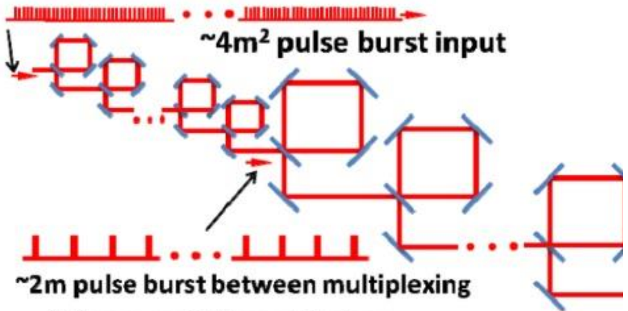
$$\ldots\; {}^{in}\tilde{p}_3(t)\quad {}^{in}\tilde{p}_2(t)\quad {}^{in}\tilde{p}_1(t)\quad {}^{in}\tilde{p}_0(t) = {}^{in}\tilde{A}_0\cdot\tilde{p}_s(t)\cdot e^{i\omega_0 t}$$



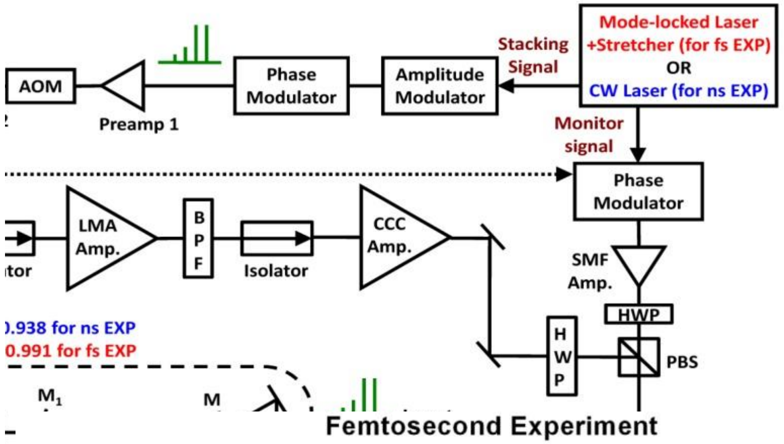
GTI Resonant Cavity

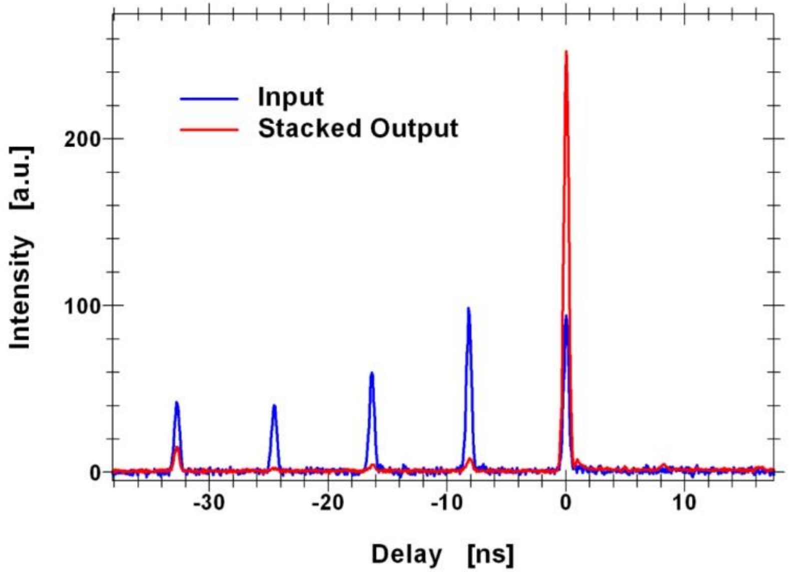


(a) m-GTI cascade

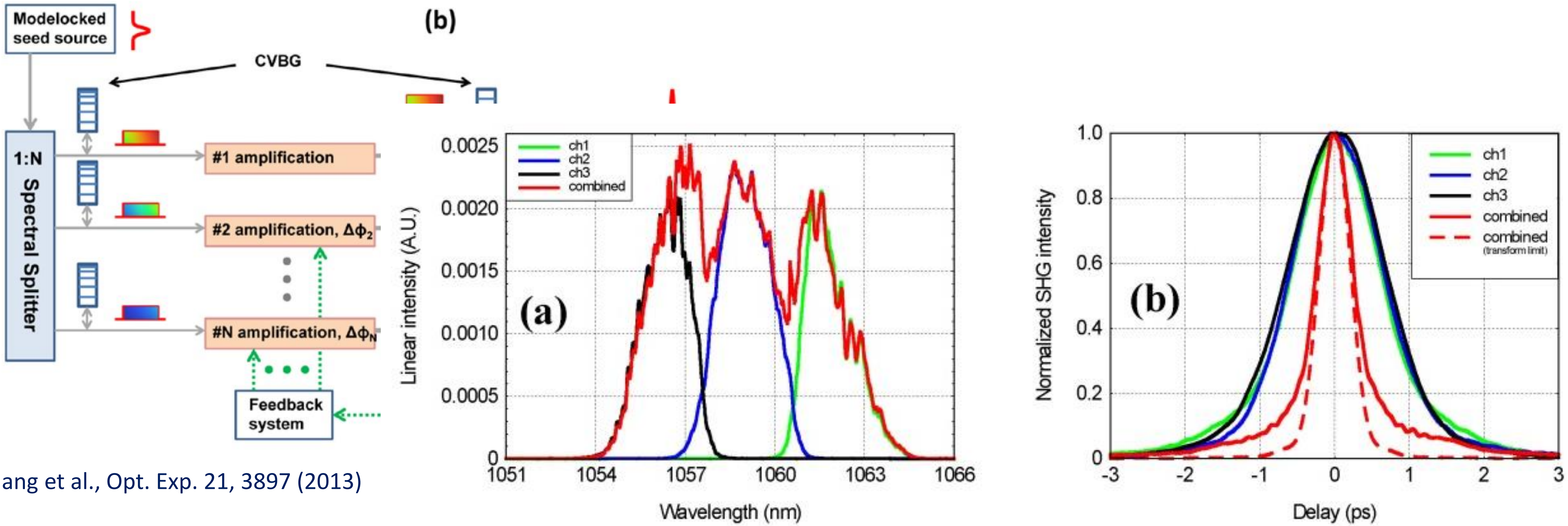


(b) m×m GTI multiplex





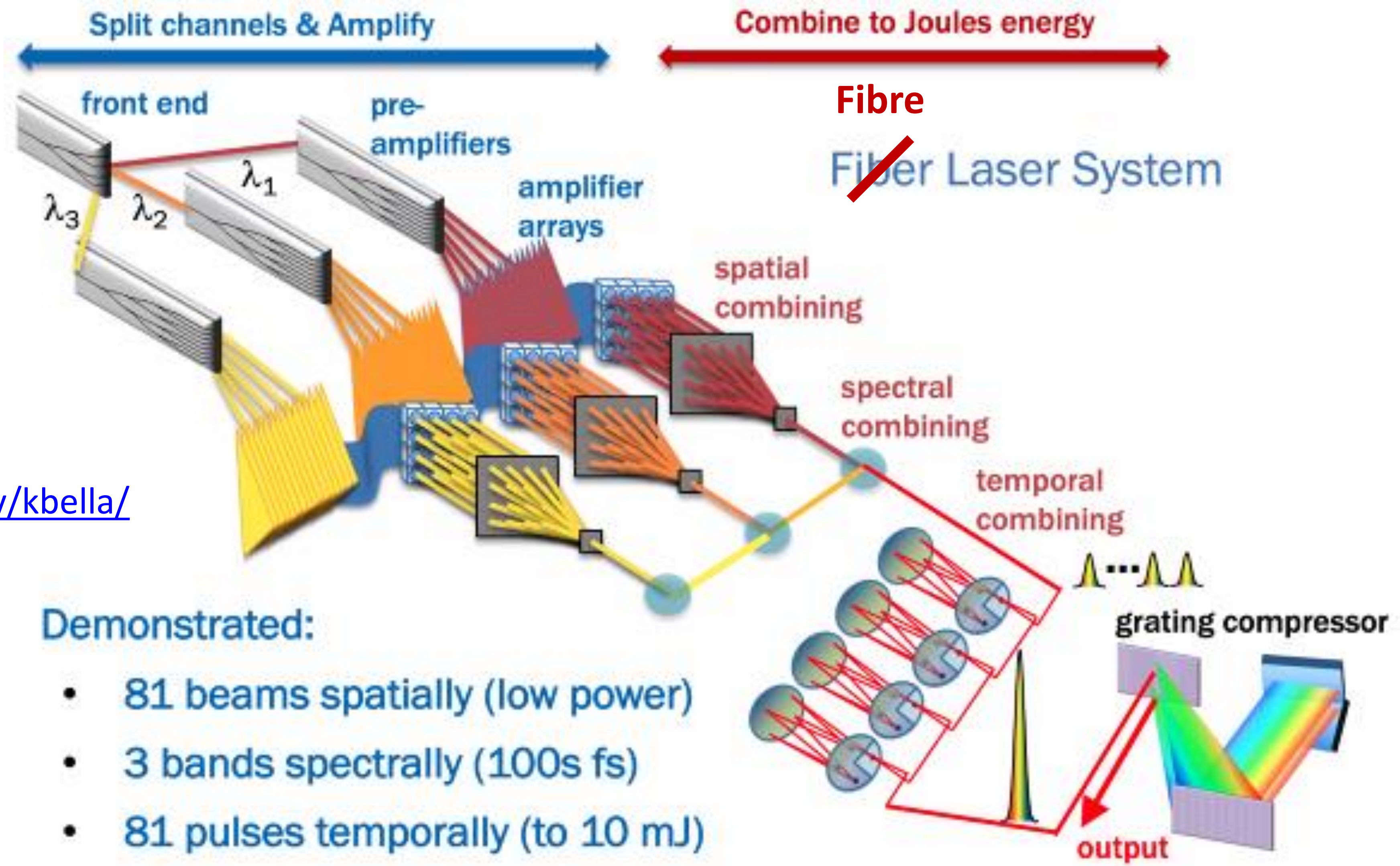
Spectral combination



Chang et al., Opt. Exp. 21, 3897 (2013)

- Seed split **spectrally** with filters and amplified in different fibre channels.
- Amplified pulses combined on spectral filters and compressed.
- Feedback from TPA detector.

Do everything! k-BELLA



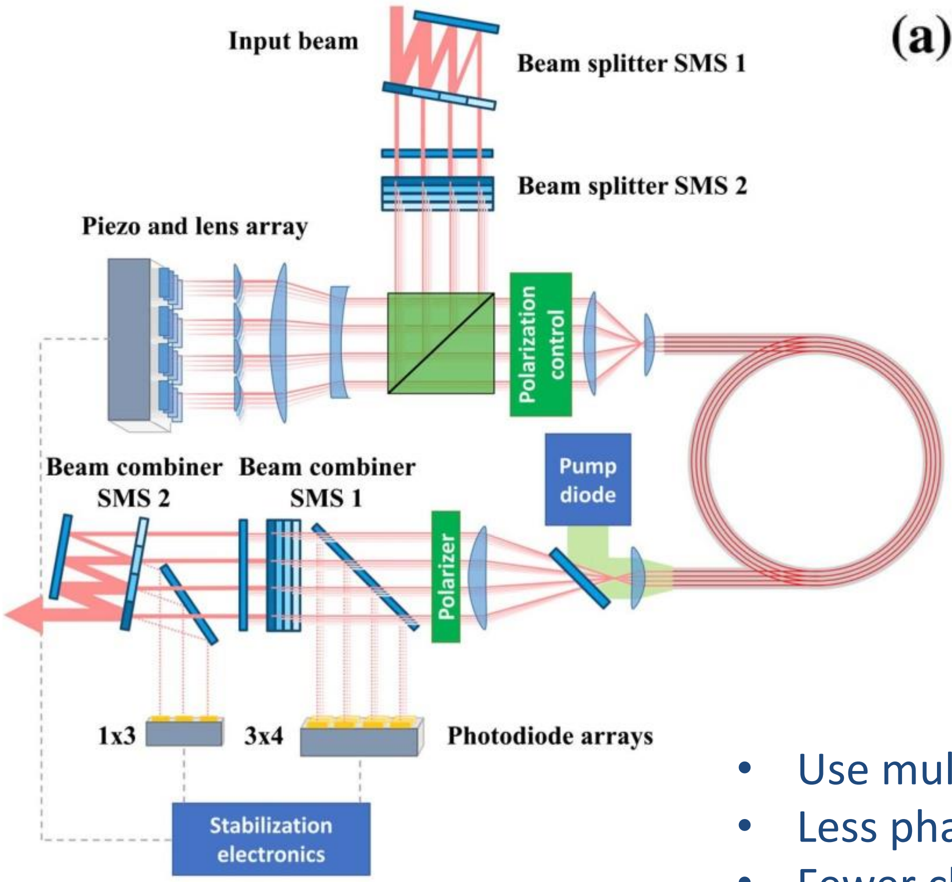
Demonstrated:

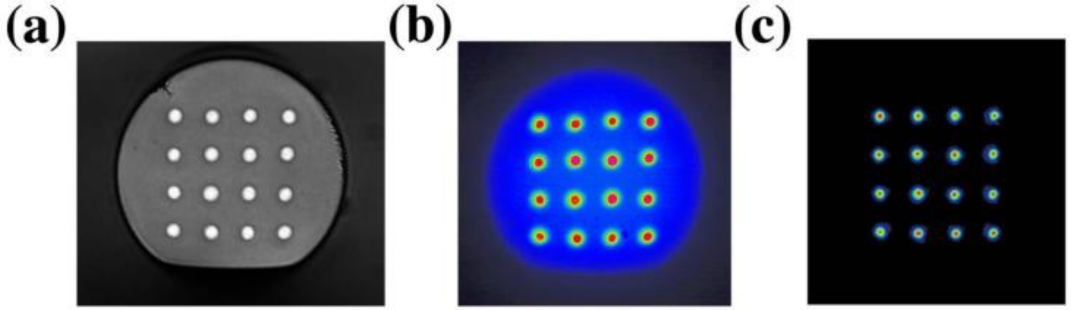
- 81 beams spatially (low power)
- 3 bands spectrally (100s fs)
- 81 pulses temporally (to 10 mJ)

https://bella.lbl.gov/kbella/

Concept: R. Wilcox, A. Galvanauskas, W. Leemans
https://www2.lbl.gov/LBL-Programs/atap/Report_Workshop_k-BELLA_laser_tech_final.pdf

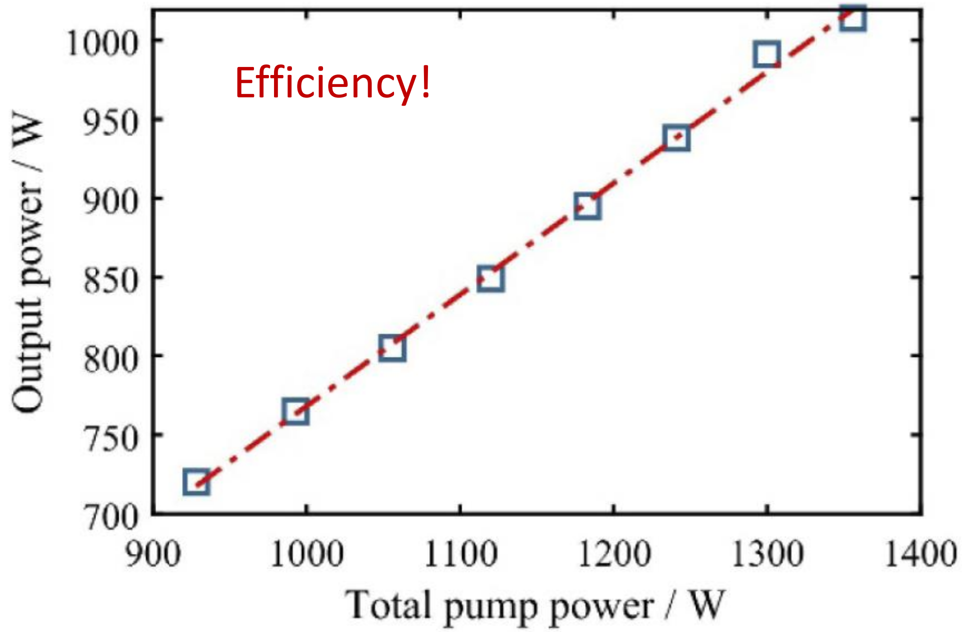
Multicore fibres





Klenke et al.,
Opt. Letts. 43, 1519 (2018)

- Use multicore fibre.
- Less phase difference to correct.
- Fewer channels.

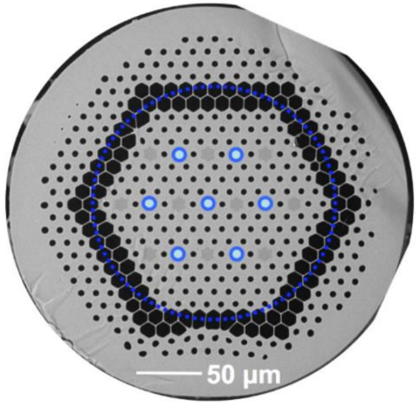


Efficiency!

Klenke et al., Opt. Letts. 47, 345 (2021)

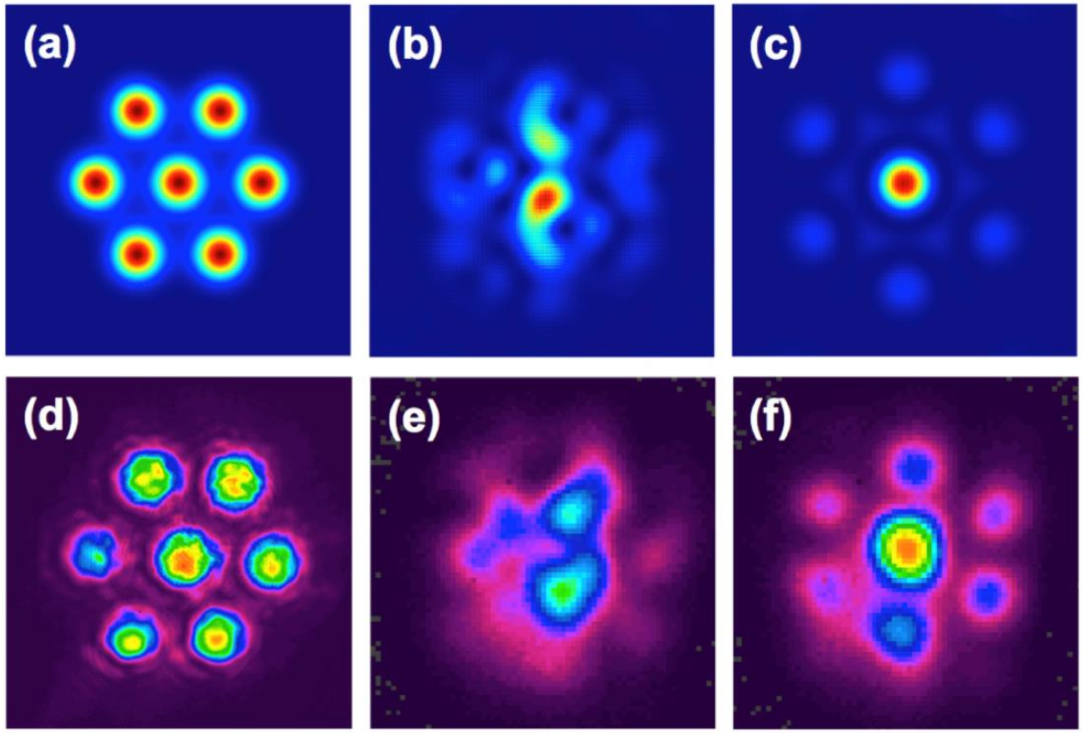
- **ps pulses – 70W, 40ps.**
- **fs pulses – 500W & 600mJ, 500fs.**

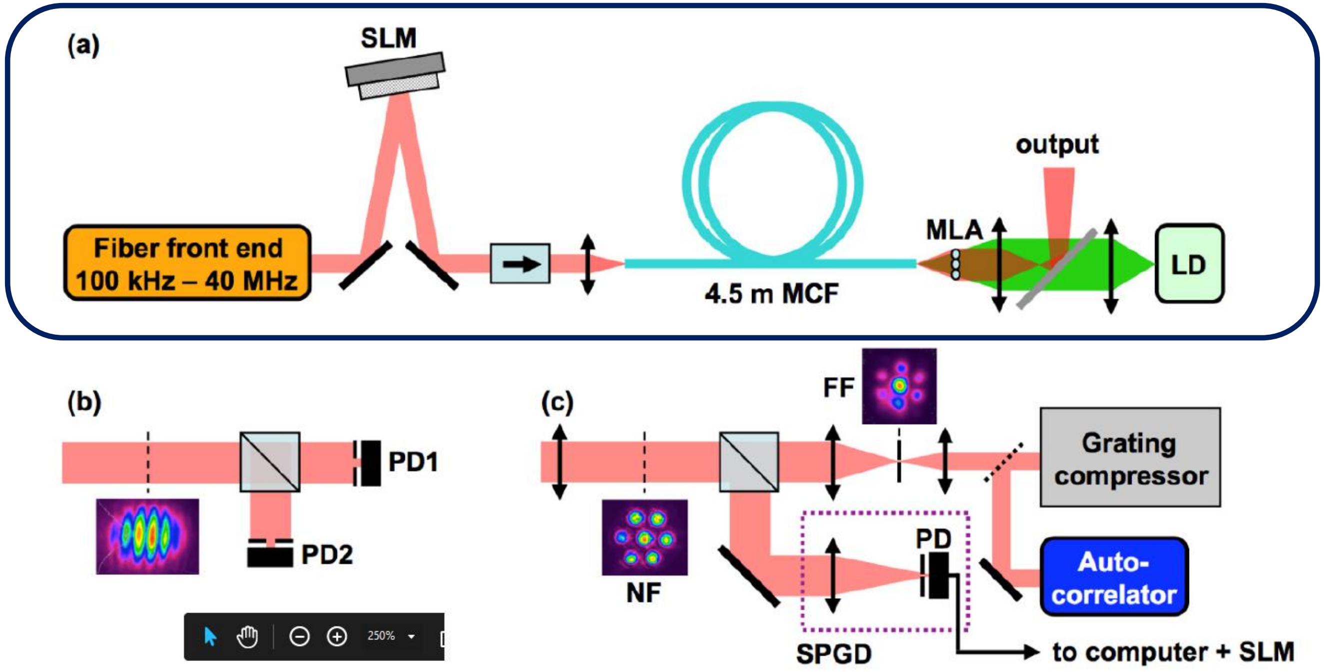
Tiled aperture multicore fibre combination



Rameriz et al., Opt. Exp. 23, 5407 (2015)

- 7 core Yb fibre
- 690fs (a/c), 2.6W
- 49% coupling (76% theoretical max.)





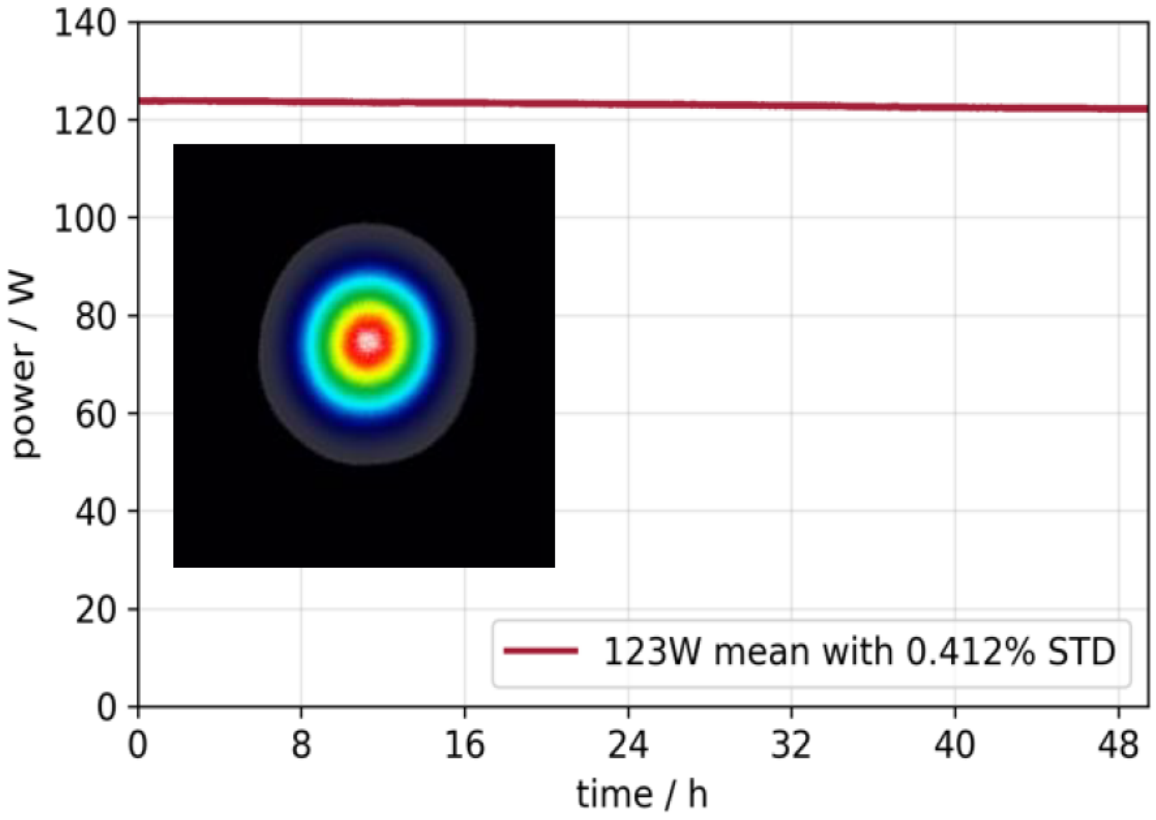
Thulium fibres and combination

Not just Yb doped fibres!

Tm cw systems combined:
Zhou et al., Proc. SPIE 7843, High-Power Lasers and Applications V, 784307(2010)
P Honzatko et al., Laser Physics Letters 10, 095104 (2013)

Coherent combination of pulsed Tm doped fibres:

- **120fs, 228μJ,** > 120W.
- Stable > 48hr operation.



C. Gaida et al., proc. CLEO/Europe-EQEC, 1 (2021)

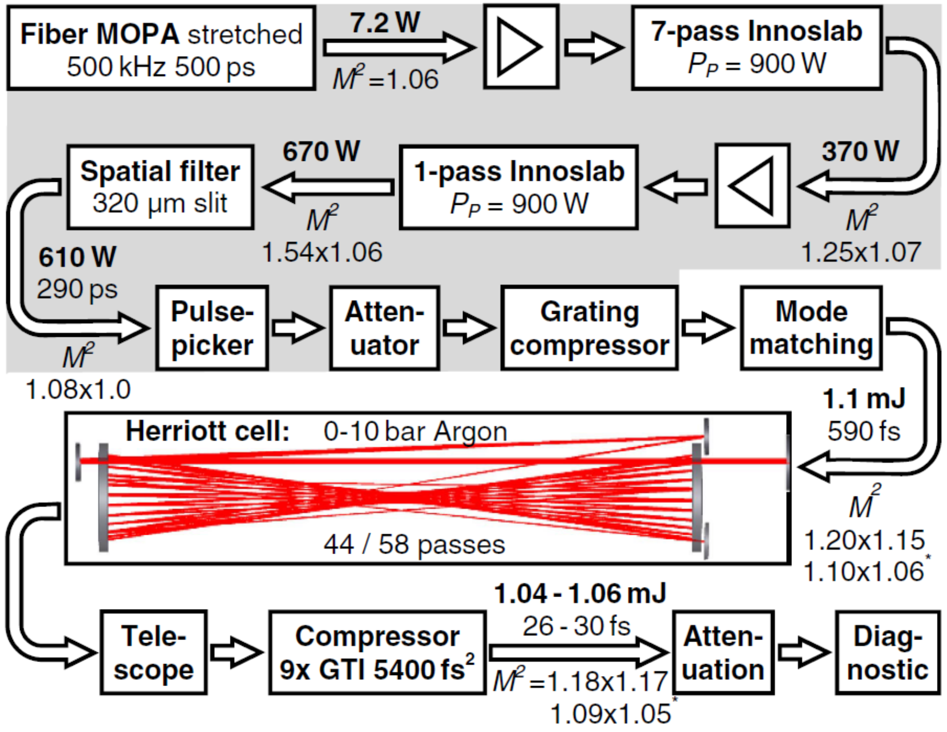
Coherent combination of fibre lasers

Highly successful technology:

- 16 pulsed fibre lasers combined – 100kHz, **10mJ,** 1kW, **120f**s.
  Müller et al., Opt. Letts. 45, 3083 (2020)
- 64 continuous wave fibre lasers combined.
  Bourderionnet et al., Opt. Exp. 19, 17053 (2011)
- 8 channels combined with spatial and temporal division – **12mJ**, 56kHz, **260fs.**
  Kienel et al., Opt. Letts. 41, 3343 (2016)
- 2 fibre lasers combined **passively** in Sagnac interferometer – 1.1mJ, 50kHz, 300fs.
  Guichard et al., Opt. Letts. 40, 89 (2015)

All experiments carried out with identical fibre amplifiers
How does this scale to > 1000 fibres?

Multipass cells for pulse shortening

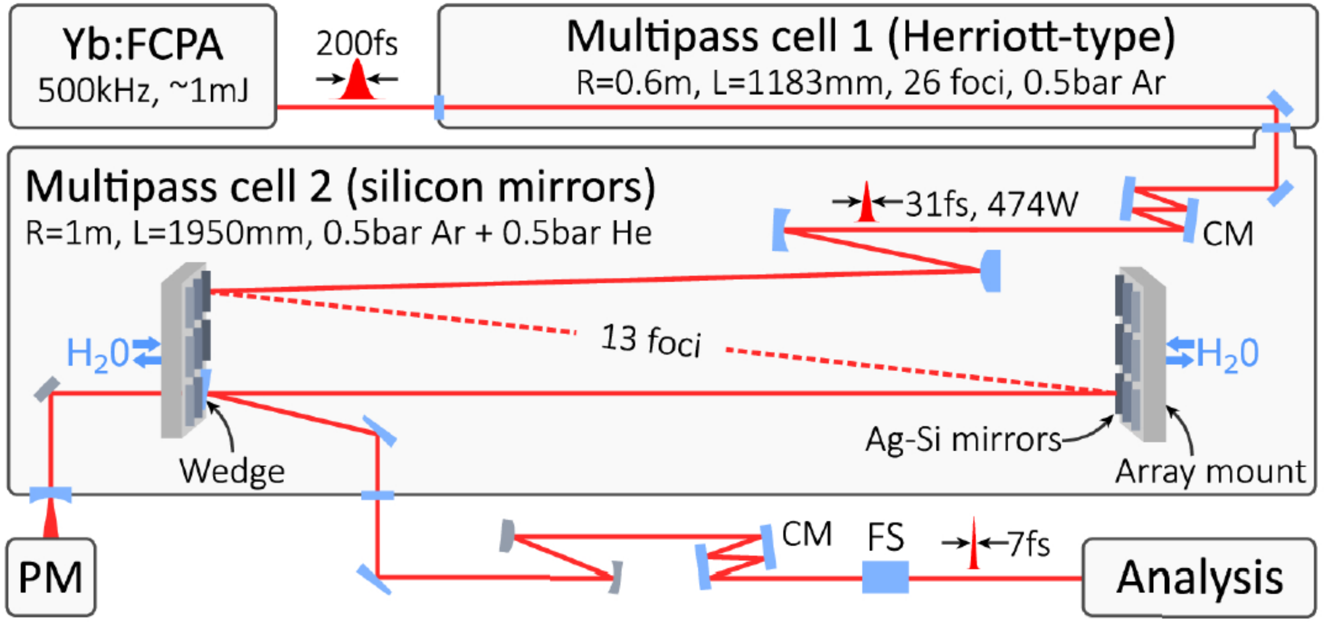


Russbueldt et al., Opt. Letts. 44, 5222 (2019)

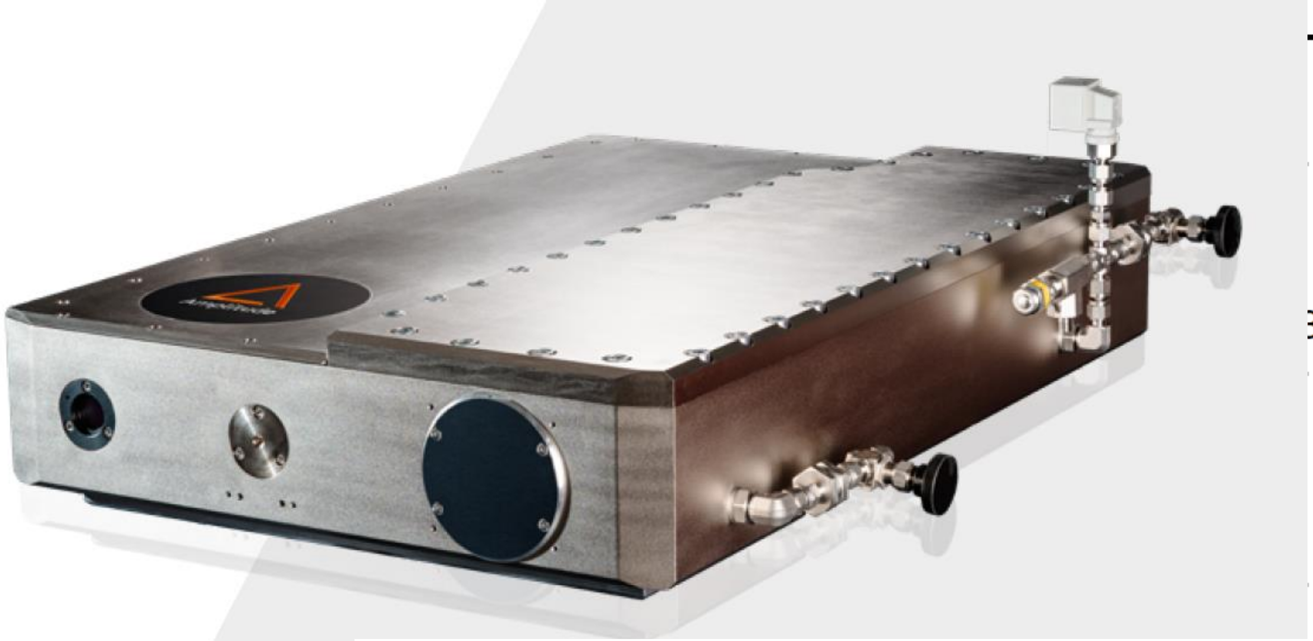
- 600fs to 30fs
- 96% transmission
- > 500W, > 1mJ, Yb:fibre

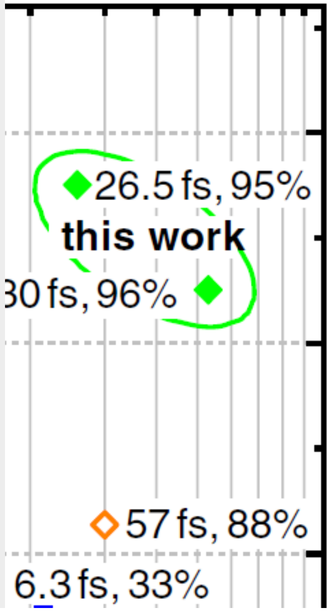
Müller et al., Opt. Letts. 46, 2678 (2021)

- 200fs to 7fs
- 82% transmission
- > 380W, > 700µJ, Yb:fibre



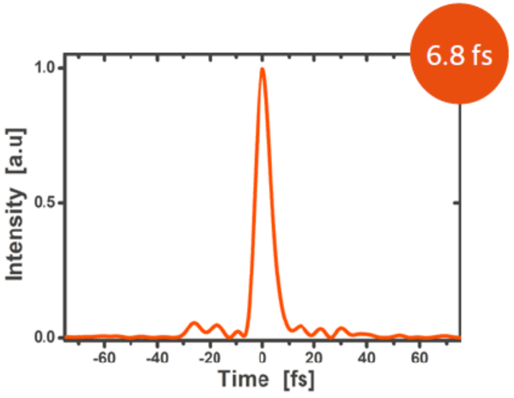
Pulse broadening





Russbueldt et al.,
Opt. Letts. 44, 5222 (2019)

Specifications	Compress 10	Compress 50
Input Average Power	Up to 300 W	
Input Energy	Up to 3 mJ	
Input Pulse Duration	< 150 fs to 1 ps	
Operation Wavelength	1030 nm and 515 nm	
Repetition Rate	from single shot up to 40 MHz	
Throughput	up to > 80%	up to > 50 %
Compression Ratio	up to > 10	up to > 50
Output Pulse Compression	down to < 20 fs	down to few cycle
Long Term Stability	< 1% rms over 100 hours	

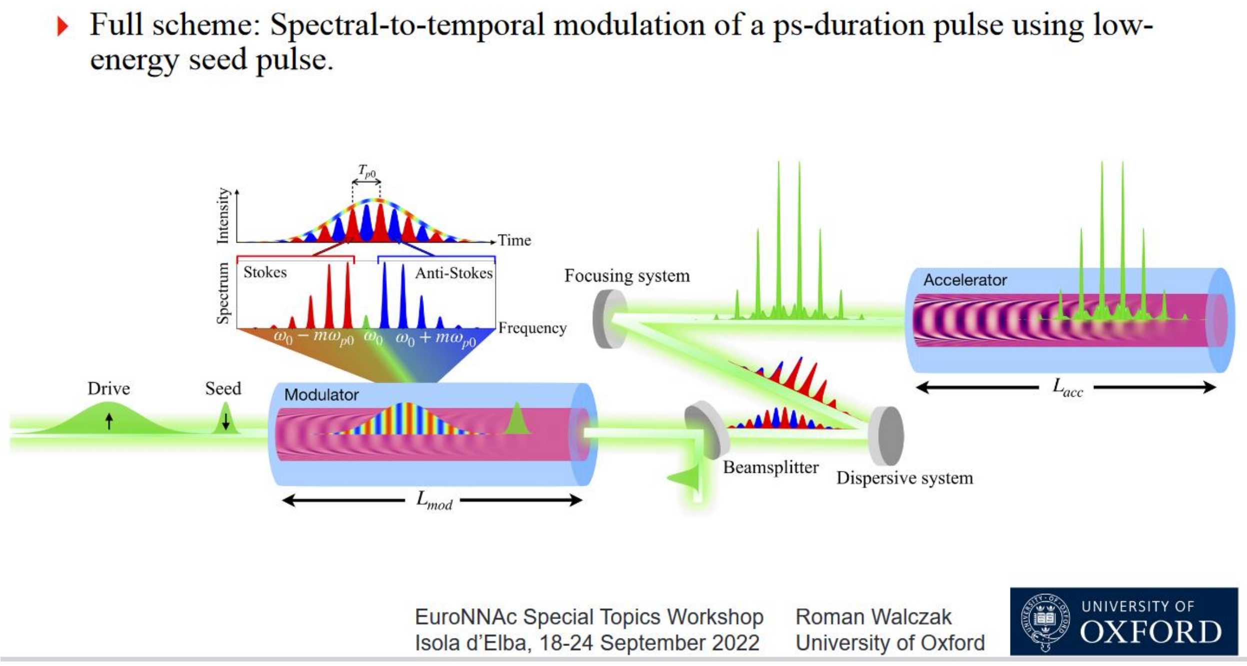


Sub-two cycle pulse generation with COMPRESS 50

Different approaches to driving LWFA

Multi-pulse – use train of low energy pulses to build up large amplitude wakefield – MP-LWFA, REMPI.

S.M. Hooker et al. *J. Phys. B: At. Mol. Opt. Phys.* 47 234003 (2014)
J. Cowley et al. Phys. Rev. Lett. 119, 044802 (2017)
P. Tomassini et al. Physics of Plasmas 24, 103120 (2017)

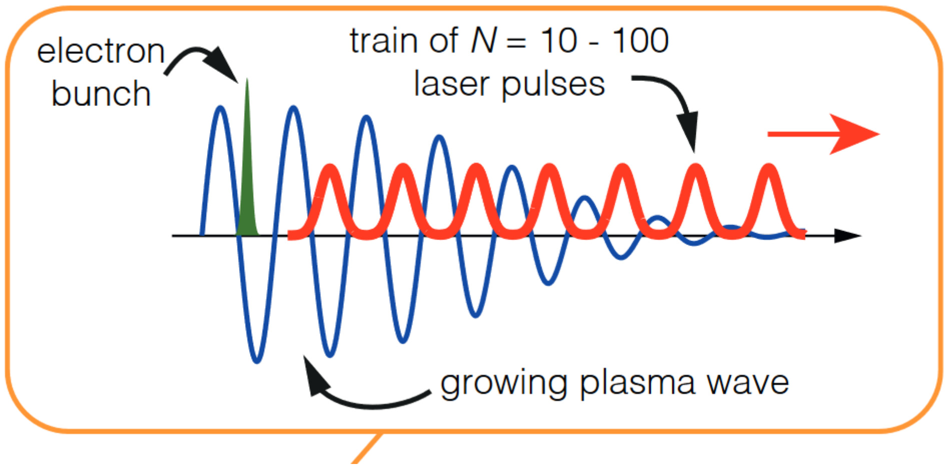


- Full scheme: Spectral-to-temporal modulation of a ps-duration pulse using low-energy seed pulse.

EuroNNAc Special Topics Workshop
Isola d'Elba, 18-24 September 2022

Roman Walczak
University of Oxford

MP-LWFA



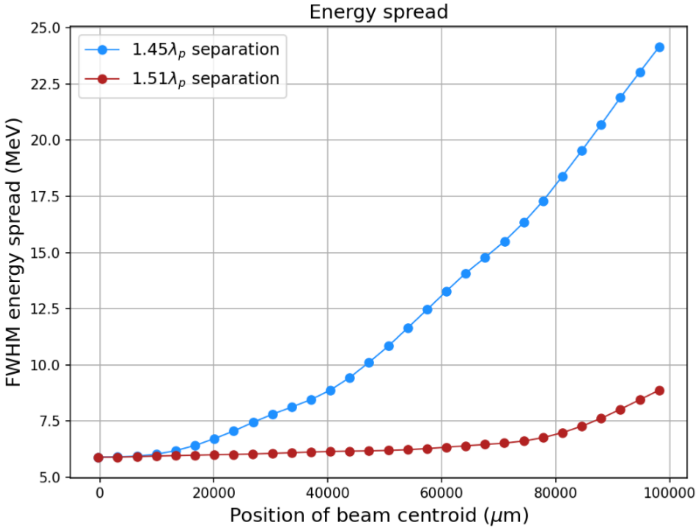
Modulation of ps pulse to create MP-LWFA train – Opens up use of different lasers.

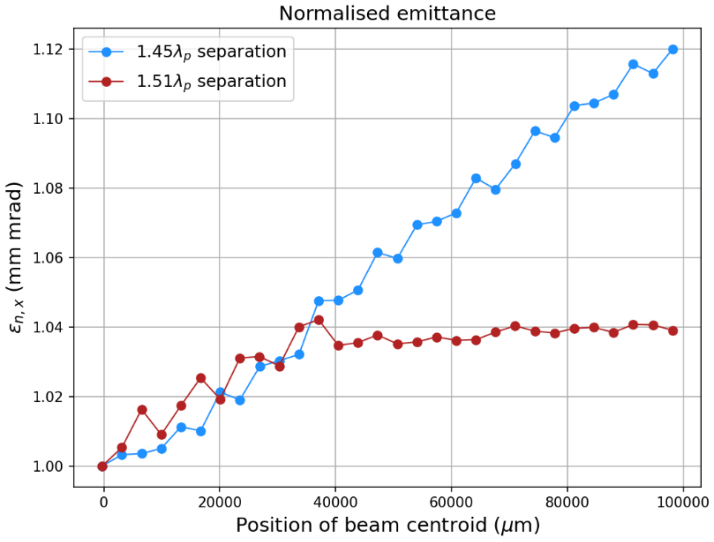
O. Jakobsson et al. Phys. Rev. Lett. 127, 184801 (2021)

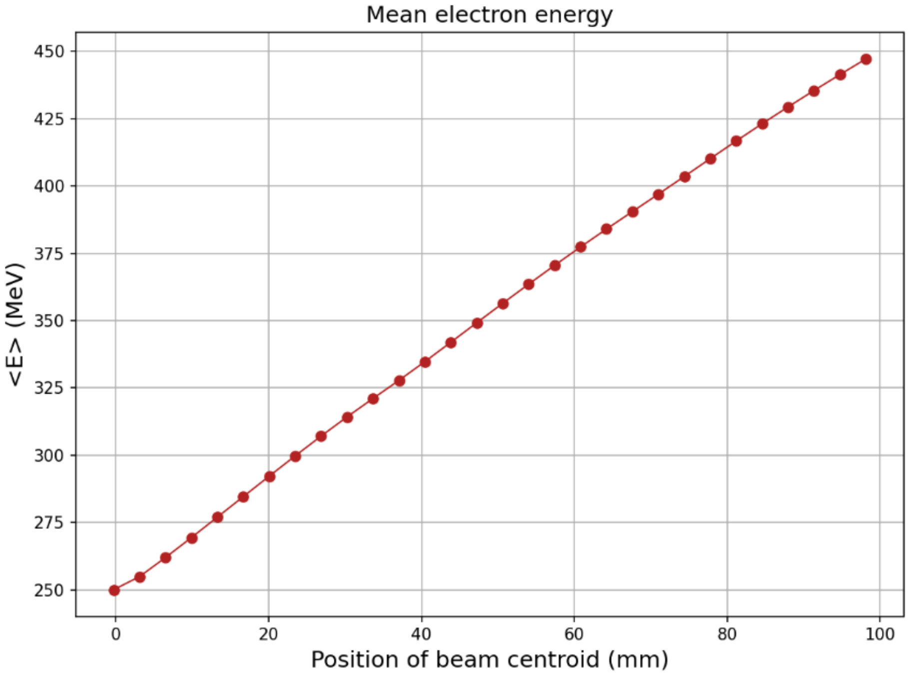
Fibre laser driver simulations

What can we do with a different (efficient!) laser?

Fibre laser: 2J, 150fs,
250MeV to **450MeV** in 100mm.
Gradient **2 GV/m.**







Energy spread: FWHM 2.4% - 3.5%.
Emittance: 1 mm mrad – 1.04 mm mrad.

Simulations not optimised!

Combined fibres have shown 120fs, 10mJ pulse energy and

20% measured WPE.

Interstage coupling?

Simulations: Jonathan Christie

Summary

Presented technology options for laser driven plasma wakefield acceleration:

- Different laser media? Th, Yb doping, CO_2?
- Coherent combination: Tiled aperture or filled aperture.
  - Binary combination.
  - Enhancement cavities – stack and dump, interferometric extraction.
  - Multicore fibres.

- Spectral broadening – open up other laser options?
- Multi-pulse
- Picosecond pulse

Lots of work to do, but very promising options:

I think we have 10s kHz solutions that can be efficient enough.

What else do we need?

Staging

High rep rate plasma sources

Staging

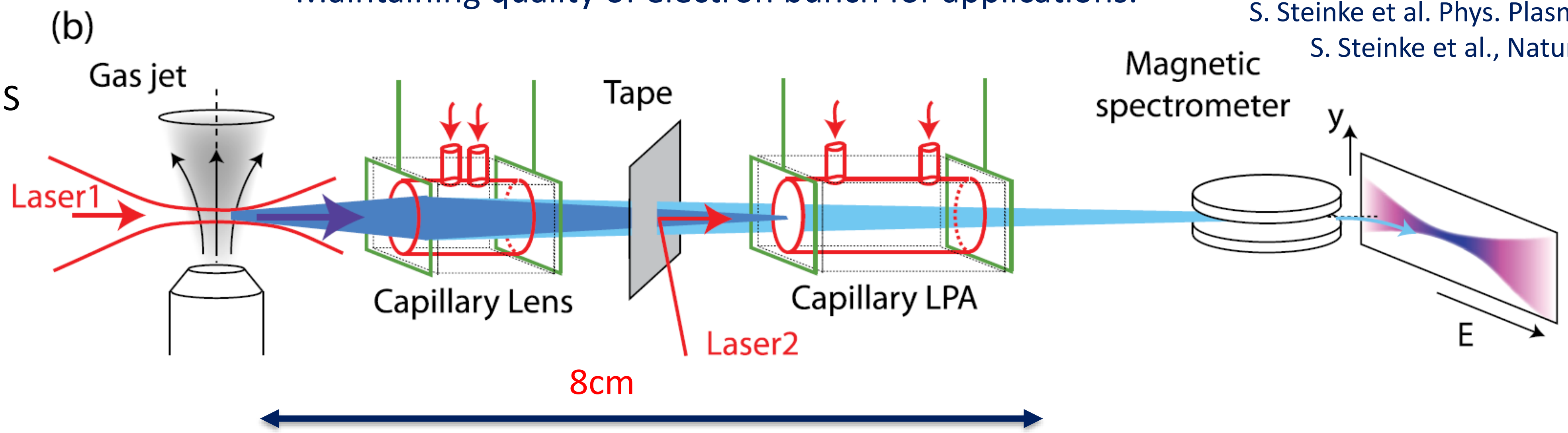
To reach TeV energies for a collider, need multiple 10 GeV stages.

Challenges:

- Capturing charge from first stage and injecting into second.
- Coupling in laser light without degrading electron bunch.
- Keeping distance between stages short – want to maintain high accelerating gradient.
- Maintaining quality of electron bunch for applications.

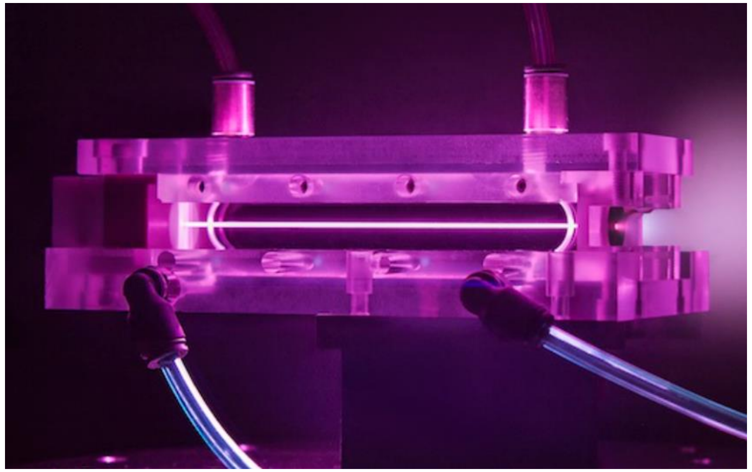
S. Steinke et al. Phys. Plasmas, 23, 056705 (2016);
S. Steinke et al., Nature 530, 190 (2016)

LBNL, US

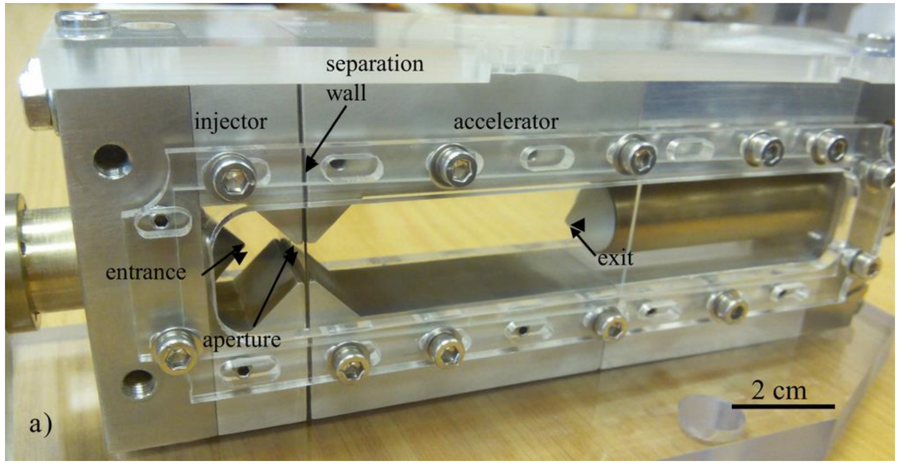


- 3.5% charge capture efficiency.
- Some electrons gain 100MeV in second stage.
- **Short in-coupling distance but low laser energy – how long can plasma mirrors operate?**
- **Solid state holed optics? Laser intensity?**

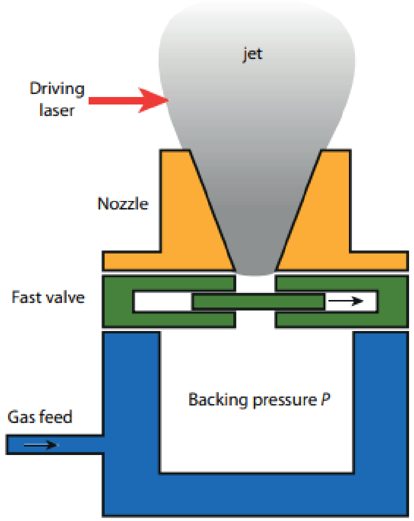
Gas targets – capillaries, cells, jets



- Complex construction.
- Vulnerable to laser damage.
- Designed for laser guiding.
- Requires HV sources.
- Less gas load.
- Harder optical access.
- Waveguide.



- Complex construction.
- Vulnerable to laser damage.
- No inherent guiding mechanism.
- Flexible design.
- Less gas load.



- Simple.
- Less vulnerable to damage.
- No guiding mechanism.
- Difficult to manufacture complex shapes.
- Easy optical access for diagnostics.
- Potentially large gas load into vacuum.

All options under active development and have been used successfully.

Laser Guiding

- Optical fibre – light guided as the refractive index decreases with distance from axis.

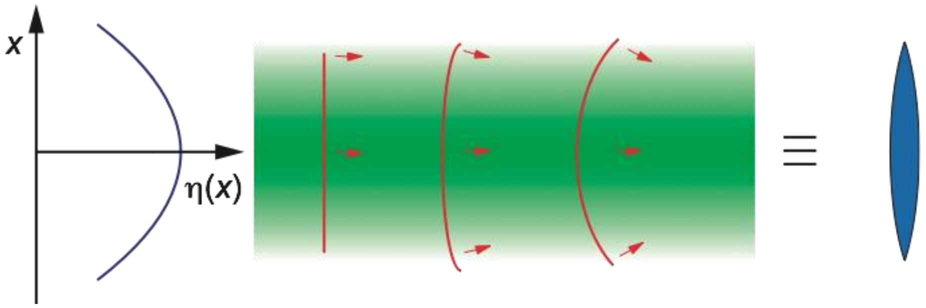
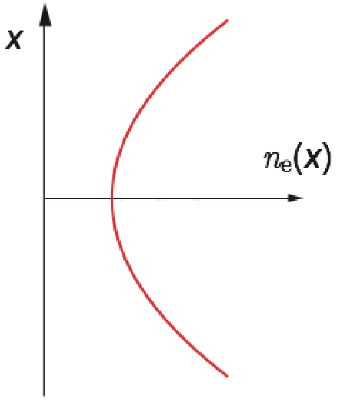


Fig: Prof. S. Hooker

- Can we do this in plasma? Yes!
- Transverse variation of electron density gives correct refractive index profile.
- No need to rely on self-guiding.



$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r) e^2}{\gamma m_e \epsilon_0 \omega^2}$$

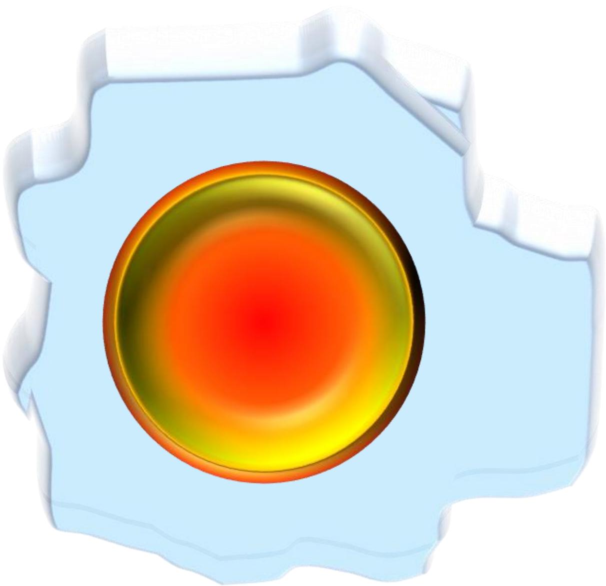


Fig: Dr. C. Arran

A plasma optical fibre!

Axicon formed HOFI plasma channels

- Capillary discharge systems successfully generate plasma waveguides.
- Can we do this without HV and structure in the laser beam?

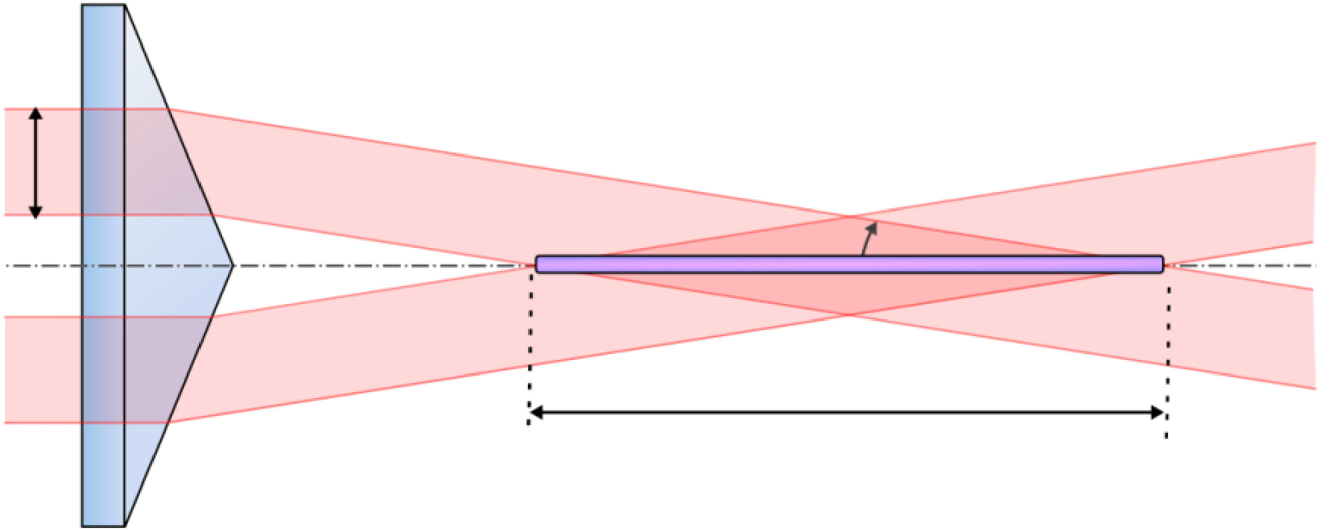


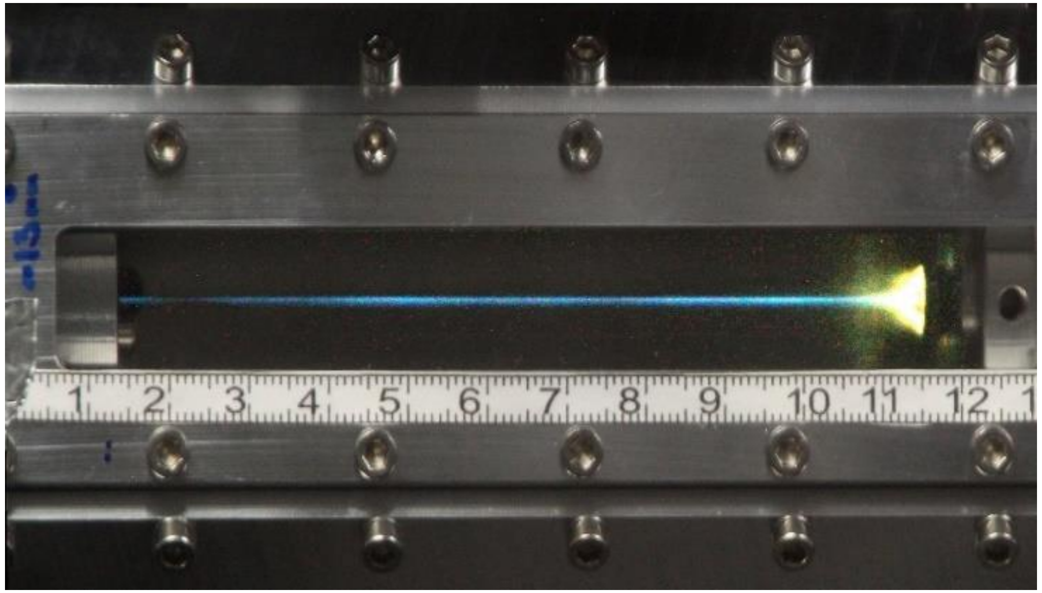
Fig: Dr. R. Shalloo & Prof. S.M. Hooker

R.J. Shalloo et al. PR AB 22, 041302 (2019)
A. Picksley et al. PR AB 23, 081303 (2020)
A. Picksley et al. PR E 102, 053201 (2020)

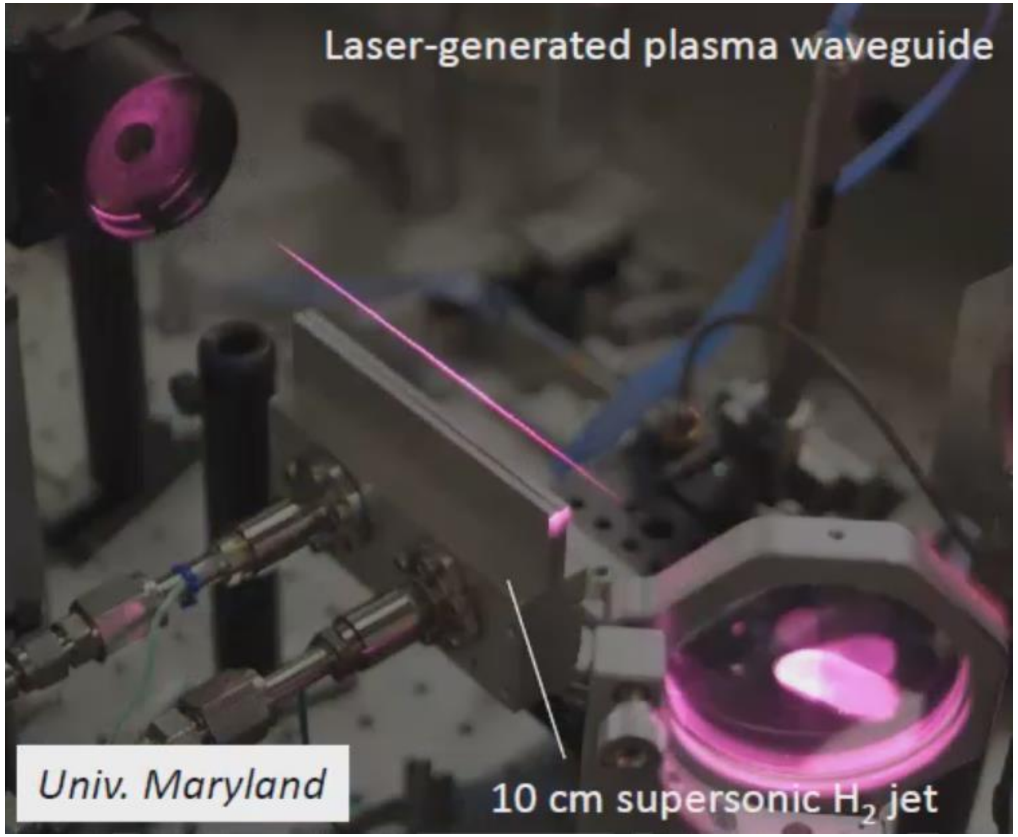
- Axicon lens creates long interference region.
- Optical Field Ionisation creates hot electron population on axis – independent of density.
- Electron population expands outwards in nanoseconds – annulus of higher electron density, lower density left on axis.
- Waveguide for second, high energy pulse to drive wake and accelerate electrons.

Plasma waveguides

Create waveguide just using laser pulse – HOFI channels in cells



Picksley et al., Phys. Rev. Acc. Beams 23, 081303 (2020)

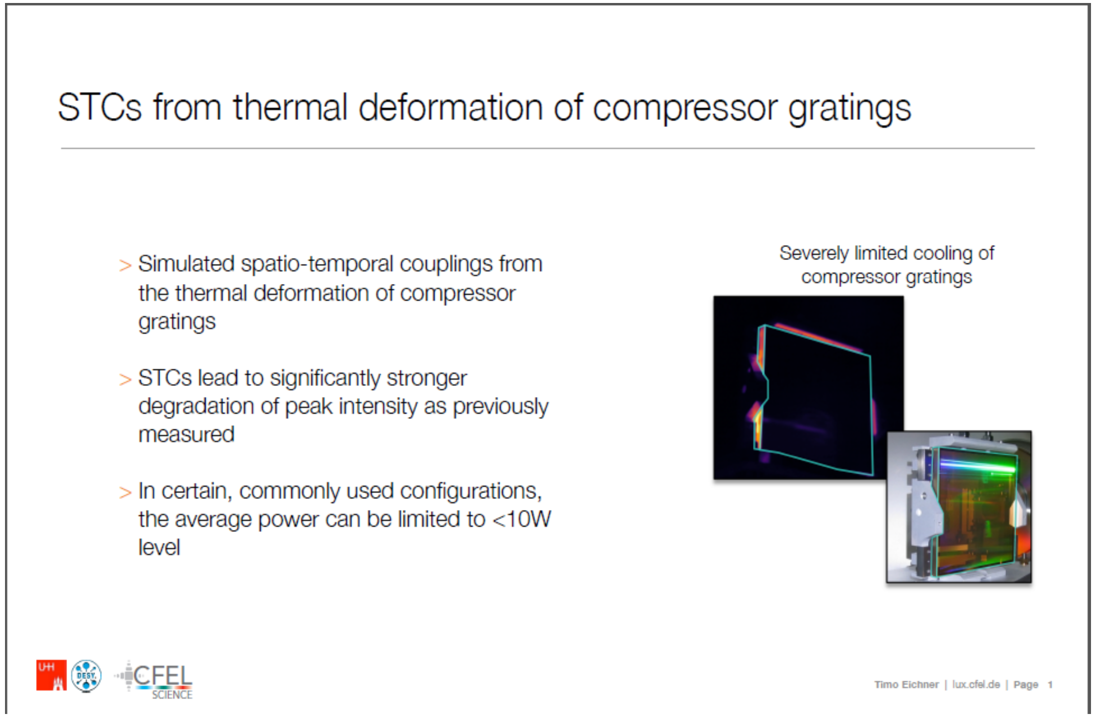


Channel above gas jet – good for avoiding damage issues

B. Miao et al., Phys. Rev. X 12, 031038 (2022)

Intensity- is just more power enough?

Slide: Timo Eichner, Hamburg, DESY



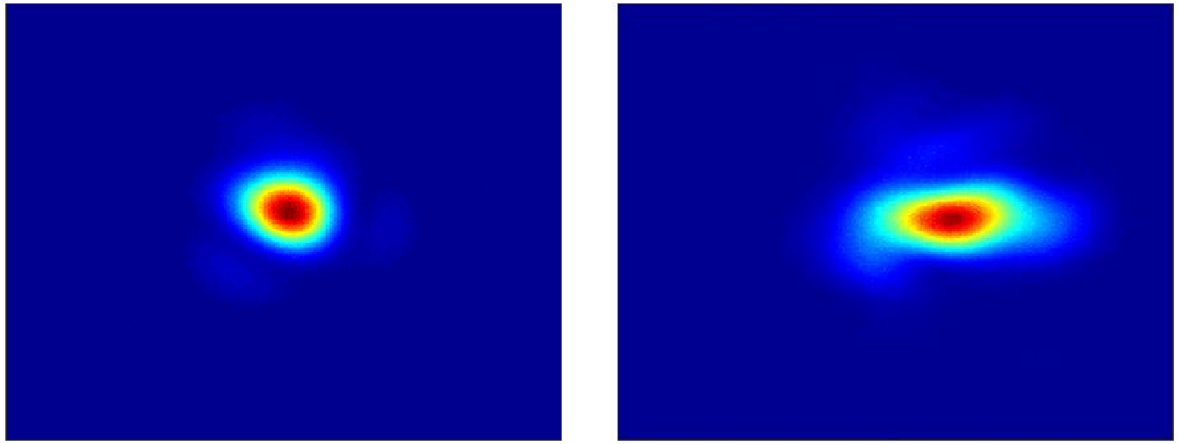
STCs from thermal deformation of compressor gratings

- Simulated spatio-temporal couplings from the thermal deformation of compressor gratings
- STCs lead to significantly stronger degradation of peak intensity as previously measured
- In certain, commonly used configurations, the average power can be limited to <10W level

Severely limited cooling of compressor gratings

Timo Eichner | lux.cfel.de | Page 1

Spatial Distortion



Slide: Christopher Thornton, RAL

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Questions

Lasers:

- Rep rate – can we reach the luminosity required for colliders?
- Efficiency – can we afford to run the facility?
- High average power – do we have optics/gratings that can handle the load?
- Power/intensity – does this need to be as high as possible? Or reduced energy for lower gradient but better coupling?
- Cooling – of laser, frequency conversion crystals?

Staging:

- Coupling – how to couple laser pulse into each stage without blowing up electron beam? Does this change with energy?
- Size – does distance between stages required reduce the gradient so much we lose advantage of plasma?
- Gradient – is there are a sweet spot to maximise geometric gradient by reducing in-coupling distance?
- Demonstration – can we do it with 100% charge capture and no/minimal emittance blow up?

Plasma sources:

- Rep rate – how quickly can we reuse/replace gas/plasma? kHz? 10s kHz?
- Gas load – do we need significantly improved vacuum management to use plasma successfully?
- Which type – optimised for different applications? Design freedom with jets to produce tailored ramps?
- Damage/longevity – do we have 24/7/365 sources for years?
- Heat – can systems/accelerator cope with heat deposition? Does this need to be removed?
- Injection – from the plasma? Or external? Hybrid options need to be fully considered.

Meta-question – how will this work be funded? Who will do it?