Ultra-broadband spectral combination of fiber lasers with synthesized pulse shaping to reach short pulse lengths for plasma accelerators

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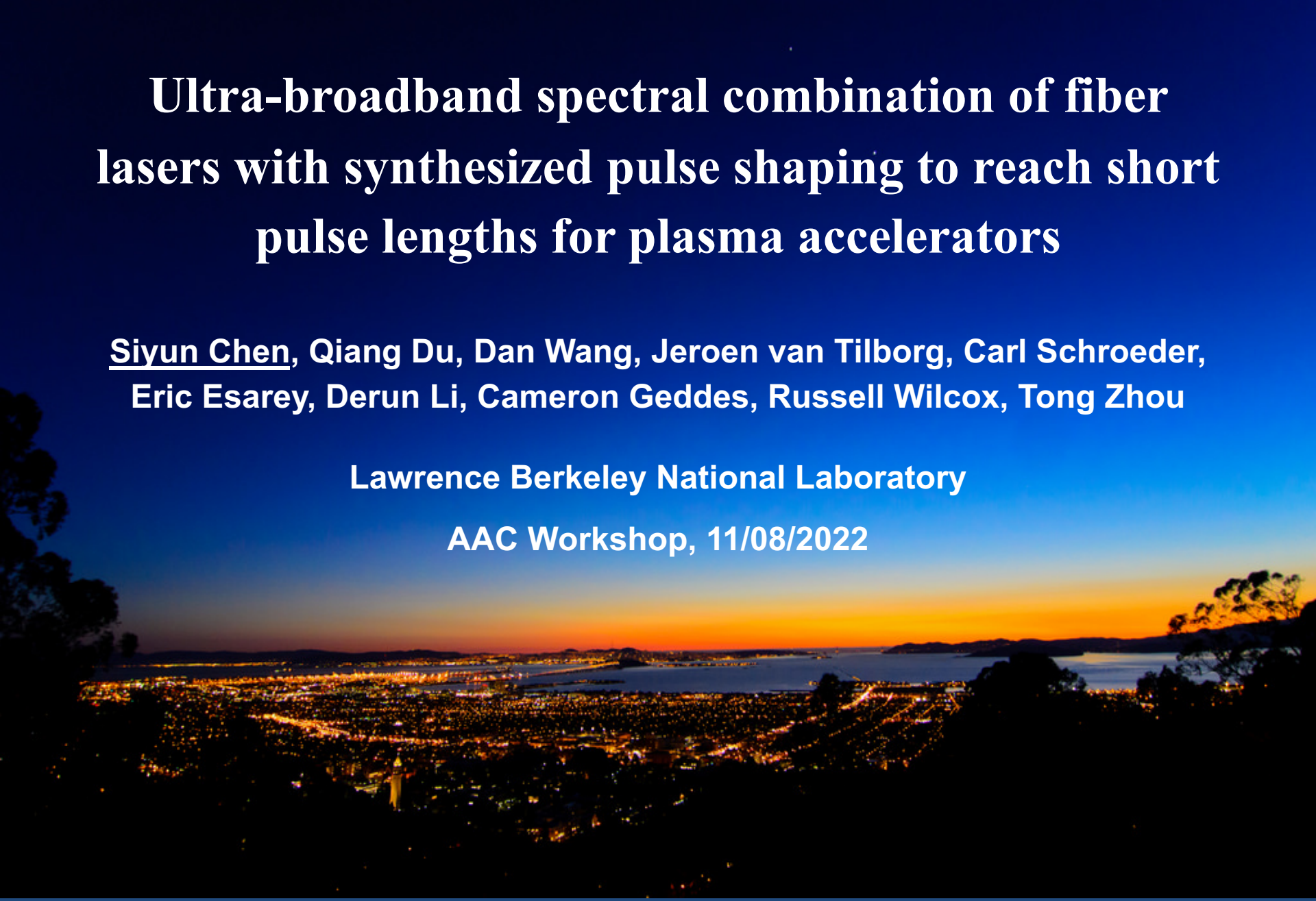
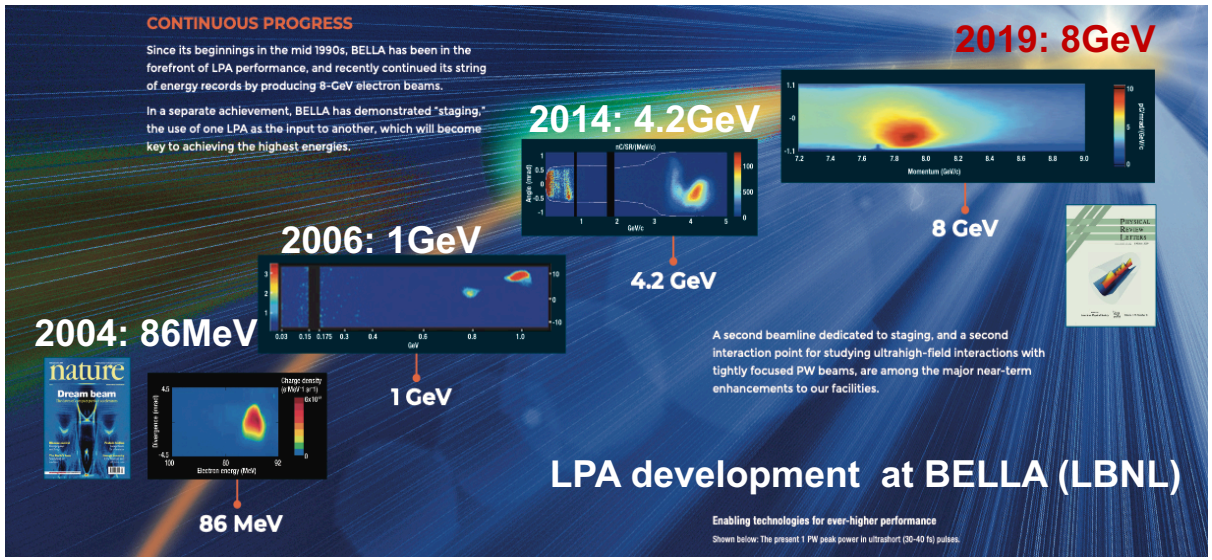
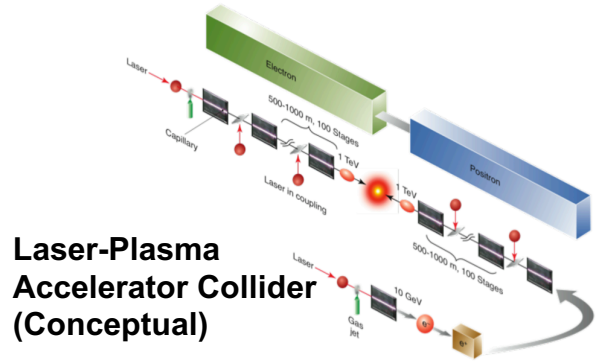
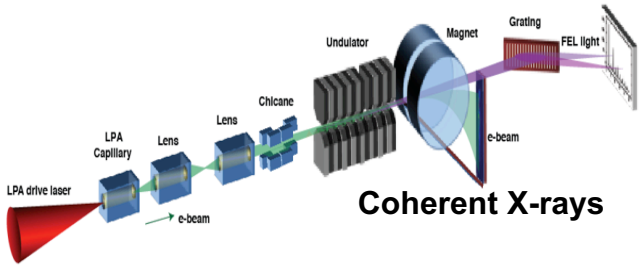


Next generation plasma accelerators need new driver laser technologies



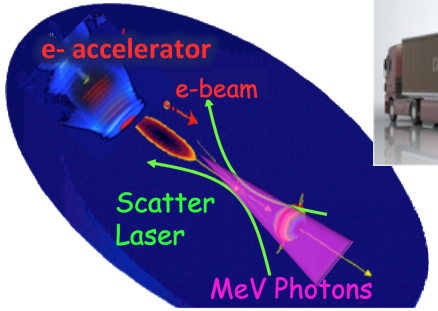


Laser-Plasma Accelerator Collider (Conceptual)



Coherent X-rays

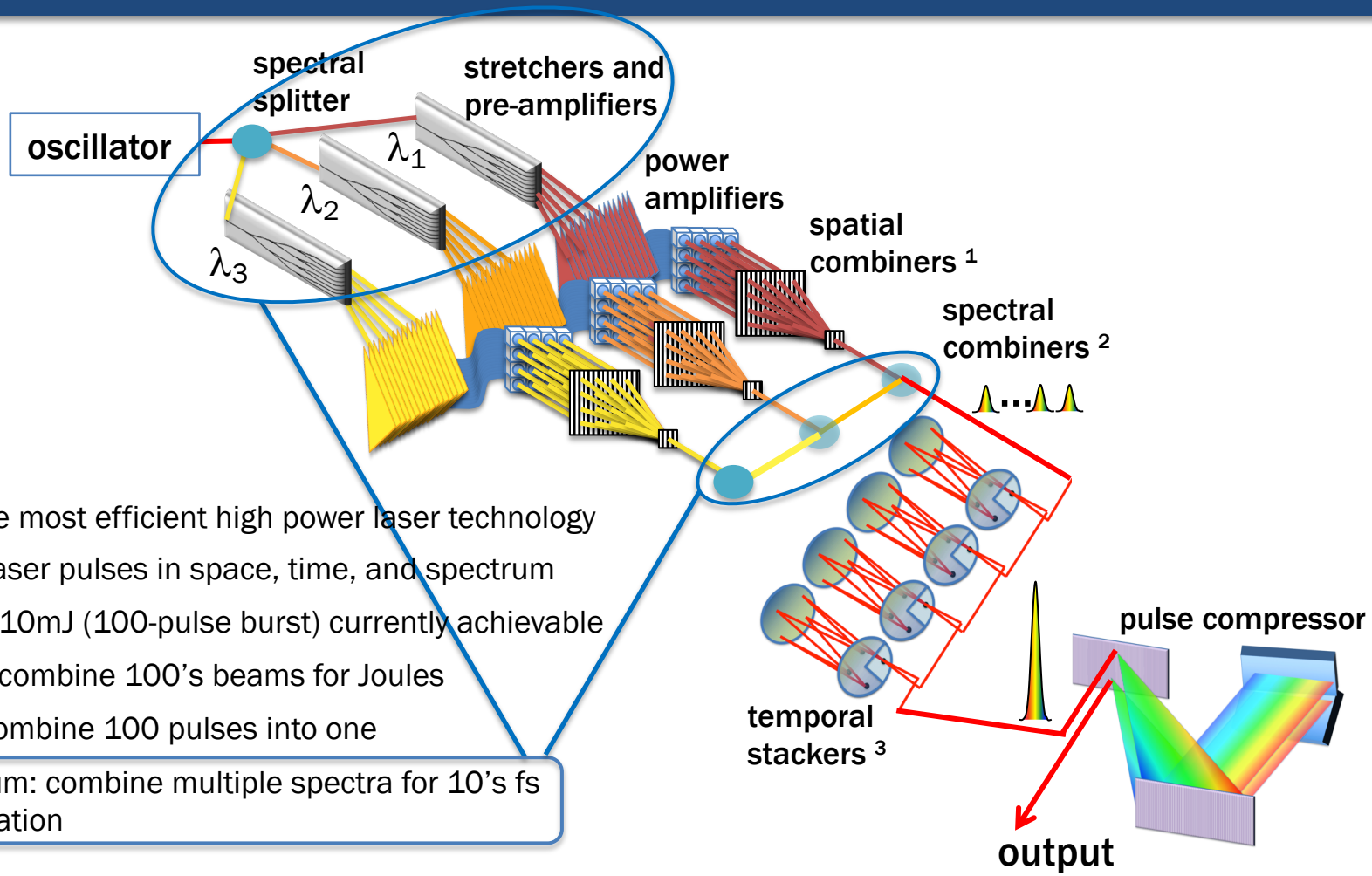
- Compact, high-energy laser-plasma accelerators (LPA) are rapid developed over the past two decades
- Current GeV LPAs operate at Hz class, driven by Ti:sapphire lasers
- LPA fluctuations (up to ~100Hz) need to be stabilized at >kHz rep-rates; LPA applications need >kHz rep-rates
- Next generation LPAs need new lasers:
  - 0.5-6 J pulse energy, 1-50 kHz rep-rate
  - 3-300 kW average power; 10's% wall-plug efficiency
  - 30-100 fs pulse duration



Medical treatment

Security screening

Multidimensional combining of fiber lasers to drive future LPAs
Spectral combining to reach required short pulse duration



- Fiber laser is the most efficient high power laser technology
- Combine fiber laser pulses in space, time, and spectrum
  - Per fiber: 10mJ (100-pulse burst) currently achievable
  - In space: combine 100's beams for Joules
  - In time: combine 100 pulses into one
  - In spectrum: combine multiple spectra for 10's fs pulse duration

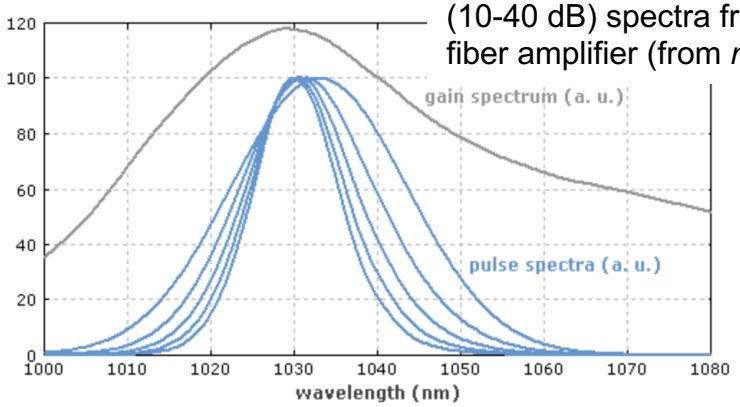
[1] T. Zhou et al. *Optics Letters* 21, 4422 (2017)
[2] W. Chang et al. *Optics Express* 21, 3897 (2013)
[3] T. Zhou et al. *Optics Express* 23, 7442 (2015)

Prior art on generating short pulses from Yb:fiber systems & Challenges

Pulse duration from high-energy Yb fiber amplifiers limited to >300fs (without compensation):

- Gain narrowing and saturation
- High-order dispersions

Simulated seed and amplified (10-40 dB) spectra from an Yb fiber amplifier (from *rp-photonics*)



Shortest pulse from a single fiber amplifier channel

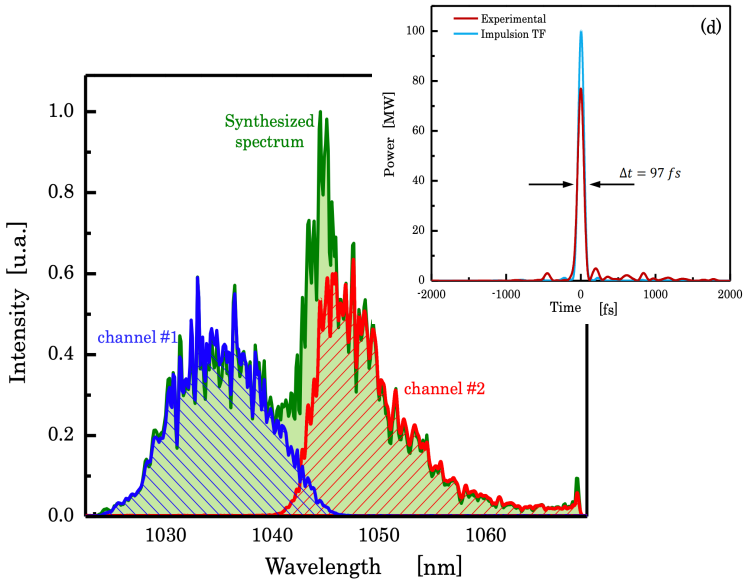
- 130fs, 250μJ
- Pulse shaping (intensity & phase)

L. Lavenu, et al. Opt. Express 25, 7530-7537 (2017).

Shortest pulse from spectrally combined Yb:fiber systems

- ~100fs, 10μJ, combining 2 channels
- One pulse shaper (phase) before splitting

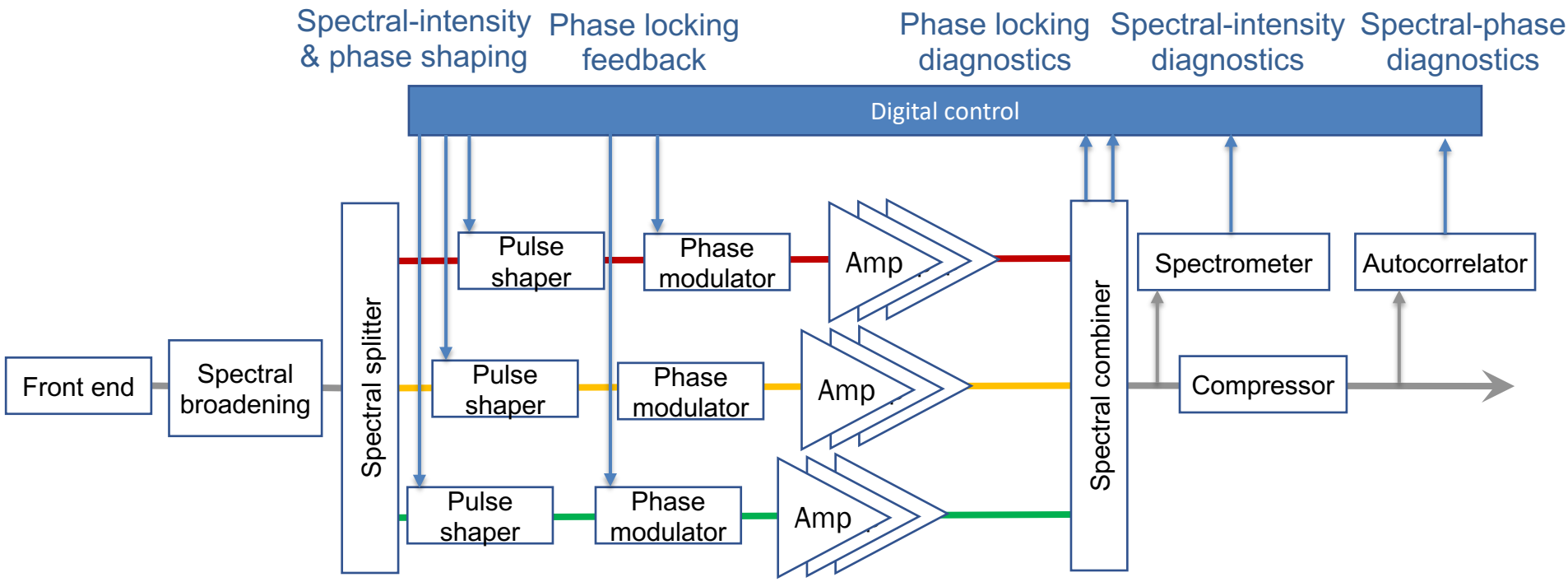
F. Guichard, et al. Proc. SPIE 9728, Fiber Lasers XIII: Technology, Systems, and Applications (2016).



But LPA drivers require pulse durations as short as 30fs

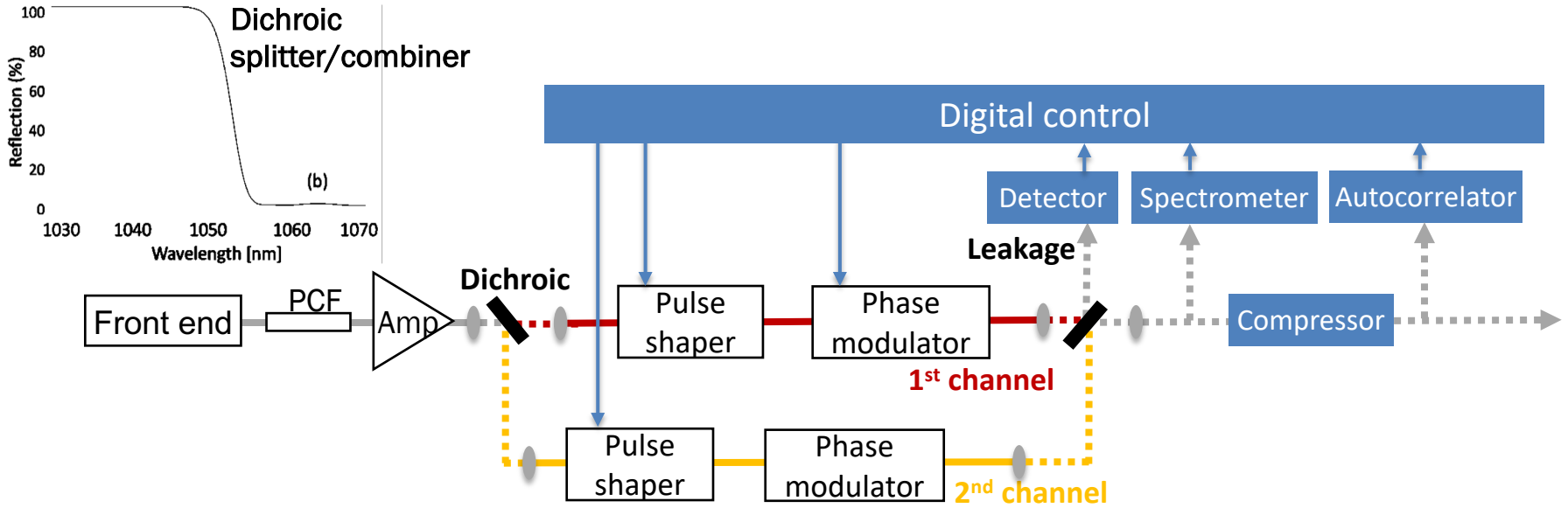
- Critical to demo spectral combining to 30-50 fs
- Need ~100nm bandwidth, while current high-resolution pulse shapers only cover <50nm

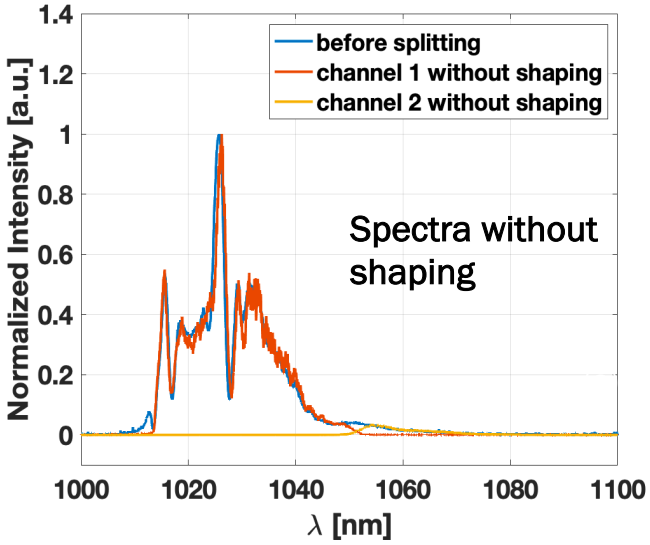
Ultra-broadband spectral combining with coherently-spectrally synthesized pulse shaping

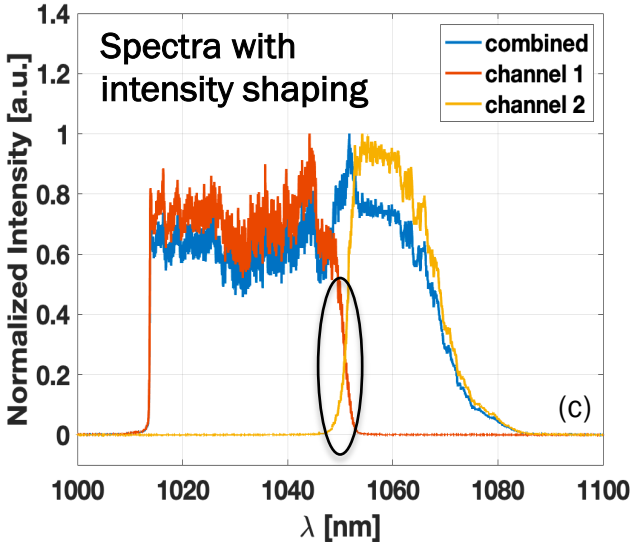


- Spectral combination covering the full gain bandwidth of Yb^{+3} ions (~100nm) in fibers
- Coherently-spectrally synthesize high-resolution pulse shapers to achieve full-band spectral-intensity & phase shaping

Proof of principle: ~50fs, 2-channel spectral combining & pulse shaping



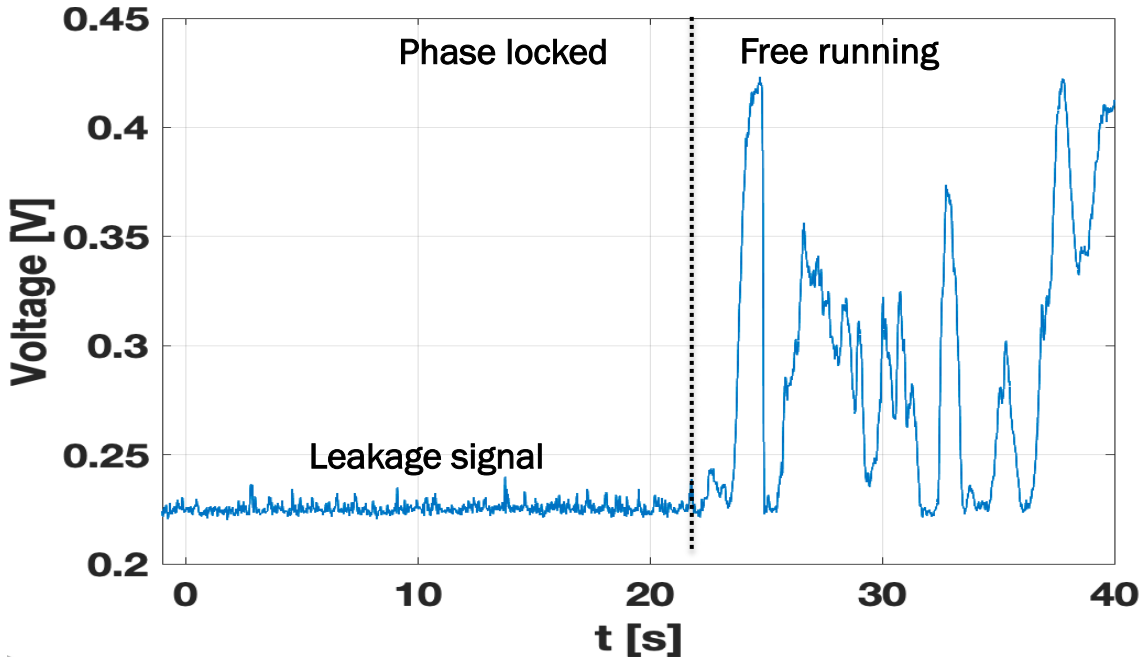




- Ch1 & Ch2 outputs nearly non-interferometric
- Ch1 & Ch2 leakages highly interferometric
- Shortest combined pulse needs Ch1 & Ch2 outputs in phase at the overlapping spectrum, thus out of phase for their leakages
- Phase control is done by minimizing the leakage signal

Phase control is done by diagnosing the leakage port

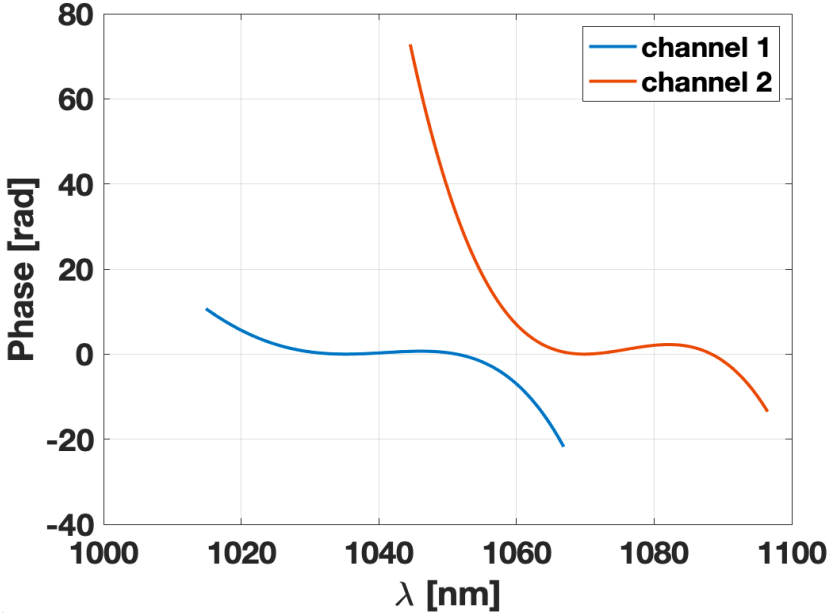
- Ch1 & Ch2 coarse delays matched by maximizing leakage interference contrast
- Ch1 & Ch2 phases synchronized by minimizing the leakage signal (destructive interference)
- 94.5% combining efficiency is achieved after phase control



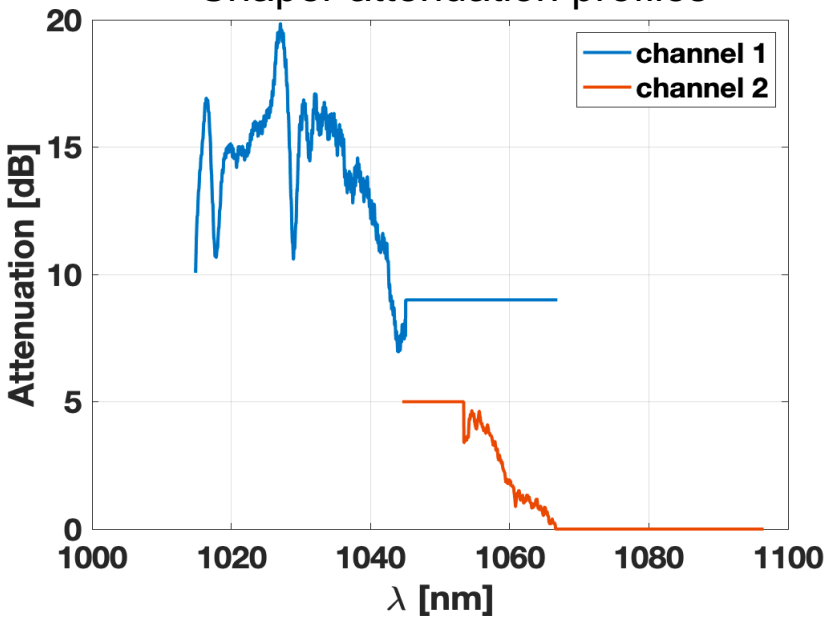
Phase and attenuation profiles of the pulse shapers

- The spectral phases are compensated in each channel, leading to a flat spectral phase across the whole combined spectrum
- The pulse shapers provide high-resolution spectral-intensity attenuation, smoothing and flattening the combined spectrum

Shaper phase profiles

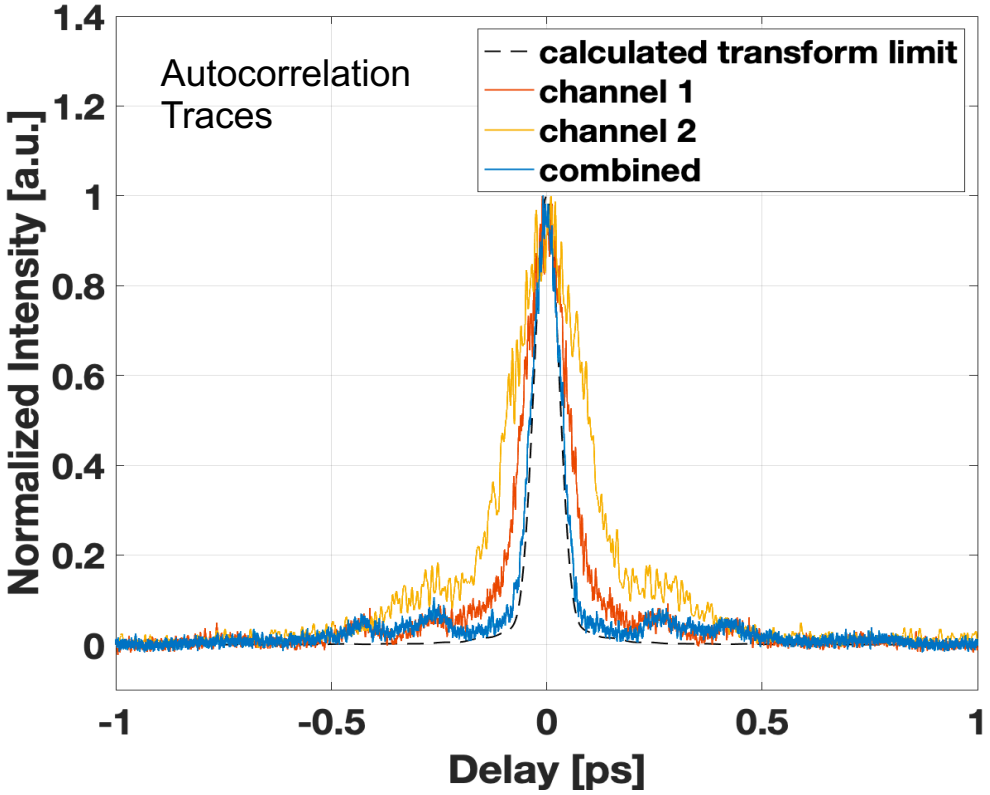


Shaper attenuation profiles



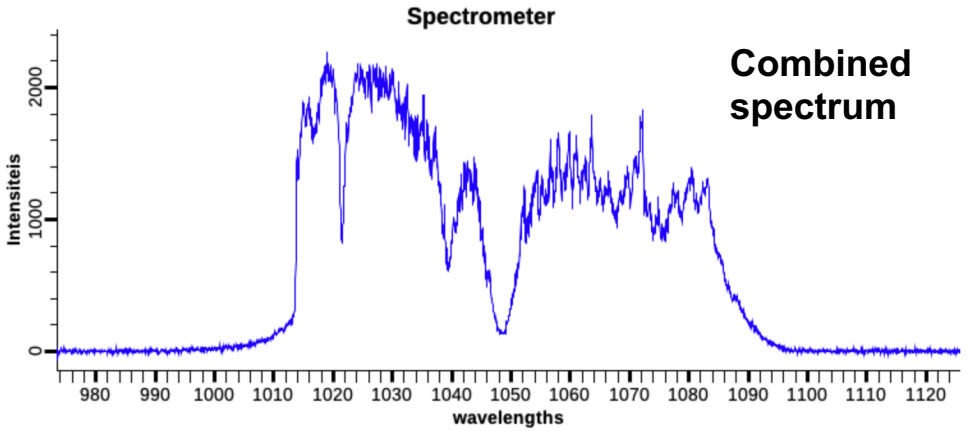
54-fs spectrally combined pulse with synthesized shaping

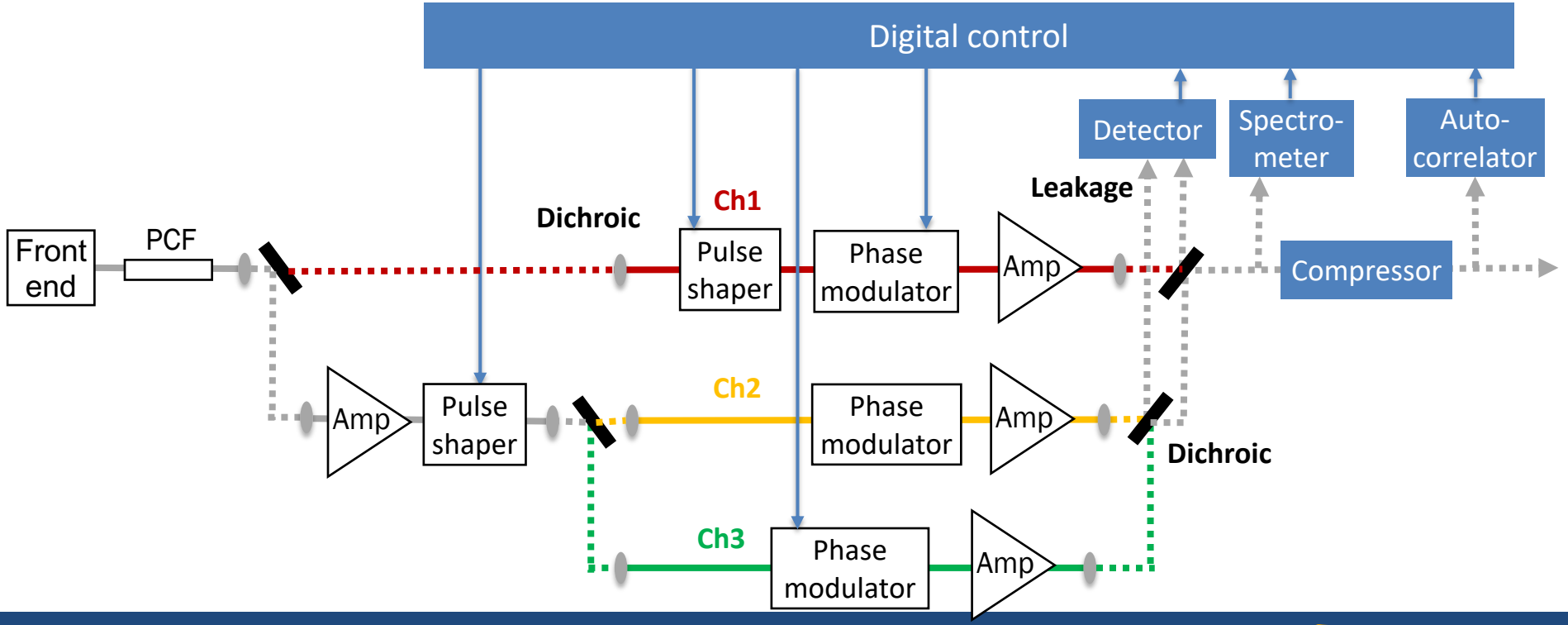
- Achieved Ch1&2 delay matching, spectral intensity & phase shaping, phase synchronization
- Combined & compressed pulse is measured to be 54-fs, close to transform limit (50-fs)
    - Ch1 compressed pulse duration is 84-fs, and Ch2 is 122-fs
- **54 fs is the shortest pulse duration from a spectrally combined Yb:fiber system**
- **This work is the first demonstration of coherent spectral synthesis of pulse shapers**



Latest: Add spectral channel & amplifier array; Aim at <40fs pulses

- Add more spectral channels with amplifiers in each channel provides a path toward high energy, 10's fs fiber lasers to drive LPAs
- Latest: Achieved >80nm shaped spectrum via combining 3 phase-shaped channels
  - Phase control in progress
  - <40fs pulses expected





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