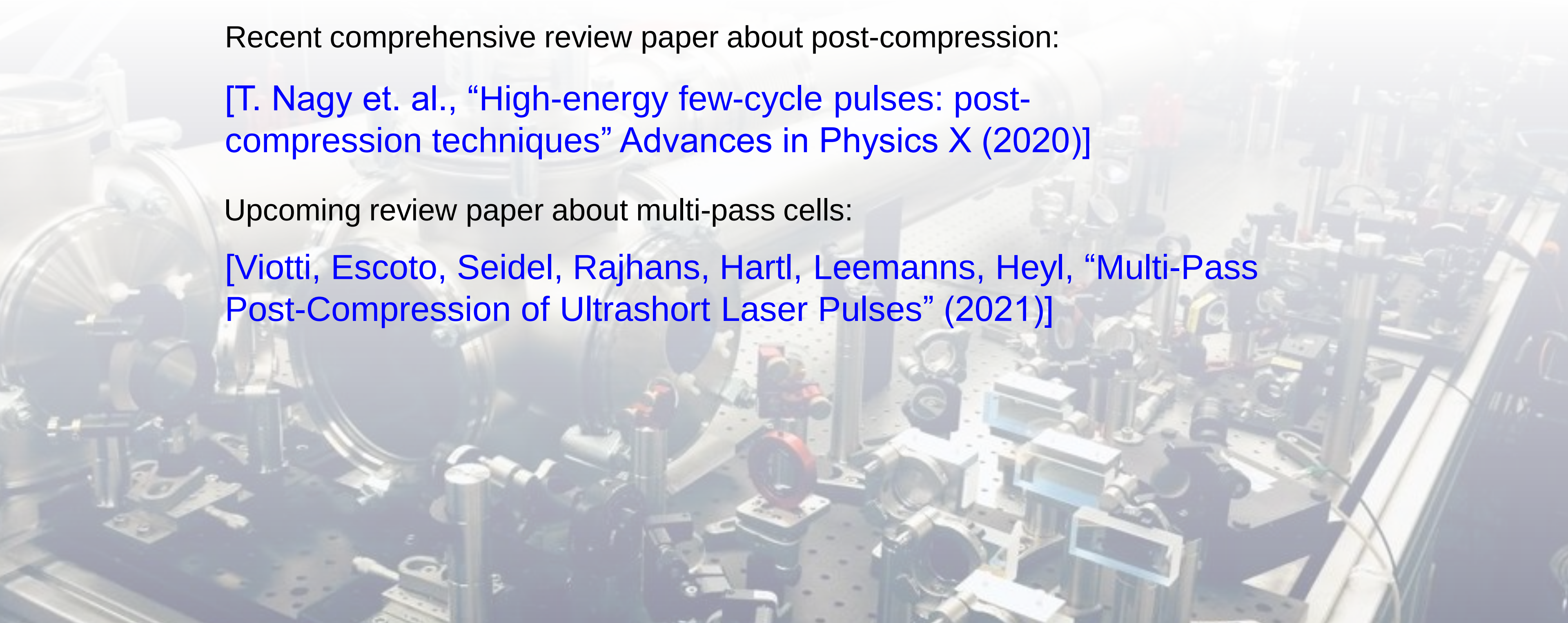
Ultrafast Sources 2021: Lecture 24, June 29, 2021

Lecture overview

- Introduction & motivation: Post-compression
- Post-compression using hollow-core fibers and other techniques
- Post-compression using multi-pass cells



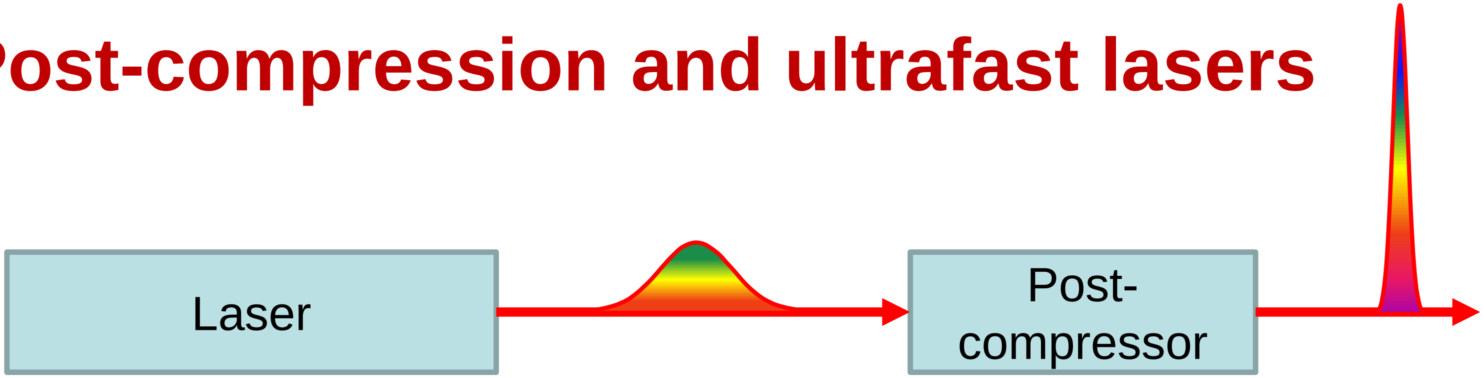
Recent comprehensive review paper about post-compression:

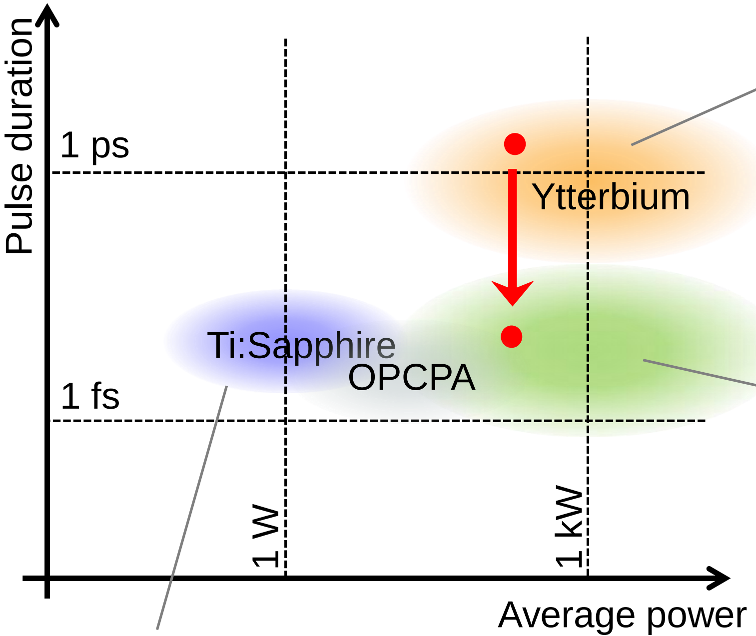
[T. Nagy et. al., "High-energy few-cycle pulses: post-compression techniques" Advances in Physics X (2020)]

Upcoming review paper about multi-pass cells:

[Viotti, Escoto, Seidel, Rajhans, Hartl, Leemanns, Heyl, "Multi-Pass Post-Compression of Ultrashort Laser Pulses" (2021)]

Post-compression and ultrafast lasers





Ytterbium-based lasers

- 10 kW average power possible
- Pulse duration > 200 fs -1 ps

5 – 50 fs pulses at few 100 W - few kW average power

Ti:Sapphire-based lasers

- A few Watt average power
- Pulse duration: ~ 30 fs

SPM – A reminder

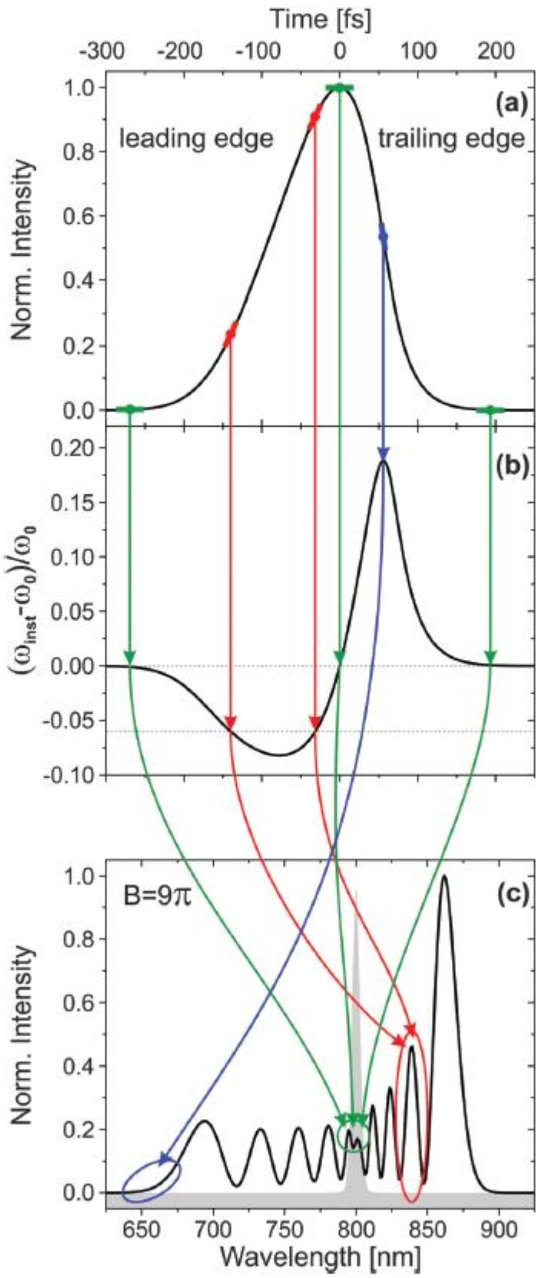
$$\left|A(z,t)\right|^2$$

$$n = n_0 + n_2 I(t)$$

$$\varphi = \omega_0 t - k_0 z(n_0 + n_2 I(t)) = \varphi_0 + \varphi_{NL}$$

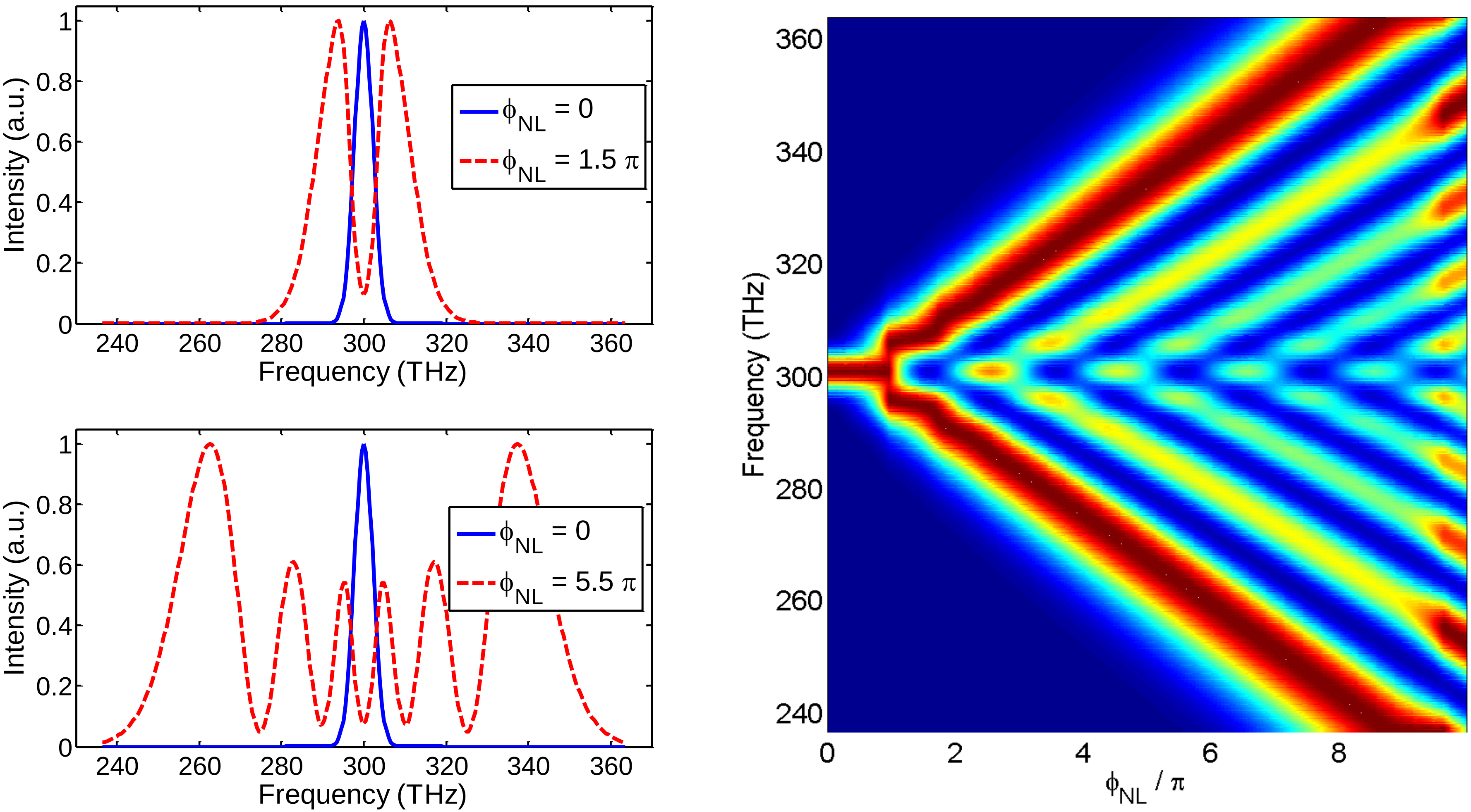
$$\varphi_{NL} = -k_0 z n_2 I(t)$$

$$\Delta\omega = \frac{d\varphi_{NL}}{dt}$$



[T. Nagy et. al., ADVANCES IN PHYSICS: X (2020)]

SPM modifies spectrum



Spectral bandwidth is proportional to the amount of nonlinear phase accumulated:

$$\phi_{NL} \approx (M - \frac{1}{2}) \times \pi$$

M is the number of spectral peaks.

Pulse propagation: pure dispersion Vs pure SPM

- Pure dispersion

(1) Pulse’s spectrum acquires phase.

(2) Spectrum profile does not change.

(3) In the time domain, pulse may be stretched or compressed depending on its initial chirp.

- Pure SPM

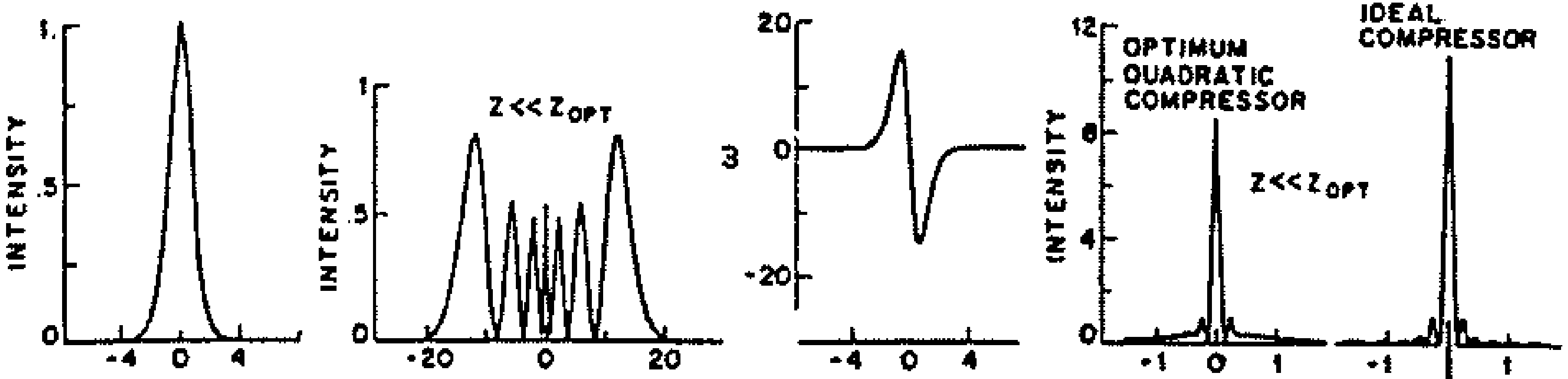
(1) Pulse acquires phase in the time domain.

(2) Temporal pulse profile does not change (much).

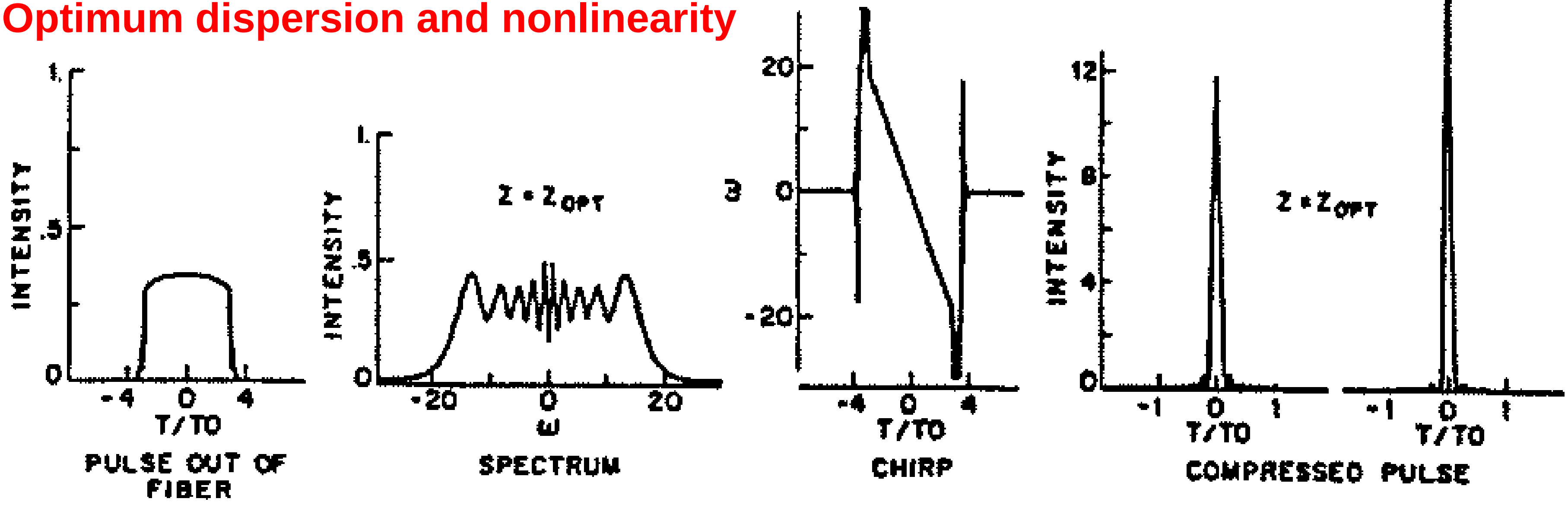
(3) In the frequency domain, pulse’s spectrum may be broadened or narrowed depending on its initial chirp.

Dispersion matters in spectral broadening

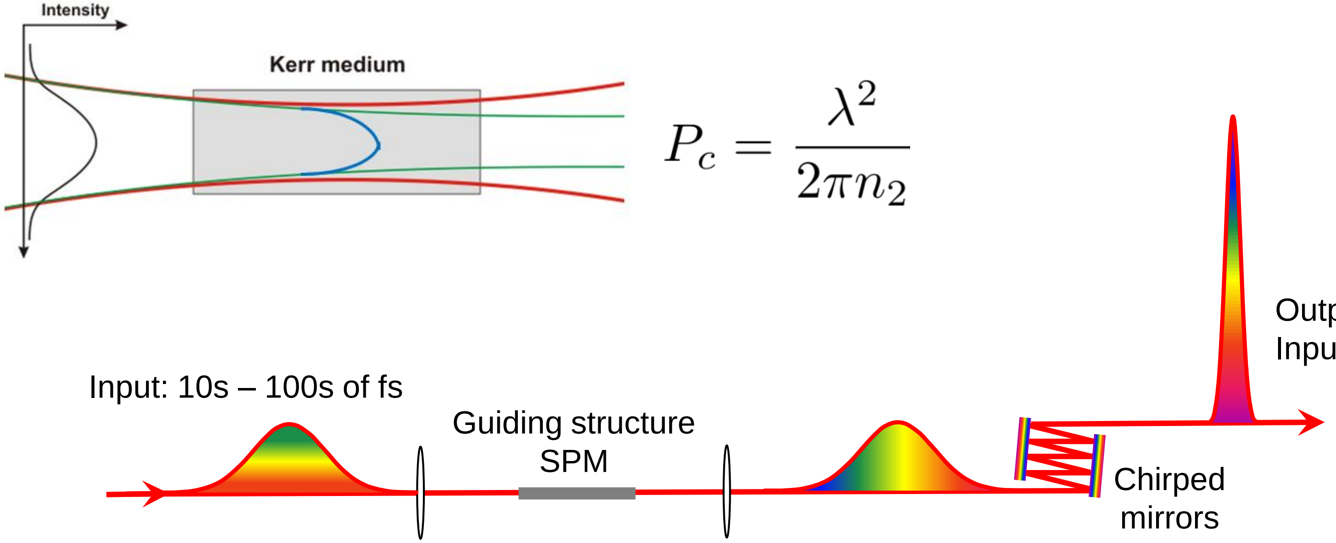
Dispersion negligible using short fiber, SPM dominates



Optimum dispersion and nonlinearity



Post-compression



$$P_c = \frac{\lambda^2}{2\pi n_2}$$

Input: 10s – 100s of fs

Guiding structure
SPM

Chirped
mirrors

Output:
Input duration to few cycle

Pioneering fiber broadening work:

[R.H. Stolen et al., Phys Rev A. 978;17:1448–1453 (1978)]

Pioneering bulk broadening:

[C. Rolland et al., J Opt Soc Am B. 1988;5:641–647 (1988)]

Pioneering hollow core fiber (HCF)/capillary work:

[M. Nisoli et al., Appl Phys Lett. 1996;68:2793–2795 (1996)]

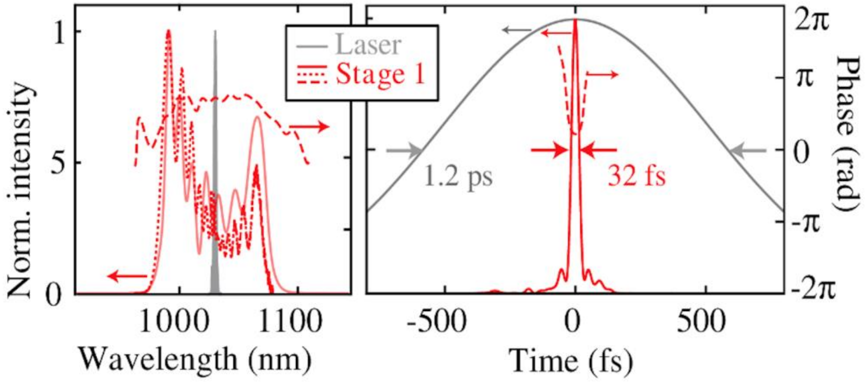
Pioneering multi-plate work:

[C.-H. Lu et al., Optica. 2014;1:400-406 (2014)]

Multi-pass cell (MPC) post-compression

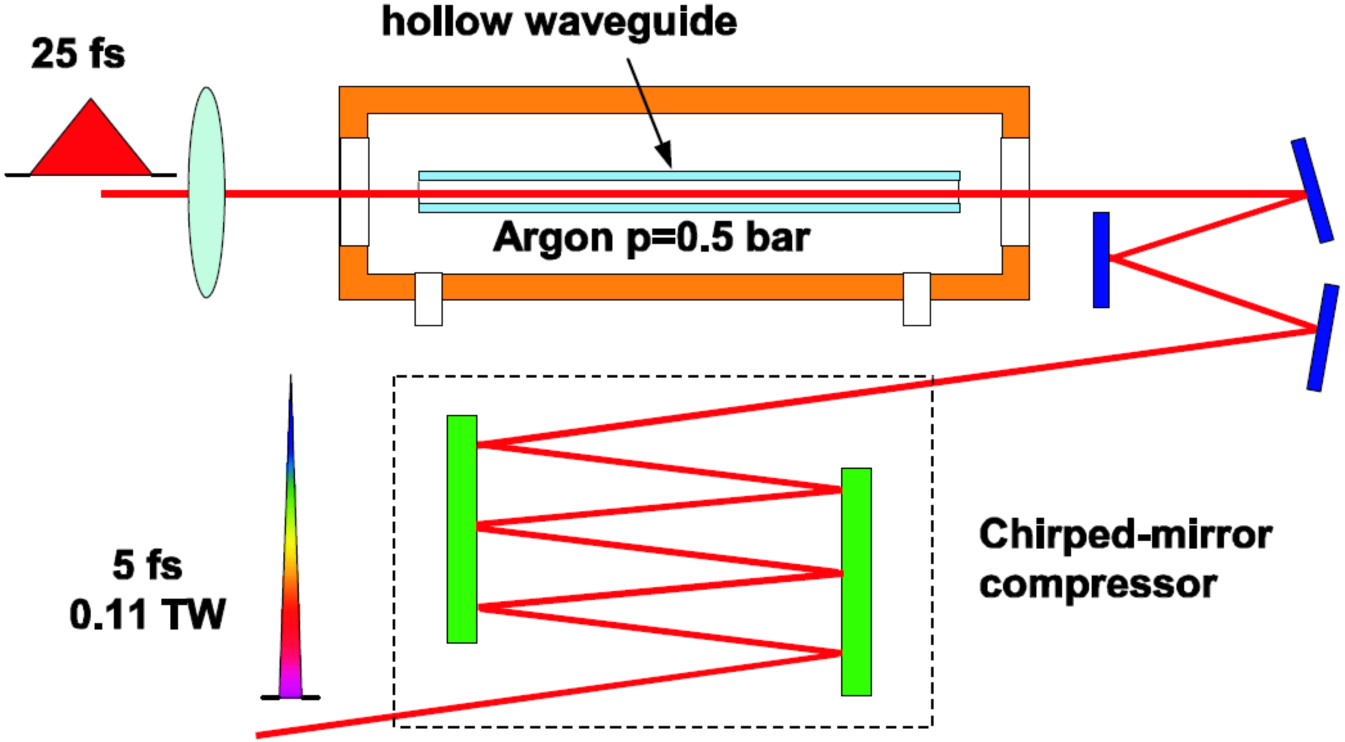
[P. Russbueldt et. al., IEEE Sel. Top. Quantum Elec. (2015)]
[J. Schulte et. al., Optics Letters 41(19), pp. 4511-4514 (2016)]
[A. Vernaleken et al., DE102014007159B4 (2017)]

Recent record example (single stage):



Hollow fiber compression of mili-joule pulses

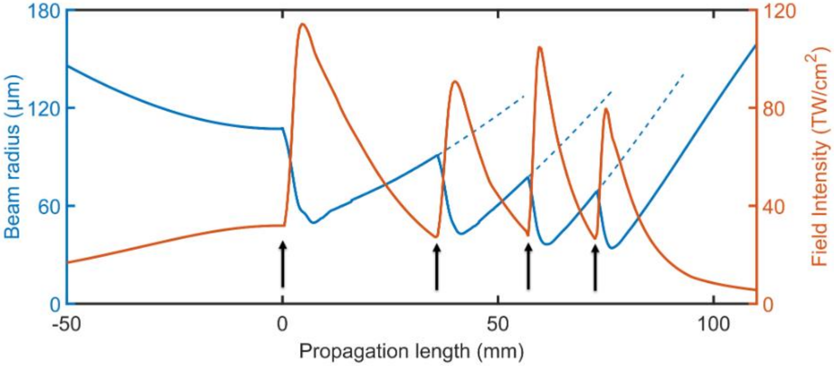
Self focusing threshold in fused silica is 4 MW. For ~100 fs pulse, the pulse energy allowed in a fused silica fiber is ~400 nJ before fiber breakdown.



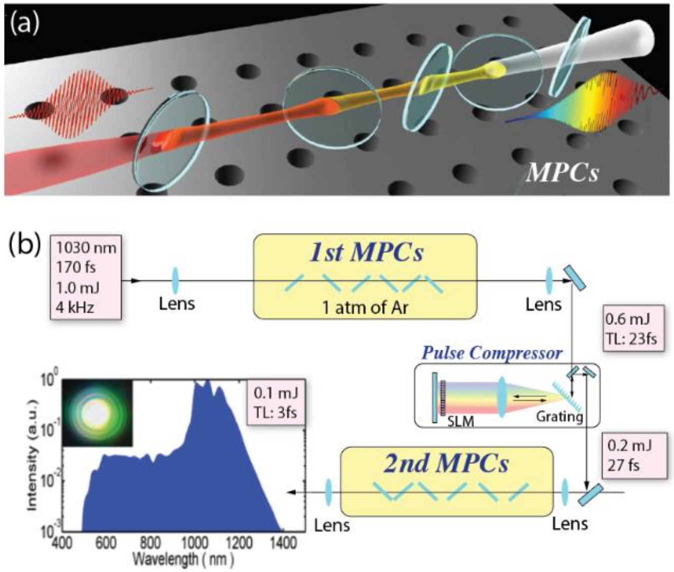
Bulk media have ~3 orders of magnitude larger n_2 than gases. To avoid damage, the beam is guided through the hollow core, which can contain gas of variable pressure

[M. Nisoli et al., Appl Phys Lett. 1996;68:2793–2795 (1996)]

Multi-plate spectral broadening



source: Y.C. Cheng, et al, Opt. Express 2016

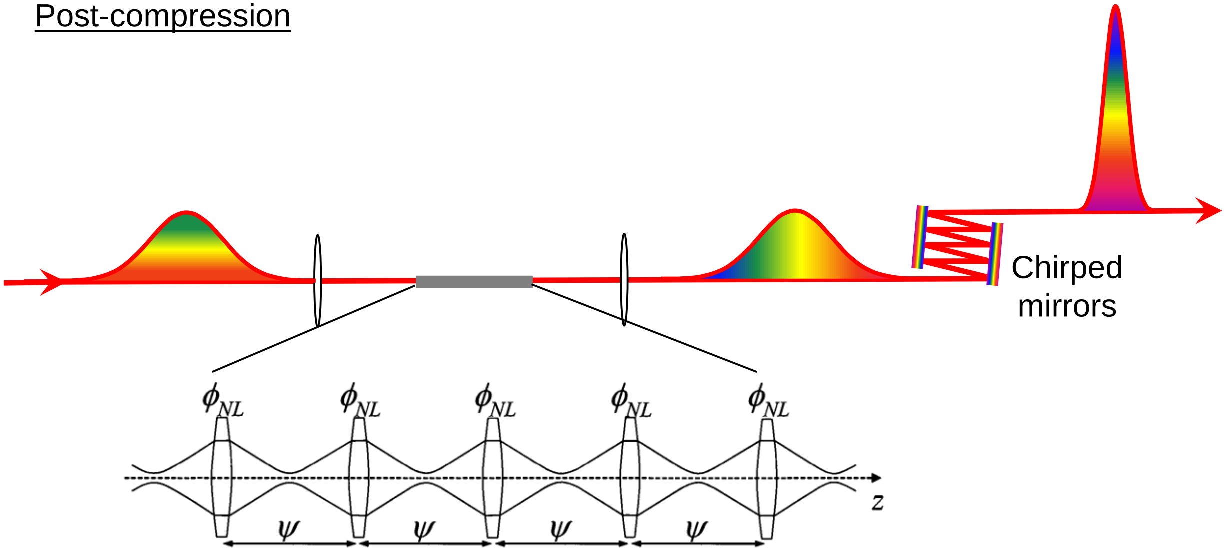


source: C.H. Lu, et al, CLEO/Europe-EQEC 2017

The beam is repeatedly focused by Kerr lensing through several fused silica plates before it diverges

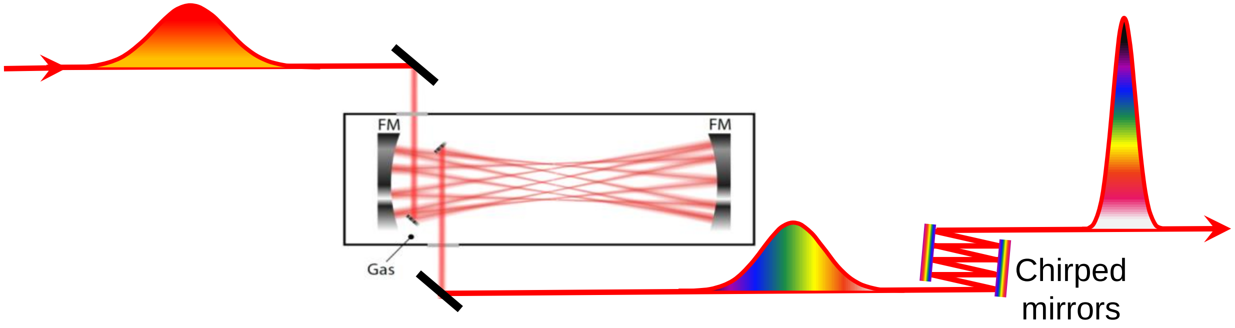
A new light guiding concept

Post-compression



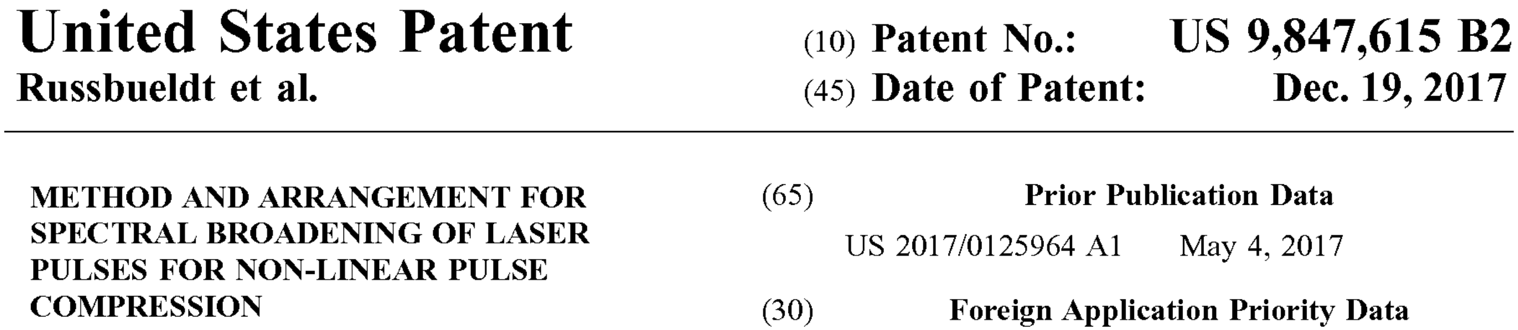
[A. Vernaleken et al., DE 10 2014 007 159 B4 2017.04.13 (2017)]

Multi-pass cell



Gas or glass plate typically used as nonlinear medium

A new pulse compression approach



United States Patent
Russbueldt et al.

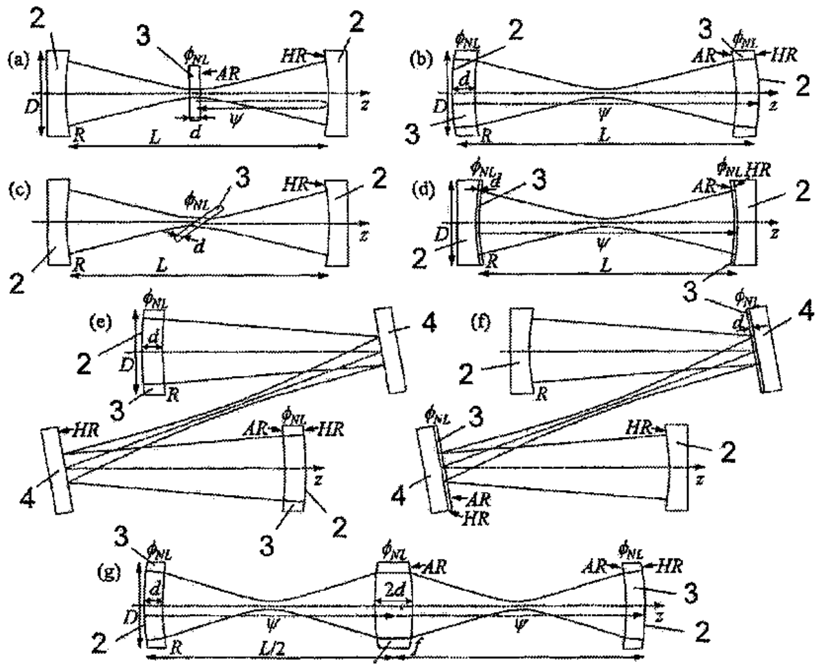
(10) **Patent No.:** **US 9,847,615 B2**
(45) **Date of Patent:** **Dec. 19, 2017**

METHOD AND ARRANGEMENT FOR SPECTRAL BROADENING OF LASER PULSES FOR NON-LINEAR PULSE COMPRESSION

(65) **Prior Publication Data**

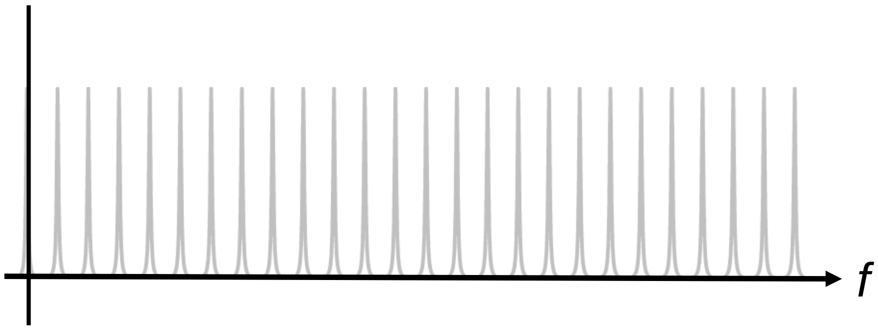
US 2017/0125964 A1 May 4, 2017

(30) **Foreign Application Priority Data**

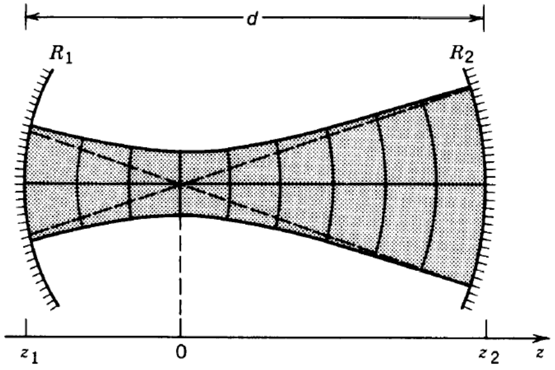


Resonator: spectral and spatial modes

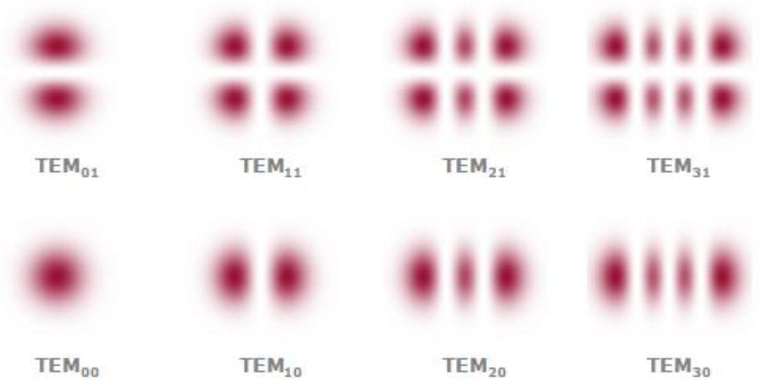
Spectral modes



Spatial mode formation



Spatial modes

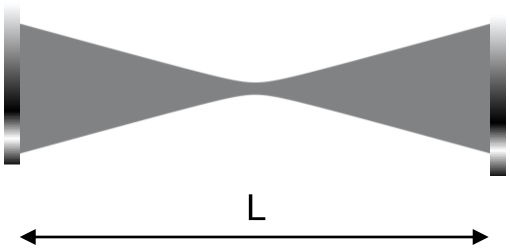


Hermite Gaussian modes

	Spatial modes	**Spectral modes**
Optical cavity	yes	yes
Pabry Perot Etalon	no	yes
Multi-pass cell	yes	no

Resonator modes in multi-pass cells

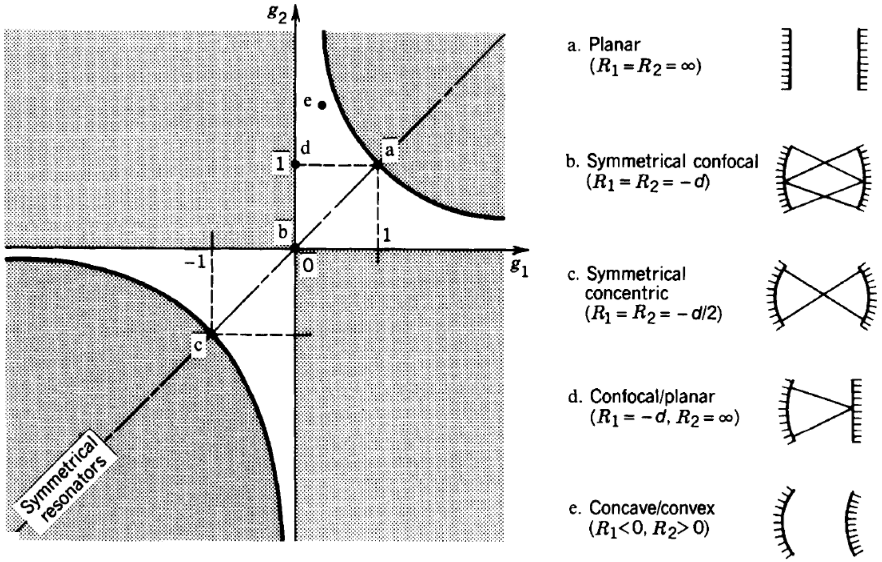
Multi-pass cells have spatial modes, no spectral modes!



Stability requirement for optical resonator:

$$0 < C = L/R < 2$$

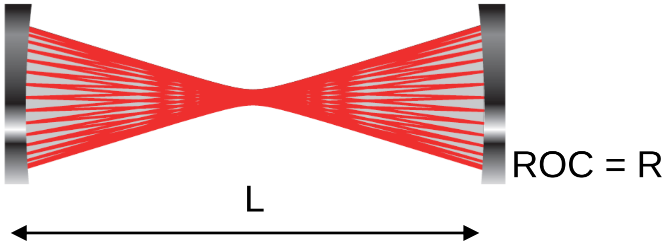
$$p = \left|\frac{A+D}{2}\right| < 1$$

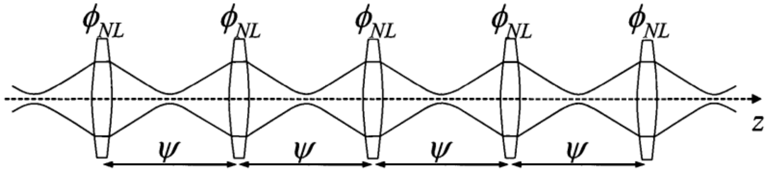


$$g = 1 + L/R$$

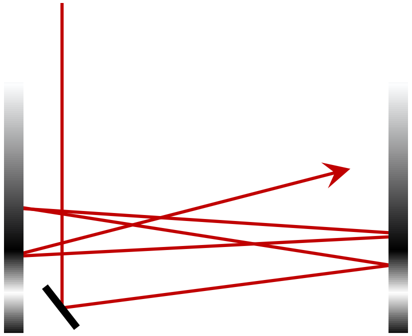
[Saleh, Teich, Fudamentals of Photonics]

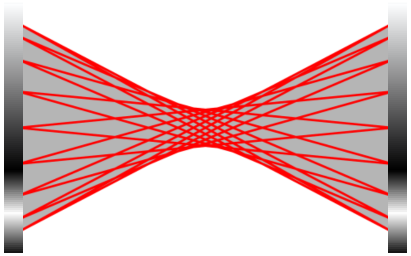
Stability requirement also applies for multi-pass cell!





MPC basics: The reentrant Herriott cell





Recap ABCD ray matrix formalism:

$$\begin{pmatrix} x_2 \\ \theta_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} x_1 \\ \theta_1 \end{pmatrix}$$

Reentrant 1:1 imaging after N round trips:

$$\begin{pmatrix} x_1 \\ \theta_1 \end{pmatrix} = \begin{pmatrix} A_N & B_N \\ C_N & D_N \end{pmatrix} \begin{pmatrix} x_1 \\ \theta_1 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ \theta_1 \end{pmatrix}$$

=> $A_N = 1, D_N = 1$

Gouy phase accumulated after N round-trips:

$$\xi = \mathrm{sgn}(B_N) \cos^{-1}\left(\frac{A_N + D_N}{2}\right)$$

[D. R. Herriott et. al., Applied Optics (1965)]

MPC basics:The reentrant Herriott cell

Gouy phase accumulated after N round-trips:

$$\xi_N = \mathrm{sgn}(B)\cos^{-1}\left(\frac{A_N + D_N}{2}\right)$$

$$A_N = 1, D_N = 1$$

=> $\xi_N = 2\pi k$

Gouy phase accumulated per pass:

$$\xi_p = \xi_N/2N = \pi k/N$$

$$M_p = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

$$\pi k/N = \mathrm{sgn}(B)\cos^{-1}\left(\frac{A_p + D_p}{2}\right)$$

$$M_f = \begin{pmatrix} 1 & 0 \\ -2/R & 1 \end{pmatrix}$$

Condition for reentrant Herriott pattern:

=> $C = \frac{L}{R} = 1 - \cos(\pi k/N)$

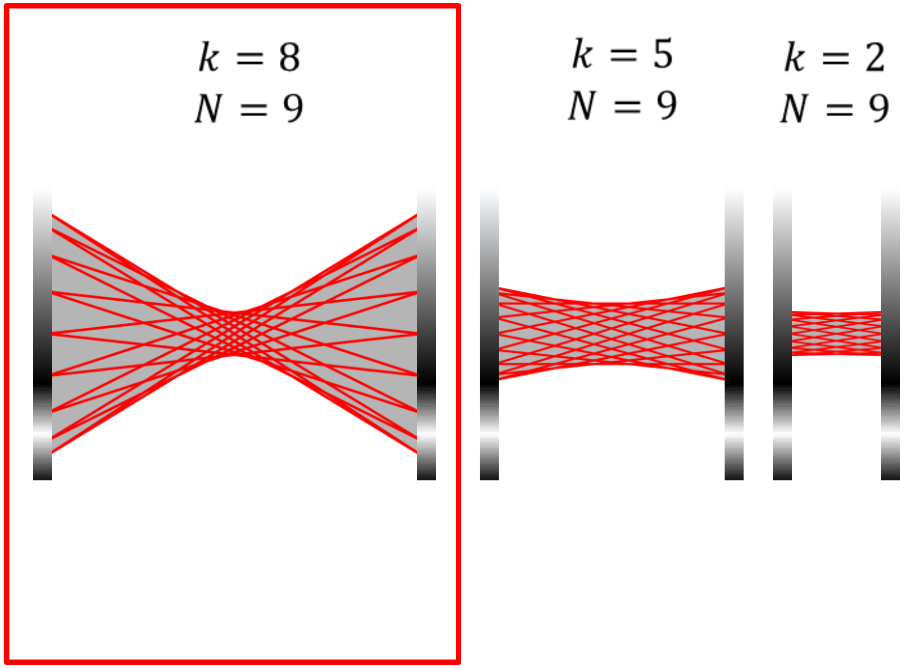
Stability condition:

$$0 < C = L/R < 2$$

N – number of round trips
k – integer 1…N

MPC basics: The reentrant Herriott cell

$$C = \frac{L}{R} = 1 - \cos(\pi k/N)$$



Commonly used scenario for gas-filled MPCs

$$C = 1 - \cos(\pi(N-1)/N) \longrightarrow 2 - 1/N$$

Gouy phase „clock“

Example: N = 17:

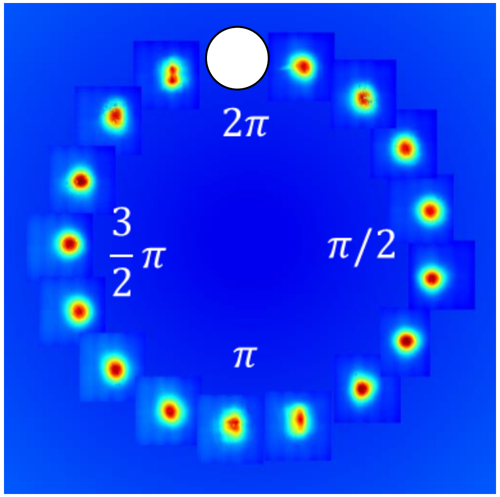


Image of MPC mirror

Properties:

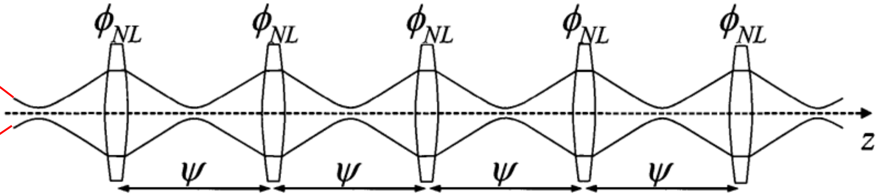
- Angular advance = Gouy phase aquired
- Spots appearing on oppsite sites resemble FT of each other
- Spots in circle show beam properties similar as scan through focus (as typically done for M^2 scan)

MPC mode-matching

Recap complex beam parameter:

$$q = z + i z_R$$

$$q_2 = \frac{A q_1 + B}{C q_1 + D}$$



Ansatz to find mode-matched beam properties:

$$q = \frac{Aq + B}{Cq + D}$$

Use Gaussian beam equations to caculate properties of mode-matched beam:

Focal spot size: $$w_0^2 = \frac{R\lambda}{2\pi}\sqrt{C(2-C)} = \frac{R\lambda}{2\pi}\sin(\pi k/N) \overset{k/N\to 1}{\approx} \frac{R\lambda}{2N}$$

Mirror spot size: $$w_m^2 = \frac{R\lambda}{\pi}\sqrt{\frac{C}{2-C}} = \frac{R\lambda}{\pi}\tan(\pi k/2N) \overset{k/N\to 1}{\approx} \frac{2R\lambda N}{\pi^2}$$

Mirror fluence: $$F_{\mathrm{m}} = \frac{2E}{R\lambda}\sqrt{2/C-1} = \frac{2E}{R\lambda}\frac{1}{\tan(\pi k/2N)} \overset{k/N\to 1}{\approx} \frac{\pi E}{R\lambda N}$$

Focus intensity: $$I_0 = \frac{4P}{R\lambda}\frac{1}{\sqrt{C(2-C)}} = \frac{4P}{R\lambda}\frac{1}{\sin(\pi k/N)} \overset{k/N\to 1}{\approx} \frac{4PN}{\pi R\lambda}$$

$$C = \frac{L}{R} = 1 - \cos(\pi k/N)$$

R – ROC, *L* – MPC length
N – number of round trips
k – 1…N-1, free integer
E – pulse energy
P – peak power
λ - wavelength

Spectral broadening limits

Focal spot size for mode-matched MPC:

$$\omega_0^2 = \frac{R\lambda}{2\pi}\sqrt{C(2-C)} \qquad C = \frac{L}{R} = 1 - \cos(\pi k/N)$$

R – ROC,
L – MPC length
N – number of round trips
k – 1…N-1, free integer
P – peak power
λ - wavelength

$$I(z) = I_0 \frac{\omega_0^2}{\omega(z)^2} \qquad I_0 = \frac{2P}{\pi w_0^2}$$

B-integral for single pass through gas-filled MPC:

$$B = \frac{2\pi n_2}{\lambda}\int_{-L/2}^{L/2} I(z)dz = \ldots \quad = \frac{4\pi^2 P n_2}{\lambda^2} k/N$$

Consider B for critical power: $P_c = \frac{\lambda^2}{2\pi n_2}$

$$B_c = 2\pi k/N$$

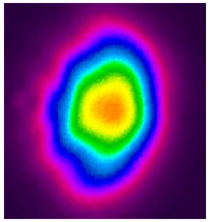
Max. spectral broadening factor approximated for large broadening: $F_c \approx 0.88 B_c$

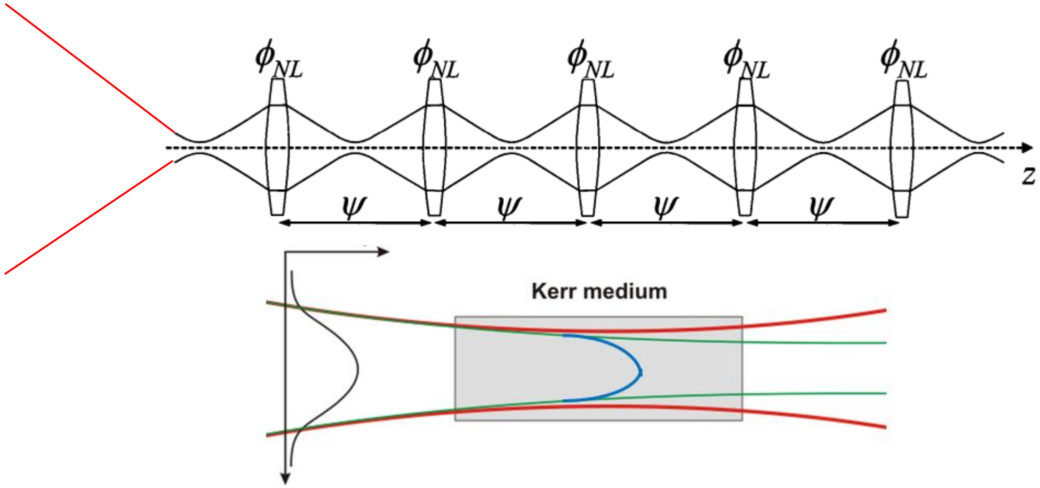
Max spectral broadening factor for MPC with N round trips (2*N* passes):

$$F_c \approx 11\pi N$$

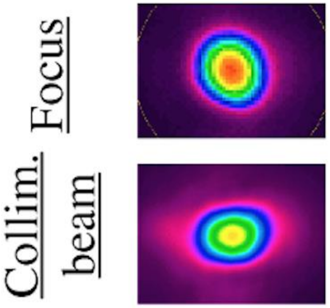
Spatial beam quality

Input
beam profile

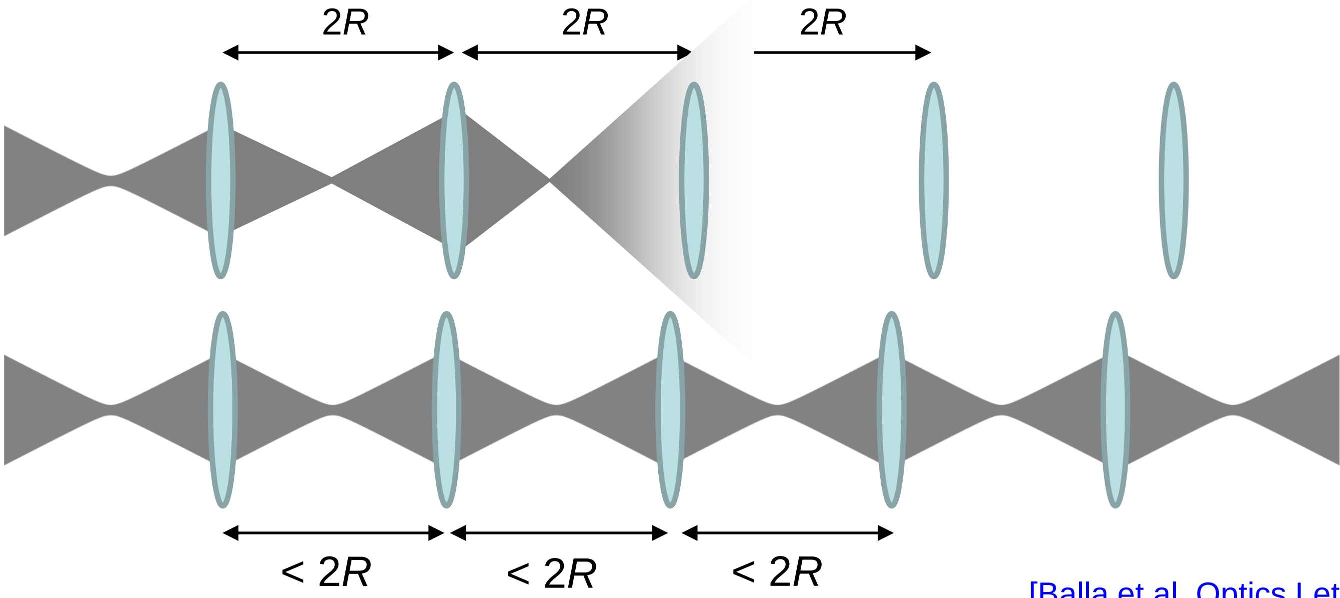




Beam profile
after broadening

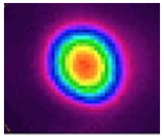


MPC stability requirement: $0 < C = L/R < 2$



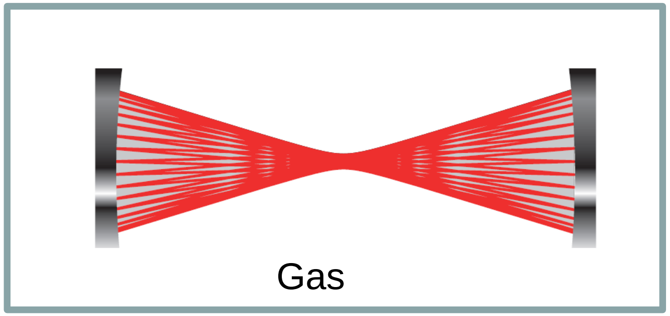
Beam collapse

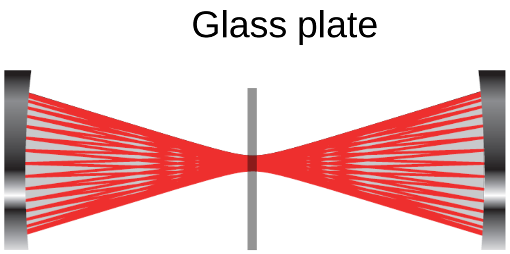
Beam stays
mode-matched



[Balla et al. Optics Letters, 45 (9) (2020)]

Gas vs bulk MPCs





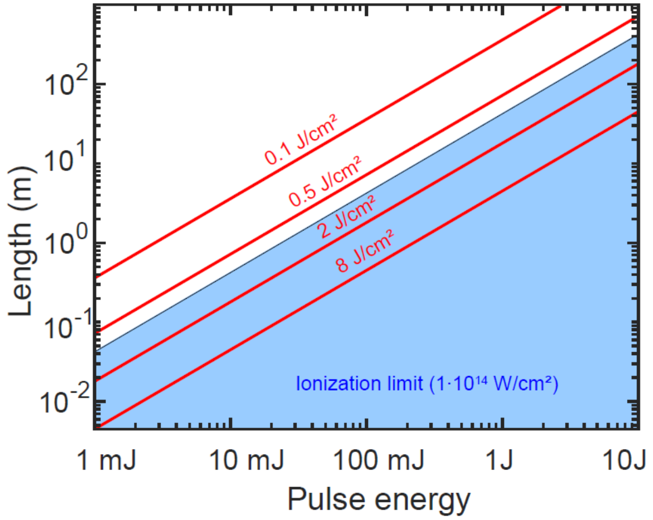
- Small nonlinearity -> high pulse energies possible
- Gases are immune to damage
- Peak power is limited by critical power
- Very large spectral broadening / compression ratios possible

- About 3 orders of magnitude higher nonlinearity compared to gas-filled MPC
- Very easy to implement on optical table
- Peak power can exceed the critical power of the nonlinear material!
- Compression ratios typically smaller compared to gas-filled MPCs

Pulse energy limits

Limits:

- Ionization: I_{th} – intensity limit at focus (gas-filled MPCs)
- LIDT: F_{th} – fluence limit at mirrors



Focal spot size for mode-matched MPC:

$$\omega_0^2 = \frac{R\lambda}{2\pi}\sqrt{C(2-C)}$$

Gaussian beam eqns. =>

$$\underbrace{\frac{F_{\mathrm{th}}R\lambda}{2\sqrt{2/C-1}}}_{\text{Mirror fluence limit}} > E_{\max} < \underbrace{I_{\mathrm{th}}R\lambda\tau\frac{1}{4}\sqrt{C(2-C)}.}_{\text{Ionization limit}}$$

Energy scaling options

- Wavelength
- Operation close to stability edge
- Geomtrical scaling: R, L

Photo: T. Metzger, Trumpf Scientific.

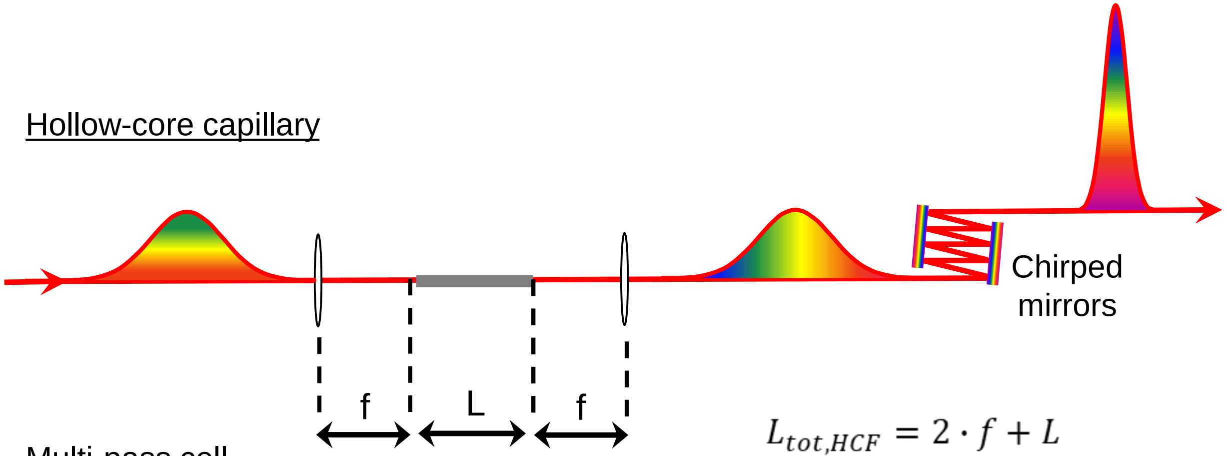
MPCs vs. HCFs

R – ROC, *L* – MPC length
N – number of round trips
k – 1…N-1, free integer
E – pulse energy
P – peak power
λ – wavelength
n_2 – nonlinear index
A_{eff} – effective mode area

Limits:

- Ionization: I_{th} – intensity limit at focus (gas-filled MPCs)
- LIDT: F_{th} , I_{th} – fluence and intensity limit at mirrors

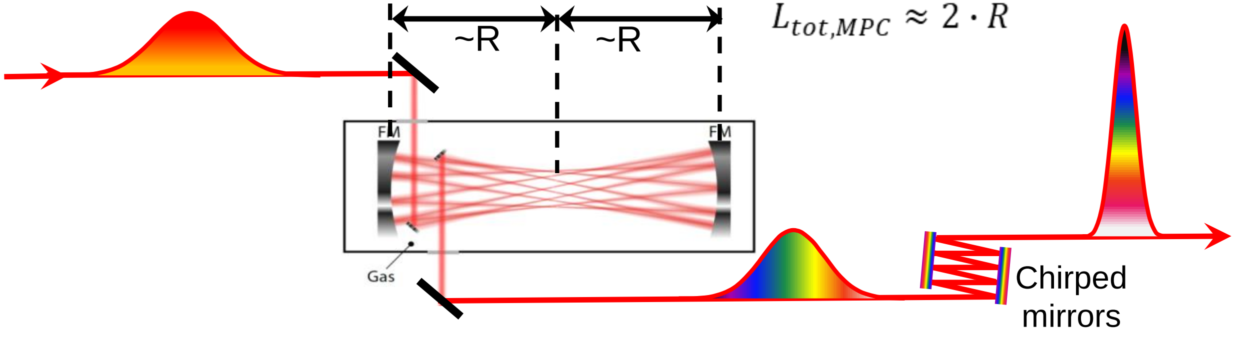
Hollow-core capillary



$$B_{\mathrm{HCF}} = \frac{2\pi}{\lambda} n_2 P \frac{L}{A_{\mathrm{eff}}} \propto L$$

$$L_{tot,HCF} = 2 \cdot f + L$$

Multi-pass cell



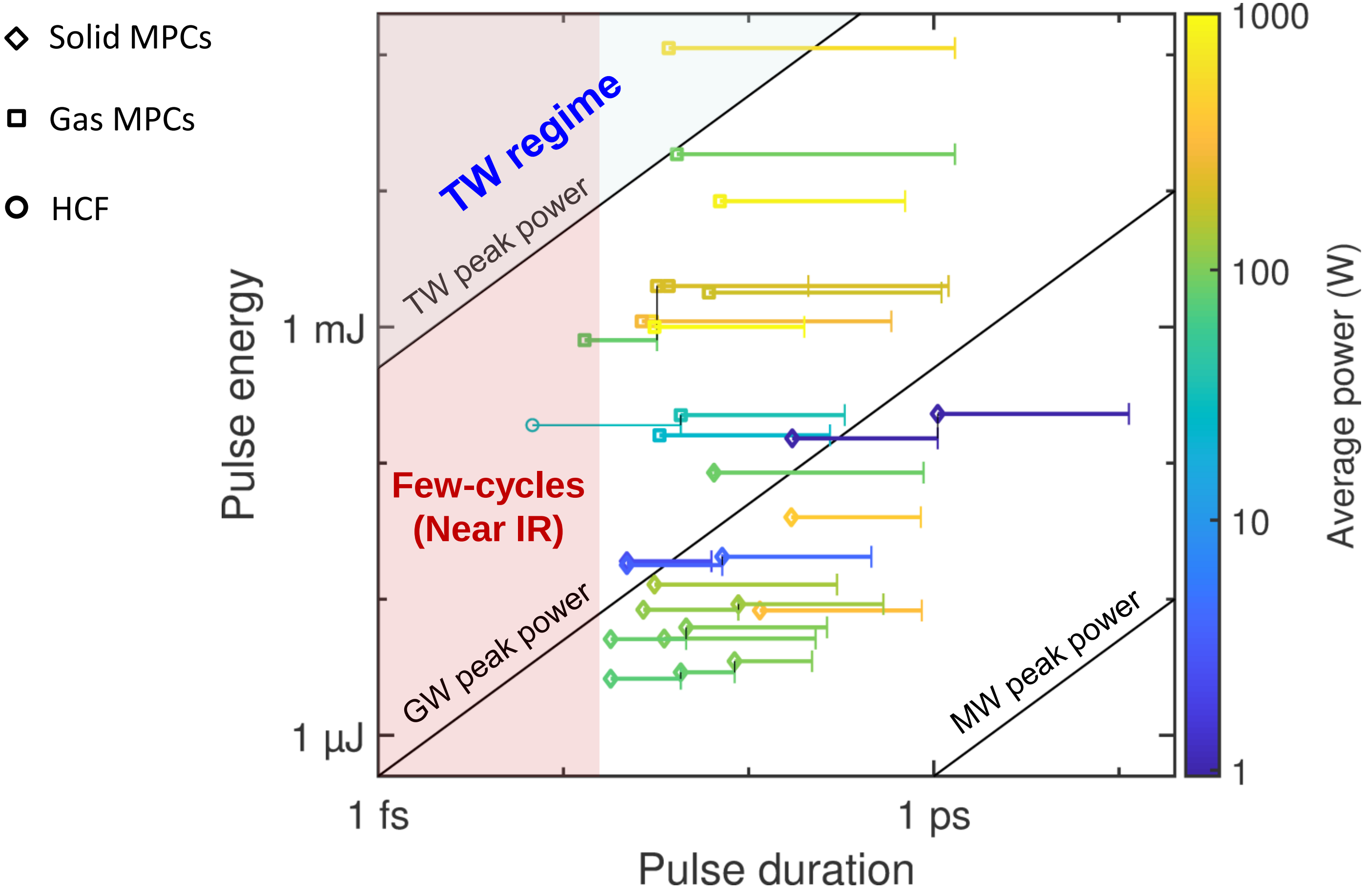
$$L_{tot,MPC} \approx 2 \cdot R$$

$$B_{\mathrm{MPC}} = \frac{8\pi^2}{\lambda^2} n_2 P N \propto N$$

MPCs and HCF setups have same length limit for small B, but HCF length increases with B, MPC length does not!

[T. Nagy et. al., ADVANCES IN PHYSICS: X (2020)]

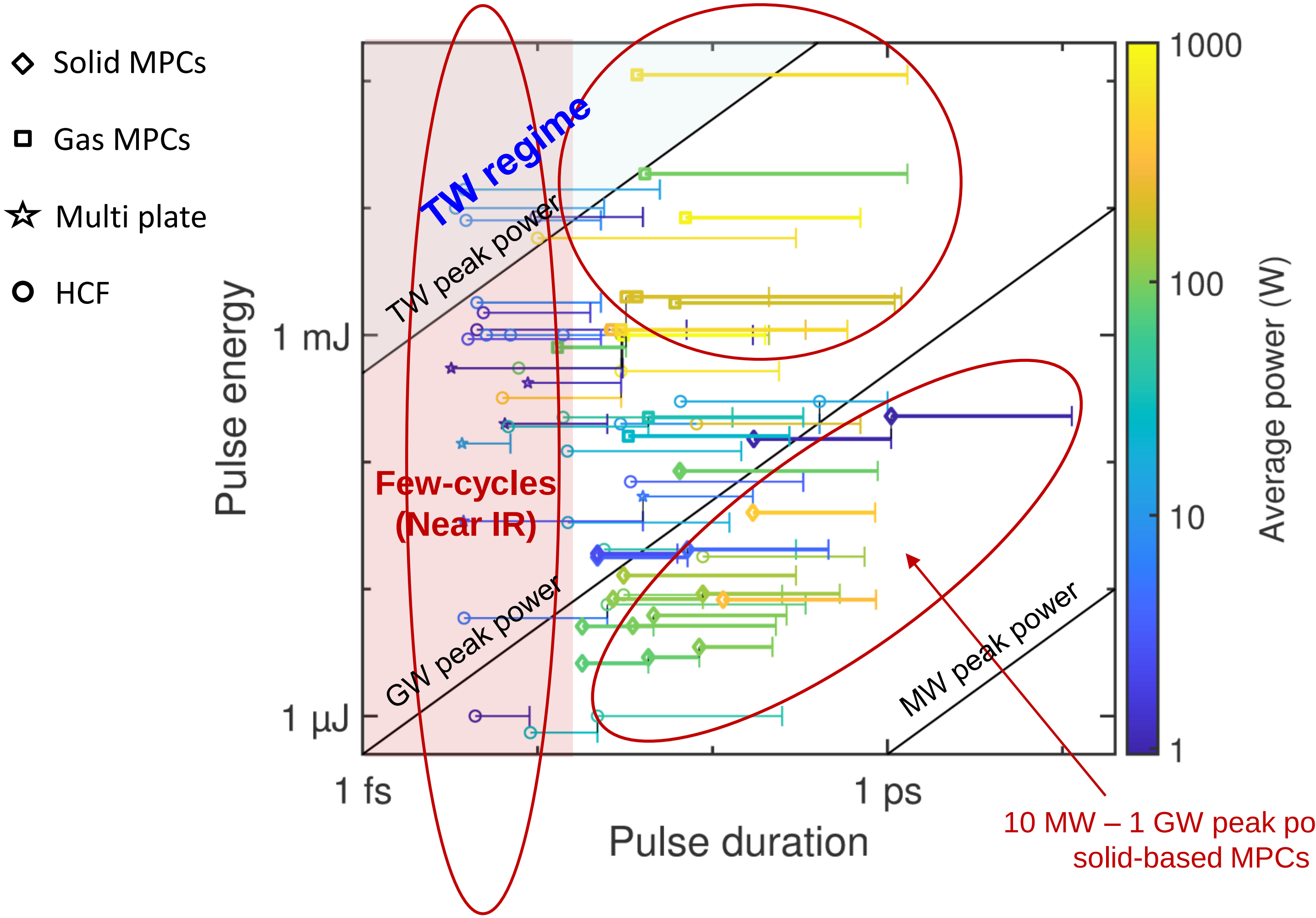
MPC – post-compression: Parameter overview



Diagonal lines: Peak power assuming Gaussian pulse

Important parameter regimes: TW, MW, few-cyles, high-pulse energy

Post-compression: Parameter overview



Few cycle: HCF, multi-plate

High pulse energy, large compression factor & high average power: gas MPC

10 MW – 1 GW peak power: solid-based MPCs

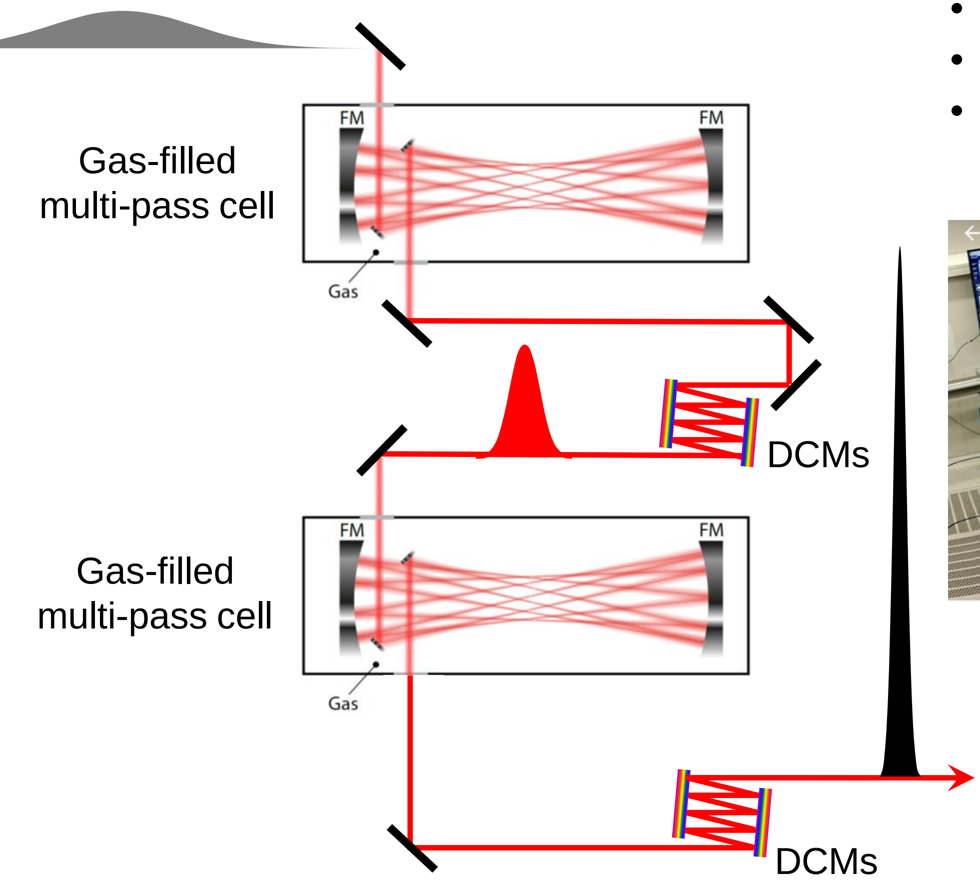
Important parameter regimes: TW, MW, few-cyles, high-pulse energy

Post-compression: method comparison

	Single-pass bulk	Solid core fiber	Hollow core fiber/ capillary	Multi-plate	Multi-pass cell	Filament
Simplicity	✓✓	✓	✓	✓	✓	✓
Beam quality	✗	✓✓	✓	✓	✓✓	✗
Compression ratio	✗✗	✓	✓	✓	✓✓	✓
Transmission (clean pulse)	✓	✓	✓✓	✓	✓✓	✗
Few-cycle generation	✗	✗	✓✓	✓✓	✓	✓
Peak power	**low-very high**	**Very low**	**medium - high**	**medium**	**low-very high**	**medium - high**
Small setup at high pulse energy	✓	✗	✓	✓	✓✓	✗

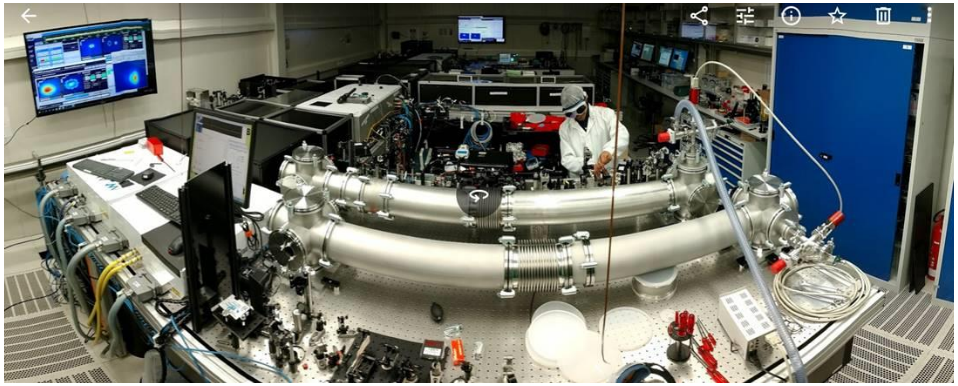
Recent works at DESY

Input: 1.2 ps, 1030 nm, 2 mJ,
100 kHz/10 Hz burst mode



Parameters

- Kr-filled multi-pass cell’s
- Cell length: ~ 2 m
- Cell mirror size: 3” , silver mirrors in 2nd cell
- Number of passes through 2nd cell: 12 (~ 24 m!)

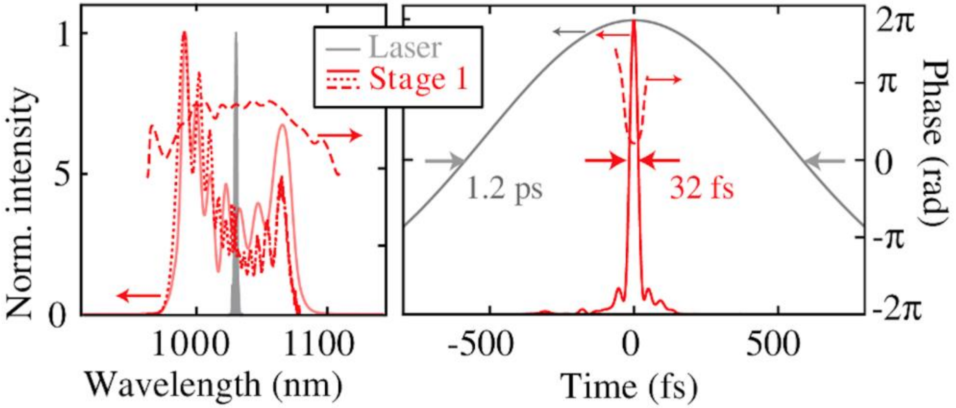


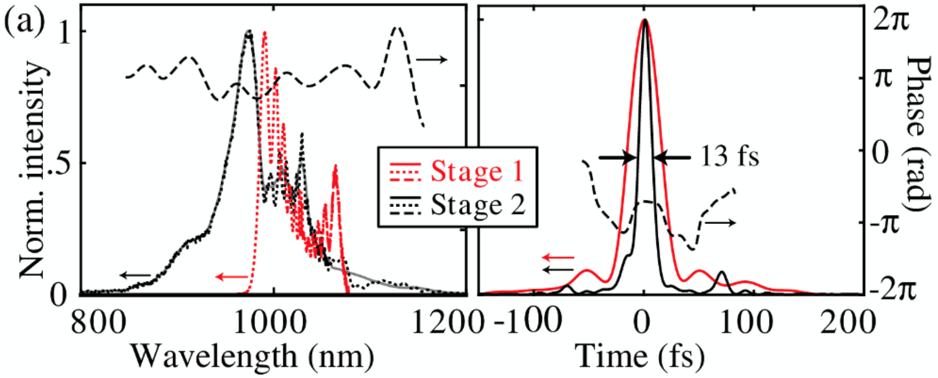
[P. Balla, A. Bin Wahid et al. Optics Letters, 45 (9) (2020)]

Recent works at DESY

Key parameters:

- Two Krypton-filled MPCs
- 200 W in-burst average power
- 2.25 mJ input pulse energy, < 50% total transmission



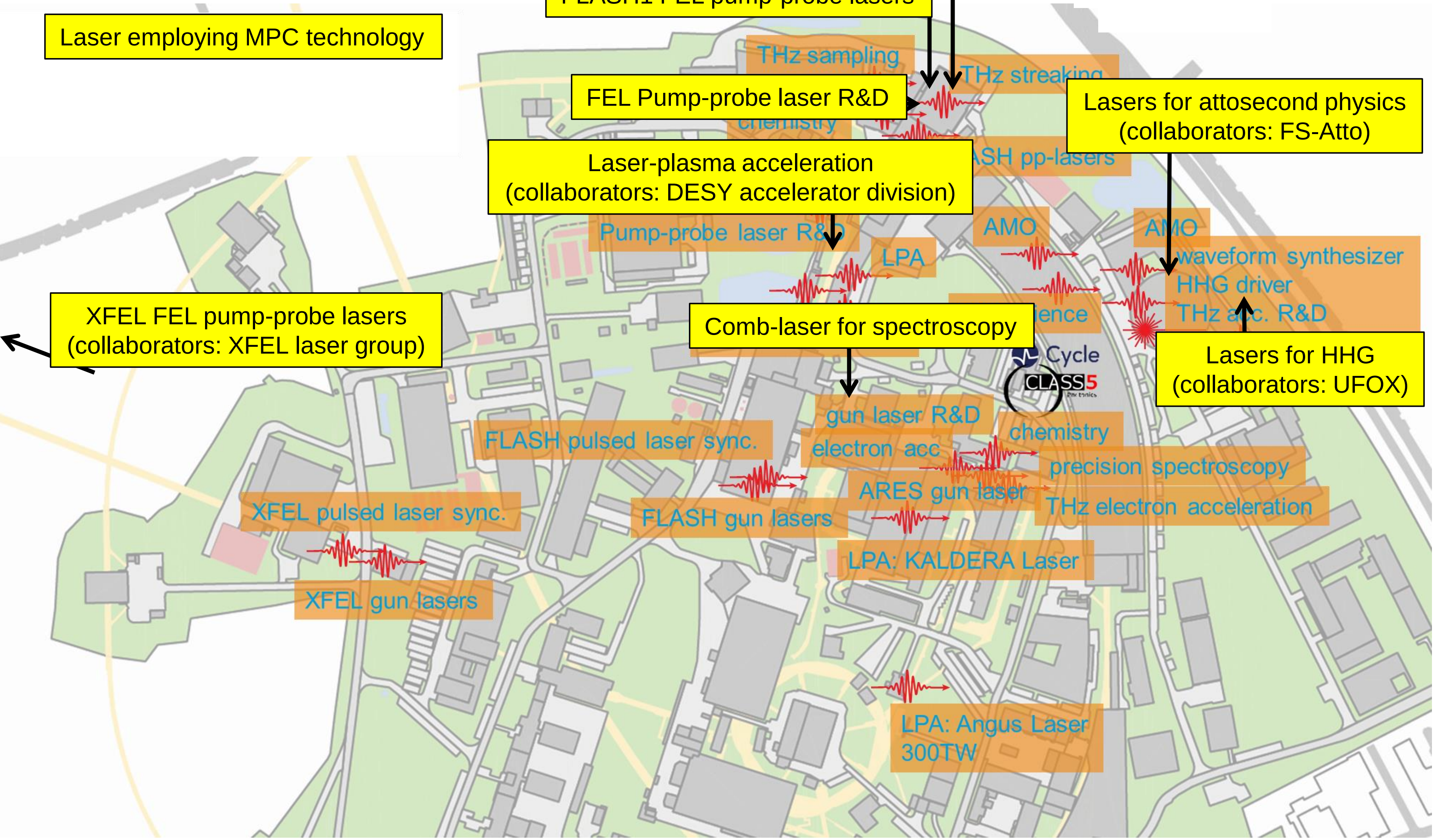


[P. Balla, A. Bin Wahid et al. Optics Letters, 45 (9) (2020)]

MPC-based ultrafast laser development at DESY

Ultrashort-pulse lasers

Laser employing MPC technology



FLASH2 FEL pump-probe lasers

FLASH1 FEL pump-probe lasers

FEL Pump-probe laser R&D

Lasers for attosecond physics
(collaborators: FS-Atto)

Laser-plasma acceleration
(collaborators: DESY accelerator division)

XFEL FEL pump-probe lasers
(collaborators: XFEL laser group)

Comb-laser for spectroscopy

Lasers for HHG
(collaborators: UFOX)

Ongoing research directions

Hot topic developments within ultrafast science!

- Pulse energy scaling
- Few-cycle pulse generation
- TW-class pulse production
- Employ MPCs for other nonlinear processes