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Ultrafast fibre lasers

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Ultrafast fibre lasers are fundamental building blocks of many photonic systems used in industrial and medical applications as well as for scientific research. Here, we review the essential components and operation regimes of ultrafast fibre lasers and discuss how they are instrumental in a variety of applications. In regards to laser technology, we discuss the present state of the art of large-mode-area fibres and their utilization in high-power, chirped-pulse amplification systems. In terms of commercial applications, we introduce industrial micromachining and medical imaging, and describe emerging applications in the mid-infrared and extreme-ultraviolet spectral regions, as facilitated by frequency shifting induced by fibre frequency combs.

Outline

Introduction - Brief History

- 1950 - First **endoscope fiber developed** , becoming the first application of optical fiber.
- 1960s-1970s - **Long distance data transmission** , continue to evolve rapidly till today
- 1980s - The application of fiber lasers didn't attract much attention till the development of diode lasers, demonstrating the **first EDFA (Erbium Doped Fiber Amplifier)**
- 1990s - **Ultrafast fibre lasers** developed from the demand for short pulses for communication and also as replacement for mature solid-state lasers.
- Today more than 40 companies for ultrafast fibre lasers for diverse applications : ophthalmology, micromachining, medical imaging and precision metrology.

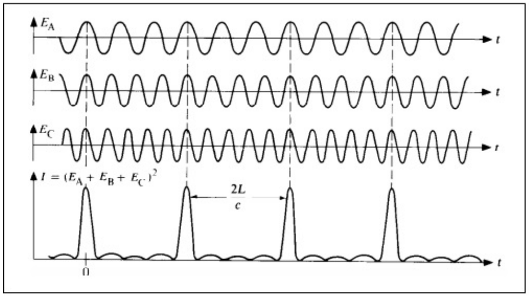
Article Outline Review

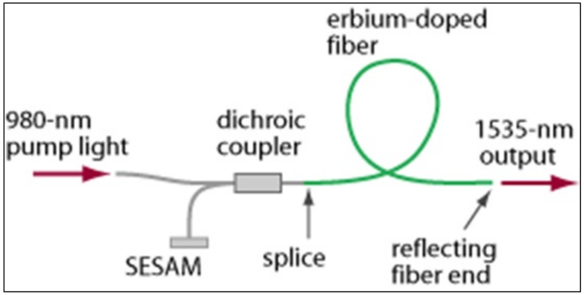
This article review few topics:

- Amplification schemes, frequency broadening via supercontinuum generation and overcoming nonlinear limitations
- Two recent developments : Fiber frequency combs and fiber base XUV sources
- Overview of current research directions and possible out

Basic Design Concepts and Applications

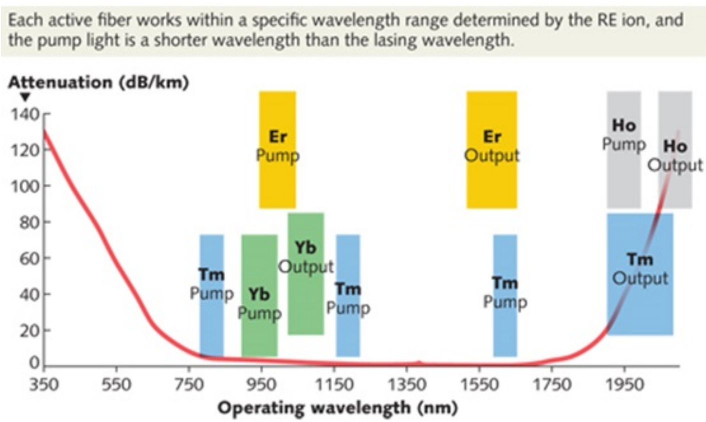
- Most ultrafast lasers are based on passively mode-locked lasers oscillator which are than amplified in several stages to reach desired output parameters.

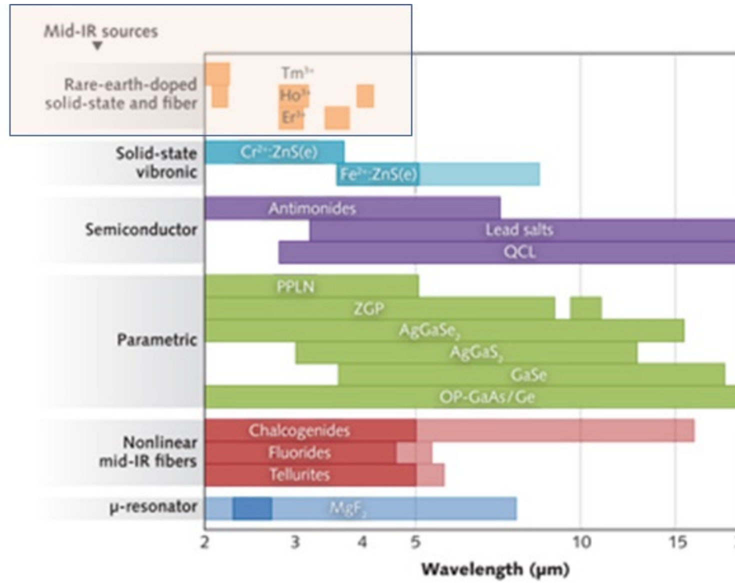




- Commercially $1.55\mu m$ and $1.05\mu m$ are dominant.
- Today, ultrafast fibre laser research has shifted to mid-IR regime near $2.0\mu m$ and $3.0\mu m$.

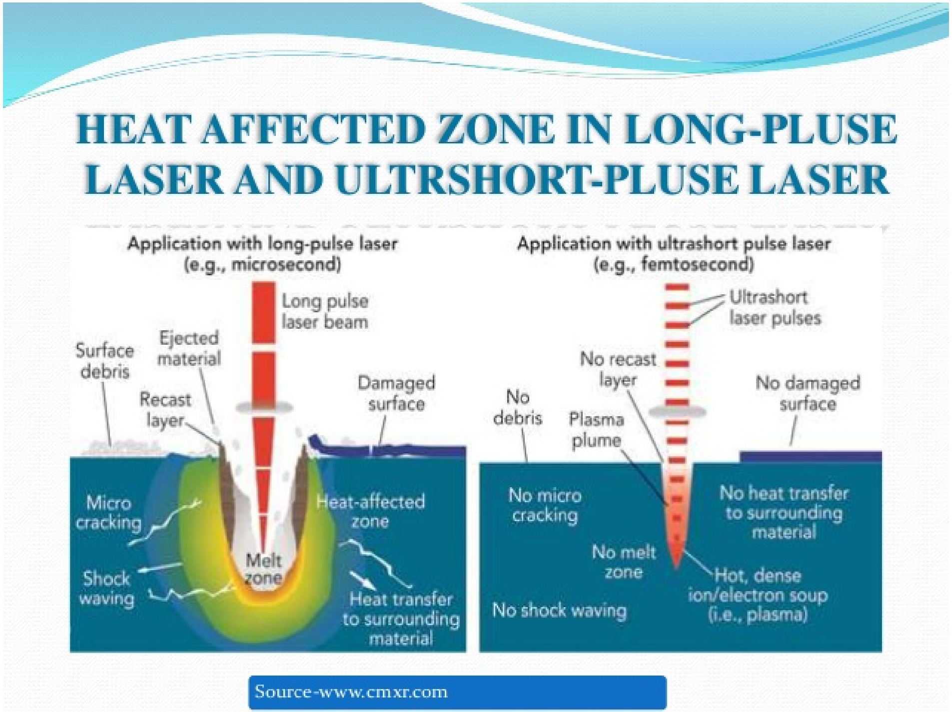
Basic Design Concepts and Applications





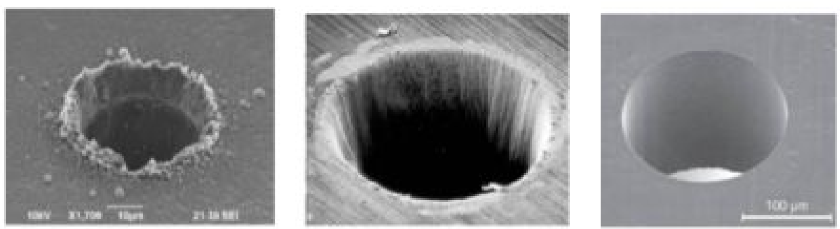
Ultrafast Fibre Source for Micromachining

- New mode locked fiber laser schemes achieve pulse repetition rates in the range of approx. 1.7-10MHz, making them ideal for a variety of micromachining applications (>10MHz are generally undesirable due to plasma shielding effect).



Ultrafast Fibre Source for Micromachining

- Chirped Pulse Amplification (CPA) technique is employed with typically $5 - 10\mu m$ core diameter fibers to generate sub-picosecond pulses with pulse energies of approx. $1\mu J$
- Higher energy pulses are required to process dielectrics and metals - 10s $\mu J - mJ$ range.
- Such sub-picoscond pulse duration achieve superior hole drilling quality which is one of the most driving motivation for developing such fibre lasers.



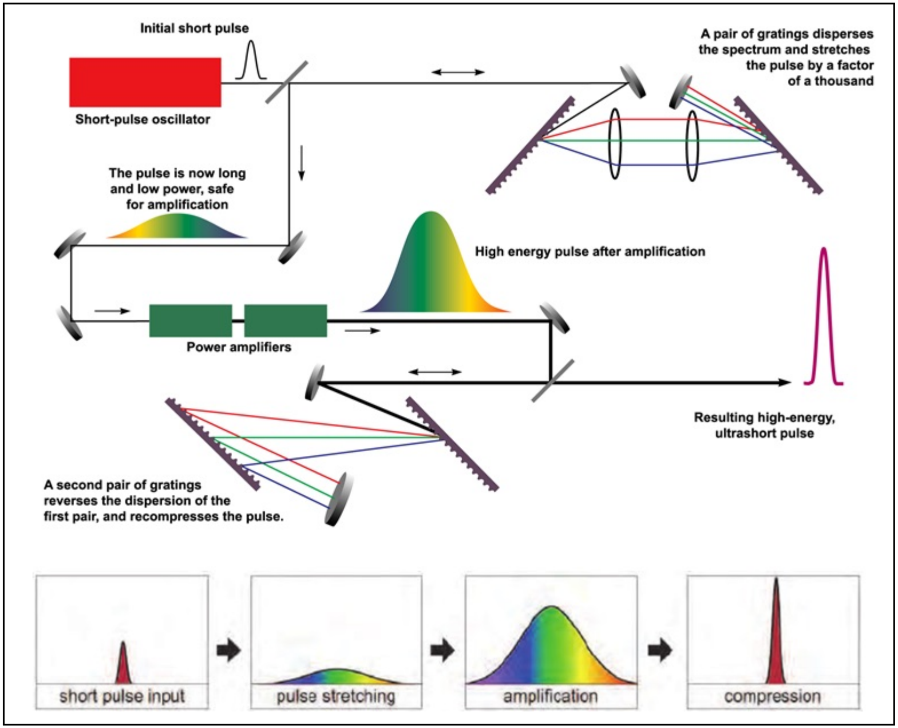
Nanosecond
HAZ (Heat Affected Zone)
Melt zone adds variability

Picosecond
Less HAZ
Rough surface adds variability

Femtosecond
No HAZ
Low variability

Ultrafast Fibre Source - Amplification Scheme

- Using current fiber technology oscillator pulses stretching and re-compression X10,000.
- pulses energies of several millijoules can be generated.



Large Mode Core Area Fibers

- Nonlinear effects due to scattering in fiber limits the highest power density in core, therefore limits single mode operation.

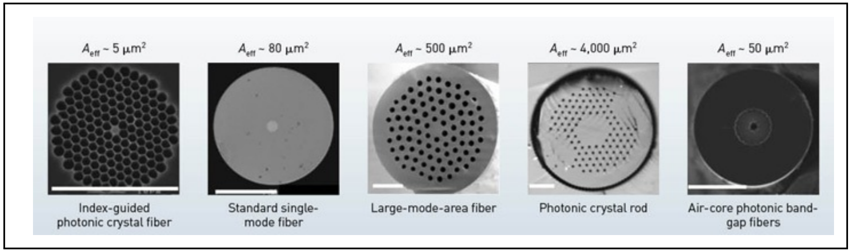
SRS $$P_{th}(SRS) \approx \frac{16 A_{eff}}{g_R L_{eff}}$$

g_R : Raman gain coefficient (1×10^{-13} m/W)

SBS $$P_{th}(SBS) \approx \frac{21 A_{eff}}{g_B L_{eff}}$$

g_B : Brillouin gain coefficient (5×10^{-11} m/W)

- New fiber designs can reach larger core diameter with single mode operation to increase nonlinear threshold limits.



- **Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power**

Jay W. Dawson, Michael J. Messerly, Raymond J. Beach, Miroslav Y. Shverdin, Eddy A. Stappaerts, Arun K. Sridharan, Paul H. Pax, John E. Heebner, Craig W. Siders and C.P.J. Barty

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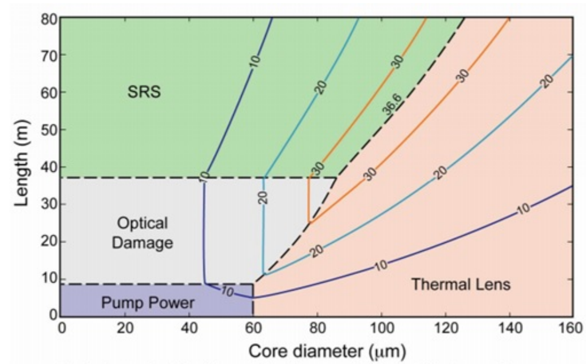


Fig. 2. Contour plot of the minimum of six of the seven physical power limits (power units are in kW) discussed in section II (SBS has been ignored in this case) using the parameters in Table 1 but increasing the pump brightness B_{pump} by 5X and allowing the core diameter and fiber length to vary. Now four limits come into play in this plot, the pump power limit in the blue (lower left section of plot), the SRS limit in green (upper left section of plot), an optical damage limited region in gray (middle left section of the plot) and the thermal lens limit in red (right side of graph).

Achievements- High Avg. Power-High Peak Power

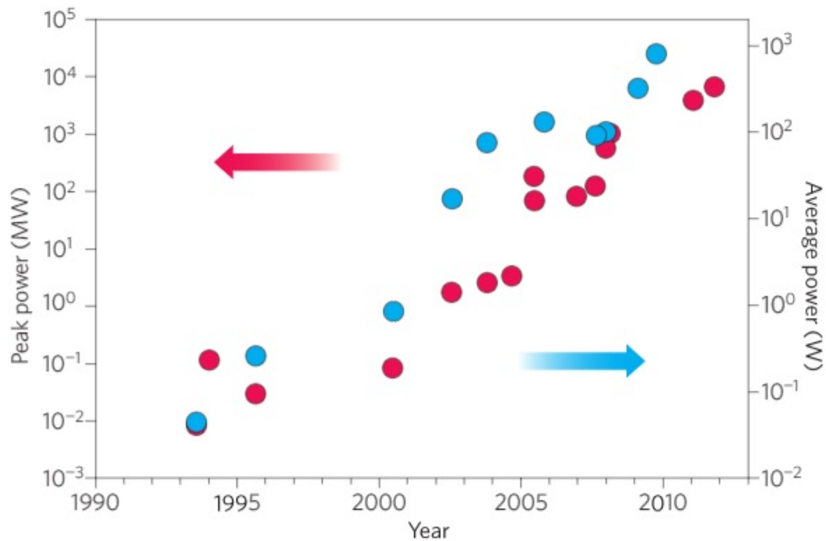
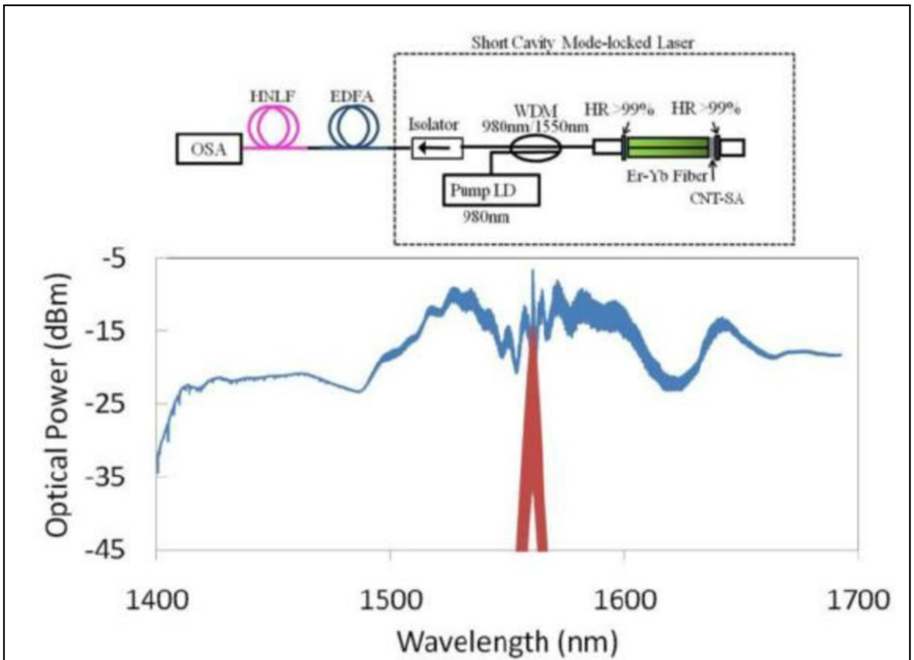


Figure 2 | Development of output power over the years. Development of average power (blue circles) and peak power (red circles) for fibre-based chirped pulse amplification systems over time. The maximum peak power from fibre lasers is presently 5.6 GW, although a fibre laser with a multi-terawatt peak power and an average power of over 10 kW has been proposed[93]. (Figure courtesy of T. Eidam.)

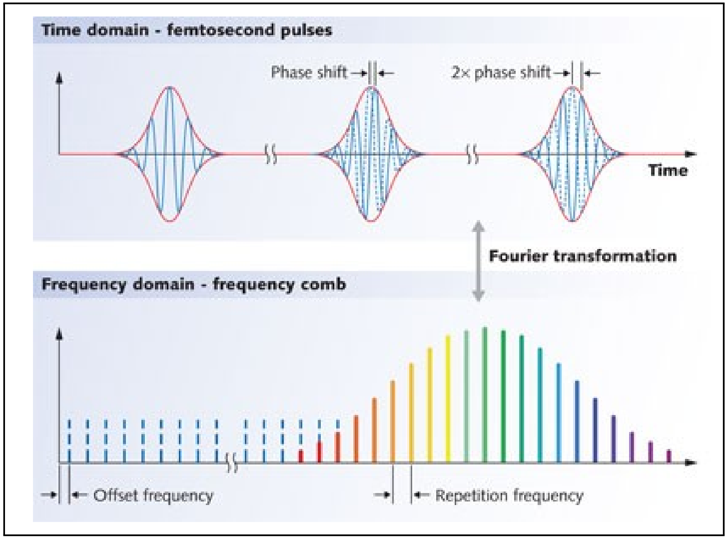
Ultrafast fibre sources for imaging

- Ultrafast fiber laser is far more advantageous then non-coherent sources used for spectroscopy such as : arc lamps or other CW laser such as argon and krypton.
- Ultrafast fibre lasers offer wide spectrum, coherence, shorts pulses, good beam quality, narrow spectral lines.



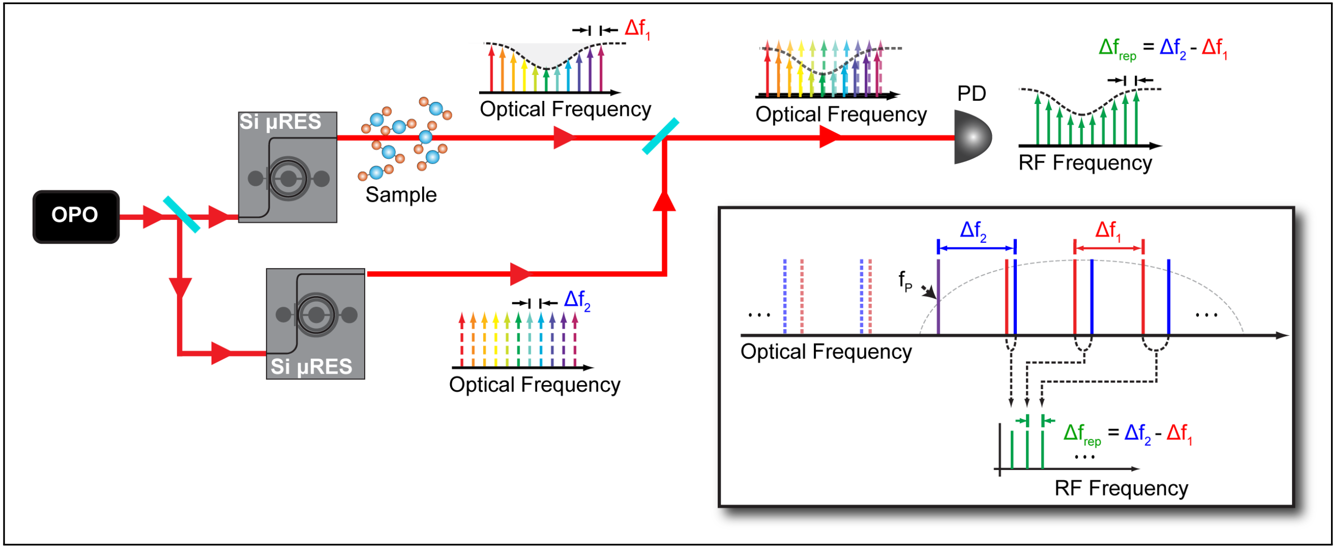
Fiber laser frequency combs

- Frequency combs are time/frequency ruler



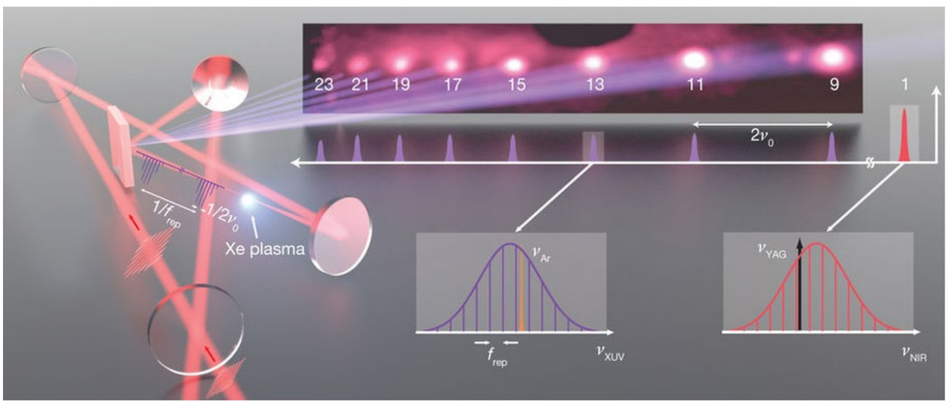
Fiber laser frequency combs

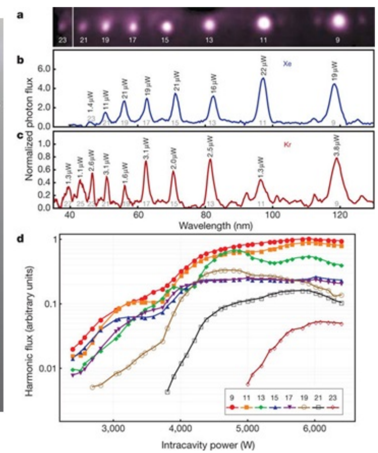
- Er fiber laser allow commercial optical combs for their simplicity of construction and self passive carrier phase stability



Fiber laser XUV Sources

- Generated by HHG (High Harmonic Generation) of femto-second fiber laser, and intra cavity enhancement schemes.
- 10-20 μW power levels achieved with the wavelength of 50-100 nm.





- Coherent combining of fiber lasers

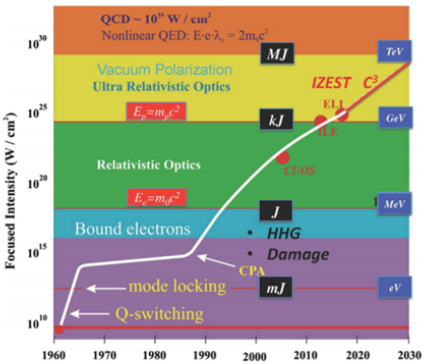


Fig. 1. The evolution of laser intensity in relation to electron energy regimes.

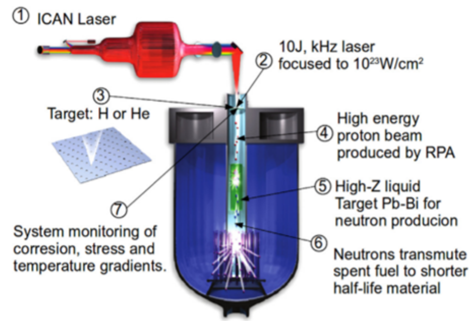


Fig. 3. Schematic of an ADR system with fiber front end. The fiber-based proton accelerator drives a spallation neutron source, which can be used for transmutation of minor actinides into less toxic elements. © Phil Sanders, used with permission.

Summary

- Huge impact of ultrafast fibre laser for various applications has enlarged research activities and commercial products.
- Ultrafast fibre lasers rapid development will continue due to advancment in the fiber based components and research (high power fibers, various fiber designs, special materials, pump diode laser, etc..)