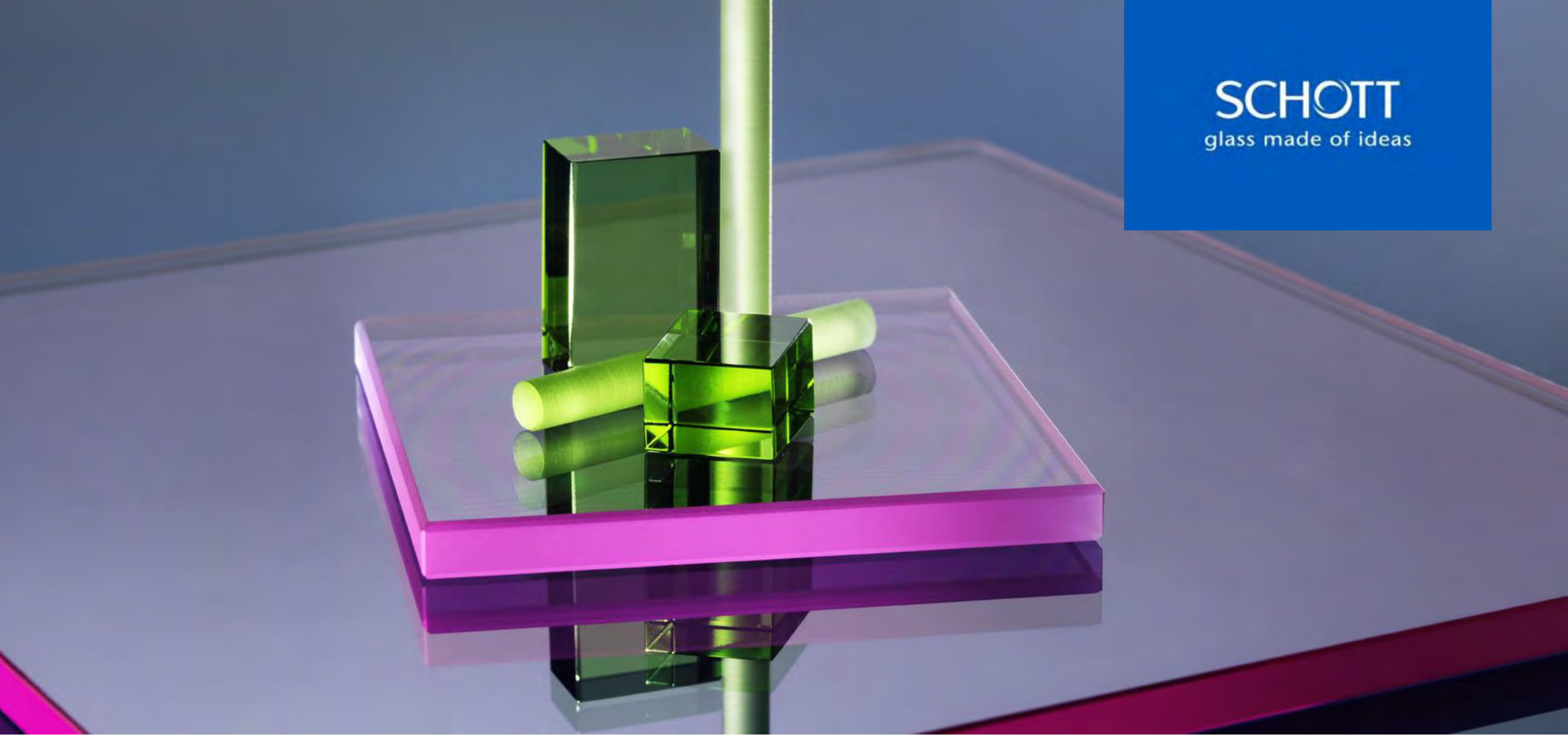

Laser damage threshold of AR coatings on phosphate glass

Optical Coatings for Laser Applications
Wednesday, 12th April 2017, Buchs SG, Switzerland

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Why glass in laser applications? : Advantages

Crystal (e. g. Nd:YAG, Ti:Sapphire)

- High laser gain
- High strength
- High thermal conductivity

Glass (e. g. LG760, LG950)

- Nearly unlimited dimensions (→ casting, redraw process)
- High homogeneity (optical, chemical)
- Types with possibility for chemical tempering available
- Processable with standard tooling
- Comparatively good price
- Larger emission width
- Properties a function of composition and/or processing. (minimization of disadvantages for each specific situation)
- Properties of glass composition thoroughly studied. (optimized glass for a particular laser quickly identified)

Why glass in laser applications? : Disadvantages

Crystal (e. g. Nd:YAG, Ti:Sapphire)

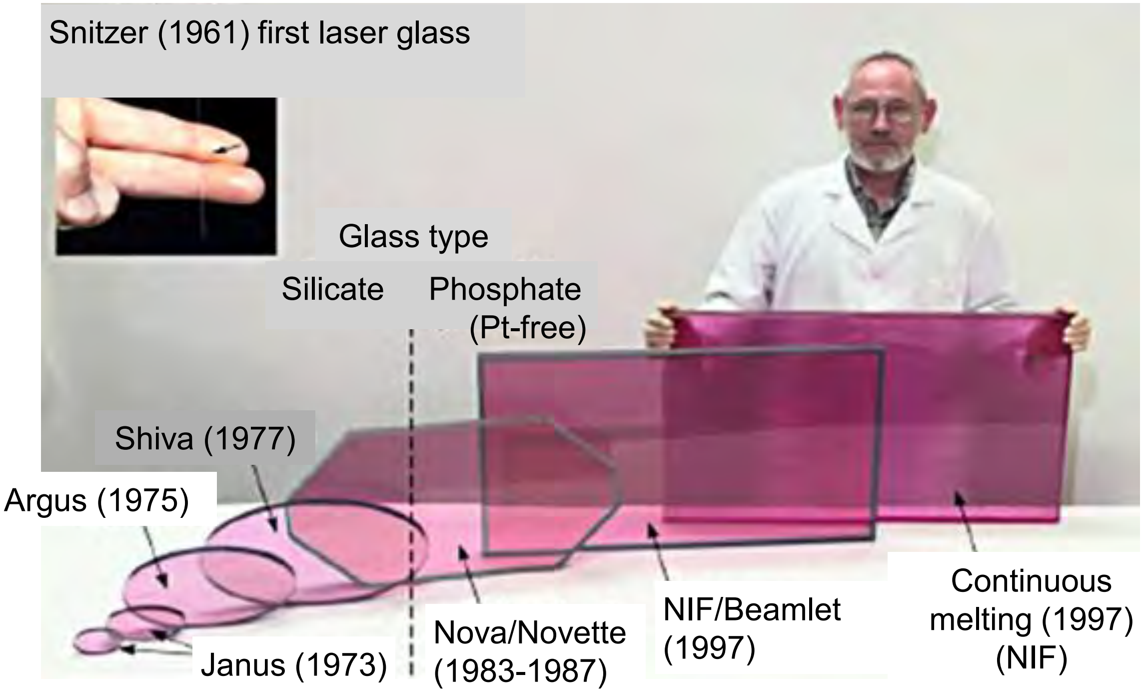
- Usually single crystals with limited dimensions
- Normally expensive
- Stress birefringence
- optical inhomogeneity
- concentration profile

Glass (e. g. LG760, LG950)

- Poor thermo-mechanical properties:
- high thermal expansion
- low fracture toughness
- low thermal conductivity
- changes in refractive index with temperature
- Soft; scratches easily
- Phosphate chemically not stable (absorbs water and converts to phosphoric acid)
- Laser damage:
- nonlinear index and self focusing
- bulk damage from inclusions

Nd^{3+} doped broadband glasses for high power applications

- High power ultra-short pulse (broadband) systems



LIDT

- Slabs typically uncoated, but challenge for AR on big rods
- Typical LIDT spec for 10 ns pulses @ 1550 nm : 10 to 30 J/cm^2

SCHOTT glass made of ideas

… have enabled cutting edge laser projects

Novette, 1981-1983

NOVA 1984-1987

Beamlet 1991

LaserFocusWorld

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National Energetics' 10 petawatt laser system passes major milestone

09/07/2016

By John Wallace

Senior Editor

Laser MegaJoule, 2001-2004

NIF, 2001-2004

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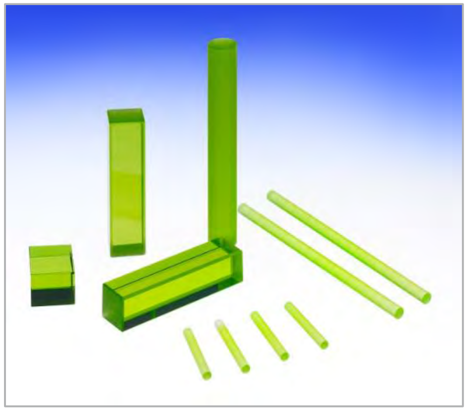
Er^{3+} and Yb^{3+} co-doped glasses for "eye-safe" lasers



Applications

- Medical (e. g. surgery, dermatology, epilation)
- Defence (e.g. range finders)

Advantages

- Absorption in the cornea, lens, and vitreous humour of the eye (easier replaceable than the retina)
- Superior beam quality demonstrated with Er-Yb doped phosphate glass
- Stable operation with passive/no cooling in the –40 to +50°C range
- Easy co-doping with sensitizers for more efficient pumping (Yb, Cr, Ce)

LIDT

- Typical LIDT spec for 10 ns pulses @ 1550 nm : 5 to 25 J/cm^2

The issues with processing phosphate glass

Polishing

- Material is soft and scratches easily, fissures
- It can easier take on contamination such as polishing grains/oxide
- The aqueous slurry chemically attacks the glass

Cleaning

- Hydrolysis of P_2O_5 to phosphoric acid at the surface (also issue for stocking)
- Temporal drying of contamination induces inhomogeneous chemical attack and digs after cleaning
- Grains are more engraved and not easily removed
- Necessary thorough cleaning can scratch the surface

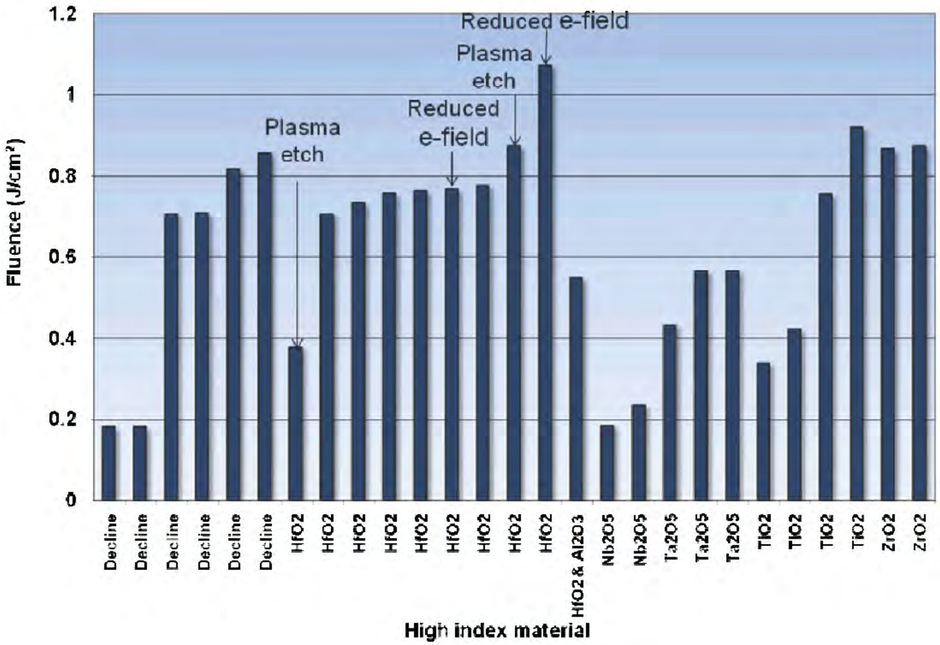
Coating

- Low adhesive strength of coating (adhesive tape test)
- Large difference in thermal expansion between coating and glass
- Humidity can penetrate pinholes and micro fractures, chemically attack the glass & burst the coating

All this can additionally contribute to lowering the LIDT.

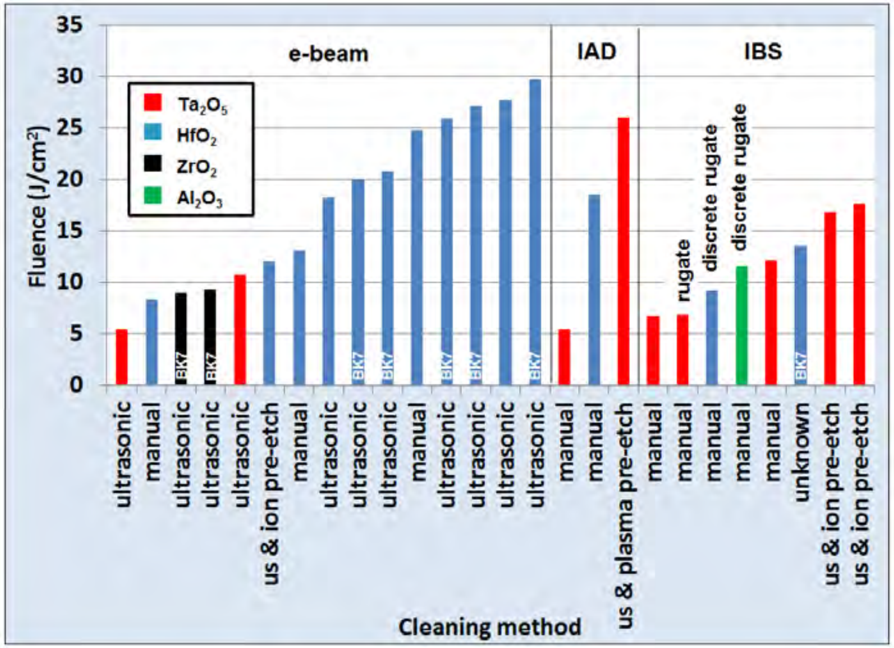
LIDT in Literature

LIDT competition of the Boulder Damage Symposium



Distribution of laser resistance as a function of high index material (mirrors 786 nm, 200 fs)

C. Stolz, SPIE 7504, 75040S (2009)



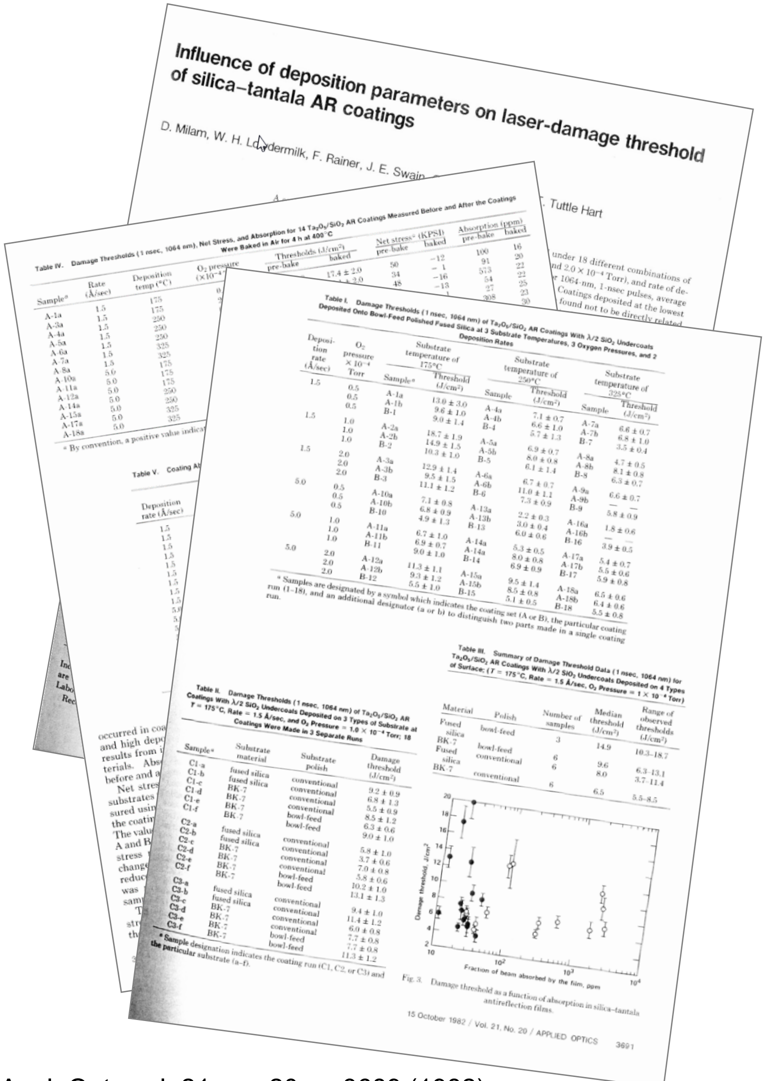
"S" polarization laser resistance of Brewster angle polarizing beamsplitter as a function of deposition process, coating material, substrate, and cleaning method (1064 nm, 10 ns)

C. Stolz, SPIE 8885, 888509 (2013)

LIDT in Literature

Article data

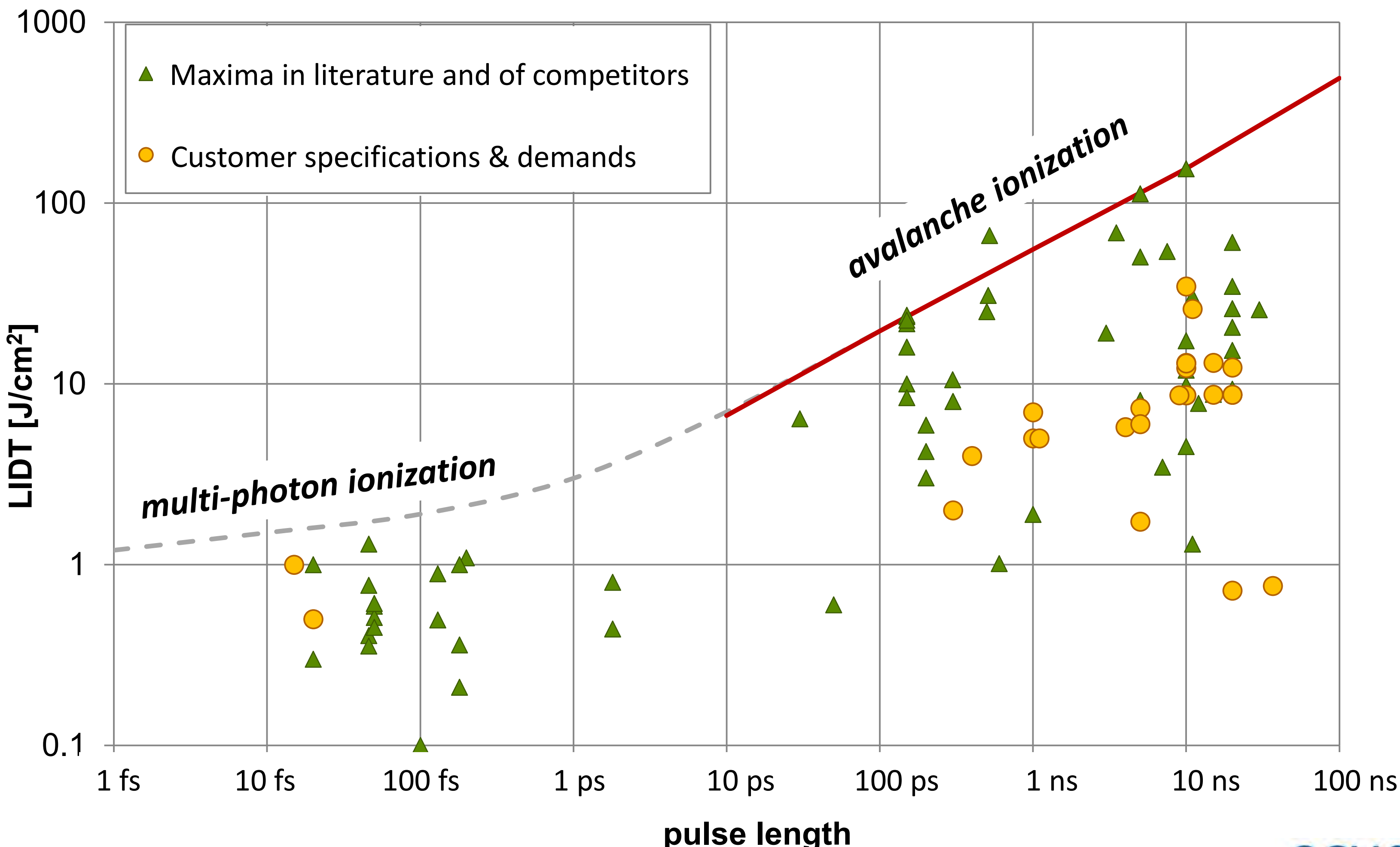
- Hundreds of articles have been scanned to determine the state of the art. (e. g. almost 50 years of SPIE proceedings of Boulder Damage Symposium)
- A lot of immediate information: e. g. HfO2 better than TiO2, annealing better than not annealing, but mostly only qualitative because particular
- Some articles contain lots of interesting data never properly statistically analyzed.
- No joint statistical analysis of data from various sources.



Milam, Appl. Opt., vol. 21, no. 20, p. 3689 (1982)

LIDT in Literature

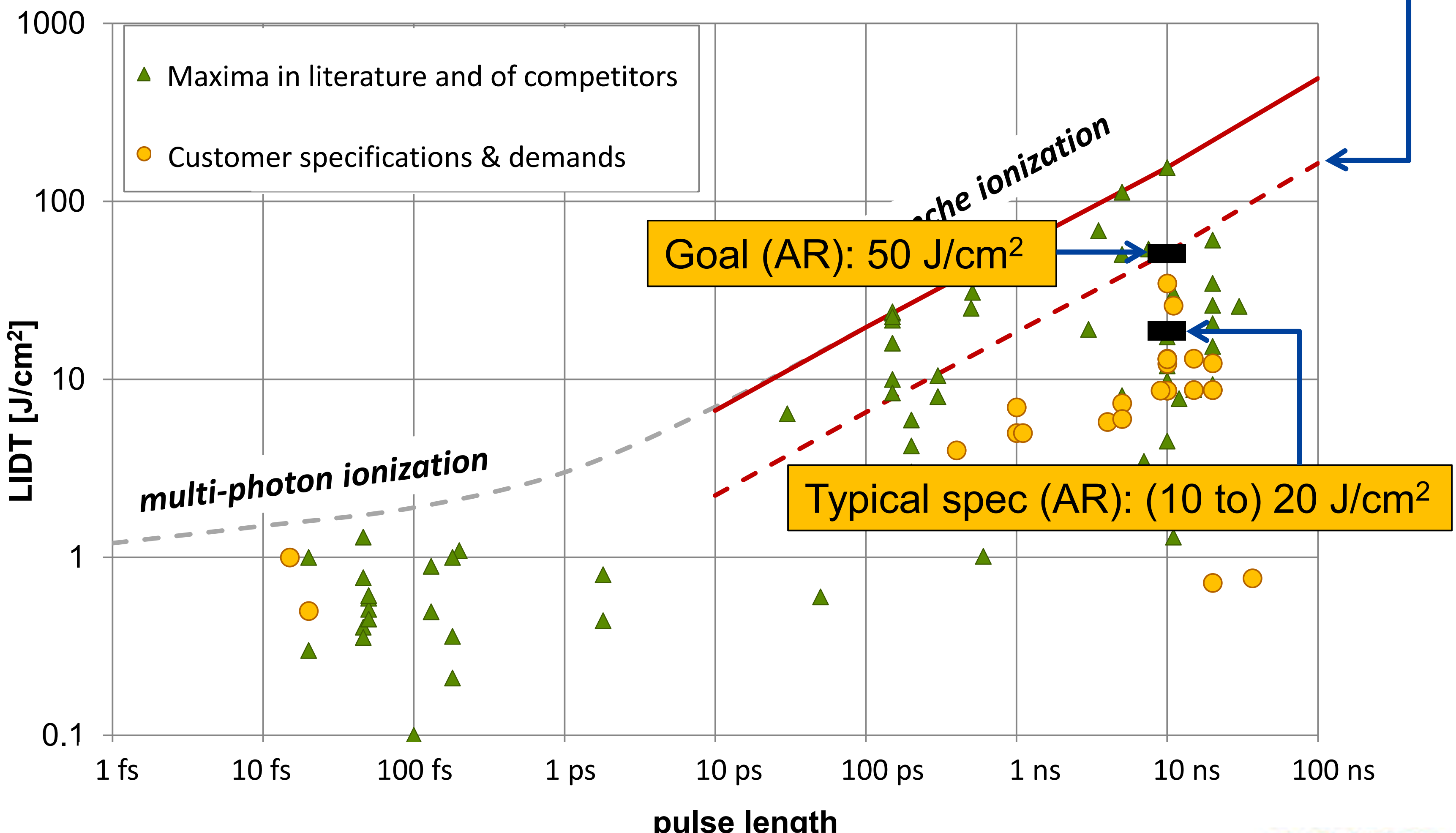
LIDT of mirrors (values scaled to 800 nm wavelength)



LIDT in Literature

Dashed line factor 3 lower as "guide to the eye" for AR values

LIDT of mirrors (values scaled to 800 nm wavelength)



SCHOTT glass made of ideas

LIDT in Literature

Design of experiment and statistical analysis

- Usually a method to quantitatively acquire data on correlations with minimal experimental effort
- Then mathematically describe behavior in multi-dimensional parameter space (with interactions, probabilities, confidence intervals)

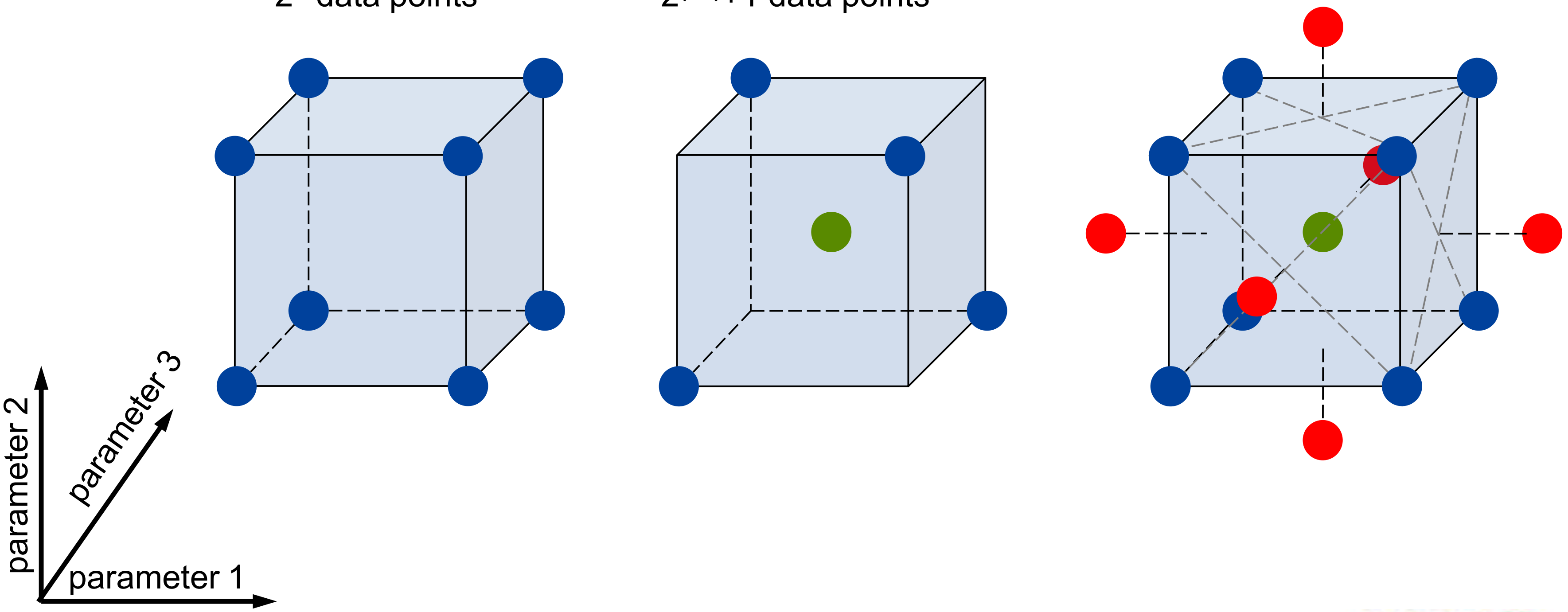
full factorial design

2^n data points

fractional factorial design

$2^{(n-i)}+1$ data points

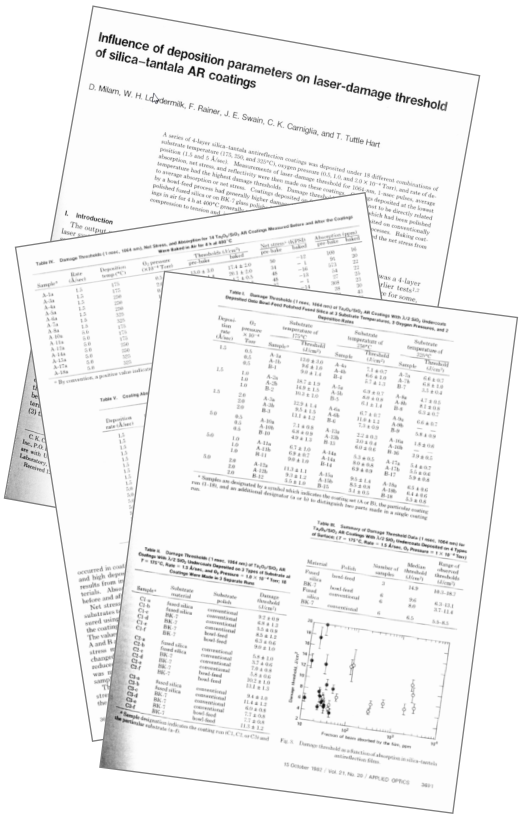
response surface design



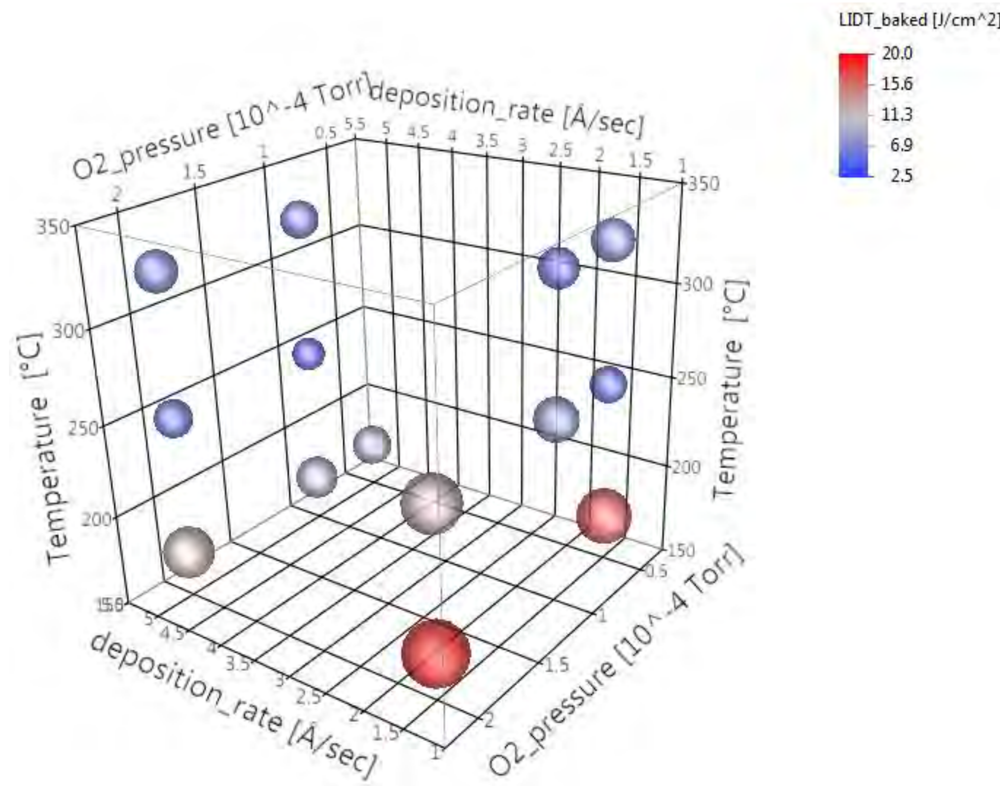
LIDT in literature

As if there was a Design Of Experiment …

- LIDT data and process parameter information from several articles
- Scaled in wavelength and pulse length

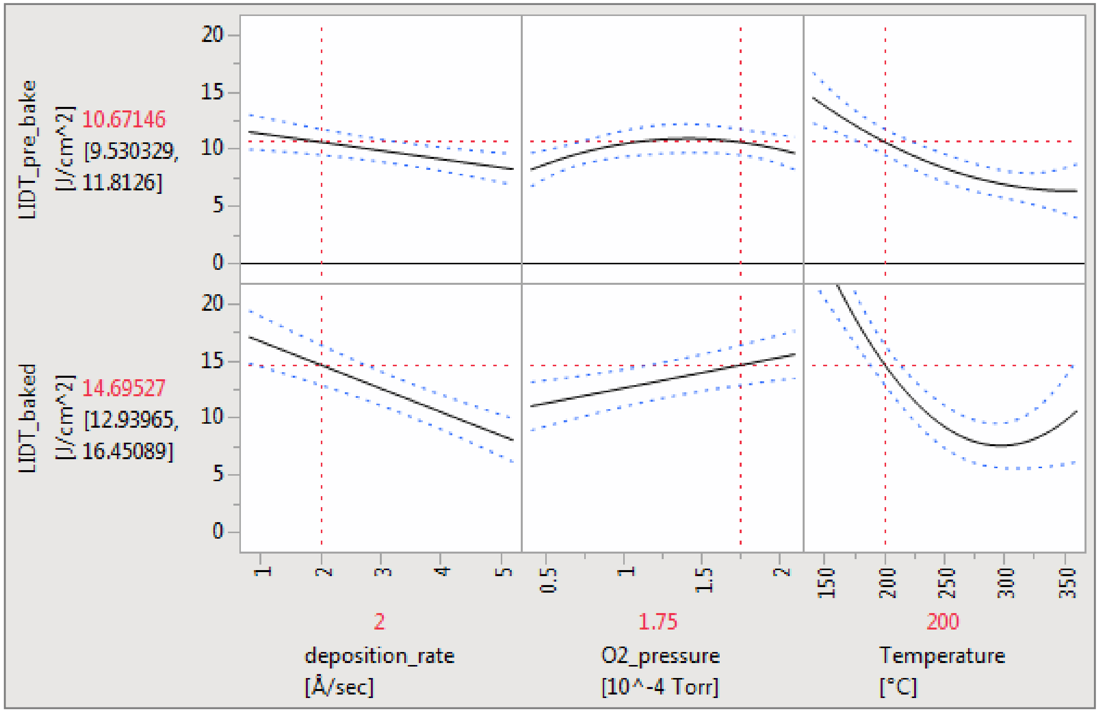

Influence of deposition parameters on laser-damage threshold of silica–tantala AR coatings

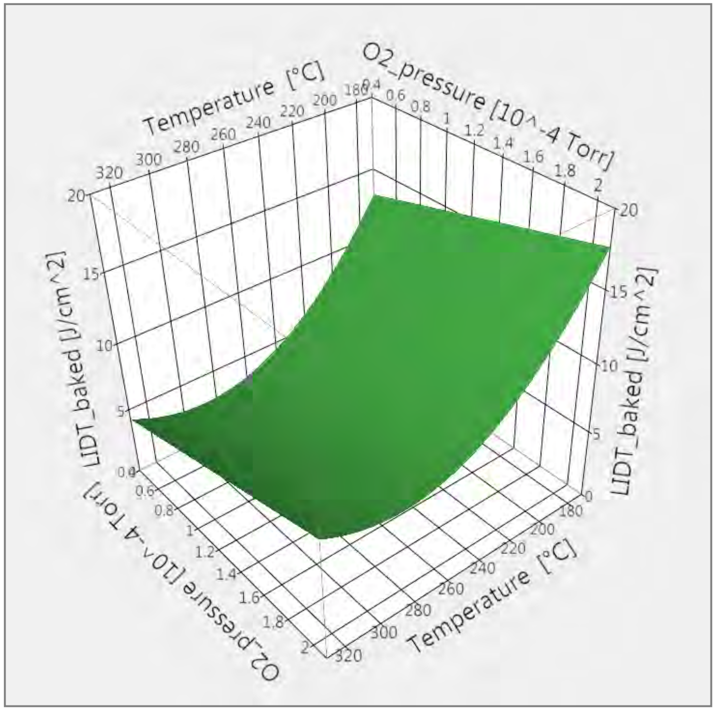
D. Milam, W. H. Lowdermilk, F. Rainer, J. E. Swain, C. K. Carniglia, and T. Tuttle Hart



LIDT in literature

- … analyzed statistically
- Some examples :





LIDT in literature

Results for silicate glasses (in literature basically N-BK7 & fused silica)

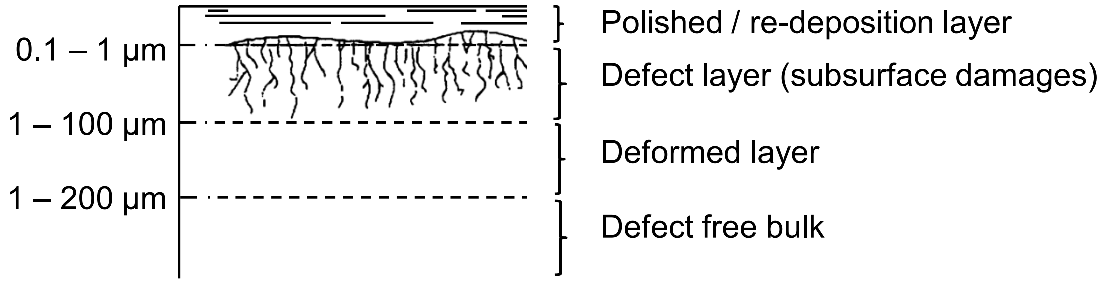
- Wet-chemical etching before finishing
- Super polishing (surface defects) and reduction of sub-surface damages
- Thorough cleaning (sequence of agents, rubbing, ultra-sonic)
- Pre-deposition ion etching (e. g. Ar^+)
- Electron beam evaporation or ion beam sputtering, not magnetron sputtering or IAD
- Low deposition rate
- Medium to high oxygen pressure
- Not too high deposition temperature
- Layer materials: low: SiO_2, high: Sc_2O_3, HfO_2, Ta_2O_3, but not TiO_2
- Final thermal annealing

- Optical design to reduce maxima of electric field distribution
- Optical design with maxima of electric field distribution within layers, not at interfaces
- Optical design with maxima of electric field distribution within layers of large bandgap materials

Parameters: Sub-surface damages

Minimizing subsurface damages

- Scratches and fissures lower the LIDT
- Key LIDT influence parameter: (sub-)surface damage density, (nano-)scratch/fissure density
- Process parameters: slurry grain material, slurry grain size distribution, pad type, pH value, …
- Polishing: Sequence of various material removing steps: Grinding/lapping, pre-polishing, finishing
- Each operation induces subsurface damages, the size of which depends on the grain size
- Each subsequent operation shall remove all damages induced by previous one.



D. W. Camp, SPIE Vol. 3244, p. 356 (1998)

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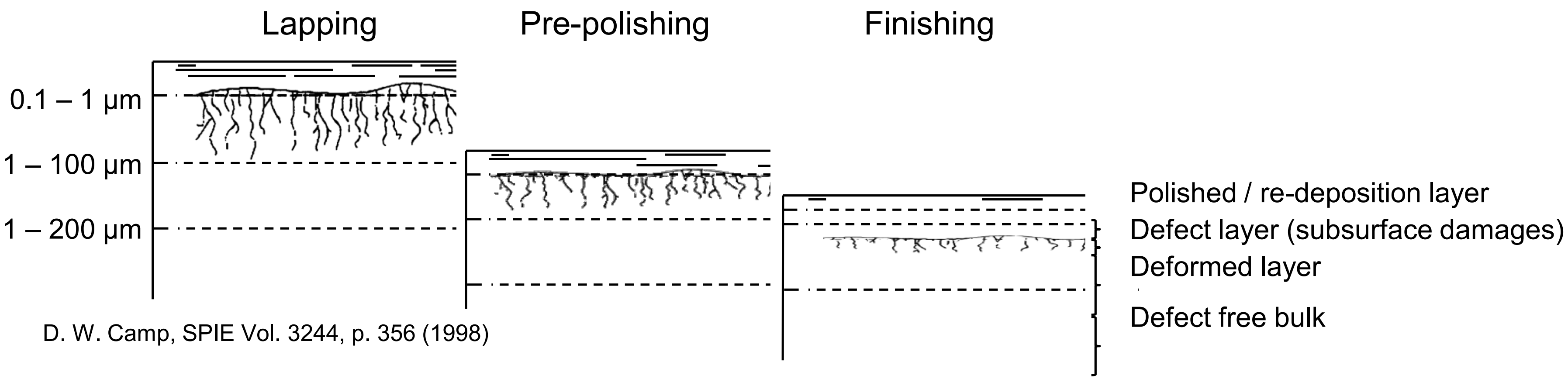


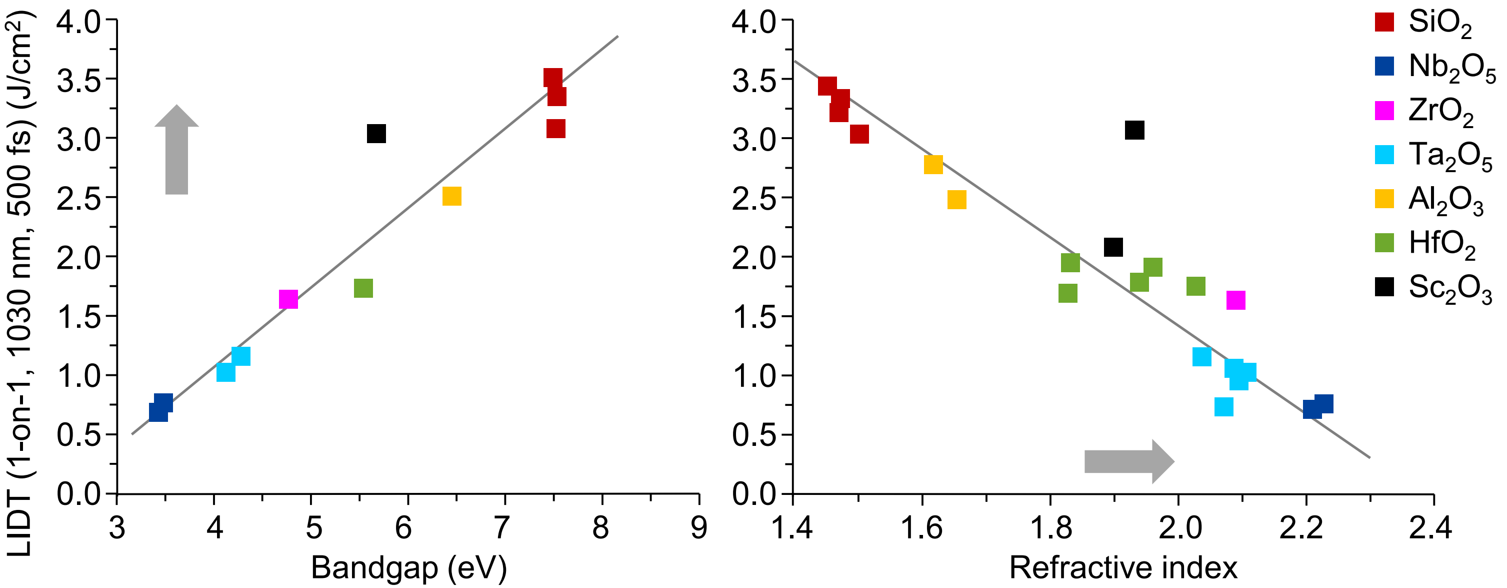
D. W. Camp, SPIE Vol. 3244, p. 356 (1998)

- several types of polished samples tested:
  - o Conventional pitch polishing vs. low sub-surface damage pitch polishing
  - o Pitch vs. double side, colloidal silica vs. ceria

Parameters: High index layer material

Coating material

- Low index material of choice: SiO_2
- High index material: trade-off between index and bandgap
- Materials tested:
  - o HfO_2 vs. Ta_2O_5 vs. AL_2O_3

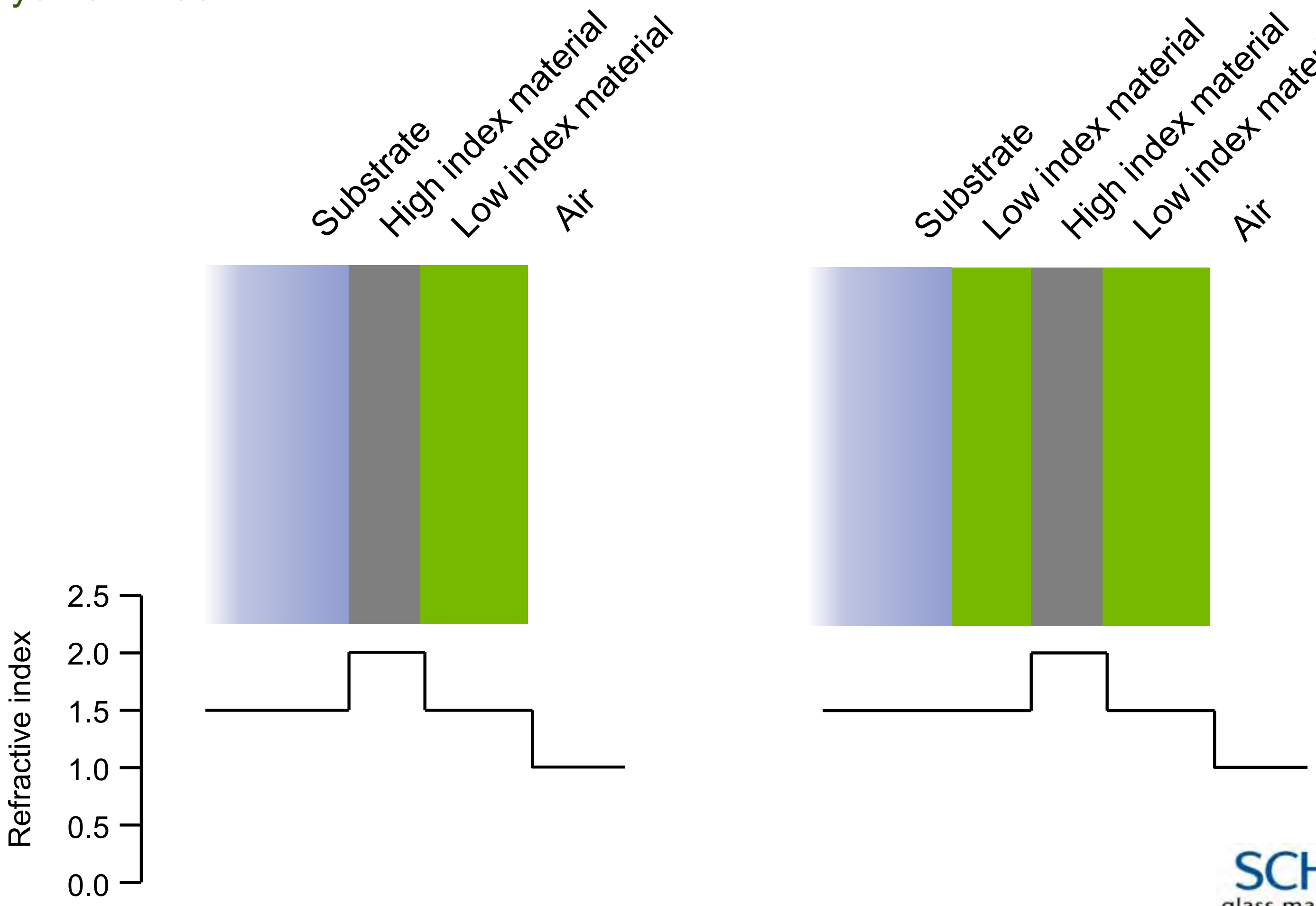


L. Gallais, SPIE 8530, 85300K (2012);

Parameters: layer sequence / coating design

Optical design

- o Simple solution (alternating high & low index) vs.
- o 1st layer low index



Parameters: coating temperature and annealing

Coating temperature and annealing

- Phosphate glass: Heat conductivity is very low and thermal expansion big.
- Glass is usually very strong under compressive stress. Glass “breaks”/rips under tensile stress. Thus, heating glass up is OK – cooling it down bears high risks of destruction for large components.
- Under this point of view, depositing under low temperature is advantageous. Parameters:
  - Depositing at low temperature (only high enough for stabilizing against heating up by process)
  - At elevated temperature (300°C)
- Particularly, coatings deposited at low temperature yield higher LIDT
  - after thermal annealing than vs.
  - before annealing

Parameters

Substrate material

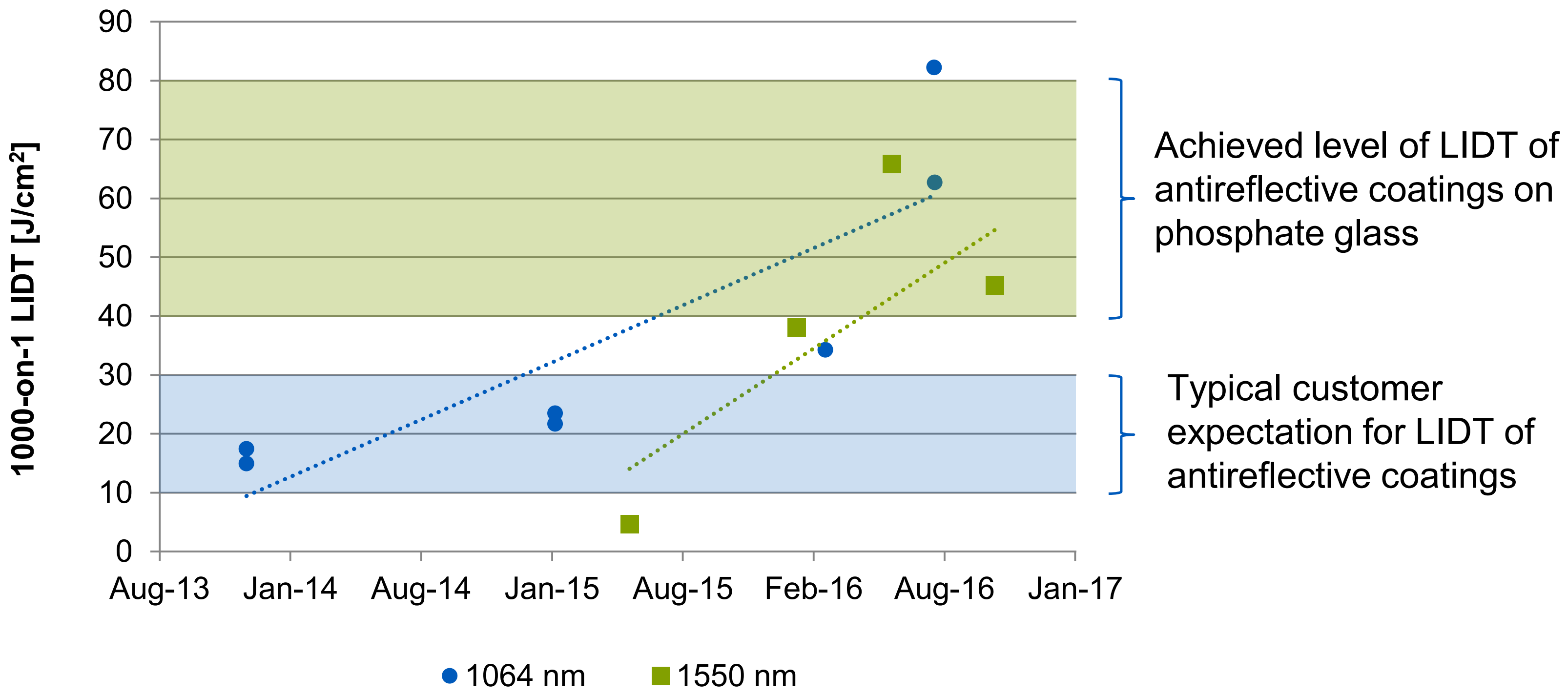
- Phosphate laser glass vs.
- fused silica and N-BK7

Cleaning & etching

- Different ways of “best effort” cleaning phosphate glass (choice of detergents, timing)
- With/without pre-deposition ion etching

Results

- Scaled to 10 ns:



LG-760 rod (2wt% Nd^{3+}, ca. Ø25x250 mm^3)
double side AR coated
with LIDT > 50 J/cm^2 (10 ns, 1064nm)