Design and optimisation of a pulsed CO_2 laser for laser ultrasonics

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- Optimising the parameters
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- Laser chemistry
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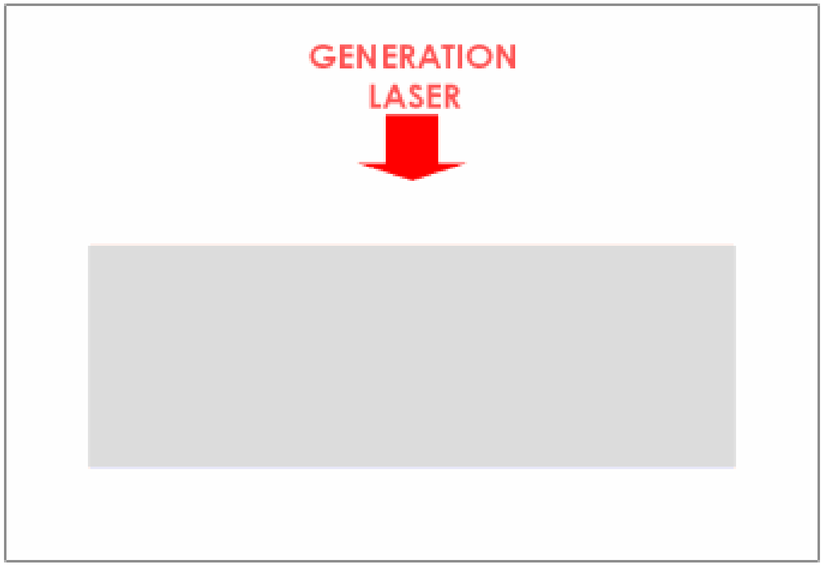
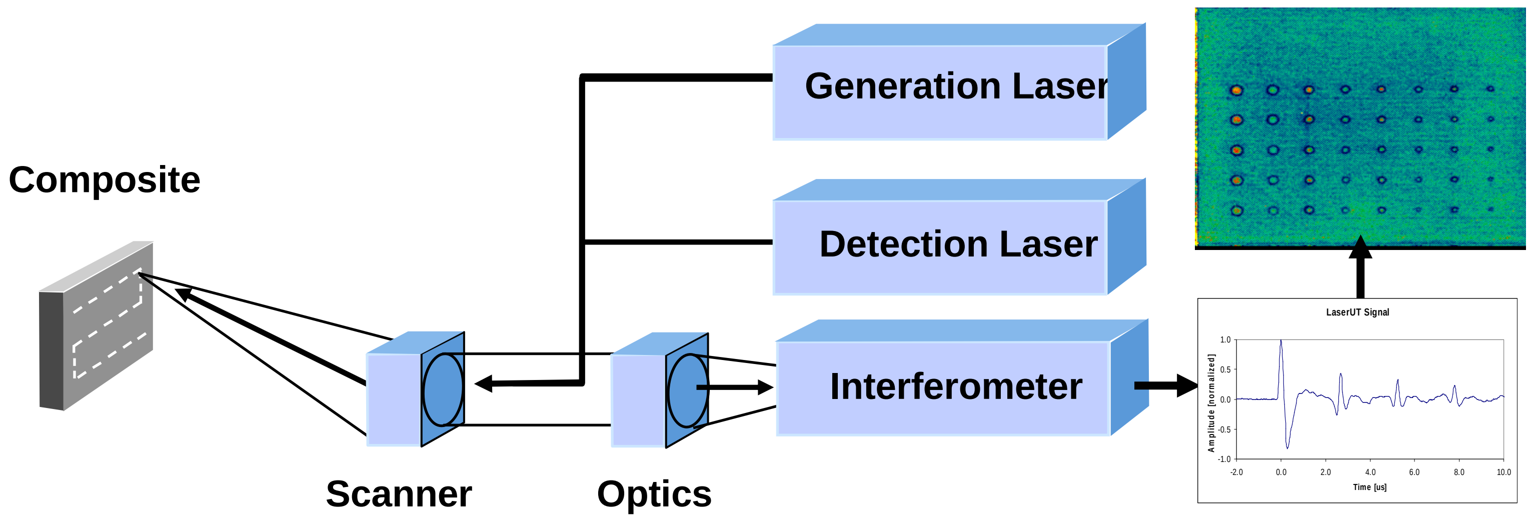
  Bloody hell, not more problems!
- Final system performance
  Working at last!

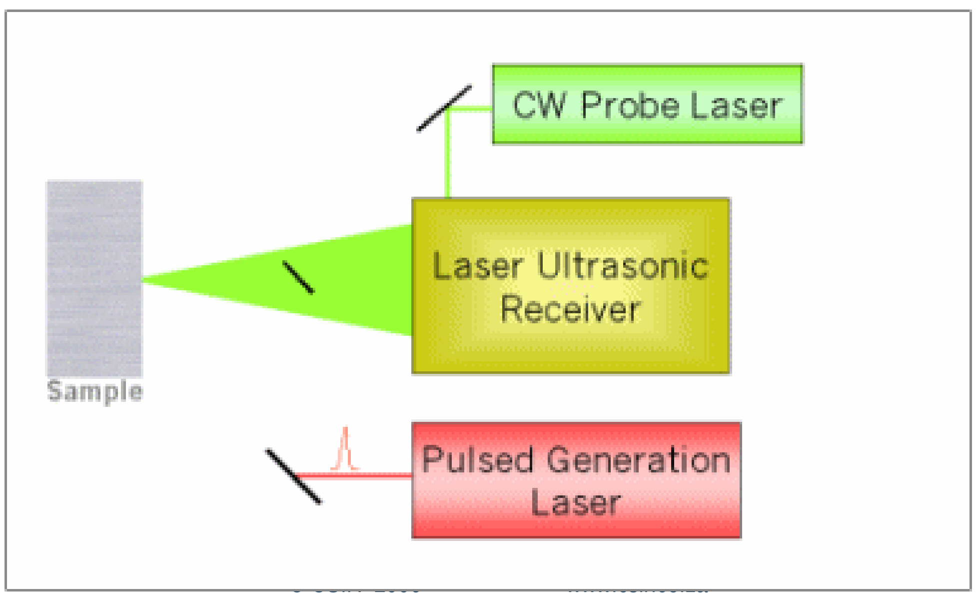
Laser ultrasonics – basic principles

- Optical absorption leads to thermal expansion
- Thermal expansion causes ultrasonic waves in sample
- Long pulse laser, coupled to an interferometer detects mechanical displacements produced by ultrasonic waves
- Ultrasound can be detected optically using an optical heterodyne technique



Laser ultrasonics – basic principles





Optimising the parameters

How do you design a laser for this application?

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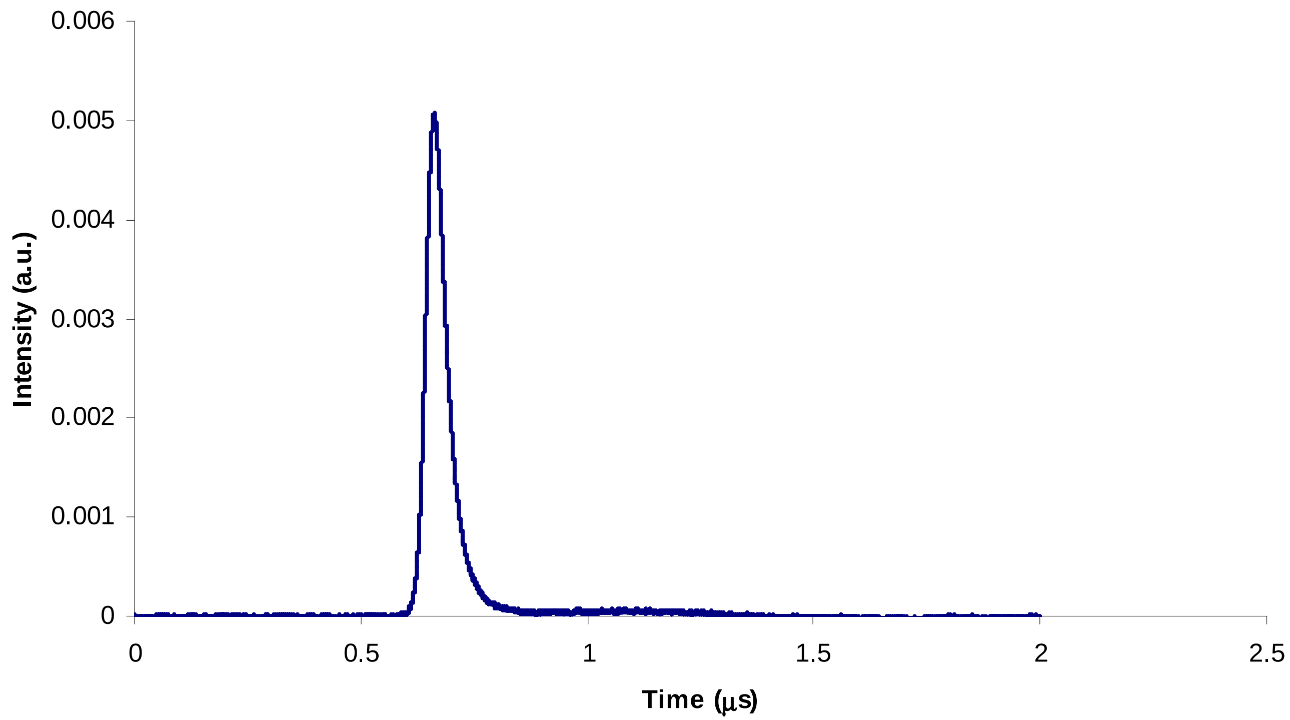
Objective

- Optimise the parameter set
  - Maximise energy,
  - Maximise repetition rate,
  - Maximise acoustic signal efficiency. ➡ Short time pulses



Laser parameters

- Choices and consequences

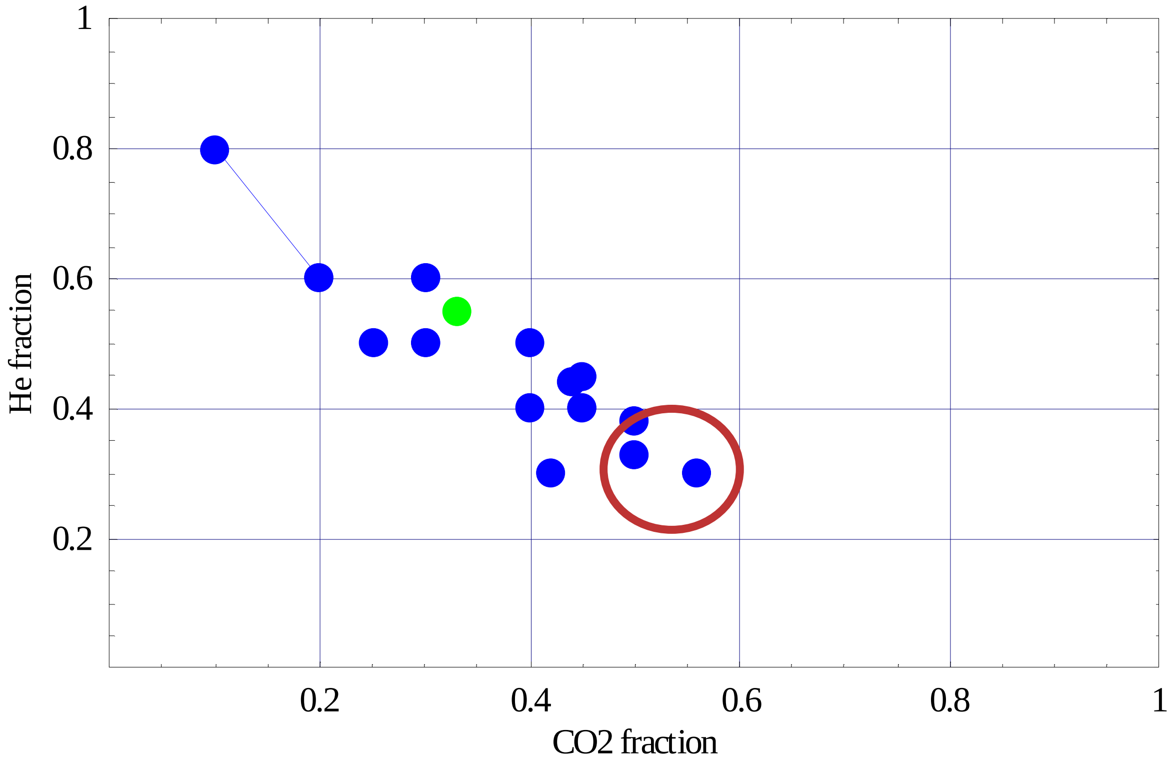
Pulse Envelope	*Factors affecting this are:*		
OC Reflectivity	HV	N_2	CO_2

Energy	*Factors affecting this are:*		
OC Reflectivity	HV	N_2	CO_2

Stability	*Factors affecting this are:*			
Electrodes	HV	Acoustics	Pre-ionisation	Catalysts

Lifetime	*Factors affecting this are:*		
OC Reflectivity	HV	Catalysts	Gas Mix

Gas influences



Laser chemistry

Impact of gas mix on laser chemistry

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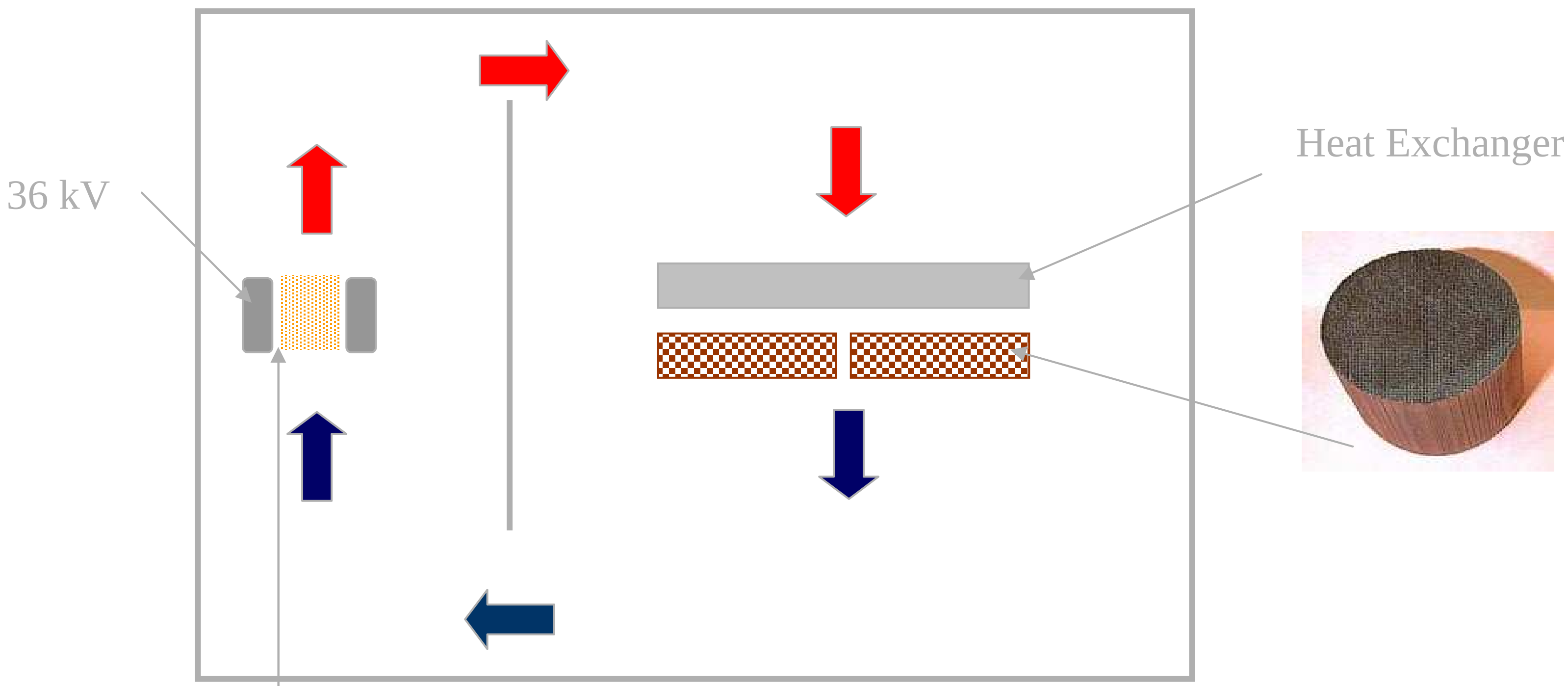
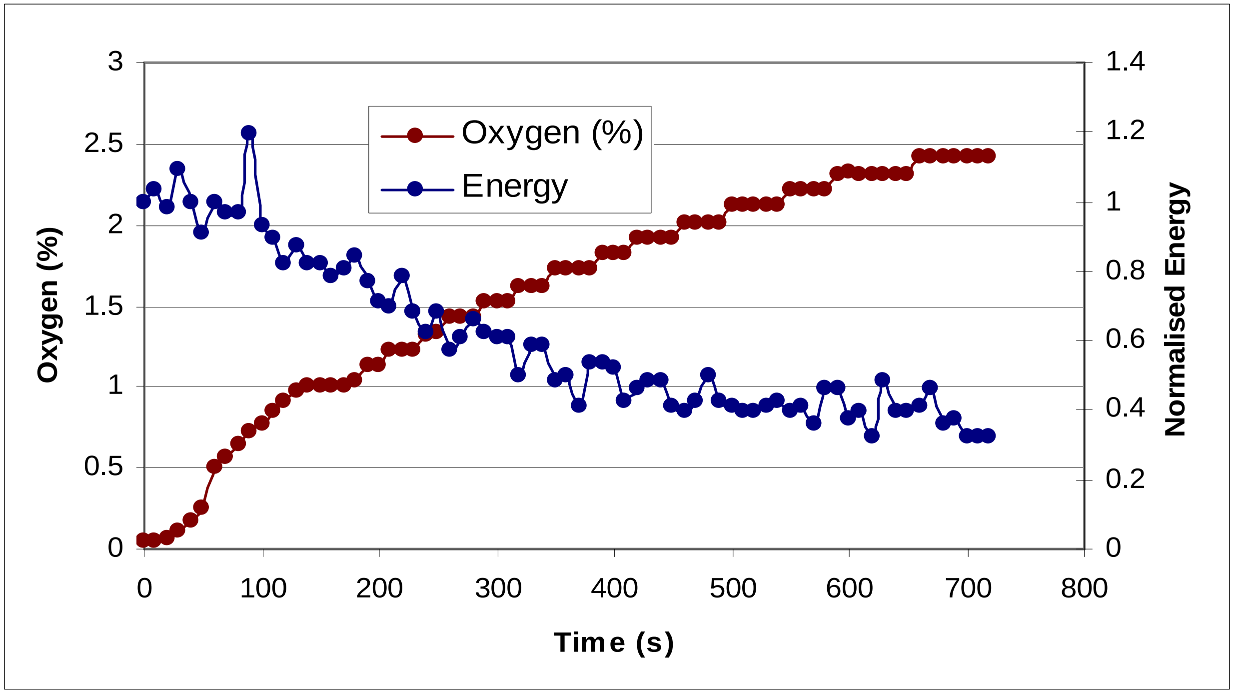
Problem statement



$$2\,CO_2 \rightarrow 2\,CO + O_2$$

$$2\,CO_2 \leftarrow 2\,CO + O_2$$

Typical problem



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Approach

Take a guess

Compute the consequences

Compare to experiment

But, cannot determine rate laws from reaction stoichiometry!

Basic chemistry (rate laws)

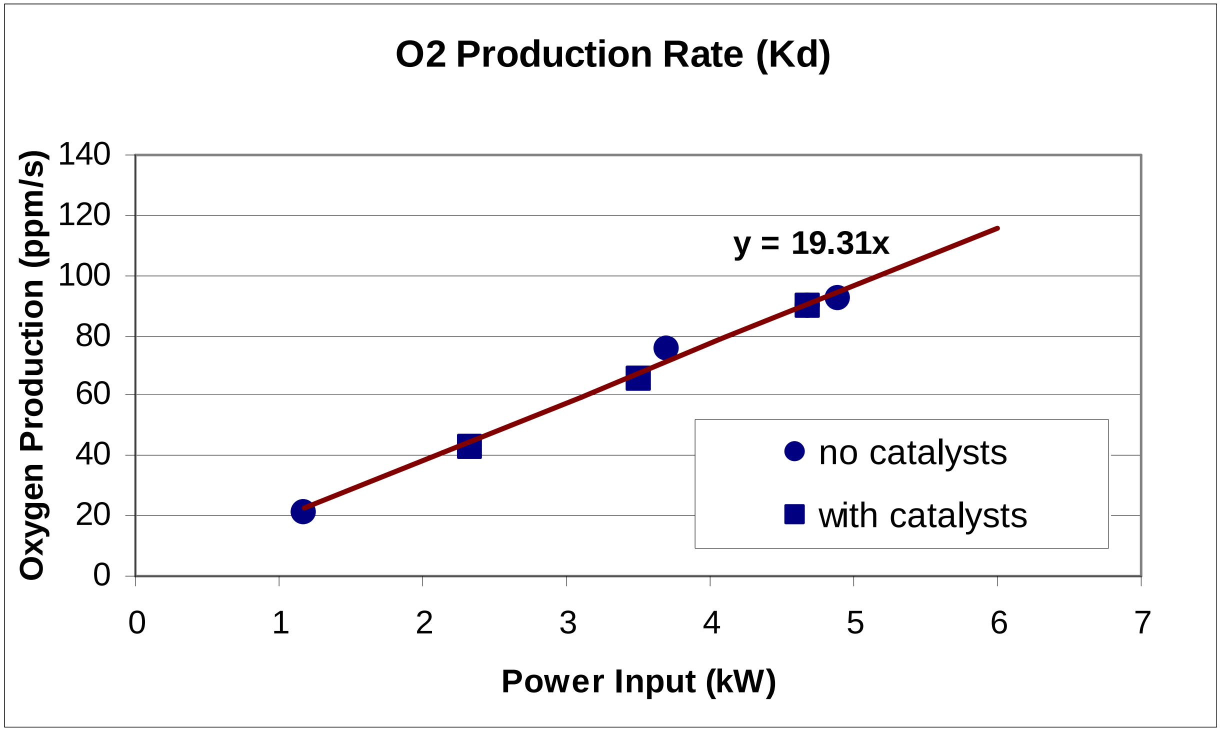
$$\frac{\partial [O_2]}{\partial t} = -k_c M_g [O_2]^n [CO]^m - k_T [O_2]^p [CO]^q + k_d$$

oxygen recombination (catalysts)

oxygen generation (discharge)

- Can we explain?
- Can we predict?
- Can we improve?

Discharge parameters



~ 90ppm/s @ 400Hz and 22.5kV

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A word on mathematics

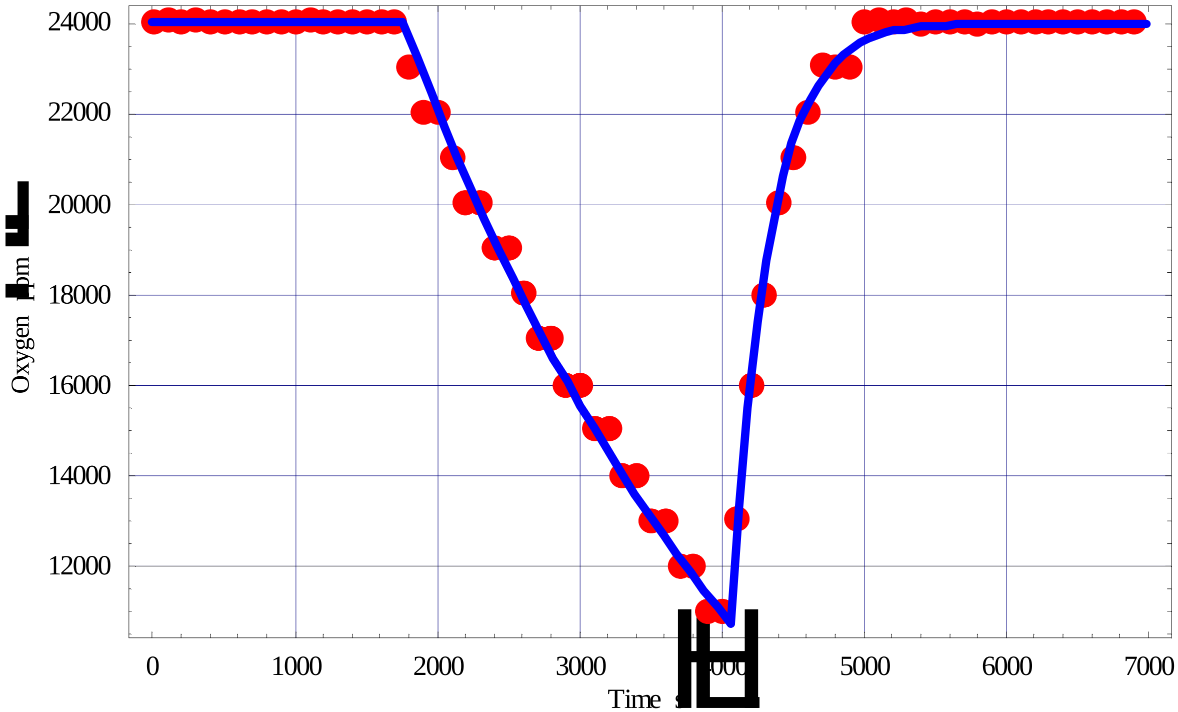
$$\dot{x}(t) = k_d - k_T x(t) - k_c M_g x^n(t)$$

n = 0 or 1	Already solved (easy)
n = 2	Riccatti equation (require a particular solution)
Any n?	Numerically only

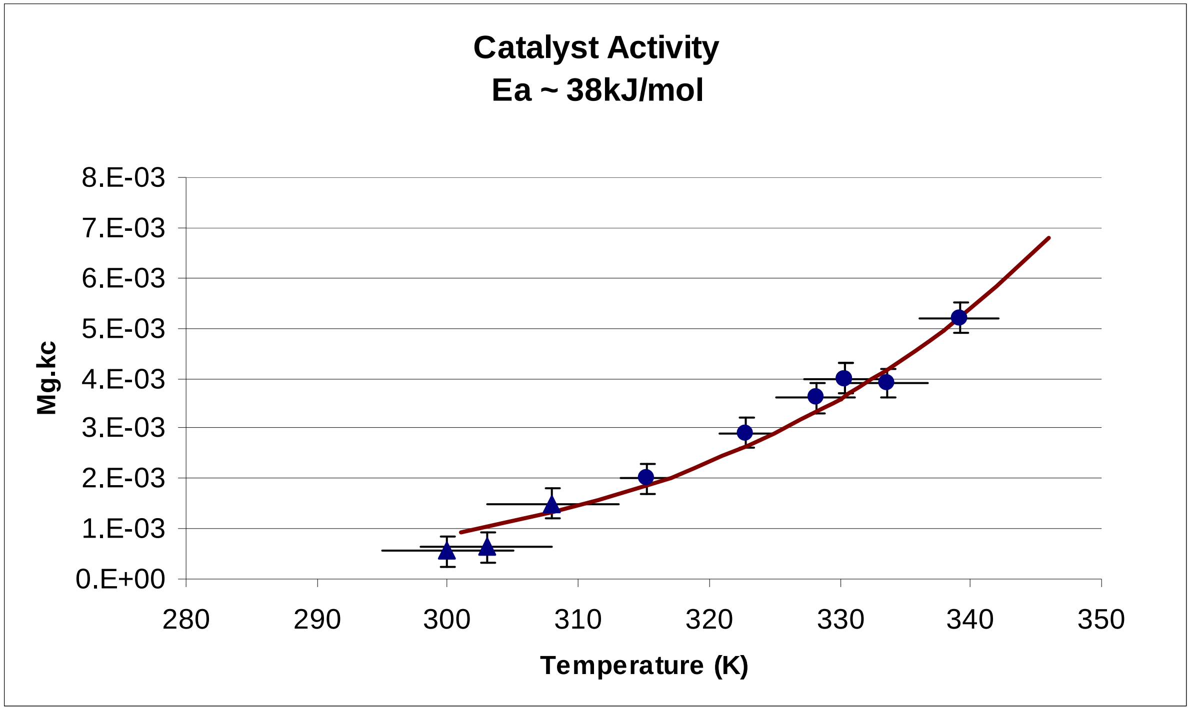
BUT, remove constant and you have an easy to solve Bernoulli equation!

With catalysts

$$\dot{x}(t) = k_d - (k_T + k_c M_g)x(t) \longrightarrow x(t) = \left(x_o - \frac{k_d}{k_T + k_c M_g} \right) \exp(-(k_T + k_c M_g)(t - t_o)) + \frac{k_d}{k_T + k_c M_g}$$



Recombination rate



$$k_c(T) = A\exp\left(-\frac{E_a}{RT}\right)$$

$$T(T_0, P) = T_0 + \frac{RT_0}{P_0 ldvC_v} P$$

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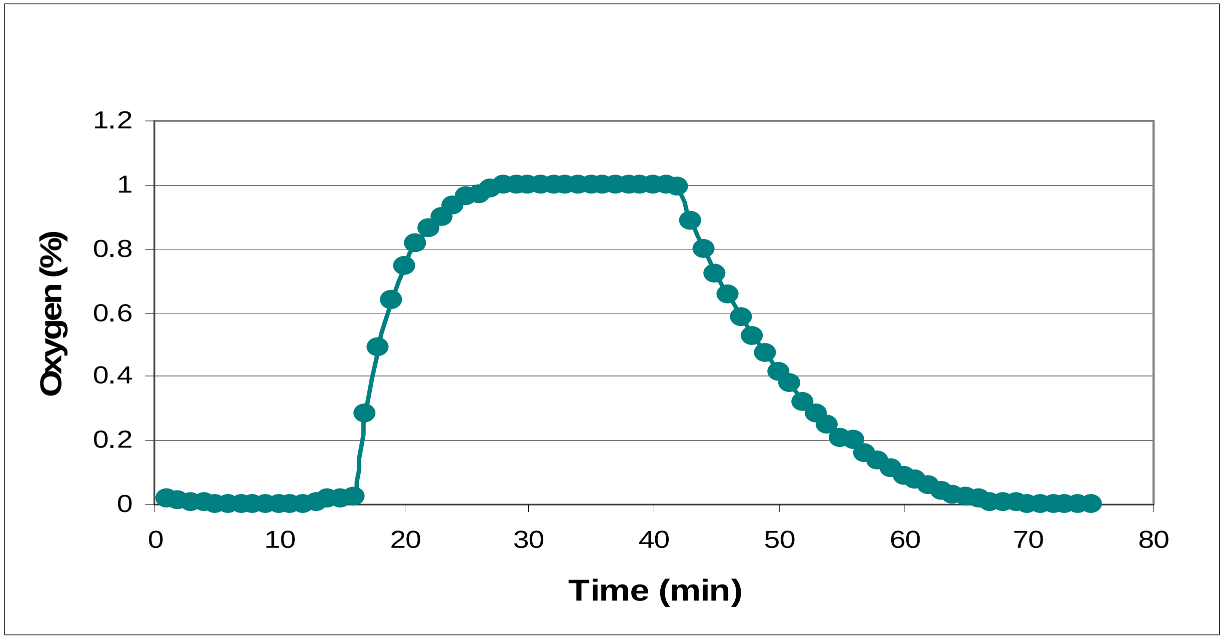
Predictions

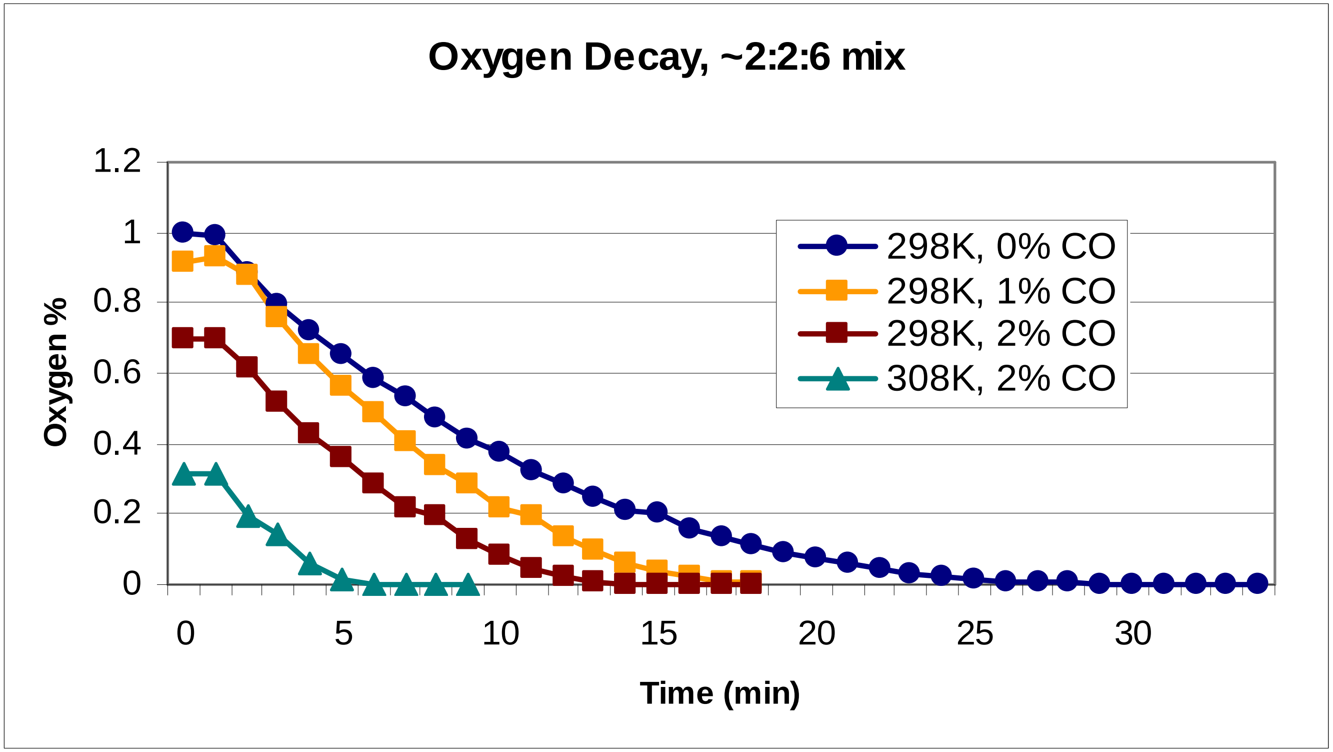
1. **Oxygen levels will stabilise**

$$x(t=\infty)=x_{eq}=\frac{k_d}{k_c M_g}$$



Predictions

2. Increasing the initial reactant concentrations decreases the time to equilibrium; increasing the temperature will decrease equilibrium levels.



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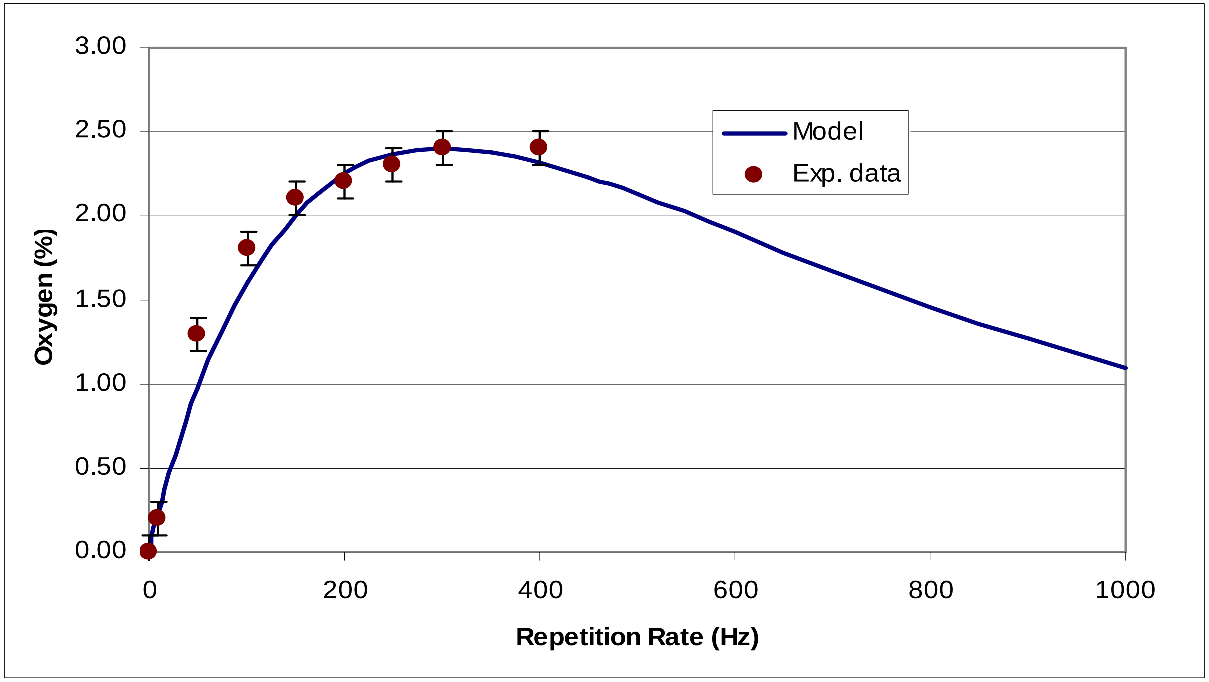
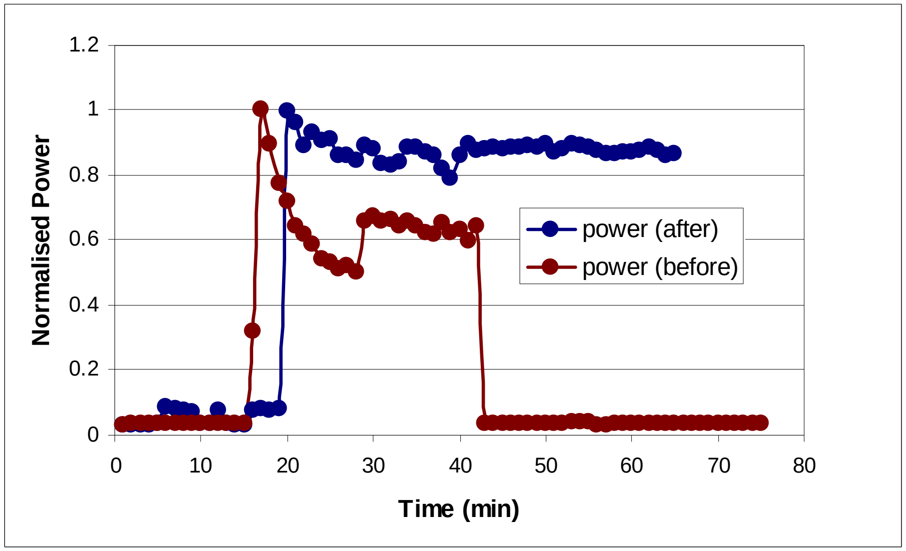
Predictions

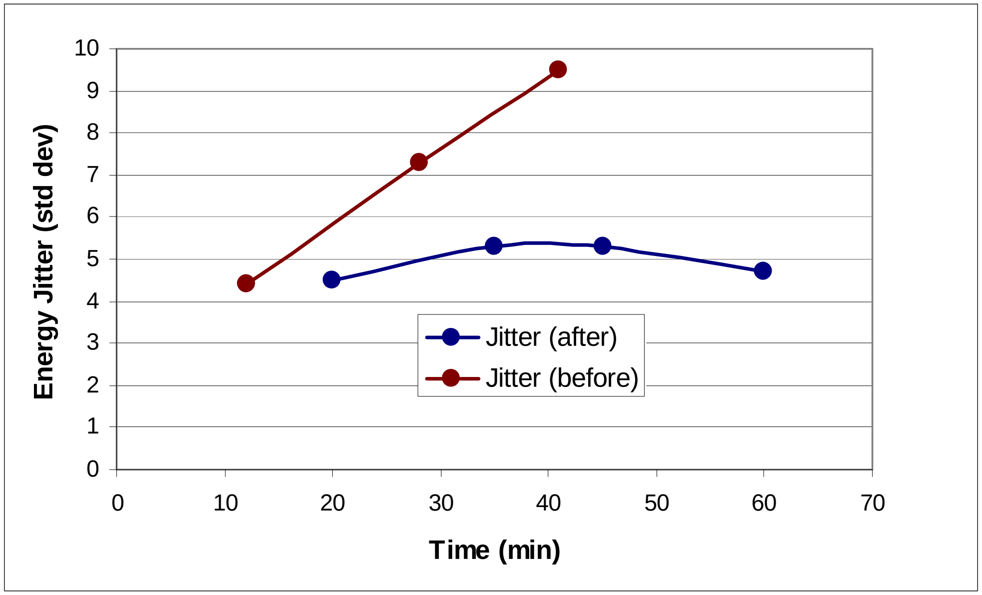
3. The equilibrium values can decrease with increasing power!

$$P^* = \left(\frac{P_0 l d v C_v}{RT_0}\right) \cdot \frac{E_a - 2RT_0 - \sqrt{E_a(E_a - 4RT_0)}}{2R}$$



Outcome





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Discharge disturbances

Acoustics and shocks

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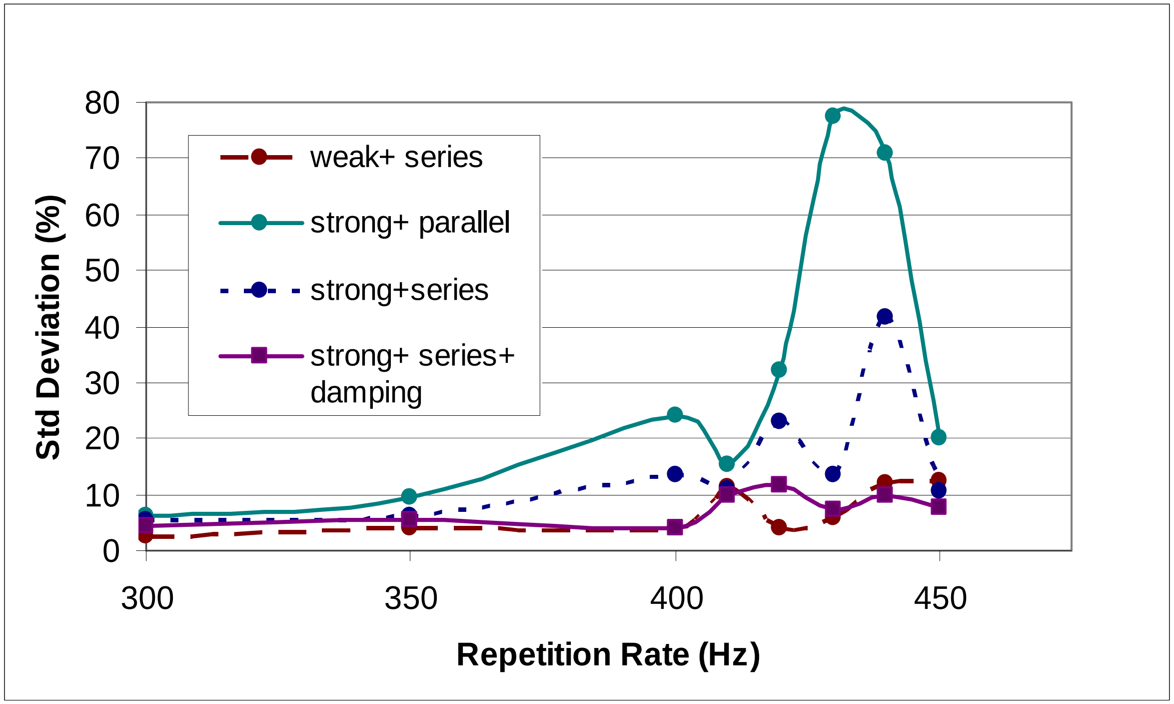
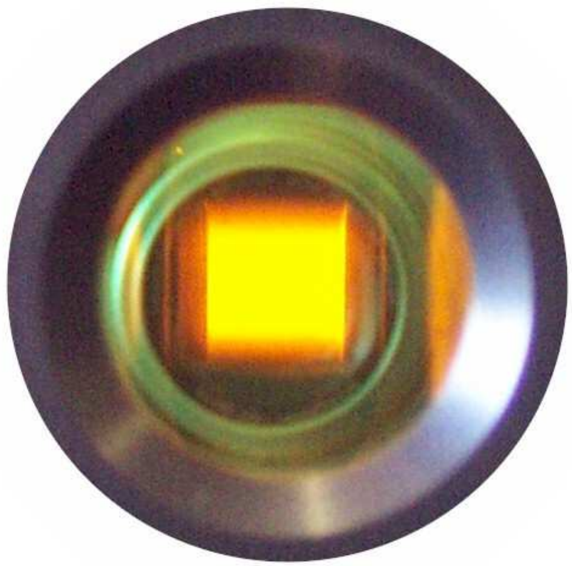
Acoustics



Std Deviation (%)
80
70
60
50
40
30
20
10
0
300
350
400
450
Repetition Rate (Hz)
weak+ series
strong+ parallel
strong+series
strong+ series+ damping

Stable discharge



Final system

In operation at Lockheed Martin for the JSF

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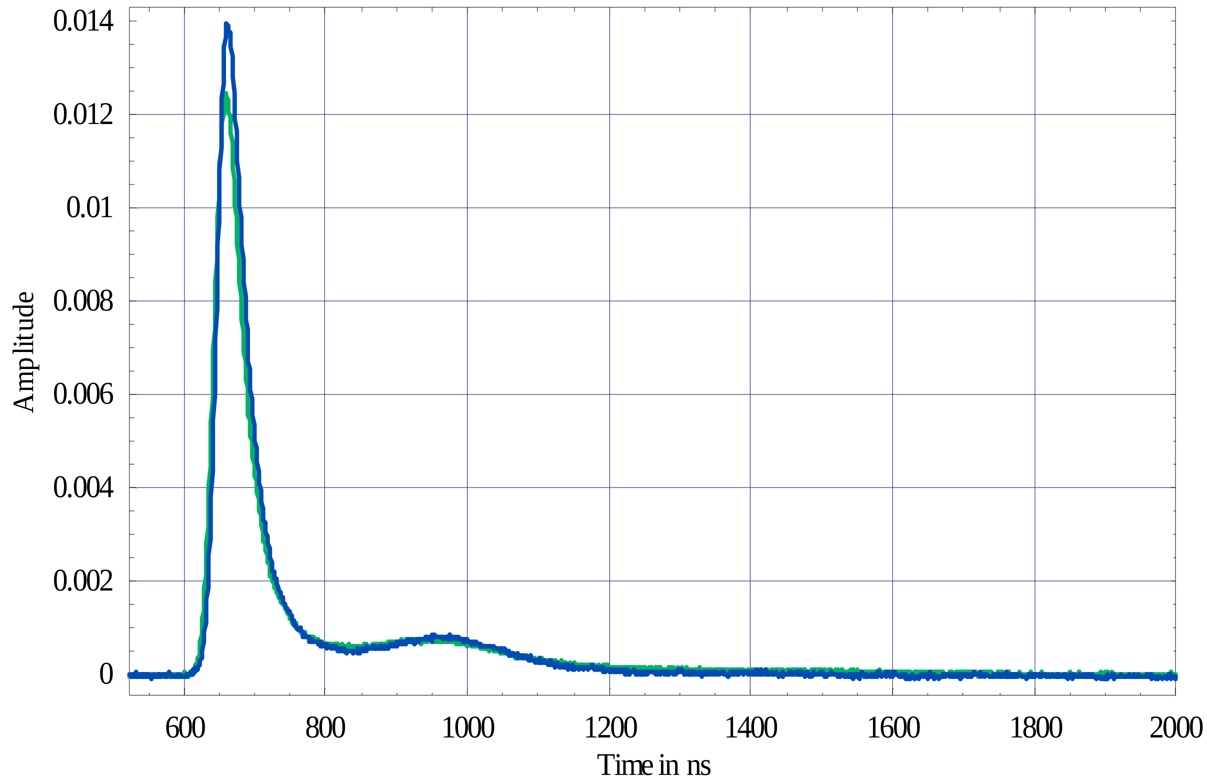
Final laser

- 6x improvement in efficiency
- 2x improvement in energy
- 2x improvement in production throughput



With some very interesting science along the way …

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