Optics and Photonics Department

Simulations of Pulsed Sodium LGS
An (Incomplete) Overview

Ron Holzlöhner [1]

Simon Rochester [2,3]

Domenico Bonaccini Calia [1]

Dmitry Budker [2,3]

James Higbie [4]

[1] Laser Guide Star Department, ESO

[2] Rochester Scientific, LLC

[3] Dept. of Physics, UC Berkeley

[4] Dept. of Physics, Bucknell University

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Outline

- Introduction, recap of some sodium physics
- Comparison of current pulsed laser LGS systems
- Selected detailed simulation results
- Proposal of measurement campaign (2012)

Why use pulsed lasers for sodium LGS?

- Laser physics: Some laser types hard to run in continuous wave (cw)
- Facilitates frequency conversion (SFG/SHG)
- Short pulses can mitigate SBS in relay fibers (e.g. at Subaru)
- Prediction of peak efficiency by Bradley (1992): 80–125 MHz

Challenges:

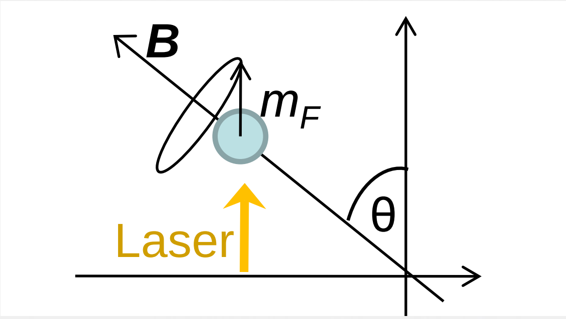
- Spectral envelope dictated by pulse width: Overlap with Na-Doppler?
- High peak powers may induce stimulated emission in sodium
- Nonlinear effects in relay fibers may further broaden spectrum (Subaru)
- Possible damage of anti-reflective coatings

Almost all sodium LGS currently in operation are pulsed !

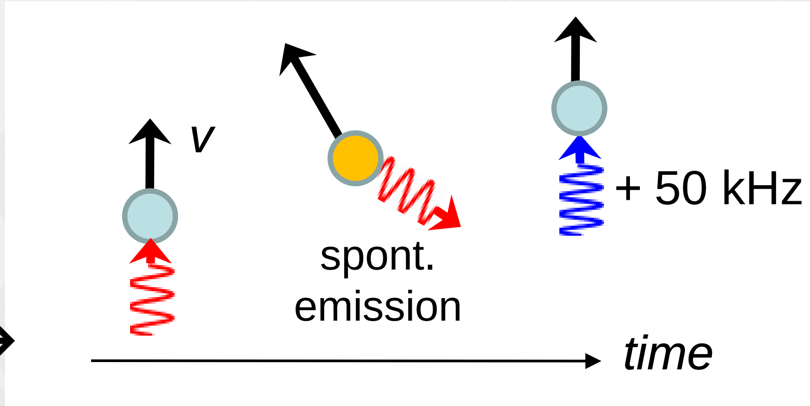
The “Three Evils” of Sodium LGS

- Three major impediments of cw sodium LGS:

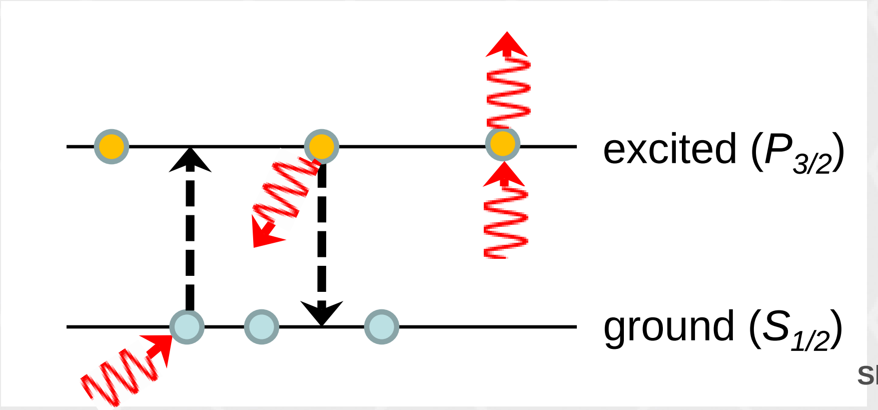
1) Larmor precession



2) Recoil (radiation pressure) →



3) Transition saturation



What is crucial for good return flux?

Most Important:

- Laser power, sodium abundance (seasonal)
- Circular polarization state ☼
- D_{2b} repumping (power fraction q≈12%, 1.710 GHz spacing) ☼
- (Peak) power per velocity class ☼
- Overlap with sodium Doppler curve (but: implicit repumping) ☼
- For return flux on ground: zenith angle, atmospheric transmission^2

Somewhat Important:

- Angle to B-field (θ), strength of B-field |*B*| (hence geographic location)
- Atomic collision rates (factor 10 variation across mesosphere)

Less Important:

- Seeing, launched wavefront error, launch aperture (beware: spot size)
- Sodium profile, Spectral shape (for given number of velocity classes)

Could improve on the crucial parameters (☼)

Bloch Equation Simulation

- Schrödinger equation of density matrix, first quantization

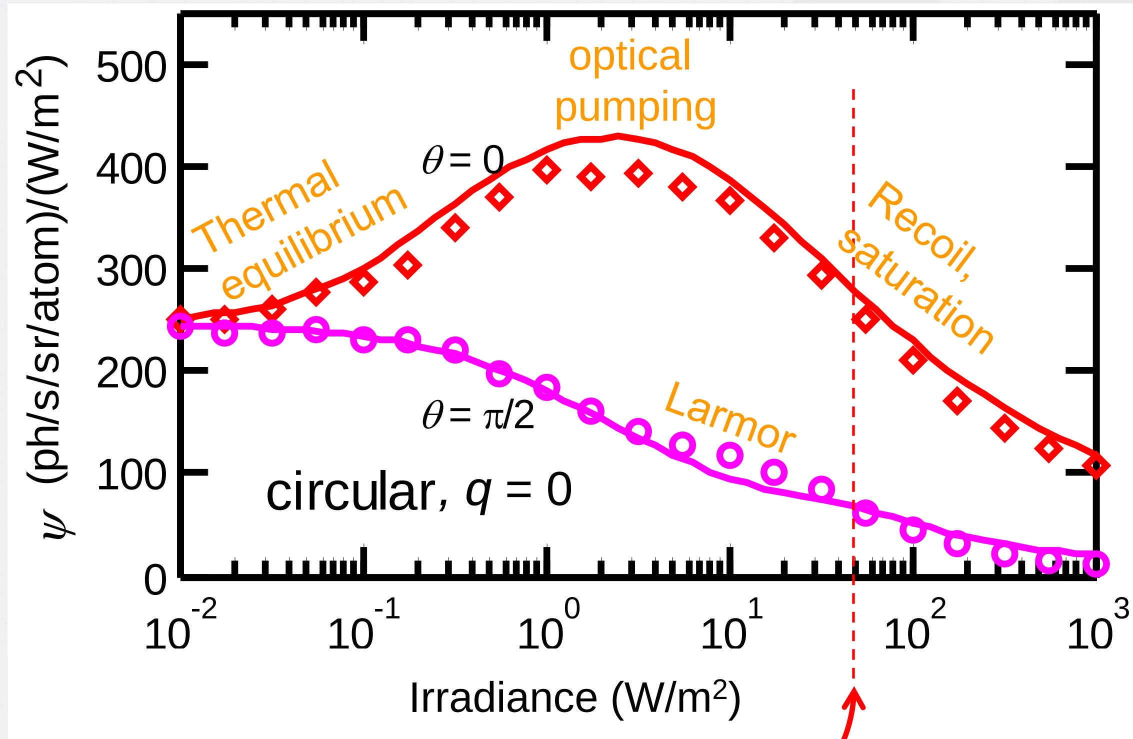
  $d\rho/dt = \mathbf{A}\rho + b = 0$

- Models ensemble of sodium atoms, 100–300 velocity groups
- Takes into account all 24 Na states, Doppler broadening, spontaneous and stimulated emission, saturation, collisional relaxation, Larmor precession, recoil, finite linewidth lasers
- Collisions change velocity and spin ("*v*-damping,*S*-damping")
- More rigorous and faster than Monte Carlo rate equations
- Based on AtomicDensityMatrix package, http://budker.berkeley.edu/ADM/
- Written in Mathematica v.6+, publicly available

["Optimization of cw sodium laser guide star efficiency", Astronomy & Astrophysics, in print]

Efficiency per Atom

- Model narrow-line cw laser, circular polarization
- ψ : Return flux per atom, normalized by irradiance [unit ph/s/sr/atom/(W/m^2)]
- θ: angle of laser to B-field (design laser for $\theta = \pi/2$)
- Symbols: Monte Carlo simulation, lines: Bloch

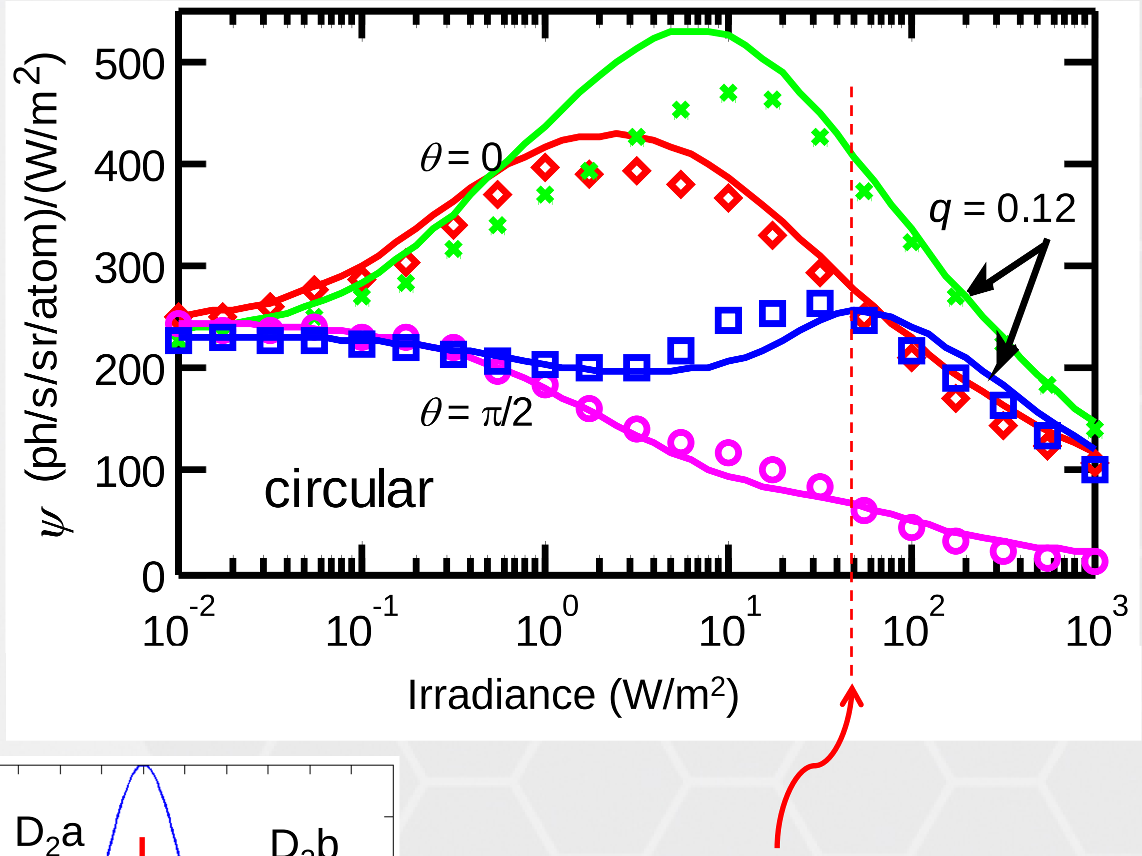


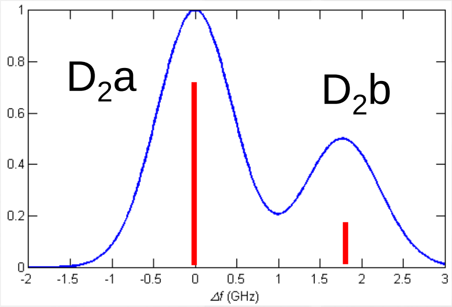
20W laser in mesosphere

Low efficiency at I = 50 W/m^2 due to Larmor and recoil

Efficiency per Atom with Repumping

- Model narrow-line cw laser, circular polarization
- ψ : Return flux per atom, normalized by irradiance [unit ph/s/sr/atom/(W/m^2)]
- θ: angle of laser to B-field (design laser for $\theta = \pi/2$)
- Symbols: Monte Carlo simulation, lines: Bloch
- q: repumping fraction (12% in D_2b laser line 1.71 GHz towards blue)



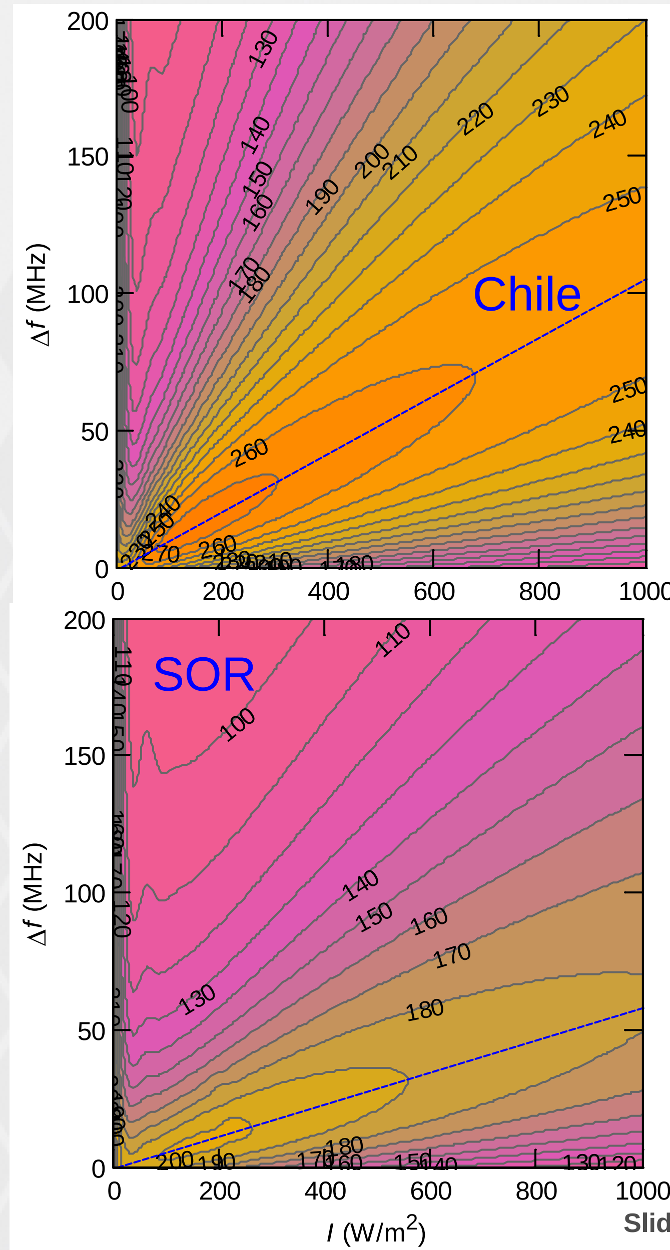


Lessons: a) repump, b) do not exceed ~100 W/m^2

Spectral Irradiance

- Modeling cw lasers with finite bandwidth and repumping (steady-state and time domain approaches, agreement)
- 20W-class (~50 W/m^2) cw systems optimal with narrow-band lasers (few MHz)
- Linear dependence of optimal laser bandwidth Δf on irradiance: e.g. about 10W/m^2/MHz in Chile (B = 0.23 G) and 17W/m^2/MHz in New Mexico (SOR, B = 0.48 G)
- Interesting for spot tracking formats (e.g. 3µs, 10 kHz rep rate) with 400W peak power
- Ultimately limited by Doppler width

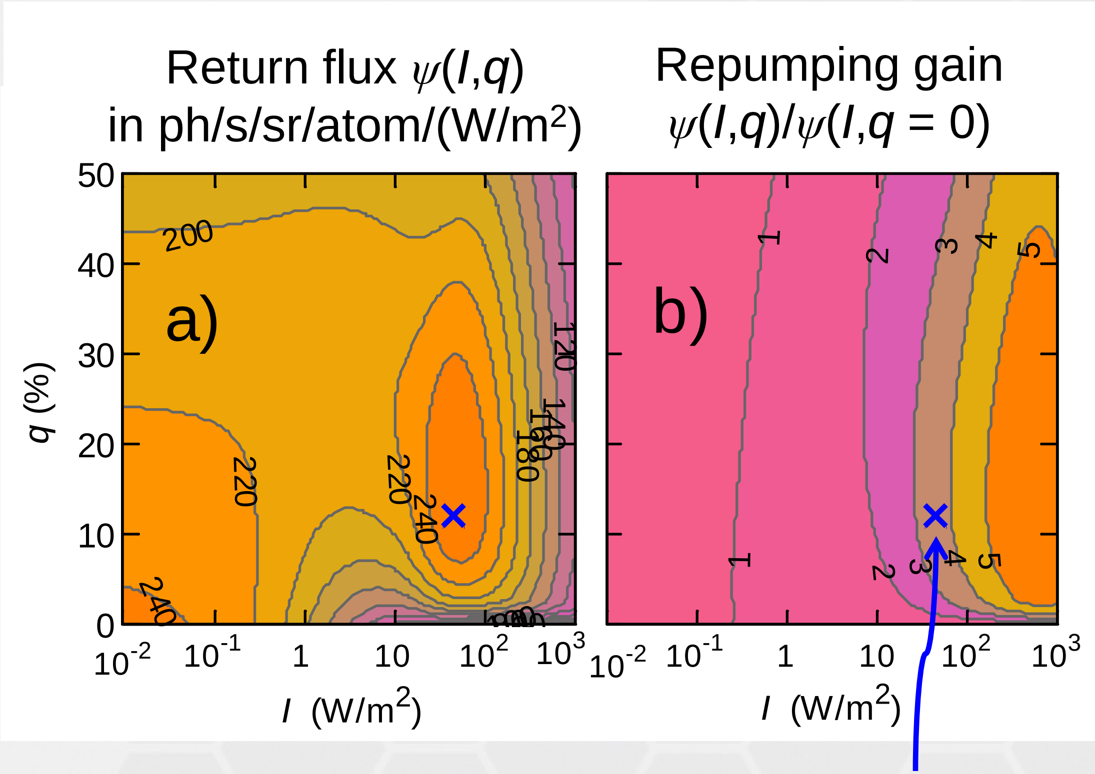
R. Holzlöhner *et al.*, “Optimization of cw sodium laser guide star efficiency”, A&A **510**, A20 (2010)



Taylor bandwidth to peak power

Optimization of repumping

- ψ in ph/s/sr/atom/(W/m^2)
- Even weak repumping is very beneficial
- Gain depends on irradiance and *B*, can reach factor 3.5 and more
- “Recycle” atoms from lower ground state
- Local optimum in a) depends on parameters



20W laser
q = 12%

R. Holzlöhner *et al.*, “Optimization of cw sodium laser guide star efficiency”, A&A **510**, A20 (2010)

Repumping a must in next-generation LGS systems

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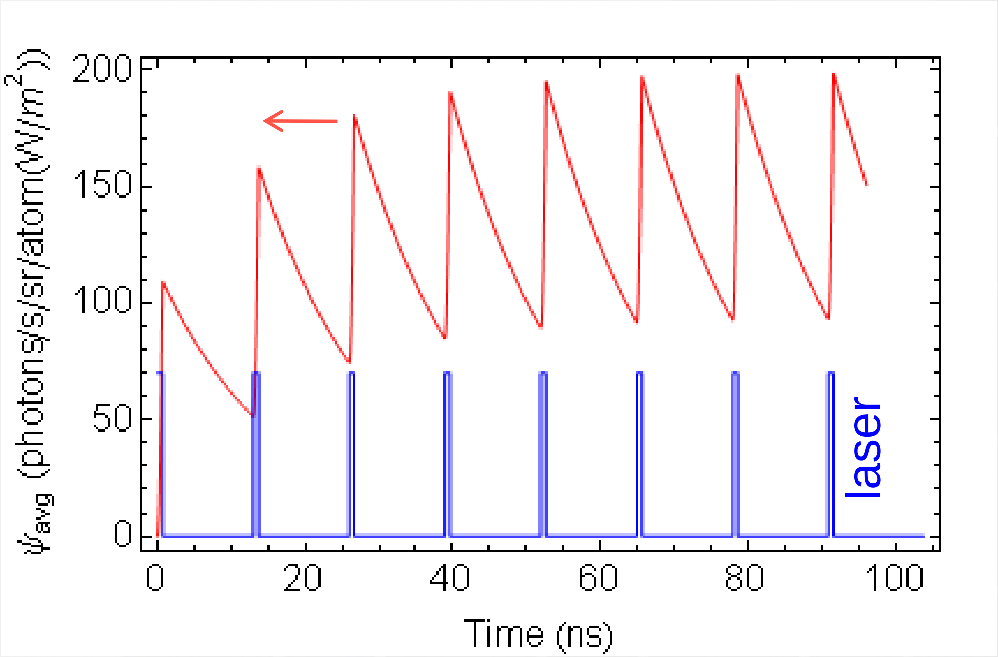
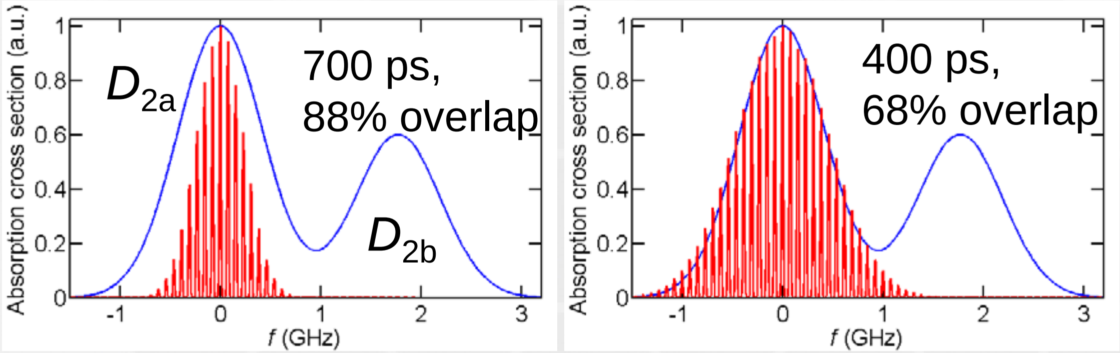
Short Pulse Lasers

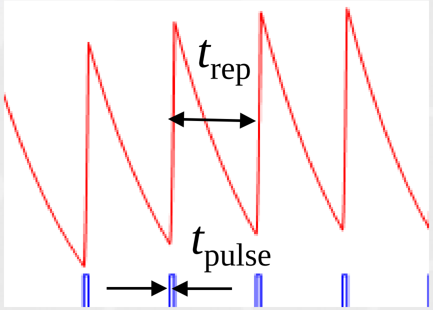
- Study of transient and periodic laser excitation
- Much more computationally demanding (time scale: 16ns)
- Example: Gemini North format, 700ps pulses, 76MHz rep rate (5.4% duty)
- Period 13ns < 16ns Na lifetime ➔ averaging effect in time
- BUT: Large bandwidth





Bandwidth issues if pulses become too short

Definition of two key quantities



- Peak irradiance, averaged over sodium lifetime τ

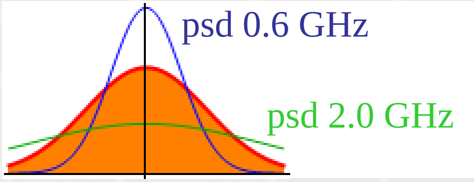
$$I_{\text{peak},\tau} = \frac{t_{\text{rep}} P_{\text{avg}}}{t_{\text{int}}^2 A} \left(t_{\text{pulse}} + \int_{t_{\text{pulse}}}^{t_{\text{int}} - t_{\text{pulse}}} e^{-t/\tau} dt \right), \qquad t_{\text{int}} = \min\left(t_{\text{pulse}} + \tau, t_{\text{rep}} \right),$$

$I_{\text{peak},\tau}$ long-pulse limit: peak pulse power, short pulses: P_{avg}/A with spot area A

- Normalized overlap with sodium Doppler curve $(\Psi \sim \kappa\, C_{\text{Na}})$

$$\kappa = \int_{-\infty}^{\infty} e^{-(f/\sigma_{\text{Na}})^2/2} \, \text{psd}(f)\, df \Big/ \int_{-\infty}^{\infty} \text{psd}(f)\, df, \qquad 0 < \kappa < 1,$$

If laser psd is Gaussian: $\kappa = \dfrac{\sigma_{\text{Na}}}{\sqrt{\sigma_{\text{Na}}^2 + \sigma_{\text{Laser}}^2}}$



Comparison of Pulsed Laser Formats

Before I start …

- Sorry if some laser parameters are off
- …or if some laser formats are missing
- Pulsed laser simulations not validated in experiment yet — we need a measurement campaign!

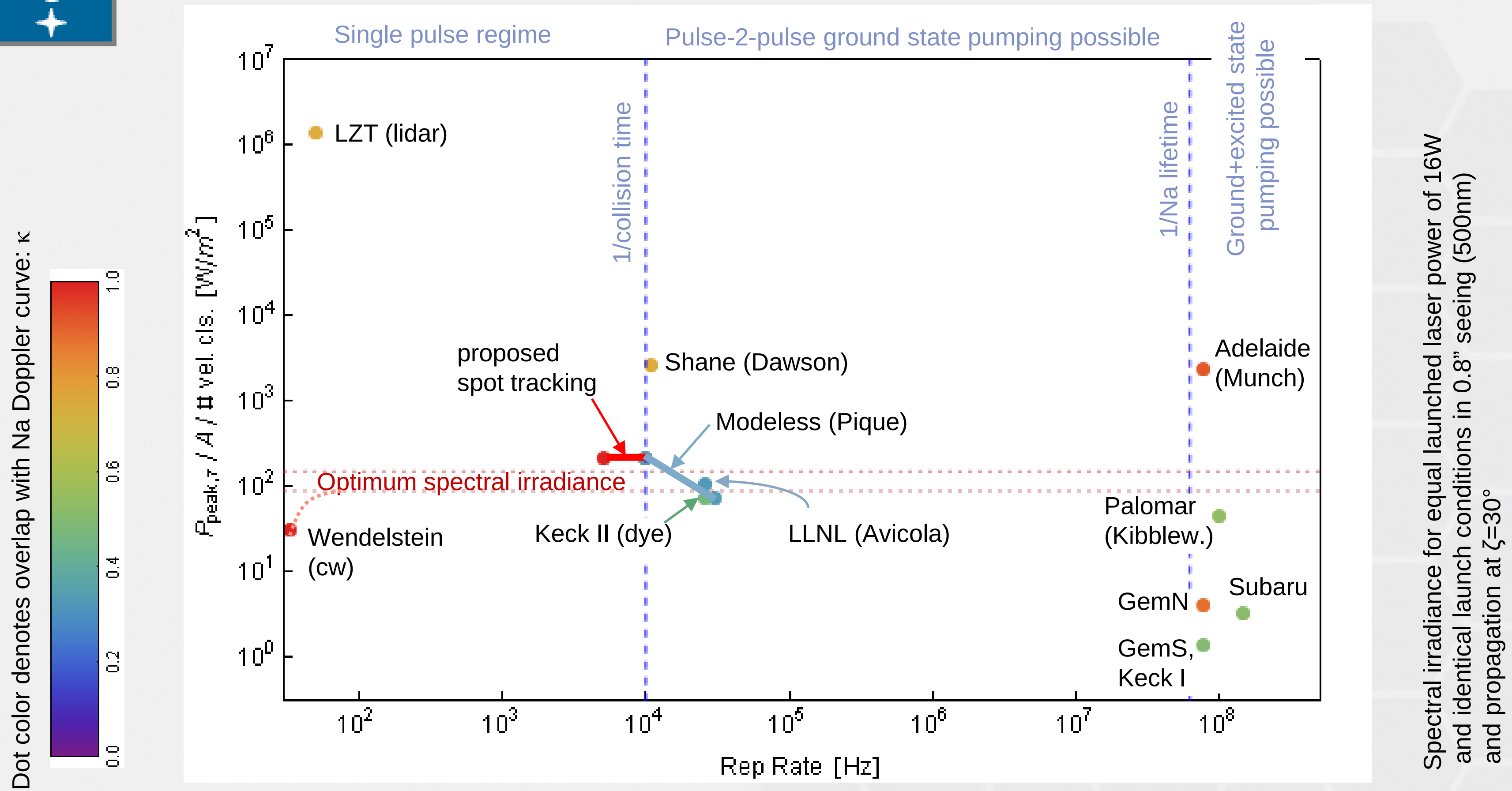
Pulsed Laser Parameter Table

Observatory Name	f_{rep} [Hz]	t_{pulse} [s]	Macro period/pulse	# laser lines	Actual FWHM [Hz]
LZT lidar (Hickson/Pfrommer)	50	8 n	1	3–4	2 × 460 M ?
Grenoble modeless (Pique)	10k–30k	50 n	1	1	2.9 G
Shane 3m (Dawson)	11 k	150 n	1	7–9	6 × 150 M ?
LLNL (Avicola)	26 k	32 n	1	1	3.0 G
Keck II (dye laser)	26 k	100 n	1	1	2 .0 G
Adelaide (Munch)	76 M	1 n	417 1)	1	450 M
Gemini North (LMCT)	76 M	700 p	1	1	550 M (?)
Gemini South, Keck I (LMCT)	76 M	350 p	1	1	1.8 G
Palomar (Kibblewhite)	100 M	800 p	20 2)	1	1.6 G
Subaru	143 M	800 p	1	1	1.7 G
Pulse tracking (proposed)	10k–5k	2.5μ–5μ	1	1	75 M
Wendelstein (cw)	cw	cw	1	1	5 M

1) 3 μs × 800 Hz macro

2) 150 μs × 330 Hz macro

Comparison of Pulsed LGS Formats



- 3 regimes delineated by inverse collision time (100 μs) and Na lifetime (16 ns)
- Good efficiency requires spectral irradiance near 100 W/m²/v.c. *and* high overlap (red dots)
- Most laser are far from transform-limited ➔ wider spectra, may or may not be good
- The Adelaide and Palomar lasers use macro-pulses (bursts), multiplying the peak power
- Long-pulse lasers can achieve intra-pulse optical pumping (e.g. spot tracking)

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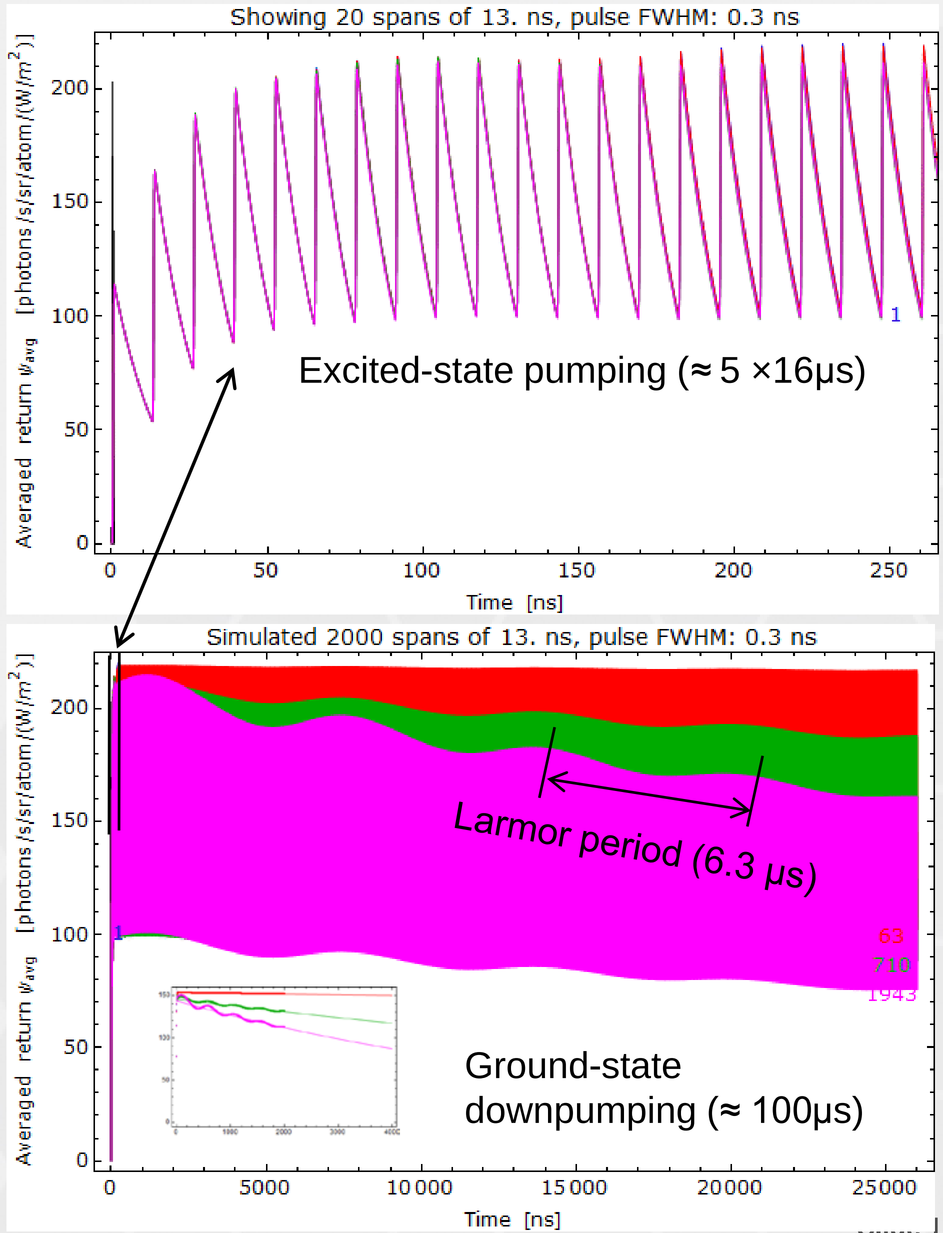
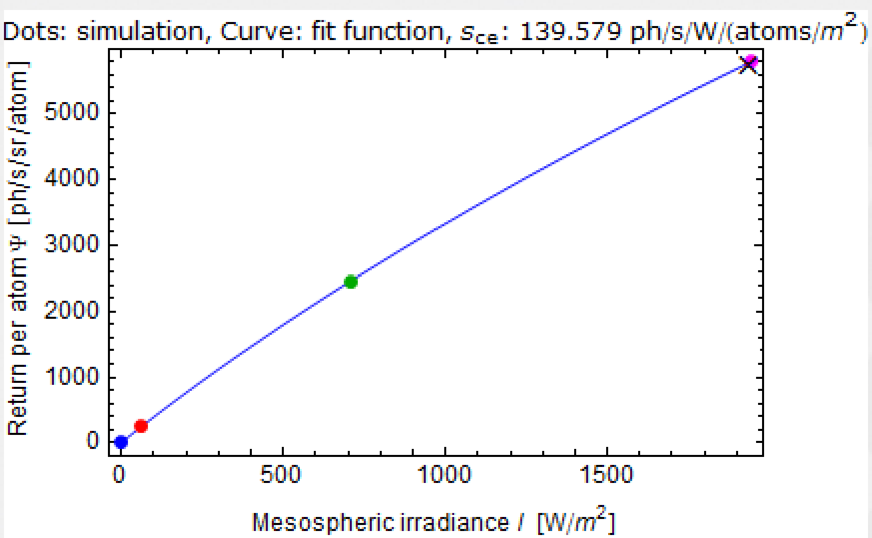
Quasi-cw Format: Gemini South

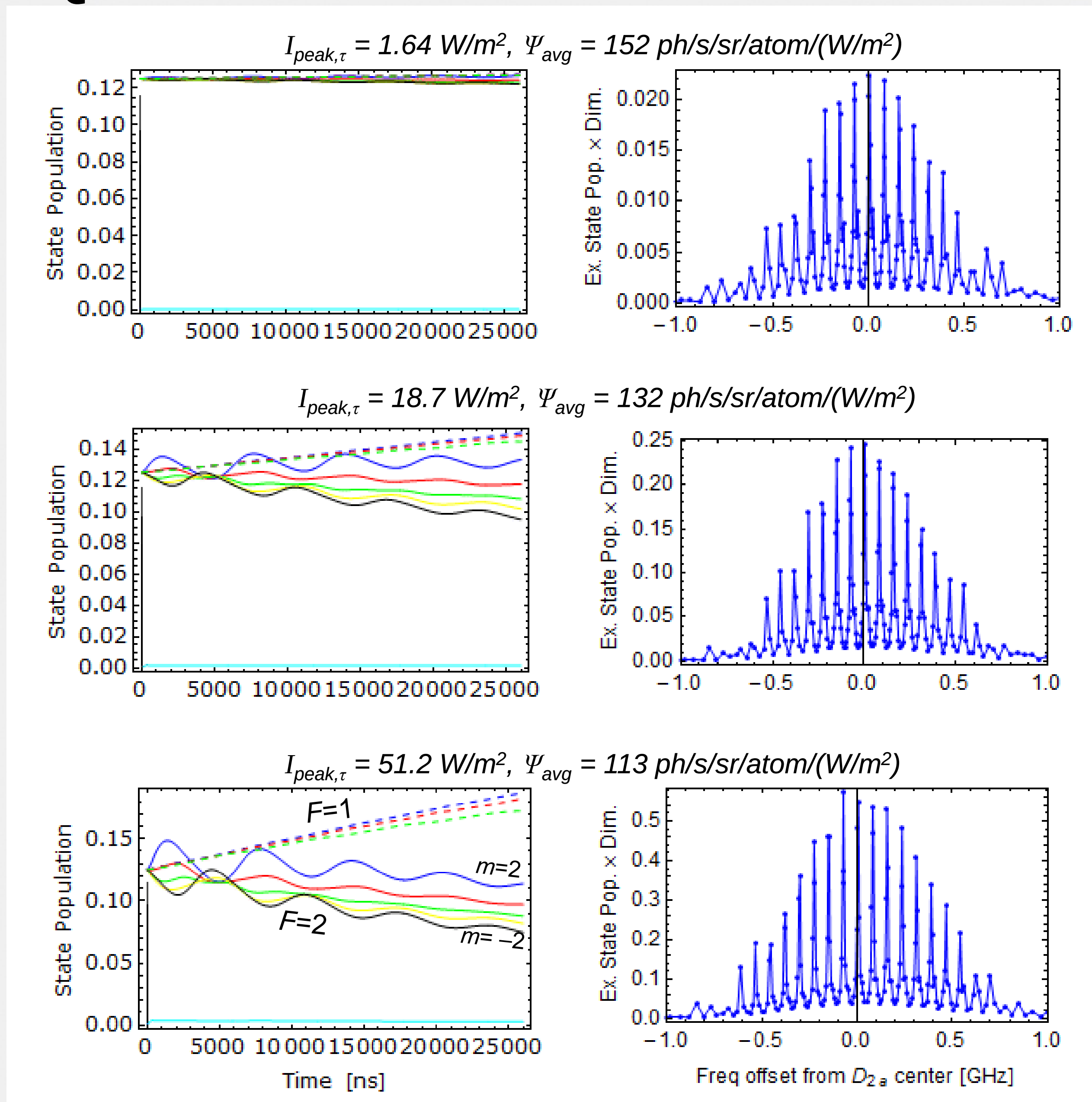
- Example of 300 ps pulses, 76MHz rep rate, circular polarization, B=0.23G, q=0
- At zenith, θ = 69º (GemS)
- No D_{2b} repumping ➔ slow downpumping (≈ 100 μs)
- $\Psi(I)$ curve quite flat ➔ linearity



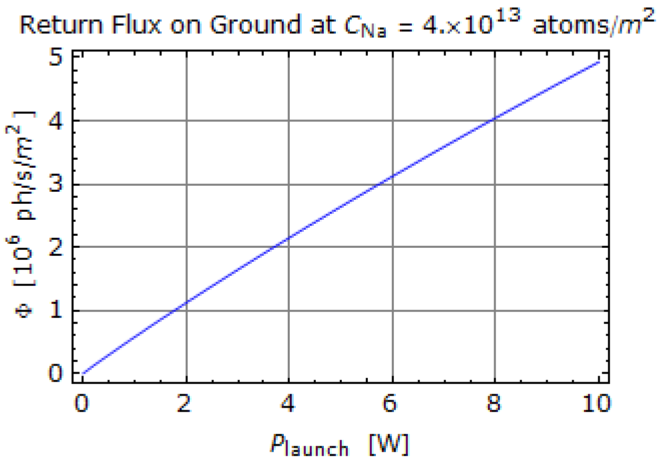


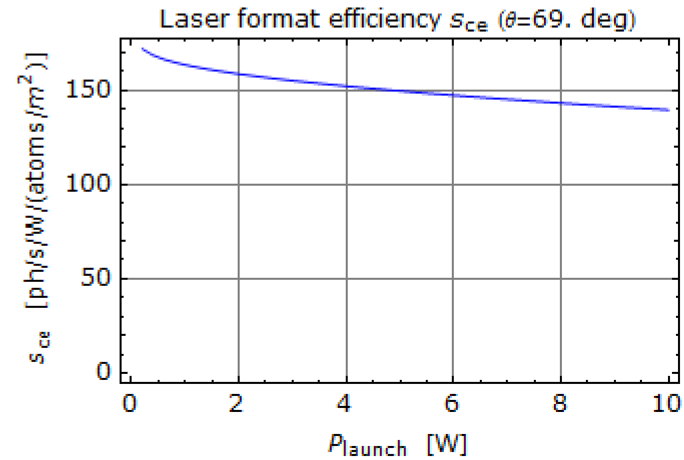
Quasi-cw Format: Gemini South

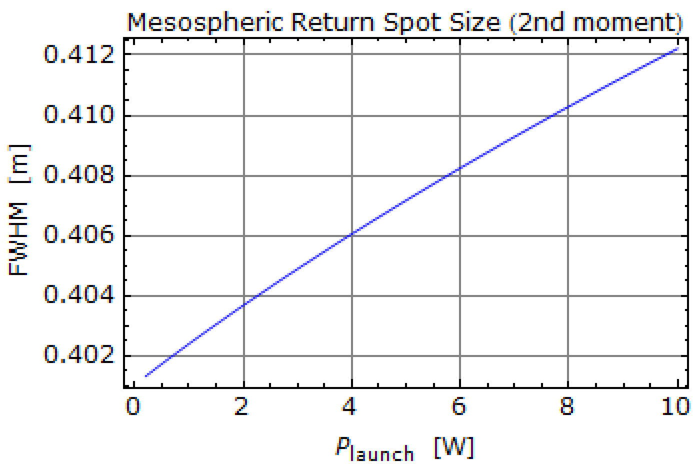
- At higher average irradiance, evidence of downpumping ➔ *F*=2 ground states depleted
- Simulating the steady state is very CPU-intensive
- Wide spectrum (κ = 0.5)



Quasi-cw Format: Gemini South







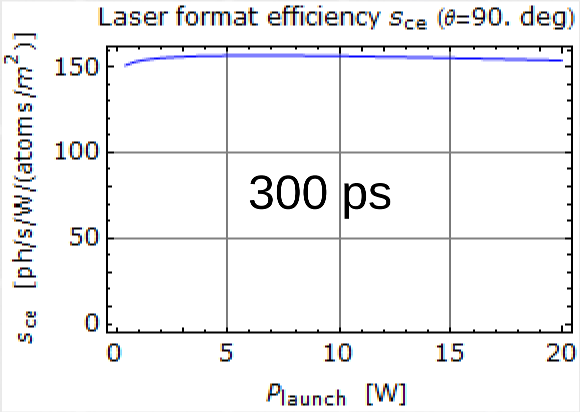
- Upper limit for return flux: 5 Mph/s/m^2 at zenith and C_{Na} = 4 ×10^{13} atoms/m^2 (10W in air)
- Upper limit for s_{ce}: 140 ph/s/W/(atoms/m^2) at $\theta = 69^{\circ}$
- Boost return with longer pulses and D_{2b} repumping

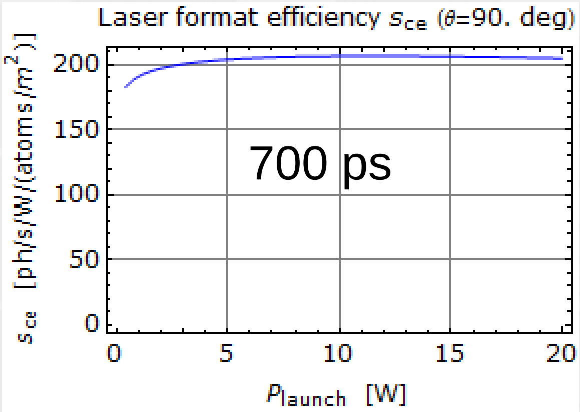
Figure of merit:

$$s_{ce} = \frac{\Phi\, X\, H^2}{P\,(T_a)^{2X}\, C_{\mathrm{Na}}}$$

Comparison: 300 ps vs. 700 ps Pulses

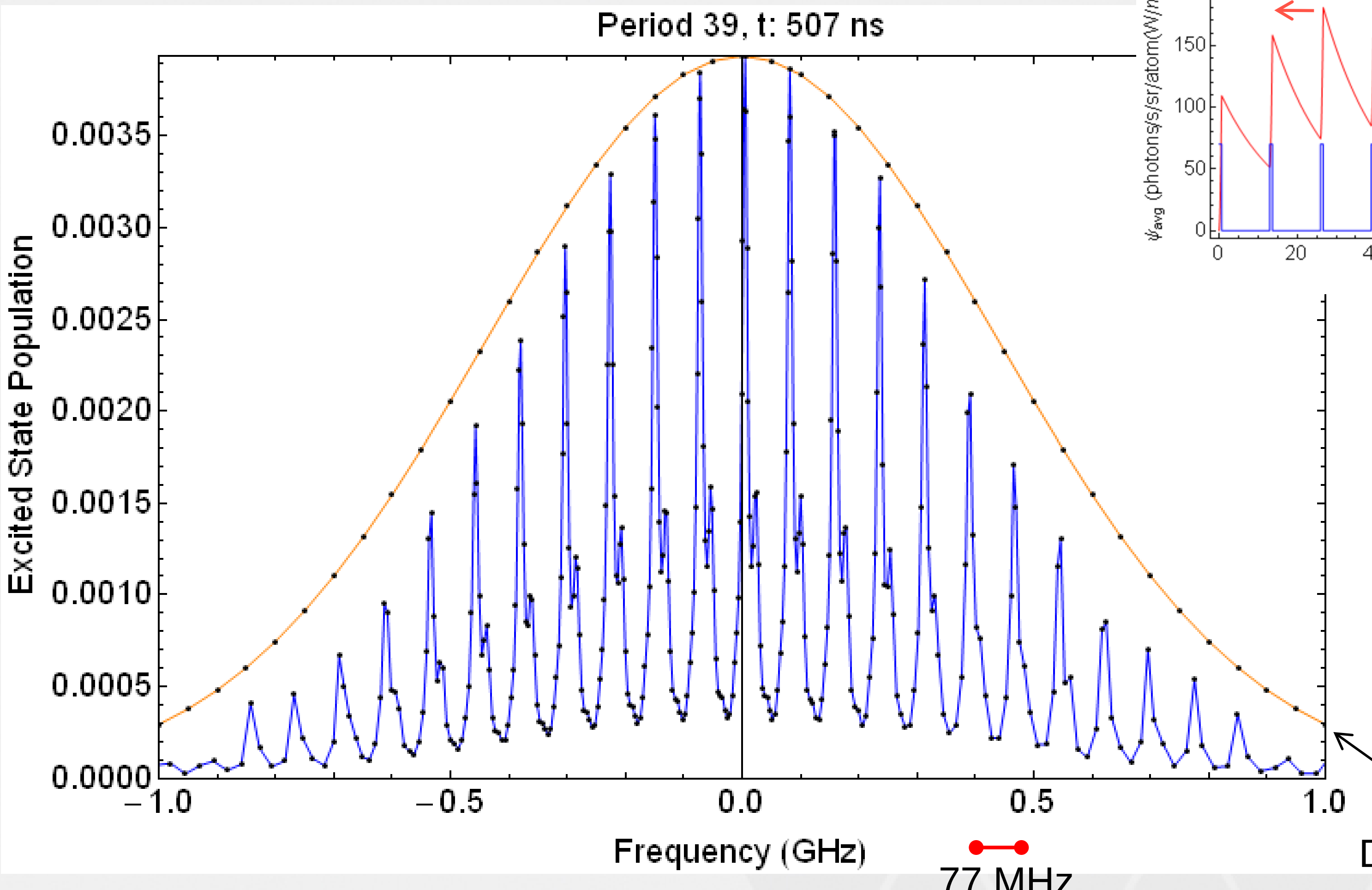
- Direct comparison of 300 ps vs. 700 ps pulse duration
- Roughly modeling GemS vs. GemN (but measured linewidth in GemS is larger)
- $\theta = 90^{o}$, $q = 0$, $B = 0.23$G
- Simulated 200 pulses (thus 1/10 of span in previous slides)
- s_{ce} ratio: 205/153 = 1.34 vs. overlap ratio: 0.85/0.57= 1.48
- *But*: Far from steady state
- For 700 ps with q = 12% at $\theta = 90^{o}$ s_{ce}: 215 ph/s/W/(atoms/m²), stable

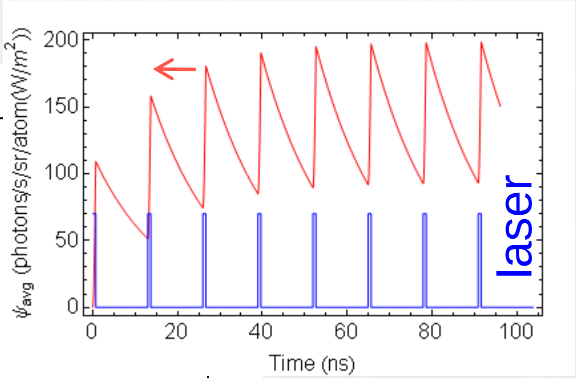




CW and pulsed Na laser optimization

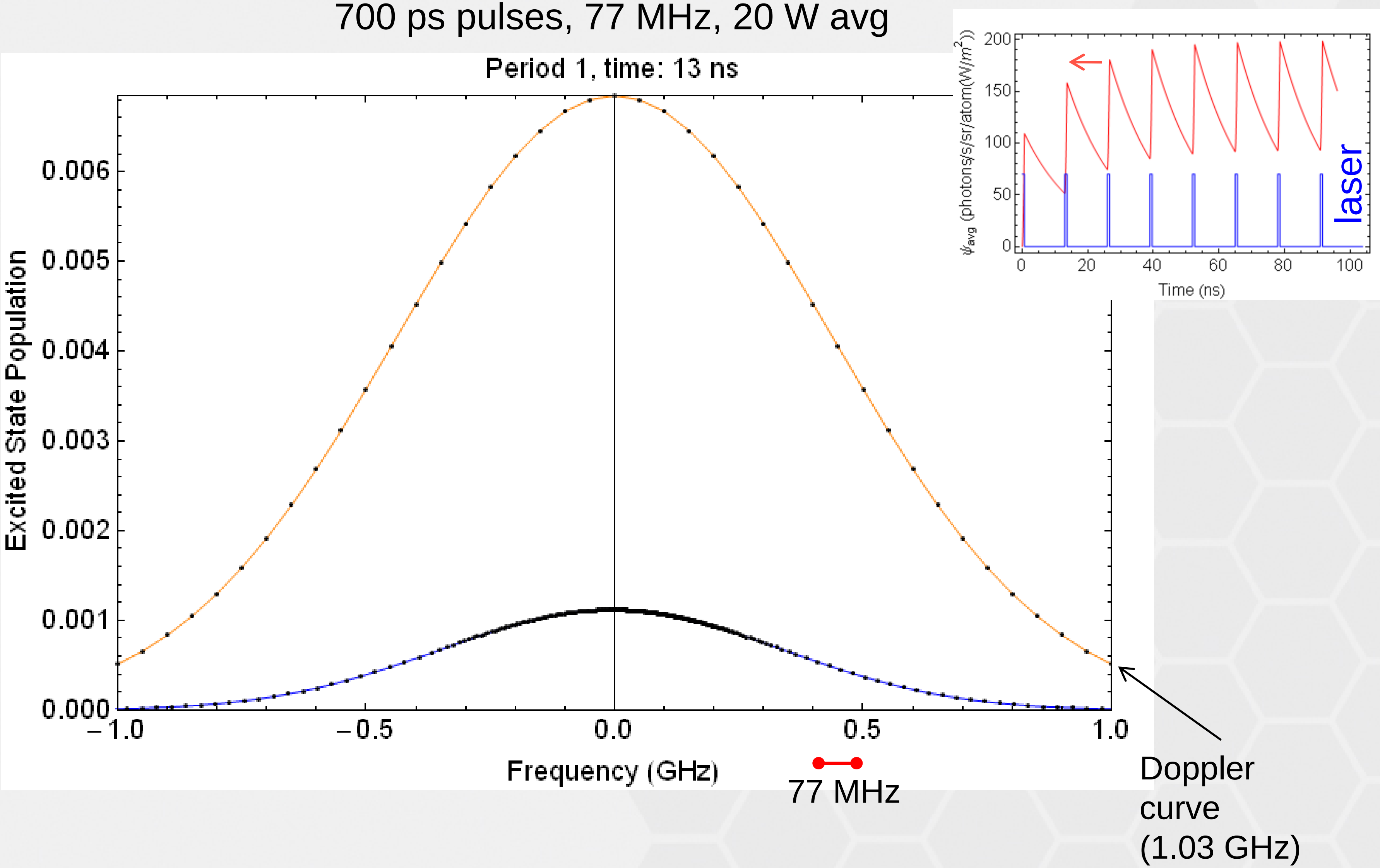
400 ps pulses, 77 MHz, 20 W avg





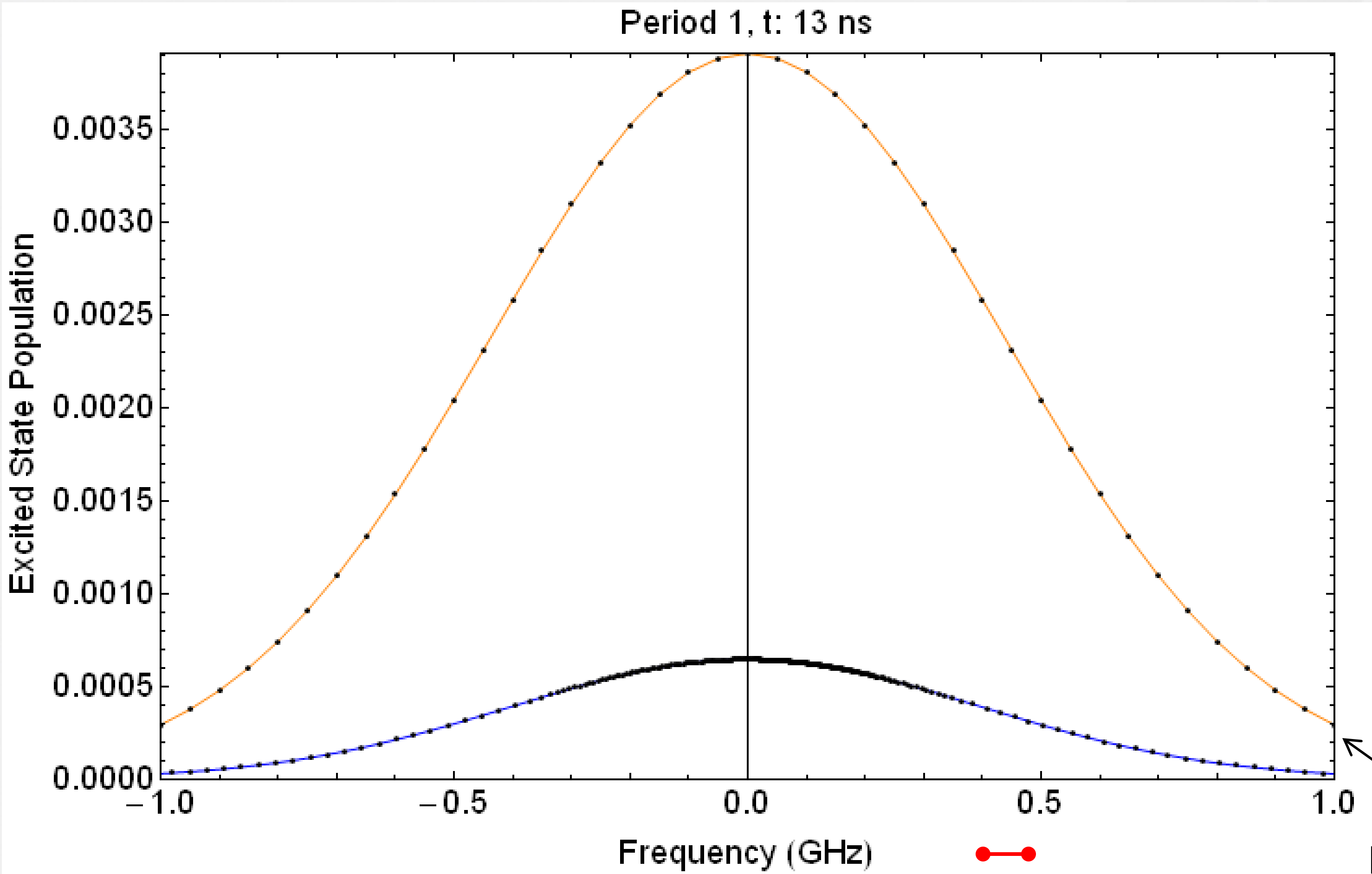
CW and pulsed Na laser optimization

700 ps pulses, 77 MHz, 20 W avg



Excited State Spectrum

400 ps pulses, 77 MHz, 20 W avg

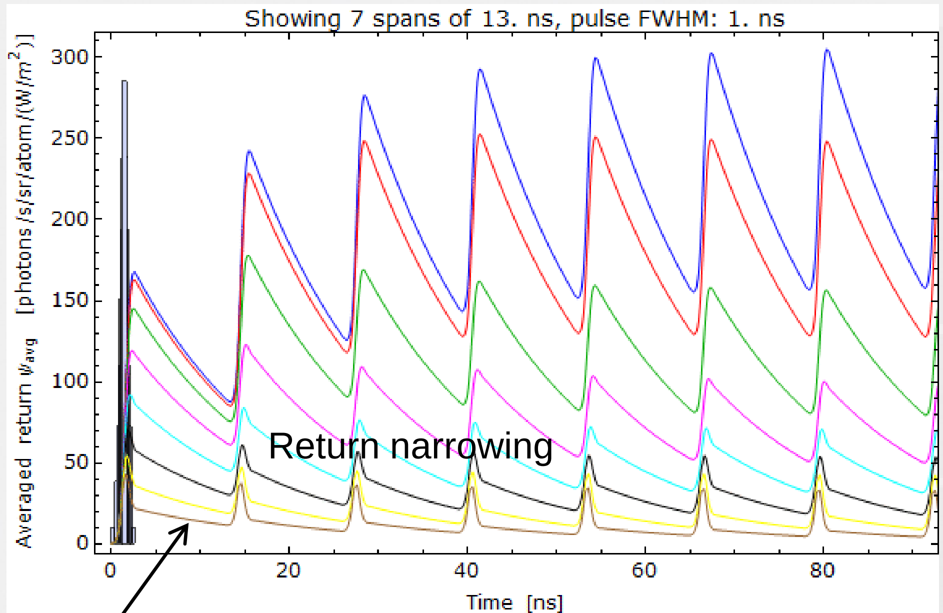


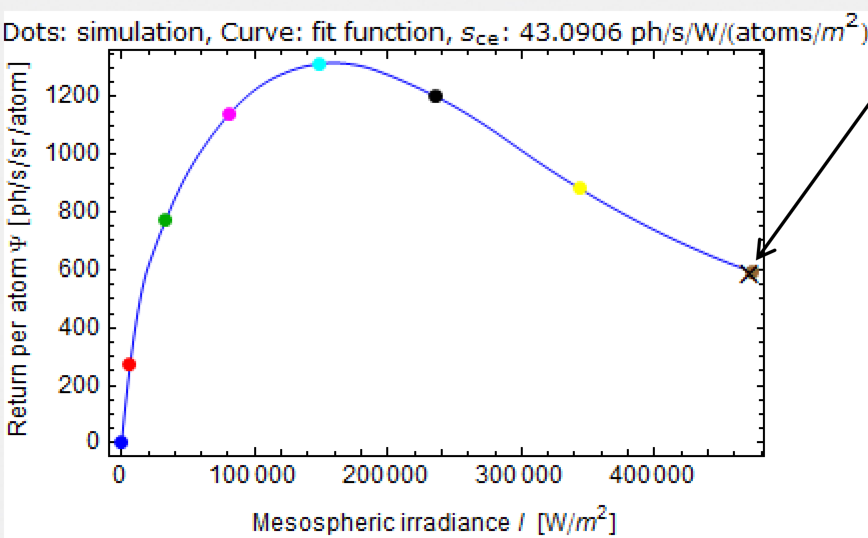
77 MHz

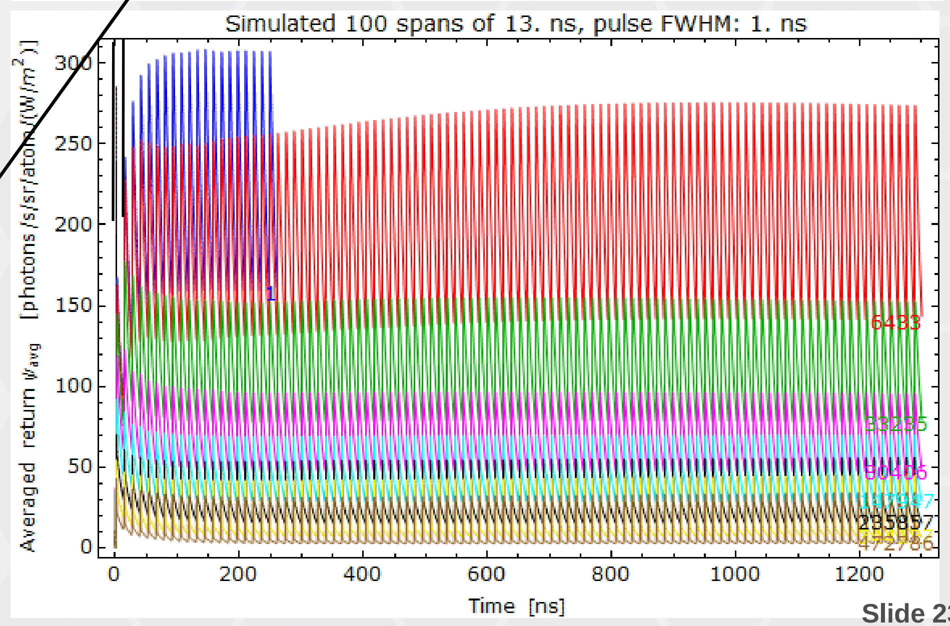
Doppler curve (1.03 GHz)

Micro-Macro Format: Adelaide

- Short macro pulses (3 μs, 800 Hz) ➔ high peak power
- $\theta = 90^{\circ}$, $q = 0$, $B = 0.23\text{G}$, circ.
- Efficiency decays with irradiance (roll-back)
- Return pulses narrow in time
- Evidence of strong saturation

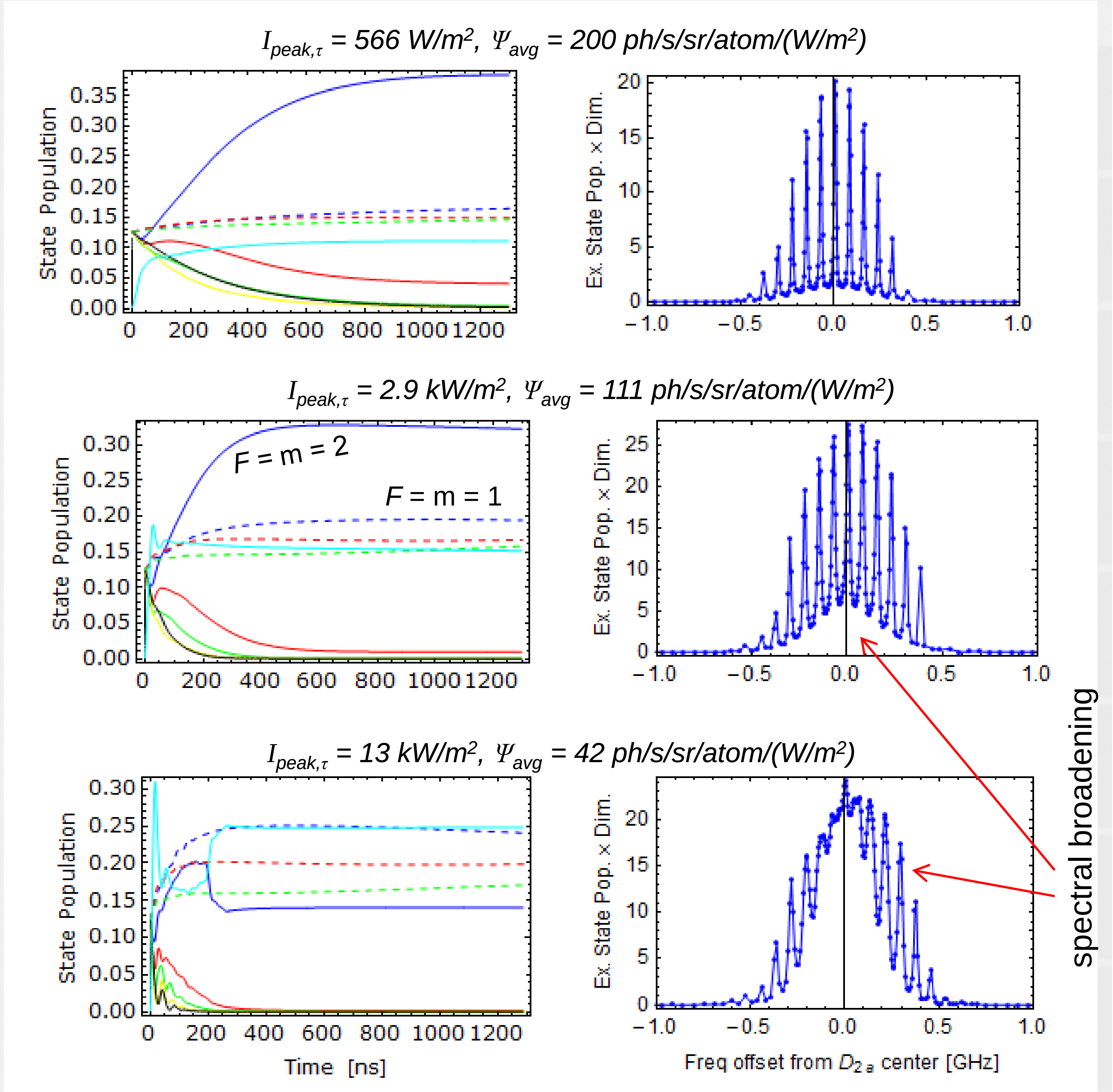




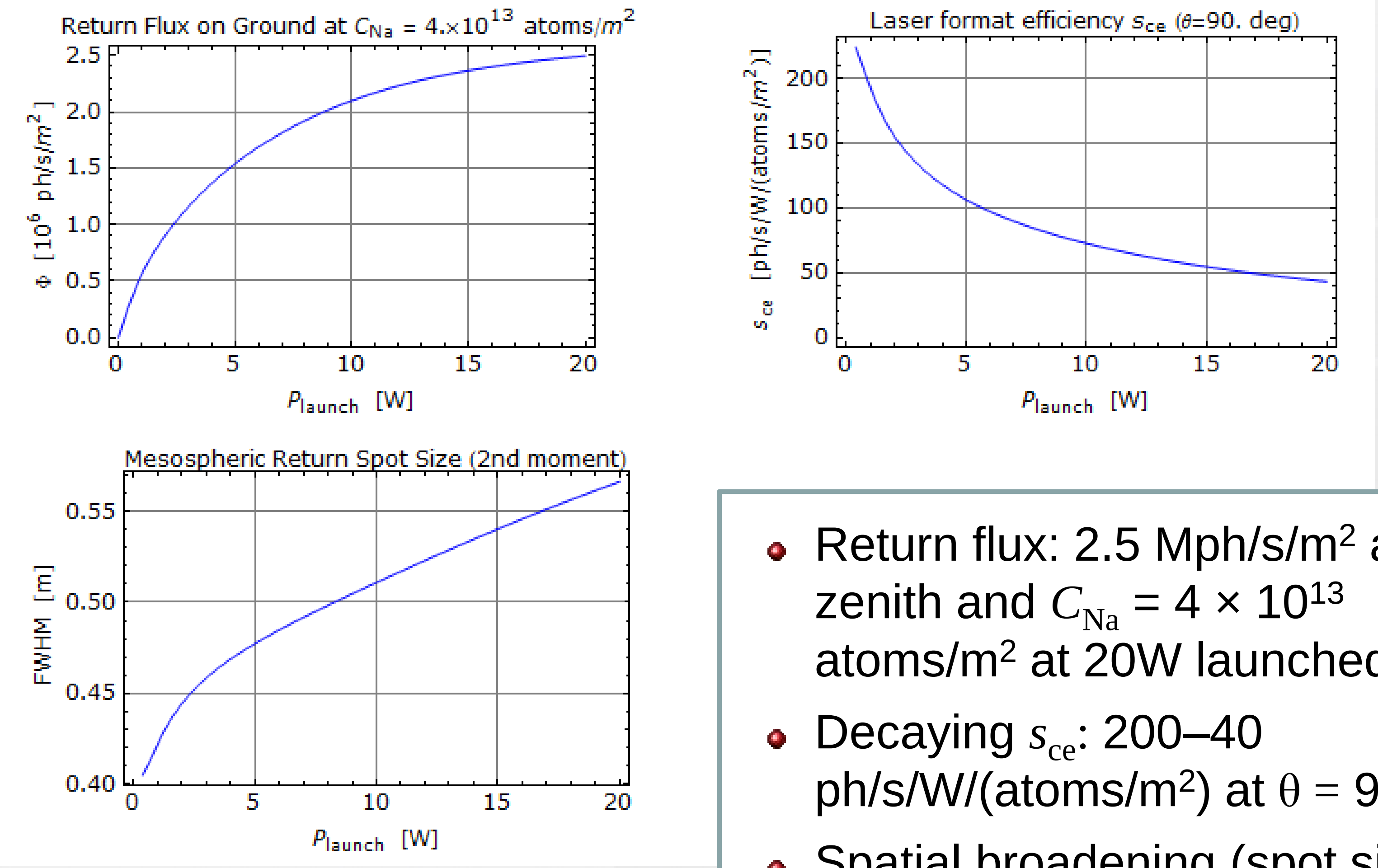


Micro-Macro Format: Adelaide

- Downpumping not severe, but strong spectral broadening
- At higher irradiance, return peaks for ~16ns, then drops (stimulated emission)
- Significant nonlinearity



Micro-Macro Format: Adelaide



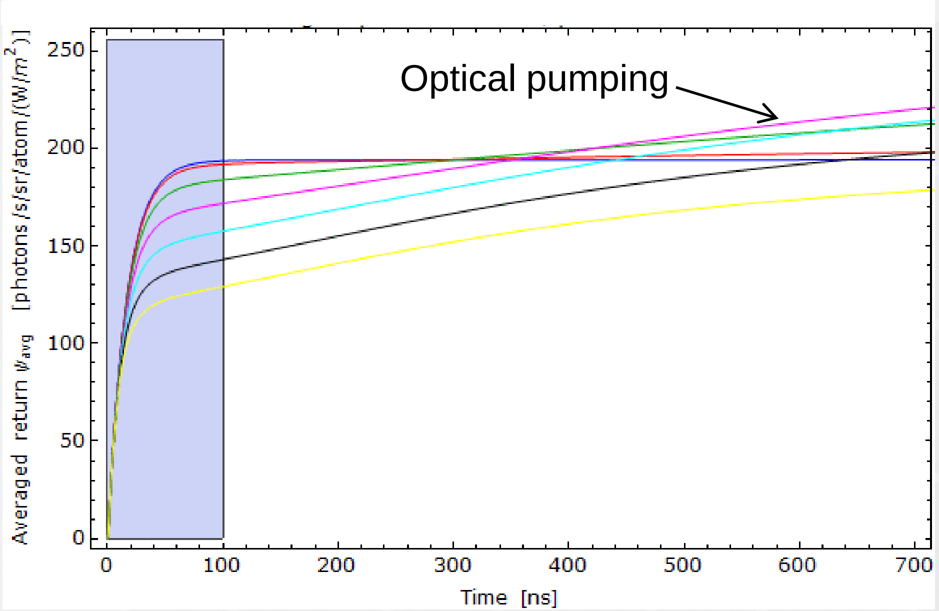
- Return flux: 2.5 Mph/s/m² at zenith and C_{Na} = 4 × 10¹³ atoms/m² at 20W launched
- Decaying s_{ce}: 200–40 ph/s/W/(atoms/m²) at $\theta = 90^o$
- Spatial broadening (spot size)
- Raise return with longer macro-pulses (or *shorter* micro-pulses)

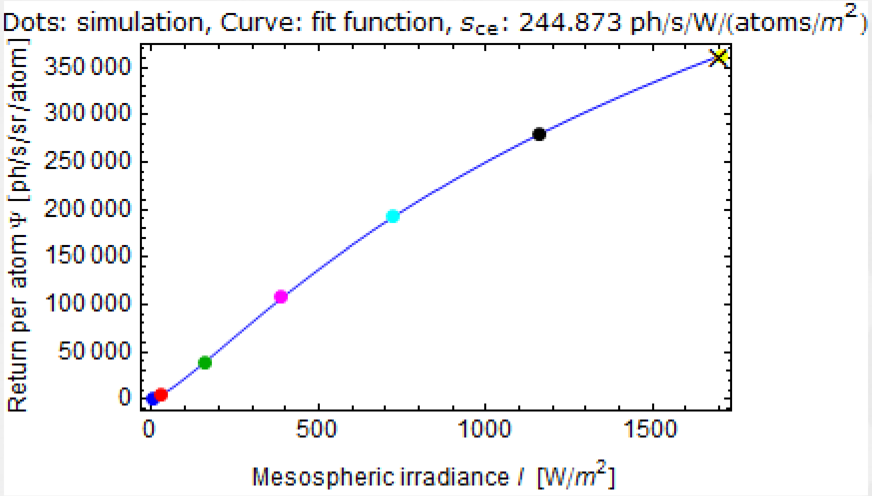
Figure of merit:

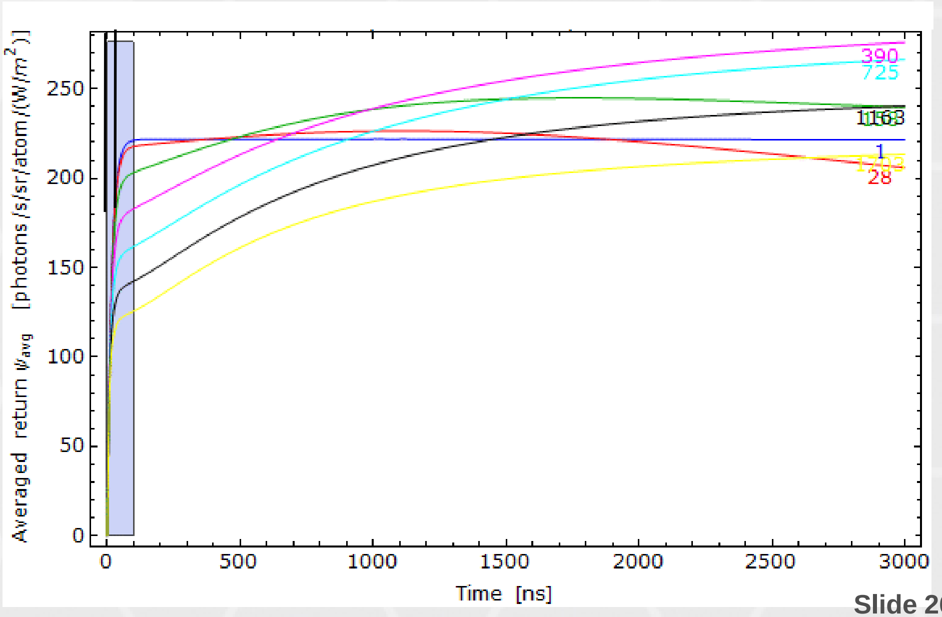
$$s_{ce} = \frac{\Phi\, X\, H^2}{P\,(T_a)^{2X}\, C_{\mathrm{Na}}}$$

Proposed Pulse-Tracking Format

- Long pulses (3 µs, 5–10 kHz) ➔ ≈400W peak power, 50 MHz
- $\theta = 90^{\circ}$, q=12%, B = 0.23G, circ.
- Optical pumping within pulses
- No ground-state pumping from pulse to pulse possible
- $\Psi(I)$ curve quite flat ➔ linearity

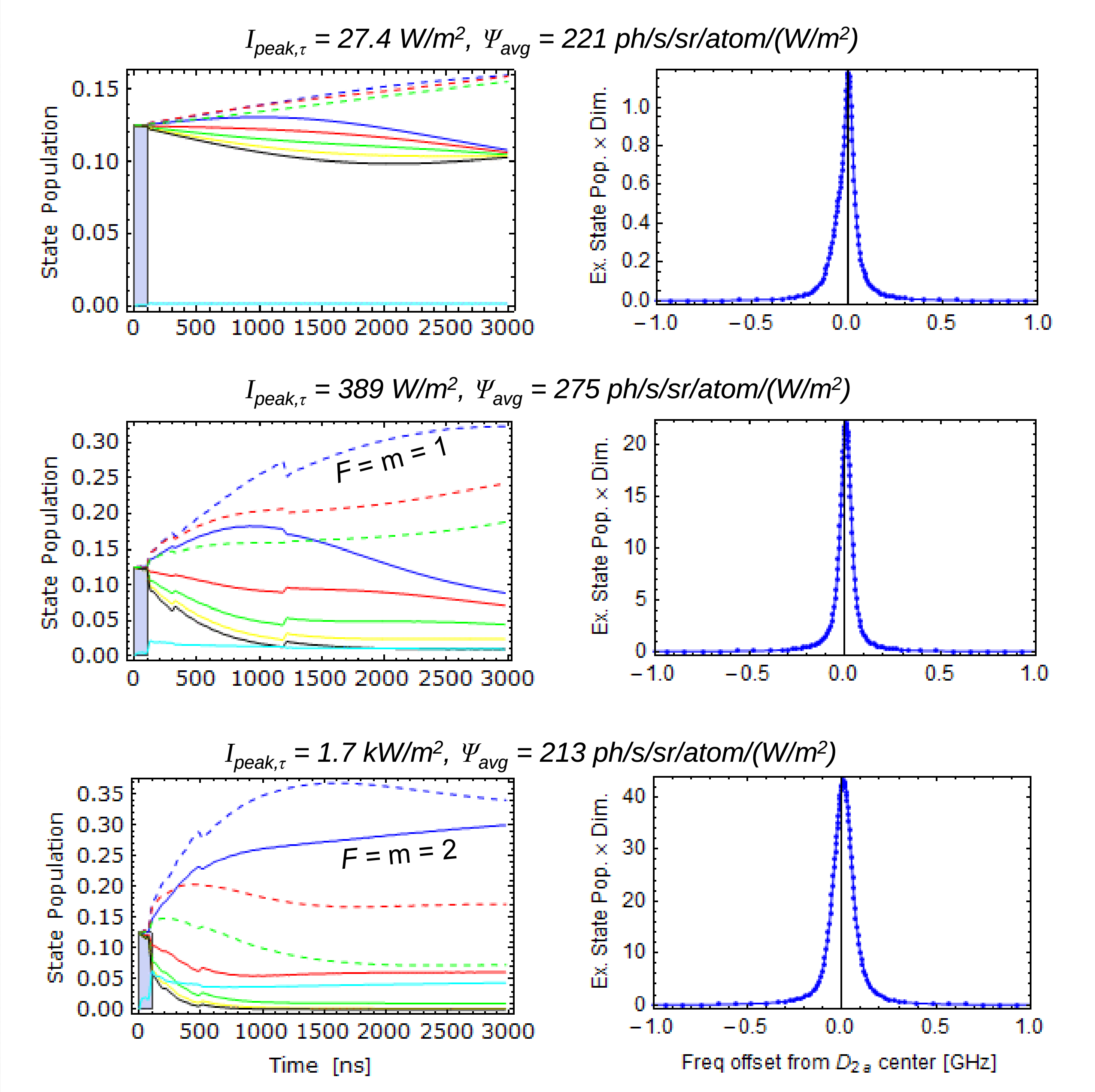




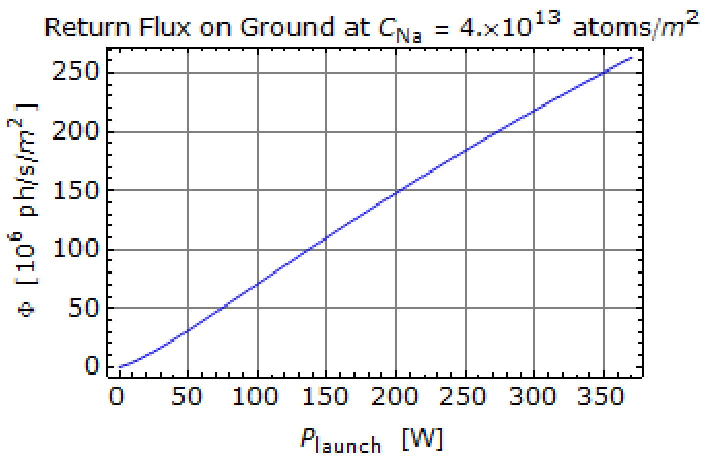


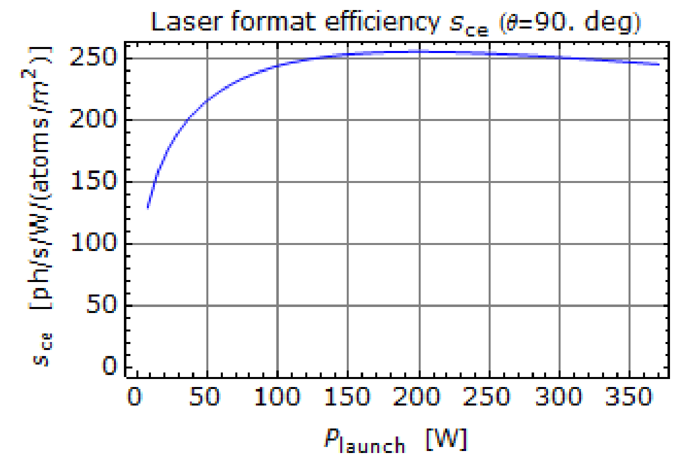
Proposed Pulse-Tracking Format

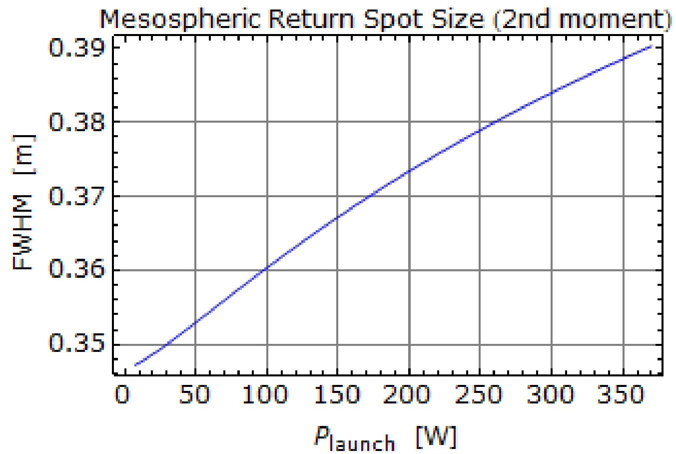
- Transient behavior throughout pulse
- Despite repumping, *F*=1 states hard to suppress
- Laser bandwidth and repumping can be further optimized
- Goal of 100 W/m^2/vc can be achieved with laser bandwidth of few tens of MHz
- Add. advantage: Recoil contained



Proposed Pulse-Tracking Format







- Return flux: 260 Mph/s/m^2 at zenith and C_{Na} = 4 × 10^{13} atoms/m^2 at 370W launched
- Hence 7.8 Mph/s/m^2 on avg. (duty cycle 3μs×10kHz=0.03)
- Little spatial broadening
- s_{ce}: 250 ph/s/W/(atoms/m^2) at θ = 90º ➔ same as cw

Figure of merit:

$$s_{ce} = \frac{\Phi\, X\, H^2}{P\,(T_a)^{2X}\, C_{\mathrm{Na}}}$$

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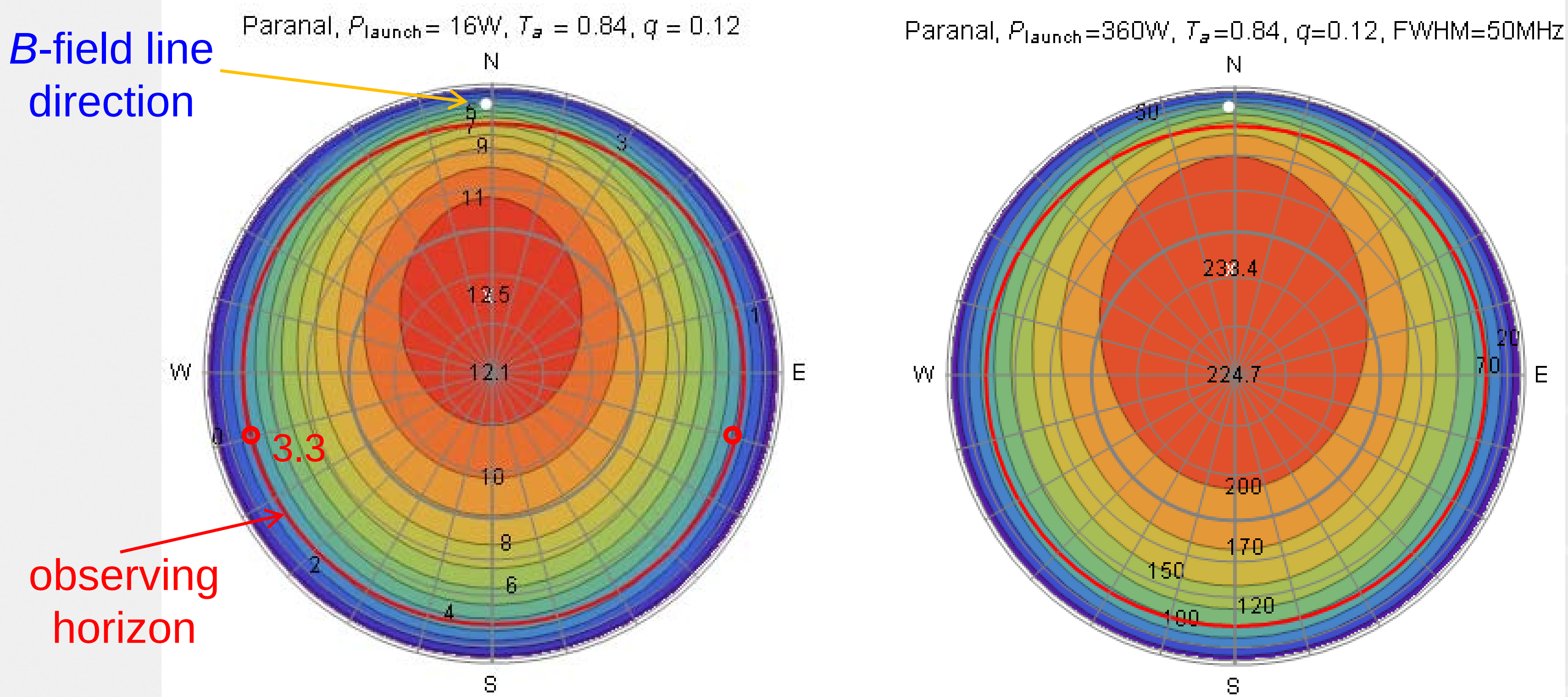
Sky plots for Armazones/Paranal

Return flux on ground [10^6 ph/s/m^2]



16 W

360 W

R. Holzloehner et al., SPIE 2010

- Reminder: Flux at ζ = 60° only 27% of zenith flux!

Return flux scales almost linearly

Simulation is One Side — Let's Measure!

- ESO has built the cw 20W-"Wendelstein" mobile LGS Unit
- Initial experiments in Bavaria successful, but bad weather (presentation tomorrow in 1:30–3:00pm Laser Systems session)
- We propose a measurement campaign on Mauna Kea in Q3/2012
- Shoot from inside the domes, set up on altitude platform
- Use common observing and photometry procedures
- Test in daytime, then half technical night per telescope
- Joint publication

Simulation is bliss, seeing is believing… ***(numericists' proverb)***

Conclusions

- Compared a variety of pulsed LGS formats
- Two key quantities: Avg. peak irradiance $I_{\mathrm{peak},\tau}$, overlap κ
- Goal: $I_{\mathrm{peak},\tau} \approx 100$ W/m^2/vel.cls. , $\kappa \rightarrow 1$
- Laser physics and freq. conversion impose limits on $I_{\mathrm{peak},\tau}$, κ
- Existing pulsed LGS can be optimized
- Best efficiency: Long-pulse formats exciting a few vel.cls. or cw with circular polarization and D_{2b} repumping
- Proposal of spot-tracking format (2.5–5μs, 10–5 kHz) with high efficiency. But: unusual/problematic pulse duration

Proposal of Q3/2012 measurement campaign on Mauna Kea