Title: Innovations and applications of high-power optical pumping

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URL: http://pirsa.org/17080033

Abstract:

Innovations and applications of high-power optical pumping

Bill Hersman

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Founder and CEO, Xemed LLC

Outline

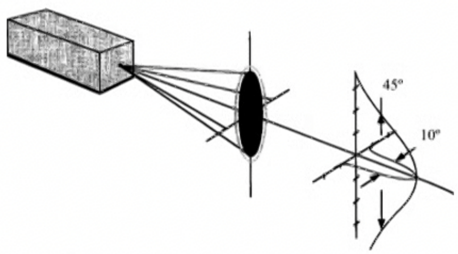
Background and status

- Stepped-mirror enables narrowing a stack of diode array bars using a single external cavity
  - Hyperpolarized xenon-129 MRI
  - Polarized 3He filling station for neutron spin analysis

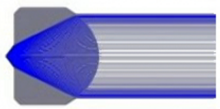
Work in progress:

- Higher external cavity magnifications
- Multiplexing with an atomic line filter in the external cavity
  - Diode Pumped Alkali Laser
  - Four-wave mixing, upscaling to 420nm

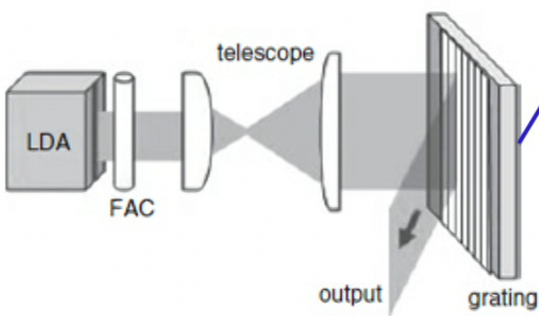
Wavelength-locked diode laser



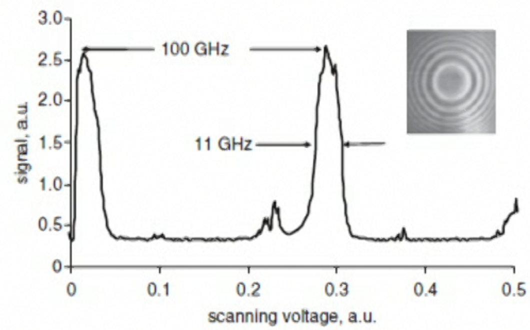
- Diode facet has dimensions 1 μm × 100 μm
- Output is diffraction limited along "fast-axis"
- Fast-axis collimating micro-lens achieves parallel output in one dimension
- Slow-axis is multimode and diverging



- External elements can feed back power, selected for wavelength and/or transverse mode
- A single grating can lock the wavelength of ~25 emitters

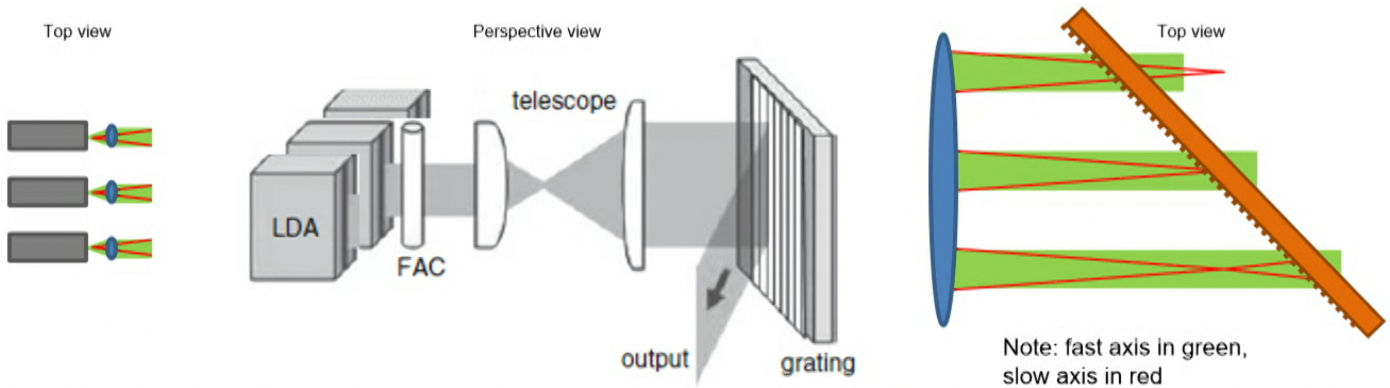


Grating inclined at Littrow angle selects wavelength



Challenge: narrowing a stack

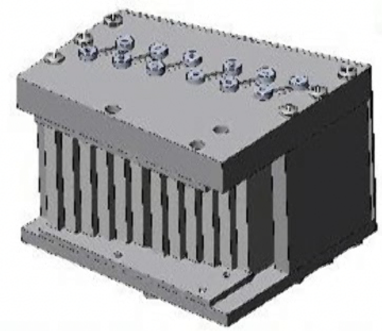
- Diode bar has ~50 emitters; stack of diode bars has ~500 emitters
- Fast axis is parallel-to-parallel from FAC to grating
- Slow axis is point-to-point from facet to grating

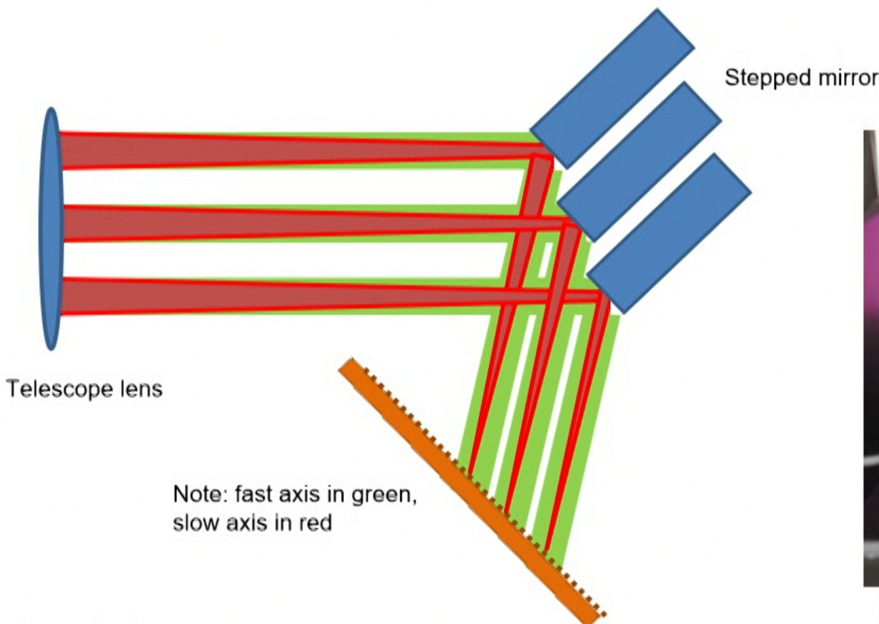


- Multiple beams from diode array bars placed side-by side cannot all focus on a grating at the Littrow angle
- Only the central bar will be properly focused on the grating

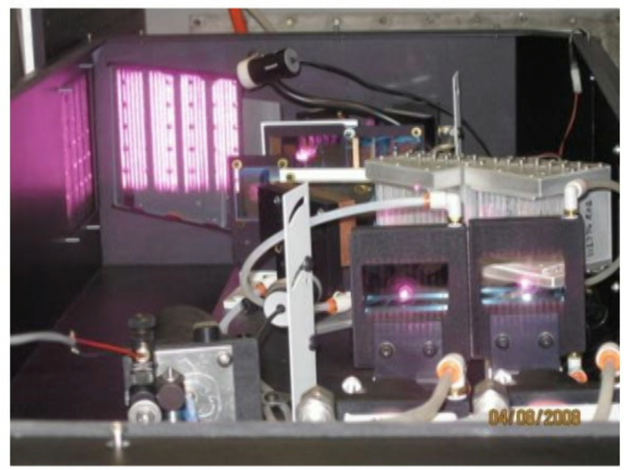
Solution: narrowing a stack

- A stepped-mirror corrects path-lengths, equalizing object to image distances from FAC to a grating at the Littrow angle
- Also compresses dark spaces between bars





Stepped mirror
Hersman, Distelbrink, Zhu, US patent #7769068



Pump laser system incorporates 24 x100 W bars, with wavelength locked output of over 1.5 kW

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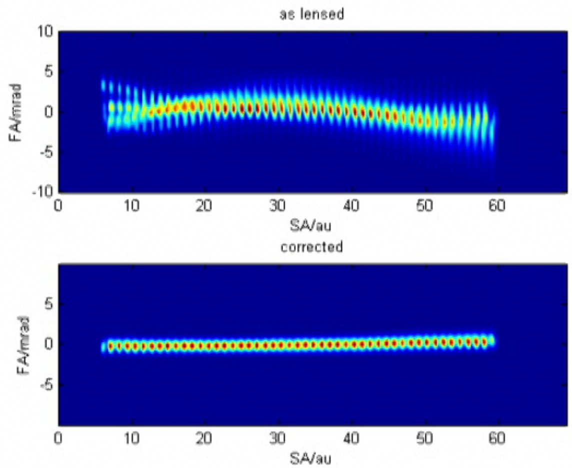
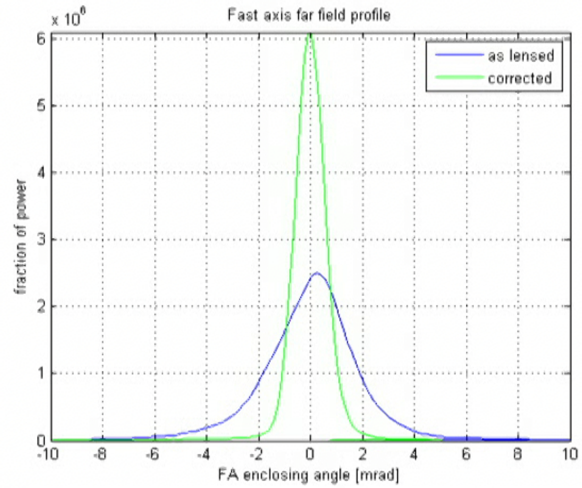
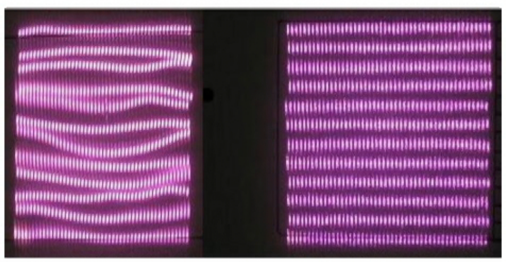
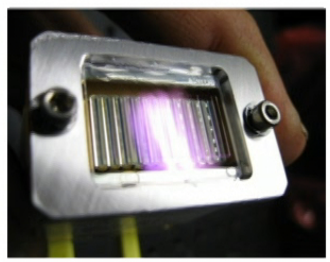
Even narrower…

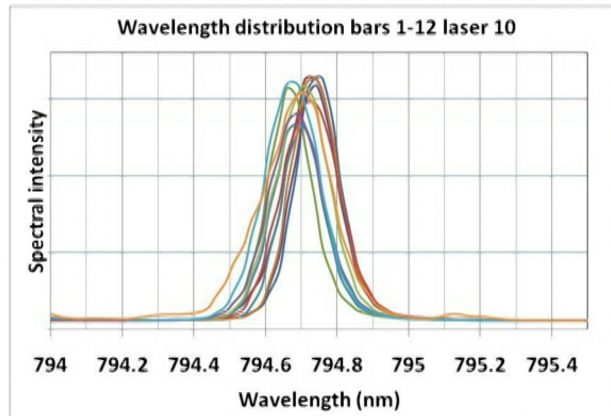
Correction of individual emitters improves laser spectrum by factor 2.5



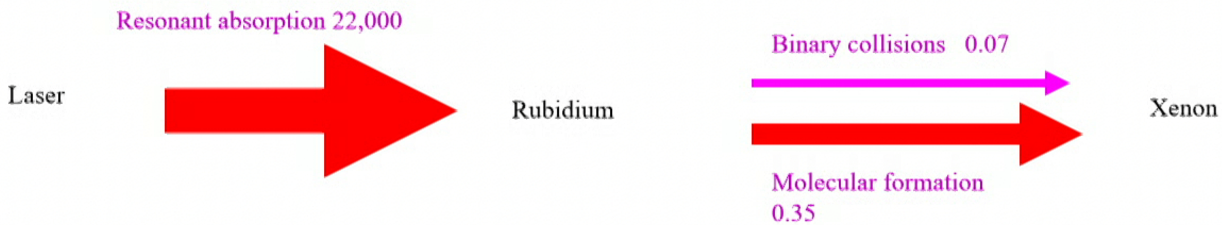


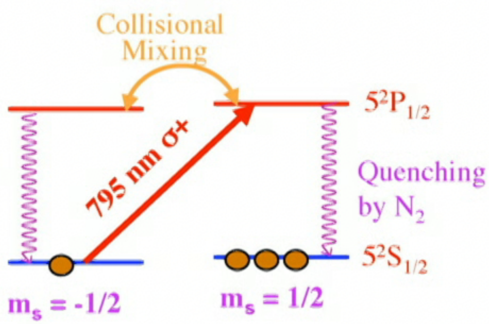


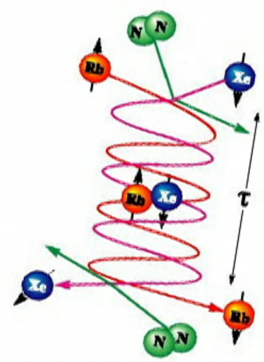


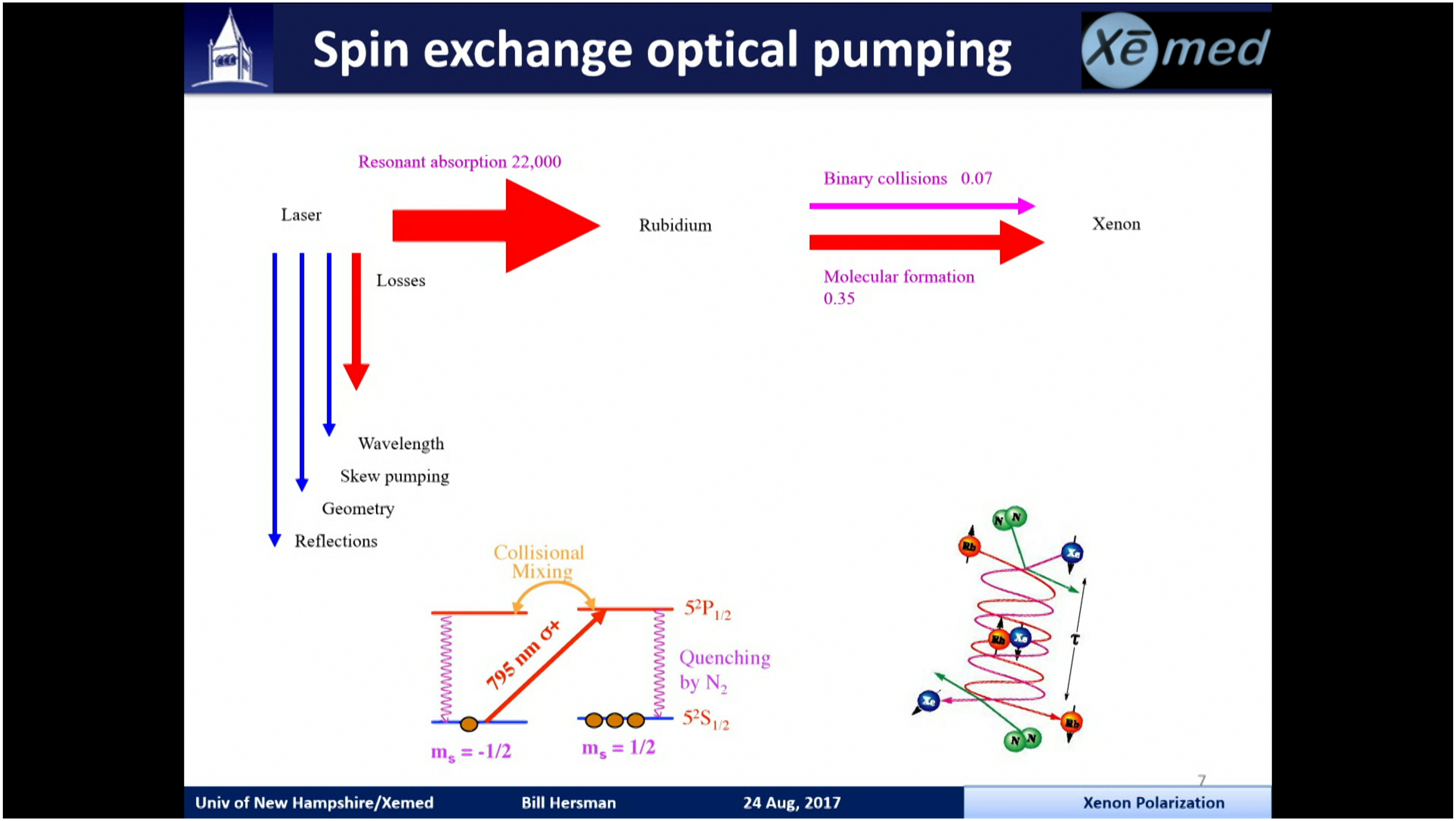


Spin exchange optical pumping








Spin exchange optical pumping
Xēmed
Resonant absorption 22,000
Laser
Rubidium
Binary collisions 0.07
Xenon
Molecular formation
0.35
Losses
Wavelength
Skew pumping
Geometry
Reflections
Collisional
Mixing
$5^2P_{1/2}$
795 nm σ+
Quenching
by N_2
$5^2S_{1/2}$
$m_s = -1/2$
$m_s = 1/2$
τ
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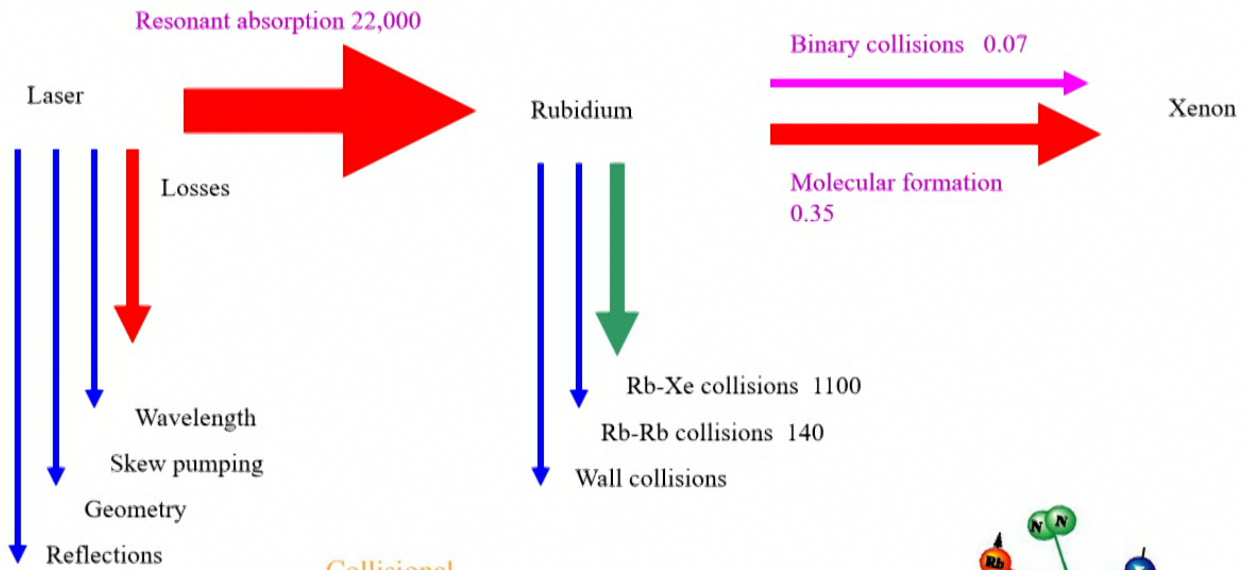
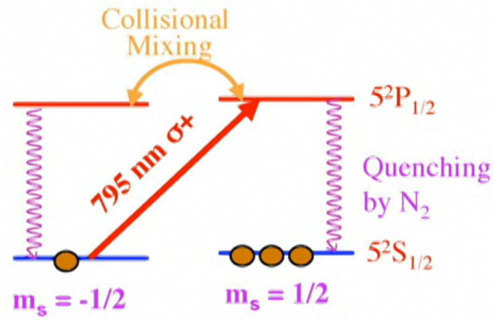
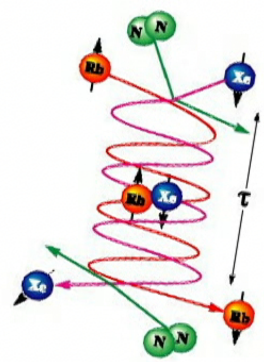
Univ of New Hampshire/Xemed
Bill Hersman
24 Aug, 2017
Xenon Polarization

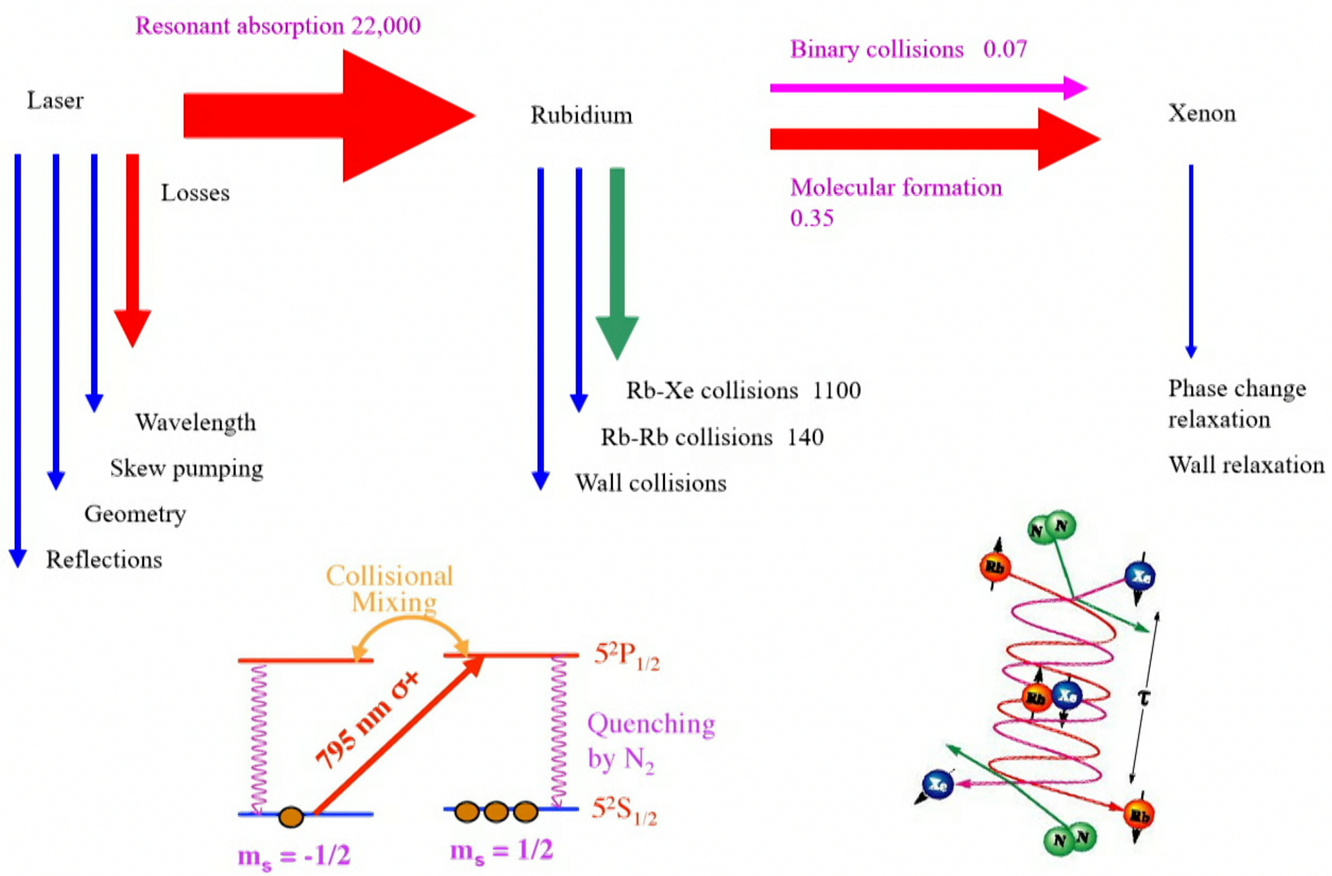
Spin exchange optical pumping





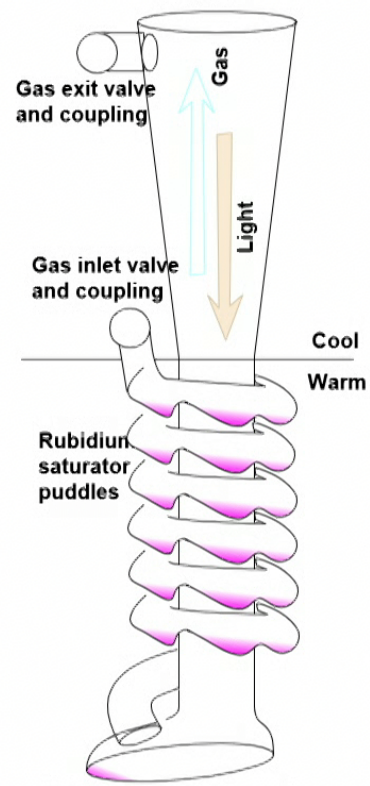


Spin exchange optical pumping



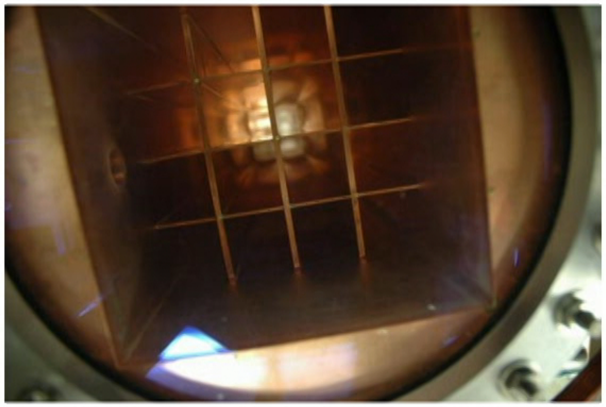
Polarizer cell design

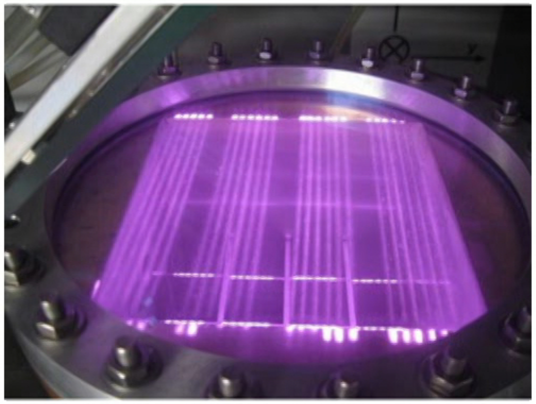
- Long polarizing cell and high rubidium density aid in efficient diode laser photon utilization
- Counter-flow high-velocity operation allows higher-polarization xenon to be subjected to higher-polarization rubidium
- Mixture is saturated in rubidium saturator helix before entering polarizing cell
- Rubidium is extracted from gas in presence of laser before leaving polarizing cell
- Published *Phys. Rev. Lett.* **96** 053002 (2006)



High power polarization chamber Xēmed

- Two spectrally-narrowed 12-bar stacks deposit 1.4kW into the gas
- Polarization is subdivided into multiple heat-exchanger channels
- Immersion of copper column in flowing hot oil allows efficient thermal reservoir for removing kilowatt laser power
- Produces 2.5 L/hr at 54% polarization





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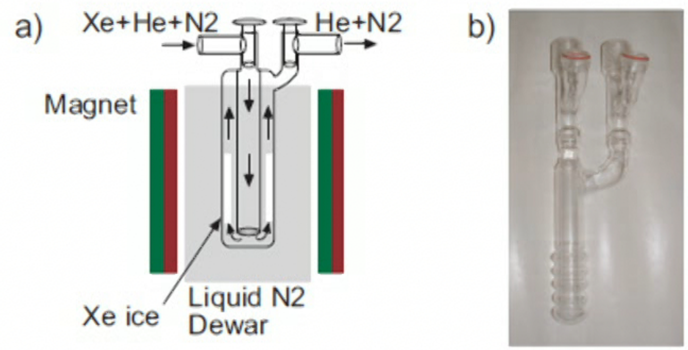
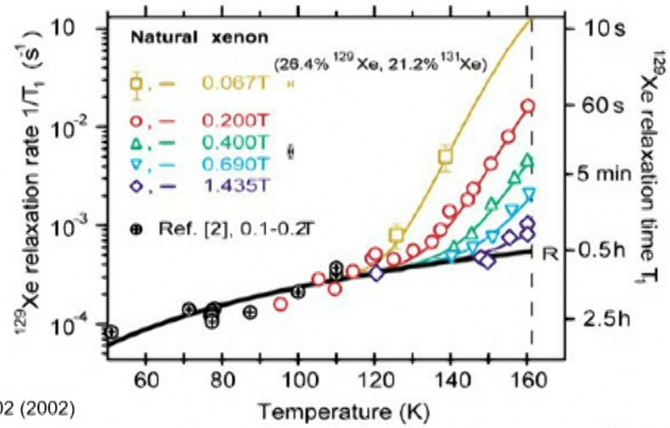
Original cryogenic accumulation

- Pure xenon can be isolated from the flowing mixed gases by separating cryogenically
- Solid xenon nuclear polarization relaxes rapidly at temperature near the phase transition
- Fast-freezing and quick cooling to LN2 temperature in strong magnetic field preserves polarization
- Fast-thawing of large accumulated quantities proved more challenging



Original configuration

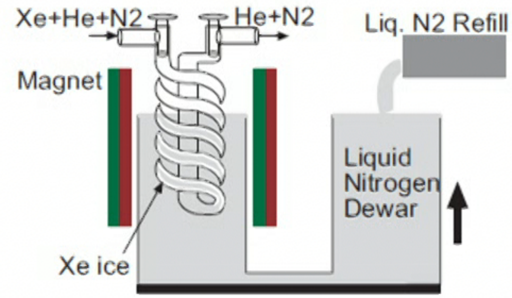


N. Kuzma, et al, PRL 88:147602 (2002)

Rising-dewar freeze-out

- Mixed gases enter cryogenic accumulator, spiraling downward
- Beginning at the lowest quarter of the glassware, the dewar slowly rises throughout the accumulation
- Hyperpolarized xenon is frozen to the glass surface beginning near the bottom, and finishing near the top
- Removing the dewar and replacing with warm water immersion quickly thaws the xenon into the breathing bags

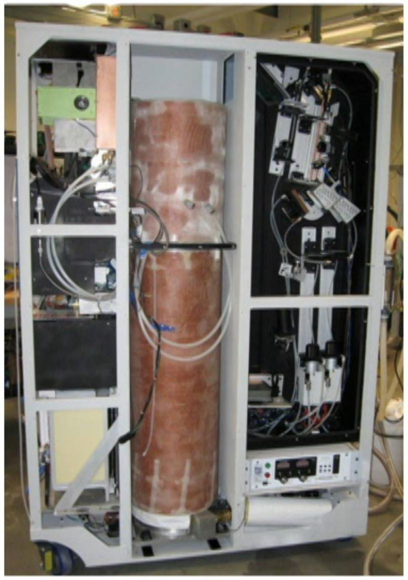
a)



b)

Assembly

- Laser of 1.4 kW, copper column, rising dewar freeze-out, 4 bag delivery, computer control, on-board diagnostics and logging
- Robust, portable, remote internet control



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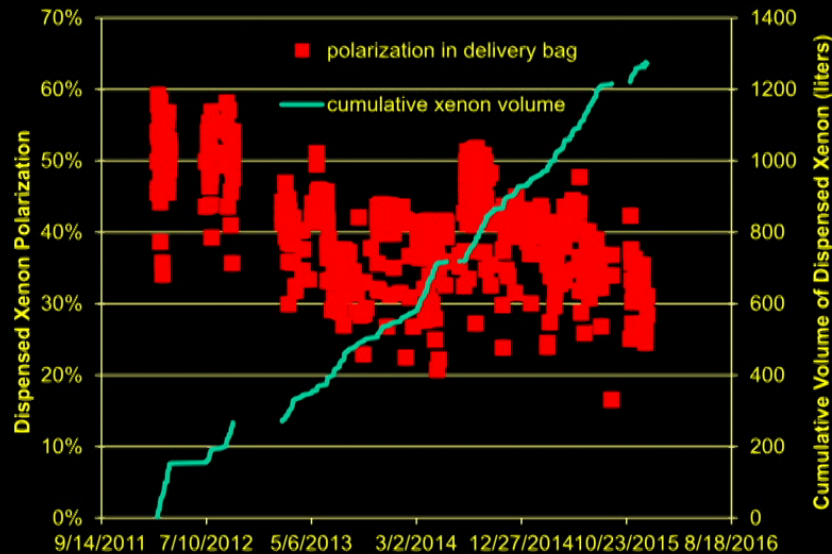
Gas administration bag system

- Tedlar bag and poly connector connects directly to polarizer
- Gas lifetime in the bag can reach ~1.5 hr at low field, much longer at 3T
- Mouthpiece and bag constitute a non-significant risk medical device, exempt from 510K filings
- Custom fabricated by a certified medical device company
- Optimized to compensate for the lower viscosity (flow) of xenon

Date: 08/24/2017

Hyperpolarizer/Imaging agent

- Xemed produces XeBox hyperpolarizers since 2004.
- Custom proprietary laser technology delivers kW power of linewidth-narrowed laser light
- Custom cryogenic accumulation system minimizes polarization losses during thawing.
- Automated production process is standardized and under computer control.



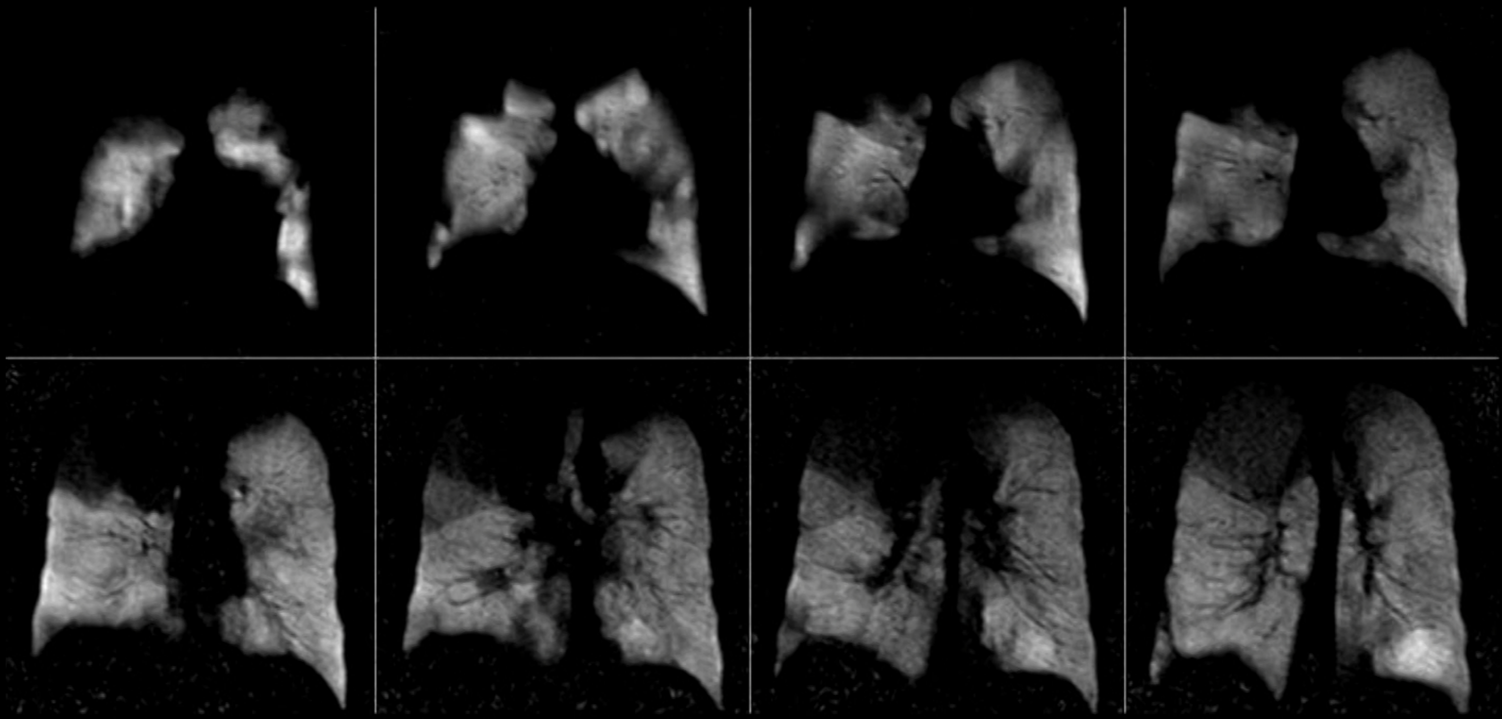
- No on-site expert required. Xemed can diagnose and optimize remotely.
- MagniXene® polarization between 35% to 60% in the dose bag after thawing
- Output productivity: up to 6 L/hr, with polarization of up to 60%.

Date: 08/24/2017

Spin Density – Healthy Subject

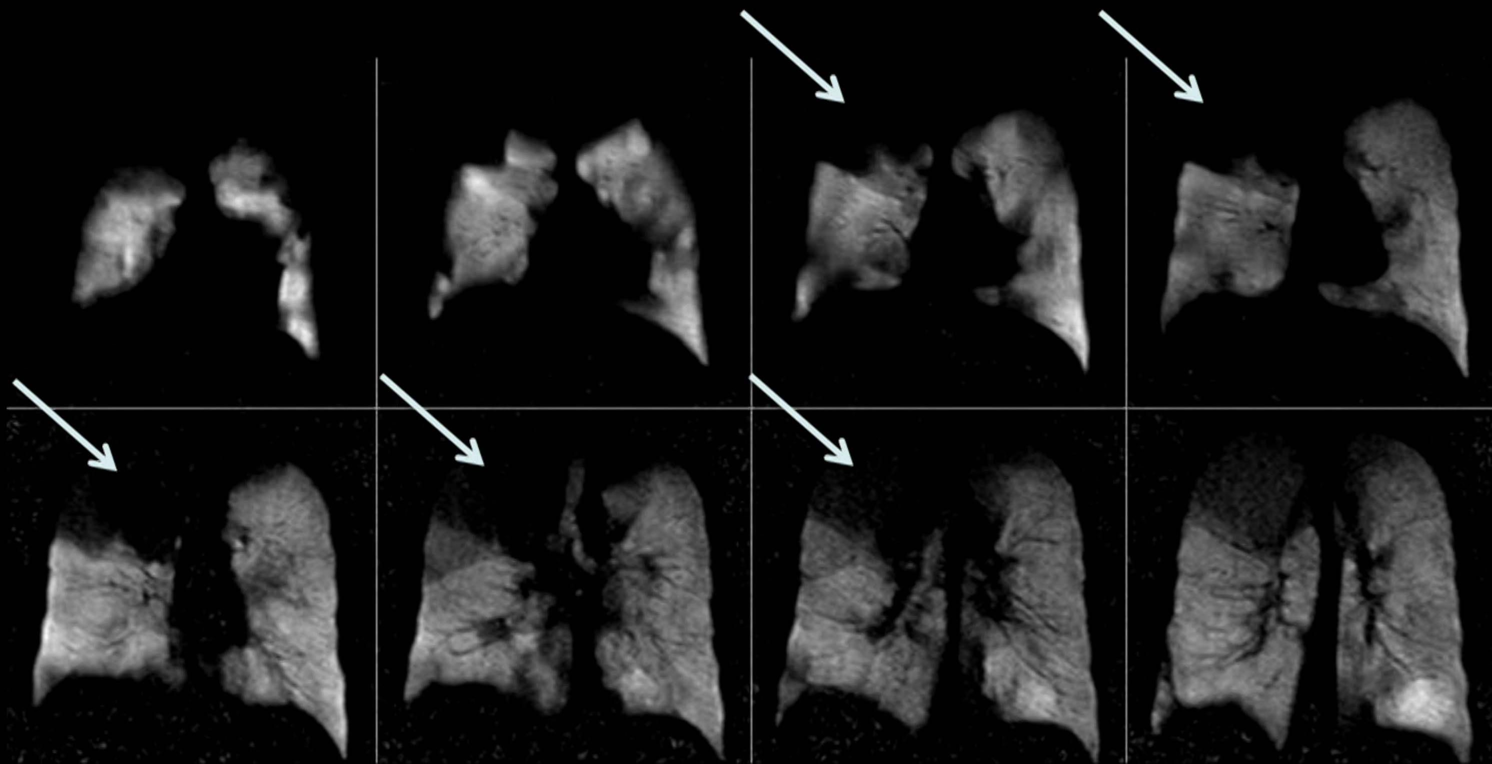
FLASH spin density acquisition, 2.1 x 2.1 x 10 mm^3, acceleration factor 2

Spin Density – COPD Subject



FLASH spin density acquisition, 3.1 x 3.1 x 15 mm^3, acceleration factor 3

Spin Density – COPD Subject

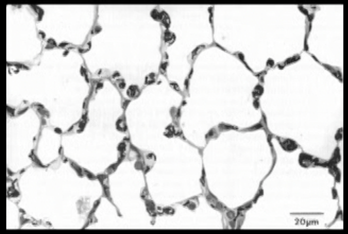


FLASH spin density acquisition, 3.1 x 3.1 x 15 mm^3, acceleration factor 3

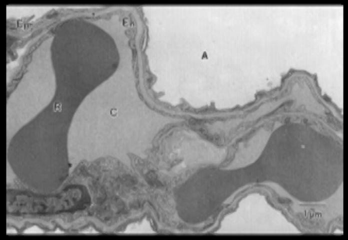
^{129}Xe in the lung

inhaled hyperpolarized ^{129}Xe

Alveoli



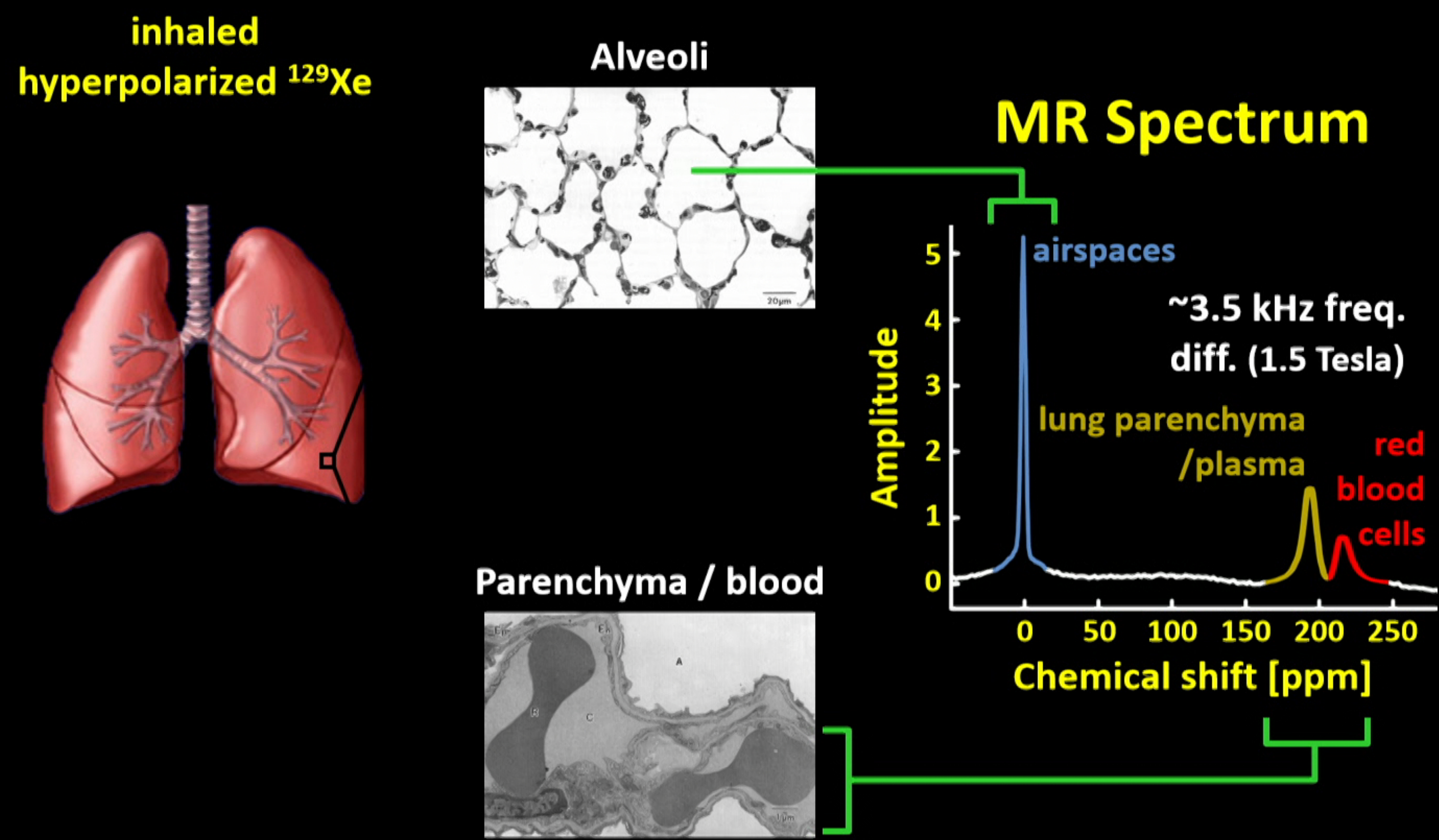
Parenchyma / blood



~3.5 kHz freq. diff. (1.5 Tesla)

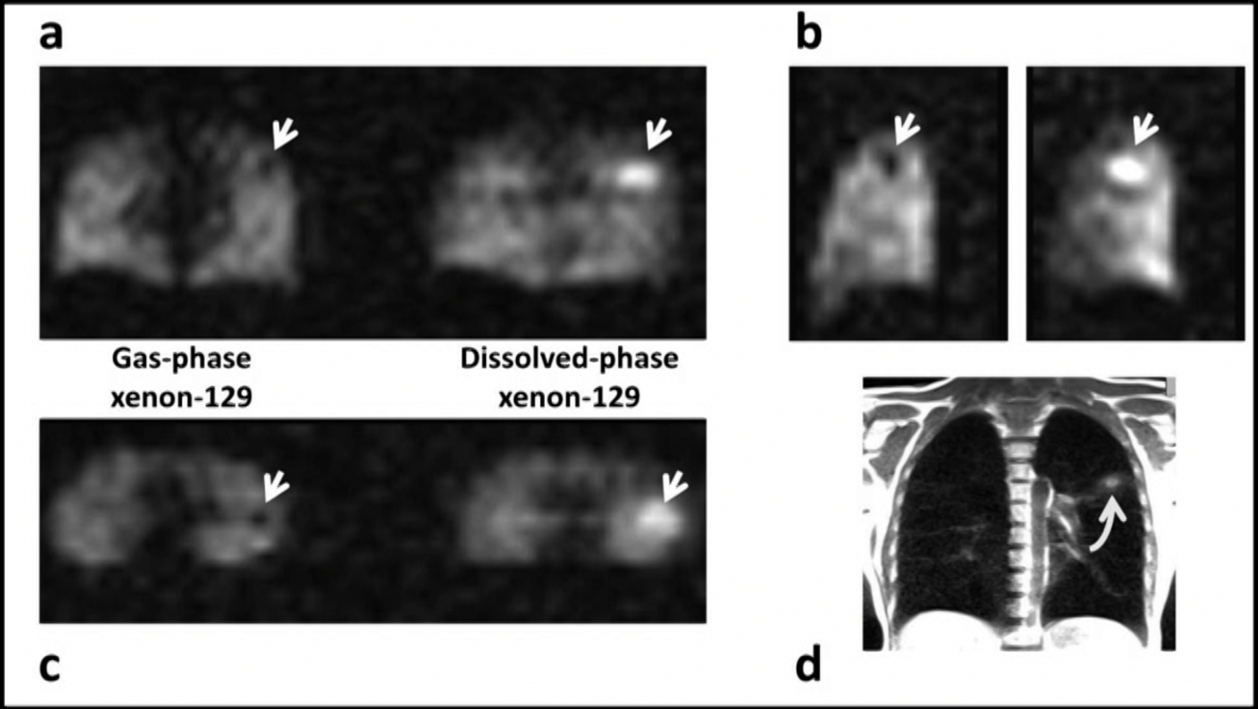
Lung rendering adapted from: dir.niehs.nih.gov/dirlrb/mcb/proj-cox.htm Micrographs from Albertine (1996)

^{129}Xe in the lung



Lung rendering adapted from: dir.niehs.nih.gov/dirlrb/mcb/proj-cox.htm Micrographs from Albertine (1996)

Simultaneous Imaging of Ventilation Distribution and Gas Uptake

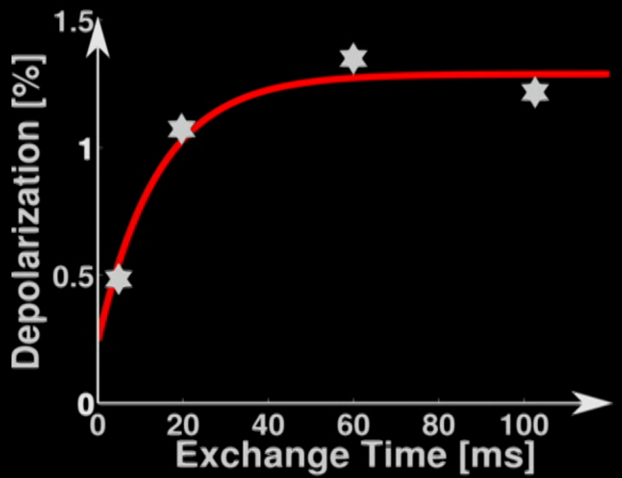


Mugler 3rd JP, Altes TA, Ruset IC, et.al. Simultaneous magnetic resonance imaging of ventilation distribution and gas uptake in the human lung using hyperpolarized xenon-129. Proc Natl Acad Sci U S A 2010;PNAS published ahead of print November 22, 2010, doi:10.1073/pnas.1011912107

Depolarization vs. Exchange Time

Dissolved phase can be selectively quenched multiple times, drawing down the gas phase signal, improving signal-to-noise

Data for each image voxel



Diffusion model

$$f_D(t) = \lambda \frac{V_t}{V_a}\left(1 - \frac{8}{\pi^2} e^{-t/\tau_c}\right)$$

Depolarization vs. Exchange Time

Dissolved phase can be selectively quenched multiple times, drawing down the gas phase signal, improving signal-to-noise

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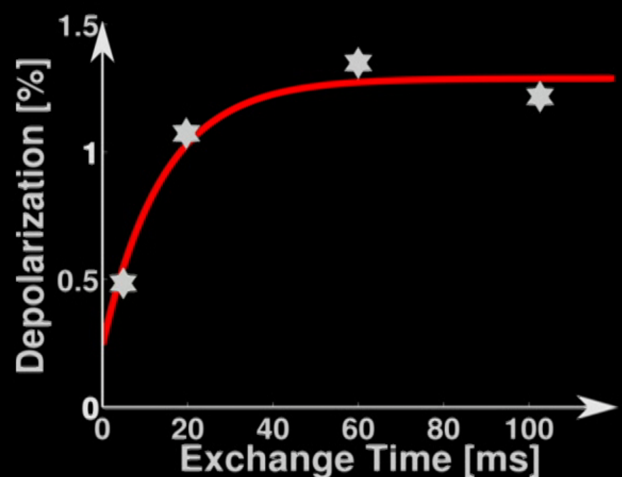


Diffusion model

$$f_D(t) = \lambda \frac{V_t}{V_a}\left(1 - \frac{8}{\pi^2} e^{-t/\tau_c}\right)$$

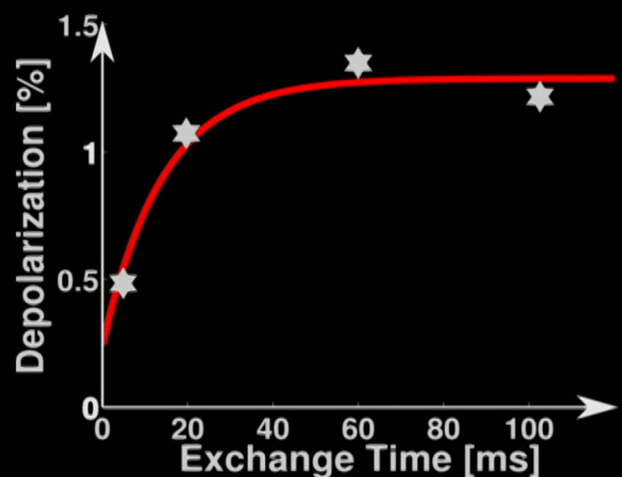
Max. Depolarization
MXTC-F

Tissue to alveolar volume ratio = V_t / V_a

Depolarization vs. Exchange Time

Dissolved phase can be selectively quenched multiple times, drawing down the gas phase signal, improving signal-to-noise

Data for each image voxel



Diffusion model

$$f_D(t) = \lambda \frac{V_t}{V_a}\left(1 - \frac{8}{\pi^2} e^{-t/\tau_c}\right)$$

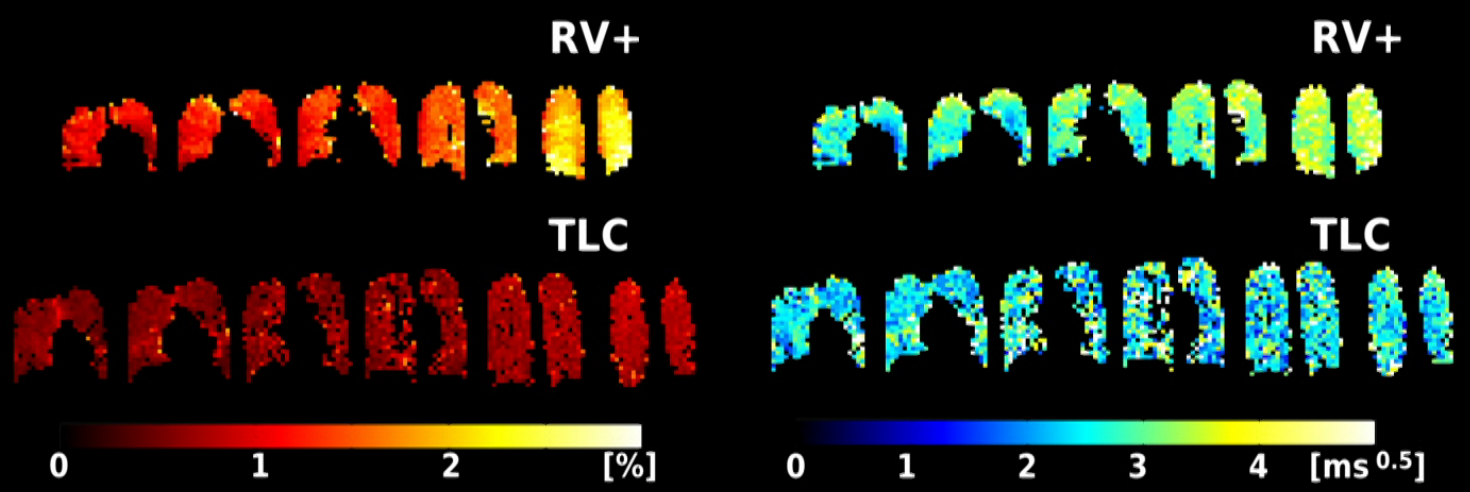
Time Constant τ_c
MXTC-S
tissue thickness

Max. Depolarization
MXTC-F
Tissue to alveolar volume ratio = V_t / V_a

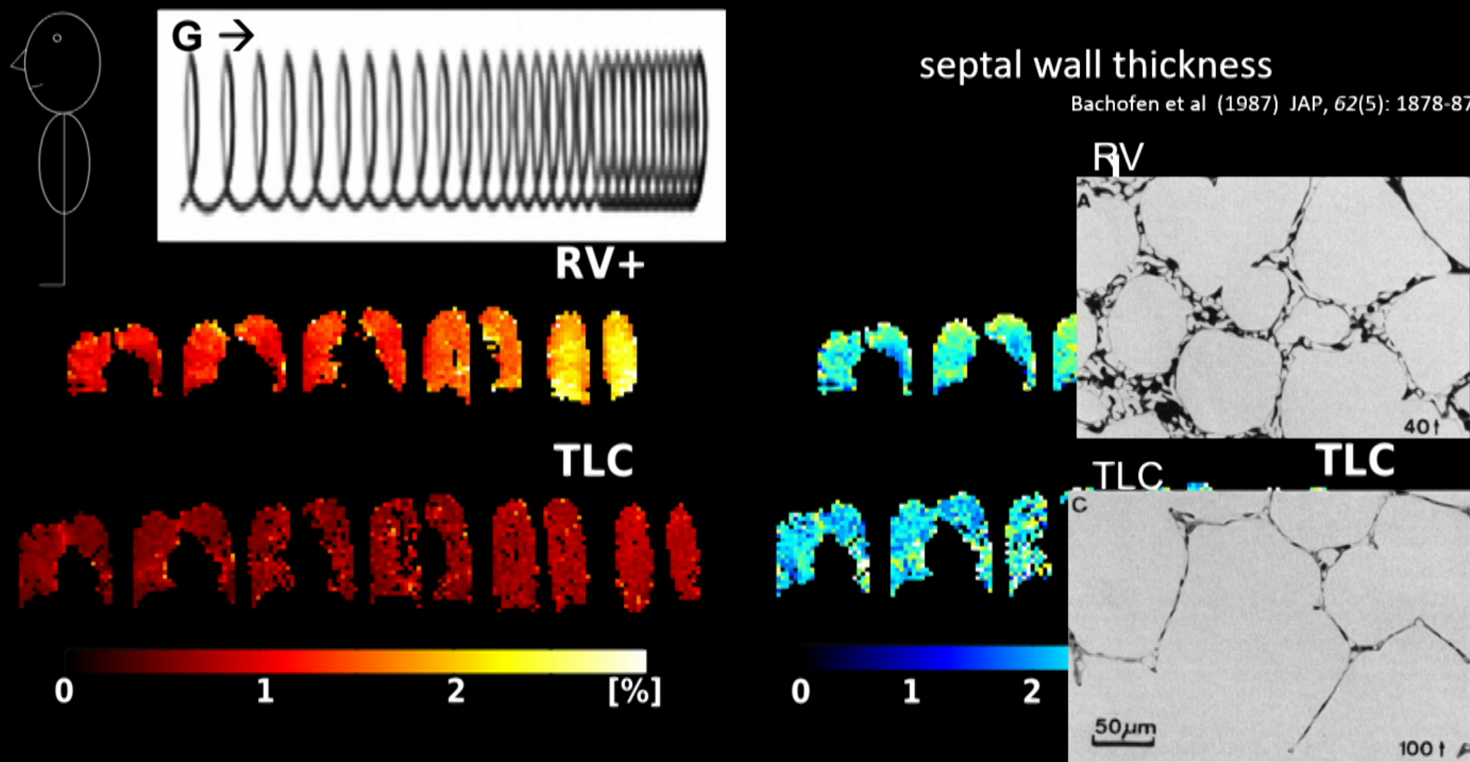
MXTC – Ventilation Volume Dependence

tissue to alveolar volume ratio
MXTC-F

septal wall thickness
MXTC-S



MXTC – Ventilation Volume Dependence

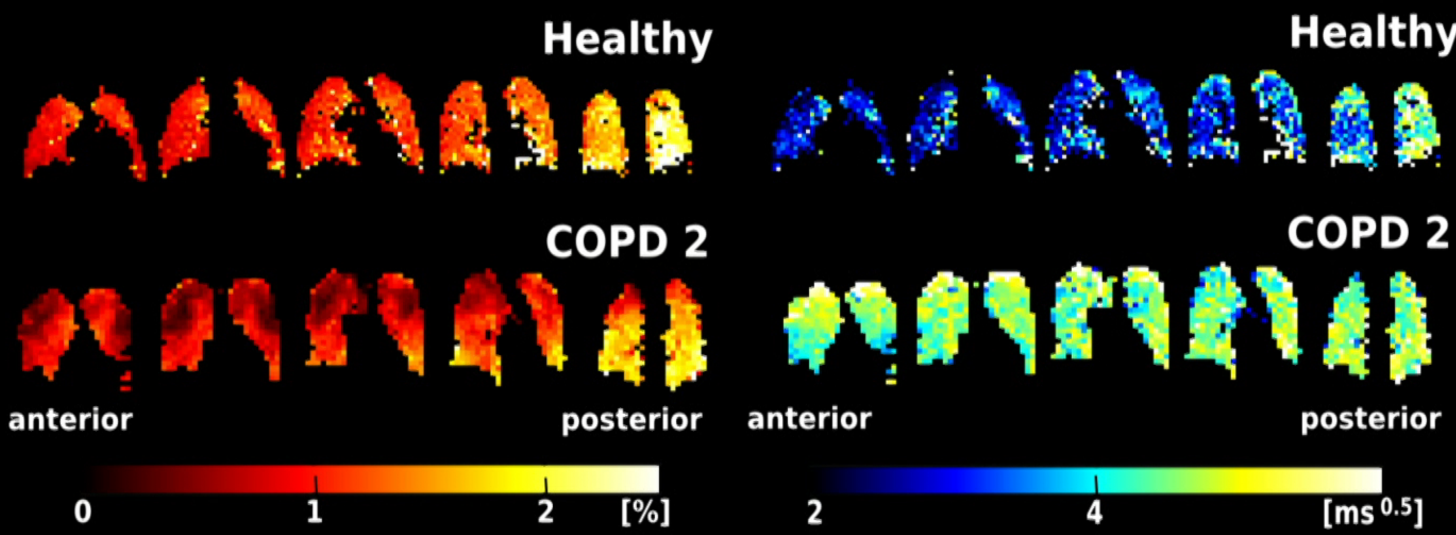


Gravity induced tissue compression at low lung volumes

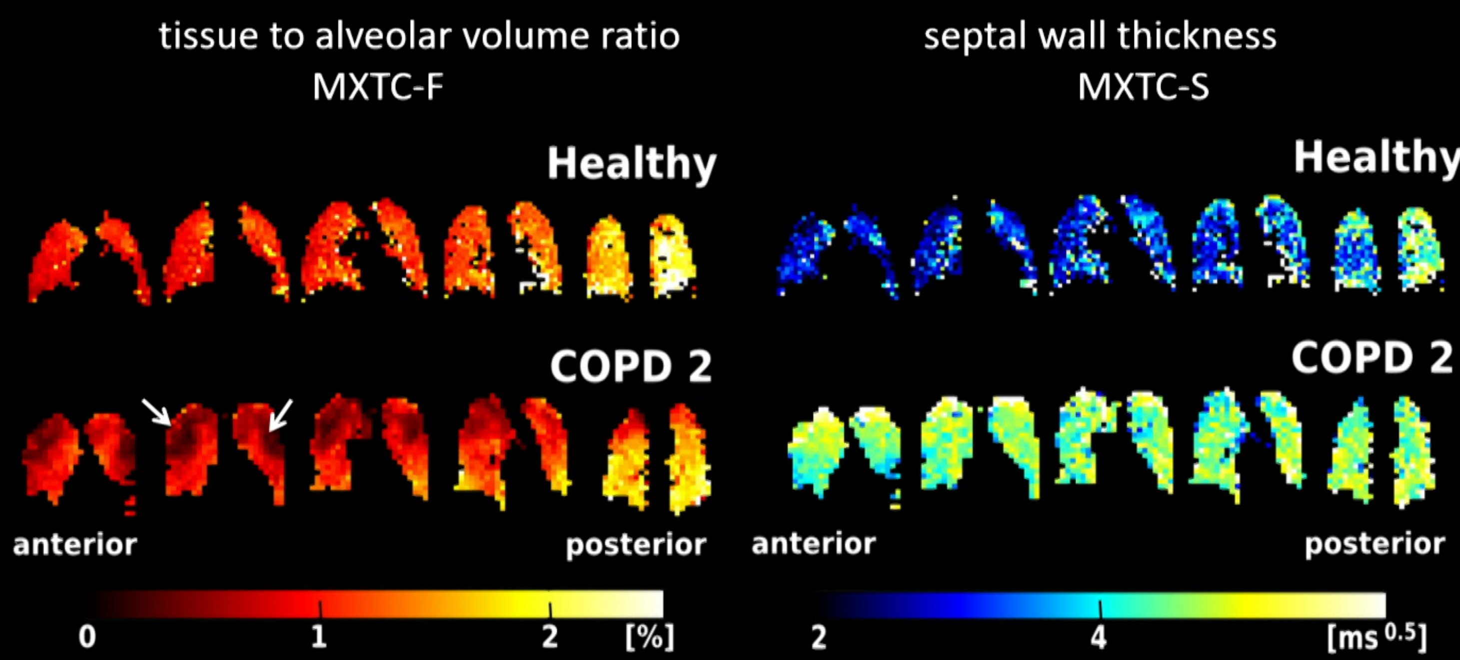
MXTC – COPD

tissue to alveolar volume ratio
MXTC-F

septal wall thickness
MXTC-S



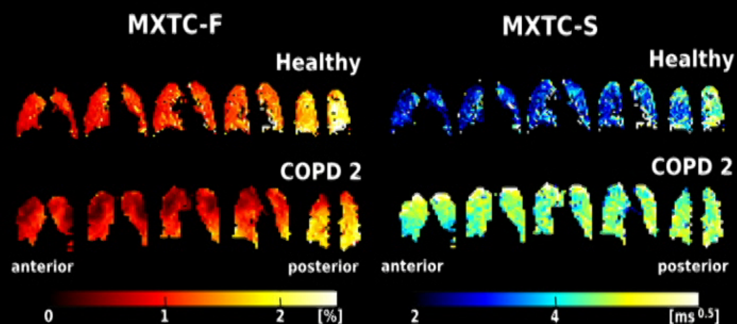
MXTC – COPD

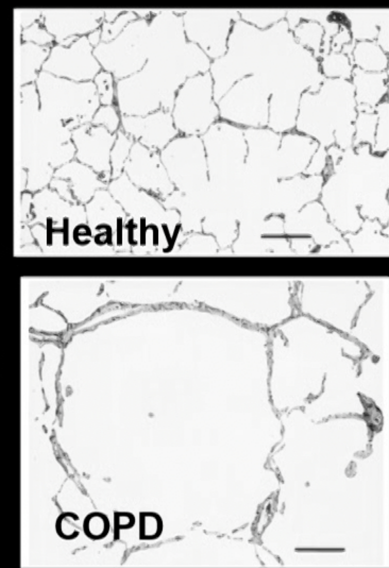


COPD:

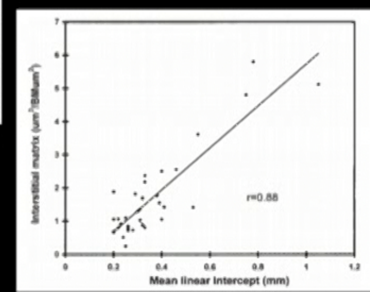
- Regions of decreased tissue density

MXTC – COPD





tissue thickness
vs. alveolar size



Vlahovic et al (1999)
ACCM ,160:2086-2092

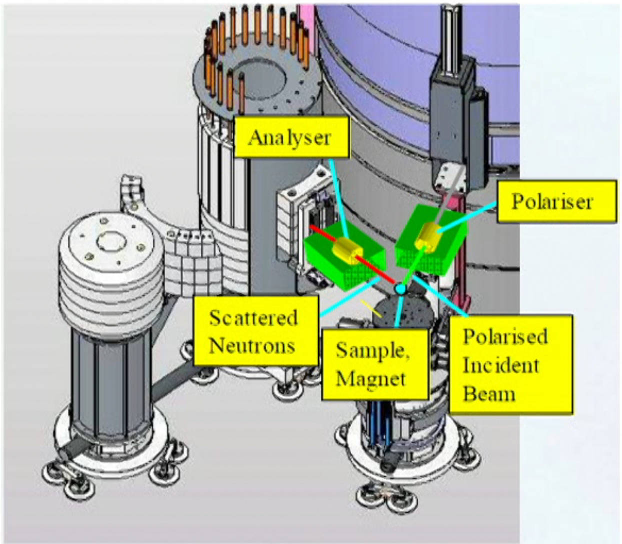
COPD:

- Regions of decreased tissue density
- Elevated septal wall thickness

Polarized Helium-3 as a neutron analyzer

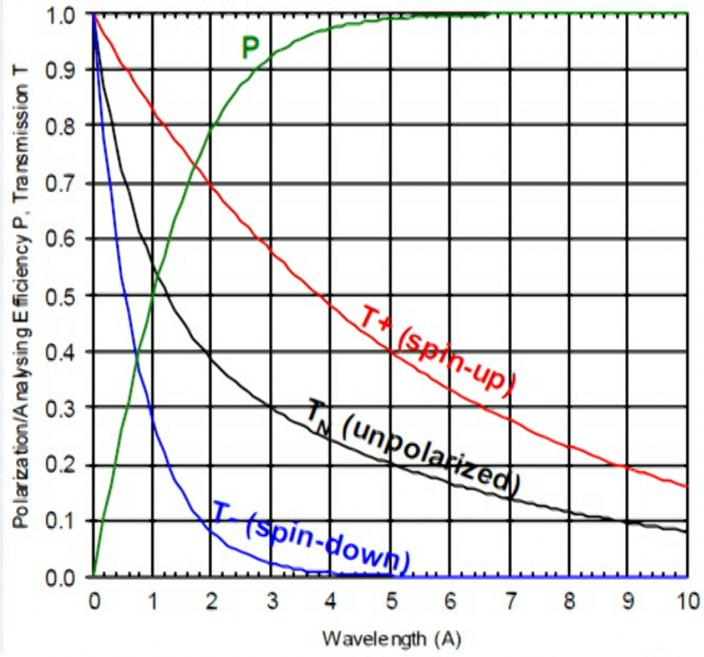
Xēmed

- If placed in a neutron beam, polarized 3He absorbs neutrons whose spin is anti-aligned
- Attenuation depends on neutron velocity, integrated 3He density, 3He polarization



(Courtesy Sergey Danilkin, ANSTO)

^{3}He polarization = 75%
Cell pressure x length =10 bar- cm
Silicon window thickness = 4 mm/window



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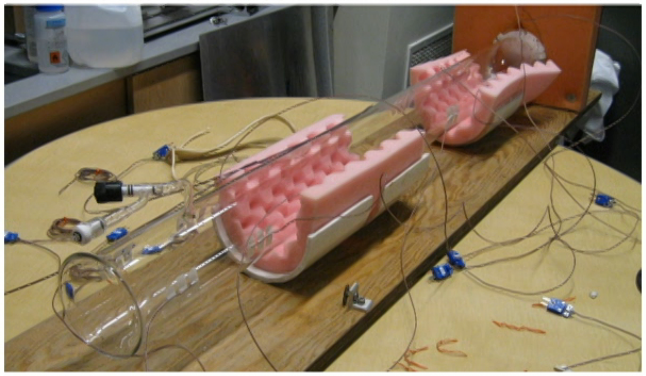
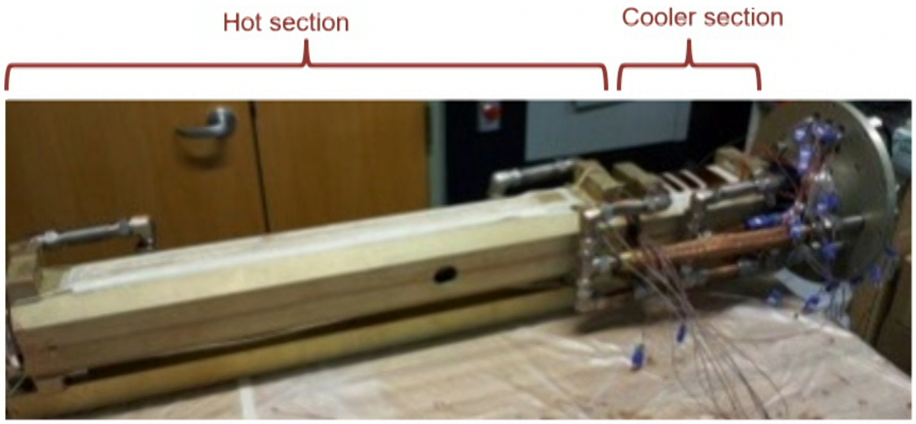
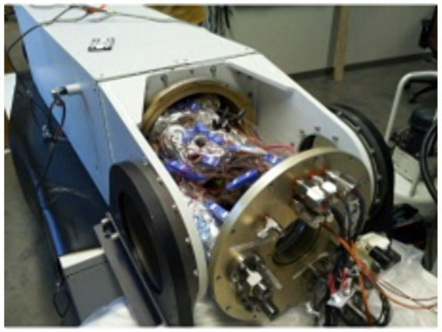
Glass cell encased in pressure vessel



- Up to 8.5 liter glass cell
- Two thermal zones
- Hot section below
- Cool section above
- Laser enters from above
- Alkali density depleted in upper region

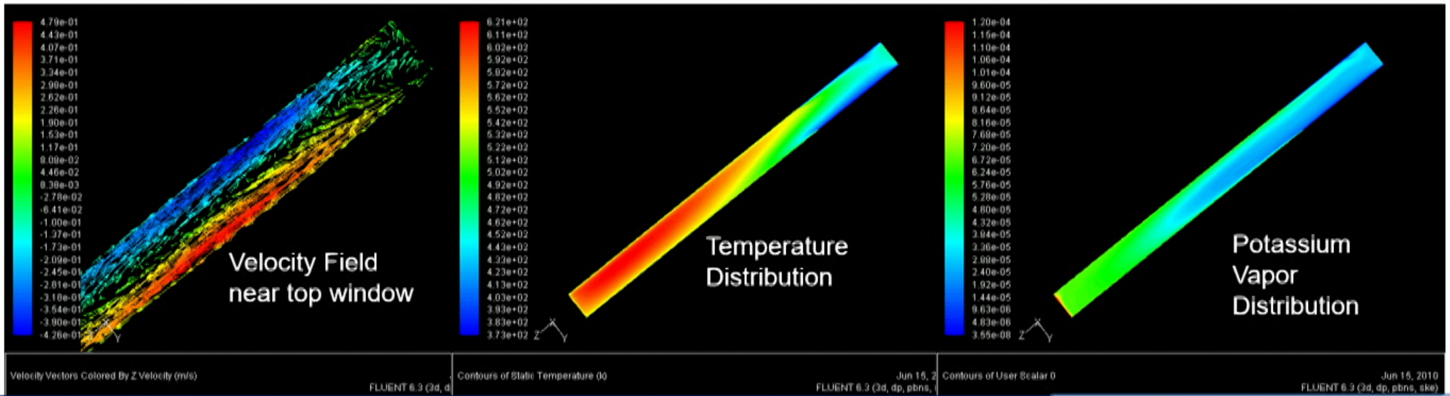
Mike Souza, Princeton Glass





Gas circulation

- In vertical orientation, buoyancy causes alkali to accumulate at the top of the cell, leading to an unstable thermal runaway.
- Tilting the cell creates *steady* asymmetric temperature, velocity, and alkali distributions.
- Shear layer promotes heat and mass transfer between upward and downward streams.
- Circulating flow creates an alkali-depleted region near the top window.
- FLUENT simulation of cell tilted at 45° (1200 W, 5.8 amagat) velocity ~.45 m/s



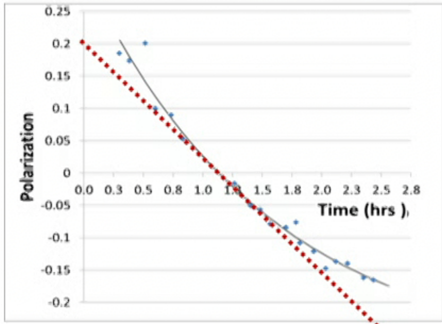
Zeppelin-3 Assembly

Xēmed

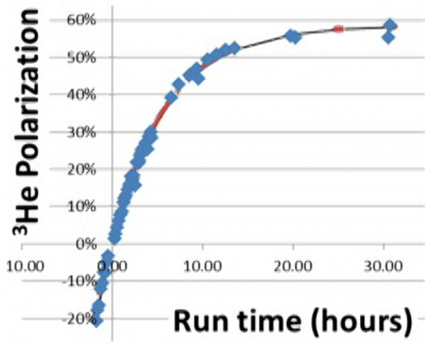
- Zeppelin-3 3He polarizer in final stages of assembly (2014)

Zeppelin-3 Testing

- Polarizes up to 50 L of 3He in 8.5 L cell at 6 amagat



Slope at zero gives spin up rate of 20% per hour



Spinup data Aug. 14-15 2014. System parameters were 1400W of laser power, cell temperature 238°C

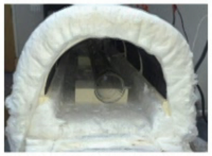
- Internally funded extension of the project yielded one long-term test, with polarization saturating at ~55%

Zeppeliun-4 Cell preparations

- We tested 8.2, 1.5, and 0.35 liter cells at pressures up to 5 atm.
- Surface treatments:
  - Bare glass (aluminosilicate, GE180)
  - Sol-gel (rotated until dry, sintered, obtained clear coating with only a few defects)
  - Chemical tempering (Pyrex filled with KOH (or KCl+KOH), heated to melt salt with occasional rotation)
- Cells are baked under UHV and charged with 1g to 5g of 5:1 mixture of K:Rb for hybrid pumping by low temperature (<300 °C) distillation

Original Cell Design with tubulations for the valve and for the alkali retort

Modified cell design with drain tubes installed.



Rotation device used in coating and drying sol-gel layers in borosilicate cells. (right) Bake out oven used to dry the cells and sinter the coatings.

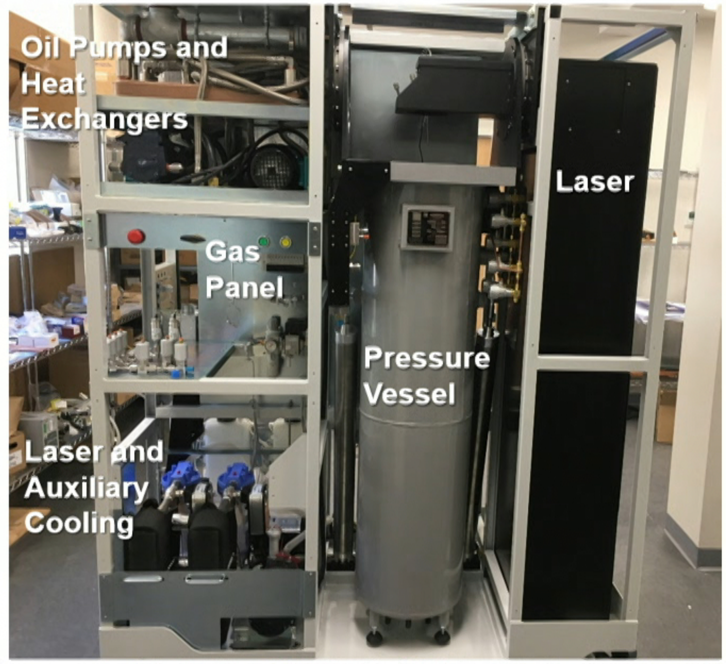
External testing: cell T1

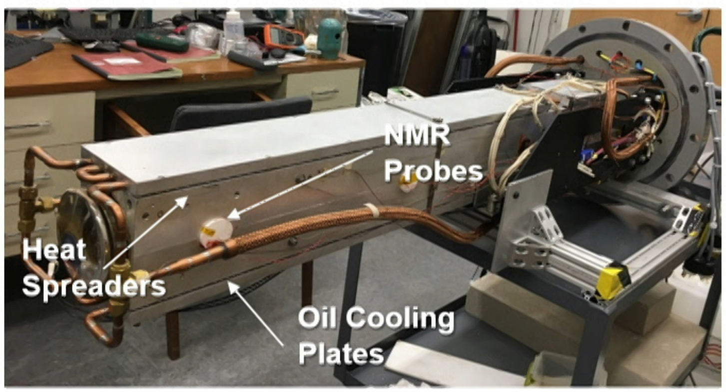
Xēmed

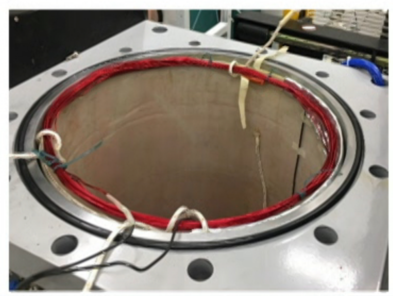
- Cell lifetime tested in uniform magnetic field

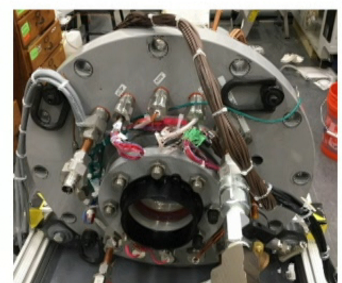
Cell Name	Material/Coating	Vol. liter	*Ex situ* T1 (hr)
Hilton1 Polarizing Cell	Pyrex with sol-gel coating	8.2	
Heil He-3 Transport Cell	Supremax	1	64-100
Souza1 He-3 Transport Cell	GE 180	0.35	
Souza Polarizing Cell I (SPC1, with retort)	GE 180 with Pyrex Retort prior to alkali charging	1.5	6.9 Hrs
SPCI (no retort, with Rb, no bakout)	**GE 180, charged with Rb:K, no bakeout**	**1.5**	**45-73**
Souza Polarizing Cell II (SPCII, with retort)	GE 180 with Pyrex Retort	0.35	7.2
SPCI II (no retort, with Rb)	GE 180, UHV bake out with harged with Rb:K,	0.35	10
Anderson1 (A1, with K/Rb mixture)	**Pyrex with sol-gel coating, UHV bake-out 5 g 5:1**	**8.2**	**21-29**
Anderson2 (A2, no Rb, no bakeout)	Pyrex with sol-gel coating m noit	8.2	5.8
Anderson2 (A2, no Rb, UHV bakeout)	Pyrex with sol-gel coating, baked-out	8.2	4.3
Anderson2 (A2, no Rb, UHV bakeout)	Pyrex with sol-gel coating, baked-out	8.2	

Assembly: Zeppelin-4





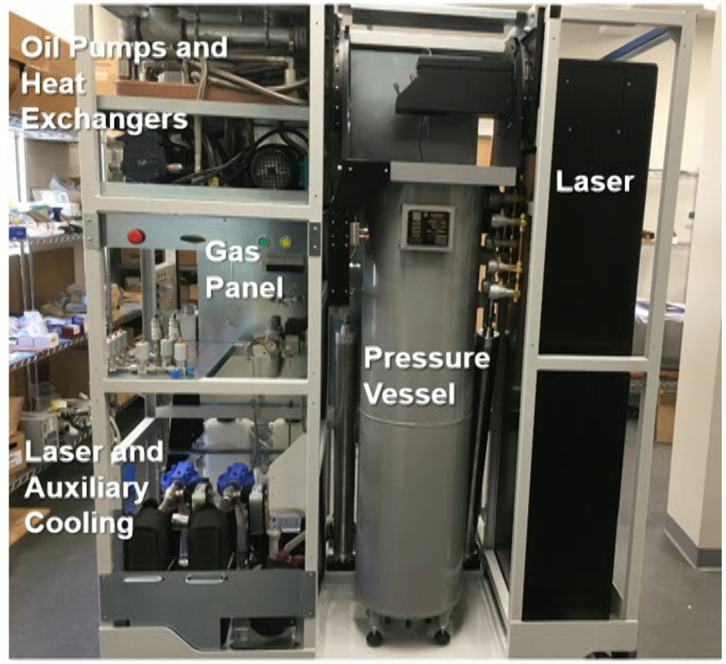


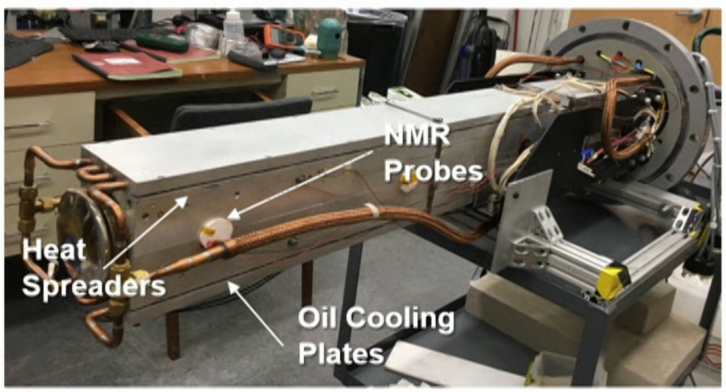


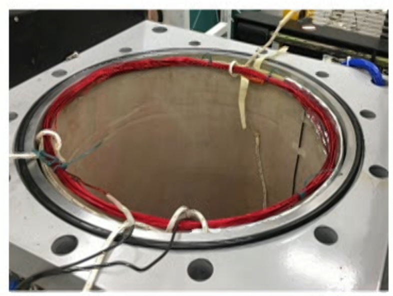
Assembly: Zeppelin-4

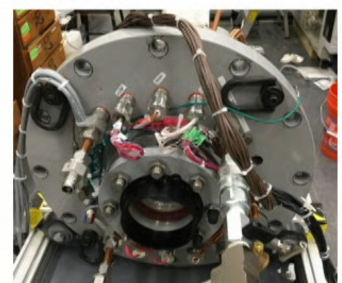
Xēmed

- ASME certified pressure vessel 250psig
- Steel vessel serves as magnetic return yoke
- Rather than stabilizing cell temperature with a flowing bath of hot silicon oil, the Z4 cell is heated by electric heaters and cooled by flowing silicon oil
- Energized by a narrowband 3kW laser (described next)





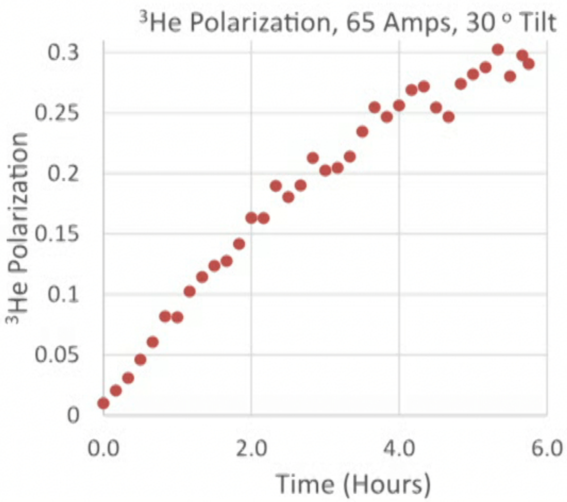




Performance: Zeppelin-4

Xēmed

- First tests of Zeppelin-4 revealed thermal instability: adding more cooling for 3kW laser
- Cell T1 degrades during operation in polarizer... (Why?? Gas purity? Alkali loading?)
- Laser temporarily transferred to xenon polarizer for similar demonstrations
- Z4 now reassembled for next helium-3 tests in Sept, 2017



Cell Name	Material/Coating	Vol. liter	*Ex situ* T1 (hr)	*In situ* T1 (hr)
Hilton1 Polarizing Cell	Pyrex with sol-gel coating	8.2		3.3-4.2
Heil He-3 Transport Cell	Supremax	1	64-100	--
Souza1 He-3 Transport Cell	GE 180	0.35		--
Souza Polarizing Cell I (SPC1, with retort)	GE 180 with Pyrex Retort prior to alkali charging	1.5	6.9 Hrs	
SPCI (no retort, with Rb, no bakout)	**GE 180, charged with Rb:K, no bakeout**	**1.5**	**45-73**	**10.6**
Souza Polarizing Cell II (SPCII, with retort)	GE 180 with Pyrex Retort	0.35	7.2	
SPCI II (no retort, with Rb)	GE 180, UHV bake out with harged with Rb:K,	0.35	10	
Anderson1 (A1, with K/Rb mixture)	**Pyrex with sol-gel coating, UHV bake-out 5 g 5:1**	**8.2**	**21-29**	**7.5-8.5**
Anderson2 (A2, no Rb, no bakeout)	Pyrex with sol-gel coating m noit	8.2	5.8	
Anderson2 (A2, no Rb, UHV bakeout)	Pyrex with sol-gel coating, baked-out	8.2	4.3	
Anderson2 (A2, no Rb, UHV bakeout)	Pyrex with sol-gel coating, baked-out	8.2		4.8-8

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Further laser scaleup

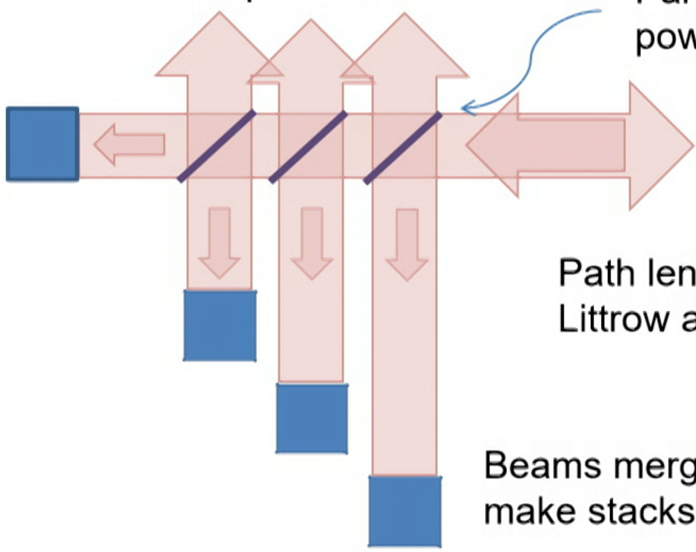
Xēmed

- How many "seed photons" can be prepared using a single external cavity?
  - Currently the grating is low-efficiency to allow the output beam to emerge as zero-order diffraction
  - A high-efficiency grating would retain more light in the cavity, while reducing the power to the output beam

- Can this wavelength selected light be distributed to more stacks?
- How many diode laser bar stacks can be locked with a single cavity?
- **Several? hundred? more?**

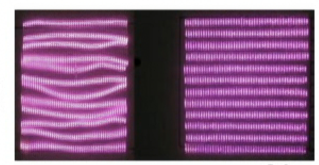
Power splitting – idler beam

- A transverse beam composed equally of light from all stacks is wavelength-locked in an external cavity and returned.
- Power splitters siphon an equal fraction of this returned power to each stack
- Positions of stacks are staggered so that optical path lengths are equalized



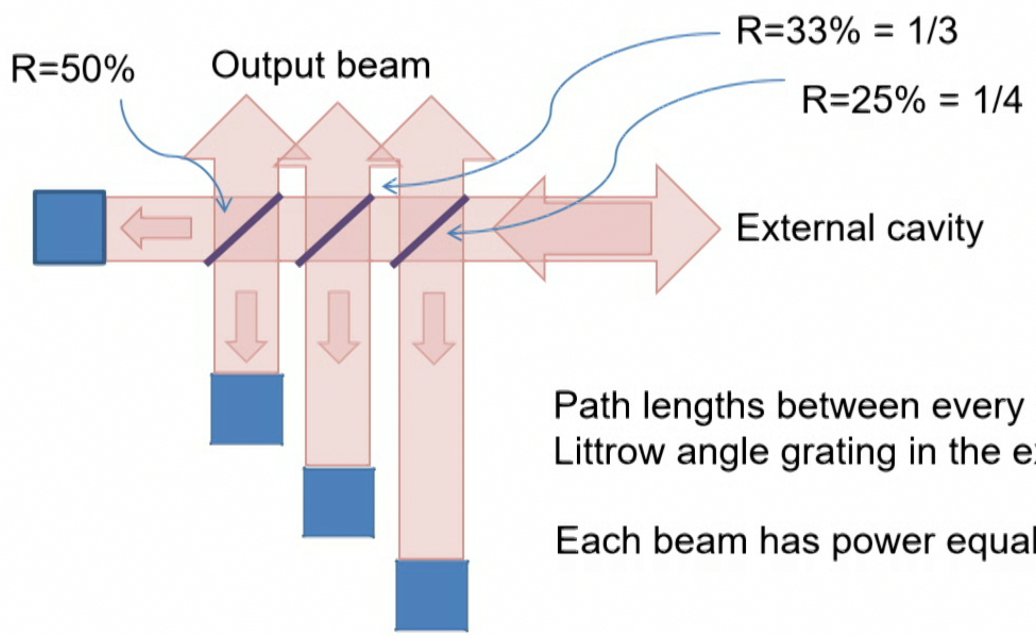
Path lengths between every bar's FAC and the Littrow angle grating in the external cavity are equal

Beams merge since correction plates make stacks optically identical



Power splitting – fraction 1/n

- Primary beams impinging on splitters go partially to output, partially toward external cavity
- Output beams have equal power, originating from various sources

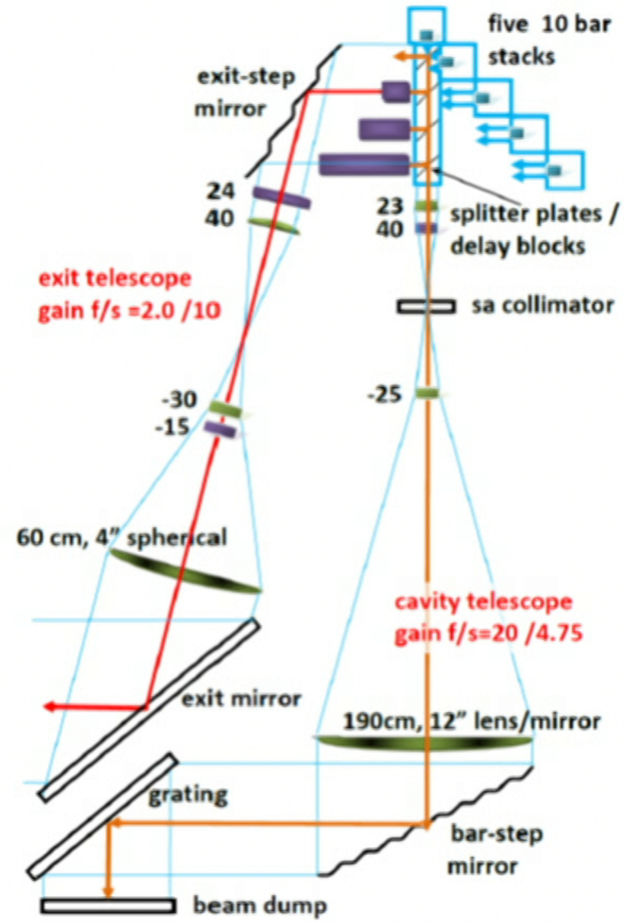


Path lengths between every bar's FAC and the Littrow angle grating in the external cavity are equal

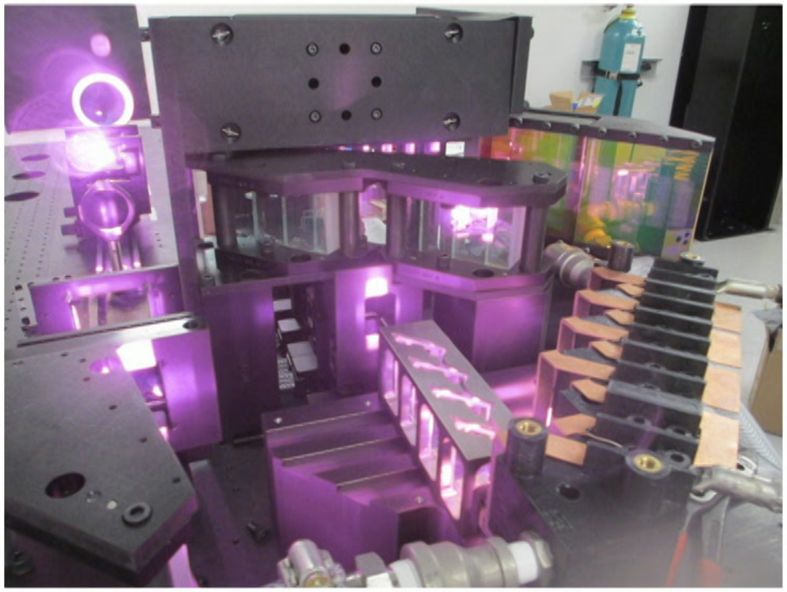
Each beam has power equal to that of a stack

3 kW prototype – design

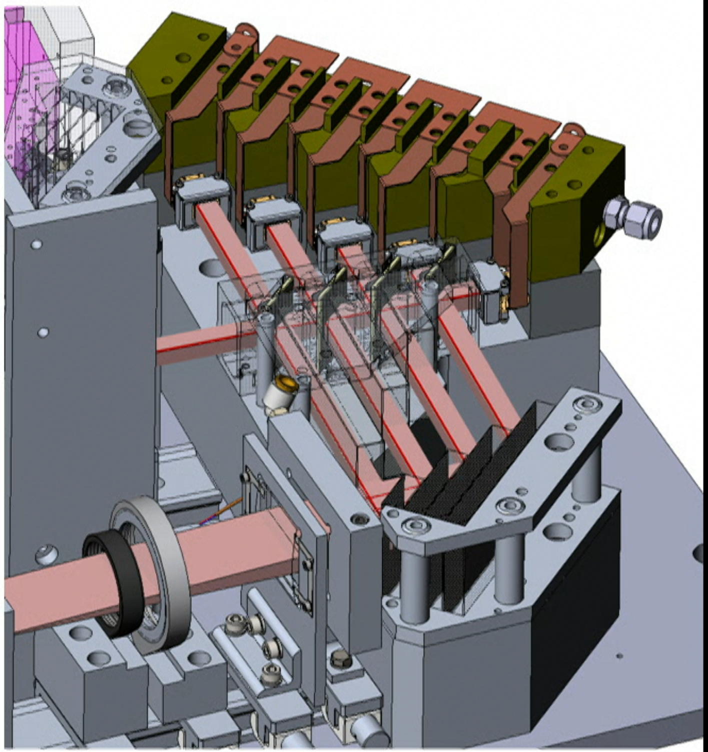
- Detailed design incorporates 5 stacks, ten bars
- Fast-axis magnification M=20 should provide resolution better than 50 pm
- Distributes 10 bar idler beam over two gratings, 5 bars each
- Slow-axis magnification M=4.75 distributes beam over grating



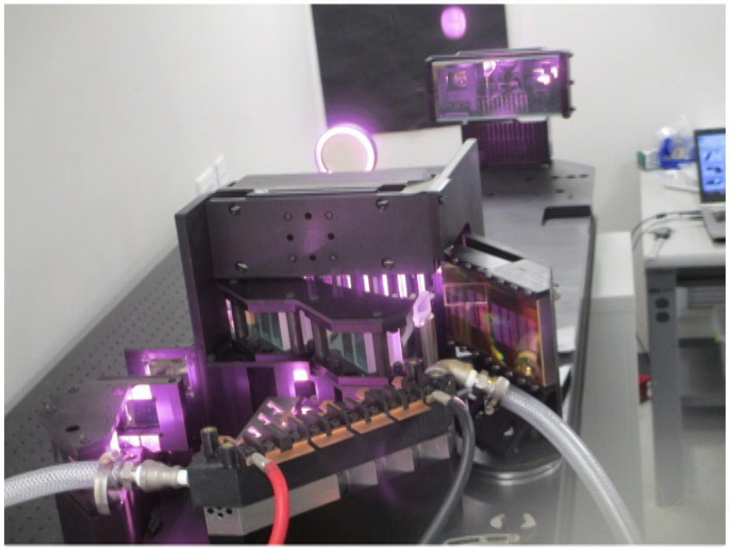
3 kW prototype – assembly

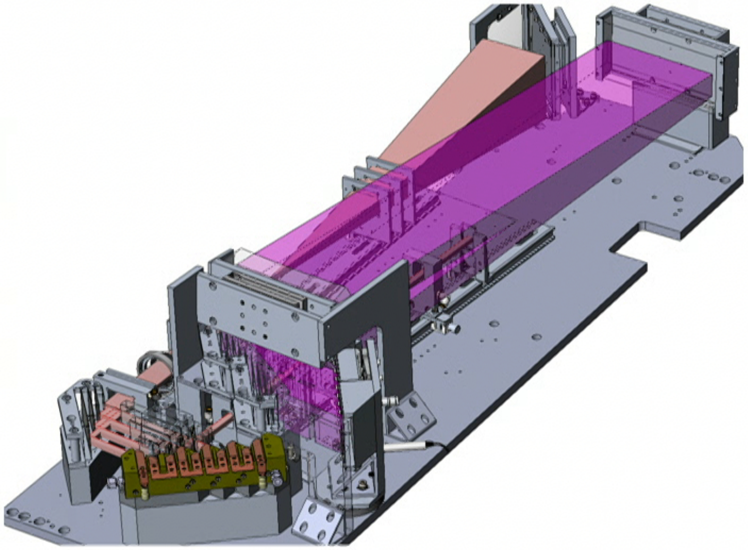


- Laser mount positions laser stacks mechanically, and provides water cooling, and electrical power
- Beam splitters merge power from five stacks into idler beam



3 kW prototype – cavity

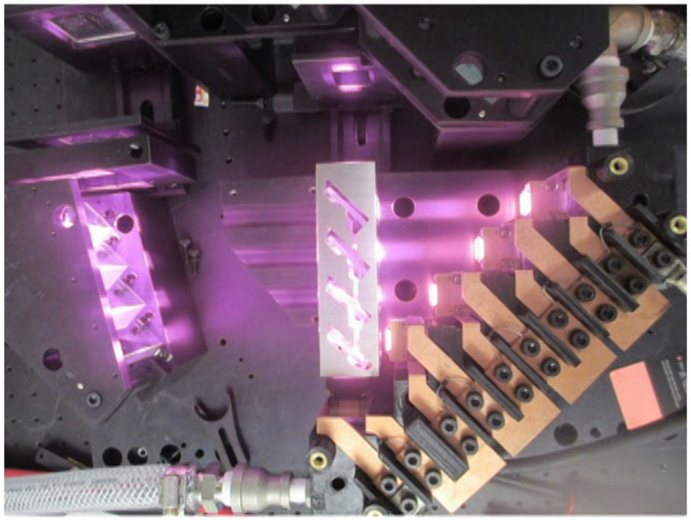


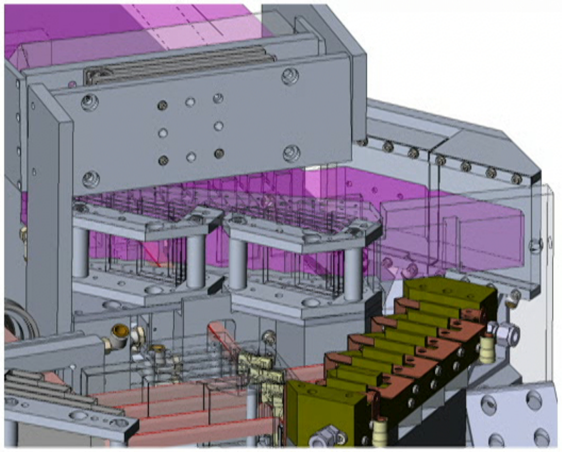


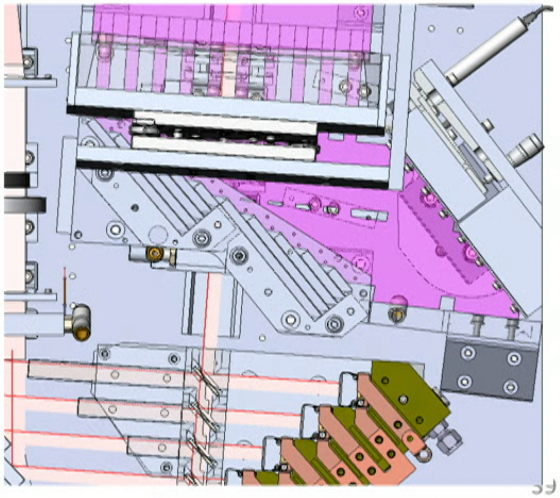
- External cavity beam traverses length of laser eight times, two for expanding, two as a parallel beam to the grating, then four returning back to laser stacks.
- Step mirror deflects cavity beam onto grating(s)

3 kW step mirror – assembly

- Final 10 step mirror deflects the beam from each bar to the grating
- Deflection angles must be identical to precision of 10 microradians
- Assembled of flat mirrored plates polished to quarter wavelength precision

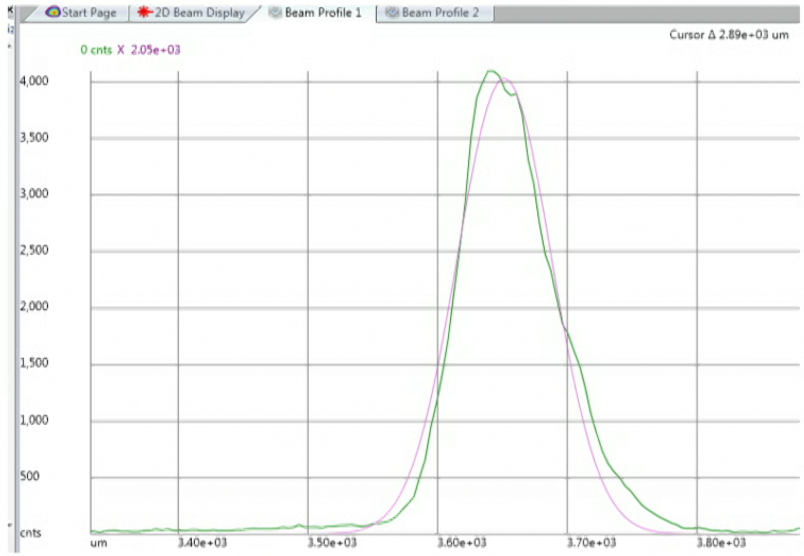




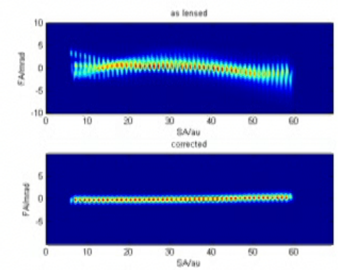


Spectral resolution – 1 bar, 1 stack

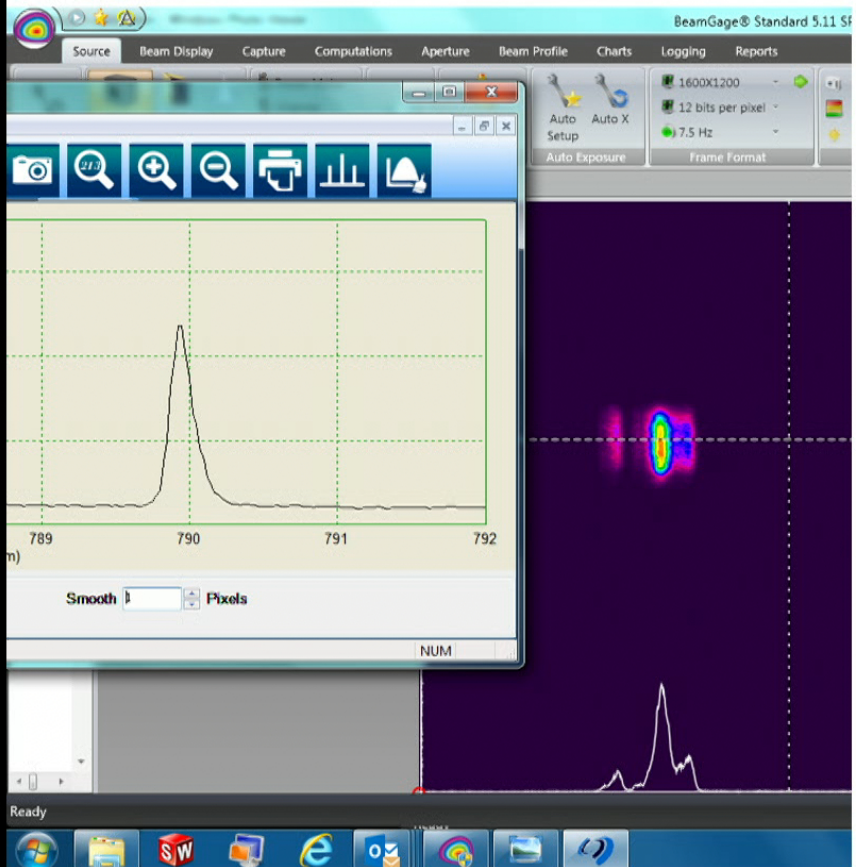
- Single bar, single stack narrowing with magnification M=20 measured with a McPherson one-meter Cherny-Turner monochronometer 2061 and an Ophir SP620U beam profile camera.
- Horizontal scale in microns 100 microns per division: dispersion 0.353pm/micron;



- FWHM = 31pm
- Compare with FWHM ~16pm resolution at magnification M=39
- Limited only by quality of PowerPhotonics correction optics.



Resolution – 10 bars, 5 stack



- Sum of ten peaks, each 42pm wide, with different central wavelengths.
- Partially overlapping peaks, contribute to a broad peak with width approximately 170pm FWHM.
- Final step mirror provides deflection of final beam with, different surface for different bars.
- Placed rotatable prism in the beam path of an individual bar, demonstrated that the wavelength of each peak can be manipulated at will.
- Fixture to provide tunable wavelength for each peak is in future plans.
- Ultimate resolution of complete laser is expected below 50pm.

ALF-based pump laser system

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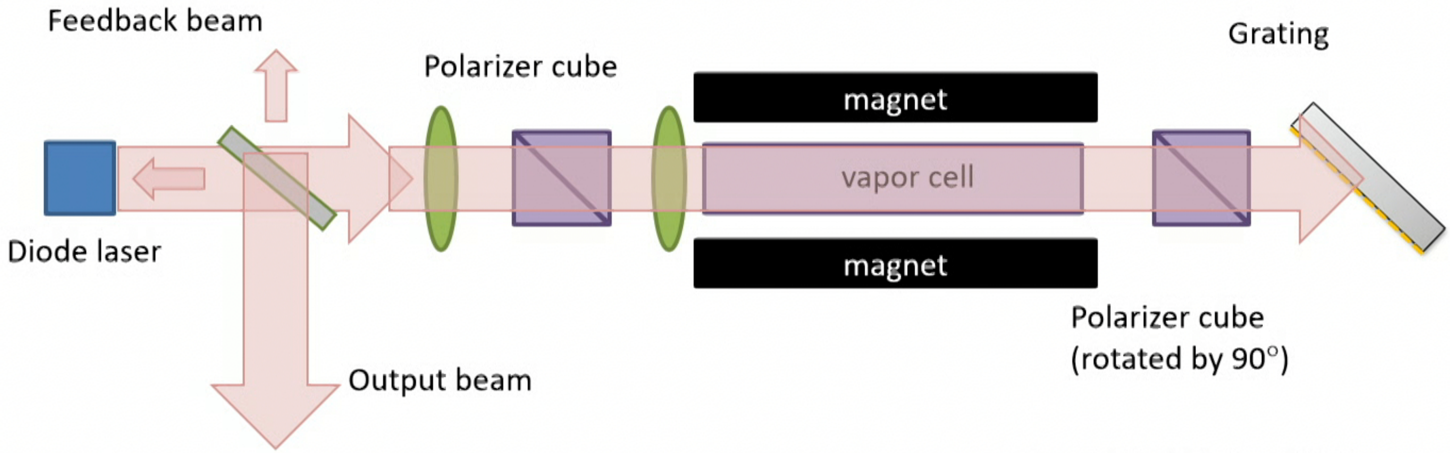
- Beams are passed through a vapor cell in a magnetic field between two crossed polarizers. Rotation of the polarization within the atomic line (either by the Faraday or Voigt effect) allows feedback of photons within a range of ~0.001nm.

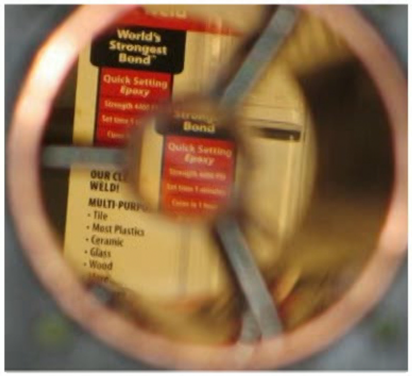


Separately funded by Xemed IR&D

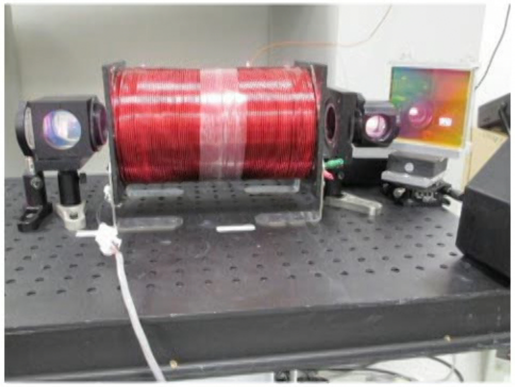
F.W. Hersman, M.S. Hersman, patent pending

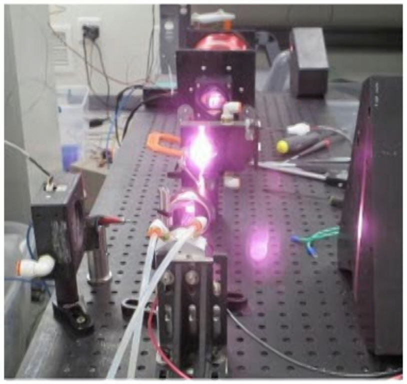
ALF-based pump laser operation

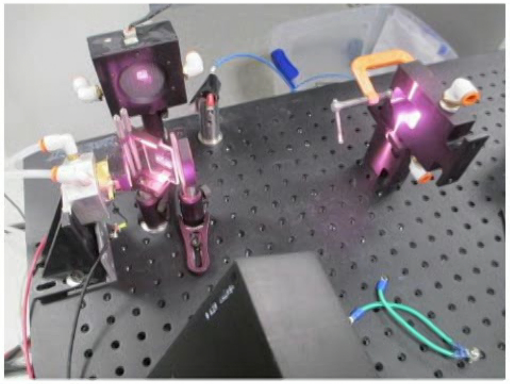
- Prototype assembled January 2017 using a commercial vapor cell (Thorlabs), a custom-wound solenoid, and a regulated thermal environment to establish a known vapor pressure
- A stack of diode array bars delivers multiple beams to an afocal telescope. A beam splitter deflects a portion of the outgoing laser light in a transverse direction for power and spectral measurements, and also a portion of the returning light in the other transverse direction.
- Linewidth measured with one-meter monochromator
- Efficiency measurements performed for a range of ALF cell temperature, magnetic field, power, and slit-width settings.



Rubidium vapor cell (with wedge windows) positioned inside a magnet coil and a thermal bath environment at room temperature.

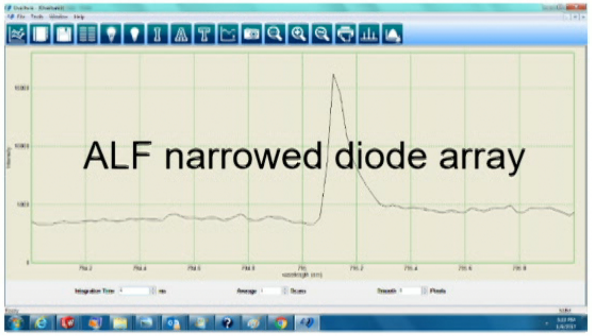


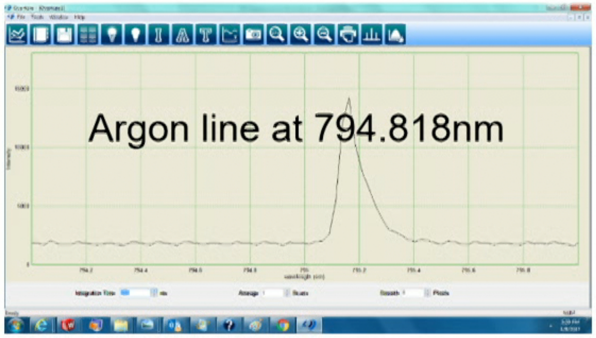




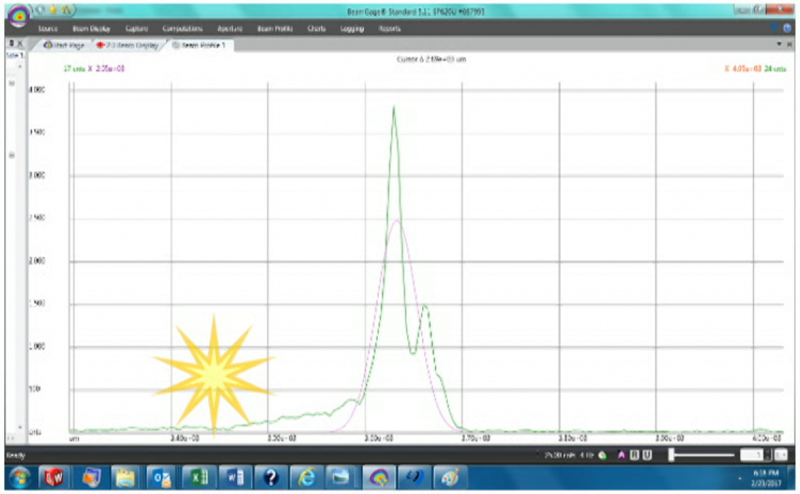
ALF-based pump laser linewidth

- Calibrations confirm correct 795nm wavelength and linewidth below the spectrometer resolution of ~7pm, probably less than 1pm





Ocean-optics spectrometer, resolution ~0.1nm



Output line-shape acquired with one-meter Czerny-Turner monochrometer shows peaks corresponding to Rb-85 and Rb-87. Wavelength increases to the left 100µm = 35pm.

ALF-based laser locking efficiency

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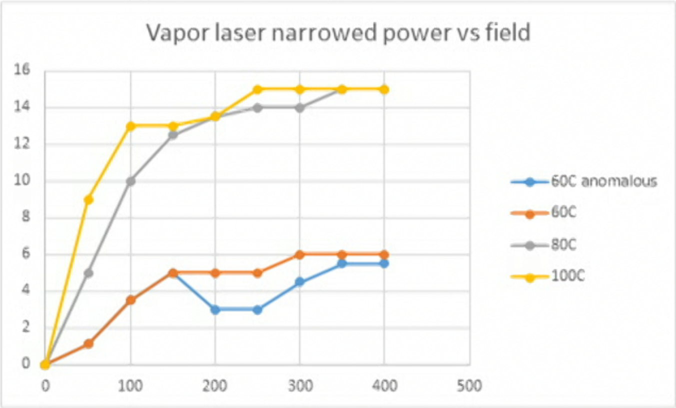
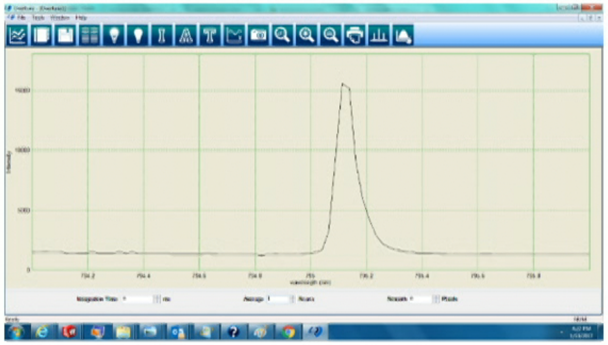
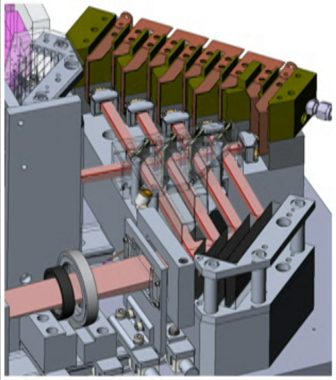
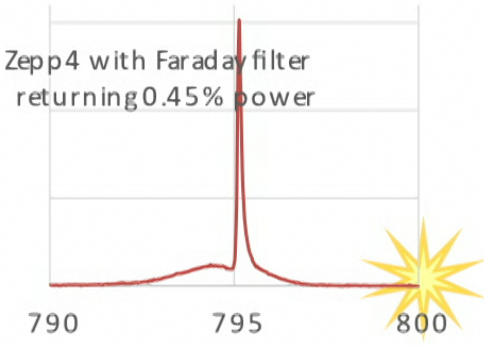
- High-efficiency is achieved for a broad range of settings.





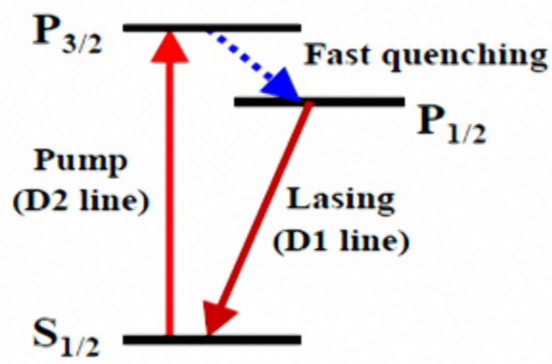


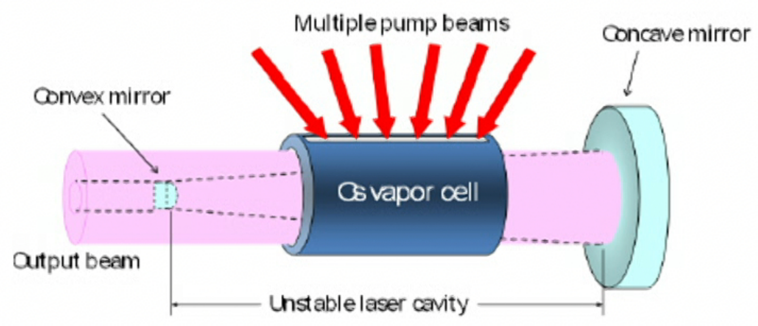
ALF installed into Zepp4 laser's external cavity, replacing x20 telescope



Diode Pumped Alkali Laser

- Optical pumping rubidium vapor from ground state $S_{1/2}$ to $P_{3/2}$, followed by fast quenching to $P_{1/2}$ achieves population inversion.
- Converts incoherent photons from millions of separate lasers into a high-power coherent diffraction-limited beam: weaponizing the light
- May be capable of destroying missiles from rogue nations during boost phase.





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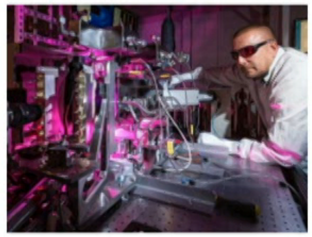
Missile Defense Agency DPALs

- **2017: Lawrence Livermore demonstrated a 30 kW average power DPALS and plans to complete a preliminary design for a 120 kW system.**

The key laser system characteristics of DPAL are:

- High Power and Efficiency
  - MW-Class power potential
  - High electro to optical (EO) efficiency
- Near Diffraction-limited Beam Quality
- Short Wavelength
  - 795nm (vs 1 micron for other lasers)
- Size-Weight and Power performance (low SWaP)



DPAL strengths in both power and efficiency are derived from both the LLNL-designed gain cell and by the unique, world-class diodes produced for DPAL by Lasertel of Tucson Arizona. LLNL works closely with Lasertel to produce DPAL-specific pump diodes, and the partnership helped DPAL achieve MDA's 30kW milestone in September of 2016. The DPAL team is currently focused on beam quality.

PJ Wissoff LLNL, April 2017

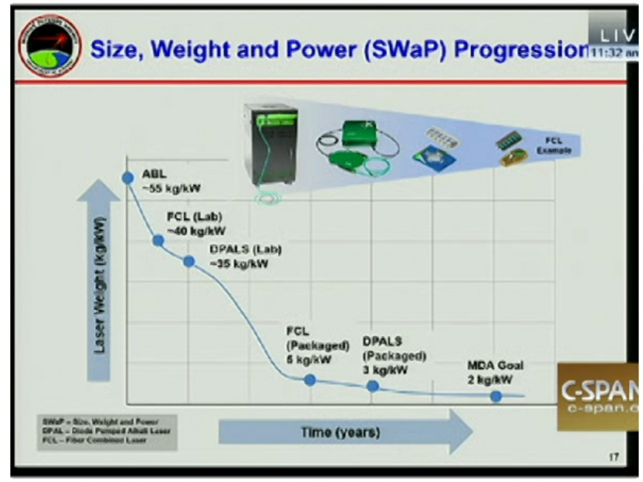
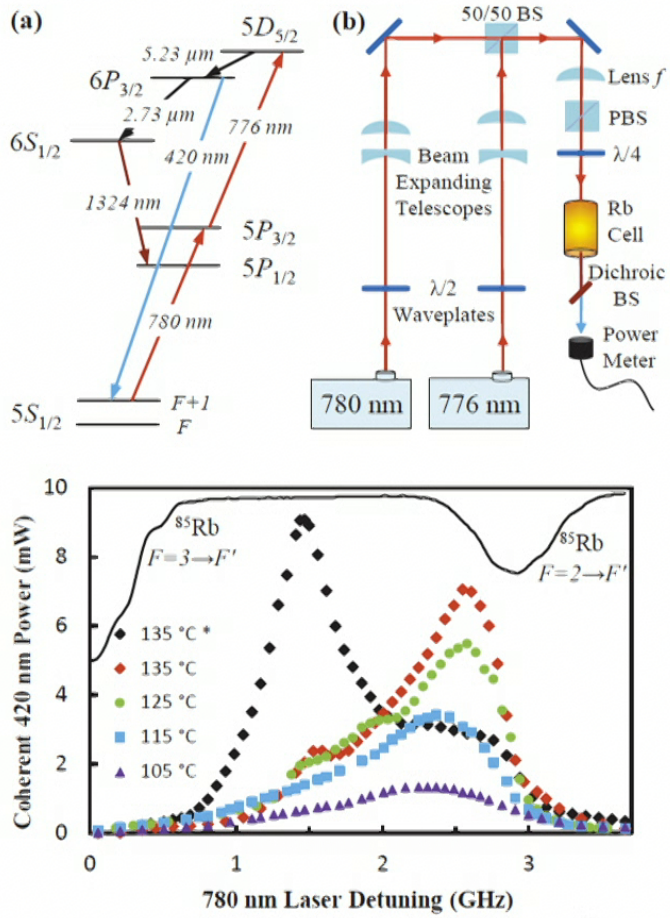


Figure 2. MDA's laser Size, Weight and Power plans. Source: Vice Admiral James Syring, "Ballistic Missile Defense System Update," Presentation at the Center for Strategic and International Studies, January 20, 2016. Video online at https://www.c-span.org/video/?403405-1/discussion-ballistic-missile-defense.

- **2019: In FY 2019, MDA plans to demonstrate a 120 kW DPALS.**
- **2022: By 2022 MDA plans to produce a prototype 300 kW class laser using the technology selected in FY 2019.**

Four-wave mixing

- Several authors demonstrated frequency upconversion by two-photon excitation of rubidium via four-wave mixing
- Sell *et al* achieved 9.1mW of 420nm using 390mW at 780nm and 205mW at 776nm.
- We seek to demonstrate similar efficiencies in the kilowatt regime (suggestions welcome!)



Summary and outlook

Xēmed

- Xenon polarizer apparatus has reached commercial status.
- Imaging technology improvements and clinical trials seek ways to address medical needs.
- 3He polarizer poised to offer ~50L quantities with high spinup rates.
- Puzzled by changing lifetimes in operating glass optical pumping cells, limiting 3He polarization to ~60%

XeBox model "Bernoulli" production line

- Technology for higher power lasers with even narrower linewidths have been demonstrated
- Applications in Diode Pumped Alkali Lasers and Four Wave Mixing Frequency Upconversion may be forthcoming

Acknowledgements

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