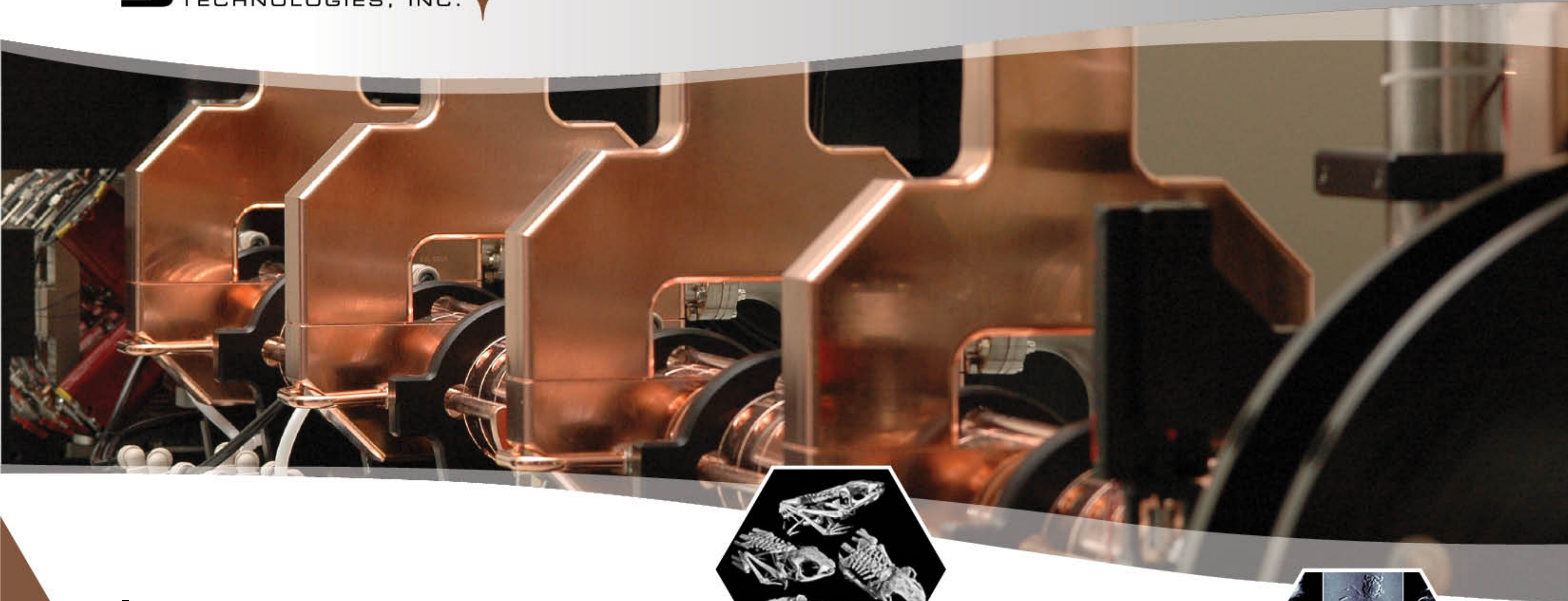
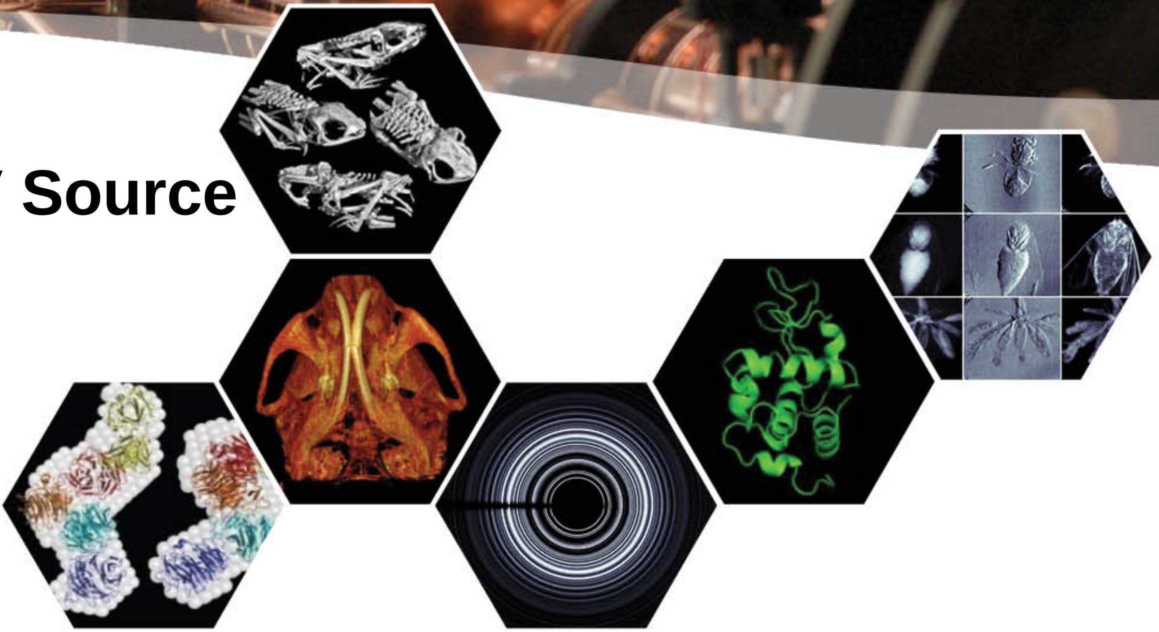
illuminating x-ray science™



The Compact EUV Source

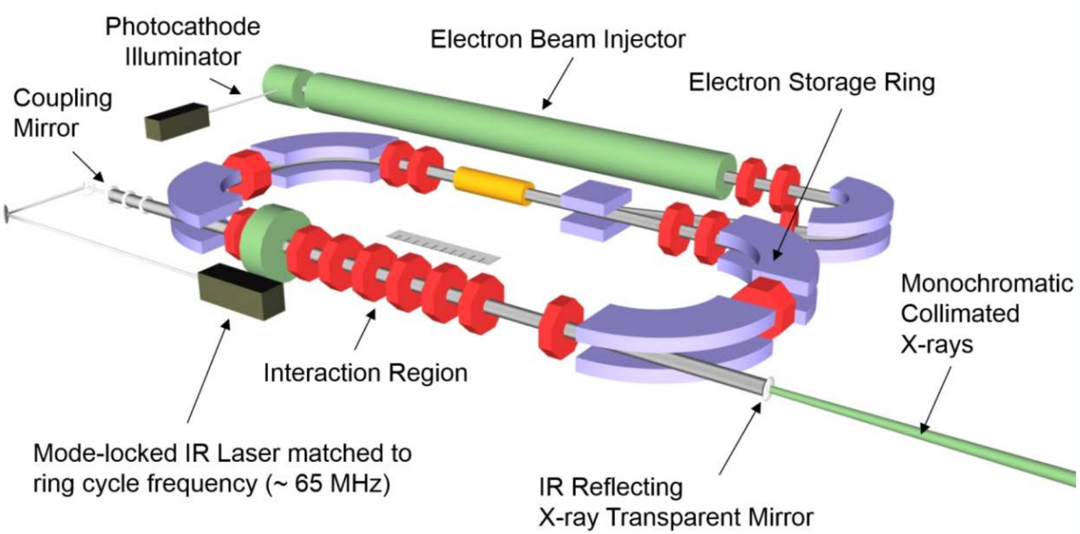


Our Company

Lyncean Technologies, Inc.

- **Origin:** spinoff of SLAC National Accelerator Laboratory, Stanford University
- **Founded:** in 2002 by Prof. Ron Ruth (Stanford), Dr. Roderick Loewen, and Jeff Rifkin.
- **Current Product:** the Lyncean Compact Light Source (CLS) and measurement solutions
- **Unique Core Competency:** High performance accelerator based light source technology
- **Funding:** ~$34M to date ($4.7M equity, $29M in government grants received)
- **Commercialization Status:** First product sold (2012) and in operation (2015), building sales pipeline in R&D market and developing the business in industrial / medical markets (start 2016)
- **IP Position:** 8 Issued US patents (1 with selected intl. coverage; 2 patents pending (semiconductor X-ray CD Metrology + EUV Compact Source)
- **Location:** Fremont, CA, USA
- **Current Markets:** R&D serving University and Government Labs

Lyncean Compact X-ray Light Source
Commercial Electron Storage Ring

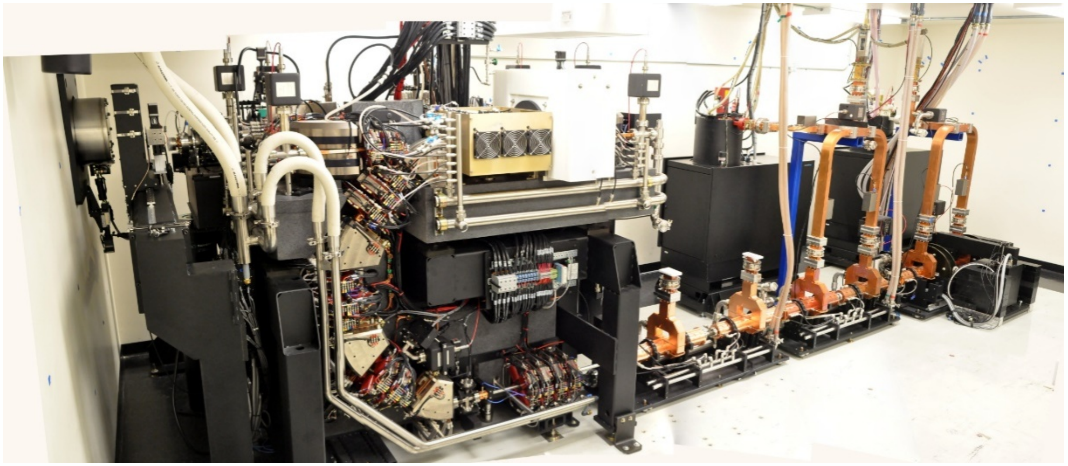


X-rays created via Inverse Compton Scattering through the synchronous interaction between low energy (25 to 45 MeV) electron beam and high power picosecond IR laser pulse

Interaction occurs 65 million times/second, creating a high flux, high brilliance light source

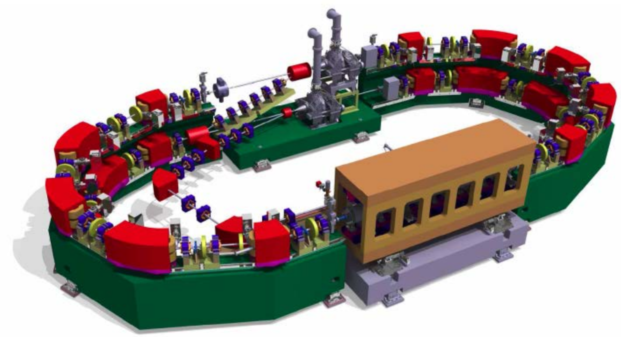
X-rays are monochromatic and tunable from 8 to 35 keV

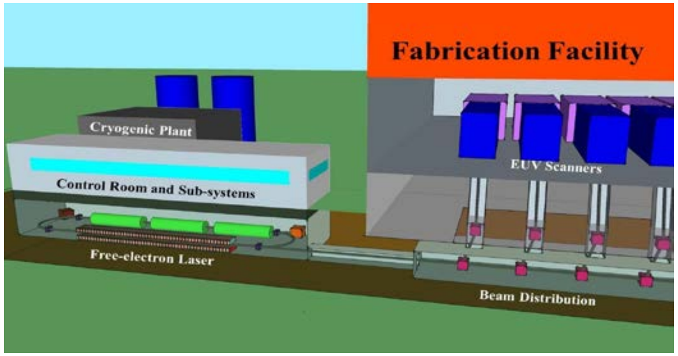
- First installation at Technical University Munich, Germany for imaging applications
  - In operation since Apr 2015
- Running continuously for 2 years with high availability



www.lynceantech.com

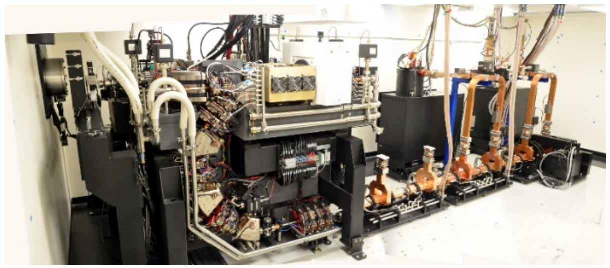
Accelerator Based EUV Sources

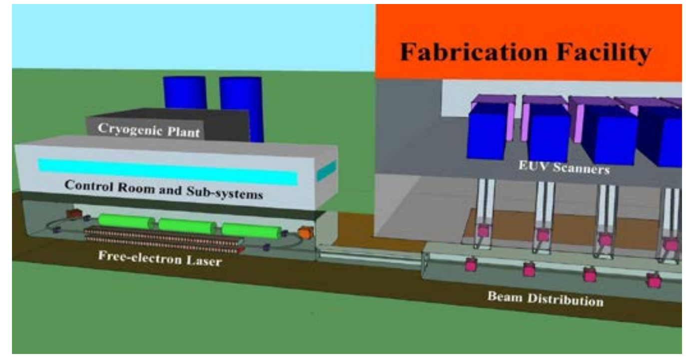




Type	Miniature Conventional Synchrotron	EUV Free Electron Laser (Linear Accelerator)
Tech Risk	Low – Standard Technology	Low/Med Similar Systems Exist
Size	Small 5m x 12m	Very Large (>100m long)
Price	~30M$	$300M - $500M
EUV Power	10 W	10-20 kW
Applicability	Metrology – Low Power Can serve multiple tools	Litho – serving multiple scanners (~10)
Practicability	"Like Lyncean CLS" - simple	"Like a FEL facility" - complex Practical Issues (e.g. Radiation)

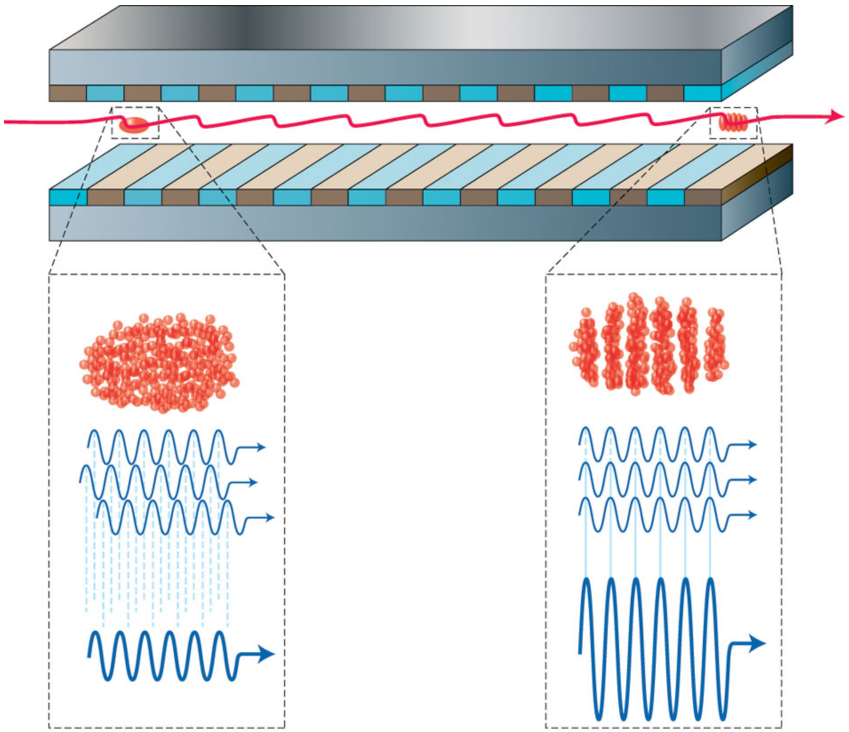
Accelerator Based EUV Sources





Type	Lyncean Compact EUV Source	EUV Free Electron Laser (Linear Accelerator)
Tech Risk	Low – Standard Technology	Low/Med Similar Systems Exist
Size	Small 5m x 12m	Very Large (>100m long)
Price	~30M$	$300M - $500M
EUV Power	**1 kW**	10-20 kW
Applicability	**Litho – serving 1 scanner**	Litho – serving multiple scanners (~10)
Practicability	"Like Lyncean CLS" - simple	"Like a FEL facility" - complex Practical Issues (e.g. Radiation)

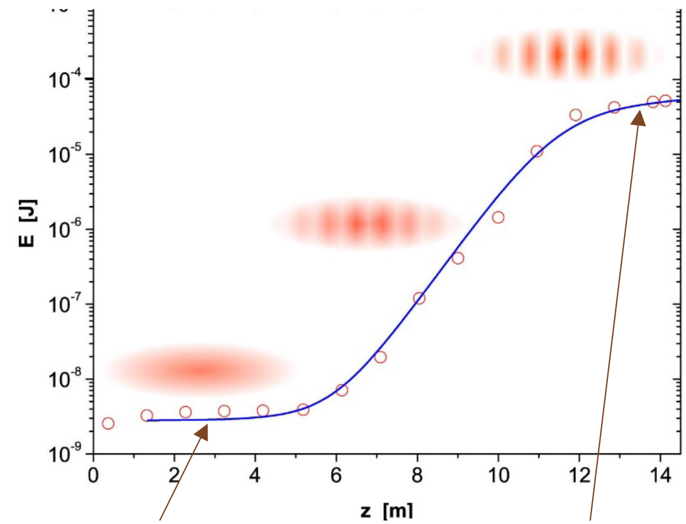
High Power with Coherent Emission



Incoherent emission:
electrons randomly phased

Coherent emission:
electrons bunched at
radiation wavelength

Power versus Undulator Length



Incoherent Emission
Synchrotron Regime
→ Low Power

Coherent Emission
Free Electron Laser
→ Very High Power

Coherent emission **extracts orders of magnitude more energy** from the beam than incoherent emission, but **requires low emittance, low energy spread electron bunches** for coherence

Coherent Emission in a Compact Storage Ring?

Current generation multi-bend achromat (MBA) storage rings achieve low emittance, low energy spread equilibrium electron beams compatible with coherent emission

- Recirculated electron beam: no wasted energy, no beam dump and issues with generating radioactive material
- Looks like a great idea,

BUT

Conventional wisdom: **“Coherent emission destroys the electron beam quality and the ring will not lase”**

Is that strictly true? Are there ways around it?

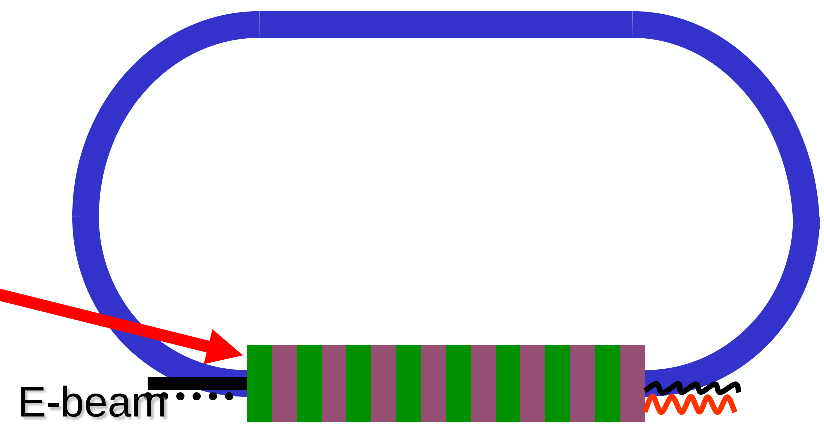
Coherent Emission in a Compact Storage Ring?

First consider beam characteristics of a 5-bend achromat lattice ***without*** coherent emission from undulator

Parameter	Symbol	Value
Electron Energy [MeV]	Ee	497
Charge per Bunch [nC]	Ne	3.00
Revolution Frequency [MHz]	$frev$	9.99
Average Bunch Current [A]	$Bunch\ Iavg$	0.030
Normalized Emittance x [mm-mrad]	$\varepsilon n\ x$	5
Normalized Emittance y [mm-mrad]	$\varepsilon n\ y$	0.0167
Energy damping time Ring [ms]	$\tau\delta$	7.65
Beam Current [A]	$Iavg$	1.98
Total Transverse Damping Time [ms]	$\tau x,y$	15.30
RMS equilibrium Energy Spread	$\sigma E\ /Ee$	0.047%
RMS Bunch Length [mm]	σs	3.02
Bunch Peak Current [A]	$I\ peak$	120.00
Lambda undulator [cm]	lu	1.7
Pierce Parameter 1D	ρ	0.00094
Betafunction inside undulator [m]	β	3.7
1-D Gain Length [m]	Lg	0.83

Similar ring designed at SLAC for FACET II

→ "Real" design



Coherent Emission in a Compact Storage Ring?

<u>Energy spread:</u> must be small compared to Pierce parameter for compact gain length

Parameter	Symbol	Value
Electron Energy [MeV]	*Ee*	497
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1-D Model:

$$L_G \approx L_{G0}\left[1+\left(\frac{\sigma_\delta}{\rho}\right)^2\right],$$

$$L_{G0} = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$$

Our case:

L_{G0}= 0.83 m

L_G= 1.04 m

Coherent Emission in a Compact Storage Ring?

<u>Electron Emittance:</u> keep small compared to $\lambda/4\pi$ for compact gain length

Parameter	Symbol	Value
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Our case:

$\lambda/4\pi = 1.1$ mm mrad

Slightly higher emittances are allowable (verified by 3-D calcs[1]) and have small effect if β function is chosen correctly

[1]Baxevanis et al, PRSTAB,2013

Coherent Emission in a Compact Storage Ring?

Electron Emittance: keep small compared to $\lambda/4\pi$ for compact gain length

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Our case:

$\lambda/4\pi = 1.1$ mm mrad

Slightly higher emittances are allowable (verified by 3-D calcs[1])

Our case:

L_G increase ~30%

Coherent Emission in a Compact Storage Ring?

→ Production of coherent emission feasible, but what about the negative effects on the beam?

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Increase in energy spread

Increase in emittance

Some flexibility in relaxing L_G left

→ Goal < 2m

Effects of Coherent Emission

- Steady state analysis reported in literature[1]
- Coherent emission interaction modulates electron energy → microbunching + increased energy spread
- Microbunching is washed out in a fraction of one turn by momentum compaction and energy spread
- Effect on emittance is very small, can be ignored

[1]Huang et al., NIMA 593, 120 (2008).

→ **Energy spread is the main effect that needs to be controlled**

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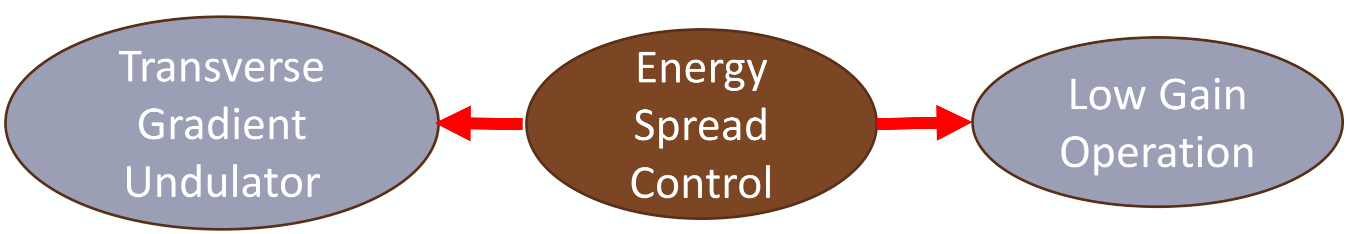
Tolerate Higher Spread

Reduce Source of Spread



Higher Energy Spread Tolerance Transverse Gradient Undulator (TGU)

Resonance condition for coherent emission:

$$\boxed{\lambda_r = \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_0^2}{2}\right)}$$

By canting undulator poles, generate a linear gradient:

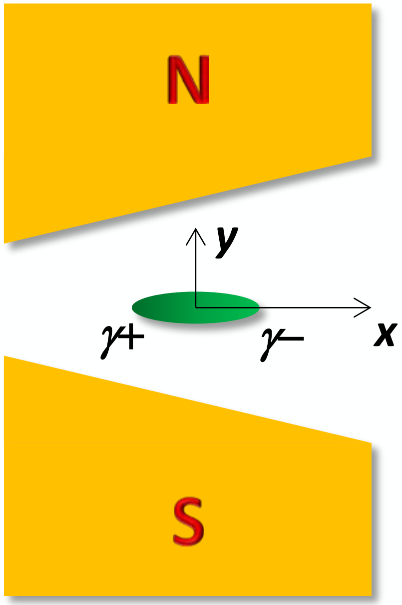
$$\boxed{\frac{\Delta K}{K_0} = \alpha x}$$

Sort e-beam energy by dispersion η so that:

$$\boxed{x = \eta \frac{\Delta\gamma}{\gamma_0}}$$

Resonance satisfied for all energies if:

$$\boxed{\eta = \frac{2 + K_0^2}{\alpha K_0^2}}$$



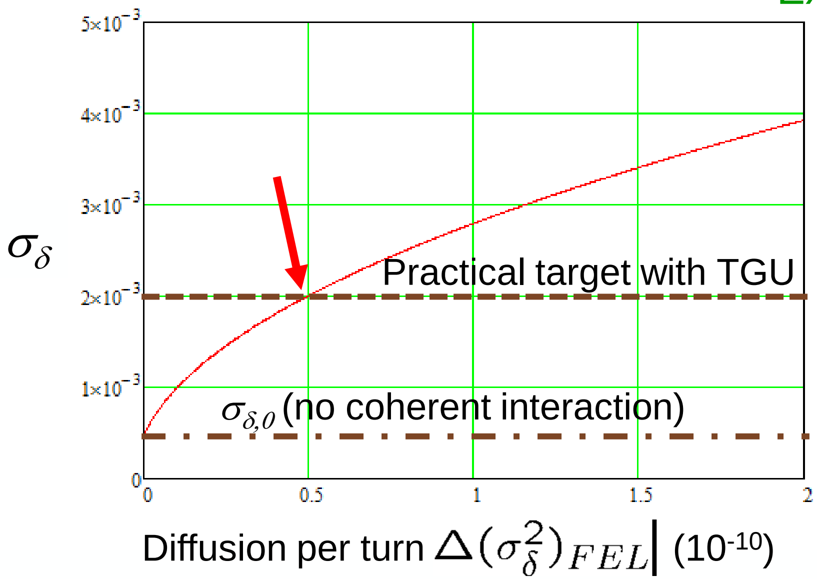
Price to pay: Increase in gain length for coherent emission
Our parameter set: Allowable energy spread 0.047% → 0.2%
Gain length increase 1m → 1.6m

T. Smith et al., J. App. Phys. **50**, 4580 (1979)

Steady State Operation of Storage Ring with Coherent Emission

Differential equation describing dynamics of energy spread σ_δ evolution[1]:

$$\frac{d\sigma_\delta^2}{dt} = -\underbrace{\frac{\sigma_\delta^2}{\tau_s}}_{\text{damping}} + \underbrace{\frac{\sigma_{\delta 0}^2}{\tau_s}}_{\text{Quantum Excitation}} + \underbrace{\frac{\Delta(\sigma_\delta^2)_{FEL}}{T_0}}_{\text{Coherent Interaction}}$$



Need to keep energy diffusion per turn < 0.5 10^{-10}!

[1]Huang et al., NIMA 593, 120 (2008).

Energy Diffusion vs. Extracted Power

For a periodic undulator the diffusion relates to the extracted power:

$$\Delta(\sigma_\delta^2)_{FEL} \approx 2\frac{\rho P}{P_{beam}}$$

Extracted Coherent Optical Power

Electron Beam Power (1GW)

To keep diffusion at 0.5 10^{-10} the **extracted coherent power can only be 50 W!**

→ Similar to incoherent, **too low!**

→ To achieve **1 kW optical output power need to reduce energy diffusion by 20X**

Summary Parameters

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- Transverse gradient for energy tolerance
- Low gain operation (<<1% of laser saturation)
- 1 kW coherent EUV output
- Self-seeding (regenerative amplification) for short undulator (6 gain lengths)

→ 0.2% (Optimum Compromise)

→ 0.0049 (TGU)

→ 2.0 (Emittance, TGU, 3-D)

How Available can a Compact Storage Ring EUV Source be?

- Large synchrotron uptime (% of scheduled operation) is >>95%
→ Benchmark that is reasonably achievable and can be exceeded
- Lyncean Compact Light Source (academic use) has 5 days of scheduled maintenance per quarter (~5% of calendar time, single shift per day)
→ Reduction to 2-3 calendar days per quarter is a reasonable target for industrial application

Conclusions

- Design elements and conceptual feasibility of a 1kW coherent EUV source based on a small electron storage ring established
- Next step is optimization of design with integrated simulation components
- Followed by conceptual design study in preparation for engineering design
- Components are using standard, practical and established technology
- Extensible to higher power and shorter wavelengths (e.g. 6.x nm for future needs)

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