Technology Development Toward High Duty Cycle Source of Inverse Compton Scattering X-Rays

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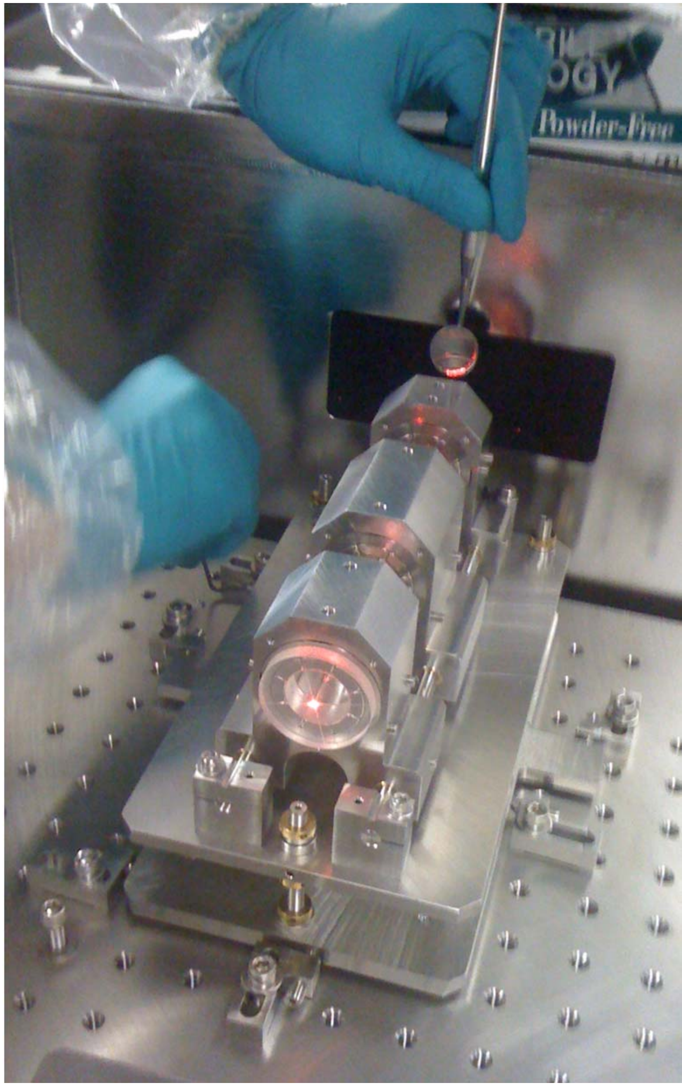
North American PAC,
Chicago IL, 13-Oct-2016

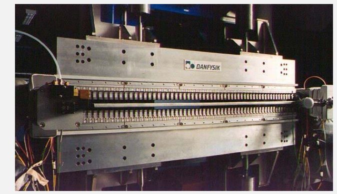


Outline

- **ICS source applications**
- ICS source development

Inverse Compton light sources

- Synchrotron light sources are critical elements of the scientific infrastructure
- Inverse Compton Scattering (ICS) offers a possibility of bringing the light source capabilities to the users



$\lambda_0 > 1\ \text{cm}$

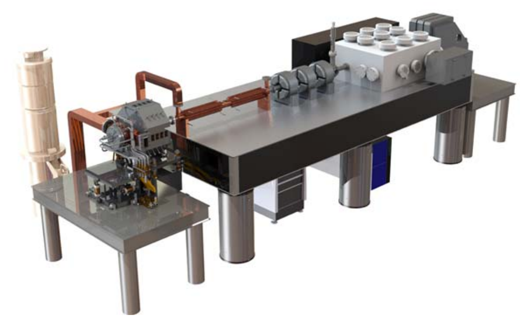
$\gamma \sim 10^4$

$\lambda_0 \sim 1\ \mu\text{m}$

$\gamma \sim 10^2$

$$\lambda_s \propto \lambda_0 / \gamma^2$$

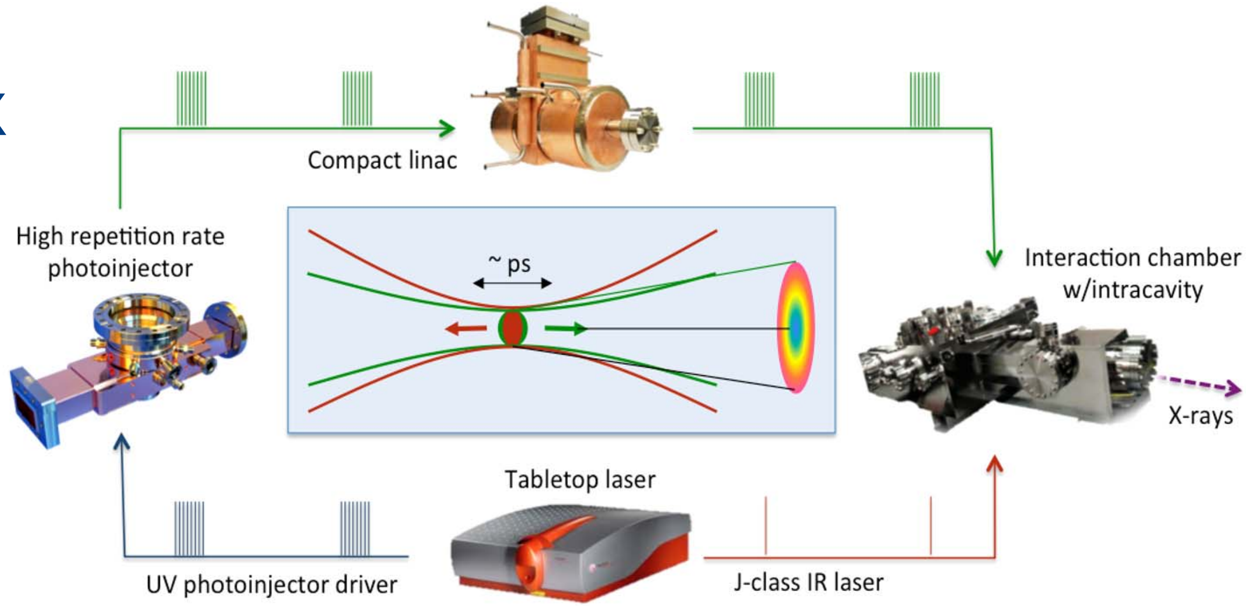
~ 1 km



~ 10 m

ICS photon flux

- Photoinjector
- J-class picosecond laser
- 10^4 interactions per second



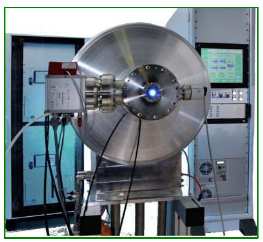
$$N_s \approx \frac{N_0 N_e \sigma_{th}}{A}$$

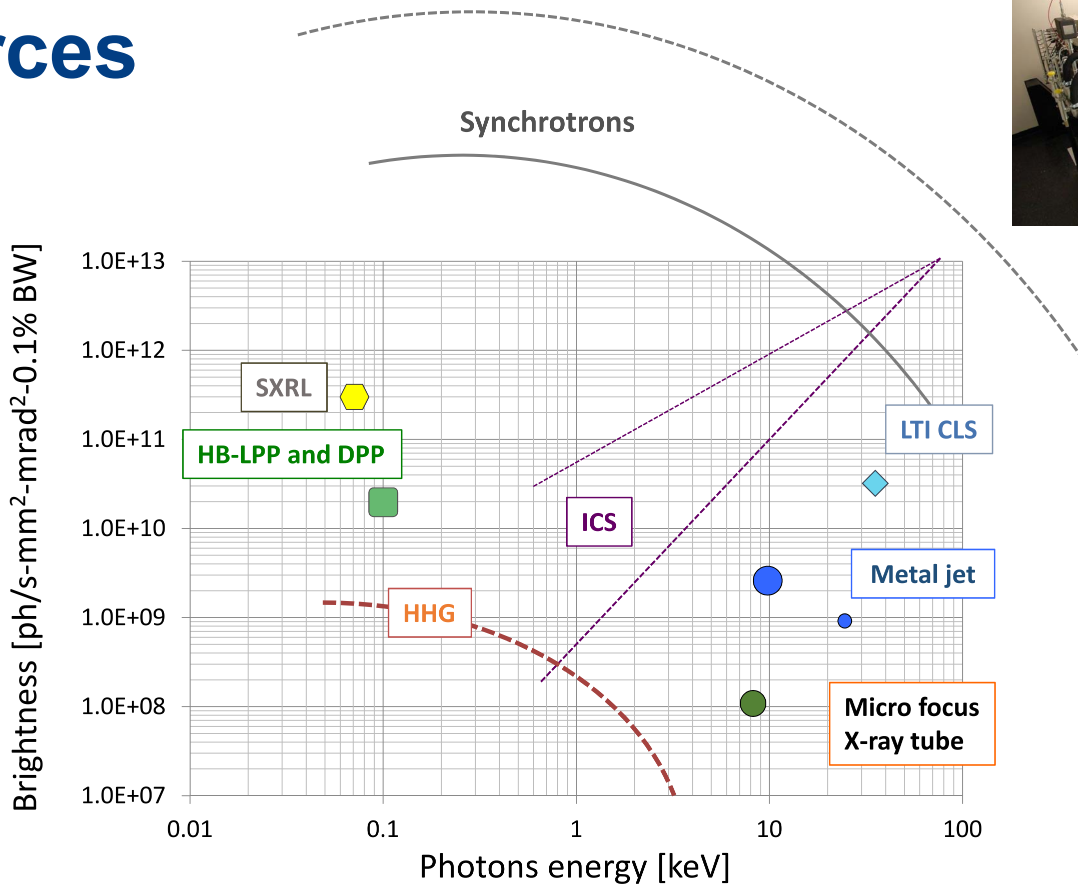
$$\sigma_{ICS} \approx \sigma_{th} \quad \text{for} \quad \gamma << \lambda_0 / \lambda_e \sim 10^5$$

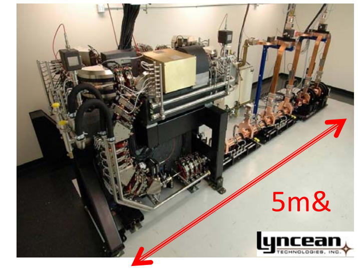
$$\sigma_{th} = \frac{8\pi}{3} r_e^2 = 6.65 \times 10^{-25} \text{ cm}^2$$

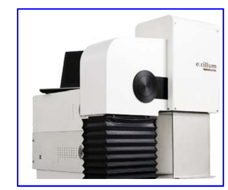
50 MeV (45 keV) 350 pC per pulse 300 mJ YAG laser 20 μm RMS spot size 5 x 10^3 enhancement	• 5 x 10^7 single shot photon flux • 2 x 10^6 in 1% bandwidth • 10^{10} ph/s in 1% bandwidth B_s ~ 10^{13} ph/s-mm-mrad-0.1%

Comparison to other sources



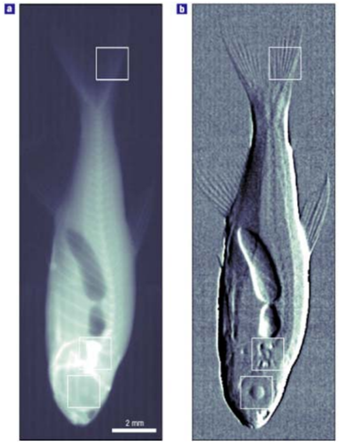




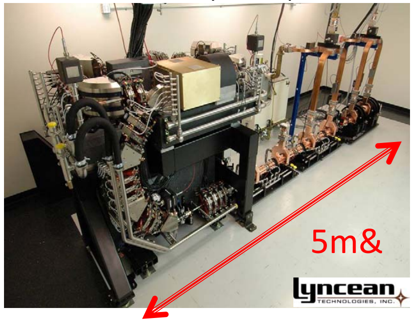


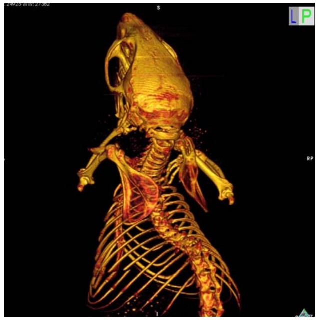
Phase contrast imaging

- Large market (motivated early attempts to commercialize ICS)
- Can reduce dose (or improve contrast) by x100
- Demonstrated with ICS (not on humans)
- Insensitive to bandwidth, but sensitive to spot size at the IP
- Dose requirement 10^{13}-10^{16} photons/scan
- COO requirement (at least 20-30 scans per day)
- Doctors want the source to move around patients
- Safe beam disposal adds costs



F. Pfeiffer et al. ,Nature Physics 2, 258 - 261 (2006).





K. Achterhold, presented at OSA Workshop on Compact EUV & X-ray Light Sources, Maastricht, 2015

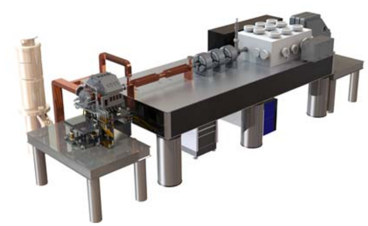
Beta testers?

- Most research users can get an access to synchrotrons and are not motivated to invest in ICS
- ICS requires development
- ICS cost per photon is much higher than in an X-ray tube and even from a light sources
- A number of companies and institutions attempted to commercialize ICS over the last 2 decades (mostly in vain with the exemption of Lyncean CLS, which sold a single unit to a research institution)
- Technology push, not a market pull

CAD scan equivalent dose

< $1

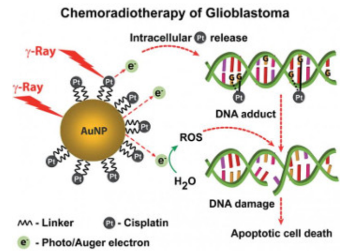
< $100 (often $0)



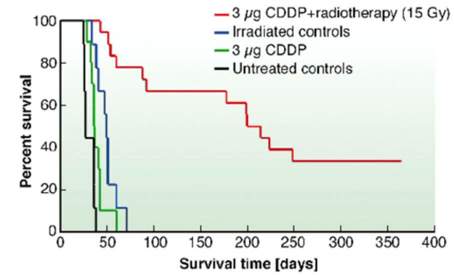
>> $100

New applications

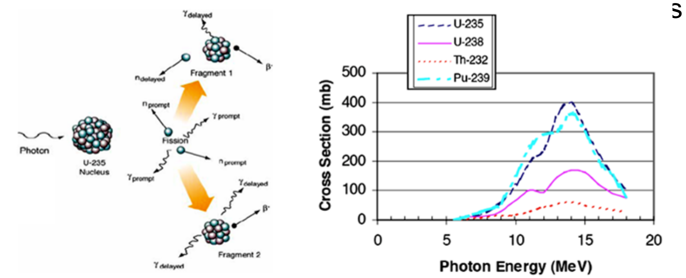
- Photoactivation therapy (70-90 keV)
- MeV gamma rays applications:
  - active interrogation
  - NRF
  - nuclear waste inspection and management
  - medical isotopes, etc.
- CD nanometrology for integrated circuits
  - In-line metrology have a significant economic value (waiting for the functional testing is prohibitively expensive)
  - Optical ellipsometry is reaching its resolution limits



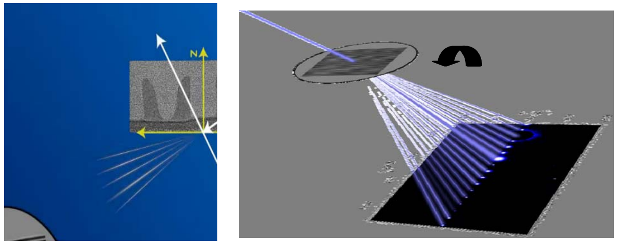
S. Setua et al, Nanoscale 6, 10865 (2014).



ESRF Highlights, Photoactivation of Platinum
s (2004).



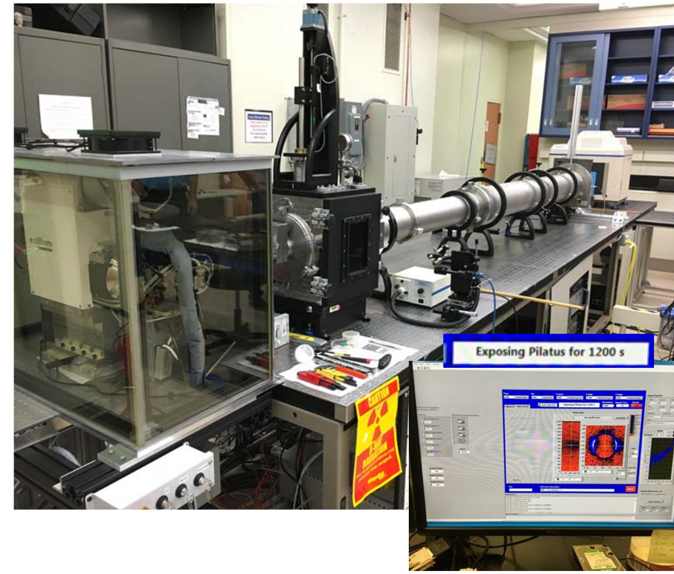
J.L. Jones *et al.,* Neutrons Workshop at ONR, October 2006

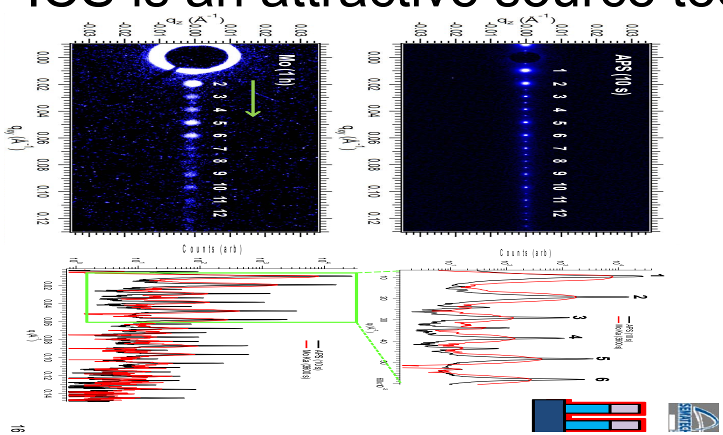


courtesy of R.J. Kline, NIST

CD metrology

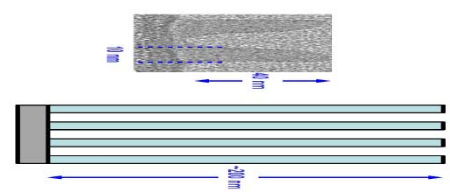
- Tested at synchrotrons and with the X-ray tubes (Mo Kα source 2x10^6 ph/s on target)
- Has to have a small footprint
- ICS is an attractive source technology





Required Flux for 10 sec Single Shot Measurement

Material	Tall fin	Short fin	High-K Coated	Resist
Photons	10^8 ph/s	$2x10^9$ ph/s	10^8 ph/s	$>10^{10}$ ph/s



Ideal Source Requirements

Property	Value
Energy	>20 keV
Energy res	<1 %*
Divergence	<0.5 x 1.5 mrad
Spot size	<100 µm

courtesy of R.J. Kline, NIST

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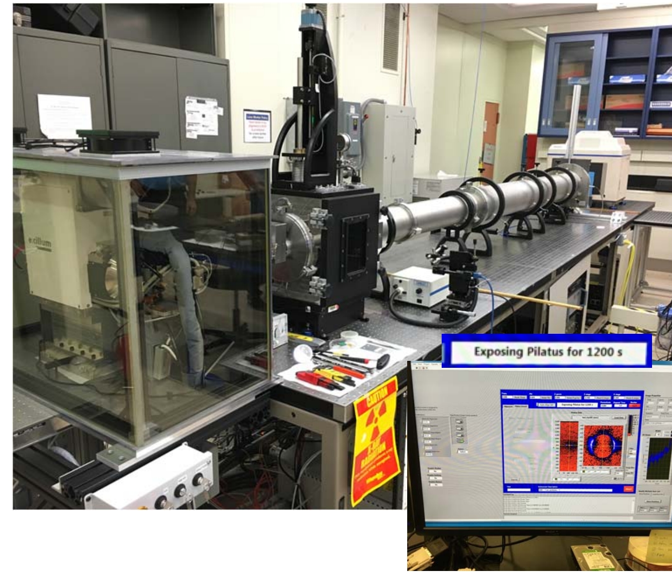

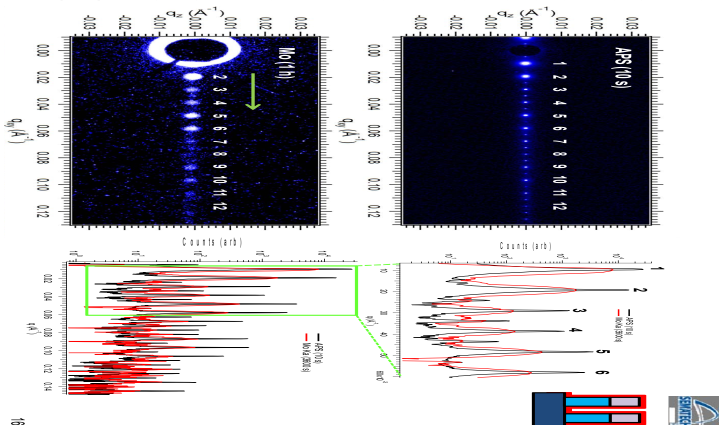

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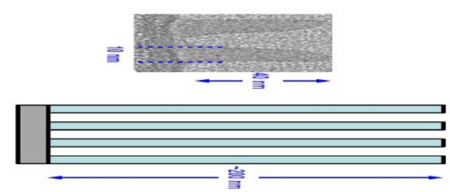


Ideal Source Requirements

Property	Value
Energy	>20 keV
Energy res	<1 %*
Divergence	<0.5 x 1.5 mrad
Spot size	<100 µm

10^9 ph/s
in 1% BW !

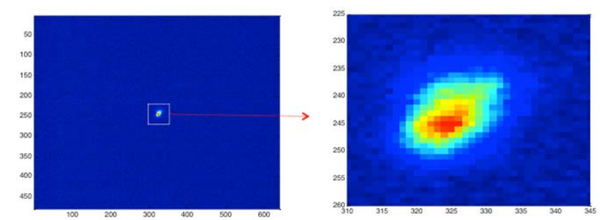
courtesy of R.J. Kline, NIST

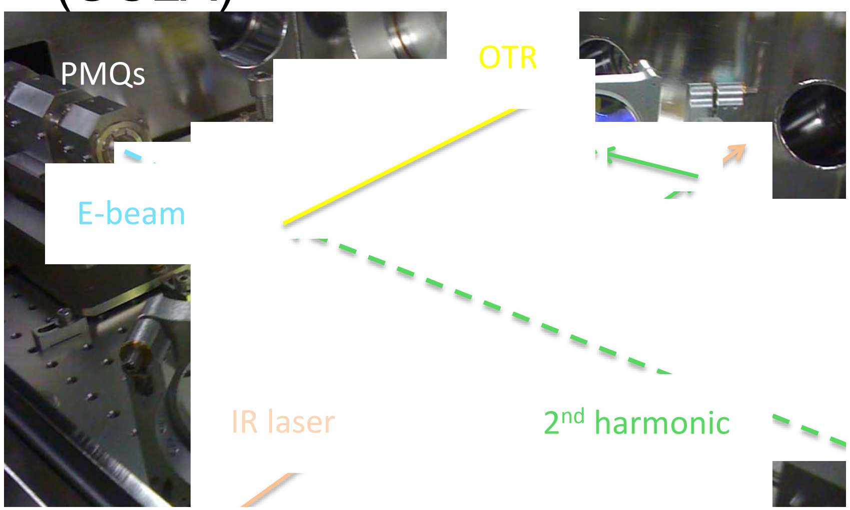
Outline

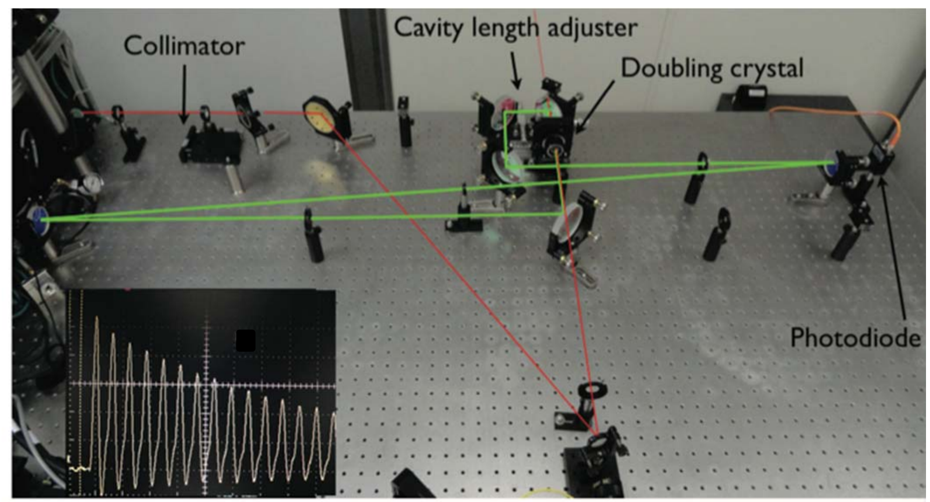
- ICS source applications
- **ICS source development**

ICS RING cavity experiment (2010)

- Achieved < 15 μm e-beam spot size in a pulse train and tested RING cavity
- Stopped in 2011; in 2016 restarted the program (UCLA)

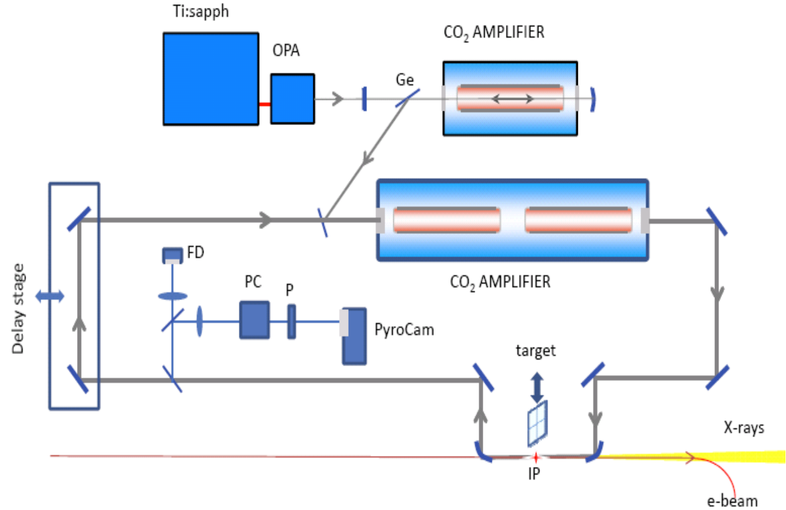


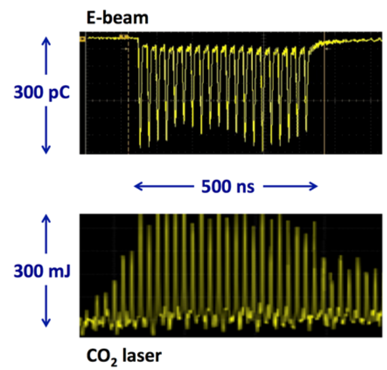


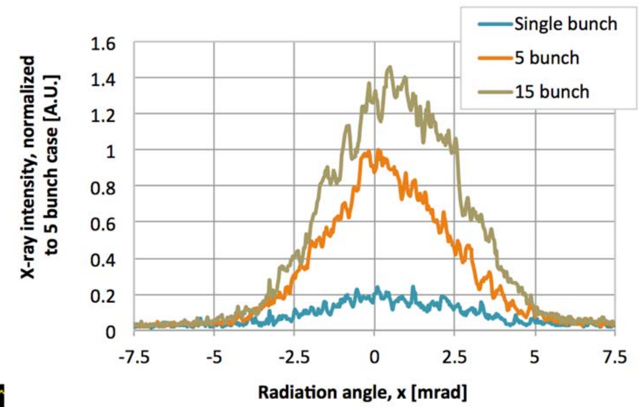


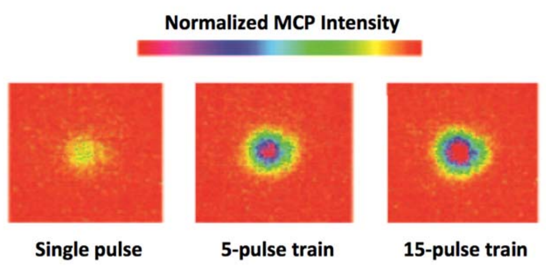
CO2 pulse train ICS (2015)

- Demonstrated multi-bunch ICS interaction at 40 MHz
- Linear gain from 1 to 5 pulses (10^8 photons in a 5-pulse train)
- Improved output stability in a pulse train mode



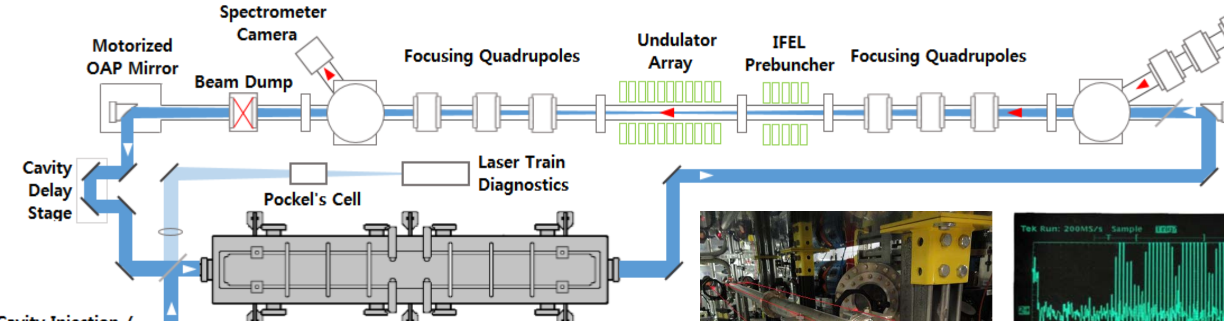


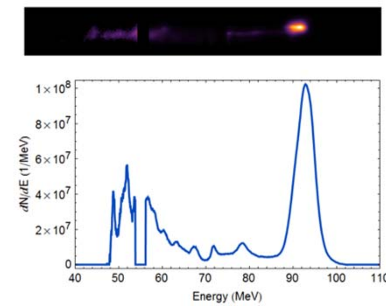


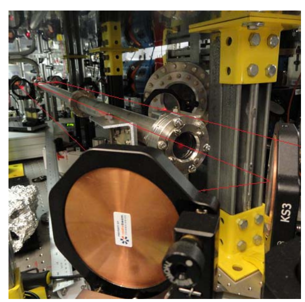


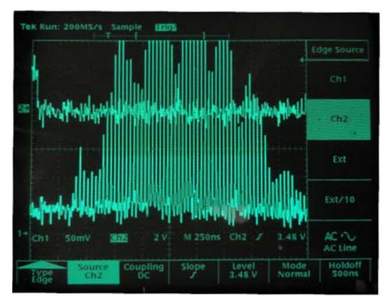
IFEL-ICS in a pulse train mode

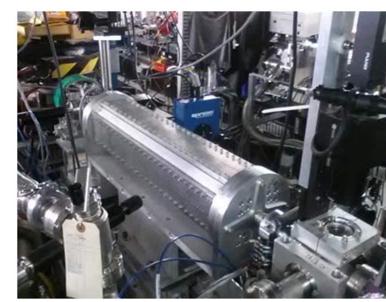
- The goal is to demonstrate IFEL in a similar CO2 pulse train configuration
- Eventually combine IFEL and ICS, to reach gamma ray energy range in a compact configuration





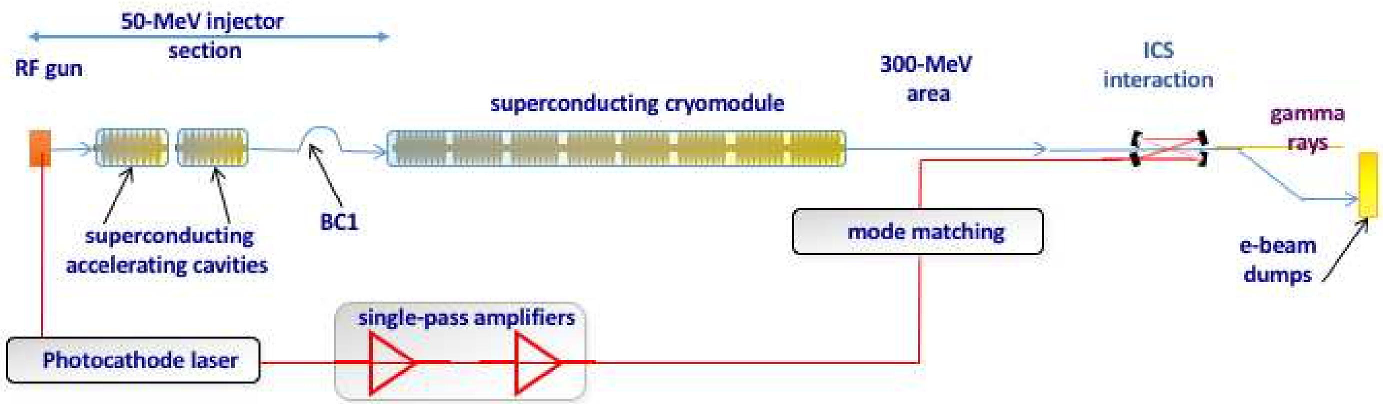






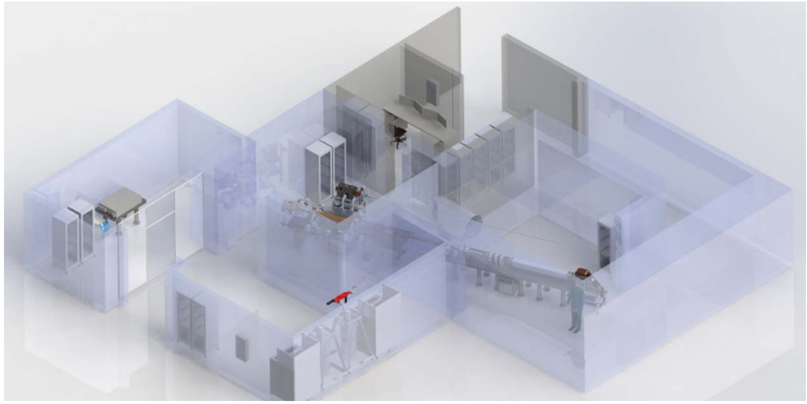
SCRF ICS at Fermilab

- Use Fermilab SCRF linac for high average power gamma ray source
- Challenges: 3 MHz repetition rate optical cavity, and synchronization over 1000+ pulse trains



ICS at UCLA

- UCLA new Samurai lab will host 70 keV ICS source
- Partially supported by UCLA medical school
- Primary interest in photoactivation therapy)
- An opportunity to build a stand alone prototype



Summary

- ICS is a promising source technology
- RadiaBeam is working with the US National Labs, Universities and industrial partners to develop a commercial stand alone ICS source

Acknowledgement:

- R. Agustsson, S. Boucher, T. Campese, B. Jacobson, A. Ovodenko (RadiaBeam); J. Duris, P. Musumeci, J. Rosenzweig, Y. Sakai, N. Sudar (UCLA); M. Babzien, M. Fedurin, I. Pogorelsky, M. Polyanskiy, T. Shaftan, C. Swinson (BNL); D. Mihalcea, P. Piot (NIU); J. Ruan (Fermilab).
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- Thank you!