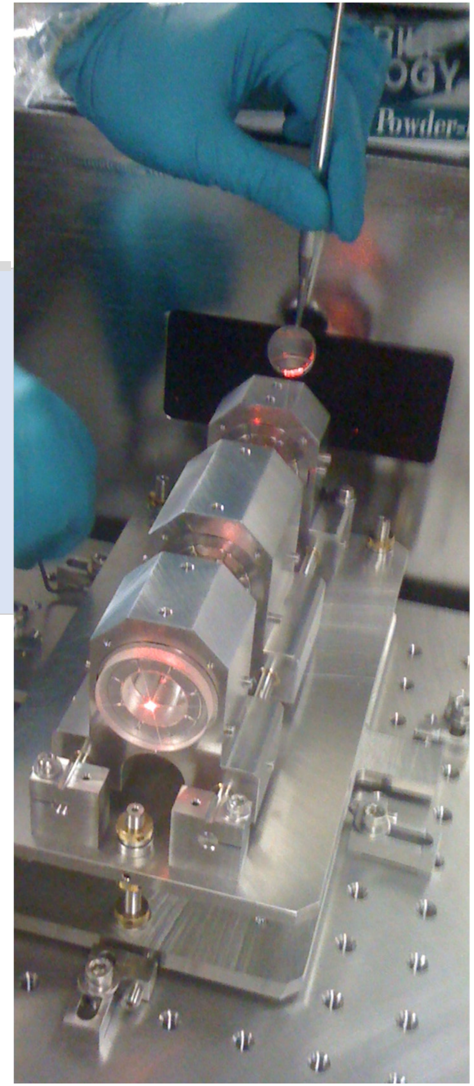
RadiaBeam UCLA

A Compact High Rep-Rate γ-ray Source Based on IFEL Interactions

Alex Murokh (RadiaBeam Technologies LLC.)
Pietro Musumeci and Nick Sudar (UCLA)

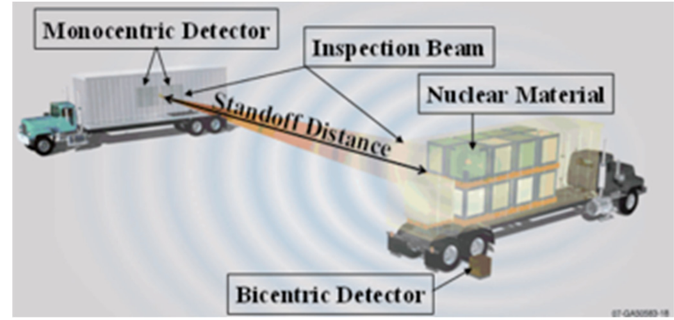
IPAC19

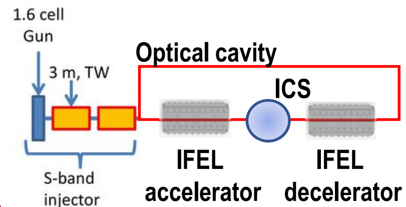
May 23, 2019, Melbourne, Australia



Motivation

- Investigation of nuclear structure using **photonuclear reactions**.
- New methods of identification and remote characterization of **nuclear materials**
- New ways of producing more efficiently **radioisotopes** currently used in medicine
- **Polarized positrons** production for the next lepton collider





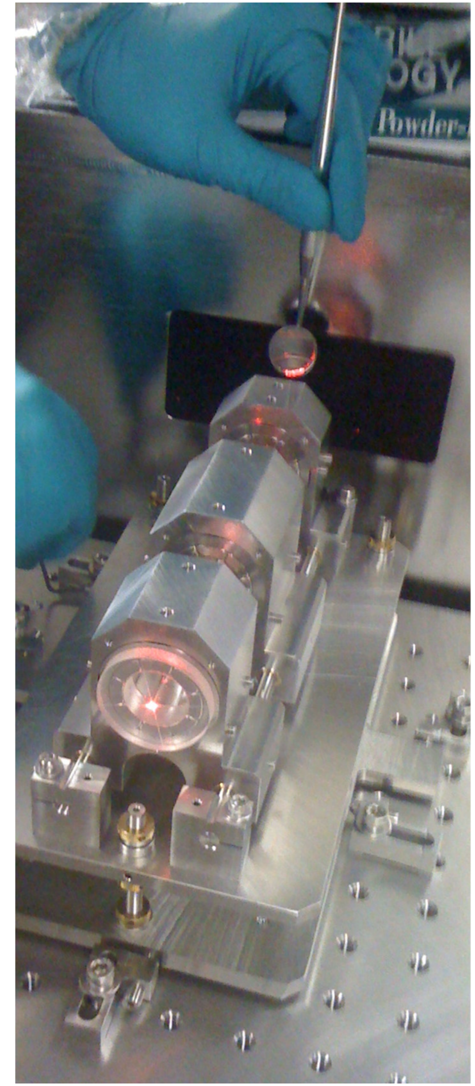
~ 10^{11} ph/s in 1%BW

Proposed IFEL-ICS gamma ray source

- ICS laser has enough power to accelerate e-beam in Inverse Free Electron Laser (IFEL) with ~ GeV/m gradient
- We propose to complete ICS laser cavity with a compact IFEL accelerator and decelerator structures, to achieve gamma ray source of similar or better performance, that would fit on 3 optical tables.

Outline

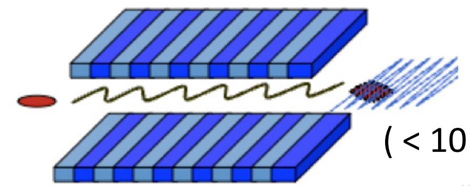
- IFEL overview and UCLA Rubicon experimental program
- Towards high repetition rate IFEL system
- Optical energy recovery high repetition rate IFEL-ICS gamma ray source



Inverse Free Electron Laser

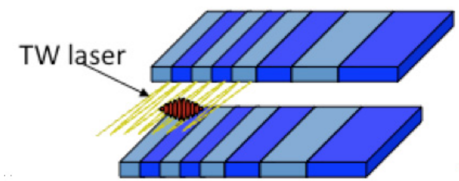
- Undulator magnet enables e-beam and laser beam energy exchange in vacuum (i.e. seeded or SASE Free Electron Lasers)
- The same scheme can be applied for e-beam acceleration (IFEL), which unlike FEL uses:
  1) **high intensity seed laser (compare to e-beam power) to enable significant acceleration**
  2) **strongly tapered undulator to maintain resonance while the beam is accelerated**

FEL $P_L \propto P_B \rho$



P_B ~ 1kA x 1 GeV ~ 1 TW

IFEL $P_L > P_B$

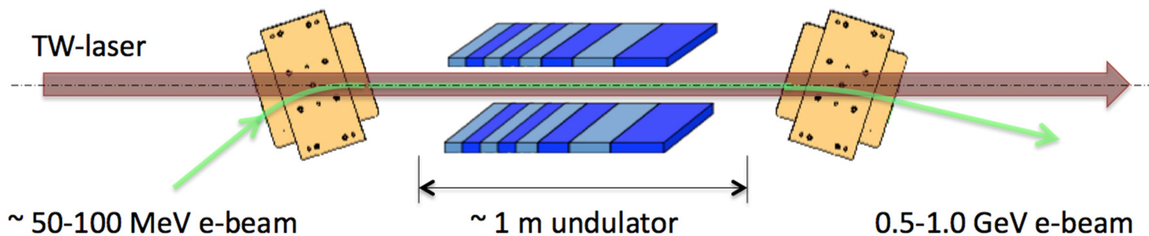


R.B. Palmer, J. Appl. Phys. 43, 3014 (1972).
E. D. Courant, C. Pellegrini, W. Zakowicz, Phys. Rev. A 32, 2813 (1985).
N. M. Kroll, P. L. Morton, and M. N. Rosenbluth, IEEE J. Quantum Electron. 17, 1436 (1981).

IFEL edge

- Requires only ~10 TW class laser to reach GeV energies and **GeV/m gradients**
- Good repeatability and **brightness**
- **High rep. rates** are possible !
- **Same laser** can be used to drive Inverse Compton Scattering (ICS)

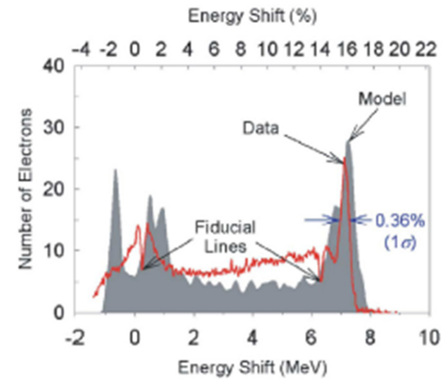
- Free space, in-vacuum acceleration:
  - **no energy losses to the media,**
  - **no field at the boundary,**
  - **long interaction lengths (>1 m) are possible,**
  - **laser energy can be recycled for high r. r.**



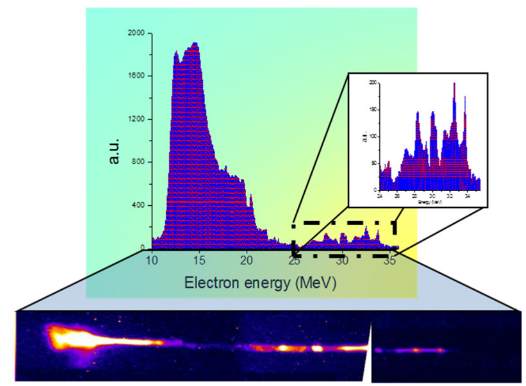
IFEL could make a very compact GeV energy booster for practical applications (XFEL, ICS, etc.) !

IFEL challenges

- Need to achieve a good beam capture and a good accelerating gradient at the same time.
- Spatial and temporal overlap of electron and laser beams has to be maintained at the level of 10s μm and 100 fs, respectively
- High rep. rate (pulse train) configuration require laser source operating at 10s of MHz



W. Kimura et al. PRL 92, 054801 (2004)

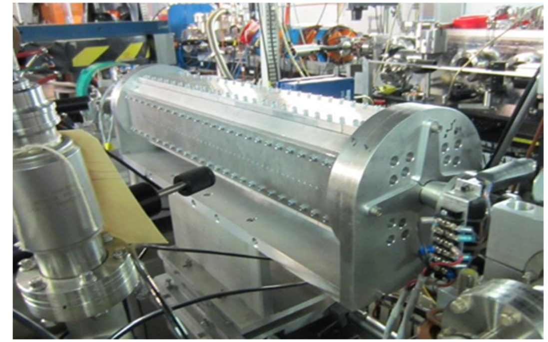


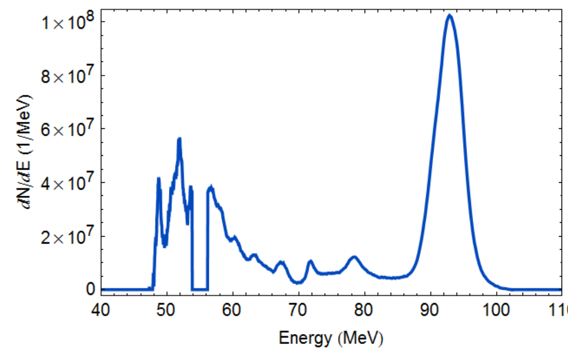
P. Musumeci et al. PRL 94, 154801 (2005)

Rubicon Experiment

RUBICON (RadiaBeam-UCLA-BNL-IFEL-Collaboration)

- ✓ RUBICON demonstrated 100 MV/m acceleration and ~ 50% capture (2013)
- ✓ Relatively high quality beam (~2 μm emittance, 2% ΔE/E) at the output, consistent with ICS requirements
- ✓ GIT (Genesis Informed Tapering) code was developed to enable period by period undulator tapering optimization
- ✓ A generation of UCLA students acquired hands-on experience of designing, assembling, tuning and retuning of Rubicon–styled strongly tapered helical undulators



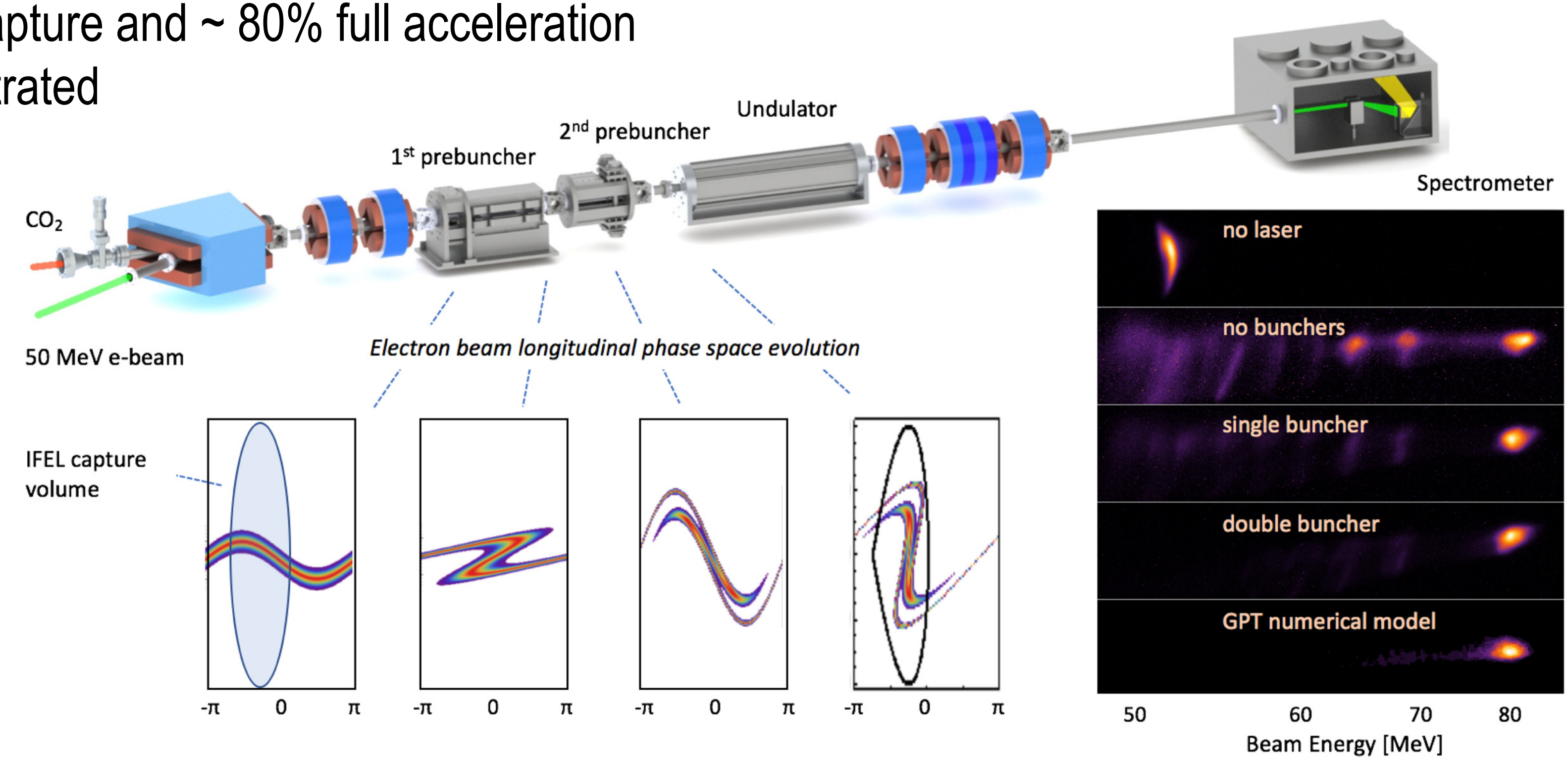


J. Duris et al, Nature Comm. 5, 4928, 2014

Double-Prebuncher (2017)

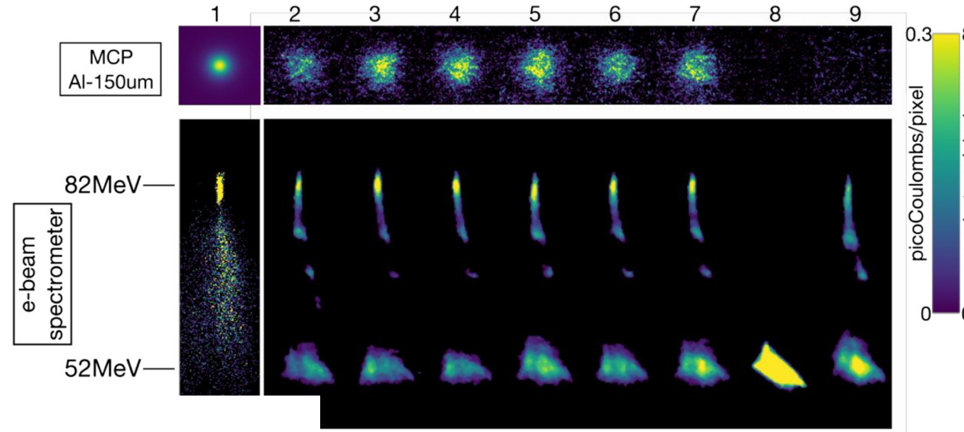
N. Sudar "Maximizing capture in ponderomotive potential: double buncher results," Physics & Applications of High Efficiency Free-Electron Lasers, California NanoSystem Institute, April 2018

>95% capture and ~ 80% full acceleration demonstrated

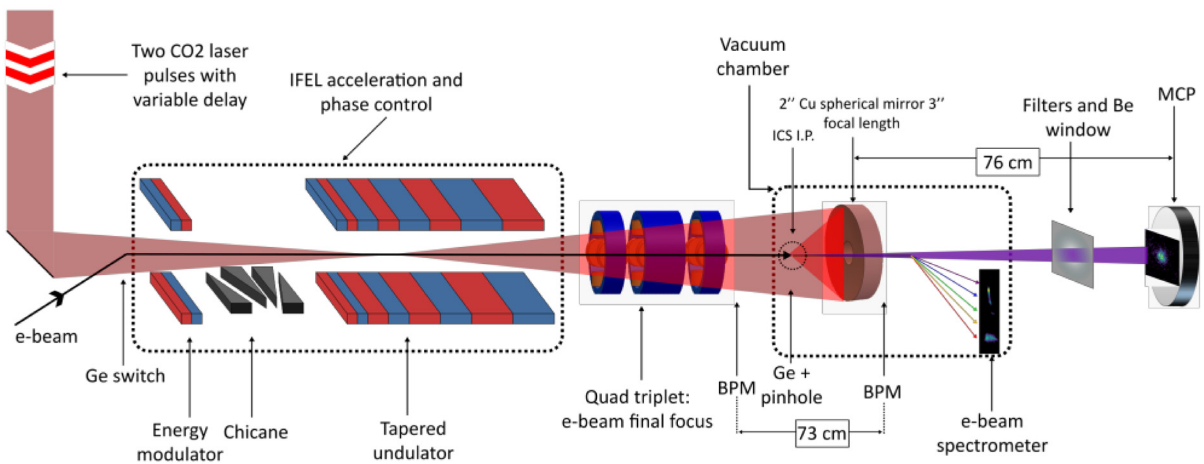


RUBICON-ICS (2017)

- Demonstrated for the first time stable generation of 12 keV X-rays by IFEL accelerated electron beam



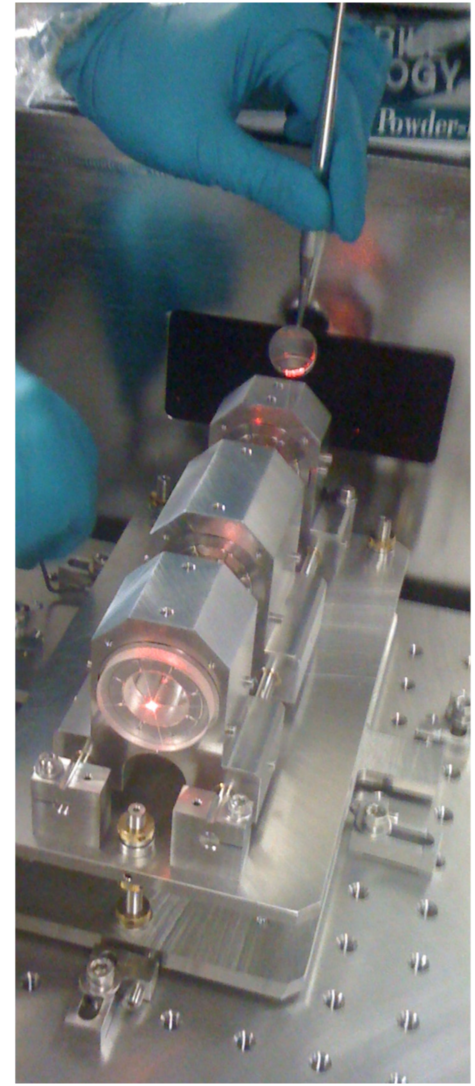
I. Gadjev et al., Scientific Reports 9, 532 (2019)



- A practical proof of beam brightness preservation in IFEL

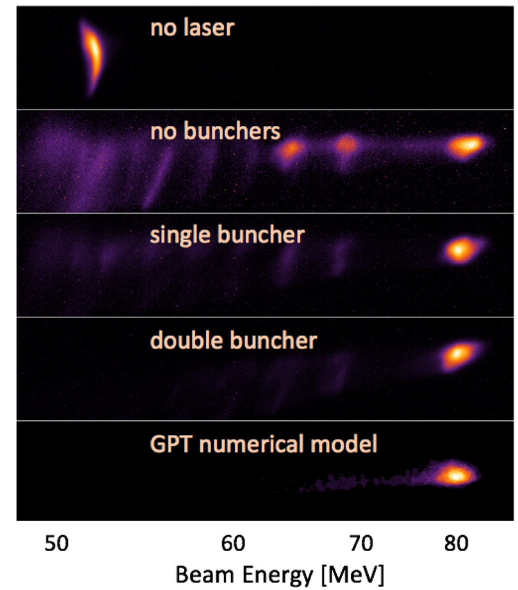
Outline

- IFEL overview and UCLA Rubicon experimental program
- **Towards high repetition rate IFEL system**
- Optical energy recovery high repetition rate IFEL-ICS gamma ray source



IFEL challenges after Rubicon crossing

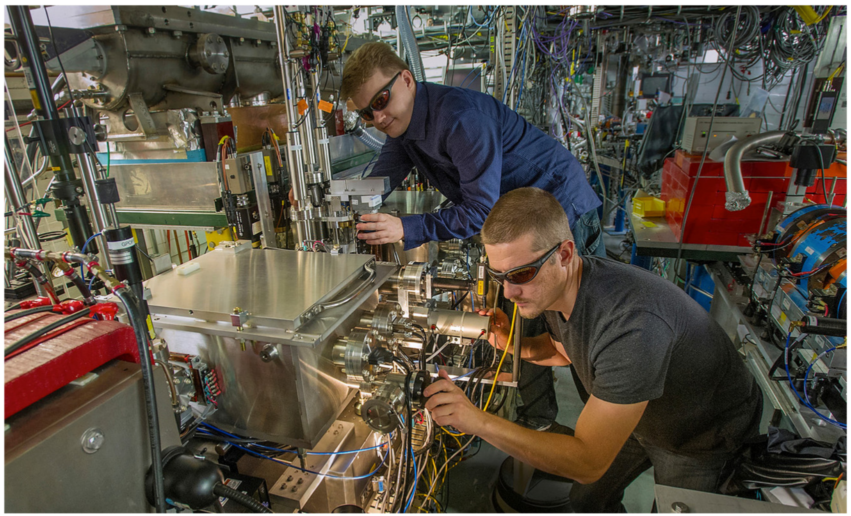
- ✓ Need to achieve a good beam capture and a good accelerating gradient at the same time.
- ✓ Spatial and temporal overlap of electron and laser beams has to be maintained at the level of 10s μm and 100 fs, respectively

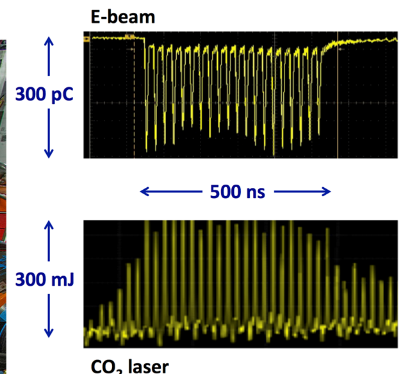


High rep. rate (pulse train) configuration require laser source operating at 10s of MHz

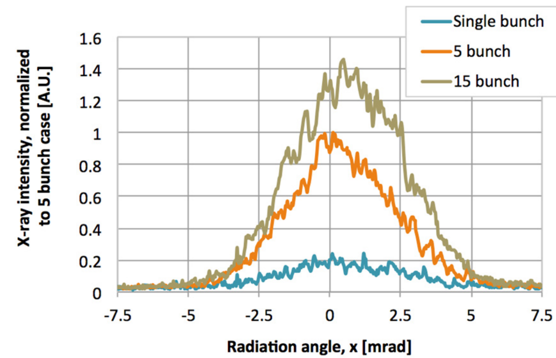
Recirculated ICS experiment (2015)

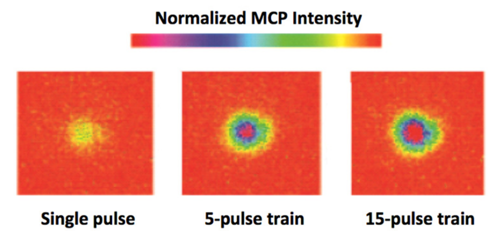
- Used CO_2 active cavity to study ICS in a pulse train regime (40 MHz)
- Demonstration for the first time of the significant ICS photon yield gain via pulse train interaction



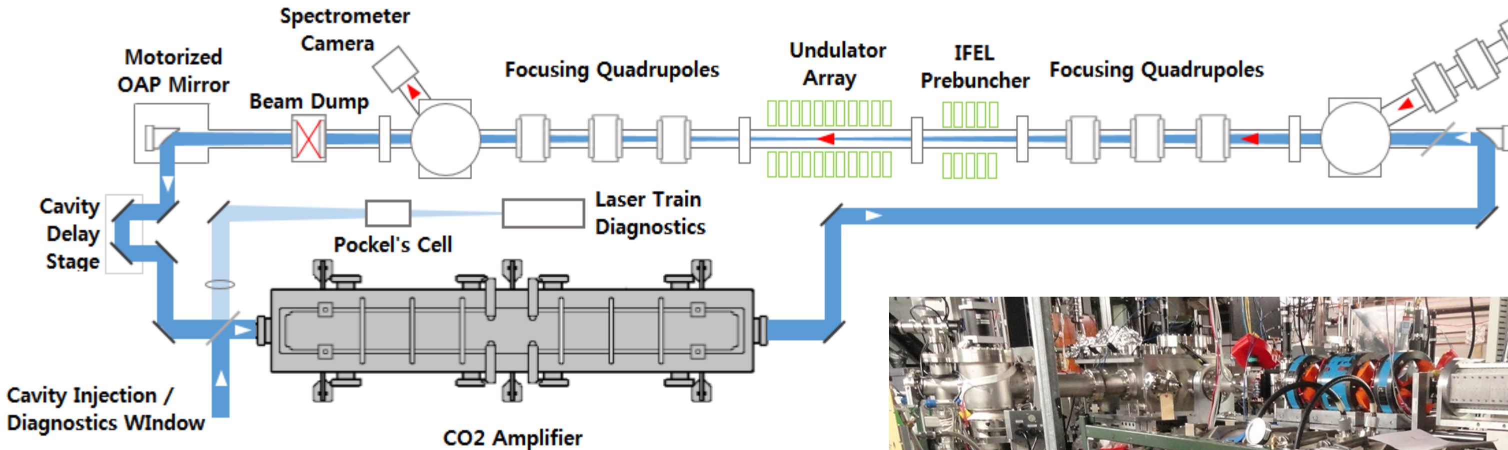


A. Ovodenko et al., Appl. Phys. Lett. 109, 253504 (2016)

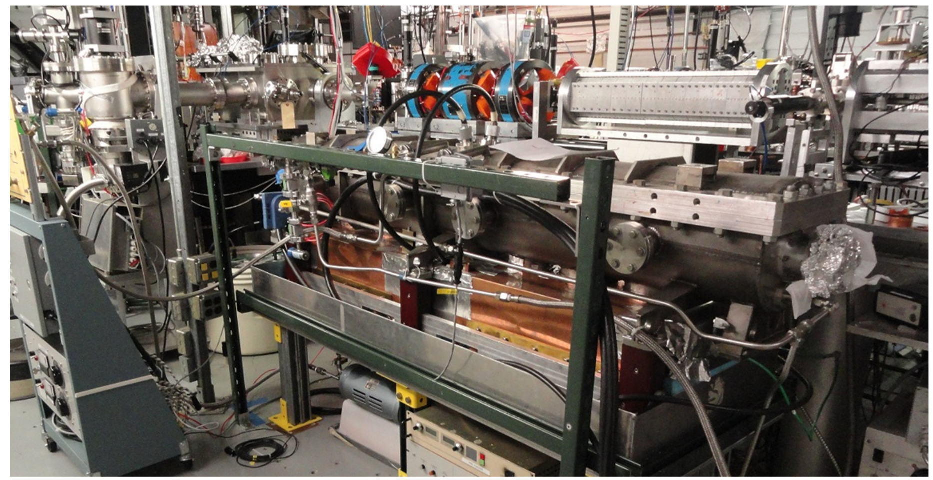




Recirculated IFEL experiment (2017-2019)



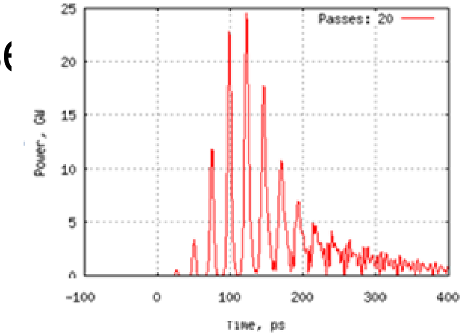
- Used the same active cavity approach as in a recirculated ICS experiment to demonstrate Rubicon IFEL operating in a pulse train mode.

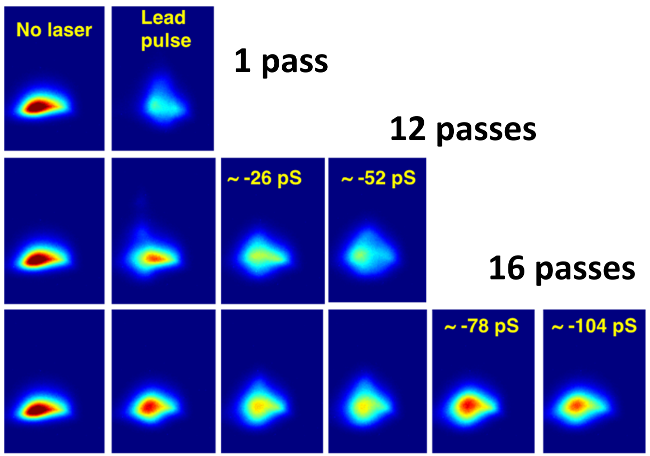


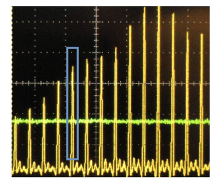
Recirculated IFEL experiment (2017-2019)

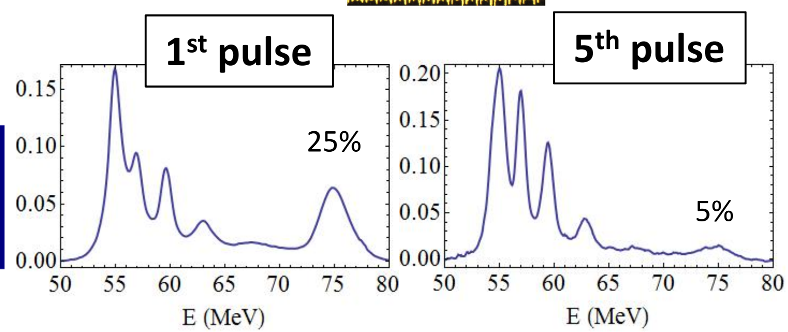
- Measured clear signs of e–beam interaction with the laser pulse train, using delay stage to move e-beam along the pulse
- The efficiency of the interaction was limited by the dispersion and pulse splitting in the CO_2 amplifier after multiple passes

5ps pulse splitting to 150ps after 20 passes in 4atm amplifier







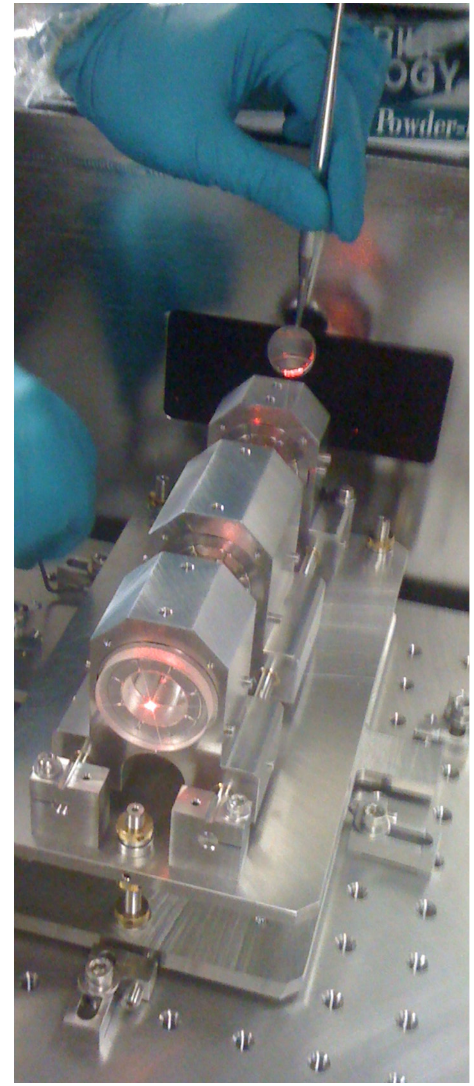


Switching to optical wavelength

- All previous experiments were carried out at the Accelerator Test Facility at BNL, which provided a unique combination of high brightness electron beam, TW-class CO_2 laser, and user friendly environment to carry the IFEL / ICS program
- It is time, however to switch to the solid state optical wavelength lasers:
  - ✓ Off the shelf 10 TW - class lasers, optical hardware and diagnostics are readily available;
  - ✓ GeV/m acceleration is achievable
  - ✓ Gamma ray range ICS can be achieved with lower e-beam energy (1 GeV electrons → 20 MeV gammas)
- Need to solve laser re-amplification problem at optical wavelength, to achieve high repetition rate (10s of MHz rep. rate is too fast for solid state high power amplifiers)

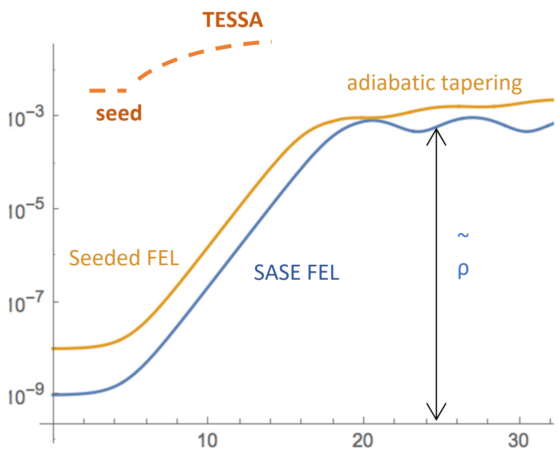
Outline

- IFEL overview and UCLA Rubicon experimental program
- Towards high repetition rate IFEL system
- **Optical energy recovery high repetition rate IFEL-ICS gamma ray source**

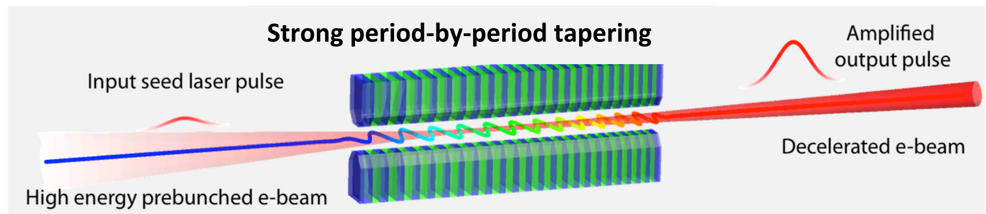


TESSA (Tapering Enhanced Stimulated Superradiant Amplification)

- IFEL in deceleration configuration = TESSA (inspired by Rubicon success)
- Requires seed pulse of high intensity (larger than P_{SAT})
- Tapering is optimized using GIT algorithm (Genesis Informed Tapering) developed at UCLA for Rubicon



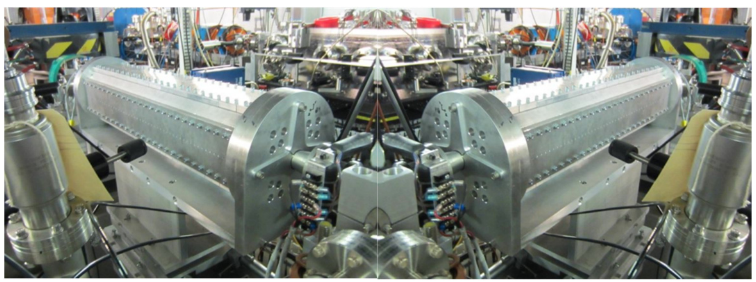
J. Duris, A. Murokh, P. Musumeci, "Tapering Enhanced Stimulated Superradiant Amplification," New J. Phys. 17, 063036 (2015).



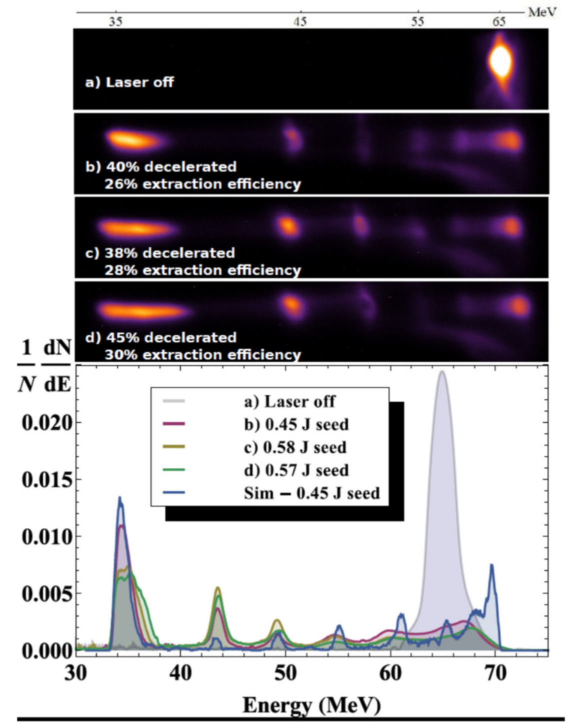
- TESSA is interesting in and of itself as a light source
- It can also be used as a fast intracavity laser amplifier

TESSA proof-of-concept experiment

- Pilot experimental test was carried out by UCLA at ATF BNL at 10 μm
- Demonstrated > 30% energy extraction from the electron beam in a 50 cm undulator !



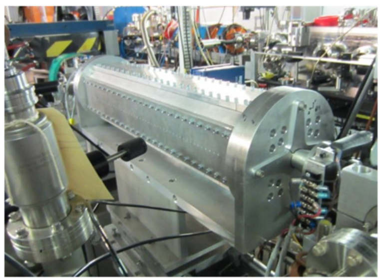
Nocibur ≡ Rubicon with reversed tapering scheme

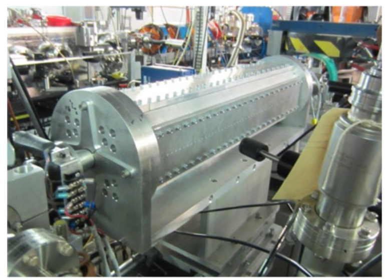


N. Sudar et al., Phys. Rev. Lett. 117, 174801 (2016)

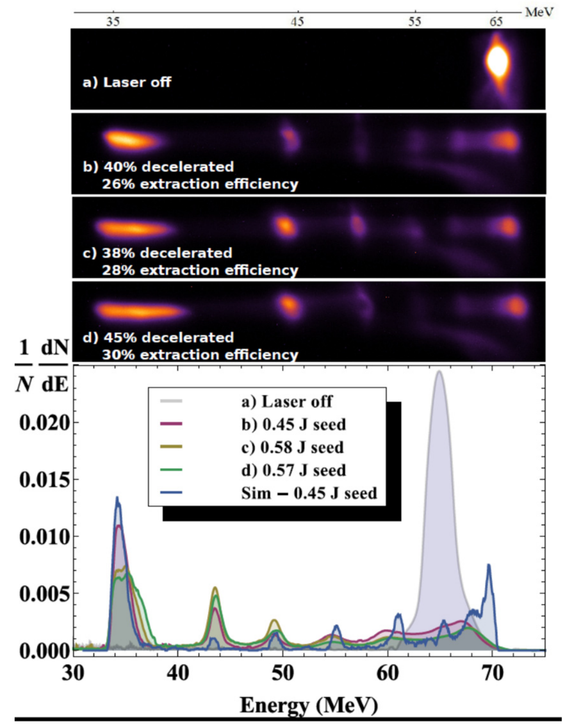
TESSA proof-of-concept experiment

- Pilot experimental test was carried out by UCLA at ATF BNL at 10 μm
- Demonstrated > 30% energy extraction from the electron beam in a 50 cm undulator !





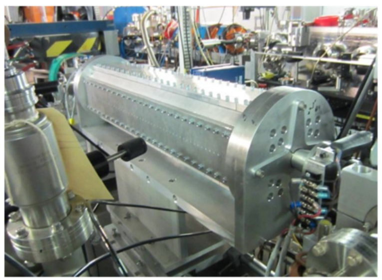
Nocibur ≡ Rubicon with reversed tapering scheme

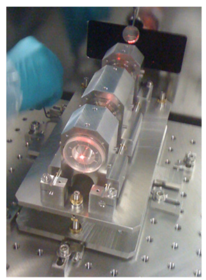


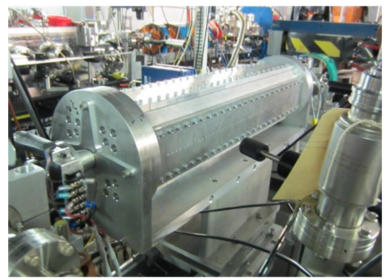
N. Sudar et al., Phys. Rev. Lett. 117, 174801 (2016)

TESSA proof-of-concept experiment

- Pilot experimental test was carried out by UCLA at ATF BNL at 10 μm
- Demonstrated > 30% energy extraction from the electron beam in a 50 cm undulator !

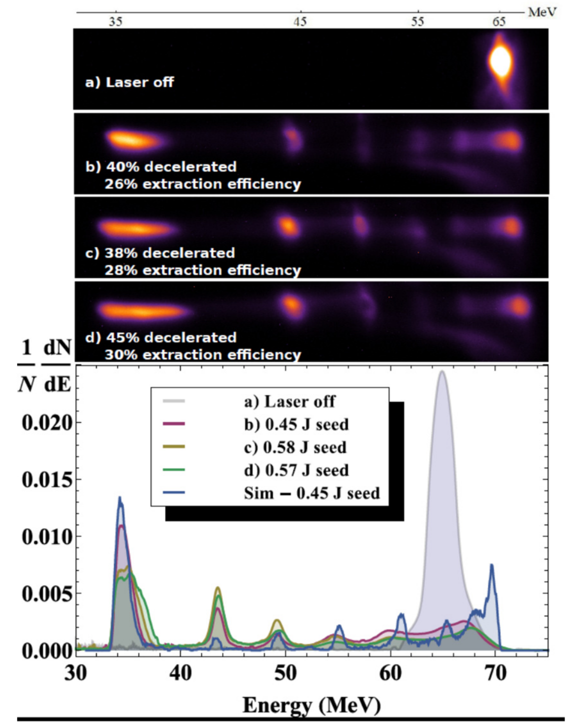






Nocibur ≡ Rubicon with reversed tapering scheme

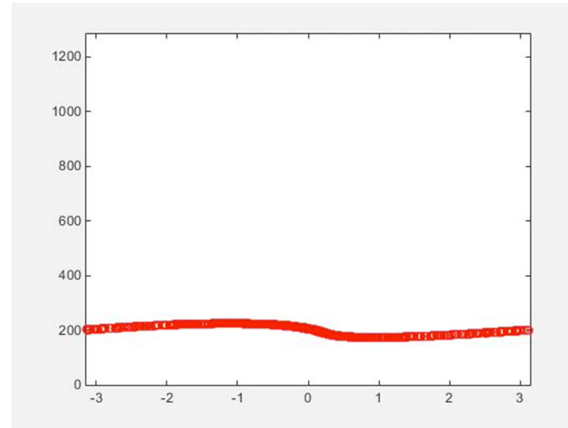
Rubicon → ICS→ Nocibur



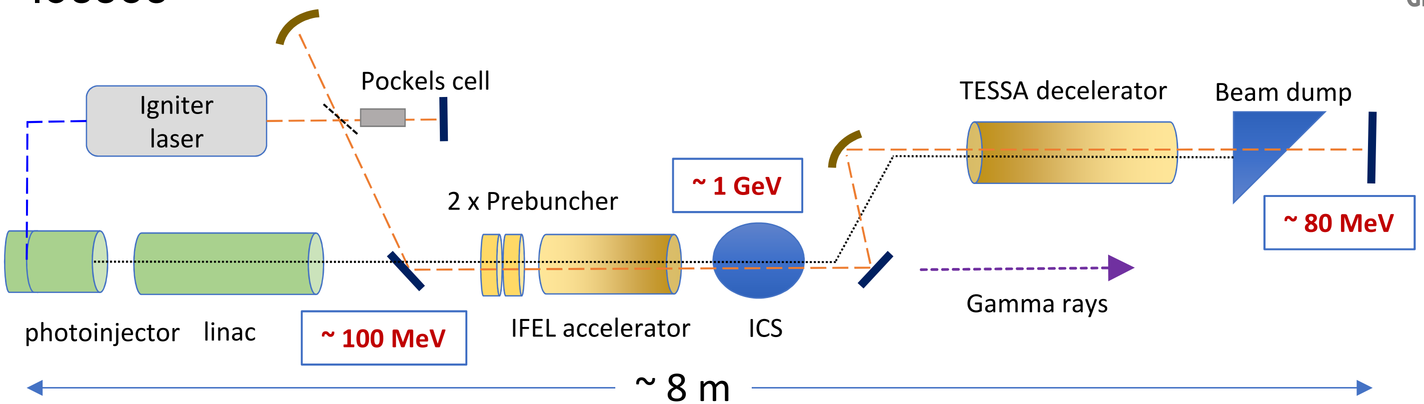
N. Sudar et al., Phys. Rev. Lett. 117, 174801 (2016)

Optical Energy Recovery ICS Source

- Two laser pulses are injected into the optical cavity and interact with ~100 bunch e-beam pulse train at ~ 20 MHz
- TESSA decelerator is tuned to accelerate below the IFEL input energy to compensate for optical losses



GIT simulations (UCLA)

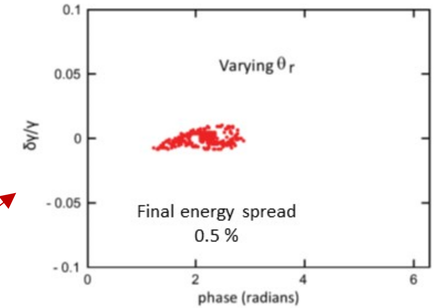


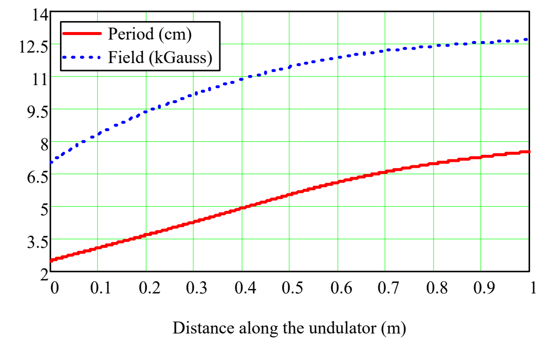
10^8 ph/shot
100 Hz
100 pulses per train

~ 10^{11} ph/s in 1%BW

Next steps

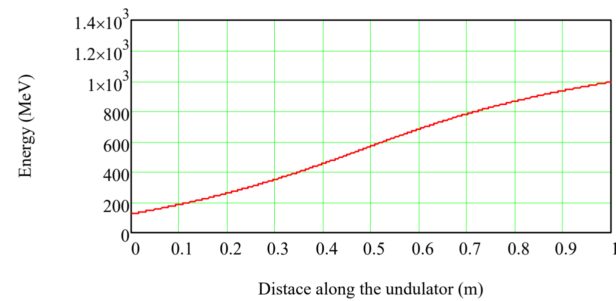
- Start to end numerical model needs to be developed to consider beam dynamics effects in ICS module and the bend
- New detrapping loss mitigation strategy (under development at UCLA)
- Modular approach to experimental demonstration: GeV/m IFEL within a passive optical cavity is recently proposed at SLAC





Very similar scenario to the IFEL working point analyzed at:

J. P. Duris, P. Musumeci, and R. K. Li, “Inverse Free Electron Laser Accelerator for Advanced Light Sources”, Phys. Rev. ST AB 15, 061301 (2012).



Conclusions

- Compact tunable IFEL-ICS gamma ray source could find multiple applications in research, medicine and security
- IFEL driver uniquely enables high flux and compact geometry at the same time, and can share the laser source with ICS
- IFEL accelerator combined with decelerator (TESSA) enables laser energy recovery and very high repetition rates
- Looking for funding and collaborators to initiate experimental program
- Acknowledgement:

  - J. Rosenzweig (UCLA), J. Duris (SLAC), S. Zholents (APS), the entire **ATF BNL team**
  - US DOE SBIR grants No. DE-SC0007703, DE-SC0013749, DE-SC0017102