Optical Energy Recovery Linac ICS Gamma-ray Source

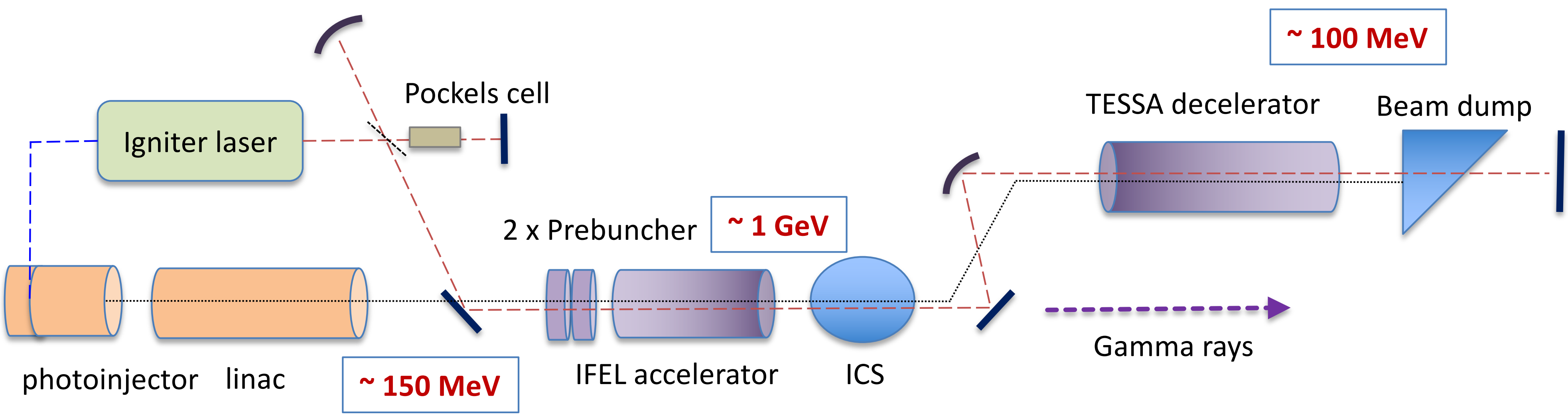
Alex Murokh
RadiaBeam Technologies LLC.

Physics & Applications of High Efficiency Free-Electron Lasers
California NanoSystem Institute, April 12 2018

Optical Energy Recovery ICS Gamma Source

High intensity 10 MeV class gamma ray source, comprising of:

1. NCRF 150 MeV injector operating in pulse train mode
2. ~ 10 TW igniter laser (i.e. 1064 nm)
3. IFEL 1 GeV energy booster stage
4. ICS interaction chamber
5. **TESSA** decelerator for laser power recovery

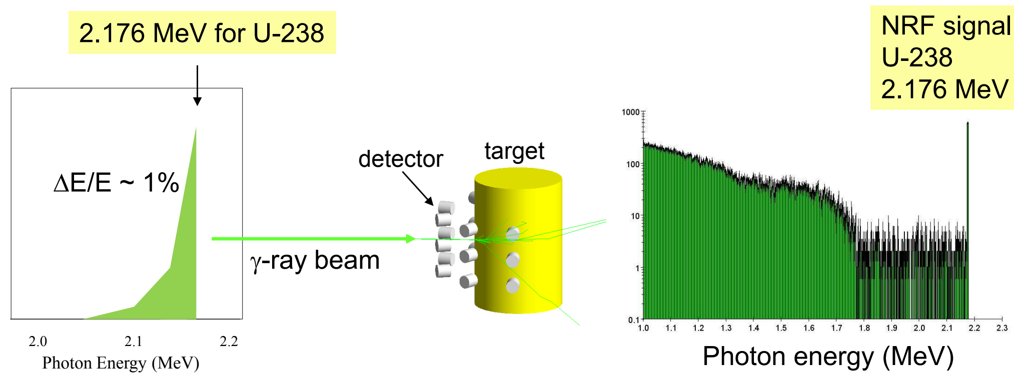


Outline

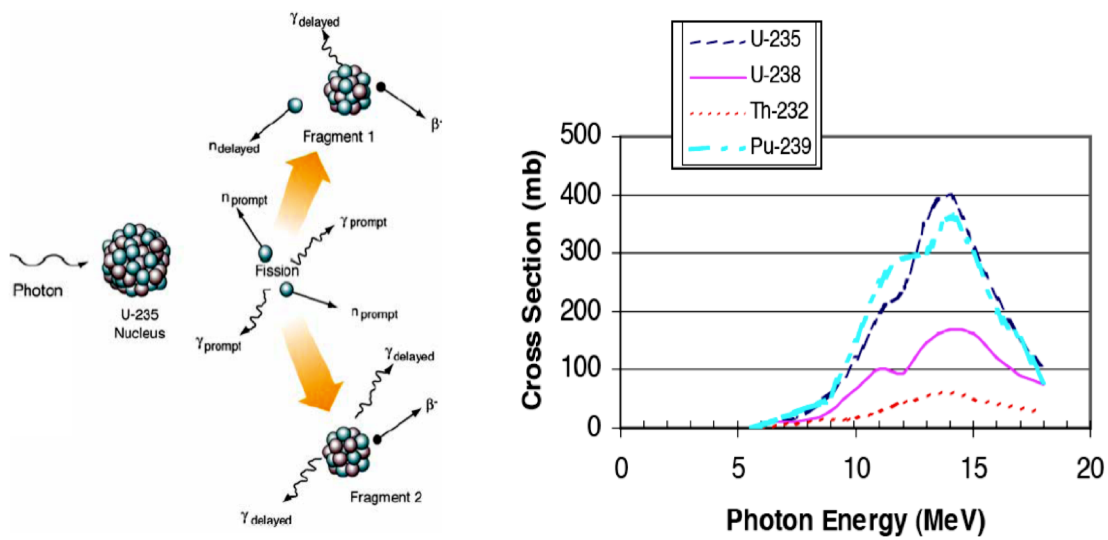
- Motivation for monochromatic ICS gamma source
- IFEL-ICS gamma ray ICS
- IFEL-TESSA optical energy recovery ICS

Monochromatic MeV gamma rays applications

- Nuclear spectroscopy and NRF for NP R&D
- NRF for SNM detection
- Nuclear waste inspection
- Medical isotopes production
- Stand off active interrogation via photofission
- **cargo inspection**



R. Hajima, Japan Atomic Agency ERL Group (2008).

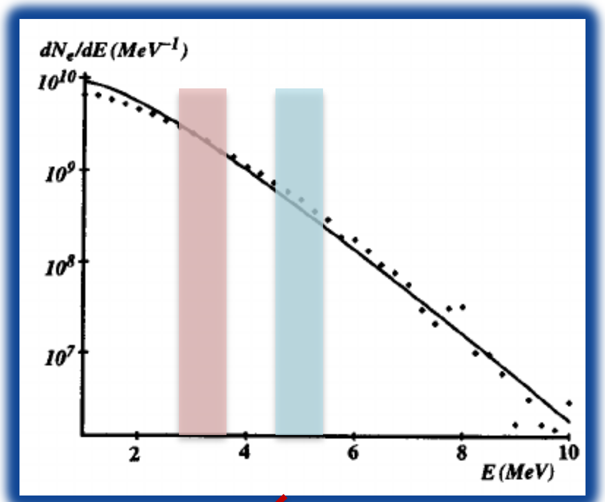


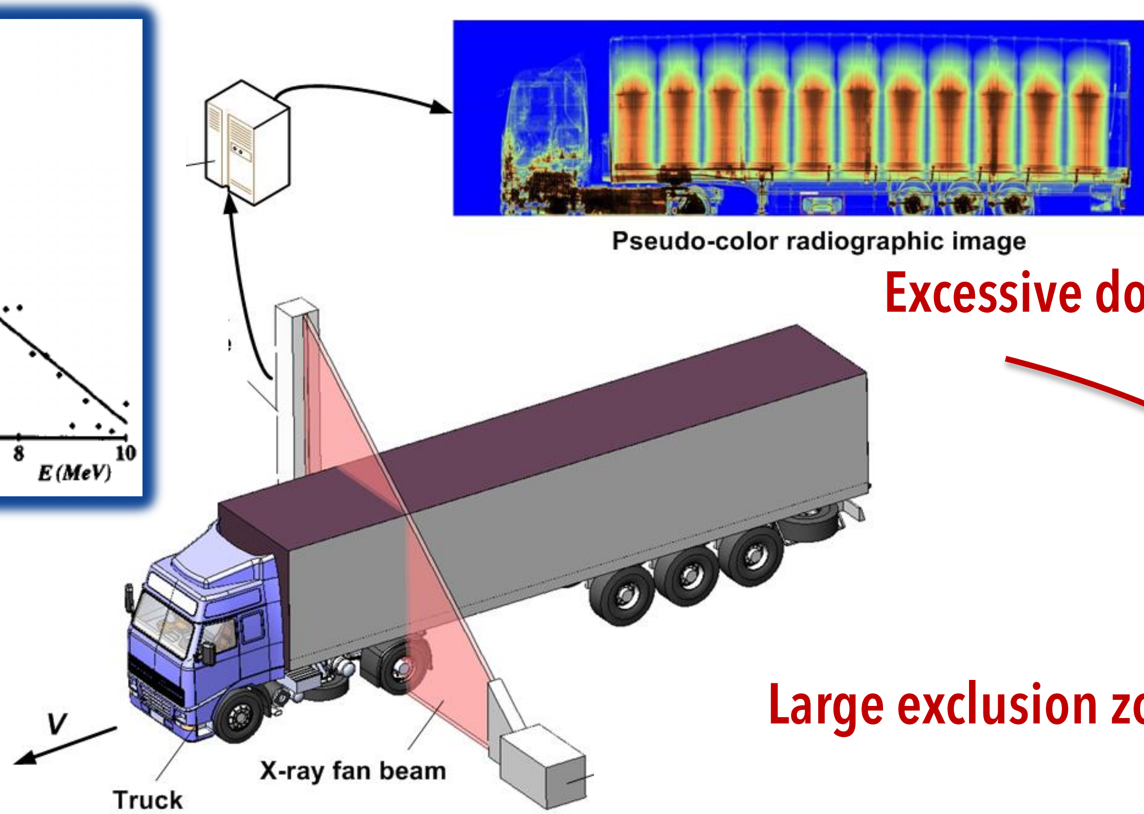
J.L. Jones *et al.*, Neutrons Workshop at ONR, 2006

Cargo inspection linac system

Disadvantages of the bremsstrahlung source

- Materials differentiation requires multi-color imaging
- Bremsstrahlung target produces continuous spectrum



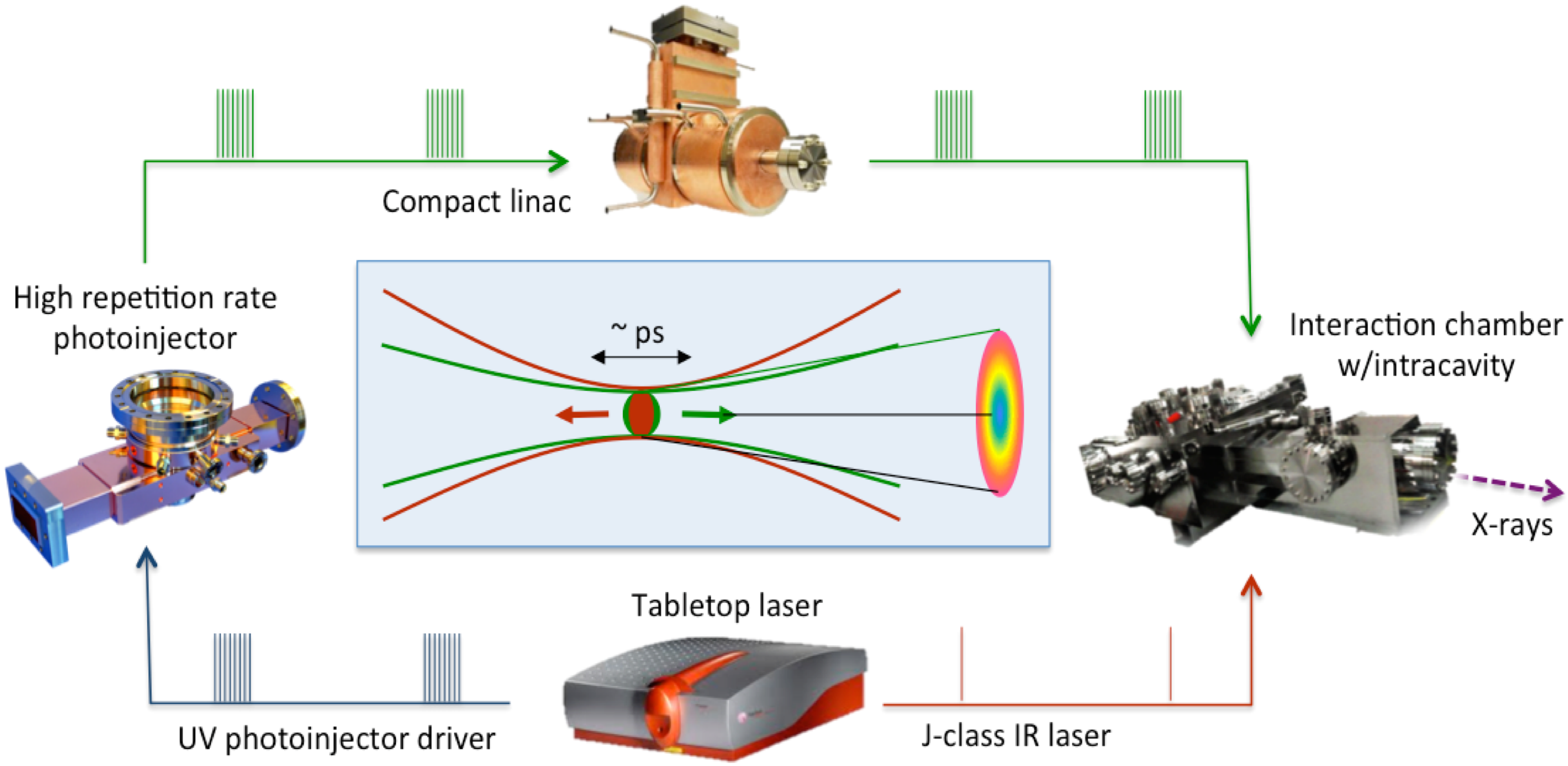


Excessive dose on target

Large exclusion zone

No stand off capability

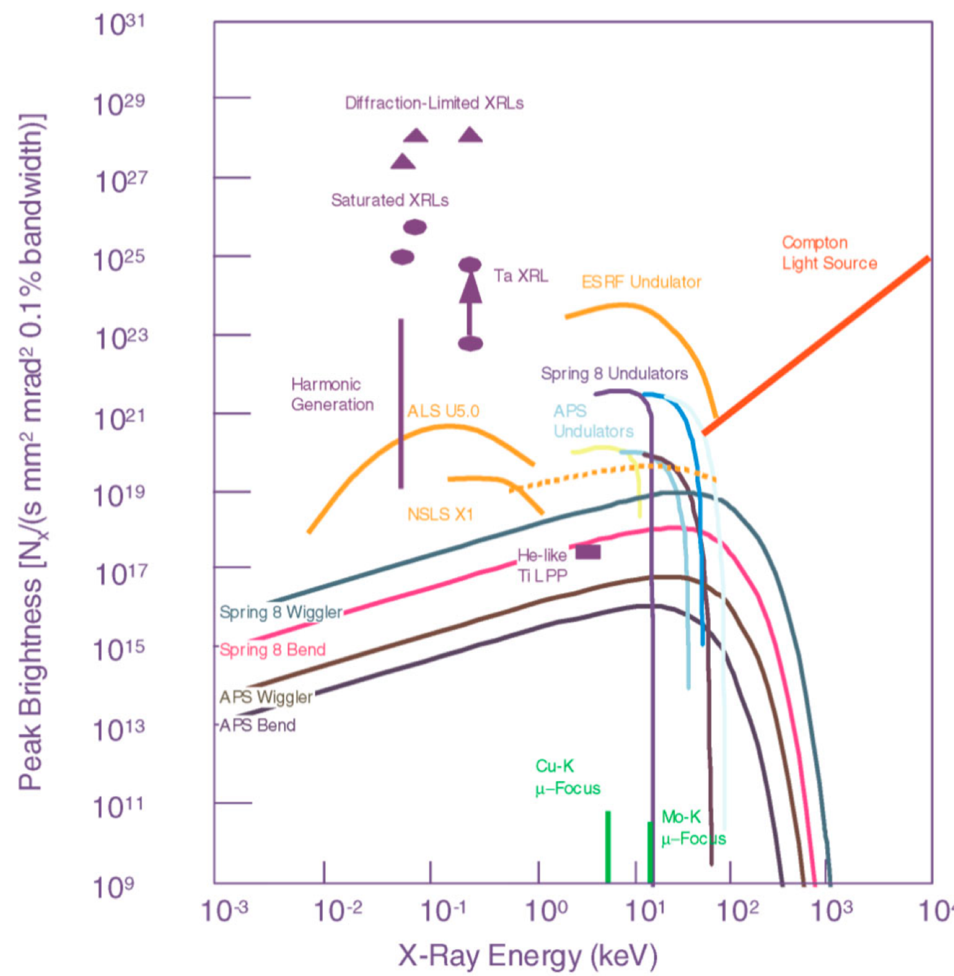
Inverse Compton Scattering (ICS)



- Scattering intense ultrafast optical laser pulse off GeV class e-beam produces narrow bandwidth directional gamma ray beam
- Maximum practical photon flux per interaction ~ 10^7 in 1 % bandwidth
- Practical applications intensities require 10^3 – 10^5 interactions/second

ICS gamma source features

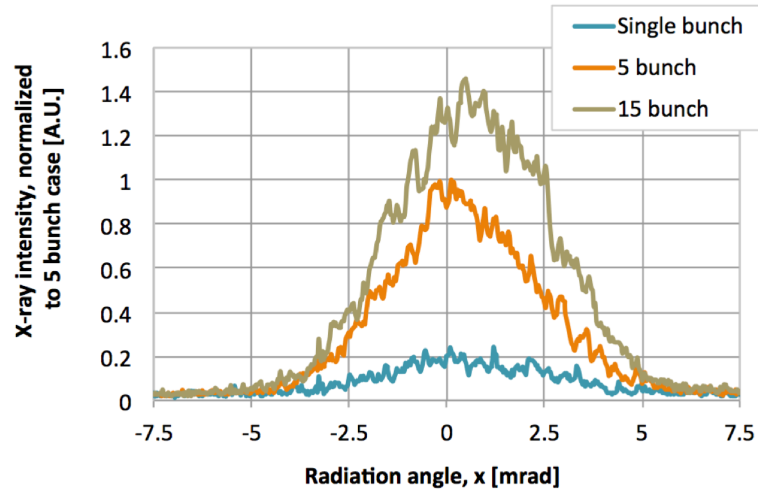
- *Uniqueness* – light sources do not reach MeV energies
- *Tunability and high spectral brightness*
- *High efficiency* at high energy $E_{ph}/E_e \sim\gamma$
- Favorable transverse *brightness* scaling ($\sim\gamma^3$)
- *Directionality* ($\sim1/\gamma$)



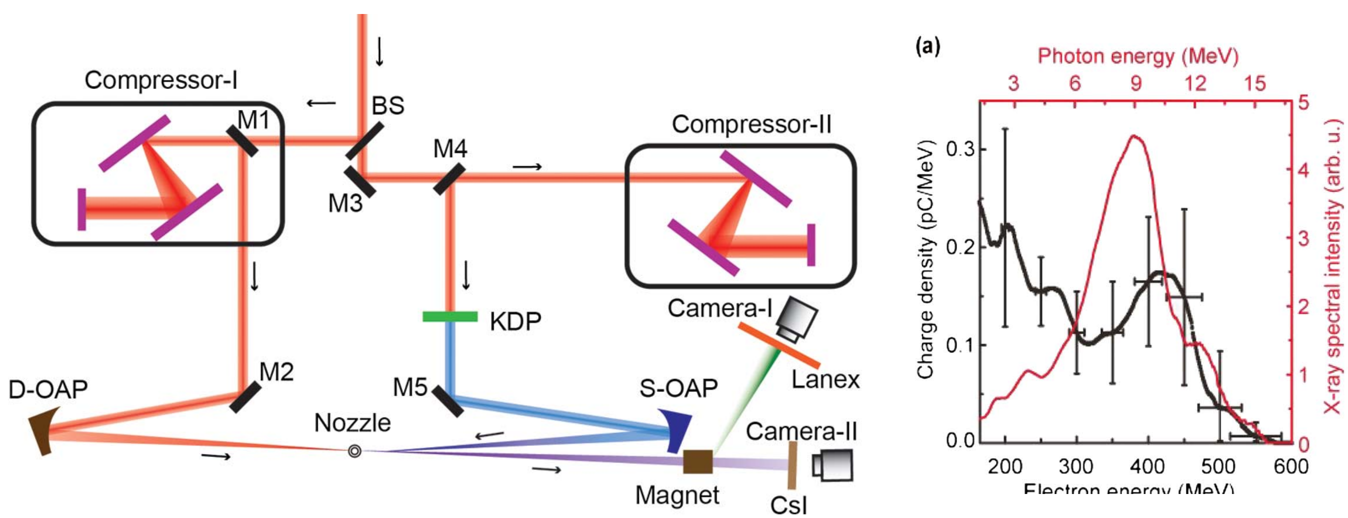
F.V. Hartemann *et al.*, *PR ST AB* **8**, 100702, 2005

ICS features yet to be shown at the same time

- High flux
  - Maximized single shot intensity
  - High rep. rate
- Compactness

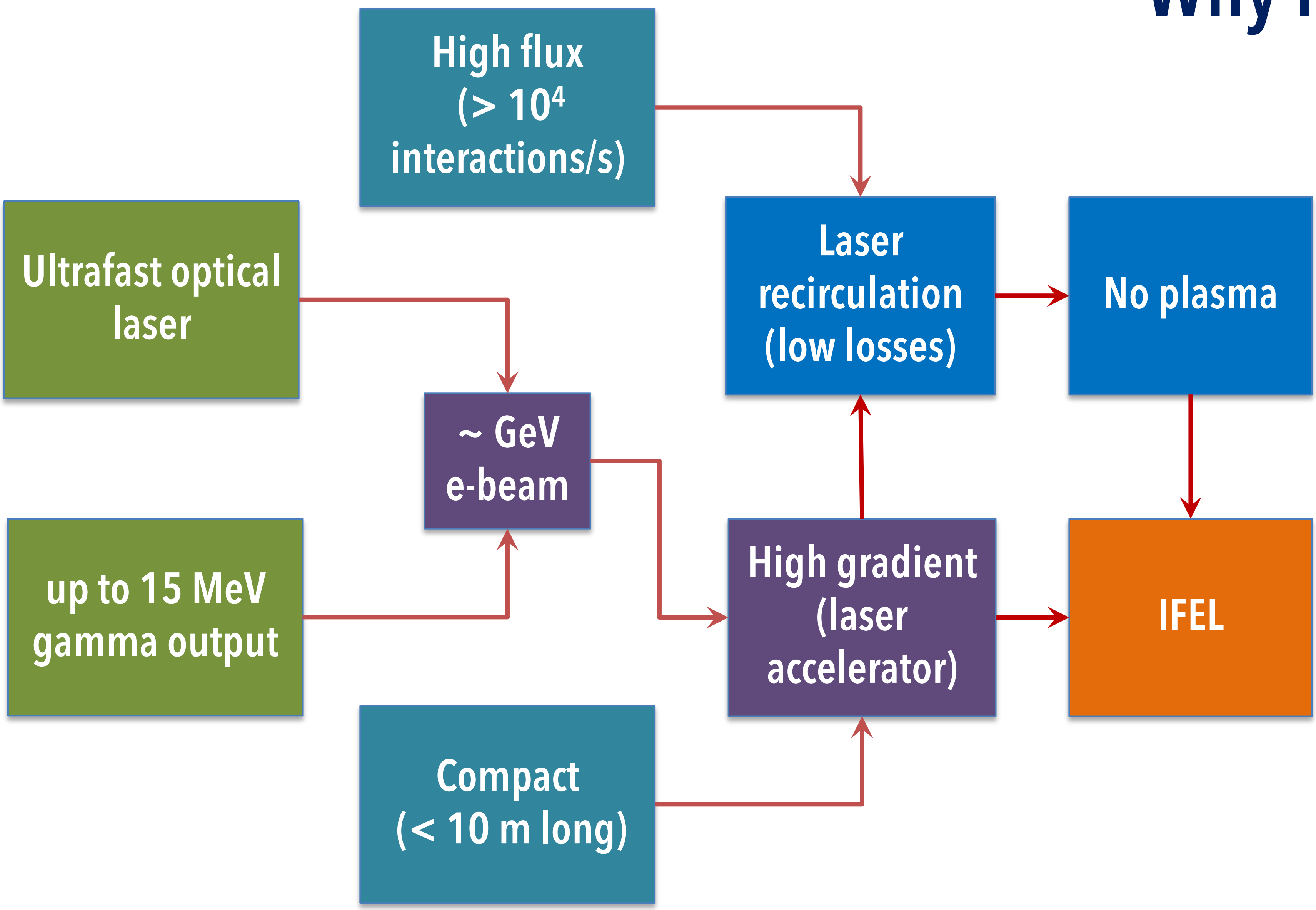


A. Ovodenko et al., Appl. Phys. Lett. **109**, 253504 (2016)



C. Liu et al. Opt. Lett. **39** (14), 4132 (2014).

Why IFEL?


High flux
(> 10^4 interactions/s)
Ultrafast optical laser
~ GeV e-beam
up to 15 MeV gamma output
Compact
(< 10 m long)
Laser recirculation
(low losses)
No plasma
High gradient
(laser accelerator)
IFEL

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- Motivation for monochromatic ICS gamma source
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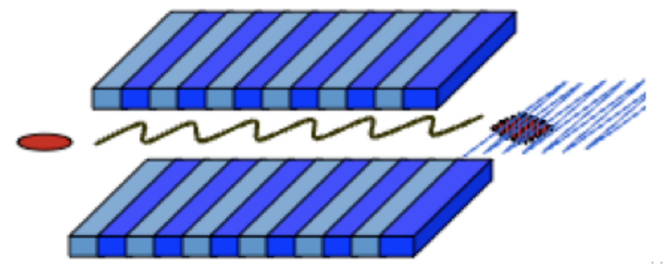
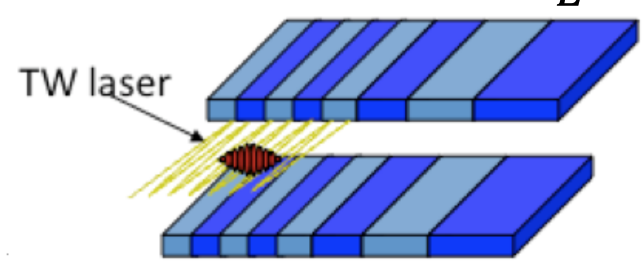
Inverse Free Electron Laser (IFEL)

- Unlike in FEL, to achieve a significant energy exchange rate IFEL employs:
  1) **much higher intensity laser, and**
  2) **a strong tapering undulator**
- IFEL is an in-vacuum accelerator (no losses, high rep rates are possible)
- requires ~10 TW laser to reach GV/m
- the same laser is perfect for ICS

FEL $P_L \propto P_B \rho$



IFEL $P_L > P_B$

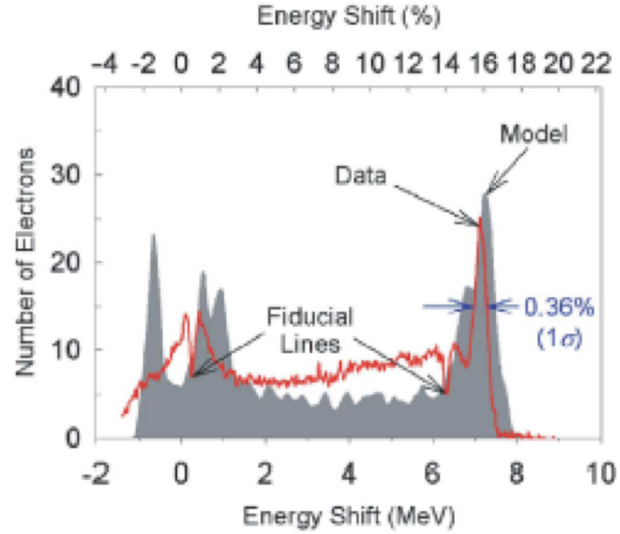


R.B. Palmer, *J. Appl. Phys.* **43**, 3014 (1972).

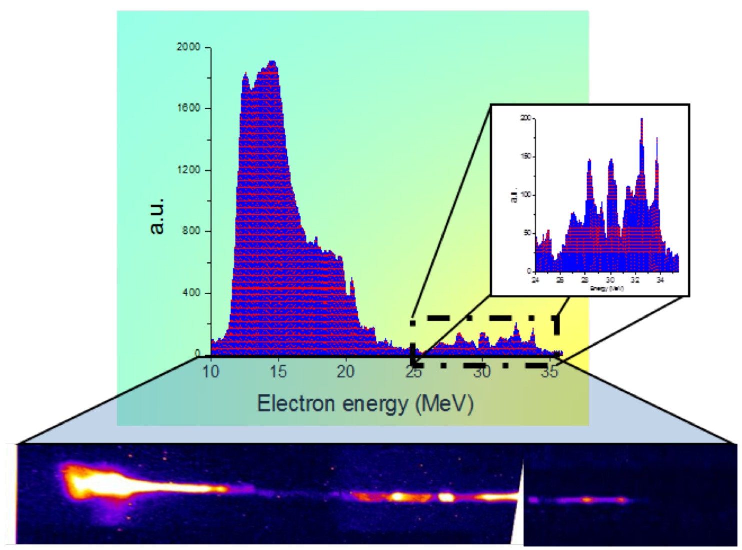
E. D. Courant, C. Pellegrini, and W. Zakowicz, *Phys. Rev. A* **32**, 2813 (1985).

IFEL proof-of-concept Experiments

- STELLA2 experiment at ATF, BNL **(2001)**
  - Gap tapered undulator
  - 30 GW CO_2 laser (10 μm is a convenient wavelength for IFEL)
  - Staged prebuncher + accelerator
  - Good capture
- UCLA Neptune IFEL experiment **(2003)**
  - Strongly tapered period and amplitude
  - 400 GW CO2 laser
  - Accelerating gradient up to 75 MeV/m
- However in 2006 DOE deprioritized IFEL R&D due to synchrotron radiation losses at TeV energies



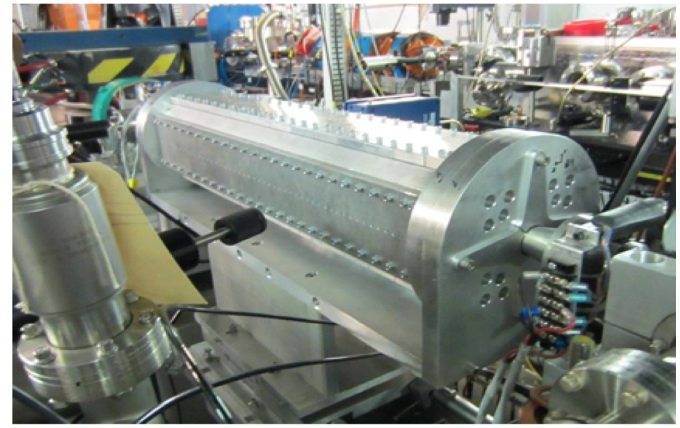
W. Kimura et al. PRL **92**, 054801 (2004)

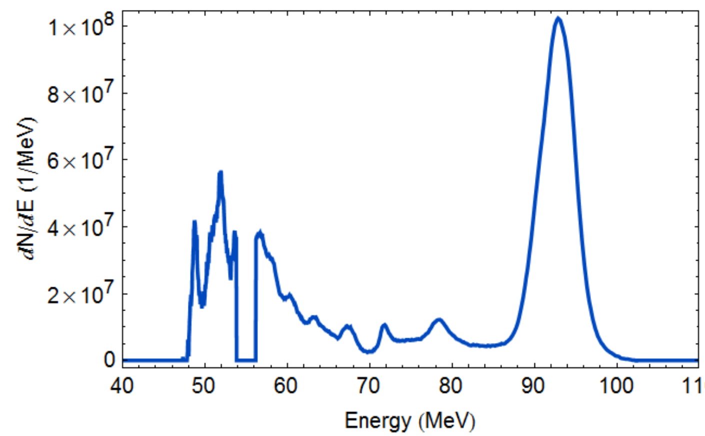


P. Musumeci et al. PRL **94**, 154801 (2005)

RUBICON

- RUBICON demonstrated 100 MV/m acceleration and ~ 50% capture (2013)
- GeV/m is feasible to achieve in a purpose build system
- Observed high quality beam at the output consistent with ICS requirements





UCLA results from RUBICON experiments
J. Duris et al, *Nature Comm*. **5**, 4928, 2014

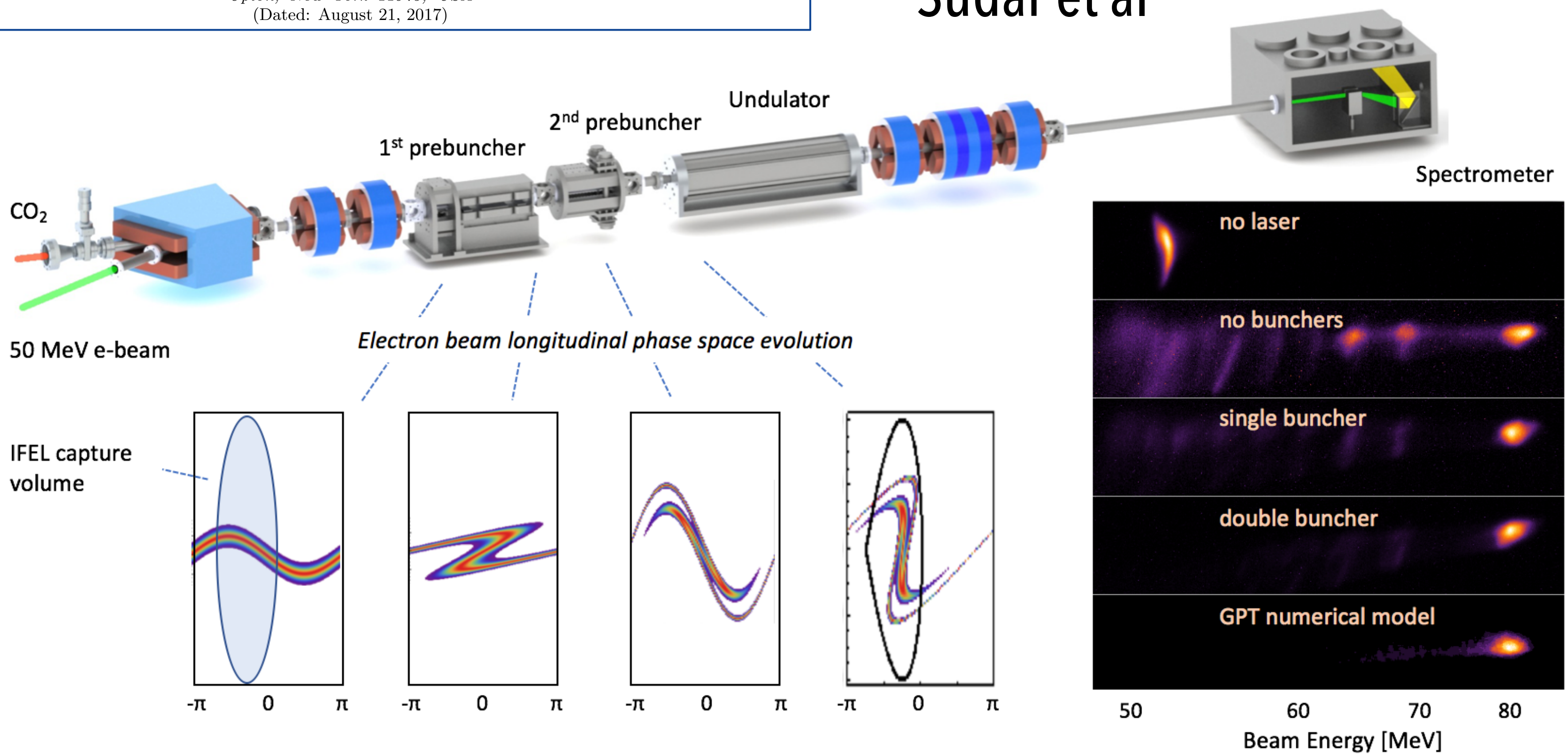
Double prebuncher

Demonstration of cascaded modulator-chicane micro-bunching of a relativistic electron beam

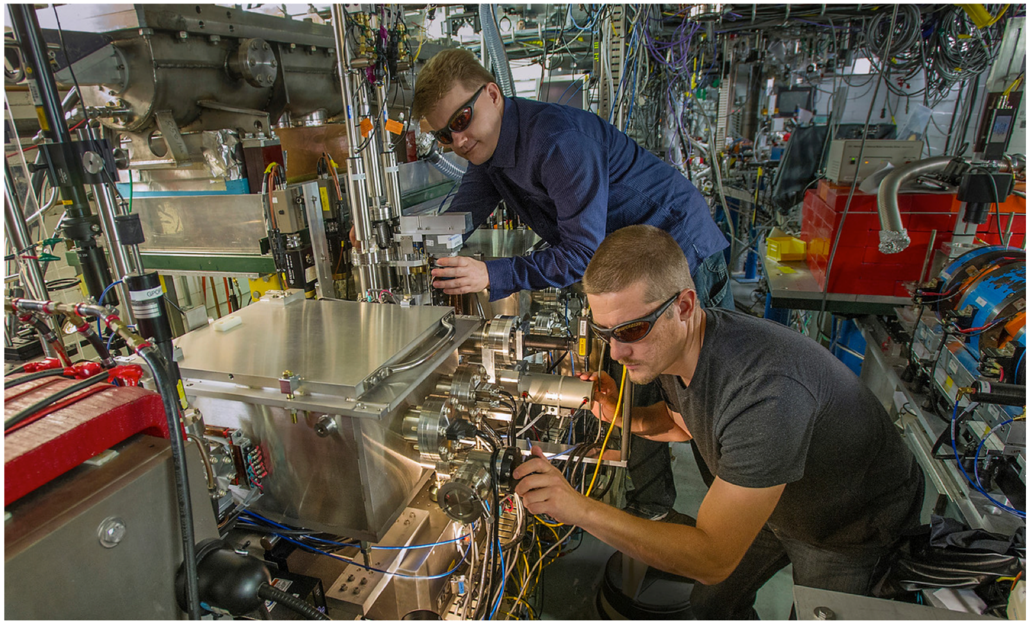
N. Sudar, P. Musumeci, I. Gadjev, Y. Sakai, S. Fabbri
Particle Beam Physics Laboratory,
Department of Physics and Astronomy University of California Los Angeles
Los Angeles, California 90095, USA

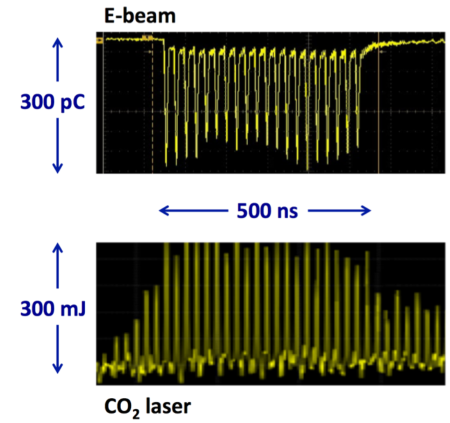
M. Polyanskiy, I. Pogorelsky, M. Fedurin, C. Swinson, K. Kusche, M. Babzien, M. Palmer
Accelerator Test Facility Brookhaven National Laboratory
Upton, New York 11973, USA
(Dated: August 21, 2017)

- Double buncher enabled improving IFEL capture to >80%
- Recently demonstrated by N. Sudar et al

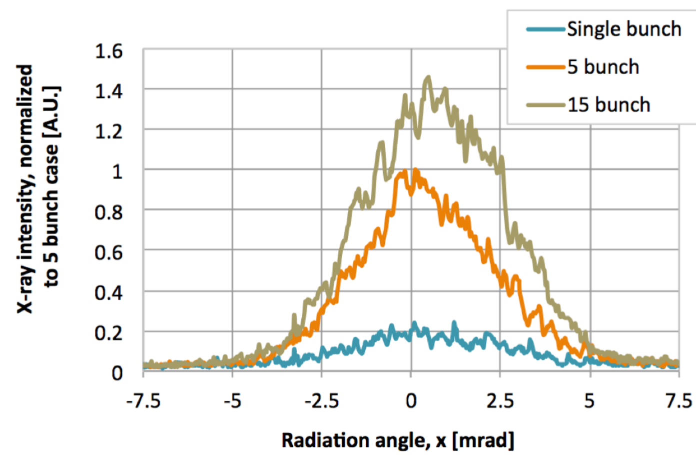


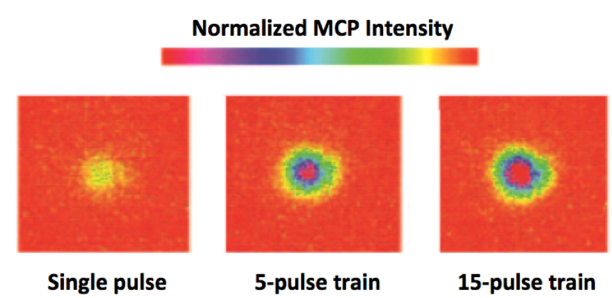
Recirculated ICS experiment





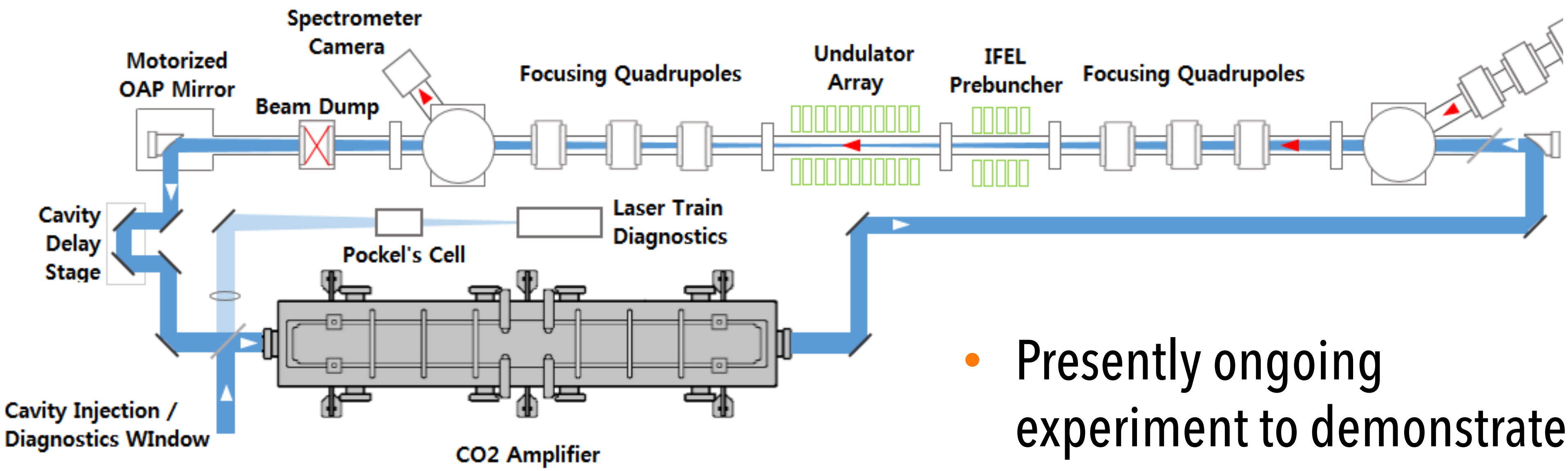
A. Ovodenko et al., Appl. Phys. Lett. **109**, 253504 (2016)

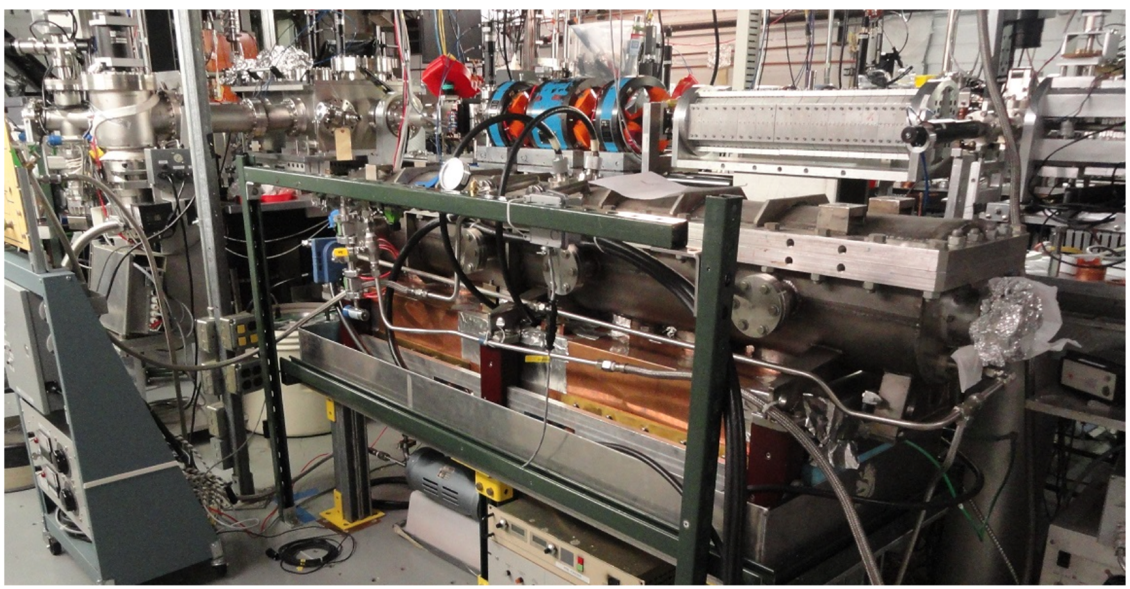




- Used CO2 active cavity to study ICS in a pulse train regime (40 MHz)
- Demonstration for the first time of the significant ICS photon yield gain via pulse train interaction (2015)

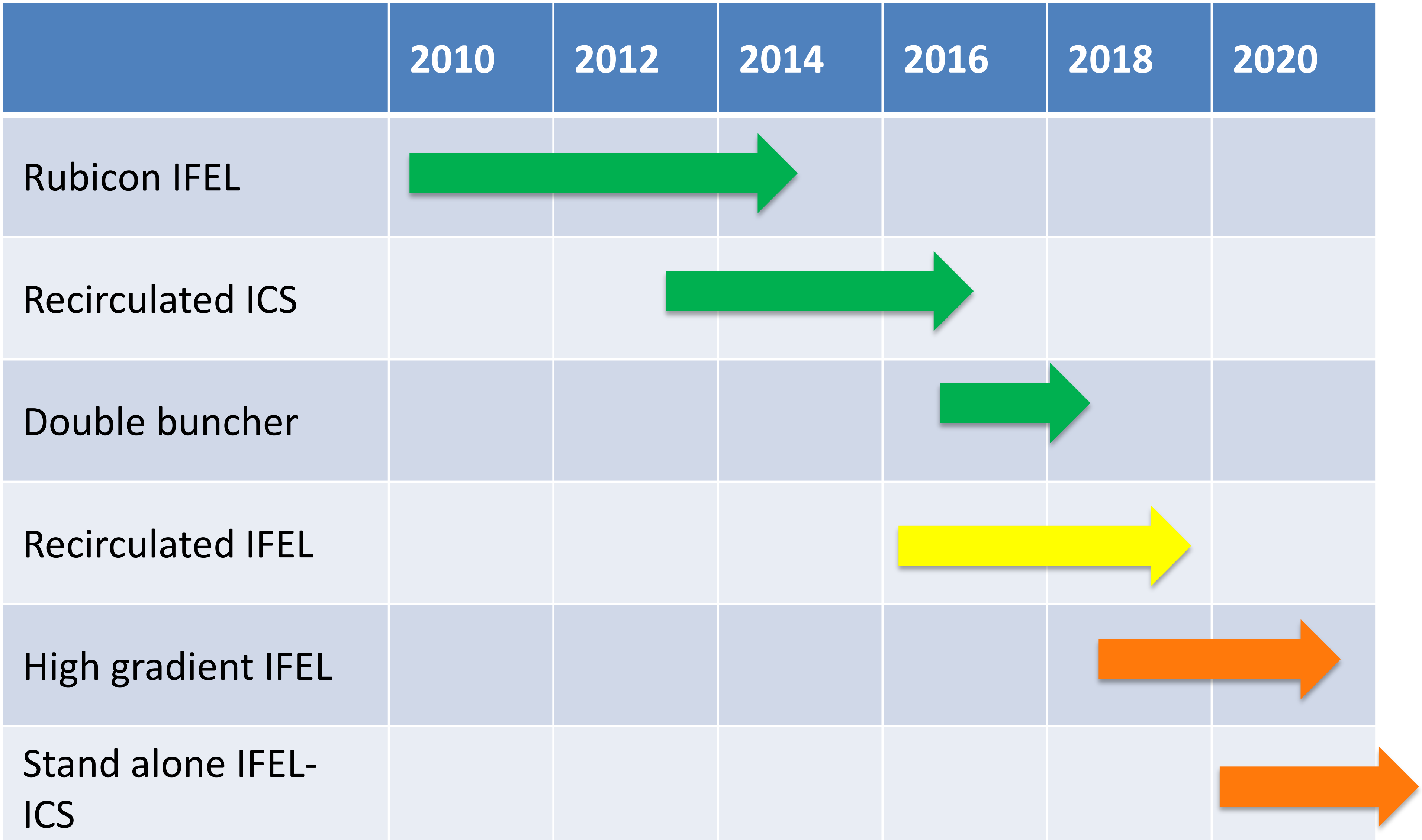
Recirculated IFEL (work in progress)





- Presently ongoing experiment to demonstrate pulse train IFEL at 20 MHz
- Collaboration of RadiaBeam, UCLA and BNL (2017-18)
- A necessary step before developing a combined IFEL –ICS gamma ray source

IFEL-ICS gamma ray source summary



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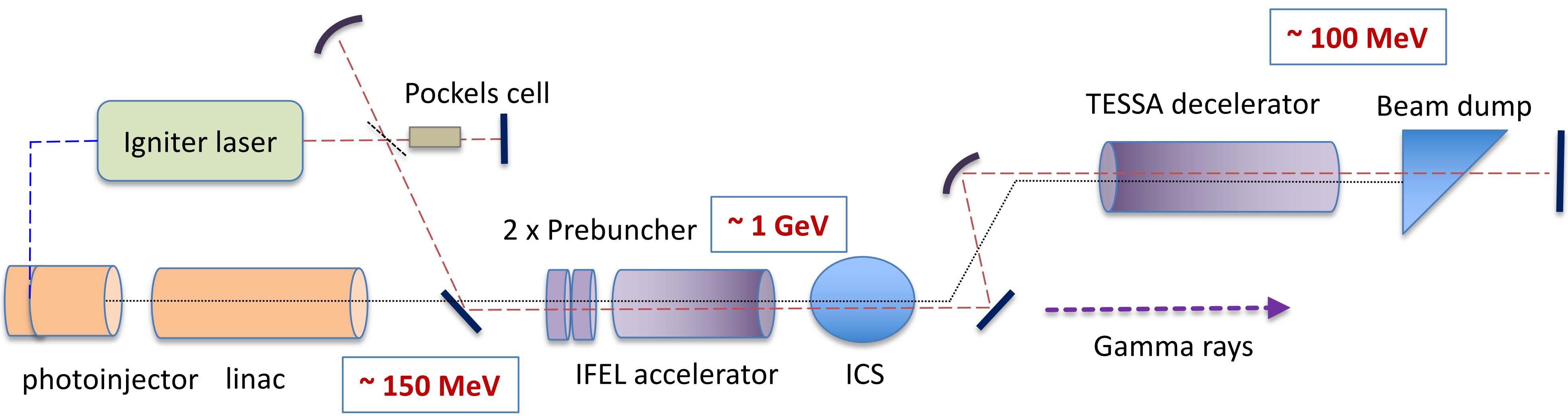
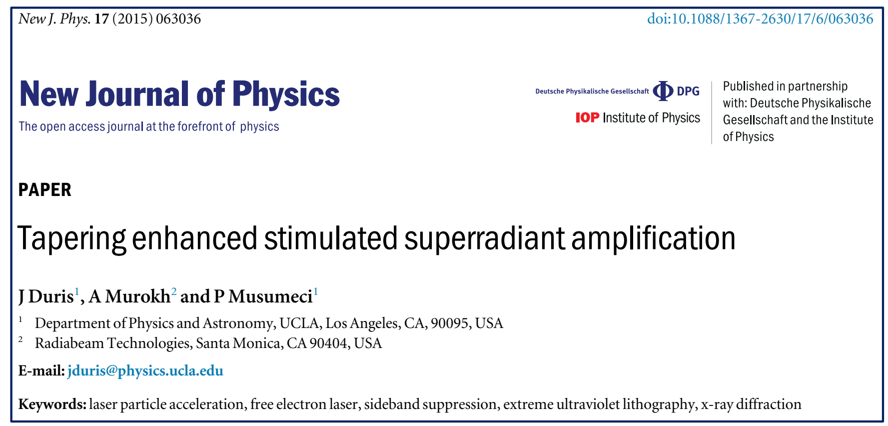
5. TESSA decelerator for laser power recovery

- Limited flux
- Pulse trains require substantial laser development
- GeV beam dump



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 IFEL


New J. Phys. 17 (2015) 063036
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PAPER

Tapering enhanced stimulated superradiant amplification

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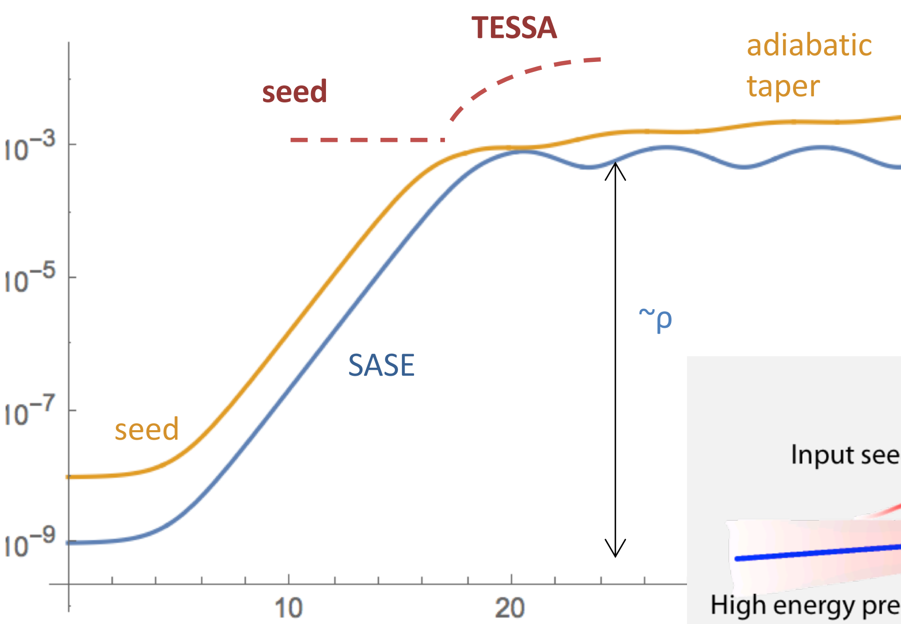
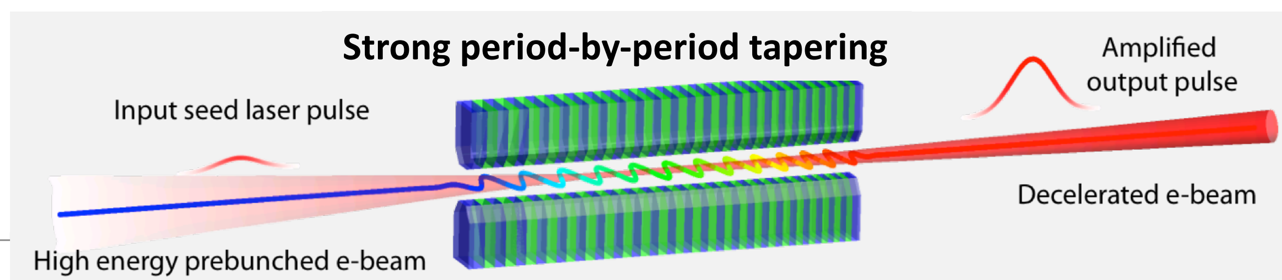
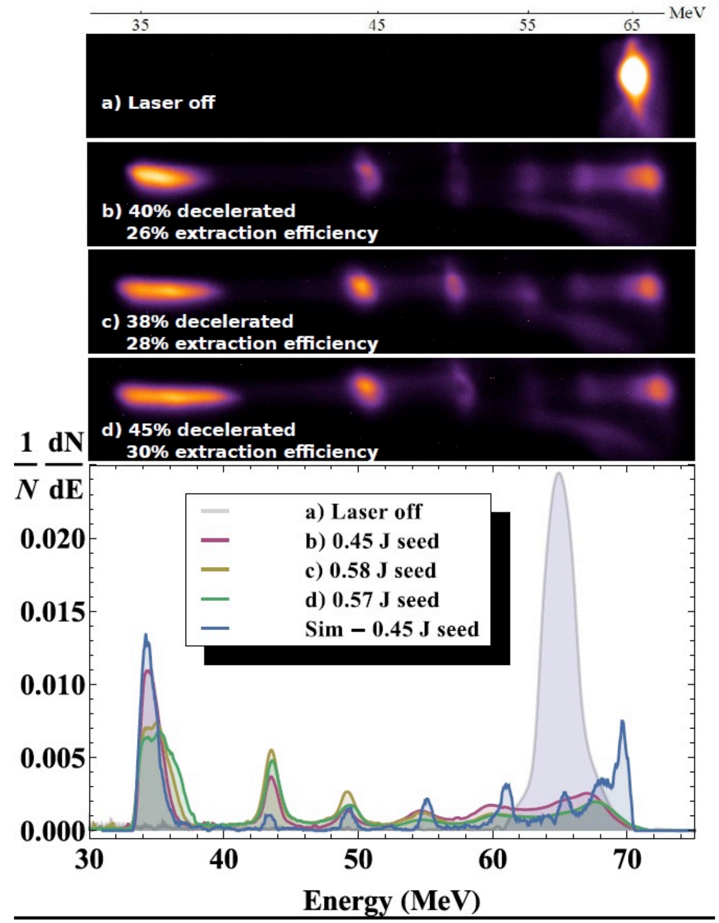
Keywords: laser particle acceleration, free electron laser, sideband suppression, extreme ultraviolet lithography, x-ray diffraction

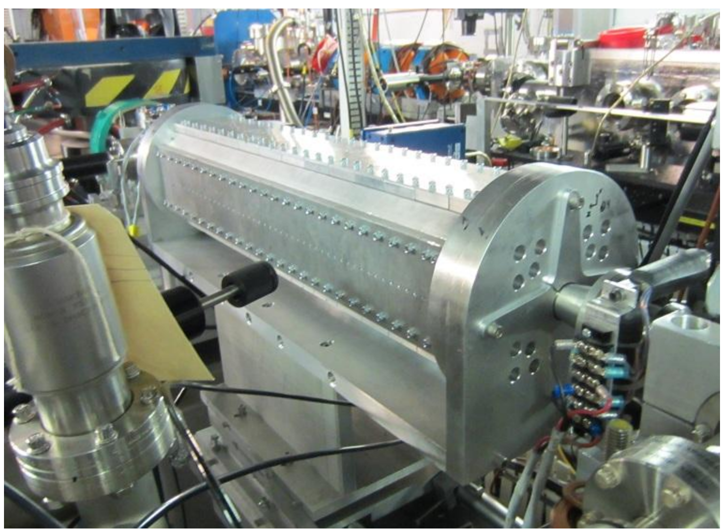




TESSA proof-of-concept experiment

- Numerical studies at 13.5 nm are very promising
- Pilot experimental test was carried out by UCLA at BNL ATF at 10 μm
- Demonstrated > 30% energy extraction from the electron beam in a 50 cm undulator !





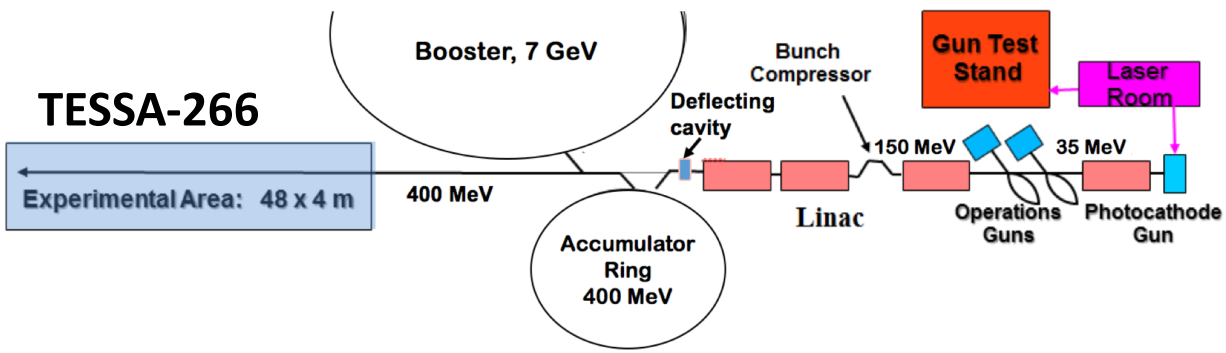
PRL **117**, 174801 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

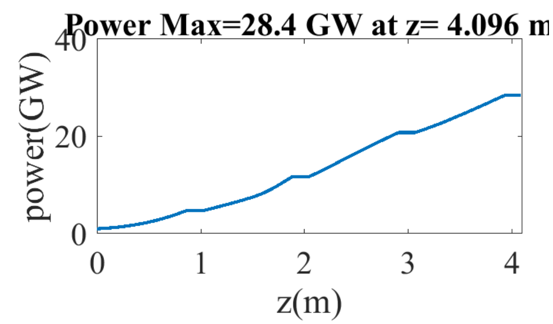
High Efficiency Energy Extraction from a Relativistic Electron Beam in a Strongly Tapered Undulator

N. Sudar, P. Musumeci, J. Duris, and I. Gadjev
Particle Beam Physics Laboratory, Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095, USA

TESSA-266

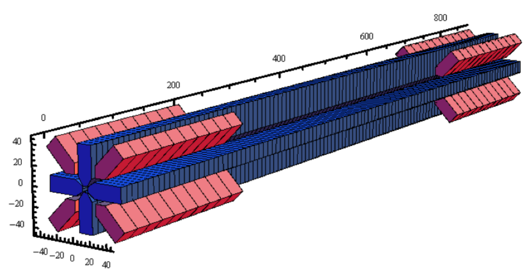
- Next goal is to show high gain amplification and study system dynamics and optimization experimentally at a shorter (and friendlier) wavelength
- The site of the experiment is LEA tunnel at Argonne (former LEUTL)
- A thorough design study for TESSA-266 is underway in collaboration with UCLA, Argonne, and RadiaSoft

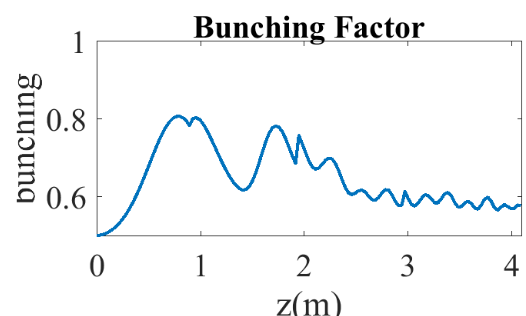




TESSA Electron Beam Requirements

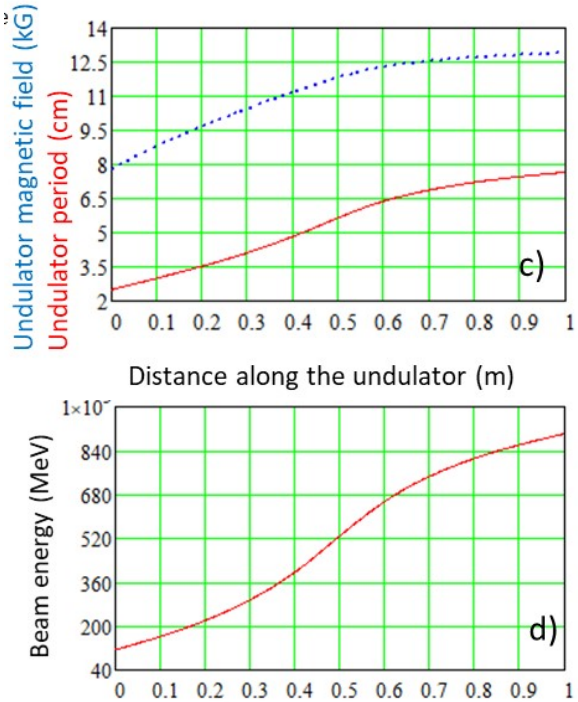
Property	Value
Energy	300 MeV
Energy Spread	0.02 % to 0.1 %
Peak Current	1 kA
Emittance (Normalized)	2 μm
spot size (rms)	30 μm to 40 μm
$\beta_{x,y}$	0.54 m to 1 m

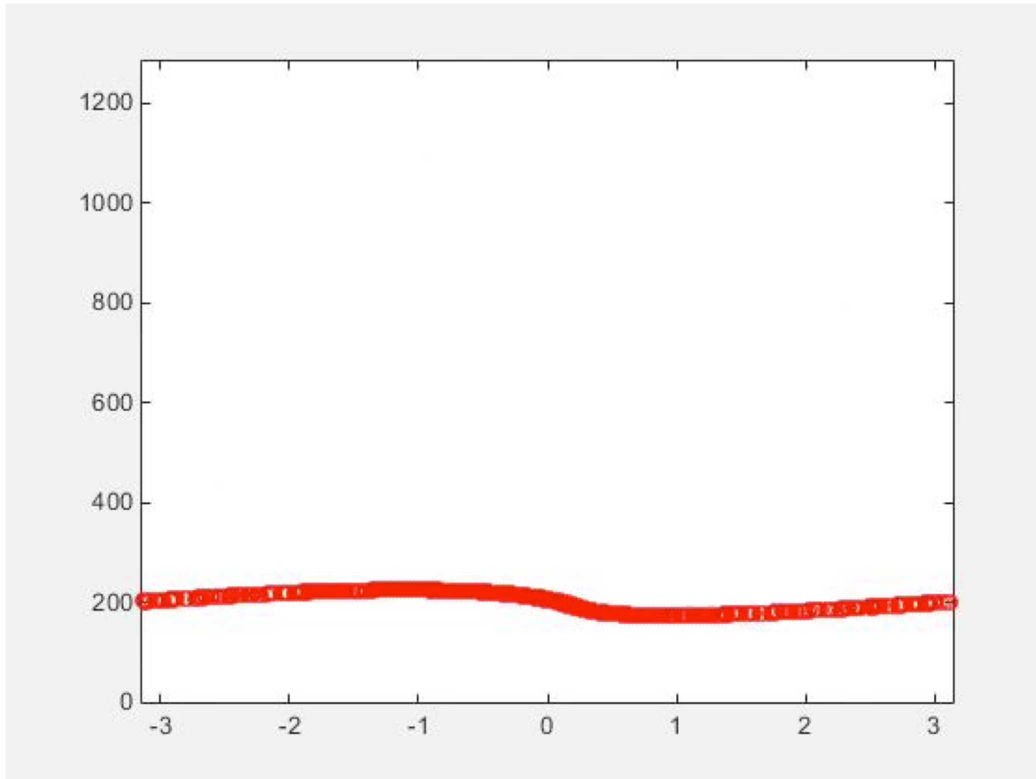




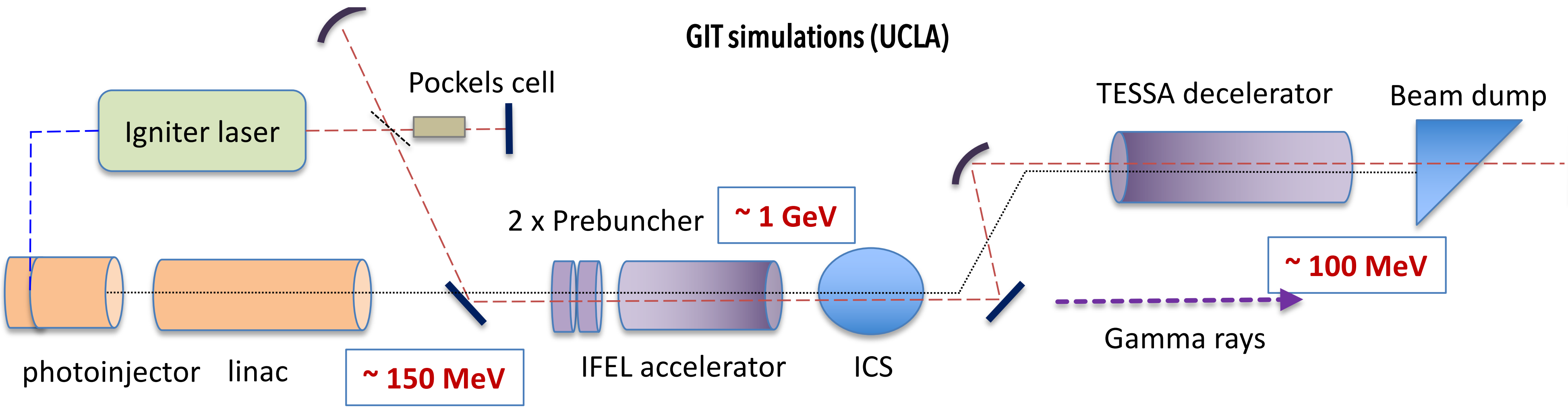
15% efficiency in 4 m

IFEL+TESSA

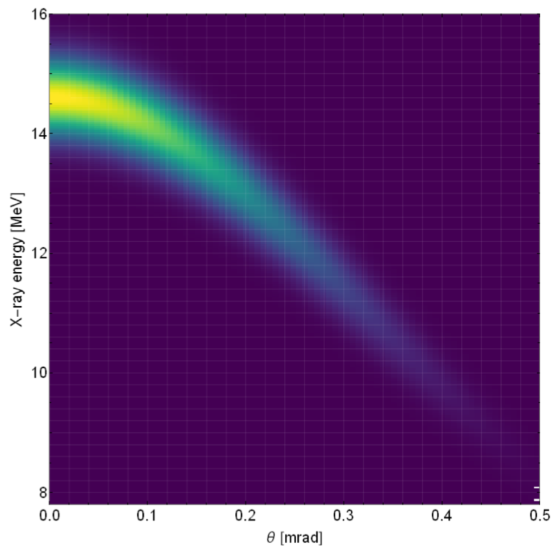




GIT simulations (UCLA)



ICS design study

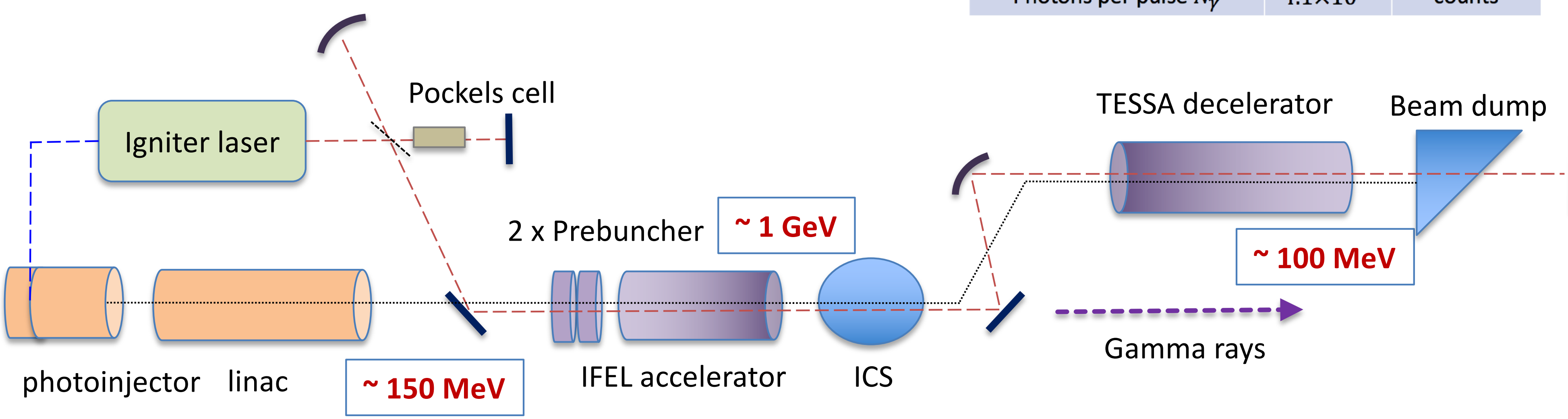


- 4 x 10^8 ph/shot
- 100 Hz
- 100 pulses per train
- 4 x 10^{12} ph/s
- ~ 10^{11}ph/s in 1% BW

Electron beam	Value	Units
Normalized emittance ϵ_n	0.2	mm-mrad
Transverse size σ_x	10	µm
Energy E	900	MeV
Energy Spread $\Delta E/E$	10^{-4}	-
Charge	0.125	nC
Bunch length σ_z	200	fs

Laser	Value	Units
Transverse size w_0	20	µm
Pulse Energy	1	J
Wavelength λ_L	1053	nm
Pulse length	200	fs

Gamma-rays	Value	Units
Opening angle	8	mrad
Central energy	14.6	MeV
Photons per pulse N_γ	4.1×10^8	counts



Conclusions and Acknowledgement

- Compact tunable gamma ray source could find multiple applications
- IFEL driver uniquely enables high flux and compact geometry at the same time
- IFEL accelerator combined with decelerator (TESSA) enables laser energy recovery and very high repetition rates
- Acknowledgement for contributions and useful discussions:
  - P. Musumeci, J. Rosenzweig (UCLA)
  - J. Byrd, S. Zholents (APS)
  - A. Courjaud, P.-M. Paul (Amplitude)

- Thank you !

If anyone is interested in visiting RadiaBeam on Friday after the workshop we are somewhat on the way to LAX, in Santa Monica on Stewart & Olympic

There will be BBQ