Optical Energy Recovery Linac ICS Gamma-ray Source

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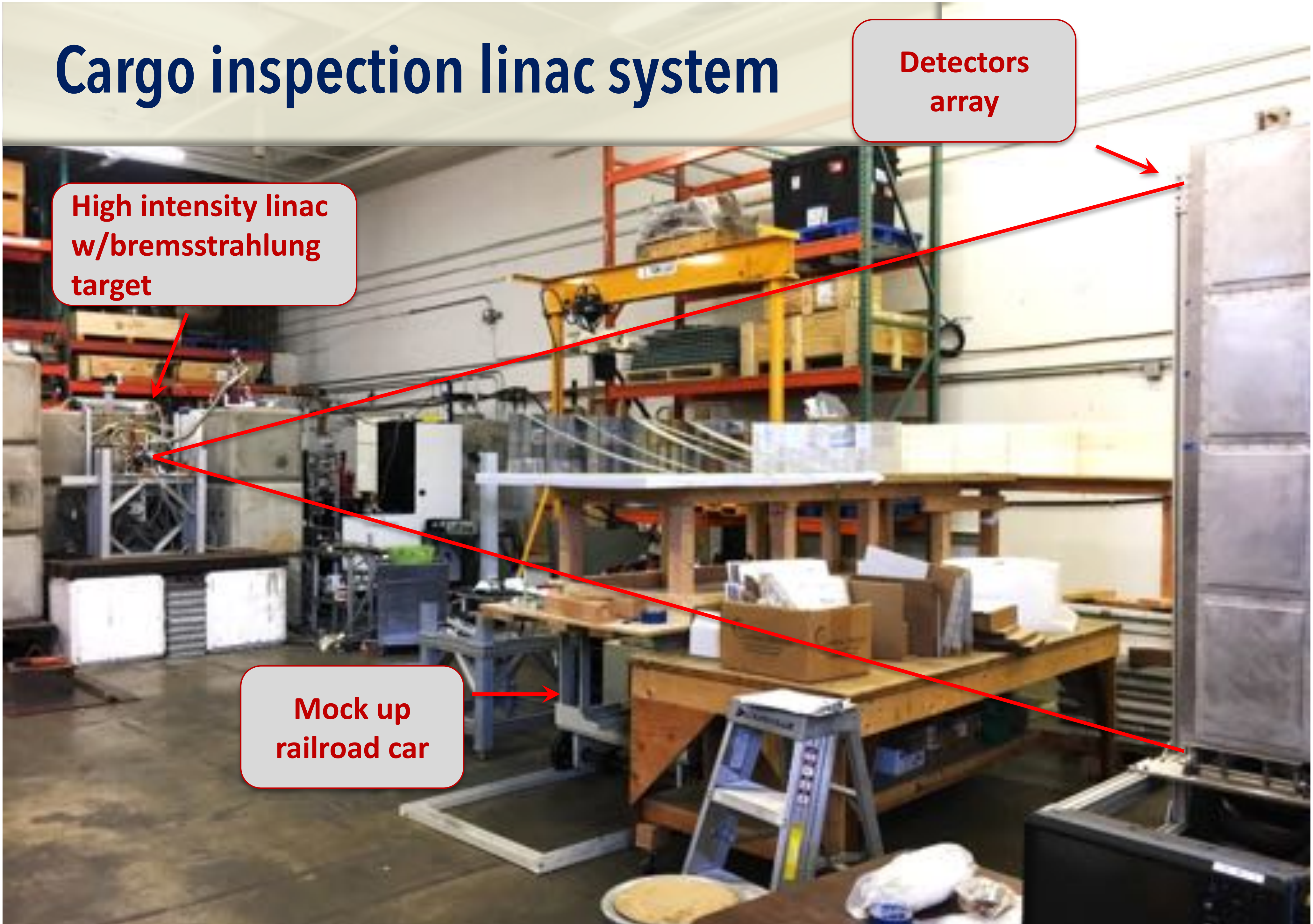
RadiaBeam Technologies LLC.

June 24 – 29, 2018,
Brasov, Romania

Outline

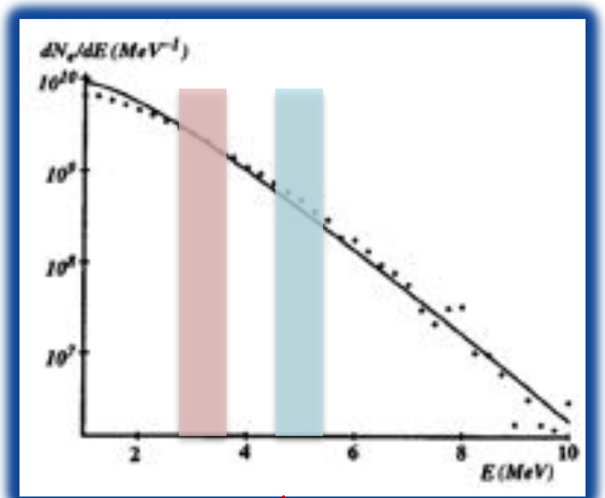
- Introduction
- Inverse FEL ICS driver
- IFEL-based optical energy recovery ICS source

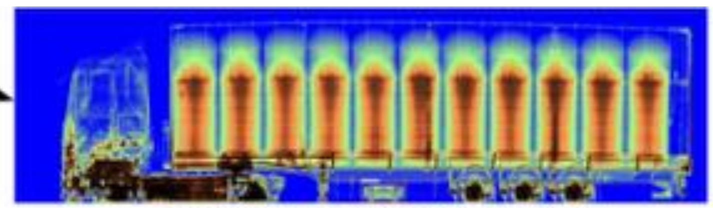
Cargo inspection linac system



Disadvantages of the bremsstrahlung source

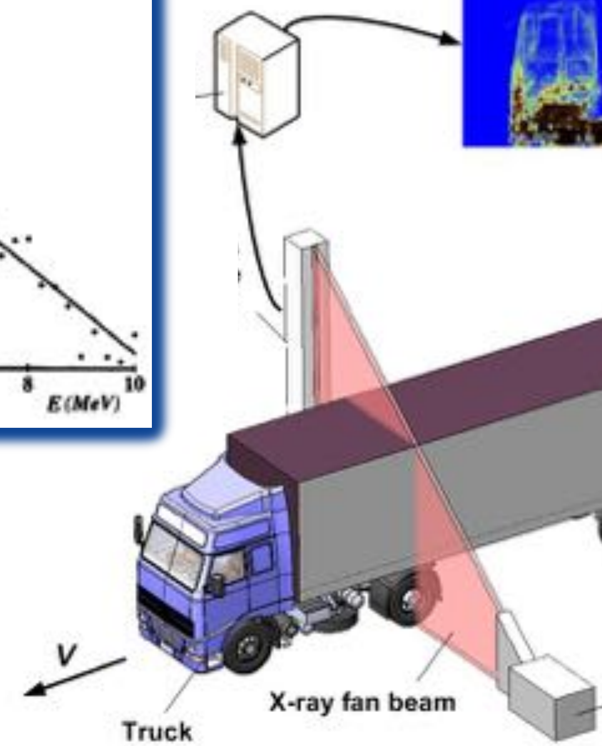
- Materials differentiation requires multi-color imaging
- Bremsstrahlung target produces continuous spectrum





Pseudo-color radiographic image

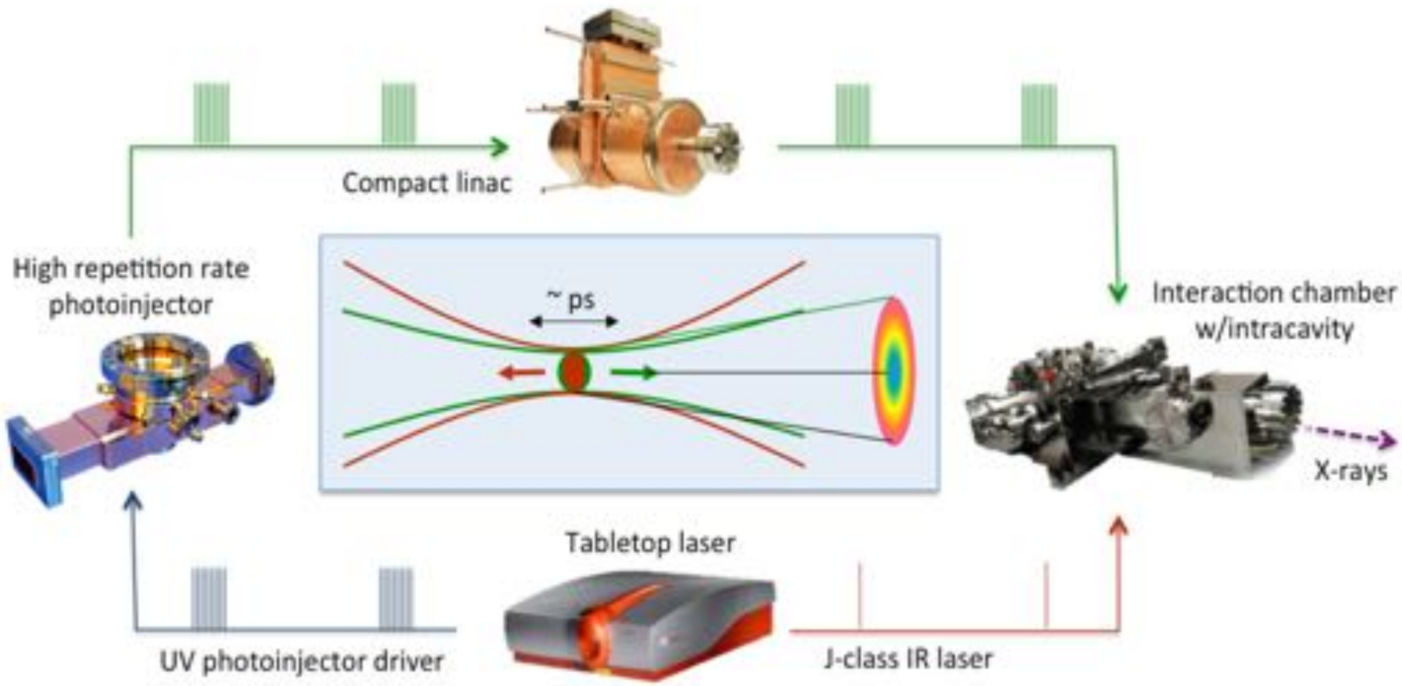
Excessive dose on target



No stand off capability

Large exclusion zone

Inverse Compton Scattering (ICS) value proposition

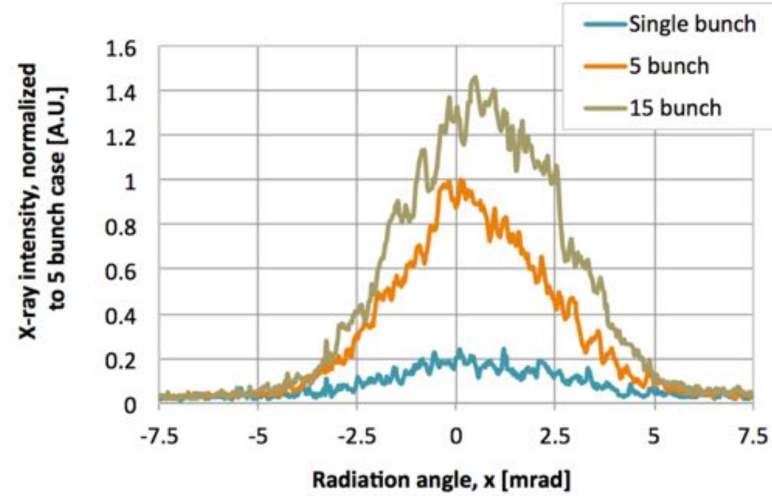


- *Uniqueness* – light sources do not reach MeV energies
- *Tunability and high spectral brightness*
- *High efficiency* at high energy $E_{ph}/E_e \sim\gamma$
- Favorable transverse *brightness* scaling $(\sim\gamma^3)$
- *Directionality* $(\sim 1/\gamma)$

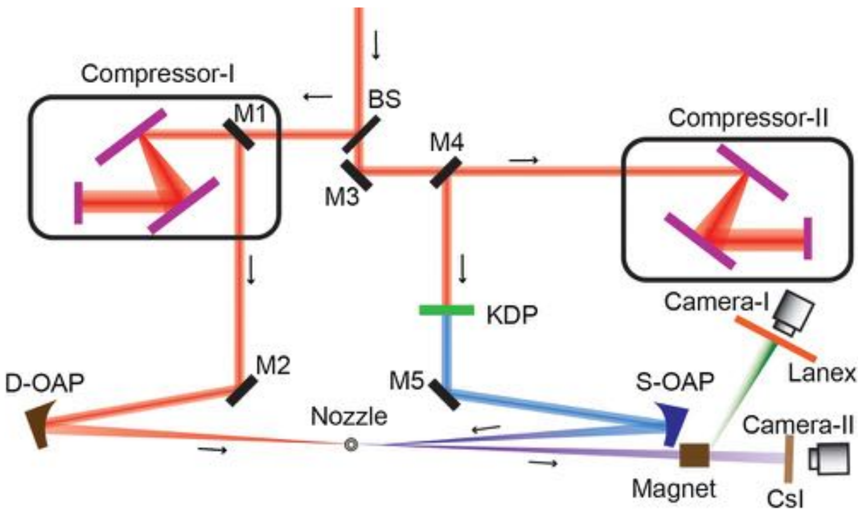
ICS challenges

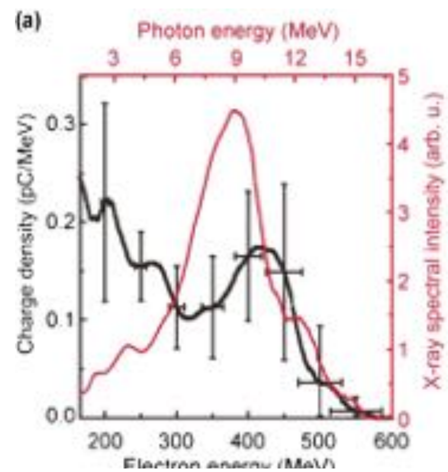
The key ICS features yet to be achieved simultaneously are:

- High flux (pulse train interaction)
  - Maximized single shot intensity
  - High rep. rate (laser recycling)
- Compact GeV-class e-beam driver



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





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

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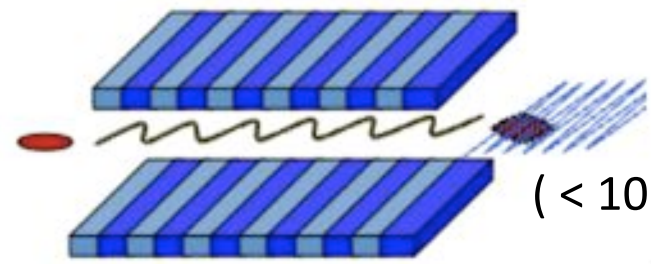
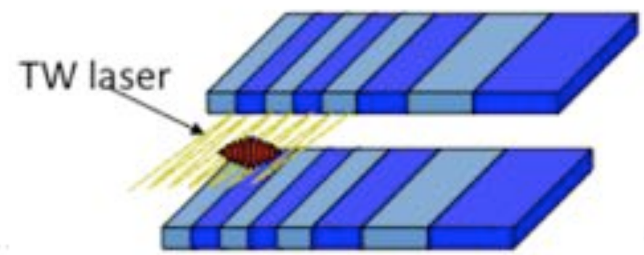
Inverse Free Electron Laser (IFEL)

- Undulator magnet enables resonant electron and laser beam interaction in vacuum (i.e. Free Electron Laser)
- The same principle can be applied for e-beam acceleration (IFEL) by using:
  1) **high intensity laser, and**
  2) **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 $P_L > P_B$

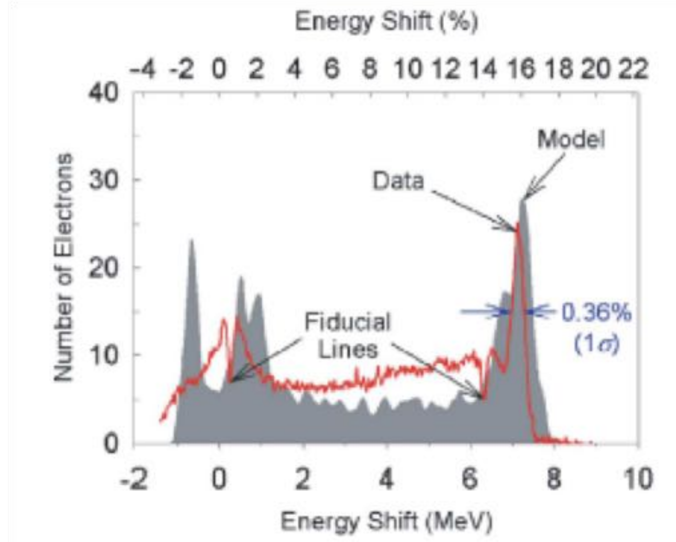


R.B. Palmer, *J. Appl. Phys.* **43**, 3014 (1972).

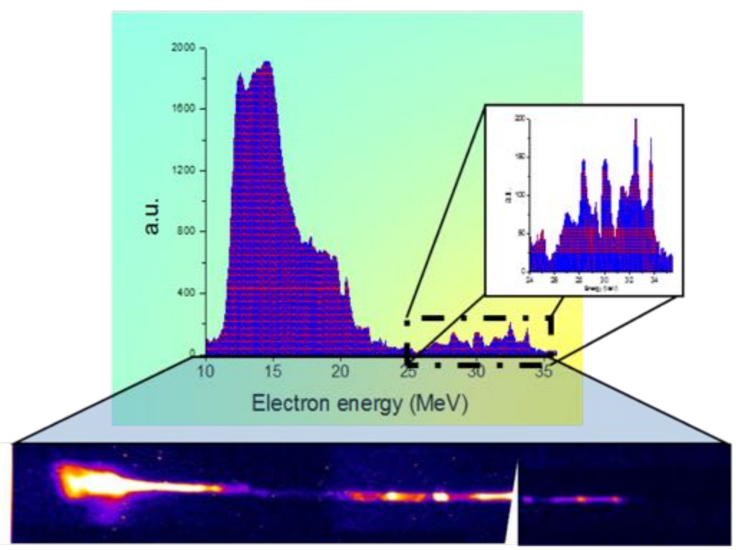
E. D. Courant, C. Pellegrini, and W. Zakowicz, *Phys. Rev. A* **32**, 2813 (1985).

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)

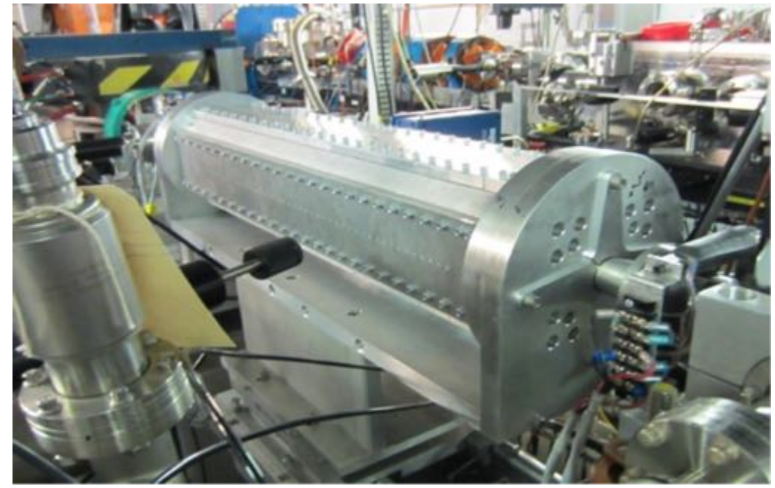


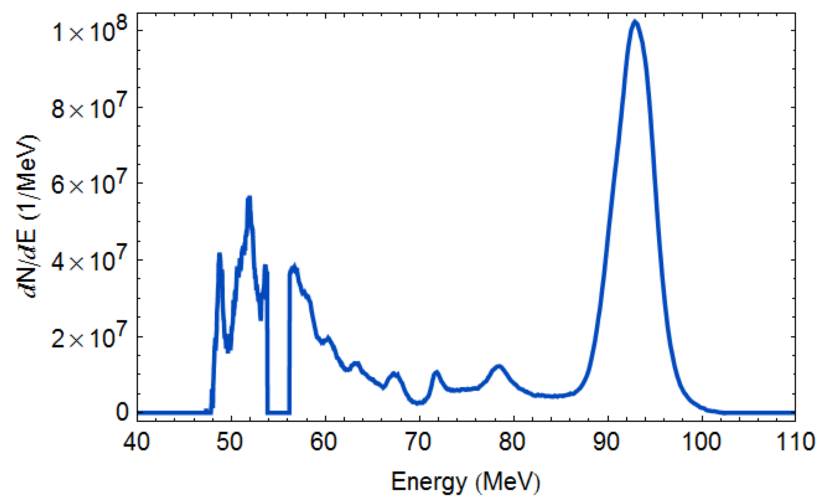
P. Musumeci et al. PRL **94**, 154801 (2005)

RUBICON experiment

(**R**adiaBeam-**U**CLA-**B**NL-**I**FEL-**Co**llabor**a**tio**n**)

- RUBICON demonstrated 100 MV/m acceleration and ~ 50% capture (2013)
- GeV/m is feasible to achieve in a purpose build system
- Relatively high quality beam (~2 μm emittance, 2% ΔE/E) at the output, consistent with ICS requirements





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

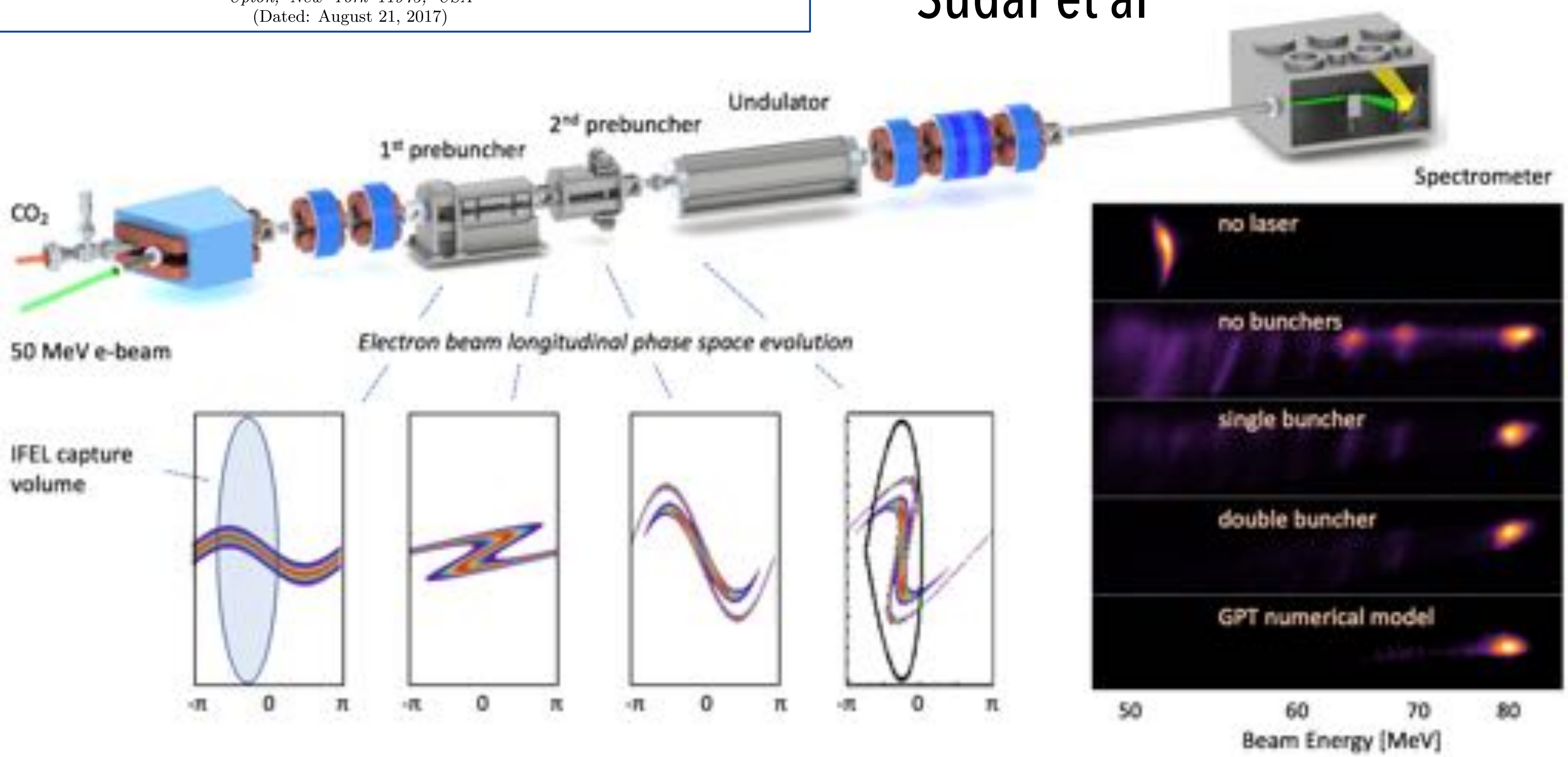
Double prebuncher

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

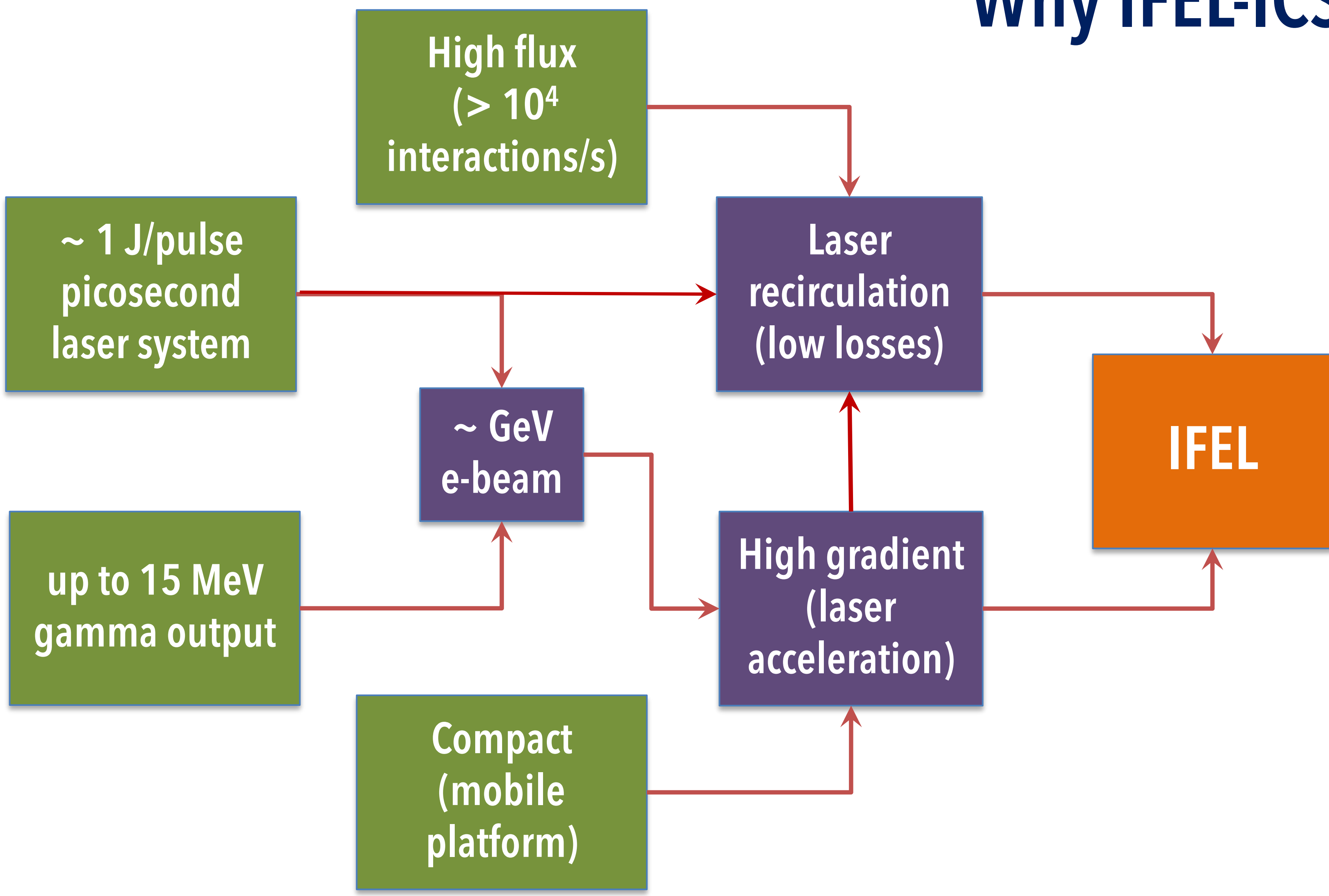
N. Sudar, P. Musumeci, I. Gadjev, Y. Sakai, S. Fabbri
Particle Beam Physics Laboratory,
Department of Physics and Astronomy University of California Los Angeles
Los Angeles, California 90095, USA

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

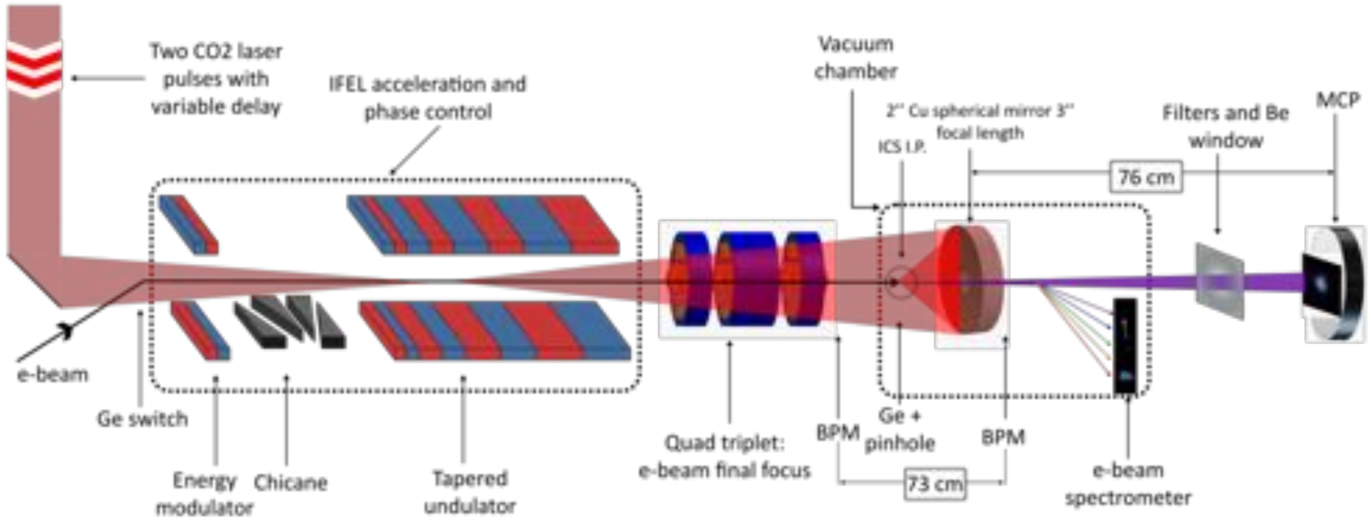


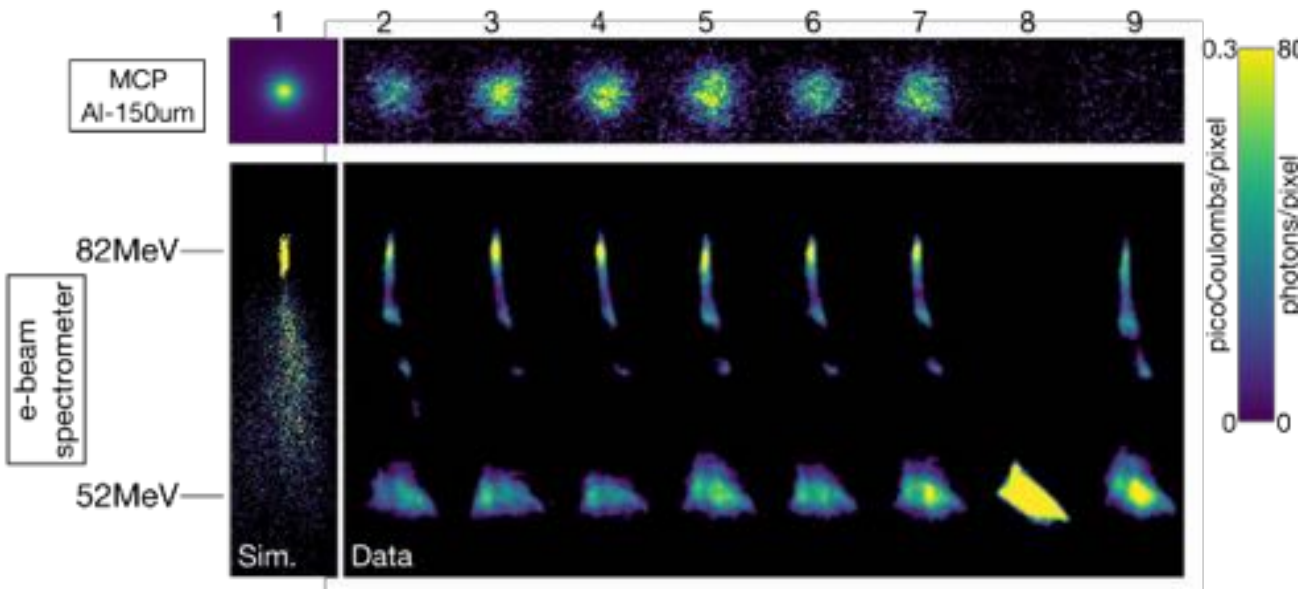
Why IFEL-ICS?


High flux (> 10^4 interactions/s)
~ 1 J/pulse picosecond laser system
Laser recirculation (low losses)
~ GeV e-beam
IFEL
up to 15 MeV gamma output
High gradient (laser acceleration)
Compact (mobile platform)

RUBICON-ICS

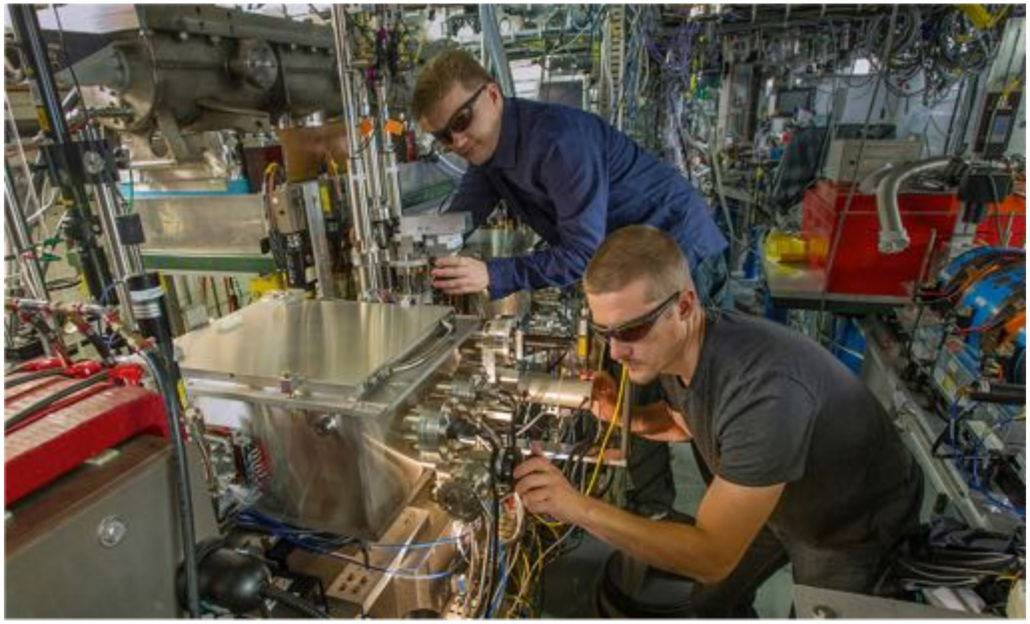
I. Gadjev et al., https://arxiv.org/ftp/arxiv/papers/1711/1711.00974.pdf (2018).

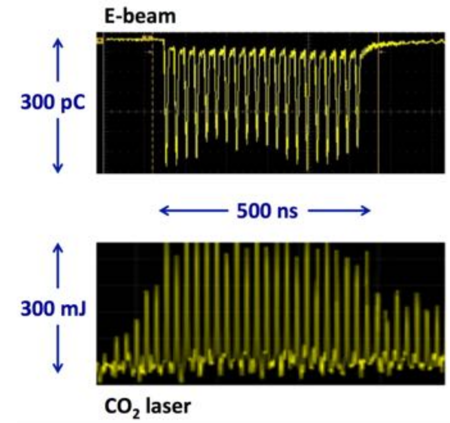




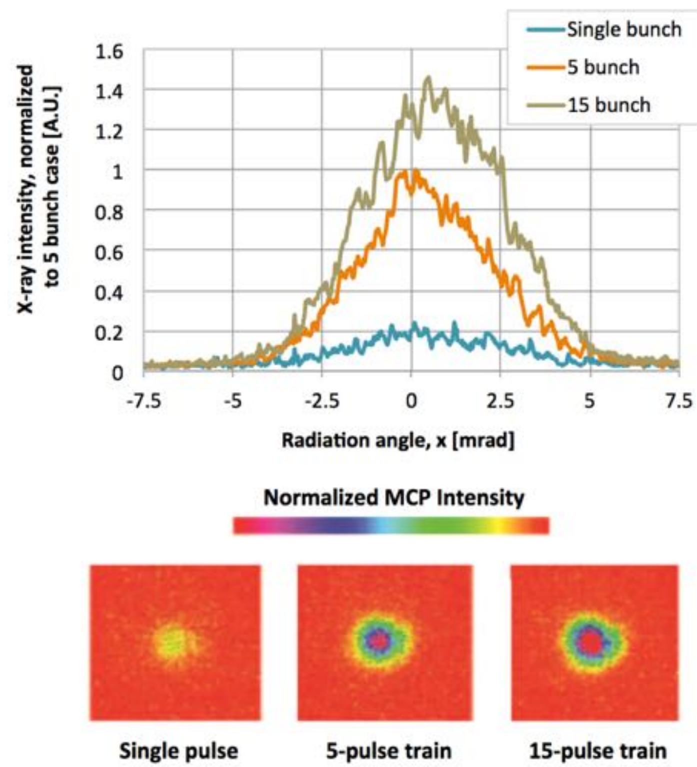
Demonstrated stable generation of 12 keV X-rays by IFEL accelerated electron beam

Recirculated ICS experiment



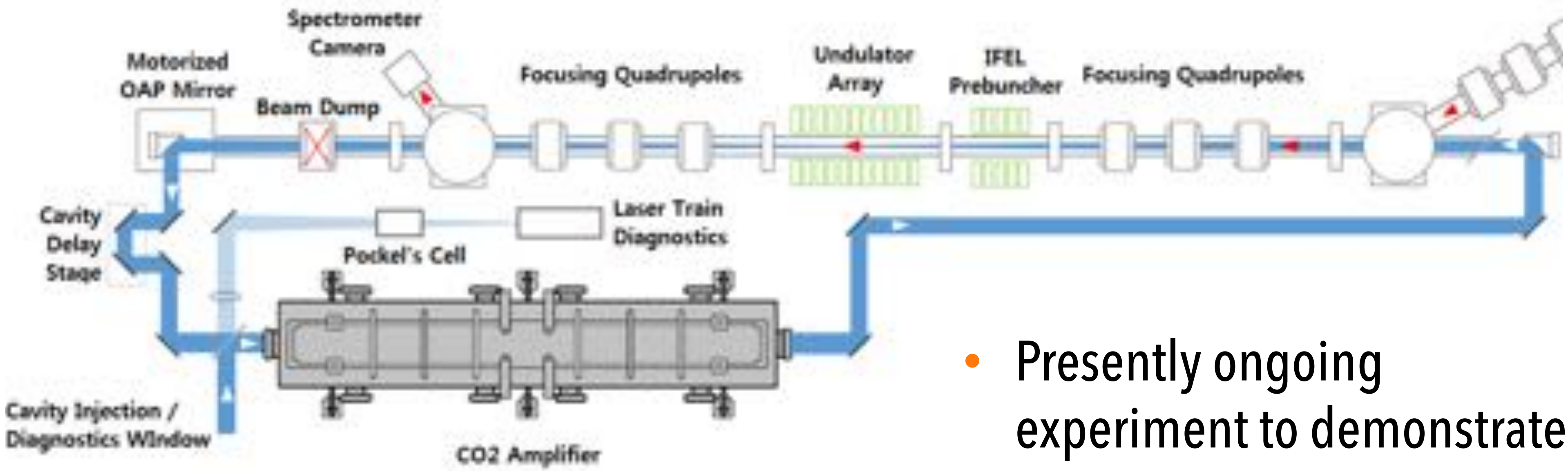


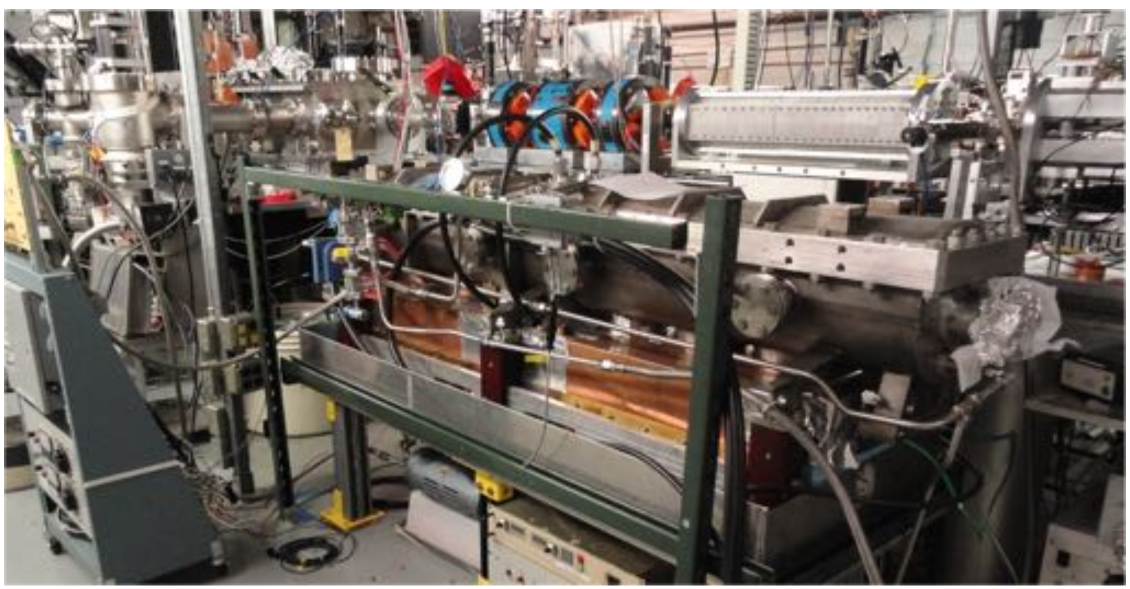
A. Ovodenko et al., Appl. Phys. Lett. **109**, 253504 (2016)



- 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 (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 roadmap

	2010	2012	2014	2016	2018	2020
Rubicon IFEL						
Recirculated ICS						
Double buncher						
IFEL-ICS						
Recirculated IFEL						
High gradient IFEL (~ GeV/m)						

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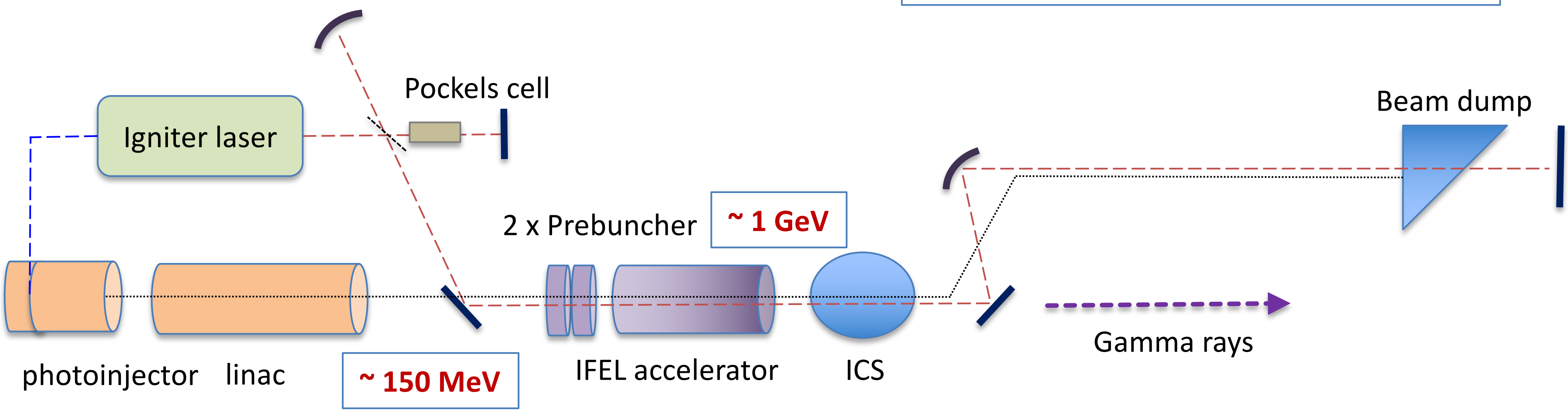
IFEL - ICS Gamma Source

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

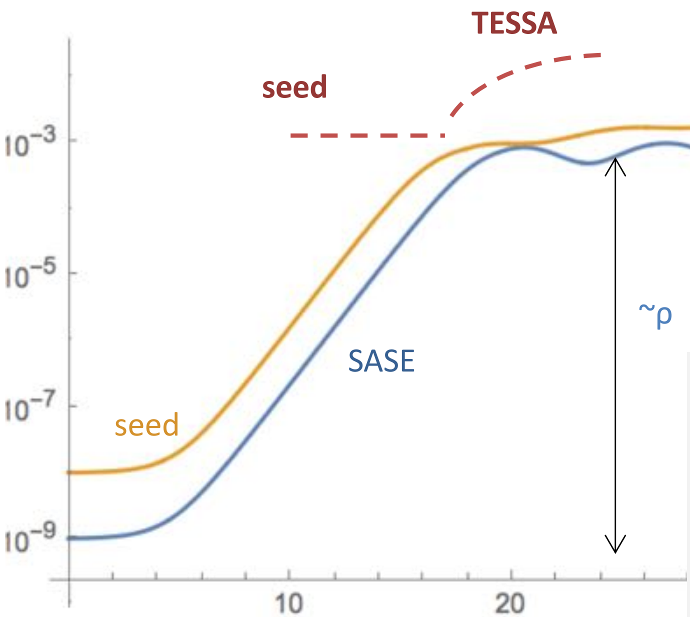
1. NCRF 150 MeV injector operating in pulse train mode
2. ~ 10 TW igniter laser (i.e. 1064 nm)
3. IFEL 1 GeV energy booster stage
4. ICS interaction chamber

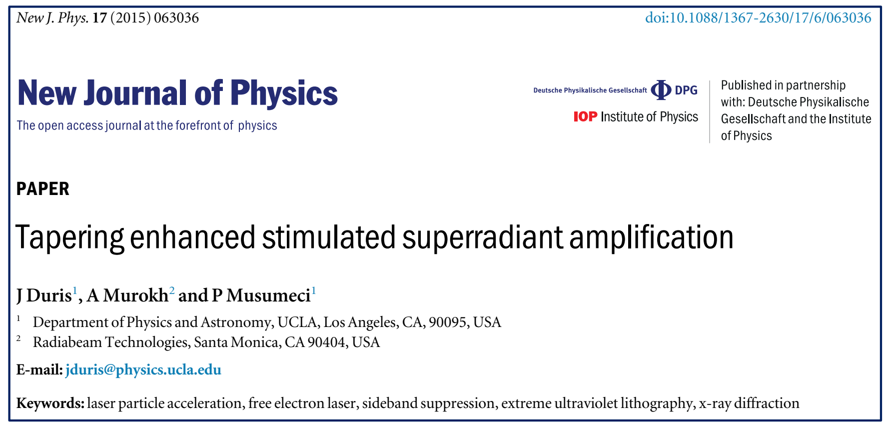
- **Pulse trains require substantial laser development**
- **GeV beam dump**



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 doi:10.1088/1367-2630/17/6/063036

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PAPER

Tapering enhanced stimulated superradiant amplification

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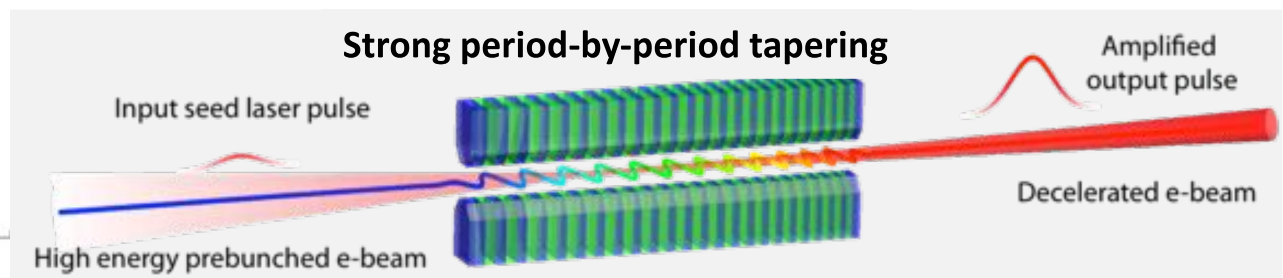
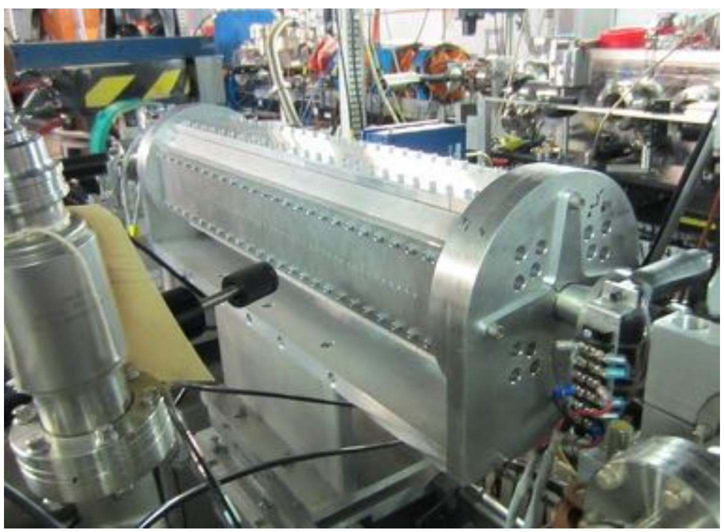
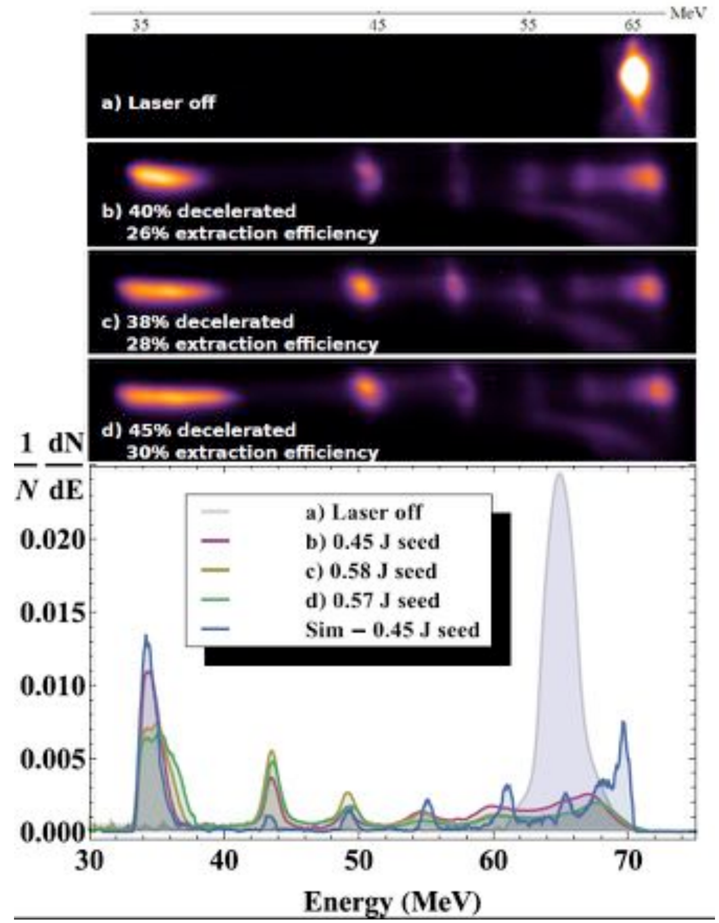
Keywords: laser particle acceleration, free electron laser, sideband suppression, extreme ultraviolet lithography, x-ray diffraction

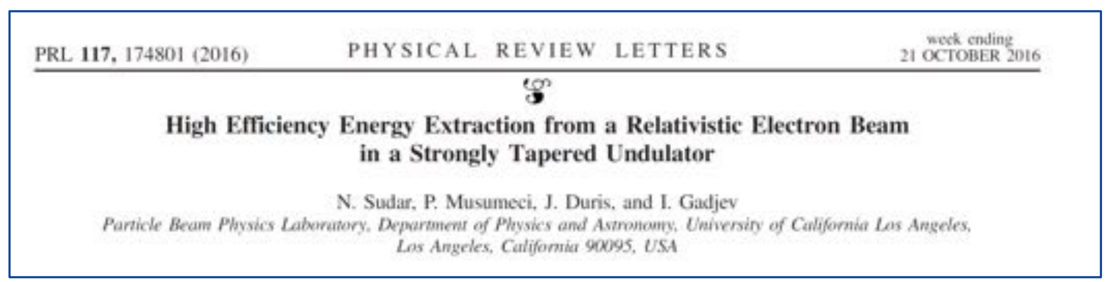


TESSA proof-of-concept experiment

- 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 !





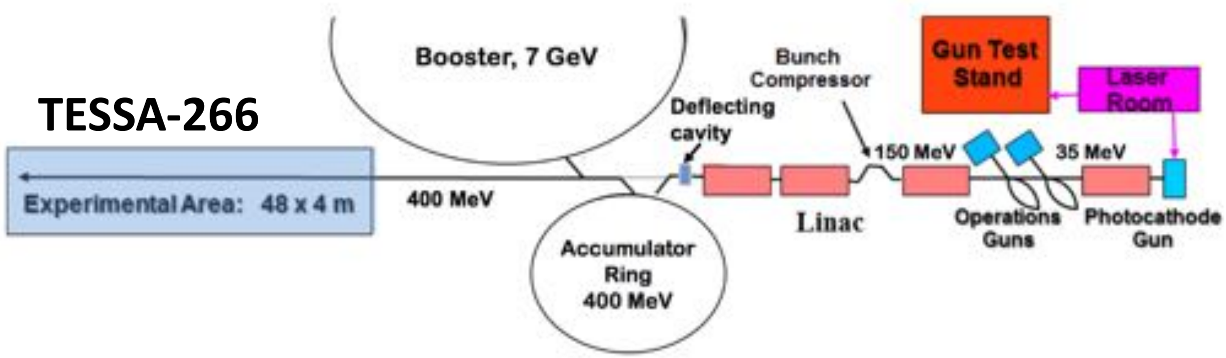

PRL 117, 174801 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

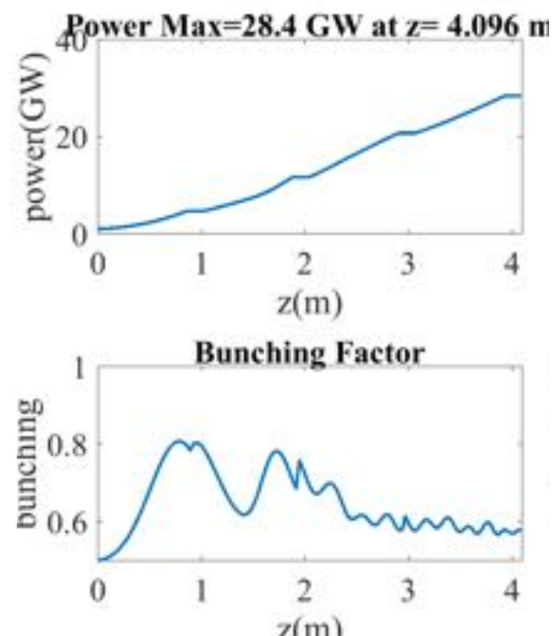
High Efficiency Energy Extraction from a Relativistic Electron Beam in a Strongly Tapered Undulator

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

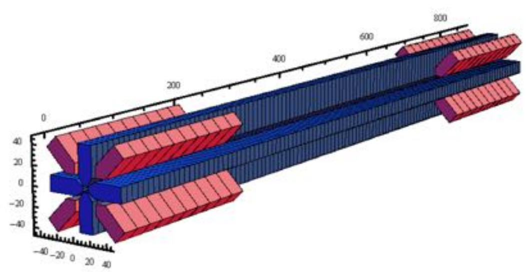
- Next goal is to show high gain amplification and study system dynamics and optimization experimentally at a shorter (and friendlier) wavelength
- The site of the experiment is LEA tunnel at Argonne (former LEUTL)
- A thorough design study for TESSA-266 is underway in collaboration with UCLA, Argonne,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

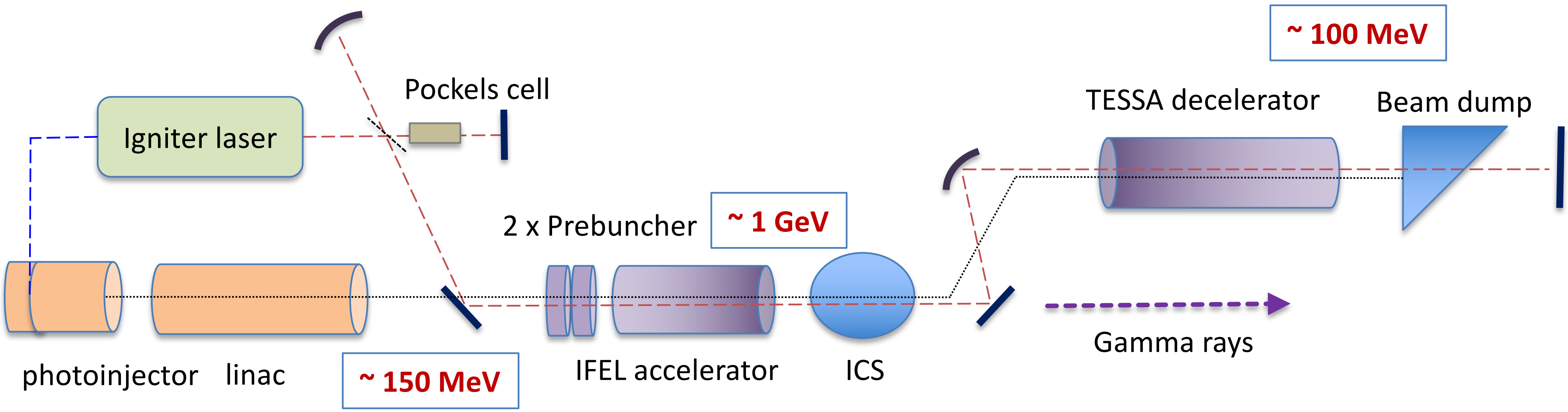


15% efficiency in 4 m

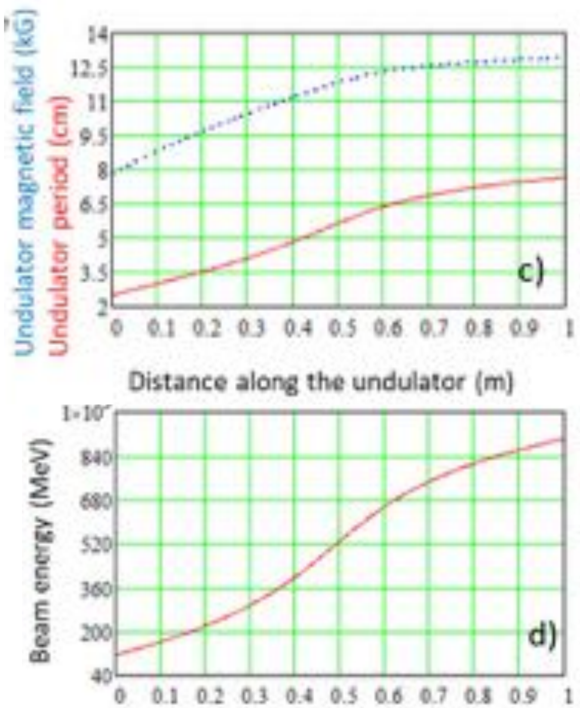
Optical Energy Recovery ICS Gamma Source

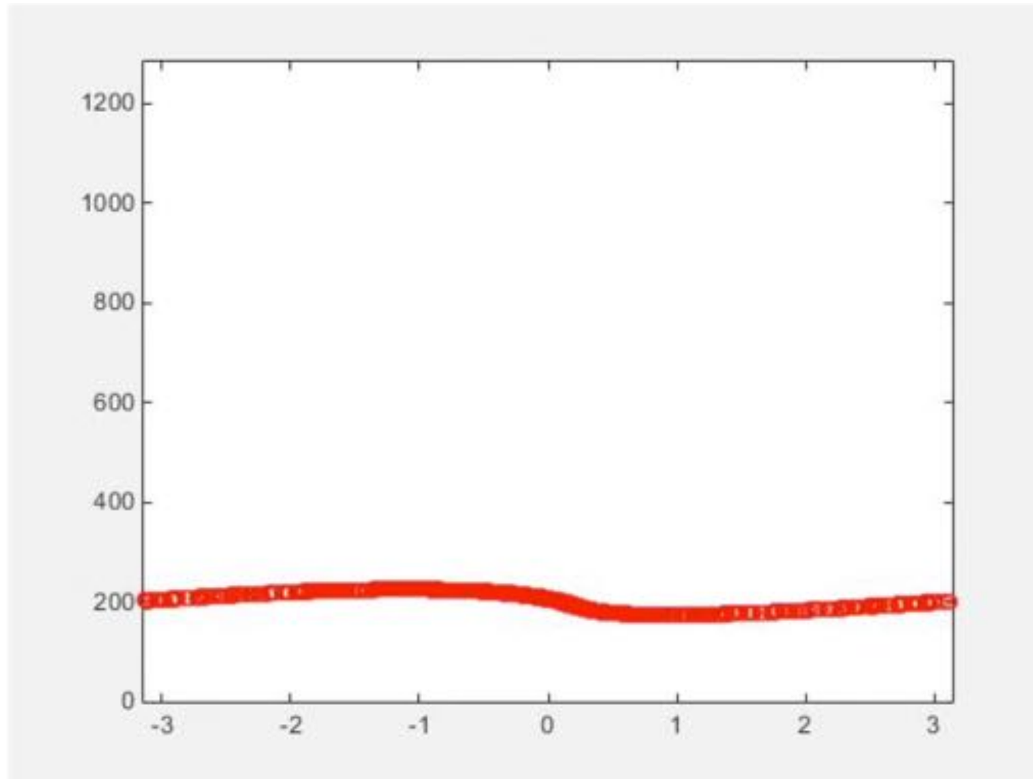
High intensity 10 MeV class gamma ray source, comprising of:

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

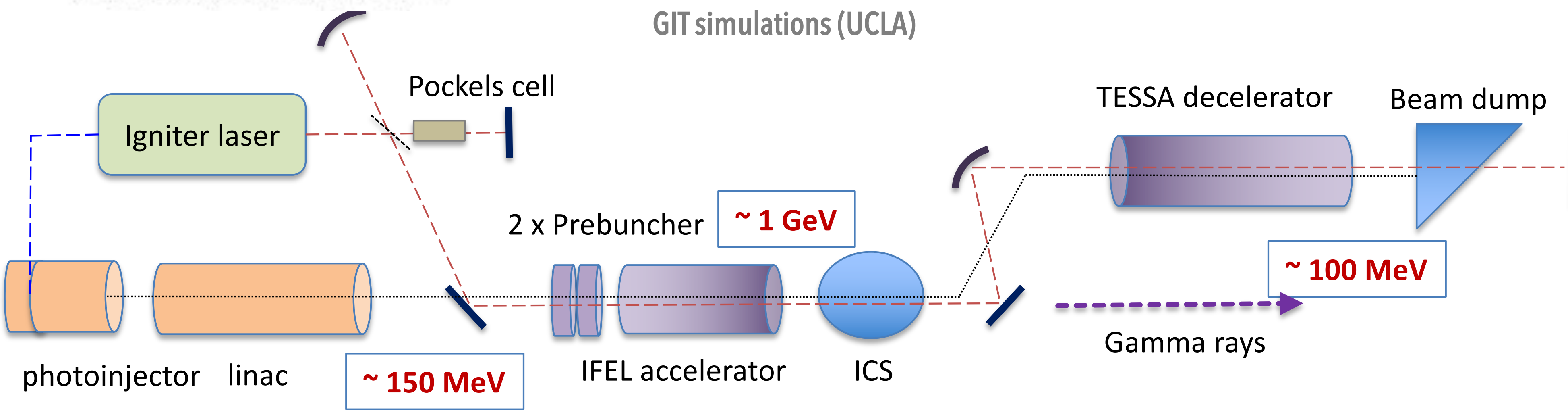


IFEL+TESSA





GIT simulations (UCLA)

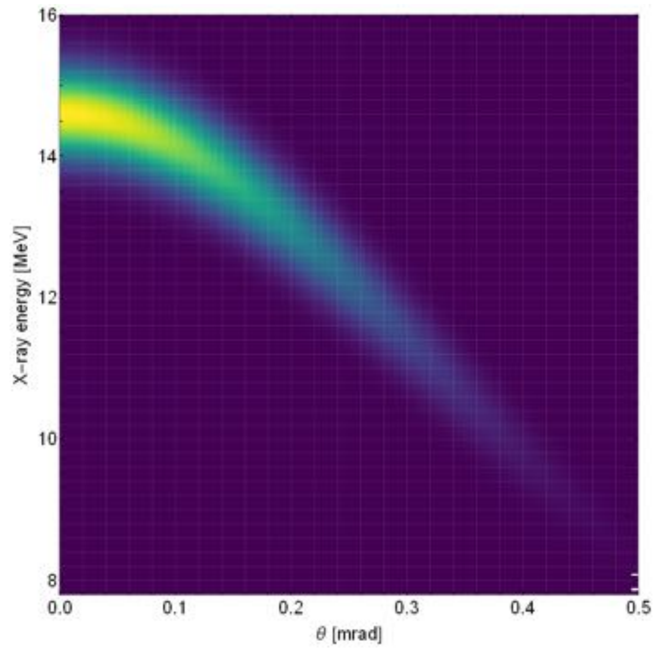


ICS design study

Electron beam	Value	Units
Normalized emittance ϵ_n	2	mm-mrad
Transverse size σ_x	20	μm
Energy E	900	MeV
Energy Spread $\Delta E/E$	10^{-2}	-
Charge	0.125	nC
Bunch length σ_z	200	fs

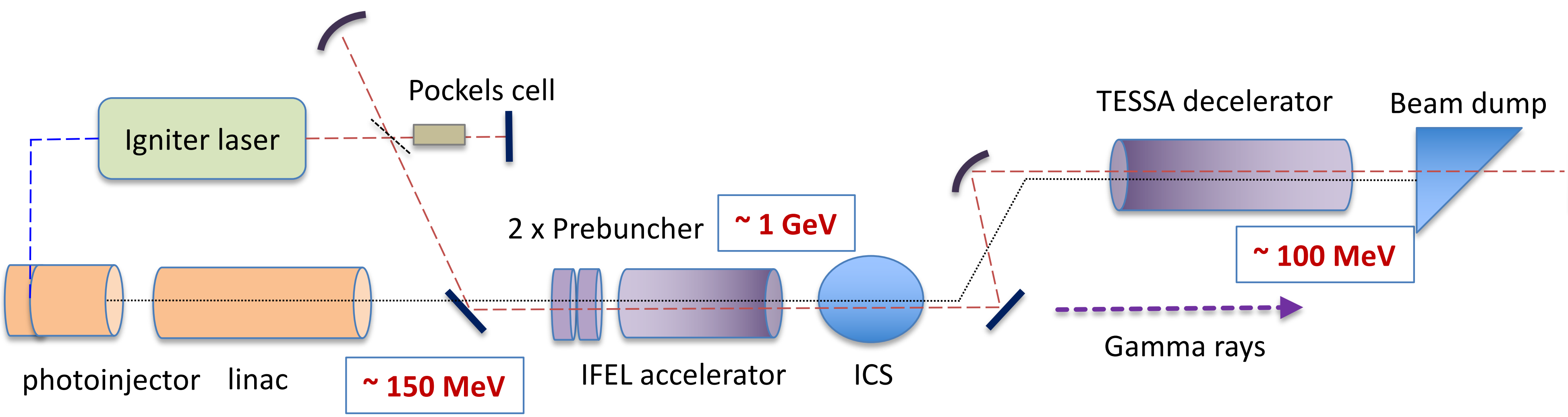
Laser	Value	Units
Transverse size w_0	20	μm
Pulse Energy	1	J
Wavelength λ_L	1053	nm
Pulse length	200	fs

Gamma-rays	Value	Units
Opening angle	8	mrad
Central energy	14.6	MeV
Photons per pulse N_γ	1×10^8	counts

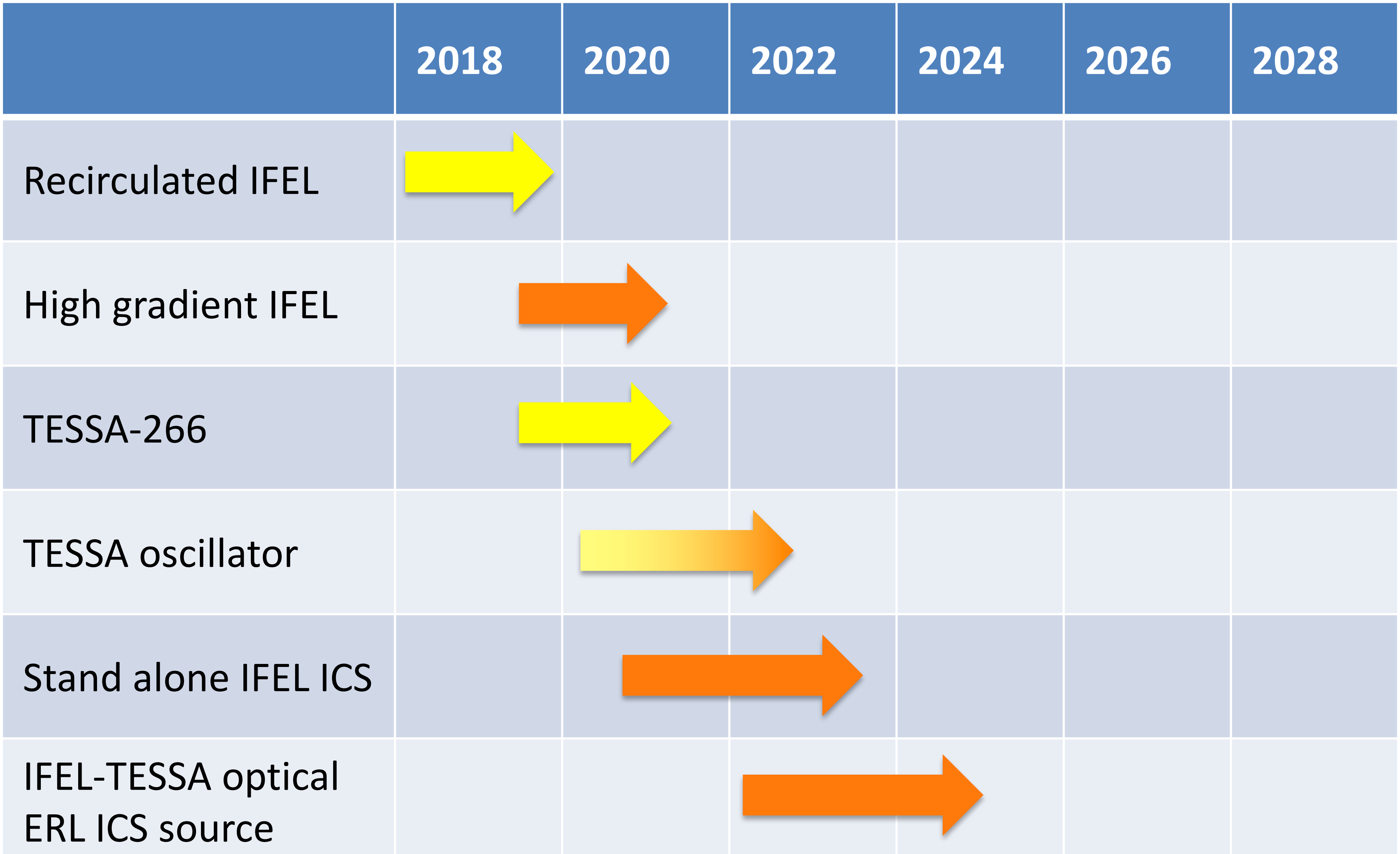


- 10^8 ph/shot
- 100 Hz
- 100 pulses per train

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



IFEL-ICS gamma ray source roadmap



Conclusions and Acknowledgement

- Compact tunable gamma ray ICS source could find multiple applications in research, industry, 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
- Acknowledgement for contributions and useful discussions:
  - P. Musumeci, J. Rosenzweig, N. Sudar (UCLA)
  - A. Arodzero, S. Boucher, A. Ovodenko (RadiaBeam)
  - J. Byrd, S. Zholents (APS)
  - A. Courjaud, P.-M. Paul (Amplitude)

- Thank you !