Towards High Efficiency Industrial FEL

Alex Murokh*, RadiaBeam Technologies LLC.
Pietro Musumeci, University of California, Los Angeles
Alexander Zholents, Argonne National Laboratory
Stephen Webb, RadiaSoft LLC.
Sergei Nagaitsev, Fermilab

2017 Free Electron Laser Conference, Santa Fe, NM   August 25, 2017

Industrial Lasers

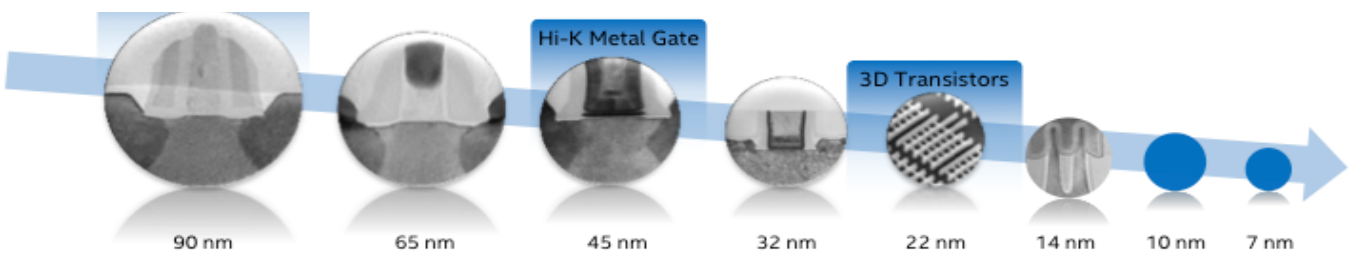
- Industrial lasers play critical role in modern manufacturing, materials processing, printing, and other high throughput industrial processes
- $3.5 billion industry in 2017
- $1.3 billion micro-materials segment (semiconductor industry, fine materials processing) represents high added value applications and is rapidly growing (~20% year over year)

Revenues by sector	2015	2016 est.	2017 proj.
Marking	$ 543	$ 560	$ 569
Marco-materials	$ 1,428	$1,492	$ 1,565
Micro-materials	$895	$ 1,105	$ 1,299
Total	$ 2,866	$ 3,157	$ 3,432

http://www.industrial-lasers.com/articles/print/volume-32/issue-1/features/industrial-lasers-continue-solid-revenue-growth-in-2016.html

Industrial Applications

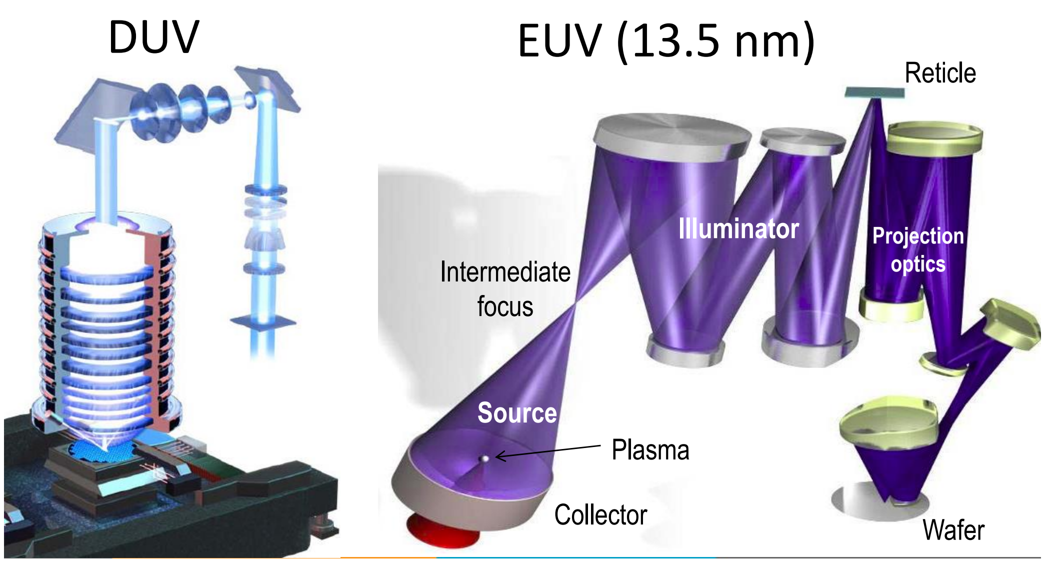
- FEL technology is unique due to its scalability to any desired operating wavelength from THz to X-rays
- At shorter wavelengths (< 100 nm), outside the range of state-of-the-art industrial lasers, FEL can fulfill the needs of growing micro-material processing segment
- Semiconductor industry HVM offers a prime example of high added value application (EUV lithography), where there is a demand for short wavelengths light sources on a massive scale
- EUVL light source at 13.5 nm illustrates FEL industrial potential



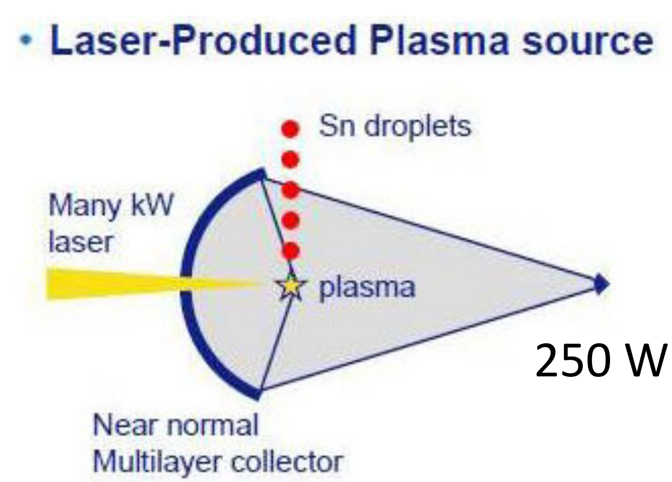
LE 248 nm	LE → immersion → LE^2 → SADP → SAQP 193 nm laser	LE 13.5 nm

EUVL challenge

- EUVL process implies ultraprecise projection of the mask image on wafer in a high throughput setting (>120 wph per scanner)
- Reflective optics at EUV are far from perfect (R < 70%), so high power EUV light source is required (250 W in the intermediate focus).
- Development of high power laser produced plasma (LPP) source was a monumental effort, and only recently achieved 250 W target
- LPP is expensive (~$100 million per scanner w/10-20 scanners per foundry, plus high operating cost)

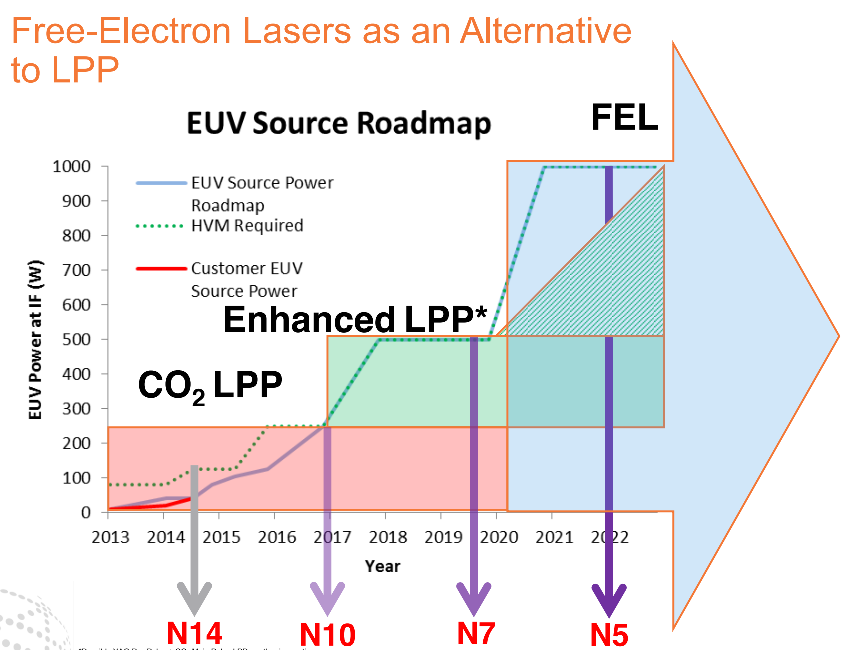


Courtesy of P. Naulleau (LBNL)



Possibility for FEL EUVL source

- FEL @ 13.5 nm in theory has a number of advantages compare to LPP:
  - No media, no heat and no contamination
  - Scalable to non-granular design (one source per foundry instead of one source per scanner)
  - Consistent with the cost and scale of the modern foundry facilities
- To compete with LPP, FEL have to offer significant cost advantages, to compensate the risks associated with the new technology



E. R. Hosler *et al* Proc. of SPIE **9422**, 94220D-1 (2015)

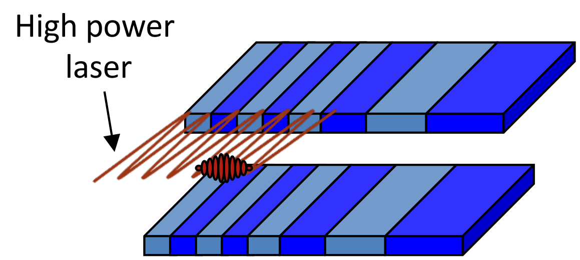
Courtesy of P. Naulleau (LBNL)

Industrial FEL

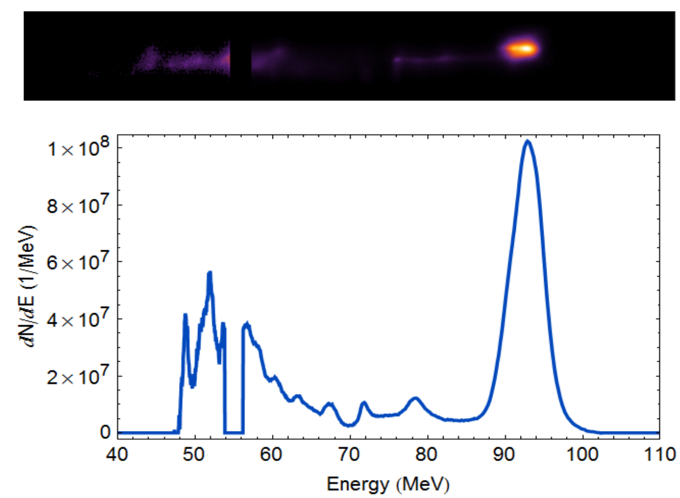
- Industrial applications require improvements to the FEL cost efficiency by 1-2 orders of magnitude
- One approach is beam energy recuperation (SCRF CW + ERL)
- Another approach is a major improvement to FEL efficiency

FEL efficiency: lessons from Inverse FEL

- In a conventional SASE FEL the electrons-photons energy exchange rate peaks (near saturation) at about **~ 1 MeV/m**
- UCLA experiment on RUBICON IFEL achieved ~ **100 MeV/m** acceleration
- In IFEL, e-beam and laser exchange energy in vacuum, thus the process is reversible
- 100 MeV/m in-vacuum decelerator would make a very efficient radiator, so can we design FEL which operates as IFEL in reverse?
- IFEL experiments demonstrated that strong energy exchange and very high efficiency FEL schemes are possible within the state of the art technological framework



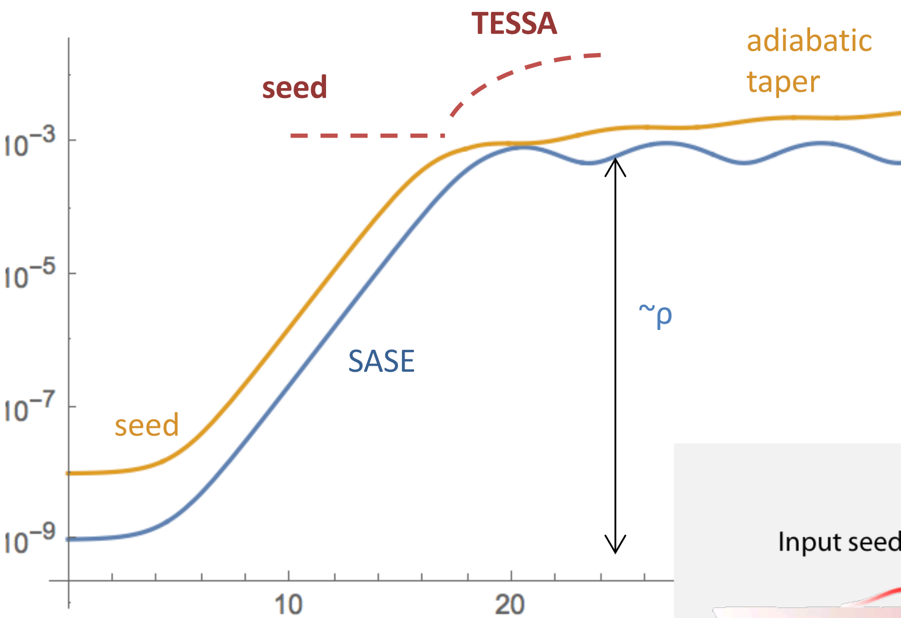
In an IFEL the electron beam absorbs energy from a radiation field.

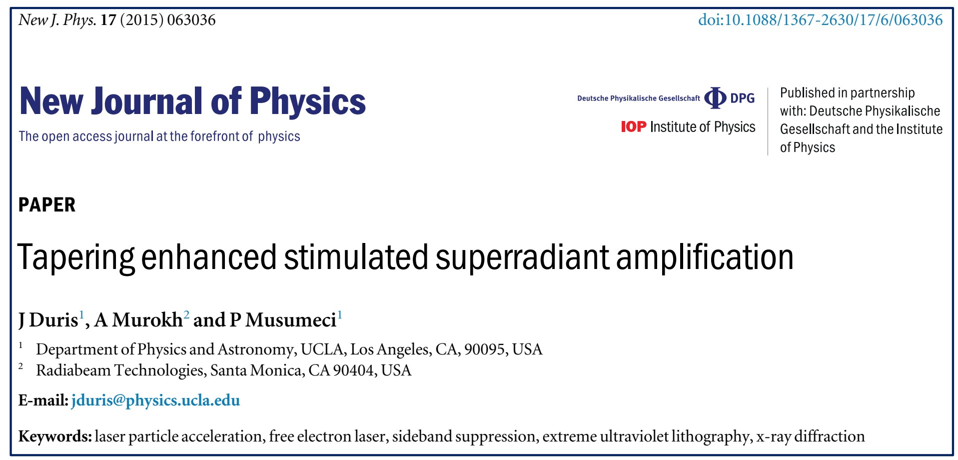


UCLA results from RUBICON experiments
J. Duris et al, *Nature Comm*. **5**, 4928, 2014

TESSA

- Inverse IFEL = TESSA (**T**apering **E**nhanced **<u>S</u>**<u>timulated</u> **S**uperradiant **A**mplification)
- 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

New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics
Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

PAPER

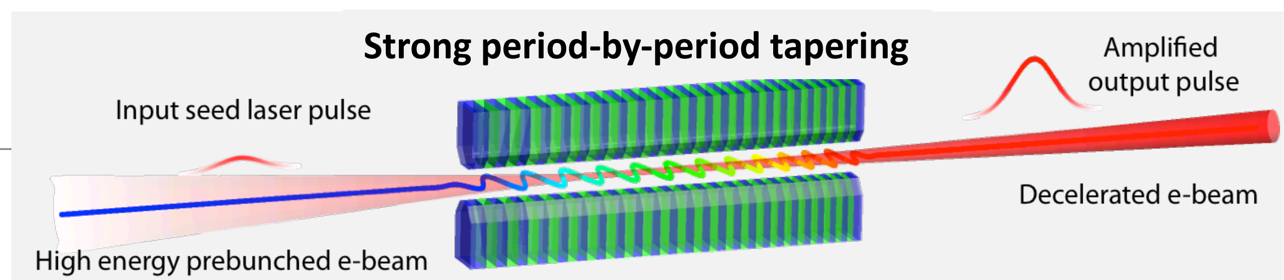
Tapering enhanced stimulated superradiant amplification

J Duris[1], A Murokh[2] and P Musumeci[1]

[1] Department of Physics and Astronomy, UCLA, Los Angeles, CA, 90095, USA
[2] Radiabeam Technologies, Santa Monica, CA 90404, USA

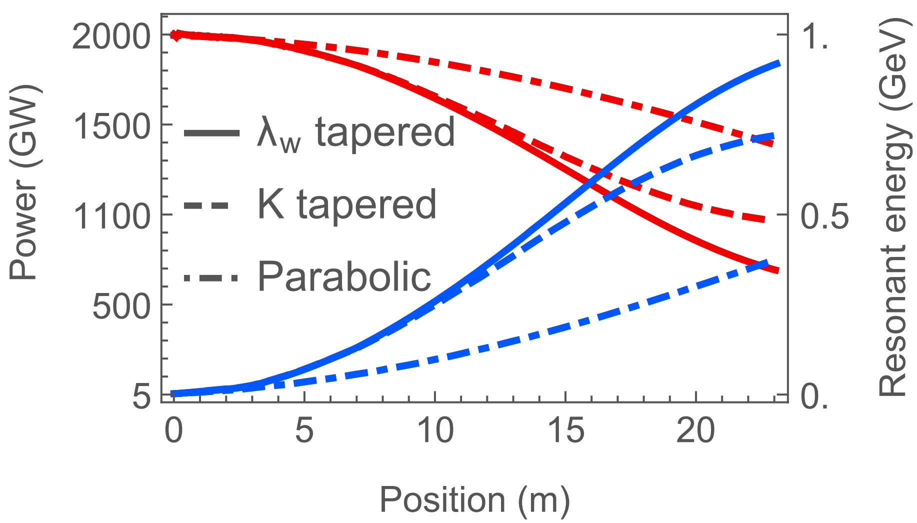
E-mail: jduris@physics.ucla.edu

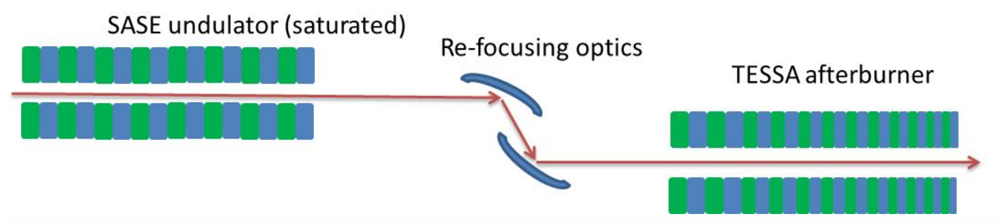
Keywords: laser particle acceleration, free electron laser, sideband suppression, extreme ultraviolet lithography, x-ray diffraction



TESSA at EUV

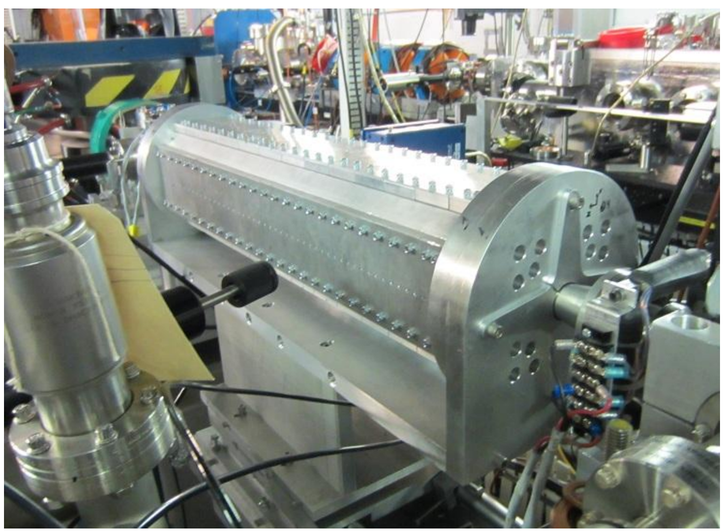
- GIT simulations of TESSA at EUV
- E-beam decelerates from 1 GeV to 320 MeV in 23 m undulator,
- Laser power increases from ~ 5 GW seed to > 1 TW at the output
- W/capture ~ 80%, the overall energy efficiency **> 50% is possible**
- *Sensitive to peak current (4 kA for this working point, may not be easy to achieve at 1 GeV energy)*
- *5 GW seed does not exist (but can be generated by refocusing SASE or in an oscillator)*

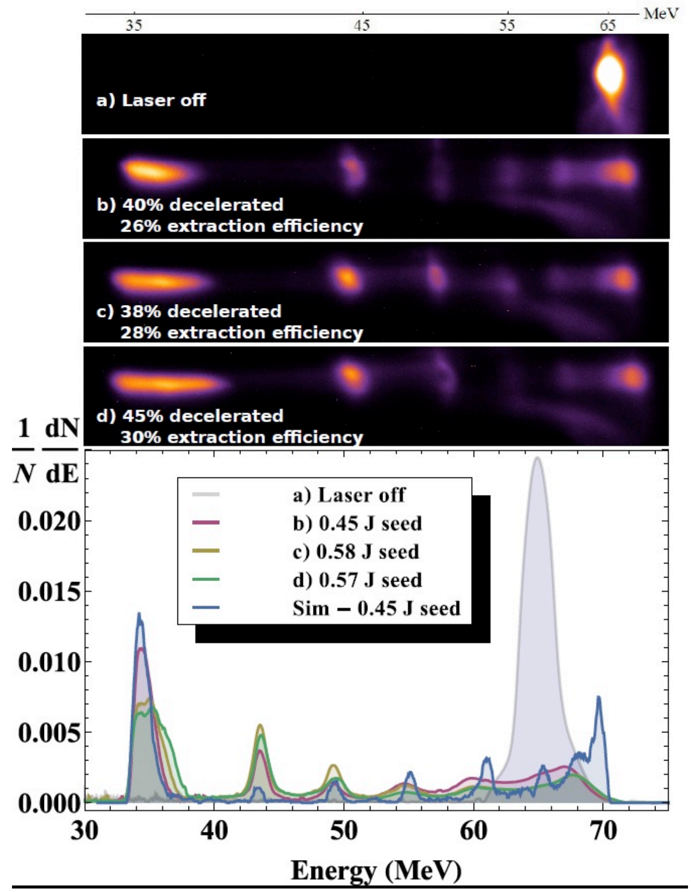




TESSA proof-of-concept experiment

- 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

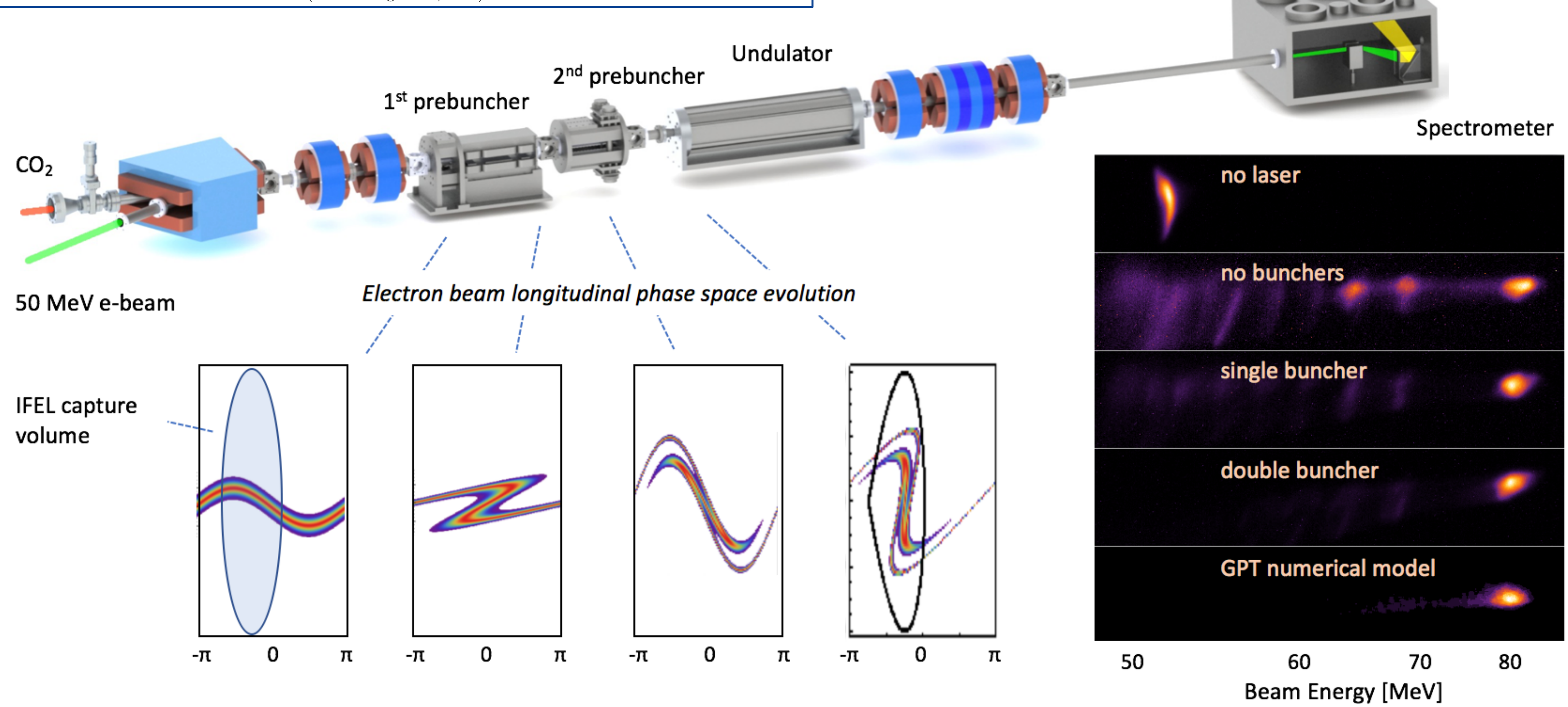
Double buncher experiment

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

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

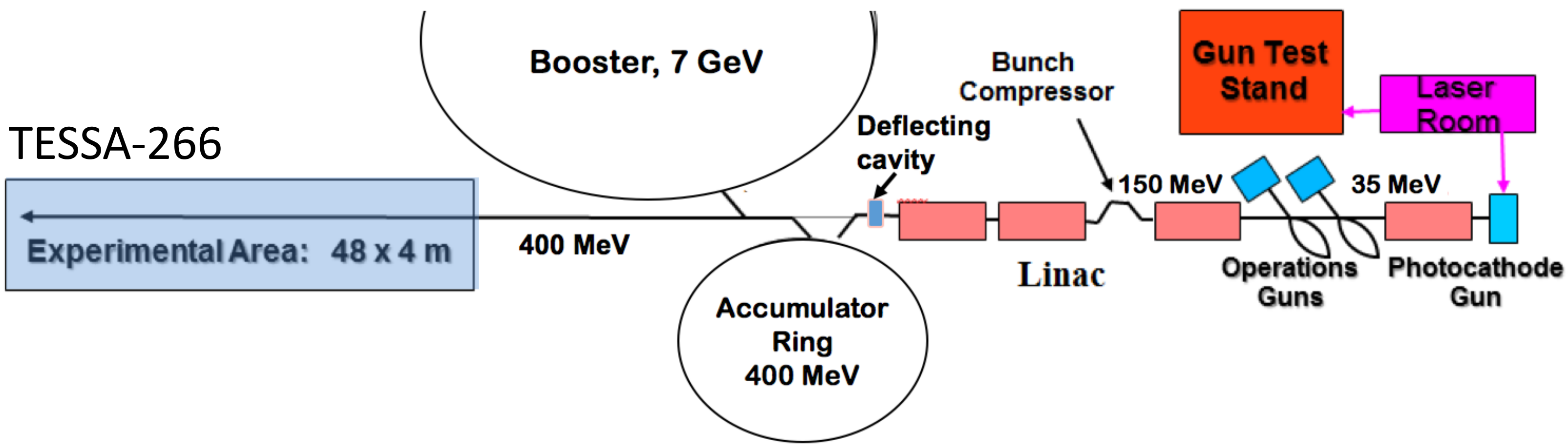
N. Sudar, P. Musumeci, I. Gadjev, Y. Sakai, S. Fabbri
Particle Beam Physics Laboratory,
Department of Physics and Astronomy University of California Los Angeles
Los Angeles, California 90095, USA

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)



TESSA-266

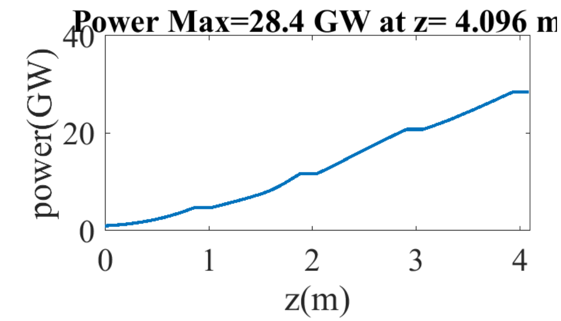
- So far, TESSA concept has been developed, and demonstrated at 10 μm, including efficient beam capture with the double buncher
- Next goal is to show high gain amplification and study system dynamics and optimization experimentally at a shorter (and friendlier) wavelength (266 nm)

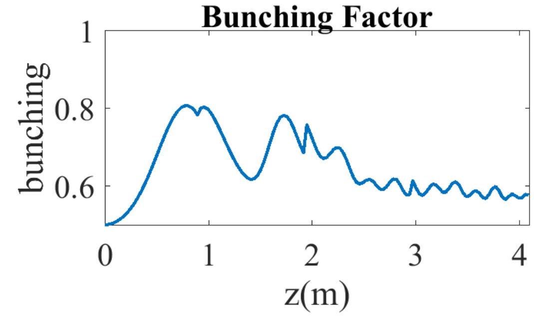


- The site of the experiment is LEA tunnel at Argonne (former LEUTL)
- A thorough design study for TESSA-266 is underway in collaboration with UCLA, Argonne, and RadiaSoft

TESSA-266

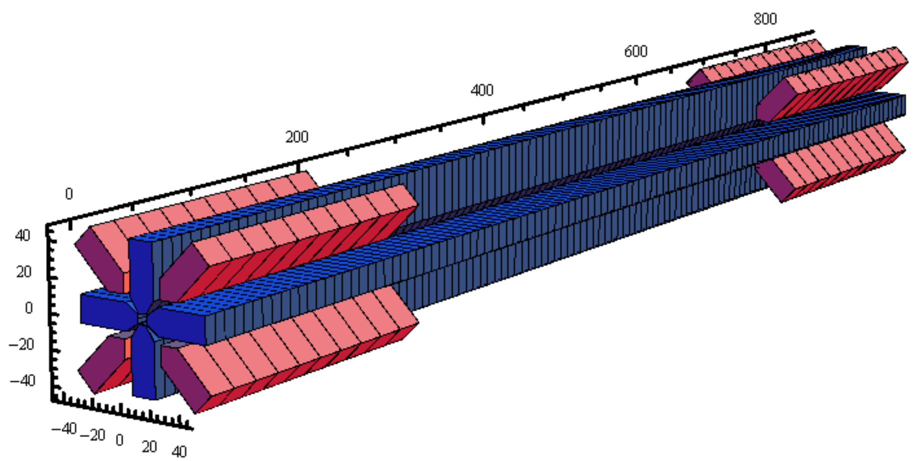
- Start to end simulations are in progress
- The goal is to reach **15%** FEL efficiency in 4 meter undulator at 266 nm
- Laser amplification gain > 20
- Strong focusing helical undulator design and optimization is in progress
- Anticipate the start of the construction phase in Summer 2018





TESSA Electron Beam Requirements

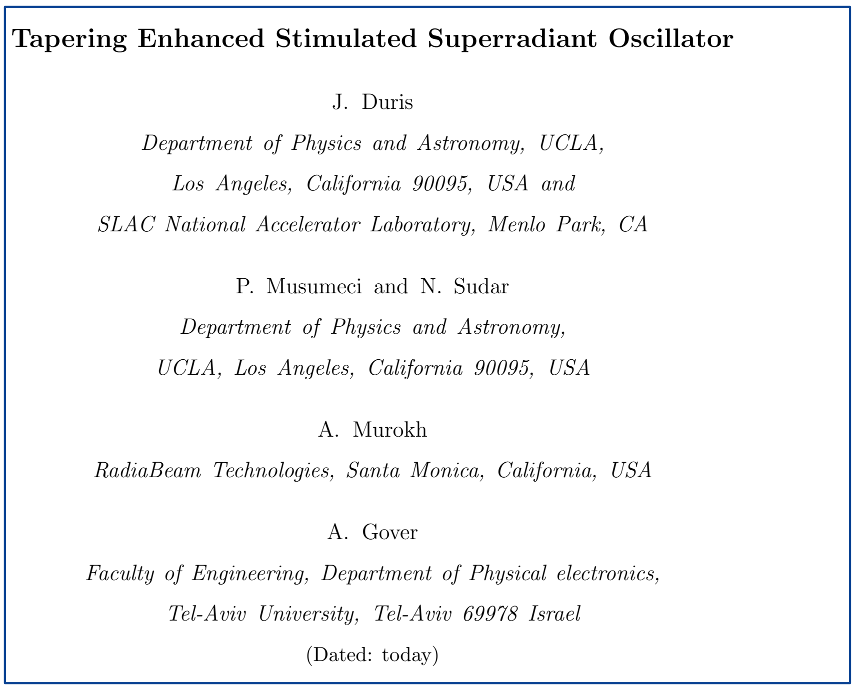
Property	Value
Energy	300 MeV
Energy Spread	0.02 % to 0.1 %
Peak Current	1 kA
Emittance (Normalized)	2 μm
spot size (rms)	30 μm to 40 μm
$\beta_{x,y}$	0.54 m to 1 m



Courtesy of Youna Park (UCLA) and Chris Hall (RadiaSoft)

Road Map

- Beyond TESSA-266 we have to show high average power and high efficiency oscillator configuration
- Considering the possibility of moving TESSA-266 to Fermilab to demonstrate oscillator regime with SCRF linac
- The ultimate goal is TESSA at EUV in a high duty cycle mode



Tapering Enhanced Stimulated Superradiant Oscillator

J. Duris

Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA and SLAC National Accelerator Laboratory, Menlo Park, CA

P. Musumeci and N. Sudar

Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

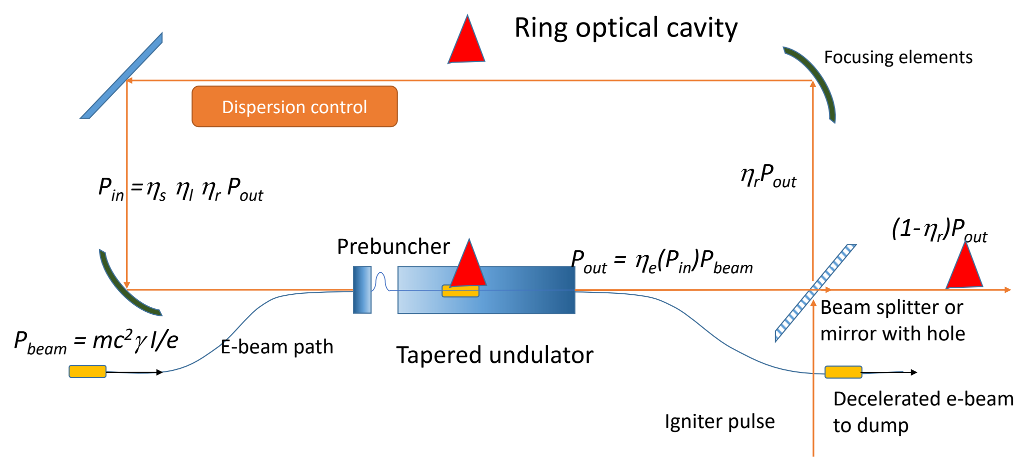
A. Murokh

RadiaBeam Technologies, Santa Monica, California, USA

A. Gover

Faculty of Engineering, Department of Physical electronics, Tel-Aviv University, Tel-Aviv 69978 Israel

(Dated: today)



Conclusions and Acknowledgement

- The advances in FEL and accelerator science and technology open up possibilities for industrial grade systems
- More specifically, a possibility of EUV FEL for semiconductor industry has triggered important discussions about industrial FEL efficiency, reliability and architecture
- TESSA is a novel approach to develop very high efficiency FEL, and experimental validation is in progress
- This work is being supported by DOE grants No. DE-SC0017102 and DE-SC0017161
- We thank for the support, contributions and useful discussions:

  Youna Park, Nick Sudar, Claudio Emma (UCLA); Ron Agustsson, Bryce Jacobson (RadiaBeam); Christopher Hall, David Bruhwiler (RadiaSoft); Joe Duris, Aaron Tremaine, Tor Raubenheimer (SLAC); Yin Sun (ANL); Patrick Naulleau (LBNL).
- See MOP011, TUP022, TUP052, WEP079 papers for more details