Inverse Compton Scattering at FAST

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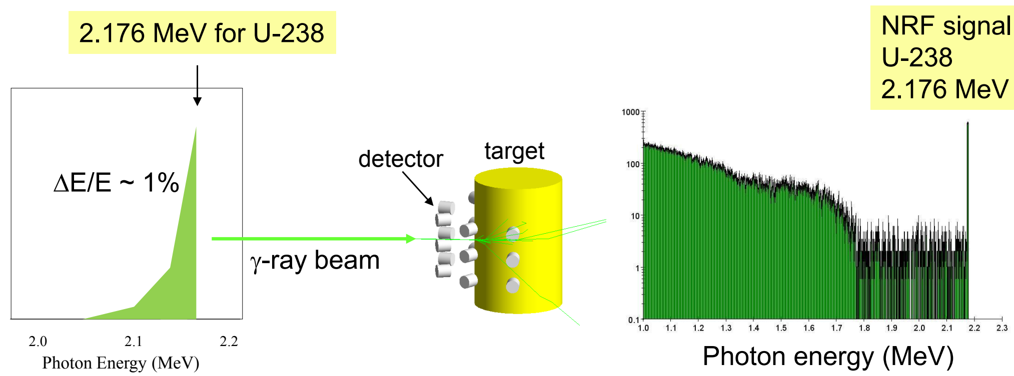
Fermilab Workshop on Megawatt Rings and
IOTA/FAST Collaboration Meeting, May 10 2018

Outline

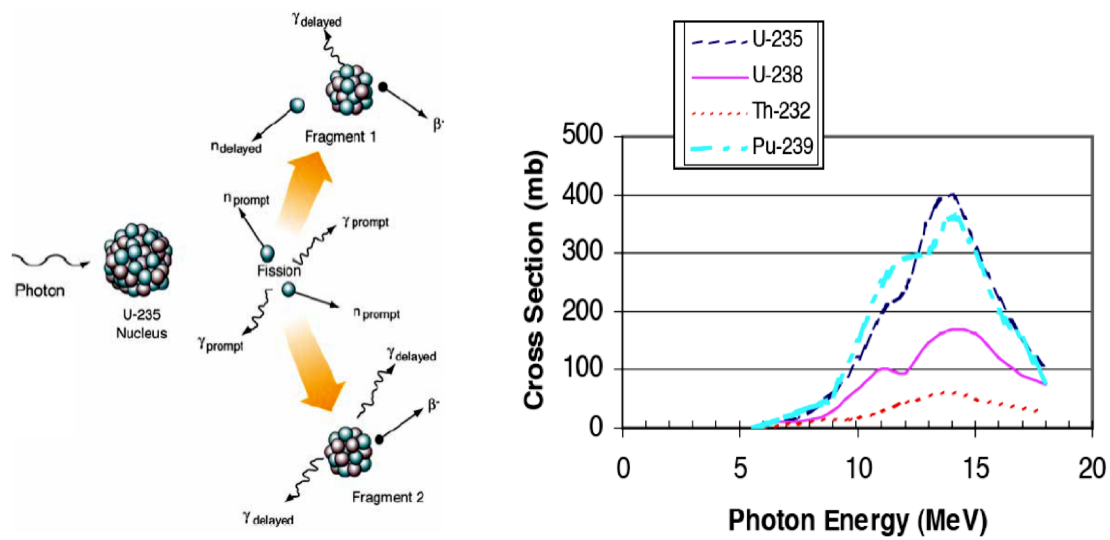
- Motivation and background for ICS program at FAST
- FAST ICS Project Overview
- Future opportunities at FAST

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).

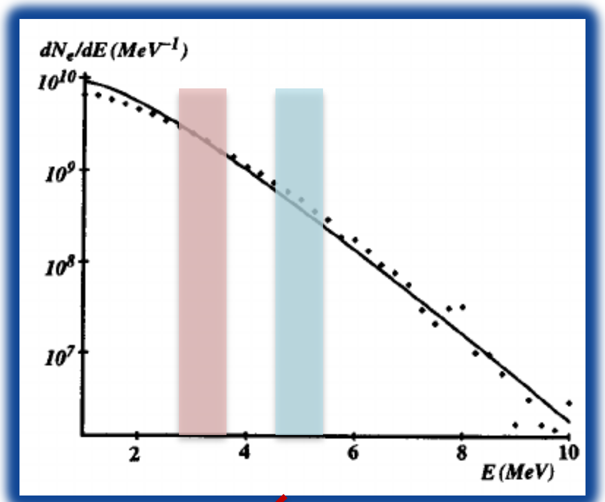


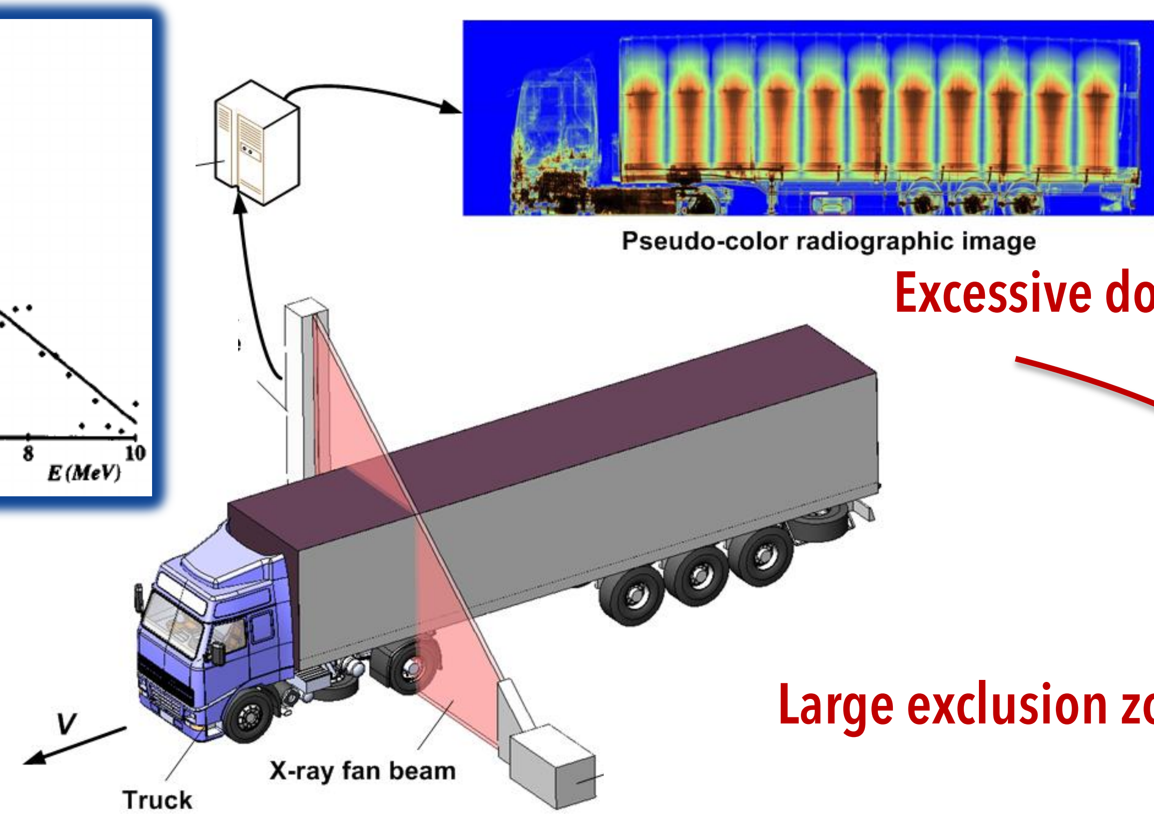
J.L. Jones *et al.*, Neutrons Workshop at ONR, 2006

Cargo inspection linac system

Disadvantages of the bremsstrahlung source

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



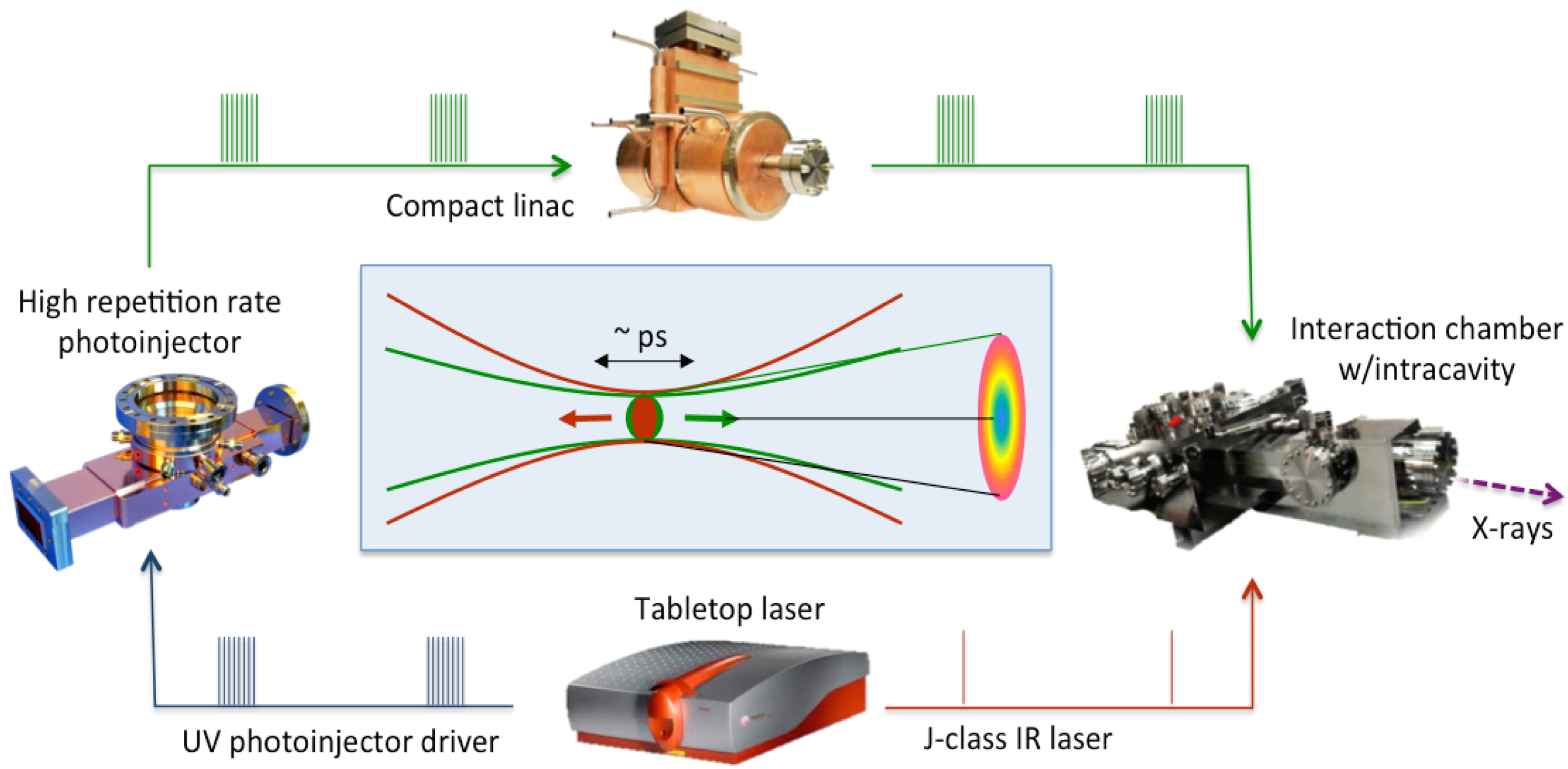


Excessive dose on target

Large exclusion zone

No stand off capability

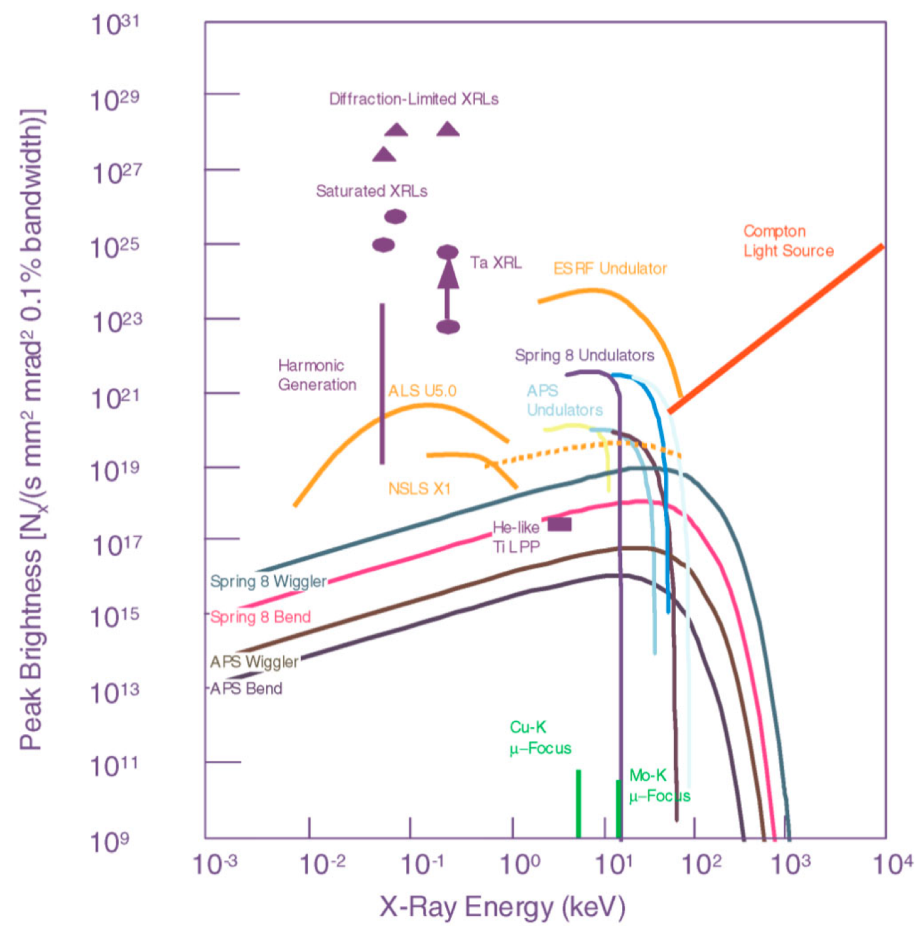
Inverse Compton Scattering (ICS)



- 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

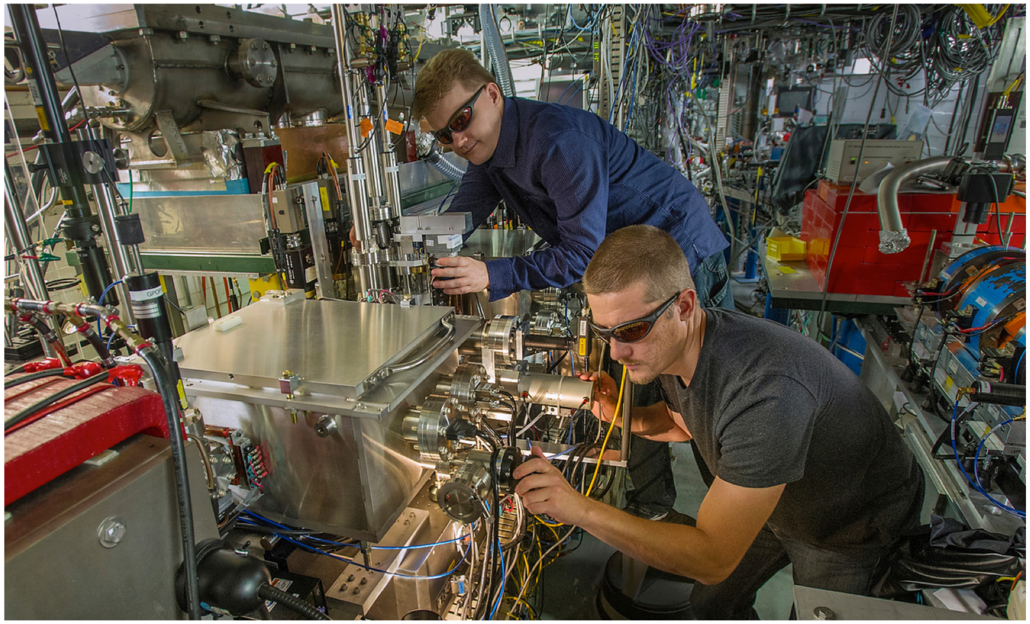
ICS gamma source features

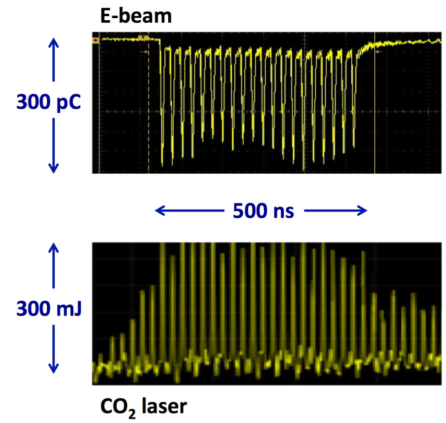
- Uniqueness – light sources do not reach MeV
- Tunability
- High efficiency at high energy $E_{ph}/E_e \sim\gamma$
- Favorable transverse brightness scaling ($\sim\gamma^3$)
- Directionality ($\sim 1/\gamma$)
- Need compactness and high r.r. (eventually, at the same time)



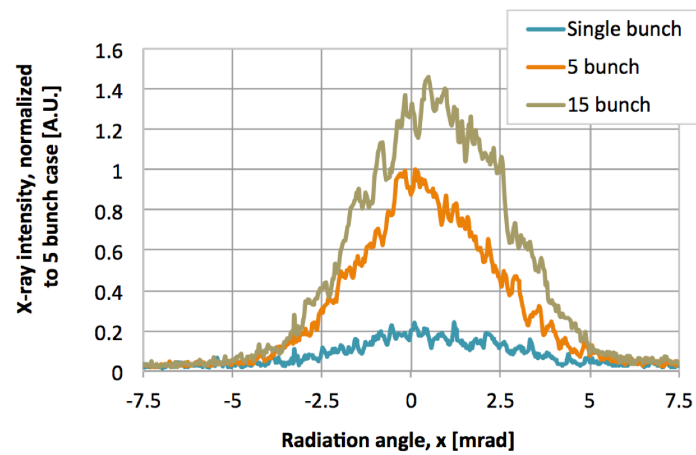
F.V. Hartemann *et al.*, *PR ST AB* **8**, 100702, 2005

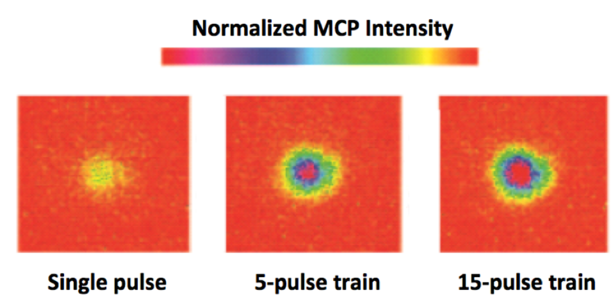
Recirculated ICS experiment





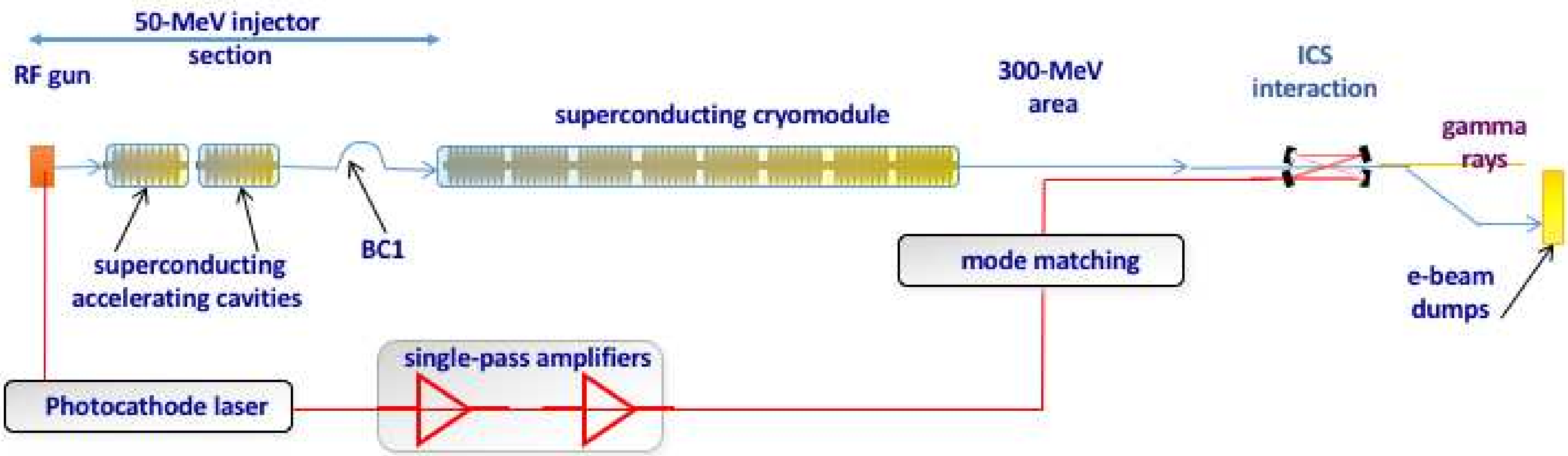
A. Ovodenko et al., Appl. Phys. Lett. **109**, 253504 (2016)





- 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)

Inverse Compton Scattering (ICS) at FAST



- Demonstrate and optimize ICS performance with SCRF linac at 3 MHz and > 1000 pulses per train
- Enable high flux tunable output available for users and applications R&D

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Team Members & Collaborators

Northern Illinois University

- Philippe Piot (NIU faculty + Fermilab Scientist)
- Daniel Mihalcea (research scientist)
- Matthew Urfer (MS)
- Aaron Fetterman (PhD, Joining 5/15)
- Aleksei Halavanau (Physics student)

radiabeam TECHNOLOGIES

- Alex Murokh (research scientist)
- Tara Campese (engineering support)

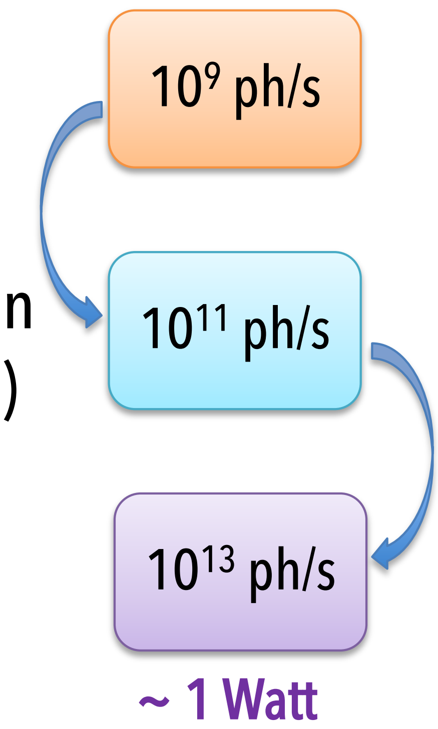
Fermilab

- Jinhao Ruan (laser scientist)

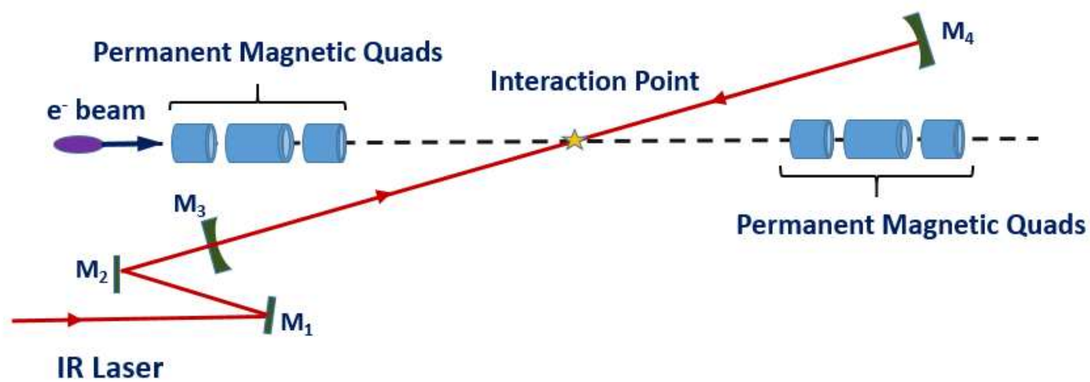
Technical Objectives

- **Use IR portion of the photoinjector laser output to develop a high-repetition rate interaction region synched to the existing SRF linac**

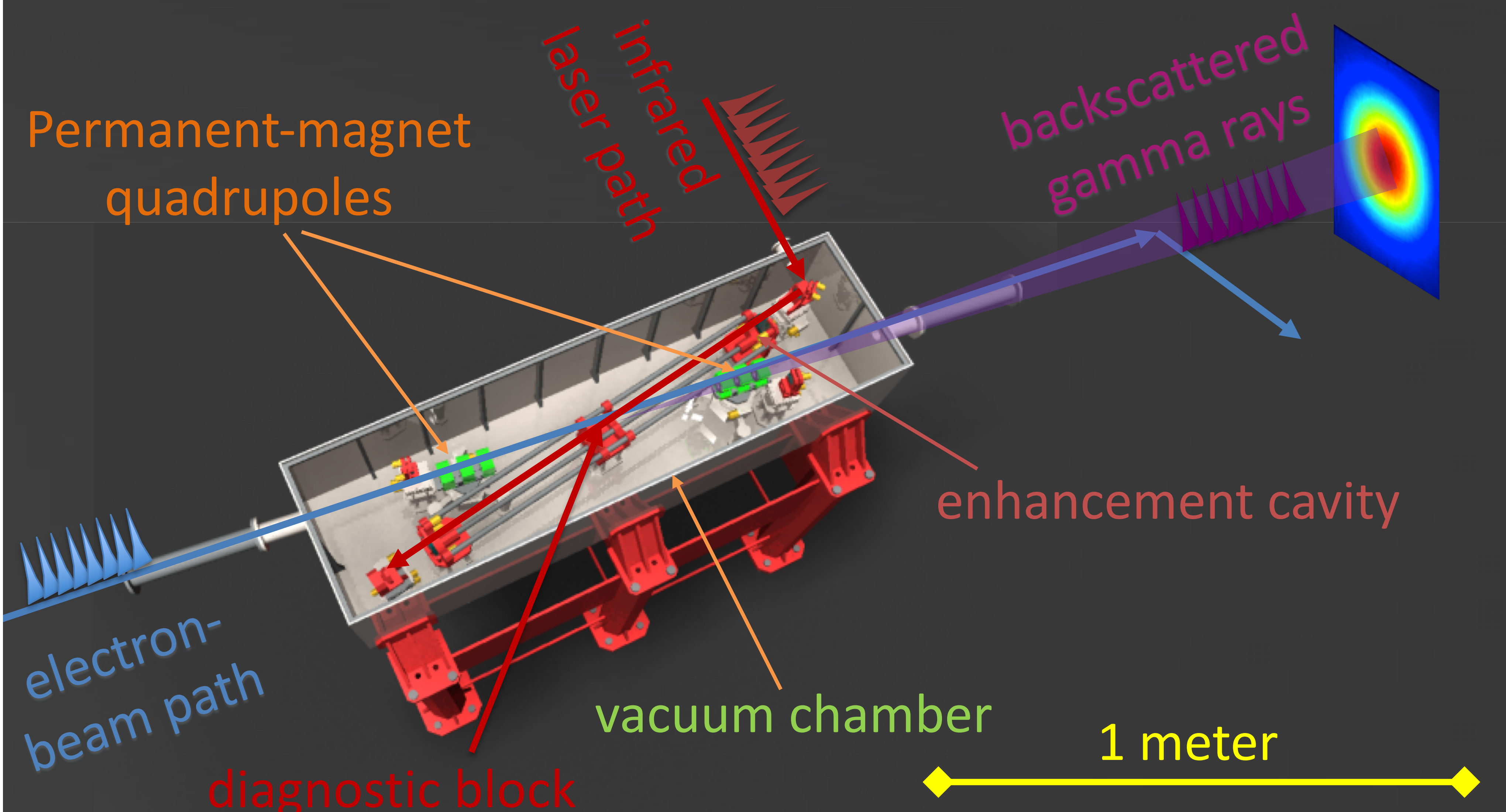
1. Design, develop, install and commission the interaction region (including ICS chamber and final focus systems)
2. Upgrade the laser currently available
3. Develop a recirculating optical cavity
4. Combine SRF linac with optimized optical cavity to produce high-flux gamma rays



THE PROJECT IS FOCUSED ON THE INTERACTION REGION DEVELOPEMNT (SIMPLIFIED DIAGRAM)

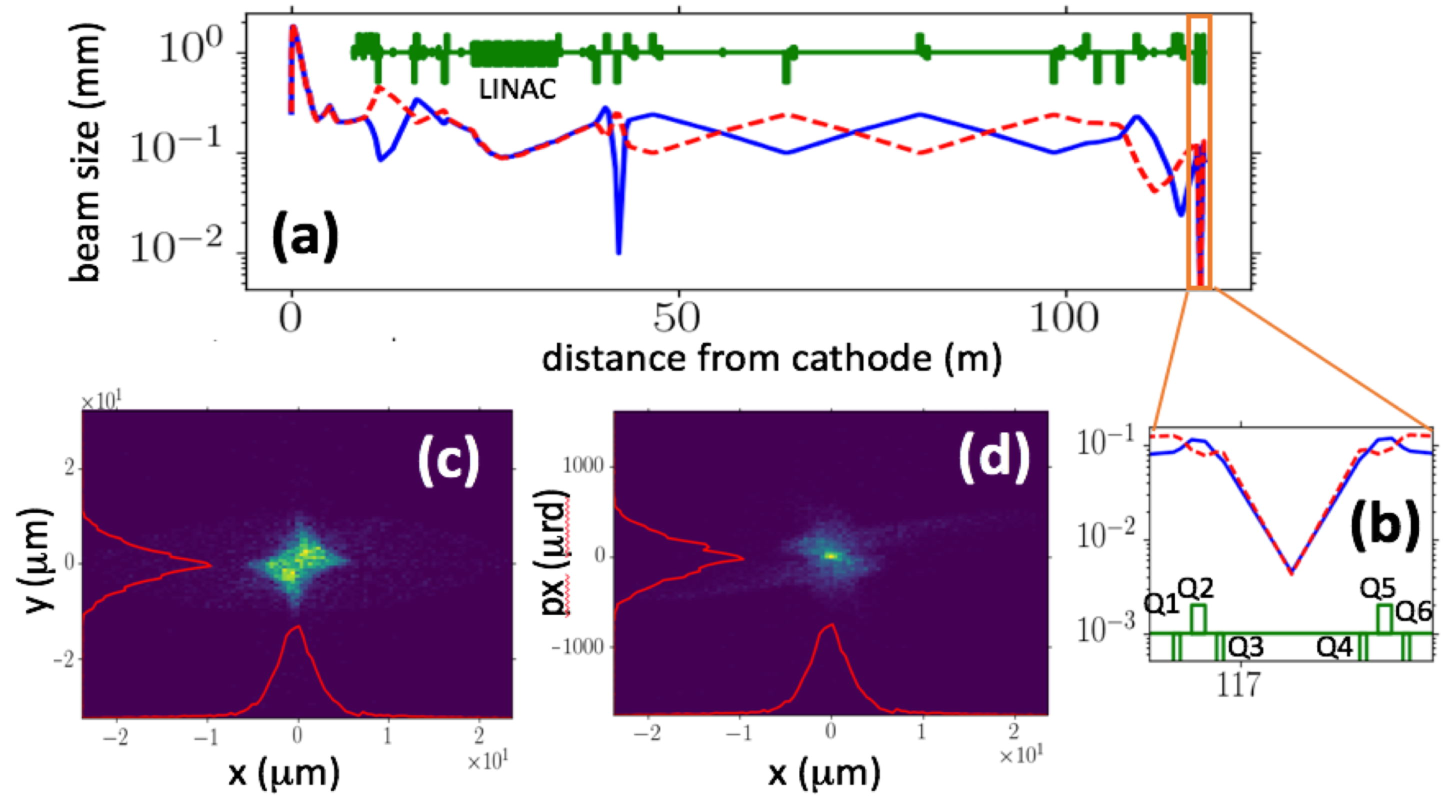


Schematics of the interaction region



Beam dynamics optimization

- Performed cathode-to-IP simulations
- Comprehensive optimizations

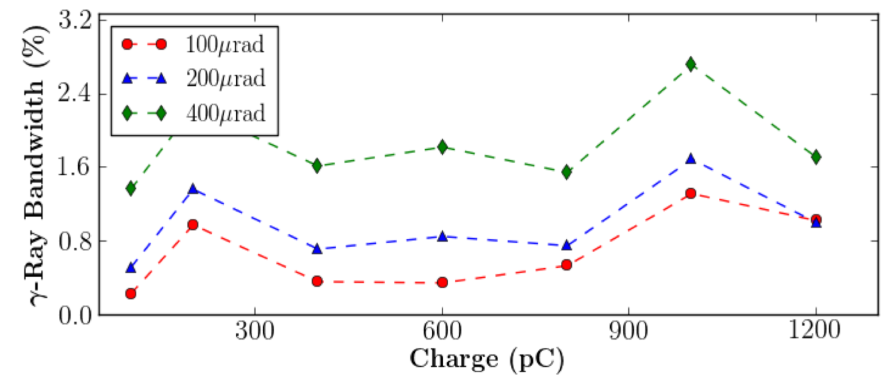


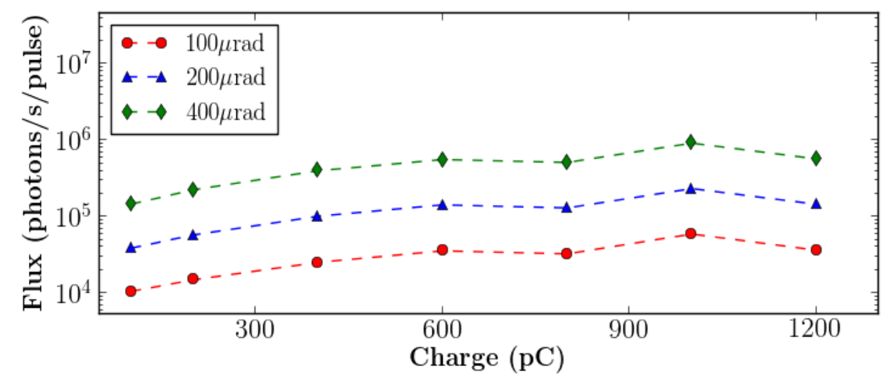
ICS performance modeling

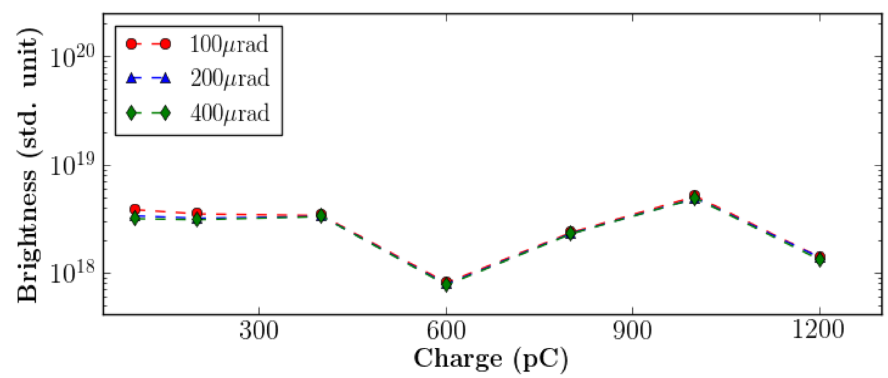
- Initial working point at low charge (~ 100 pC)

Electron beam		Laser beam	
Beam energy	259 MeV	Wavelength	1053 nm
Beam charge	100 pC	Pulse energy	100 mJ
Energy spread	0.06 %	Bandwidth	0.2 %
Emittance (n)	0.34 μm	Etendue	0.1 μm
Duration	5.0 ps	Duration	3.0 ps
Beam size x/y	12/13 μm	Waist	30 μm

Opening angle	100 μrad	200 μrad	> 10 mrad
Brightness	3.9×10^{18}	3.4×10^{18}	4.1×10^{17}
Flux (photons)	5.1×10^{4}	3.9×10^{5}	3.0×10^{6}
Bandwidth (%)	0.24 %	0.52 %	49.2 %
Spectral density	4.0 /eV-s	6.6 /eV-s	1.1 /eV-s

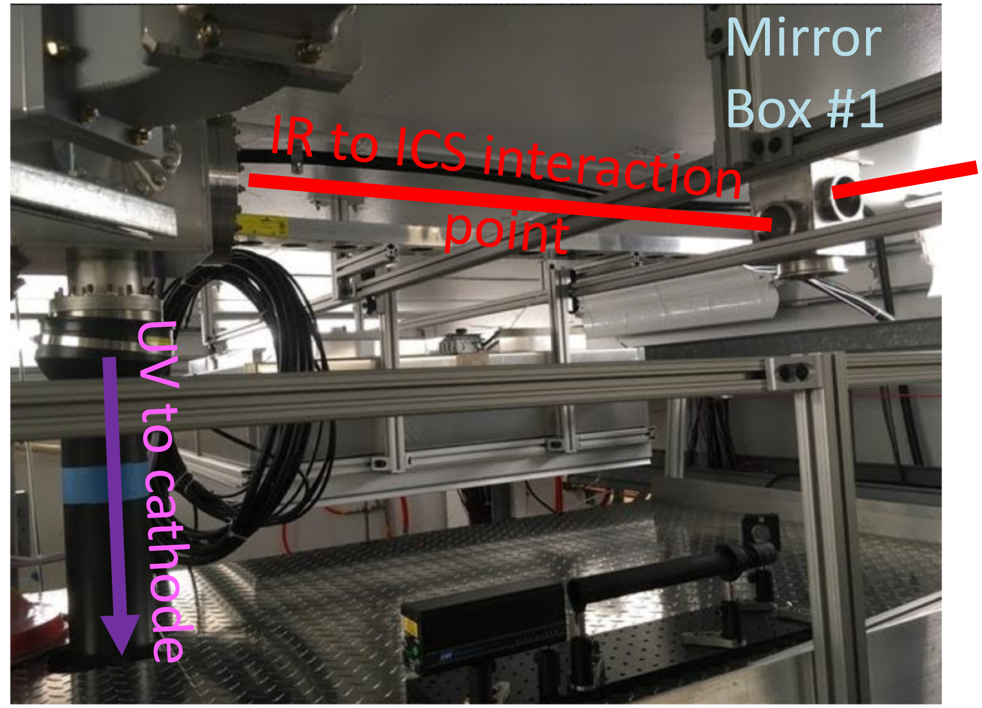


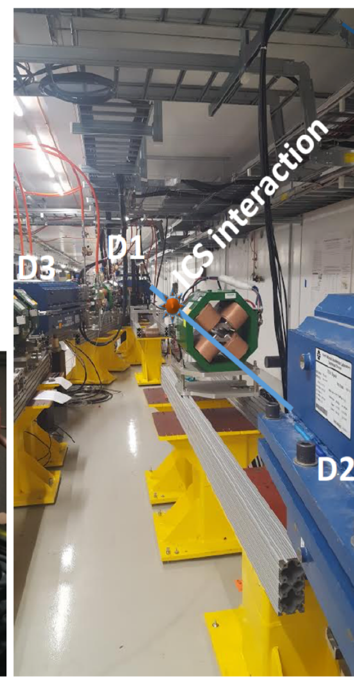


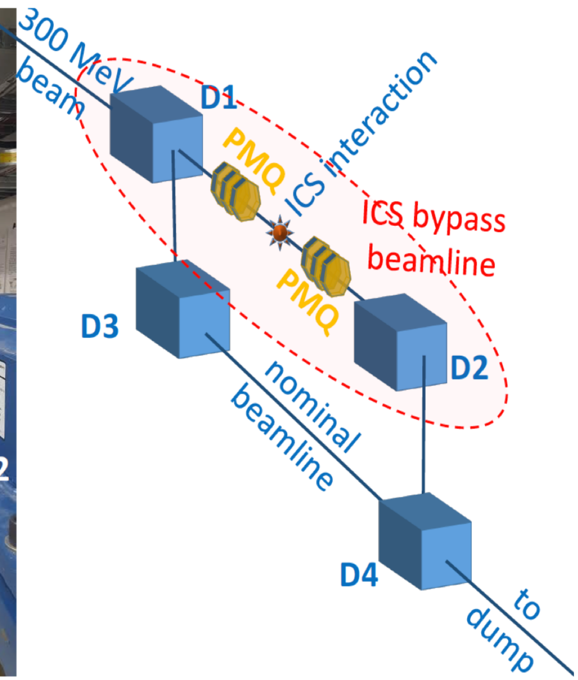


Present Status

- Identified beamline location
- 100-m transport line for IR pulse under way
- one high-energy laser amplifier has been procured
- UHV chamber housing IP under design
- PMQs in progress







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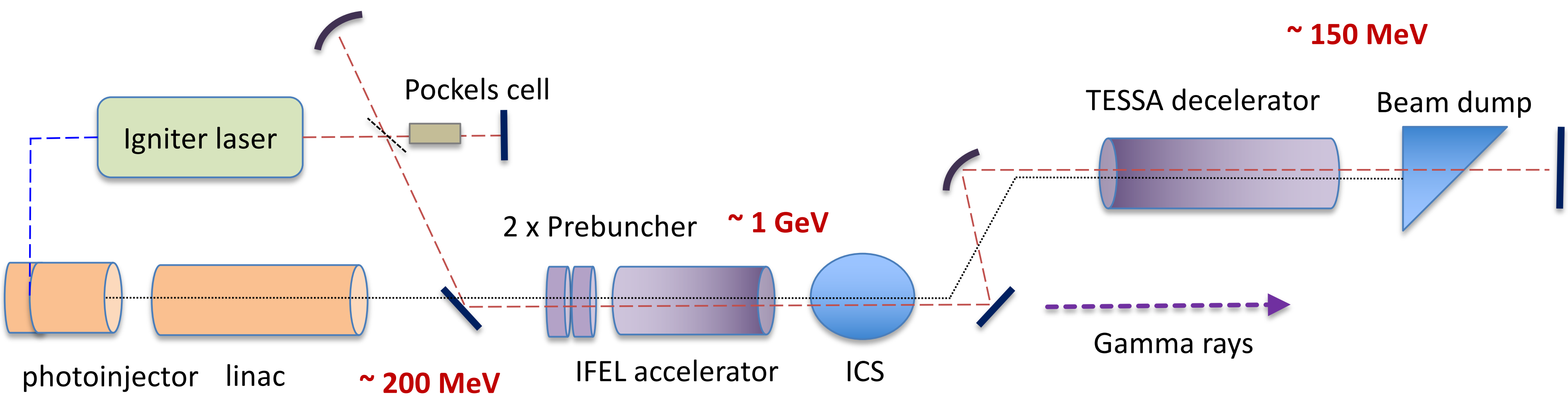
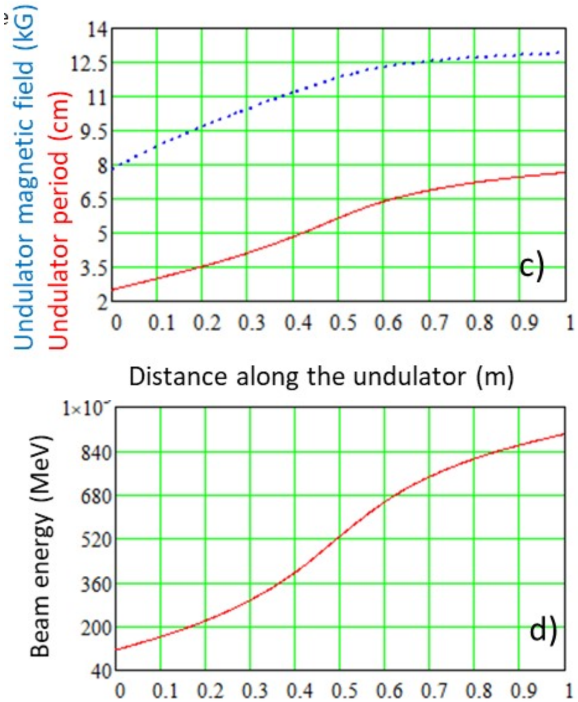
IFEL-ICS-TESSA Optical Energy Recovery

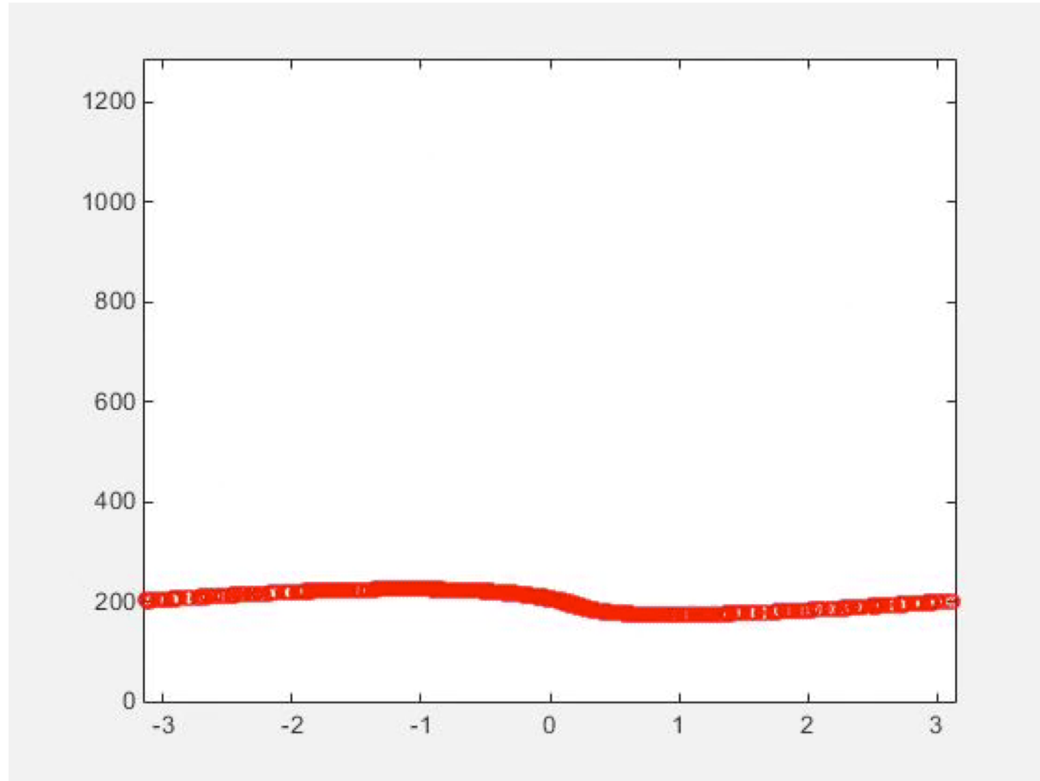
One can go from 1 MeV to 10 MeV using laser acceleration:

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

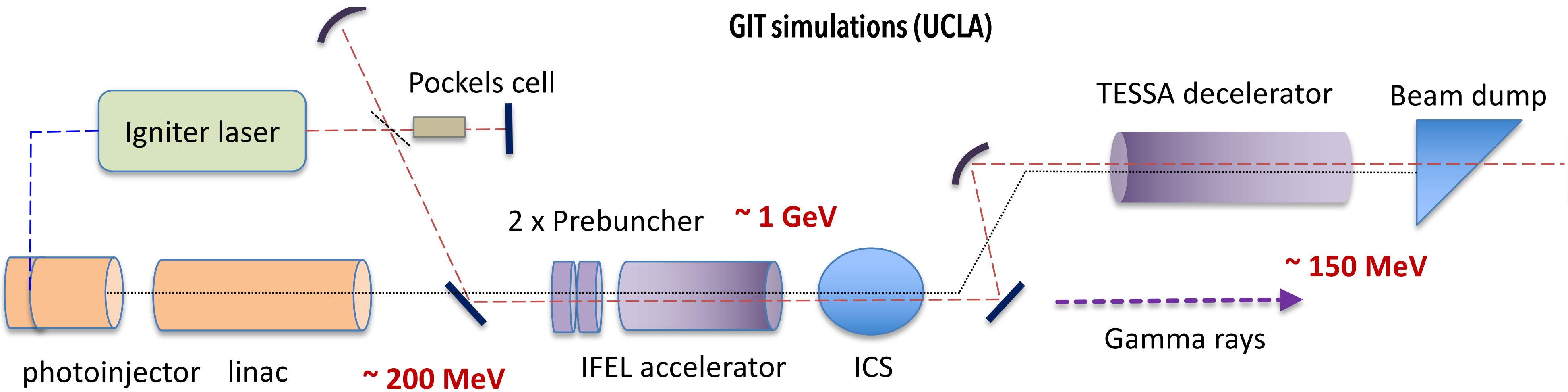


IFEL+TESSA





GIT simulations (UCLA)

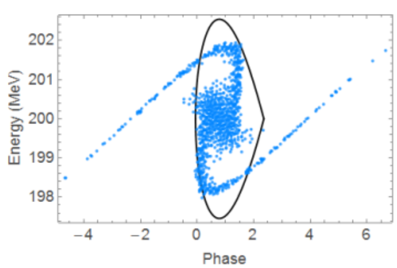


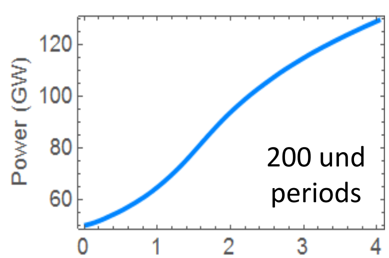
TESSA Oscillator

- TESSA offers possibility of very high efficiency e-beam to light energy conversion (~10 % vs. ~0.1 % for a conventional SASE FEL)
- There are industrial opportunities for such source (i.e. EUV lithography)
- The ongoing project at APS LEA beamline will explore TESSA at 266 nm, and the next step is an SRF linac driven oscillator (TESSO)

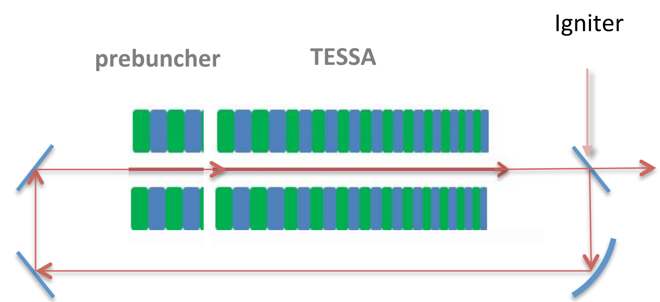
Parameter	Value
E-beam energy	250 MeV
Current	500 A
Charge	1 nC
Emittance	1 µm
Repetition rate	1 MHz
Undulator length	4 m
Laser wavelength	1 µm
Rayleigh range	48 cm
Laser waist	1.8 m
Input peak power	50 GW
Output peak power	127 GW
Net efficiency	54%
Average power	120 kW

- 250 MeV * 500 A = 125 GW peak beam power
- 250 MeV * 1 mA = 250 kW average beam power
- Seed laser power is 50 GW (40% of beam power)
- Diffraction of stimulated radiation limits undulator length to 4 m to keep gap small
- Prebunching to capture more (nearly all) charge increases net efficiency to 50%





For more info see recent UCLA workshop on high efficiency FEL: https://conferences.pa.ucla.edu/high-efficiency-free-electron-lasers/



J. Duris et al. TESSO. Under review in PRAB, arXiv:1704.05030v2

Conclusions and Acknowledgement

- Compact tunable gamma ray source could find multiple applications
- FAST facilities offers excellent opportunities to study long pulse train ICS process and high flux applications
- NIU-Fermilab-RBT collaboration FAST ICS project is under construction (experimental phase within a year)
- In the future, FAST ICS program has a natural synergy with TESSO, and also IFEL-ICS high duty cycle R&D programs
- Acknowledgement:
  - DNDO ARI support
  - NIU, Fermilab, RBT personnel contributions and encouragements
- Thank you !