RadiaBeam Inverse Compton Scattering (ICS) Experiments at ATF

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ATF Users Meeting
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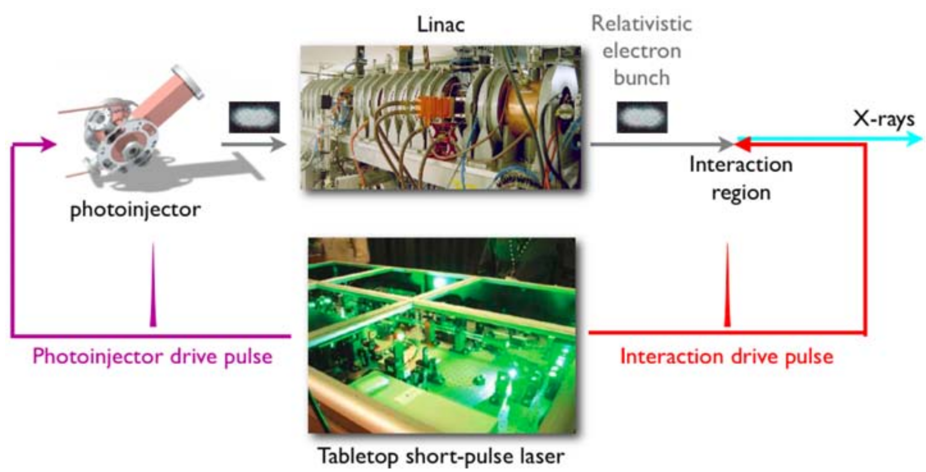
Outline

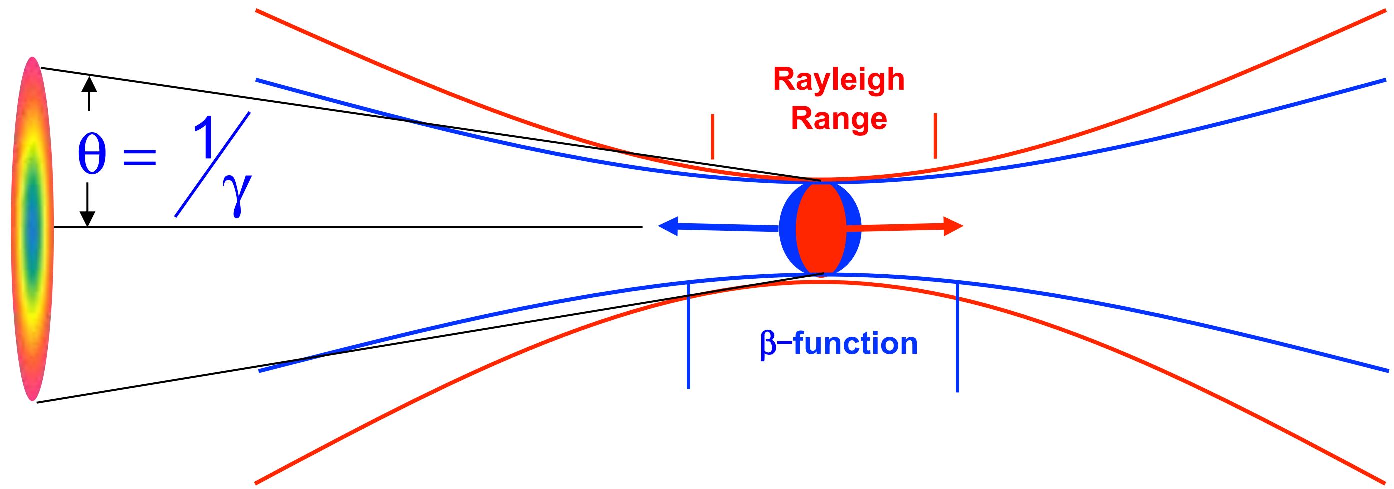
- **ICS challenges**
- Inverse-Compton Gamma-ray Source (IGS) experiment report
- Inverse Compton Source for Extreme Ultraviolet Lithography (new proposals)

ICS potential

- Synchrotron light sources are very successful and attract users with the background in research, industry, medicine and defense.
- ICS carries a potential of bringing light source quality X-rays to the users.
- ICS path to the market has many challenges.



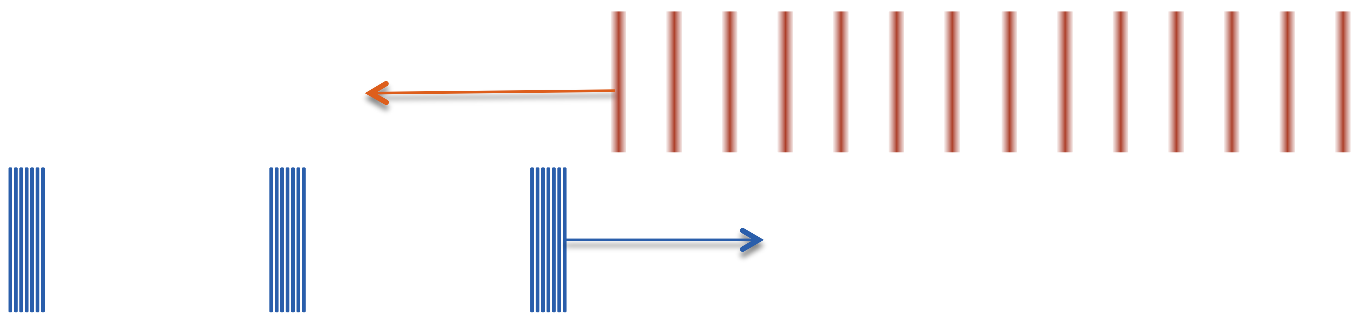
ICS challenges: *efficiency*



- Compton cross-section is very small
- At reasonable laser intensities ($a_l<1$) the process is linear, and ICS efficiency depends on maintaining maximum interaction density at IP:
  - e-beam and laser spatial and temporal overlap and minimal size;
  - precise and stable 3-D alignment;
  - good emittance, low energy spread, quality optics for electron and photon beams.

ICS challenges: *average power*

- In the best case scenario photon output per interaction is about 10^8-10^9 X-ray photons per pulse
- A typical potential users requirement is ~ 10^{12} cps
- State of the art high average power picosecond lasers and e-beams have different temporal profile



- The only solution to the average power problem is in multiple recycling of the laser beam to match e-beam burst mode profile.

ICS challenges: *funding*

- A lot of progress on ICS science has been made in national laboratories (LBNL, BNL ATF, LLNL).
- The technology is not far enough in the development cycle to attract private funding.
- Users would consider purchasing a turn key commercial ICS systems, but first someone has to fund the development.
- The type of application that can drive further development:
  1. Serve a large enough addressable market to absorb the development costs.
  2. ICS should offer a solution for the obvious and unmet need within the application.
  3. Publicly funded light source facilities should not be competing for the same users.

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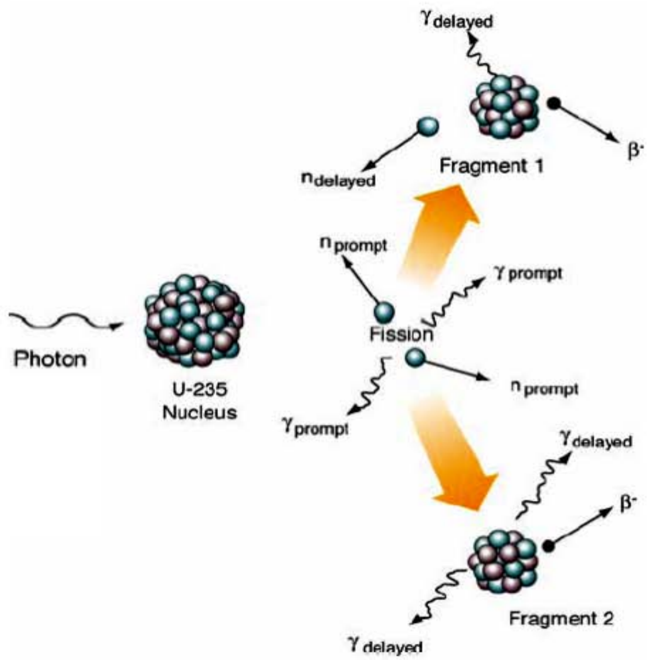
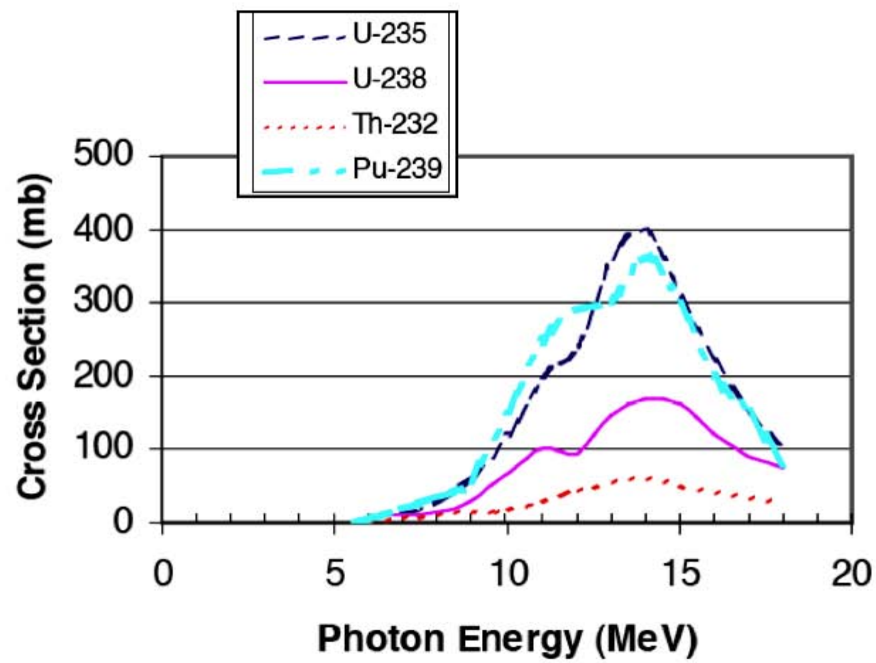
Photofission detection

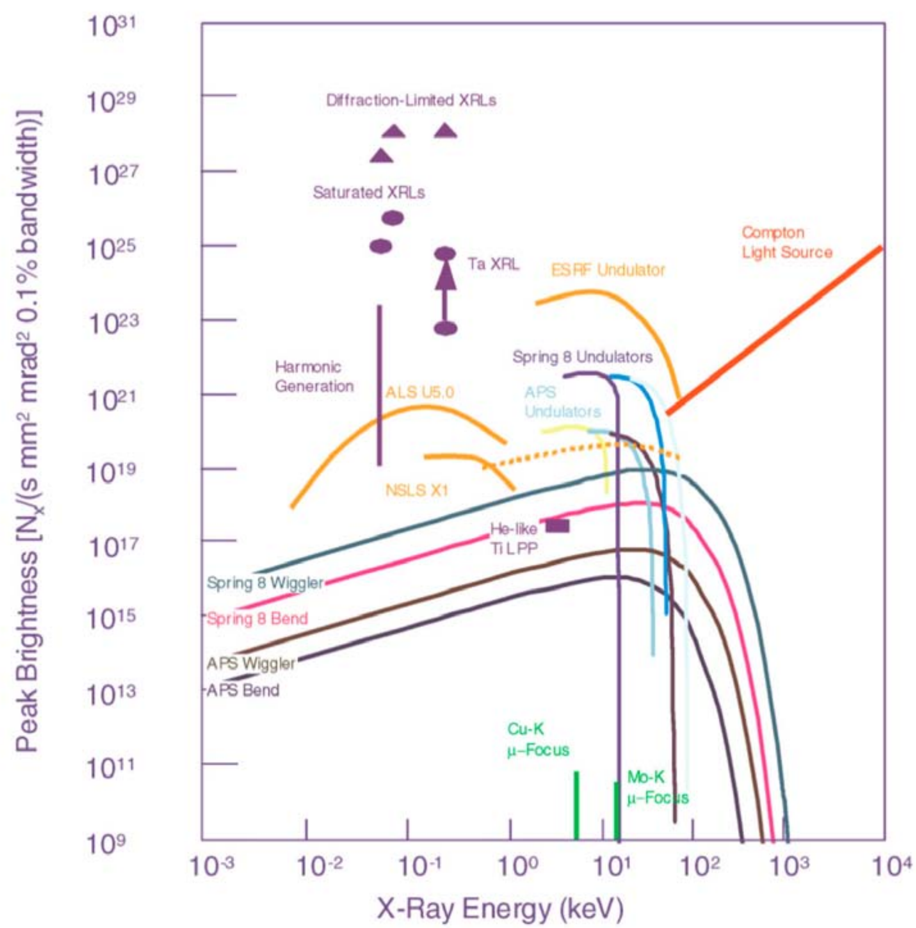
- Photon-induced fission produces signals of prompt neutrons and gammas and delayed neutrons and gammas
- Delayed neutrons/gammas are a characteristic signal of SNM





ICS gamma ray source

- High efficiency at high energy (~ 1% extraction efficiency, like FEL!)
- Directionality (1 m diameter beam at 1 km distance)
- Light sources do not reach these energies
- Border line “transportable” system
- Disadvantage: in DOD terminology, ICS is TRL 2-3 on a scale of 9, so the funding capacity is very limited at this time



[F.V. Hartemann *et al.*, *Phys. Rev. ST AB* **8**, 100702, (2005).]

IGS project at ATF

- DTRA funded Phase II SBIR project (2010-2011)
- Goal: demonstrate burst mode ICS operation enhancement with re-circulated laser
- Outcome:

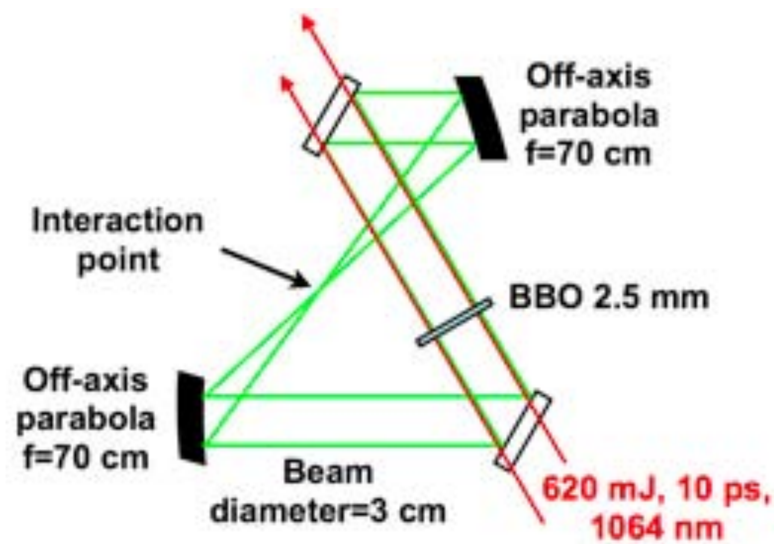
1. The primary objective was not achieved
2. Good progress, however, on the laser recirculation, ICS quality e-beam pulses generation and infrastructure development
3. Some valuable experience applicable to future efforts

R. Agustsson, S. Boucher, L. Faillace, P. Frigola, T. Hodgetts, A. Ovodenko, M. Ruelas, R. Tikhoplav (**RadiaBeam**)

M. Babzien, O. Chubar, M. Fedurin, T. Shaftan, V. Yakimenko (**BNL**), I. Jovanovic (**Penn State**), W. Brown (**MIT**), A. Tremaine (**LLNL**)

IGS design: laser recirculation

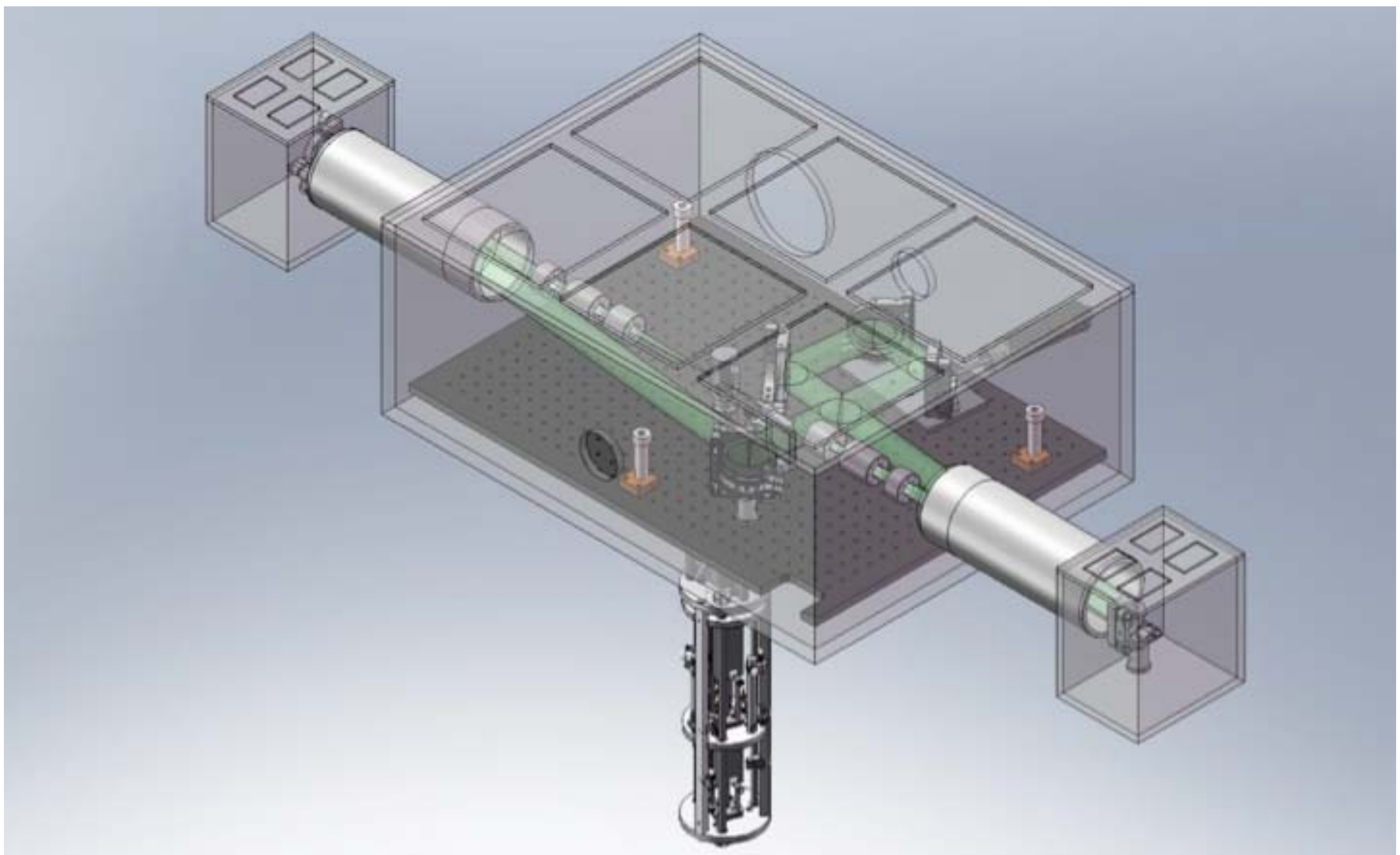
- **R**ecirculation **I**njection by **N**onlinear **G**ating (**RING**)
  - Initially Developed at LLNL by I. Jovanovich
- Advantages: simple, inexpensive, can handle high power



[I. Jovanovic *et al*., *Nucl. Instr. and Meth. A*, **578** 160 (2007).]

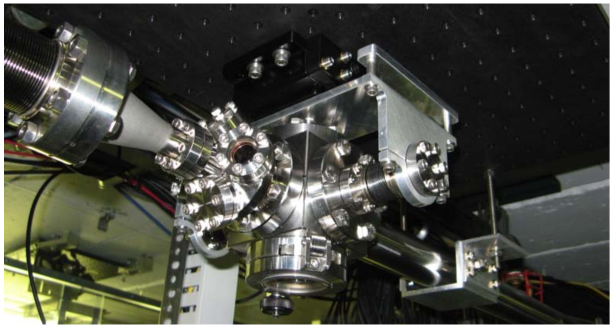
IGS design: interaction chamber

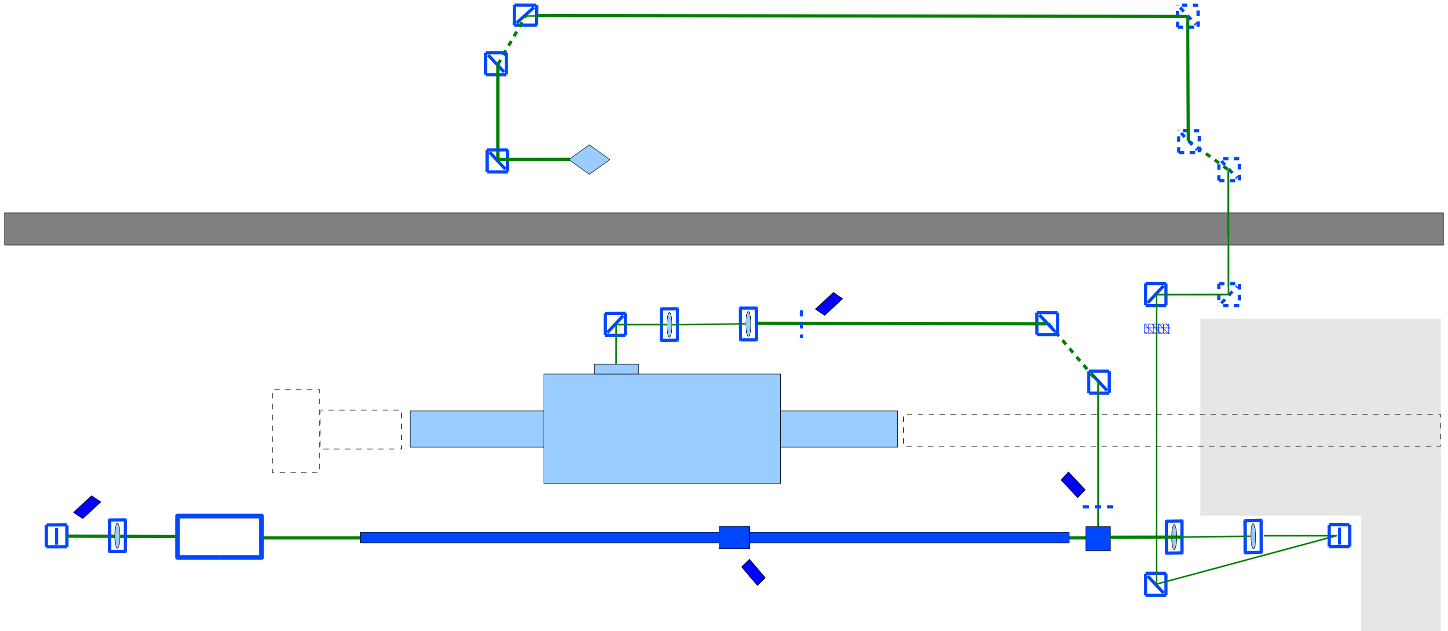
- In-vacuum RING optics (12.5 ns round trip)
- PMQ focusing/defocusing and diagnostics at the IP



IGS design: IR laser system

- Transport of ATFYAG laser to EH
- Two passes through spatial filter and amplifier to achieve 100 mJ at the IP
- Matching optics into the interaction chamber





IGS design: projected performance

- Design performance: ~ 10^7 X-rays per pulse (at ~ 160 keV)
- With the RING resonator expected enhancement is factor of ~20

m

RMS pulse duration	5.0E-12	s
charge	**6.0E-10**	C
n-emittance	2.5E-06	m-rad
e-beam energy	**66**	MeV
RMS beam size	1.5E-05	m
gamma	129	
peak power beam	3.2E+09	W
# electrons/bunch	3.8E+09	
e-beam energy	4.0E-02	J

RMS pulse duration	5.0E-12	s
RMS beam size	1.5E-05	m
Laser wavelengh	5.3E-07	m
Laser pulsed energy	**0.1**	J
peak power laser	8.0E+09	W
photon energy	3.7E-19	J
# photons	2.7E+17	

e-beam pulse length	1.5E-03	m
beta function	1.2E-02	m
laser pulse length	1.5E-03	m
ZR	5.3E-03	m

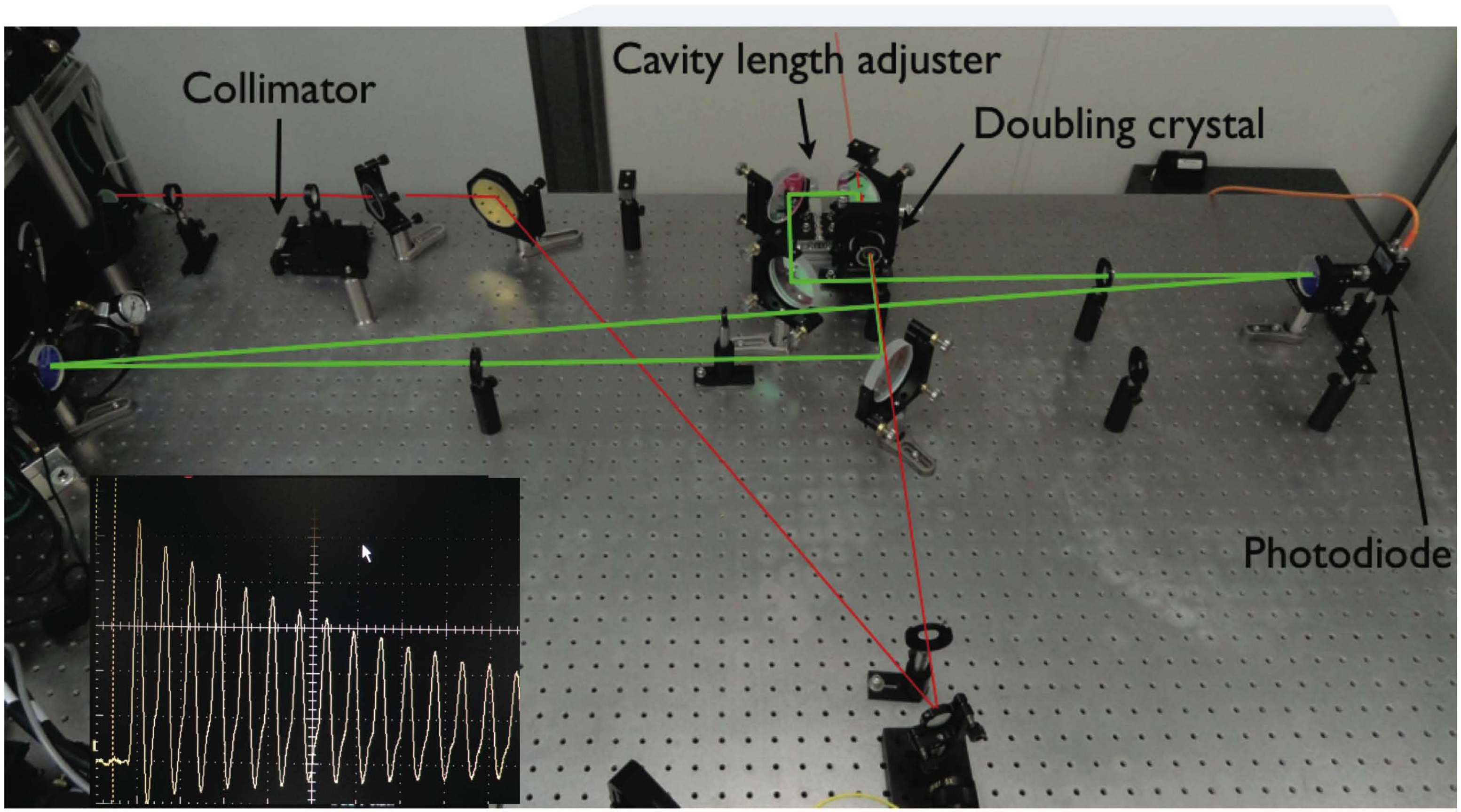
pulse lengths ratio	1.0	
beam size ratio	1.0	
peak current	48	A
aL	0.01	

X-rays output

# X-rays	2.4E+07	
X-ray energy	1.6E+05	eV
X-ray wavelength	7.9E-12	m
X-ray beam energy	5.9E-07	J

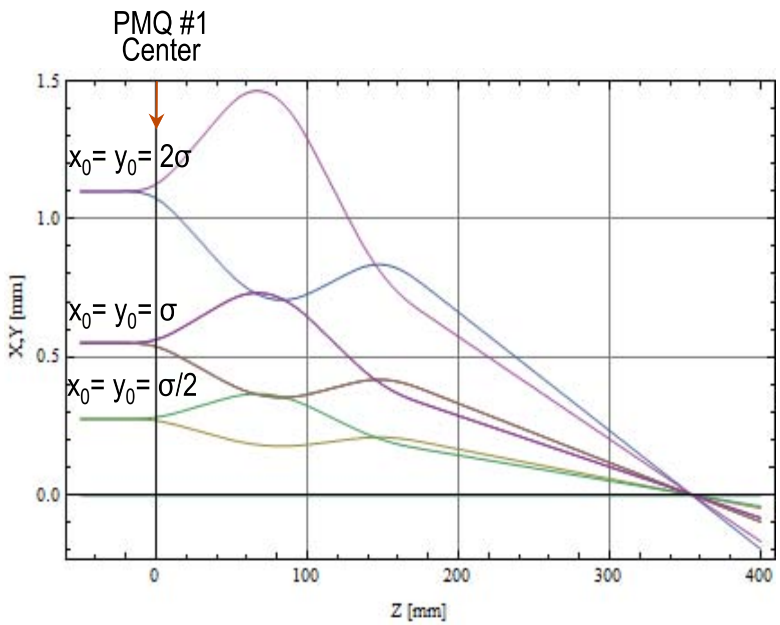
RING commissioning

- Successful bench top test (~ 3% losses per round trip)
- Excellent spatial stability of the focal spot (publication pending)

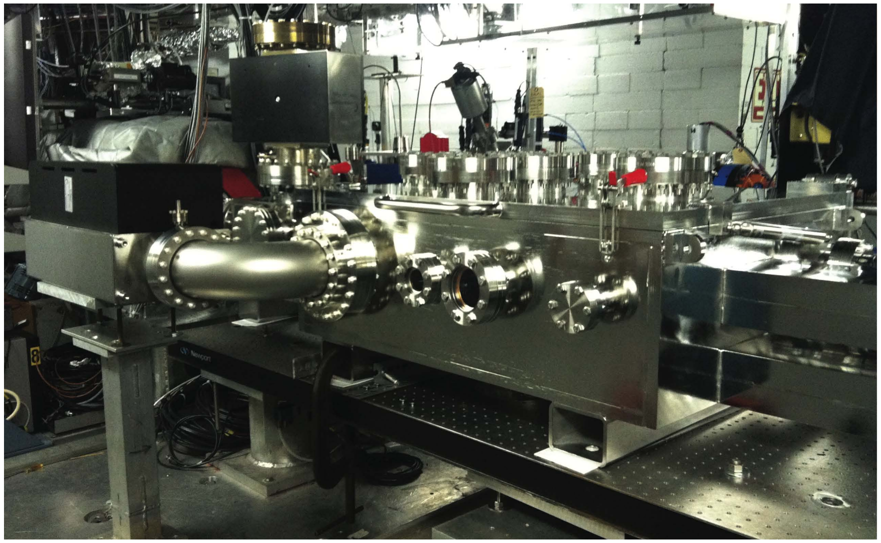
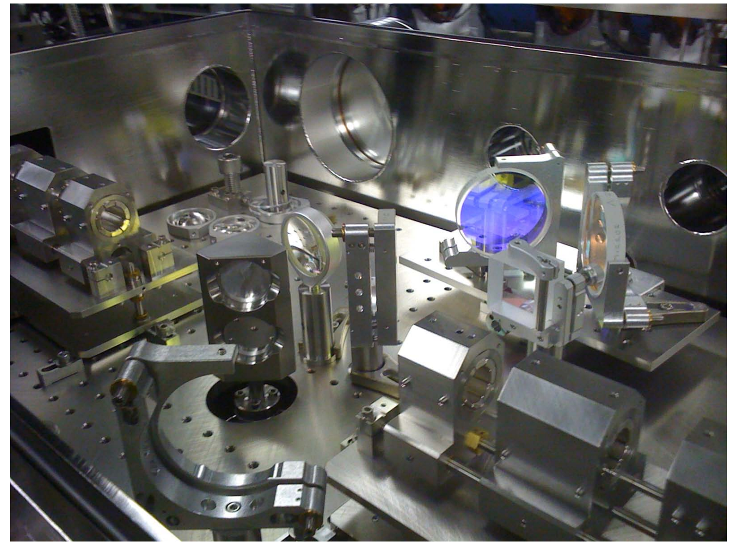
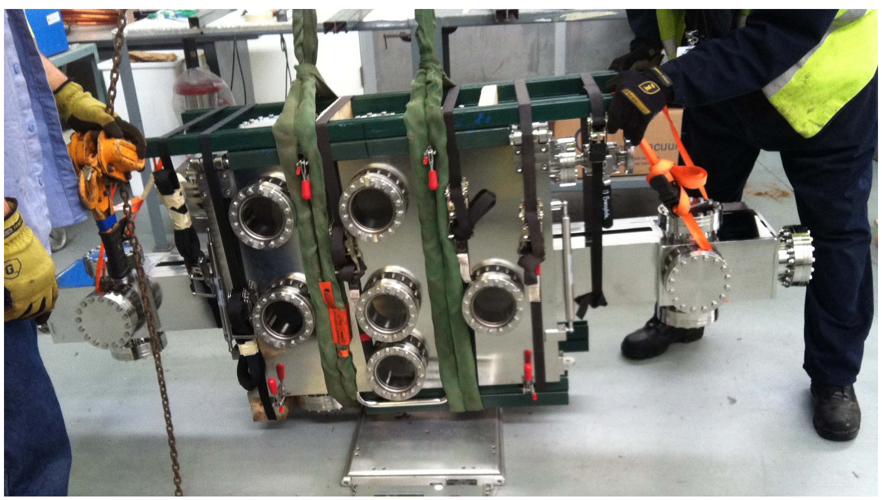
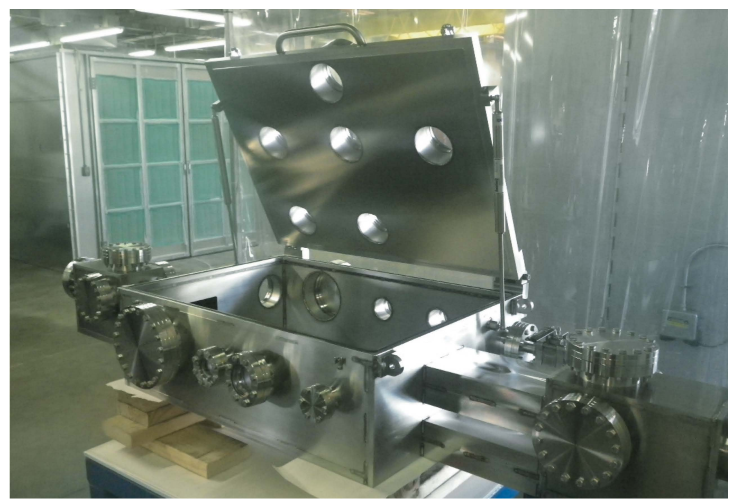


PMQ system

- Spot size at the IP ~ 15 μm RMS
- In-vacuum PMQ triplets fabricated for focusing and also to clear the beam downstream of IP

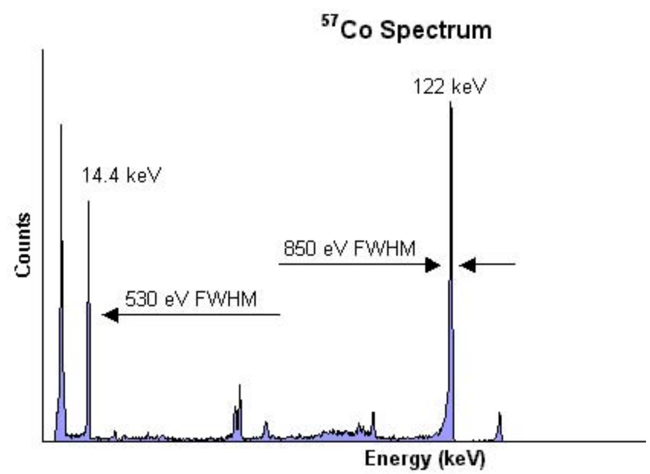


Interaction chamber

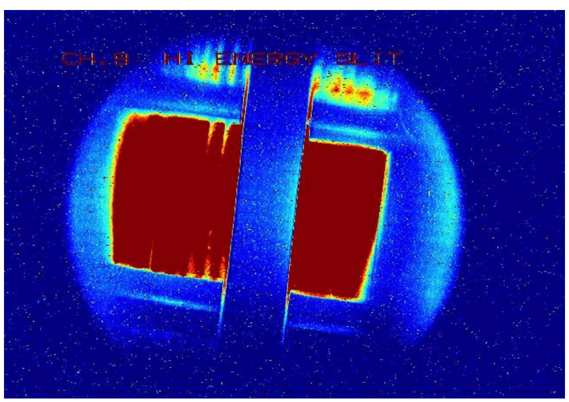
Detection issue

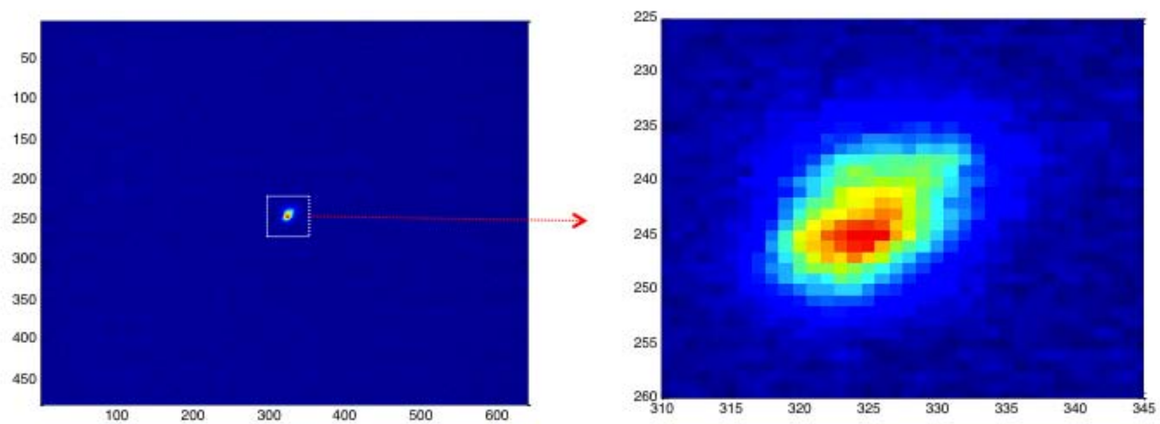
- Original plan was to use Amptek "spectrometer"
- More detailed analysis revealed that Amptek is a bolometer working in photon counting mode, not suitable for picosecond pulse detection
- Plan B was using scintillating screen, but signal to noise is an issue, since 160 keV photons are hard to detect (long penetration depth), and experiment was not planned properly with this problem in mind.



Experimental Results

- ✓ Produced 20-bunches pulse train e-beam 300-600 pC/ bunch
- ✓ Achieved 15 μm e-beam at the IP
- ○ ~ 50 mJ IR laser at the IP (run out of time to fully commission spatial filter and intra-vacuum RING cavity)
- x No X-rays were detected





Conclusions

- It was attempted to demonstrate the burst mode ICS operation at the ATF, but a combination of a detection method planning error and aggressive schedule and budgetary constrains prevailed..
- The experiment came fairly close, and we are looking forward to the future opportunities to continue this work.
- Valuable experience has been gained, and some useful hardware has been developed.
- ATF staff was very supportive and instrumental throughout design, implementation and commissioning stages of this project (thank you)!
- The project was supported by DTRA Phase II SBIR Contract *No.* HDTRAI-10C-0001

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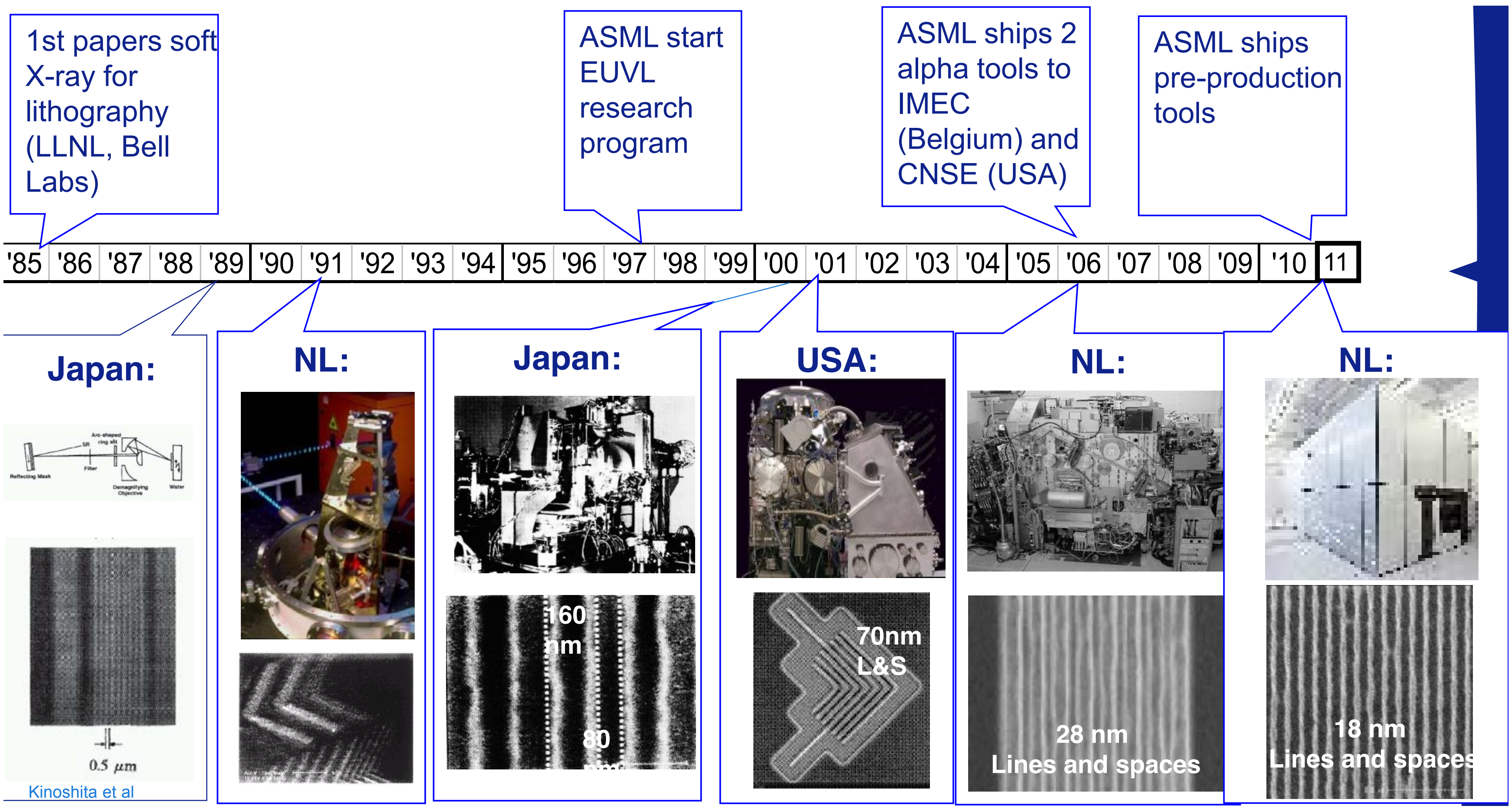
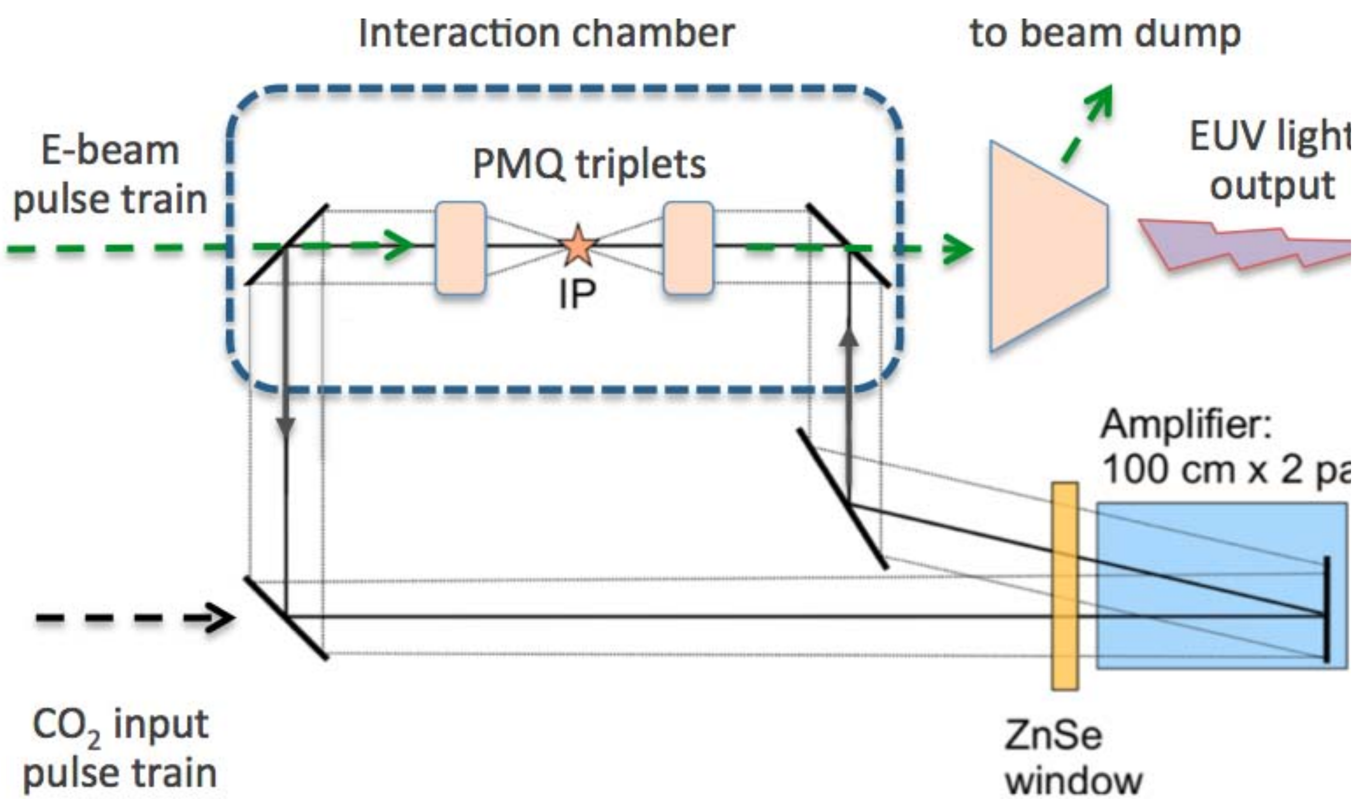
Motivation

- EUVL is the next big thing in the semiconductor industry to enable ~ 10 nm features



EUVL ICS System

- CO2 laser is ideal match for the wavelength (gamma ~ 20)
- Burst mode 1 J class CO2 is available via re-amplification
- NCRF e-gun and CO2 can in principle achieve 1 kHz rr



New EUVL ICS Project at ATF

- DOE Phase I SBIR Award No. DE-SE0007703

- **Phase II goal:** <u>scaled experiment at ATF BNL</u>
  1. Peak brightness demonstration
  2. Pulse train ICS demonstration

- **Phase I technical objectives:**
  1. EUVL ICS single shot system optimization
  2. Design of the CO_2 laser recirculation/reamplification
  3. Design studies of e-beam dynamics
  4. Design of the interaction chamber
  5. Phase II experimental planning

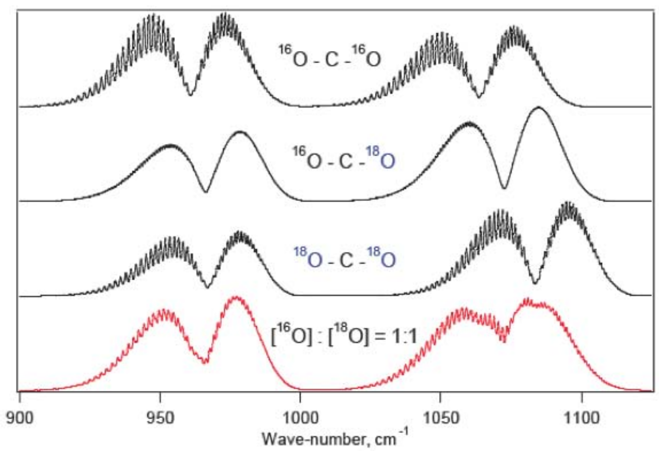
Scaled experiment design

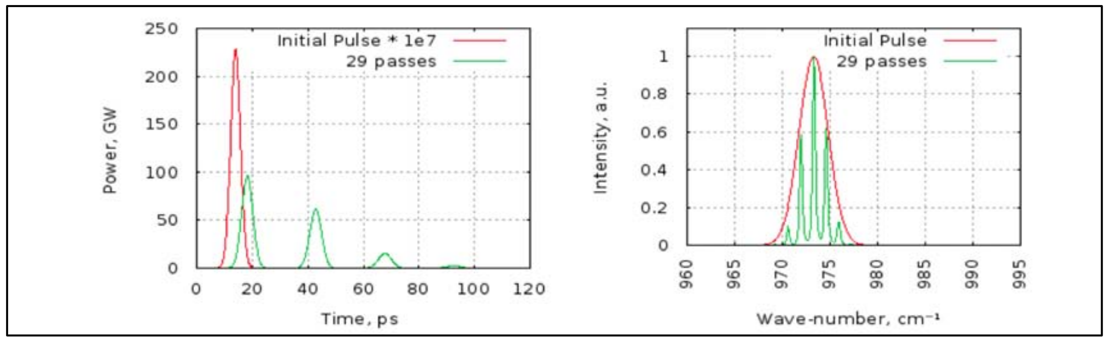
- Proper scaling requires the same optical properties for e-beam and laser.

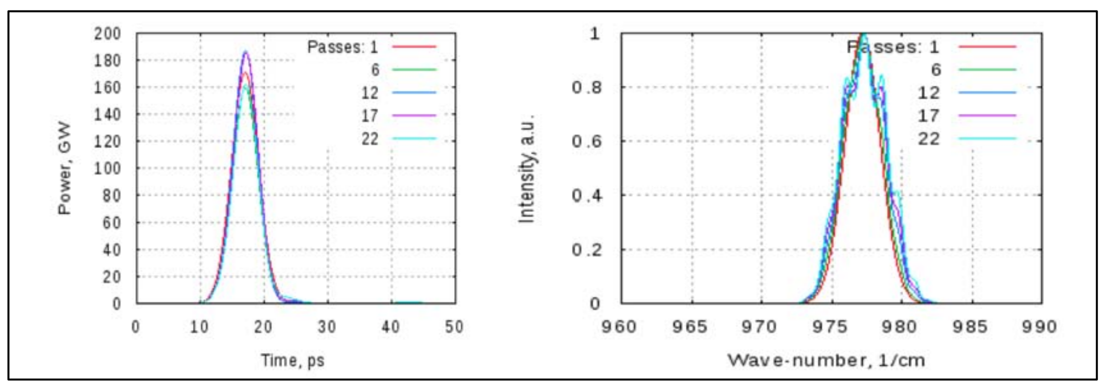
Initial working point parameters	**Phase II ATF**	**EUVL ICS**
Electron beam bunch charge	0.6 nC	0.6 nC
Electron beam energy	60 MeV	10 MeV
Electron and laser bunch lengths, RMS	5 psec	5 psec
Electron beam spot size at IP, RMS	30 μm	50 μm
Electron beam normalized emittance	5.0 mm-mrad	2.5 mm-mrad
Electron beam peak current	50 A	50 A
Electron beam beta function at IP	2 cm	2 cm
Laser wavelength	10.6 μm	10.6 μm
Laser pulsed energy	1.5 J	2.3 J
Laser beam spot size at IP, RMS	50 μm	50 μm
Dimensionless laser amplitude	0.25	0.30
Laser Rayleigh range	3 mm	3 mm
Peak X-rays energy	6.2 keV	170 eV (**7 nm**)
Maximum X-rays flux per interaction	**1 x 10^9**	**1 x 10^9**

Pulse train system design

- ATF code to optimize the molecular composition of the amplifier, to maintain good bandwidth after multiple passes.
- Leveraged on the similar studies for IFEL in 2010.

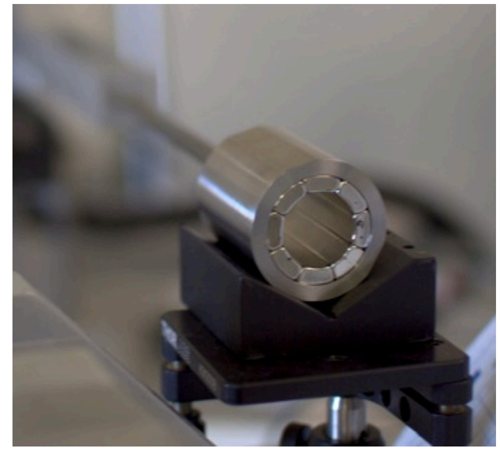


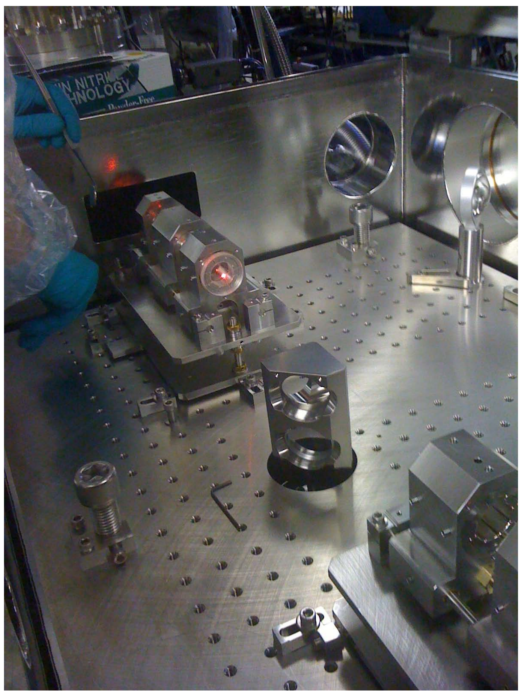


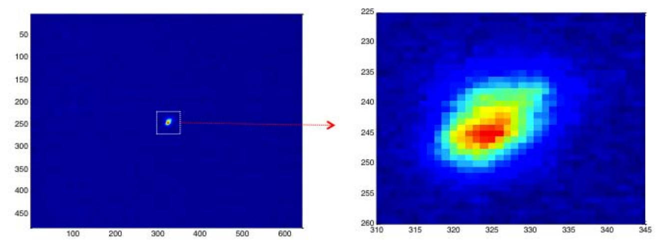


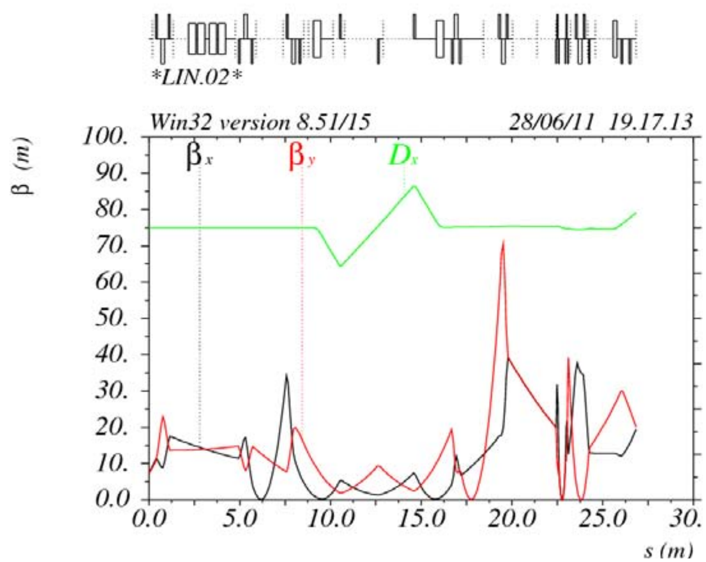
E-beam transport optimization

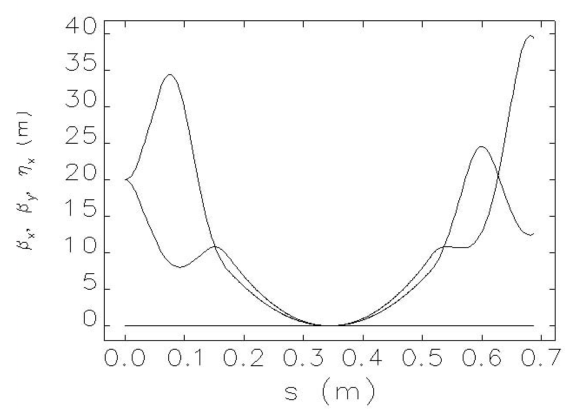
- ELEGANT simulations and final focus optimization
- PMQs design



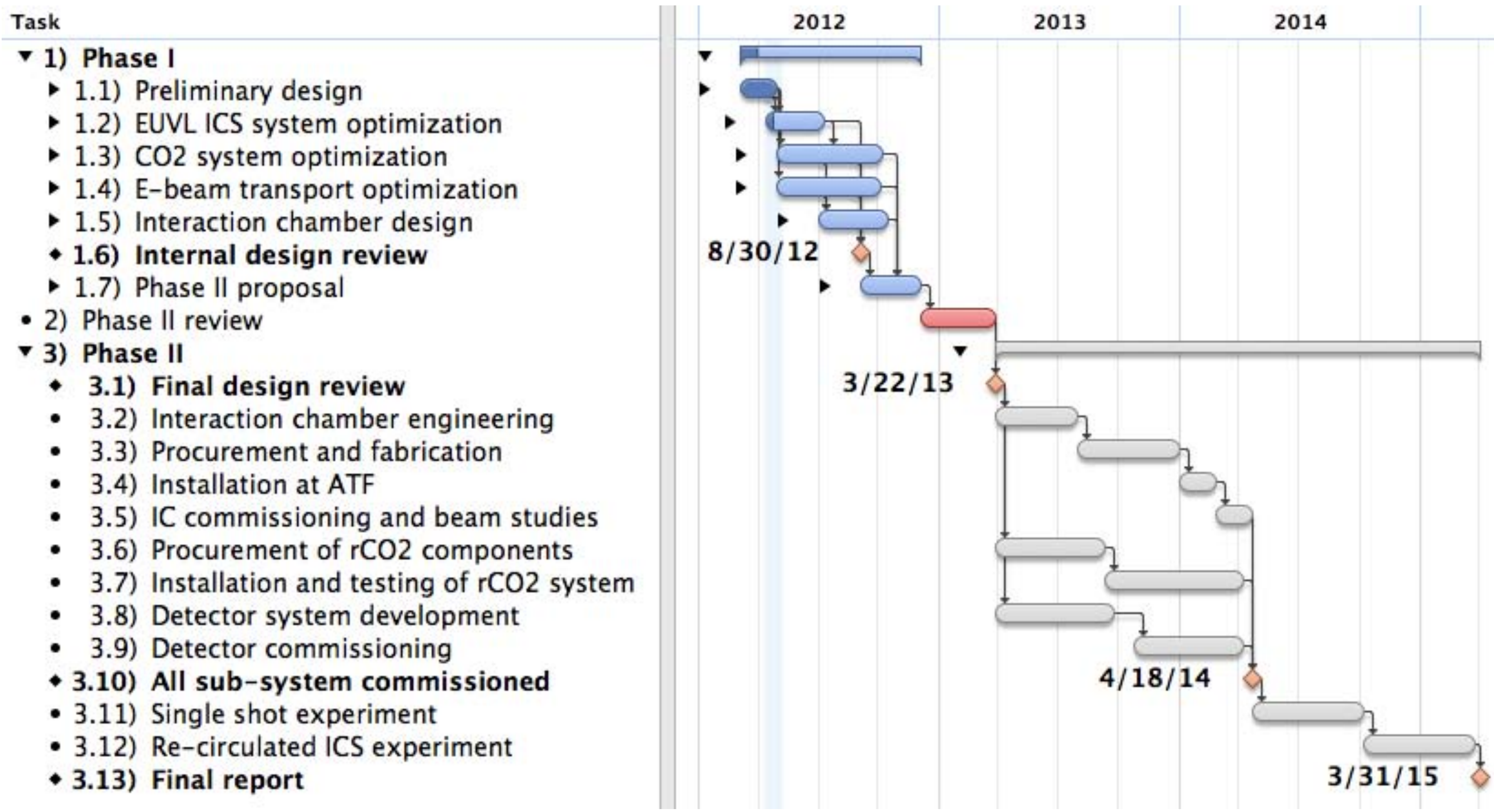








Schedule



Task
2012
2013
2014
1) Phase I
1.1) Preliminary design
1.2) EUVL ICS system optimization
1.3) CO2 system optimization
1.4) E-beam transport optimization
1.5) Interaction chamber design
1.6) Internal design review
1.7) Phase II proposal
2) Phase II review
3) Phase II
3.1) Final design review
3.2) Interaction chamber engineering
3.3) Procurement and fabrication
3.4) Installation at ATF
3.5) IC commissioning and beam studies
3.6) Procurement of rCO2 components
3.7) Installation and testing of rCO2 system
3.8) Detector system development
3.9) Detector commissioning
3.10) All sub-system commissioned
3.11) Single shot experiment
3.12) Re-circulated ICS experiment
3.13) Final report
8/30/12
3/22/13
4/18/14
3/31/15