Inverse Compton Scattering Gamma-Ray Source at ASTA

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Fermilab

Outline

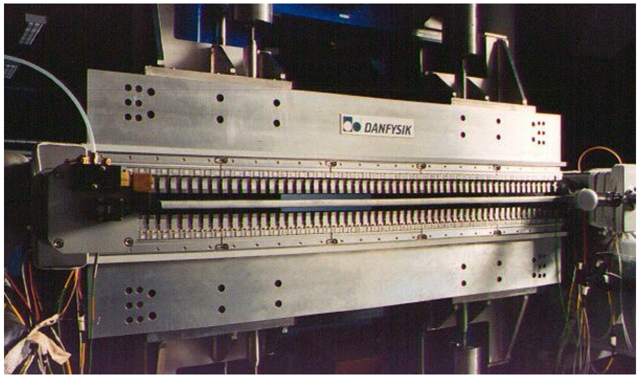
- **Concept of inverse Compton scattering (ICS) light sources**
- Gamma-ray beams applications
- Gamma-ray ICS source parameters at ASTA
- Technical Implementation
- Conclusions

X-ray light sources

- Synchrotron radiation X-ray light sources are very successful (over a dozen in operation, many under construction/upgrades)
- Ever growing demand from users in many disciplines
- Large facilities based of multi-GeV storage rings

Scaling to optical wavelength

- If undulator is replaced with the laser, one can make a light source much smaller



$$\lambda_s \propto \lambda_0 / \gamma^2$$

$$\lambda_0 > 1 \text{ cm}$$

$$\gamma \sim 10^4$$

Football stadium size facility

Undulator radiation

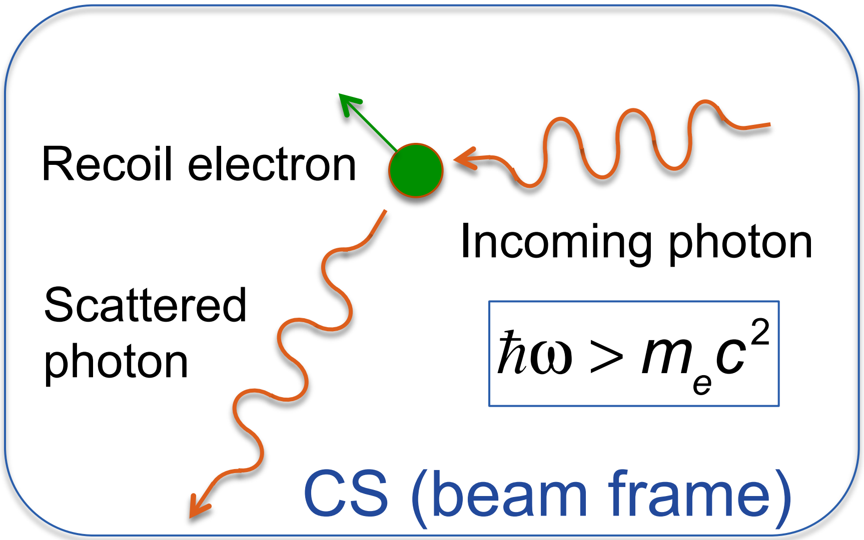
$$\lambda_0 \sim 1\ \mu\text{m}$$

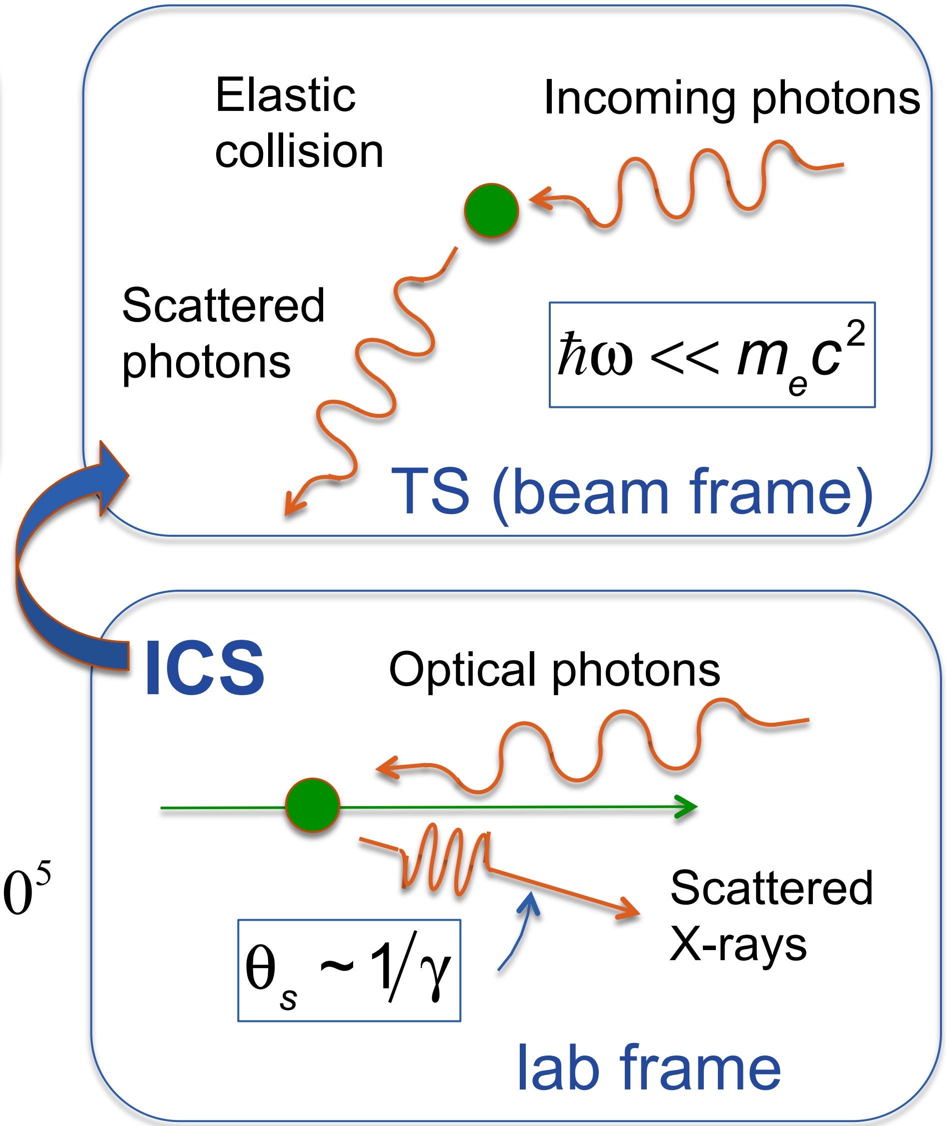
$$\gamma \sim 10^2$$

Room size installation

Inverse Compton Scattering

Inverse Compton Scattering (ICS)





$$k_s \approx 4\gamma^2 k_0 \left(\frac{1}{1 + a_L^2 + \gamma^2 \theta_s^2} \right)$$

$$\sigma_{ICS} \approx \sigma_{th} \quad \text{for} \quad \gamma << \lambda_0 / \lambda_e \sim 10^5$$

$$\sigma_{th} = \frac{8\pi}{3} r_e^2 = 6.65 \times 10^{-25} \ \text{cm}^2$$

ICS vs. undulator radiation

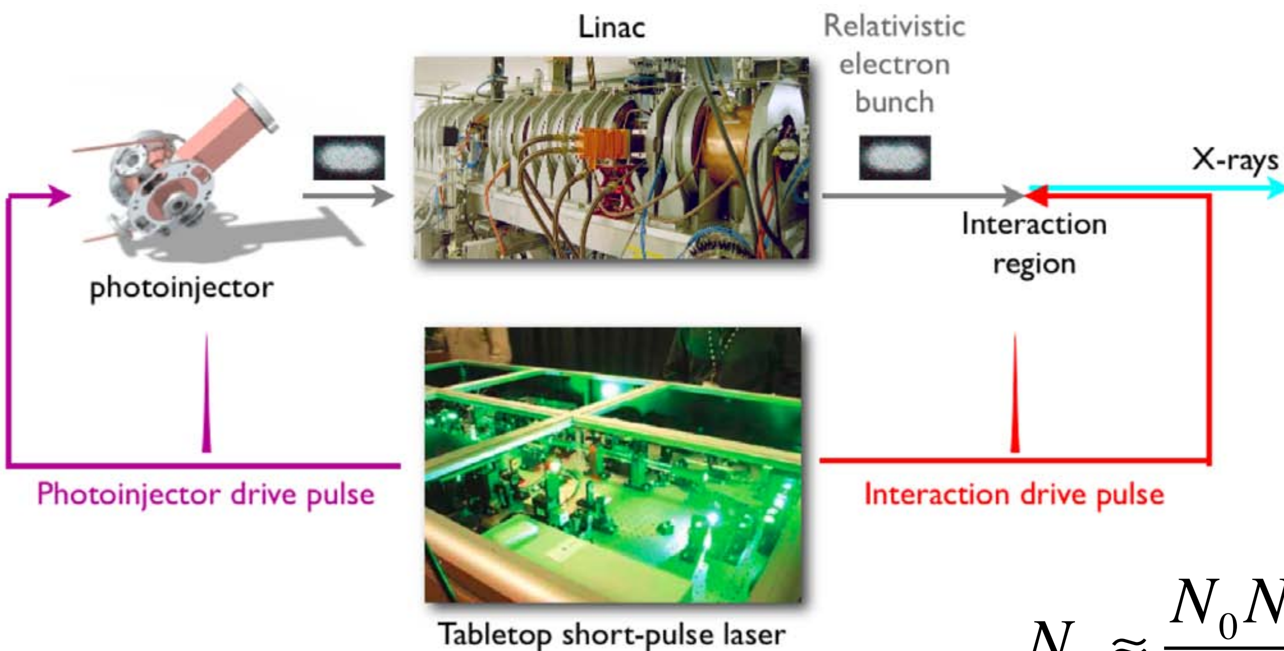
- Good news: ICS is a classical process very similar to the undulator radiation
- Bad news: need high intensity laser to match undulator radiation efficiency

$$\beta_\perp \bar{\gamma} \sim 1 \quad \Rightarrow \quad \begin{cases} K_U \approx 1 \\ B \sim 1\ \mathrm{T} \end{cases} \Leftrightarrow \begin{cases} a_L \approx 1 \\ I \sim 10^{18}\ \mathrm{W/cm^2} \end{cases}$$

- 1 J - class, picosecond laser focused to a spot size of ~ 10 μm

Photoinjector driven ICS

- Picosecond beams focused to a small spot size means photoinjector e-beam system



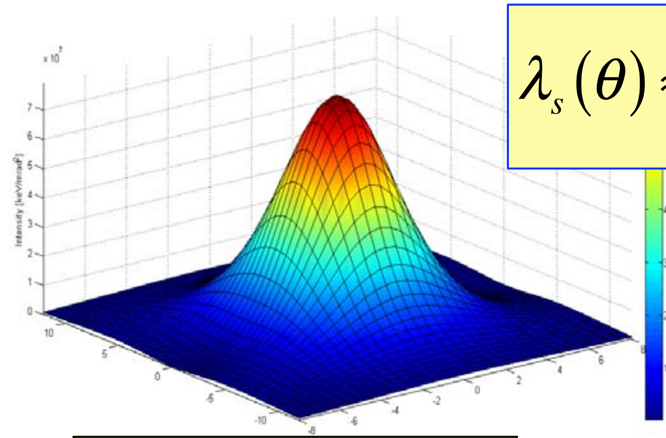
$$N_s \approx \frac{N_0 N_e \sigma_{th}}{A}$$

- 1 nC, 1 J, 10 μm RMS → ~ 10^9 photons/interaction

Source bandwidth

- Finite intrinsic bandw
  - ✓ off-axis red-shift
  - ✓ 3D laser focus
  - ✓ laser bandwidth
  - ✓ emittance
  - ✓ e-beam energy spread

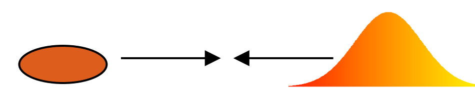
$$\lambda_s(\theta) \approx \frac{\lambda_0}{4\gamma^2}\left(1+\gamma^2\theta^2\right)$$



Red-shift

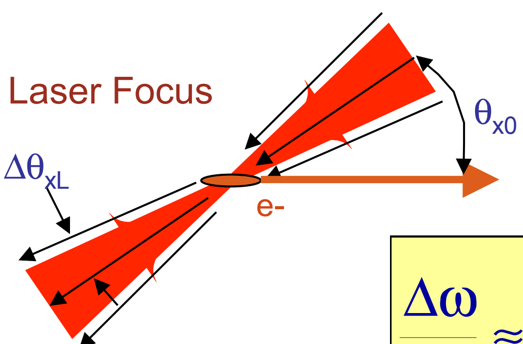
off-axis

$$\frac{\Delta\omega}{\omega} \approx 2\sqrt{\frac{\Delta\omega_0^2}{\omega_0^2}+\frac{\Delta\gamma^2}{\gamma^2}}$$



Laser Bandwidth/Energy Spread/Emittance

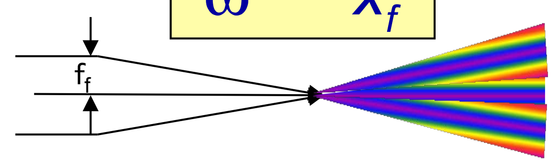
3D Laser Focus



[courtesy of W. Brown]

$$\frac{\Delta\omega}{\omega} \approx \Delta\theta_{xL}^2 \approx \left(\frac{\lambda_0}{\pi w_0}\right)^2$$

$$\frac{\Delta\omega}{\omega} \approx \frac{\varepsilon_{nx}^2}{x_f^2}$$



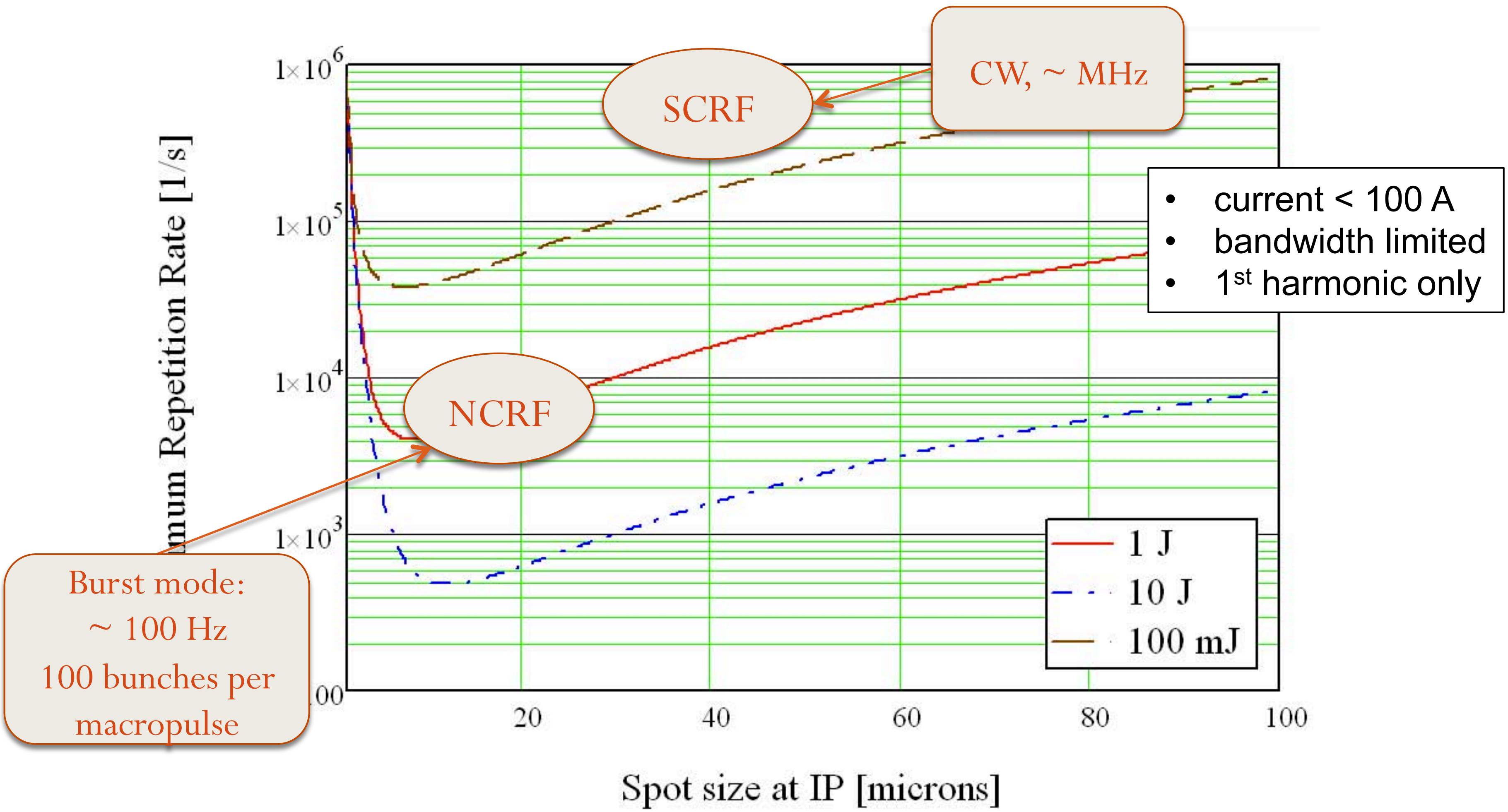
Photon yield requirements

- Best photon yield $< 10^9$ per interaction (so far, experimentally at optical wavelength $\sim 10^7$)
- Best spectral brightness $\sim 10^7$ photons in 1% bandwidth
- Most applications require $\sim 10^{10}$-10^{11} cps in 1 % bandwidth

- Hence, the optimized ICS operations regime is 10^4-10^5 interactions per second.

ICS for Phase-Contrast Imaging

- Repetition rate to achieve 10^{11} cps in 1 % bandwidth:



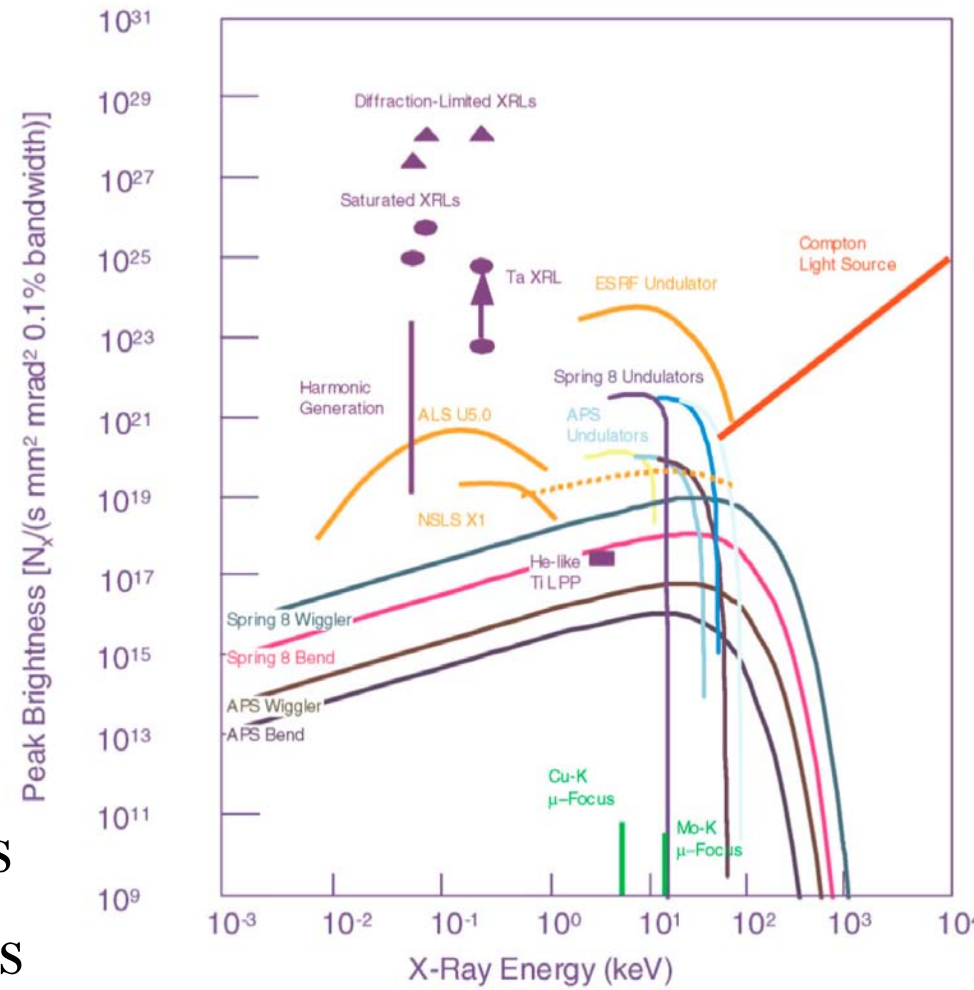
ICS technical challenges

- A minimum required is ~ 10^4 interactions per second, with the 1 J class laser
- Laser re-circulation via optical cavity
- Photoinjector has to operate in a bunch train mode
- E-beam concerns: quality, repeatability and sub-ps synchronization to the laser over pulse train duration For practical applications the entire system has to be high fidelity and turn key…

- It is hard to beat X-ray Light Sources

ICS gamma ray source

- High efficiency at high energy (~ 1% energy extraction efficiency, like FEL!)
- Directionality (~1 mrad)
- Source brightness scales like ~ γ^4 !
- Uniqueness – light sources do not reach MeV energies



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

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- **Gamma-ray beams applications**
- Gamma-ray ICS source @ ASTA
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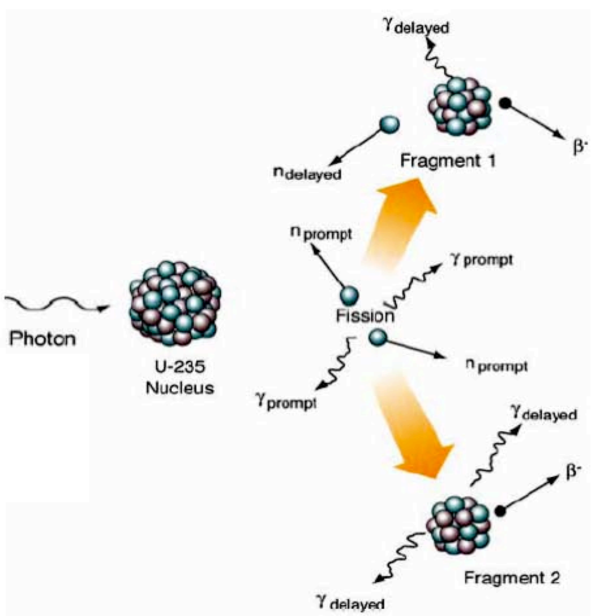
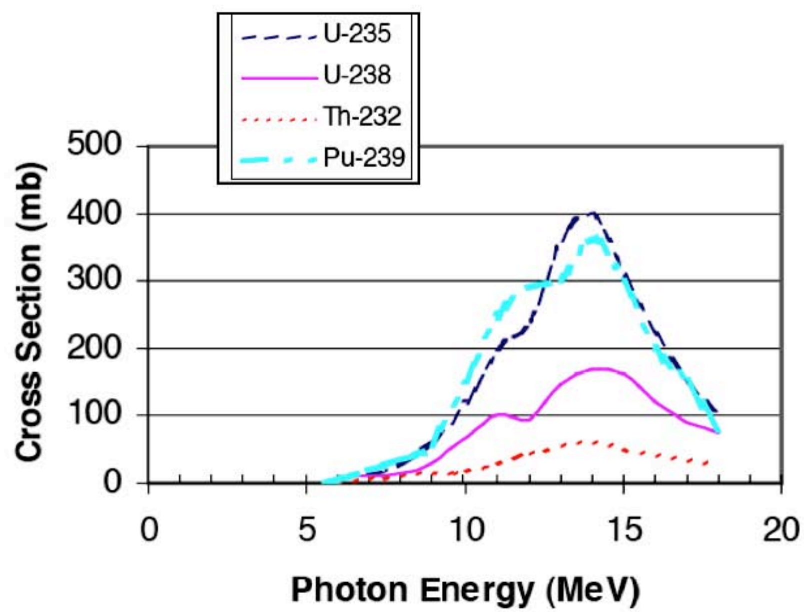
Applications: nuclear threat detection

- Gamma-ICS source can be used to detect concealed special nuclear materials (SNM) via photofission
- Low beam divergence, moderate scattering in atmosphere → stand-off distances up to 1 km!

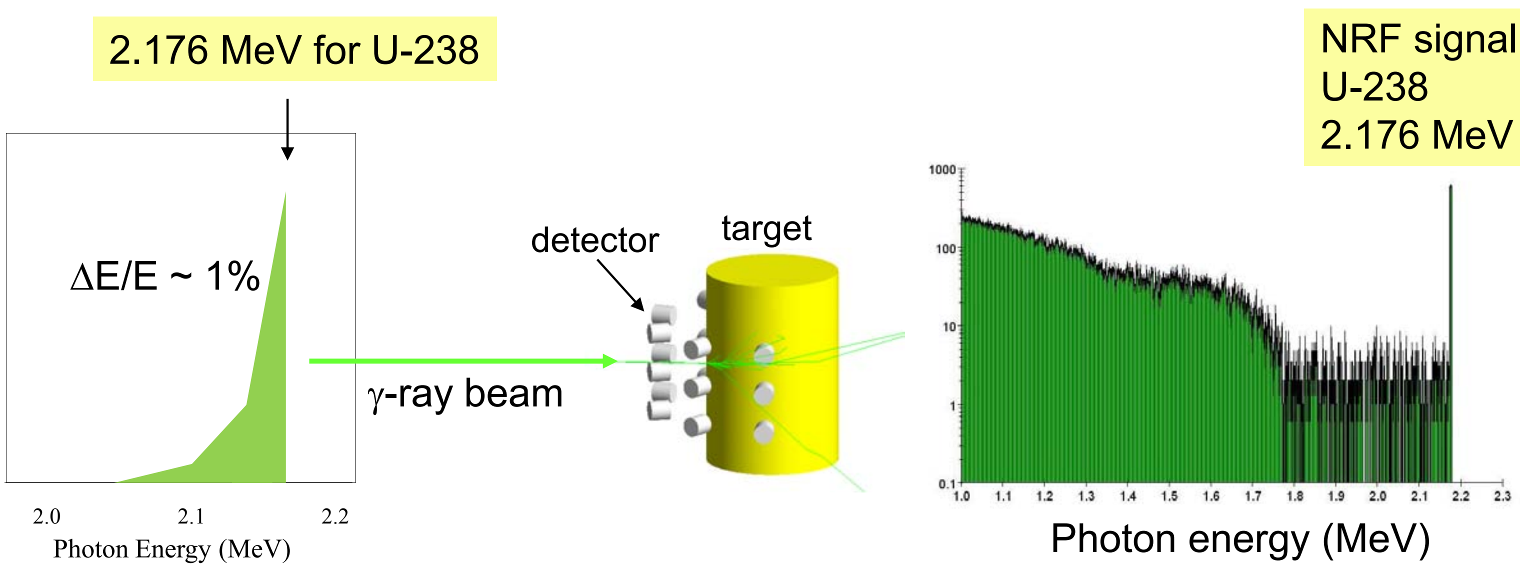




[J.L. Jones *et al.*, Neutrons Workshop at ONR, October 2006.]

Applications: nuclear waste analysis

- With high degree of monochromaticity nuclear resonance fluorescence (NRF) detection is also possible.
- NRF can also be used for SNM detection (LLNL)

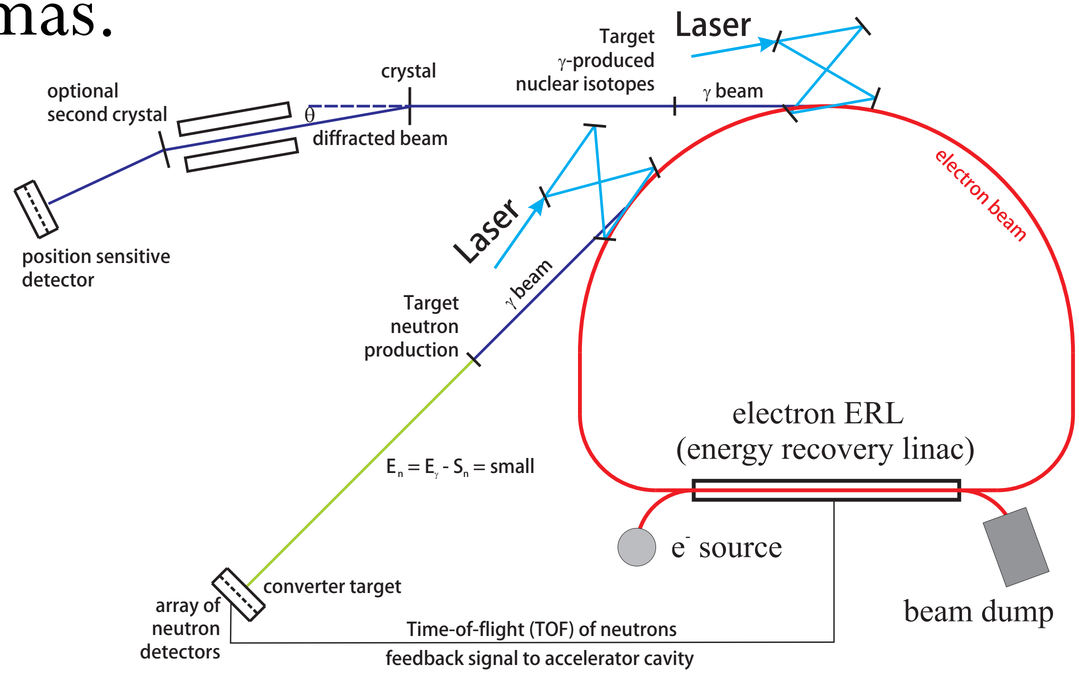


[R. Hajima, Japan Atomic Agency ERL Group (2008).]

Applications: medical isotopes R&D

- ERL based gamma ray sources for isotopes production
- Even more interesting is generation of specific activity radioisotopes via photo-excitation by tuning to specific energy gammas.

mother isotope	$T_{1/2}$	daughter isotope	$T_{1/2}$
^{44}Ti	60.4 a	^{44}Sc	3.9 h
^{52}Fe	8.3 h	^{52}Mn	21 m
^{68}Ge	288 d	^{68}Ga	68 m
^{81}Rb	4.6 h	^{81}Kr	13 s
^{82}Sr	25.0 d	^{82}Rb	76 s
^{90}Sr	28.5 a	^{90}Y	64 h
^{99}Mo	66 h	^{99m}Tc	6.0 h
^{188}W	69 d	^{188}Re	17 h
^{224}Ra	3.7 d	^{212}Pb*	10.6 h
^{224}Ra	3.7 d	^{212}Bi*	61 m
^{225}Ac	10 d	^{213}Bi*	45 m



[D. Habs, P.G. Thirolf *et al* " Medical Application Studies at ELI-NP", 2012]

Applications: nuclear physics research

γ beam revolution of *nuclear physics*:
similar to laser revolution of *atomic physics* in'60s

γrays: opens new nuclear physics

-measurement of neutron cross section of rare nuclei by inverse process of (γ,n)

-*nuclear resonance fluorescence* and *spectroscopy*

-particular excitation

*nuclear electroweak excitation such as parity measurement

*isomer creation

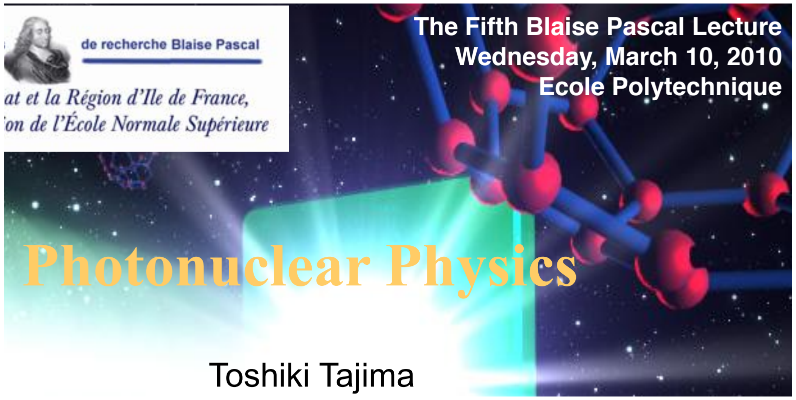
*particular excitation and interaction with inner-shell electrons

-manipulation of nuclei by more than one gamma pulse

*consecutive excitation to higher levels

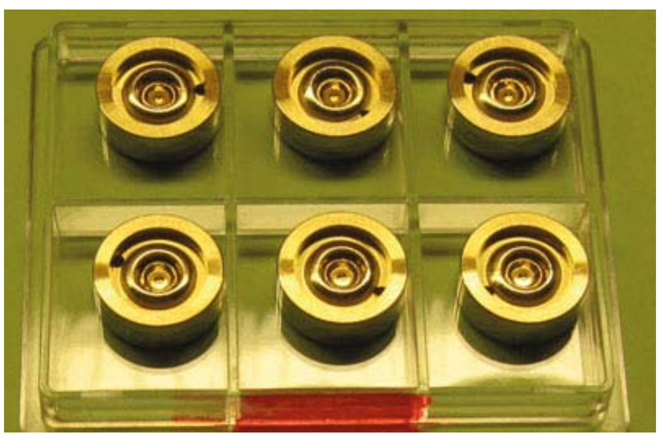
*exploration of exotic nuclear states?

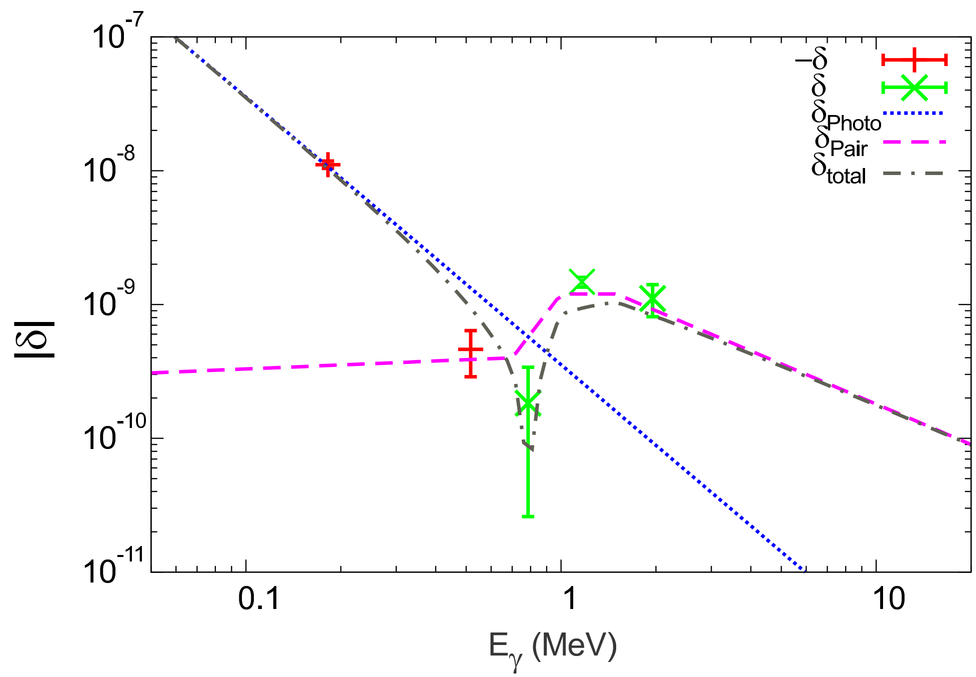
*quantum control of nuclear states



Applications: gamma ray "optics"

- Observation of "refractive" behavior above 0.7 MeV:
  - potentially new area of active research
  - possibility of making gamma-ray optics
  - possibility of ultra-monochromatic gamma beams (1E-6)





[D. Habs *et. al.* " The Refractive Index of Silicon at γ Ray Energies", PRL 2012]

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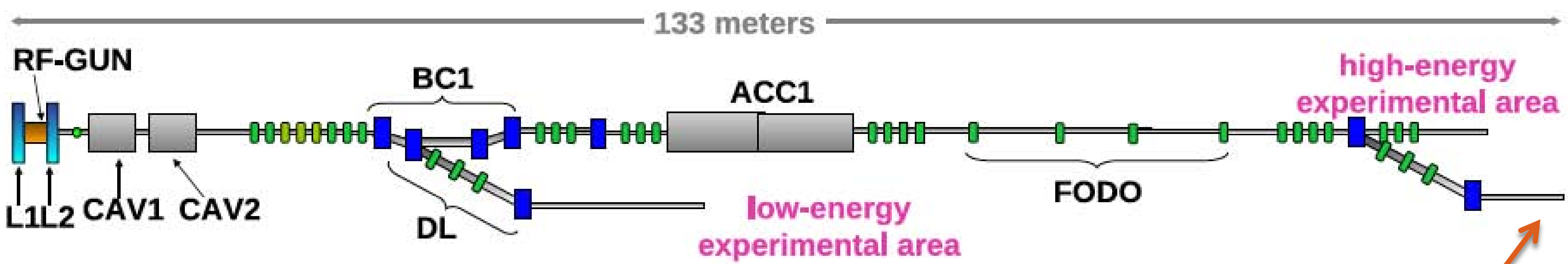
Gamma ICS @ ASTA



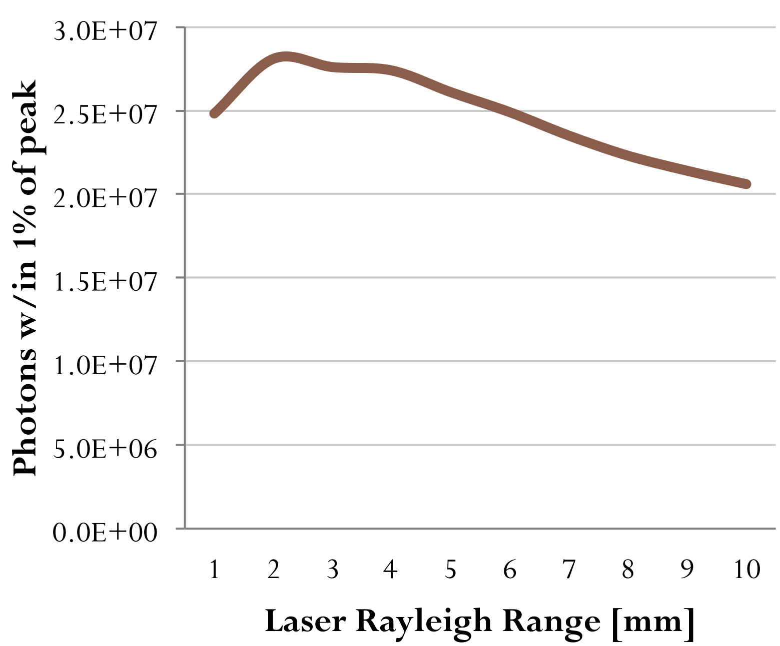
E-beam	
Charge	3 nC
Bunch length	~ 30 ps
Normalized emittance	~ 5 μm
Energy	500-1000 MeV
RMS spot size @ IP (	~ 20 μm
Beta function	~ 10 cm
Laser	
Pulsed energy	~ 1 J
Wavelength	~ 1 μm
Raleigh range	5 mm

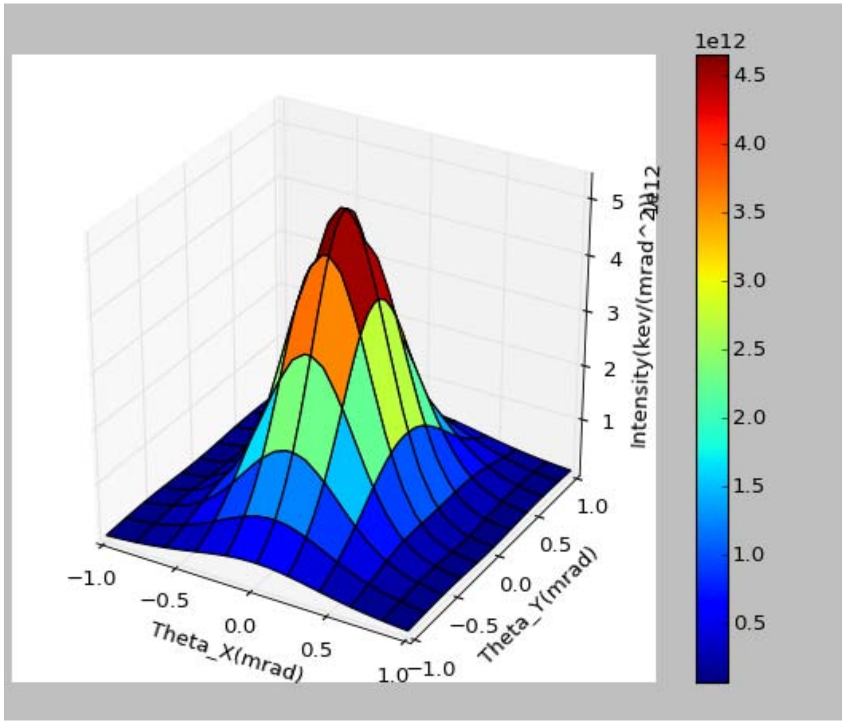
Gamma rays (single shot)	
Total flux	~ $1x10^9$
Gamma-rays energy	5-20 MeV
Flux in 1 % bandwidth	~ $3x10^7$

Pulse train mode	
Rep. rate	3 MHz
# of bunches in macropulse	~ 10,000
Average flux in 1% BW	~ $3x10^{13}$ cps
Average power of gamma flux	> 10 W

Numerical model

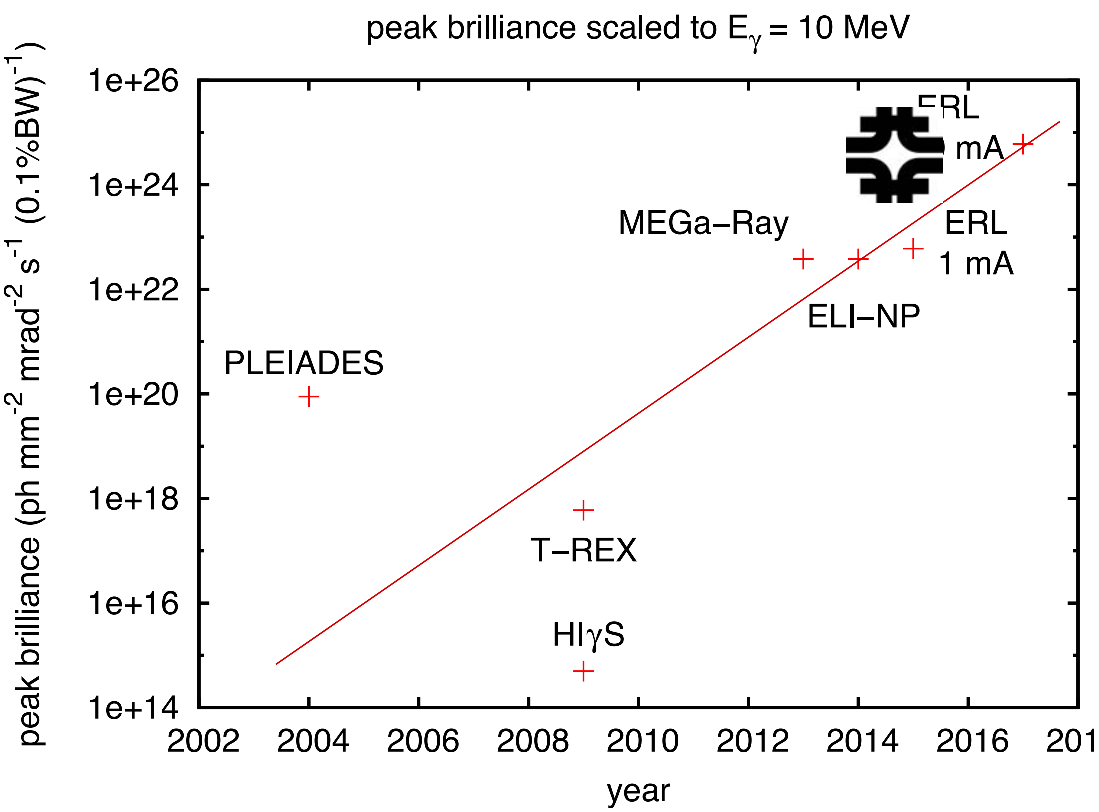
- Using W. Brown code simulated initial working point
- About 3% of photons in the 1% bandwidth
- Further optimization is possible



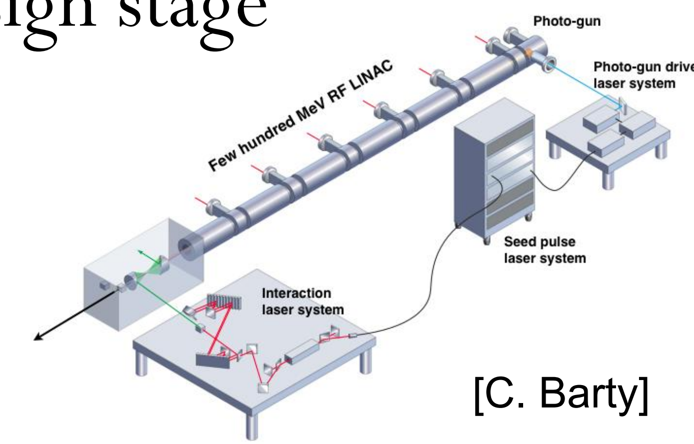


Gamma ICS @ ASTA

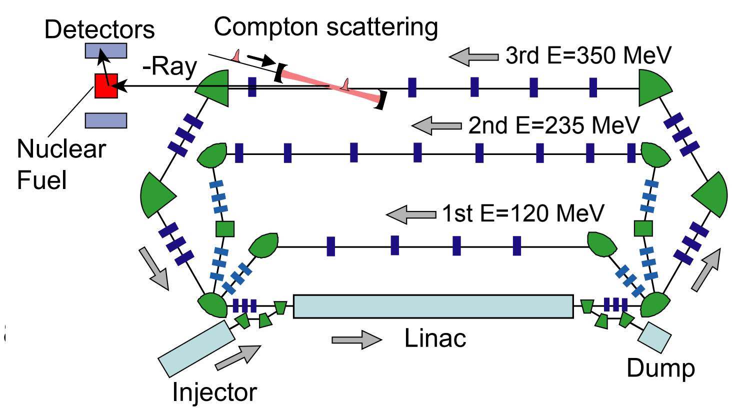
- Comparison of ASTA ICS to other gamma ICS facilities under construction/design stage



[Habs, D.; Köster, U, Applied Physics B **103**, 2011]



[C. Barty]



[R. Hajima]

Gamma ICS @ ASTA

- Comparison of ASTA ICS to other gamma ICS facilities under construction/design stage:
  - Brilliance is in line with other efforts
  - Tunability could be superior (higher energy reach, ease of adjustment)
  - Cost is smaller, leveraged on the existing facility infrastructure
  - Could be operational in 2014

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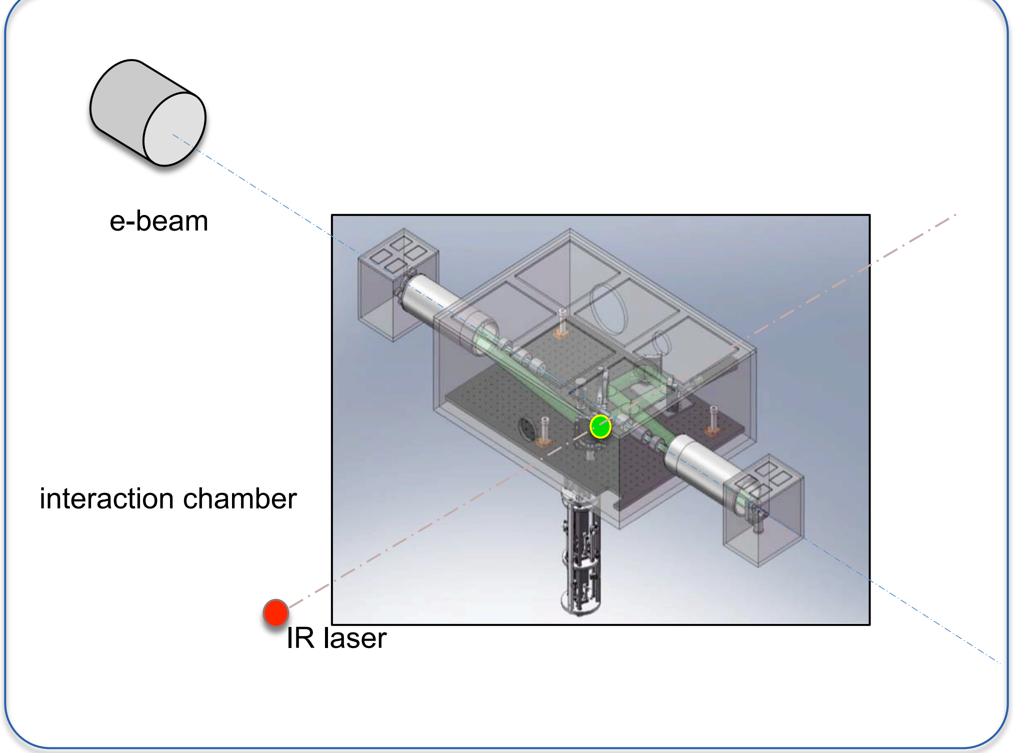
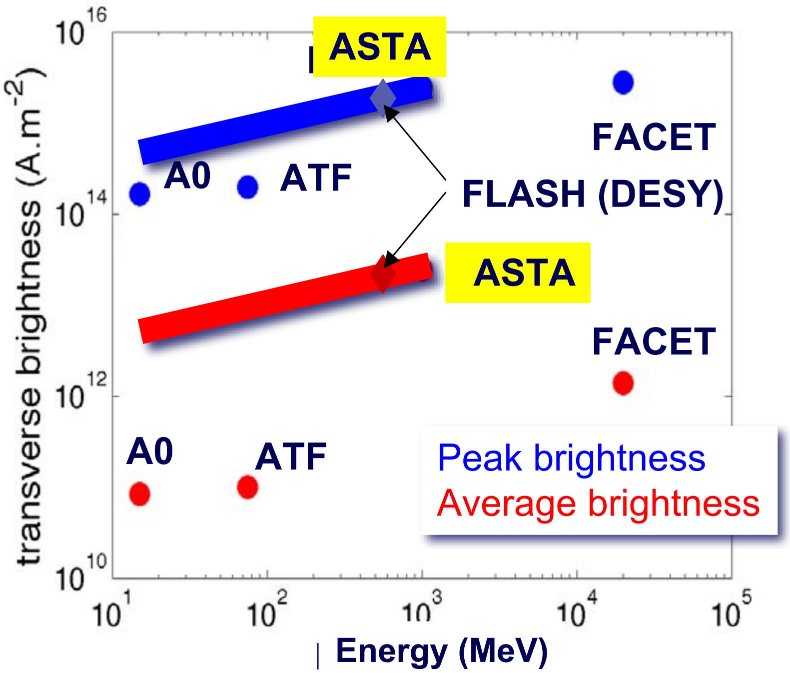
Elements of the ICS system

- High duty cycle accelerator
- Laser system (synchronized to the e-beam)
- Laser recirculation cavity
- Final focus system
- Interaction chamber
- Detectors

RadiaBeam has recently conducted a pilot scaled experiment at ATF BNL (DTRA-funded SBIR project)



✓ High repetition rate accelerator



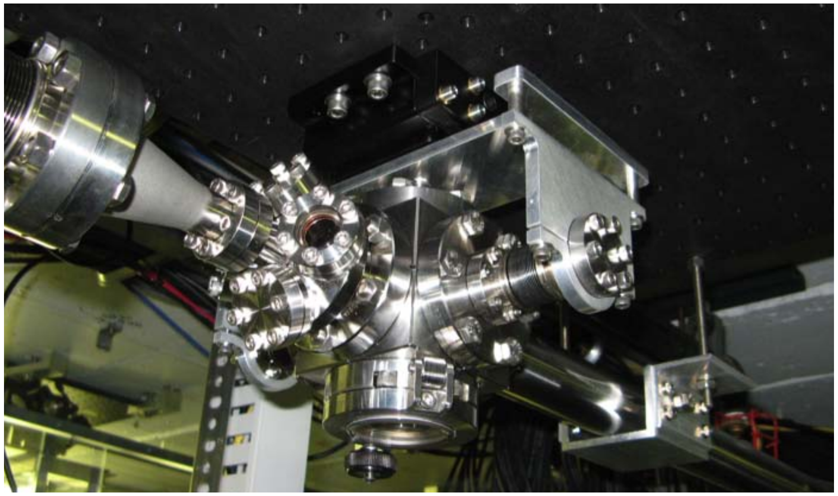
[P. Piot, AARD@ASTA, Dec. 5, 2011]

- ASTA already has the accelerator
- Standard requirements (managing beam loading, 2nd order dispersion, etc.)

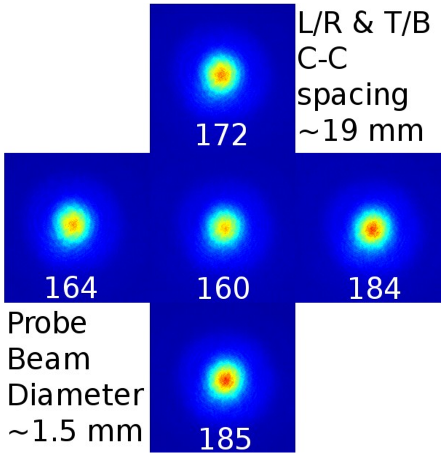
Laser system

- Start with the photo-injector drive laser (well synched)
- Added amplifier to achieve (> 100 mJ/pulse)
- Spatial filter or adaptive optics for pulse profile control
- Transport, matching and diagnostics are laborious tasks

air evacuated spatial filter



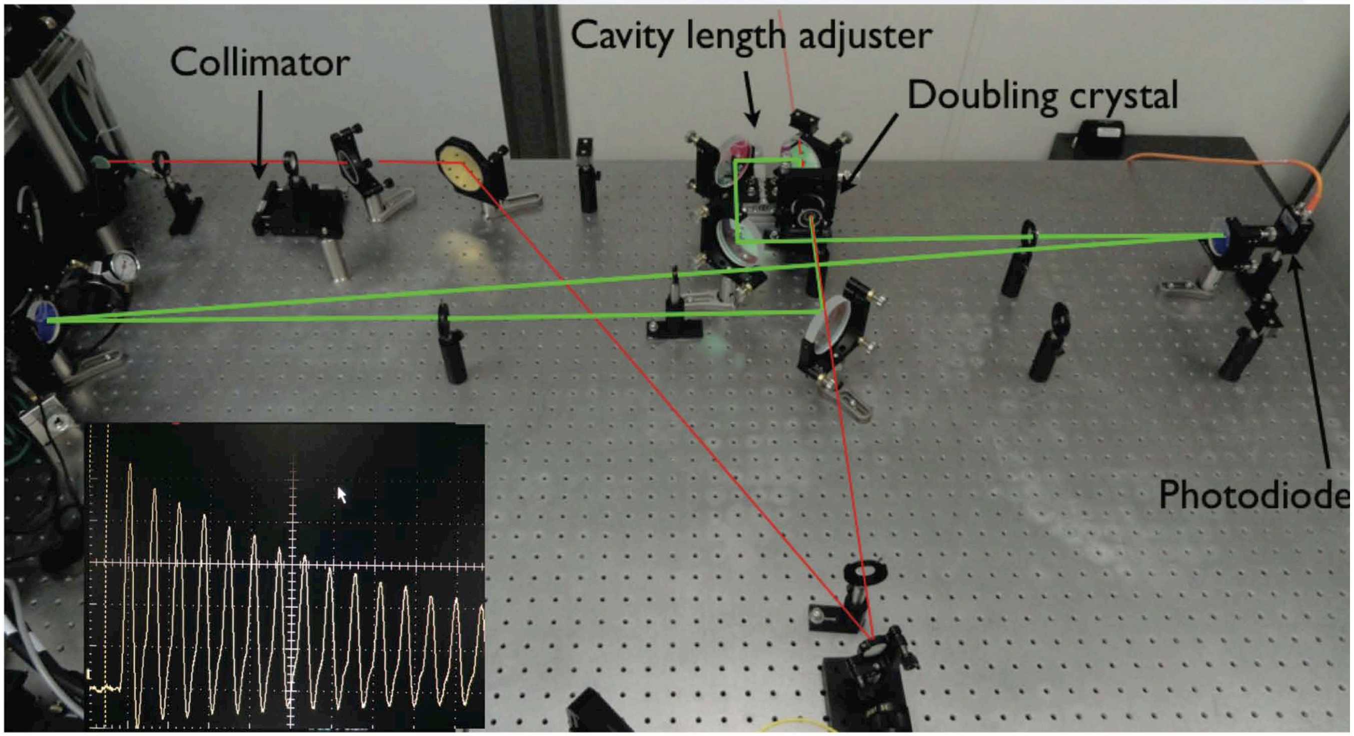
amplifier uniformity test



Laser recirculation

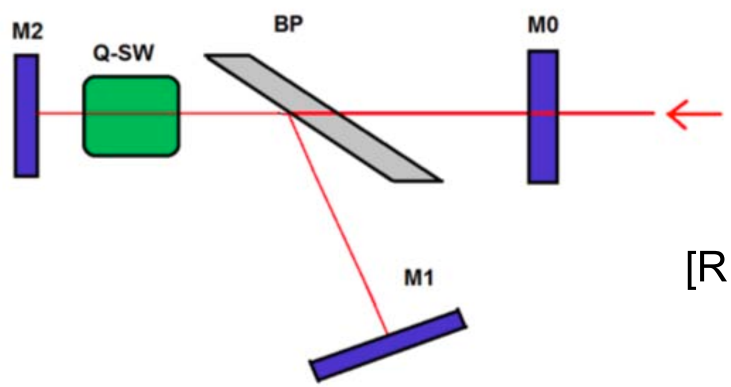
- RING recirculator (I. Jovanovich)
- Worked well at 80 MHz, but may not be so at 3 MHz

RING bench top testing



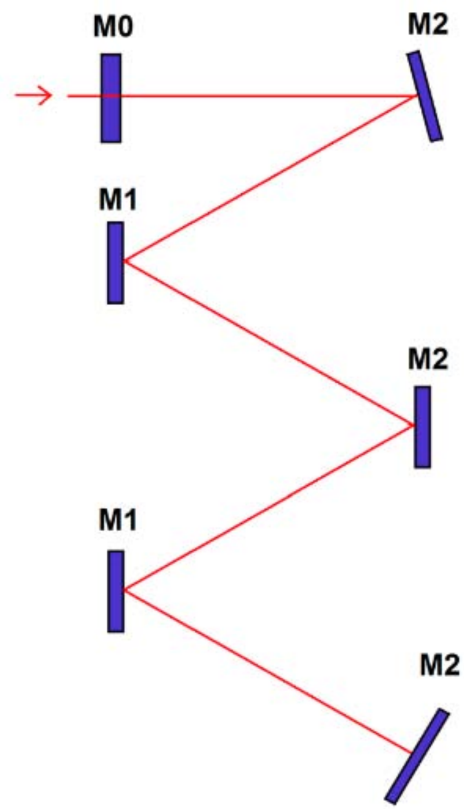
Laser recirculation

- Alternative schemes include:
  - 3 MHz cavity w/Pockels Cell
  - Fabry-Perot w/imaging mirrors



M0 –output coupler (90%-99% reflectivity mirror); M1 and M2 – near 100% mirrors; BP – Brewster plate polarizer, Q-sw – fast Pockels Cell

[R. Tikhoplav]



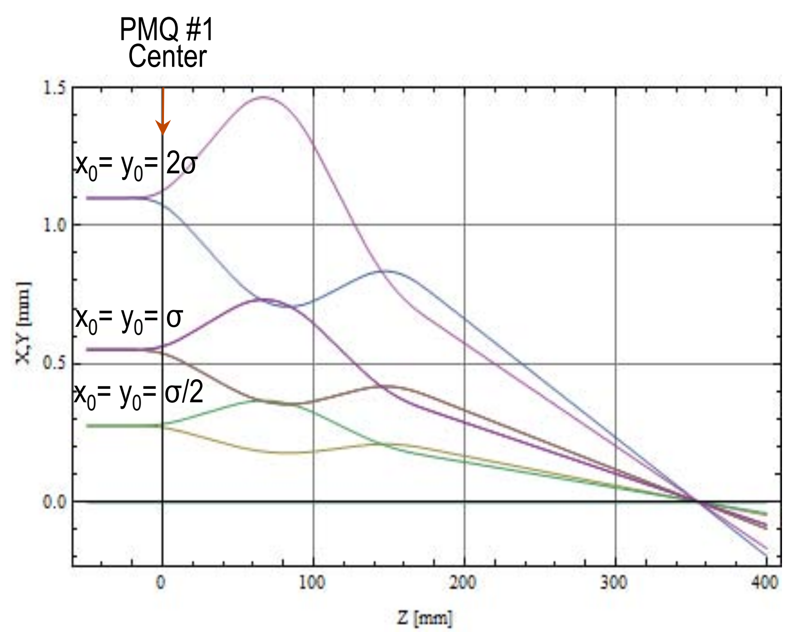
M0 –output coupler (95%-99% reflectivity mirror); M1 flat 100% mirrors; M2 curved 100% mirrors

Final focus system

- Small spot size interaction is critical to ICS efficiency
- PMQ in-vacuum final focus system was developed (~ 120T/m); alignment is important

PMQs magnetic measurements stand

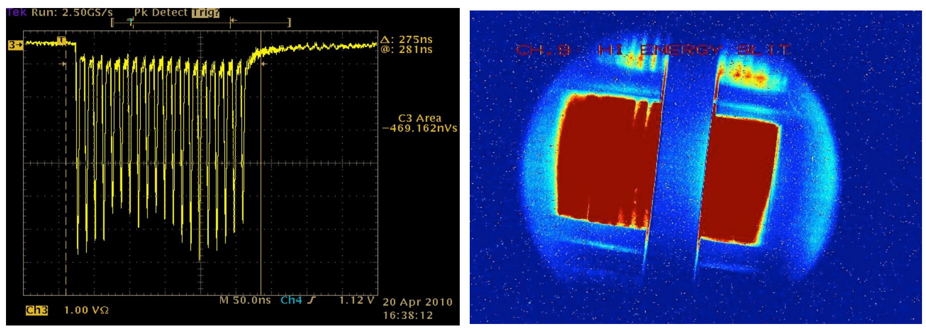
2 triplets, to focus the beam and clear it out of the chamber



Final focus system

- Beam tested with the pulse train of 20 x 0.5 nC
- 15 μm RMS spot size at IP as designed
- More recently ATF achieved 6 μm RMS with 300 pC

Pulse train generation at ATF

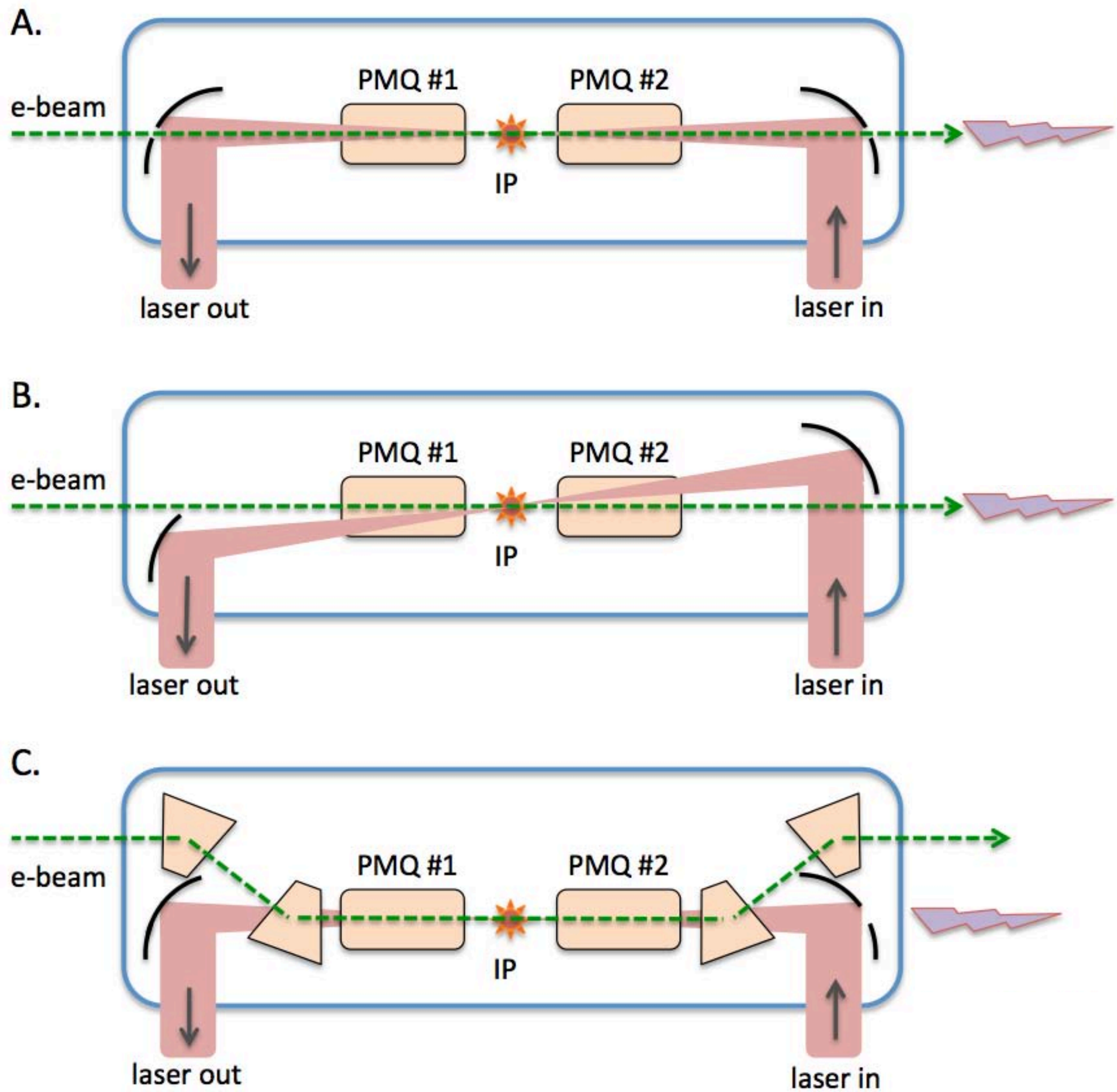


Beam measurements before, at and after IP

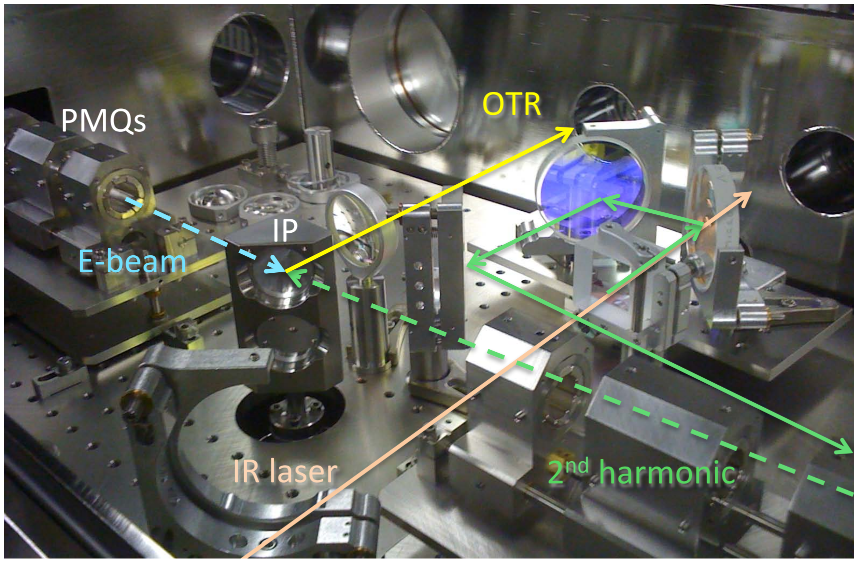
Interaction chamber design

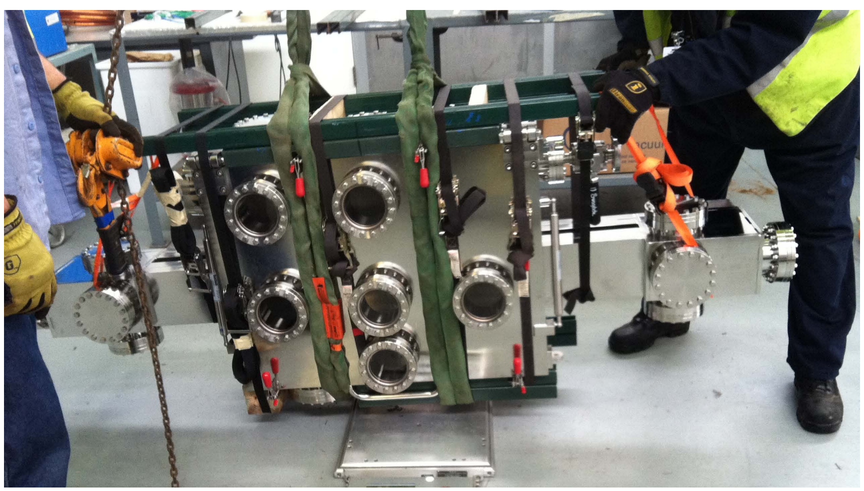
Avoid damage to the mirrors

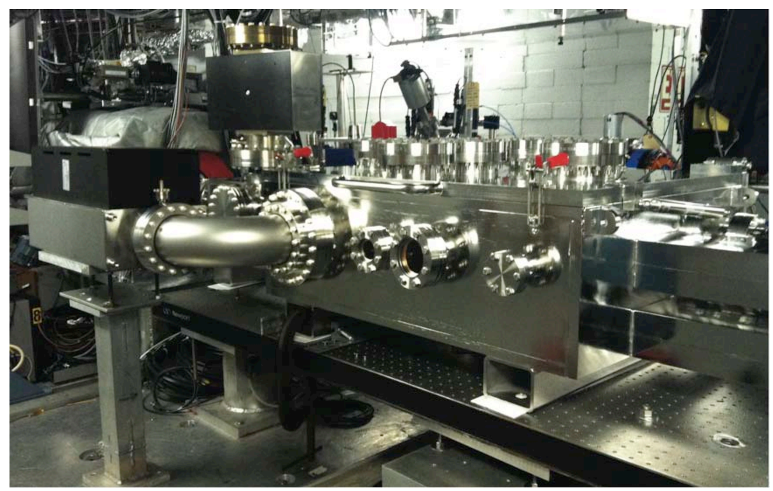
A. clearing holes
B. Interaction at angle
C. Chicane-like configuration



Interaction chamber engineering







Detector and signal-to-noise

- Detection and clean beam removal are important for improved signal to noise
- Figures of merit: response time and spectral sensitivity
- Detection system should include shielding (to protect from e-beam halo bremsstrahlung, and collimation)
- For tuning high signal-to-noise is very important

Conclusions

- High duty cycle gamma ray ICS source has many interesting applications
- ASTA facility beam parameters offer unique possibility to develop a state-of-the-art gamma ray ICS source at a relatively low cost
- Low but finite: requires dedicated beamline, laser system development, detection system, etc.
- Further system design and optimization could be a fairly straightforward task if it is of interest
- Thank you!