Narrow bandwidth Thomson photon source development using Laser-Plasma Accelerators

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Advanced Accelerator Concepts 2016
Develop compact, monoenergetic MeV photon sources

- **Motivation:**
  - Nonproliferation & related security
  - Related: medical & industrial imaging, HEDP & accelerator diagnostics

- Thomson scattering - monoenergetic photons
- Compact photon sources via laser-plasma acceleration (LPA)
- Outlook: collider & diagnostic applications, source project
Compact photon source development: address principal system size drivers

- Accelerator: compact laser plasma accelerator
  - Control $E_e$, $\Delta E_e$, $\varepsilon_e$ (divergence)

- Photon production: reduce current/laser size

- Shielding: plasma deceleration
Monoenergetic Thomson photon sources require/measure precision control of accelerator & scattering laser

Narrow $\Delta E_\gamma$ requires high quality e-beam

laser bandwidth usually negligible if $\geq$ ps

\[ \sqrt{\frac{\gamma_e^4 \sigma^2_{\gamma,FWHM}}{16} + \frac{4\sigma^2_{\gamma,FWHM}}{\gamma_e^2} + \frac{a_0^4}{4} + \left[ N_{sc} \cdot 2\gamma e \frac{\hbar \omega_L}{m_e c^2} \right]^2} < BW \]

multiple scatter

\begin{align*}
\rightarrow \text{ laser amplitude} \\
\rightarrow \text{ e- energy spread} \\
\rightarrow \text{ e- divergence}
\end{align*}

- $\Delta E_\gamma \sim 10 \% \rightarrow \Delta E_e \sim 5\%, \leq \text{ mrad}$
- $\Delta E_\gamma \sim 2\% \rightarrow \Delta E_e \sim 1\%, \leq 0.1 \text{ mrad}$

Recent LPA development combining HEP & DNN programs, demonstrates high quality beams needed for photon sources

$\Delta E_e < 1.4 \% \text{ FWHM from Colliding pulse injection control}$

$\varepsilon \approx 0.1 \mu m \text{ via Betatron emission}$

cm-scale electron focusing using plasma discharge current $I_{dis} \parallel \parallel I_{ebunch}$

Tunable 0.3 GeV – shock gas jet

Details: Mao, Swanson, Tsai: WG1

van Tilborg et al, PRL 2016. Details: van Tilborg, plenary

Details: Mao, Swanson, Tsai: WG1

Plateau, PRL 2012
High performance LPAs developed meet key photon source beam requirements

- $\Delta E_\gamma$ limited$^1$ by electron quality: $\varepsilon_e$, $\Delta E_e$
  
- $\varepsilon_e$ – electron emittance dominates $\Delta E_\gamma$:
  - $\varepsilon_e \sim 0.1\mu m$ allows $\Delta E_\gamma \sim 10\%$
  
- $\Delta E_e$ – $1\% \Delta E_e$ allows $\Delta E_\gamma \sim 2\%$
  - Requires refocusing or lower $\varepsilon_e$
  - OTR experiments indicate $< 1\% \Delta E_e^2$

2: Lin et al., PRL 2012

Current LPA experiments include: Chen PRL 2013 & Golovin Nat. Sci. Rep 2016 (UNL);
Phuoc Nature Photonics 2012 (LOA); Tsai Phys. Plasmas 2015 (UT); Schumaker Phys. Plasmas 2014 (UM)
Monoenergetic Thomson photon sources require/measure precision control of accelerator & scattering laser

Narrow $\Delta E_\gamma$ requires high quality e-beam laser bandwidth usually negligible if $\geq \text{ps}$

$$\sqrt{\frac{\gamma_e^4 \sigma_{\text{FWHM}}^4}{16} + \frac{4 \sigma_{\gamma_e}^2 \sigma_{\text{FWHM}}^2}{\gamma_e^2} + \frac{a_0^4}{4} + \frac{N_{\text{sc}} \cdot 2 \gamma_e \hbar \omega_L}{m_e c^2}} < \text{BW}$$

- $\Delta E_\gamma \sim 10 \% \Rightarrow \Delta E_e \sim 5\%$, $\leq$ mrad
- $\Delta E_\gamma \sim 2\% \Rightarrow \Delta E_e \sim 1\%$, $\leq 0.1$ mrad

Low scattering cross section: quality & flux trade off

Focal depth $\sim$ Pulse length

Energy $\rightarrow$ Angle  
Energy $\rightarrow$

$$\omega \approx \frac{4 \gamma_e^2}{1 + \gamma_e^2 \theta^2 + a_0^2/2} \omega_L$$

$\gamma \sim 2E_e [\text{MeV}]$

$$\frac{N_\gamma}{N_e} \approx 4.7 \frac{a_{0,\text{max}}}{a_0} \sqrt{\frac{E_L}{\lambda L , \mu m}}$$

0.1 ph/e- in 2% $\Delta E_\gamma$: 40J at $a_0=0.15$

High yield photon production with realistic scattering laser & electron current via independent scattering laser control

- Low-$a_0$, ps laser $\leftrightarrow$ large spot/high $E_{laser}$

- High-$a_0$ short pulse scatter$^1$: Compensate nonlinear broadening of bandwidth
  - Laser frequency profile in time $w(t)$ counteracts effect of $a(t)$
  - Requires broad laser bandwidth

- Alternative: plasma guiding of pulse$^2$

- Application range of $10^8$ph/shot
  - Tens of joules unshaped
  - Joule-class shaped/guided

Laser shaping compensates nonlinearity

2: Rykovanov J. Phys. B 2014,
Reduce beam dump energy & radiation shielding: Plasma beam deceleration after photon production

85% deceleration simulated\(^1\), more possible with plasma tailoring\(^2\)

Proof-of Principle on staging experiment\(^3\): high performance requires phasing control\(^2\)

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3: Steinke et al., Nature 2016
Control of bunch phasing important to high efficiency deceleration

- Remaining energy dominated by head and tail
  - Adjusting initial phase controls head & tail ‘chirp’
  - Approaches 1D effectiveness $U_{\text{min}} \approx 0.05*U_0$
  - Further deceleration accessible via tailored density profile, loading

A. Bonnatto et al., Phys Plasmas 2015
Thomson scattering can extract beam evolution at: % $\Delta E$, 0.1$\mu$m $\epsilon$ to detail wave-particle interactions

$\leftarrow$ Emittance-conserving acceleration

$E_{e^-} = 195$ MeV $\quad E_e = 20$ MeV

10% level Photon bandwidth

Photon source prototypes collider elements at GeV-class, requires and is a tool for precise beam control

- **Application-relevant sources motivate:**
  - Compact beam refocusing
  - High performance deceleration – staging & chirp control
  - kHz compact lasers & pointing control methods
  - Synchronization of fs (drive) and ps (scattering) lasers
  - Hollow plasma channels to decouple electron & laser foci
DNN R&D Project: Demonstrate integrated LPA, efficient photon production and deceleration; develop next steps

- Dedicated laser, independent scatter laser
- LPA driven photon source at 1-9 MeV
  - Photon production: guide & control scattering laser
  - Decrease shielding: decelerate electrons
  - Photon detectors & applications
- Develop future source techniques
  - Scattering lasers at kHz
    (LPA laser via separate DOE-Sc. program)
  - Plasma control for narrower $\Delta E_{\gamma}$

Operation from FY 2017