The Birth of a Future Light Source in Wilson Basement

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LEPP/CHESS
• Light sources today and tomorrow
• ‘Holy grail’ x-ray experiments
• Physics of SR/XFELs/ERLs
• ERL Phase 1a
• Future X-ray source at Cornell
“Basement Conjecture”: successful experimental physics $\propto$ basement area
Future light source
Brilliance / Spectral Brightness

**FLUX OF PHOTONS IN UNIT SPECTRAL RANGE**

(Source Area) × (Beam Divergence)

Units: Photons/s/mm²/mrad²/0.1% bandwidth

• **Average brightness**: measure of transversely coherent flux

\[ F_c = B_{avg} \left( \frac{\lambda}{2} \right)^2 \]

• **Peak brightness**: proportional to the number of photons per coherence volume in 6D phase space ≡ the photon degeneracy

\[ \Delta_c = B_{peak} \left( \frac{\lambda}{2} \right)^3 \frac{\Delta \lambda}{\lambda} \frac{1}{c} \]
Three frontiers in source dev.

- Avg. brightness
- Short pulses (< ps) & peak brightness
- Compactness

![X-ray analog of Livingston plot]

Only 2!
Light sources worldwide

- About 70 light sources worldwide based on storage ring technology (VUV to hard X-rays), new ones are being built / designed
- 22 FELs operational, some as scientific research instruments (far IR to VUV)
- 3 XFELs in construction / committed to, plus half a dozen in CDR or earlier stages (soft to hard X-rays)
- 3 labs seriously consider building ERL as a hard X-ray light source
Exp1: ‘explosive’ proteins


Briefly: calculations were done for T4 lysozyme (diameter 32 Å, \(N_C \sim 1000\)); flux \(4 \times 10^6\) X-rays/Å\(^2\) with \(\sim 2000\) primary ionization events; elastically scattered \(\sim 200\) photons. If pulse is sufficiently short (<10 fs), \(5 \times 5 \times 5\) lysozyme nanocrystal will scatter to <2Å resolution.

**Key feature:** sufficiently short X-ray pulse can beat Henderson’s limit of radiation damage (200 x-ray photons /Å\(^2\))
Broad class of pump-probe experiments providing structural (core e⁻’s) conformational changes in the initial stages (mol. vibrational timescale 10’s fs) of photo-induced reactions

Time-resolved Laue Crystallography (Phil Anfinrud)
SR
- efficient
- avg. brightness
- many beamlines
- workhorse technology

XFEL
- peak brightness
- short pulse
- few beamlines
- new user-base

ERL
- avg. brightness
- short pulse
- many beamlines
- existing user-base
Equilibrium

Quantum Excitation vs. Radiative Damping

\[ \rho = \frac{p}{eB} \]

Emittance (hor.), Energy Spread, Bunch Length

Tighter focusing (higher tune) → stronger 6-poles for chromaticity correction → smaller dynamic aperture & lifetime
Basics of sync. rad. production

\[ \lambda' = \frac{\lambda}{\bar{\gamma}} \]

in e⁻ frame

\[ \Theta' \]

\[ \sin^2 \Theta' \]

back to lab frame

\[ \omega' \]

off-axis

on axis

after pin-hole aperture

\[ \Delta \omega' \sim \frac{1}{\bar{\gamma}} \]

\[ \omega \]

\[ \frac{dP}{d\Omega} \]

\[ \frac{\Delta \lambda}{\lambda_n} \sim \frac{1}{nN_p} \]

(for fixed \( \theta \) only!)

\[ \lambda_n = \frac{\lambda_p}{2\gamma^2 n} \left(1 + \frac{1}{2} K^2 + \gamma^2 \theta^2 \right) \]
Coherent enhancement

E.g. 5 m undulator \((K = 1.5, \lambda_p = 2 \text{ cm})\) @ 5 GeV \(\rightarrow\) converts only \(10^{-8}\) e\(^{-}\)-beam energy fraction into X-rays with desired narrow bandwidth (0.1\%) & small divergence

Radiation field from a single \(k^{th}\) electron in a bunch:

\[ E_k = E_0 \exp(i \omega t_k) \]

Radiation field from the whole bunch \(\propto\) bunching factor (b.f.)

\[ b.f. = \frac{1}{N_e} \sum_{k=1}^{N_e} \exp(i \omega t_k) \]

Radiation Intensity:

\[ I = I_0 |b.f.|^2 N_e^2 \]

1) “long bunch”: \(|b.f.|^2 \sim 1/N_e\) \(\Rightarrow I = I_0 N_e\) \(\text{incoherent (conventional) sync.rad}\)

2) “short bunch” or \(\mu\)-bunching: \(|b.f.| \leq 1\) \(\Rightarrow I \sim I_0 N_e^2\) \(\text{coherent (FELs) sync.rad}\)
Prerequisites for $e^-$-bunch:
diffraction-limited emittance
peak current 3-5 kA
energy spread $10^{-4}$

Intense relativistic electron bunch becomes effective gain medium
(e.g. use seed / amplifier setup)
Emittance basics

What exactly is emittance? (2D projected)

Liouville’s Theorem: phase space volume is “incompressible fluid”

“Adiabatic damping” of geometric emittance

\[ \varepsilon_x = \sqrt{\left\langle x^2 \right\rangle \left\langle \theta_x^2 \right\rangle - \left\langle x \theta_x \right\rangle^2} \]

\[ \theta_x = \frac{dx}{dz} \]

electron bunch

geometric \( \{ x, \theta_x \} \)

\[ \varepsilon = \frac{\varepsilon_n}{\beta \gamma} \]

\( \varepsilon_n \) is invariant since \( \{ x; p_x = mc^2 \beta \gamma \theta_x \} \) form canonically conjugate variables

normalized \( \{ x, \frac{p_x}{mc^2} \} \)
Linac based approach

- e-source
- RF structure
- μ-wave tube
- hv production

Symbols:
- $V_b$
- $V_c$
- $I_g$
- $I_b$
Linac based approach

Linac based approach

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Linac based approach
Energy recovery concept

hv production

μ-wave source

RF structure

"same-cell"

e- source
Energy recovery concept

- e-source
- RF structure
- hv production
- μ-wave source
- "same-cell"

$I_{\text{b, dec}}$, $V_c$, $V_g$

$I_{\text{b,acc}}$
• extends linac operation to high average currents
• reduces beam dump energy
ERL promise

Much smaller (×100) horizontal emittance

Much shorter (×100) pulses
Source-limited: ERL vs. future SR

• Brightness figure of merit (FOM)
  \[ \frac{I}{(\varepsilon_x + \lambda/4\pi)(\varepsilon_y + \lambda/4\pi)} \]
  for 1Å

<table>
<thead>
<tr>
<th>Light source</th>
<th>I (A)</th>
<th>(\varepsilon_x) (nm-rad)</th>
<th>(\varepsilon_y) (nm-rad)</th>
<th>FOM (A/nm²/rad²)</th>
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<tbody>
<tr>
<td>ESRF</td>
<td>0.2</td>
<td>3.7</td>
<td>0.010</td>
<td>3.0</td>
</tr>
<tr>
<td>Petra-III</td>
<td>0.1</td>
<td>1.0</td>
<td>0.010</td>
<td>5.5</td>
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<tr>
<td>NSLS-II*</td>
<td>0.5</td>
<td>1.54</td>
<td>0.008</td>
<td>20.24</td>
</tr>
<tr>
<td>UHXS(ESRF)</td>
<td>0.5</td>
<td>0.2</td>
<td>0.005</td>
<td>185.6</td>
</tr>
</tbody>
</table>

• 5 GeV ERL to achieve the same brightness per m of ID as Petra-III / NSLS-II / UHXS(ESRF) needs 1.3 / 0.6 / 0.15 µm rms normalized emittance for 80 pC bunch (0.1 A average current at 1.3 GHz bunch rep rate) assuming no emittance degradation downstream

• Comparison: ILC norm. emit. \(\sqrt{\varepsilon_{nx}\varepsilon_{ny}} = 0.6 \mu m\) for 3.2 nC

* without use of damping wigglers
State-of-the-art: BOEING gun

Photocathode Performance:

**Photosensitive Material:**
- Quantum Efficiency: 5% to 12%
- Peak Current: 45 to 132 amperes
- Cathode Lifetime: 1 to 10 hours
- Angle of Incidence: near normal incidence

**K₂CsSb Multialkali**

**Gun Parameters:**
- Cathode Gradient: 26 MV/meter
- Cavity Type: Water-cooled copper
- Number of cells: 4
- RF Frequency: 433 x 10⁶ Hz
- Final Energy: 5 MeV (4-cells)
- RF Power: 600 x 10³ Watts
- Duty Factor: 25%, 30 Hz, 8.3 ms

**Laser Parameters:**
- Micropulse Length: 53 ps, FWHM
- Micropulse Frequency: 27 x 10⁶ Hz
- Macropulse Length: 10 ms
- Macropulse frequency: 30 Hz
- Wavelength: 527 nm
- Cathode Spot Size: 3-5 mm, FWHM
- Temporal and Transverse Distribution:
  - Gaussian, gaussian
- Micropulse Energy: 0.47 microjoule
- Energy Stability: 1% to 5%
- Pulse-to-pulse separation: 37 ns
- Micropulse Frequency: 27 x 10⁶ Hz

**Gun Performance:**

**Emittance (microns, RMS):** 5 to 10 for 1 to 7 nCoulomb
- Charge: 1 to 7 nCoulomb
- Energy: 5 MeV
- Energy Spread: 100 to 150 keV

32 mA avg. current
State-of-the-art: JLAB FEL inj.

500 kV (350) DC gun

• Cs:GaAs photocathode
• max current 9.1 mA, routine 5 mA
• best simulated emittance 5 µm, measured ×2 larger at 60 pC
• work on 100 mA gun underway to drive high power IR FEL

9.1 mA avg. current

10 kW IR FEL
Two main limiting mechanisms:

- Phase space scrambling due to nonlinear space charge

3D Gaussian initial distribution

Optimal initial distribution

- Photocathode thermal emittance

\[ \varepsilon_{n,th} = \sigma_{x,y} \sqrt{\frac{E_{th}}{mc^2}} \]

transverse temperature of photoemitted electrons
Photocathode requirements

(1) photon excites electron to a higher-energy state;
(2) electron-phonon scattering (~0.05 eV lost per collision);
(3) escape with kinetic energy in excess to $E_{\text{vac}}$

Ideal photocathode:
- $E_{\text{th}} \rightarrow kT \leq 25$ meV
- response time $\leq 1$ ps
- high QE $\geq 10\%$
- robust

No ideal photocathode exists. NEA:GaAs has small thermal energy but slow response time (~10 ps)
Cathode Field $\leftarrow E_{th} \text{ cathode}$

- $E_{cath} = 120 \text{ MV/m}$
- $\tau_{laser} = 2.7 \text{ ps rms}$
- $\sigma_{laser} = 0.5 \text{ mm rms}$
- $\tau_{laser} \rightarrow z = 0.08 \text{ mm}$

- $E_{cath} = 43 \text{ MV/m}$
- $\tau_{laser} = 5.8 \text{ ps rms}$
- $\sigma_{laser} = 0.85 \text{ mm rms}$
- $\tau_{laser} \rightarrow z = 0.12 \text{ mm}$

- $E_{cath} = 8 \text{ MV/m}$
- $\tau_{laser} = 13 \text{ ps rms}$
- $\sigma_{laser} = 2 \text{ mm rms}$
- $\tau_{laser} \rightarrow z = 0.12 \text{ mm}$

- $2 \times 18 \text{ MV/m}$
- $2 \times 6 \text{ MV/m}$
- $2 \times 1 \text{ MV/m}$

$E_{cath} / E_{s.\text{charge}} = E_{cath} / E_{s.\text{charge}} = E_{cath} / E_{s.\text{charge}}$

same simulated emittance
Near the photocathode, the bunch typically has a pancake shape:

\[ E_{s.c.} = \frac{\sigma}{\varepsilon_0} \rightarrow q = 4\pi \varepsilon_0 E_{cath} \sigma_x^2 \]

Lower limit to the achievable emittance

\[ \varepsilon_n [\text{mm - mrad}] \geq 4 \sqrt{\frac{q[nC]E_{th}[\text{eV}]}{E_{cath}[\text{MV/m}]}} \]

In reality cathode field (gun voltage) matters much more due to nonlinear space charge.

goal: 750 kV
Emittance compensation

Axial cross section of bunch charge at cathode

Very sensitive on optics & bunch distribution details; Need computer modeling

Transverse phase space plots: (a) at cathode; (b) after drift; (c) after lens; (d) more drift
S.c. compensation concept

\[ \sigma'' + K_r \sigma = \frac{I}{2 I_0 (\beta \gamma)^3} + \frac{\varepsilon_{n, \text{th}}^2}{(\beta \gamma)^2} \sigma^3. \]

**focusing s.c. emittance**

Needle beam: \( I \rightarrow I g(\zeta) \)

\[ \sigma_{eq}(g(\zeta)) = \left( \frac{I g(\zeta)}{2 I_0 (\beta \gamma)^3 K_r} \right)^{1/2} \]

**equilibrium flow condition for slice**

\[ \delta \sigma''(\zeta) + \left[ K_r + \frac{I g(\zeta)}{2 I_0 (\beta \gamma)^3 \sigma_{eq}^2 g(\zeta)} \right] \delta \sigma(\zeta) = 0 \]

**oscillation frequency current independent**

\[ \delta \sigma''(\zeta) + 2 K_p \delta \sigma(\zeta) = 0, \]

Serafini PRE 55, 7565
Design approaches

- Cut the number of decision variables to some reasonable number (2-4) perhaps by using a simplified theoretical model to guide you in this choice
- **Large regions of parameter space remain unexplored**
- Optimize the injector varying the remaining variables with the help of a space-charge code to meet a fixed set of beam parameters (e.g. emittance at a certain bunch charge and a certain length)
- **One ends up with a single-point design without capitalizing on beneficial trade-offs that are present in the system**

*Primary challenge in exploring the full parameter space is computational speed*
• work harder
• work smarter
• get help

• processor speed
• algorithms
• parallel processing

Solution: use parallel MOGA

MultiObjective Genetic Algorithm

• throw in all your design variables
• map out whole Pareto front, i.e. obtain multiple designs all of which are optimal
• use realistic injector model with your favorite space charge code
maximize \( f_m(x_1, x_2, \ldots, x_n), \quad m = 1, 2, \ldots, M; \) 
subject to \( g_j(x_1, x_2, \ldots, x_n) \geq 0, \quad j = 1, 2, \ldots, J; \)
\( x_i^{(L)} \leq x_i \leq x_i^{(U)}, \quad i = 1, 2, \ldots, n. \) 

Definition 1. A solution \( \mathbf{x}_a \) is said to dominate the other solution \( \mathbf{x}_b \) if the solution \( \mathbf{x}_a \) is not worse than \( \mathbf{x}_b \) in all objectives and \( \mathbf{x}_a \) is strictly better than \( \mathbf{x}_b \) in at least one objective. In other words, \( \forall m \in 1, 2, \ldots, M : f_m(\mathbf{x}_a) \geq f_m(\mathbf{x}_b) \) and \( \exists m' \in 1, 2, \ldots, M : f_{m'}(\mathbf{x}_a) > f_{m'}(\mathbf{x}_b). \)

Definition 2. Among a set of solutions \( \mathcal{P} \), the nondominated subset of solutions \( \mathcal{P}' \) are those that are not dominated by any member of the set \( \mathcal{P} \).

When the set \( \mathcal{P} \) is the entire search space resulting nondominated set is called the \textbf{Pareto-optimal set}. 

\textbf{Vilfredo Pareto, 1848-1923}
10 bounded decision variables, 10 constraints
maximize Luminosity

minimize Total Cost
Evolving into optimal injector design

Parallel Multiobjective Evolutionary Algorithm
Injector decision variables

**Fields:**
- DC Gun Voltage (300-900 kV)
- 2 Solenoids
- Buncher
- SRF Cavities Gradient (5-13 MV/m)
- SRF Cavities Phase

**Positions:**
- 2 Solenoids
- Buncher
- Cryomodule

**Bunch & Photocathode:**
- \( E_{\text{thermal}} \)
- Charge

**Laser Distribution:**
- Spot size
- Pulse duration (10-30 ps rms)
  \{tail, dip, ellipticity\} \( \times 2 \)

**Total:** 22-24 dimensional parameter space to explore
Optimization results

MOO problem: \[
\begin{align*}
\text{minimize emittance} \\
\text{minimize bunch length} \\
\text{maximize bunch charge}
\end{align*}
\]

Takes some $10^5$ simulations

$E_{th} = 35$ meV (aka GaAs @ 780 nm)

FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).

FIG. 11: Longitudinal emittance vs. bunch length for various charges in the injector (nC).
• HV DC gun based photoinjector
• max **100 mA** average current, **5-15 MeV** beam energy
• norm. rms emittance ≤**1 µm** at **77 pC/bunch**
• rms bunch length **0.6 mm**, energy spread **0.1%**
Challenges

- Achieve gun voltage of $\geq 500$ kV
- Demonstrate photocathode longevity
- Cleanly couple 0.5 MW RF power into the beam without affecting its transverse emit.
- Control non-linear beam dynamics: over a dozen of sensitive parameters that need to be set *just right* to achieve the highest brightness
- Instrumentation and tune-up strategy
- Drive laser profile programming (both temporal and spatial)
Mission

• Maintain vibrant/diverse acc. physics program
• Provide *world-class x-rays* to CHESS users
• Future light source and new accel. technology *development*
3-staged approach to ERL

I – upgrade to CESR to put CHESS on the synch. rad. science frontier
II – 5 GeV SRF linac with 10’s fs pulse capability & XFEL friendly
III – diffraction-limited ERL once injector performance is established
M. Tigner, “Does accelerator-based particle physics have a future?”, Physics Today 54 p 36, 2001:

…Let me put it baldly and simplistically: If the cost of the ill-fated Superconducting Super Collider had been on the order of $1 billion rather than many times that sum, it might well not have been canceled. If the cost of CERN's Large Hadron Collider (LHC), scheduled for completion in 2005, were only of order $1 billion, it might well have been completed by now. If any of the TeV electron-positron linear collider schemes now being studied around the world could be built for something like $1 billion, one or more of them might already be under construction.
Summary

• Birth pains abound but the ‘baby’ has not arrived yet: “Mission Accomplished” when the injector delivers 100 mA, $\varepsilon_{xn} \sim 1 \mu m$ (shooting for the end of 2008)

• Future light source at CU is by no means secured; success will require the talents in the lab to come together in unprecedented way

• The adventure continues, so stay tuned…

Thank you!
Contributors to emittance

- Thermal (cathode)
  - Low thermal energy photocathodes
  - Min laser spot size
  - Max gun voltage
- RF-induced
  - Rapid acceleration
  - ‘adiabatic’ focusing and bunching
  - Transverse laser shaping
  - Temporal pulse shaping (fast emission photocathodes)
- Space charge
  - Short bunch length
  - Tight focus
  - Reduced field gradient

- Helps here, neutral elsewhere
- Helps here, may harm elsewhere
- Virtual injector allows absolute control of parameters, real system with a dozen of sensitive parameters will not

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse duration rms</td>
<td>21.5 ± 1.4 ps</td>
</tr>
<tr>
<td>Spot size rms</td>
<td>0.640 ± 0.057 mm</td>
</tr>
<tr>
<td>Charge</td>
<td>80 ± 5.8 pC</td>
</tr>
<tr>
<td>Solenoid1 Bmax</td>
<td>0.491 ± 0.010 kG</td>
</tr>
<tr>
<td>Solenoid2 Bmax</td>
<td>0.532 ± 0.010 kG</td>
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<tr>
<td>Cavity1 phase</td>
<td>-41.6 ± 1.7 deg</td>
</tr>
<tr>
<td>Cavity2 phase</td>
<td>-31.9 ± 2.0 deg</td>
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<tr>
<td>Cavity3-5 phase</td>
<td>-25.7 ± 2.0 deg</td>
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<tr>
<td>Buncher Emax</td>
<td>1.73 ± 0.04 MV/m</td>
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<tr>
<td>Cavity1 Emax</td>
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<tr>
<td>Cavity2 Emax</td>
<td>26.0 ± 0.5 MV/m</td>
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<td>Cavity3-5 Emax</td>
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<td>Q1_grad</td>
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<tr>
<td>Q2_grad</td>
<td>0.184 ± 0.002 T/m</td>
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<tr>
<td>Q3_grad</td>
<td>0.023 ± 0.002 T/m</td>
</tr>
<tr>
<td>Q4_grad</td>
<td>-0.100 ± 0.002 T/m</td>
</tr>
</tbody>
</table>

100 random seeds (outliers removed)

\[
\begin{align*}
\text{ave}(\varepsilon_x) &= 1.04 \, \mu\text{m} \\
\text{std}(\varepsilon_x) &= 0.52 \, \mu\text{m} \\
\text{ave}(\varepsilon_y) &= 0.95 \, \mu\text{m} \\
\text{std}(\varepsilon_y) &= 0.62 \, \mu\text{m}
\end{align*}
\]
Tolerances for optimum

10% increase in emittance (p-t-p)

- BunPhase: 3.5°
- Cav1Phase: 3.0°
- Ecav1: 3.8%
- Lphase: 2.4°
- B1: 0.37%
- B2: 0.85%
- Qbunch: 3.7%
- Trms: 8.0%
- Vgun: 0.39%
- XYrms: 2.4%