A Comparison of Ultimate Storage Rings and ERLs as Next-Generation X-ray Sources

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Outline

- X-ray brightness
- Energy recovery linac x-ray sources
  - Concept and promise
  - Design example
  - Challenges
- Storage ring x-ray sources
  - Strengths
  - Near-term outlook
  - Scaling of ring performance
- Ultimate Storage Rings
  - Design example
  - Challenges
- Comparison of USR and ERL x-ray sources
X-ray Brightness

- Time-averaged spectral brightness is a primary performance measure
  - Typically quoted in photons/second/mm\(^2\)/mrad\(^2\)/0.1\%BW
  - Benefit from high current, small emittance, and narrow energy spread\(^1\)

\[ B_h \sim \frac{I_{\text{beam}}}{E_x E_y \sqrt{4\sigma_\delta^2 + \left(\frac{0.4\lambda u}{hL}\right)^2}} \]

\[ E_x = \sqrt{\left(\frac{\epsilon_x}{\beta_x} + \frac{\lambda L}{8\pi^2}\right)\left(\frac{\epsilon_x}{\beta_x} + \frac{\lambda}{2L}\right)} \geq \epsilon_x + \frac{\lambda}{4\pi} \] (Plus similar for y plane)

- Comparison for conventional multi-GeV rings and linacs
  - Linac: Emittance comparable to 1Å/4π in both planes
  - Linac: Greater freedom in matching to ideal beta functions
  - Linac: Small energy spread capitalizes on long undulators
  - Ring: Easy to achieve high average current

\(^1\)S. Benson et al., doi:10.1016/j.nima.2010.07.090
ERL X-ray Source Concept$^{1,2,3}$

High-brightness, high average current 10 MeV injector

“Merger”

Multi-GeV output beam

Multi-GeV return beam

~10 MeV energy-recovered beam

Turn-around arc with undulator beamlines

ERL Beam Properties

- Emittance governed by source emittance and quantum excitation in arcs

- Energy spread governed by
  - Rf curvature and bunch length
  - Quantum excitation in bends
  - Coherent synchrotron radiation
  - Wakefields

- Must carefully control these effects
  - “Low-emittance” transport arcs
  - Low bunch charge
  - Intermediate bunch duration

- Assumed “high coherence” injector parameters\(^1\) supported by several simulation results
  - 0.1 micron normalized emittance
  - 25 mA (19 pC/bunch at 1.3 GHz)
  - 0.02% energy spread
  - 2ps rms duration

\[^1\text{G. Hoffstaetter, “Status of the Cornell ERL Project,” fls2006.desy.de}\]
An “Ultimate” ERL@APS Concept

- This design serves to illustrate the promise of an x-ray ERL
- 7 GeV linac
  - Two-pass linac shown as cost-reducing measure
- Large 7 GeV turn-around for new beamlines
  - Accelerate away from APS to put highest-quality beam into TAA
- TAA has eight 50-m straight sections
  - Accommodates 48-m undulators

M. Borland *et al.*, Proc. PAC09, MO3PBI01.
TAA Optics

Optimum beta functions for brightness and coherence

15 TME cells per superperiod

48m undulator

Booster cavity

Comparison of USRs and ERLs as Hard X-ray Sources, M. Borland, January 2011
Predicted Beam Properties

Injector modeled with IMPACT, Transport modeled with elegant.

Comparison of USRs and ERLs as Hard X-ray Sources, M. Borland, January 2011
**DC Photo-injector**

- The most popular concept
  - Inspired by JLab FEL gun
  - Emittance requirement ~15x smaller than extrapolated JLab gun

- Cornell design\(^1\) was first to use multi-objective parallel algorithm in accelerator application
  - First to achieve (in simulation) parameters needed for ultra-bright x-ray ERL

- Requires very high (750 kV) DC voltage
  - So far not demonstrated in spite of considerable effort
    - Recent KEK results (650 kV) have yet to be demonstrated \textit{with beam}
  - Another motivation for more careful look at SRF gun

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\(^1\)I. Bazarov and C. Sinclair, PRSTAB 8, 034202 (2005).
Cathode Issues

- Precision experiments have low tolerance for thermal transients due to beam interruption
  - Need to deliver uninterrupted beam for many hours
- Cathode lifetime must support this
  - JLab has seen \( \sim 600 \) C lifetime with Cs:GaAs\(^1\)
    - Require cathode re-cesiation after this
  - Optimistically, implies \( \sim 7 \) hours of operation at 25 mA
    - Results are for 8 mm dia. laser spot
    - Lifetime roughly proportional to laser spot area\(^3\)
    - ERL injectors have sub-mm laser spot diameter

- Choice of drive laser\(^2\)
  - Green:
    - 10-20\% QE, 1 ps response, 100 meV intrinsic energy
  - IR:
    - 1\% QE, 100 ps response, 25 meV intrinsic energy

\(^1\) S. Benson et al., doi:10.1016/j.nima.2010.07.090 and private communication.
\(^2\) B. Dunham, ERL09, PLT10.
\(^3\) J. Grames et al., to be published.
Consequences of Increased Emittance

With assumption of 48-m-long IDs in ERL, even relatively large emittance gives some benefit, but need at worst 0.2μm to gain ~10^2 over APS renewal.
Consequences of Increased Bunch Length

Consequences of longer initial bunch are not that dramatic. NB: lower emittance is easier with longer bunch.
Beam Loss and Halo

- JLab experience with halo\(^1\)
  - “Huge operational problem”
  - Very negative opinion about collimation (“makes the beam angry”)
  - “Only” control losses to 0.01% level\(^2\)
    - High-energy ERLs need much lower losses (≈2 PPB for APS\(^3\))

- Many sources\(^4,1\)
  - Scattered or reflected laser light
  - Field emission from gun, rf cavities
  - Space charge and nonlinear dynamics
  - Scattering from residual gas and collimators
  - Touschek scattering

- Touschek well covered\(^5,6\), but little else seems to be modeled

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\(^1\) D. Douglas, ERL09, Contribution #72.
\(^2\) G. Neil, private communication.
\(^3\) M. Borland et al., NIM A 582 (2007) 54.
\(^4\) C. Yao et al., ERL07, WG2.
\(^5\) A. Xiao et al, PAC07, 3453; Linac08, MOP092; ICAP09, TH2IOpk04.
\(^6\) G. Hoffstaetter et al., EPAC08, 1631.
A nearly three-fold reduction in power requirements seems possible:

- Operate at lower gradient (bigger linac)
- Improve cavity Q's
- Improve cyromodule design
- Reduce microphonics
- Efficient HOM extraction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Pessimistic Value</th>
<th>Optimistic Value</th>
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<td>Injector RF Power</td>
<td>kW</td>
<td>1000</td>
<td>1000</td>
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<tr>
<td>Injector Cryo Heat Load</td>
<td>W</td>
<td>40</td>
<td>40</td>
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<td>Eacc</td>
<td>MV/m</td>
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<td>16</td>
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<td>Operating Temperature</td>
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<td>Qo</td>
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<td>Peak Microphonics</td>
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<td>Qe (Perfect ER)</td>
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<td>Static Load per Cavity</td>
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<td>Second Pass Phase</td>
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<td>RF Power Overhead</td>
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<td>ERL RF Power (Perfect ER)</td>
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<td>950</td>
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<td>ERL RF Power (Imperfect ER)</td>
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<td>1286</td>
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<td>ERL Cryo Power</td>
<td>kW</td>
<td>14.7</td>
<td>6.0</td>
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<td>Total Dynamic Load</td>
<td>kW</td>
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<td>Cryo Safety Factor</td>
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<td>MW</td>
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<tr>
<td>Total AC Power (Imperfect ER)</td>
<td>MW</td>
<td>28.16</td>
<td>11.86</td>
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Collective Effects

- Short-range wakes
  - Estimates\(^1\) from Cornell are worrisome
    - Wakes use up the entire energy spread budget at 100 mA
    - Roughness and RF cavity wakes dominate
    - Possible solutions
      - Less current (less flux)
      - Increase dump energy (more rf power)
      - Longer bunch (lower brightness)
      - Larger/smoothier beam pipe (higher cost)
      - Increase ID gap (higher beam energy)
  - Very challenging to determine wakes for short bunches in long structures
    - Need higher-order codes that can compute such wakes efficiently
    - Unclear (to me) if codes are adequate at this time
  - Once wakes are determined, we have good tools to assess their effect (e.g., elegant)

\(^1\)M. Billing, ERL09, Contribution #35.
Summary: Concerns for ERL Light Sources

- Size and cost of recirculation system to maintain beam quality
- Length and cost of undulators to get high brightness and flux
  - Difficulty of precisely phasing 50-m undulators
- Cathode technology isn’t there yet
  - Must sustain 25~100 mA for high-brightness beam
  - Time response vs quantum efficiency vs intrinsic emittance
- Beam halo prediction and control
  - Modeling is not where it needs to be
  - Need to understand how to perform effective collimation
- Production of ultra-low emittances
  - High DC gun voltage still a challenge
  - Can rf gun work (cathode issue?)
- Short-range wakes are uncomfortably large
  - Need explicit wake computation, exploration of cures
- Need multiple advances in RF technology to reduce wall-plug power
Strengths of Rings

- Storage rings are extremely successful scientific facilities
  - Many thousands of users per year from dozens of scientific disciplines
- There is a good reason for this
  - Large number of simultaneous experiments
  - Easily-tunable spectra covering IR to x-rays
  - High average flux and brightness
  - Excellent stability
    - Position and angle
    - Energy and intensity
    - Size and divergence
  - Pulse repetition rates from \( \sim 300 \) kHz to \( \sim 500 \) MHz
  - Excellent reliability and availability
  - Well-understood technology

\(^1\)See, for example, M. Bei et al., NIM A 622, 518-535 (2010).
Near-Term Outlook

- From 1990's onward, increasing number of rings offered emittance of few nm
- New rings pushing to 1 nm and below
  - Emphasis is average brightness, flux, and coherence
- PETRA III\(^1\)
  - 6 GeV, 1 nm ring now in early operation
  - Large circumference with damping wigglers
- NSLS-II\(^2\)
  - 3 GeV, 0.5 nm ring under construction
  - Large circumference DBA with damping wigglers
- MAX IV\(^3\)
  - Planned 3 GeV, 0.24 nm ring, recently funded
  - 7BA with damping wigglers

\(^3\)S.C. Leeman et al., PRSTAB 12, 120701 (2009).
Methods of Decreasing Emittance

- To decrease the natural emittance, we can
  - Reduce the energy
  - Increase the bending radius
    • Larger circumference
  - Decrease $\mathcal{H}$
    • Stronger focusing
    • More frequent focusing
  - Increase damping
    • Damping wigglers

- A useful approximation$^{1,2}$

$$\epsilon \approx F(\nu_{x,\text{cell, lattice}}) \frac{E_0^2}{J_x N_d^3} \frac{P_B}{P_B + P_W}$$

$$\epsilon \propto E_0^2 \frac{\mathcal{H}/\rho^3}{\langle 1/\rho^2 \rangle}$$

Used **elegant** to simulate scaling APS to larger circumference by adding more fixed-length cells.

Emittance scaling is as expected.

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$^1$ J. Murphy, Light Source Data Book, BNL.
$^2$ H. Wiedemann, Particle Accelerator Physics.
Nonlinear Dynamics

- Weaker dipoles and/or stronger focusing → smaller dispersion
  - Emittance smaller (good)
  - Chromaticity sextupoles are less effective (bad)
- Stronger sextupoles means
  - Transverse motion is less linear
  - Smaller dynamic aperture → injection problems
  - Smaller momentum aperture → lifetime problems
- We have to add more sextupoles to compensate the aberrations

More data from the scaling simulation. Again no surprise.
Collective Effects

- **Touschek scattering**
  \[ \frac{1}{\tau} \sim \frac{N_b N_d^{1.8}}{E^{4.1}} \]

- **Intrabeam scattering**
  \[ \frac{1}{\tau} \sim \frac{N_b N_d^{5.5}}{E^{8.1}} \]

- **TMCI**
  \[ I_{thres} \sim \frac{E}{\langle \beta \rangle N_d^{1.5}} \]

- **Microwave instability**
  \[ I_{thres} \sim \frac{E^{3.3}}{N^{5.5}} \]

→ High-energy ring with many weak bunches, bunch lengthening, feedback systems

Computed with **toushekLifetime** and **ibsEmittance** (A. Xiao et al.)
## USR7: A 7 GeV, 40 Sector Ultimate Ring\textsuperscript{1,2}

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>3.16</td>
<td>km</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>0.028</td>
<td>nm</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.079</td>
<td>%</td>
</tr>
<tr>
<td>Maximum ID length</td>
<td>8</td>
<td>m</td>
</tr>
<tr>
<td>Number of dipoles</td>
<td>10</td>
<td>per sector</td>
</tr>
<tr>
<td>Horizontal/vertical tune</td>
<td>183.18/36.18</td>
<td></td>
</tr>
<tr>
<td>Natural chromaticities</td>
<td>-535/-175</td>
<td></td>
</tr>
<tr>
<td>Energy loss</td>
<td>3.7</td>
<td>MeV/turn</td>
</tr>
<tr>
<td>Beta functions (x/y) at ID</td>
<td>4.4/5.5</td>
<td>m</td>
</tr>
</tbody>
</table>

\textsuperscript{1}M. Borland, LSU Grand Challenge Workshop, 2008.
\textsuperscript{2}M. Borland, Proc. SRI09, to be published.
Sextupole Optimization

- Targeted chromaticity of 1 in both planes
- Used parallel genetic optimizer\(^1,2,3\) to tune sextupoles
  - 21 independent sextupoles
  - Also varied fractional tune
- Direct optimization of
  - Dynamic aperture
  - Touschek lifetime
- One evaluation takes about 10 hours
- Typically use 100~300 processors

\(^1\text{M. Borland, H. Shang, geneticOptimizer.}\)
\(^2\text{M. Borland et al., Proc. PAC09, to be published}\)
\(^3\text{M. Borland et al., Proc. ICAP09, to be published.}\)
USR7 Momentum Aperture (5 Ensembles)

- Local momentum aperture exceeds ±2.2%
- This is about what APS runs with today

Computed with elegant (M. Borland, et al.)

- Conservative lifetime calculation
  - Use ±2.2% aperture
  - Ignore bunch lengthening (PWD) (~6 ps rms bunch duration)
  - Ignore IBS
- If we have full coupling
  - 50 μA/bunch: ~4 hours
  - 75 μA/bunch: ~3 hours

Computed with touschekLifetime (A. Xiao, M. Borland)
Compared to the ~10 μm beam size, the dynamic aperture is very large.

- Evaluated 5 ensembles to check robustness.
- Dynamic aperture is small, but very large compared to ~10 μm beam size.

Computed with *elegant* (M. Borland, *et al.*).
Intra-Beam Scattering

- IBS is modest for full coupling

- Even with full coupling, little advantage to reducing the beam energy (assuming 50 μA/bunch)

Computed with ibsEmittance (A. Xiao, L. Emery, M. Borland)
Injection Issues

- All ring light sources use beam accumulation
  - Each stored bunch/train is built up from several shots from the injector
  - Incoming beam has a large residual oscillation after injection
    - Requires DA of ~10 mm or more
  - If there is x-y coupling, residual oscillations will result in loss on vertical small-gap chambers
    - Accumulation is incompatible with large x-y coupling

- For USR7, we must use “swap-out” injection\(^1,2\)
  - Kick out depleted bunch or bunch train
  - Simultaneously kick in fresh bunch or bunch train
  - Injector requirements and radiation issues seem manageable\(^3\)

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\(^1\) M. Borland, “Can APS Compete with the Next Generation?”, APS Strategic Retreat, May 2002.
\(^3\) M. Borland, Proc. SRI09, to be published.
Bunch Pattern and Fill Rate

- If we inject bunch trains, the fractional droop in intensity among trains is
  \[ D \approx \Delta T_{inj} N_{trains} \frac{1}{\tau} \]

- The required injector current is
  \[ I_{inj} \approx \frac{I_{ring} L_{ring}}{c \tau D} \]

- We probably want \( D < 0.1 \)
- We are considering a very large ring (3.16 km) with up to 300 mA
- For 4000-bunch beam, 20 bunches per train, and 3 hour lifetime
  - Inject a bunch train every 5 s
  - 2.9 nA average current from the injector (APS injector: 4 nA)
  - Each train has 16 nC (APS injector: 3 nC/bunch).
Collective Effects
(A Very Rough Look)

- **TMCI**
  - 400 dipoles (USR7) vs 80 (APS)
  - Similar average beta functions
  - APS threshold\(^1\) is \(\sim 4\) mA
  - USR7 may be \(\sim 360\) \(\mu\)A

- **Microwave instability**
  - APS threshold\(^1\) is \(\sim 5\) mA
  - USR7 may be \(\sim 1\) \(\mu\)A
  - For 50 \(\mu\)A need significant bunch lengthening (4x)
  - APS runs well above threshold (20 mA or more)

\[ \begin{align*}
I_{\text{thres}} & \sim \frac{E}{\langle \beta \rangle N_{d}^{1.5}} \\
I_{\text{thres}} & \sim \frac{E^{3.3}}{N^{5.5}}
\end{align*} \]

Resistive Wall Instability

- We’d like a “very small” round chamber in USR7
  - Allows magnets to be smaller and cheaper
    - Power supplies are cheaper
    - Wall-plug power reduced
  - Reduces impedance from transitions to ID chambers
    - Increases impedance of BPMs, bellows, flange gaps, ...

- Will also increase resistive wall effects
  - Growth rate scales like
    \[ \tau_r \sim \frac{L_t L_b I_{total}}{n_b \nu \beta \sigma_L^{3/2} b^3} \]

- Scaling from APS suggests we could have a \( \sim 6 \) mm beam pipe radius
  - 20 mm bore radius needed for strong sextupoles
Other Challenges and Issues

- **Ion trapping**
  - Already need gaps in beam for bunch train swap-out
  - Need simulations to assess this
- **Kickers to support swap-out**
  - Fast rise/fall times for bunch train swap-out
  - Flat-top length and uniformity (~1% required?)
- **Alignment and tolerances**
  - Sextupoles are strong, need good alignment
  - Need to carefully correct residual dispersion
- **Size and cost are a big issue**
  - Magnets can be small, integrated as in MAX-IV
  - Hybrid EM/PM magnets would have cheaper PS
- See Bei *et al.* for more detailed discussion
Brightness Comparison

Maximum-length SCU20 ($\text{Nb}_3\text{Sn}$ wire)
- APS: 100mA, 1.3% coupling, 3.8 m device
- USR7: 300mA, 100% coupling, 8.0 m device
- ERL7: 25mA, “high-coherence” parameters, 48m device

Computed with sddsbrightness (H. Shang, R. Dejus, M. Borland)
Transverse Coherence Comparison

\[ F_{coh} = \frac{(\lambda/4\pi)^2}{(E_x, E_y)} \]

- APS
- ERL7
- USR7

Photon Energy (eV)
Flux Comparison

Maximum-length SCU20 (Nb$_3$Sn wire)

APS: 100mA, 1.3% coupling, 3.8 m device
USR7: 300mA, 100% coupling, 8.0 m device
ERL7: 25mA, “high-coherence” parameters, 48m device
### ERLs and USR7 Compared

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Advantage</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>High transverse coherence</td>
<td>ERL</td>
<td>ERL has emittance and matching advantage</td>
</tr>
<tr>
<td>High average flux</td>
<td>USR7</td>
<td>ERL needs very long undulators and high current, not very plausible</td>
</tr>
<tr>
<td>High average brightness</td>
<td>Similar</td>
<td>Assuming 48m undulators in ERL, extremely small emittances, implausibly high average current</td>
</tr>
<tr>
<td>Wide tunability</td>
<td>ERL?</td>
<td>Can gaps really be smaller in ERL (impedance)?</td>
</tr>
<tr>
<td>Short bunch length</td>
<td>ERL++</td>
<td>Who cares at 1.3 GHz?</td>
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<tr>
<td>Useful repetition rate</td>
<td>Similar</td>
<td>USR7 slightly more flexible</td>
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<tr>
<td>High stability</td>
<td>USR7</td>
<td>ERL has additional sources of jitter</td>
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<tr>
<td>Less R&amp;D</td>
<td>USR7++</td>
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<tr>
<td>Less risk</td>
<td>USR7++</td>
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<tr>
<td>Lower construction cost</td>
<td>USR7</td>
<td>For same number of high-performance beamlines</td>
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<td>Lower operating cost</td>
<td>USR7+</td>
<td>Large cryoplant for ERL</td>
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<td>Lower cost/beamline</td>
<td>USR7</td>
<td>More users with full performance benefit</td>
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<tr>
<td>Higher reliability</td>
<td>USR7++</td>
<td>Large cryoplant, many rf systems for ERL</td>
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</tbody>
</table>

USR+FELs is a better strategy than ERL+FELs
Conclusions

- Storage rings are extremely successful scientific facilities
- PETRA III, NSLS-II, and MAX IV pushing performance in near term
- USR7 provides an example of a next generation
  - Comparable to ERL in performance
  - R&D needed, but no apparent show-stoppers
    - Instability calculations need detailed attention
  - In contrast
    - ERL needs extensive R&D
    - Faces multiple show-stoppers
- Rings have the track-record to make the performance promises plausible
Acknowledgements

We are grateful to many of our colleagues for stimulating discussions and suggestions on this topic, including:

- Cornell University: B. Dunham, G. Hoffstaetter, I. Bazarov
- FNAL: Y. Sun
- LBNL: J. Qiang
- TJNAF: S. Benson, D. Douglas, G. Krafft, G. Neil
- TRIUMF: L. Merminga