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ERL Staging: A Gradual Approach to an ERL Upgrade of the APS

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Ultimate APS ERL Upgrade Concept[1]

- Single-pass 7 GeV linac points away from APS to permit straight-ahead hard x-ray short-pulse facility[2,3]
- Beam goes first into new, emittance-preserving turn-around/user arc[4]
  - Second-stage upgrade would add many new beamlines
- ERL can benefit from very long undulators[5]
  - Higher flux and brightness
  - Could add these using somewhat different geometry
- Ability to store beam unchanged[1]
- Existing injector complex unchanged.

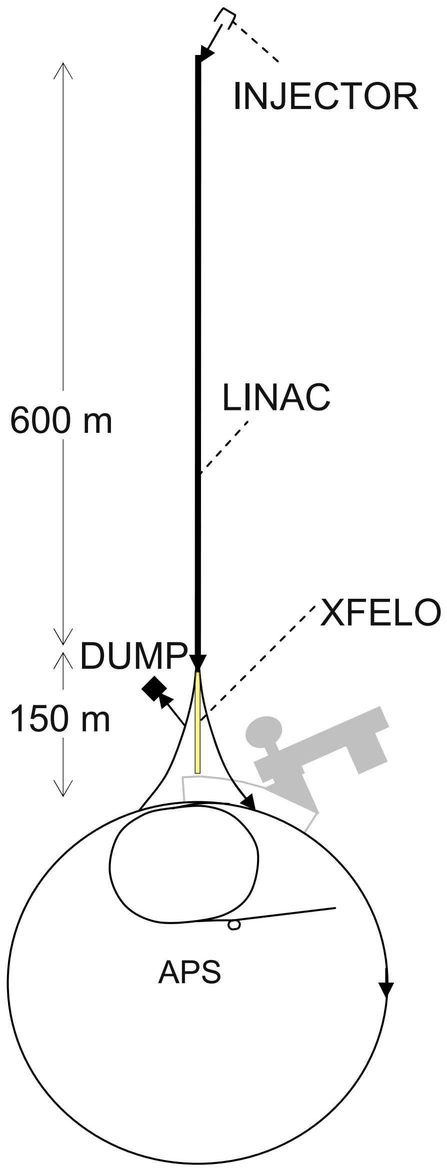
[1]G. Decker, private communication (2006).
[2]M. Borland, "ERL Upgrade Options and Possible Performance," 9/18/06.
[3]M. Borland, "Can APS Compete with the Next Generation?", May 2002.
[4]M. Borland, **private communication (2006).**
[5]S. Gruner et al., "Synchrotron Radiation Sources for the Future," 11/30/200.
[2,3,4] **M. Borland et al., NIM A 582, 54 (2007).**

ERL Upgrade in Stages

- Each stage a stand-alone upgrade to reach the final goal. Lower-risk approach to upgrading an existing x-ray source to an ERL.
- Low-emittance linac beam delivered in stages while critical injector and superconducting radiofrequency (SRF) R&D continues in parallel.
  - Assumes 0.1 mm-mr emittance source available with very low average current
  - Valuable srf operational experience attained at early stage
  - Other critical beam issues can be tested
- Microscopy and coherent imaging users benefit immediately from improved x-ray source performance, initially modest and gradually approaching "ultimate" ERL source.
- Flux-hungry users continue to use stored-beam operation.
- As an added benefit, the staged ERL also allows an XFELO to be experimentally tested, well before construction of an ultimate ERL or XFELO facility*.

* K.-J. Kim, Y. Shvyd'ko, S. Reiche, Phys. Rev. Lett. 100, 244802 (2008).
M. Borland, Proc. 2009 PAC, TU5RFP048.

ERL, Stage 1



- SRF linac points towards APS ring, 7-GeV full energy (or recirculating) – one turn thru APS
  - Assumes 20 MV/m[1]
  - Cost ~40% of ultimate ERL
- Beam parameters CEBAF-like
  - 150 μA avg. beam current (pulsed injector)
  - 1.05 MW beam power (dumped)
  - Assumes 0.1 mm-mr emittance achievable
- Energy recovery not required
- Avg. beam brightness matches APS now ("break-even")
- Geometry similar to others, but not as staging concept: D. Douglas[2], M. Borland[3], J. Lewellen[4]

[1] M. Borland et al., NIM A 582, 54 (2007).
[2] D. Douglas, JLAB-TN-98-040m(1998).
[3] M. Borland, private communication (2002).
[4] J. Lewellen, APS Light Source Note LS-298 (2003).

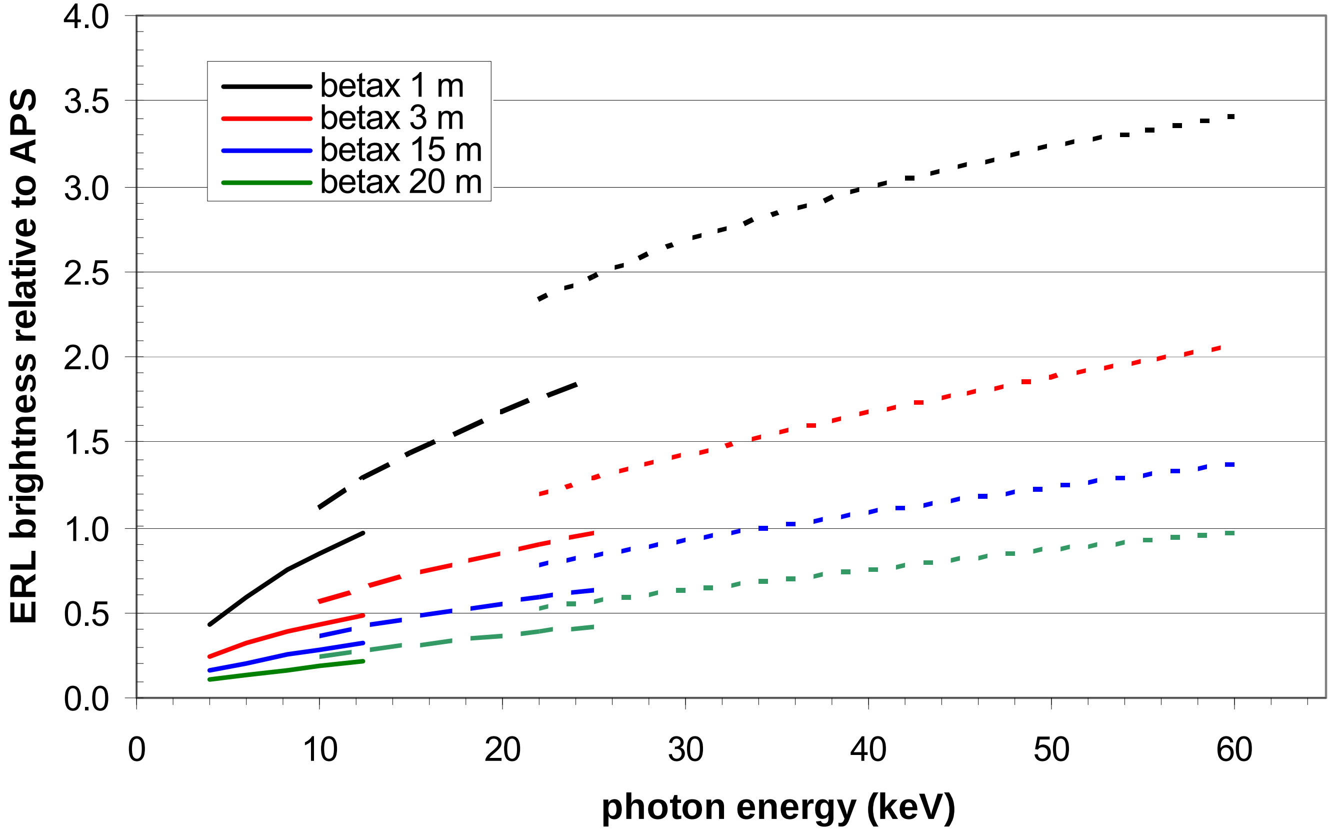
Source Performance, Stage 1

- APS lattice reoptimized to take advantage of low-emittance beam.
- β_x,β_y=(1, 1)-m solution close to optimum matching condition for min 6-D vol.; possible using the present quadrupoles.
- Emittance growth due to quantum excitation est. to be ~8 pm (one turn).
- Coherence fraction same as ultimate ERL; depends only on emittance.

$$B \propto I / \sigma_T \sigma'_T \delta\omega$$

APS: 100 mA, εx 2.5 nm, 1.2% couplg, ηx 0.17 m, δ 9.6e-4, L = 2.4 m

ERL stage 1: 150 µA, $\varepsilon x,y$ 7.3 pm, ηx 0, δ 2e-4; and for $\delta\omega$: N = 70 (U33).



Transverse Coherence Fraction Comparison

- APS now: 2.4-m undulators
- APS Renewal: 8-m undulators; 100-300x higher coherence
- ~100x for 2.4-m

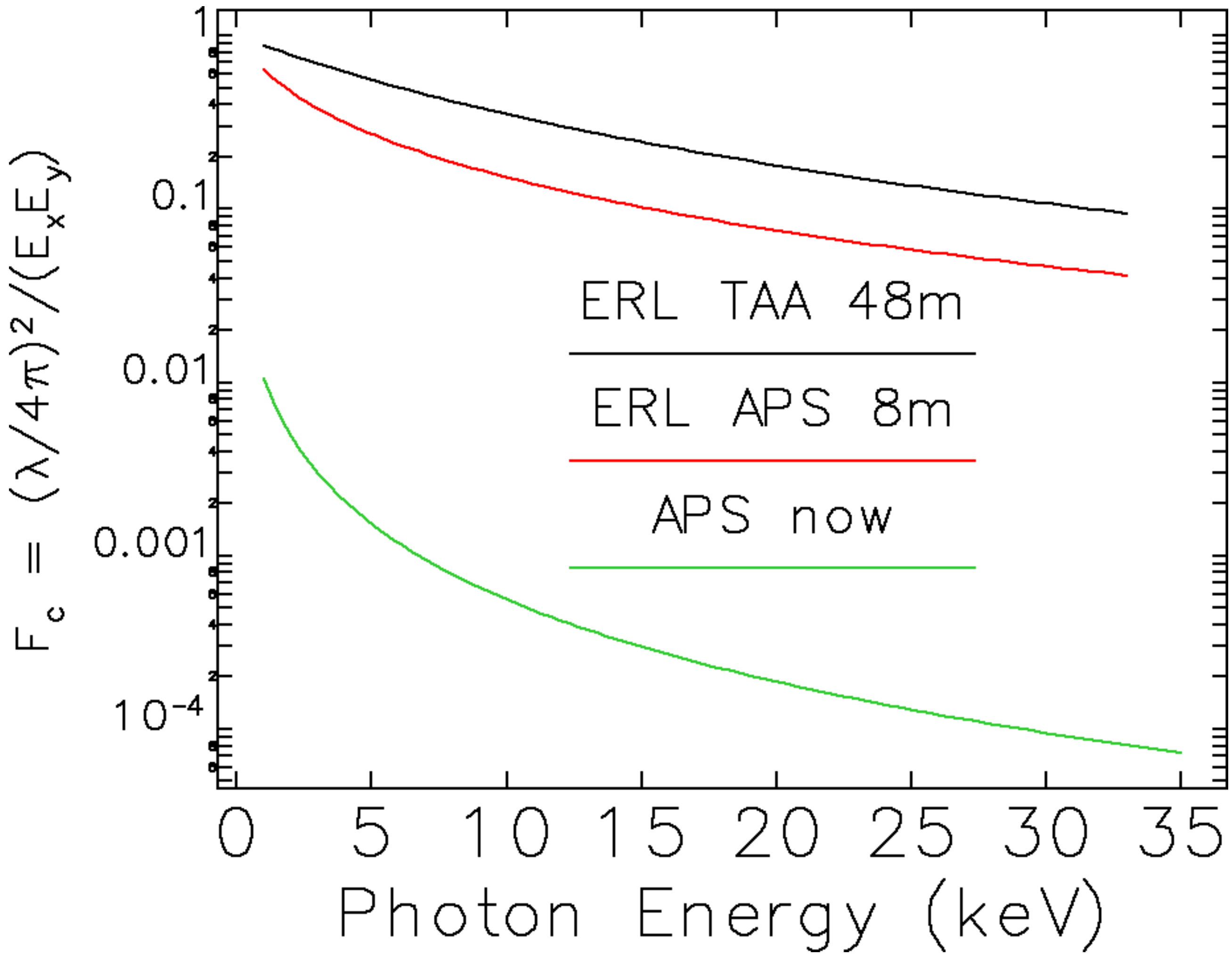


Fig. courtesy M. Borland

Injector

- Requirements for Stage 1:
  - 150 μA and 0.1 mm-mr normalized emittance
  - Assuming 1-MHz rep rate injector: 150-pC bunch charge

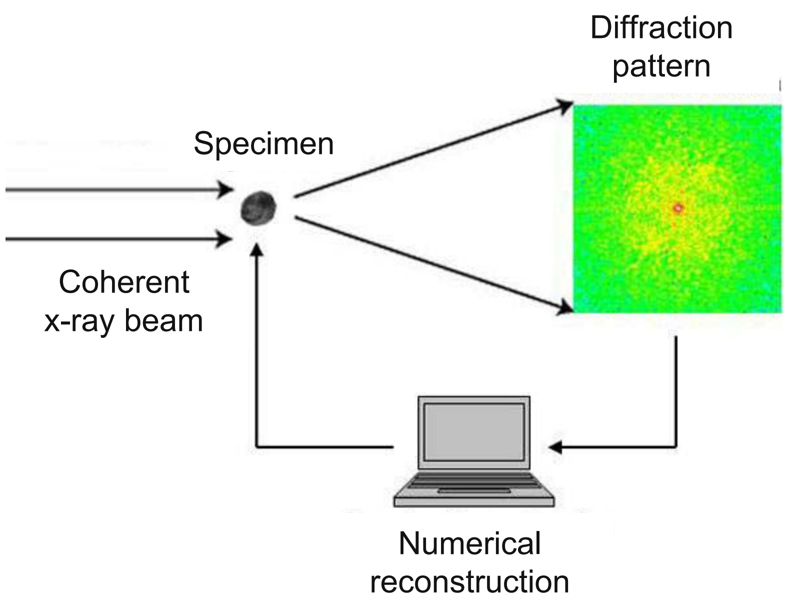
- Promising designs and results for low bunch charge; appear within striking range for Stage 1
  - SCSS: 200-400 pC, 0.7 mm-mr, 60 Hz [Shintake, Togawa et al.]
  - LCLS: 20 pC, 0.14 mm-mr, 120 Hz [Akre et al.]
  - PSI FEL injector [Ganter et al.]
  - Cornell DC injector [Dunham et al.]
  - *XFELO design: 30-40 pC, 0.1 mm-mr, 1-MHz rep rate; thermionic cathode + 100-MHz VHF gun [Ostroumov et al.]*
  - *LBNL FEL injector design: photocathode + VHF gun [Staples, Sannibale et al.]*

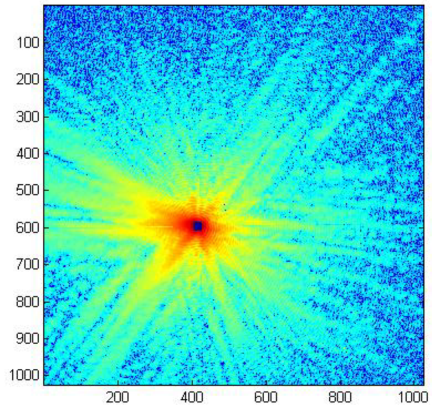
Coherent Diffraction X-ray Imaging

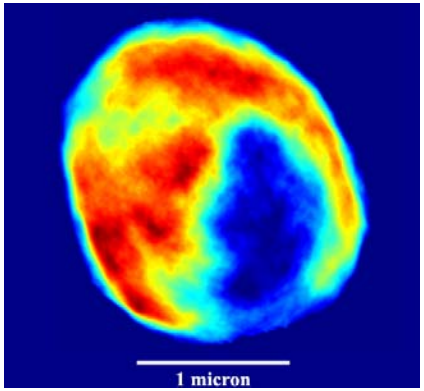
Lensless **method for imaging thick and buried structures**

- **Two-step process: record coherent x-ray diffraction pattern, recover object structure computationally**
- **Resolution limited only by wavelength and measurable signal**
- **Sensitive to phase as well as absorption of specimen**
- **Get 3D by tomographic methods**

Slide courtesy I. McNulty







resolution ~ λ / angular size

J. Miao, et al., *Nature* 400, 342 (1999)

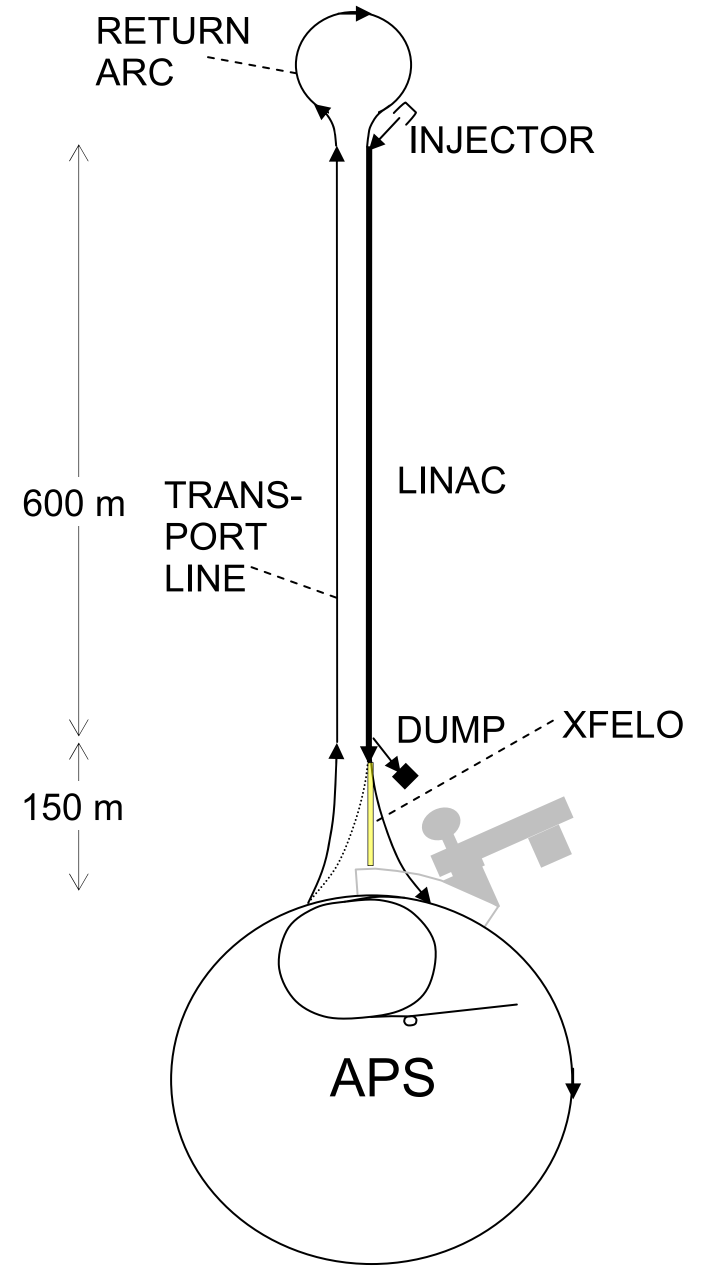
*Coherent Imaging Scientists' Perspective**

- ERL Stage 1 potentially interesting as a step towards XFEL sources.
- Typically work in 4-12 keV range.
- Desirable coherence fraction increase without having to throw away 90% of beam. Optics heat load issue mitigated, more stable.
- Break-even brightness okay, but 10x higher would get noticed
  - Relative brightness at 10 keV scales approx. linearly with beam power; higher than ~2 MW may require energy recovery
  - Relative brightness improves more rapidly at higher harmonics; can reach 10x higher relative brightness for 30 keV and 2.5 MW beam power (beam dump needs design)
- Beamlines would need to be optimized to take advantage of round photon beam and 100% throughput ($\sigma_{x,y}$ 2.7 μm, $\sigma_{x',y'}$ 2.7 μr).
- Relatively few APS users (today) could take advantage of Stage 1 special operating mode (interleaved with stored-beam operation). Stand-alone source with switchyard may be an alternate option.

*** Thanks to I. McNulty: see talk on Wed pm plenary**

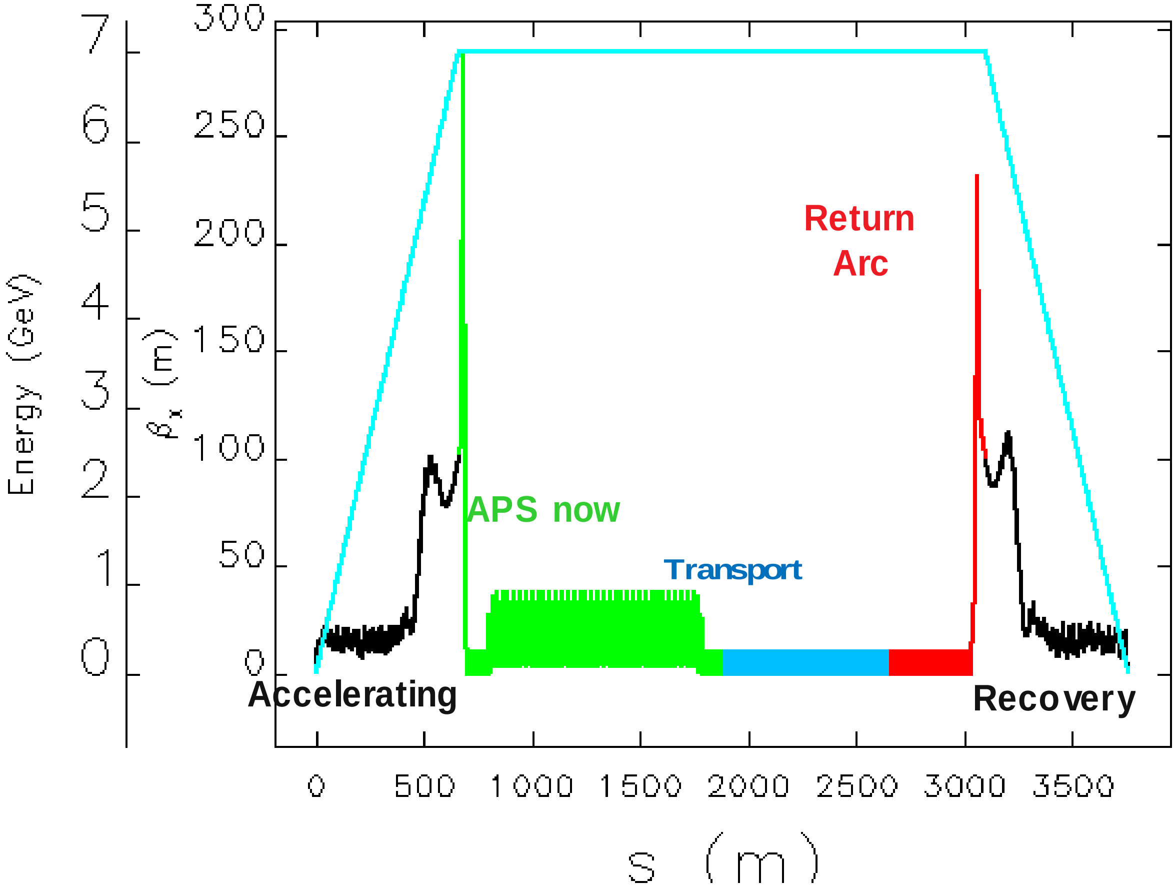
ERL, Stage 2

- Energy recovery is commissioned.
- Add return arc and merger optics.
- Add new extraction line, extended parallel to the linac.
- Allows testing energy recovery with co-propagating high-energy beams ($\leq$ 7 GeV) and modest average current (up to 1 MW beam power).
- Highest-energy demonstration of an ERL was by CEBAF at 1 GeV and ~1 μA (~1 kW); this was done for only a single-pass acceleration and deceleration.
- Highest-power FEL ERL, at JLab, operates with 1.4-MW beam power at low beam energy.



Optics

- Lattices for accelerating and recovery linacs and APS ring same as ultimate ERL.
- Transport line, return arc, and matching sections modified to accommodate ERL staging concept.
- Brightness of the APS will be slightly better than ultimate ERL due to direct injection from the 7-GeV linac.



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ERL, Stage 3 and Beyond

- Pulsed electron source can continue to be used while cw injector R&D proceeds and a prototype becomes available.
- At that point, energy recovery testing with accumulation to higher current can proceed.
- A low-energy dump can be designed for the full ERL power anticipated. Cornell gives a design for a 1-MW dump.
- In the final stage, the linac is turned around after the large turn-around arc is constructed for the ultimate ERL.

Summary

- ERL staging envisioned as a way to gradually upgrade the APS in steps, reducing overall risk.
- Energy recovery not needed in stage 1; valuable experience operating srf system and controlling the beam.
- Relatively modest injector development satisfies stage 1 source with “break-even” beam brightness and 2 orders of magnitude higher coherent fraction.
- Microscopy and coherent imaging users benefit immediately; high-flux users continue to use stored beam mode.
- Energy recovery commissioning proceeds in stage 2 with construction of modest return arc.
- Accumulation with ER proceeds with cw injector.
- Large turn-around arc constructed as final step.

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