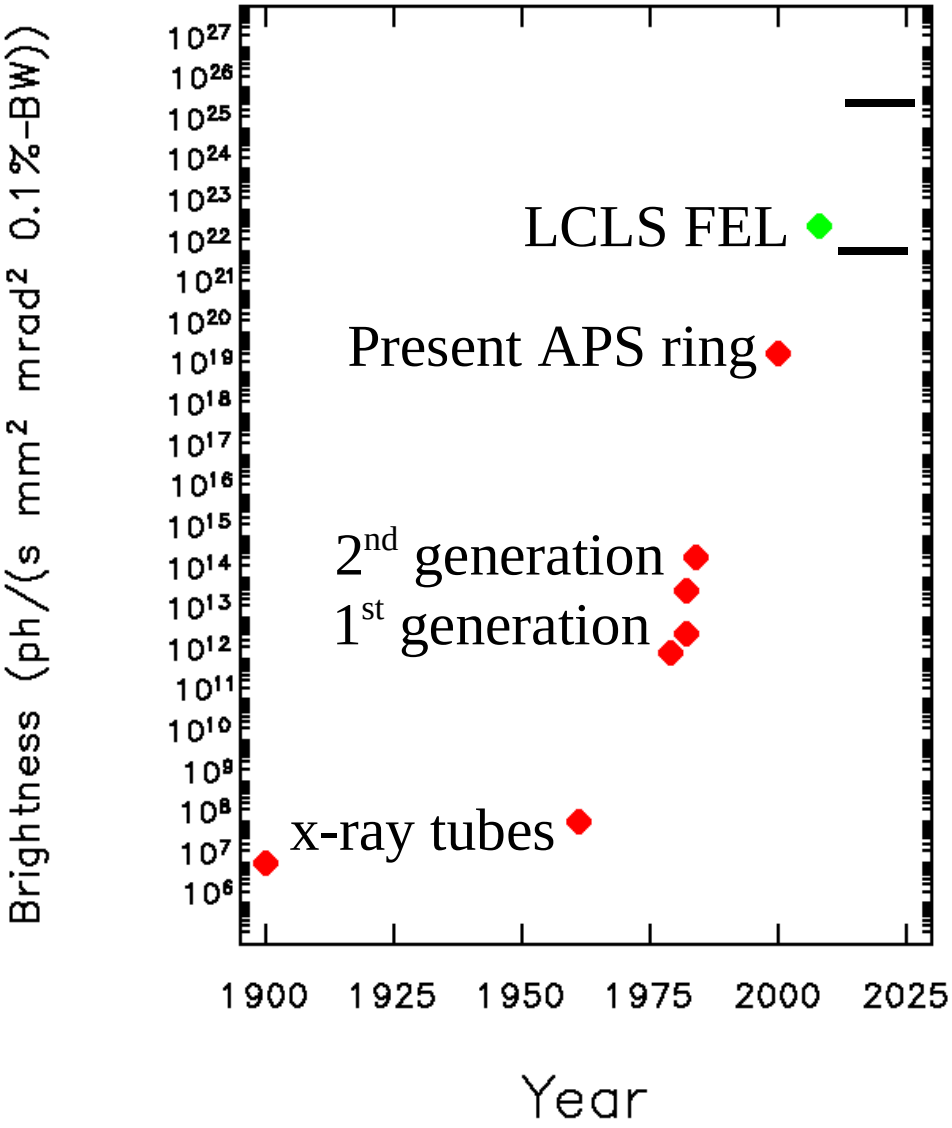
Can APS Compete with the Next Generation?

An Accelerator Physicist's View

Michael Borland
Operations Analysis Group
Accelerator Operations Division

Average Brightness of 8 keV X-ray Sources Over Time



Proposed TESLA FEL

Proposed energy-recovery linacs

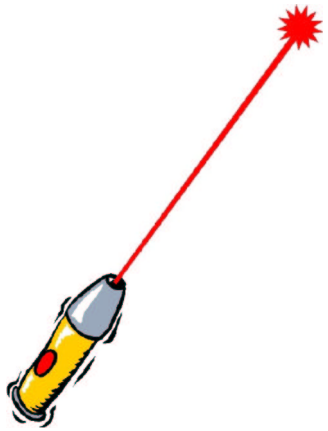
Predicted advantage in peak brightness is even greater for next generation sources (NGS).

After R. Fenner, APS

What is Brightness and Who Cares?

- Brightness measures the ability to put many photons of a specific wavelength into a small spot at a great distance

100W light bulb is powerful but not bright



0.001W laser pointer is bright but not powerful

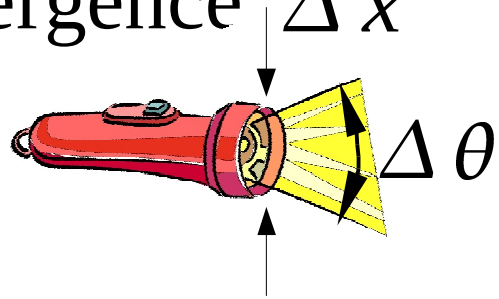
- A bright source allows more precise measurement of material properties

Brightness and Emittance

- Brightness is related to "emittance"

$$B \propto \frac{1}{\epsilon^2}$$

- Emittance is related to source size and divergence Δx



$$\epsilon \propto \Delta x * \Delta \theta$$

- A laser pointer has an emittance of ~1000nm
- The APS has an emittance of ~4nm

Why Does the Accelerator Matter?

- The brightness of the photon beam is determined (mostly) by the emittance of the electron beam
- The photon beam pulse length is determined by the electron beam pulse length
- NGS advertise
  - Lower emittance: ~0.1 nm vs ~4 nm for APS
  - Shorter pulses: 0.1-1.0 ps vs 70 ps for APS
  - Longer IDs and/or amplification of radiation

Essential Advantage of NGS

- In a storage ring, the emittance goes up as the energy goes up

$$\epsilon \propto E^2$$

- In a linac, the emittance goes down as the energy goes up

$$\epsilon \propto \frac{1}{E}$$

- For example:
  If we had added a 6.5 GeV extension to our 0.5 GeV linac, the emittance would be 1 nm.

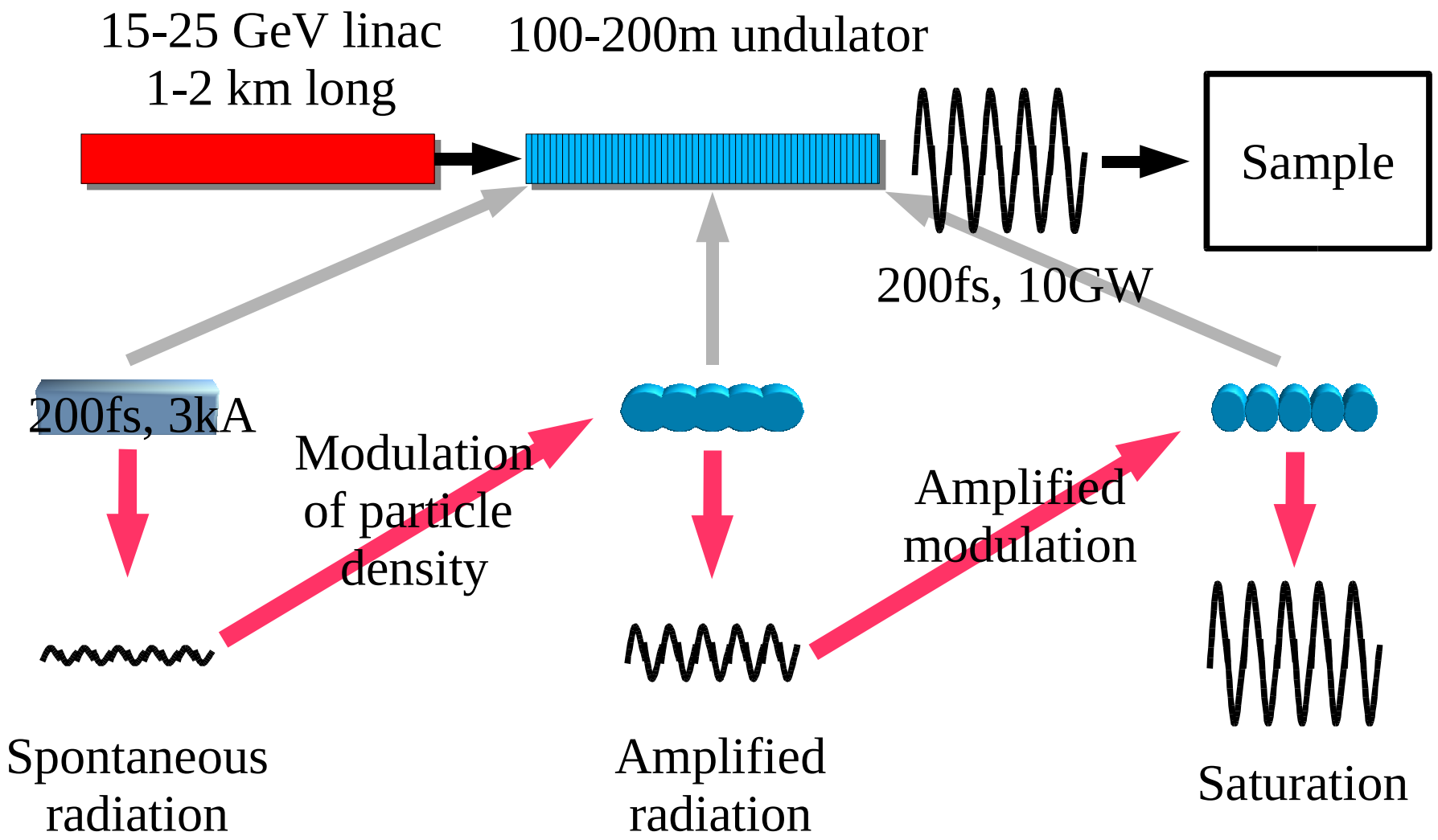
Essential Advantage of NGS

- Photon energy goes up with electron energy

$$E_p \propto E^2$$

- To make harder x-rays, we are pushed toward high energy
- With a linac, the maximum brightness "automatically" goes up
- With a ring, the maximum brightness "automatically" goes down

Next Generation Proposals
—Free-Electron Lasers —



X-ray FEL Pros and Cons

Pro

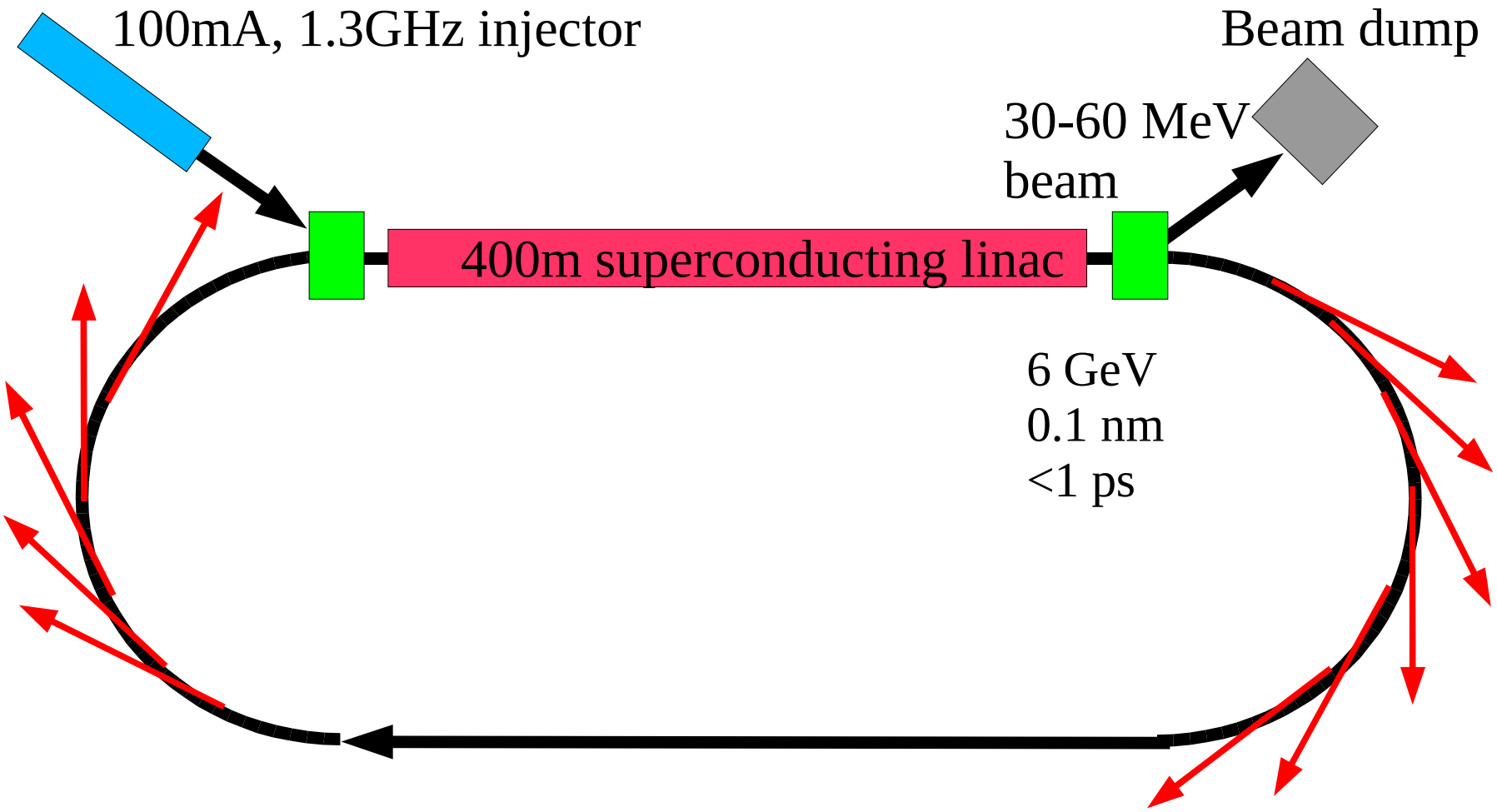
- ✔ Very high average brightness
- ✔ Extremely high peak brightness
- ✔ ~200 fs pulses
- ✔ Round beams

*Postscript: A number of people have objected that this point is inaccurate or misleading.

Con

- ✗ Destruction* of sample
- ✗ High heat-load on optics
- ✗ Poor shot-to-shot stability
- ✗ Requires electron beam quality beyond state-of-art
- ✗ Requires accelerator stability beyond state-of-art
- ✗ Very long undulators
- ✗ Few simultaneous users

Next Generation Proposals
—Energy Recover Linacs —



ERL Pros and Cons

Pro

- ✔ High average brightness
- ✔ Very high peak brightness
- ✔ 100fs to 1ps pulses
- ✔ Round beams

Con

- ✗ 1.3GHz pulse rate may be useless for timing experiments
- ✗ Requires gun that no one knows how to build
- ✗ Shortest pulses not available to all users
- ✗ Hazards from multi-100 MW electron beam

The Reality of NG Sources

- *Predictions* of brightness don't tell the whole story
  - NG sources will not exist for another 5-10 years
  - They require accelerator performance that is yet to be demonstrated
  - They will have an initial period of unreliable operation
  - They won't serve the needs of all users
- In the meantime, APS need not stand still!

APS Pros and Cons

Pro

- ✔ Exists now
- ✔ Bright source
- ✔ Very stable
- ✔ Very reliable
- ✔ Many simultaneous users
- ✔ Flexible timing

Con

- ✗ Difficult to increase average brightness
- ✗ Very difficult to make short pulses

How Do We Enhance User Productivity?

- Organizational and operations improvements
  - High reliability and availability
  - Accessibility and ease of use
  - Excellent User support
- Technical improvements
  - Accelerator
  - Beamlines
  - Insertion devices
  - Instrumentation

Options for Making APS Brighter

1. Increase the beam current from 100mA to 300mA
   - Must solve power-load problems
2. Use shorter-period undulators
   - Must replace existing IDs
3. Use longer undulators
   - Providing 7.9m for a few sectors is relatively easy
   - Providing 9.6m for a few sectors possible but expensive
   - Providing 8.9m for all users is conceivable but very expensive

Options for Making APS Brighter

4. Decrease the coupling (emittance ratio)
   - Limit is ~0.25% (~2% at present)
   - May benefit few Users
   - May hurt some Users
   - Requires improved beam stability
5. Decrease ϵ_{eff} from present value of 3.9nm
   - Working on 3nm now
   - Hard to go much lower without hardware changes
   - Benefits almost everyone

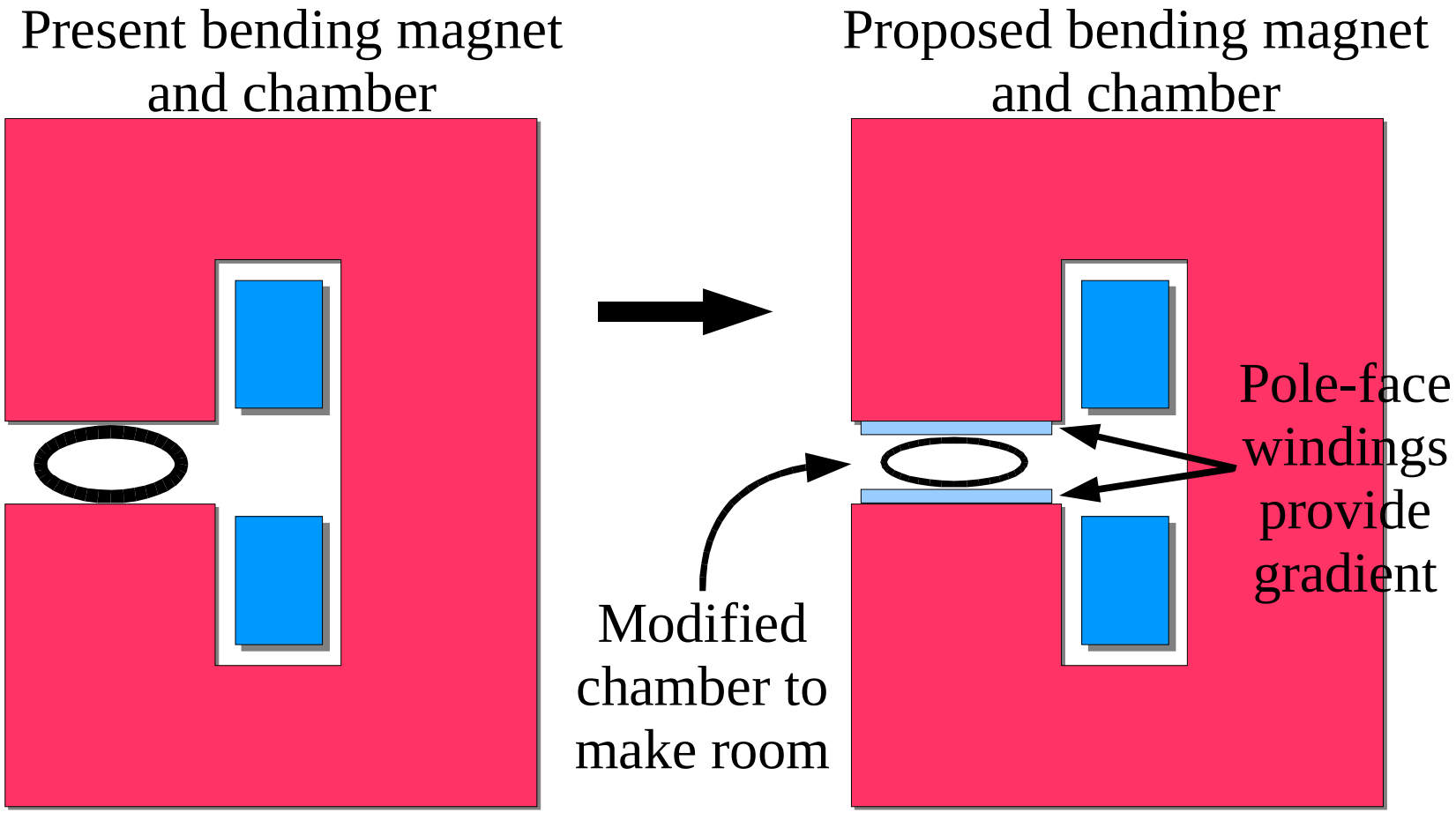
Costs of Smaller Emittance

- The brightness depends on the "effective emittance"

$$\epsilon_{eff} = \sigma_x \sigma'_x = \epsilon \sqrt{1 + (\sigma_\delta \eta)^2 / (\epsilon \beta)}$$

- Making this smaller will make the lifetime shorter
- We are already near the limit of our top-up rate, so we'll need
  - More bunches,
  - Upgraded injector, and/or
  - Faster, quieter top-up

Possibility for 1.8nm Emittance



- Can be done a few sectors at a time
- Cooling the windings will be a challenge

How Far Can We Push APS Brightness?

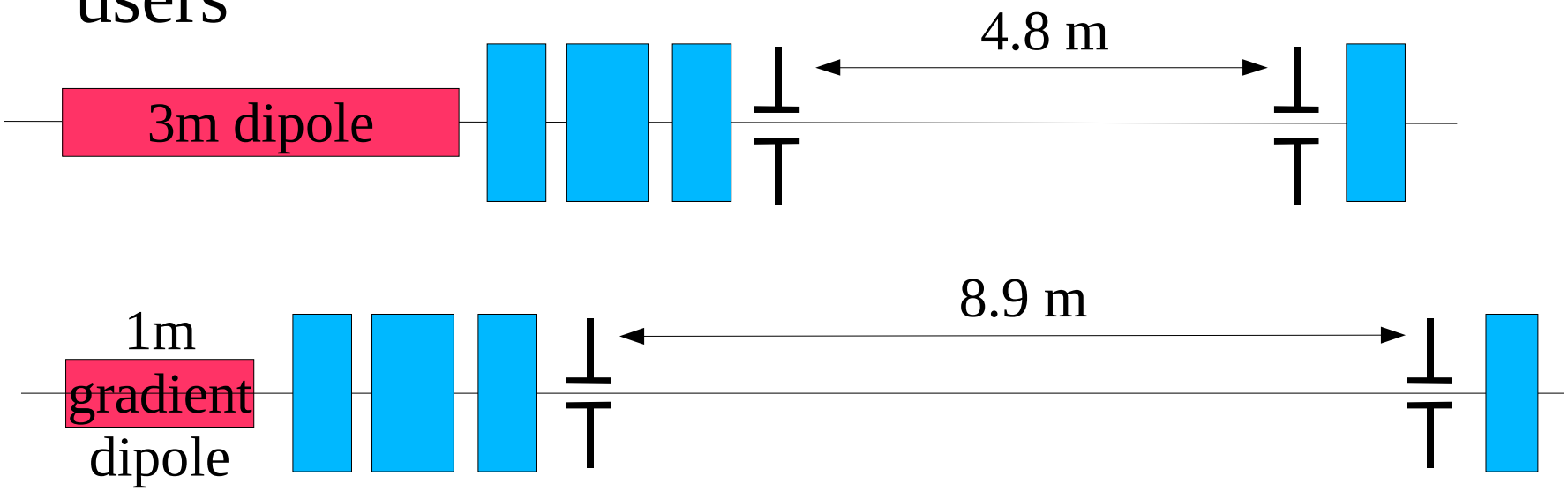
- A factor of ~100 is *conceivable*
  - ~3 x increase from current: 100mA $\Rightarrow$ 300mA
  - ~3 x increase from coupling: 2% $\Rightarrow$ 0.25%
  - ~4 x increase from emittance: 3.9nm $\Rightarrow$ 1.8nm
  - ~3 x increase from undulator length and period: L=2.4m, λ=3.3cm $\Rightarrow$ L=7.9m, λ=2.7cm
- Problems
  - Only a few Users could have the longer IDs
  - Inflexible beta functions ($\beta_x \approx 4$m, $\beta_y \approx 3$m)

More Extensive Upgrades

- Take a lesson from SPEAR:
  - Replace the storage ring
  - Keep the beamlines
- We've explored two possibilities
  - Relatively conservative upgrade using many existing components
  - Bold upgrade using cutting-edge components
- The best idea is probably somewhere in between

"Conservative" Upgrade

- The goal is ~100x brightness increase for all users



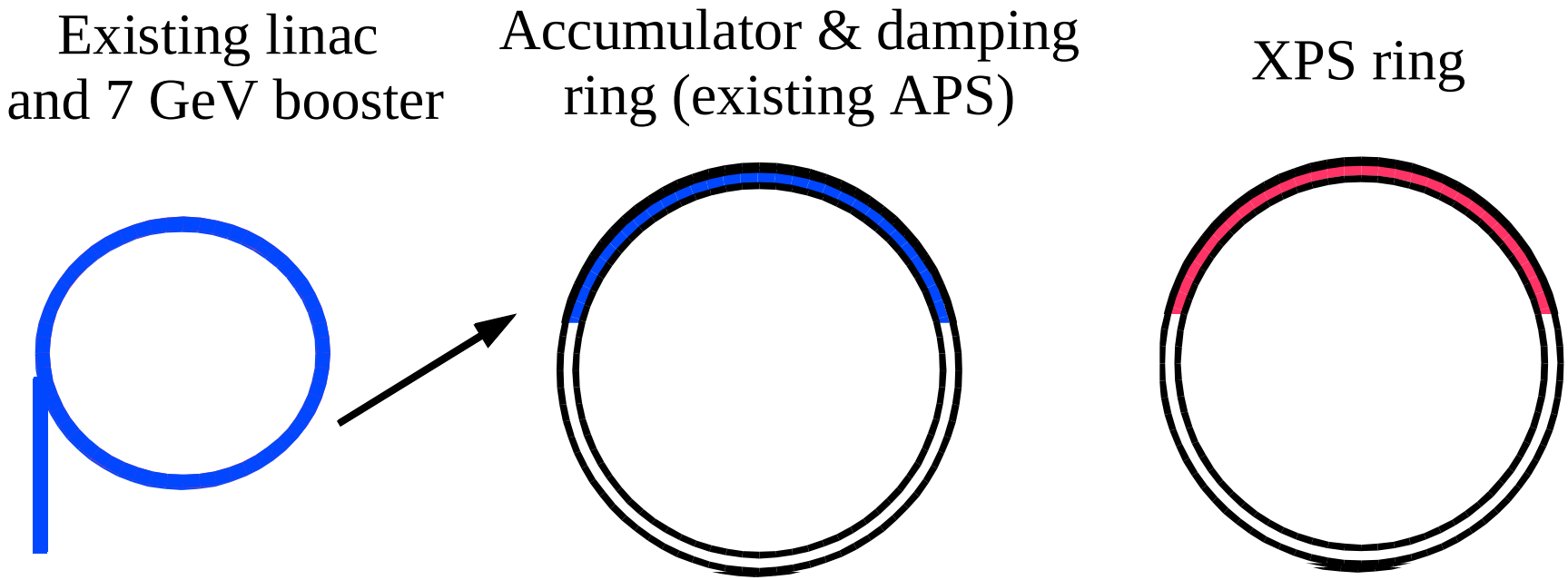
- Effective emittance may reach 1.7 nm
- Chromatic correction yet to be investigated but looks difficult

A True Next-Generation Upgrade

- Our "XPS" design is ~4000 times brighter than APS
  - Emittance is 0.075nm (same as an ERL)
  - Run 1A current (like a B-factory)
  - 10m-long IDs and flexible beta functions
- The magnet technology is very challenging
  - 12-pole variable permanent magnets instead of quadrupoles and sextupoles
  - Dipoles with strong gradient and sextupole terms
- XPS is at the borderline between the possible and impossible

XPS Accelerator Complex

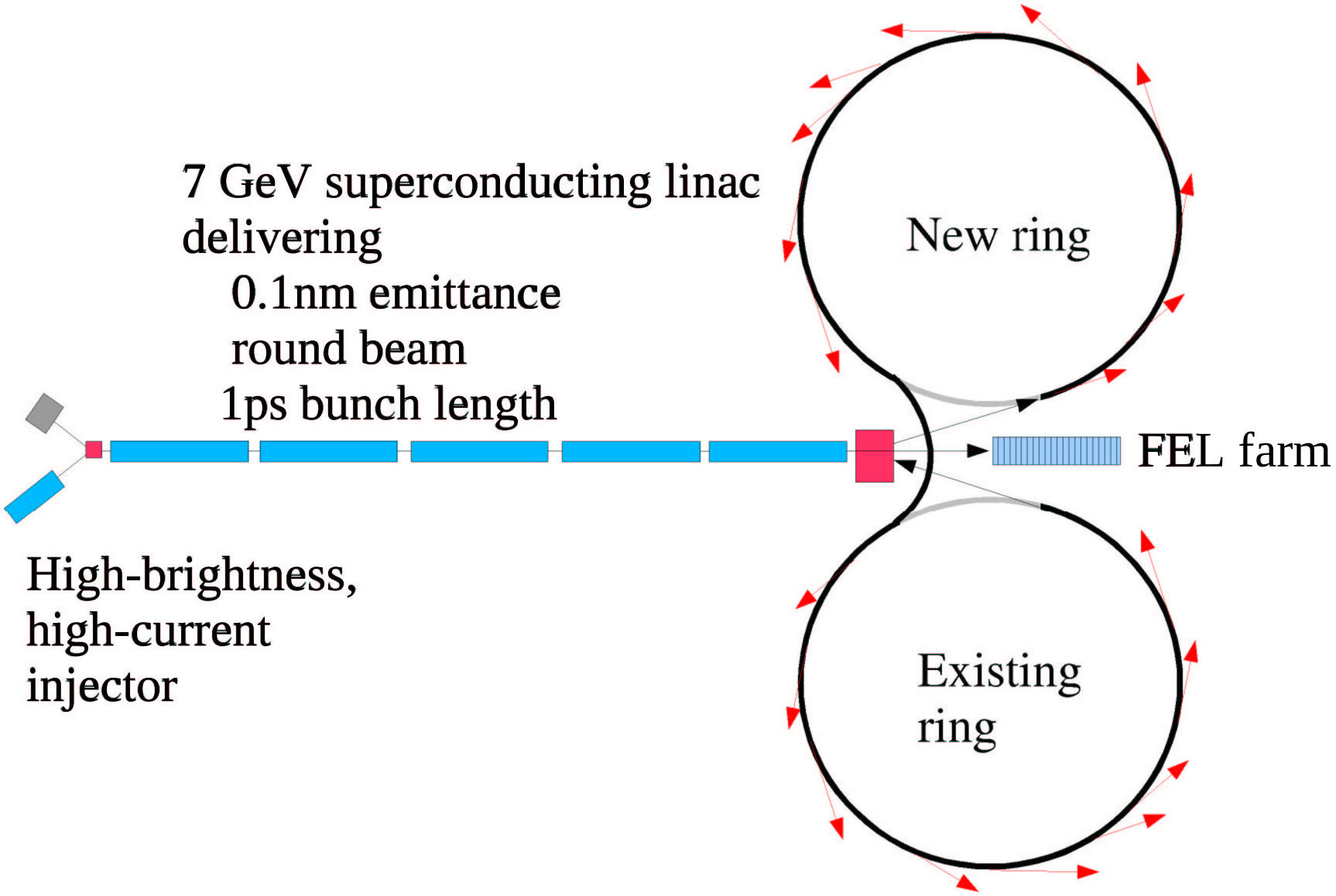
- Due to ultra-low emittance, XPS will have
  - Very short lifetime
  - Very small dynamic aperture
- Use full coupling (round beams) and on-axis injection



Another Next Generation Upgrade

- ERL proposals feature arcs that look like half a storage ring
- We can imagine upgrading APS to an ERL, with two stages
  - Circulation of ERL beam for many turns
  - Single-pass ERL when gun technology permits
- The ERL could be built and partially commissioned without disrupting APS operations
- We could double the number of beamlines

An ERL@APS Concept



Getting There From Here

- Funding for such initiatives won't come easily
- We must have the expertise to investigate potential upgrades and make convincing proposals
- We must have a convincing record of improvements to the existing facility
  - Accelerators
  - Beamlines
  - Insertion devices
  - Instrumentation

Getting There From Here

- We must have a record of outstanding productivity from APS users
  - Accessible, easy-to-use facility
  - High reliability and availability
  - Top-notch user support
  - World-class brightness and stability
  - Facilities and performance that attract the best researchers
- We must publicize our achievements

Can APS Compete with the Next Generation?

- NG sources won't exist for another 5-10 years
- Meanwhile, APS will can raise the bar through incremental improvements
- We are well-positioned to compete with the next generation.
- There are many possibilities to put APS into the same league as NG sources
- In time we may well *be* the next generation!