Energy Recovery Linac & Ultimate Light Source Overview

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Don Bilderback
CHESS & Applied Physics
dhb2@cornell.edu

- Need for better x-ray sources
- PEP-X as example of ULS
- Cornell ERL as example of ERL
- Example experiments that can use the unique properties of an ULS or ERL

Starting Perspective of 3rd Generation Storage Ring Developer/User

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My experiment could use:

- Higher spectral brightness
- More x-ray flux
- Shorter pulse length
- More coherent x-rays
- etc.

Can quantify the need for better SR beams still further!

Some user answers:

A lot of photons into a small spot	A lot of photons into a large area
A lot of coherent photons	A high coherent fraction
A lot of photons in a short pulse	A lot of photons in a long pulse
A high pulse repetition rate	A low pulse repetition rate
Not too many photons	nm spatial resolution
Femtosecond pump-probe timing stability	0.1% intensity stability
50 keV photons	280 eV photons
10^{-6} energy bandwidth (meV)	10^{-2} energy bandwidth
fast switched polarization	etc…..

Taken from talk: Performance Metrics of Future Light Sources,

by Robert Hettel, SLAC, ICXFA Future Light Sources 2010, March 1, 2010 at SLAC:

SLAC NATIONAL ACCELERATOR LABORATORY

Properties of the x-ray beam directly depend on the properties of the electron source and the properties of the magnet or insertion device producing the x-rays

The technology depends on the purpose

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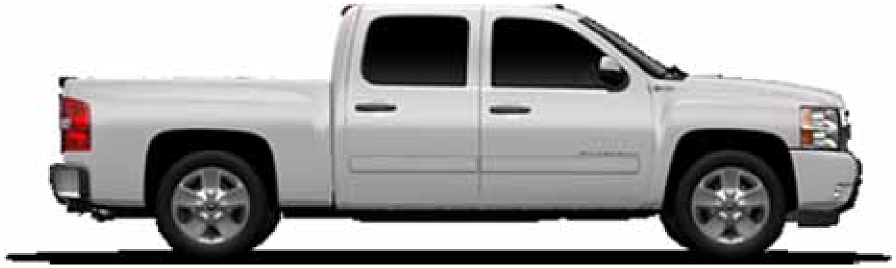
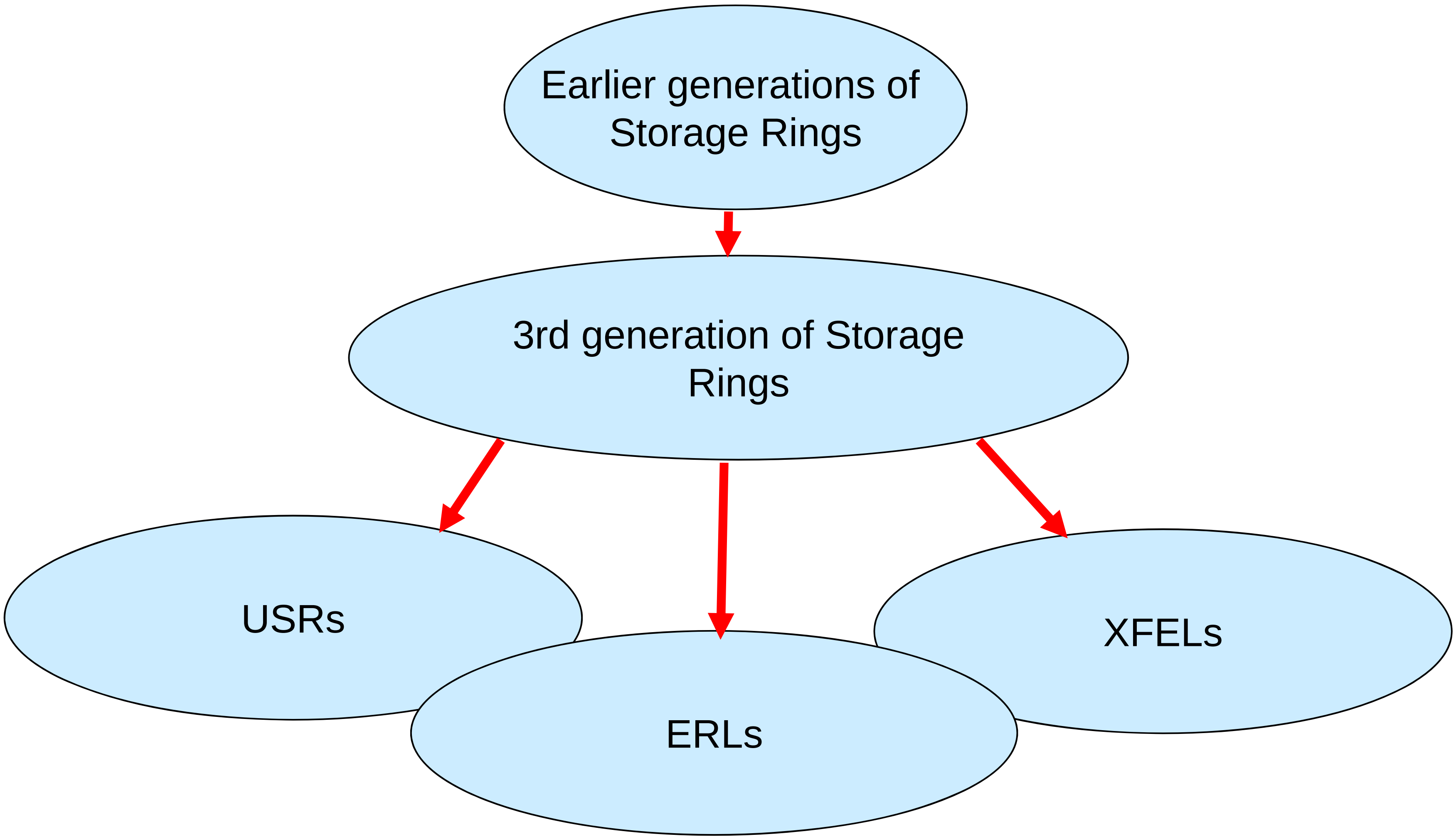
Speed: Koenigsegg CCX from Sweden.
It can go from 0 to 60 mph in 3.2 seconds



Carrying Capacity: Chevy Silverado 2011
½ Ton Pickup

Comfort & Livability
Tiffin 45' RV 2011

SR Technology



Comparison of SR, ERL, XFELs

Flux and Brilliance

Comparison of flux and brilliance between the ESRF and some proposed sources including the UHXS storage ring source, the Cornell Energy Recovery Linac, and X-ray FEL sources based on Self-Amplified Spontaneous Emission (SASE). Part of the data in this table has been taken from the report "ERL_CHESS_memo_01_002.pdf" available from http//erl.chess.cornell.edu/Papers/Papers.htm

Source Type	*ESRF Storage Ring*	*UHXS Storage Ring*	*Cornell ERL*	*LCLS SASE FEL*	*TESLA SASE FEL*
Electron Energy [GeV]	6	7	5.3	15	25
Average Current [mA]	200	500	100	7.20E-5	0.063
Hor. Emittance [nm]	4	0.2	0.15	0.05	0.02
Vert. Emittance [nm]	0.01	0.005	0.15	0.05	0.02
FWHM Bunch Length [ps]	35	13	0.3	0.23	0.09
Undulator Length [m]	5	7	25	100	200
Fundamental [keV]	8	12	8	10	12.4
Average Flux [Ph/s/.1%]	1.3E+15	2.0E+16	1.5E+16	2.4E+14	4.0E+17
Average Brilliance [Ph/s/.1%/mm^2/mrad^2]	3.1E+20	3.5E+22	1.3E+22	4.2E+22	8.0E+25
Peak Brilliance [Ph/s/.1%/mm^2/mrad^2]	3.3E+22	1.0E+25	3.0E+25	1.2E+33	7.0E+33

Pascal Elleaume, "The Ultimate Hard X-Ray Storage-Ring-Based Light Source", SLAC Beamline, 32-1 (2002).

Disclaimer: Though the comparisons are a bit dated, they are probably correct to within an order of magnitude and are highly dependent on how the electron optics are run for all the choices - and linacs have many choices.

Features of New Light Sources

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XFELs: extremely high peak-brightness, coherence and 10 fs pulse length with bunch compression

ERL and **Ultimate Ring-based Sources**:

1. High average brightness (fully coherence at 10 keV),
2. Lower peak brightness compared to XFELs
3. Higher repetition rate
4. Wide energy spectrum and ultra-high energy resolution
   - 1 nm-sized x-ray beams
   - 1 meV energy resolution
   - sub-10 ps pulses
   - desire round electron beams for many of the "probe" technologies
5. Support many photon beam lines and serves many users simultaneously
6. Many improvements are being made in accelerator hardware/software so the state-of-the-art keeps improving! Cross-fertilization of technologies.
7. We X-ray community users/developers have an opportunity to ask what new things we can do with new sources and to articulate what could be done if parameter "X" were made "better" or "improved further".

PEP-X Baseline Concept

from Bob Hettel, 5/30/2011

C = 2.2 km
Max stored bunches =3,400
RF frequency = 476 MHz

$E = 4.5$ GeV

$I = 1.5$ A

$\varepsilon_x = 150$ pm-rad

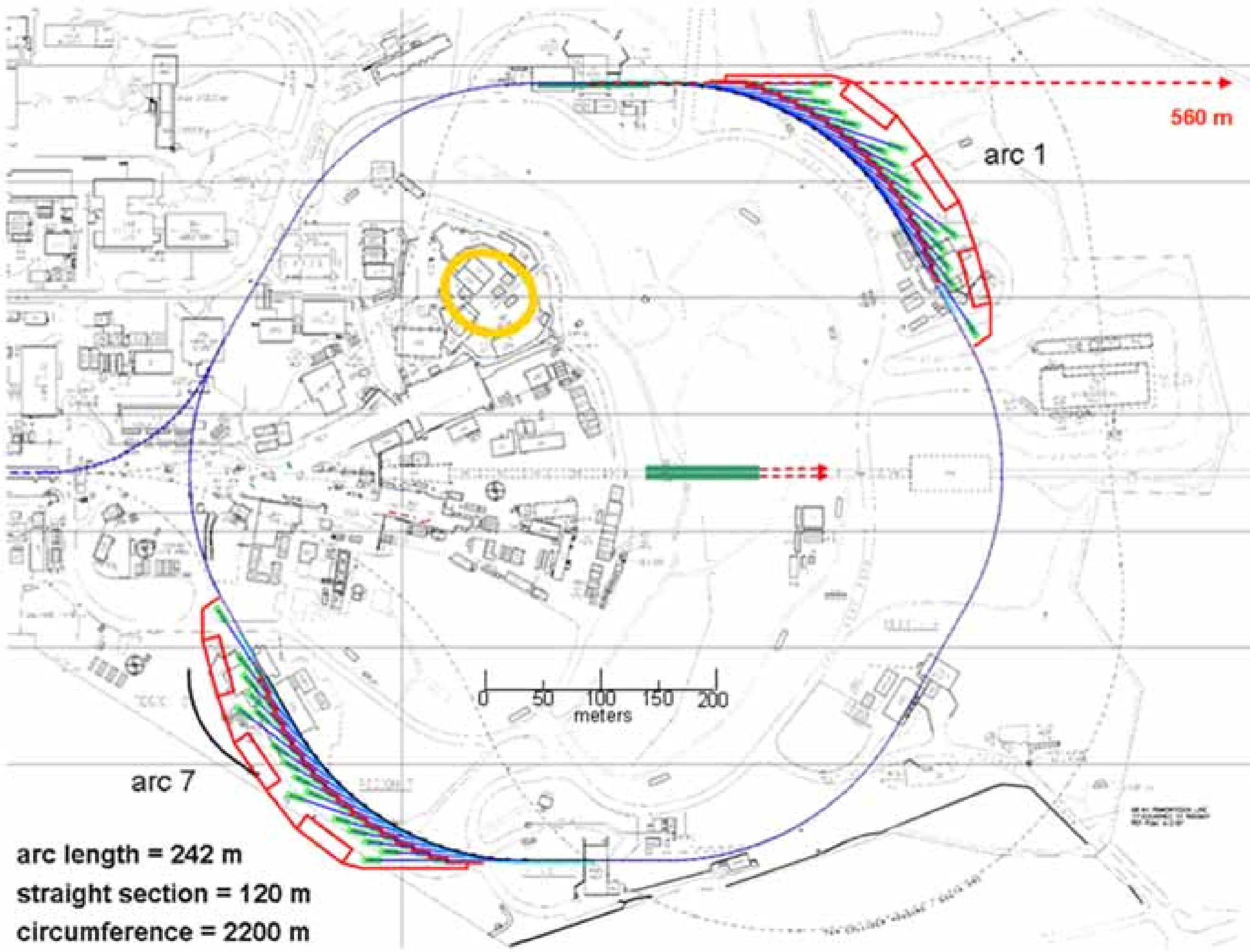
(~0.06 nm-rad w/o IBS)

$\varepsilon_y = 8$ pm-rad

$\sigma_s = 3/6$ mm
(without/with 3rd harm rf)

$\tau =$ ~1 h

top-up injection every few seconds (~7 nC, multiple bunches)



- 2 arcs of DBA cells with 32 ID beam lines (4.3-m straights)
- 4 arcs of TME cells
- ~90 m damping wigglers
- 6 ea 120-m straights for injection, RF, damping wigglers long IDs, etc.

Notes on PEP-X Design

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Notes on 3-phase PEP-X design study to date (May 2011):

1. Phase 1: Baseline design (155 x 8 pm-rad, 1500 mA, 4.5 GeV) - complete
2. ERL configurations (assuming Cornell parameters) - complete
3. "Ultimate" lattice (~15 x 15 pm, 150-200 mA, 4.5 GeV) – very preliminary

Average spectral brightness approaching 10^{23}
Short pulses 10 psec (100 fs in occasional single bunches)
High coherent fraction at 10 keV
High current translates into high flux production

PEP-X Special Operating Modes

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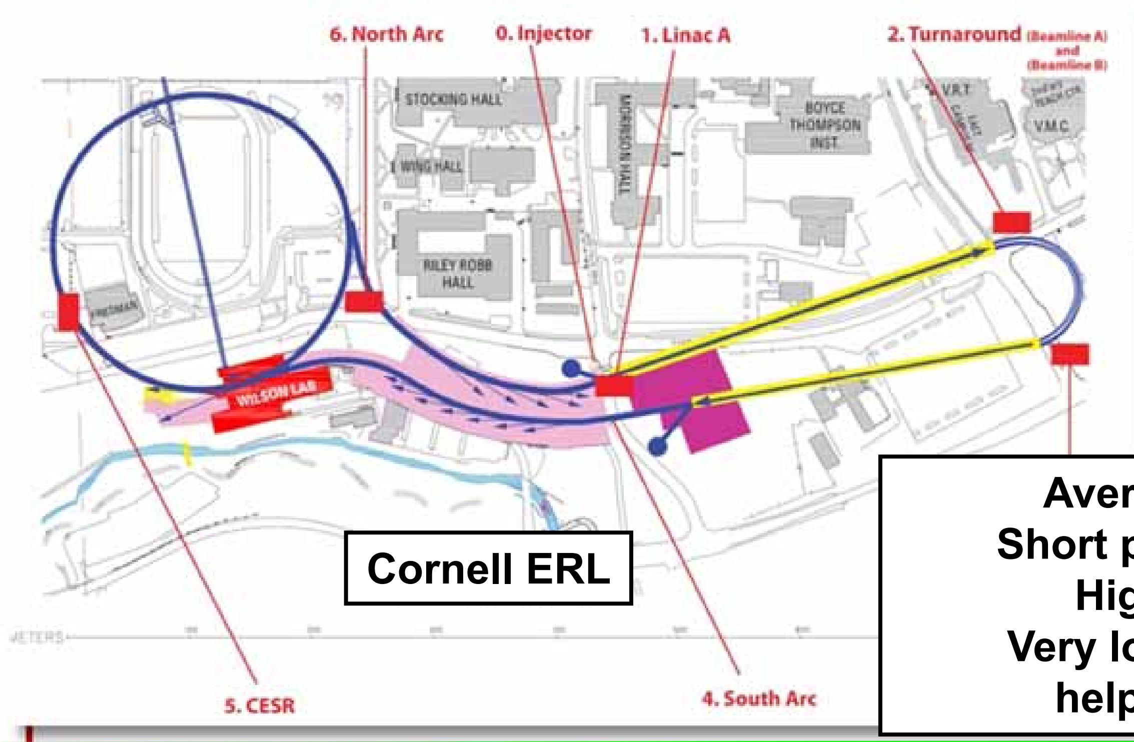
Short bunches

- The nominal rms bunch length is 3 mm which would be stretched to ~6 mm rms **(20 psec)** with a 3rd harmonic cavity in order to improve lifetime and reduce emittance growth due to IBS
- Localized bunch-shortening schemes are possible (e.g. crab cavities or y-z emittance exhange) – ps or less.
- A single short bunch (~100 fs) can be injected into a gap and allowed to circulate once or a few times around the ring. Emittance and bunch length increase as the bunch circulates due to CSR effects.

Lasing

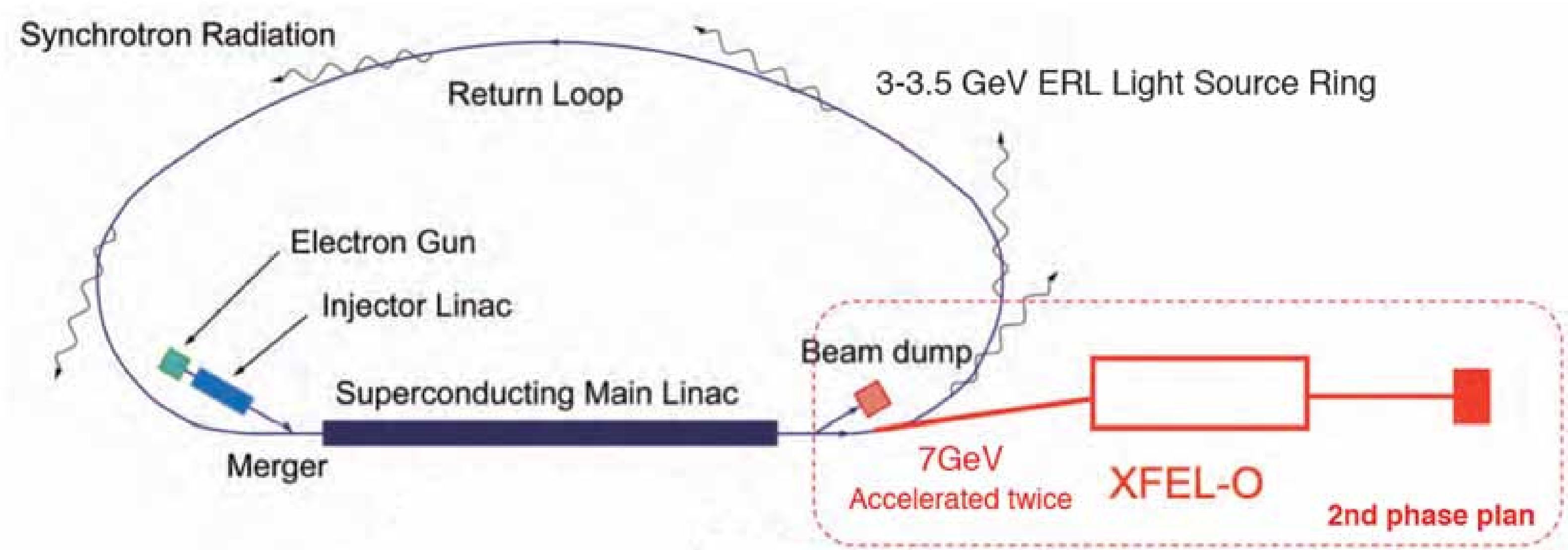
- Studies indicate that a bunch having ~200-300 A pk and an emittance on the order of 20-30 pm-rad will lase at ~ nm in a single pass through a 50-100 m undulator. This peak current might be generated with beam manipulation or with a single injected bunch (see above) and then switched into a bypass to lase. Rep rates could be multi-kHz, limited by kicker rep rate.
- Preliminary studies indicate that partial lasing at a few nm from the unkicked stored beam may be possible. The rep rate would be the bunch frequency.



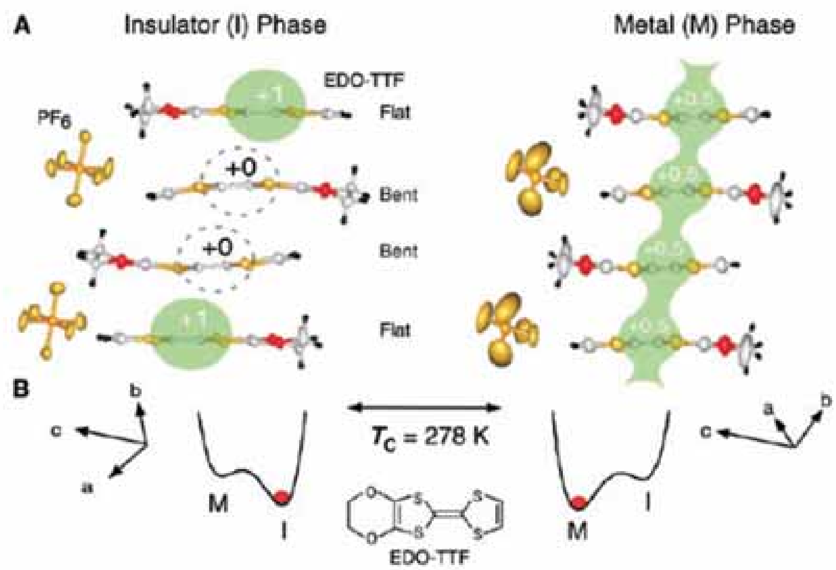
Operating Modes	A High Flux	B High Coherence	C - Short Bunch	
Energy (GeV)	5	5	5	
Current (mA)	100	25	25	
Bunch Charge (pC)	77	19	19	
Repetition Rate (MHz)	1300	1300	1300	
Geom. Emittance (pm) h/v	30	8	120/9	11/9
RMS bunch length (fs)	2000	2000	100	1000
Relative energy spread	0.0002	0.0002	0.002	

Average spectral brightness of 10^{23}
Short pulses of 2 ps (50 fs compressed)
High coherent fraction at 10 keV
Very low electron energy spread which helps long undulator performance

KEK ERL parameters: average spectral brightness of 10^{23}, of 10^{27} in XFELO mode, more numbers on poster



Tickle and Probe 1 (Timing)



photoinduced metallization ~ 1.5ps

Collet et al. Science (2005) 307, 86

dynamics of material = function of material

Taken from
Overview of Energy Recovery Linacs,
talk by Ryoichi Hijima
ERL Development Group,
Japan Atomic Energy Agency,
on 1/29/07 at
Asian Particle Accelerator Conference

Weak photo excitation makes this organic salt material attractive for applications in switching devices with room temperature operation.

Implications for:
electron-lattice interactions
strongly correlated electron systems

Chollet at end of paper “X-ray structural analysis and soft x-ray emission spectroscopy with femtosecond resolution, in addition to theoretical study, will be needed for clarifying the real mechanism of the observed gigantic photoinduced metallization and also will be important for molecular device-oriented research (ref. to Sokolowski-Titan.., Cavalleri.. & Rousse..)”

APAC 2007

Tickle and Probe 2: TRXEOL (Time-Resolved X-ray Excited Optical Luminescence)

Idea of T.K. Sham (U of Western Ontario) & collaborators

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TRXEOL has been shown to be useful for studying light emitting and electronic properties of nano-materials such as ZnO nanowires, pillars, etc. because it provides element and sometimes chemical specificity as well as access to the energy and time domain of the emission process [1].

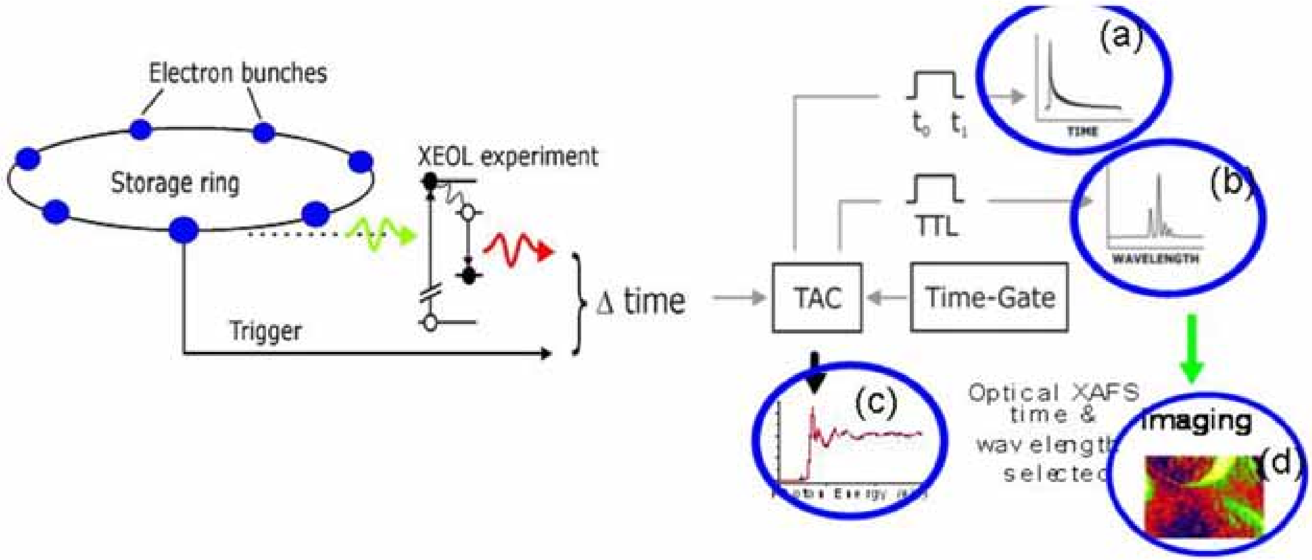

Figure.1 Schematic for TRXEOL measurement at storages rings with conventional optics. (a) lifetime, (b) time-gated XEOL, (c) Time resolved XAFS and (d) optical map

[1] T.K. Sham and Richard A. Rosenberg, ChemPhysChem, 8, 2557-2567 (2007).

0-10 nsec, prompt
50-150 nsec, delayed

APS (80 psec pump)
CLS (60 psec pump)

Going to ERL
0.1 ps – 2 ps pump

Measure luminescence decay in the ps to ns range that was not accessible with 3rd generation light sources

Near band-gap emission is too fast to be tracked by present storage ring pulses while the defect emission can reveal the details about energy transfer important for light emitting and electronic properties of nano-materials involved in energy utilization

Continuous Recording of Shock-wave Powder Diffraction Data at a 25 Nanosecond Frame Rate

by Don Bilderback

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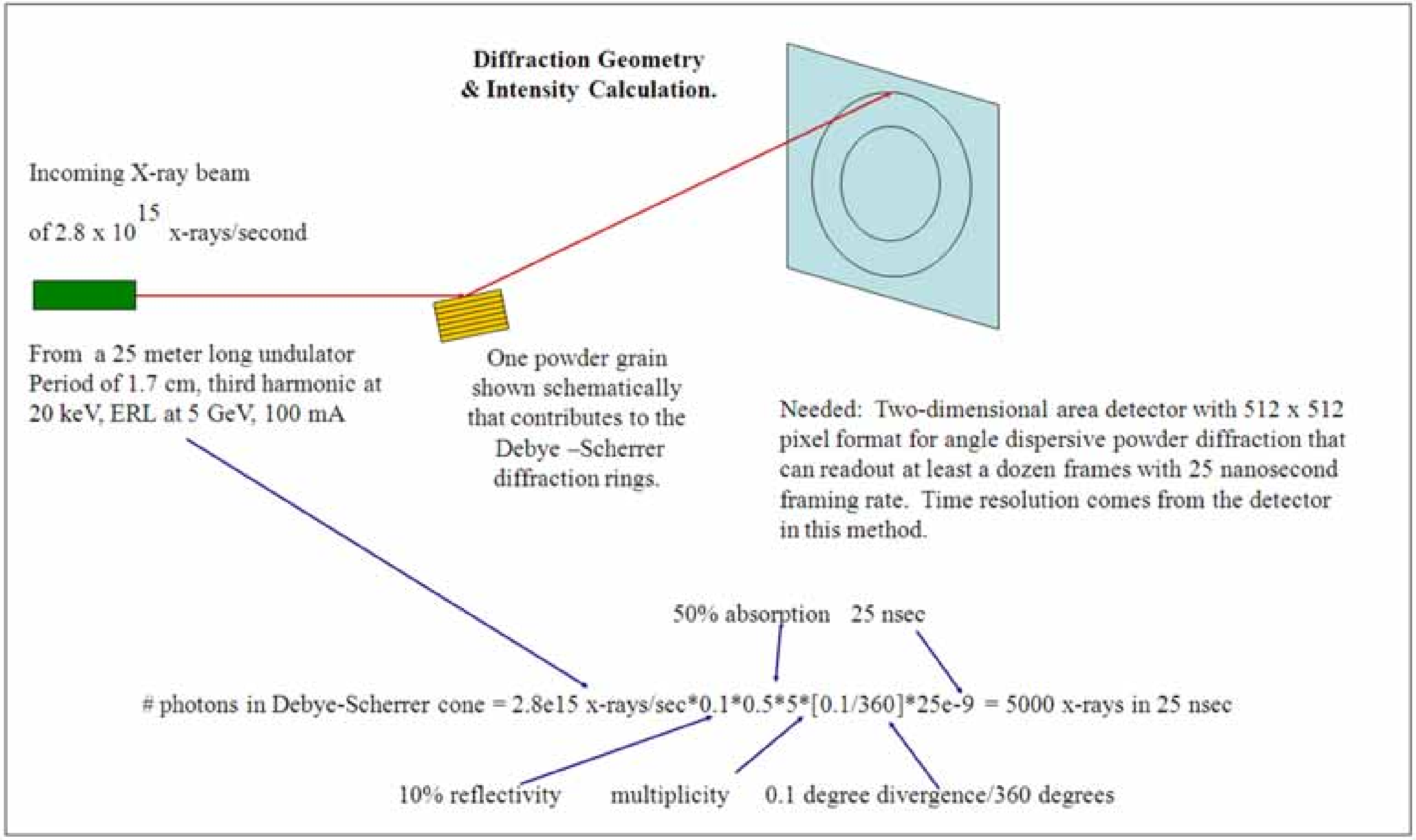

Overview: Shock waves can drive pressures momentarily to higher than center-of-the-earth values. With the ultra-high monochromatic x-ray flux from an ERL source, continuous recording of angle-dispersive powder diffraction with a 25 nsec frame rate seems feasible if the ERL and a suitable x-ray detector can be achieved.

Single-Atom Confocal Microscope Idea by Don Bilderback

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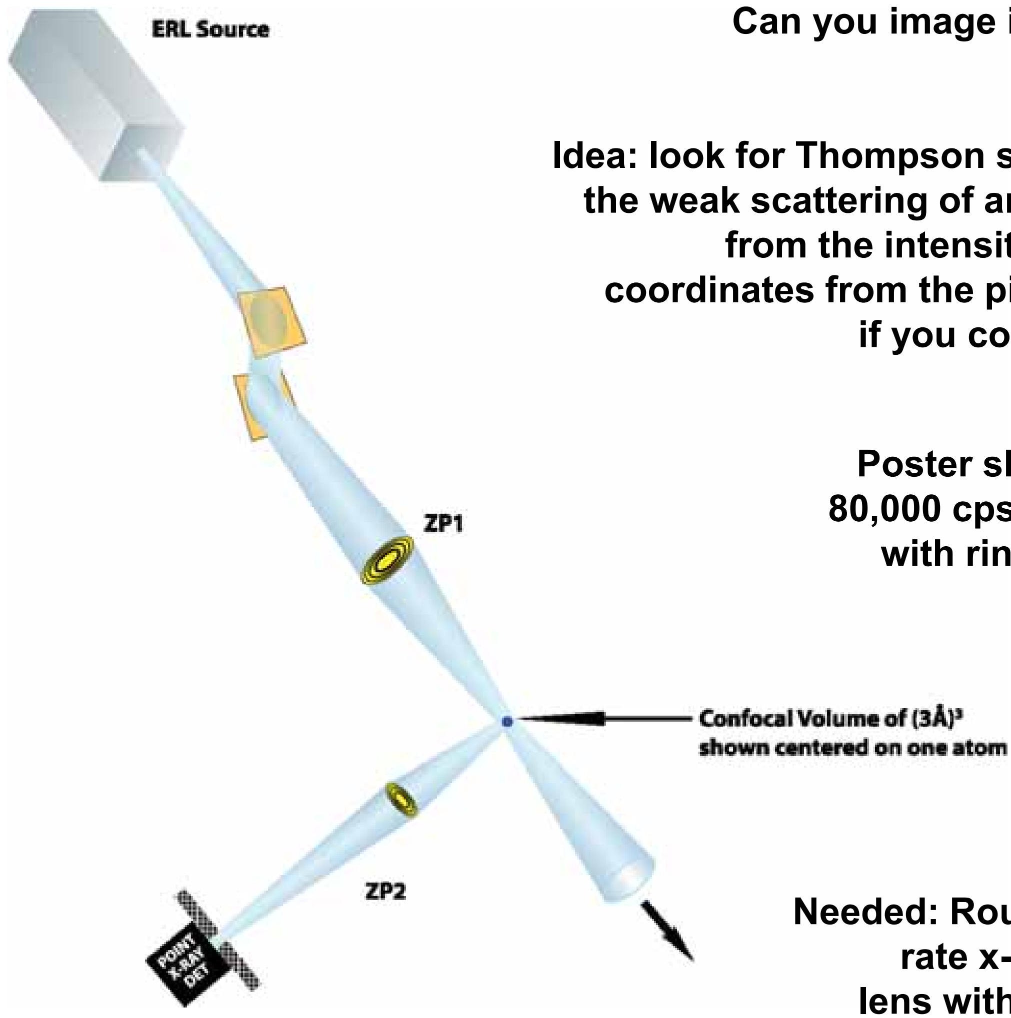

Can you image individual atoms in a nanoparticle with x-rays and "do crystallography" without a crystal?

Idea: look for Thompson scattering, atom-by-atom If you can overcome the weak scattering of an individual atom, you get the z of every atom from the intensity in the confocal volume and you get its x,y,z coordinates from the piezo stage underneath. Could find this useful if you could trace out 1000 atom positions per second

Poster shows possibility of 80 cps from Silicon atom, 80,000 cps from Erbium atom in fluorescence with ERL with ring of optics (not shown) to collect solid angle

Needed: Round source of very small size, high-repetition rate x-ray source, a coherent beam to feed 2d Laue lens with 19 keV x-rays. Very aggressive x-ray optics assumptions. No equipment exists that can do this today.

Confocal x-ray microscope concept with single atom resolution

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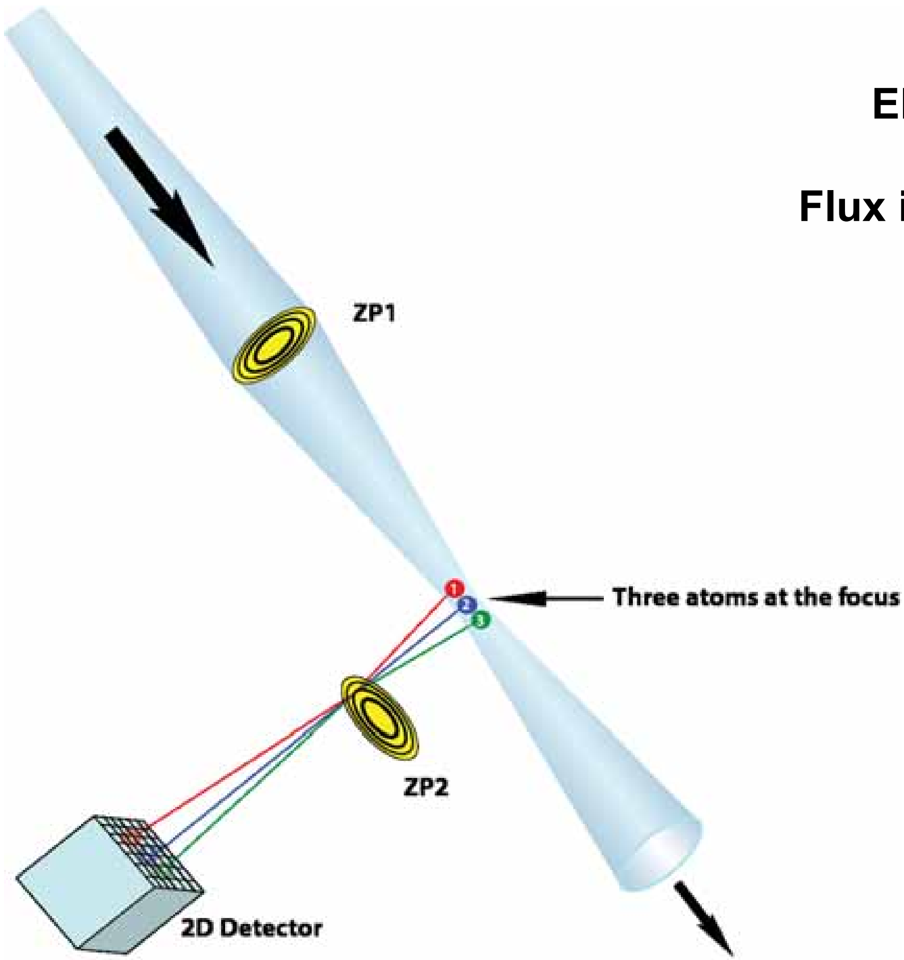

ERL, 5 GeV, 25 mA, hi-coherence mode
Confocal volume = $(3\acute{Å})^3$
Flux in focus ~ $2x10^{11}$ x-rays/sec @ 19 keV

Si sample temperature rise ~ 0.03 K
Only single ionizations expected
at 1300 MHz rep rate

Radiation damage will be an
Important issue and
needs to be studied next

END