Energy recovery linacs

Sverker Werin
MAX-lab

8 July 2003

Energy recovery linacs

Sverker Werin
MAX-lab

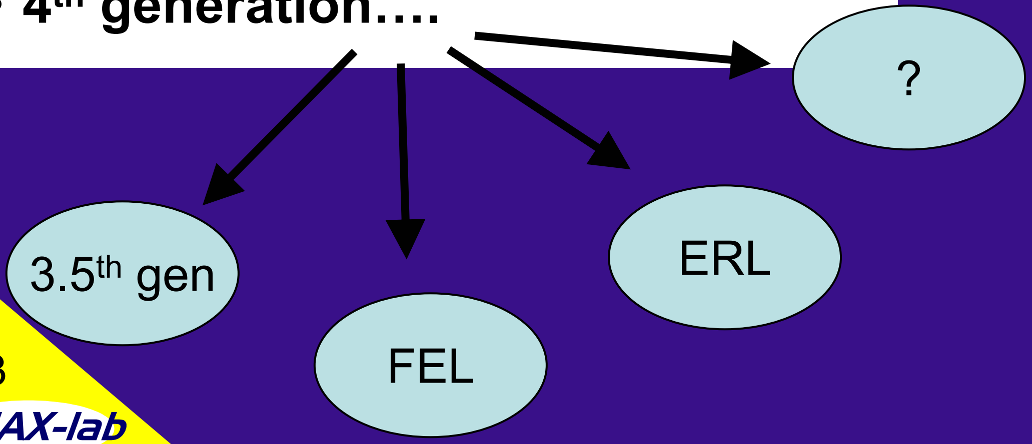
8 July 2003

- Source development
- What is an ERL?
- Quality of radiation
- Special ERL topics
- Instabilities and limitations
- Challenges and development
- ERLs yesterday, today and tomorrow

Path of development

Light sources

- **1st generation**
  parasitic SR on high energy physics storage rings
- **2nd generation**
  dedicated bending magnet sources
- **3rd generation**
  dedicated undulator sources
- **4th generation….**



Have today

- Repetition rate
- Stability
- Tunability
- Polarisation
- Brilliance – average/peak

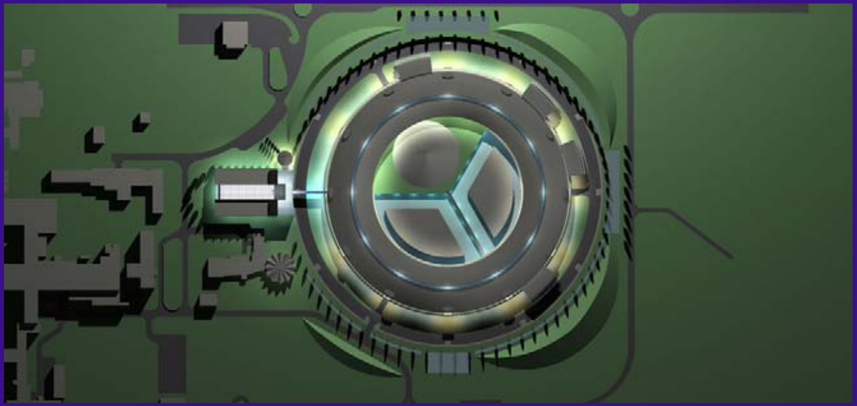
Need in the future

- Coherence
- Power
- Fs pulses
- Diffraction limited radiation
- Brilliance – average/peak

S. Werin

3.5 generation storage ring

SOLEIL SYNCHROTRON



diamond

Gives us

- Coherence
- Power
- Pulse slicing → fs pulses
- Some diffraction limited radiation
- Brilliance – average/peak

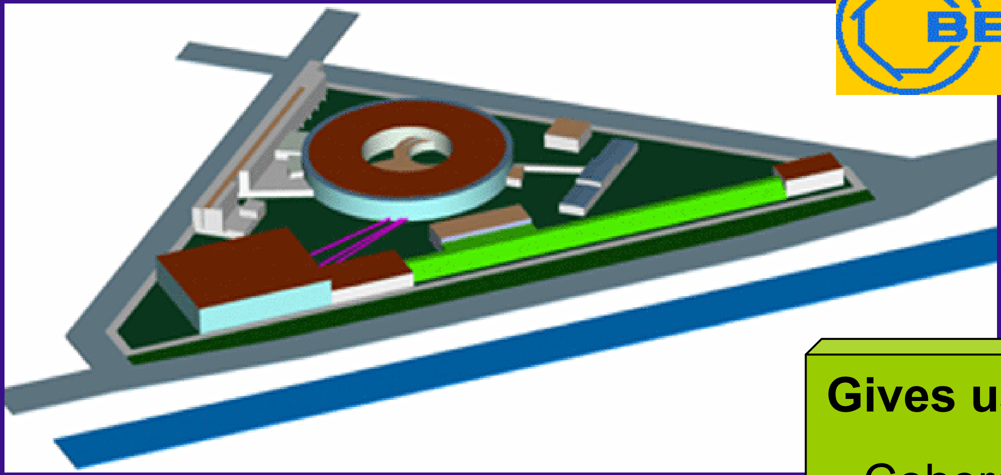
http://www.soleil.u-psud.fr

http://www.diamond.ac.uk

MAX-lab

S. Werin

Free electron laser



Gives us

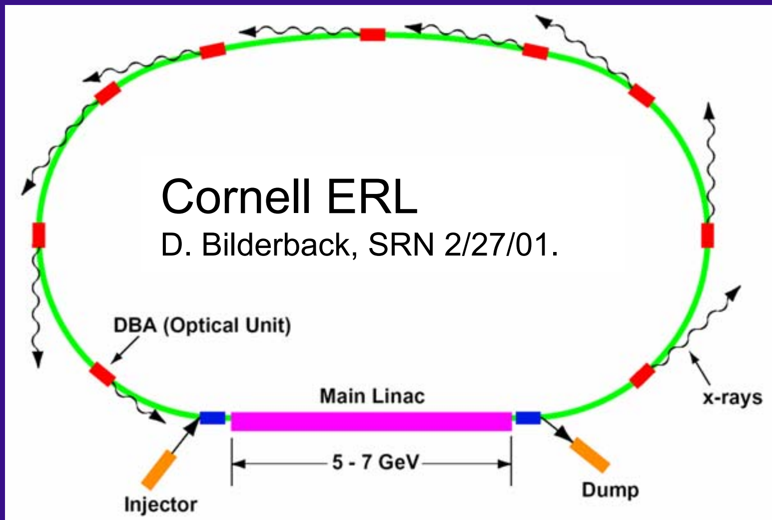
- Coherence
- Power
- Fs pulses
- Diffraction limited radiation
- Brilliance – average/peak
- Low repetition rate

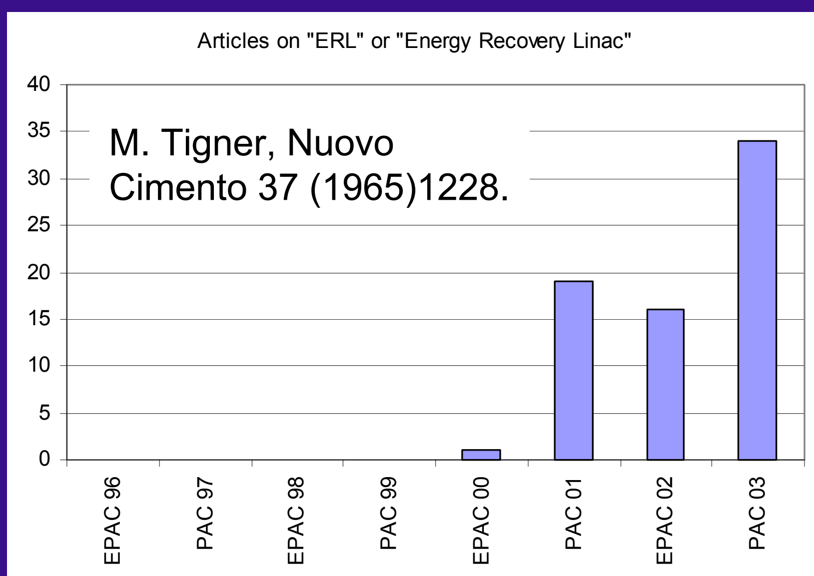
http://www.bessy.de/publications/01.felscientific/sc.html

MAX-lab

S. Werin

Energy Recovery Linac

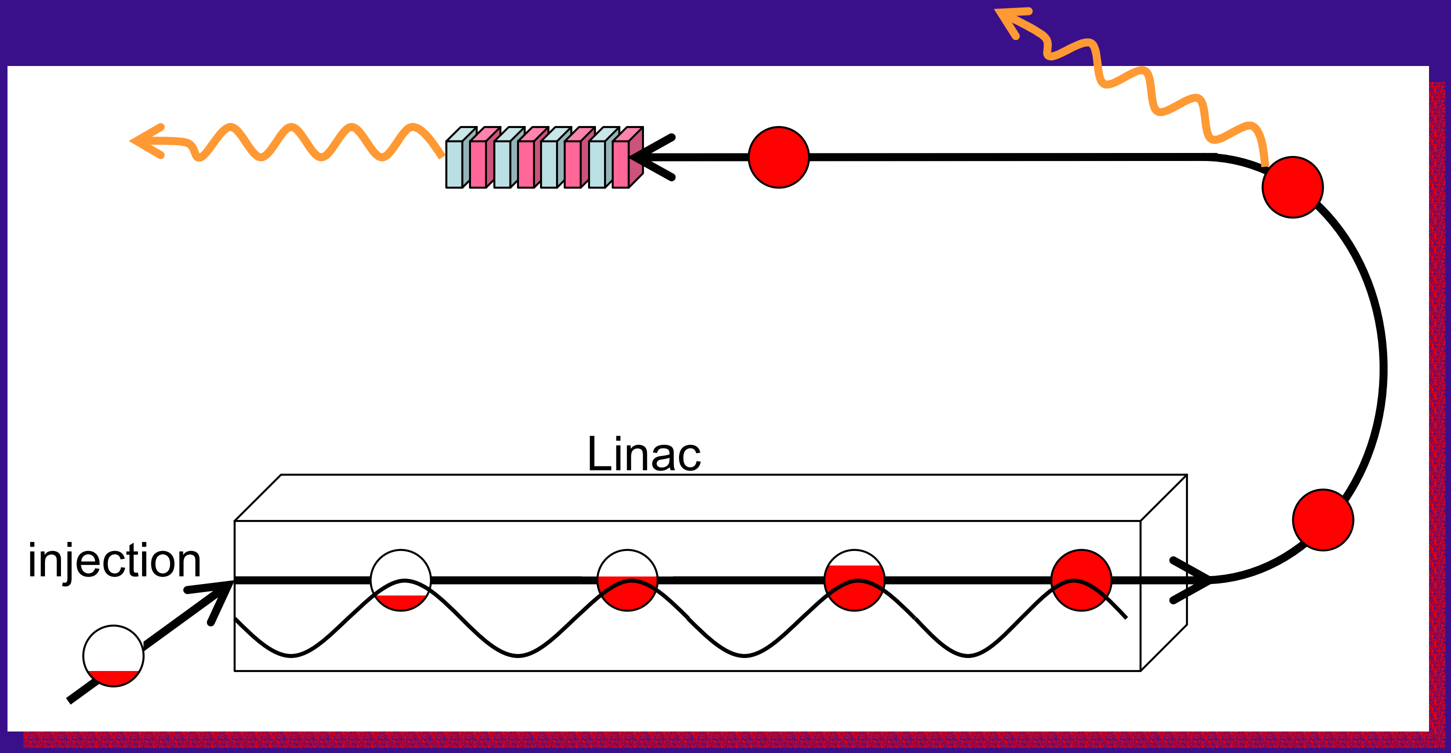




Gives us

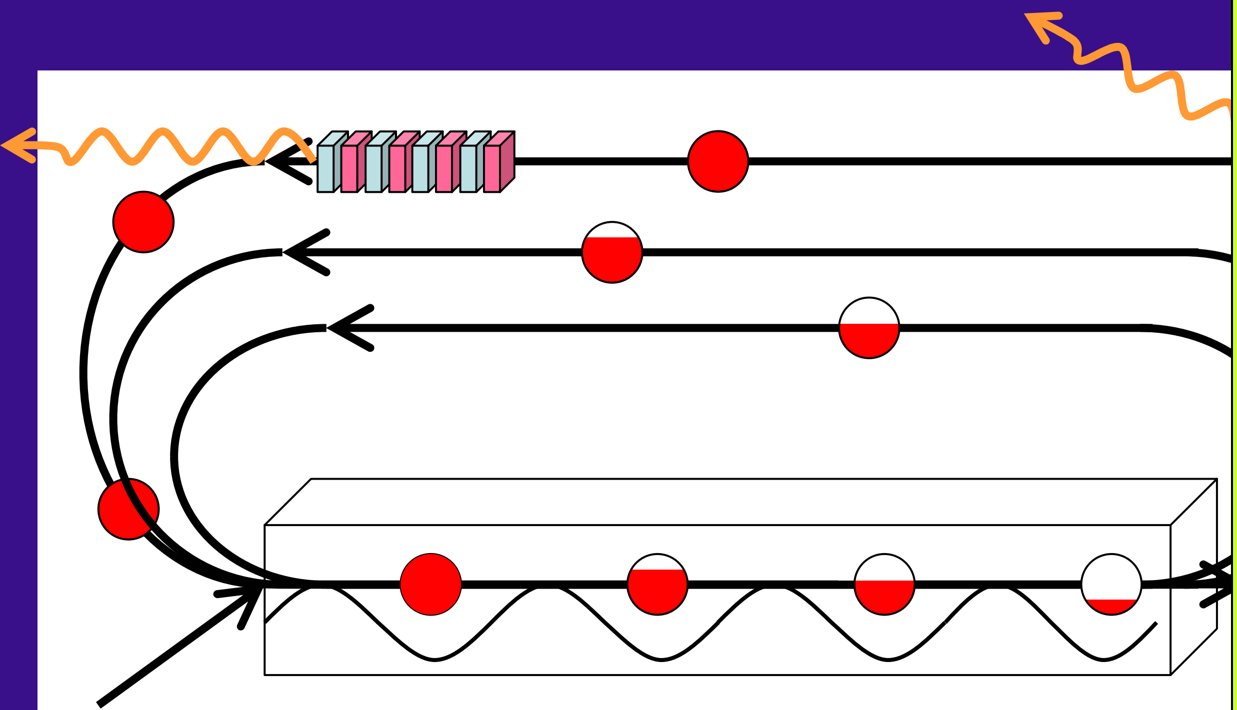
- Coherence
- Power
- Fs pulses
- +Diffraction limited radiation
- Brilliance – average/peak
- Medium repetition rate

What is an ERL?



MAX-lab
S. Werin

What is an ERL? Step 2



Opposite phase

Deceleration→

Energy given back to linac structure and stored there

- Emittance defined by source/gun (not ring equilibrium)

  <=0.1 nmRad

- Brilliance >= storage rings
- Pulse length small (not ring equilibrium)

  < 100 fs

- SC linac – save RF power, independent of current
- CW operation (gun limit)

  KHz-MHz

- Low dump energy, less radioactivity

  <10 MeV

MAX-lab
S. Werin

Linac power

$$P_{wall} = \frac{\hat{E}\, L}{Z_s}$$

Shunt impedance

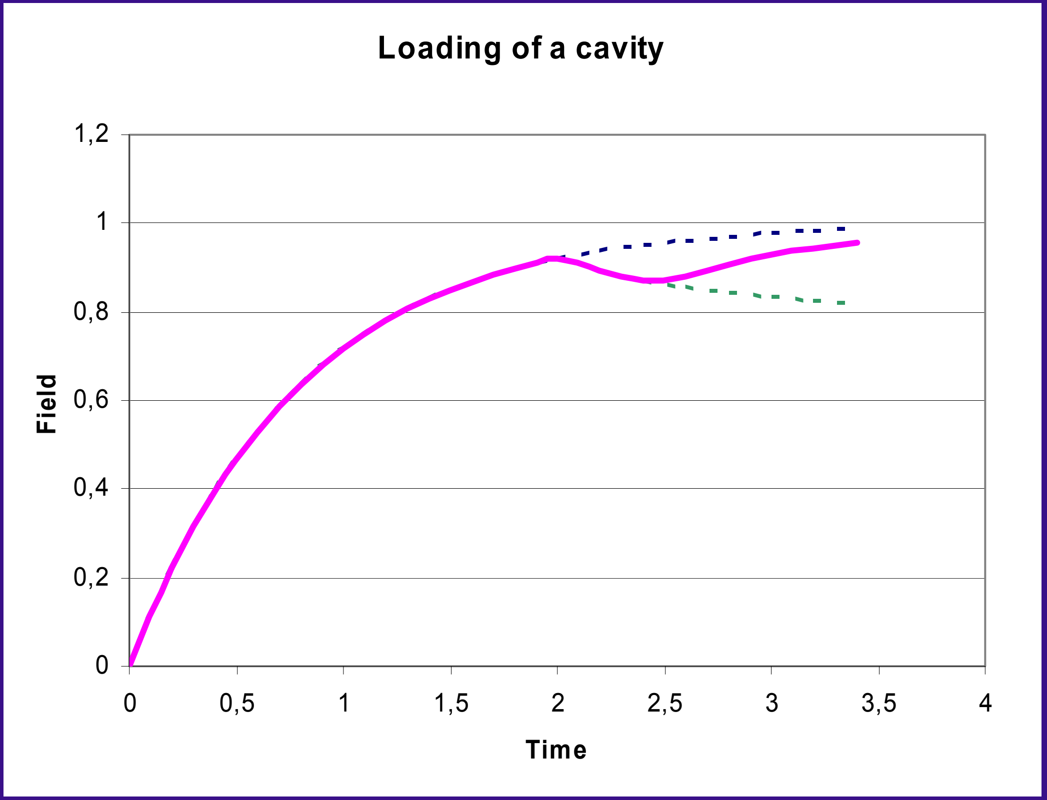
$$W = \frac{Q\, P_{wall}}{\omega}$$

Q-value

$$E = E_0\left(1 - e^{-\frac{\omega t}{Q}}\right)$$

$Q_{NC} \sim 1*10^4$

$Q_{SC-TESLA} \sim 3*10^9$



MAX-lab
S. Werin

Brilliance

$$Flux = \frac{photons}{s * 0.1\%BW * A}$$

$$Brilliance = \frac{Flux}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

$$\Sigma_x = \sqrt{\sigma_x^2 + \sigma_r^2}$$

$$\Sigma_{x'} = \sqrt{\sigma_{x'}^2 + \sigma_{r'}^2}$$

What counts

To compare

Peak brilliance

During the peak of a bunch

Average brilliance

Forever or during a macro pulse from the accelerator

MAX-lab
S. Werin

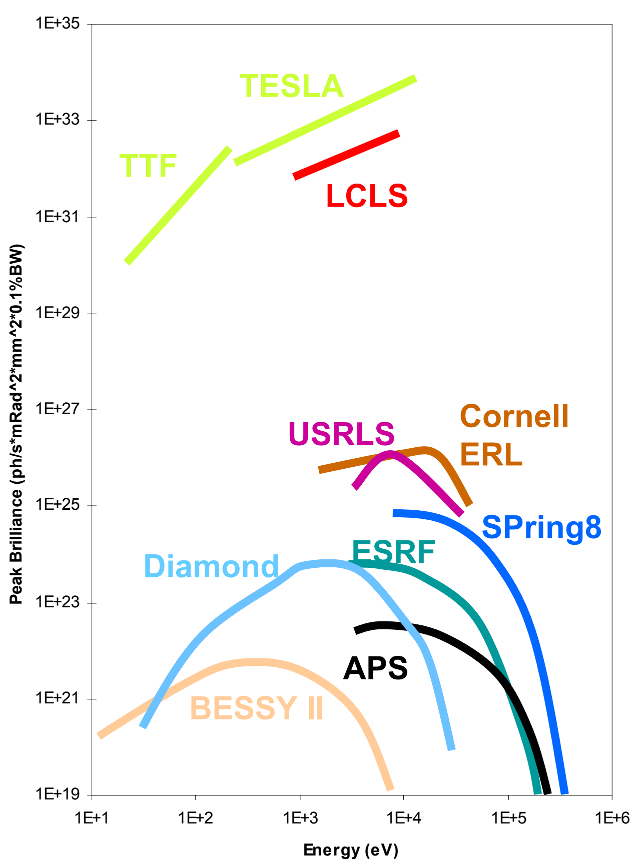
Brilliance

$$Brilliance = \frac{Flux}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

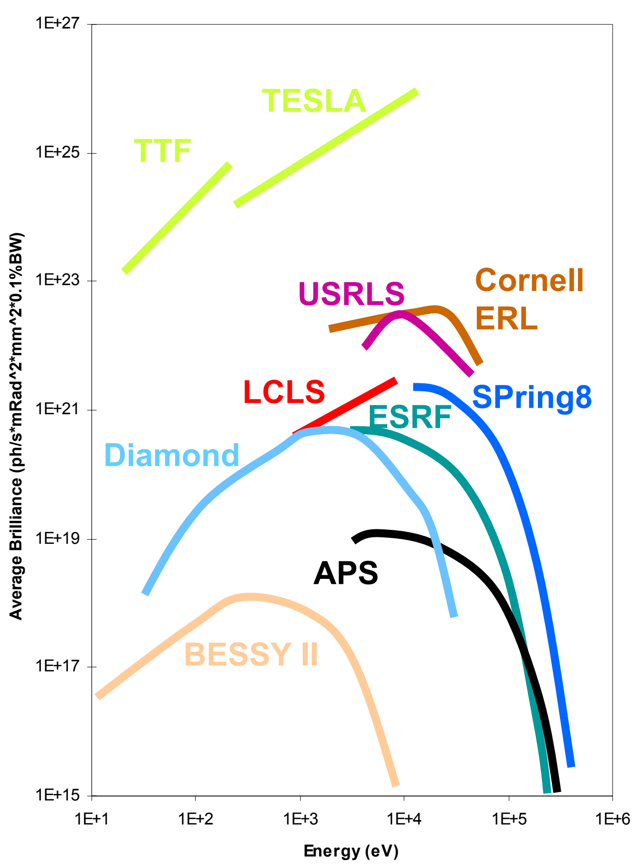
$$\Sigma_x = \sqrt{\sigma_x^2 + \sigma_r^2}$$

$$\Sigma_{x'} = \sqrt{\sigma_{x'}^2 + \sigma_{r'}^2}$$

Peak brilliance



Average brilliance



MAX-lab

S. Werin

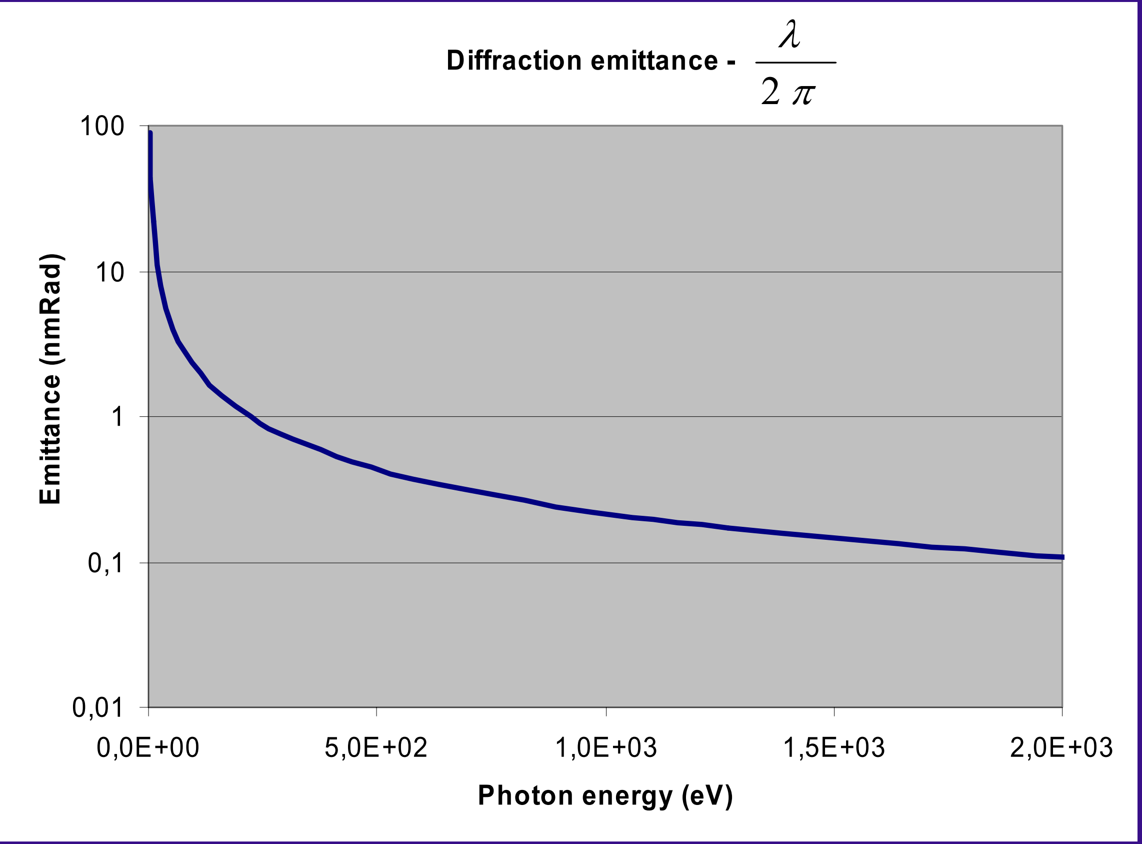
Diffraction limit

$$Brilliance = \frac{Flux}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

$$\Sigma_x = \sqrt{\sigma_x^2 + \sigma_r^2}$$

$$\Sigma_{x'} = \sqrt{\sigma_{x'}^2 + \sigma_{r'}^2}$$

$$\varepsilon = \sigma_r \sigma_{r'}$$



MAX-lab
S. Werin

Emittance comparison

Horisontal emittance

Ring

$$Emittance \propto \frac{\gamma^2}{periodicity^3}$$

ERL/Linac

$$Emittance \propto \frac{1}{\gamma}$$

Vertical emittance

Ring

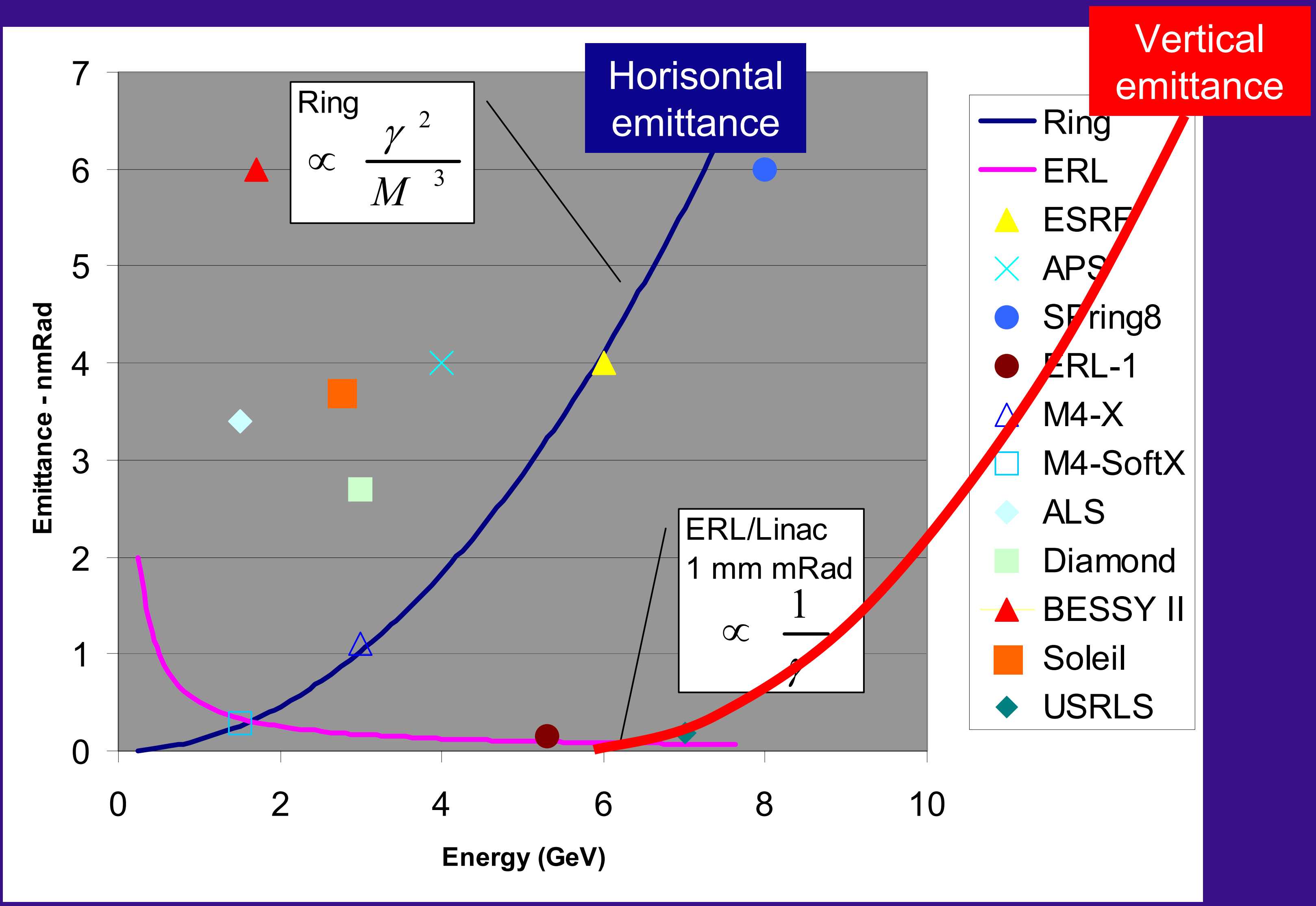
$\varepsilon_{vert} \approx 0.05\ \varepsilon_{hor}$

ERL

$\varepsilon_{vert} = \varepsilon_{hor}$

MAX-lab
S. Werin

Emittance comparison



MAX-lab
S. Werin

Pulse length

Storage ring	10 ps	Lifetime sacrifice
+ bunch slicing	50 fs	Low flux, simple
Linac (FEL, ERL)	**~ 20 fs**	Photo cathode laser, space charge, CSR (coherent synch.rad.), slippage

MAX-lab
S. Werin

Quick duty

Discuss with your neighbour

Please talk!

A 20 fs electron bunch passes a 100 period long undulator producing radiation at a wavelength of 60 nm.

How long is the radiation pulse?

The radiation from one e^- consists of a wave train with 100 periods at 60 nm ➔ 100*60 nm = $6*10^{-6}$ m

The length in time is $6*10^{-6}/c = 6*10^{-6}/3*10^{8}$ = 20 fs

Add the pulse length
and the total length will be 20 + 20 = 40 fs

MAX-lab

15 30 45 60

Energy savings …?

A 100 mA 5 GeV electron beam carries 500 MW power.

Stornorrfors powerstation

591 MW @ 1000 m^3/s

Save energy!

MAX-lab

S. Werin

Energy savings → go superconducting

LBL LUX proposal

600 MeV linac – 4 recirculations

10 KHz

	NC	SC
RF-power peak	240 MW	0.288 MW
RF-power average		
Cooling power		

MAX-lab

S. Werin

Energy savings (nasty version)

Cornell ERL2 - 5 GeV 100 mA

v.

ESRF - 5 GeV 200 mA

	Cornell	ESRF
RF-power peak	1.1 MW	2.6 MW
RF-power average	1.1 MW	2.6 MW
Cooling power	16.4 MW	0
	17.5 MW	2.6 MW

MAX-lab
S. Werin

Radiation savings …?

Dump beam powers

100 mA
5 GeV

ERL

Recovery
Dump @ 10 MeV
1 MW

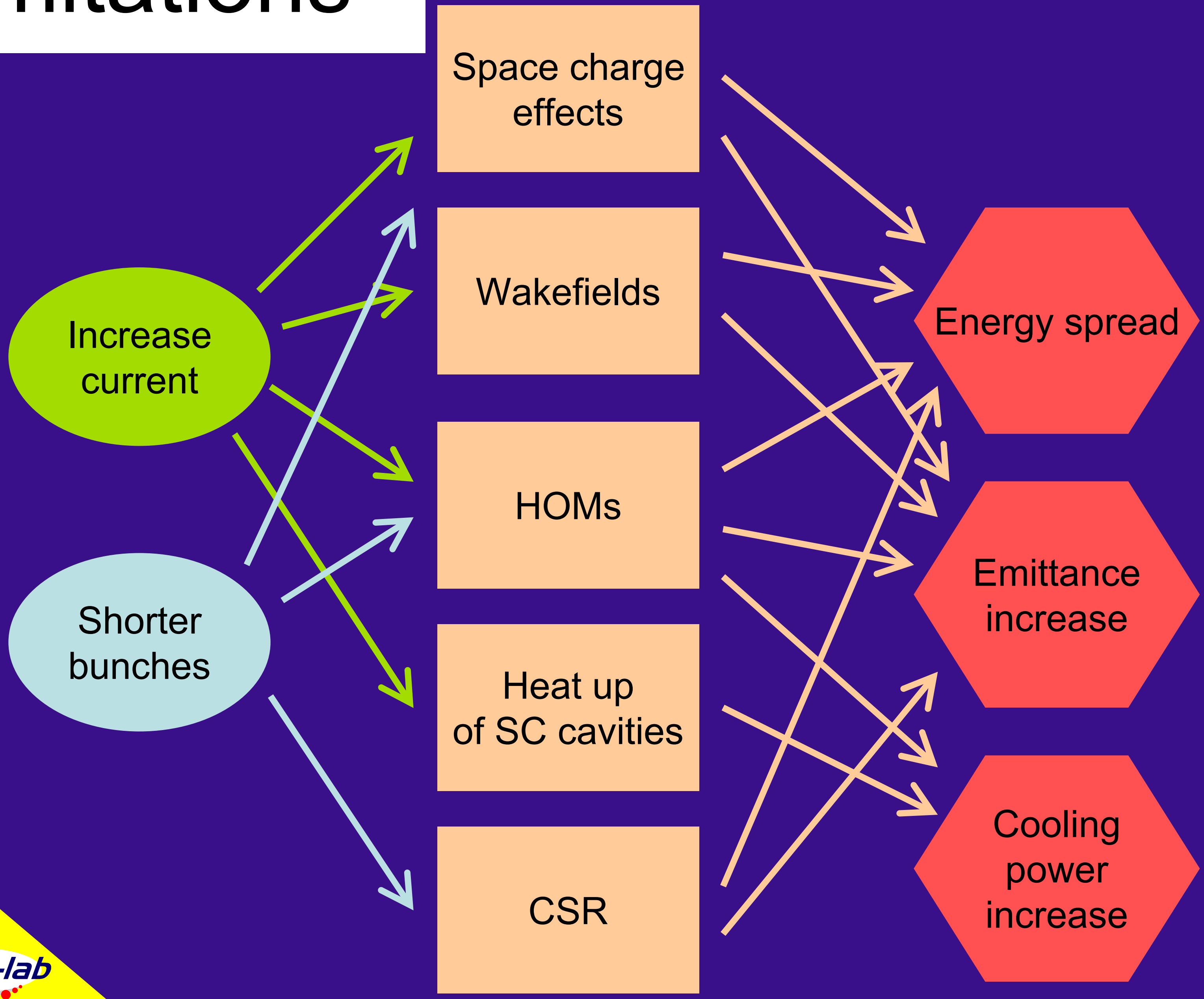
Much less neutron production

linac

NO recovery
Dump @ 5 GeV
500 MW

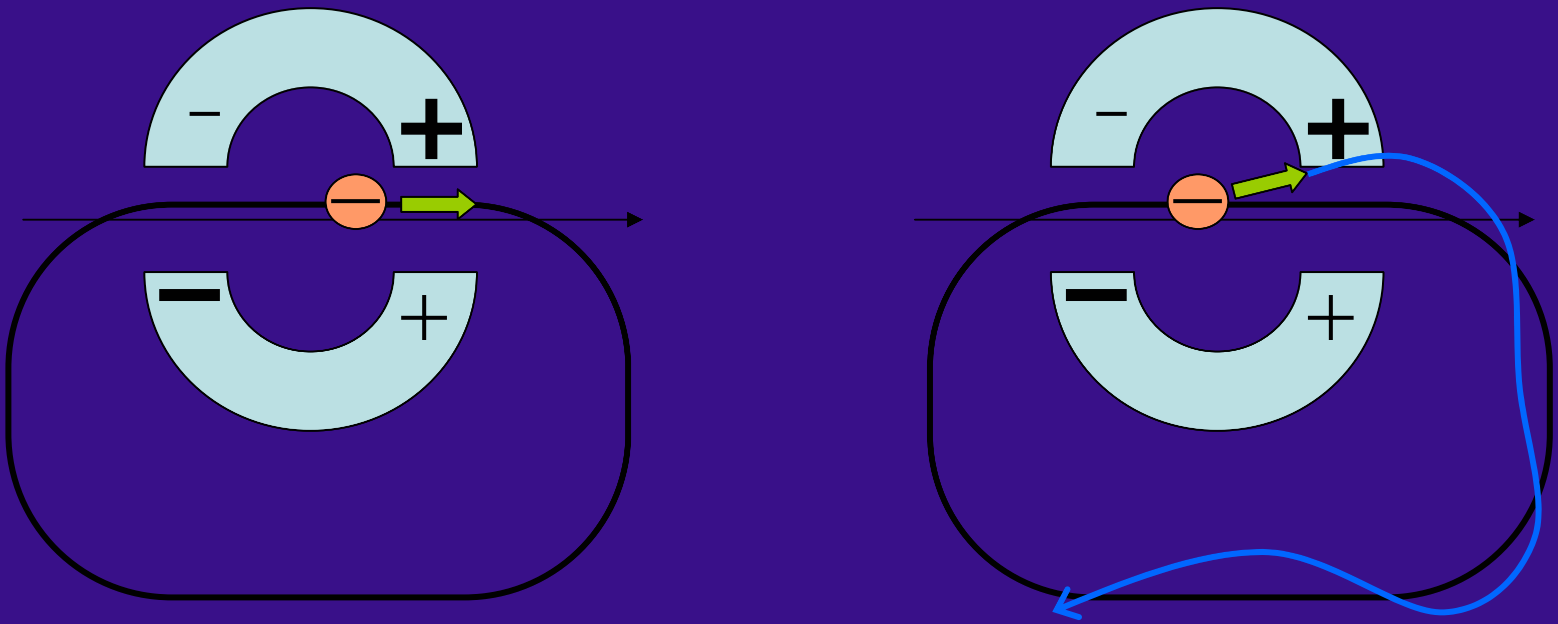
ESRF
200 mA, 5 GeV
24 hours, c 850 m
31 mW

Limitations



MAX-lab
S. Werin

Beam Break Up (BBU)



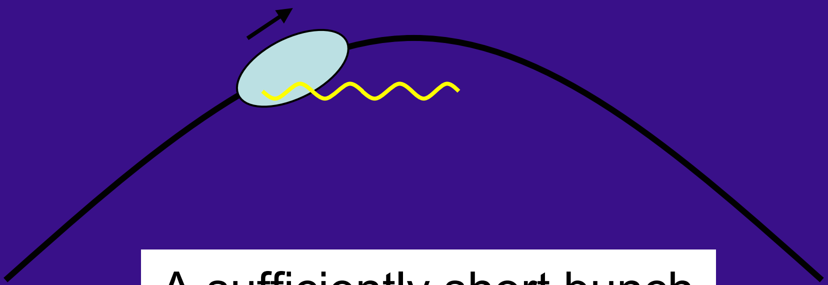
Displacement of the bunch due to transverse wakefields induced by a previous bunch beeing off center.

Damp modes

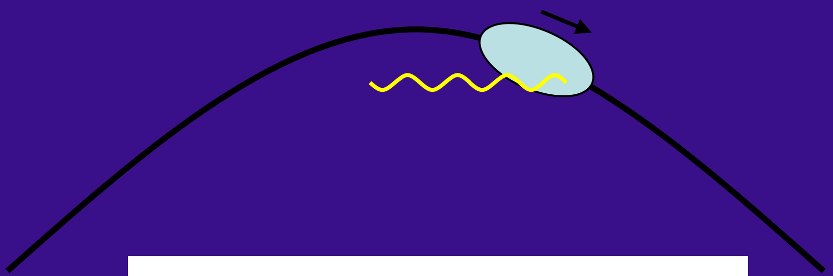
Good alignment

MAX-lab
S. Werin

Coherent Synchrotron Radiation



A sufficiently short bunch will radiate coherently.



The radiation from the tail can irradiate the head of the bunch.

$\rightarrow$ Energy spread

$\rightarrow$ Emittance growth if dispersion

Cure:

Longer bunches, less current ☹

Shielding, larger radius ☺

S. Werin

Challenges

Guns	▶ CW
Optics in arcs	▶ Multi energy, CSR
Control of RF	▶ The beam ”runs” the RF
Beam loss	▶ Messes up RF
Instabilities (BBU…)	▶ Limits current
HOM cooling	▶ More power to SC cooling

Around the world

1960

M. Tigner, Nuovo Cimento 37 (1965)1228.

1970

MUSL Univ of Illinois, 1977

1980

SCA, Stanford, 1986

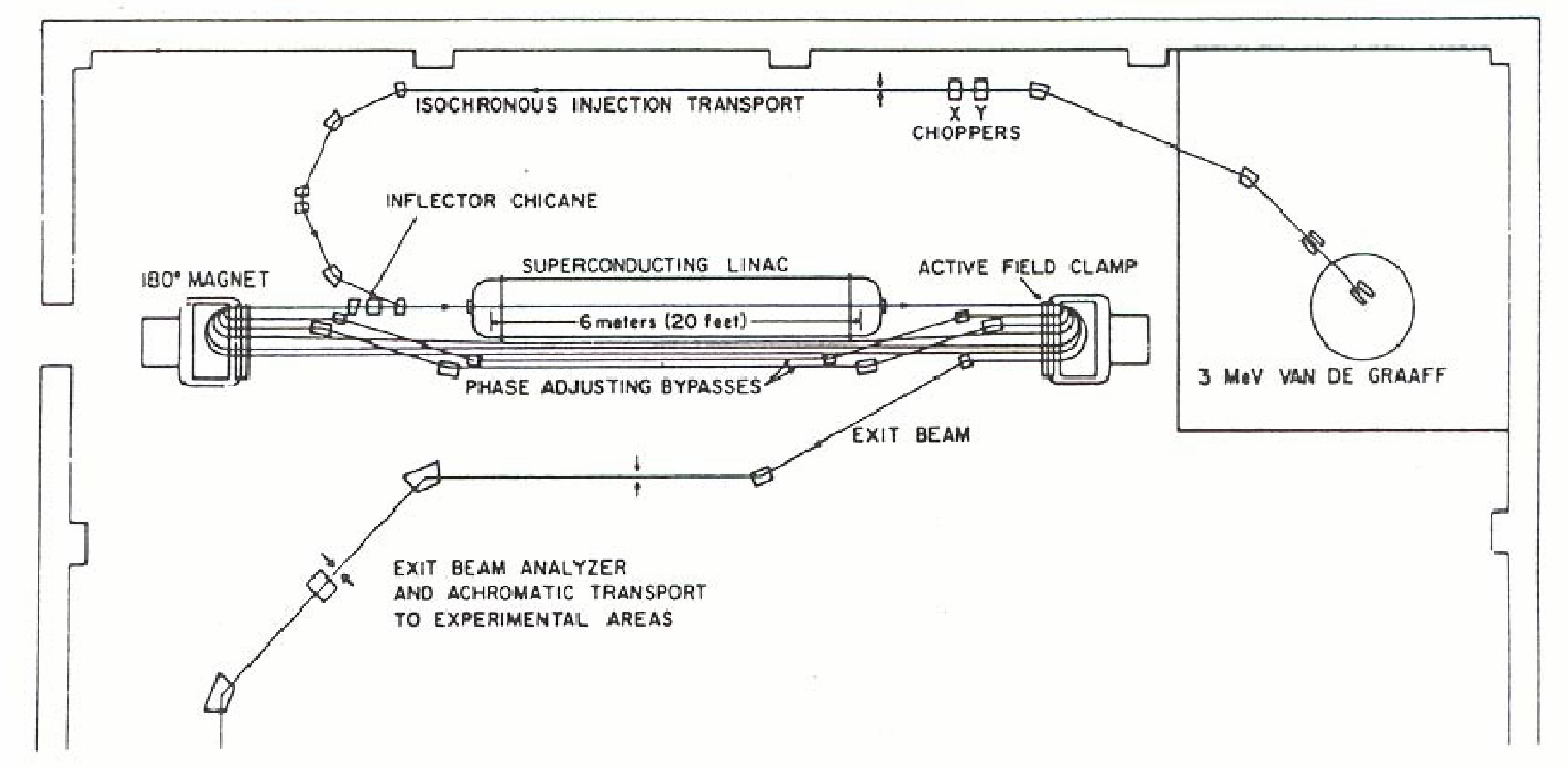
1990

S-DALINAC, 1990
CEBAF, 1995
IR FEL Jlab, 1999
JAERI, 2002

2000

LUX (LBL)
Cornell
PERL (NSLS)
4 GLS (Daresbury)
ERLSYN (Erlangen)
KEK
…

MUSL-2 – Univ. Of Illinois

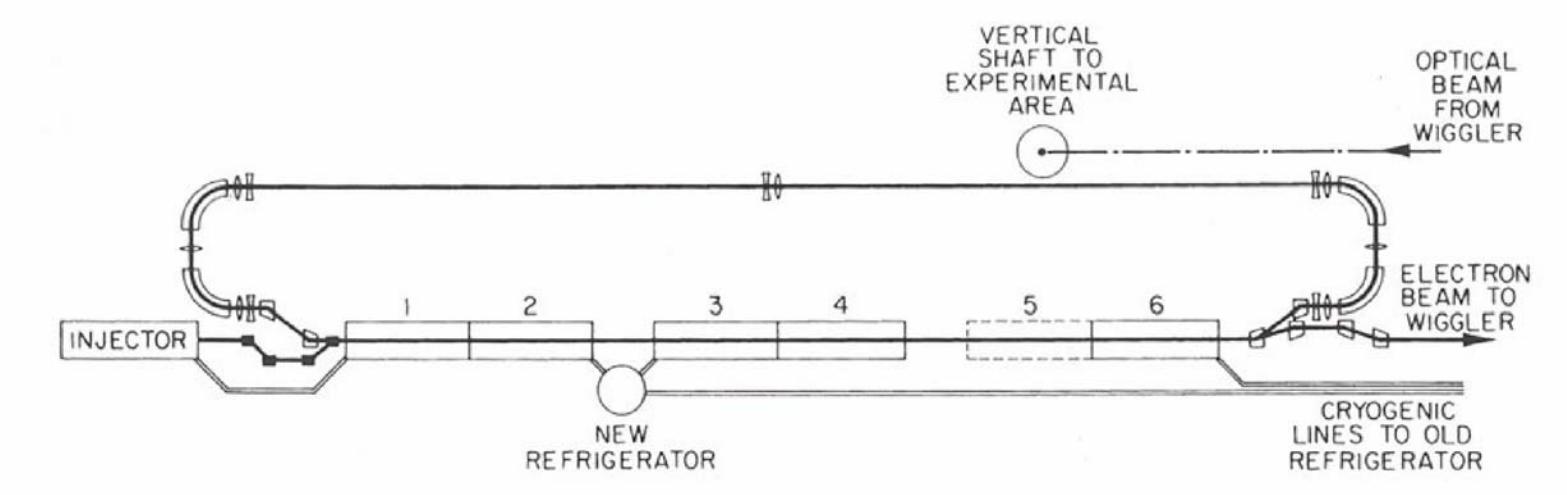


Stanford SCA

First energy recovery

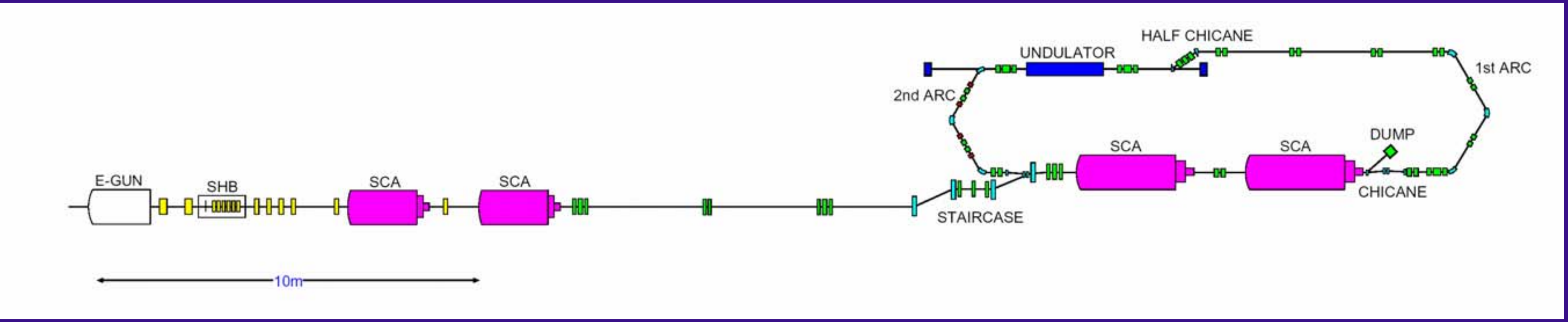
T.I. Smith, et al, NIM A 259 (1987) 1-7

50 MeV



MAX-lab
S. Werin

JAERI – ERL + FEL



17 MeV

5 mA

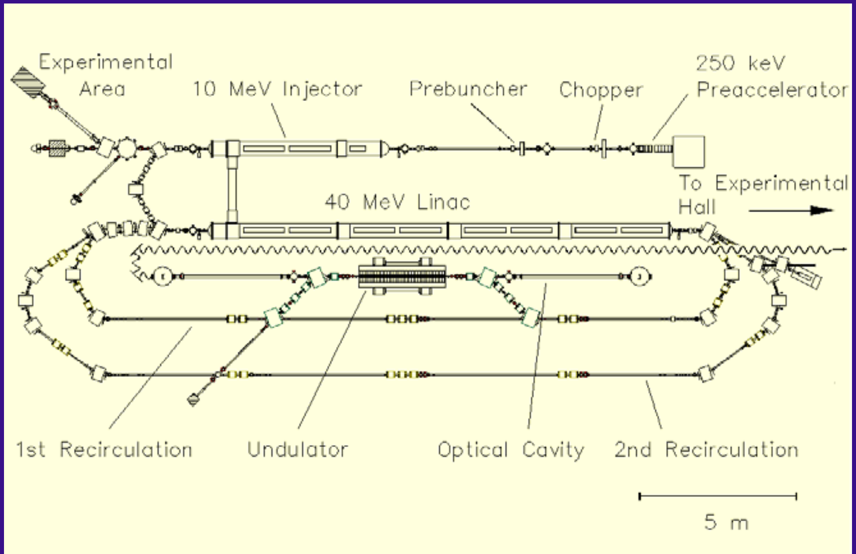
In operation

N. Nishimori et.al., EPAC 2002, Paris

MAX-lab

S. Werin

S-DALINAC - Darmstadt

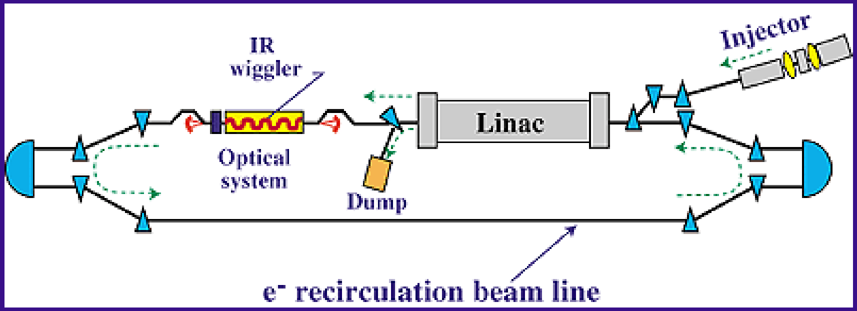


130 MeV

http://linac.ikp.physik.tu-darmstadt.de/linac/introduction.html

Jlab FEL

Jefferson Lab
Newport News, VA

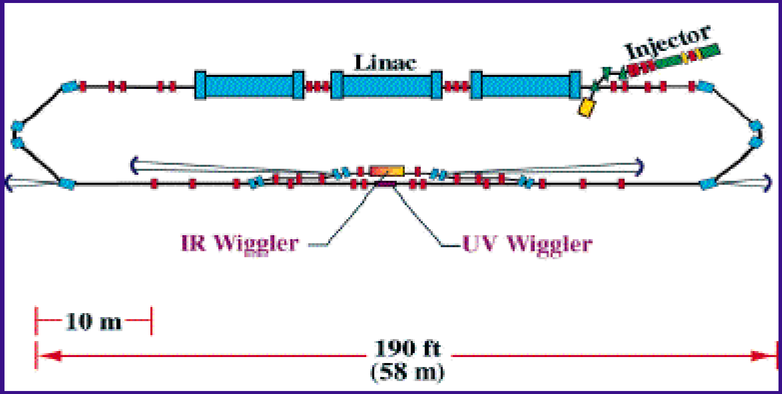


IR Demo FEL

In operation since 1999

40 MeV

5 mA



FEL upgrade

2003 -

160 MeV

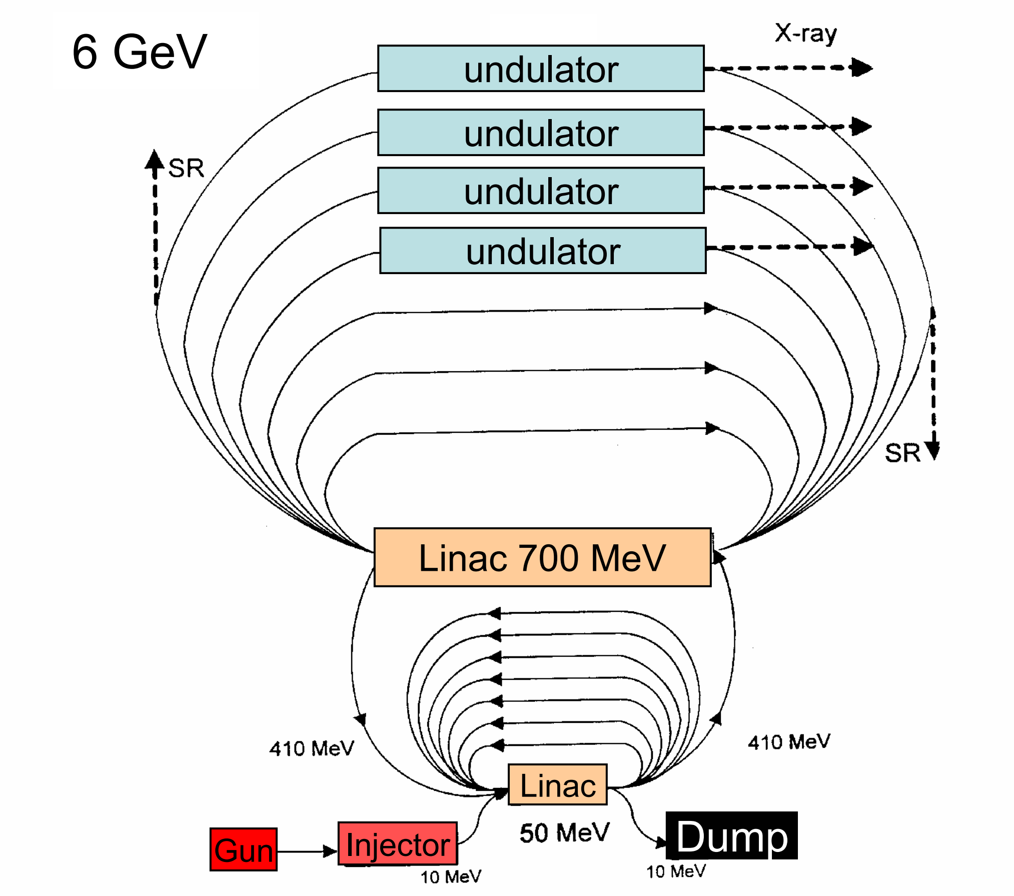
10 mA

http://www.jlab.org/FEL/feldescrip.html

MARS

Multipass
Accelerator
Recuperator
Source

Novosibirsk



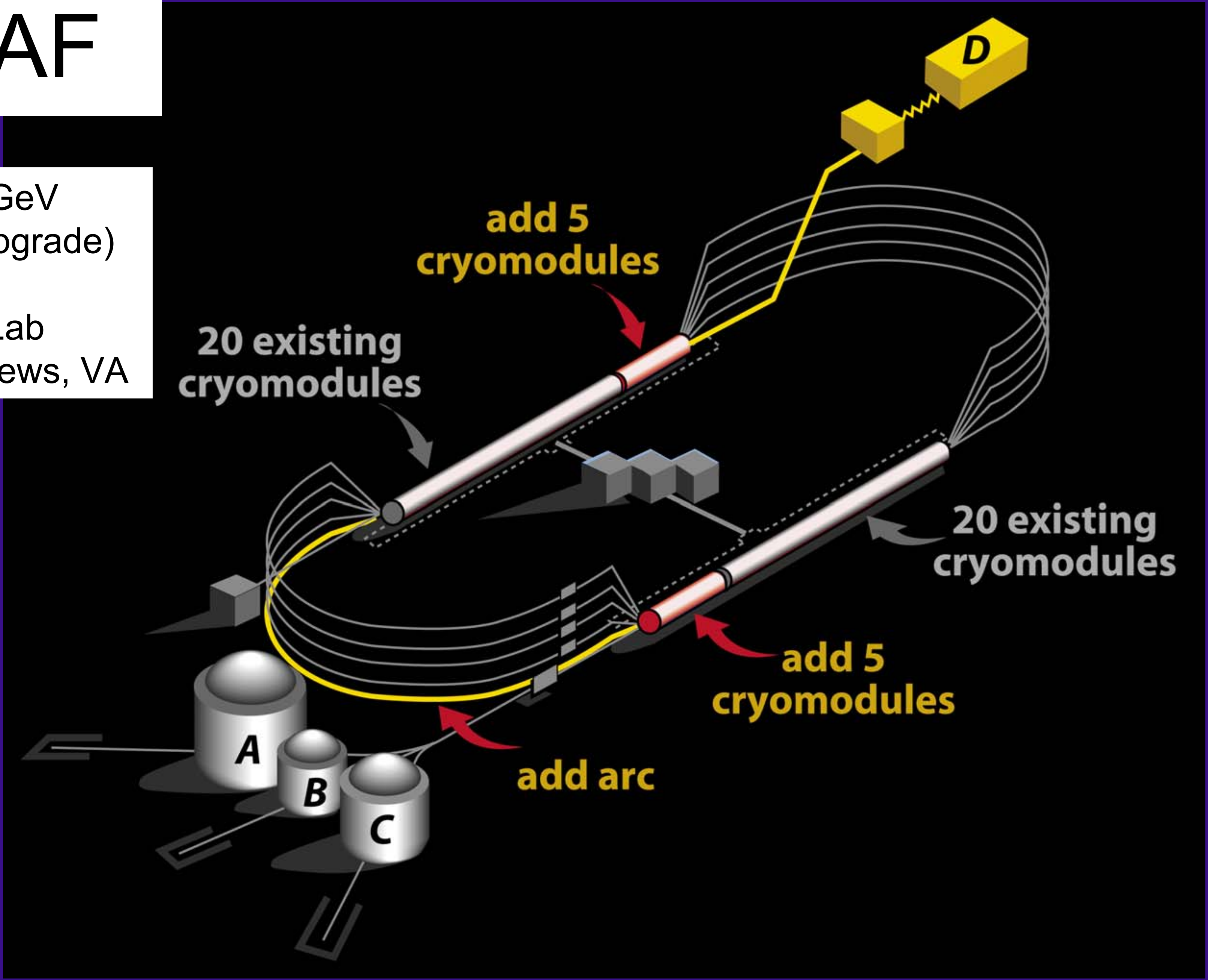
G. Kulipanov et.al. SRI 2001, ERL workshop

MAX-lab
S. Werin

CEBAF

CEBAF 6 GeV
(12 GeV upgrade)

Jefferson Lab
Newport News, VA

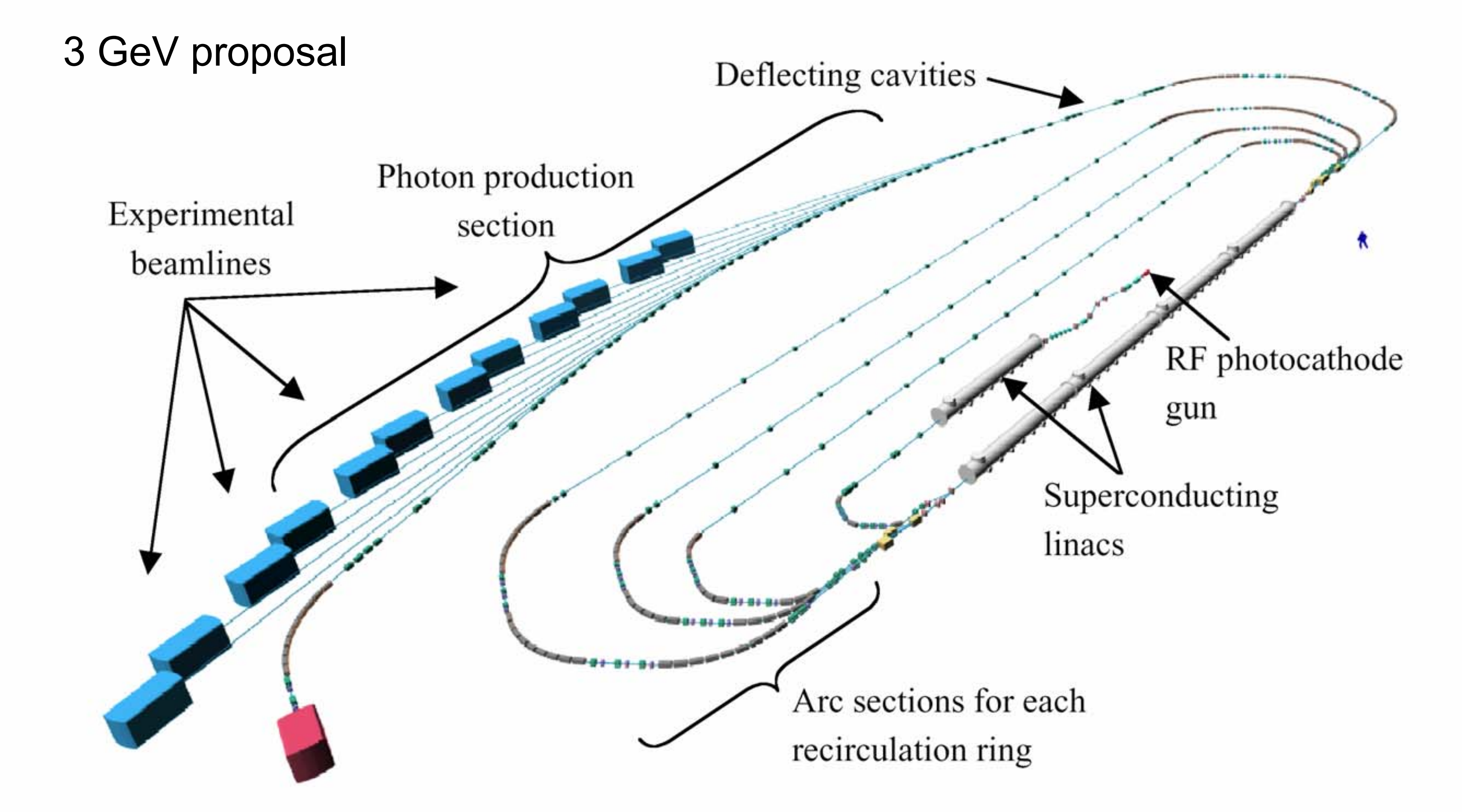


http://www1.jlab.org/ul/jpix/high/upgrade_187.jpg

LUX - LBL

Multi-user facility proposal

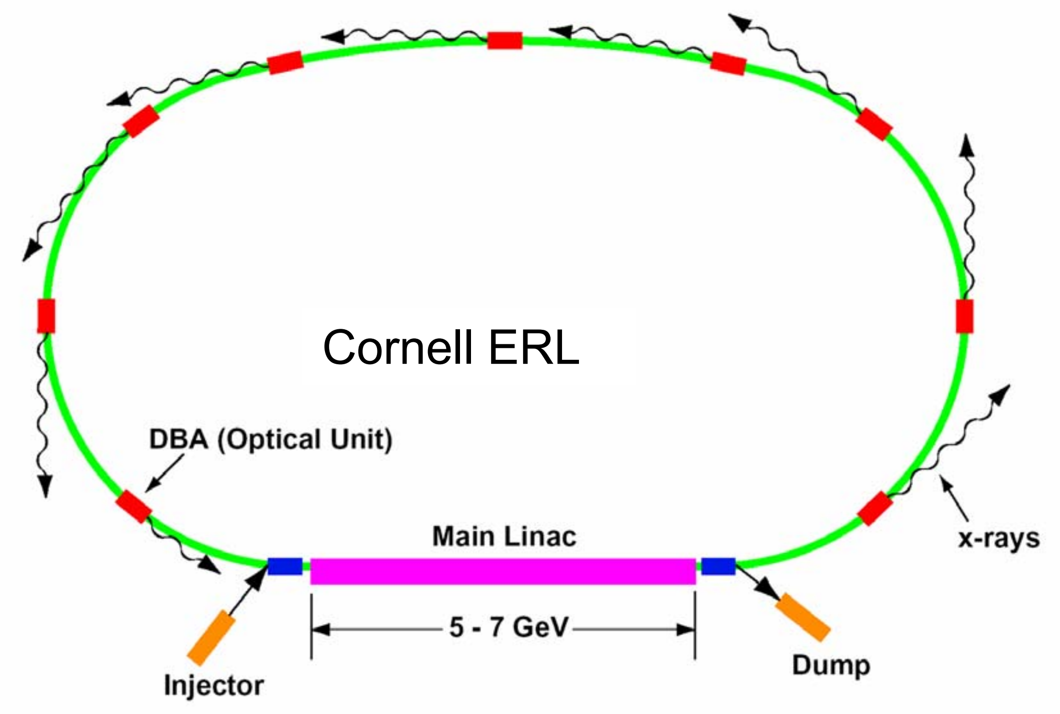
Repetition rate	10 kHz
Pulse length	< 100 fs
Current	10 μA



http://jncorlett.lbl.gov/FsX-raySource/

MAX-lab
S. Werin

Cornell-Jefferson ERL



Proposal

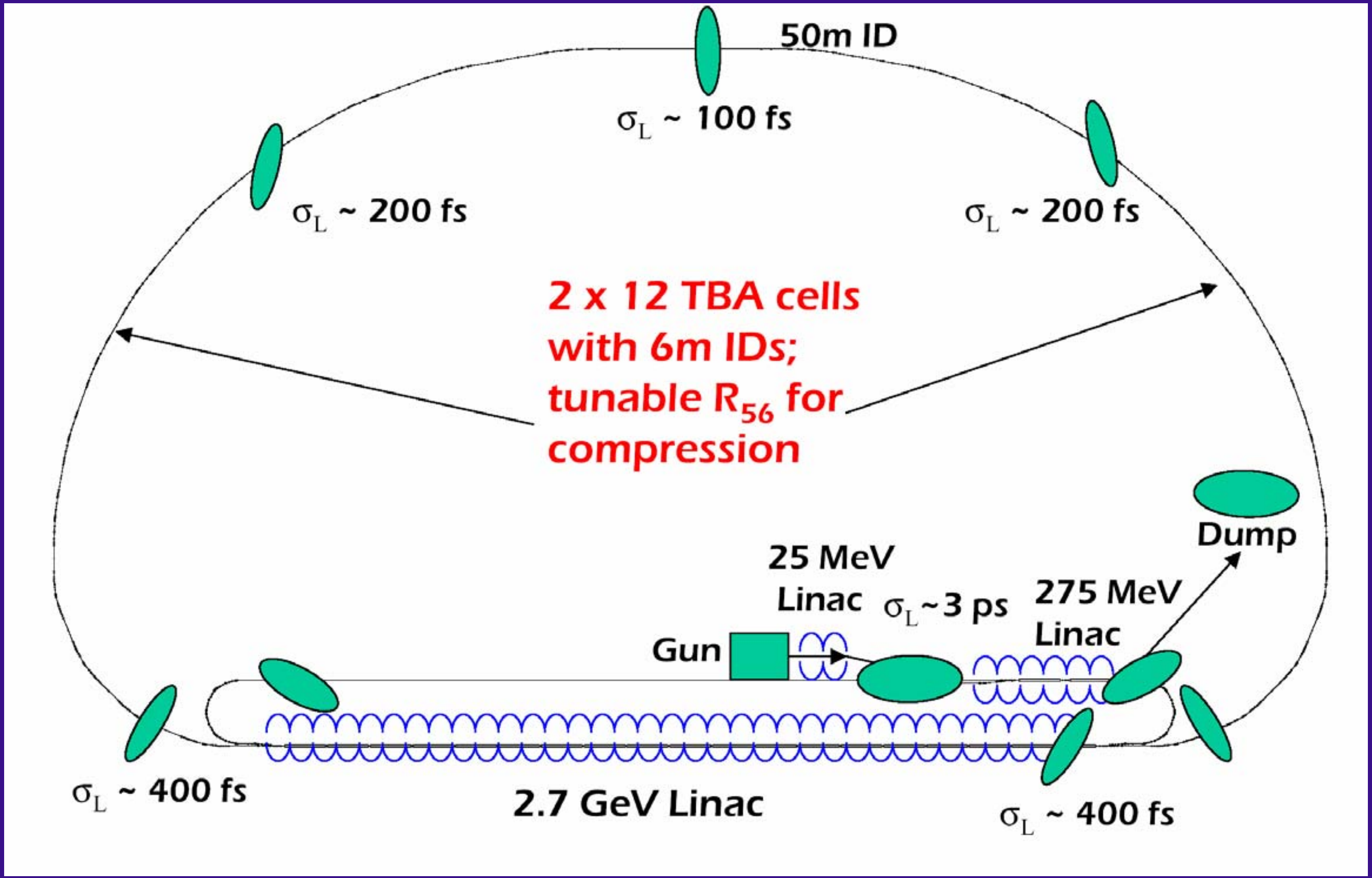
Cornell, Ithaca NY

Energy	100 MeV phase I 5 GeV phase II
Current	10/100 mA

D. Bilderback, SRN 2/27/01.

PERL

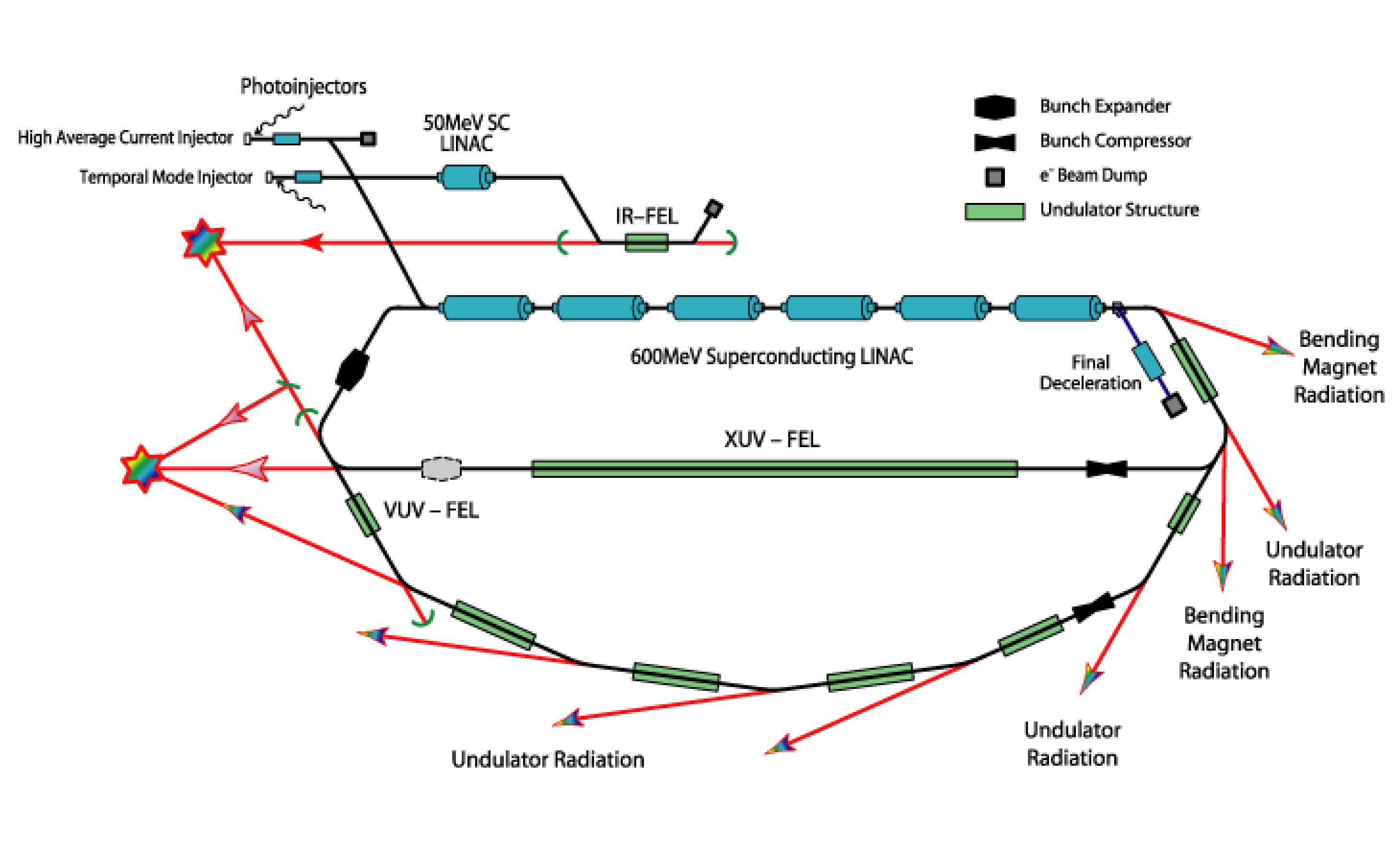
NSLS, Long Island



J. Murphy, SRI 2001, ERL workshop

4 GLS

Daresbury, UK

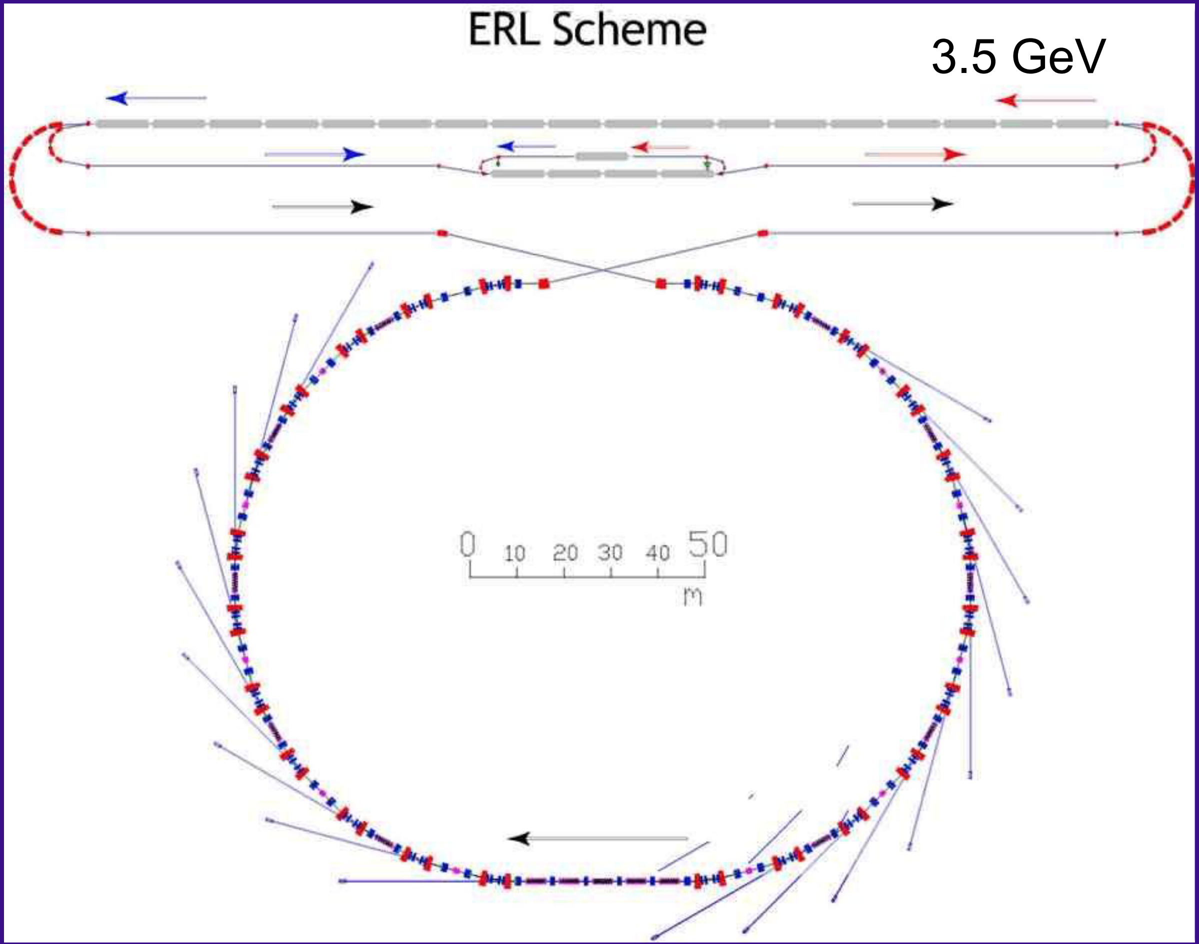


http://www.4gls.ac.uk/

MAX-lab
S. Werin

ERLSYN

Erlangen, Germany



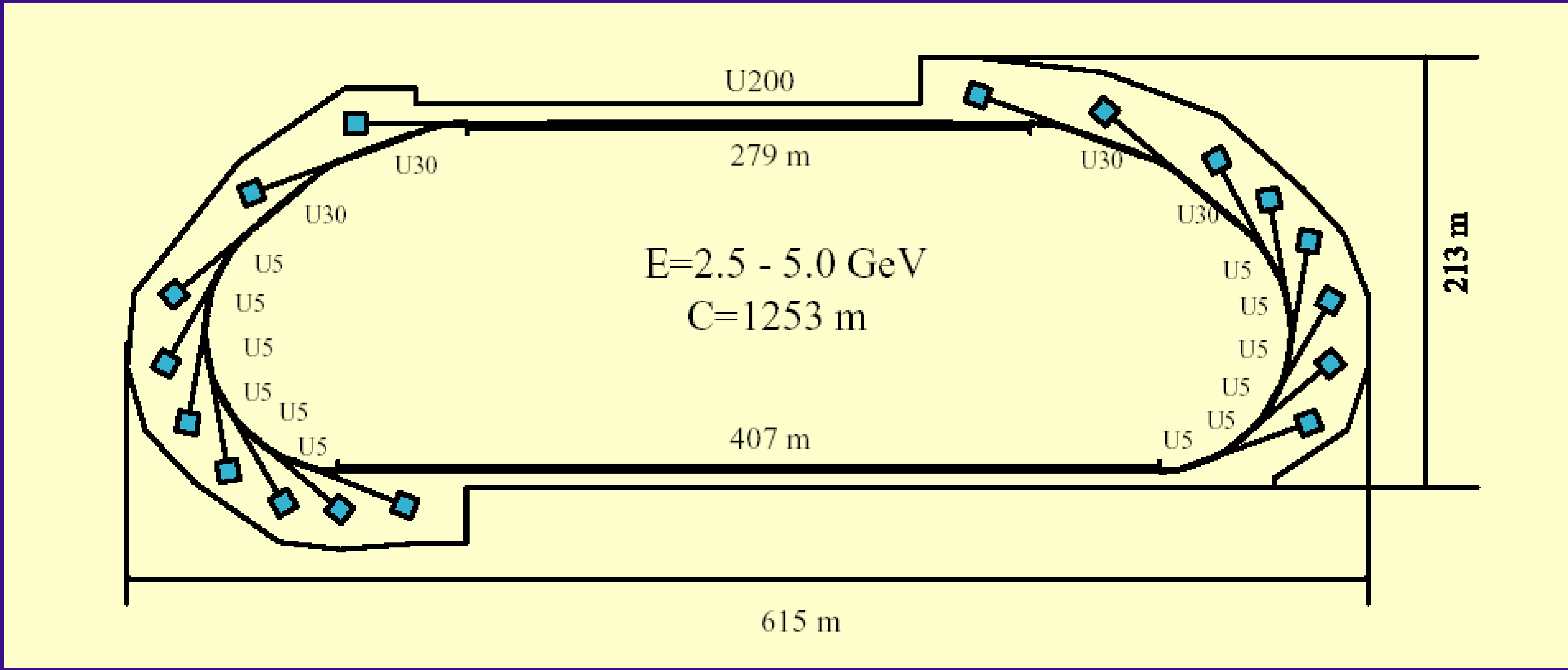
37

S. Werin

http://www.erlsyn.uni-erlangen.de/

KEK ERL

Photon Factory - KEK	
Energy	2.5 ~ 5.0 GeV
Beam Current	~100 mA
Horizontal Emittance	~0.01 nmRad
Bunch Length	1 ps ~ 100 fs



MAX-lab
S. Werin

http://conference.kek.jp/JASS02/23_harada.pdf

Summary

ERLs will give us

- **Fs pulses** (some tricks needed)
- CW (almost) KHz-MHz repetition rate
- Brilliance ≥ new rings above 5 GeV
- Diffraction limited < 2-5 KeV = ”Ultimate source”
- Reduced radiation from dump (v. linacs)

- Proof of principle done
- Many new proposals, especially in the US
- Compact CW driver for FEL

But

- Small energy savings
- Instabilities limits current
- HOMs limits short bunches

	Diffraction limit	Coherence	Fs pulses	Multi user	Brilliance, average	Brilliance, peak	Rep. rate
Storage ring	-hor, +vert	-	-	+	0	-	+
FEL	0	+	+	0	0	+	-
ERL	0	-	+	+	0	-	0

MAX-lab
S. Werin

END