FEL2004

Beam Stability Issues

René Bakker
rene.bakker@psi.ch

26TH INTERNATIONAL FREE ELECTRON LASER CONFERENCE & 11TH FEL USERS WORKSHOP

AUGUST 29 - SEPTEMBER 3
fel 2004
Trieste, Italy

- **Proceedings will become available through JACoW:**
  http://www.jacow.org
- **Preliminary proceedings available on conference web-site:**
  http://www.elettra.trieste.it/fel2004/proceedings.html
  (papers & slides of oral presentations)
- **The abstract booklet, author and affiliation index is available at:**
  http://www.elettra.trieste.it/fel2004/abook.html

Types of free-electron lasers:

- Single-pass devices
- Storage-ring FELs
- High average-power devices

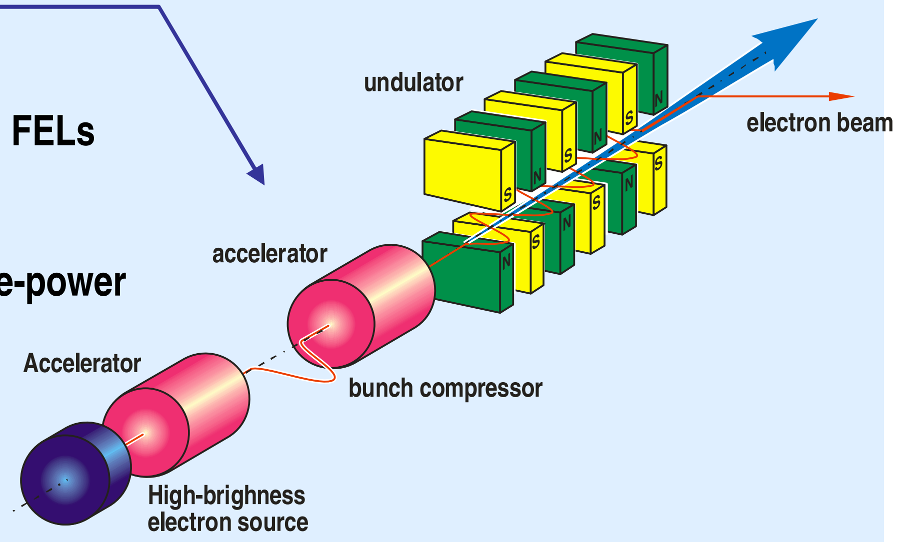
I will just discuss some examples, for an extensive view, please visit:

- the FEL2004 web-site: http://www.elettra.trieste.it/fel2004
- FEL virtual library: http://sbfel3.ucsb.edu/www/vl_fel.html

---

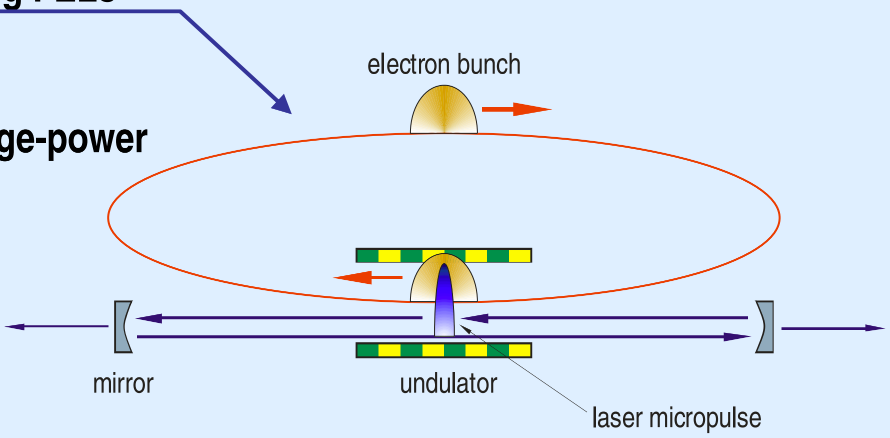
Types of free-electron lasers:

- Single-pass devices
- Storage-ring FELs
- High average-power devices



Types of free-electron lasers:

- Single-pass devices
- Storage-ring FELs
- High average-power devices

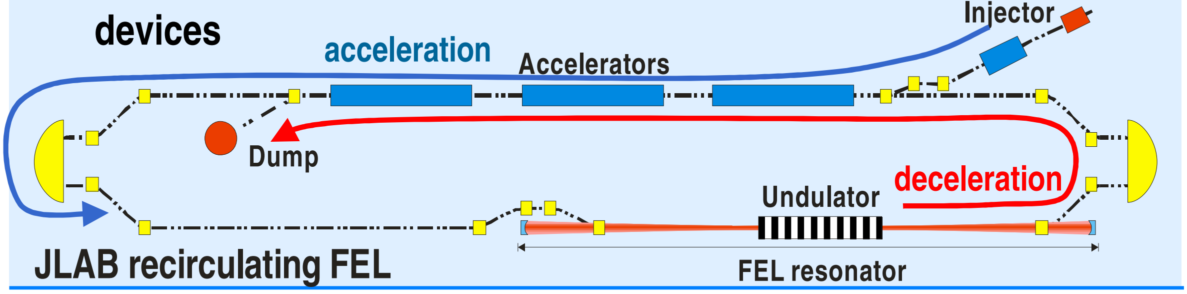


rene.bakker@psi.ch / 10-Dec-2004

Types of free-electron lasers:

- Single-pass devices
- Storage-ring FELs
- High average-power devices

FEL + ERL:
Energy Recovery Linac Concept



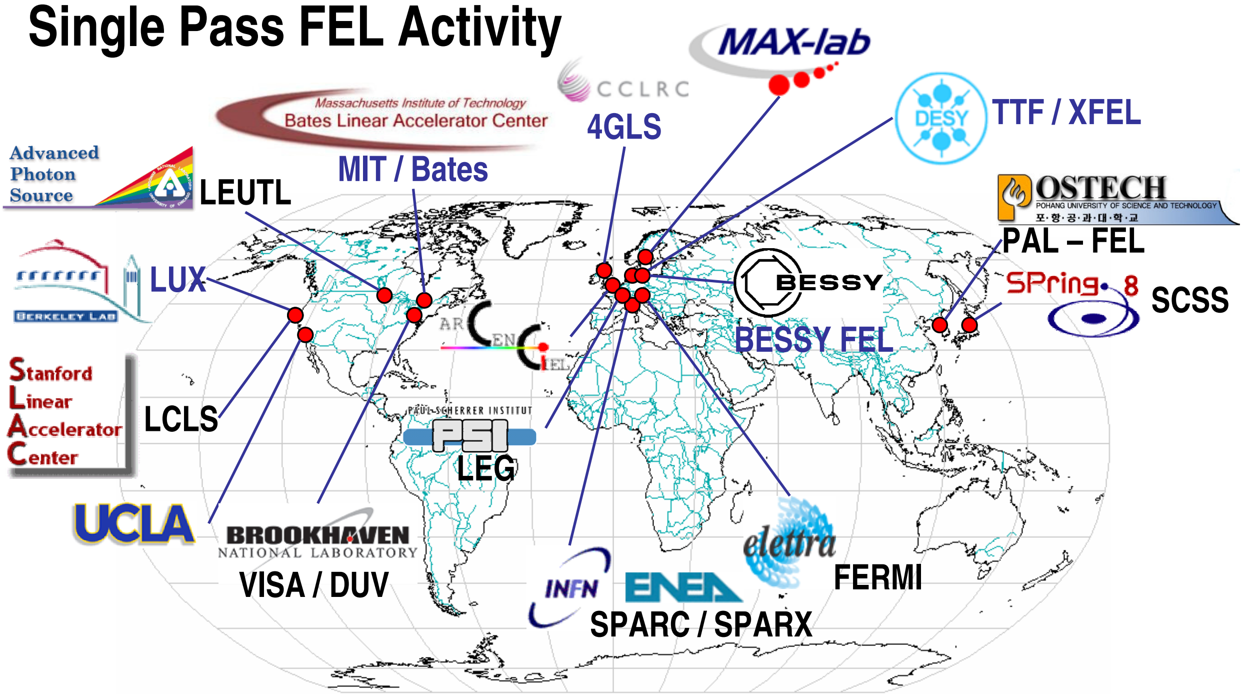
rene.bakker@psi.ch / 10-Dec-2004

Types of free-electron lasers:

- Single-pass devices: high power / short wavelengths
  VUV X-ray
- Storage-ring FELs: optical properties / spectrum
  visible VUV
- High average-power devices: IR

rene.bakker@psi.ch / 10-Dec-2004

Single Pass FEL Activity



MAX-lab

4GLS

TTF / XFEL

MIT / Bates

LEUTL

LUX

LCLS

PAL – FEL

SCSS

BESSY FEL

LEG

VISA / DUV

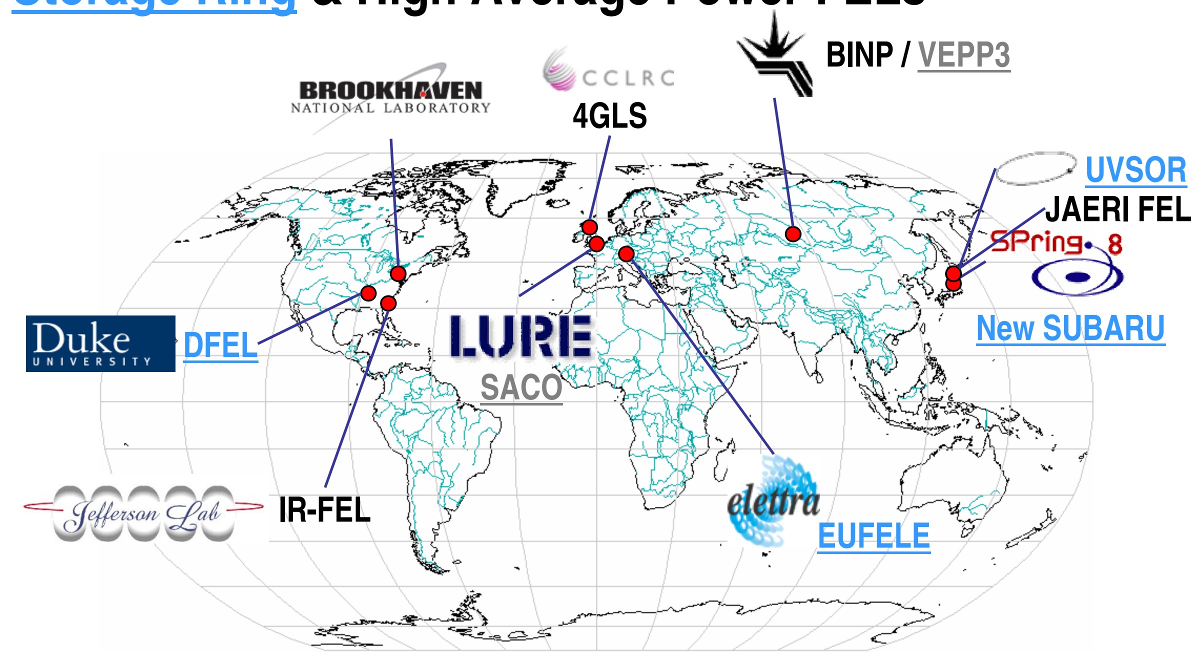
SPARC / SPARX

FERMI

SC technology / NC technology

rene.bakker@psi.ch / 10-Dec-2004

Storage Ring & High Average Power FELs



No longer operational

Existing FELs

EXISTING FELs	λ (μm)	σ_z (ps)	E (MeV)	I (A)	N	λ_0 (cm)	K (rms)	
FEL-CAT	760	15-20	1.8	5	16	2.5	0.75	RF,O
UCSB mm FEL	340	25000	6	2	42	7.1	0.7	EA,O
Novosibirsk (RTM)	120-180	70	12	10	2×33	12	0.71	RF,O
Korea (KAERI-FEL)	97-1200	25	4.3-6.5	0.5	80	2.5	1.0-1.6	MA,O
Himeji (LEENA)	65-75	10	5.4	10	50	1.6	0.5	RF,O
UCSB (FIR FEL)	60	25000	6	2	150	2	0.1	EA,O
Osaka (ILE/ILT)	47	3	8	50	50	2	0.5	RF,O
Osaka (ISIR)	40	30	17	50	32	6	1	RF,O
Tokai (JAERI-FEL)	22	2.5-5	17	200	52	3.3	0.7	RF,O
Bruyeres (ELSA)	20	30	18	100	30	3	0.8	RF,O
Osaka (FELI4)	18-40	10	33	40	30	8	1.3-1.7	RF,O
UCLA-Kurchatov	16	3	13.5	80	40	1.5	1	RF,A
LANL (RAFEL)	15.5	15	17	300	200	2	0.9	RF,O
Stanford (FIREFLY)	15-80	1-5	15-32	14	25	6	1	RF,O
UCLA-Kurchatov-LANL	12	5	18	170	100	2	0.7	RF,A
Maryland (MIRFEL)	12-21	5	9-14	100	73	1.4	0.2	RF,O
Beijing (BFEL)	5-20	4	30	15-20	50	3	1	RF,O
Dresden (ELBE1)	3-22	10	40	8	2×34	2.73	0.3-0.8	RF,O
Korea (KAERI HP FEL)	3-20	10-20	20-40	30	30×2	3.5	0.5-0.8	RF,O
Newport News (IR demo)	3, 6, 10	0.2	160	270	25	20	4.5	RF,O
Darmstadt (FEL)	6-8	2	25-50	2.7	80	3.2	1	RF,O
BNL (HGHG)	5.3	6	40	120	60	3.3	1.44	RF,A
Osaka (iFEL1)	5.5	10	33.2	42	58	3.4	1	RF,O
Tokyo (KHI-FEL)	4-16	2	32-40	30	43	3.2	0.7-1.8	RF,O
Nieuwegein (FELIX)	3-250	1	50	50	38	6.5	1.8	RF,O
Duke (MARKIII)	2.7-6.5	3	31-41.5	20	47	2.3	1	RF,O
Stanford (SCAFEL)	3-13	0.5-12	22-45	10	72	3.1	0.8	RF,O
Orsay (CLIO)	3-53	0.1-3	21-50	80	38	5	1.4	RF,O
Vanderbilt (FELI)	2.0-9.8	0.7	43	50	52	2.3	1.3	RF,O
Osaka (iFEL2)	1.88	10	68	42	78	3.8	1	RF,O
Nihon (LEBRA)	0.9-6.5	<1	58-100	10-20	50	4.8	0.7-1.4	RF,O
UCLA-BNL (VISA)	0.8	0.5	70.9	250	220	1.8	1.2	RF,S
BNL (ATF)	0.6	6	50	100	70	0.88	0.4	RF,O
Dortmund (FELICITAI)	0.42	50	450	90	17	25	2	SR,O
BNL NSLS (DUVFEL)	0.1	0.7	300	500	256	3.9	0.7	RF,SH
Orsay (Super-ACO)	0.3-0.6	15	800	0.1	2×10	13	4.5	SR,O
Osaka (iFEL3)	0.3-0.7	5	155	60	67	4	1.4	RF,O
Okazaki (UVSOR)	0.2-0.6	6	607	10	2×9	11	2	SR,O
Tsukuba (NIJI-IV)	0.2-0.6	14	310	10	2×42	7.2	2	SR,O
Italy (ELETTRA)	0.2-0.4	28	1000	150	2×19	10	4.2	SR,O
Duke (OK-4)	0.193-2.1	0.1-10	1200	35	2×33	10	0-4.75	SR,O
ANL (APSFEL)	0.13	0.3	399	400	648	3.3	2.2	RF,S
DESY (TTF1)	0.08-012	0.04	250	3000	492	2.73	0.81	RF,S

Proposed FELs

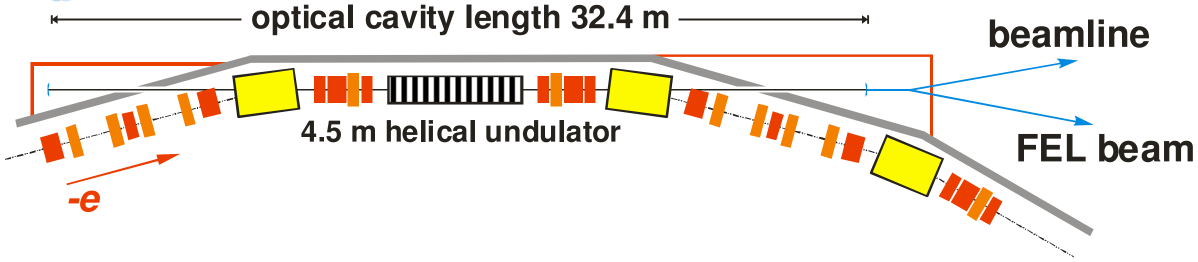
Table 2: Proposed Free Electron Lasers (2004)

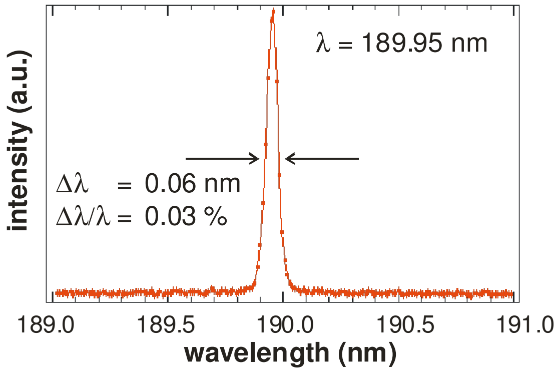
PROPOSED FELs	λ (μm)	σ_z (ps)	E (MeV)	I (A)	N	λ_0 (cm)	K (rms)	
Tokyo (FIR-FEL)	300-1000	5	10	30	25	7	1.5-3.4	RF,O
Netherlands (TEUFEL)	180	20	6	350	50	2.5	1	RF,O
Rutgers (IRFEL)	140	25	38	1.4	50	20	1	MA,O
Novosibirsk (RTM1)	3-20	10	50	20-100	3×33	6	2	RF,O
Dresden (ELBE)	30-750	1-5	10-40	30	45	5	0.4-1.6	RF,O
Daresbury (4GLS-IRFEL)	5-100	0.2-1	50	100	100	4	2	RF,O
Novosibirsk (RTM)	2-11	20	98	100	4×36	9	1.6	RF,O
Frascati (SPARC)	0.533	0.1	142	500	6×71	3	1.3	RF,S
TJNAF (UVFEL)	0.25-1	0.2	160	270	60	3.3	1.3	RF,O
Hawaii (FEL)	0.3-3	2	100	500	84	2.4	1.2	RF,O
Harima (SUBARU)	0.2-10	26	1500	50	33,65	16,32	8	SR,O
Shanghai (SDUV-FEL)	0.5-0.088	1	300	400	400	2.5	1.025	RF,O
Frascati (COSA)	0.08	10	215	200	400	1.4	1	RF,O
Daresbury (4GLS-VUV)	0.4-0.1	0.1-1	600	300	150	5	2	RF,O
Daresbury (4GLS-XUV)	0.1-0.01	0.1-1	600	2000	1000	2	1	RF,S
Duke (OK-5,VUV)	0.03-1	0.1-10	1200	50	4×32	12	3	SR,O
DESY (TTF2)	0.006	0.17	1000	2500	981	2.73	0.9	RF,S
Italy (SPARX)	0.0015	0.1	2500	2500	1000	3	1.2	RF,S
BESSY (Soft X-ray)	0.0012	0.08	2300	3500	1450	2.75	0.9	RF,S
Trieste (FERMI)	0.001-0.1	0.1	3000	2500	570-1140	3.5	1.2	RF,S
RIKEN (SPring8 SCSS)	0.00036	0.5	1000	2000	1500	1.5	1.3	RF,S
MIT (Bates X-Ray FEL)	0.0003	0.05	4000	1000	1500	1.8	2	RF,S
SLAC (LCLS)	0.00015	0.07	14350	3400	3328	3	3.7	RF,S
DESY (TESLA)	0.0001	0.08	30000	5000	4500	6	3.2	RF,S
Pohang (PAL X-FEL)	0.0003	0.1	3000	4000	6000	1.5	1.1	RF,S

W.B. Colson - THPOS58

Storage-Ring FELs

The ELETTRA Storage Ring FEL





Storage ring operation*	1.0	GeV
Tunability range	350 – 190	nm
	3.5 – 6.5	eV
Average power	≥ 1	W
Pulse length (FWHM)	~ 5	ps
Peak power	≥ 40	kW
Pulse energy	≥ 0.2	mJ
Photon flux**	≥ 10^{18}	photons/s
Polarization	circular (linear may also be possible)	
Repetition rate	4.6	MHz
Synchronization with synchrotron radiation	1:1	

*4-bunch operation, **within the laser bandwidth

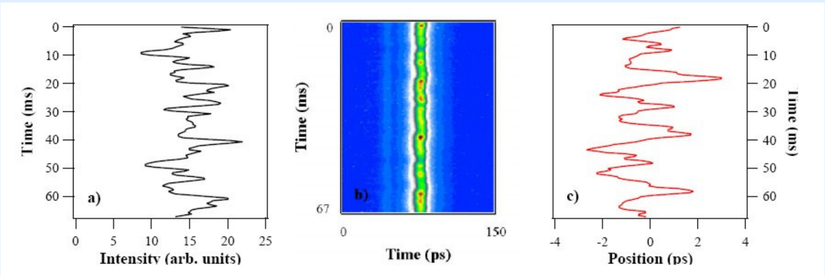
rene.bakker@psi.ch / 10-Dec-2004

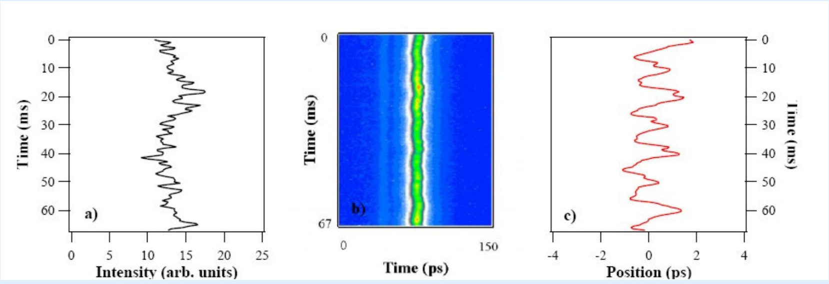
Storage-Ring FELs

Critical Issues:

- **Longitudinal stability of electron beam:**

  rountrip time of the optical cavity must match the bunch-spacing





M. Trovò
THPOS09

rene.bakker@psi.ch / 10-Dec-2004

Storage-Ring FELs

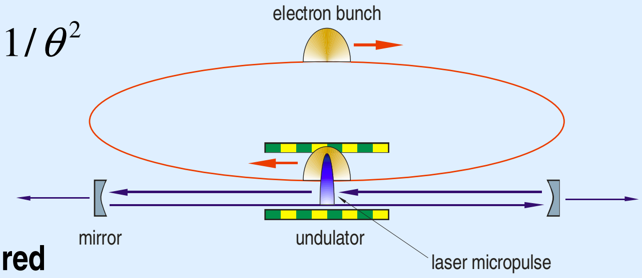
Critical Issues:

- **Longitudinal stability:**
  rountrip time of the optical cavity must match the bunch-spacing (stability of RF frequency and longitudinal modes)

- **Transverse stability:**
  wavelength $$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+K_{\mathrm{rms}}^2+(\theta\gamma)^2\right)$$
  Gain $$g \propto 1/\theta^2$$

⇩

typically micron accuricy required



rene.bakker@psi.ch / 10-Dec-2004

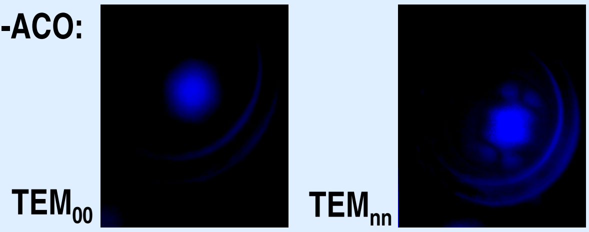
Storage-Ring FELs

Critical Issues:

- **Longitudinal stability:**
  rountrip time of the optical cavity must match the bunch-spacing

- **Transverse stability:**
  wavelength
  Gain

S-ACO:

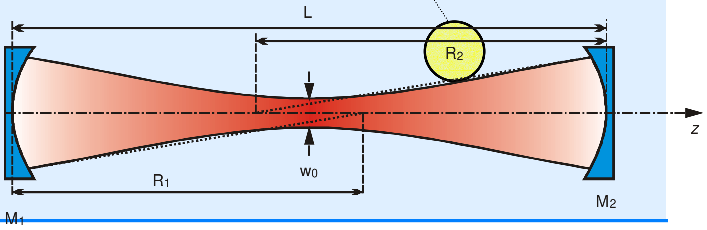


more stability ⟷ **more gain**

<u>**Transverse Cavity Stability!**</u>

⇩

heat-load



rene.bakker@psi.ch / 10-Dec-2004

Cavity Stability

- **Storage-ring FEL**
  Important issue:
  e.g., 1 W of average output power 200 W of intra-cavity power

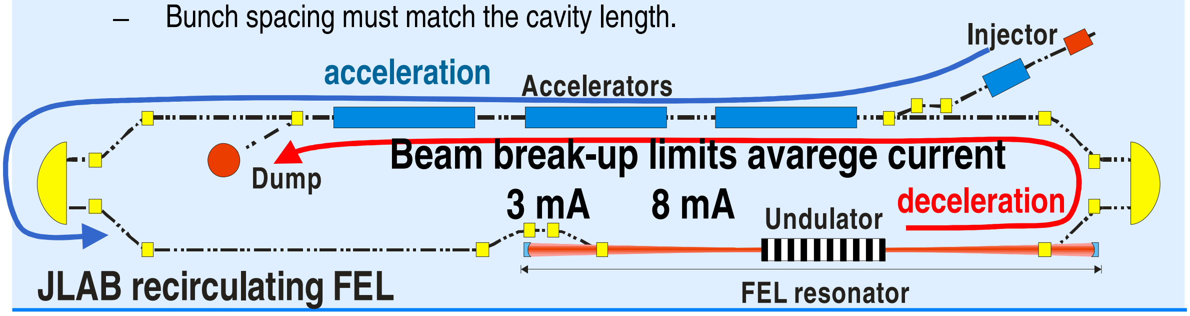
- **High average-power IR FEL**
  e.g., JLAB FEL: > 10 kW average output power, i.e., more than 100 kW average intra-cavity power.

ref: TUCOS02, TUBOS03

rene.bakker@psi.ch / 10-Dec-2004

High average-power lasers: FEL challenge (JLAB)

- **FELs need a high peak current.**
  - a factor of 4 growth in the longitudinal emittance due to space charge.
  - longer electron bunches in the injector can reduce space charge effects but reduces the machine acceptance.
  - Halo loss initially limited the average current.
- **Resonator FELs need a high average current**
  - Bunch spacing must match the cavity length.



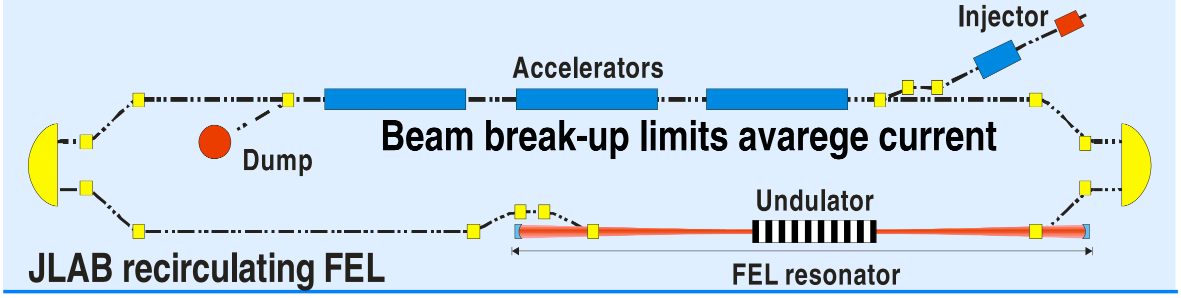
Beam break-up limits avarege current

JLAB recirculating FEL

rene.bakker@psi.ch / 10-Dec-2004

High average-power lasers: FEL challenge (JLAB)

- **Beam break-up**
  - Cavity design: suppression of HOMs
  - Clever optics (damping of transverse motion)
- **Nice presentation by T.I. Smith: WEBOS03**

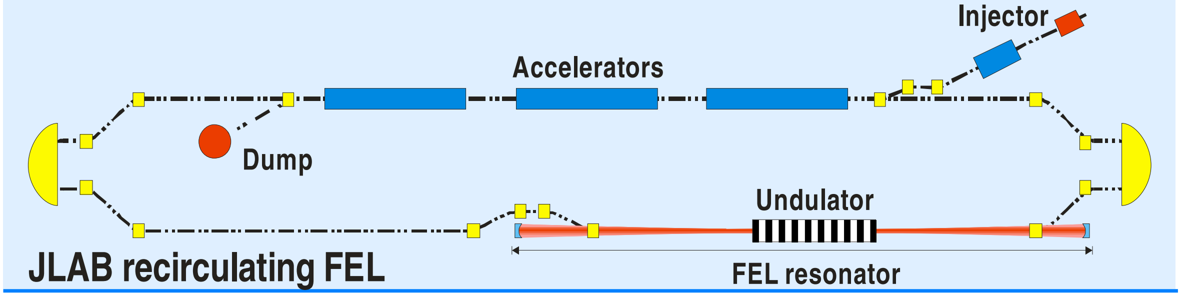


JLAB recirculating FEL

rene.bakker@psi.ch / 10-Dec-2004

High average-power lasers: FEL challenge (JLAB)

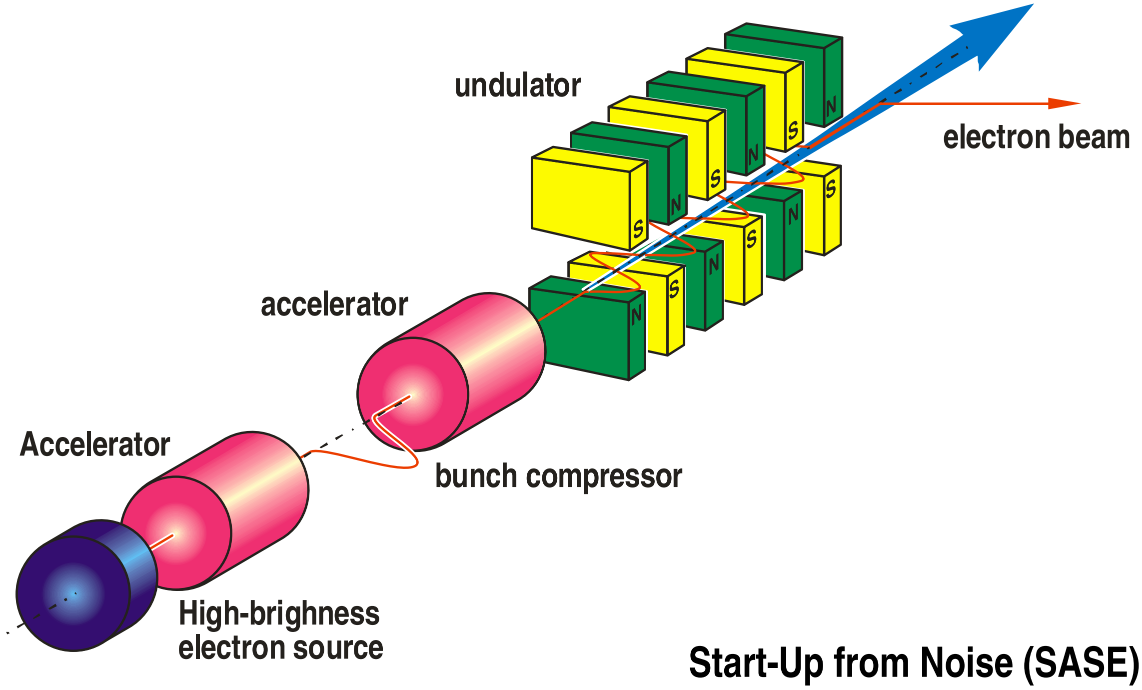
- **Challenges of recovering the beam**
  - RF kicks reversed for recovered beam
  - No two pass BPMs
  - Chromatic effects lead to betatron mismatch, causing beam loss.
  - Need energy/phase correction to third order (octupoles are required)
  - Operating close to crest does not provide enough footroom.



JLAB recirculating FEL

rene.bakker@psi.ch / 10-Dec-2004

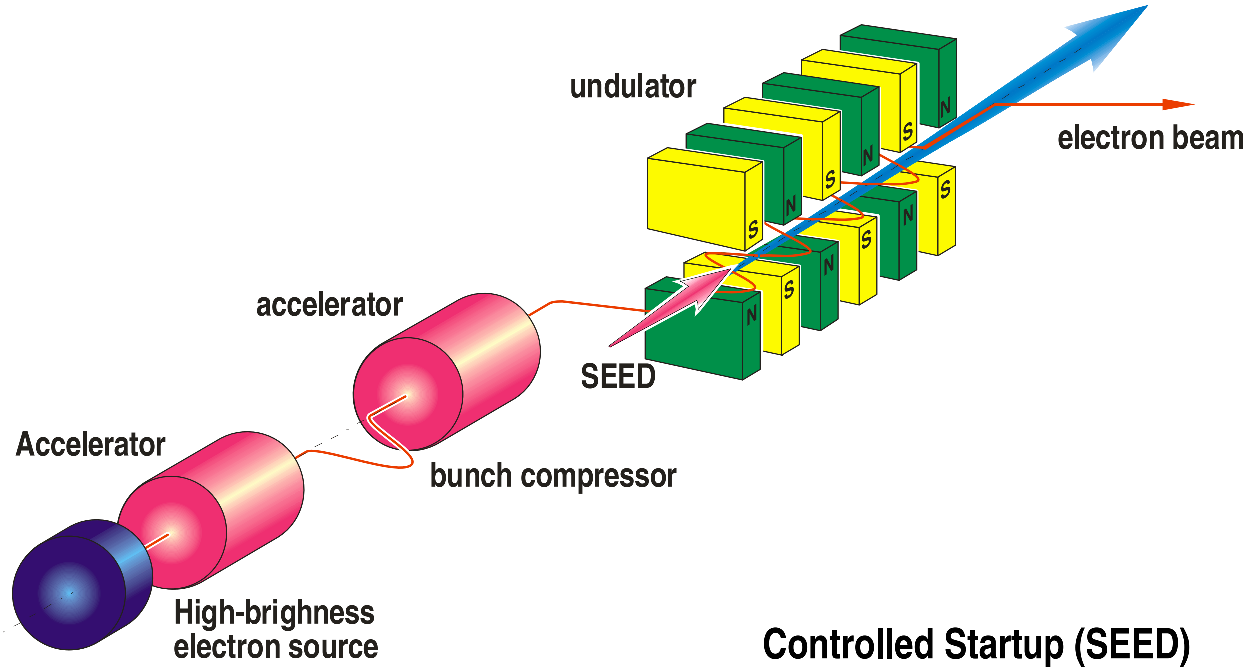
Single Pass Devices



Start-Up from Noise (SASE)

rene.bakker@psi.ch / 10-Dec-2004

Single Pass Devices



Controlled Startup (SEED)

rene.bakker@psi.ch / 10-Dec-2004

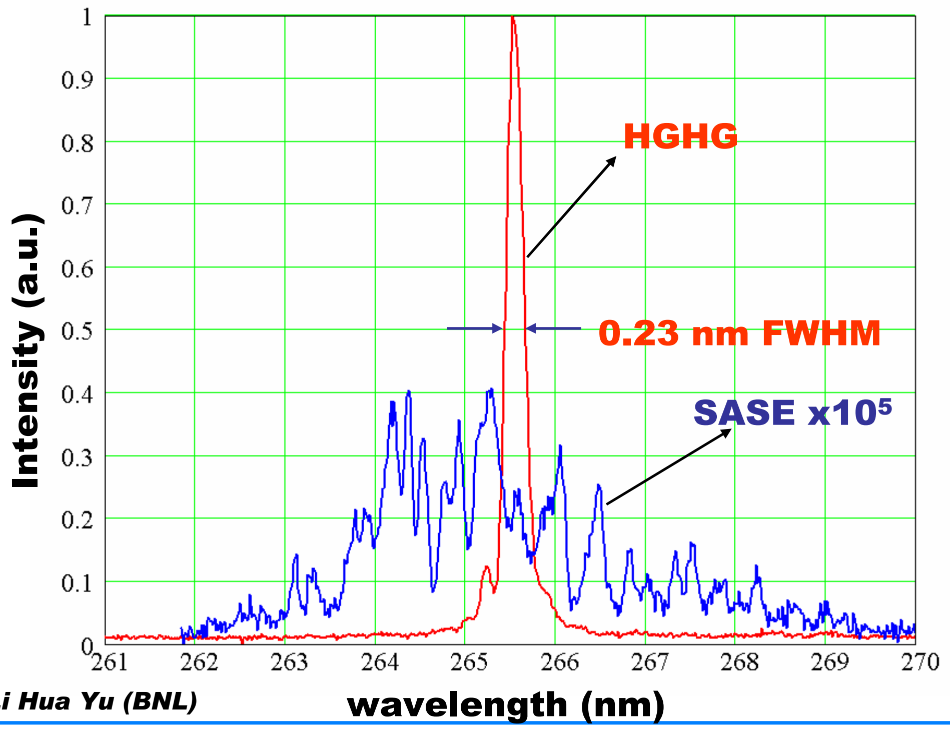
Single-Pass Devices

- **Startup from noise (auto-start): SASE**
  - Relatively easy
  - Flexible for wavelength tuning
  - High output power
  - Spiky

- **Seeded startup**
  - Improved spectral purity
  - Suppression of spiking
  - Control over the μ-pulse duration
  - (Longitudinal jitter defined by seed)

rene.bakker@psi.ch / 10-Dec-2004

Seeded FEL: HGHG (BNL)



Courtesy Li Hua Yu (BNL)

rene.bakker@psi.ch / 10-Dec-2004

Single-Pass Devices

- **Startup from noise (auto-start): SASE**
  - Relatively easy
  - Flexible for wavelength tuning
  - High output power
  - Spiky

LCLS, TTF, X-FEL, SPARC, …..

- **Seeded startup**
  - Improved spectral purity
  - Suppression of spiking
  - Control over the μ-pulse duration
  - (Longitudinal jitter defined by seed)

BESSY, FERMI, TTF, LUX, MIT, ……. LCLS, X-FEL, ……

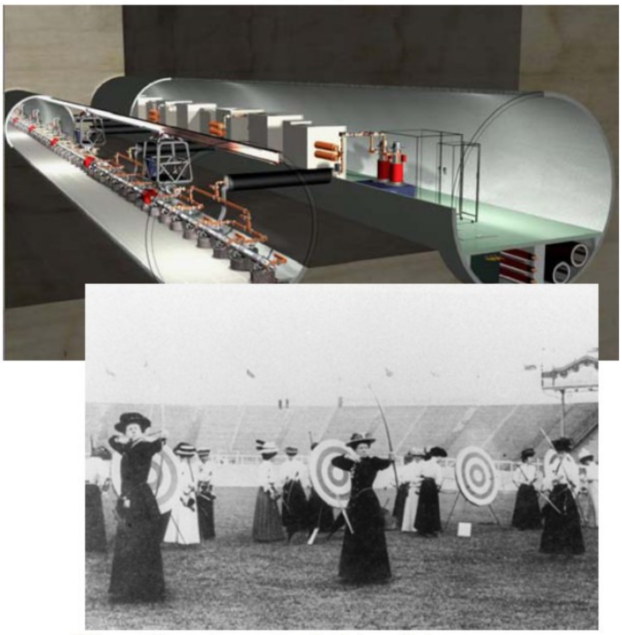
rene.bakker@psi.ch / 10-Dec-2004

Single-Pass Devices

Storage-Ring is A Spinning-Top

Very Stable and Quiet

Linac is “A Archery”



Shooting is not stable, it is a game, sometimes noisy.

Courtesy T. Shintake, RIKEN/SPring8, MOBIS01

rene.bakker@psi.ch / 10-Dec-2004

Single-Pass Devices

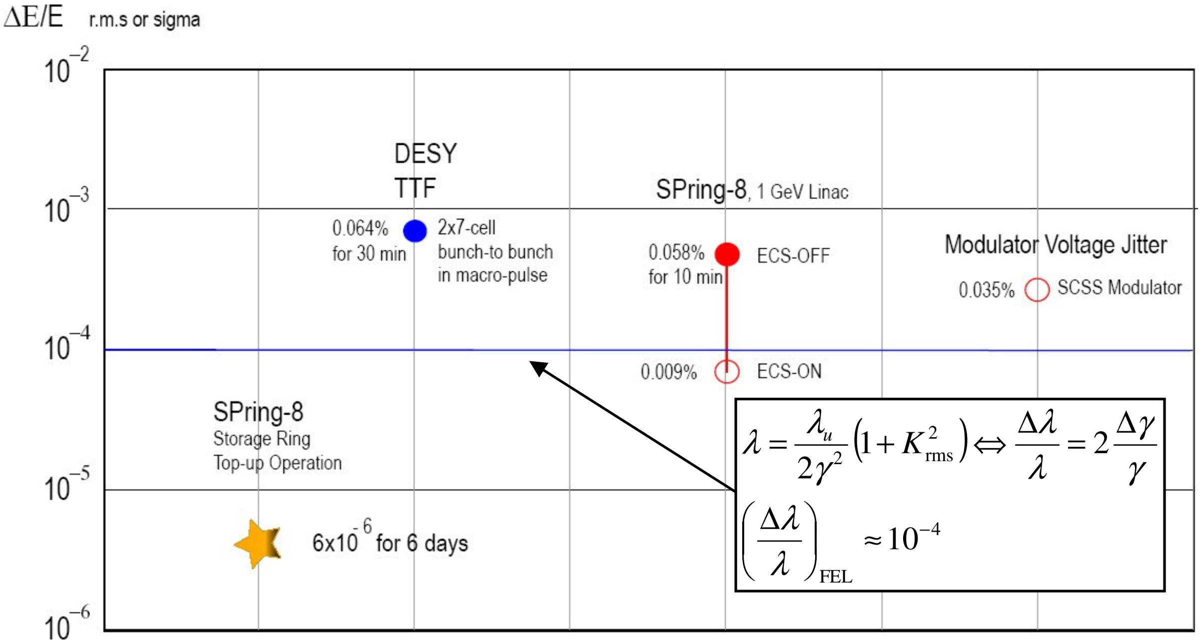
Storage Ring vs. LINAC

	Storage Ring	LINAC
Machine condition	Steady state	Transient / Pulsed
Trajectory	Closed orbit (eigen-vector)	Open trajectory (no eigen-vector)
Damping	Synchrotron damping	No damping
Beam clearing	Dynamic aperture of machine	No clearing dark currents may propagate
Noise bandwidth	~1 kHz (narrow tune resonance)	~GHz (no resonance)
Energy and intensity stability	$10^{-5} – 10^{-6}$	$10^{-2} – 10^{-3}$

Courtesy T. Shintake, RIKEN/SPring8, MOBIS01 - MODIFIED

Single-Pass Devices

Beam Energy Stability



$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+K_{\rm rms}^2\right) \Leftrightarrow \frac{\Delta\lambda}{\lambda} = 2\frac{\Delta\gamma}{\gamma}$$

$$\left(\frac{\Delta\lambda}{\lambda}\right)_{\rm FEL} \approx 10^{-4}$$

Courtesy T. Shintake, RIKEN/SPring8, MOBIS01

Single-Pass Devices

Sources of jitter

- **AC line fluctuations**
  power supply fluctuations: gun, RF, orbit, …..
- **Switch-tune pulse-to-pulse jitter**
- **Switching noise fluctuations**
- **AD/DA digitizing noise**
- **Temperature fluctuations**
  LINAC, electrical circuits ….
- **Ground motion**
  natural, human activity

Feed-back is mostly not possible
Feed-forward:
- **between micro-pulses**
- **between macro-pulses**

rene.bakker@psi.ch / 10-Dec-2004

Single-Pass Devices

Electron-Beam Stability

- **Transverse stability**
  - Low energy (injector): transverse emittance dilution
    (depends on the RF-frequency: X-band more sensitive than L-band)
  - Beam break-up at high average current operation
  - High energy (undulator): gain reduction and wavelength jitter

typically a (few) micron orbit accuracy

- **Longitudinal stability (bunch / RF phase)**
  - Energy fluctuations
  - Current fluctuations   FEL gain fluctuations
  - Temporal jitter with synchronized sources

locked to seed laser ⇐

Talking about femto-second and atto-second sources

rene.bakker@psi.ch / 10-Dec-2004

Single-Pass Devices

Transverse Orbit / Undulator

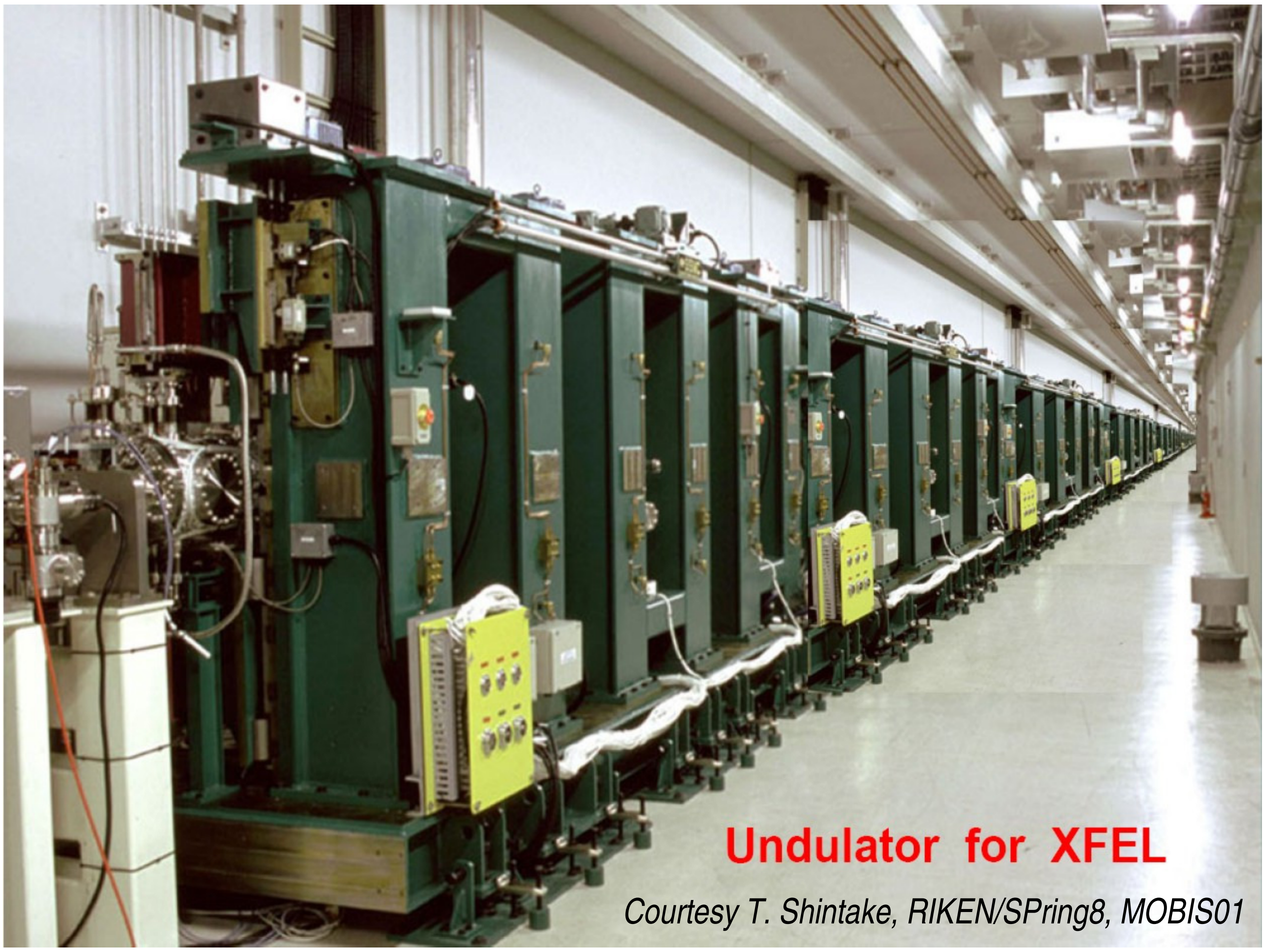
- **General guideline (not necessarily correct):**
  - **Control orbit up to 10 % of the beam diameter**

    $\varepsilon_n = 10^{-6}$ m rad, $E = 2.5$ GeV, $\beta = 10$ m $\Delta_{x,y} = 4.5$ µm (BESSY)
    $\varepsilon_n = 10^{-6}$ m rad, $E = 20$ GeV, $\beta = 10$ m $\Delta_{x,y} = 1.6$ µm (XFEL)
    $\varepsilon_n = 10^{-7}$ m rad, $E = 6.0$ GeV, $\beta = 7$ m $\Delta_{x,y} = 0.8$ µm (LEG)

- **Sextupole fields of undulator may cause tougher constraints, specifically for short-period, small-gap undulators.**

N.B. CSR in magnetic bunch-compressors may kick parts of the electron bunch off-axis in the horizontal plate.

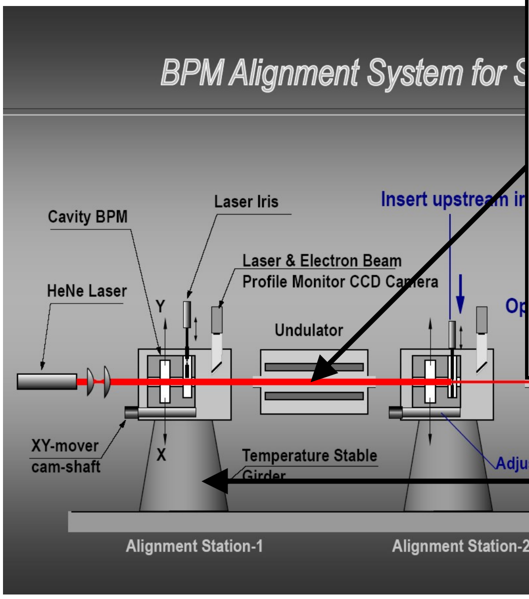
rene.bakker@psi.ch / 10-Dec-2004

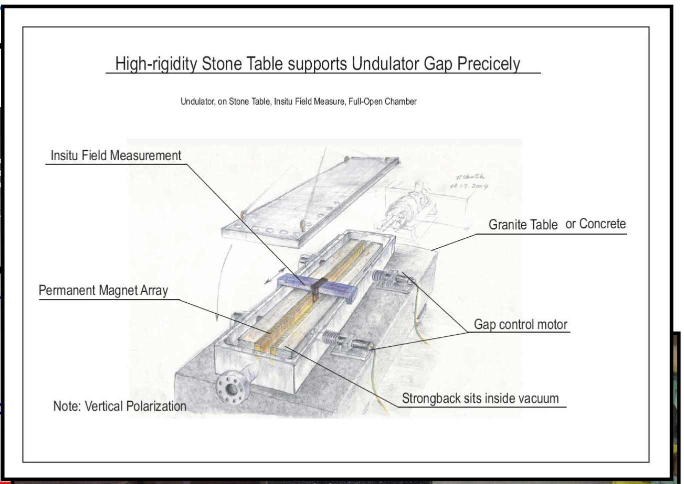


Undulator for XFEL

Courtesy T. Shintake, RIKEN/SPring8, MOBIS01

SCSS undulator concep

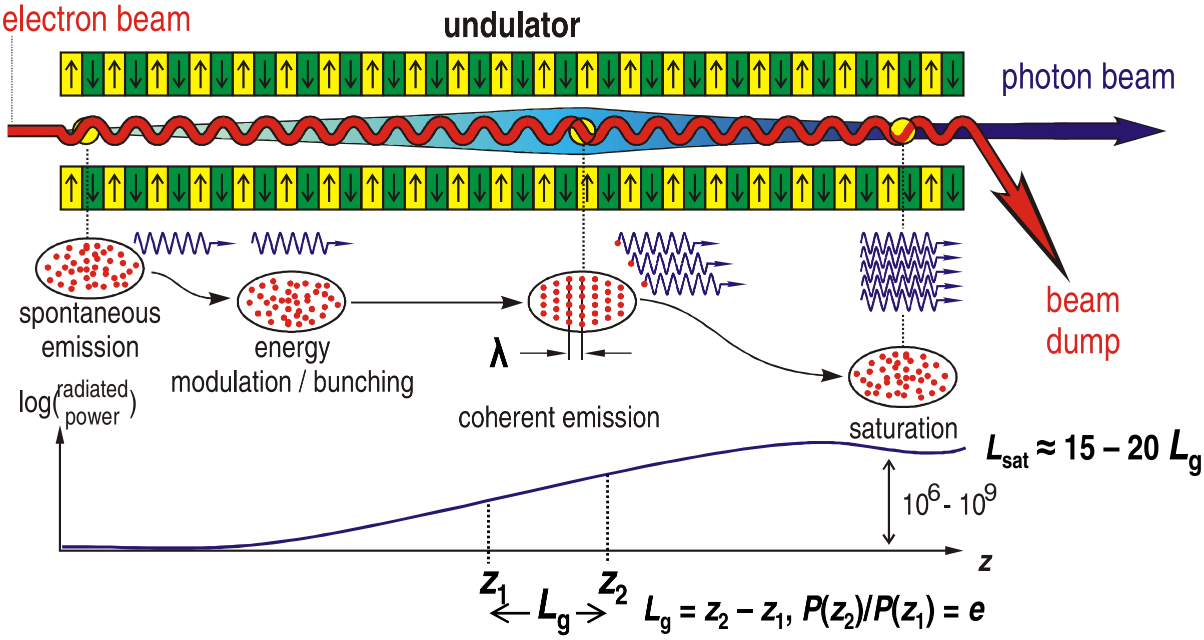



High-rigidity Stone Table supports Undulator Gap Precicely

Undulator, on Stone Table, Insitu Field Measure, Full-Open Chamber

Courtesy T. Shintake, RIKEN/SPring8, MOBIS01

Gain Length



$L_{sat} \approx 15 - 20\ L_g$

$L_g = z_2 - z_1$, $P(z_2)/P(z_1) = e$

Single-Pass Devices

Transverse Orbit / Undulator

- Electron beam orbit must be controlled over a few gain-lengths.
- Within this distance: gain reduction

$$L_g' = L_g/(1-x^2)$$

$$x = \theta/\theta_c,\ \theta_c = \sqrt{\lambda/L_g}$$

Y.-C. Chae et al (APS) MOBOS03

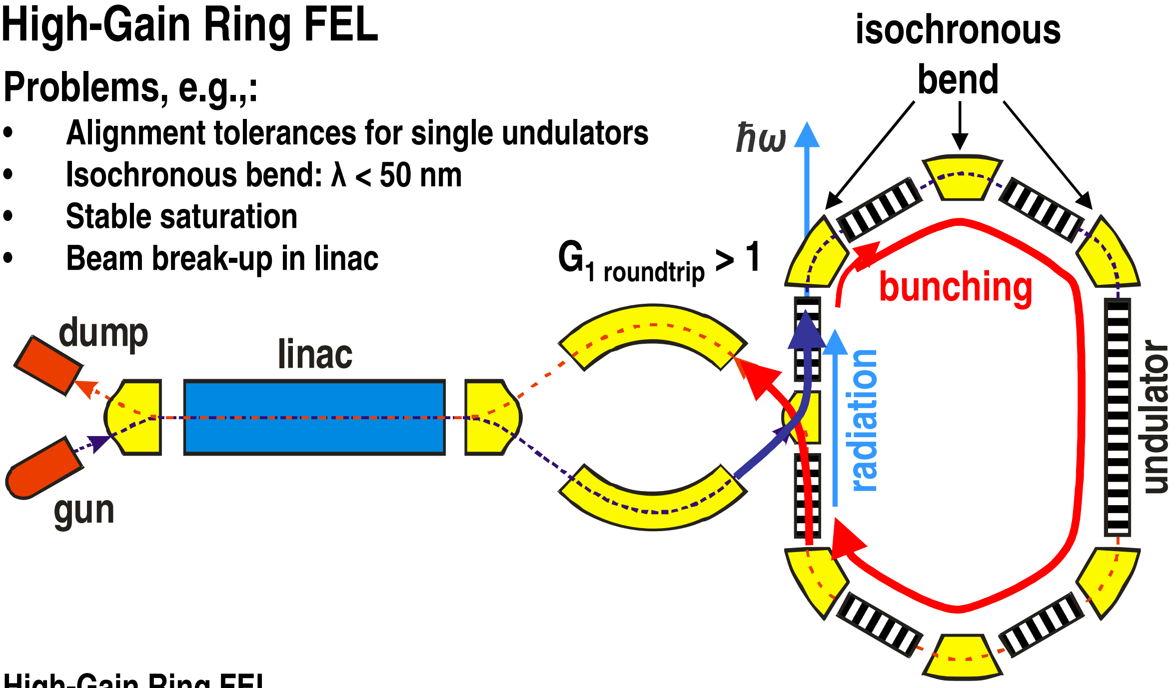
T. Tanaka, et al., FEL 2003

- Over larger distances the overlap between optical field and the electron beam may disappear. In such a case, the micro-bunching will re-initiate the FEL process over a few undulator periods only.

High-Gain Ring FEL

Problems, e.g.,:

- Alignment tolerances for single undulators
- Isochronous bend: λ < 50 nm
- Stable saturation
- Beam break-up in linac



High-Gain Ring FEL
N.A. Vinokurov, A.N. Matveenko – THPOS45