Falcon Analytics

Development Trends in High-Power Free-Electron Lasers

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TECHNION
Israel Institute of Technology

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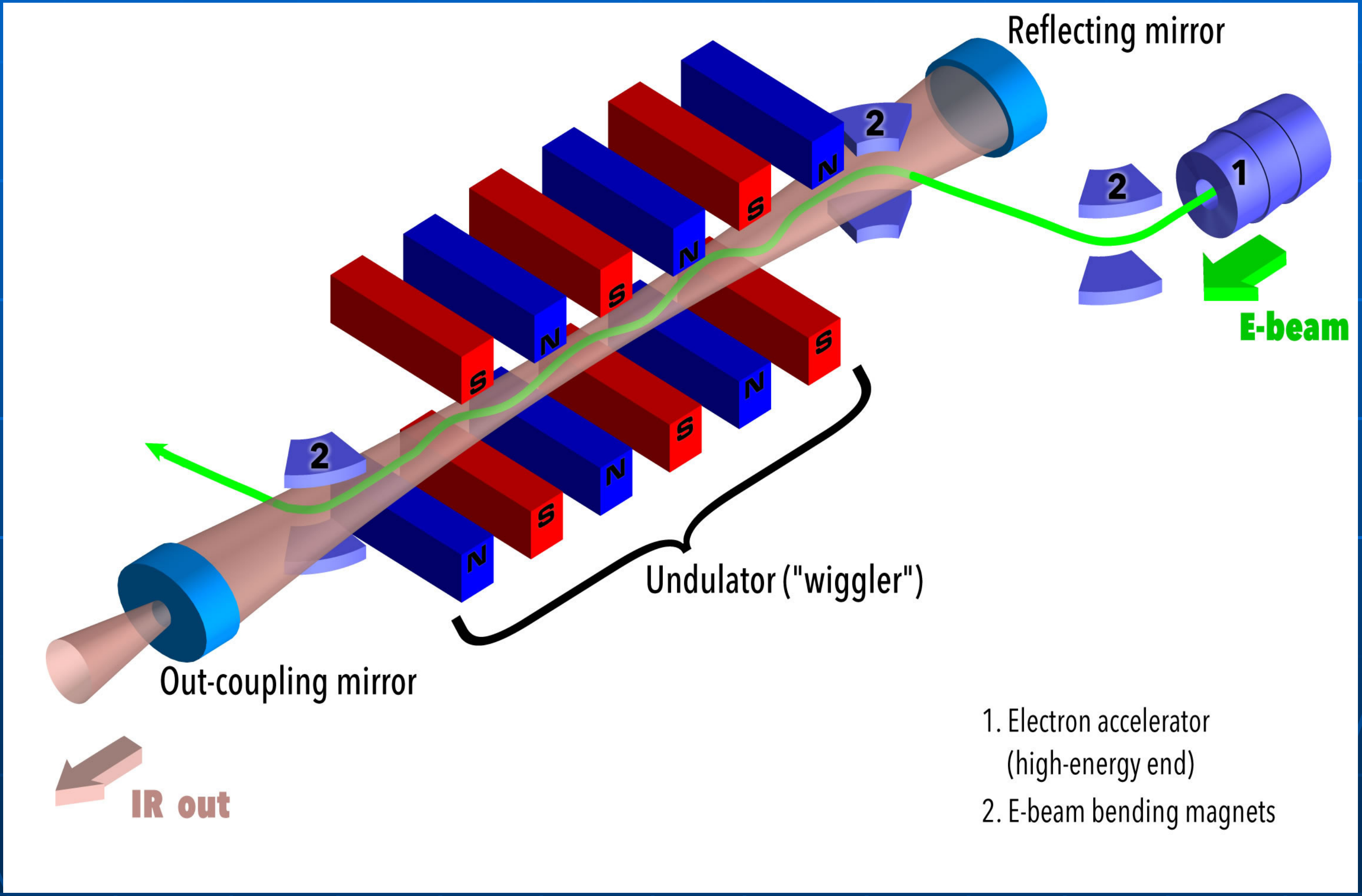
Contents

- FEL basics
- FEL technology – status
- Subsystems and working regimes
- Increasing efficiency
- System view
- Applications
- Conclusions

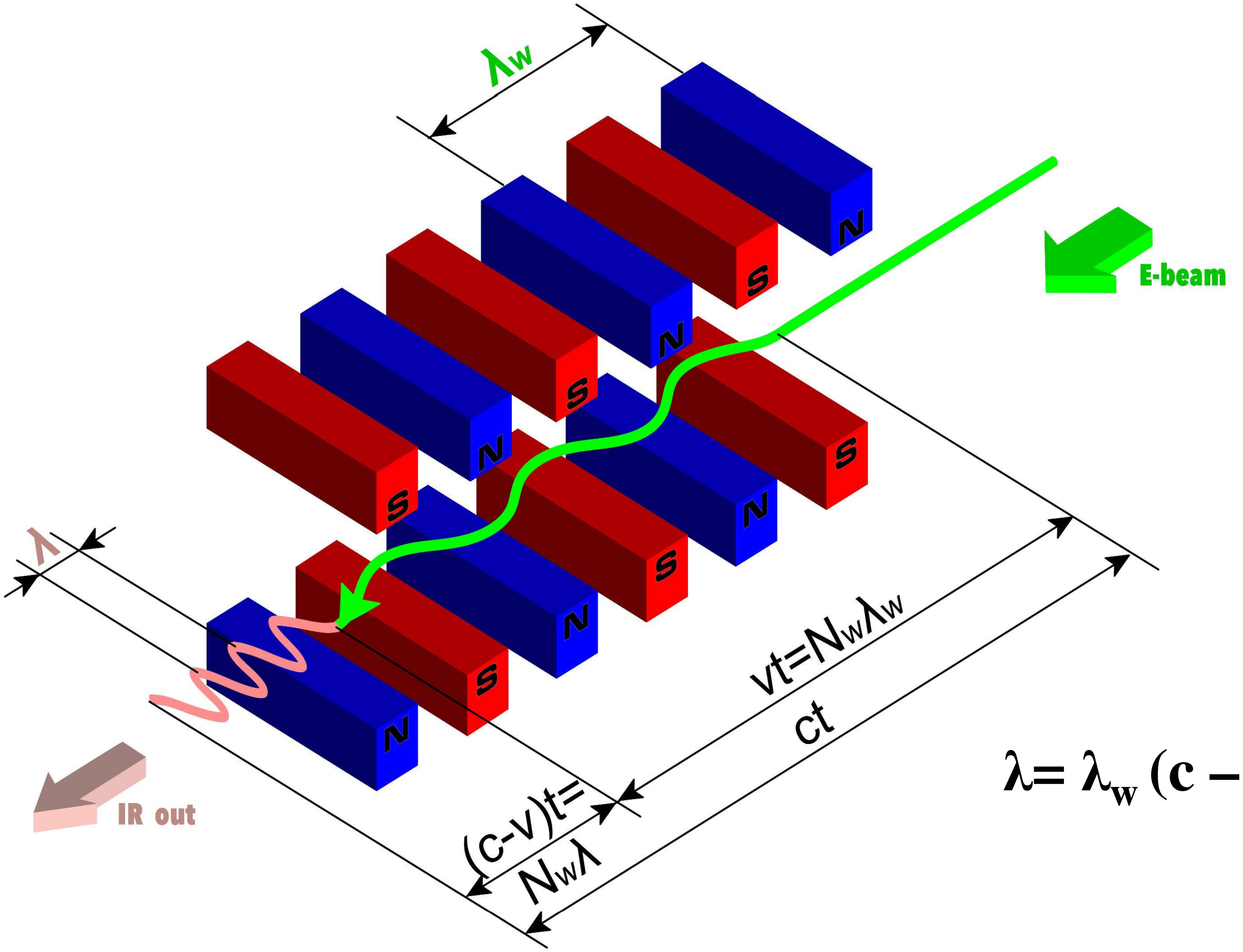
- Though called “laser”, FEL is essentially a big electron-beam vacuum tube
- Though optical or even hard X-ray radiation is emitted, the FEL is fully described by classical electrodynamics & mechanics (relativistic)

FEL – operation principle



1. Electron accelerator (high-energy end)
2. E-beam bending magnets

FEL wavelength



$$\lambda = \lambda_w (c - v) / v$$

FEL wavelength

Relativistic kinematics – speed vs. energy

$\gamma = E/m_e c^2$ – Lorentz factor

$m_e c^2 = 0.511$ MeV

electron rest mass

$\gamma = 1 / [1 - (v/c)^2]^{1/2}$

$v = c\,[1 - 1/\gamma^2]^{1/2}$

Energy	**Electron speed** v/c
$m_e c^2 + 10$ keV	0.20
$m_e c^2 + 100$ keV	0.55
1 MeV = $m_e c^2 + 489$keV	0.86
10 MeV	0.999
100 MeV	0.99999

FEL wavelength

$\lambda = k\,\lambda_W / 2\gamma^2$

λ IR wavelength

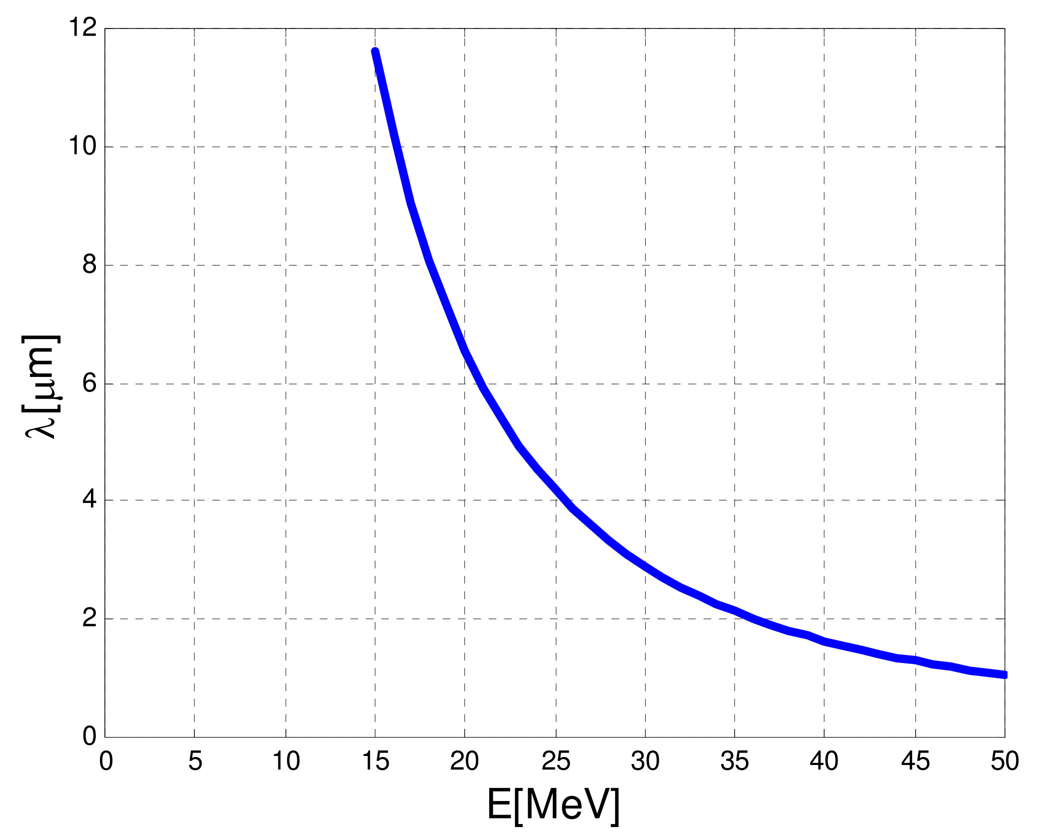
λ_W undulator period

γ Lorentz-factor

$\gamma = E/m_e c^2$

k ~ 1-2

sometimes higher (LCLS)



λ = 1-10 μm

λ_W= 2 cm

E(beam) = 15-50 MeV

$m_e c^2$ = 0.511 MeV

FEL – operation principle

- Vanderbilt University animation

http://www.vanderbilt.edu/exploration/multimedia/flash/fel/fel_works.htm

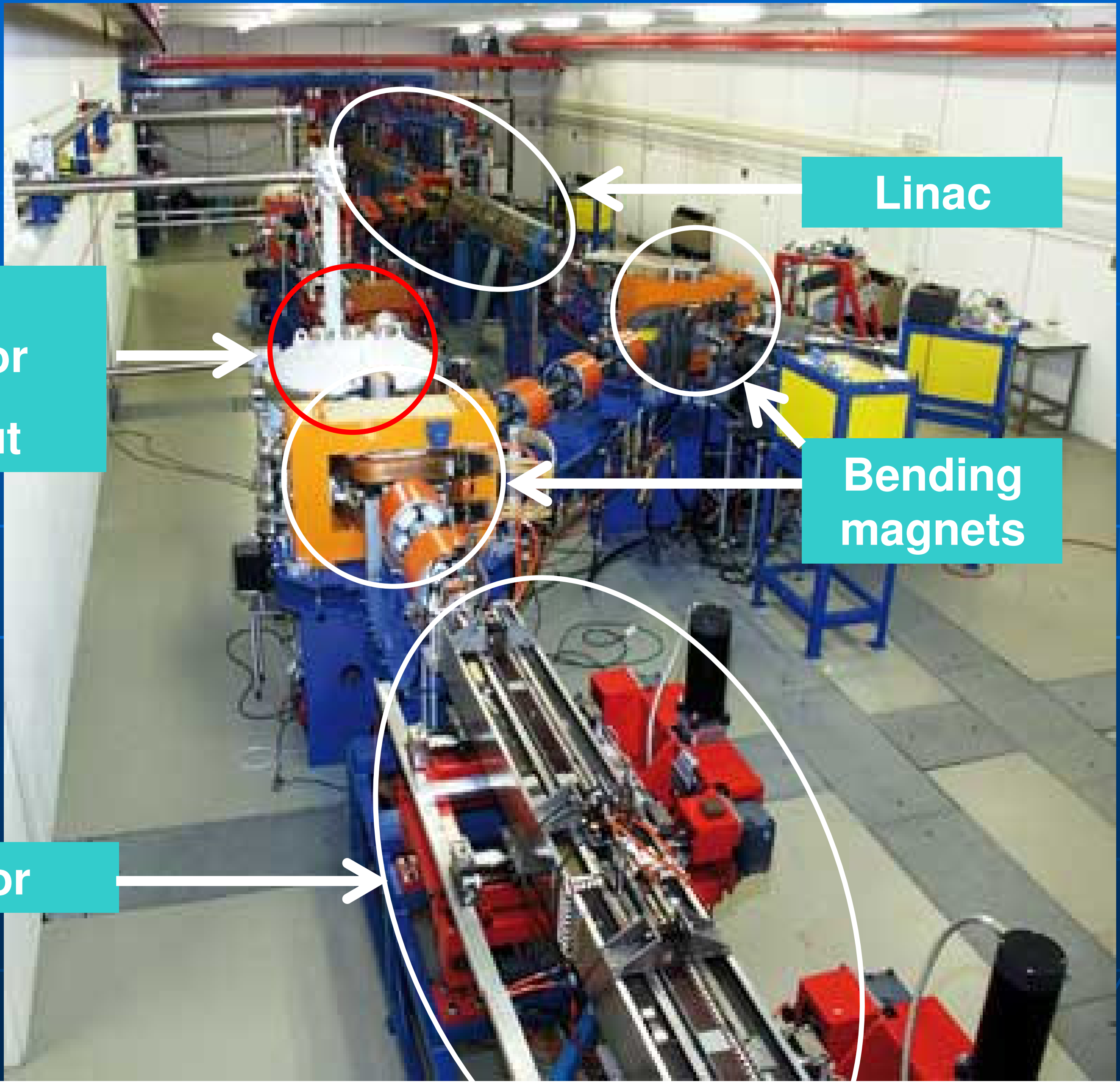
FELIX IR user facility (Netherlands)

λ=3-250μm

>100kW peak

~10W average

FELIX IR user facility (Netherlands)



Linac

Optical Resonator

IR output

Bending magnets

Undulator

FEL Advantages

- Tunability 10 GHz - 1Å
- Excellent beam quality $M^2<1.1$
- High peak power (10+ MW)
- All-electric

Challenges

- No industrial experience
- Low efficiency aim: 10%
- Ionizing radiation
- Size, cost

FEL spectral coverage

FEL technology: X-band (10 GHz) =>
X-rays (1 Å=0.1nm)

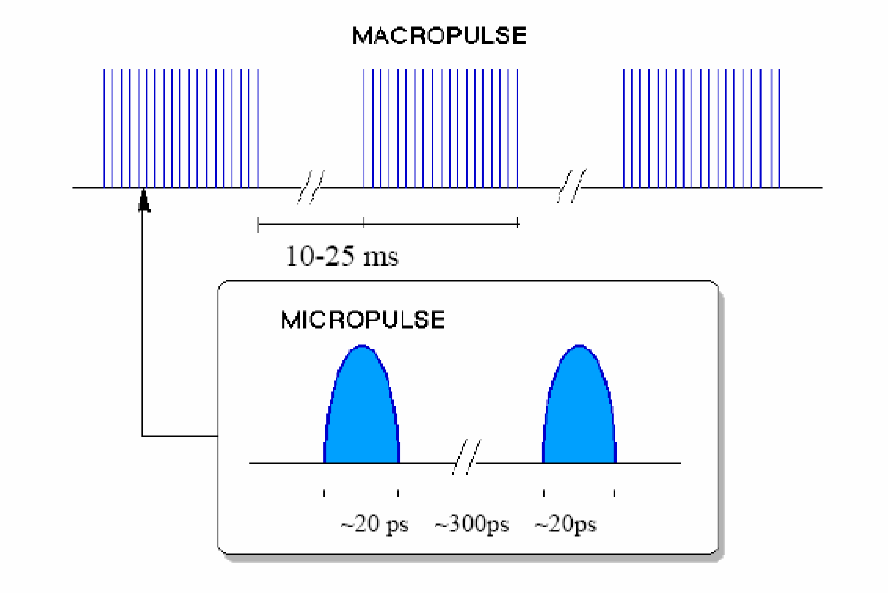
Single FEL machine: ~ 1.5-2 decades of λ
(with 2-3 undulators)

Areas of interest

X to VUV	0.1 -200 nm
Mid- to far-IR	1.5-1000 μm

FEL power

micropulse (20 ps)	1-10+	MW
MACROpulse (10 μs)	100-500	kW
Average	0.1-100	kW



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FEL maturity – signs

- New FEL user centers
- Scale-up ×40 in 2009 (SLAC)
- First commercially-built e-beamline
- US Navy -> industry (Boeing)

Operating FELs – for Scientific Research

X/UV FEL facilities

1.	LCLS – SLAC	US
2.	FLASH – DESY	Germany
3.	European UV/VUV FEL at Elettra	Italy
4.	Duke University FEL Laboratory	US

IR FEL Facilities

1.	Jefferson Lab	US
2.	FELBE – FZD	Germany
3.	FELIX – FOM	Netherlands
4.	CLIO – LCP (Orsay)	France
5.	AIST/Kawasaki	Japan
6.	Budker Institute (BINP)	Russia

FEL research facilities – in construction

X/UV

1.	SCSS – SPring-8	Japan
2.	European XFEL	Germany
3.	Swiss FEL – PSI	Switzerland
4.	MAX-IV	Sweden
5.	FERMI@ Elettra	Italy

IR

1.	Fritz Haber Institute (FHI)	Germany
2.	FLARE – Radboud University	Netherlands
3.	ALICE – Daresbury	UK

FLARE THz FEL

FLARE – Radboud University, Nijmegen, Netherlands
Wavelength: 0.1-1.5 mm

Courtesy research instruments

Scale-up: LCLS (2009)

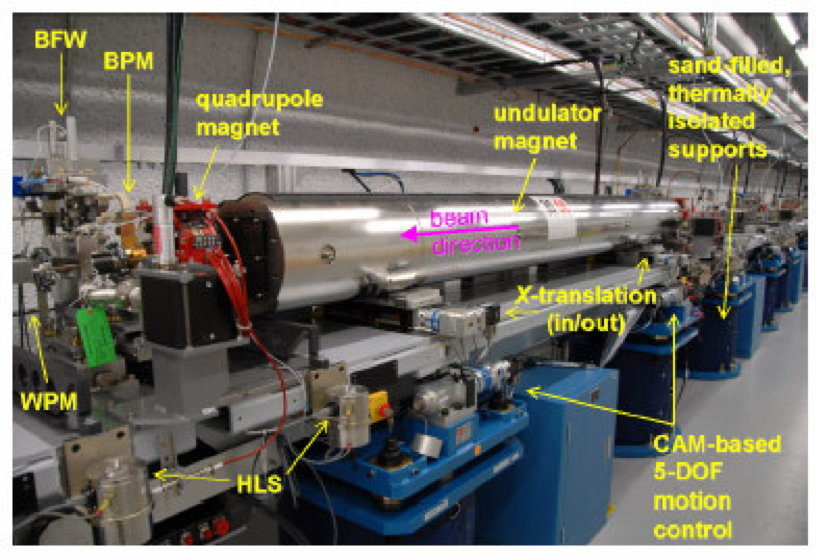
Record-short wavelength:

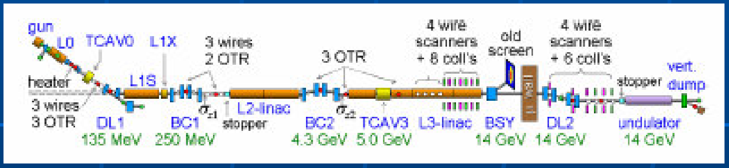
	FLASH (DESY)		LCLS
λ	**=6.5 nm**	**=>**	**0.15 nm**
E_{photon}	**=0.2 keV**	**=>**	**8 keV**

Scale-up ×40 in one blow

FEL technology is well understood!

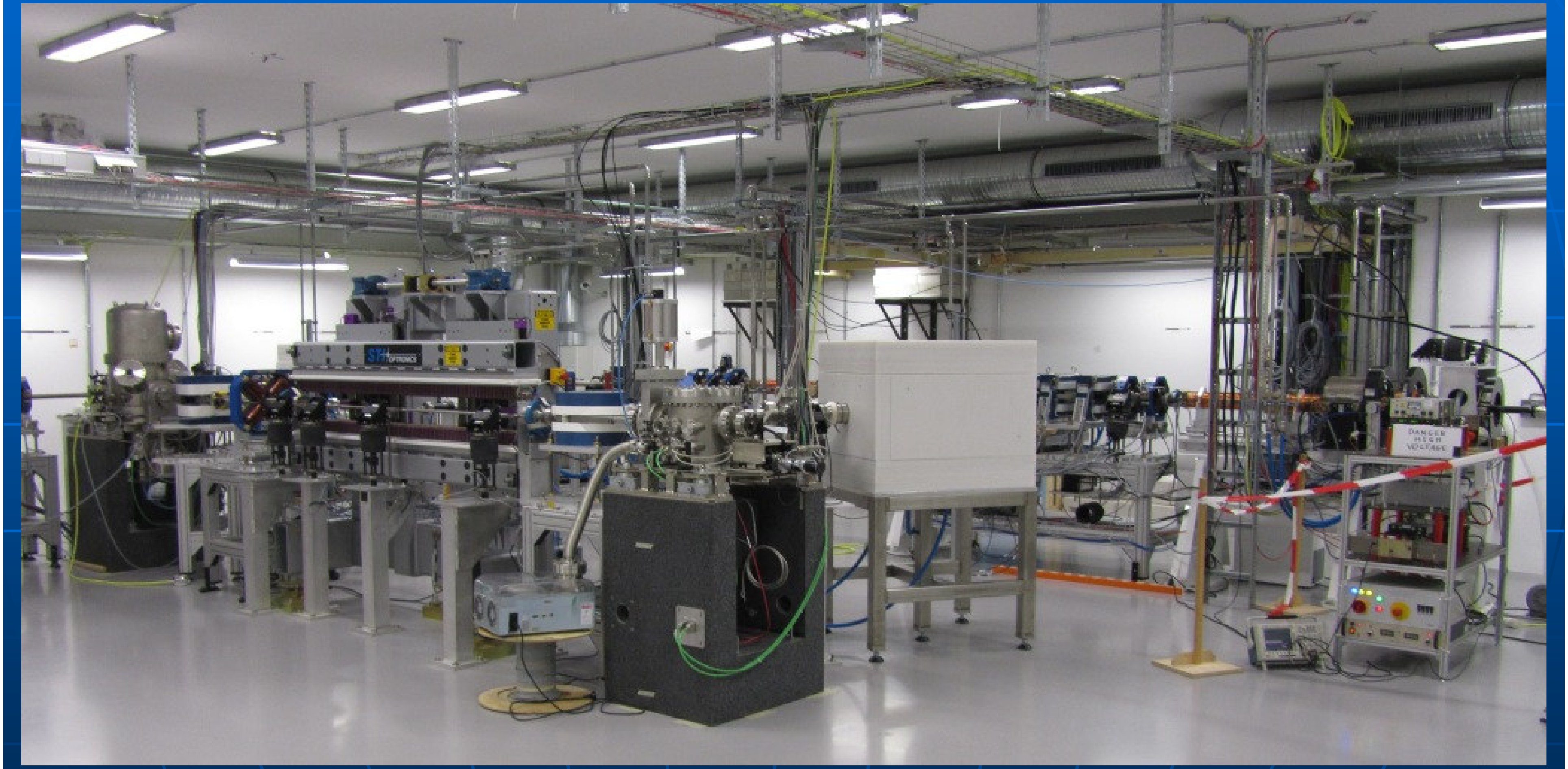
LCLS at SLAC





1 km

IR-THz FEL
at Fritz Haber Inst (Berlin)



Wavelength: 4-500 µm
P(peak)~10 MW
P(av)~10 W

In commissioning

Turn-key e-beamlime

Putting Accelerator Technology to Work

Advanced Energy Systems, Inc.

FEL Progress 1990-2010

Sub-system	***Progress***
Injection	Considerable
Acceleration	Major
FEL interaction	Considerable

Reliability up	RF sources e-beam control
Cost down	energy-recovery multi-turn accelerating RF sources control hardware

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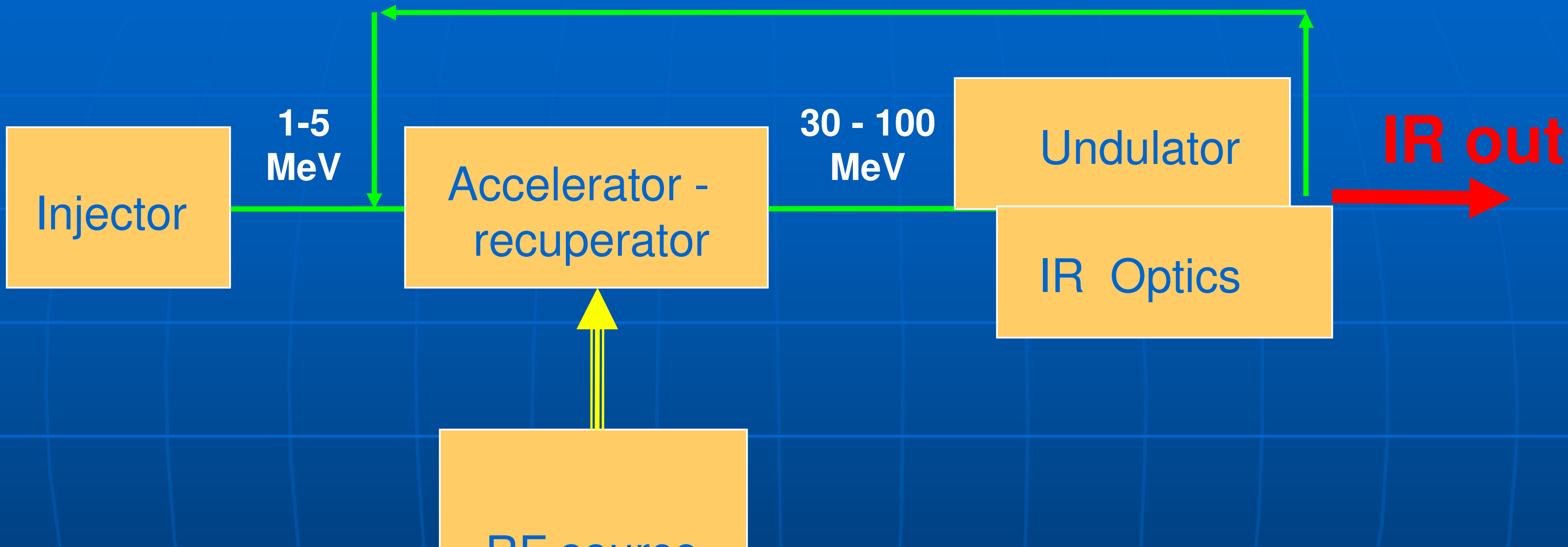
FEL Subsystems



Injector

1-5 MeV

Accelerator - recuperator

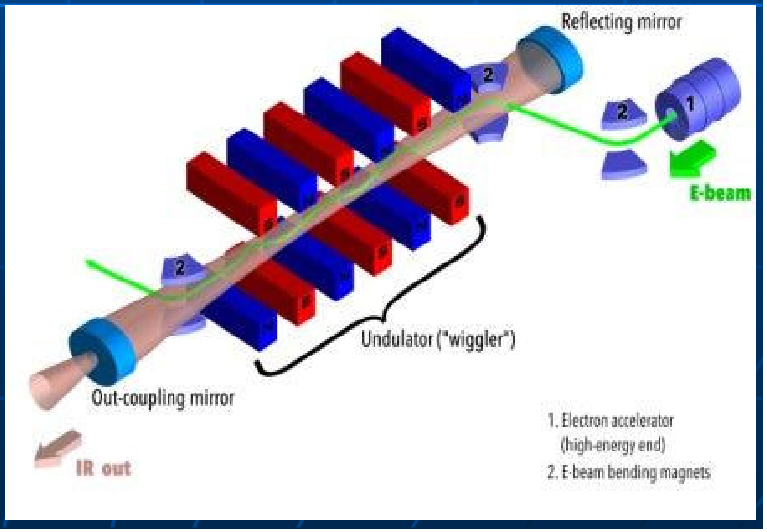
30 - 100 MeV

Undulator

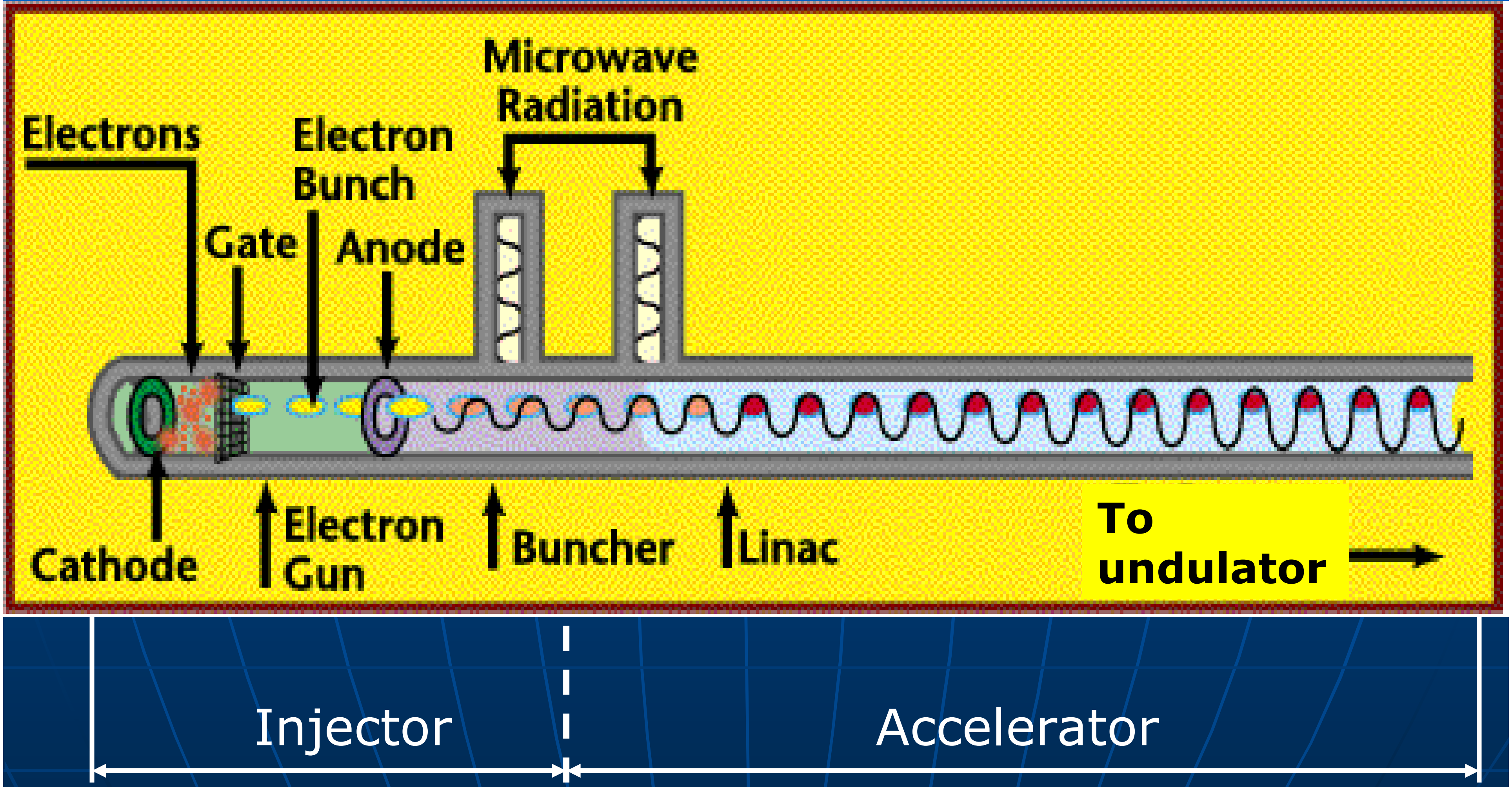
IR Optics

IR out

RF source

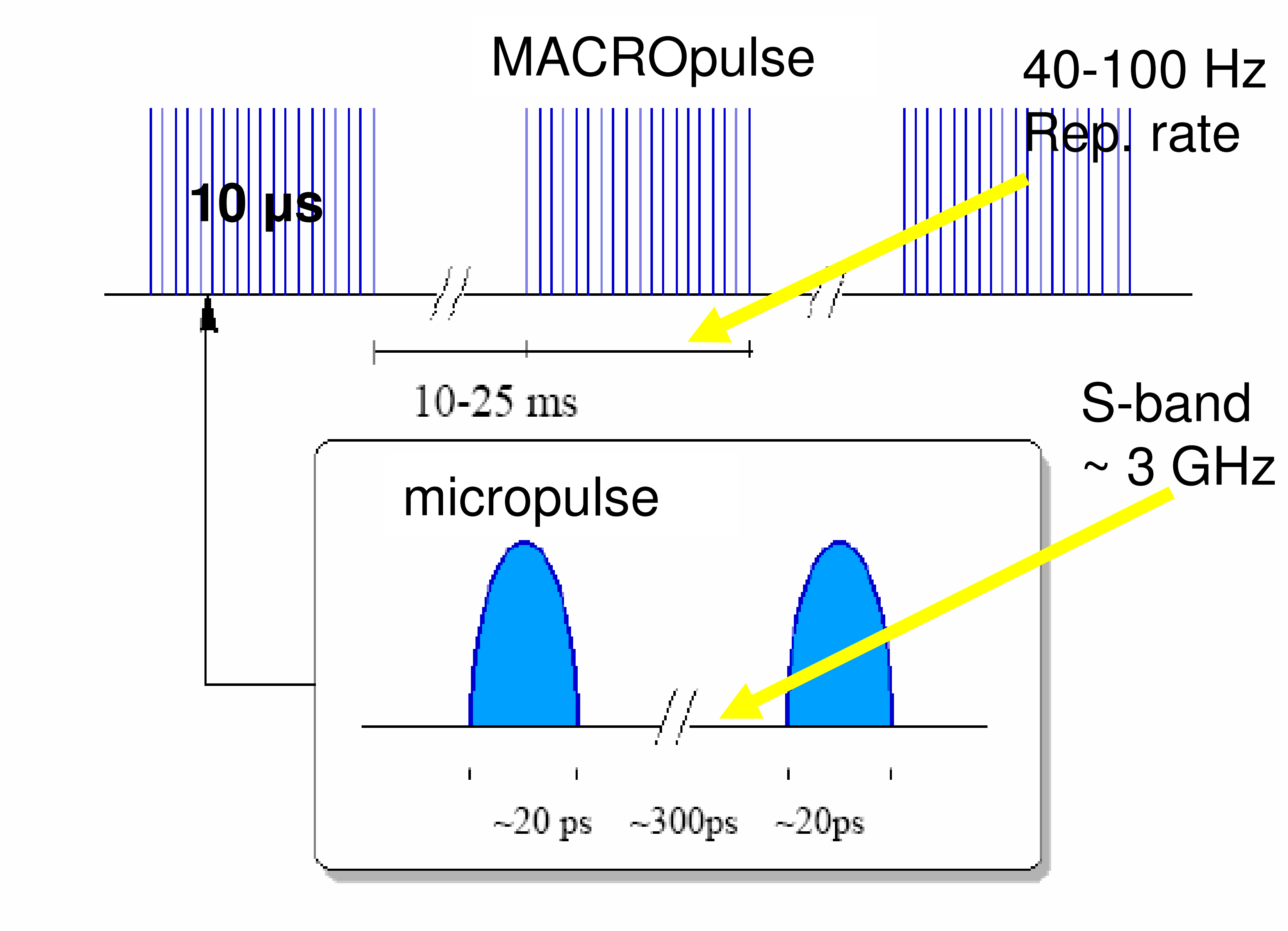


Electron acceleration system: RF-linac



RF-linac pulse structure

all numbers – for illustration only



FEL gain regimes

FEL single-pass gain (G)

$$G = [\, P(out) \,/\, P(in) \,]_{SINGLE\ PASS}$$

- Low gain G ~ 20-30%
- High (exponential) gain
  $G > 10^3$

FEL – operation modes

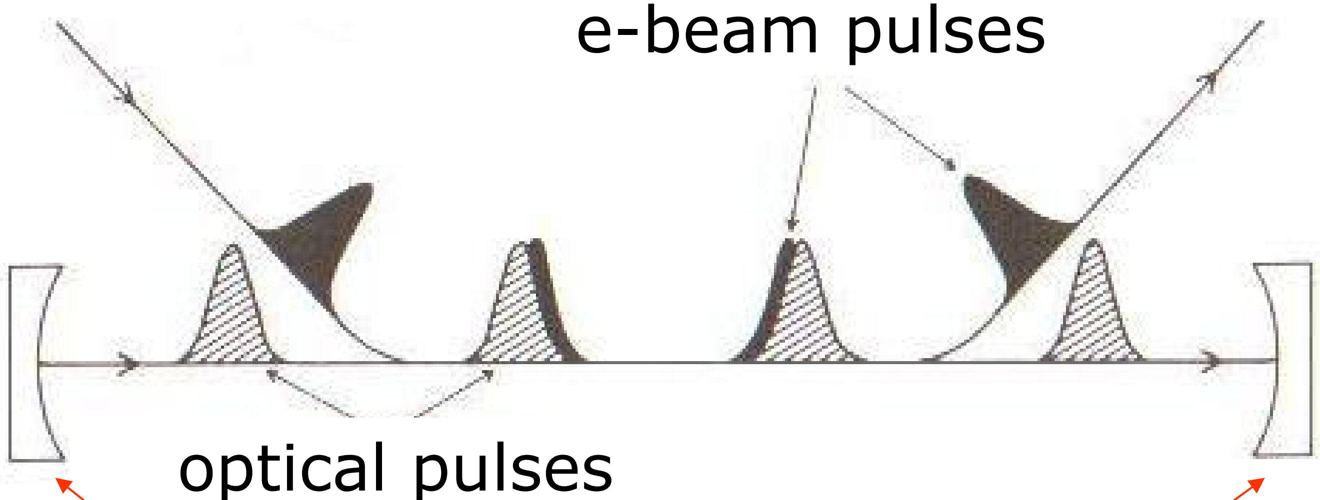
- Oscillator
  - Low-gain ~20% per pass
  - High-gain ~10^3 per pass

    Regenerative Amplifier FEL - RAFEL
- Amplifier
  - Seeded
  - Self-amplified spontaneous emission

    SASE

e-beam & optical pulses

oscillator / RAFEL



e-beam pulses

optical pulses

Mirrors – optical resonator

FEL – output power

$P(IR) \sim \eta \times P(e\text{-}beam)$

$P(e\text{-}beam) = I\,U \approx I\,E/e$

E – e-beam energy

U=50MeV, I=1A =>

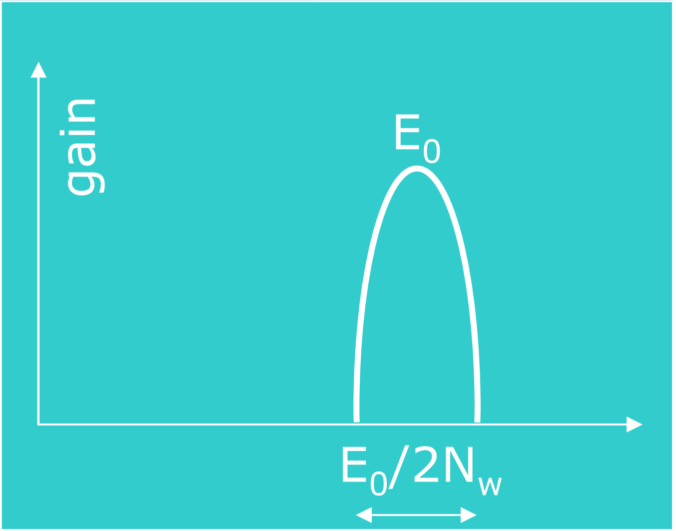
P(e-beam) =50 MW (!)

FEL – extraction efficiency η

- Low-gain regime: oscillator

  $P(IR) \approx P(e\text{-}beam) / 2N_w$

  $\eta \approx 1/2N_w \sim 2\text{-}3\%$



- High-gain regime: amplifier or "Regenerative Amplifier"

  $P(IR) \approx P(e\text{-}beam) \times \rho$ (ρ – "Pierce parameter")

  $\eta \approx \rho < 1\%$

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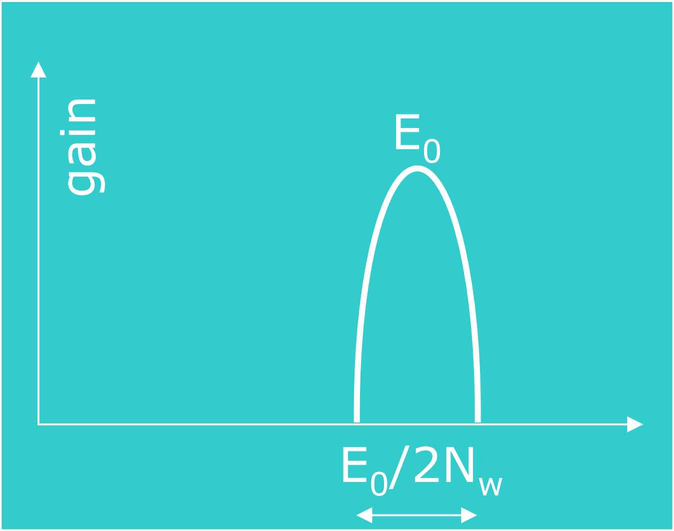
Wall-plug efficiency



Goal: 10%

$P(IR) \sim \eta \times P(e\text{-}beam)$

$\eta \sim$ 2-3% for oscillator

<1% for amplifier

Challenges:

1. **Low extraction efficiency**

(e-beam to optical energy)

2. **High RF losses in accelerator**

(cavity load)

Increasing Efficiency

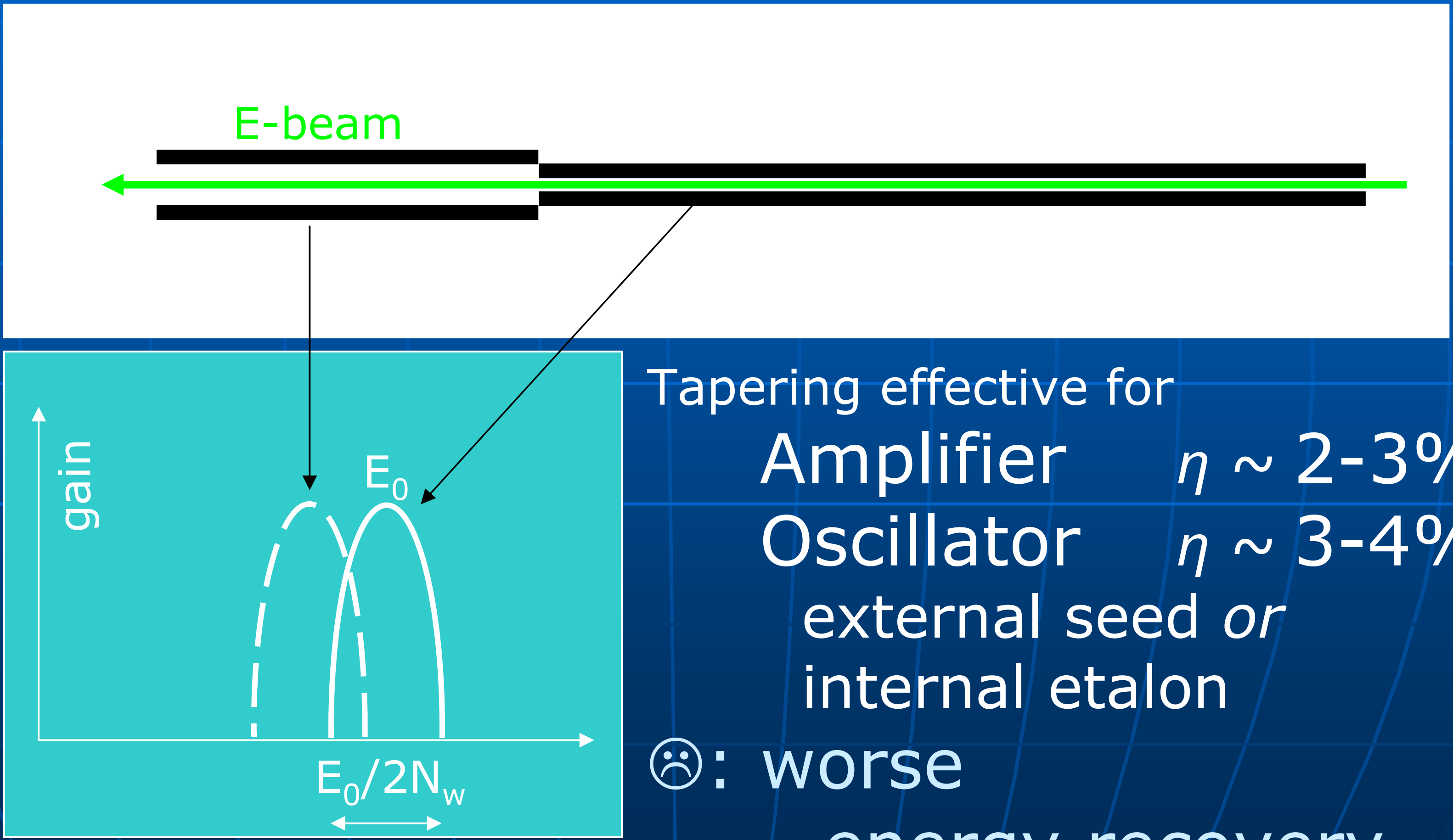
Low extraction efficiency

- Increasing extraction
- e-beam energy recovery

High RF losses in accelerator

- Decreasing RF losses

1. Increasing extraction: Tapered undulator



Tapering effective for

Amplifier $\eta \sim 2\text{-}3\%$

Oscillator $\eta \sim 3\text{-}4\%$

external seed *or*
internal etalon

☹: worse

energy recovery

higher e-beam energy spread

2. e-beam Energy Recovery

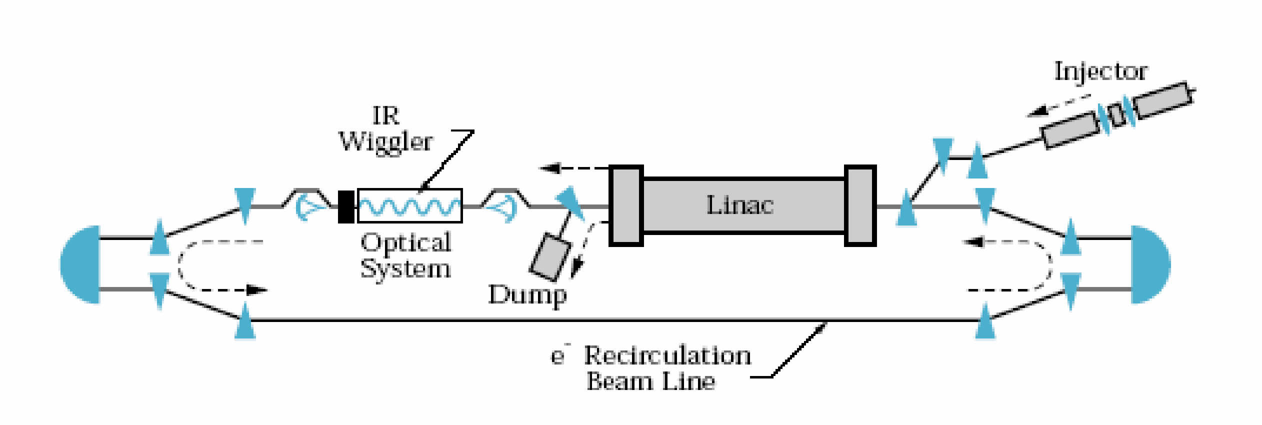
ERL – Energy Recovery Linac

20% RF-to-IR efficiency

<= 2% extraction + 90% recovery

50% DC-to-RF conversion =>

Overall efficiency ~10%



ERL FEL at Jefferson Lab (US)

3. Decreasing RF losses

RF power = e-beam load
+ Cavity Load (CL) => loss

$$CL = |E|^2 L / \rho = U^2/R$$

$$R = \rho L$$

$\rho \sim$ 5-10 MΩ/m at 180 MHz
$\rho \sim$ 50-65 MΩ/m at 3 GHz (S-band)
S-band: E=50MeV L=2m =>
CL = 20 MW (!)
w/o current !

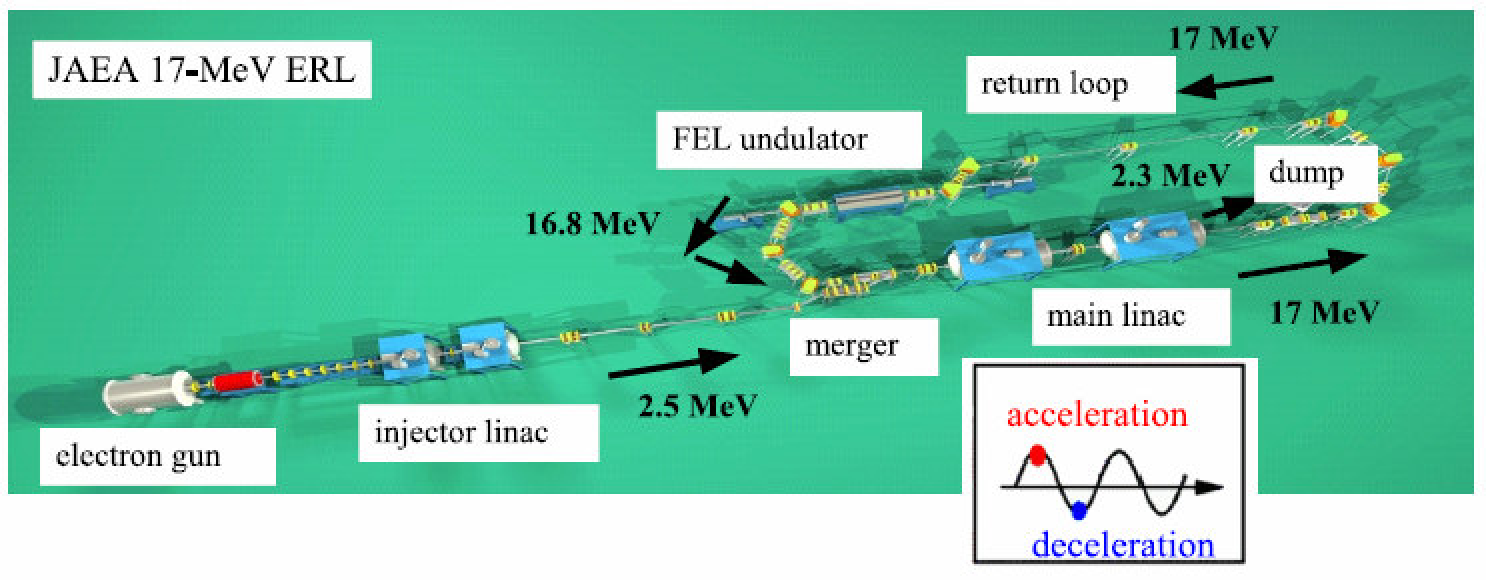
Solutions

A. Superconducting cavities
B. Multi-turn acceleration/recovery

A. SRF – superconducting RF linac

Drawbacks

- Higher cost (may be ×10)
- Power for cryo-cooling (~50kW CW for 10MeV)
- Bulky, low robustness



JAEA 1kW FEL (Japan)

B. “Warm” multi-turn Energy-Recovery Linac (ERL)

- Cavity load (CL) = U^2/R

2-turn ERL: 75% decrease in CL

$U_2=U_1/2$ =>

$CL_2 = CL_1/4$

$CL_3 = CL_1/9$

$CL_4 = CL_1/16$

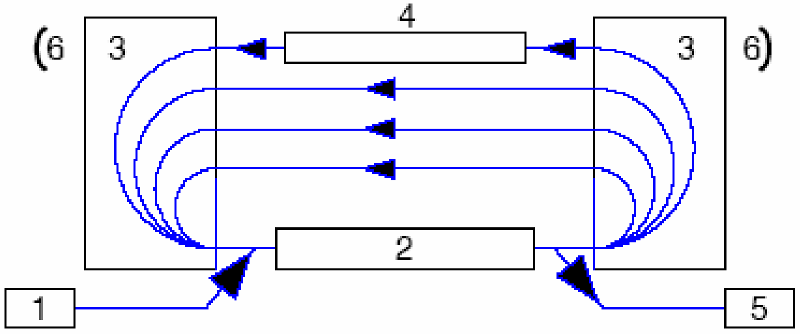


Figure 1: Scheme of the accelerator-recuperator based FEL. 1 - injector, 2 - accelerating RF structure, 3 - 180-degree bends, 4 – undulator, 5 – beam dump, 6 – mirrors of the optical resonator.

Multi-turn Energy-Recovery Linac (ERL)

Advantages

- Reduced size
- Reduced RF power
- Reduced cost

Problem

Complicated e-beam optics

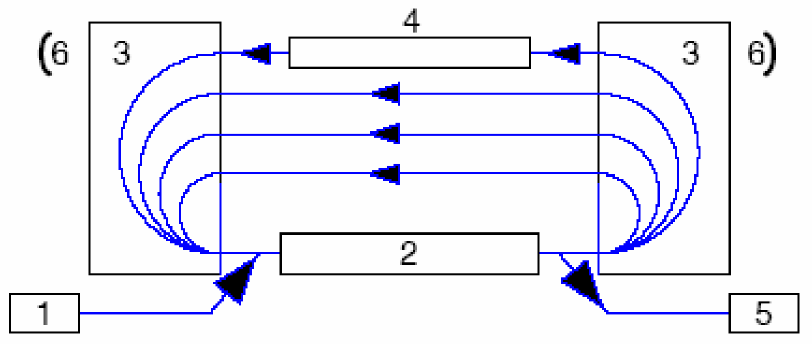
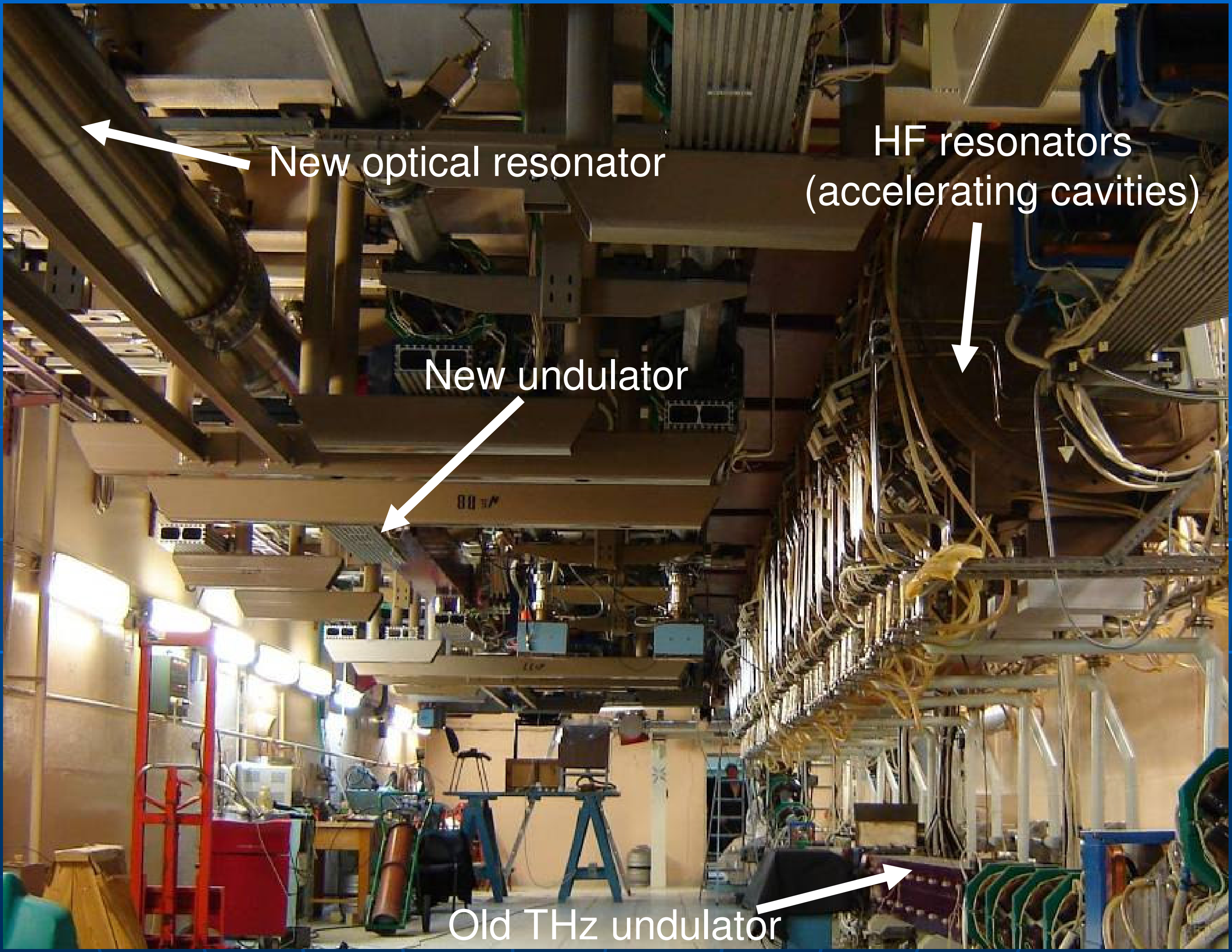


Figure 1: Scheme of the accelerator-recuperator based FEL. 1 - injector, 2 - accelerating RF structure, 3 - 180-degree bends, 4 – undulator, 5 – beam dump, 6 – mirrors of the optical resonator.

World-first multi-turn ERL FEL



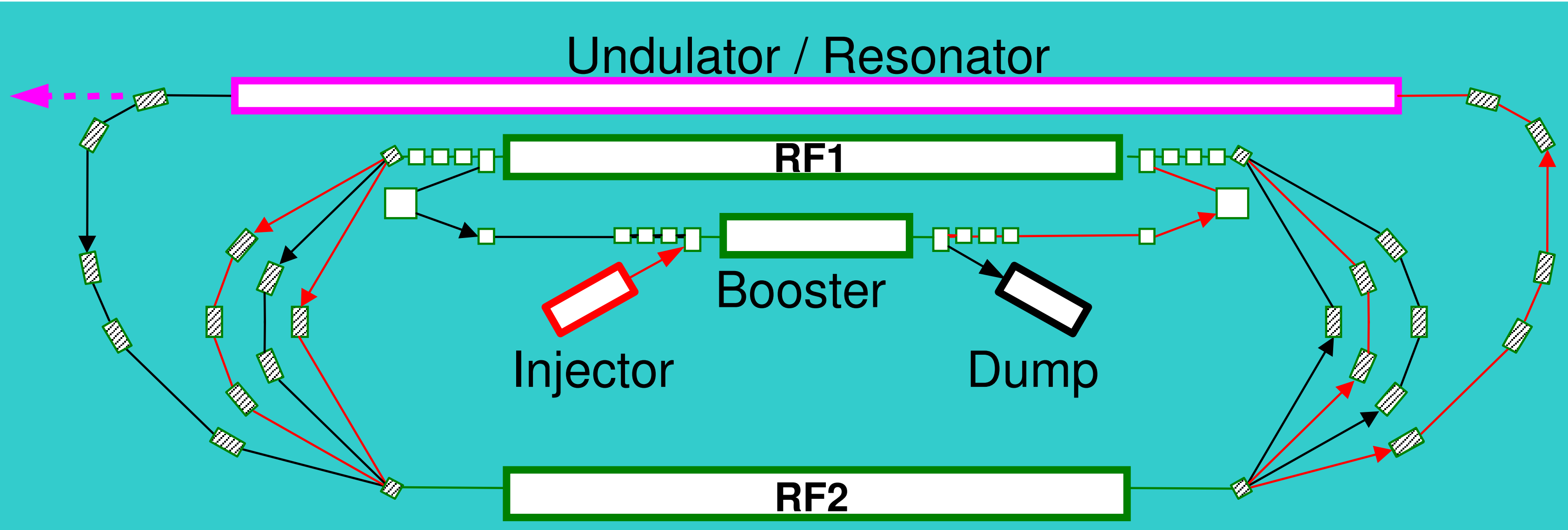
λ=40-240μm

>100kW peak

~0.5 kW average

Budker Institute of Nuclear Physics, Russia
Courtesy Prof. Vinokurov N.A.

Multi-turn **separate-track** ERL FEL



Y. Socol et al. *Phys. Rev. Spec. Topics – Accelerators & Beams 2011*
with Budker INP (Russia)
Helmholtz Zentrum Berlin

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FEL Subsystems

Injector

1-5 MeV

Accelerator - recuperator

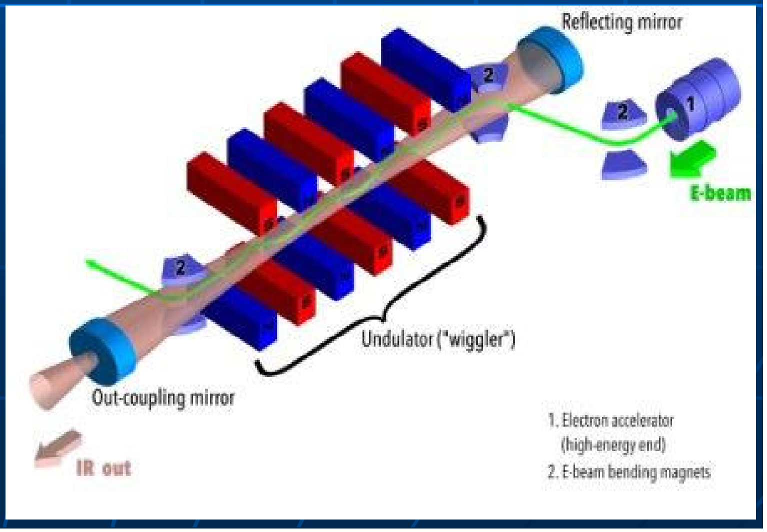
30 - 100 MeV

Undulator

IR Optics

IR out

RF source



“Bottlenecks” for high-power FEL

Injector

1-5 MeV

Accelerator - recuperator

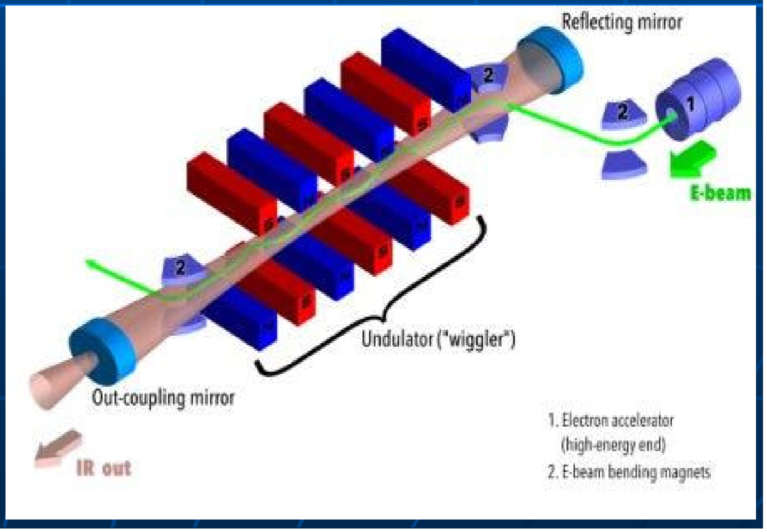
30 - 100 MeV

Undulator

IR Optics

IR out

RF source



“Bottlenecks” for high-power FEL

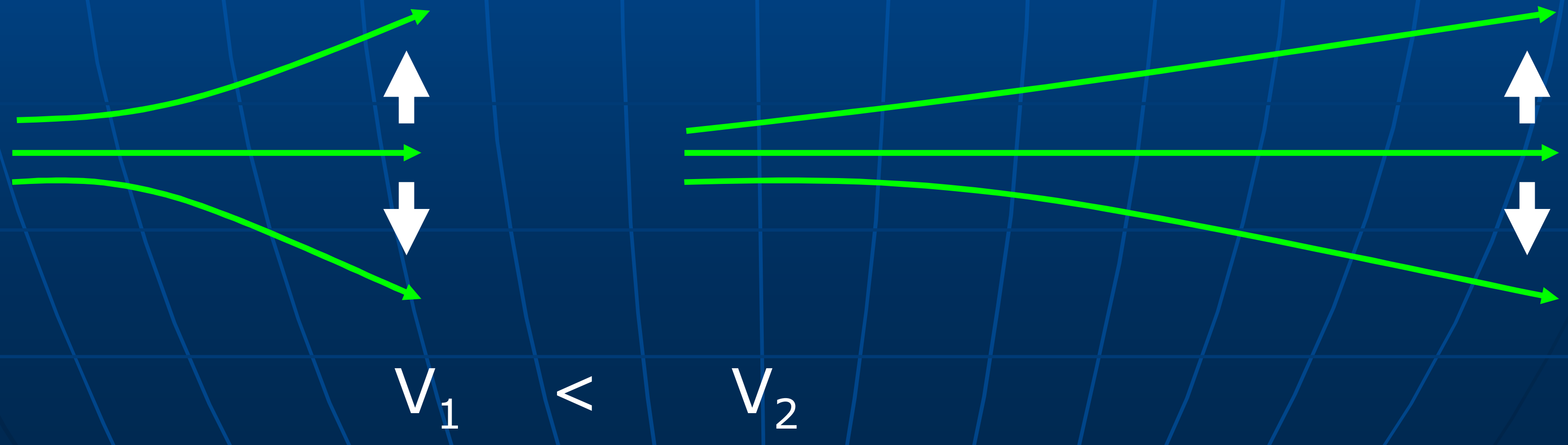
- Injector
  - High pulse current (>25 A)
  - Low energy spread (rms<0.5%)
    - Medical/industrial e-beams: rms ~ 5-10%
  - Low angular spread ($\Delta\theta\ \Delta r << \lambda$)
- IR Optics
  - High power density (> 10 MW / cm^2)
  - Presence of ionizing radiation

Why injector ?

- Space-charge e-beam spread
- “Emittance growth” –

  e-beam quality down

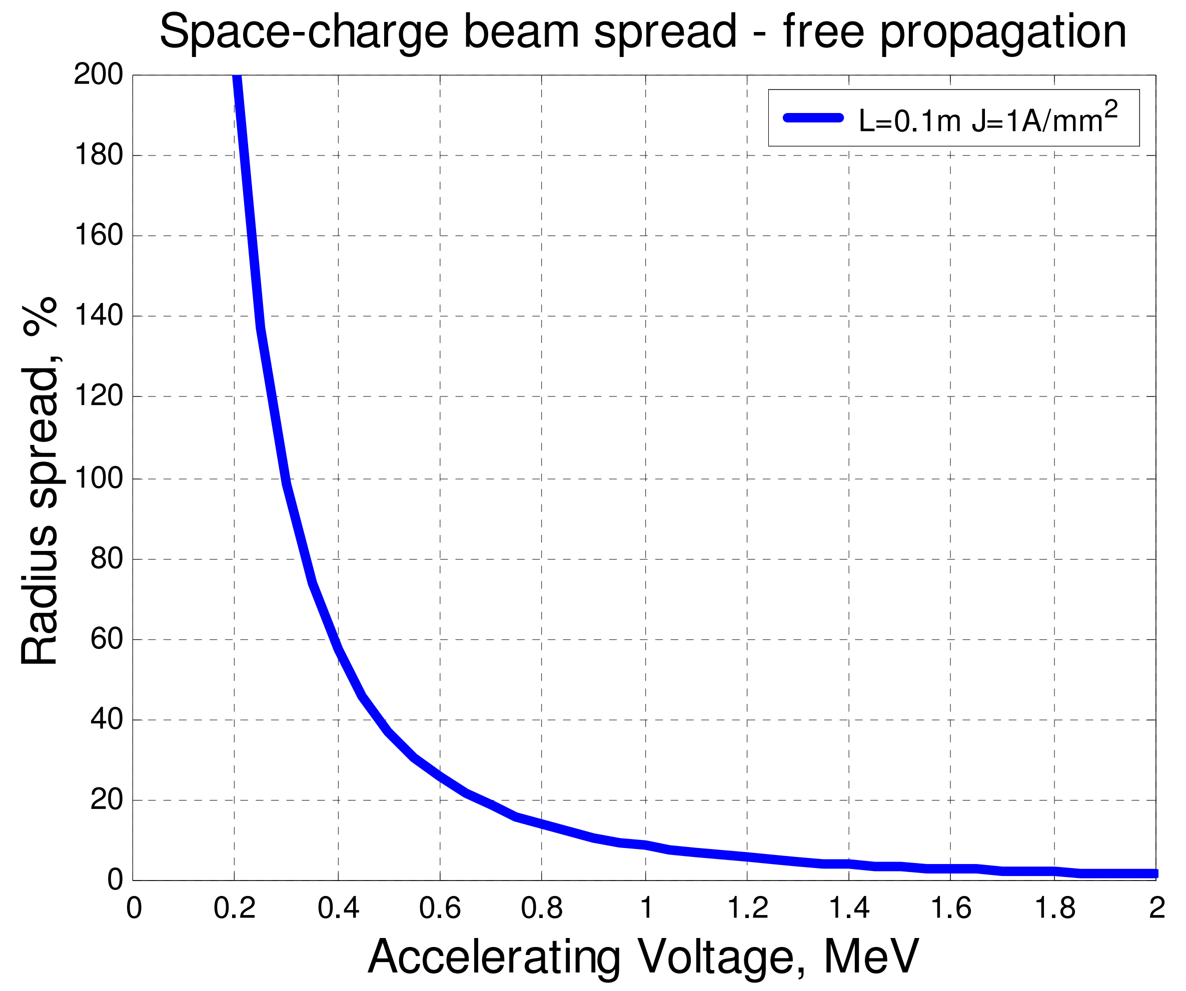
- Important at low energies



$V_1 < V_2$

Why injector ?

Space-charge: low energies



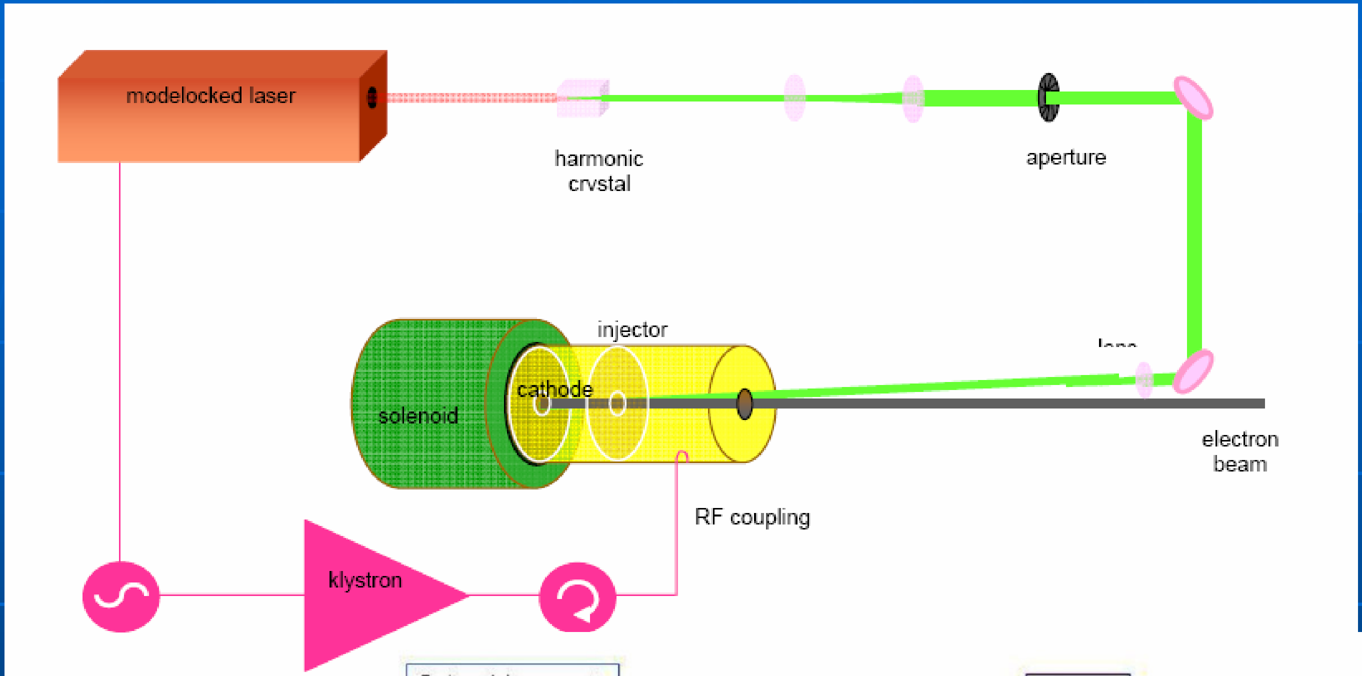
Injector => cathode

- Thermionic cathode
  - Limited current
  - Limited e-beam quality

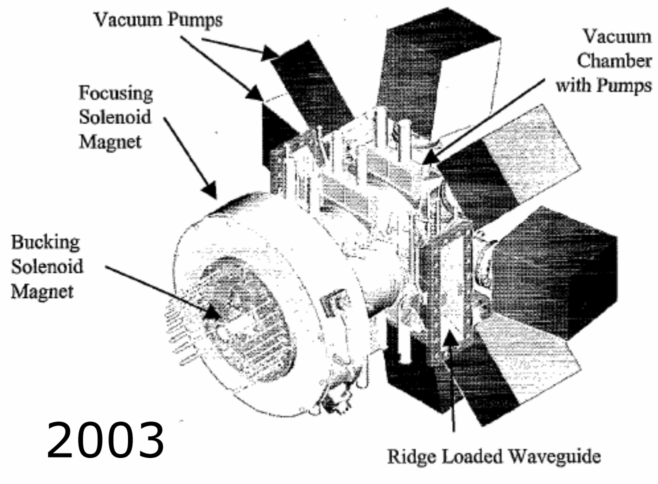
    acceptable for IR-FEL

- Photo-cathode
  - Low working time (~ hours)
  - Low stand-by time (days to weeks)
  - Size, complexity, cost (~M$)

Los-Alamos photo-cathode gun

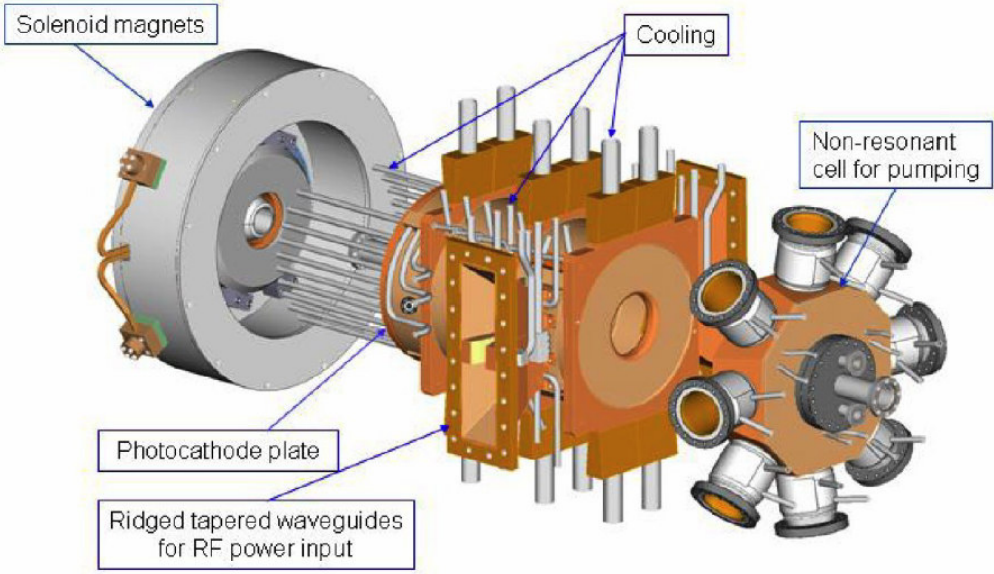


2008



2003

Figure 3. Normal-conducting CW 2½-cell RF gun.

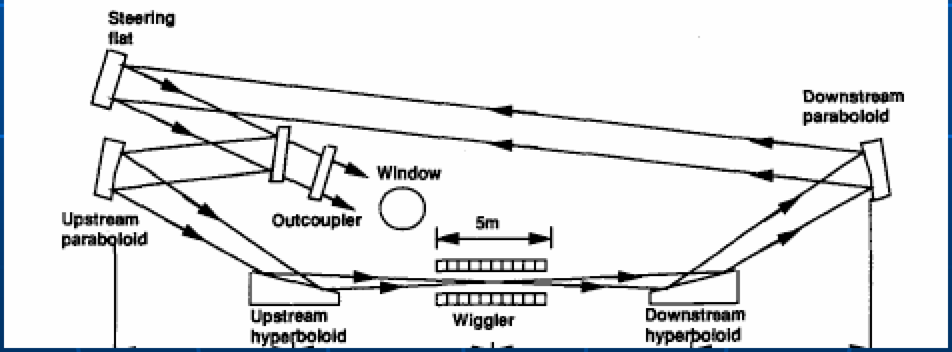


IR Optics – power handling

Problem: high flux + ionizing radiation

Anticipated solutions

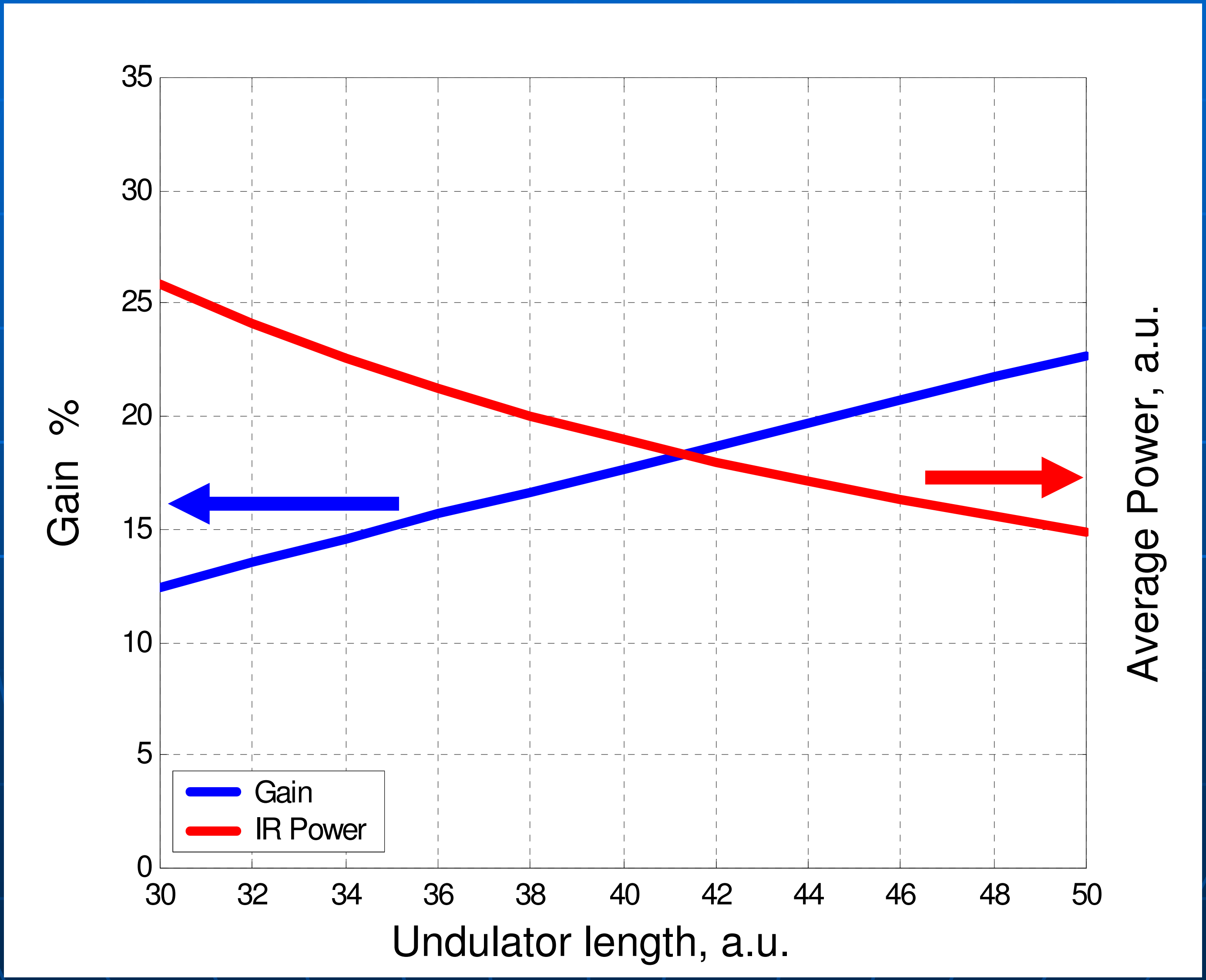
- Beam-expanding at grazing incidence



D. Dowell, IEEE J. Quant. Electr. 1991

- Metal mirrors or gratings

System: power-gain trade-off



More system problems

(partial list)

- Vibrations
  - Optical resonator
  - RF-linac
  - Liquid helium (for cryo-systems)
- Ionizing radiation

Ionizing radiation problem

P(IR)=1MW

I=1A (E=50MeV η=2%)

Interception 10^{-4} => I(eff)=0.1 mA

$D=D' I(eff)t/L^2$

D'(50MeV)~10^5 R m^2/A s

- t = 10 s
- L= 10 m – distance to crew members

D (pulse) = 1 R

D (permit) = 5 R/year!

typical shielding: 10-20 cm Fe (Pb)

1000-2000 kg/m^2

Radiation risk in perspective

- 350 R exposure: LD_{50} (if no treatment)
- 100 R

  First signs of radiation illness – vomiting, fatigue, nausea

  Life expectancy 82 -> 81.5 years
- 10 R

  Life expectancy 82 -> 81.95 (may be)

Radiation – curious facts

- I'm radioactive;
  You're too!
  - ^{14}C is present in air, plants & all living
- US FDA: non-radioactive spirits – not suitable for human consumption!

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Military and Aerospace:
US Directed Energy Weapons

Army	Navy	Air Force
↓	↓	↓
Solid state laser	FEL	Chemical laser

Navy FEL Program

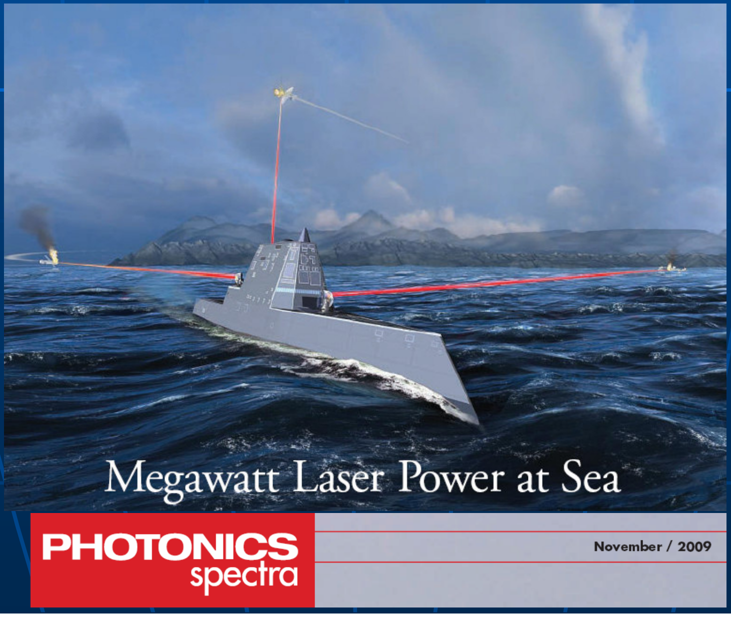
Goal : 100kW CW

Cost : $ 163M

2011: $ 23M

Boeing

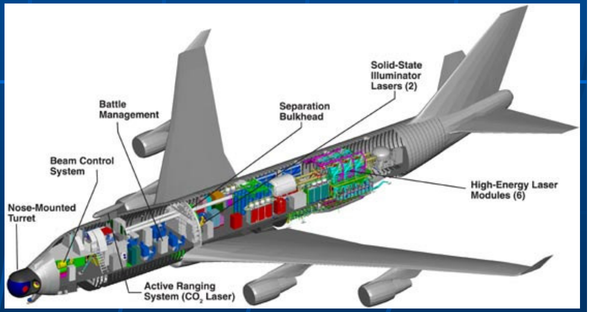
Future: 1MW CW



Megawatt Laser Power at Sea

PHOTONICS spectra

November / 2009



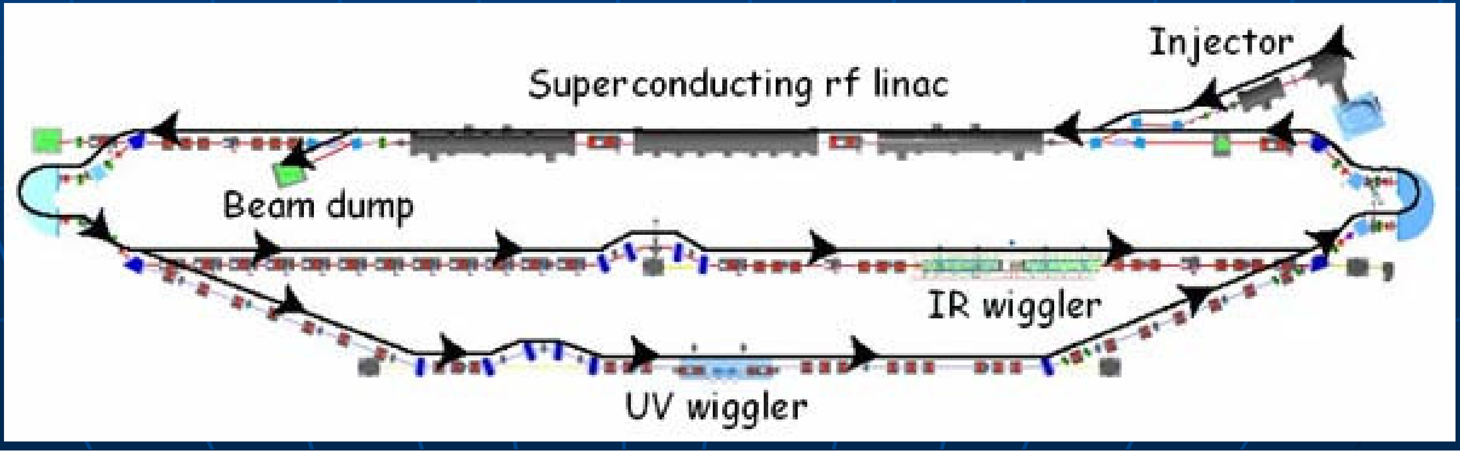
Airborne Laser (ABL)

COIL

US Navy FEL Program

Thomas Jefferson National Accelerator Facility

Year	2004	2006
Power (average), kW	10	14.2
Wavelength, µm	6.0	1.6
Duration, s	~20	~30
Achieved	once	once



US Navy FEL Program

Goal: 100kW CW (lab prototype)

Cost: $ 163M

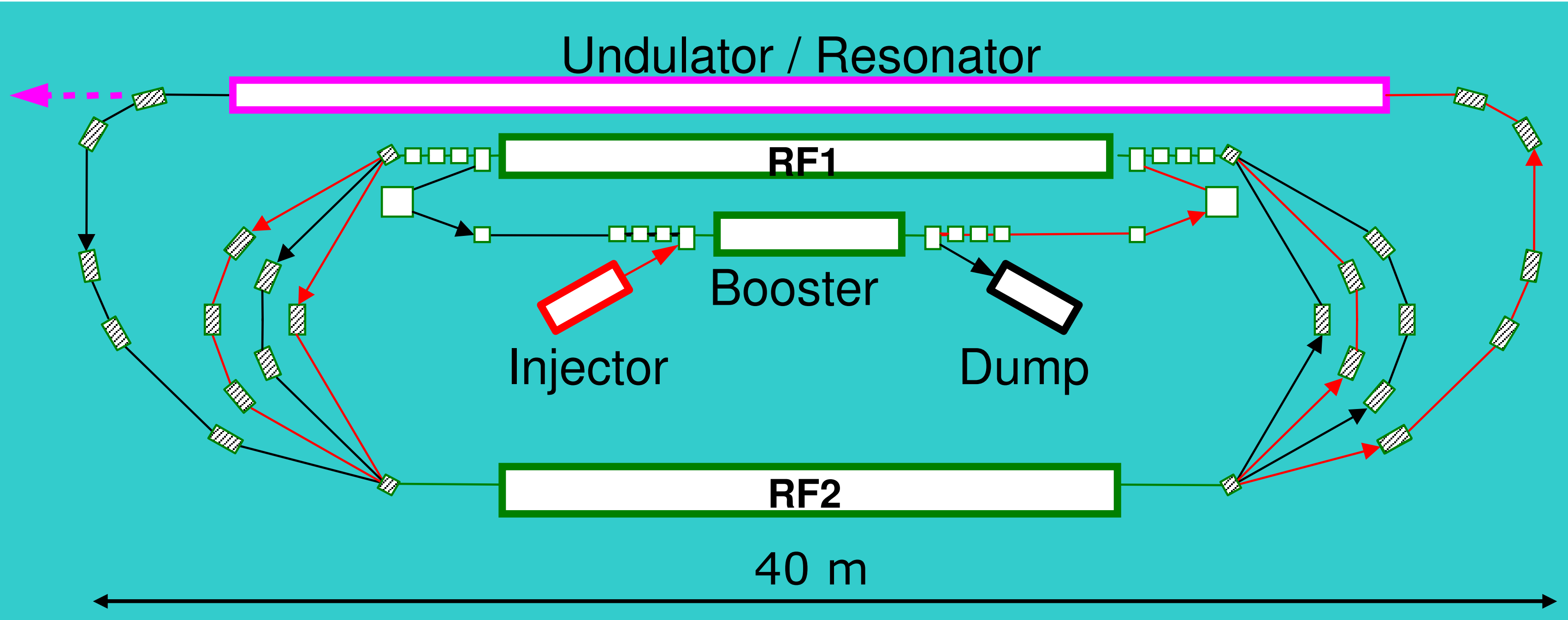
2009-2010: 2 x 7 M$
to Boeing & Raytheon

2011: $ 23M
to Boeing (design only)

Final goal: 1MW CW

Megawatt Laser Power at Sea

13.5-nm FEL for EUV lithography



Y. Socol et al. Phys. Rev. ST Accel. Beams **14**, 040702 (2011).

with Budker INP (Russia)

Helmholtz Zentrum Berlin

Photo-chemistry

- Surface treatment
- Nanotube synthesis
- Isotope separation
- ?

FEL advantages

- Tuned photons in IR-UV
- 2-photon reactions
- Ultra-short (<1ps) pulses

Anticipated trends – high-power

"It is difficult to make predictions, especially about the future"

Mark Twain ?

- Warm (normal-conducting) accelerators
- Thermionic cathodes

Conclusions

- FEL – unique tunable all-electric laser

- Breakthrough 2009-10:

  1) technological maturity proven

  2) multi-turn scheme =>

  reduced size, weight, cost

- Further progress anticipated