USPAS Course
on
Recirculated and Energy Recovered Linear Accelerators

G. A. Krafft and L. Merminga

Jefferson Lab

and

Ivan Bazarov

Cornell University

Lecture 16

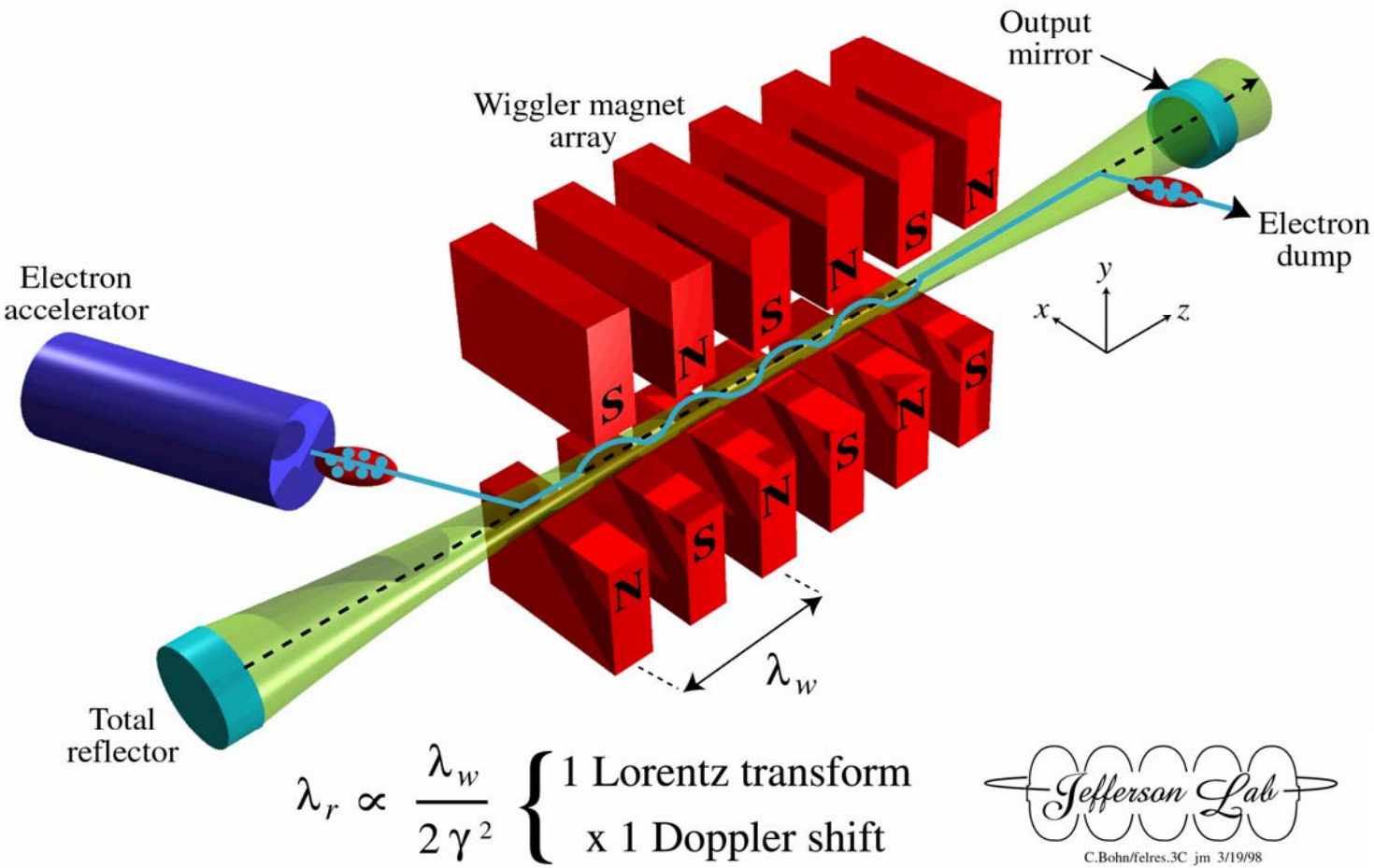
ERL-Based Free Electron Lasers

- Introduction
- Operating ERL-FELs
  - Jefferson Lab
  - JAERI
  - BINP
- Planned ERL-FELs
  - KAERI
  - 4GLS
  - NHFML
  - ARC-EN-CIEL
- An Advanced ERL-FEL Concept
  - TESLA XFEL-ERL
- Summary

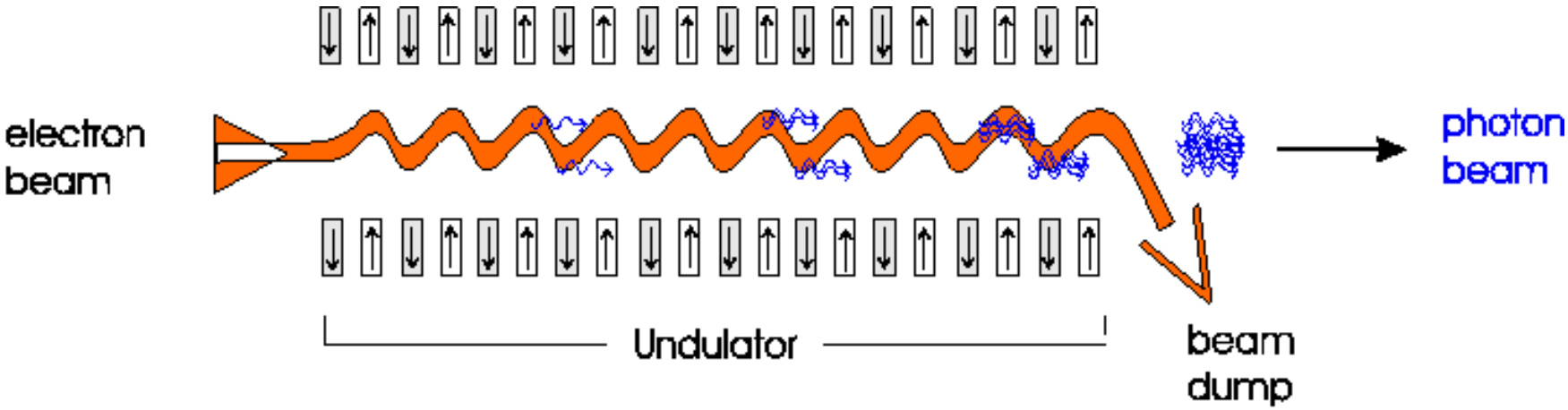
Free Electron Lasers

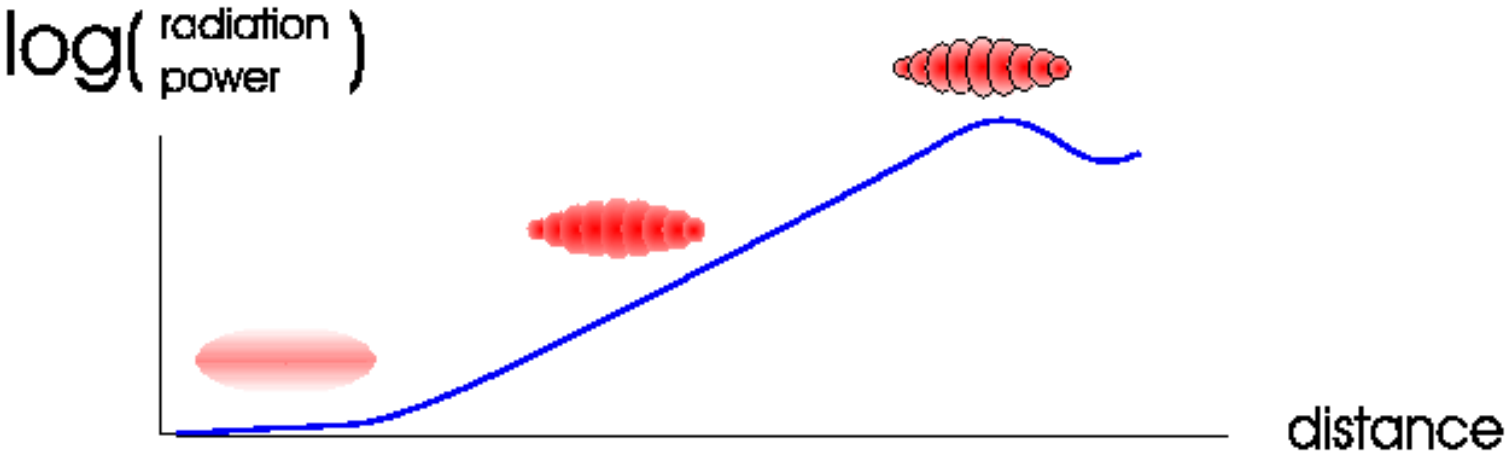
- Free Electron Lasers (FELs) are sources of tunable, coherent radiation at wavelengths varying over a wide range from mm to IR to UV and VUV and to X-rays
- An FEL consists of an electron accelerator and a wiggler magnet
- Two FEL configurations:
  - Oscillator
  - Amplifier

FEL in Resonator Configuration



FEL in Amplifier Configuration





Electron Beam Requirements

- FELs impose stringent requirements on the electron beam characteristics:
  - Energy is determined by the required wavelength via the resonance condition

$$\lambda_r = \frac{\lambda_w (1 + K^2)}{2\gamma^2}$$

  - Average current is determined by the required FEL output power, for a given wiggler design

$$P_{FEL} = \eta_{FEL} I_{ave} E_{beam}$$

Electron Beam Requirements (Cont'd)

- Bunch charge and bunch length are determined by the peak current required for sufficient gain
- Emittance and energy spread are determined by the FEL interaction:

→ For optimum coupling, the optical beam must overlap the electron beam through the wiggler

$$\varepsilon \leq \frac{\lambda_r}{4\pi}$$

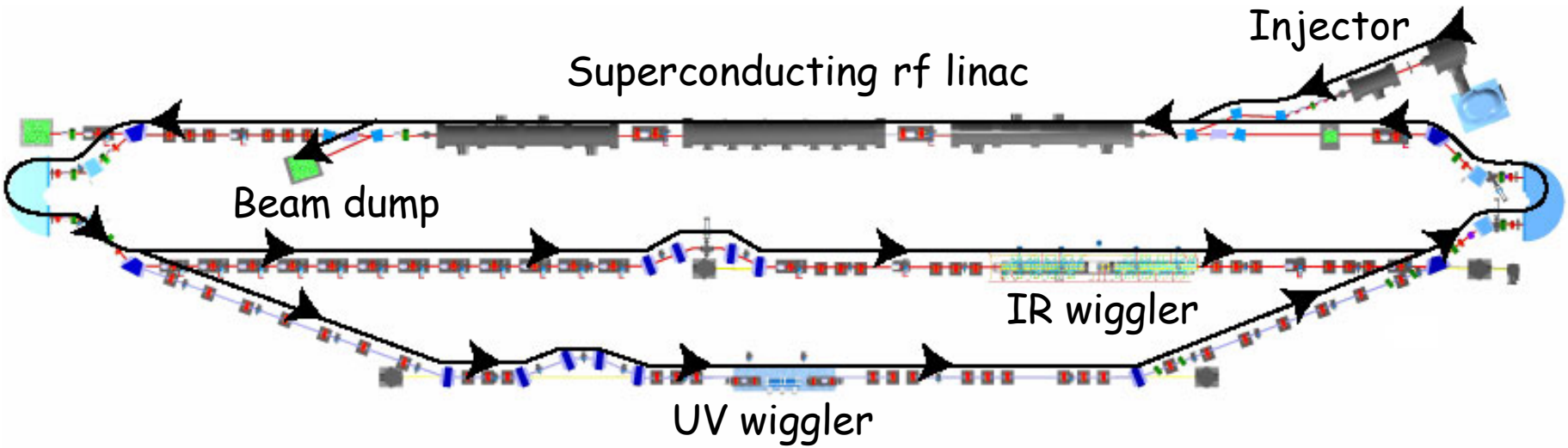
→ To ensure all electrons radiate within the bandwidth of the FEL

$$\frac{\sigma_E}{E} \leq \frac{1}{5N_w}\ \text{(osc.)}, \qquad \frac{\sigma_E}{E} \leq 10^{-4}\ \text{(ampl.)}$$

Operating ERL-FELs

- Jefferson Lab FEL
- JAERI FEL
- BINP FEL

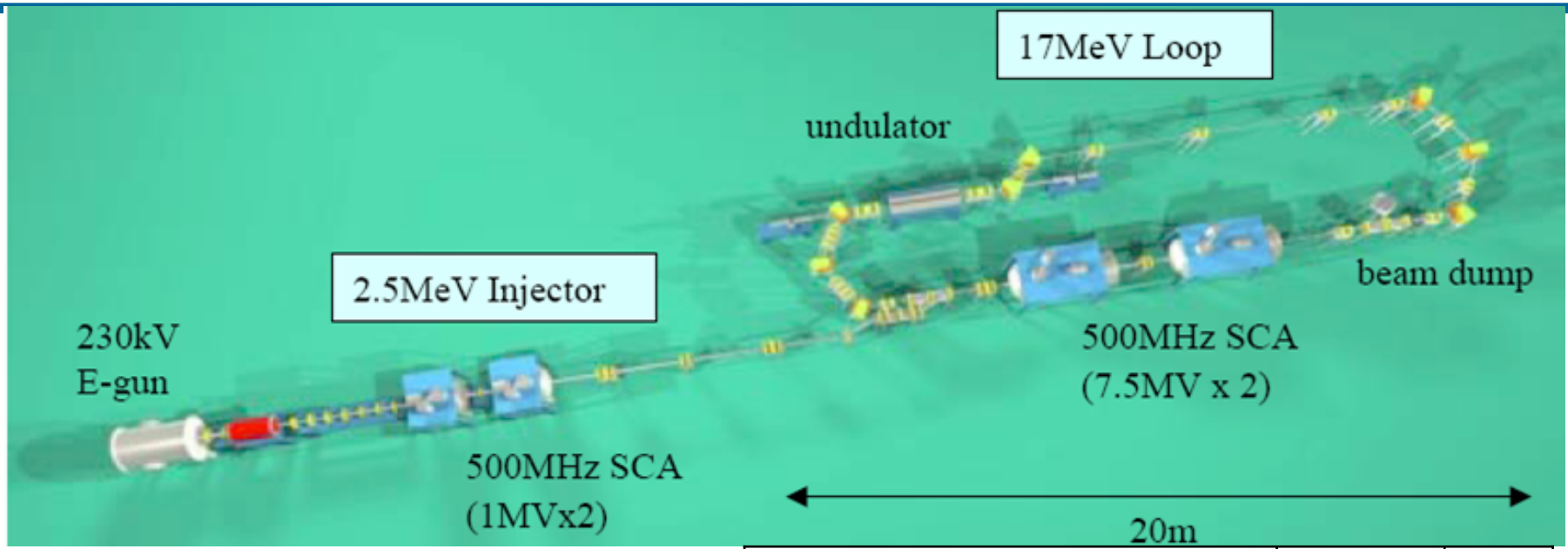
JLab 10kW IR FEL and 1 kW UV FEL



Output Light Parameters	IR	UV
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser power / pulse (microJoules)	100 - 300	25
Laser power (kW)	>10	> 1
Rep. Rate (cw operation, MHz)	4.7 – 75	4.7 – 75

Electron Beam Parameters	IR	UV
Energy (MeV)	80-200	200
Accelerator frequency (MHz)	1500	1500
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50	0.13
Normalized emittance (mm-mrad)	<30	<11
Induced energy spread (full)	10%	5%

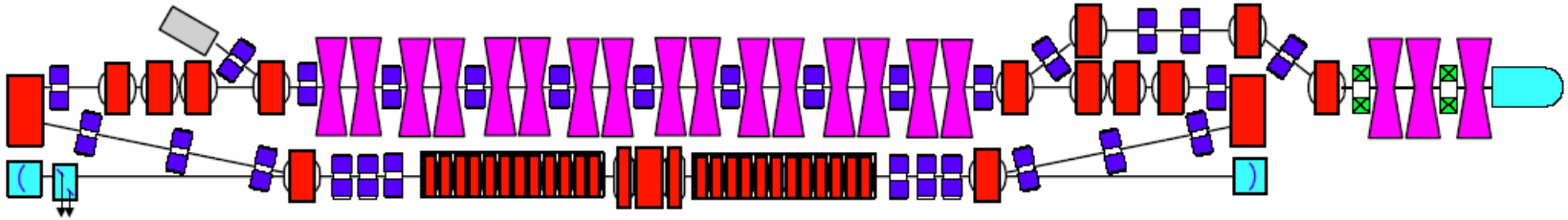
JAERI ERL-FEL



Output Light Parameters	Achieved	Goal
Wavelength range (microns)	22	22
Bunch Length (FWHM psec)	15	6
Laser power / pulse (microJoules)	10	120
Laser power (kW)	0.1	10
Rep. Rate (MHz)	10.4	83.2
Macropulse format	10ms 10Hz	CW

Electron Beam Parameters	Achieved	Goal
Energy (MeV)	17	16.4
Accelerator frequency (MHz)	500	500
Charge per bunch (pC)	500	500
Average current (mA)	5	40
Peak Current (A)	33	83
Beam Power (kW)	85	656
Energy Spread (%)	~0.5	~0.5
Normalized emittance (mm-mrad)	~40	~40
Induced energy spread (full)	~3%	~3%

BINP Recuperator FEL



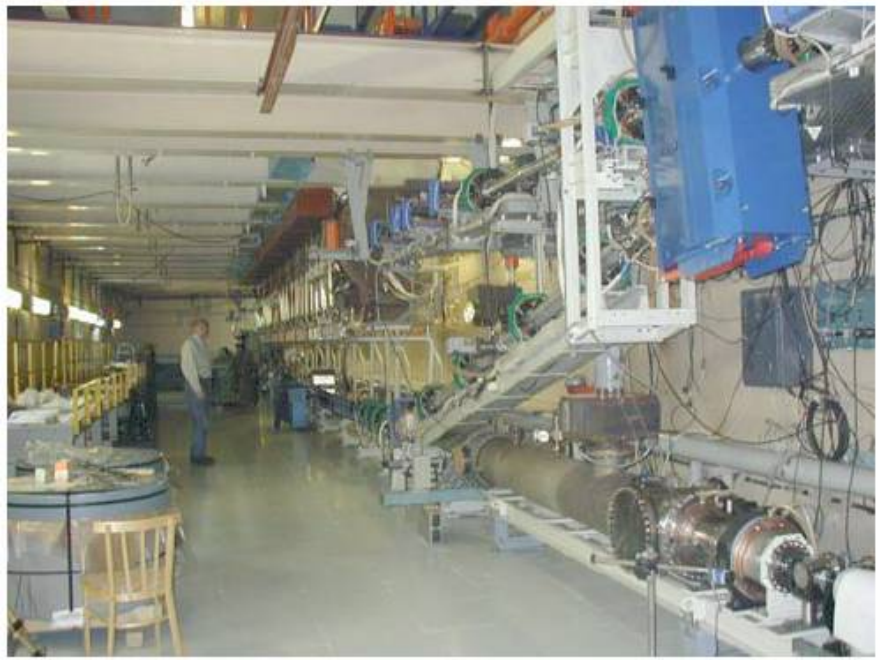
RF-Cavities Bending Magnets Quadrupoles Solenoids

Undulators Buncher Mirrors Outcoupler

Output Light Parameters	IR
Wavelength range (microns)	120-180
Bunch Length (FWHM psec)	50
Laser power / pulse (microJoules)	9
Laser power (kW)	0.2
Rep. Rate (cw operation, MHz)	22.5

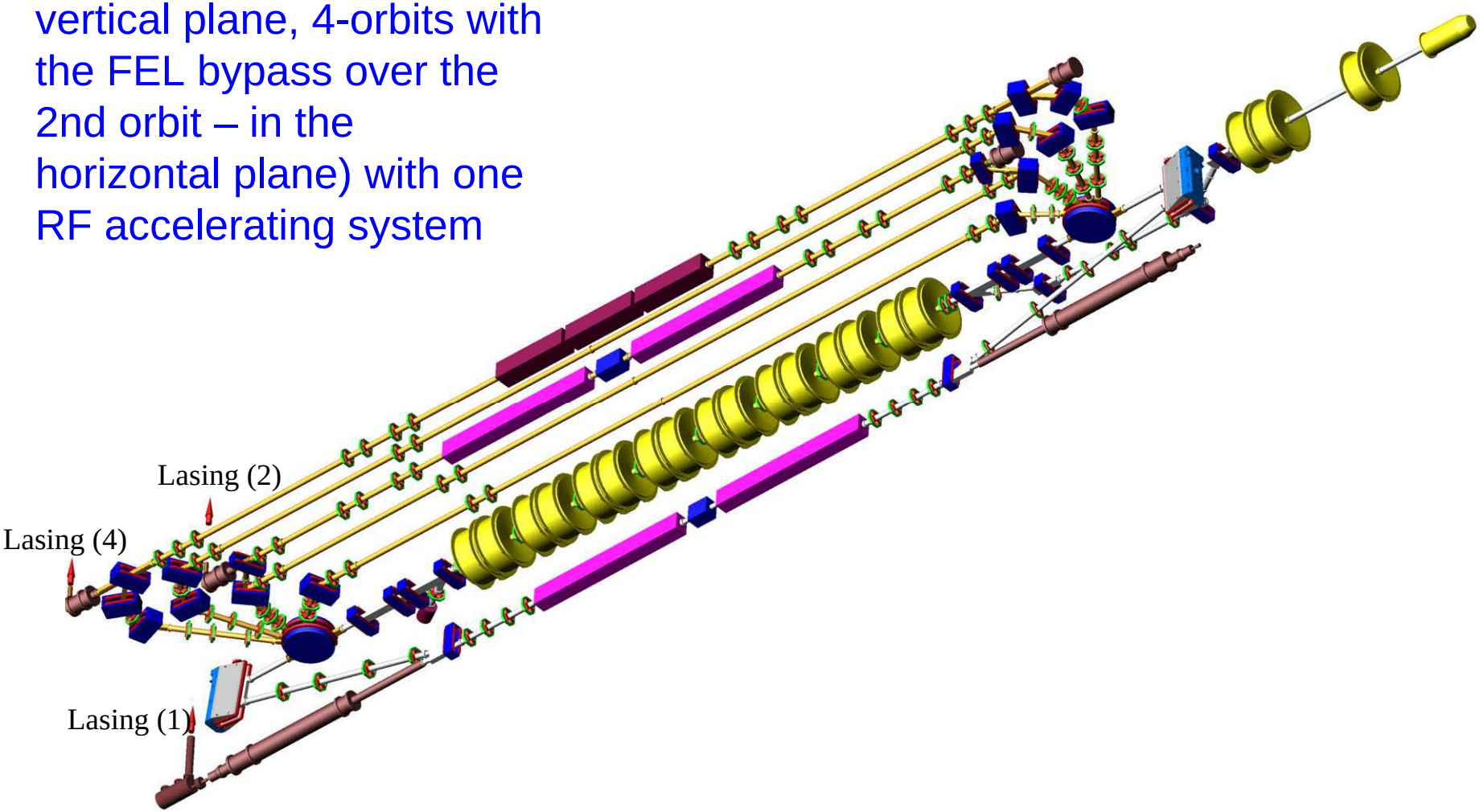
Electron Beam Parameters	IR
Energy (MeV)	12
Accelerator frequency (MHz)	180
Charge per bunch (pC)	900
Average current (mA)	20
Peak Current (A)	10
Beam Power (kW)	240
Energy Spread (%)	0.2
Normalized emittance (mm-mrad)	20

180 MHz NC RF



BINP ERL-FEL

Two ERLs (1-orbit in vertical plane, 4-orbits with the FEL bypass over the 2nd orbit – in the horizontal plane) with one RF accelerating system



Planned ERL-FELs

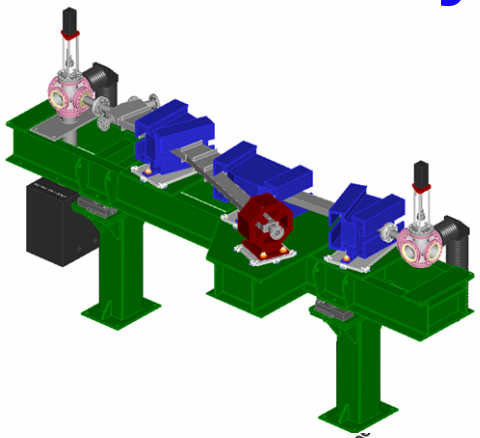
- KAERI FEL
- 4GLS
- NHMFL
- ARC-EN-CIEL

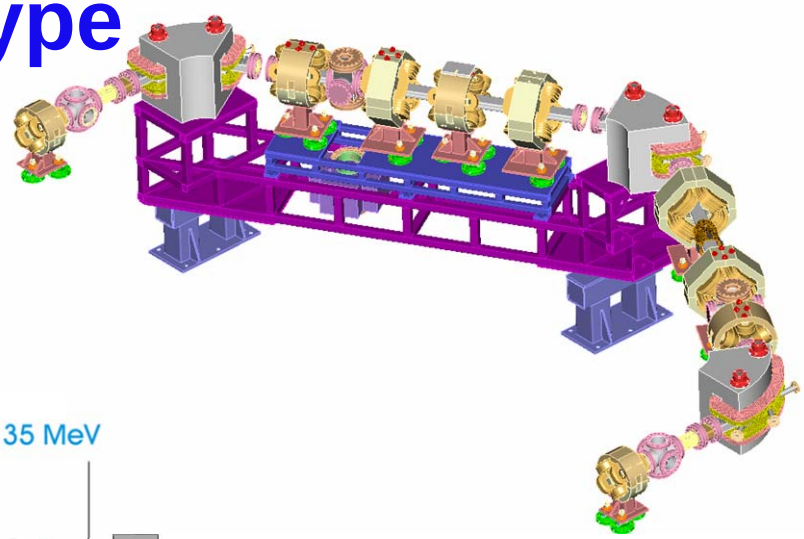
KAERI FEL

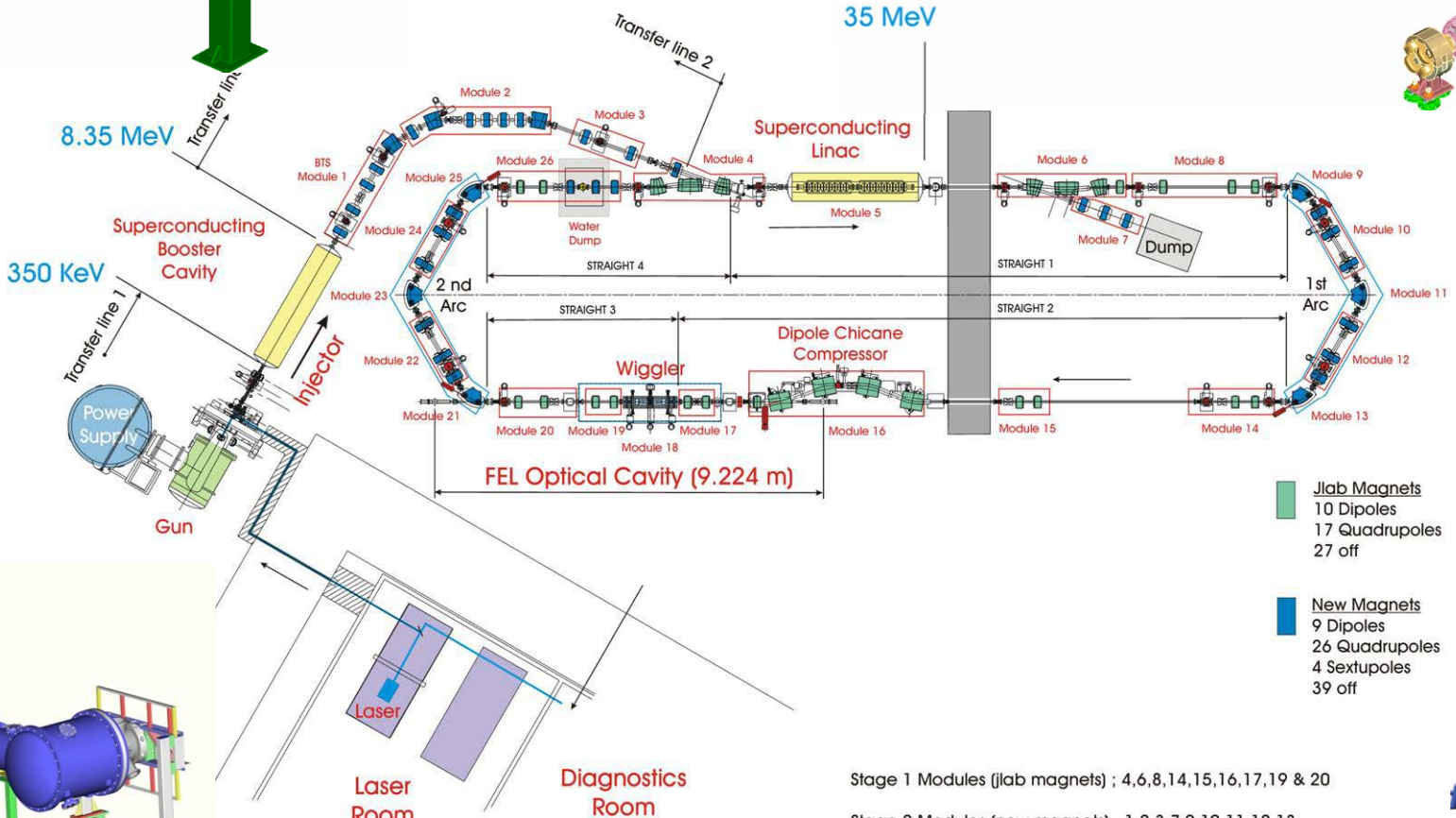
Output Light Parameters	Goal
Wavelength range (microns)	3-20
Bunch Length (FWHM psec)	20-50
Laser power / pulse (mJoules)	50-250
Laser power (kW)	1-5
Rep. Rate (MHz)	22
Macropulse format	CW

Electron Beam Parameters	Goal
Energy (MeV)	20-40
Accelerator frequency (MHz)	352
Charge per bunch (pC)	500
Average current (mA)	10
Peak Current (A)	10-25
Beam Power (kW)	200-400

Daresbury: ERL Prototype







Stage 1 Modules (jlab magnets) ; 4,6,8,14,15,16,17,19 & 20

Stage 2 Modules (new magnets) ; 1,2,3,7,9,10,11,12,13, 21,22,23, 24, 25 & 26

Stage 3 Module (Wiggler) : 18

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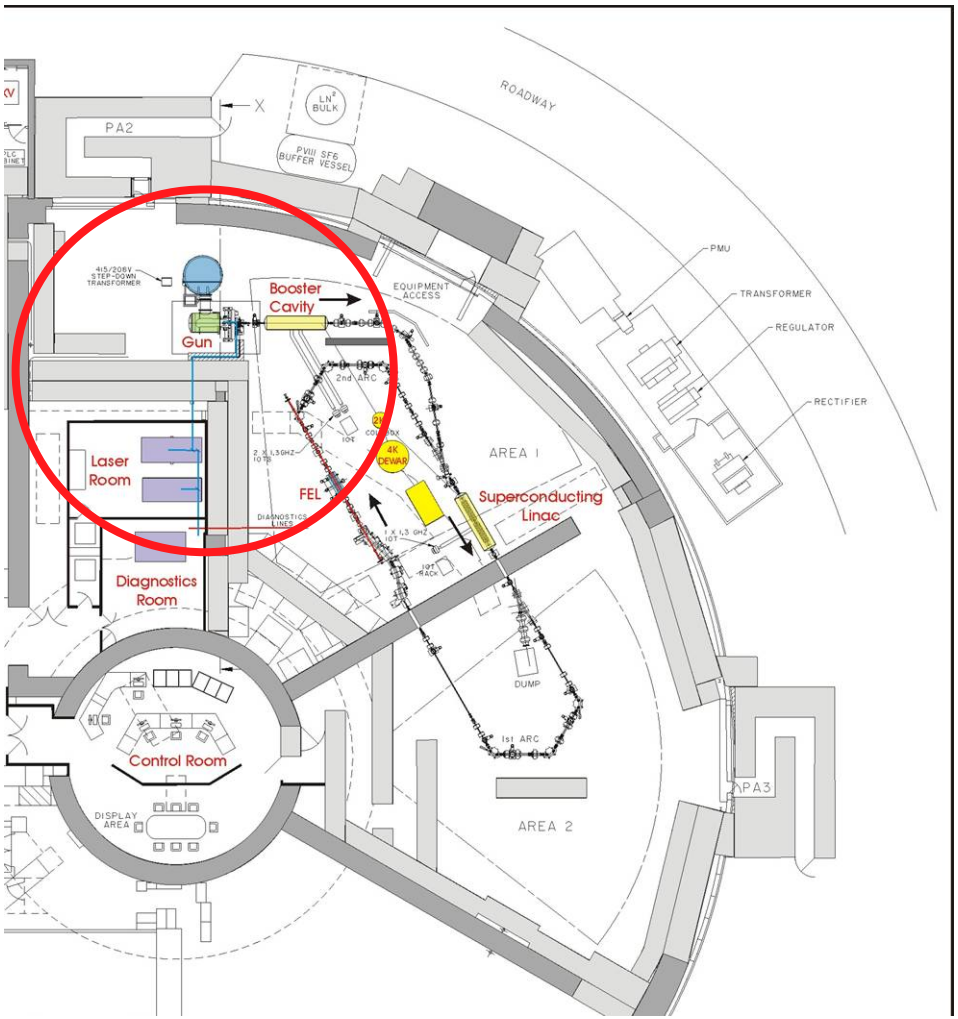
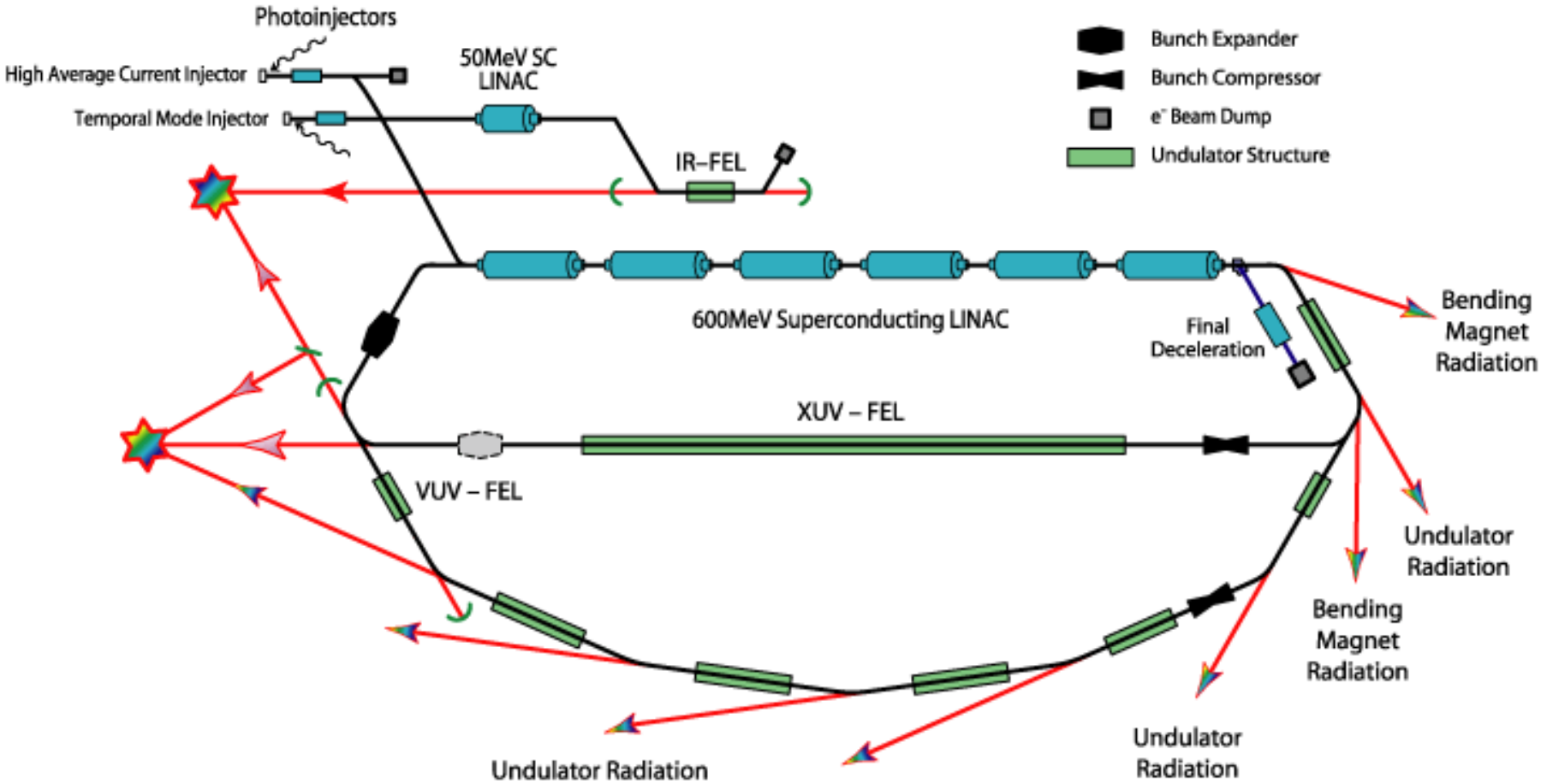
Daresbury: ERL Prototype



Electron Beam Parameters	Goal
Energy (MeV)	30-50
Accelerator frequency (MHz)	1300
Charge per bunch (pC)	>80
Average current (mA)	>0.8
Peak Current (A)	~150
Beam Power (kW)	~30

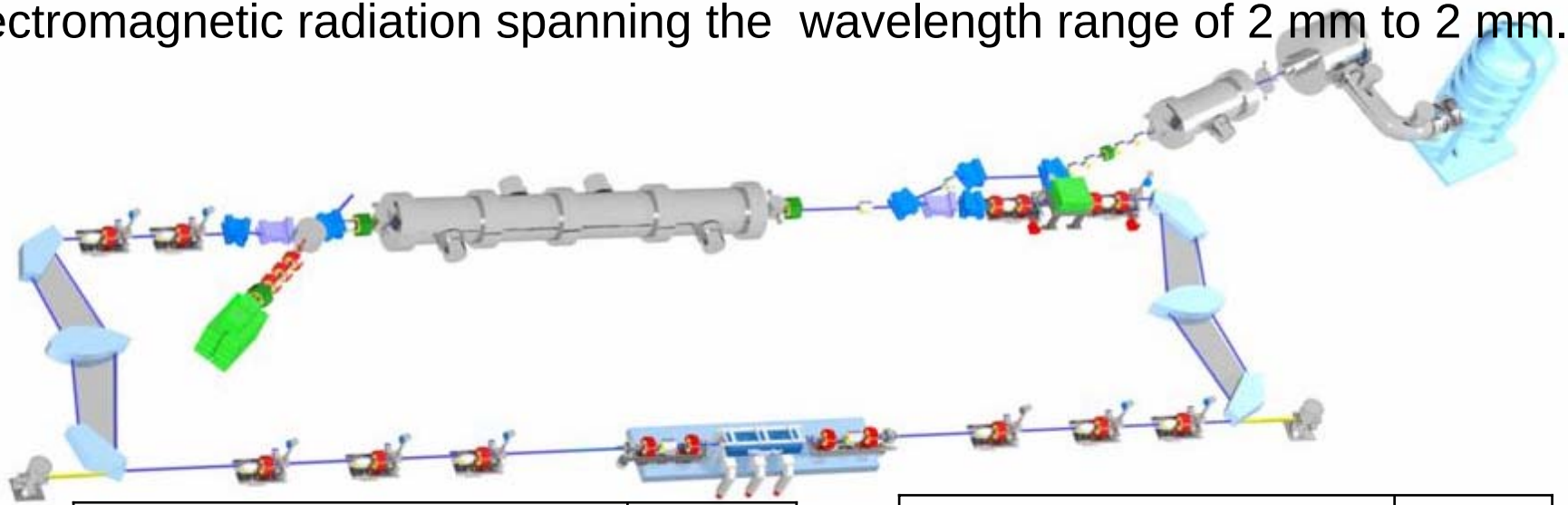
Output Light Parameters	Goal
Wavelength range (microns)	3-75
Bunch Length (FWHM psec)	0.1-few
Laser power / pulse (mJoules)	90
Laser power (kW)	0.9
Rep. Rate (MHz)	10
Macropulse format	CW

Conceptual layout of 4GLS



National High Magnetic Field Laboratory (NHMFL)

Proposal for a Concept and Engineering Design submitted to NSF in January 2005, with UCSB and JLab as partners. The goal is to produce a facility that can combine high magnetic fields (~50T) and intense electromagnetic radiation spanning the wavelength range of 2 mm to 2 mm.

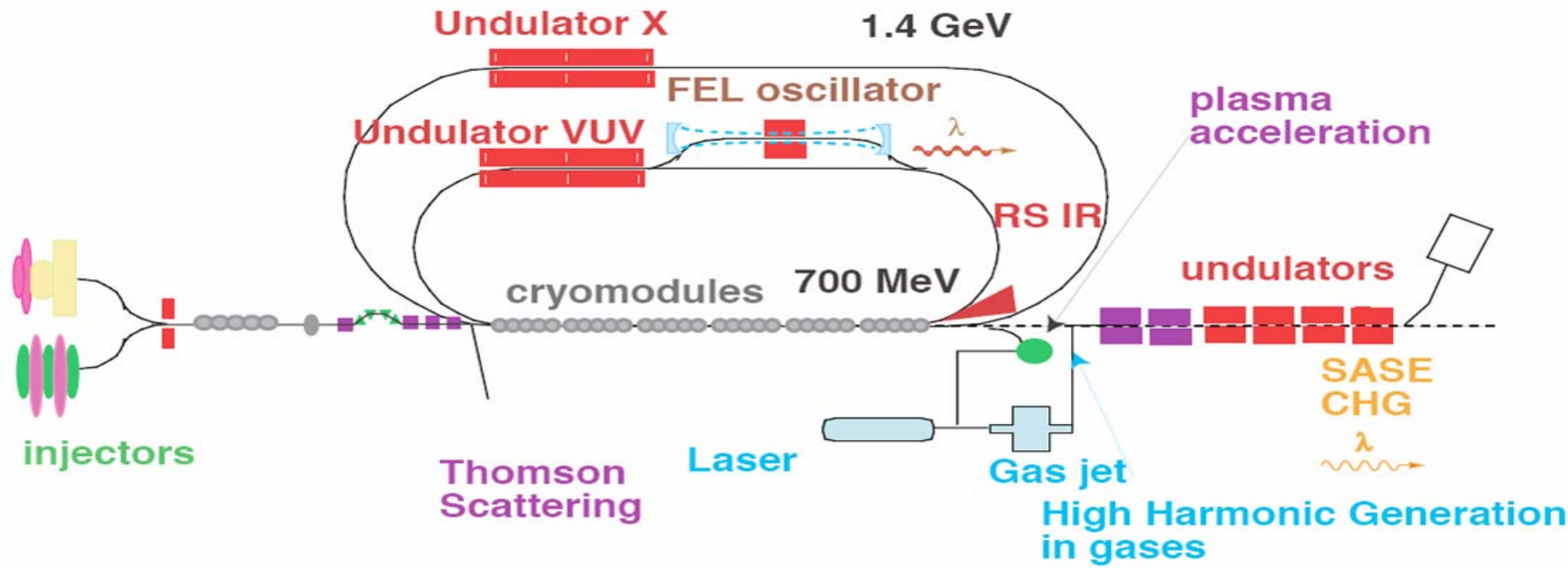


Electron Beam Parameters	Goal
Energy (MeV)	60
Accelerator frequency (MHz)	1500
Charge per bunch (pC)	135
Average current (mA)	5
Peak Current (A)	200
Beam Power (kW)	300

Output Light Parameters	Goal
Wavelength range (microns)	2-100
Bunch Length (FWHM psec)	0.5-few
Laser power / pulse (mJoules)	~25
Laser power (kW)	~1
Rep. Rate (MHz)	37.5
Macropulse format	CW

ARC-EN-CIEL - SACLAY

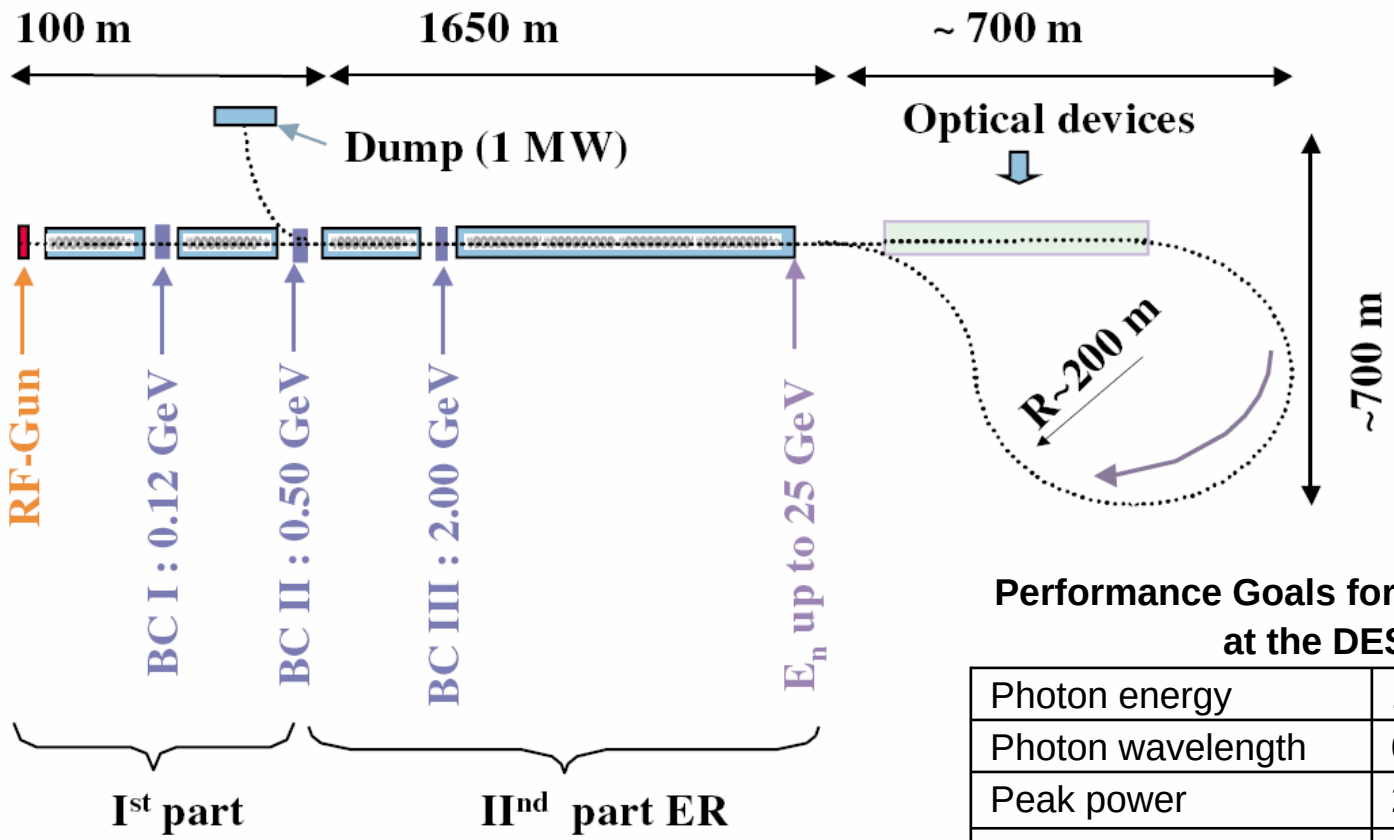
(ARC-EN-CIEL: Accelerator-Radiation Complex for ENhanced Coherent Intense Extended Light)



An Advanced ERL-FEL Concept

TESLA XFEL ERL

TESLA XFEL ERL

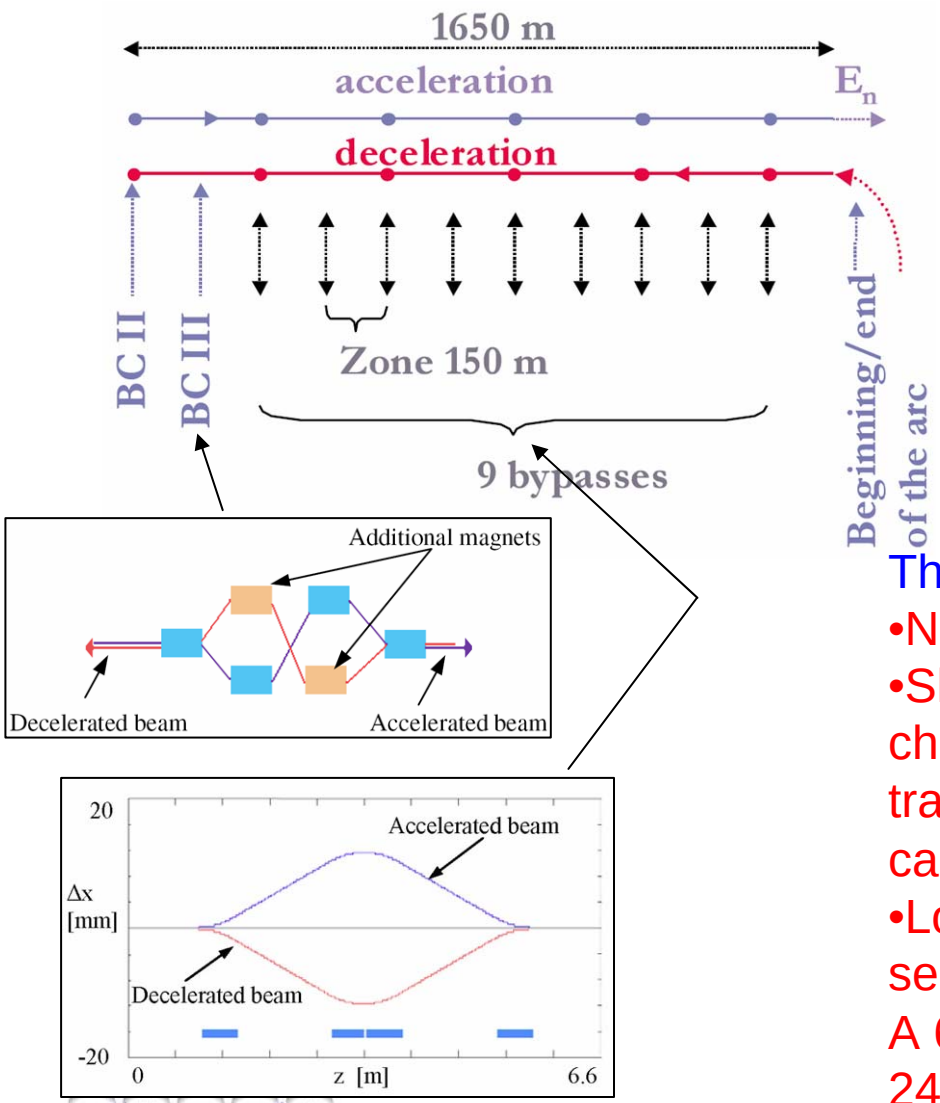


Proposed ER operation would have a rep rate of 1 MHz instead of DESY XFEL rep rate of 10 Hz, increasing the average power and brilliance by a factor of 10^5

Performance Goals for SASE FEL Radiation at the DESY XFEL

Photon energy	12.4 – 0.2 keV
Photon wavelength	0.1 – 6.4 nm
Peak power	24 – 135 GW
Average power	66 – 800 W
# photons/ pulse	1 – 430 x 10^{12}
Peak brilliance	5.4 – 0.6 x 10^{33} **
Average brilliance	1.6 – 0.3 x 10^{25} **
** in units of photons / (s mrad^2 mm^2 0.1% b.w.)	

How to avoid beam quality degradation due to beam-beam interactions of the counter-propagating beams?



At a 1 MHz rep rate there are 6 bunches in the ERL at a given time, thus 12 collision locations separated by 150 meters.

The proposed solution is to avoid collisions altogether!

Three suggested beam time structures:

- Nominal beam: 1 μpulse every μs
- Short trains of bunches: The bypass chicanes are about 4.5 m in length. Bunch trains of this length (~20 RF cycles, 15 ns) can repeat every μs without colliding.
- Long trains: The return arc plus the straight section for undulators is about 2000 m long. A 6.7 μ s train of bunches can repeat every 24 μs without colliding.

Summary: A bright future

- ERLs provide a powerful and elegant paradigm for high average power free electron lasers.
- The pioneering ERL FELs have established the fundamental principles of ERLs.
- The multitude of ERL-FEL projects and proposals worldwide promises an exciting next decade as:
  - Three currently operating ERL-FELs will reach higher performance
  - At least four more are in serious planning stages and will likely be constructed
  - New advanced concepts are being explored

Many thanks to Todd Smith for providing much of the material.