ERL based FELs

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Electrostatic ERL-FELs

- University of California Santa Barbara (UCSB)
- College of Judea and Samaria, Israel
- Korea Atomic Energy Research Institute, South Korea (KAERI)
- FOM Nieuwegein, the Netherlands

RF LINAC ERL-FELs (Operating)

- Jefferson Lab, Newport News, Virginia, USA
- JAERI, Ibaraki, Japan
- BINP, Novosibirsk, Russia

RF LINAC ERL-FELs (Planned)

- KAERI
- 4GLS
- NHFML-Florida
- SACLAY

RF LINAC ERL-FELs (Advanced Concepts)

- MAX-lab
- TESLA
- BNL
- Budker

Electrostatic Accelerator based ER-FELs

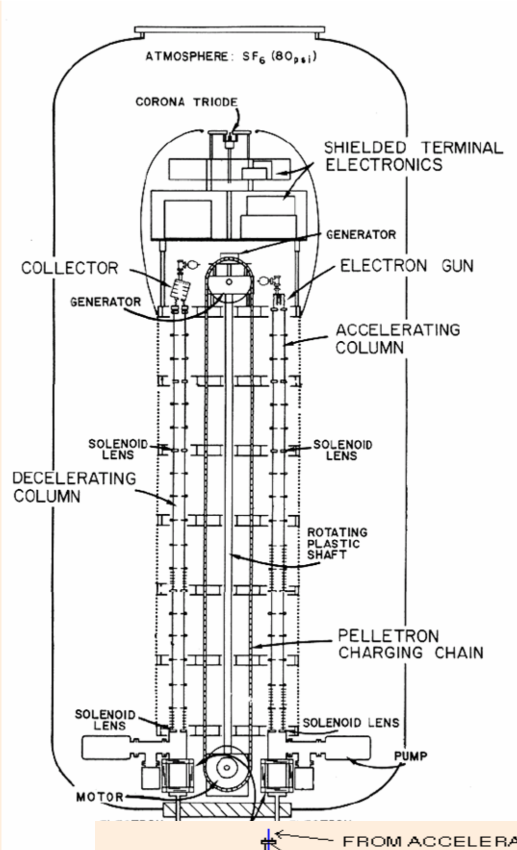
UCSB [NIM **A**237 (1985) 203-206]

KAERI [NIM **A**375 (1996) 28-31]

Israeli EA-FEL [NIM **A**407 (1998) 16-20]

Dutch Fusion-FEM [NIM **A**429 (1999) 9-11]

References = First Lasing



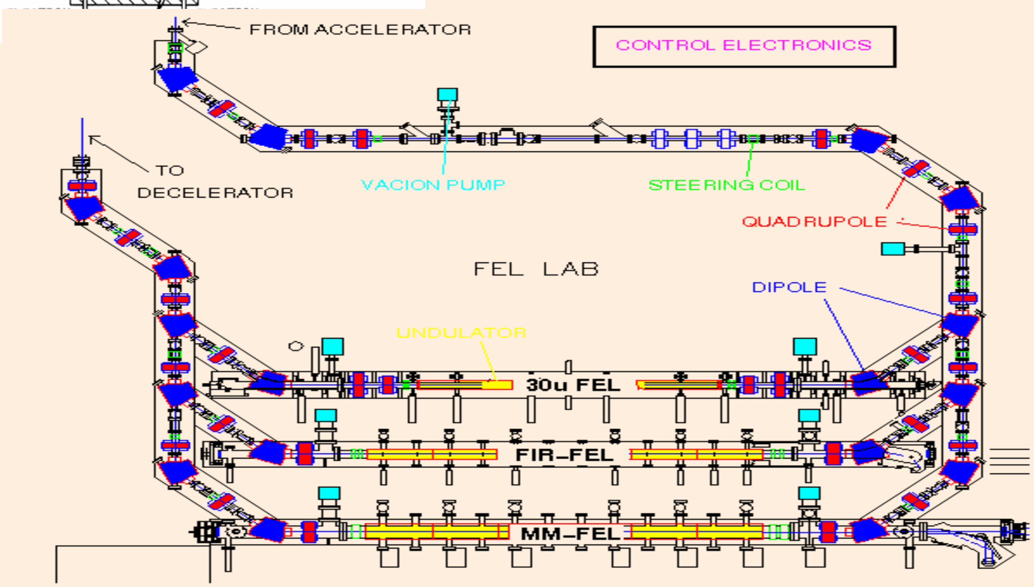
THE UCSB FREE-ELECTRON LASERS

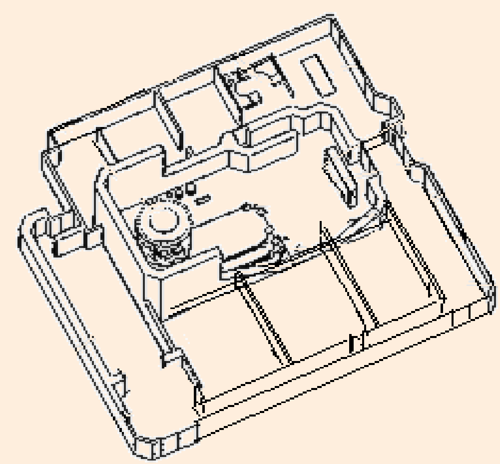
A SOURCE OF TUNABLE, COHERENT, HIGH POWER FAR-INFRARED RADIATION

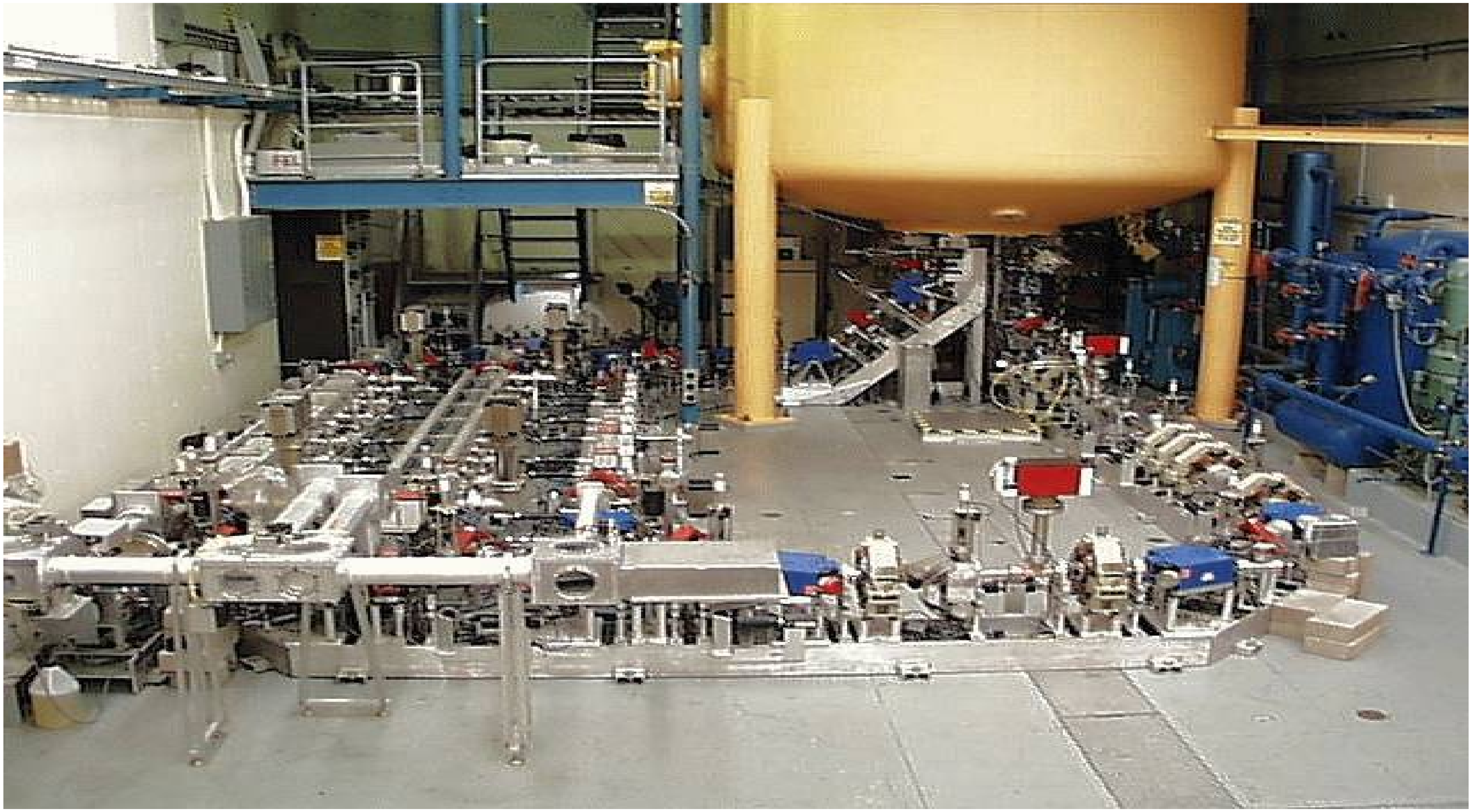
Center for Terahertz Science and Technology

University of California, Santa Barbara

http://sbfel3.ucsb.edu/

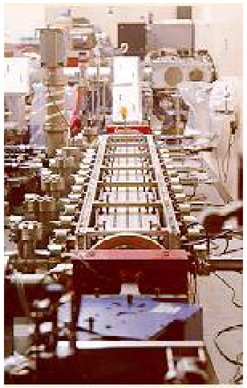




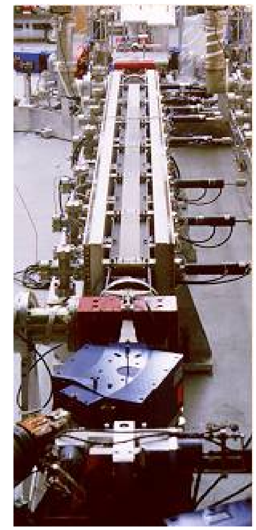


The main FEL laboratory room showing the MM, FIR, and 30 μm FELs (center), part of the optical transport system (left), the beam switchyard, and the lower portion of the 6 MV Electrostatic accelerator tank (yellow). Two foot thick concrete walls provide radiation shielding.

MM
FEL



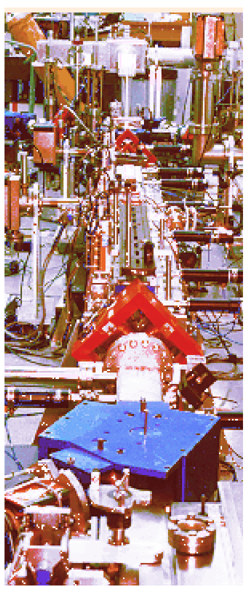
WAVELENGTH RANGE: 2.5 mm -> 338 µm
POWER: 1 -> 15 KW depending on wavelength and coupler
PULSE LENGTH: 1 -> 6 µs



FIR
FEL

WAVELENGTH RANGE: 338 -> 63 µm
POWER: 1 -> 6 KW depending on wavelength and coupler
PULSE LENGTH: 1 -> 20 µs

50µm
FEL



12-Mar-96 -- 12 Watts @ 42 µm wavelength measured in users' lab (40 W at diagnostic box)

23-Aug-95 -- Lased on third harmonic for first time at 50µm wavelength but did not reach saturation.

THE UCSB 2MV, CW, MM-WAVE FEL

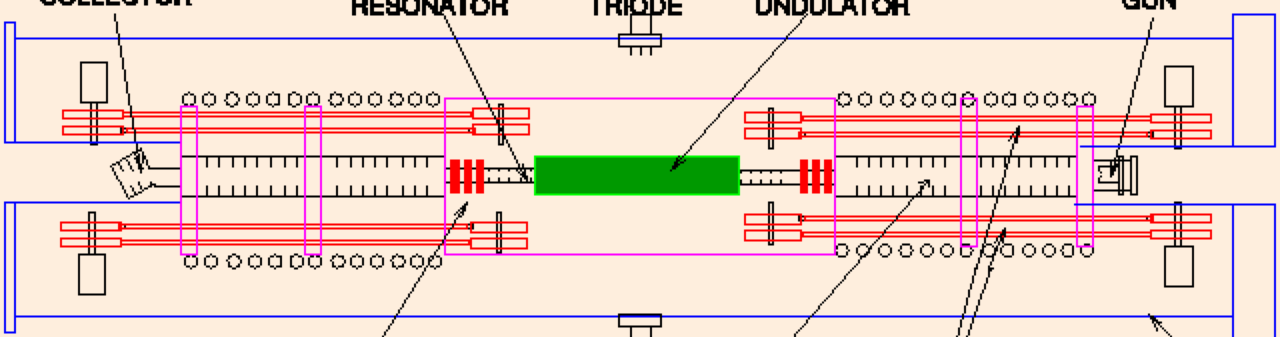
keywords: fel, free electron laser, fir, far infrared, millimeter wave, continuous wave, undulator

[gif 141K][jpeg 50K]

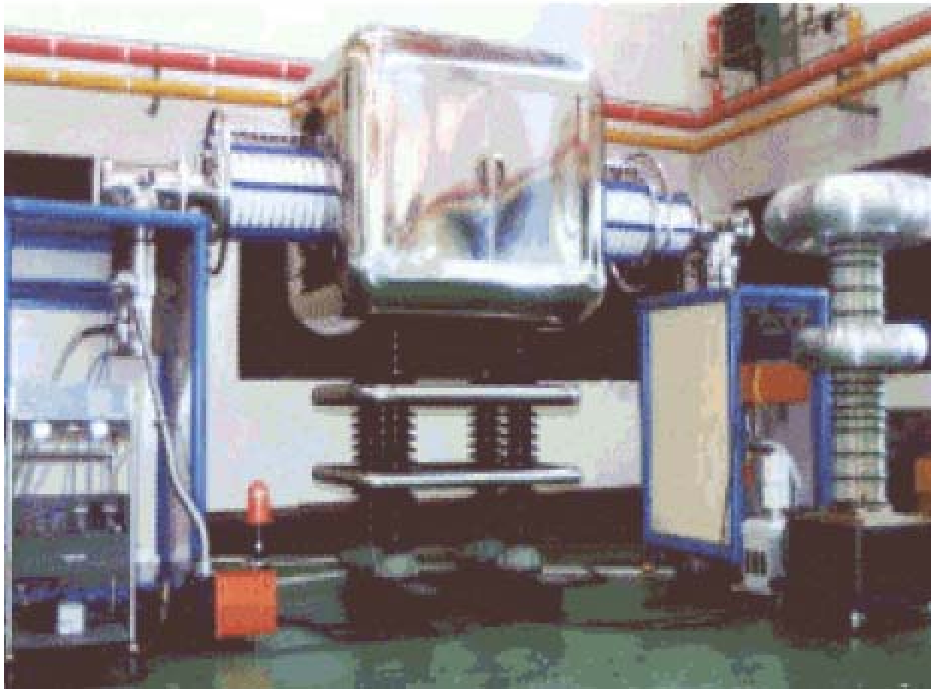
This will be a continuous-wave (CW), millimeter-wave Free-Electron Laser that is expected to have unique properties, including high **average** power and stable, single-frequency operation, and will also demonstrate "next generation" principles. The FEL and accelerator form a self contained unit. Most accelerator components were purchased from NEC[1].

(Note: Work on this project has been temproarily suspended since September, 1997, pending procurement of additional funding)

FEL DESIGN PARAMETERS **CONTROL SYSTEM** **TIMELINE** **FUTURE POSSIBILITIES**



KAERI MMW FEL and Parameters

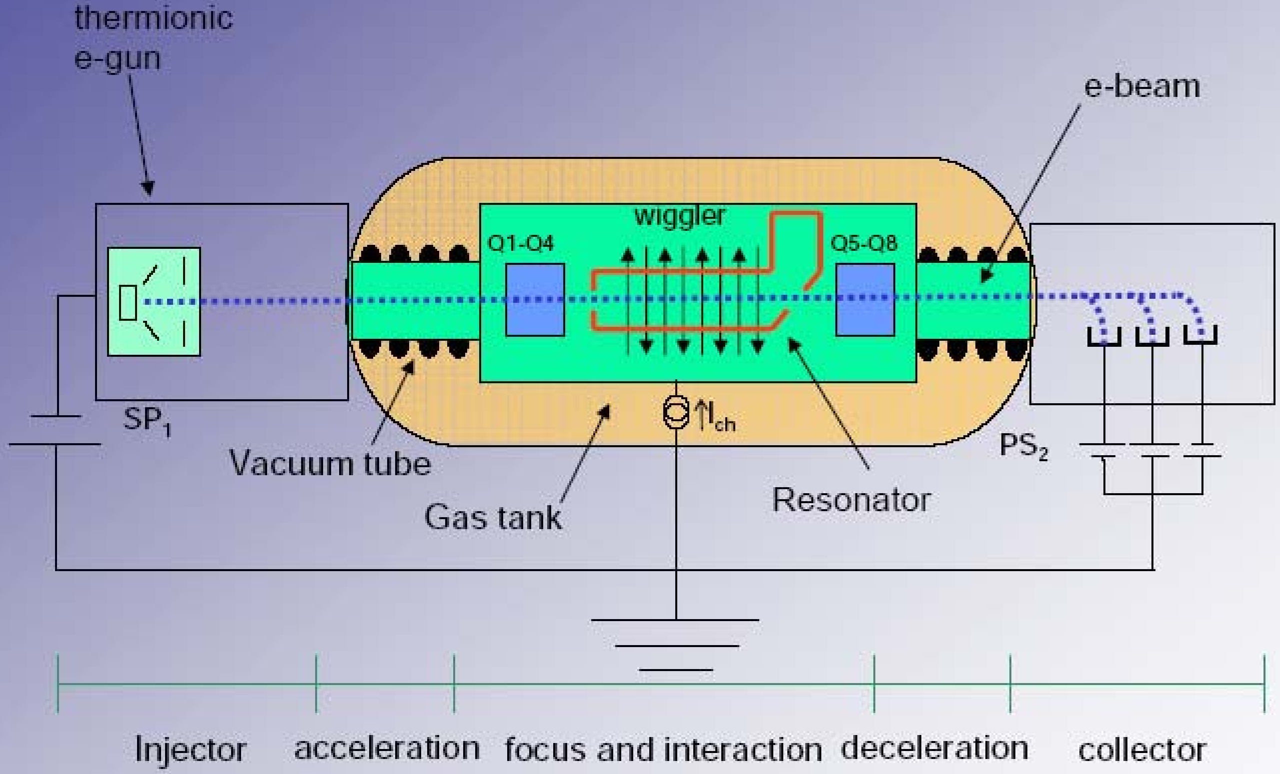


Electron Beam	Energy	430 keV
	Current	2 A
	Emittance	20 π mm·mrad
	Pulsewidth	30 μs
Undulator	Type	Helical, PM
	Period	33 mm
	No. of periods	28
	Magnetic field	1.33 kG
Laser Beam	Wavelength	3~10 mm
	Mode	TM_{11}
	Power	1 kW

B.C. Lee el al, *Free Electron Laser projects at KAERI*, Proceedings of the Second Asian Particle Accelerator Conference, Beijing, China, 2001

The Israeli FEL

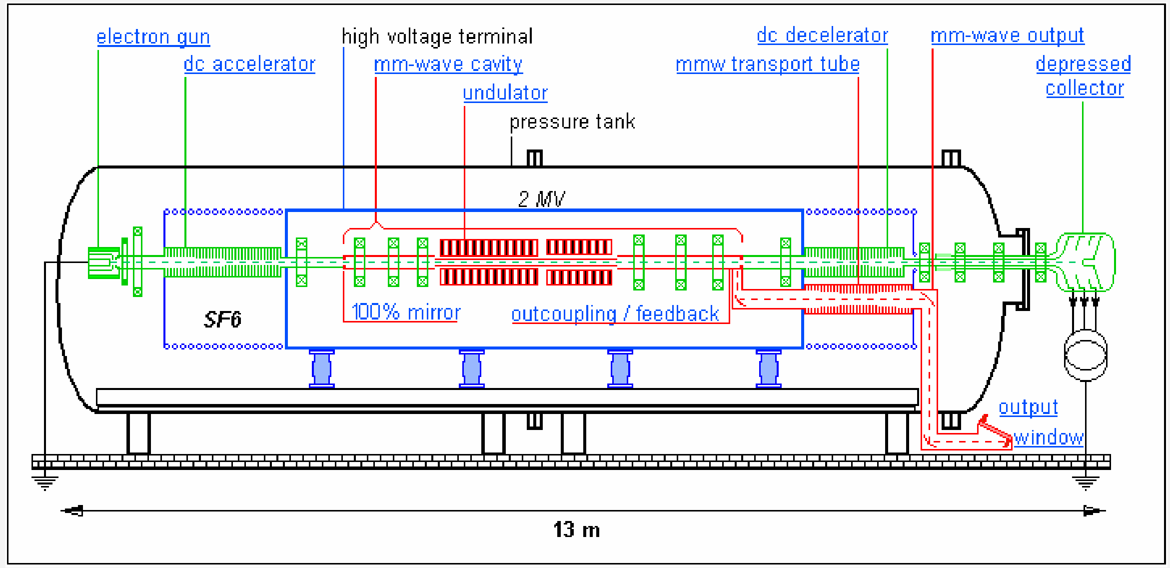
Inner Cavity Electrostatic Accelerator FEL Configuration



Operational parameters of the Israeli EA-FEL.

	Present	Short – term	Long – term
Tuning range:	70 – 130 GHz	50 – 130 GHz	30GHz - 1THz
Peak intensity:	10 kW	30 kW	30 kW
Average power:	-------	1 kW	30kW
Pulse duration:	5 - 30 µS	5 – 1000 µS	5 µS – CW 1-100 pS
Beam dimension:	5 cm	Focusable down to 5 mm	Focusable down to 5 mm
Spatial coherence:	Diffraction limited	Diffraction limited	Diffraction limited
Temporal coherence:	single mode $\frac{\Delta f}{f} < 10^{-5}$	$\frac{\Delta f}{f} < 10^{-7}$	$\frac{\Delta f}{f} < 10^{-7}$

Y. Pinhasi, *Free-electron lasers and their radiation applications*, Proceedings of the Second International Conference on Mathematical Modeling and Computer Simulation of Metal Technologies (MMT-2002), The College of Judea and Samaria, Israel, 2_38-47



The electron beam line consists of an 80-keV, 12-A thermionic triode electron gun, a 2-MV electrostatic accelerator, an undulator and a waveguide resonator mounted in a high-voltage terminal, an electrostatic decelerator and a depressed collector. The entire system is enclosed in a pressurized SF6-tank of 11 m length for high voltage insulation. Frequency tuning is done by variation of the terminal voltage. Design output was 1 MW CW at 130-260 GHz, at a system efficiency of 50%. 800 kW in a few ms pulse was demonstrated.

W. H. Urbanus, *High-power electrostatic free-electron maser as a future source for fusion plasma heating: Experiments in the short-pulse regime*, PRE 59, (1999) 6058-6063.

RF Linac based ER-FELs

(History)

S.O. Schreiber and E.A. Heighway (Chalk River)

Double Pass Linear Accelerator - Reflexotron

IEEE NS-22 (1975) (3) 1060-1064

D.W. Feldman et al, (LANL)

Energy Recovery in the LANL FEL

NIM A259 (1987) 26-30

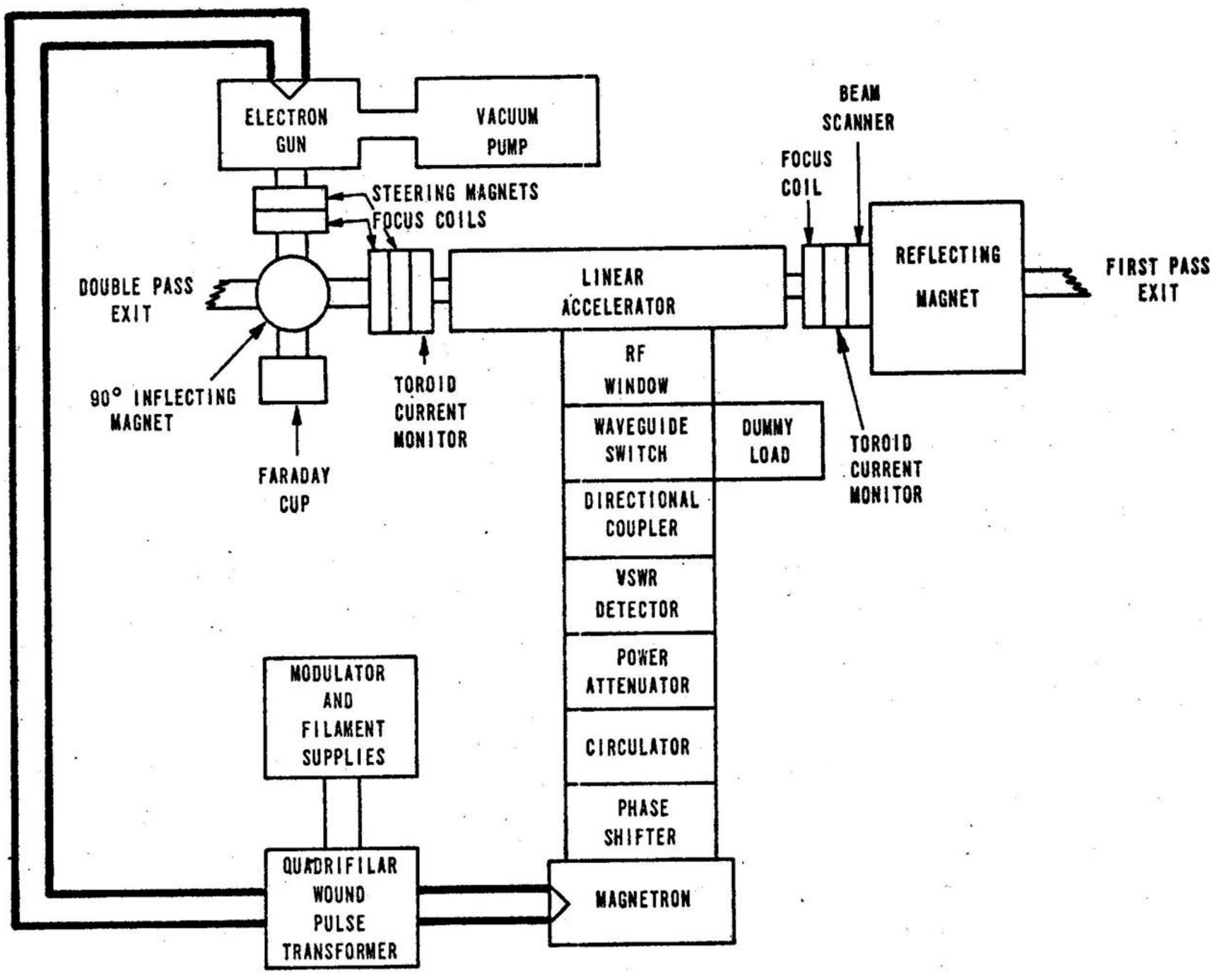
T.I. Smith et al, (Stanford University)

Development of the SCA/FEL for use in Biomedical and Materials Science Research

NIM A259 (1987) 1-7

S.O. Schreiber and E.A. Heighway (Chalk River)

Double Pass Linear Accelerator - Reflexotron



IEEE NS-22 (1975) (3) 1060-1064

D.W. Feldman et al,

Energy Recovery in the Los Alamos FEL

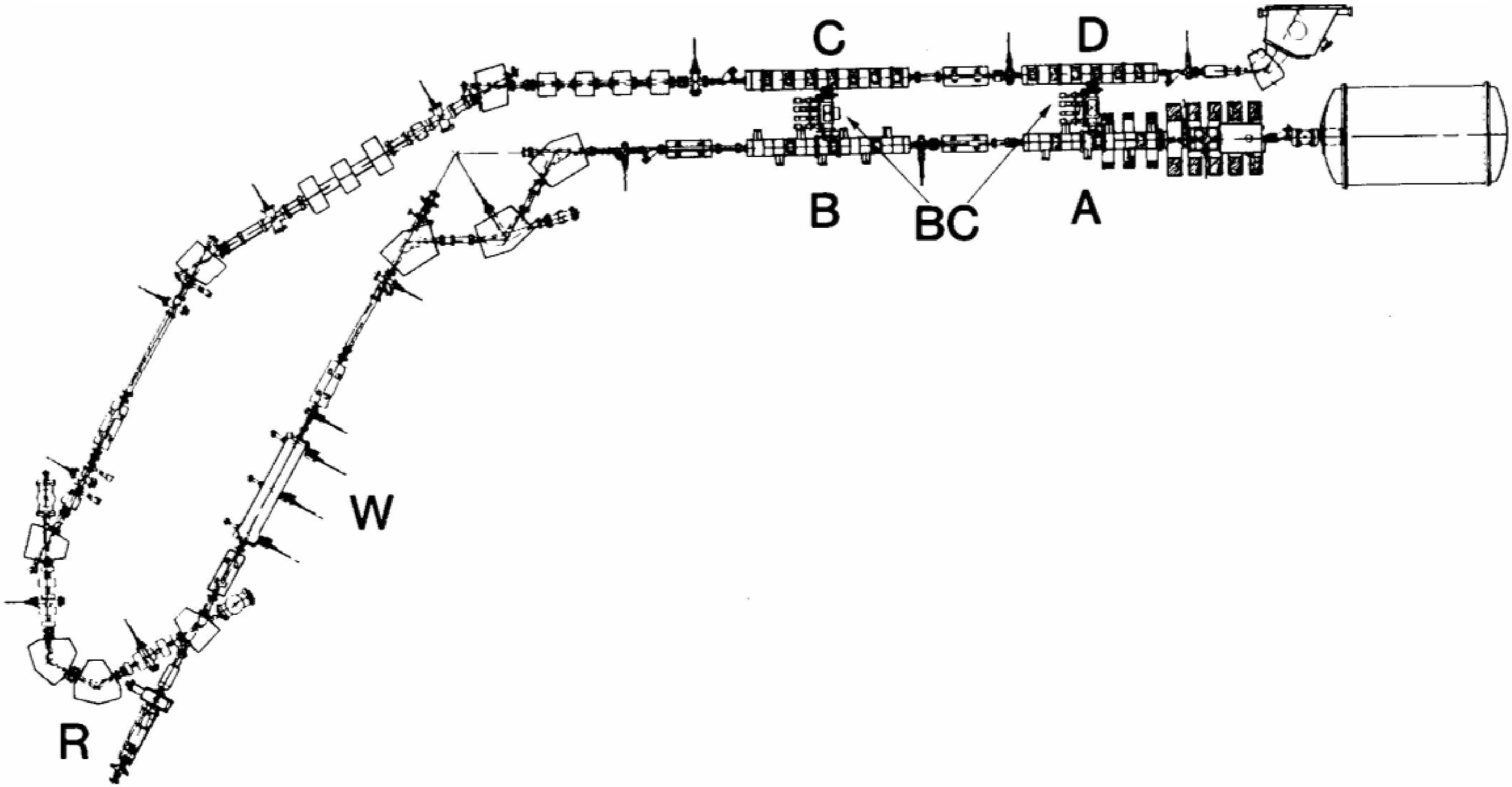
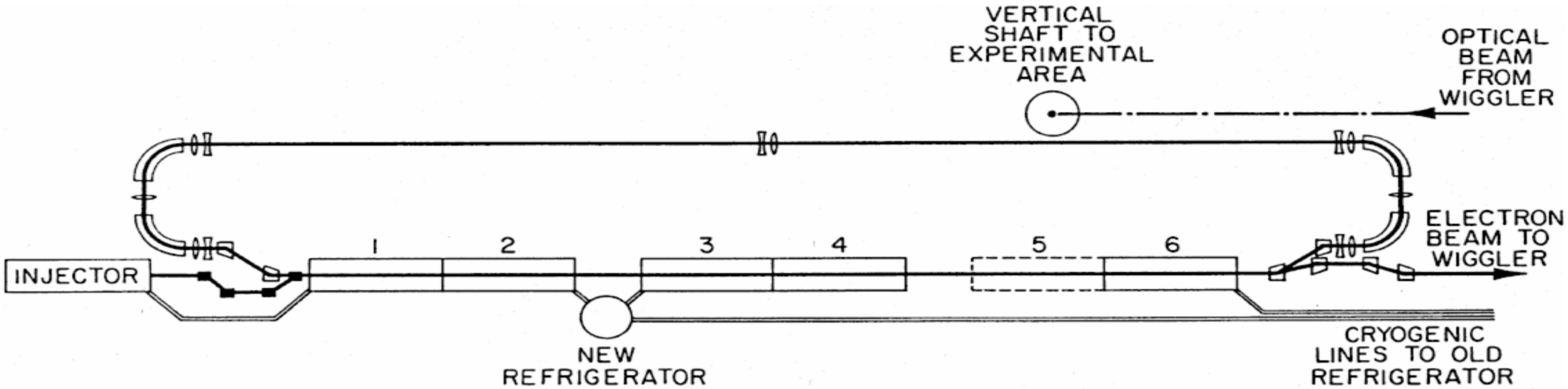


Fig. 1. Energy-recovery beamline arrangement.

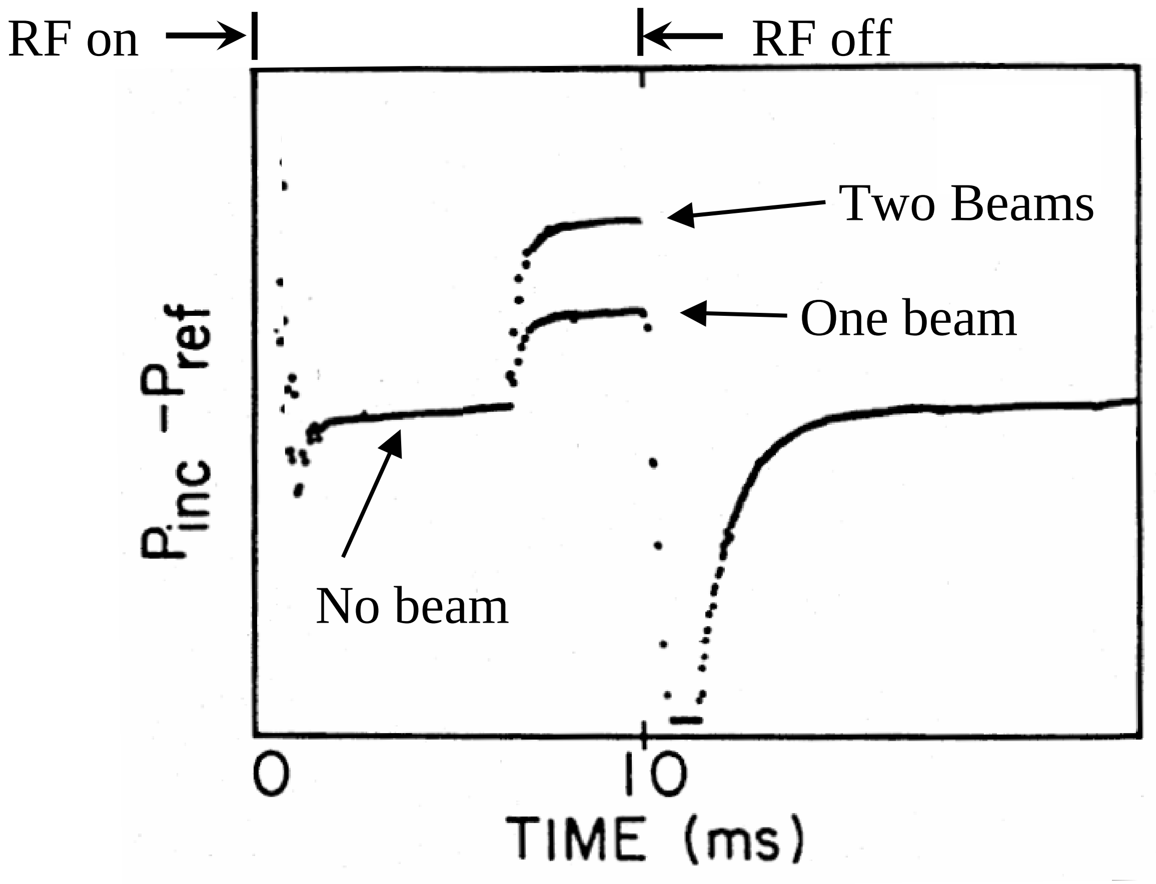
NIM **A**259 (1987) 26-30

SCA as configured in 1986 for the Visible FEL Oscillator Experiment



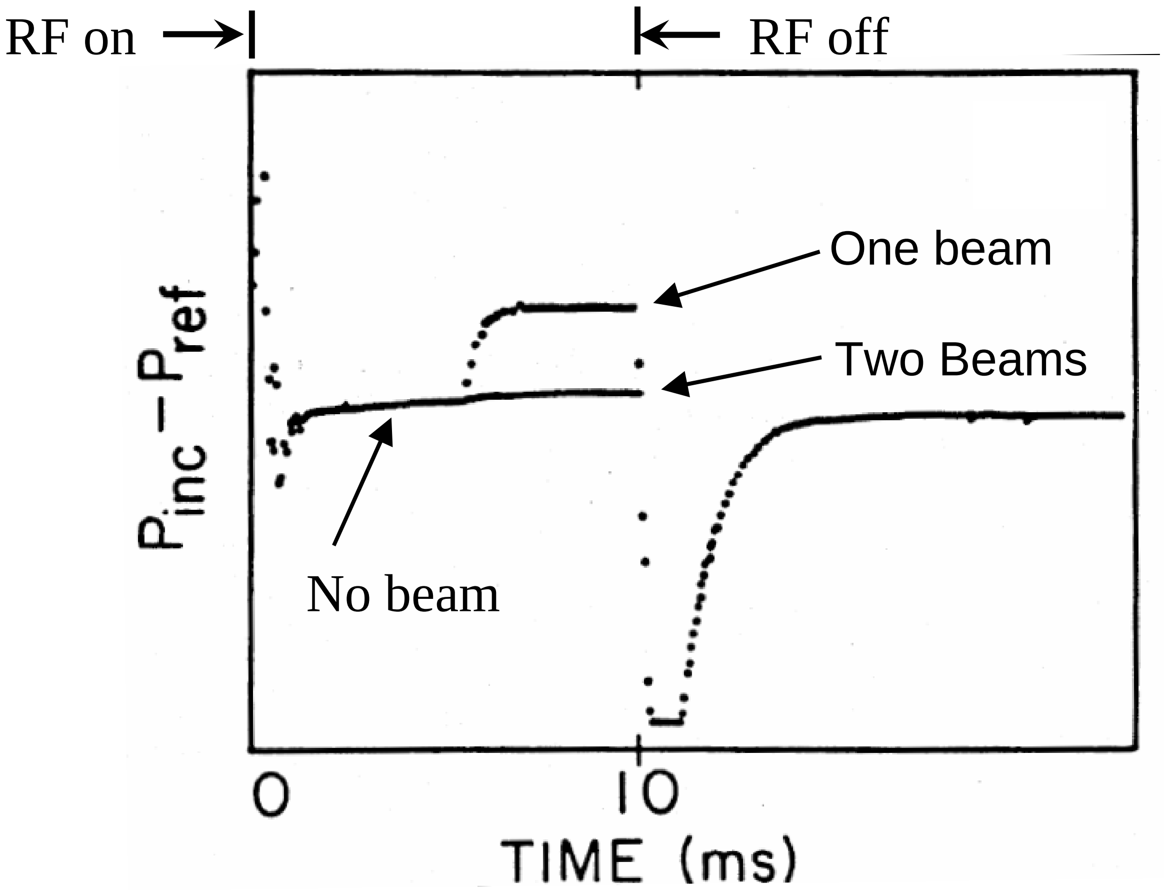
FEL 1986 Oral Presentation

Klystron Power Required when Configured as a Two-Pass Accelerator



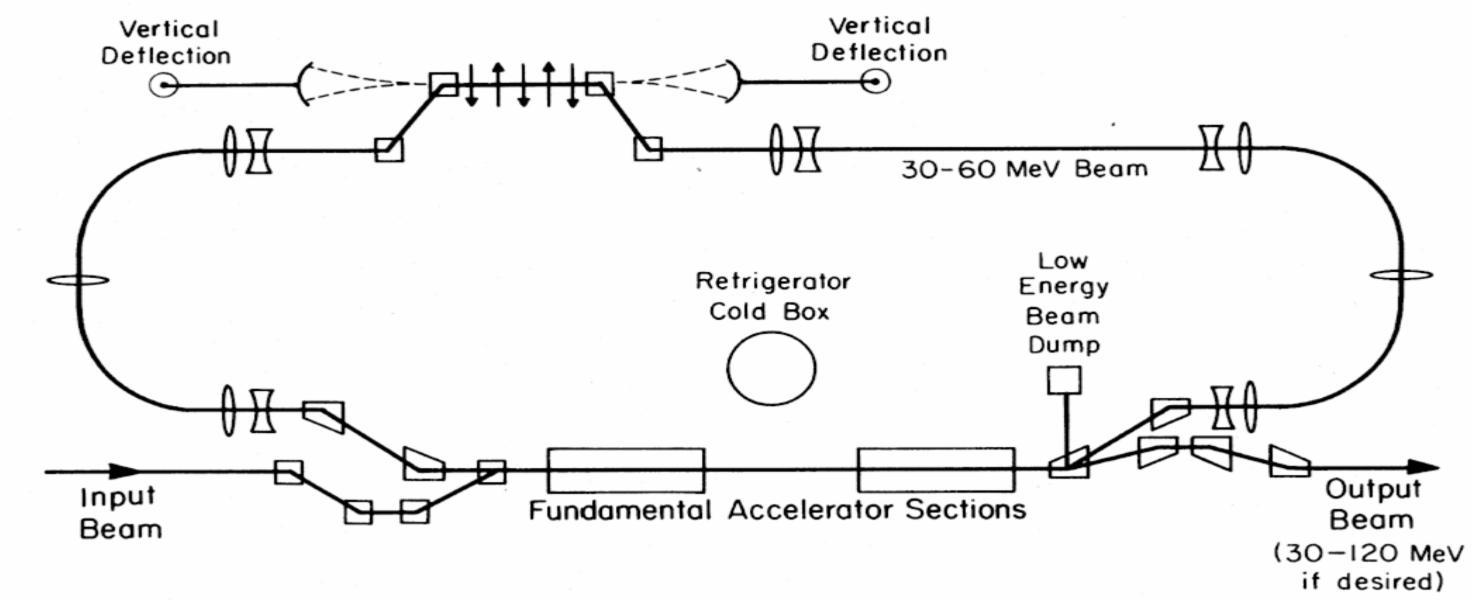
FEL 1986 Oral Presentation

Klystron Power Required when Configured as an Energy Recovery LINAC



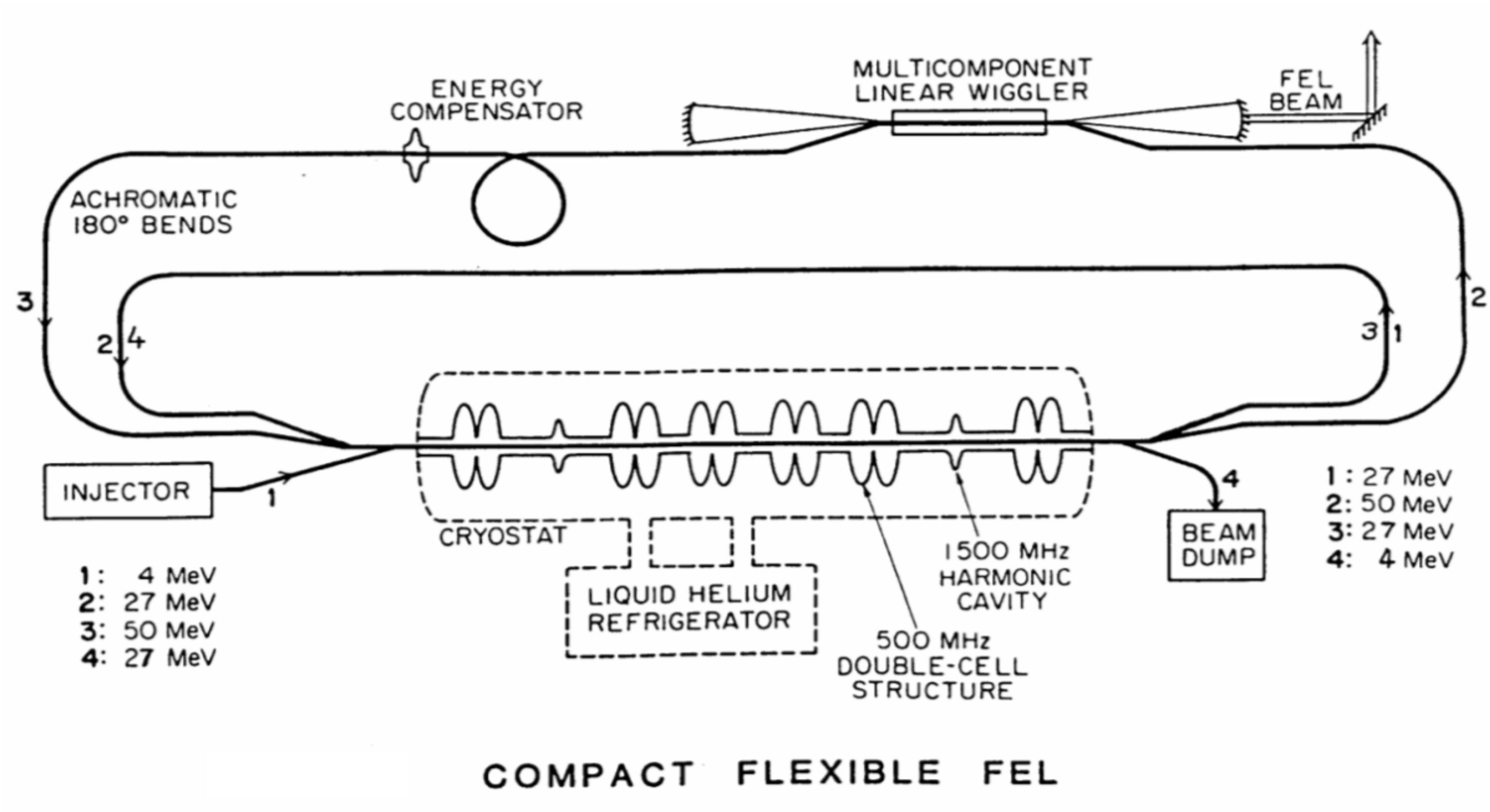
FEL 1986 Oral Presentation

Proposed Configuration for ERL based FEL



FEL 1986 Oral Presentation

A Compact (1 kW) Energy Recovered FEL for Biomedical and Materials Science Applications



R Rohatgi, H.A. Schwettman, T.I. Smith, PAC 87, 230-232

Operating

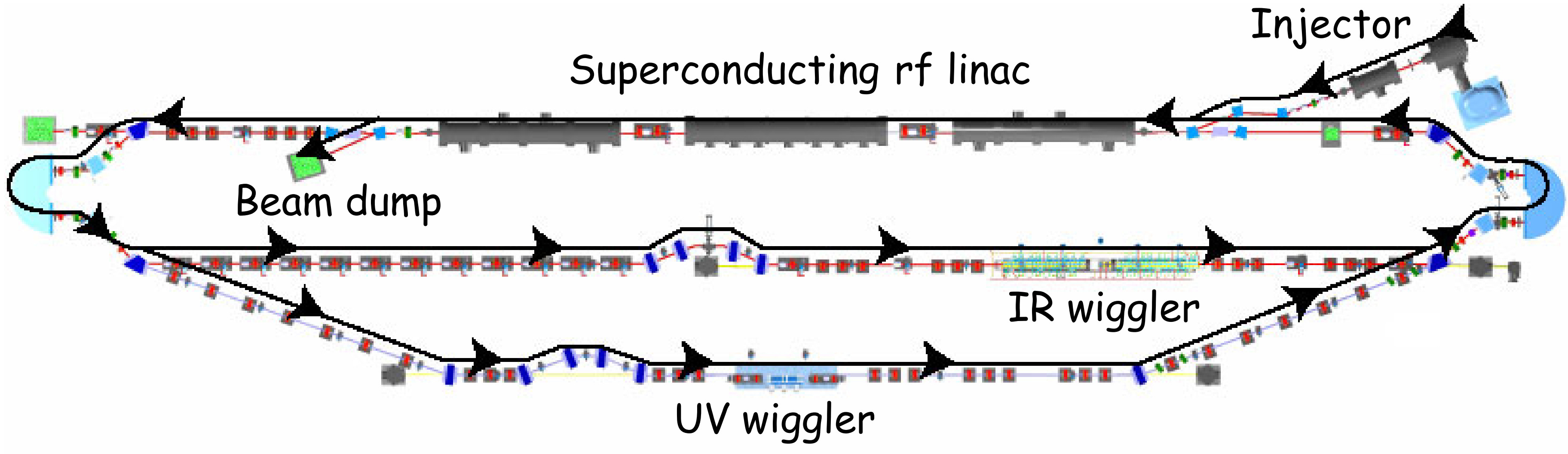
RF Linac based ER-FELs

JLab [2004 FEL Conf. Proc., 229-232]

JAERI [2004 FEL Conf. Proc., 301-303]

BINP [2004 FEL Conf. Proc., 226-228]

JLab 10kW IR FEL and 1 kW UV FEL

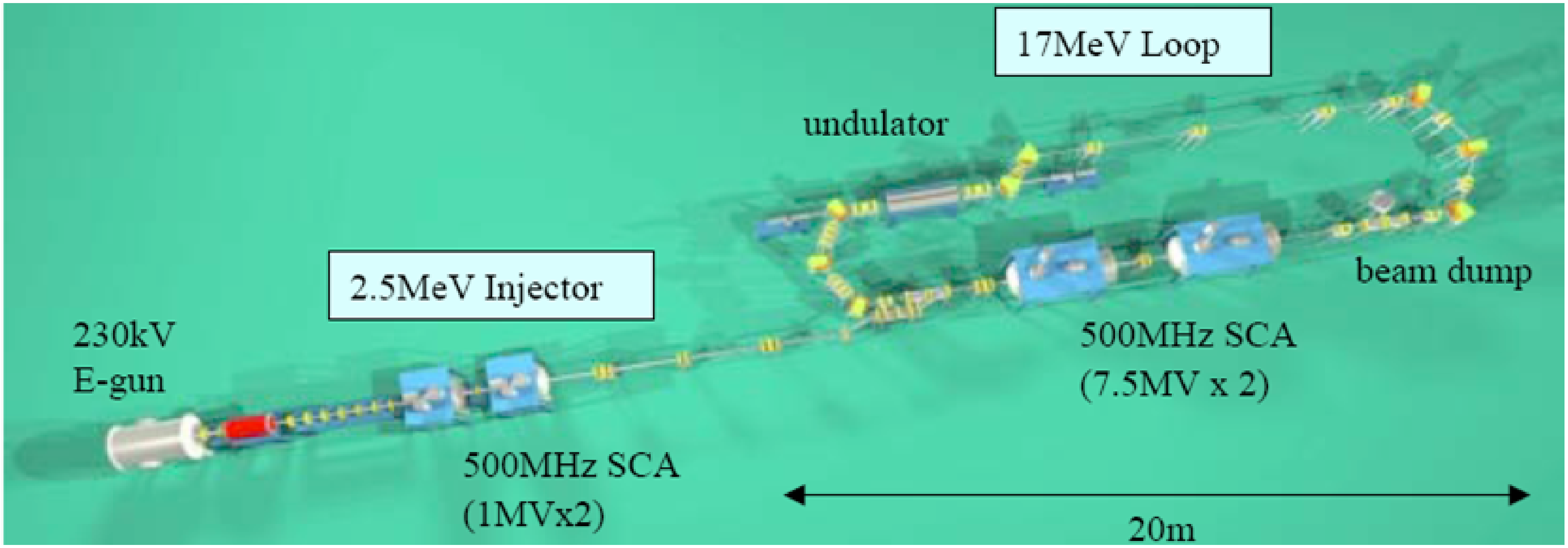


Output Light Parameters	**IR**	**UV**
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser power / pulse (microJoules)	100 - 300	25
Laser power (kW)	>10	> 1
Rep. Rate (cw operation, MHz)	4.7 – 75	4.7 – 75

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%

S. Benson et al, *High power lasing in the IR upgrade at Jefferson Lab*, 2004 FEL Conference Proceedings, 229-232.

JAERI ER-FEL

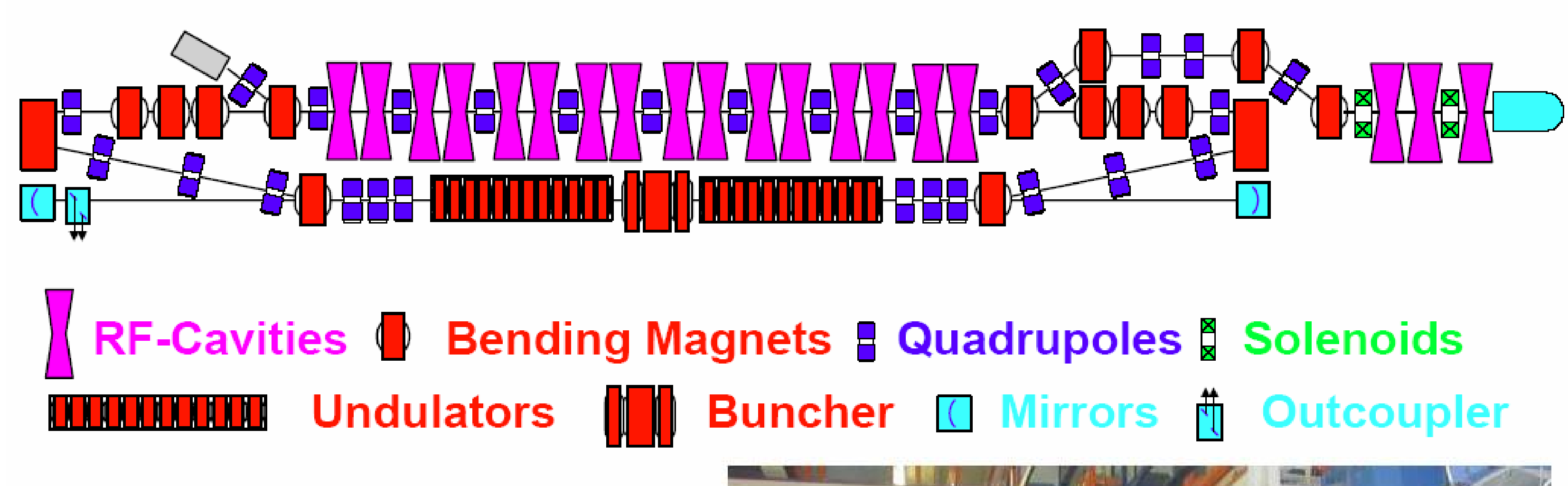


Output Light Parameters	**Achieved**	**Goal**
Wavelength range (microns)	22	22
Bunch Length (FWHM psec)	15	6
Laser power / pulse (microJoules)	10	120
Laser power (kW)	0.1	10
Rep. Rate (MHz)	10.4	83.2
Macropulse format	10ms 10Hz	CW

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%

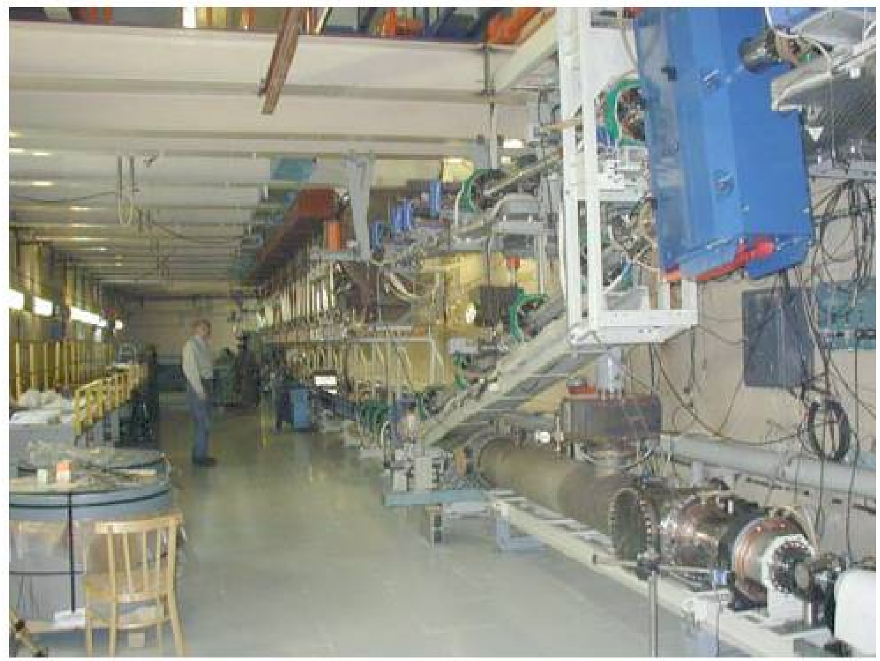
R. Hajima et al, *Recent results of the JAERI Energy-Recovery Linac FEL*, 2004 FEL Conference Proceedings, 301-303

Novosibirsk Free Electron Laser



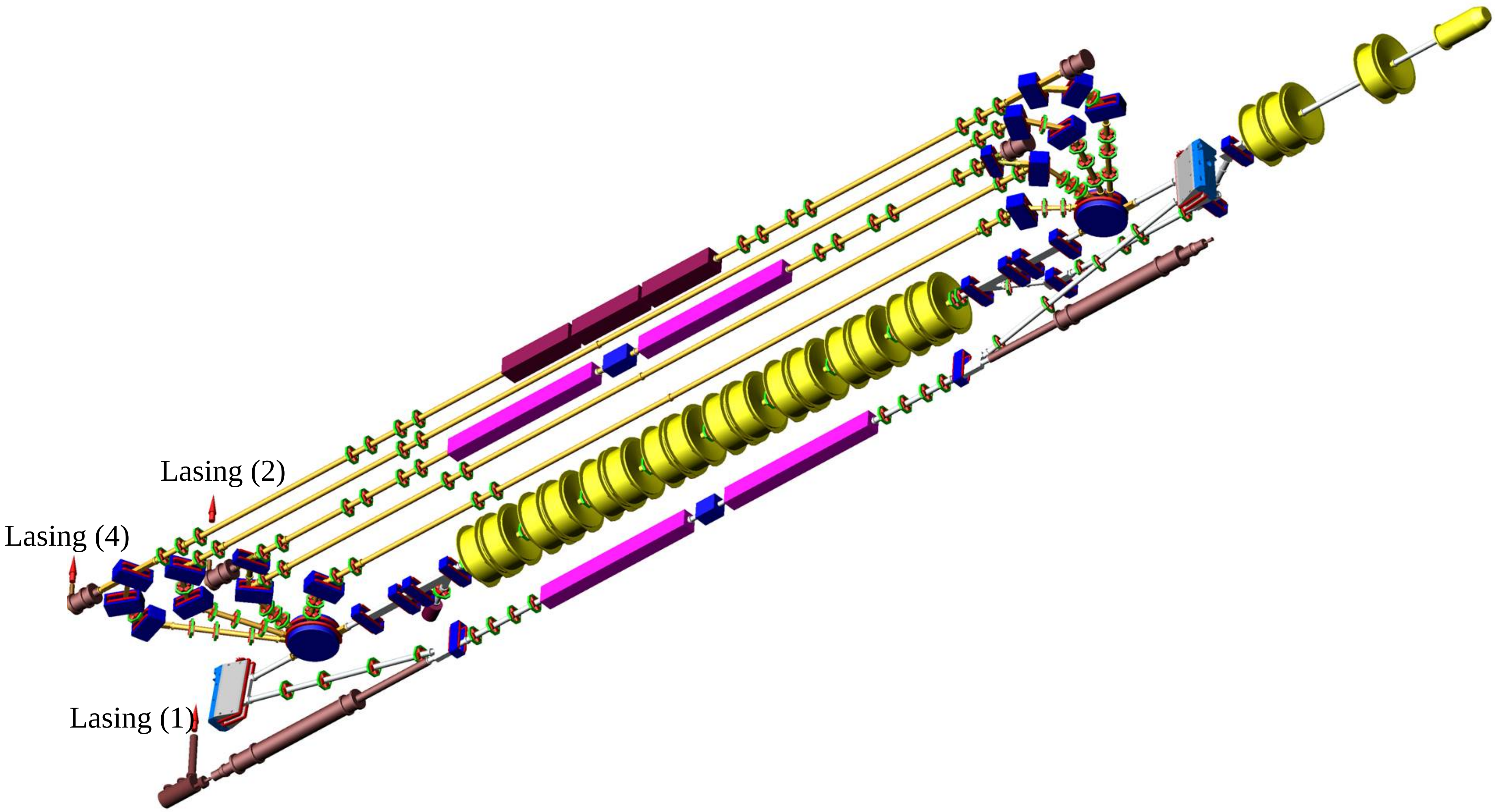
Output Light Parameters	IR
Wavelength range (microns)	120-180
Bunch Length (FWHM psec)	50
Laser power / pulse (microJoules)	9
Laser power (kW)	0.2
Rep. Rate (cw operation, MHz)	22.5

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



V.P. Bolotin et al, , *Status of the Novosibirsk Terahertz FEL*, 2004 FEL Conference Proceedings, 226-228

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

RF Linac based ER-FELs

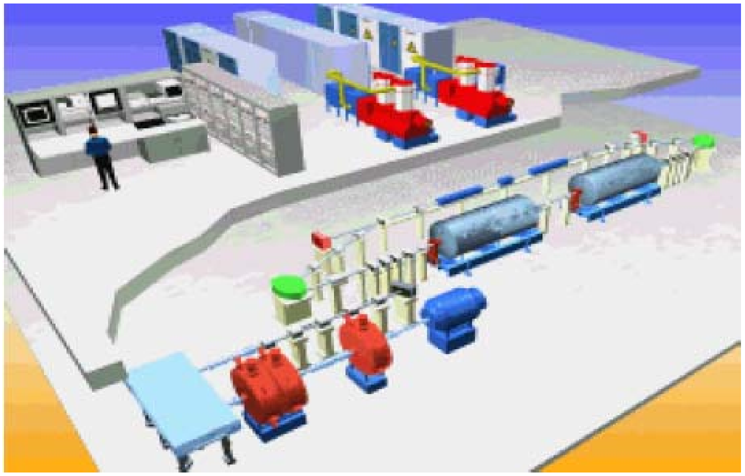
KAERI [NIM **A**528 (2004) 106-109]

4GLS [M.W. Poole et al, PAC 2003]

NHMFL [Proposal to NSF (Jan 2005)]

SACLAY [M.E. Couprie et al, EPAC 2004]

KAERI

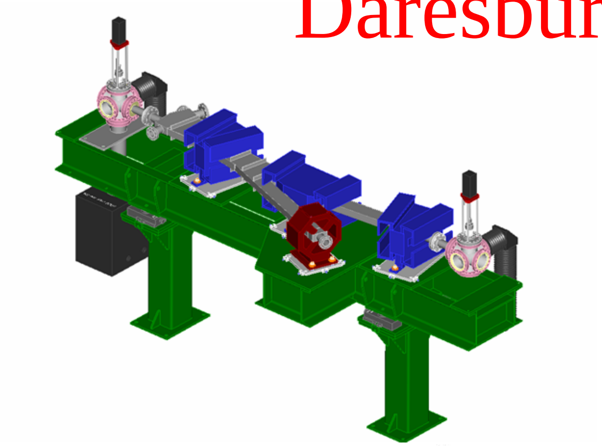


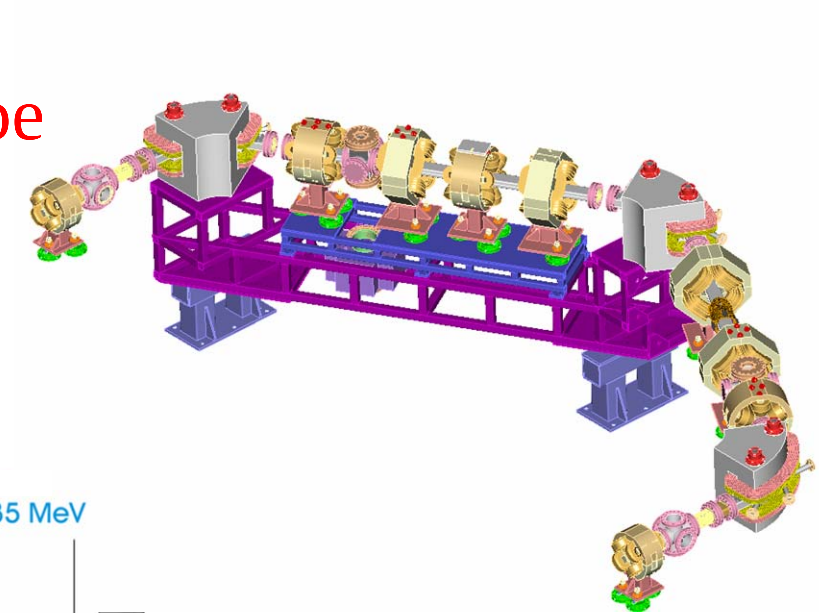
Output Light Parameters	Goal
Wavelength range (microns)	3-20
Bunch Length (FWHM psec)	20-50
Laser power / pulse (μJoules)	50-250
Laser power (kW)	1-5
Rep. Rate (MHz)	22
Macropulse format	CW

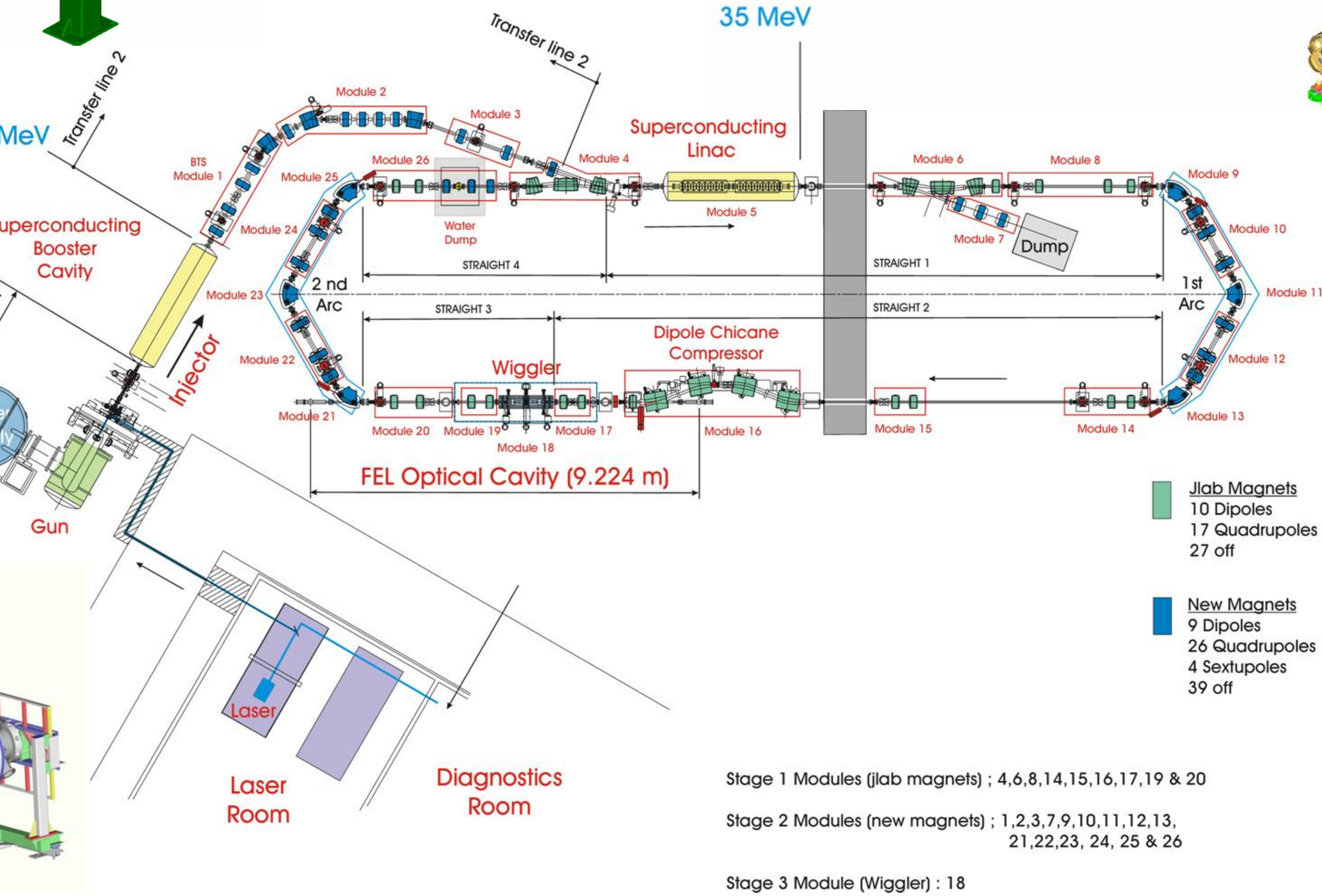
Electron Beam Parameters	Goal
Energy (MeV)	20-40
Accelerator frequency (MHz)	352
Charge per bunch (pC)	500
Average current (mA)	10
Peak Current (A)	10-25
Beam Power (kW)	200-400

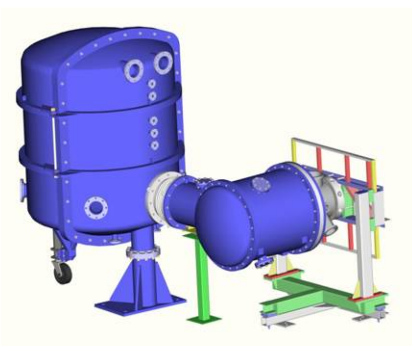
B.C. Lee, et al, *High-Power infrared free electron laser driven by a 352 MHz superconducting accelerator with energy recovery*, NIM **A**528 (2004) 106-109

Daresbury: ERL Prototype

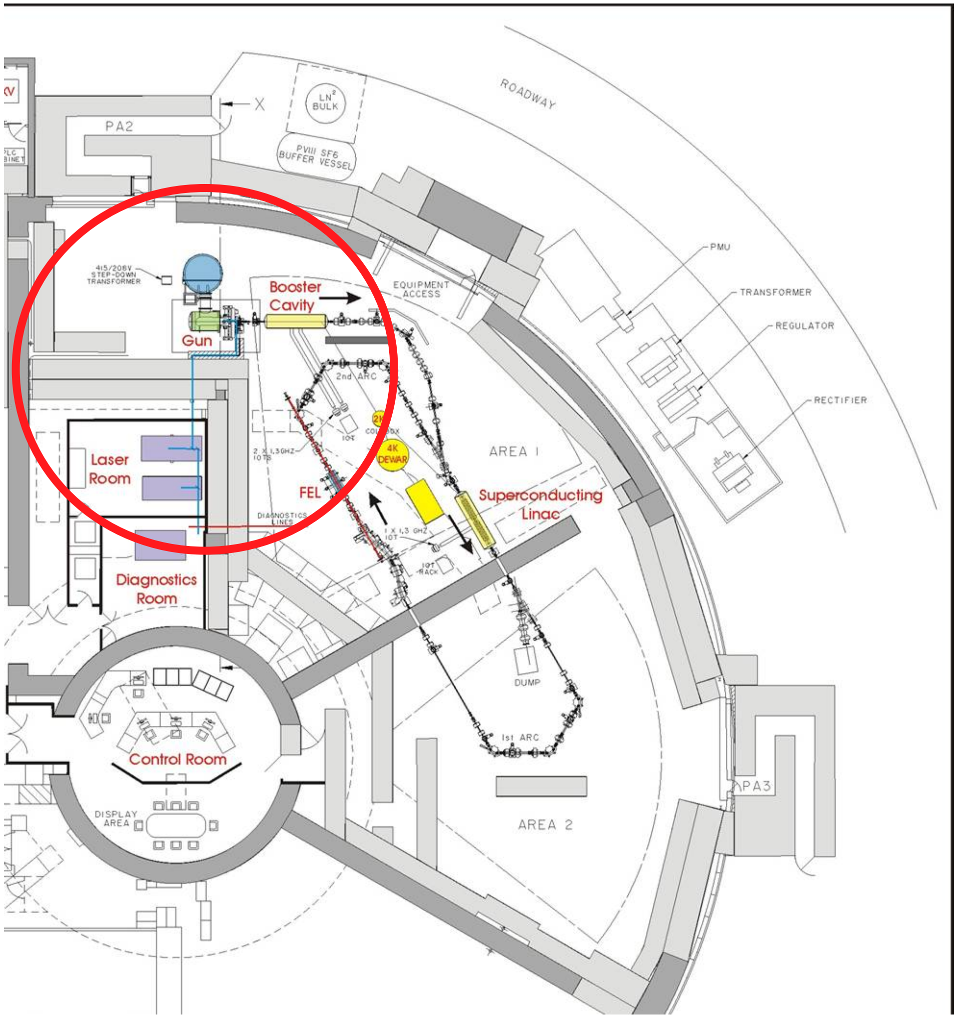








ERL Prototype

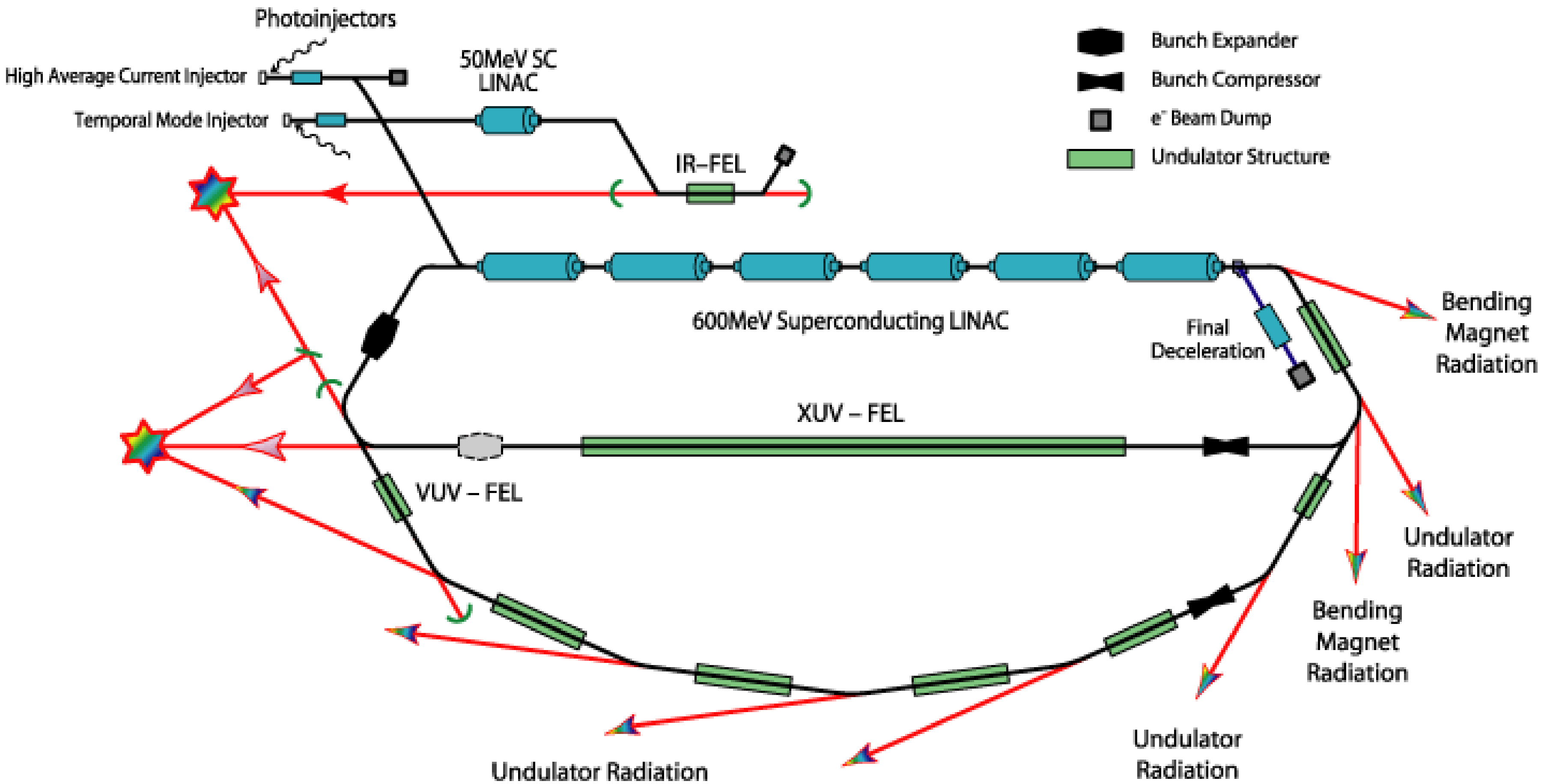


Electron Beam Parameters	Goal
Energy (MeV)	30-50
Accelerator frequency (MHz)	1300
Charge per bunch (pC)	>80
Average current (mA)	>0.8
Peak Current (A)	~150
Beam Power (kW)	~30

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

M.W. Poole et al, PAC 2003 *4GLS: A new type of 4th generation light source facility*

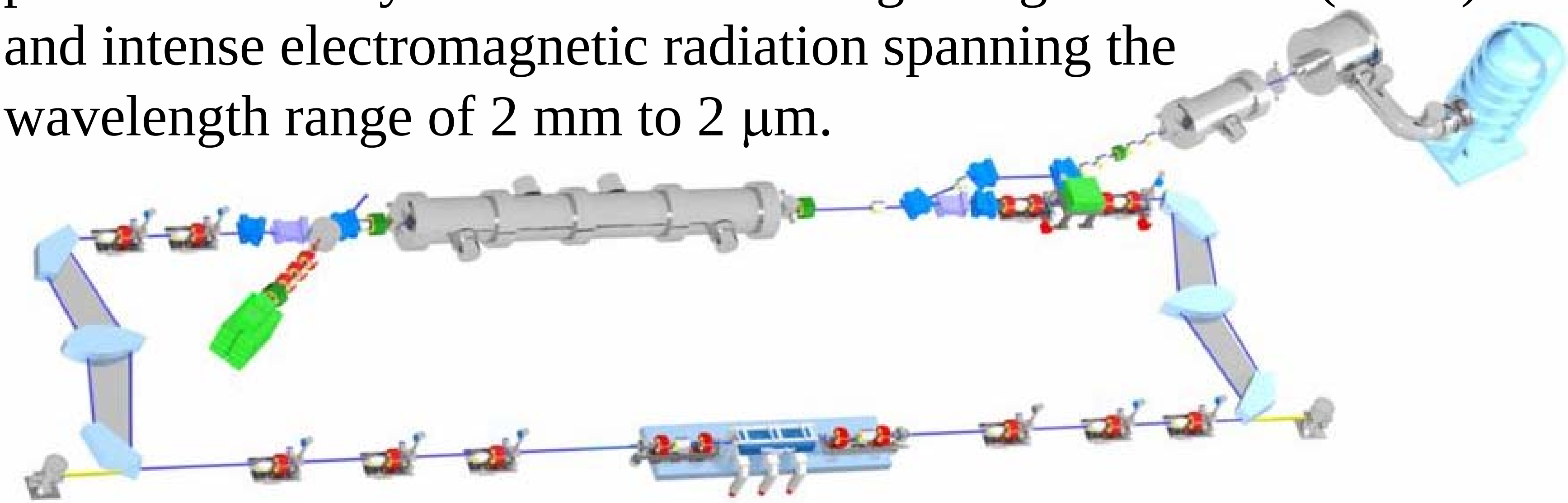
Conceptual layout of 4GLS



M.W. Poole et al, PAC 2003 *4GLS: A new type of 4th generation light source facility*

National (US) 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 μm.

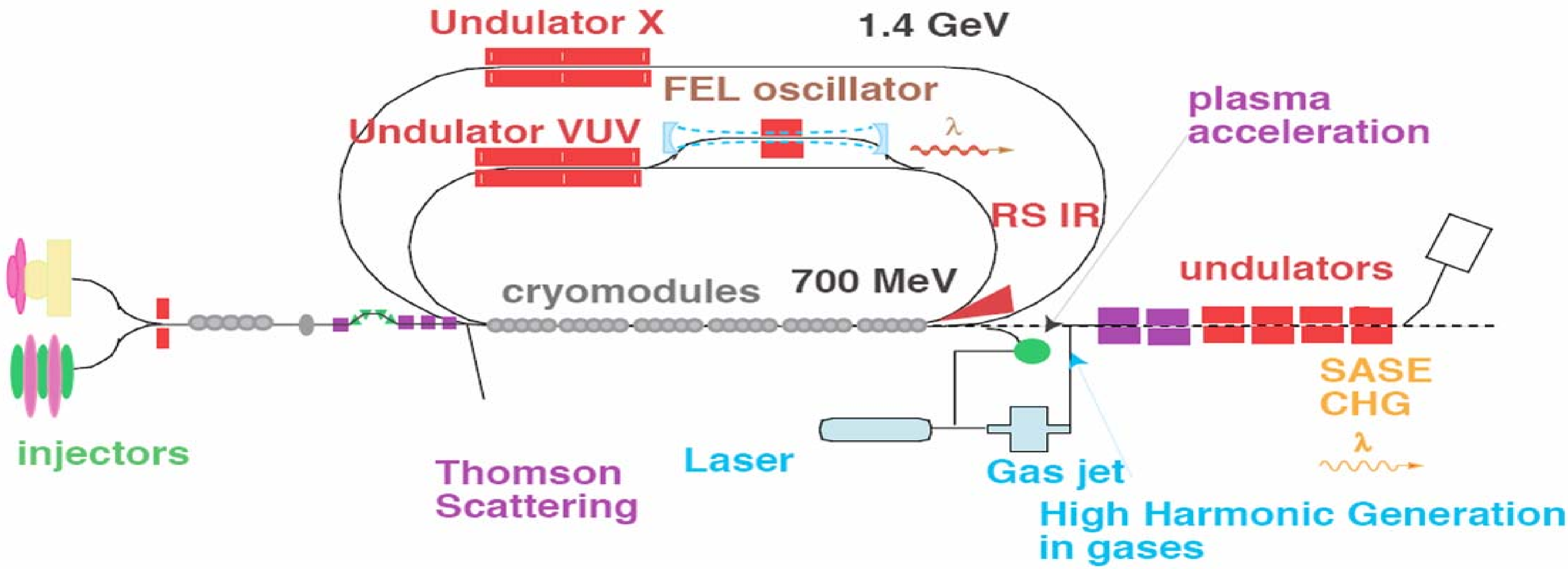


Electron Beam Parameters	**Goal**
Energy (MeV)	60
Accelerator frequency (MHz)	1500
Charge per bunch (pC)	135
Average current (mA)	5
Peak Current (A)	200
Beam Power (kW)	300

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

SACLAY

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



M.E. Couprie et al, *"ARC-EN-CIEL" A proposal for a 4th generation light source in France*, Proc. EPAC 2004, 366.

Advanced Concepts

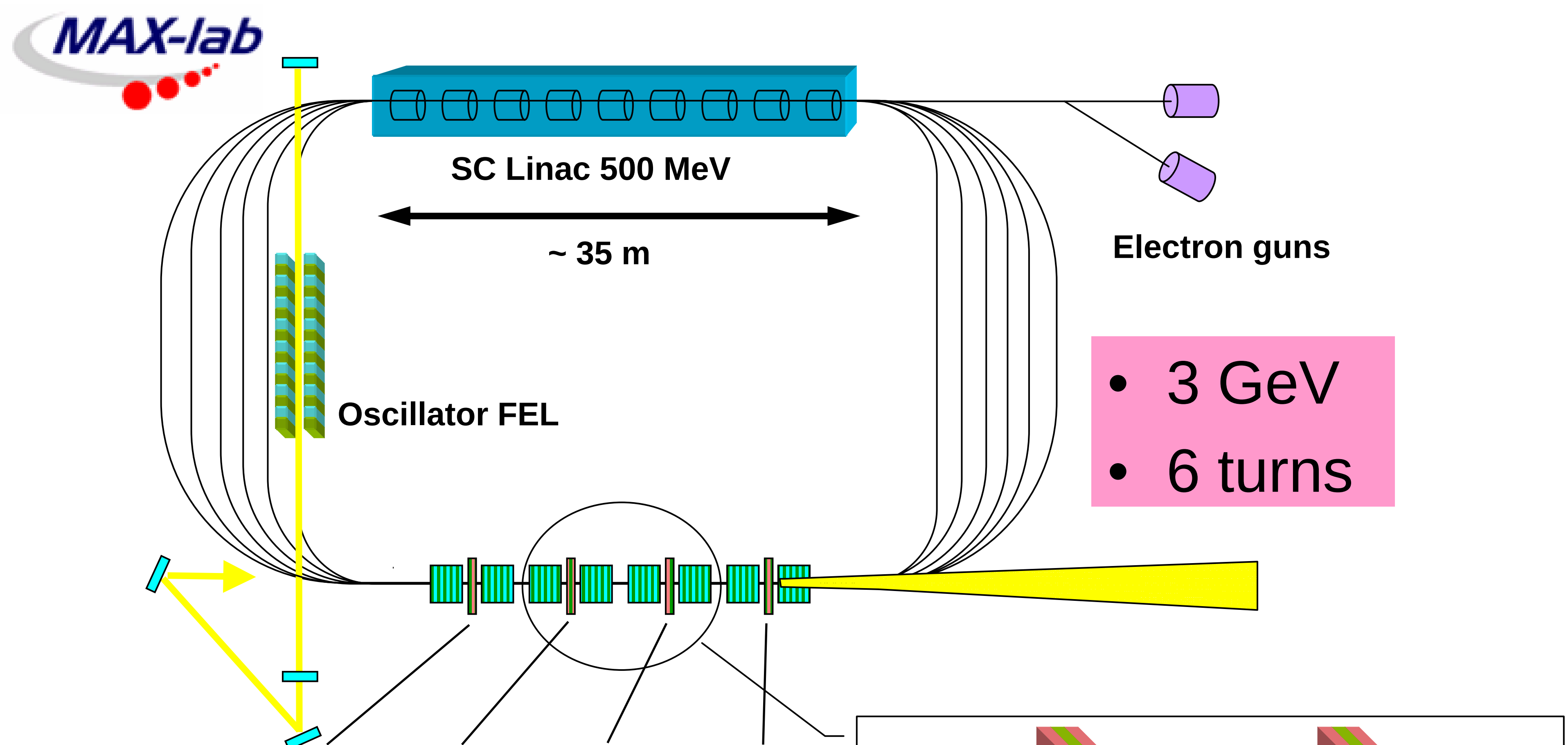
RF Linac based ER-FELs

MAX-lab [NIM A 507 (2003) 470–474]

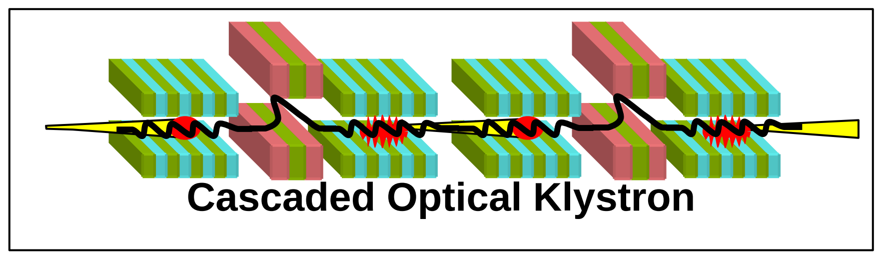
BNL [2004 FEL Conference proc, 570-573.]

Budker [NIM A 528 (2004) 491-496.]

DESY [PRST-AB 8, 010701 (2005)]



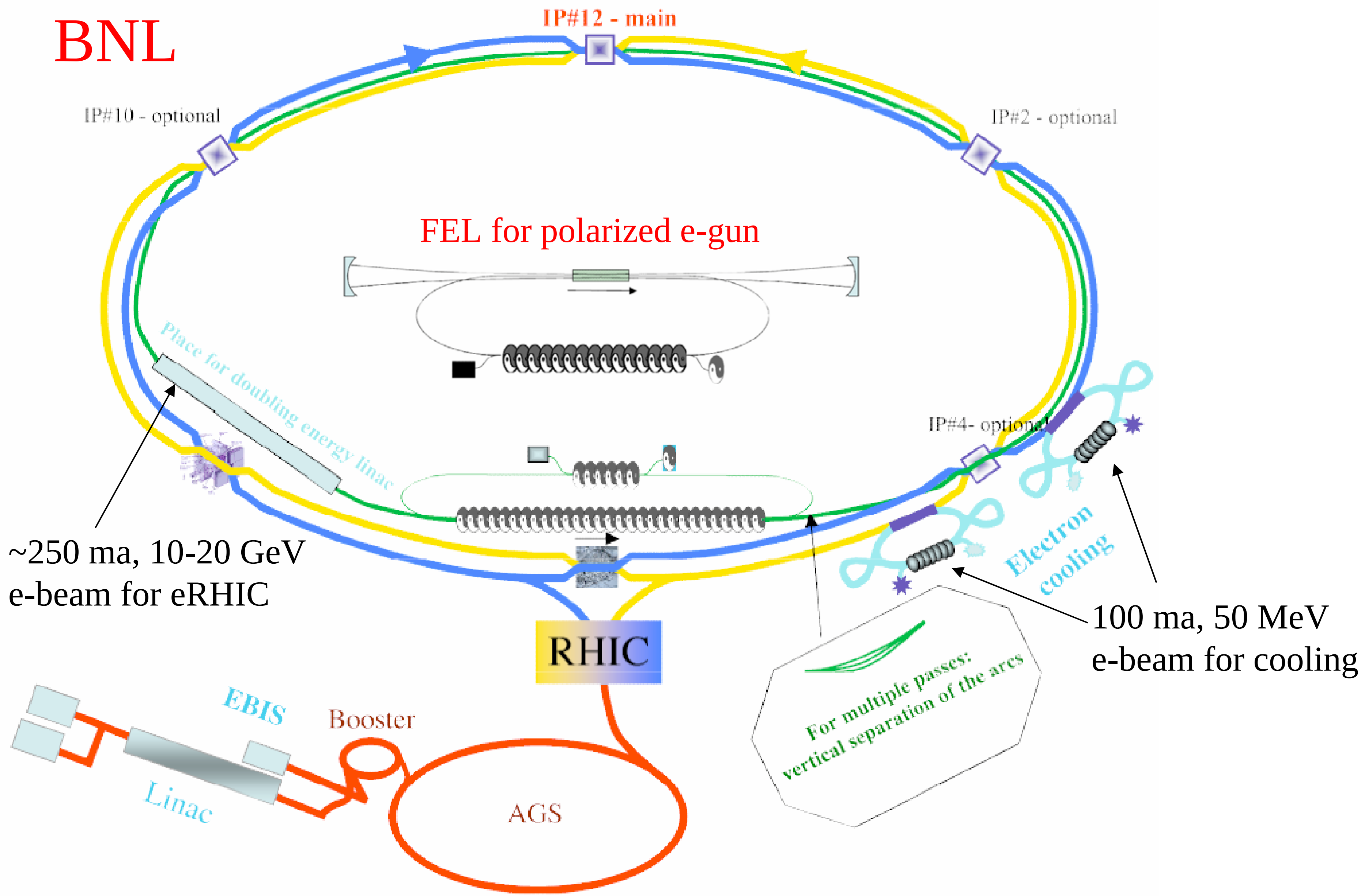
- 3 GeV
- 6 turns



	Stage 1		Stage 2		Stage 3		Stage 4	
e-energy	500 MeV		1.5 GeV		2.5 GeV		3.0 GeV	
U Period	0.06	0.025	0.06	0.025	0.05	0.015	0.015	0.015
K	3.916	1.98	4.5	2.37	2.93	1.75	2.3	2.3
λ(nm)	260	37	37	5.3	5.3	0.76	0.76	0.76/ 0.11

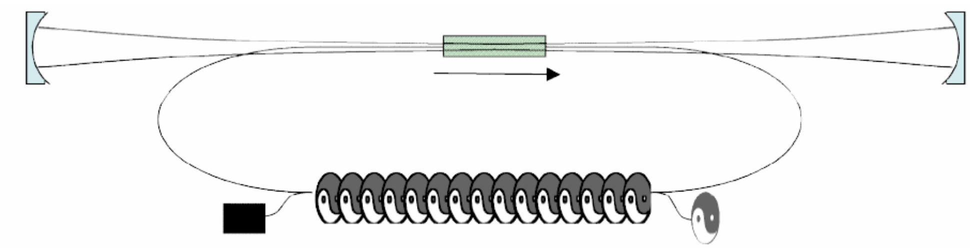
M. Eriksson et al, *A cascaded optical klystron on an energy recovery linac – race track microtron*, NIM A 507 (2003) 470–474

BNL



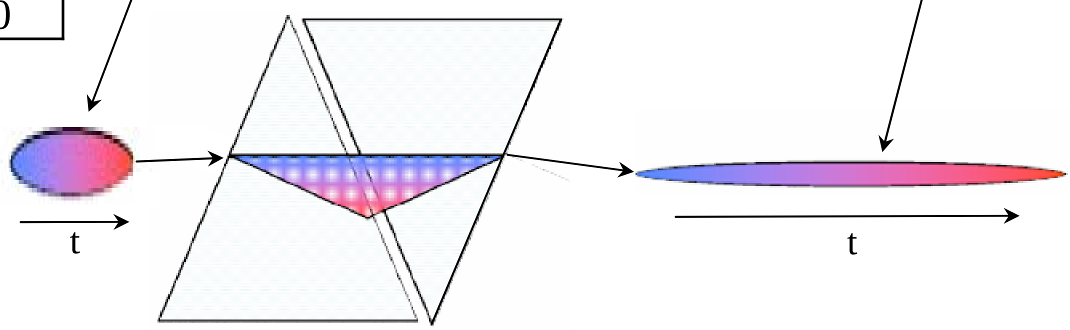
V.N. Litvinenko et al, *High Current Energy Recovery Linac at BNL*, 2004 FEL Conference proceedings, 570-573.

BNL: FEL for polarized e-gun



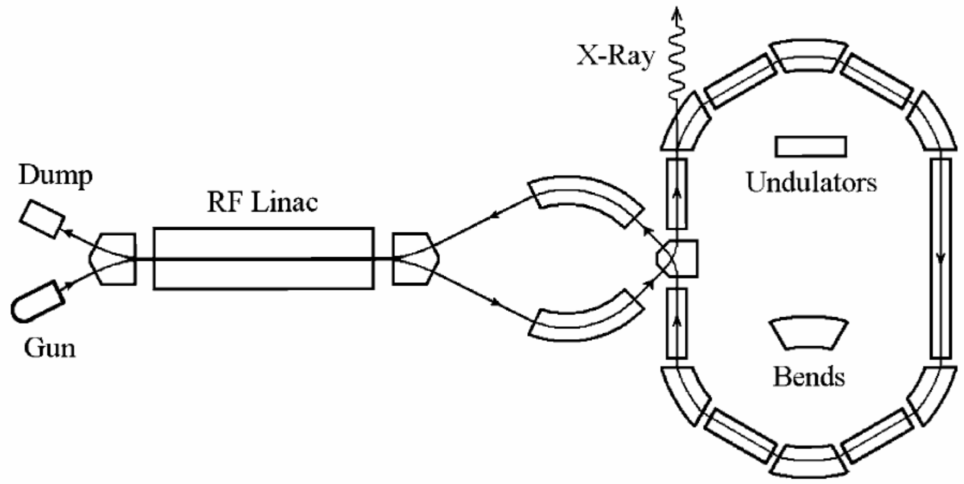
Electron Beam Parameters	
Energy (MeV)	~160
Accelerator frequency (MHz)	703.75
Charge per bunch (pC)	180
Average current (mA)	5
Peak Current (A)	36
Beam Power (kW)	800

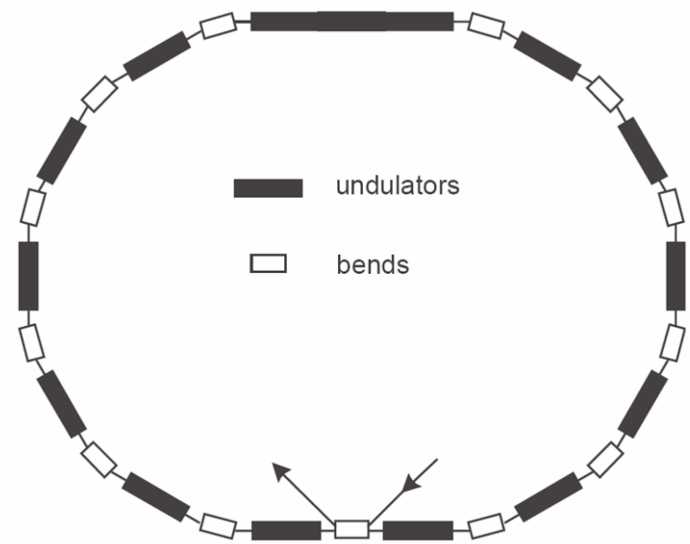
Output Light Parameters	
Wavelength range (microns)	0.4-1
Bunch Length (FWHM psec)	~5
Laser power / pulse (μJoules)	~150
Laser power (kW)	2-6
Rep. Rate (MHz)	28.15
Macropulse format	CW
Chirp (μm/ps)	5
Final bunch lencth (ps)	~150



Daniel Anderson et al, *Linac-Ring eRHIC*, Appendix A of the eRHIC ZDR

BINP



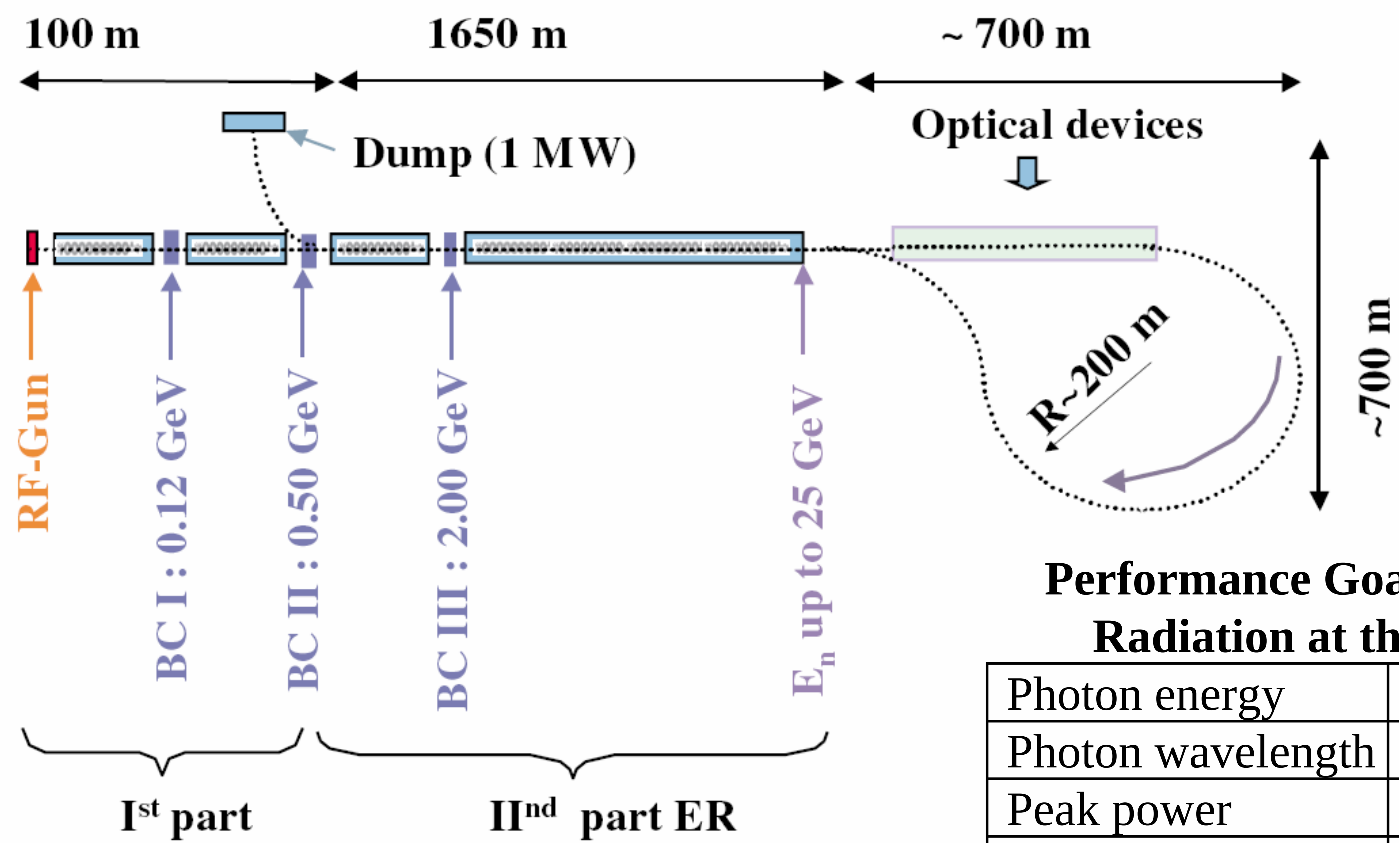


Soft X-ray ring FEL parameters	
Energy (GeV)	0.485
Peak current (kA)	0.3
Relative energy spread (%)	0.05
Normalized rms emittance (μm)	5
Undulator period (m)	0.03
Undulator deflection parameter (K)	2
Radiation wavelength (Å)	500
Undulator section length (m)	12
Undulator first and last section length (m)	5
Bend angle (deg)	60
Bend length (m)	10
Bend $\int \gamma_x \, ds$	3.1
Bend $\int \gamma_y \, ds$	6.22
Distance between first and last undulator ends (m)	2

X-ray ring FEL parameters	
Energy GeV	14.35
Peak current (kA)	2
Relative energy spread (%)	0.008
Normalized rms emittance (μm)	1.2
Undulator period (m)	0.03
Undulator deflection parameter K	3.71
Radiation wavelength (Å)	1.5
Undulator section length (m)	18
Undulator first and last section length (m)	18
Bend angle (deg)	30
Bend length (m)	6
Bend $\int \gamma_x \, ds$	0.864
Bend $\int \gamma_y \, ds$	1.245
Distance between first and last undulator ends (m)	2

N.K. Vinokurov, O.A. Shevchenko, *High gain ring FEL as a master oscillator for X-ray generation*, NIM A 528 (2004) 491-496.

DESY



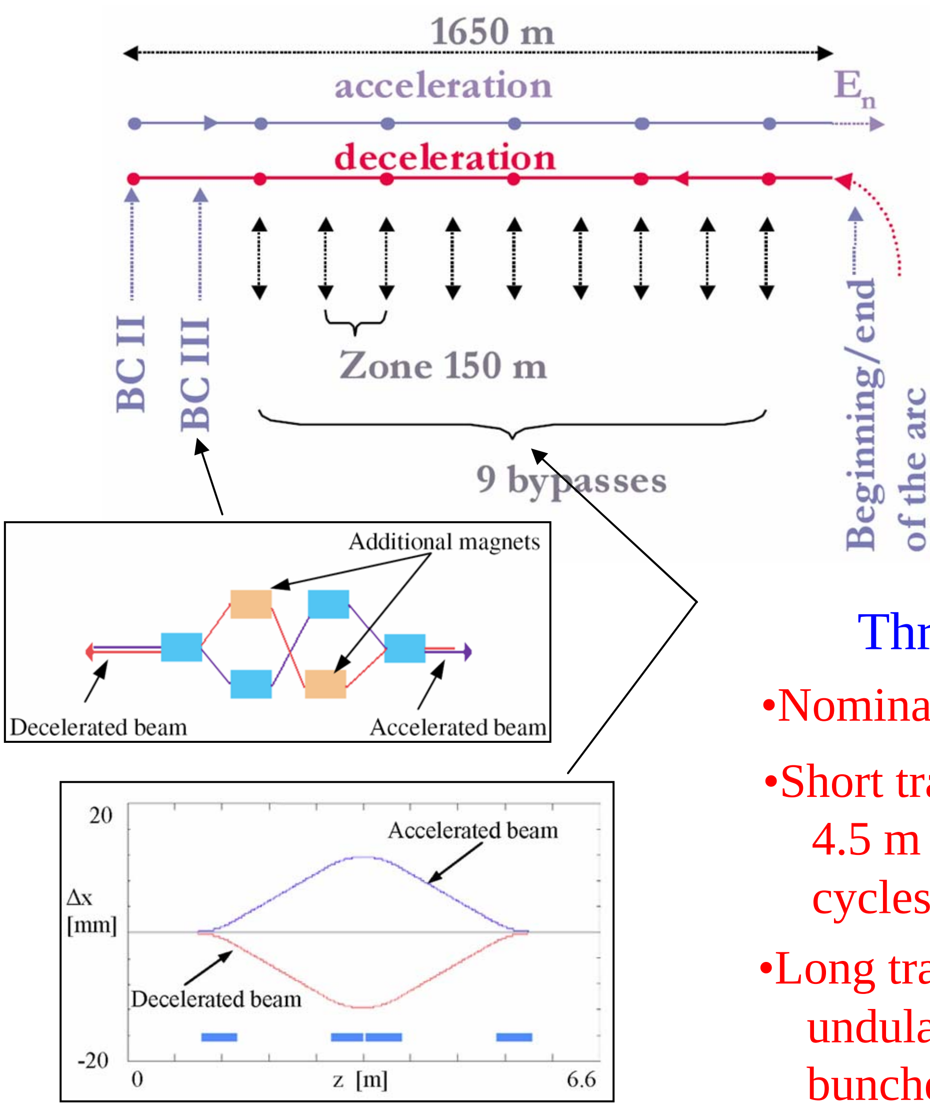
Performance Goals for SASE FEL Radiation at the DESY XFEL

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.)	

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

J. Sekutowicz et al, *Proposed continuous wave energy recovery operation of an x-ray FEL*, PRST-AB 8, 010701 (2005).

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 ER Linac 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 μs train of bunches can repeat every 24 μs without colliding.

Summary

Energy recovery RF linac based FELs are proliferating at an astonishing (or satisfying) rate.

•Three are currently operational

•At least four more are in the serious planning stages

•Innovative ideas are being explored and suggested