Future FEL's

J. N. Corlett

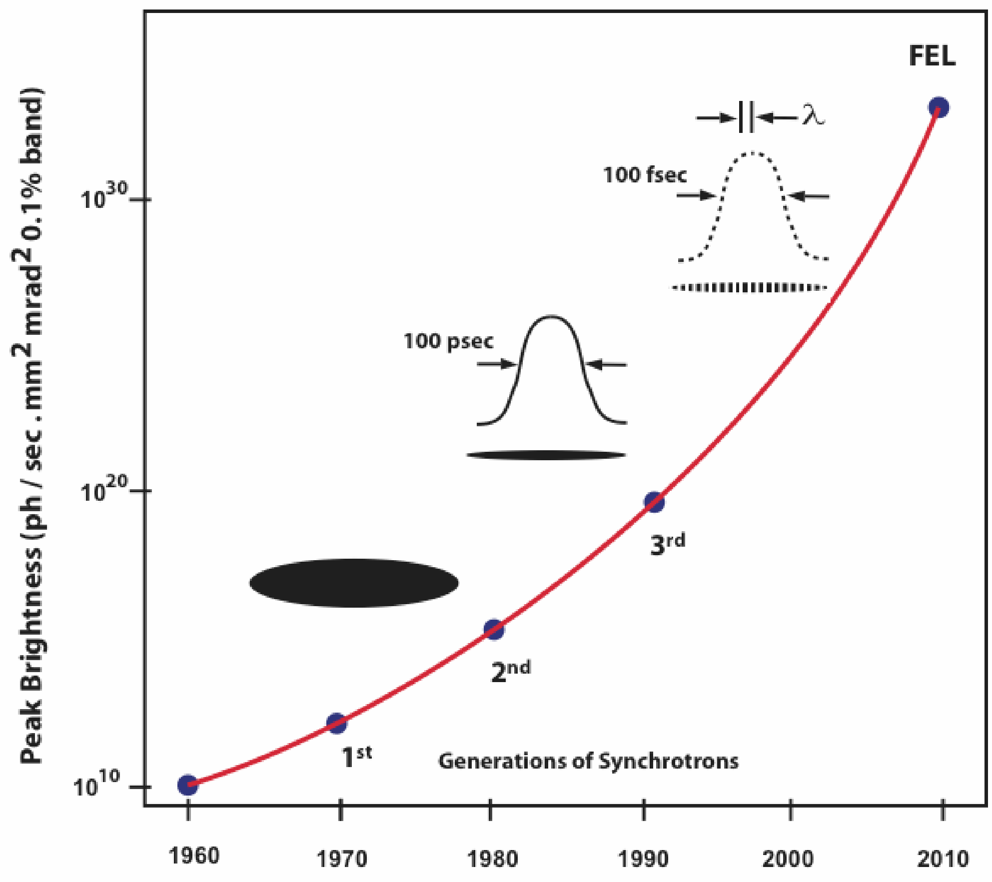
LBNL

12th International workshop on RF Superconductivity, SRF 2005

Cornell University, July 2005

Evolution of synchrotron radiation sources

- Future generations of light sources will likely utilize novel techniques for producing x-rays tailored to application needs
  - Free electron laser (FEL)
  - Energy recovery linac (ERL)
  - Beam manipulation (optical and electron)
    - High average power
    - High Peak power
    - Temporal coherence
    - Spatial coherence
    - Ultra-short pulses
    - Synchronization



Applications for FEL's

- Industrial applications
  - Plastics surface processing
  - Micromachining
  - Metal surface processing
  - Electronic materials processing

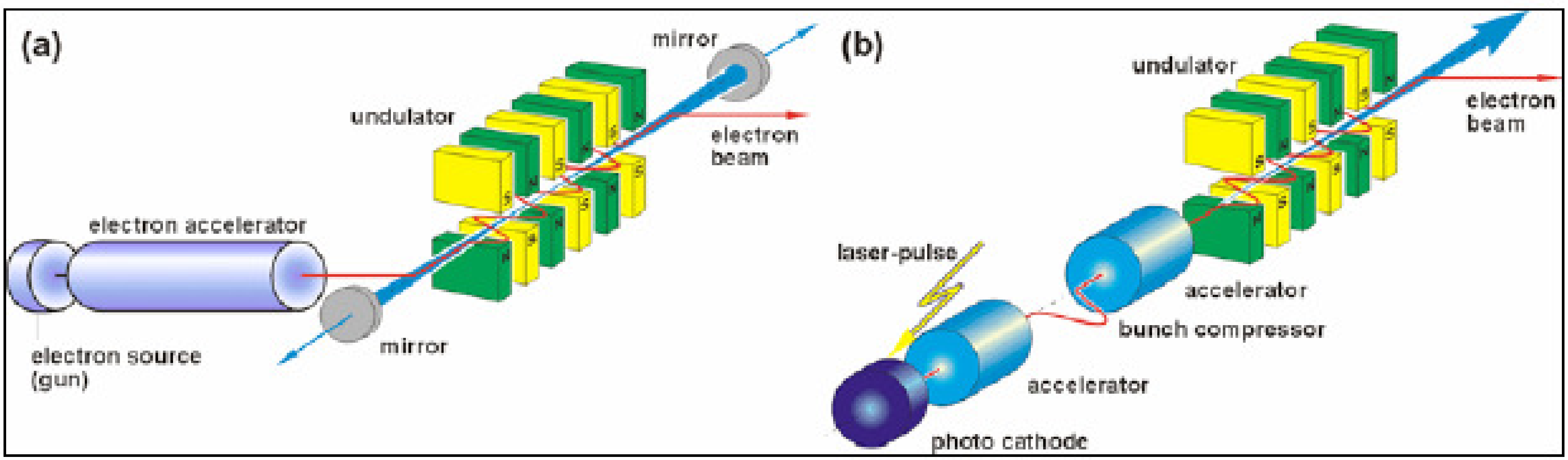
- Directed energy beams

- Scientific applications
  - Apply existing x-ray techniques to enhanced experiments
  - Diffraction and spectroscopy techniques (nuclear positions and electronic, chemical or structural probes)
    - Non-linear x-ray processes
    - Coherent spectroscopies and imaging
    - Time-domain explorations

FEL process occurs in undulator in optical cavity, or single-pass

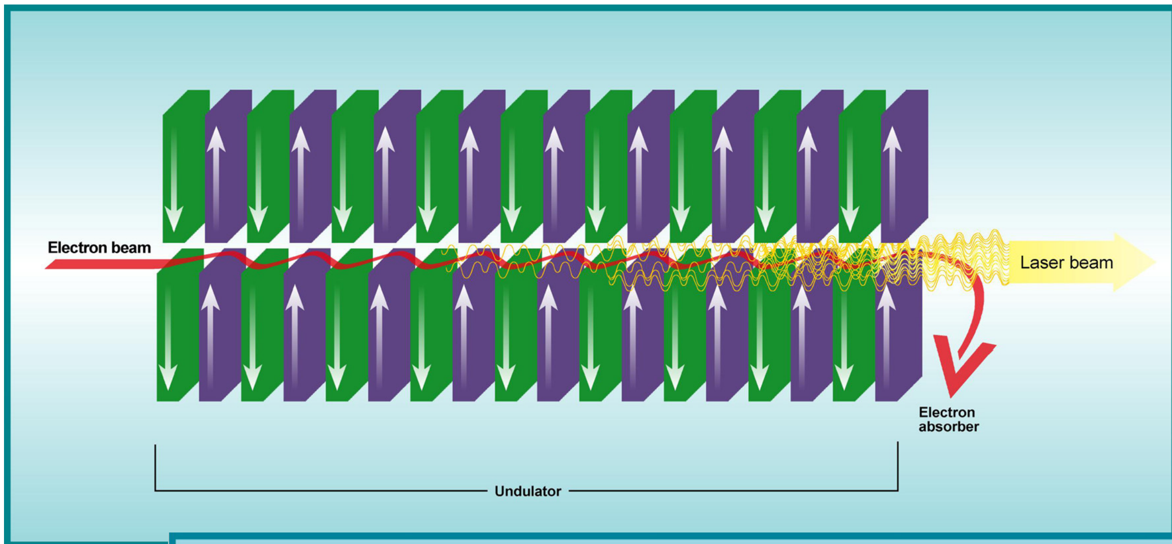
- Oscillator configuration generally limited in wavelength >~160 nm by availability of mirrors
  - Some advanced schemes proposed which avoid mirrors

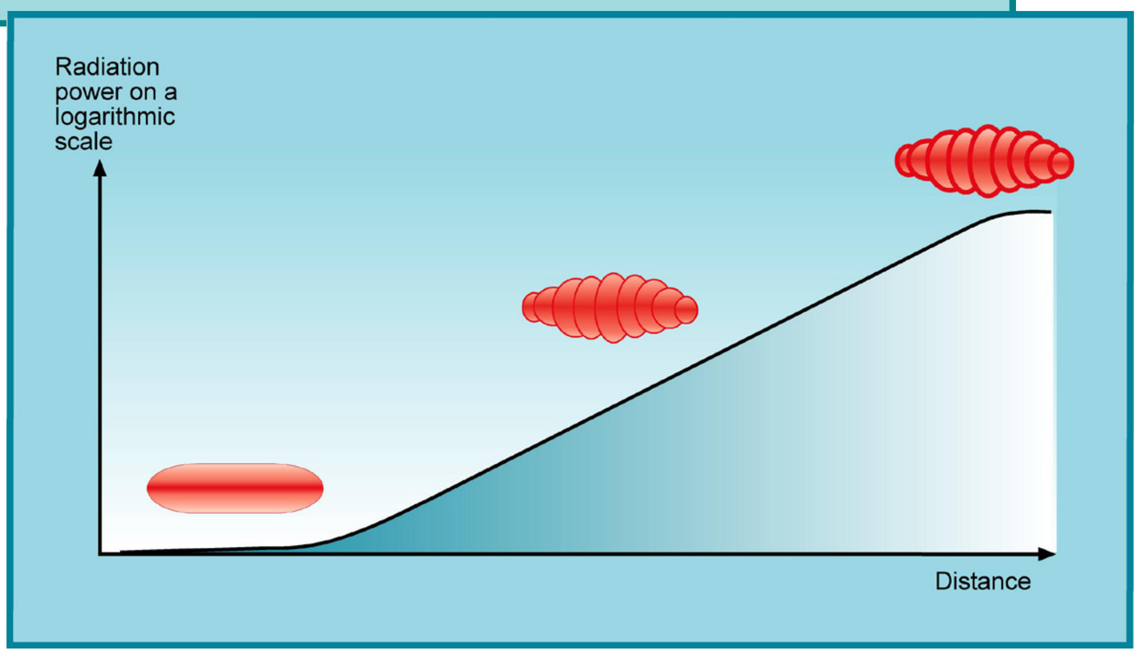
- Single-pass FEL allows the hard x-ray regime to be reached
  - LCLS, European X-ray FEL aimed at Å regime
  - nm wavelengths achievable with few GeV electron beams



BESSY FEL TDR

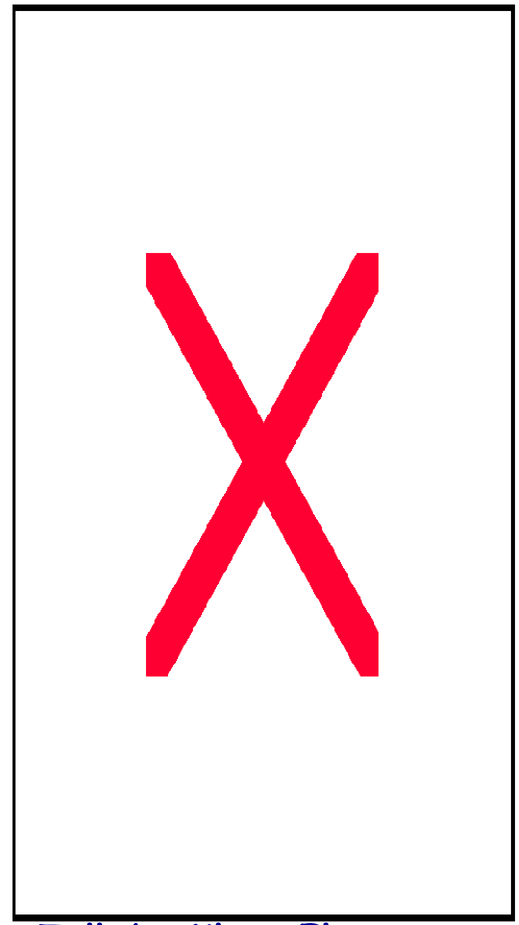
SASE FEL output grows from shot noise in the beam





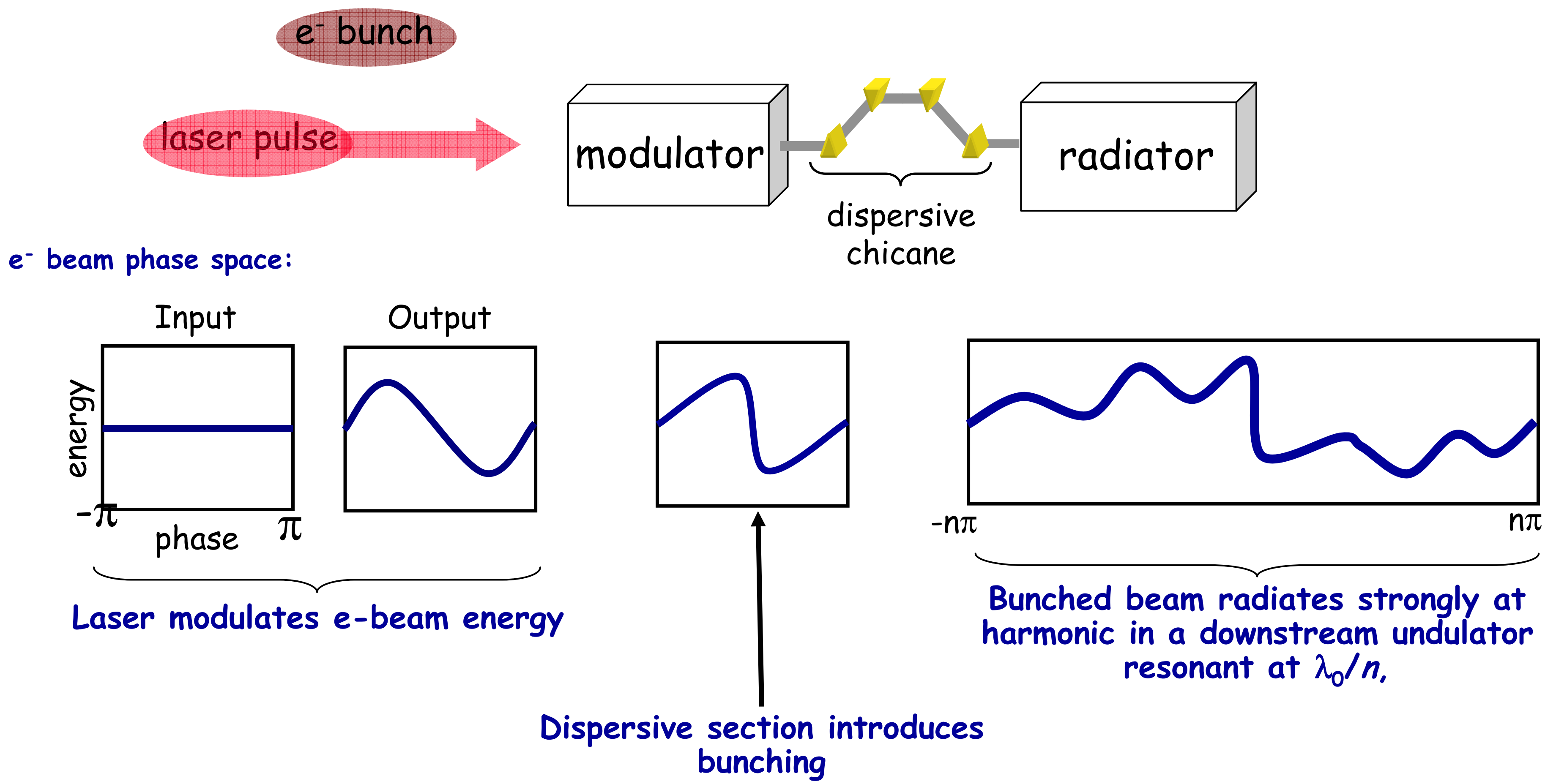
http://xfel.desy.de/xfelhomepage/index_eng.html

The European X-Ray Laser Project XFEL



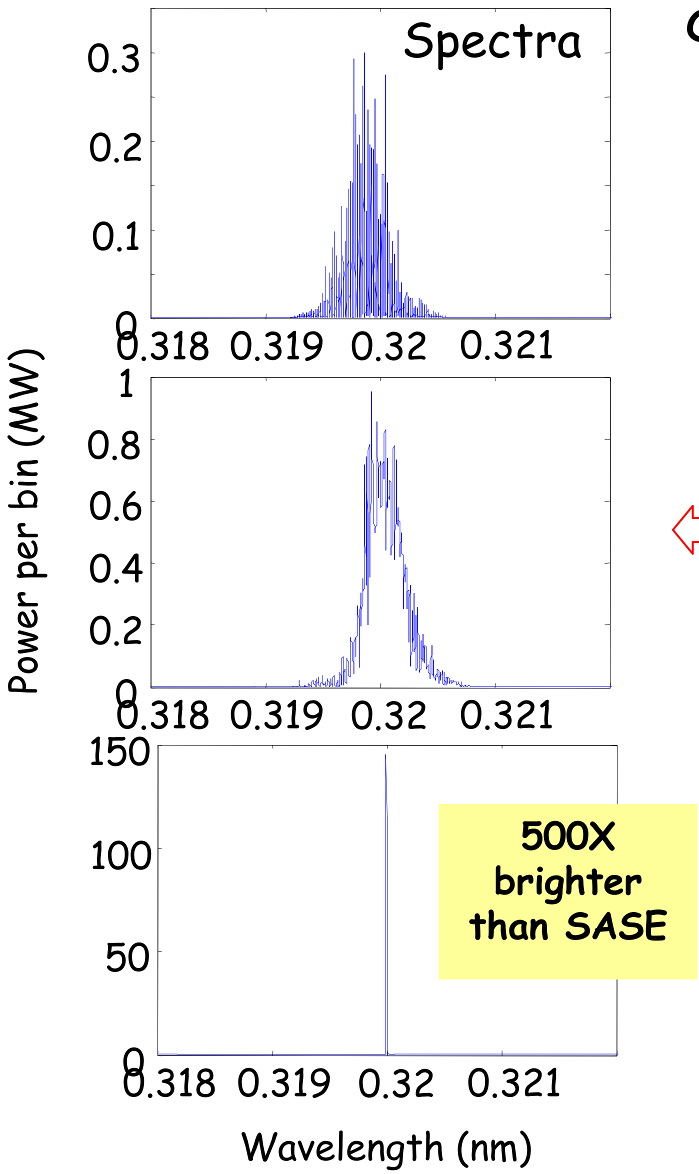
Talk by Klaus Floettmann

High Gain Harmonic Generation (HGHG) - seed the FEL with a laser pulse and radiate at a shorter-wavelength



L.-H. Yu et al, Science 289 932-934 (2000)
L.-H. Yu et al, Phys. Rev. Let. Vol 91, No. 7, (2003)

Comparison of seeded and SASE characteristics

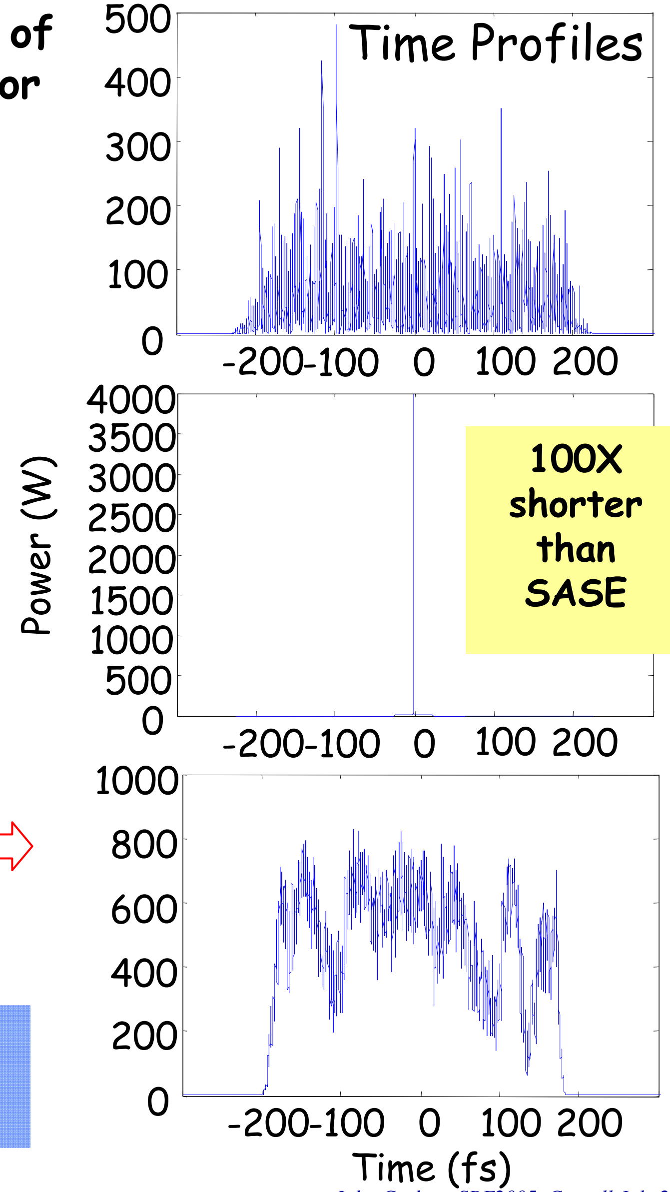


Output from simulation of FEL with 30 m undulator

SASE

Seeded with 1 fs HHG XUV

Seeded with 500 fs UV

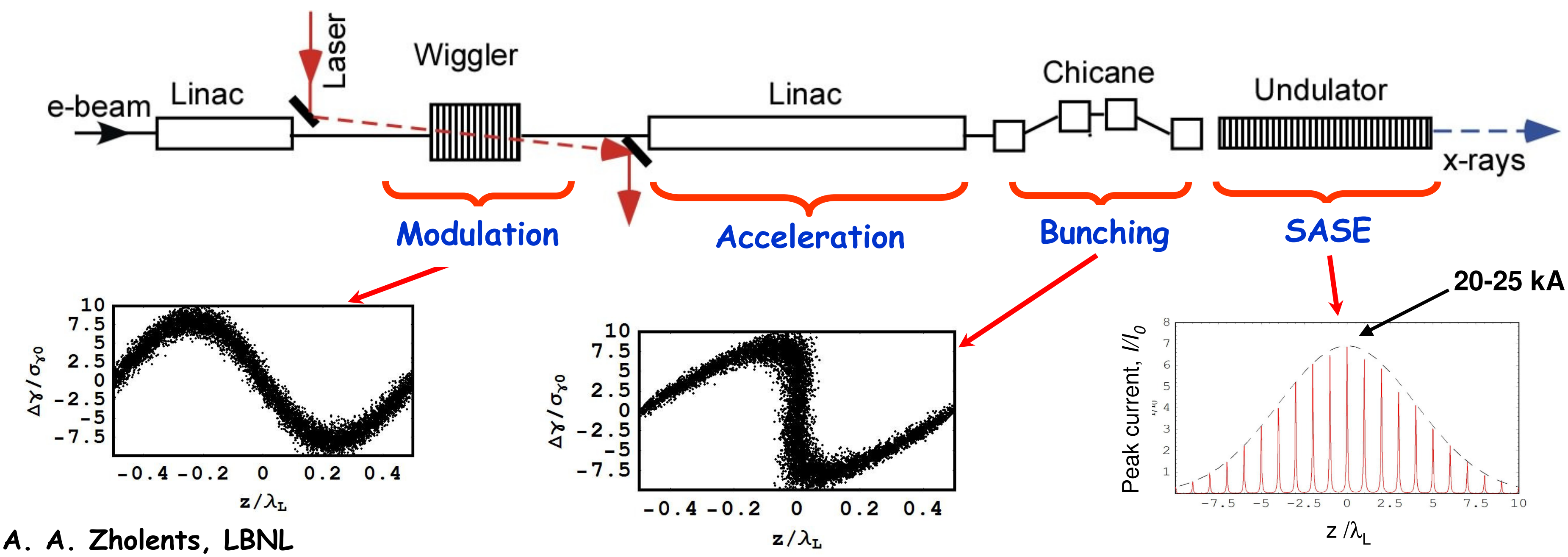


W. Graves, MIT

Techniques using optical manipulation of beams offer enhancement of FEL performance

- Improved performance
  - Pulse output stability
  - Temporal coherence
  - Synchronization with seed laser
  - Pulse duration control

- *Another example - Enhanced* Self-Amplified Spontaneous Emission (ESASE)



A. A. Zholents, LBNL

FEL performance drivers

- Electron beam energy γ
  - High gradient accelerator
- Electron beam emittance ε
  - High brightness gun, minimize emittance growth in accelerator
- Peak current I_{peak}
  - Bunch compression, minimize distortion from RF and longitudinal wakefield
- Energy spread σ_E
  - High brightness gun, minimize distortion from longitudinal wakefield
- Electron beam energy stability
  - Minimize accelerator and laser systems timing, phase and amplitude variations
- Timing of laser pulse with respect to electron bunch
  - Minimize accelerator and laser systems timing, phase and amplitude variations

$$\lambda_{x-ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + K^2\right)$$

$$\frac{\varepsilon_n}{\gamma} \approx \frac{\lambda_{x-ray}}{4\pi}$$

$$\text{Power/undulator length} \sim f\left(I_{peak}, \frac{\varepsilon_n}{\gamma}, \sigma_E\right)$$

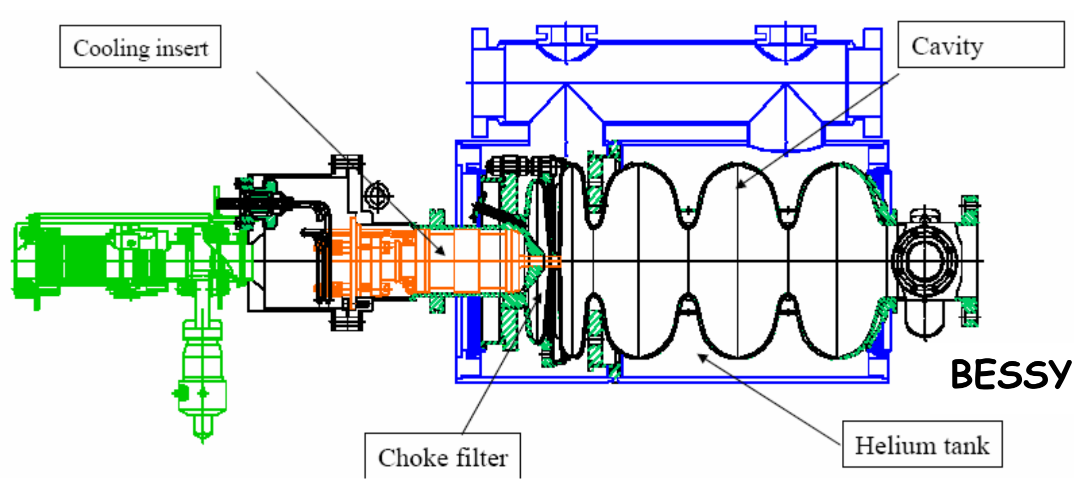
SRF technologies under development for future FEL's

SRF electron gun

- Flexible pulse format
- High repetition rate
  - Potential for high beam power
- Low emitance
- Low energy spread
- Stable fields
- Lock photocathode laser and RF phase

- *Photocathode laser*
- *Cathode*

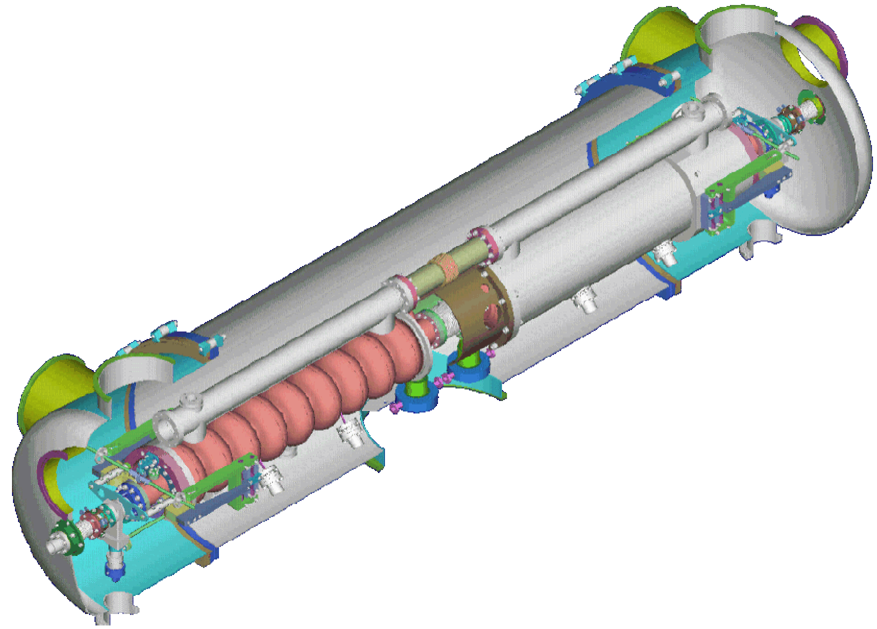
BROOKHAVEN NATIONAL LABORATORY — Jefferson Lab — Advanced Energy Systems, Inc.

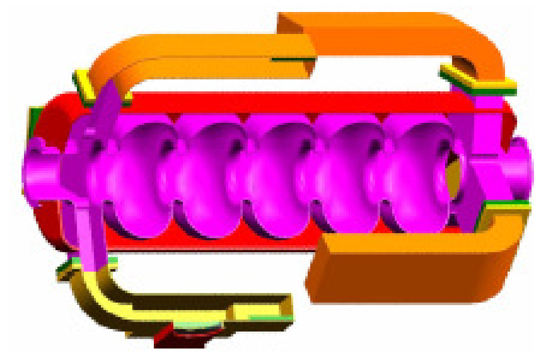


BESSY / PITZ

SRF technologies under development for future FEL's

Superconducting rf linac
- Small perturbations from wakefields
  - Large iris aperture
- CW operation
    - High gradient (~20 MV/m)
  - High repetition rate
  - High beam power
  - Flexible pulse rate
  - Flexible pulse pattern
  - Highly stable cavity fields
    - RF feedback and controls
      - Electron beam energy and timing stability
  - HOM suppression
- Energy recovery option

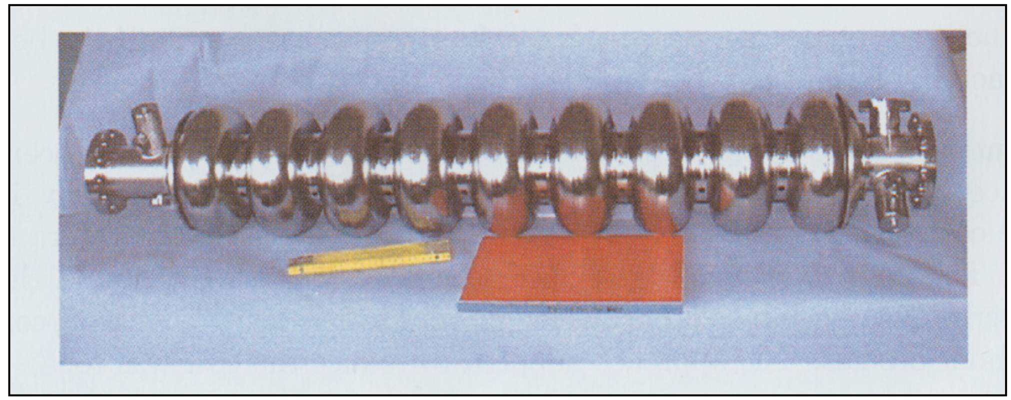


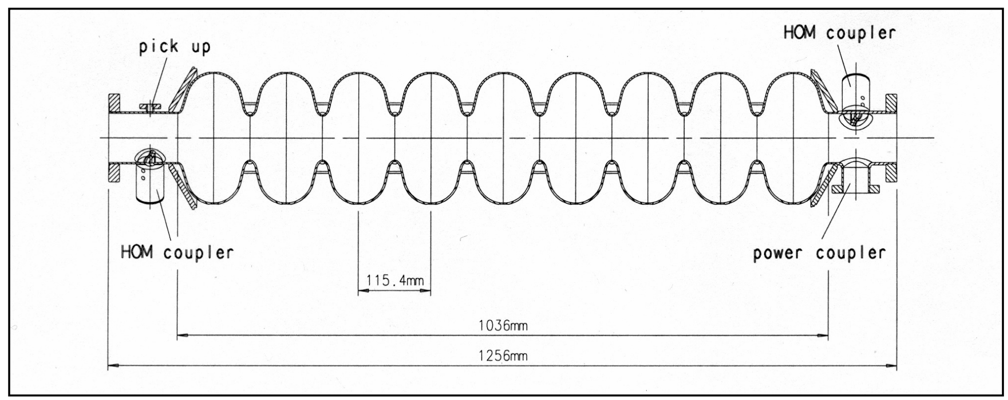


Harmonic cavities
- Linearize longitudinal phase space
- Deflecting cavities for electron beam diagnostics

CW operation with TESLA technology

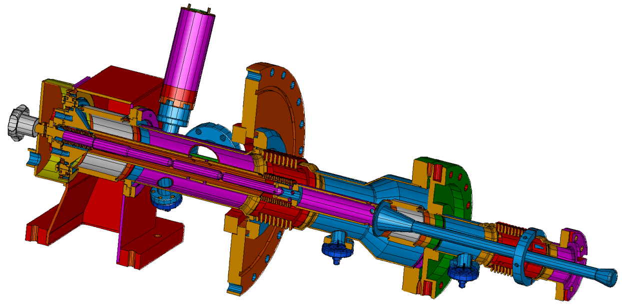
	TESLA	CW "LUX"
E_{acc} [MV/m]	23.4	20
Operation mode	Pulsed	CW
Pulse length [ms]	1.37	CW
Repetition rate [Hz]	5	CW
Duty factor [%]	0.685	100
Beam current [mA]	9.5	0.03
Bandwidth [Hz]	520	50
Q_o	10^{10}	10^{10}
Q_{ext}	$2.5x10^6$	$2.6x10^7$
RF power/ cavity	1.85 MW	10 kW
Dynamic load at 2K per cavity [W]	0.4	42





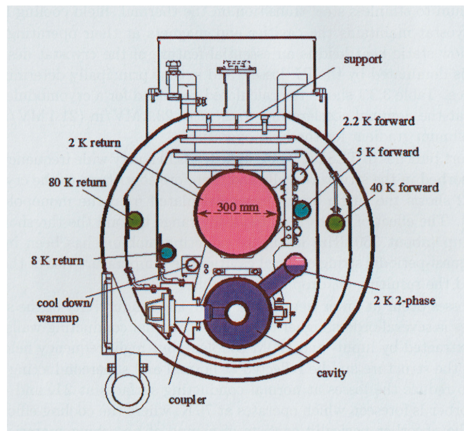
Accelerating linac CW considerations

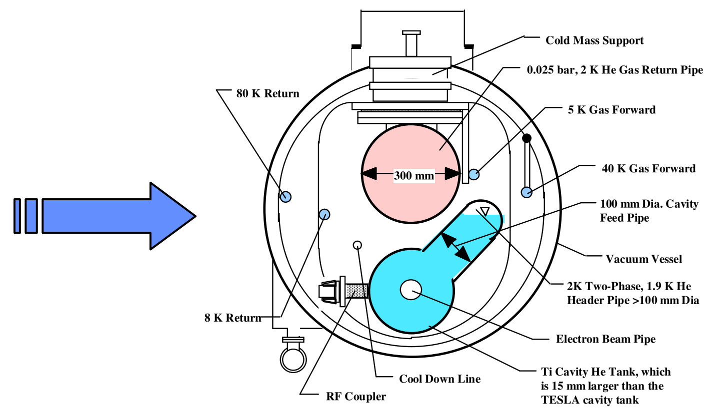
- Input coupler



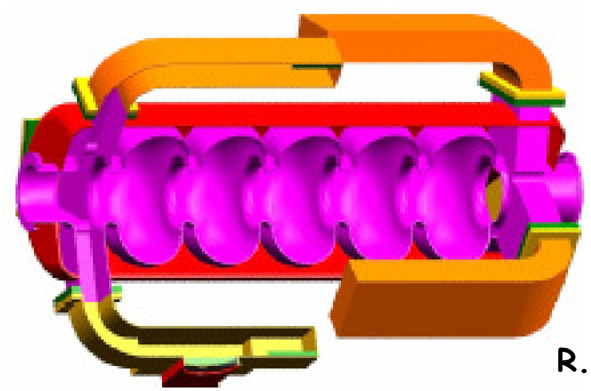
TESLA TDR, DESY

- Heat transport from cavity





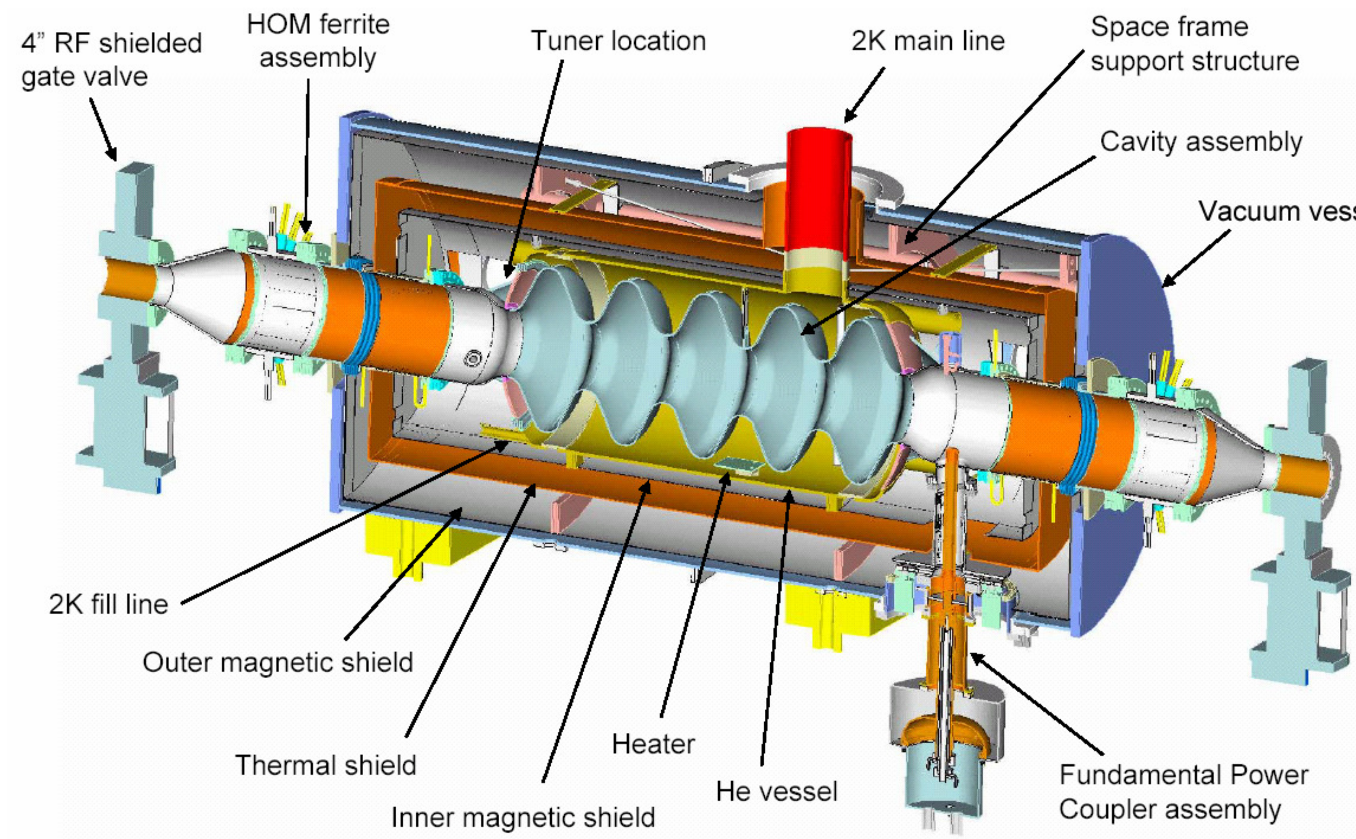
- HOM damping



R. A. Rimmer, J-Lab

BNL 703.75 MHz CW scrf cryomodule

e-RHIC and future FEL applications



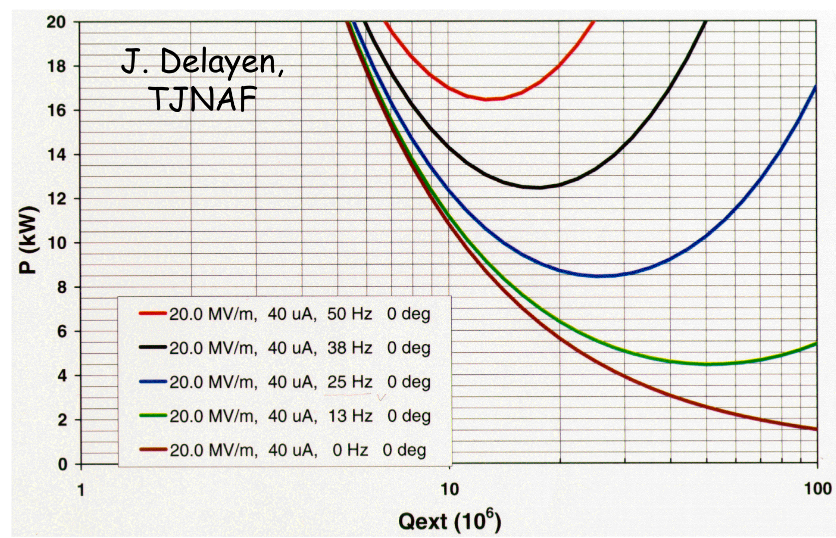
BNL, TJNAF, AES

Feedback control of tuning variations

- Tight coupling minimizes RF power requirements
  - ß ~ 1 for power optimization
  - May be limited by feedback bandwidth required for stability
- Random tuning variations
  - Slow perturbations e.g. from variations in He pressure
  - Faster perturbations from microphonics at acoustic frequencies - structural resonances
- Tight phase and amplitude control
- $\Delta\phi < 0.01°$, $\Delta V/V < 10^{-4}$
  - FEL output pulse energy stability
  - Synchronization, seeding

$$P_g = \frac{P_c}{4\beta}\left\{(1+\beta+b)^2 + \left[2\,Q\,\frac{\Delta f}{f} - b\,\tan(\Psi_B)\right]^2\right\}$$

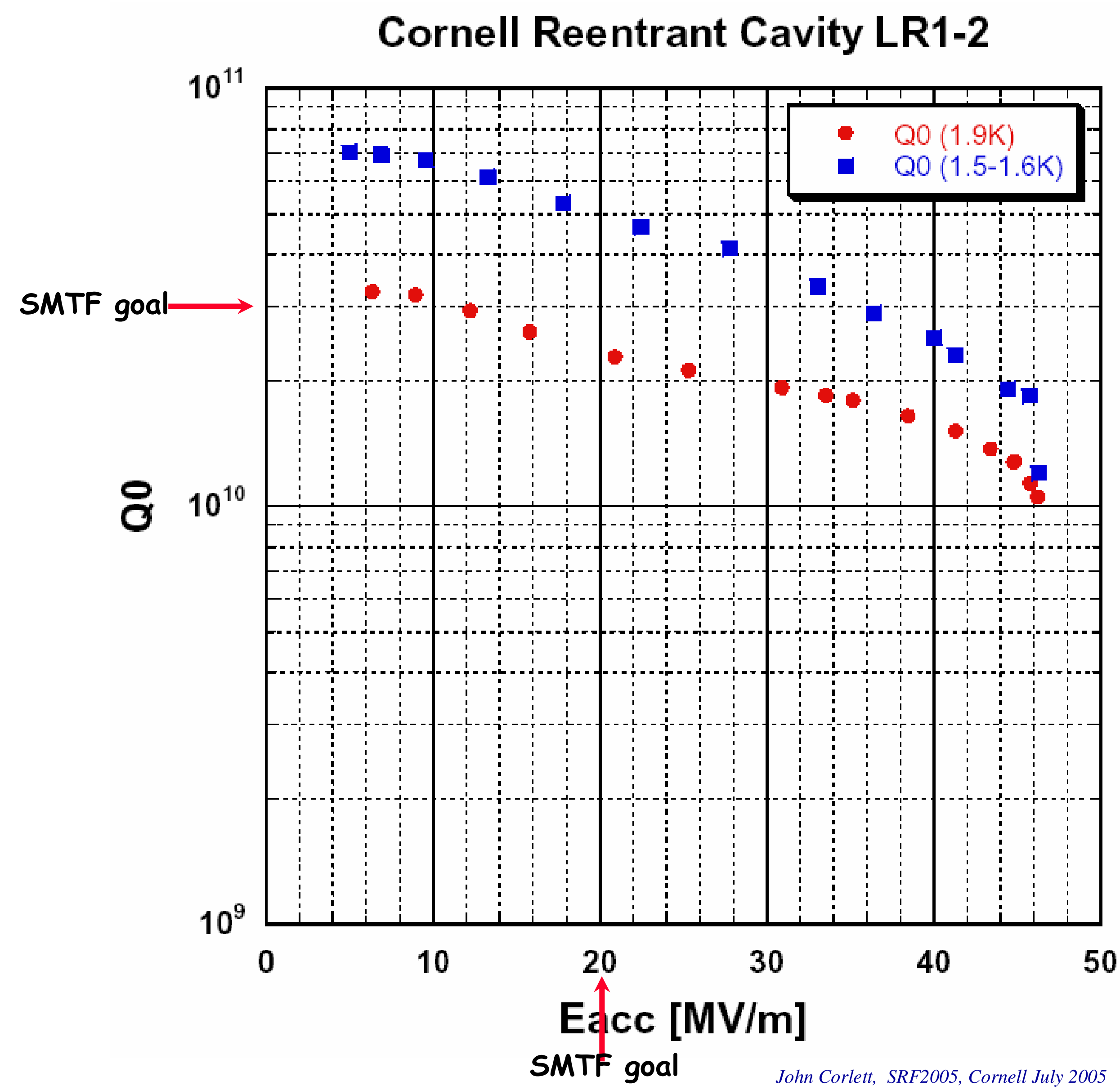
$$\beta_c = \frac{Q_0}{Q_{ext}};\quad b = \frac{P_{beam}}{P_C}$$



High Q_o reduces power dissipation in liquid helium

- SMTF goal for CW systems
  - Q_o 3×10^{10} at 20 MV/m
  - Installed cryomodule

$$R_{BCS} \propto \frac{1}{T} f^2 e^{-\frac{a}{T}}$$



SCRF-based FEL proposals and facility concepts

Proposals

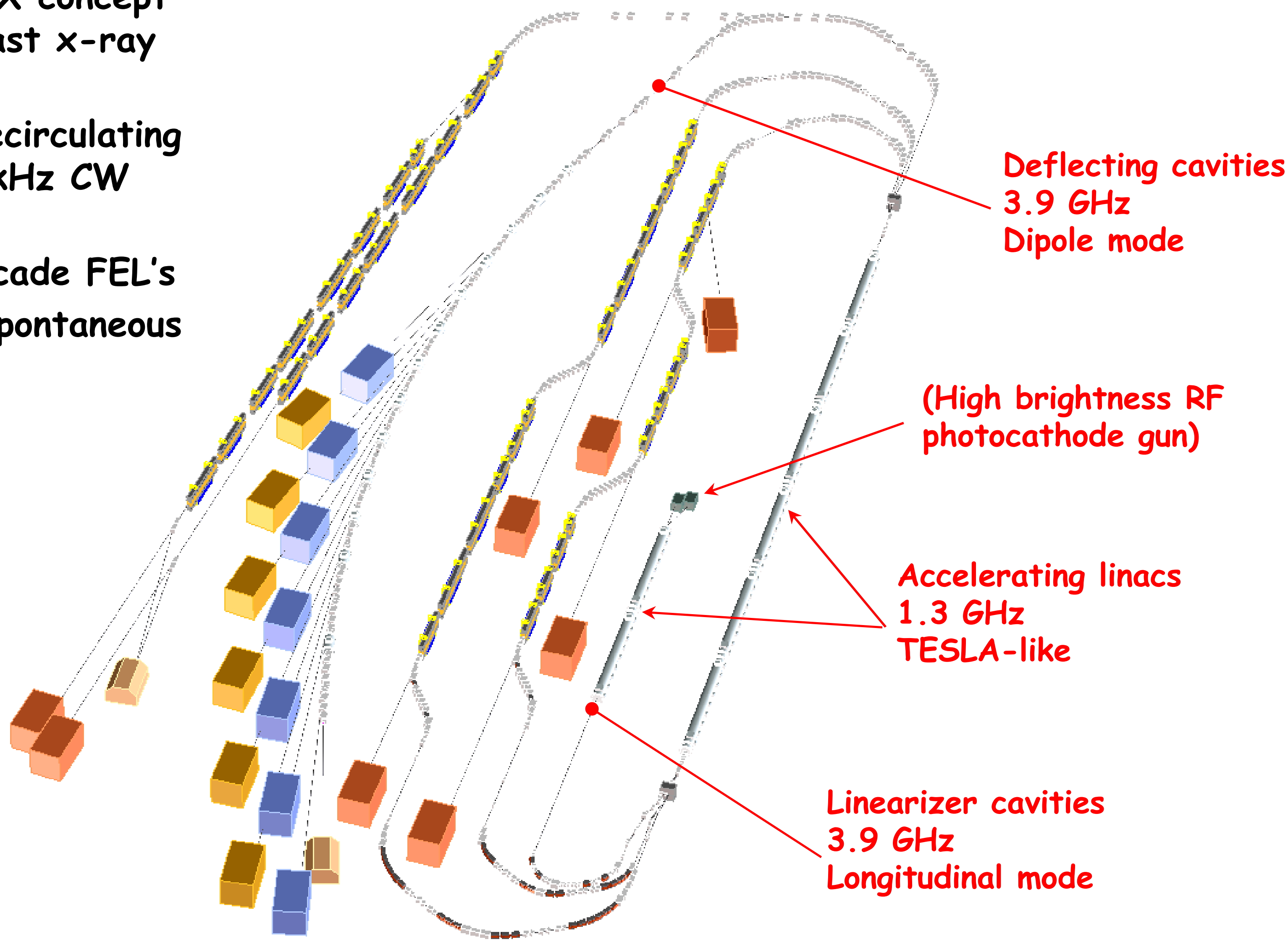
- European X-ray FEL: single-pass linac SASE
- BESSY FEL: single-pass linac HGHG
- KAERI: ERL SASE
- NHMFL: ERL SASE
- 4GLS: ERL HGHG + SASE
  - Daresbury ERLP: ERL SASE (construction)

Concepts

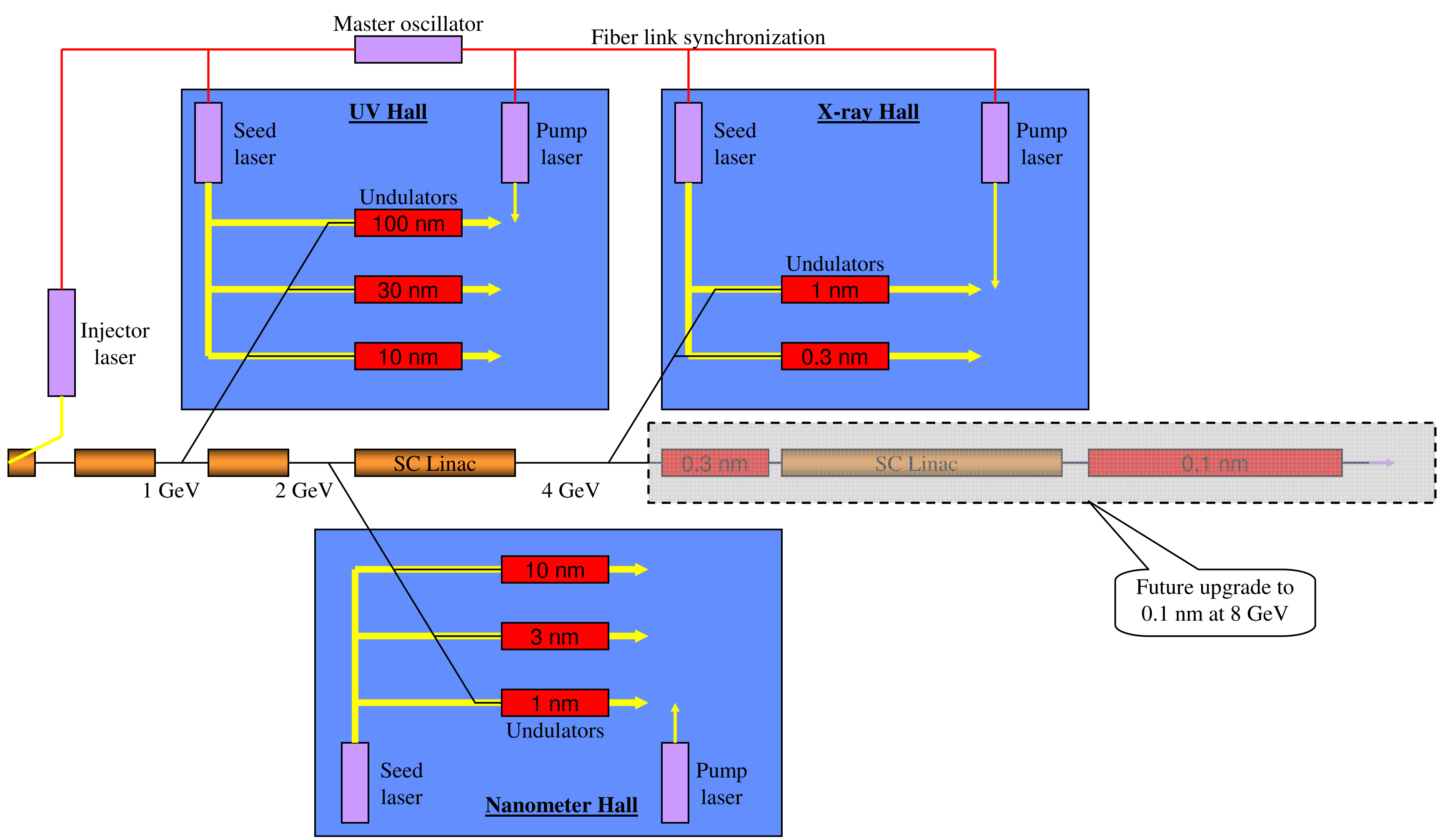
- Arc-en-Ciel: recirculating linac / ERL HGHG + SASE
- BNL e-RHIC: ERL SASE, HGHG, DOK
- Max-lab: ERL optical klystron
- DESY X-FEL: ERL SASE
- BINP: ERL SASE oscillator
- LUX: recirculating linac HGHG + spontaneous
- MIT-Bates X-ray FEL: single-pass linac HGHG + SASE

CW superconducting rf systems in LBNL LUX concept

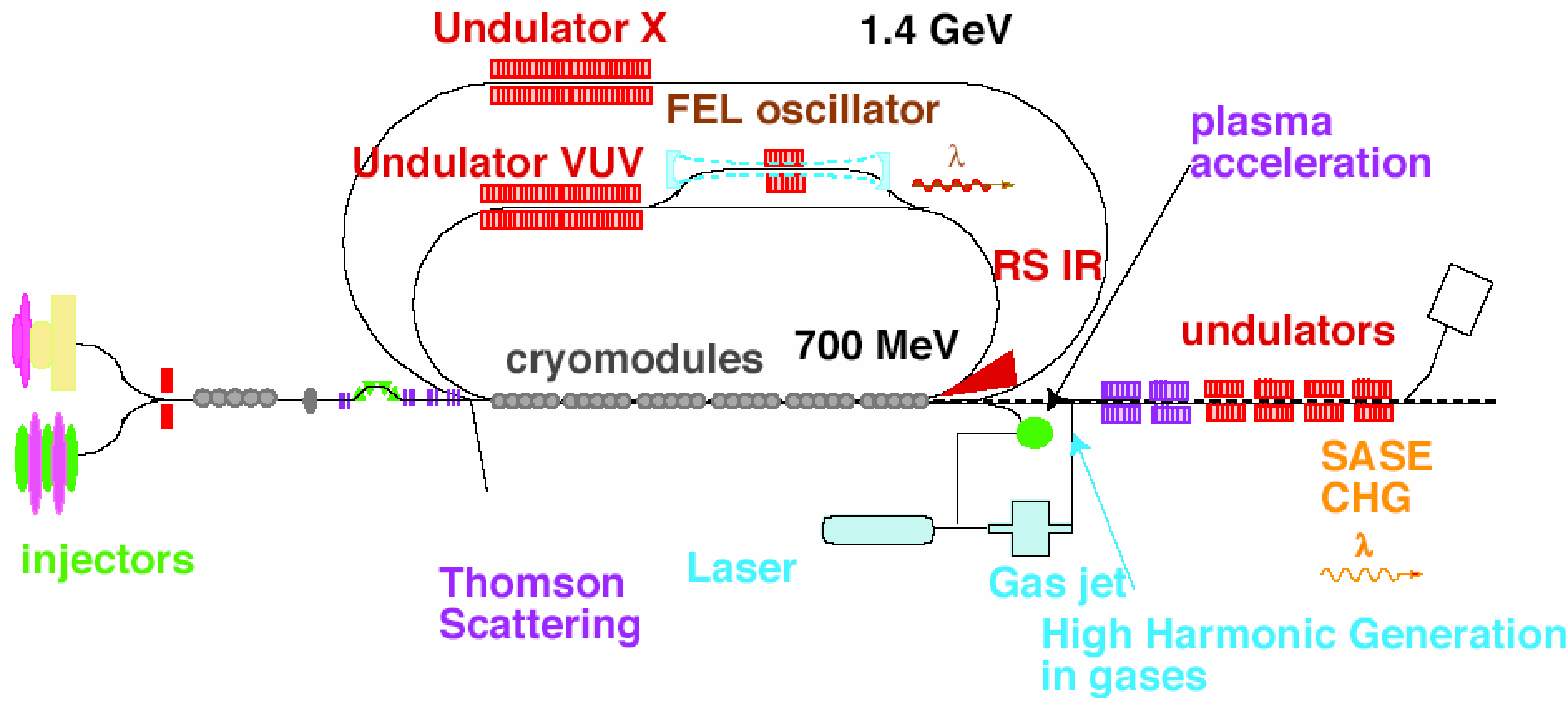
- The LBNL LUX concept for an ultrafast x-ray source
- Based on a recirculating linac and 10 kHz CW operation
- Harmonic cascade FEL's
- Compressed spontaneous emission



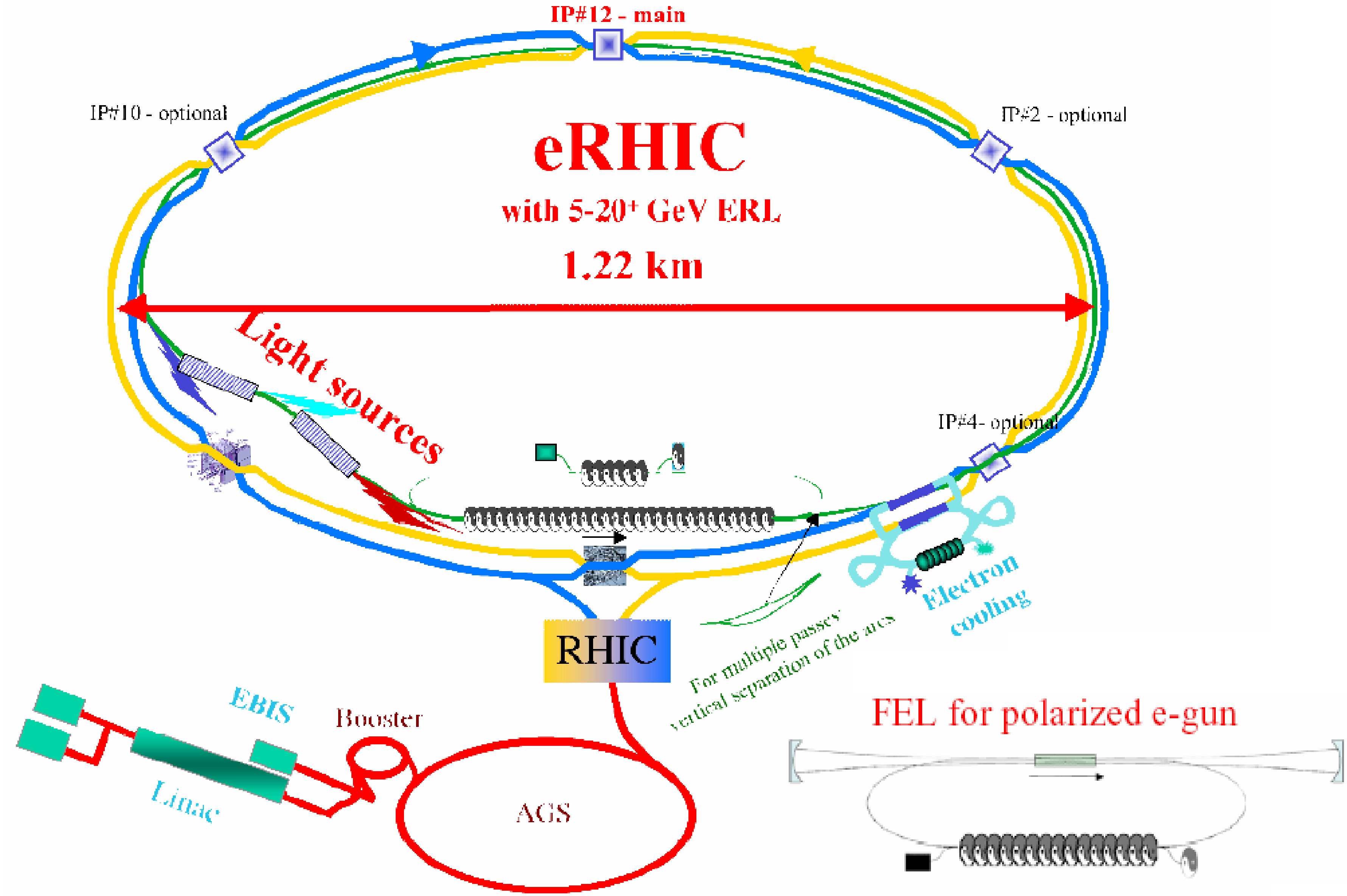
MIT-Bates X-ray laser facility concept



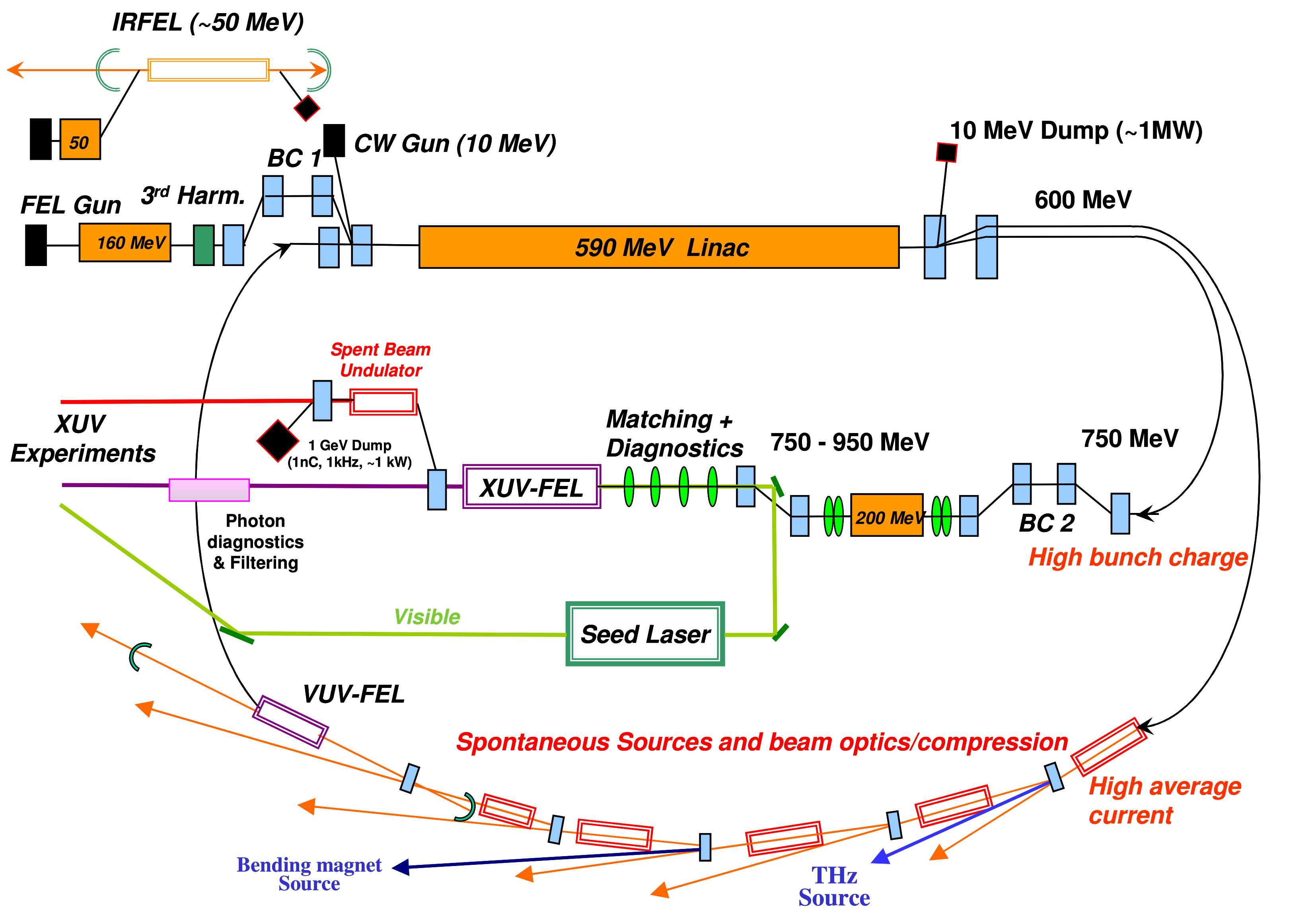
Arc en Ciel concept



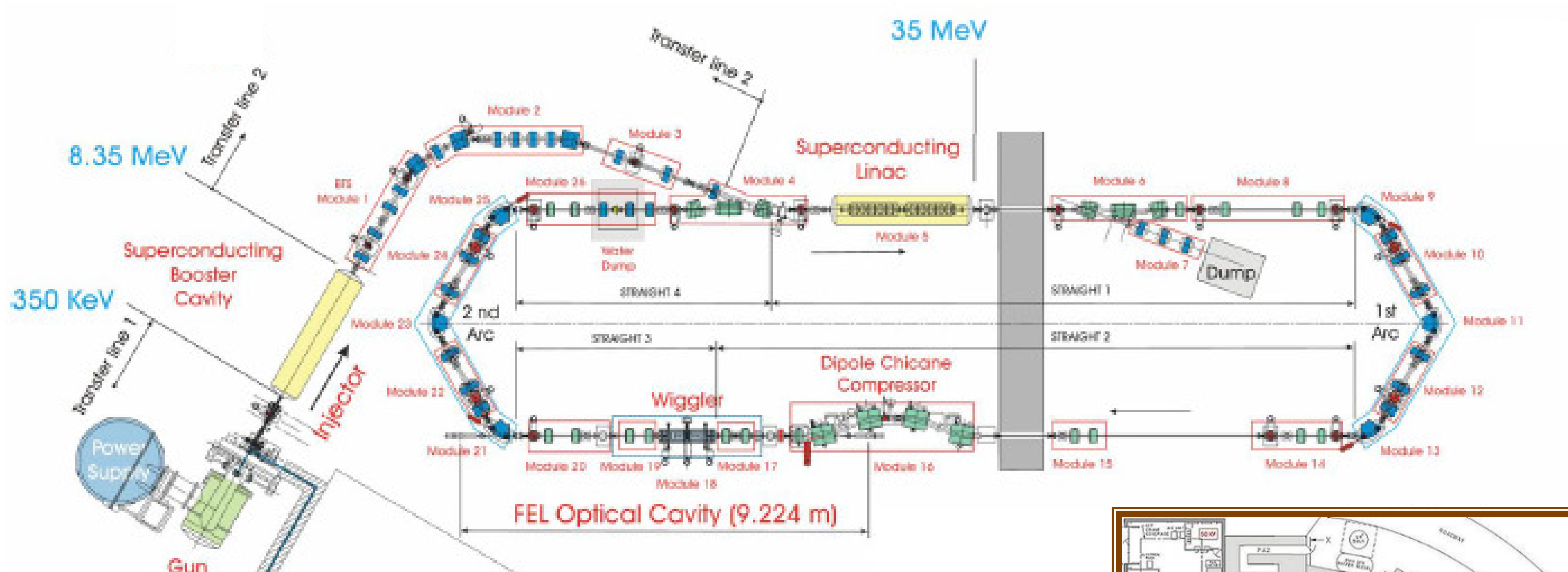
BNL FEL concept



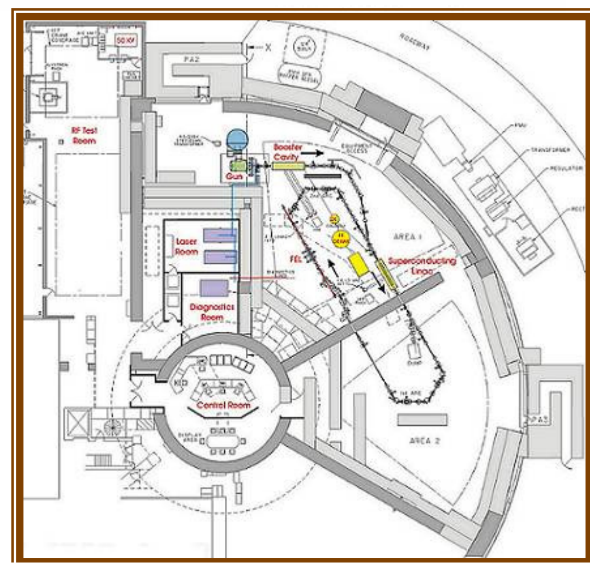
Daresbury 4GLS proposal



Daresbury ERLP - test bed for 4GLS

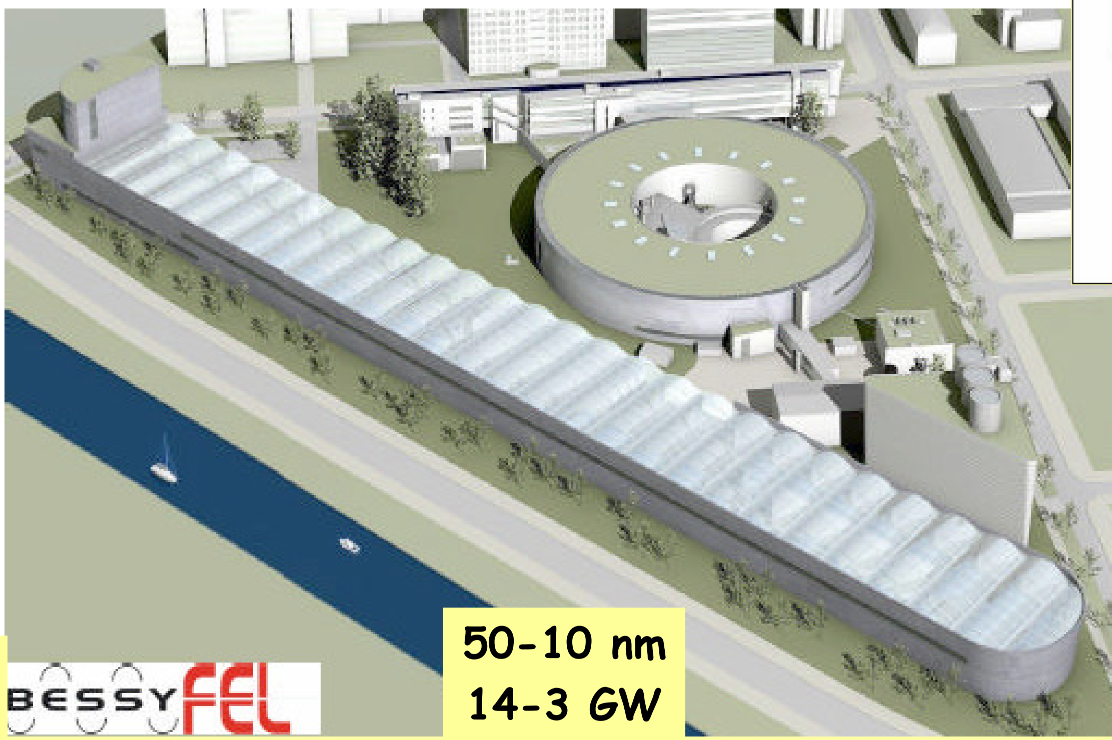


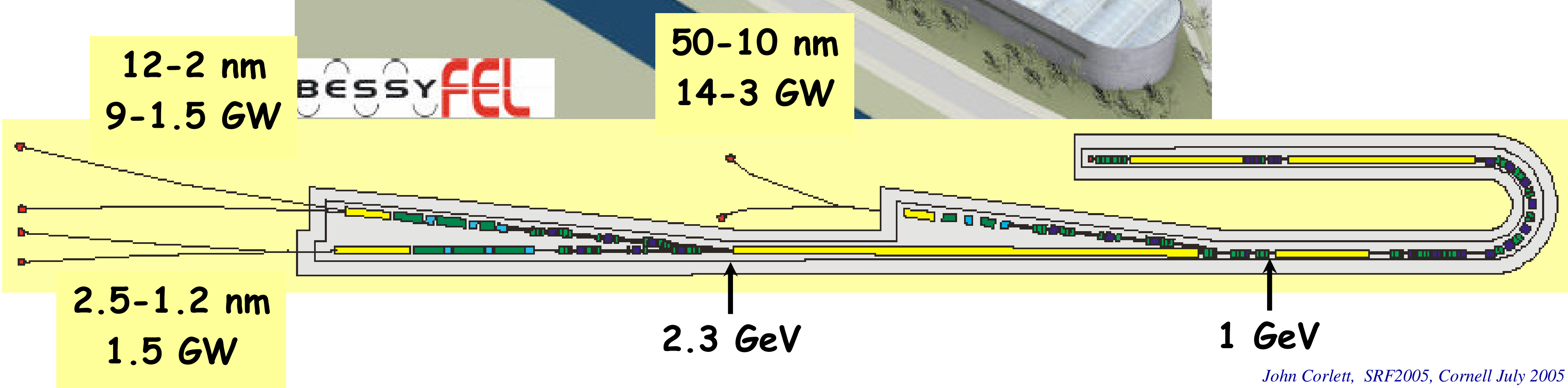
Electron beam parameter	Performance goal
Enegry (MeV)	30 - 50
RF frequency (GHz)	1.3
Charge per bunch (pC)	>80
Average current (mA)	>0.8
Peak current (A)	~150
Beam power (kW)	~30



BESSY FEL proposal

- VUV-soft x-ray facility using harmonic cascade FEL's
- TESLA scrf technology developed for CW operations

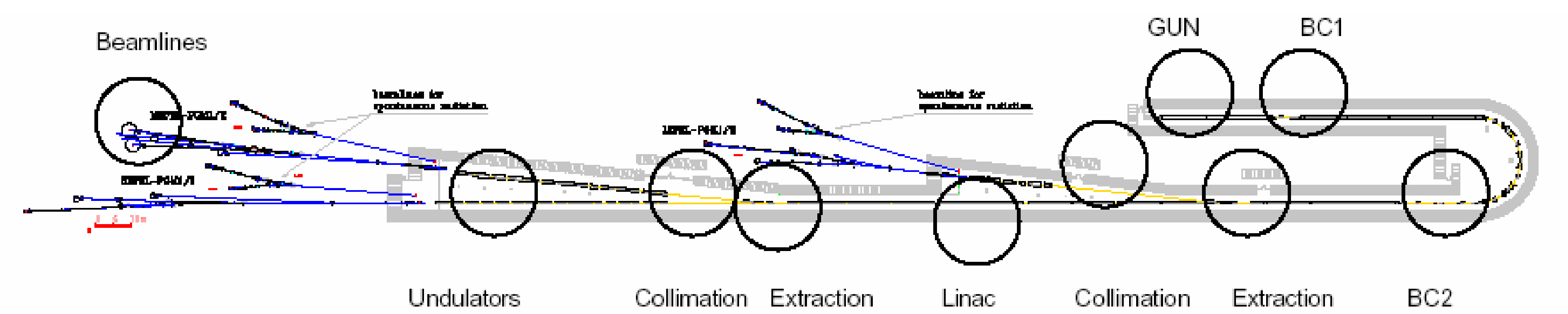




BESSY FEL proposal

R&D activities for the BESSY FEL

- **Gun:** Developing scrf gun for flexible bunch rate
- **Linac:** TELSA modules modified for 16 MV/m, CW operation
- **Bunch compression:** 2.5 nC bunch to 2 kA, 1 ps
- **Beam extraction:** highly stable kickers to feed the FEL lines
- **Collimation:** to shield undulators
- **Undulators:** Variable polarization APPLE-II type
- **Beamlines:** for short pulses, high resolution, direct beam



Future FEL's - summary

- Multiple proposals for SRF-based FEL facilities
- Innovative ideas and advanced concepts are being explored

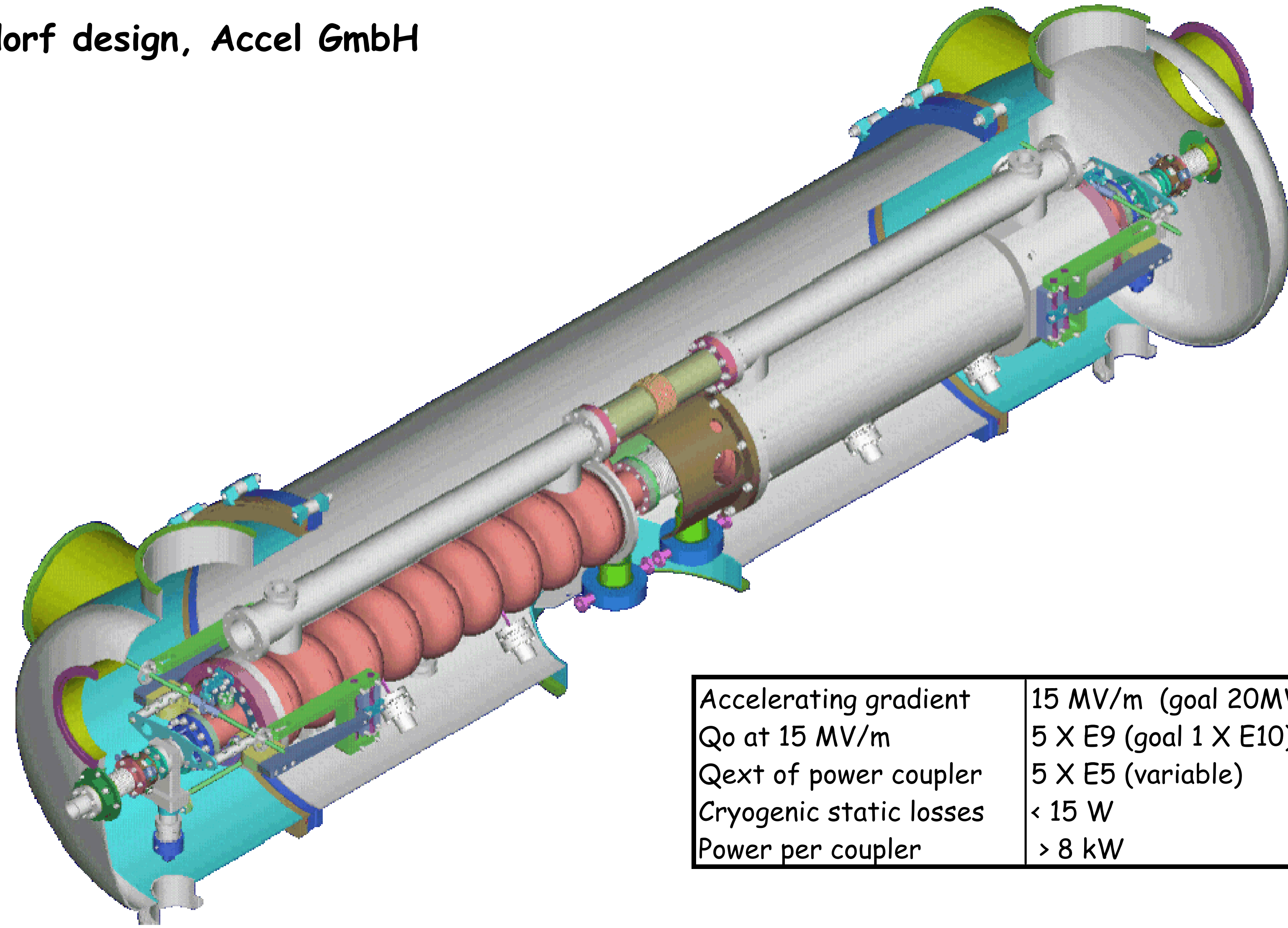
- Development of SRF technologies is critical for application in future FELs
  - High-gradient CW, HOM-damped, stabilized, high-Q_o structures
  - High rep-rate high-brightness rf guns
  - Harmonic cavities

An exciting future for FEL development

Future successes will lean heavily on SRF development

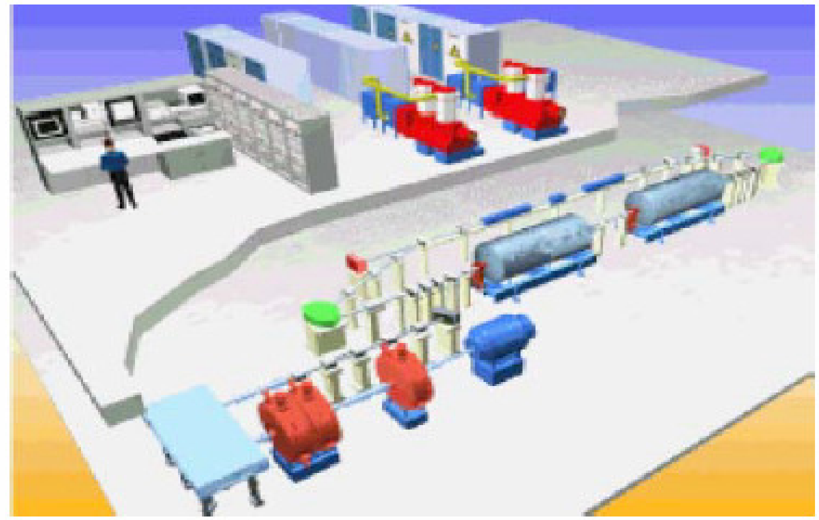
Implementation "TESLA" cavities in CW cryomodule

Rossendorf design, Accel GmbH



Accelerating gradient	15 MV/m (goal 20MV/m)
Qo at 15 MV/m	5 X E9 (goal 1 X E10)
Qext of power coupler	5 X E5 (variable)
Cryogenic static losses	< 15 W
Power per coupler	> 8 kW

KAERI proposal

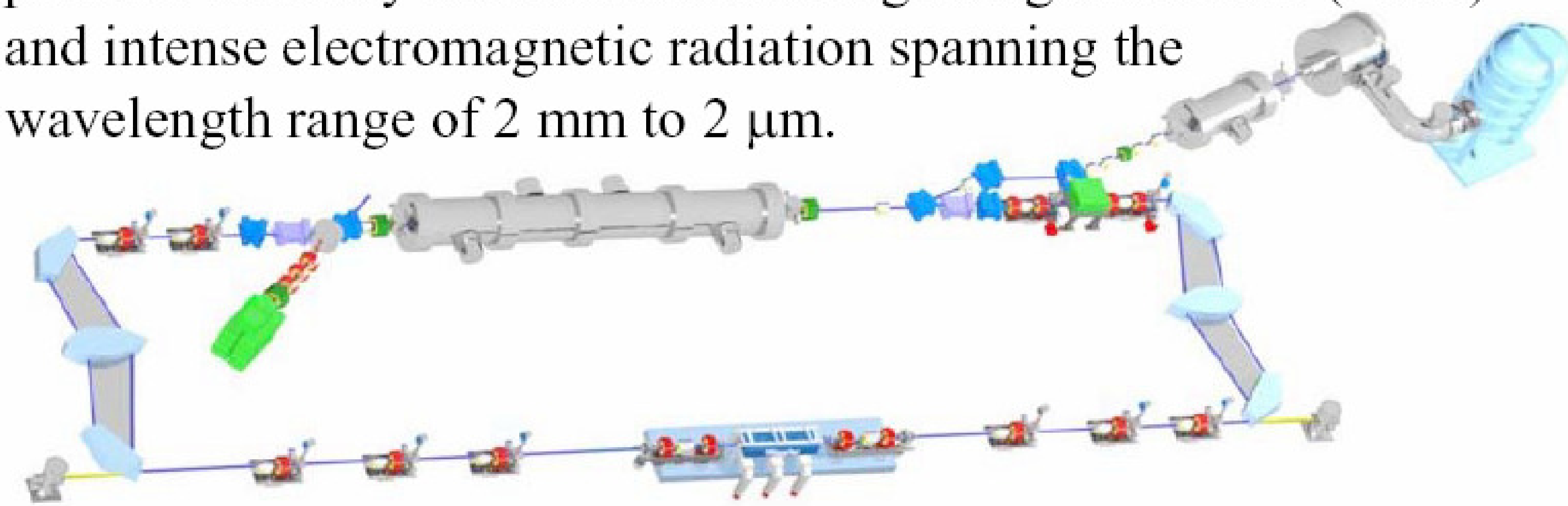


Output Light Parameters	Goal
Wavelength range (microns)	3-20
Bunch Length (FWHM psec)	20-50
Laser power / pulse (mJoules)	50-250
Laser power (kW)	1-5
Rep. Rate (MHz)	22
Macropulse format	CW

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

NHMFL proposal

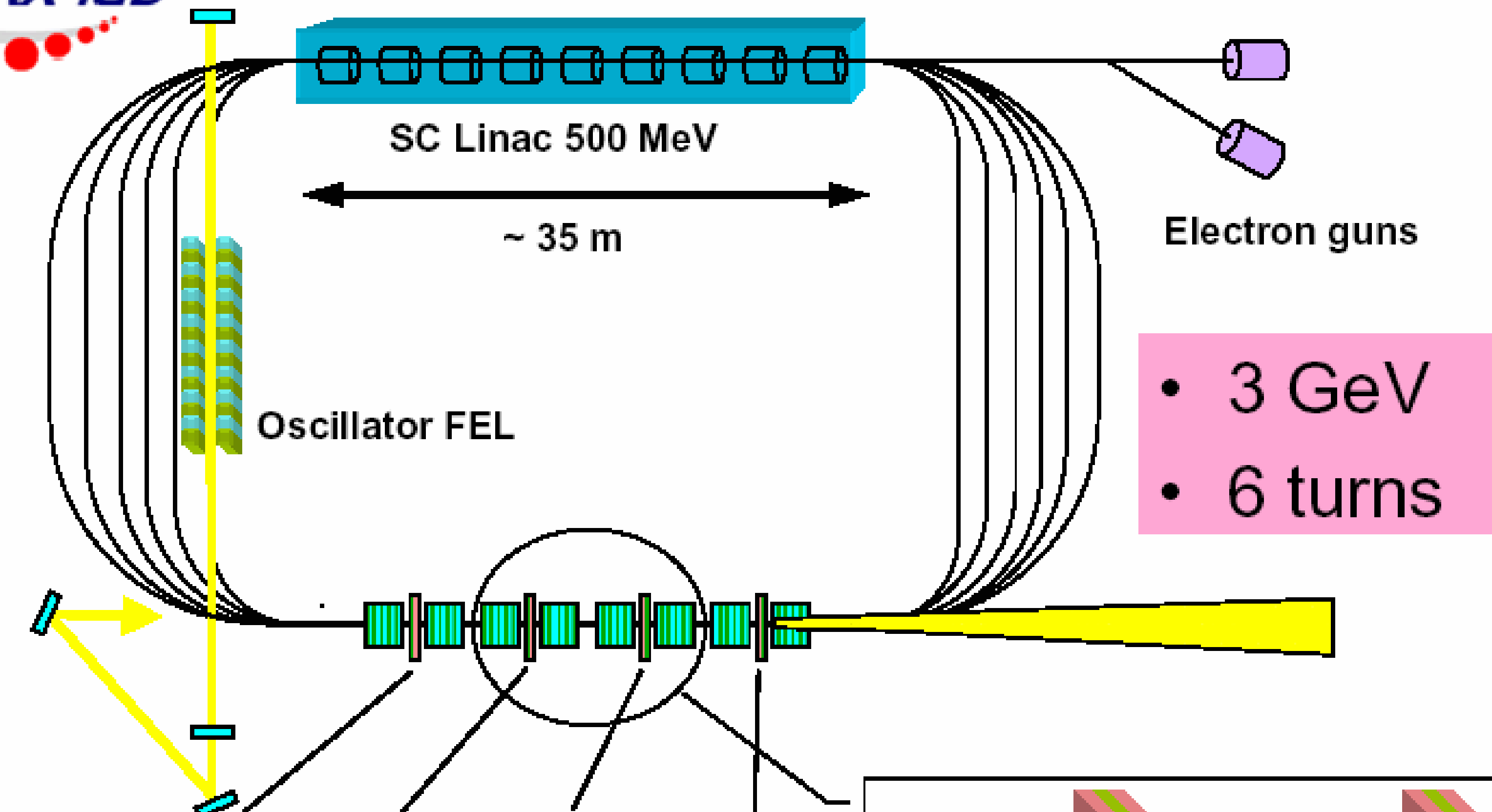
Proposal for a Concept and Engineering Design submitted to NSF in January 2005, with UCSB and JLab as partners. The goal is to produce a facility that can combine high magnetic fields (~50T) and intense electromagnetic radiation spanning the wavelength range of 2 mm to 2 μm.



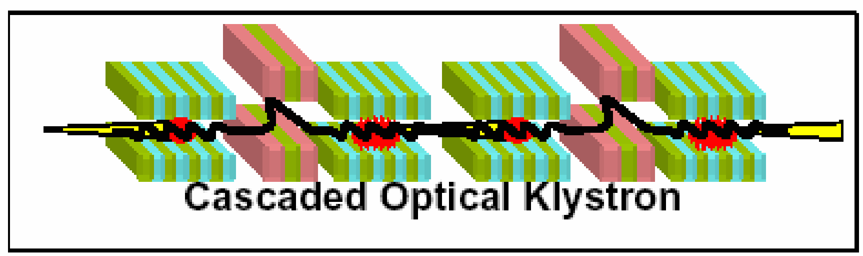
Electron Beam Parameters	Goal
Energy (MeV)	60
Accelerator frequency (MHz)	1500
Charge per bunch (pC)	135
Average current (mA)	5
Peak Current (A)	200
Beam Power (kW)	300

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

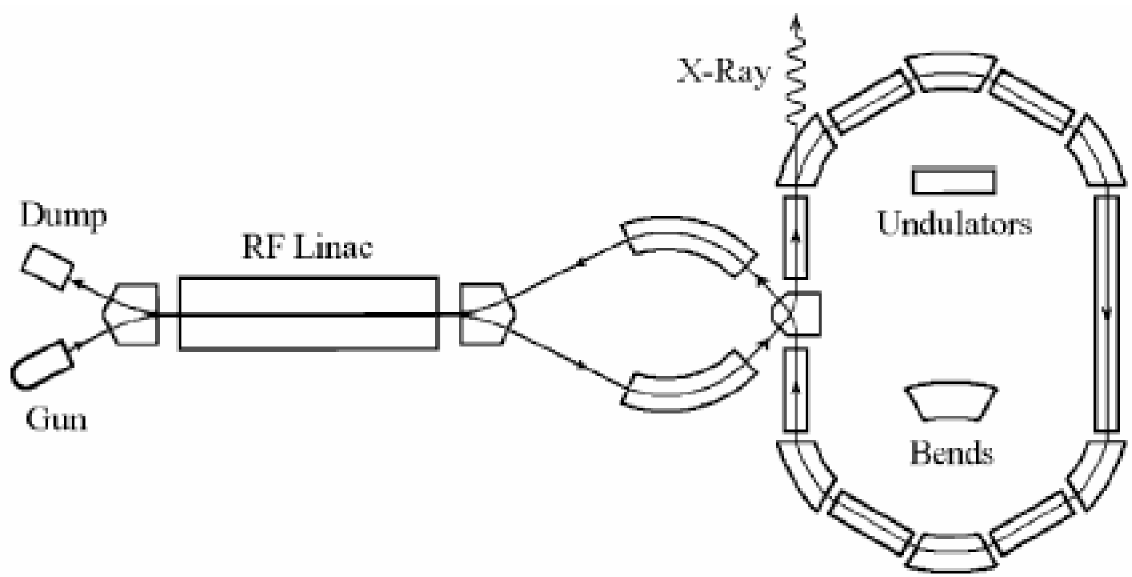
MAX-Lab concept



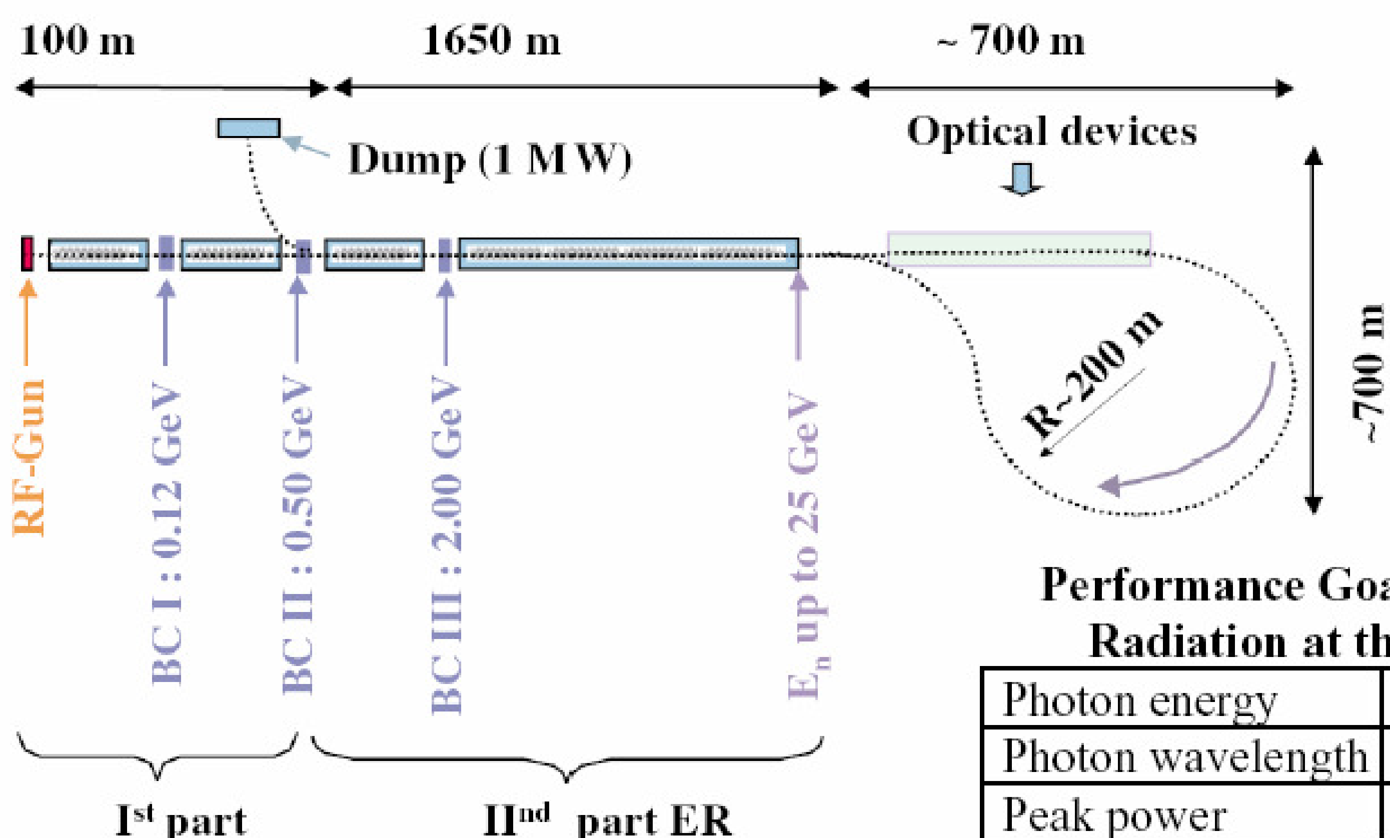
	Stage 1		Stage 2		Stage 3		Stage 4	
e-energy	500 MeV		1.5 GeV		2.5 GeV		3.0 GeV	
U Period	0.06	0.025	0.06	0.025	0.05	0.015	0.015	0.015
K	3.916	1.98	4.5	2.37	2.93	1.75	2.3	2.3
λ(nm)	260	37	37	5.3	5.3	0.76	0.76	0.76/ 0.11



BINP concept



DESY X-FEL ERL concept



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.)	