Performance Achievements and Challenges for FELs based on Energy Recovered Linacs

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Jefferson Lab

Newport News, VA USA

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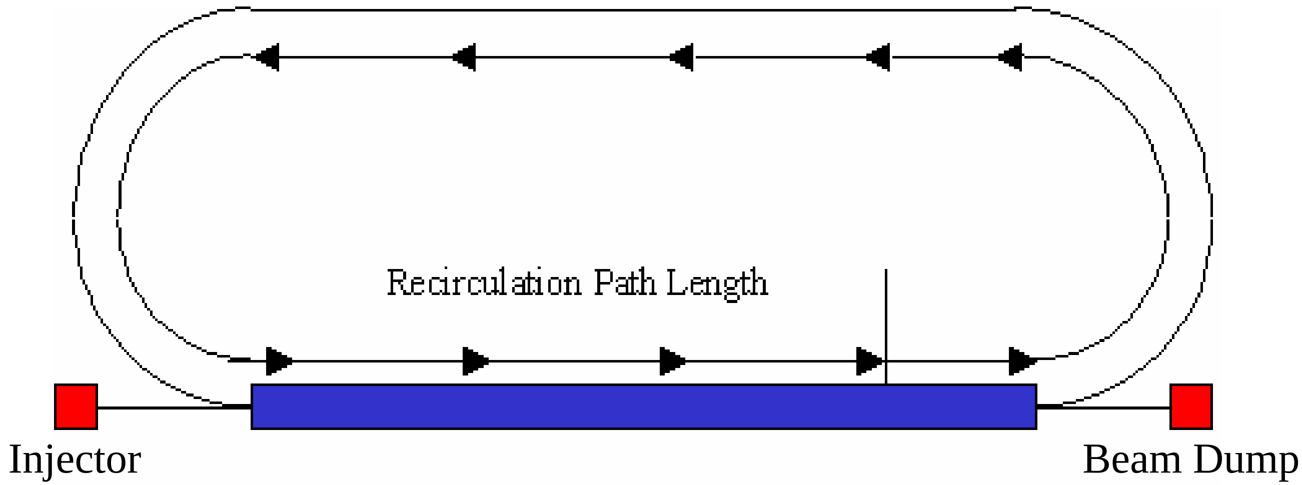
Outline

- **Introduction to (RF!) ERLs as FEL drivers***
- **Current Status**
  - **—Jefferson LAB FEL**
  - **—JAEA FEL (9:30 Talk)**
  - **—BINP FEL (17:30 Talk)**
  - **—4GLS (9:00 Talk)**
- **Future Challenges and Developments**
  - **—Electron Sources, Drive Lasers**
  - **—Beam Breakup, Advanced Beam Optics Designs**
  - **—HOM Power**
  - **—Optical Cavities**
  - **—High Average Power X-FEL**

***See T. Smith, ERL2005, for DC ERLs**

Beam Energy Recovery in an RF Linac

$$\frac{d\gamma}{dt} = \frac{e\vec{E} \cdot \vec{\mathrm{v}}}{mc^2}$$

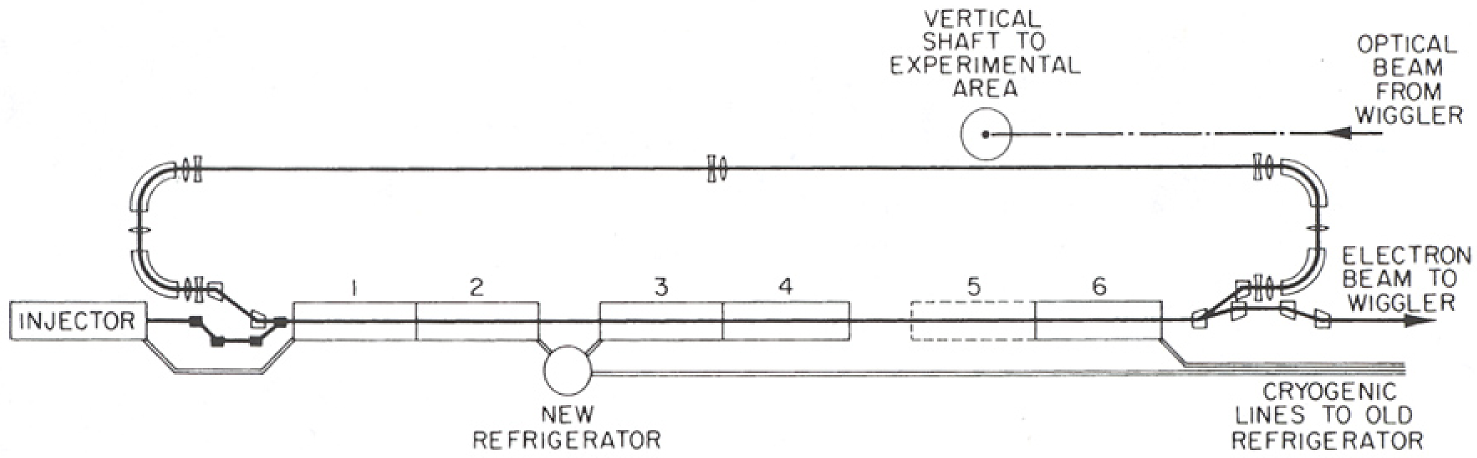


Recirculation path length in standard configuration front-to-back recirculated linac. For energy recovery choose it to be $(n + 1/2)\lambda_{RF}$. Then

$$E_{\mathrm{Injector}} \approx E_{\mathrm{Beam\,Dump}}$$

SCA/FEL Energy Recovery Experiment

- Same-cell energy recovery was first demonstrated in a superconducting linac at the Stanford SCA/FEL in July 1986 (NIMA **259,** 1 (1987); Led off the conference 20 years ago!)
- Beam was injected at 5 MeV into a 45 MeV linac (up to 95 MeV in 2 passes), 150 μA average current (12.5 pC per bunch at 11.8 MHz)
- The previous "Recyclotron" beam recirculation system could be not used to produce the peak current required for lasing and was replaced by a doubly achromatic single-turn recirculation line.
- Nearly all the energy was recovered. No FEL inside the recirculation loop.



Power Multiplication Factor

- **An advantage of energy recovered recirculation is nicely quantified by the notion of a power multiplication factor:**

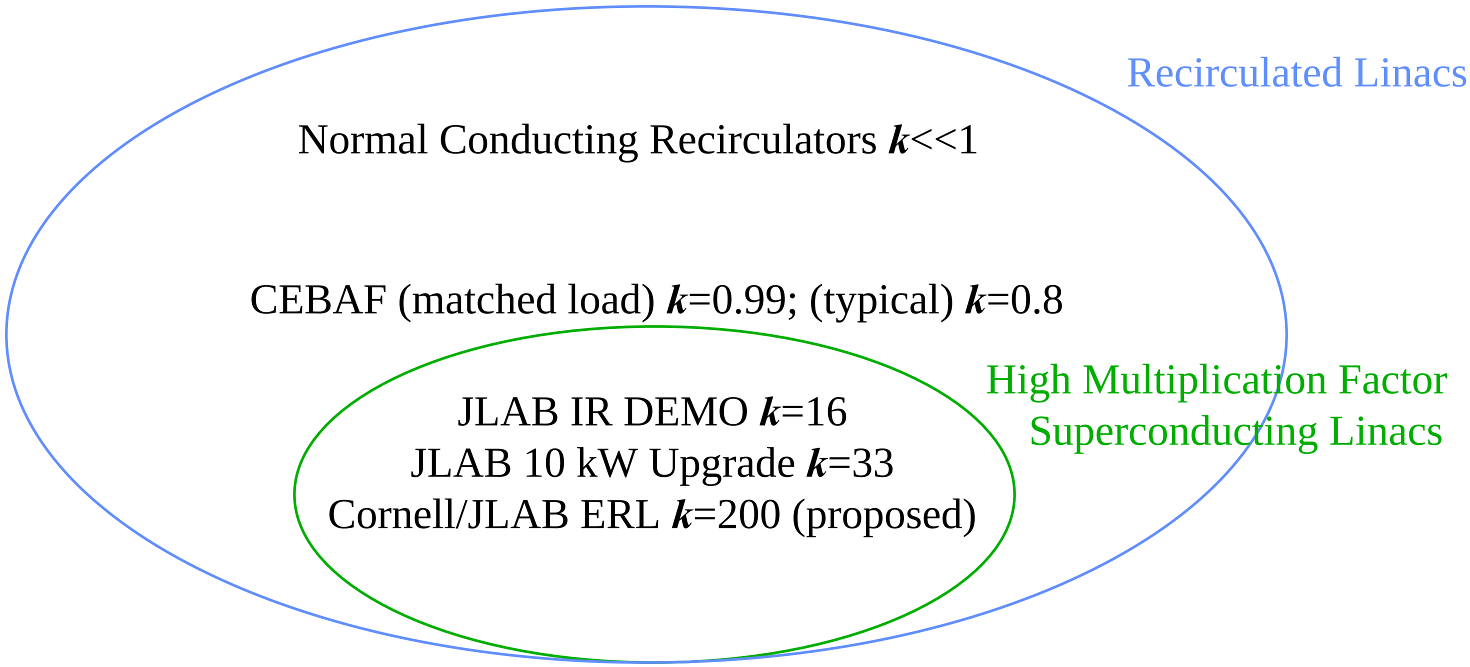
$$k = P_{b,ave} / P_{rf}$$

where $P_{b,ave}$ is the average beam power and P_{rf} is the RF power needed to accelerate the beam

- **By the first law of thermodynamics $k < 1$ in any linac not recirculated. Beam recirculation with beam deceleration somewhere is necessary to achieve $k > 1$**

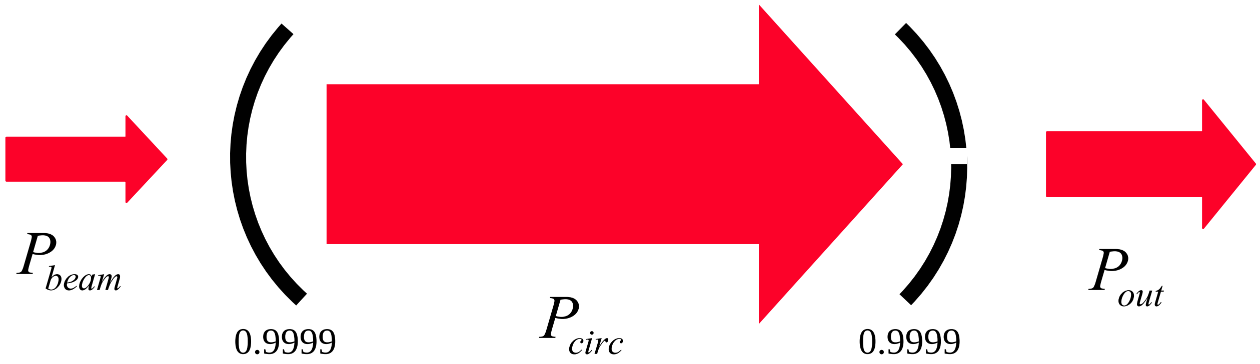
- **If energy IS very efficiently recycled from the accelerating to the decelerating beam $k >> 1$**

High Multiplication Factor Linacs



Use the words "High Multiplication Factor Linac" for those designs that feature high ***k***.

Photon Energy/Detailed Balance



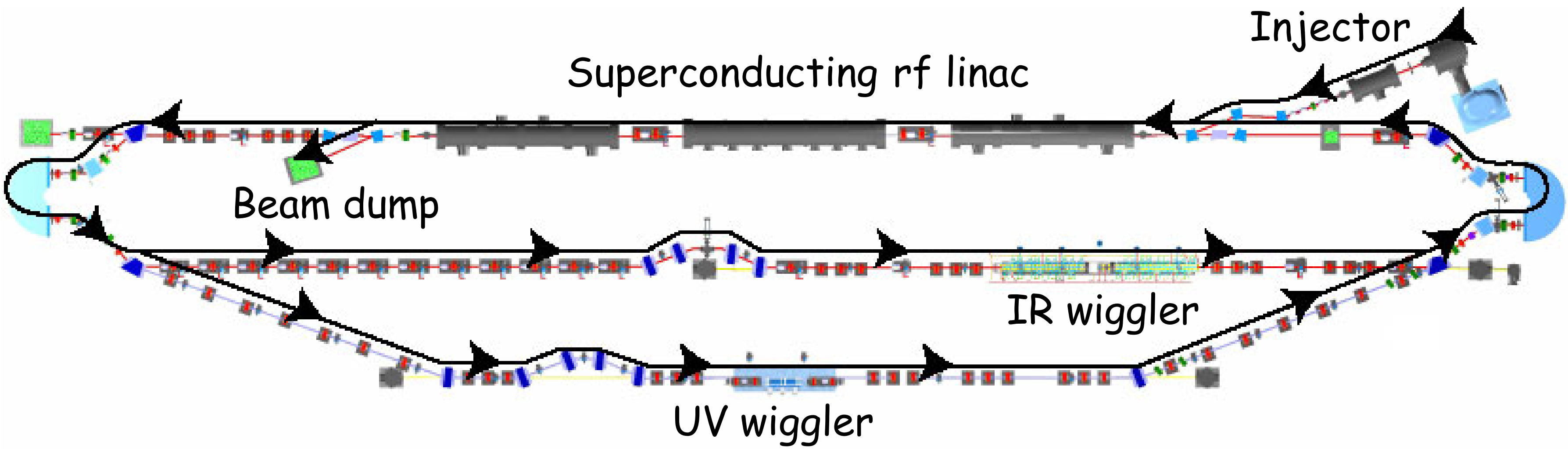
$$P_{out} + 2(0.0001)P_{circ} = \zeta P_{beam} = \zeta k P_{rf}$$

where *ζ* is the fraction of beam energy converted to photons per pass

$$\frac{P_{out}}{P_{rf}} = \eta_{rf \to photons} \approx \zeta k$$

RF to photon conversion efficiency is maximized when *k* is as high as possible

JLab 10 kW IR FEL and 1 kW UV FEL



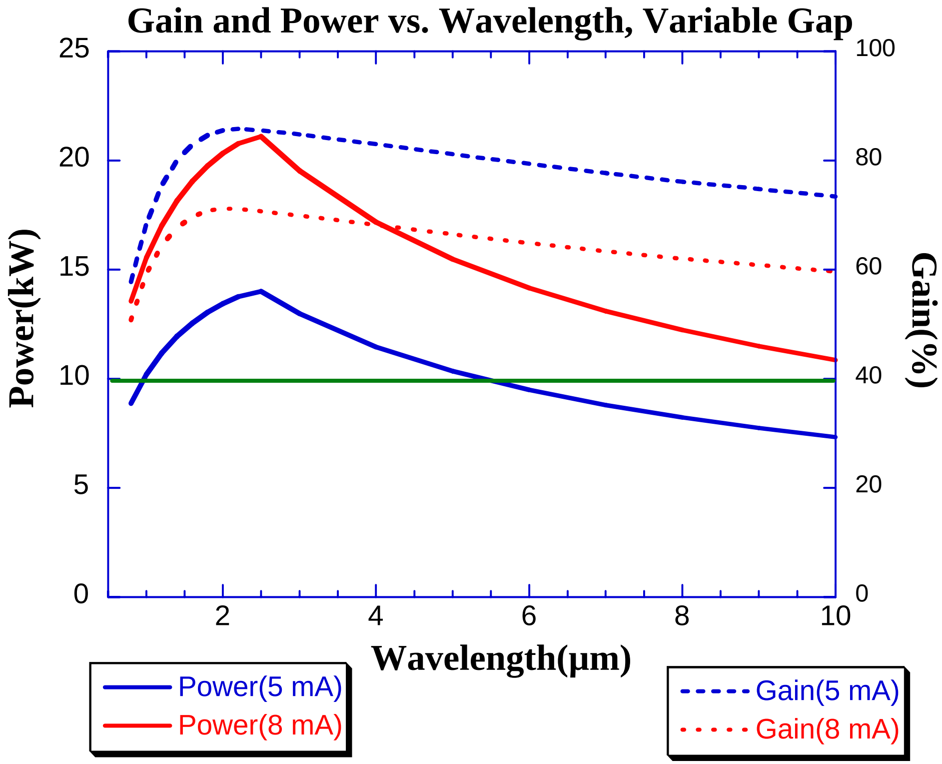
Output Light Parameters	IR	UV
Wavelength range (microns)	**0.9 - 10**	**0.25 - 1**
Bunch length (FWHM psec)	**0.2 - 2**	**0.2 - 2**
Laser energy / pulse (microJoules)	**100 - 300**	**25**
Laser power (kW)	**>10**	**> 1**
Rep. Rate (cw operation, MHz)	**4.7 – 75**	**4.7 – 75**

Electron Beam Parameters	IR	UV
Energy (MeV)	**80-150**	**150**
Accelerator frequency (MHz)	**1500**	**1500**
Charge per bunch (pC)	**135**	**135**
Average current (mA)	**10**	**5**
Peak Current (A)	**>300**	**>250**
Beam Power (kW)	**1500**	**750**
Energy Spread (%)	**0.40**	**0.20**
Normalized emittance (mm-mrad)	**<10**	**<8**
Induced energy spread (full)	**12%**	**6%**

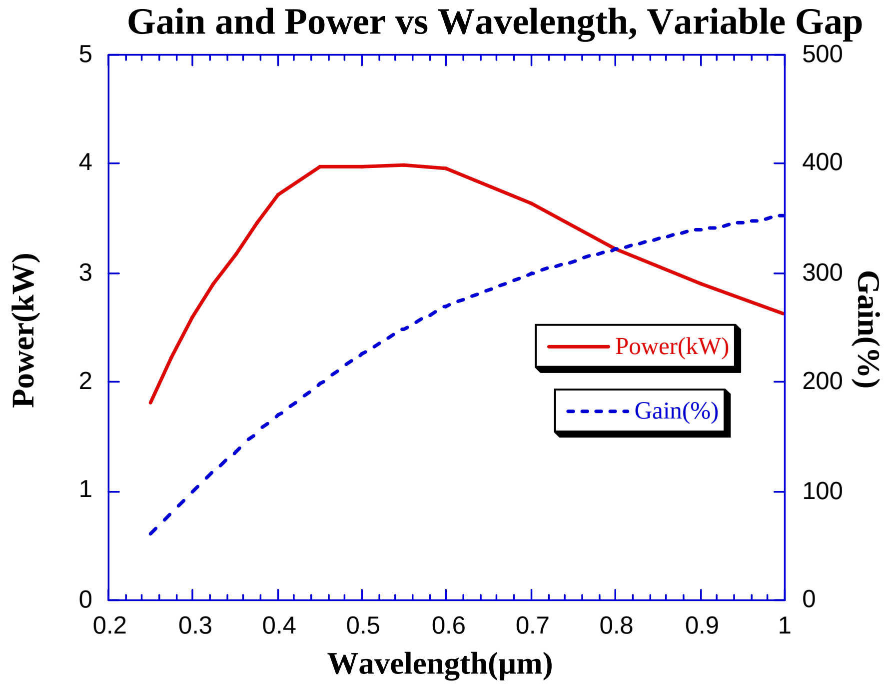
Courtesy: T. Smith and S. Benson

IR/UV Upgrade FEL Performance

IR Upgrade, 140 MeV linac



UV Upgrade, 160 MeV linac



Courtesy S. Benson

Summary of High Power Lasing To Date

Short wavelength results to date:

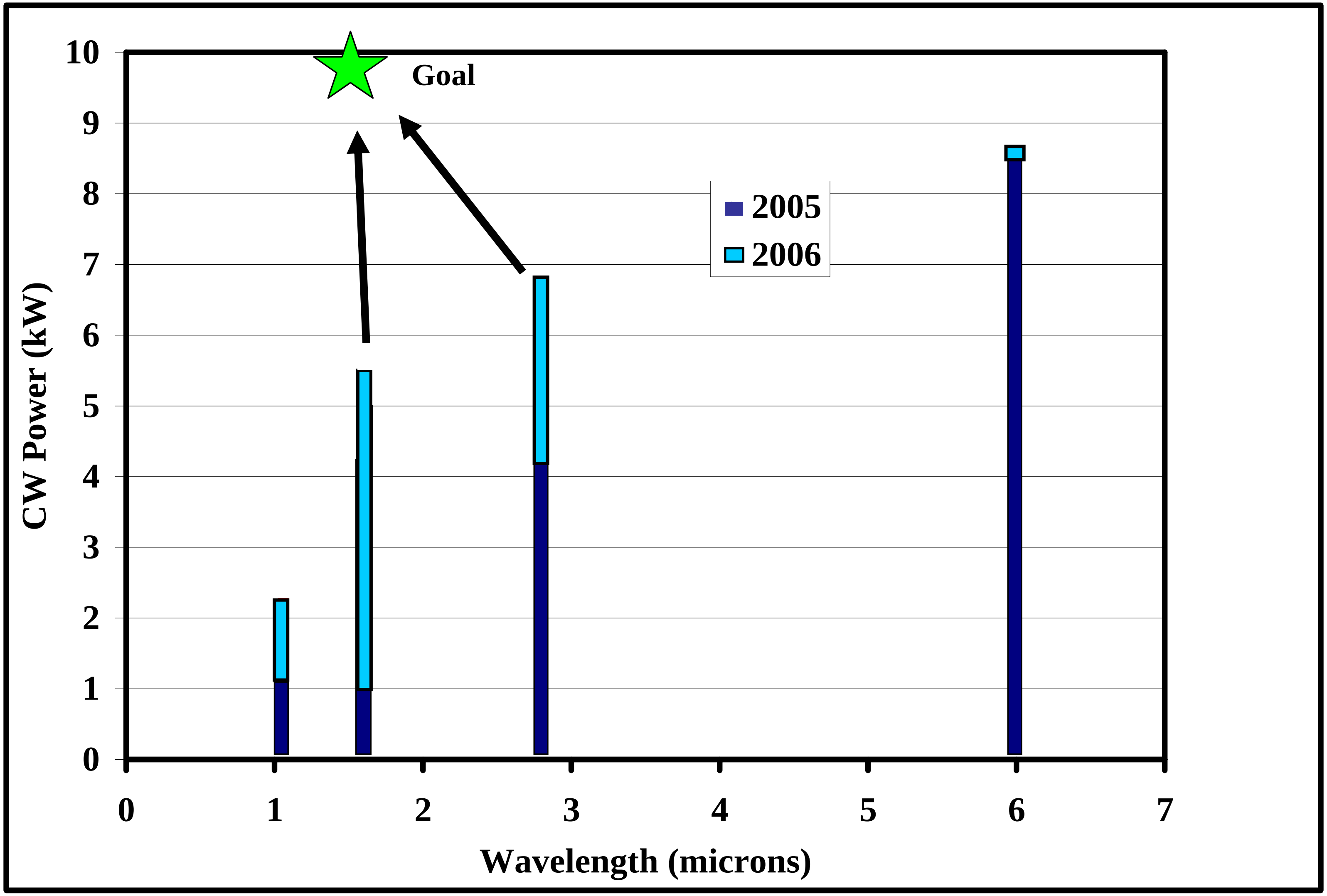
wavelength (µm)	**1.1**	**1.6**	**2.8**	**6.0**
pulsed (kW)	**2.5**	**5.4**	**6.7**	**10.6 (1 sec)**
cw (kW) *	**2.2**	**5.4**	**6.7**	**8.5**

**** world record average powers for tunable laser sources***

- **short wavelength performance improves as we develop and test low absorption (< 100ppm) dielectric coatings for high power optics**
- **we have evolved from 2500 ppm at 10µm to <200 ppm at 1µm**

Courtesy F. Dylla and S. Benson

Progress Toward 10 kW Goal



JLab High Brightness Gun

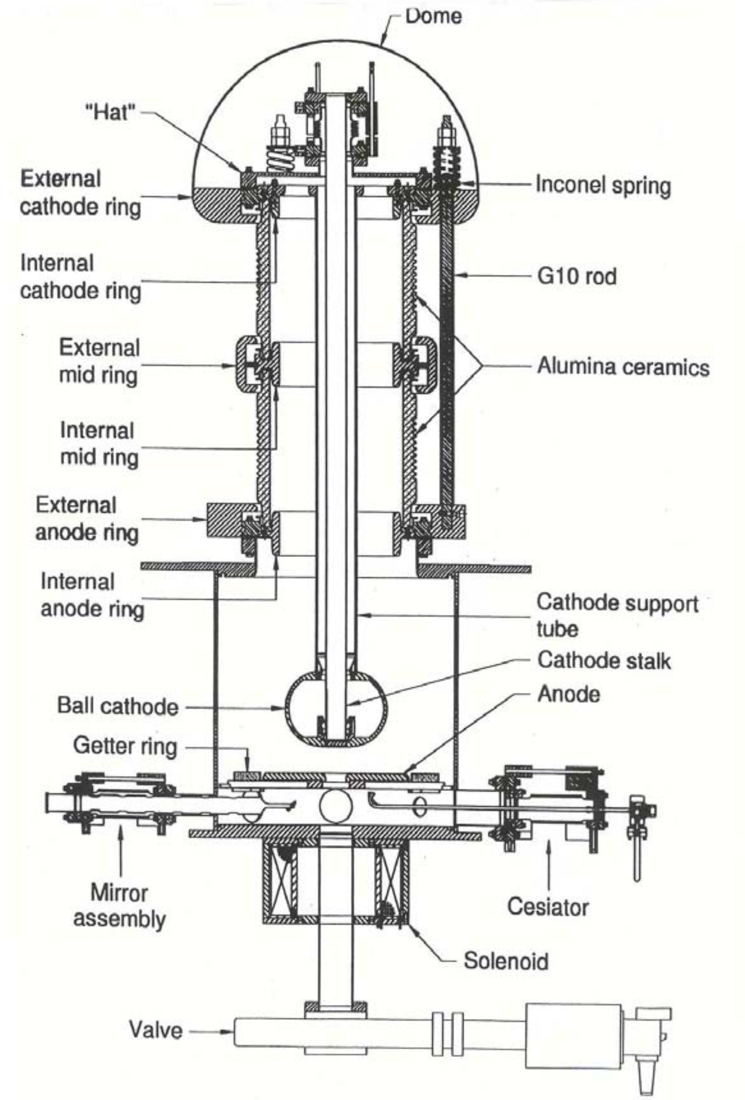
Highest brightness cw electron source in world

Extremely reliable

Delivered 5.5 kiloCoulombs from one cathode

Same cathode for 2 years, 400 Coulomb/cesiation

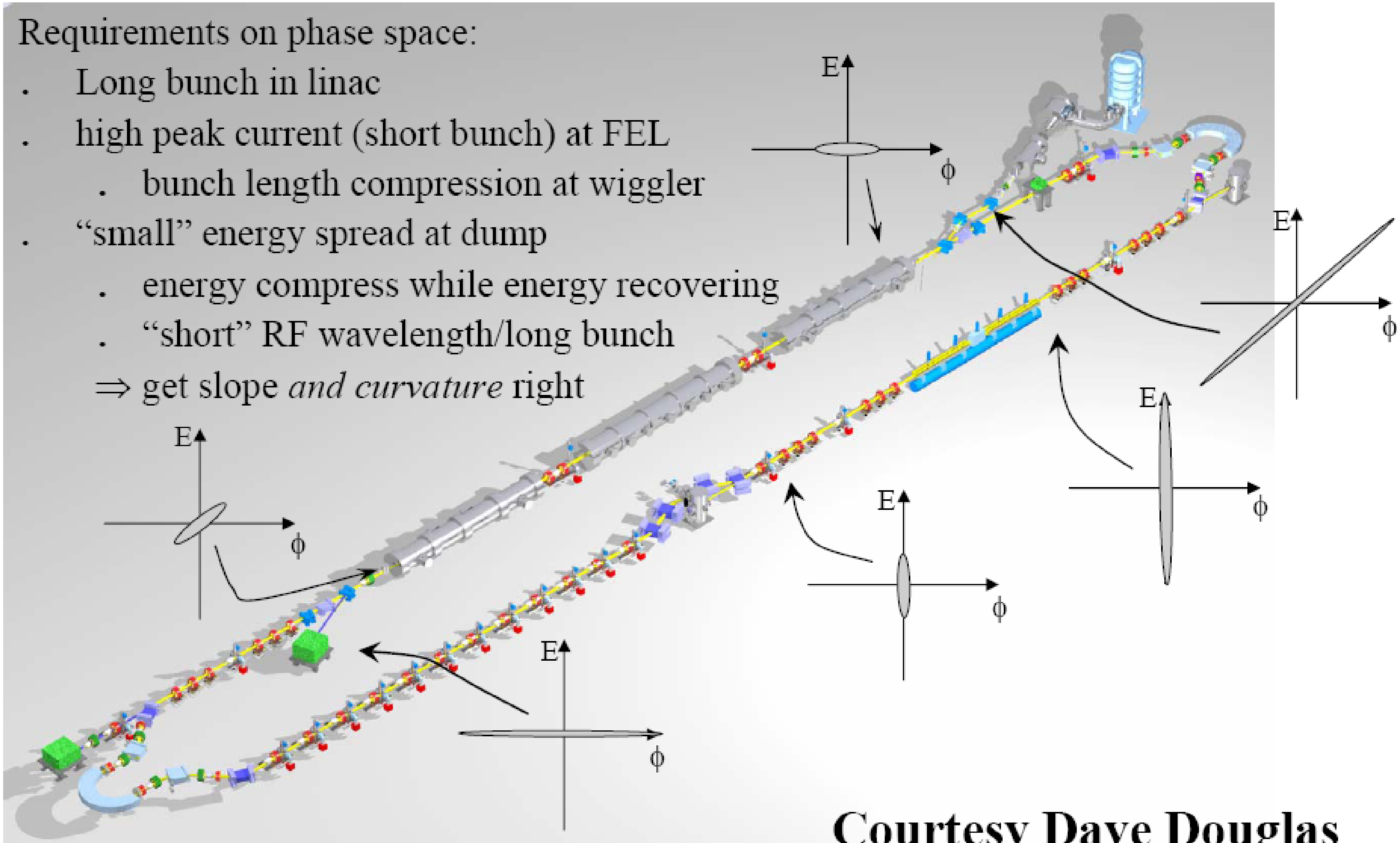
Low halo, low field emission



Longitudinal matching: high order terms <u>important</u>

Requirements on phase space:

- Long bunch in linac
- high peak current (short bunch) at FEL
  - bunch length compression at wiggler
- "small" energy spread at dump
  - energy compress while energy recovering
  - "short" RF wavelength/long bunch
  - $\Rightarrow$ get slope *and curvature* right



Courtesy Dave Douglas

Controlling nonlinearities with sextuples and octupoles is validated by high order transport measurement

Figure 1: initial optimized setup

Figure 2: lower trim quads to -185 g from initial -215 g

Figure 3: raise trim quads to -245 g

Figure 4: quads back at -215, but sextupoles 2000 g below design, at 10726 g-cm

Figure 5: back to start: trim quads -215 g sextupoles at 12726 g-cm

Transfer Function Measurements on IR Upgrade

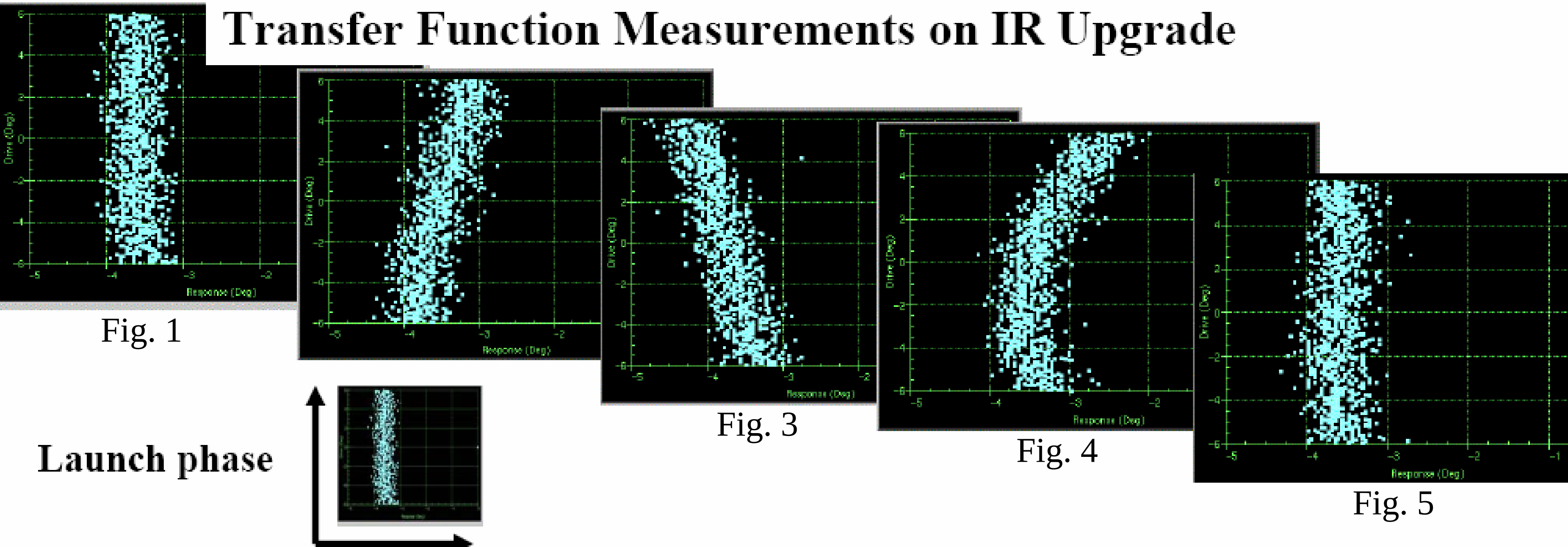
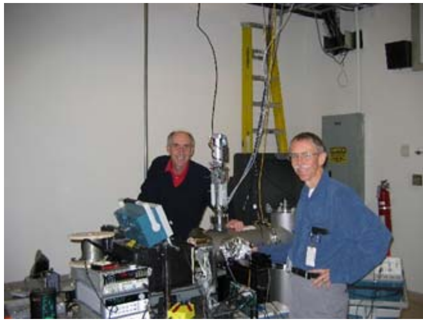


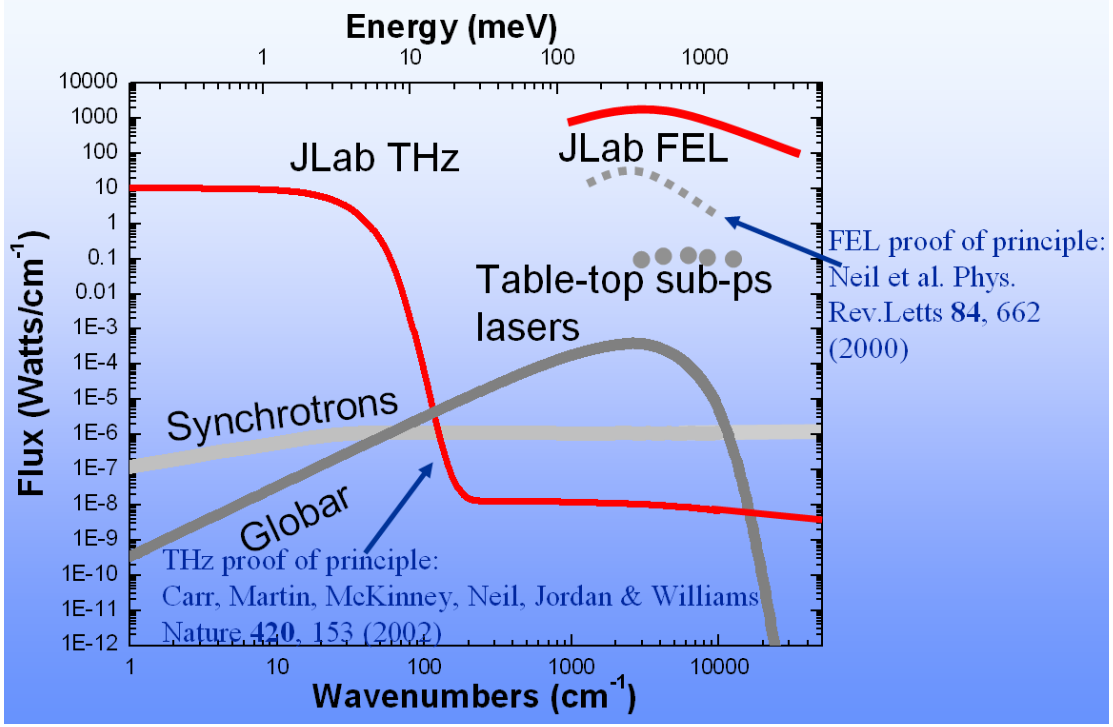
Fig. 1 Fig. 3 Fig. 4 Fig. 5

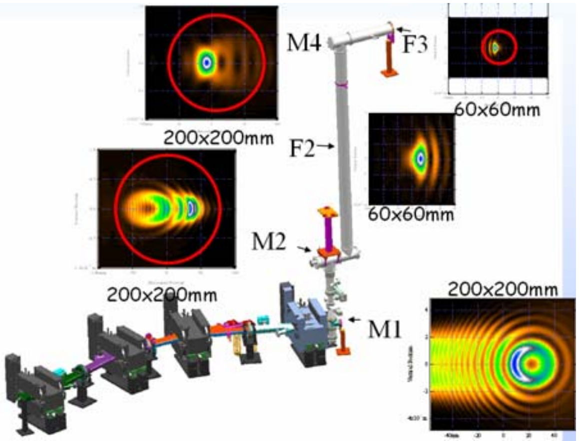
Courtesy Dave Douglas, S. Benson

Jefferson Lab THz User Facility

- High Power (up to 100 watts av. 10 MW peak)
- Broadband
- 3mm source (*f*/7) imaged at diamond window in dedicated lab
- Niche areas - imaging and linear/non-linear pump-probe dynamics
- User program just starting up







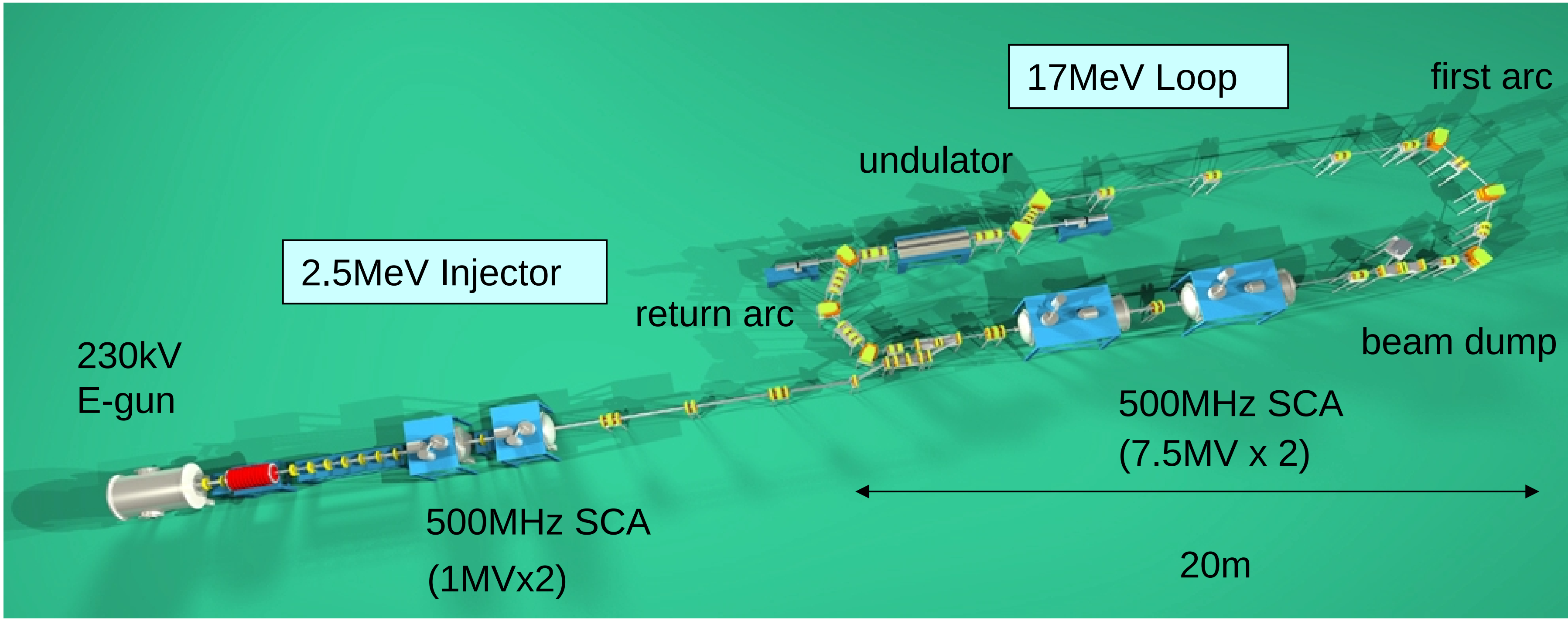
Courtesy: G. Williams

Jefferson Lab User Program

- Dynamics in nanosystems, & systems driven far-from equilibrium.
  - H impurities in Si (Luepke, William & Mary)
  - Carbon nanotube production (Smith, NASA)
- Magnetism, and spin dynamics.
  - Pulsed laser deposition of magnetic thin films (Reilly, W&M)
- Quantum coherence and control.
  - High harmonic generation (Jones, University of Virginia)
- Fundamental optical physics.
  - Bose-Einstein condensates, far-off resonance traps Sukenik (ODU)
- Laser-tissue interactions.
  - Localized heating of fatty tissue (Anderson, Harvard)
- Nuclear physics.
  - Search for light, neutral, spin-zero boson (Baker, Yale)
- Microfabrication.
  - UV int. with ceramics (Helvajian, Aerospace Corp)

Courtesy: G. Williams

17 MeV-ERL for a high-power FEL at JAEA

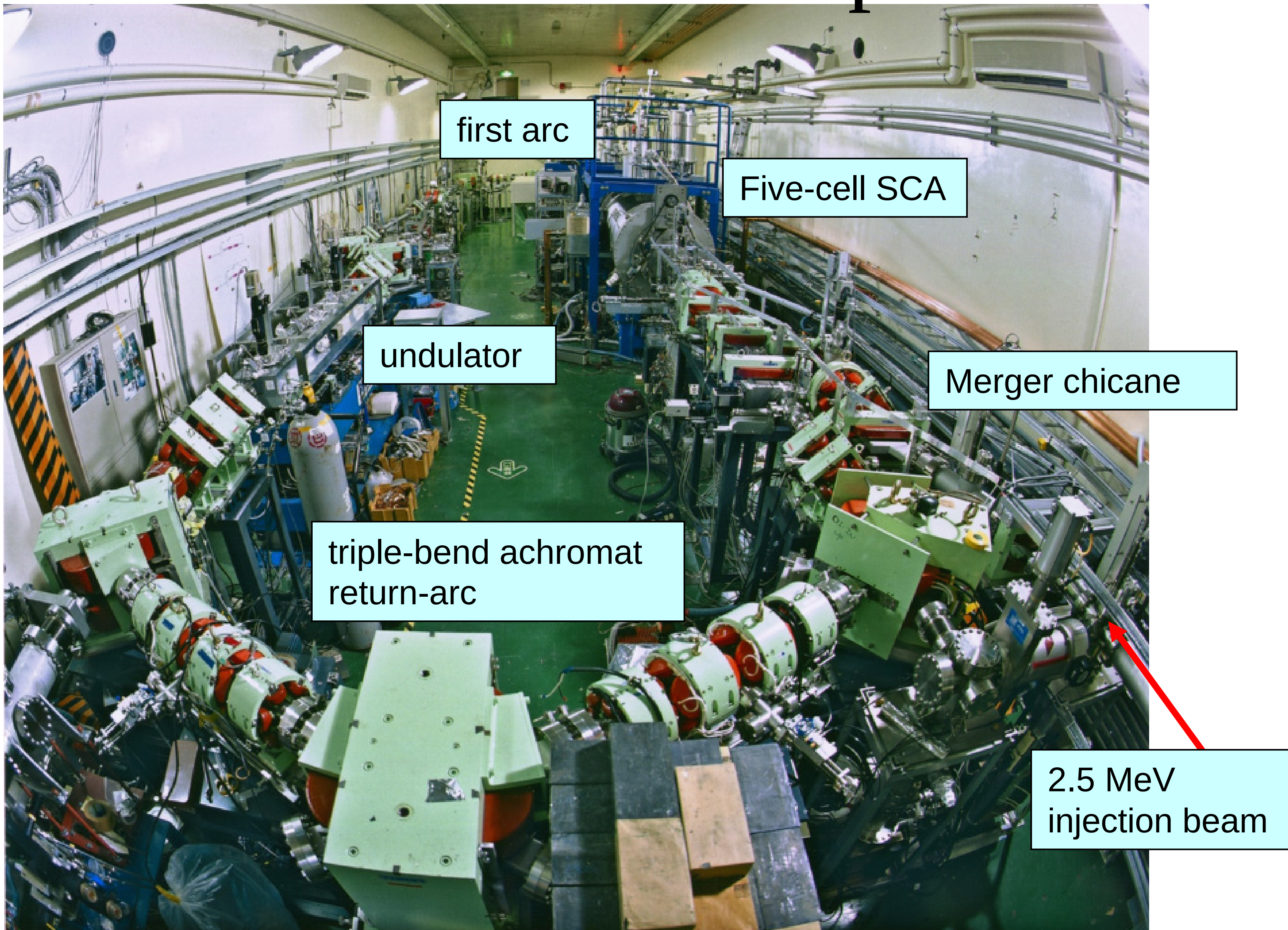


2.5 MeV injector consists of 230 keV thermionic cathode gun, 83 MHz sub harmonic buncher, and two single-cell 500 MHz SCAs.

17 MeV loop consists of a merger chicane, two five-cell 500 MHz SCAs, a triple-bend achromat arc, half-chicane, undulator, return-arc, and beam dump.

Courtesy: N. Nishimori

17 MeV ERL loop



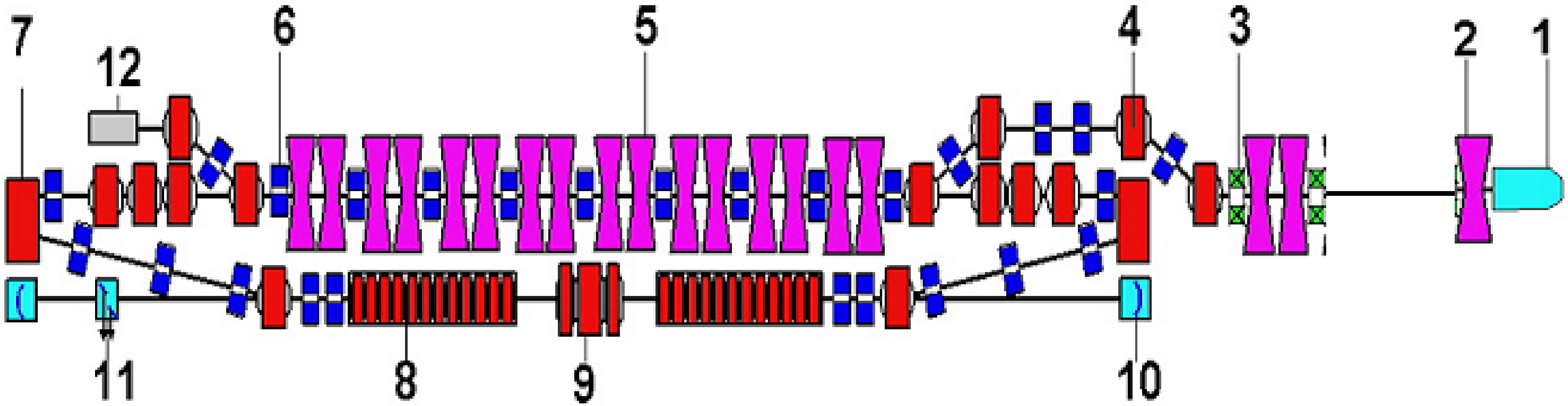
Summary

- We have doubled the electron bunch repetition rate by upgrading the gun grid pulser and RF power supply for injector SCA modules.
- The energy acceptance of the triple bend achromat return arc has been increased from 7% to 15% by replacing quadrupole magnets and beam ducts.

- We have achieved 0.7 kW FEL oscillation in average at 22 μm wavelength using 8 mA electron beam at 230 μs macropulse.
- The FEL extraction efficiency has been measured with a wire scanner and the peak efficiency reaches 2.8%.
- We have found that a magnetic bunch compression in the first arc with off crest acceleration in main SCA modules is indispensable to realize the high-efficiency FEL.

- We will continue our experimental study on the beam dynamics in the triple bend achromat arcs during high-efficiency FEL oscillation.

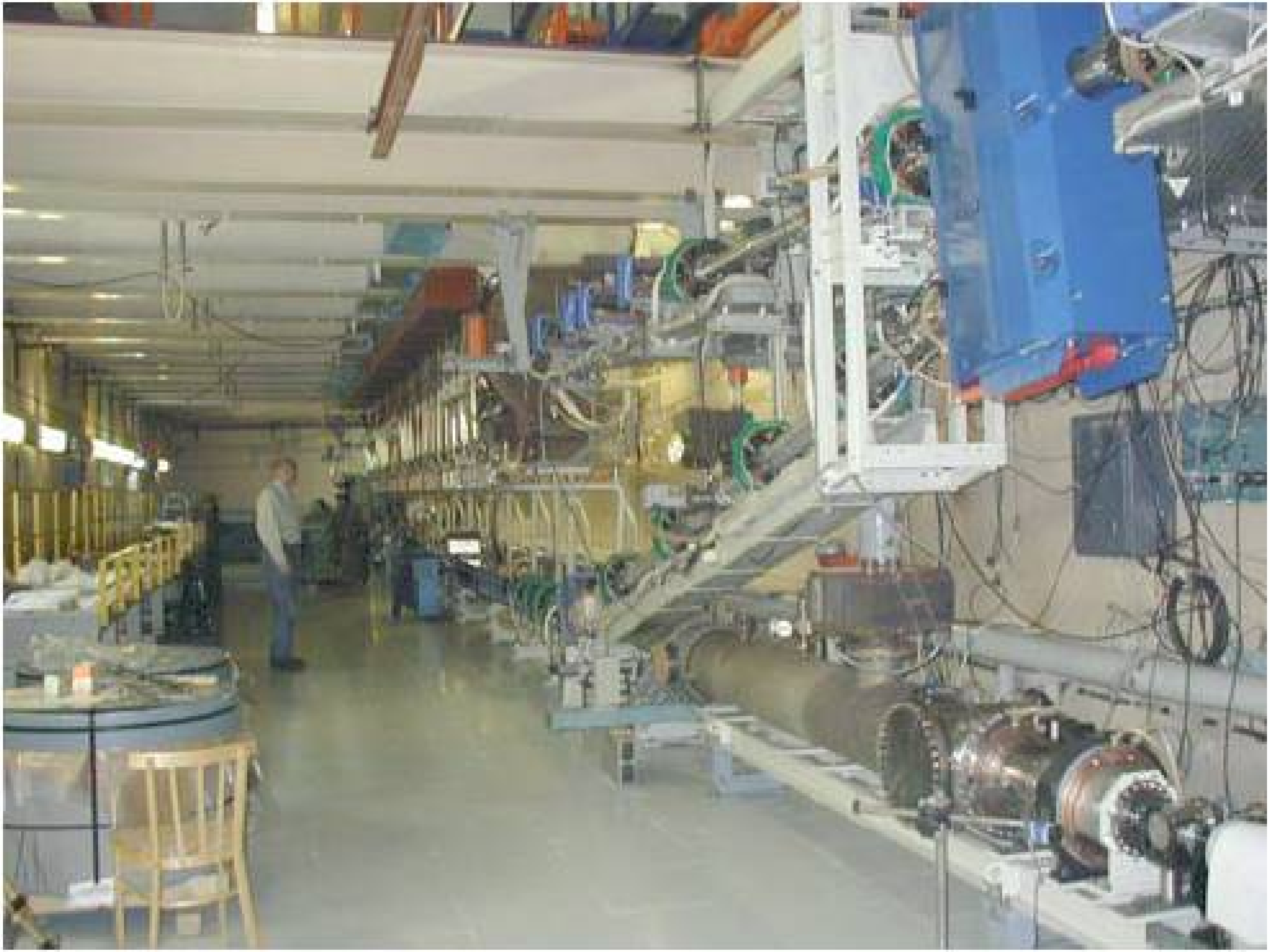
Layout of the Novosibirsk FEL (1st stage)



1 – an electron gun, 2 – RF bunching cavity, 3 – focusing solenoid, 4 – a small bending magnet, 5 – accelerating RF cavity, 6 – quadrupole lens, 7 – magnetic mirror (bend at 165^0) , 8 – undulator, 9 -buncher, 10 – optical cavity mirror, 11 – scrapers with calorimeters, 12 – absorber.

The electron beam from the injector after its passage through the buncher (a bunching RF cavity), drift section, 2 MeV for-accelerating cavities and the main accelerating structure is directed to the undulator, where a fraction of its energy is put into the laser radiation. After that, the beam returning to the main accelerating structure in a decelerating phase, looses its energy practically to its injection value (2 MeV) is dropped into the absorber.

Courtesy: G. Kulypanov

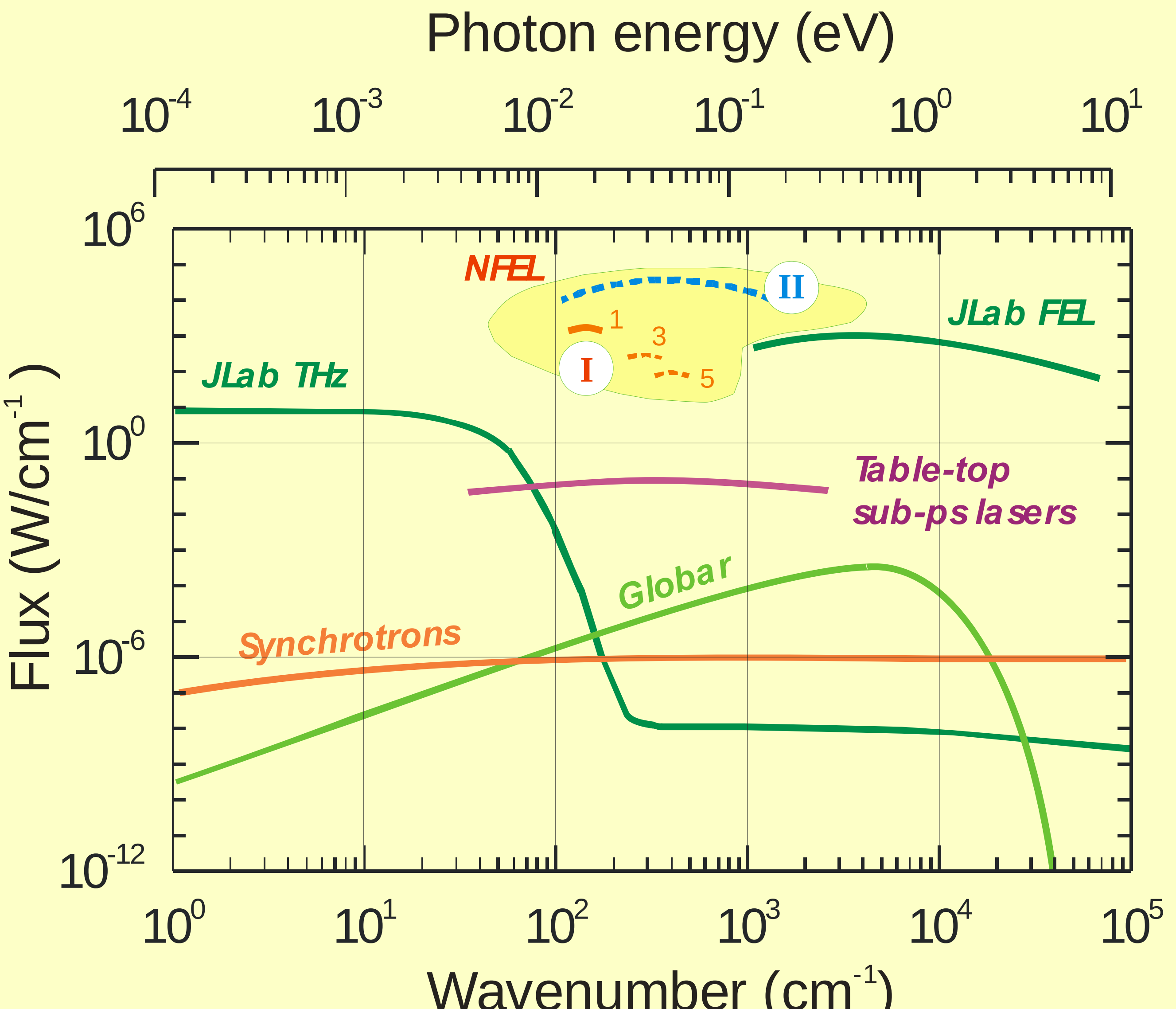


Parameters of the 1st stage accelerator-recuperator

	May 2005	Plans
RF frequency, MHz	180	180
Bunch repetition rate, MHz	11.2	90
Maximum average current, mA	20	150
Maximum electron energy, MeV	12.8	14
Normalized beam emittance, mm*mrad	32	15
Electron bunch length in FEL, ns	0.07	0.1
Peak current in FEL, A	10	20

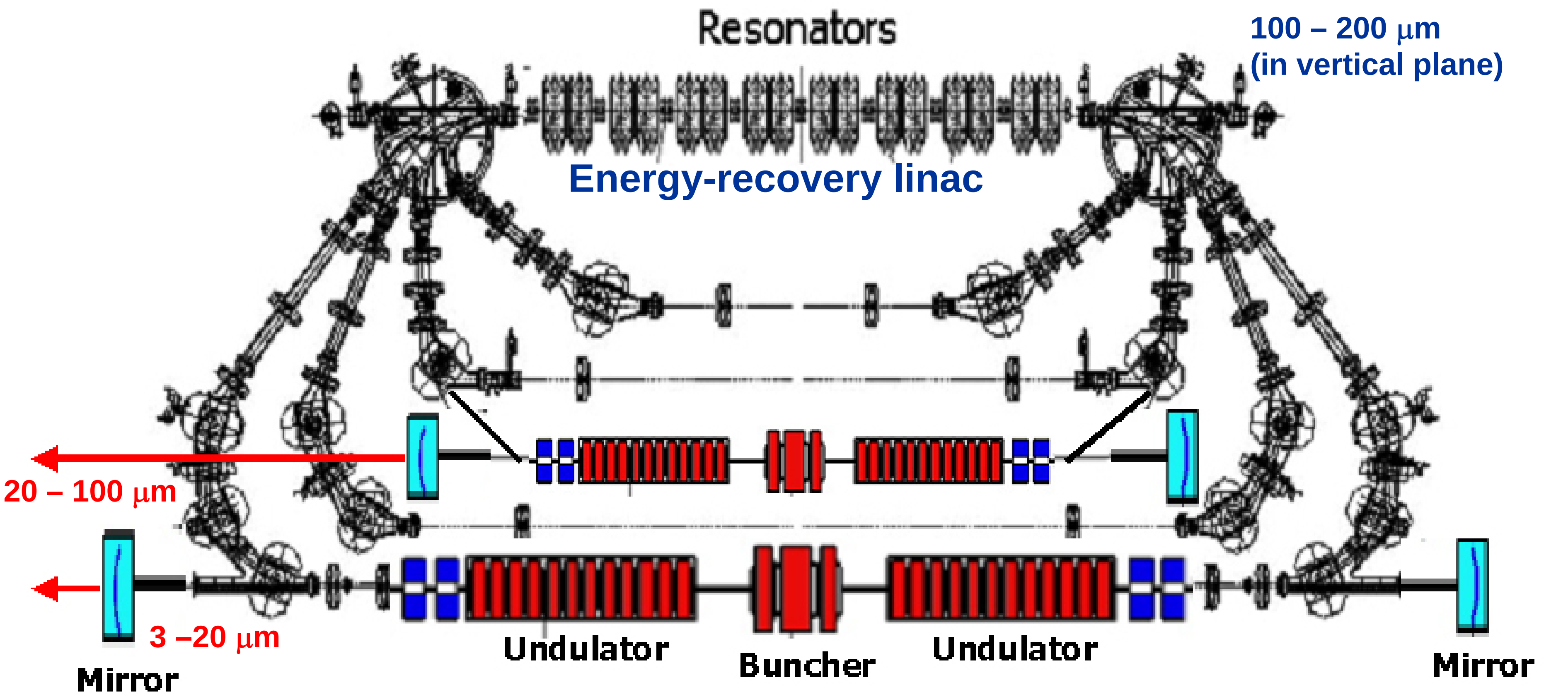
Have energy recovered the largest average current to date!

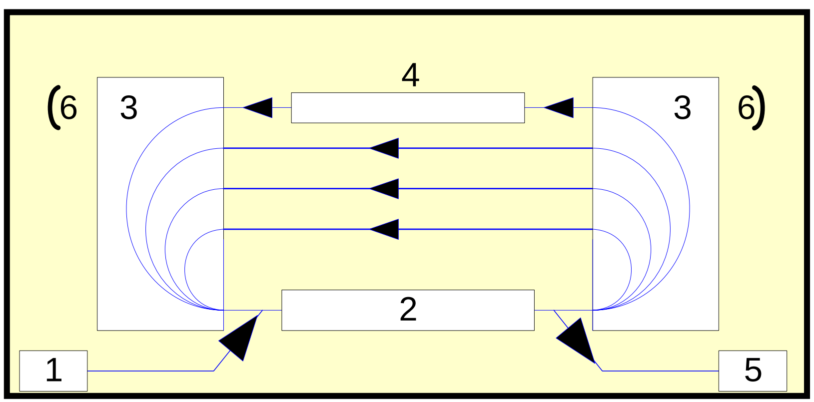
Average spectral power density of the light sources



NFEL – Novosibirsk FEL, 1, 3, 5 – number of harmonic (1st stage), II – 2nd stage

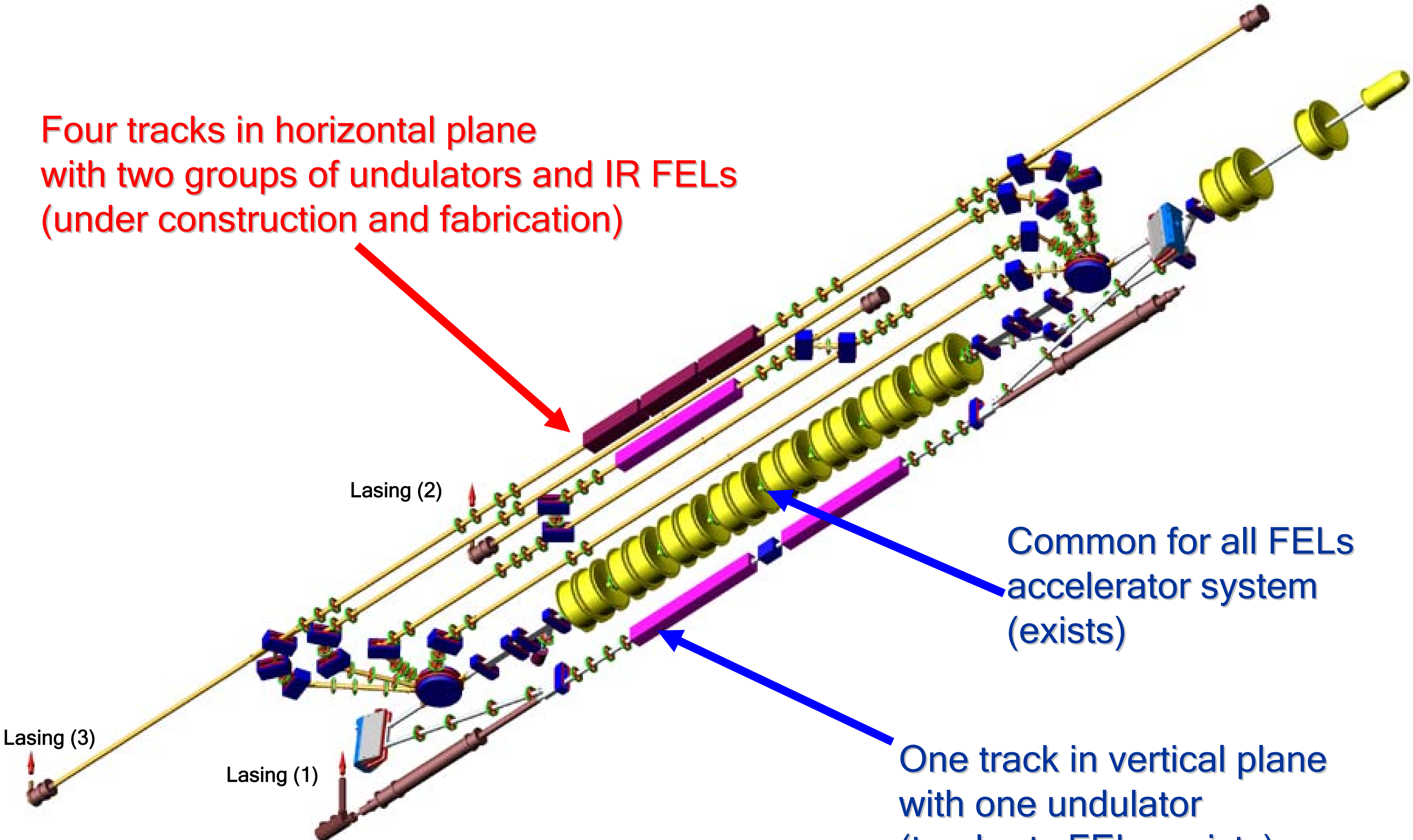
2-nd stage Novosibirsk FEL, under construction
(prototype of MARS)





Radiation wavelength	3 – 100 μm
Average power	10 – 100 kW
E-beam energy	up to 40 MeV
Maximum repetition rate	90 MHz
Maximum mean current	150 mA

Full scale Novosibirsk FEL (bottom view)



Schedule of 2-nd stage of the Novosibirsk Accelerator-Recuperator and FEL:

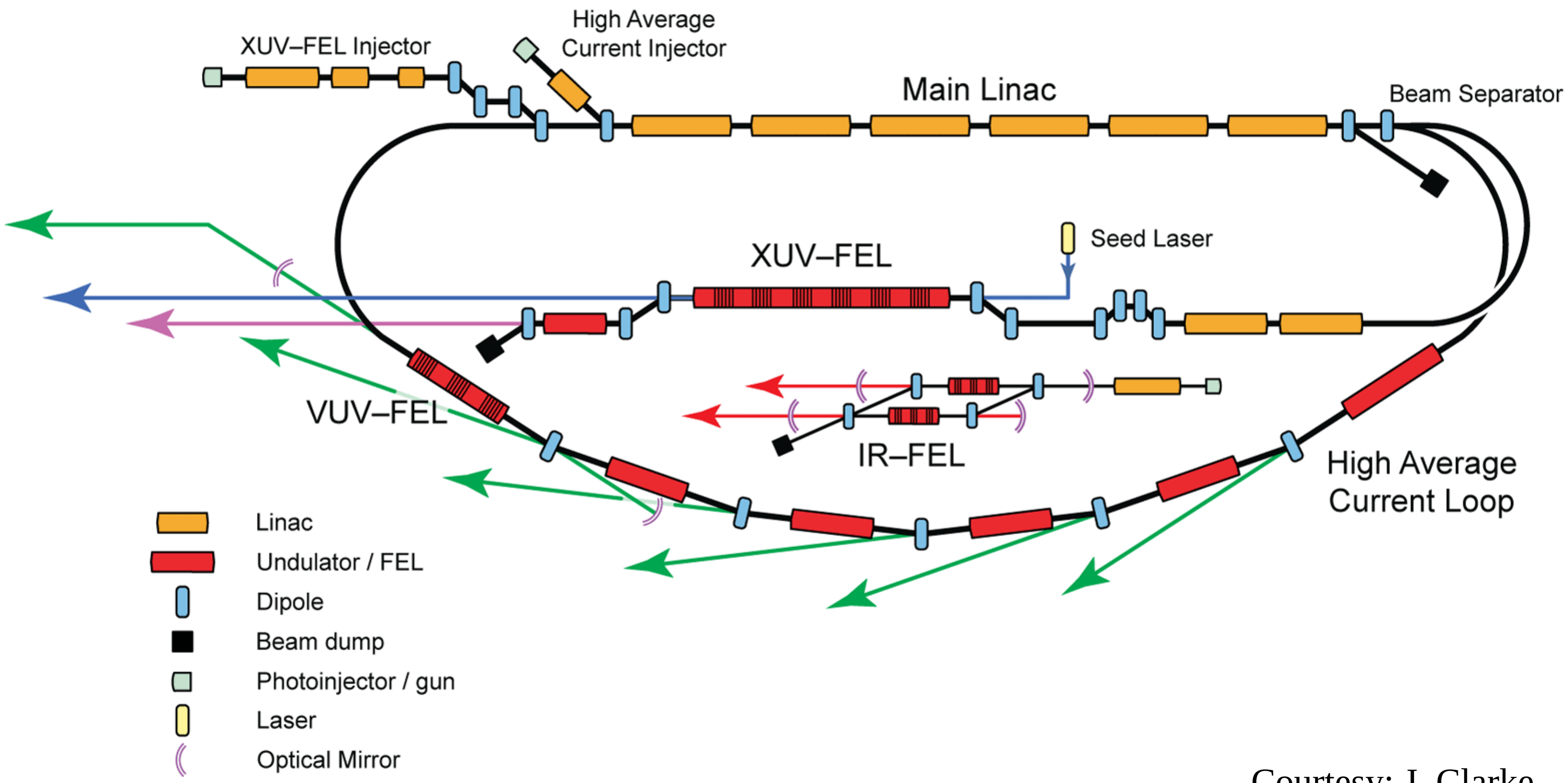
design effort and documentation - 2005 (finished)

manufacture of all elements and systems - 2006 (in progress)

assembly - 2007

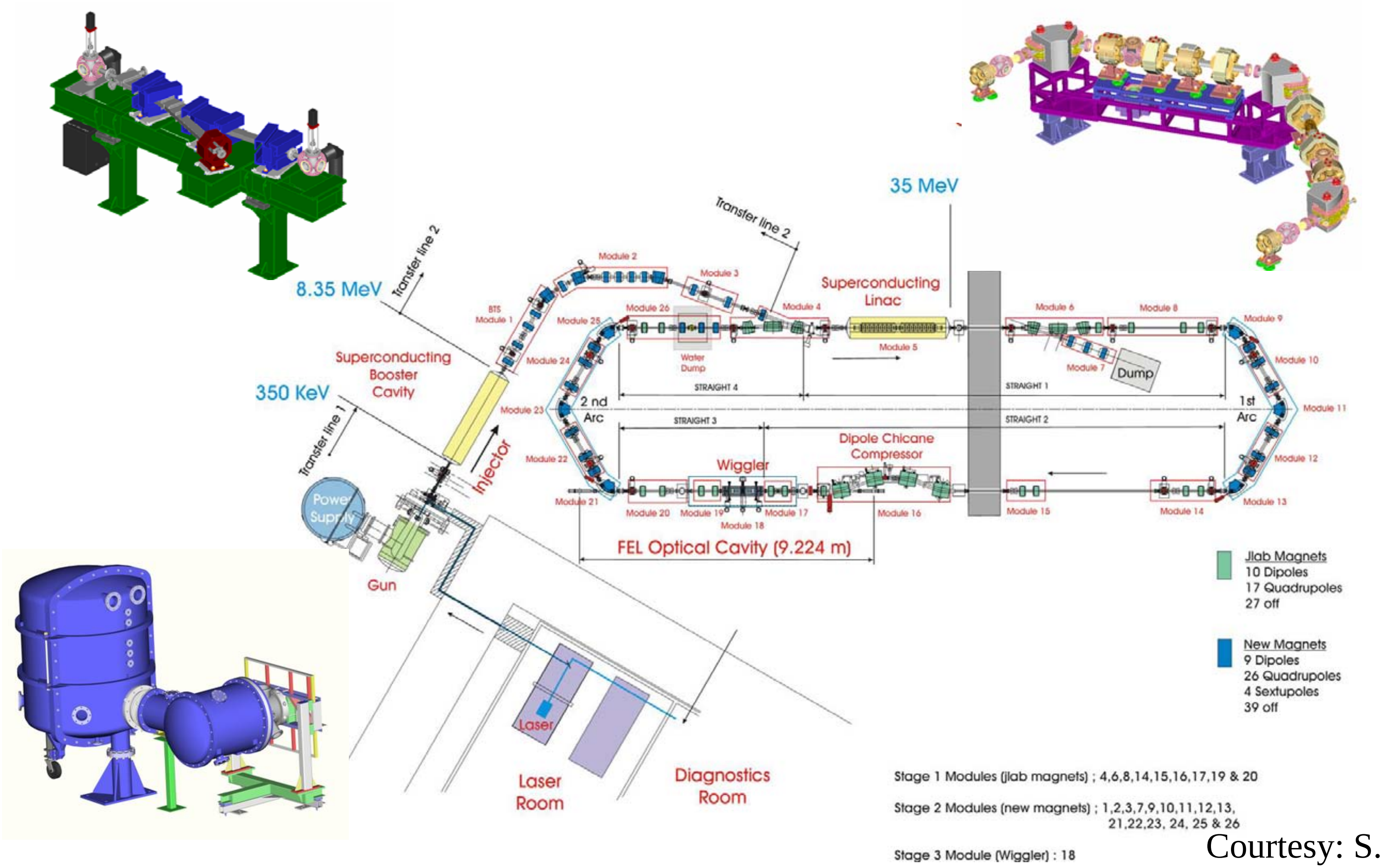
commissioning - end of 2007

4GLS Schematic



Courtesy: J. Clarke

Daresbury: ERL Prototype



Courtesy: S. Smith

Status

Laser system ready

RF power supply under test on site

Gun ceramic – major source of delay – at Daresbur (~1 year late)

Accelerator modules arrive April/July 2006

4 K commissioning May 06

Gun commissioning August-October 06

2K commissioning October 06

Complete machine ready December 06

Energy Recovery Spring 07

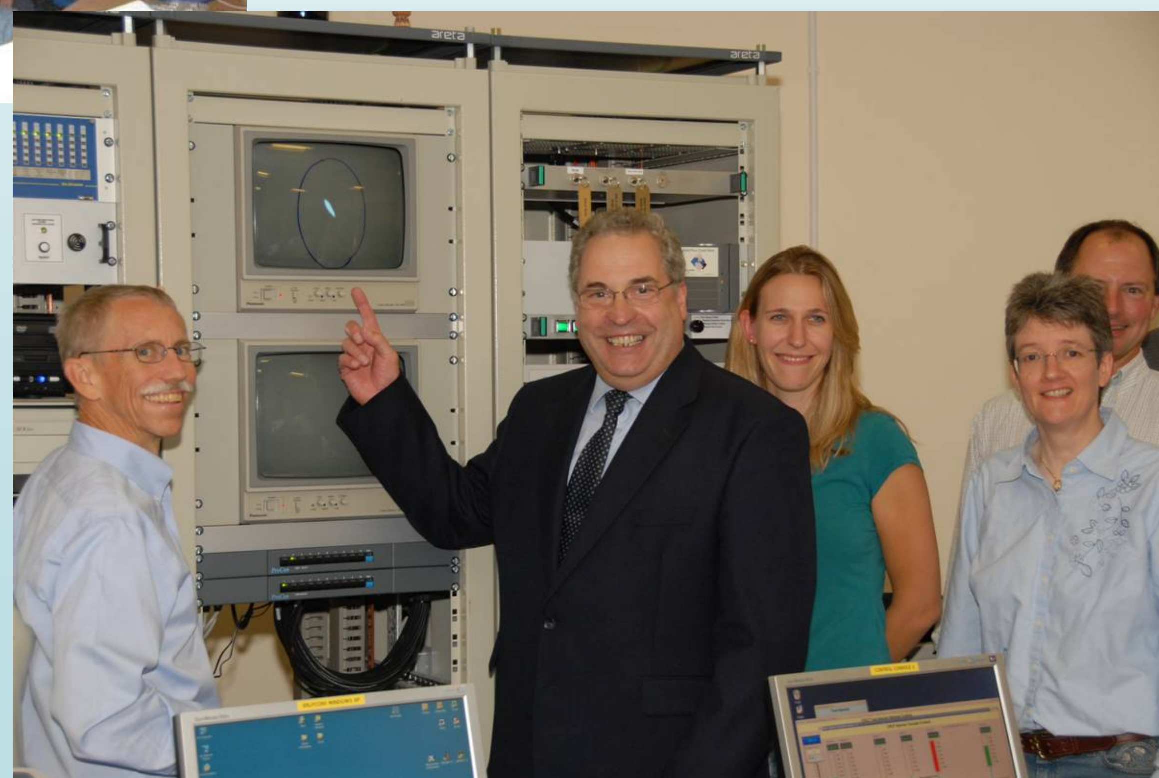
Exploitation 2007……

Coming soon

ERLP @ Daresbury

A World Class ERL based Facility for the Development of Accelerator/Photon Science and Technology...

First Beam at ERLP



Wednesday afternoon

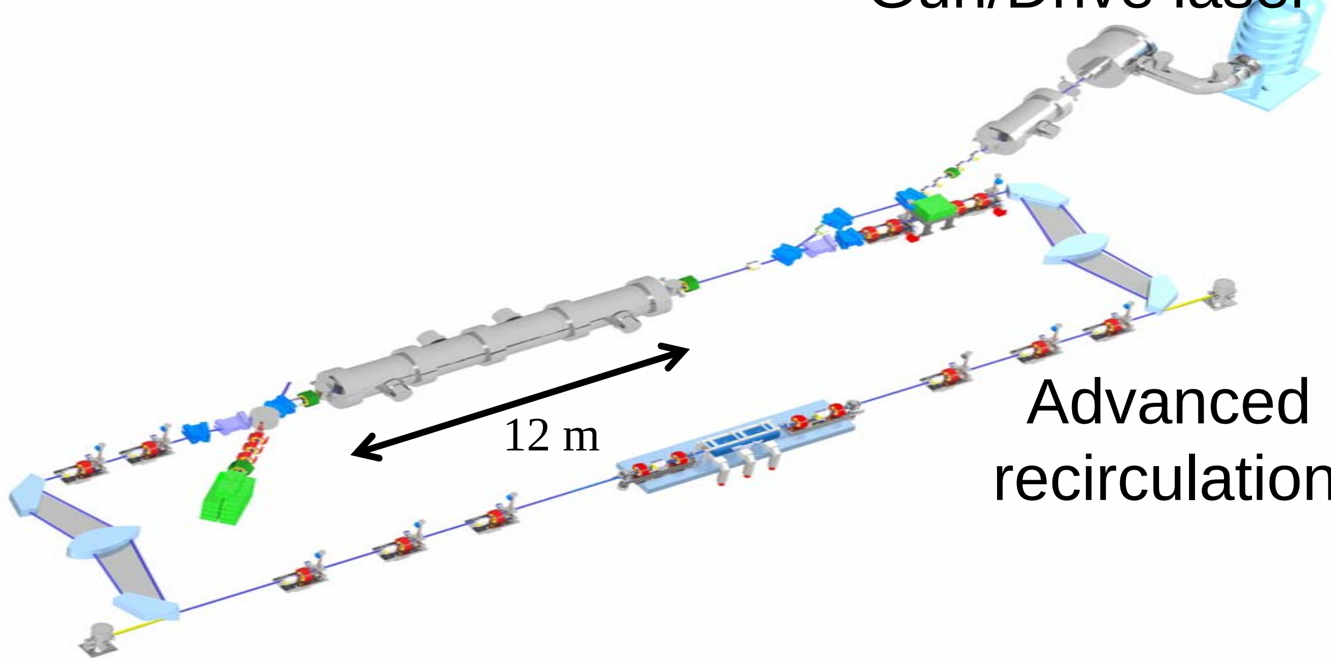
August 16, 2006!

Towards a 100 kW FEL

Small 22 m x 5 m footprint

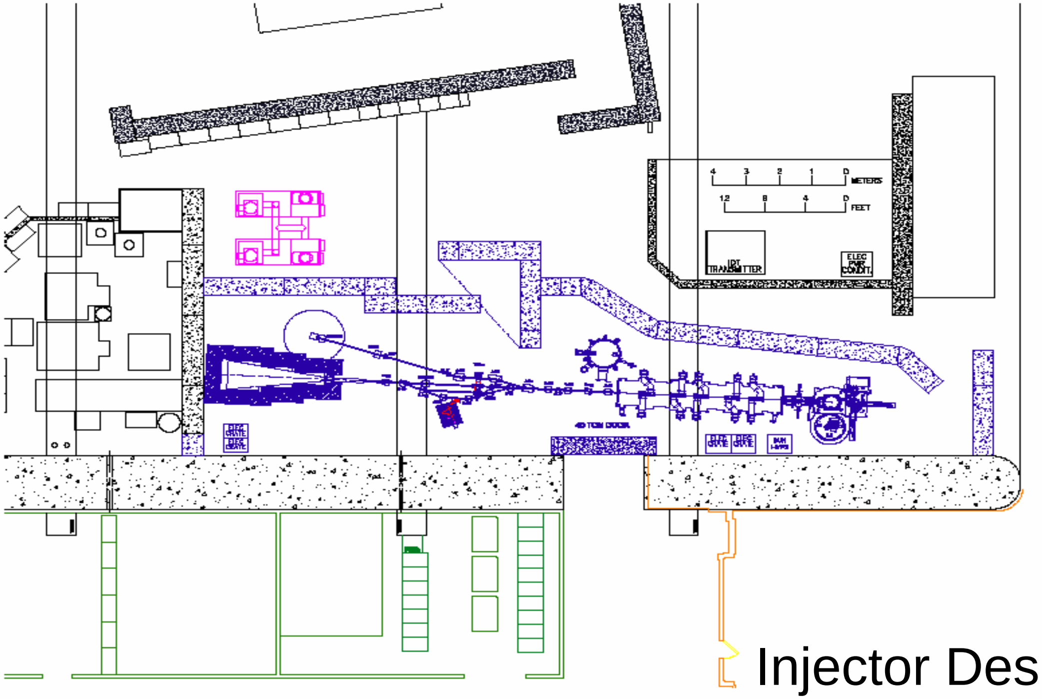
120 MeV, 100 mA electron beam

1 to 2.2 microns design wavelength



Courtesy: Dave Douglas

Phase I ERL Injector Layout



Injector Design Parameters:

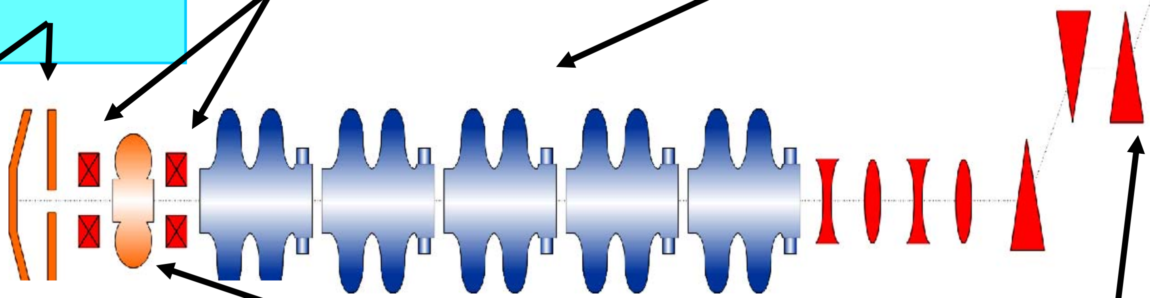
Beam Energy Range	5 – 15 MeV
Max Average Beam Current	100 mA
Max Bunch Rep. Rate @ 77 pC	1.3 GHz
Transverse Emittance, rms (norm.)	~ 0.1 μm
Bunch Length, rms	2.1 ps
Energy Spread, rms	0.02 %

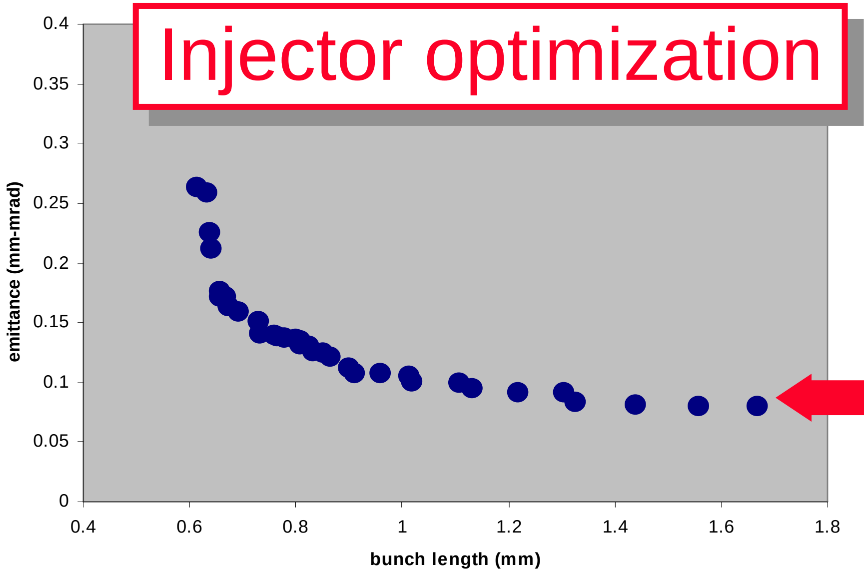
Courtesy:
C. Sinclair

Calculated Performance

CORNELL UNIVERSITY
CHESS / LEPP

Cornell ERL Prototype Injector Layout

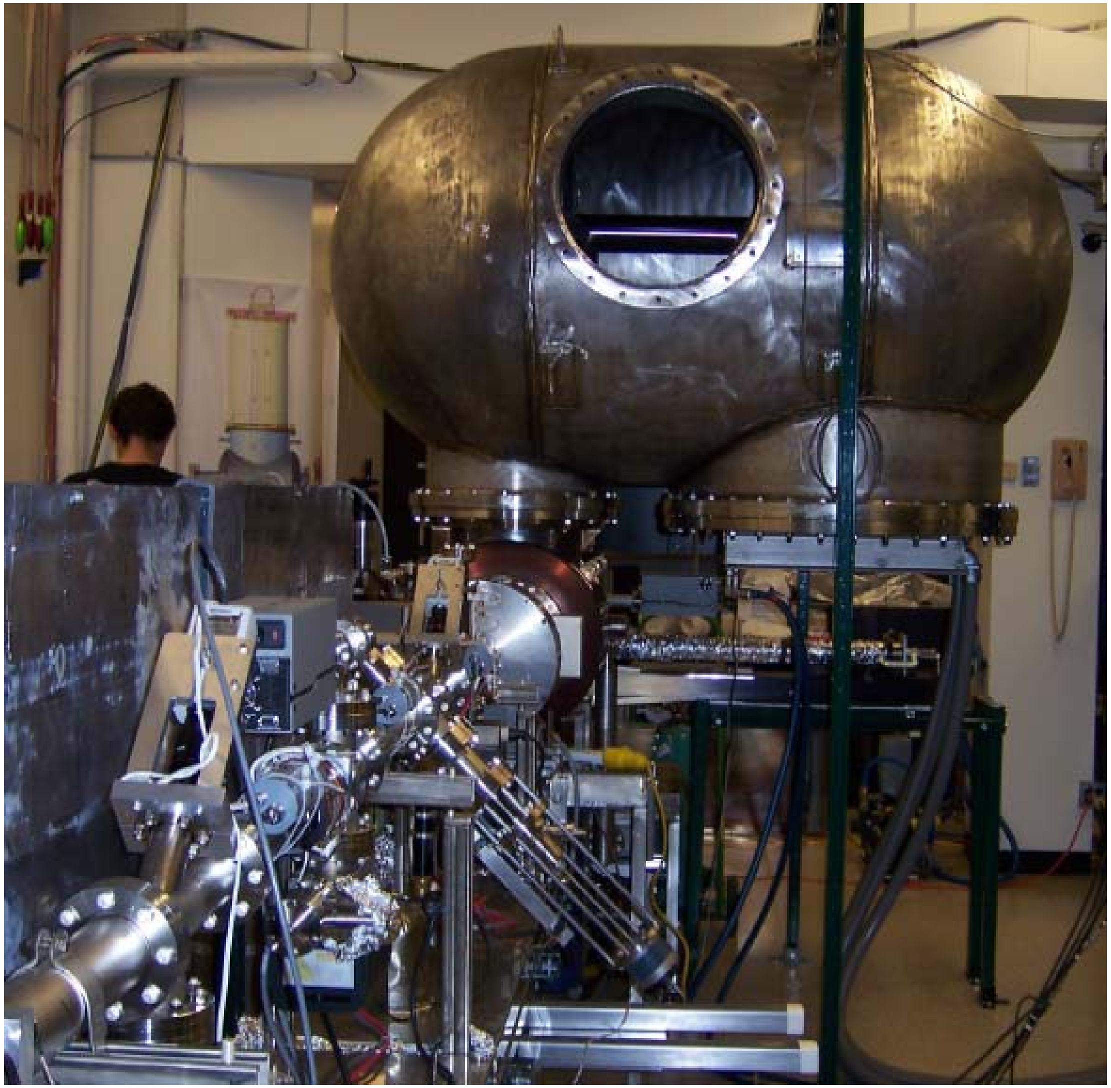




0.1 mm-mrad, 80 pC, 3ps

Courtesy of I. Bazarov

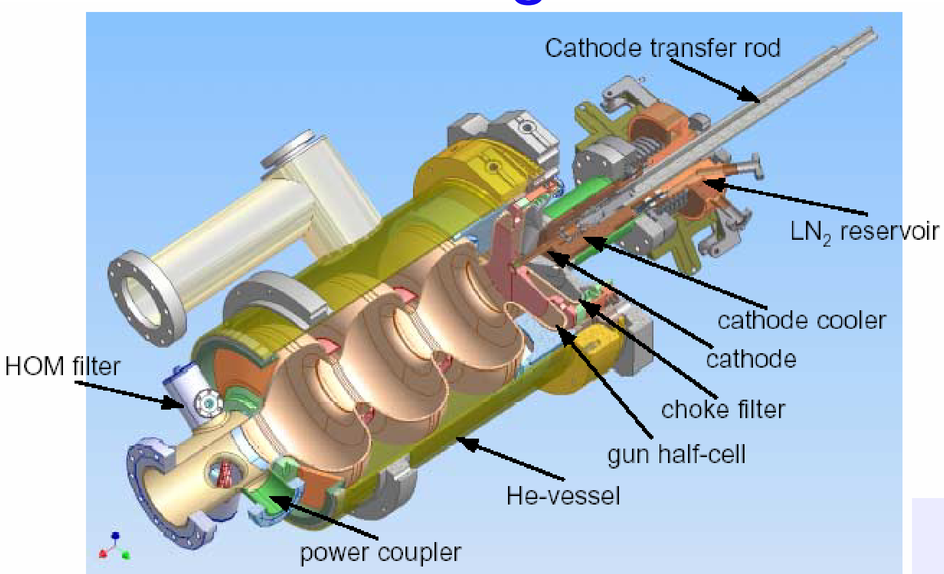
Beam line looking toward gun

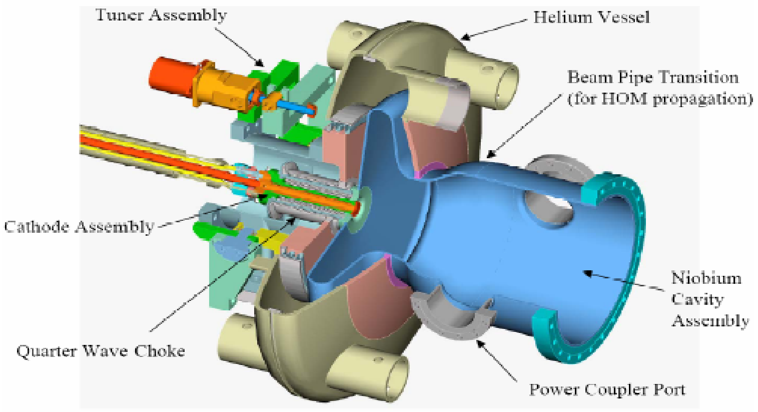


Courtesy:
C. Sinclair

SRF photoinjectors

- High CW RF fields possible
- Significant R&D required





Rossendorf upgrade experiment:
1.3 GHz, 10 MeV
77 pC at 13 MHz and 1 nC at up to 1 MHz (1 mA)
EPAC06, Paper WEPLS043, 2469 (2006)

BNL/AES/JLAB development:
1.3 GHz ½-cell Nb cavity at 2K
Test diamond amplified cathode

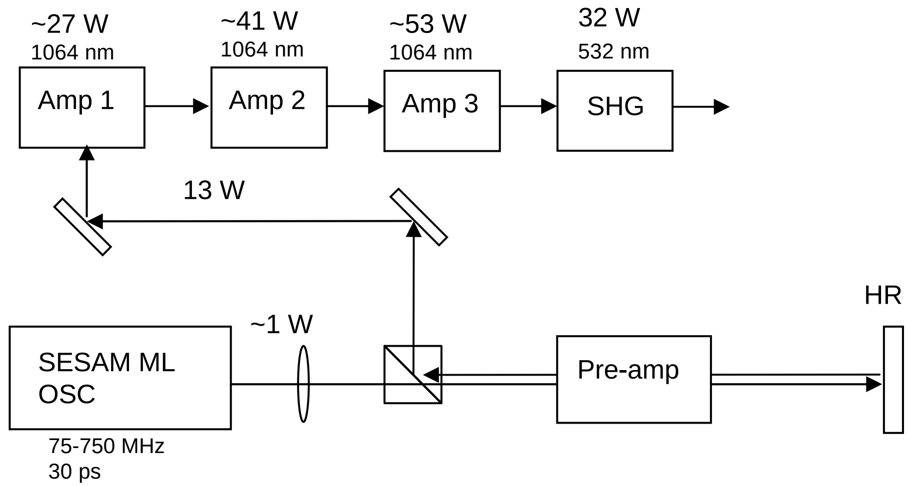
AES/BNL development:
703.75 MHz ½-cell Nb photoinjector

Cornell Advanced Laser Work

- Demonstrate each of the key laser beam properties one by one
  - —Operated fundamental-frequency mode-locked Yb-fiber laser at 50 MHz, at a power level suitable for amplification to final requirements
  - —Operated at 26th harmonic to produce 1300 MHz
  - —Operated the amplifier chain up to 100 nJ/pulse (>130 W average at 1300 MHz) in the IR
  - —Second harmonic generation of the green at energy/pulse consistent with 25 W
  - —Longitudinal pulse stacking to make flat 35 psec optical pulses, with very low losses
- Need to
  - —Generate flat transverse distributions, needed for small emittance
  - —Generate pulse modes for beam diagnostics
- "So, as you can see, we have demonstrated all of the hard stuff about the laser"

Courtesy: C. Sinclair

ADVANCED DRIVE LASER PERFORMANCE

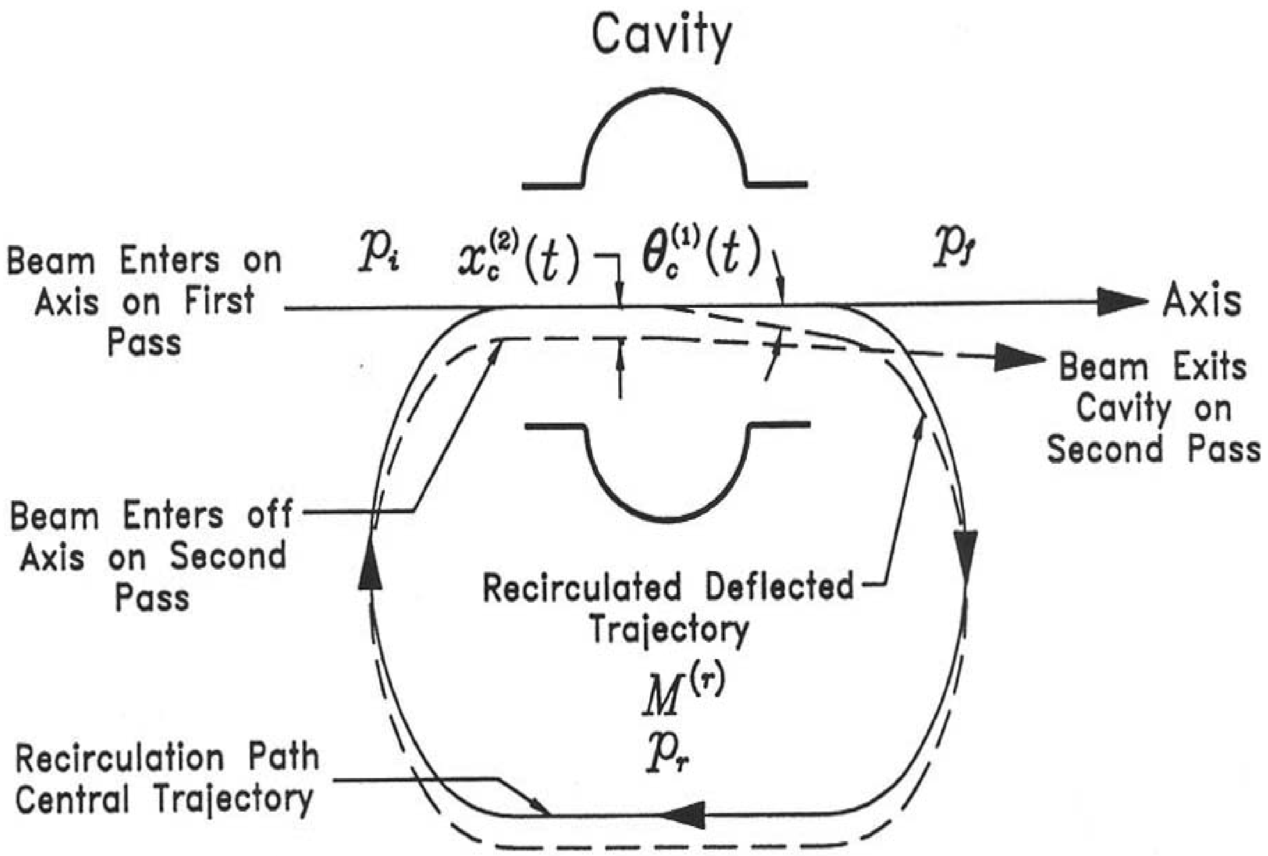


CLEO 2005 Paper CMJ4, "**High-Average-Power Picosecond Drive Source for Photocathode Injectors",** A. Dergachev **et al**
PRST-AB (2005), "**Characterization and performance of a high-power all-solid-state drive laser for application in high-current photo-cathode injectors", S. Zhang, D. Hardy, G. Neil, and M. Shinn**

- Oscillator and gain modules run on 115V, single phase power.
- Preamp is unsaturated in the first pass, saturated on the second.
- Subsequent gain modules are all saturated.
- SHG conversion efficiency with 30 ps pulses exceeds 50% (74.85 MHz PRF)
- Amplitude noise < ±0.3% (74.85 MHz PRF)
- Currently obtain ~ 10 W of SHG at 748.5 MHz (not optimized)
  - Funded through a Joint Technology Office (US-DoD) contract

Courtesy: M. Shinn

Multipass BBU Instability



From: N. Sereno Thesis

Threshold Current

Growth Rate

$$\mathrm{Im}(\omega) \approx -\frac{\kappa \sin(\omega_\lambda t_r)}{2t_0} - \frac{\omega_\lambda}{2Q_\lambda}$$

$$\kappa = (R/Q)_\lambda k_\lambda^2 e T_{12} I_0 t_0 / 2$$

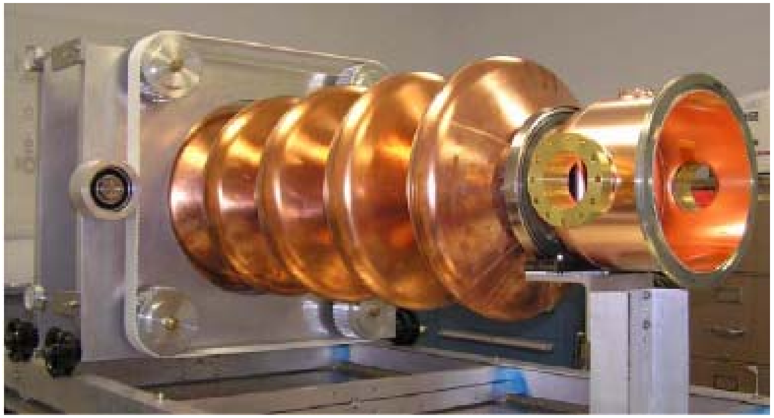
If the average current exceeds the threshold current

$$I_{th} = \frac{1}{e} \frac{2\omega_\lambda}{(R/Q)_\lambda Q_\lambda k_\lambda^2 \left| T_{12} \sin(\omega_\lambda t_r) \right|}$$

have instability HOM damping frequency beam optics

BNL/AES 1 Amp Cavities

Developed for 0.5 A RHIC ERL Electron Cooler



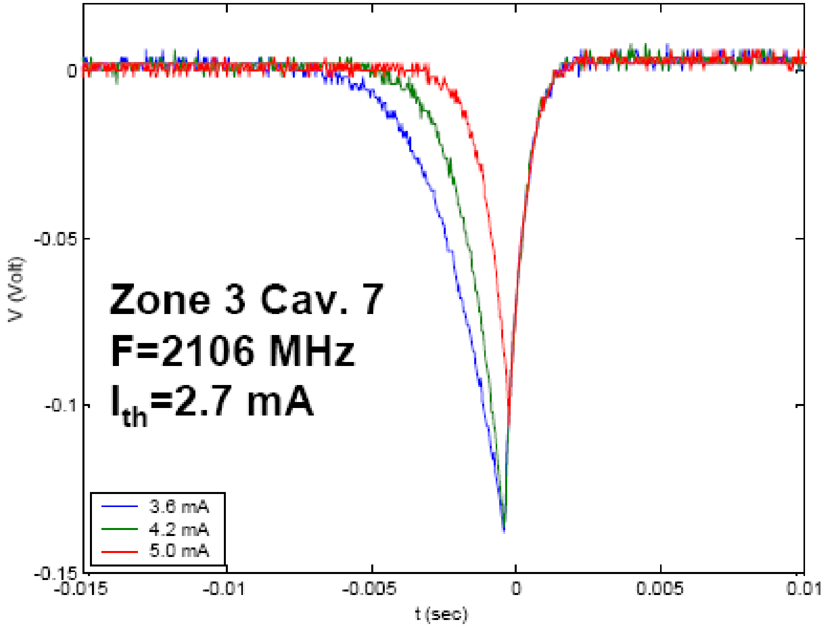
copper model 703.75 MHz

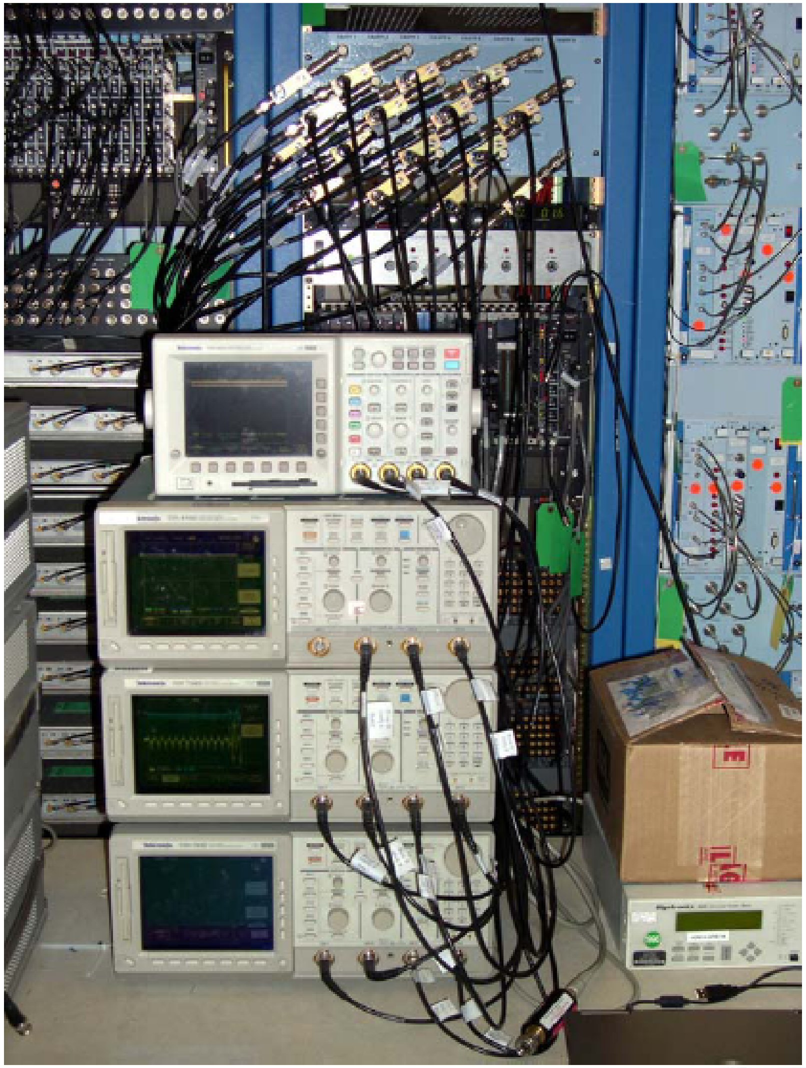
niobium cavity during vertical test

Courtesy: Ilan Ben-Zvi

Regenerative BBU in the JLAB FEL Upgrade

Tennant, Pozdeyev, and Jordan





HOM power, measured by Schottky diodes, vs. time for I_b=3.6, 4.2, and 5 mA. The rise time depends on the beam current as

$$\tau = \tau_0 \frac{I_{th}}{I - I_{th}}$$

Stabilization by Feedback and Beam Optics

JLab/Cornell/Stanford Collaboration

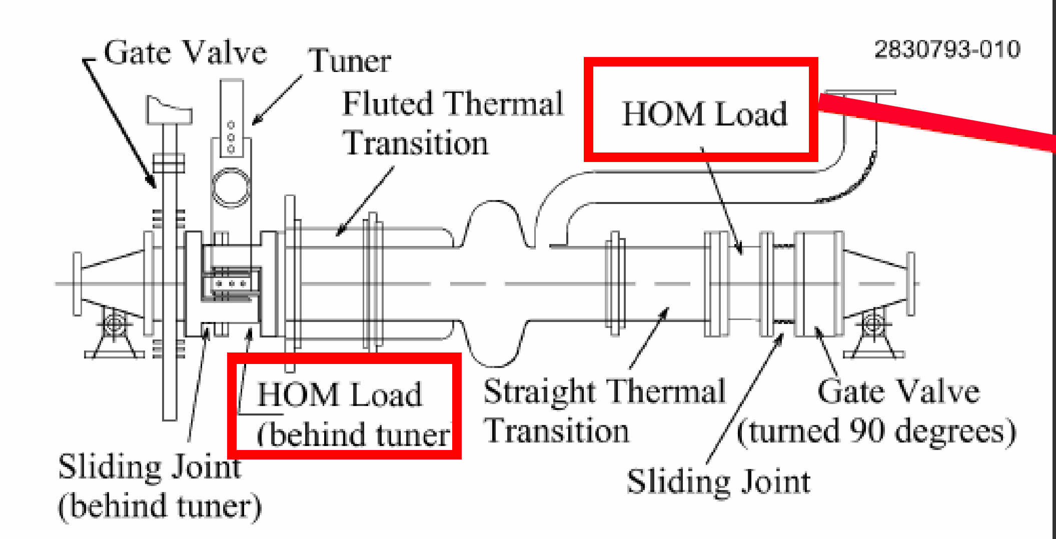
		Effect on 2106 MHz HOM	Considerations for Implementation
Q-Damping	Damping Circuit	5 x I_{th}	• Works for only *1 mode per cavity* • Not as effective at raising the threshold as beam optical methods • Long term stability of system • Does **not** effect beam optics
	3-Stub Tuner	1.5 x I_{th}	
Beam Optics	Phase Trombone	*Stabilized*	• Can *stabilize* the mode against BBU • What are the effects on other HOMs? • Do they prevent reaching the requirements needed for a suitable lasing configuration?
	Pseudo-Reflector	*Stabilized*	

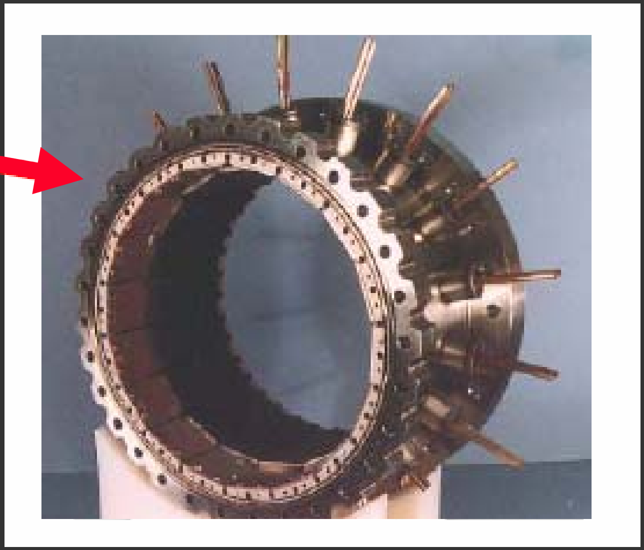
Numerical BBU simulations checked out in detail against experiment

HOM damper:
Beam-pipe absorber

Cornell University

S.C. storage ring cavities are using ferrite based beam pipe absorbers since many years. Example: CESR





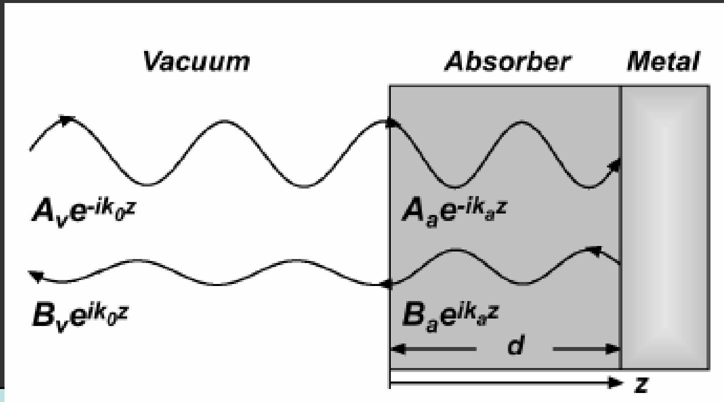
Based on the good performance of these absorbers, many ERL proposals adopted this concept.

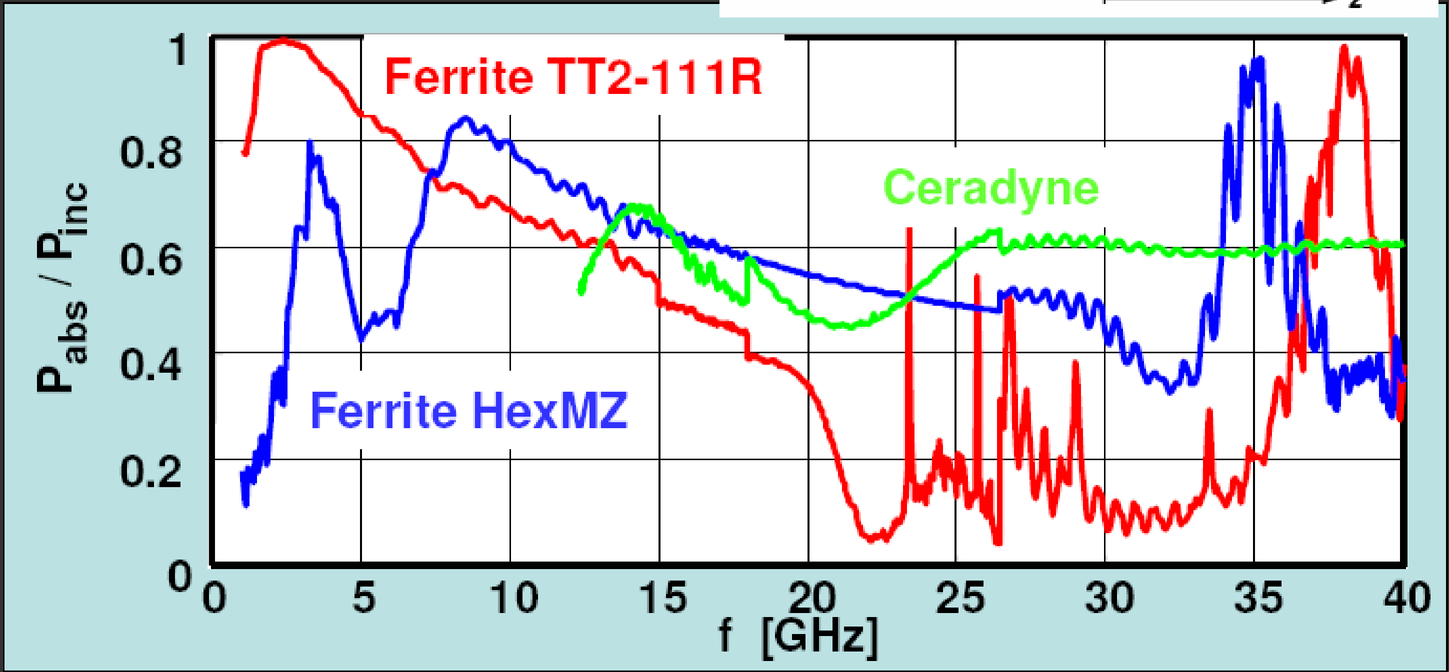
But: High frequency HOM spectrum in ERLs requires efficient absorption at multi-10 GHz frequencies.

Cornell ERL Absorber: Measured RF losses at 80 K

Cornell University

Measured RF absorption efficiency at 80 K as function of frequency for different materials





High Power Optical Cavities

DESIGN CONSIDERATIONS FOR NEXT GENERATION OPTICAL CAVITIES

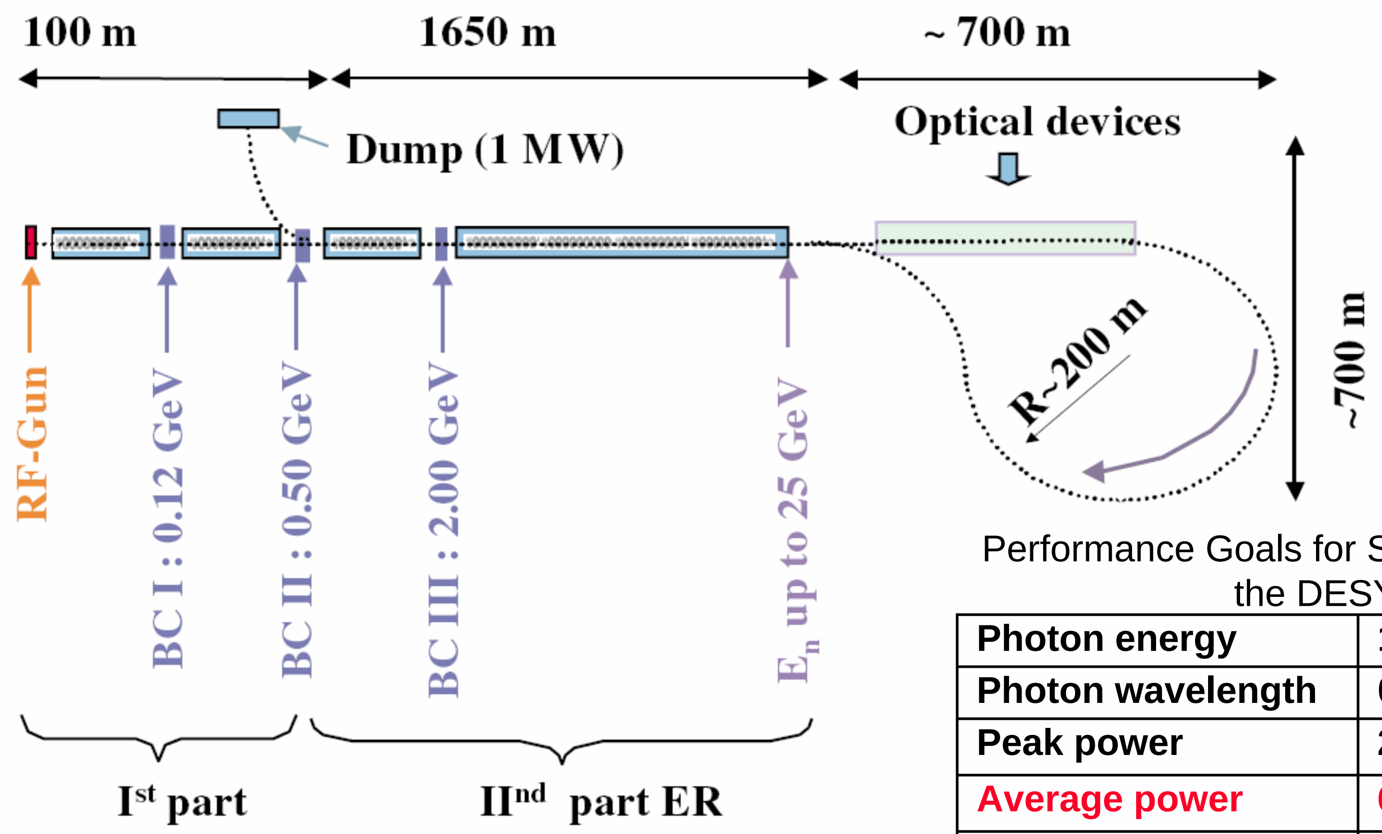
- **Loss is the bane of all high power laser builders, and FELs are no different.**
- **Absorptive loss leads to mirror distortion, which can lead to lower output and poorer beam quality.**
- **Scatter loss is constrained by the beam pipe and the subsequent absorption on components causes pressure rise and component drift.**
- **Optical cavities and beamlines must be designed with these effects in mind.**
- **Mirror coatings and substrates must be chosen to mitigate the effects of power loading from out-of-band radiation as well as that from the fundamental.**

Courtesy: M. Shinn

Beam Diagnostics

- **Because the average current is approaching that in storage rings, one would expect that the more standard diagnostics (BPMs, Profile monitors, Current monitors, etc.) would follow the standard techniques previously developed at rings**
- **What's unique to the ERLs and ERL FEL sources is the need to diagnose and control short bunches, the need to deal with tune up modes, and the high average beam power**
- **Many longitudinal techniques are being explored in X-FEL work. Mainly they are highly disruptive and might not be technically useful in the high average current regimes we are pushing into.**
- **Real time non-interceptive measurements of bunch longitudinal distribution and phase space, based on, e.g. electro-optic techniques or on coherent synchrotron, coherent edge, or coherent undulator radiation, may provide the final answer. There is no unambiguous method demonstrated yet.**
- **Much interesting work is needed on this topic.**

TESLA XFEL ERL



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

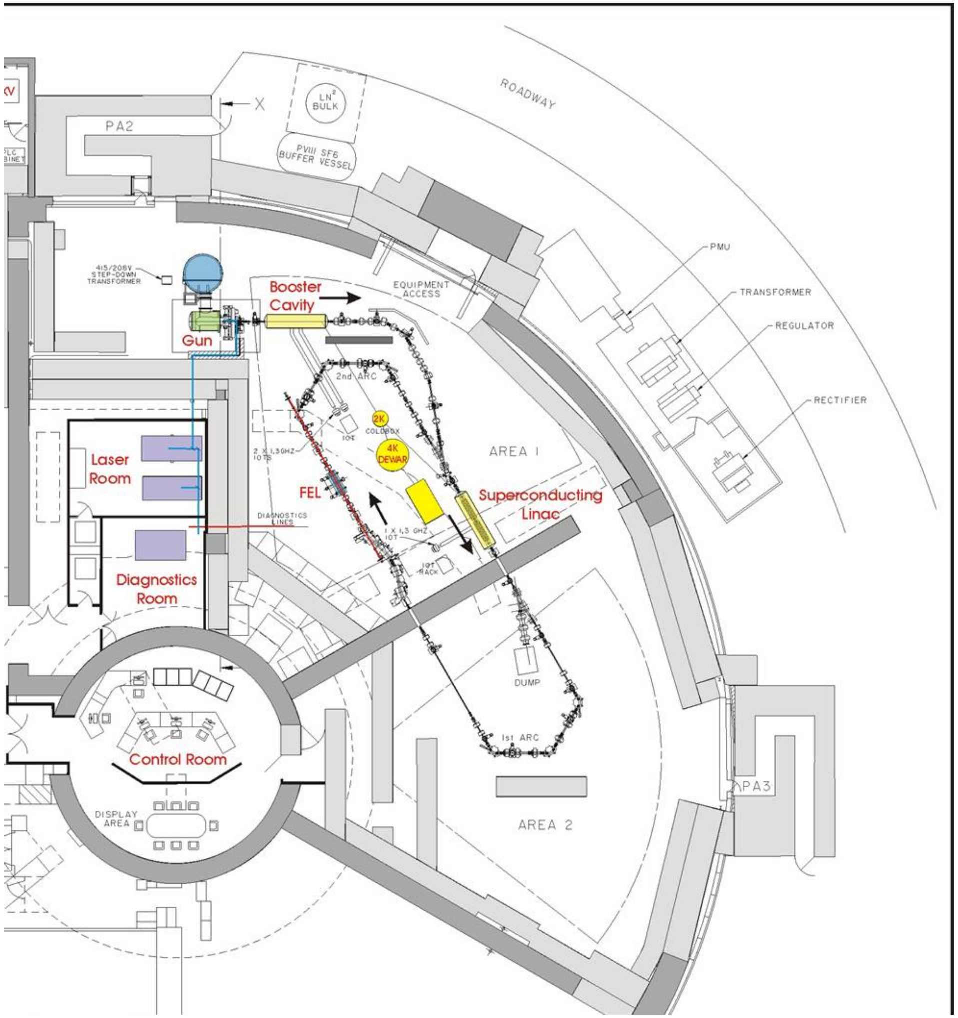
Summary

- **The field of ERL-based FELs continues to grow and the performance of devices continues to improve**
- **Upgrade paths for at least two orders of magnitude in average beam power (at least for the electrons and maybe for photons), though not trivial, seem to exist**
- **Many new ideas are being explored, some in conjunction with future light source applications of Energy Recovered Linacs**
- **The field seems to be thriving, and there is no shortage of interesting problems to work on**

Laser Development

- 50 MHz fundamental frequency mode-locked Yb fiber oscillator
- Harmonic mode-locking to reach 1300 MHz
- Yb fiber amplifier(s) to reach ~ 130 W in the IR. (100 nj/pulse)
- Frequency multiplication in LBO to give > 20 W in the green after pulse shaping
- Initial transverse shaping with aspherics, temporal shaping with pulse stacking
- Pattern control with BBO Pockels cell

Daresbury: ERL Prototype



Electron Beam Parameters	Goal
Energy (MeV)	**30-50**
Accelerator frequency (MHz)	**1300**
Charge per bunch (pC)	**>80**
Average current (μA)	**13**
Peak Current (A)	**53**
Beam Power (kW)	**0.455**

Output Light Parameters	Goal
Wavelength range (microns)	**3-10**
Bunch length (FWHM psec)	**1.5**
Laser energy/ pulse (μ Joules)	**9**
Macropulse average laser power (kW)	**0.7**
Rep. Rate (MHz)	**81.25**
Macropulse length @20 Hz rep rate (μsec)	**100**

Courtesy: S. Smith