A Review of ERL Prototype Experience and Light Source Design Challenges

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Accelerator Physics
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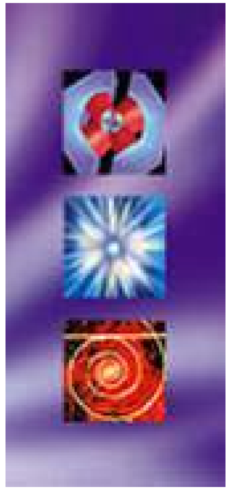
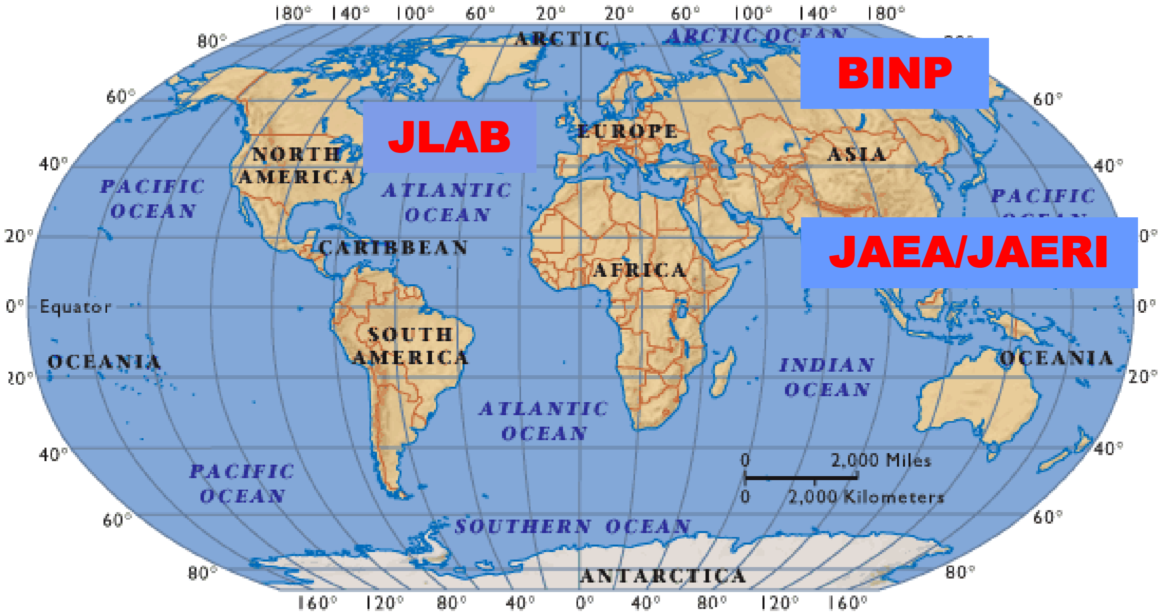


CCLRC Daresbury Laboratory

Content

- **Existing light source ERLs**
  - JLAB experience
- **Challenges of future light sources**
  - Why?
  - 4GLS
- **Prototype facilities for ERL light sources**
  - Cornell injector
  - KEK/JAEA collaboration
  - BNL ERL
  - **Daresbury Energy Recovery Linac Prototype**
- **Conclusions**

Operational ERL-FEL Sources



Three Oscillator FELs

Advantage of ERL vs Storage Ring

•Non-equilibrium conditions

•Source characteristics determined by injector

•Shorter bunches=>more flexible bunch pattern

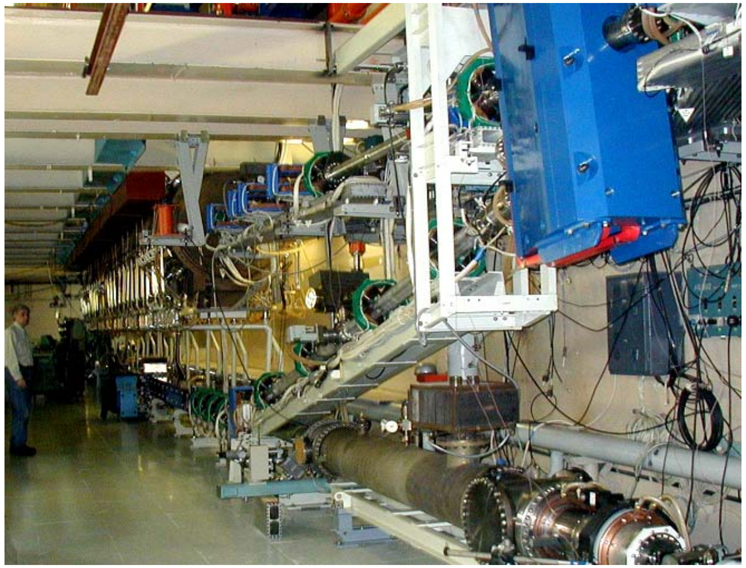
Advantage of ERL vs Linacs

•Improvement in efficiency

•Enormous Increase in average current (CW) and FEL power

•Reduced dump activation

BINP Status of 1st Stage FEL

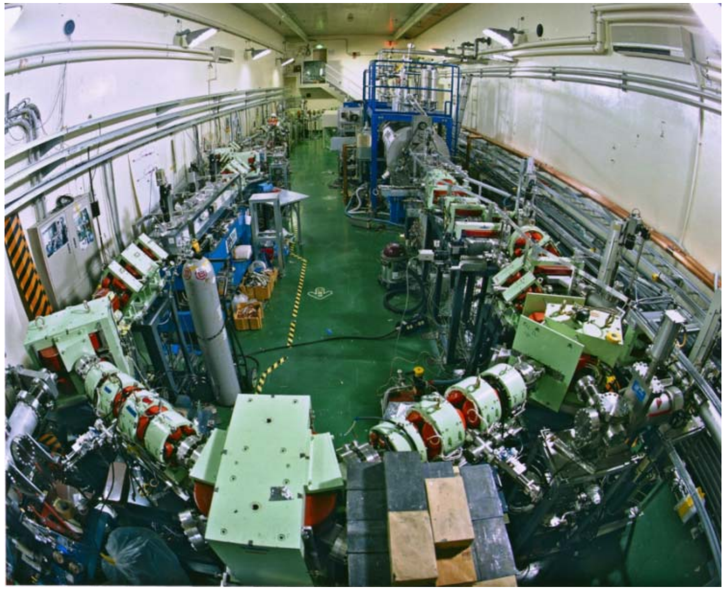


Electron Beam Parameters	IR
Energy (MeV)	12
Accelerator frequency (MHz)	180
Charge per bunch (pC)	900
Average current (mA)	20
Peak Current (A)	10
Beam Power (kW)	240
Energy Spread (%)	0.2
Normalized emittance (mm-mrad)	20

	May 2006	Plans
• Wavelength, mm	0.12 - 0.235	0.1...0.2
• Pulse duration, ps	70	20...100
• Pulse repetition rate, MHz	5.6 - 11.2	90
• **Average power, W**	**400**	1000
• **Relative line width at half-height**	**$3{\cdot}10^{-3}$**	$10^{-2}\ldots3{\cdot}10^{-3}$

The power and relative line width in the terahertz region are record parameters !!

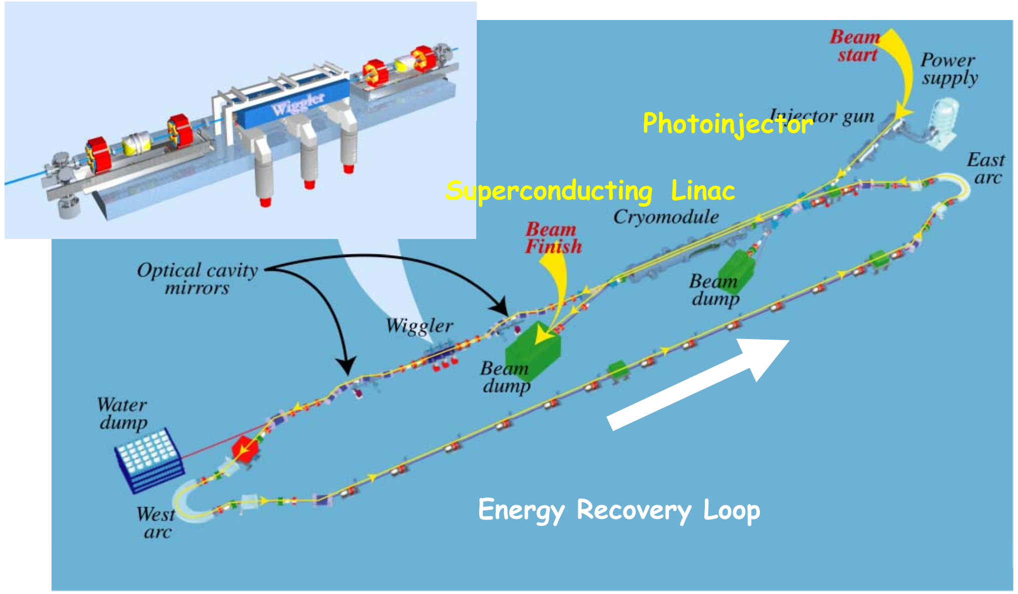
JAEA ERL-FEL Status



Electron Beam Parameters	Achieved	Goal
Energy (MeV)	17	16.4
Accel Frequency (MHz)	500	500
Charge/bunch (pC)	500	500
Average Current (mA)	**10**	40
Peak Current (A)	60	83
Beam Power (kW)	170	656
Energy spread (%)	~0.5	~0.5
Normalized Emittance (mm mrad)	~40	~40
Induced Energy Spread (full)	7%	~3%

Output Light Parameters	Achieved	Goal
Wavelength Range (μ)	22	22
Bunch Length (FWHM psec)	8	6
Laser Power/Pulse (μJ)	33	120
Laser Power (kW)	0.7	83.2
Duty Cycle	0.03	CW

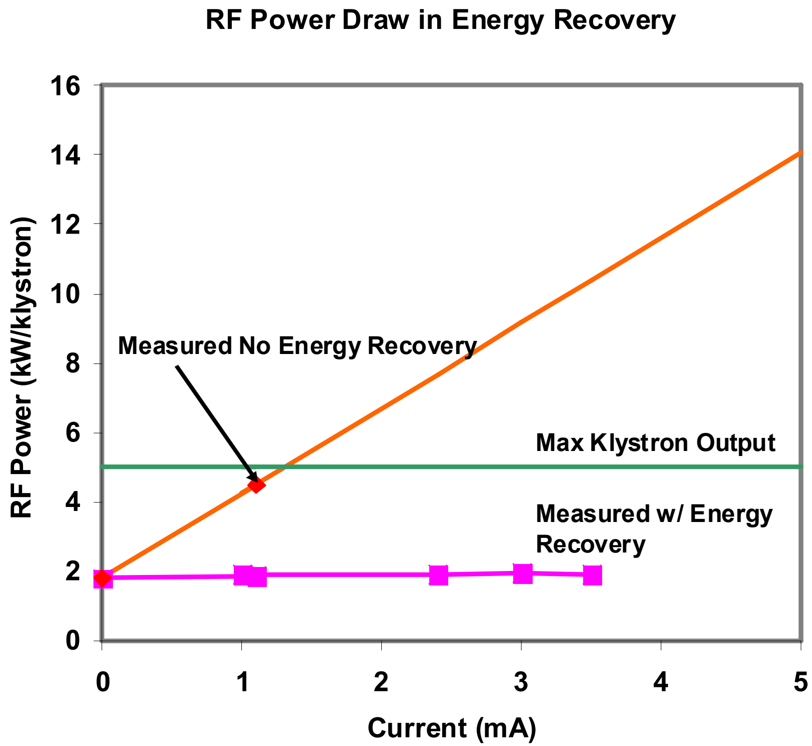
JLab



JLab ERL-based
Free Electron Laser

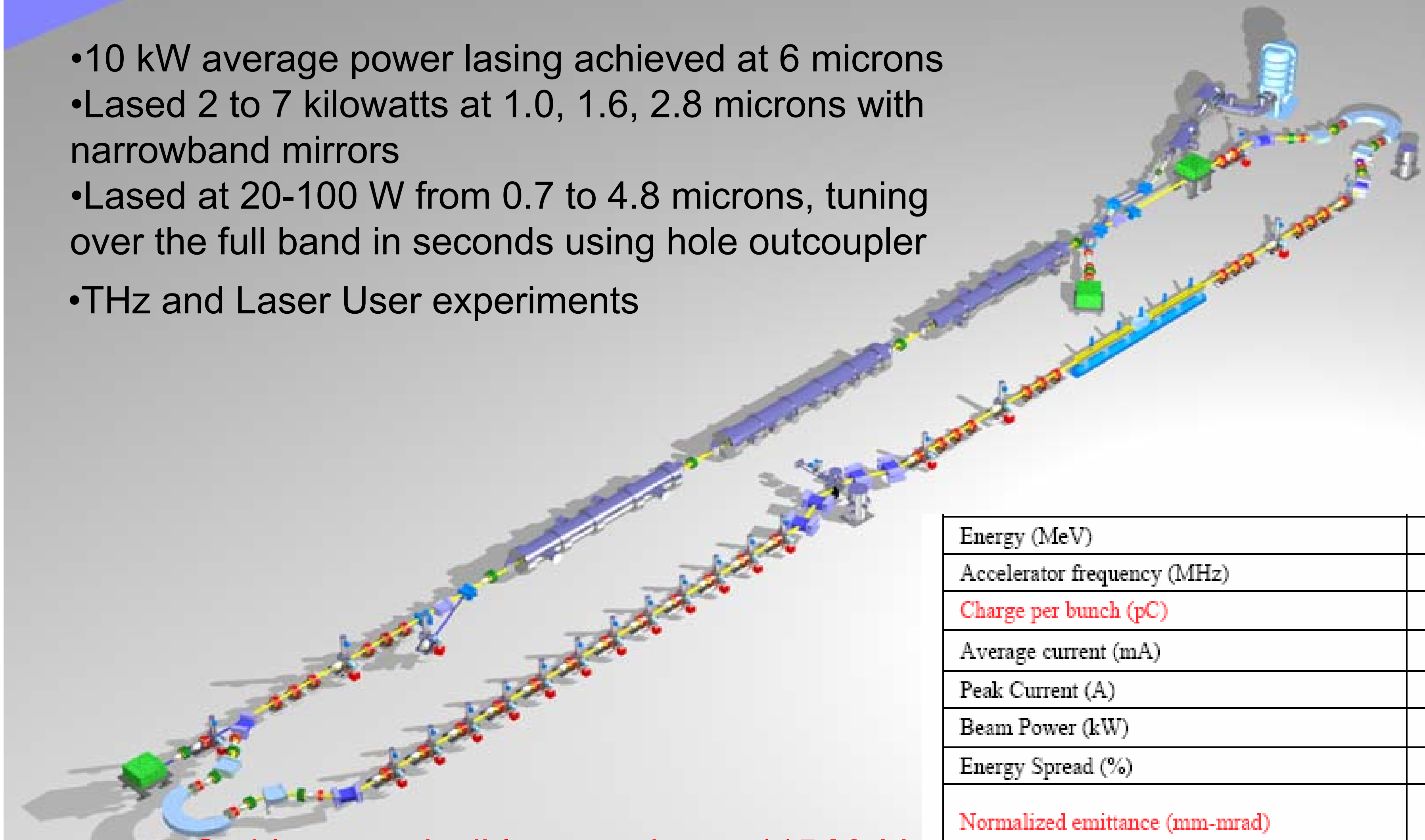
1 MW class electron beam, (100 MeV x 10mA), comparable to beam power in CEBAF accelerator (1GeV x 1mA), but supported only by klystrons capable of accelerating 10-100 kW electron beam.

First high current energy recovery experiment at JLab FEL, 2000



JLab ERL 10 kW IR-FEL Status

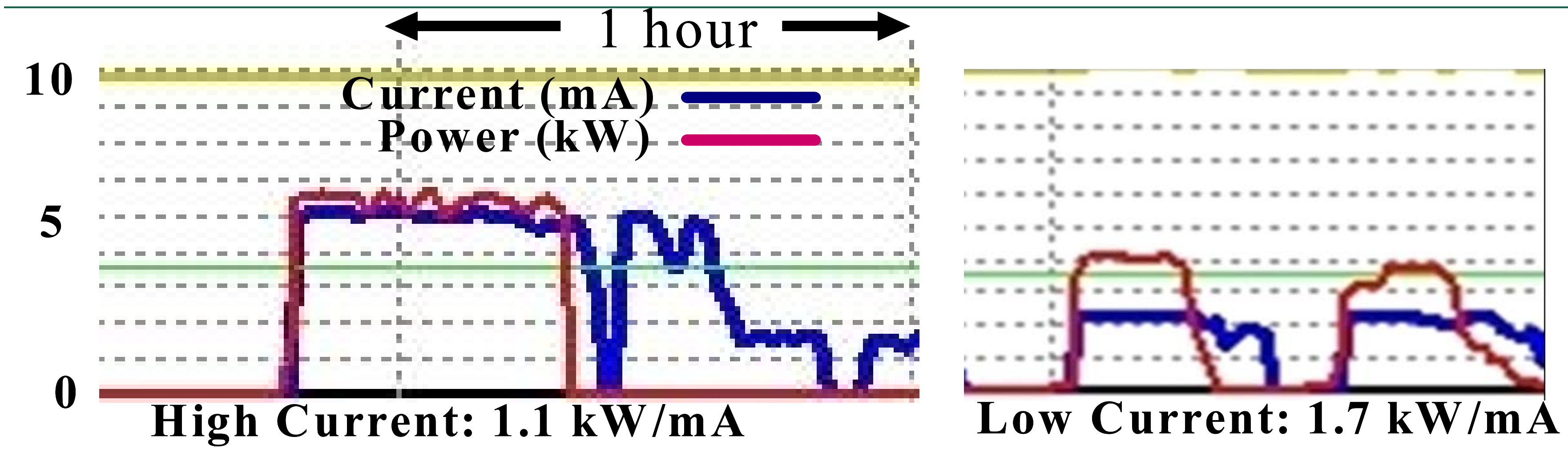
- 10 kW average power lasing achieved at 6 microns
- Lased 2 to 7 kilowatts at 1.0, 1.6, 2.8 microns with narrowband mirrors
- Lased at 20-100 W from 0.7 to 4.8 microns, tuning over the full band in seconds using hole outcoupler
- THz and Laser User experiments



Stable, reproducible operation at 115 MeV

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

JLab Experience



FEL Physics

- Power has been limited due to a roll off in efficiency at high powers. The cause of this is still under investigation

Accelerator Physics

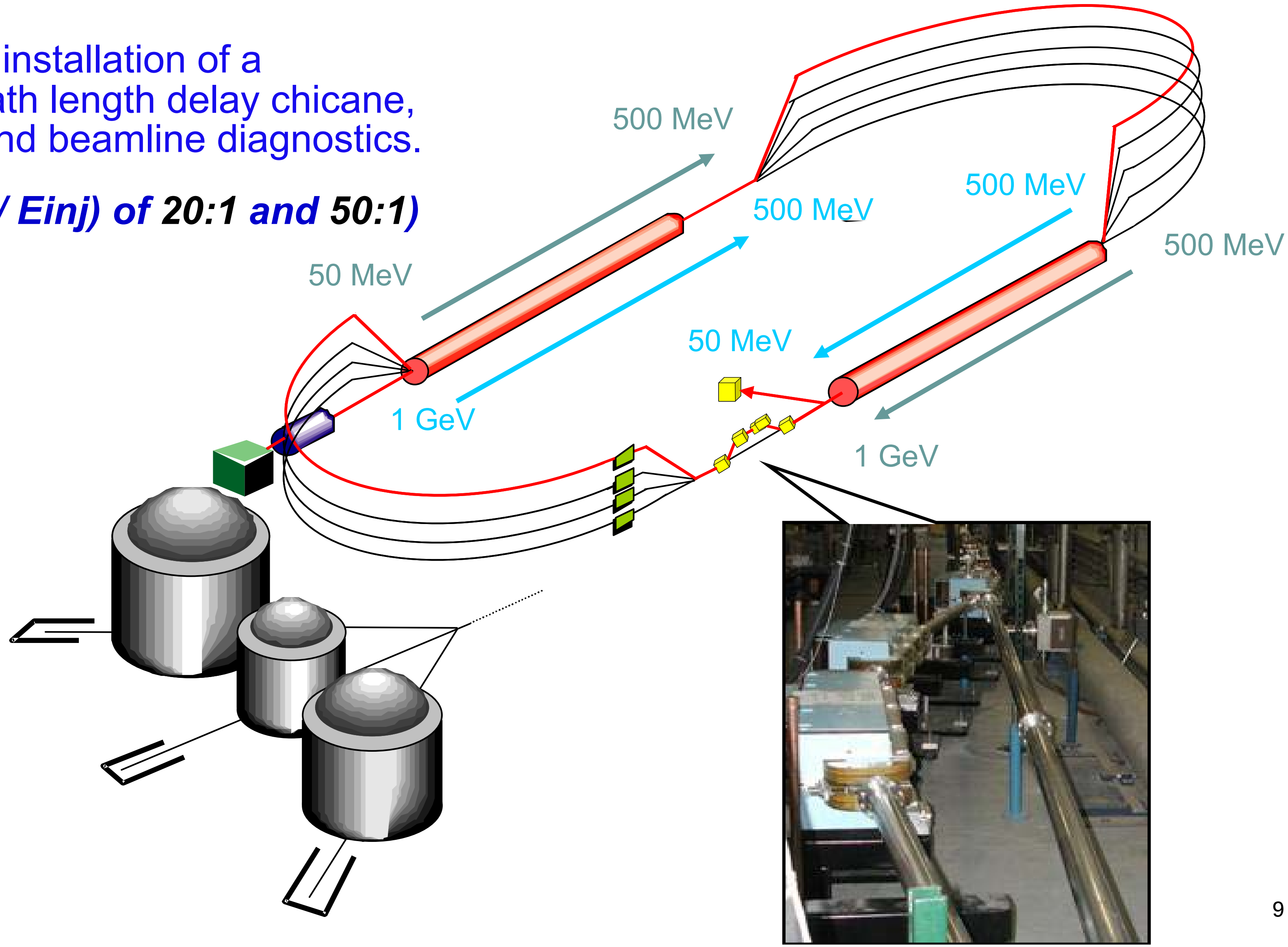
- BBU characterization and suppression, linac control, beam loss, halo etc. etc.

CEBAF-High energy demonstration of ER

Jefferson Lab

Special installation of a $\lambda_{RF}/2$ path length delay chicane, dump and beamline diagnostics.

(Efinal / Einj) of 20:1 and 50:1)



Summary

Exisiting ERL oscillator ERLs are excellent demonstrators of the ERL principle.

- CW Average currents of up to ~10 mA (20 mA at high emittance)
- High repetition rates:-75 MHz
- High efficiency > 99.97%
- Stable user operation
- High average photon power

Test bed for future ERL based sources (including CBAF...)

- Bench mark physics studies / simulations
  - BBU, space charge, wakefields, longitudinal gymnastics ...
- FEL design and modelling
- SC linac control & operational experience
- Diagnostics
- Halo
- Beam loss and aperture

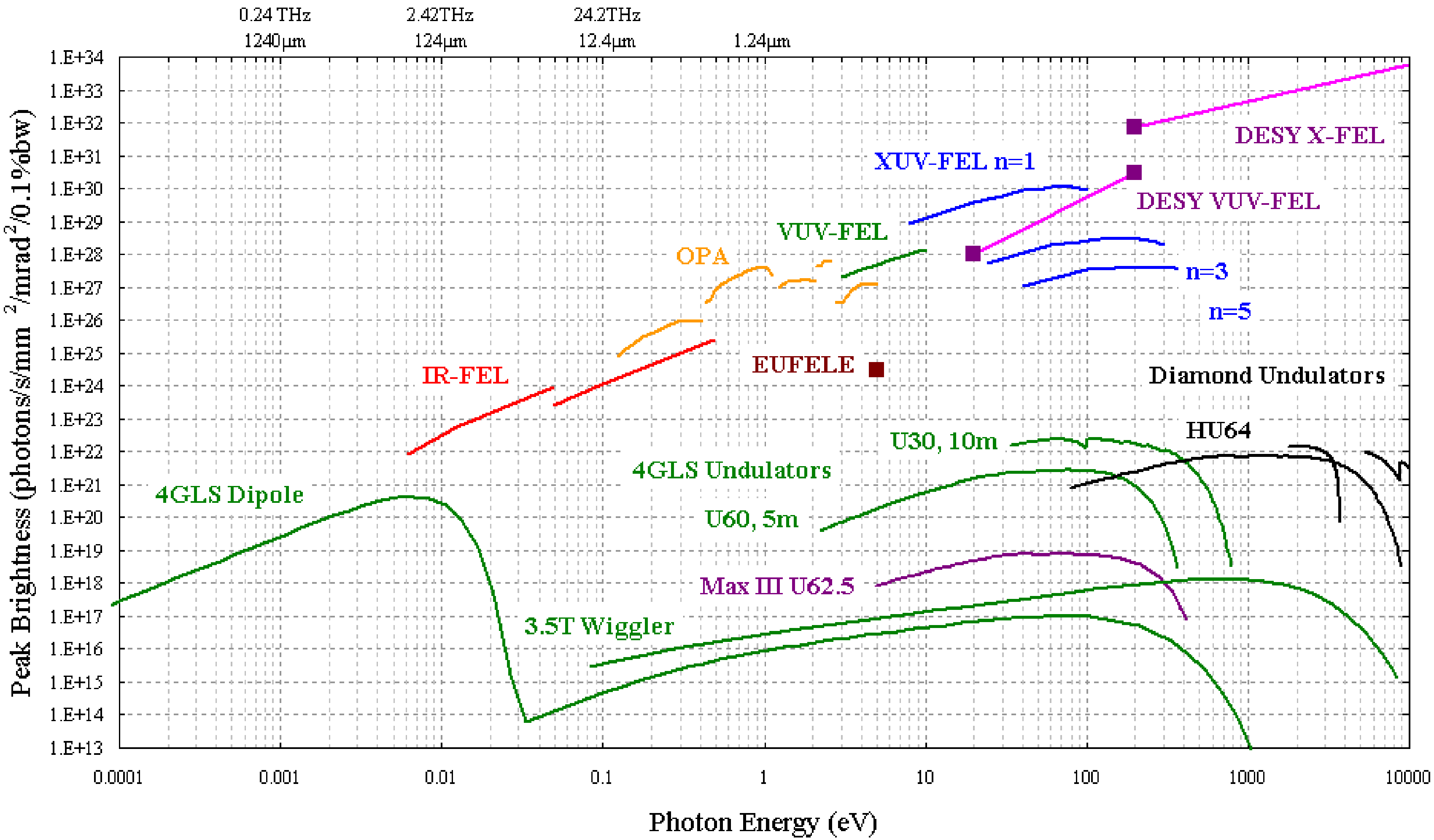
Producing world leading sources of THz and IR

"Proposed" ERL Light Source Projects projects

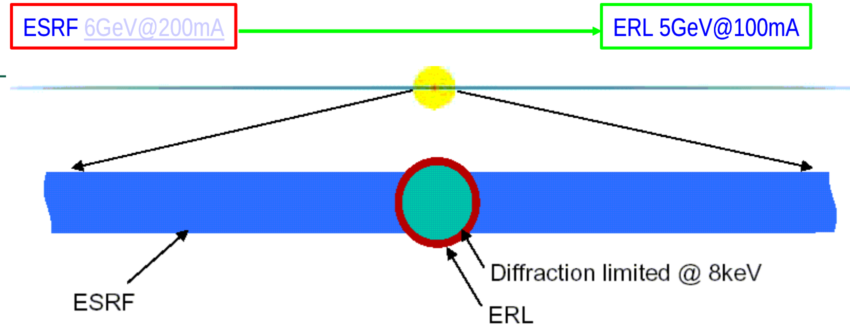
- **Oscillator FEL**
  - Kaeri Similar to JAERI FEL
  - National High Magnetic Field Laboratory (Florida)
  - PK-FEL 30-40 MeV, 1 mA (avg), 5 mm mrad (TESLA cavities in Stanford/Rossendorf module c.f. ERLP)
  - JLab 100 kW IR-FEL
- **High Gain FELs**
  - 4GLS (not in the energy recovery loop)
  - BESSY II , X-FEL , LUX (all have mentioned ERL options)

  Repetition rates are currently generally low enough to make the complexity of recovery un-attractive
- **Spontaneous Emission**
  - MARs
  - Cornell 5 GeV X-Ray ERL
  - KEK 5GeV ERL
  - JAEA 6GeV ERL at Naka site
  - APS
  - ARC-EN-CIEL SACLAY (similar to 4GLS)
  - 4GLS Daresbury ...

Why ERLS?


0.24 THz
1240μm
2.42THz
124μm
24.2THz
12.4μm
1.24μm
Peak Brightness (photons/s/mm²/mrad²/0.1%bw)
1.E+34
1.E+33
1.E+32
1.E+31
1.E+30
1.E+29
1.E+28
1.E+27
1.E+26
1.E+25
1.E+24
1.E+23
1.E+22
1.E+21
1.E+20
1.E+19
1.E+18
1.E+17
1.E+16
1.E+15
1.E+14
1.E+13
DESY X-FEL
XUV-FEL n=1
DESY VUV-FEL
VUV-FEL
OPA
n=3
n=5
EUFELE
IR-FEL
Diamond Undulators
HU64
U30, 10m
4GLS Undulators
4GLS Dipole
U60, 5m
Max III U62.5
3.5T Wiggler
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
Photon Energy (eV)

X-ray ERL e.g. Cornell



courtesy Ivan Bazarov

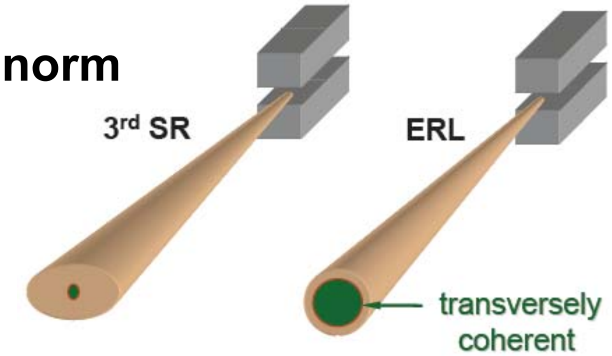
High flux

100 mA, 2 ps, 77 pC, norm emitt 0.3 mm mrad

25m undulators, small gap, short period undulators

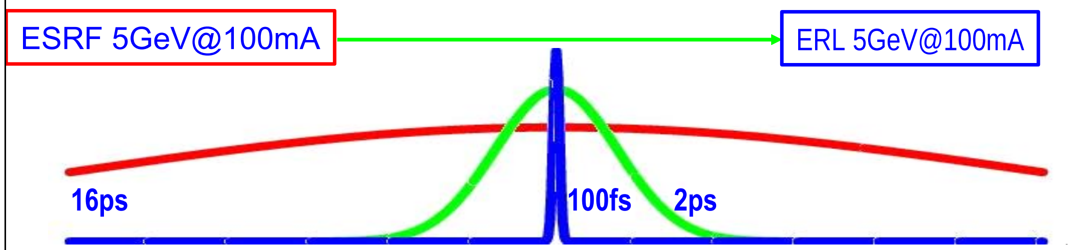
High coherence mode

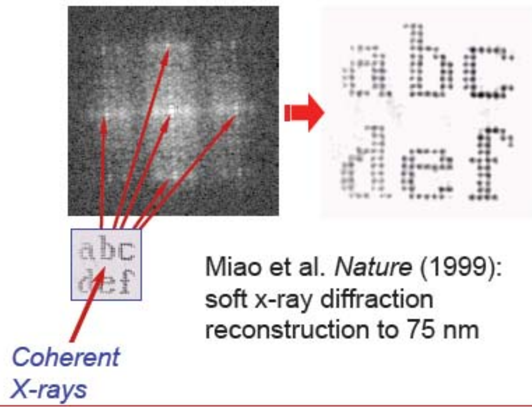
25 mA, 2 ps, 19 pC, norm emitt 0.08 mm mrad



Ultra fast

1 mA, 50 fs, 1000 pC, norm emitt, 5 mm mrad

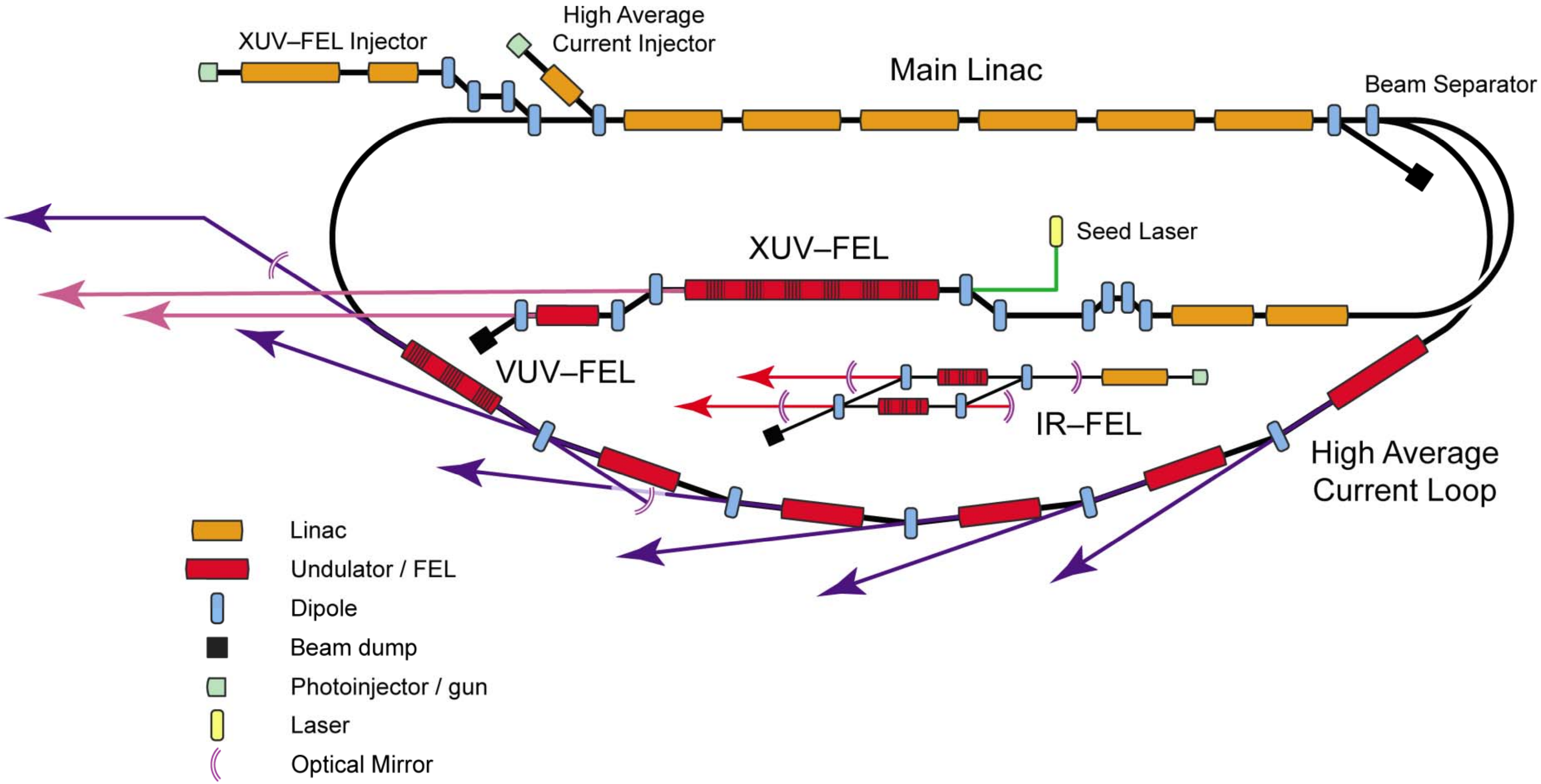




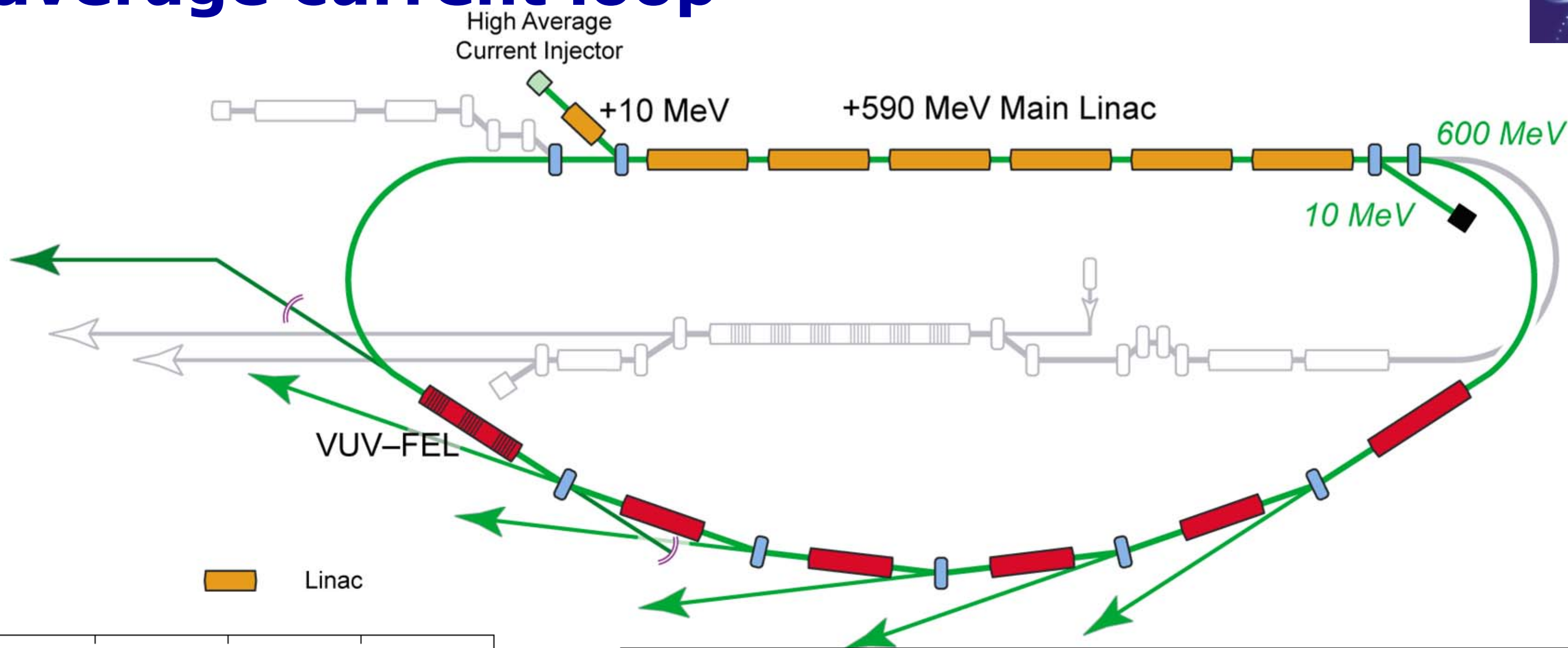
Miao et al. *Nature* (1999): soft x-ray diffraction reconstruction to 75 nm

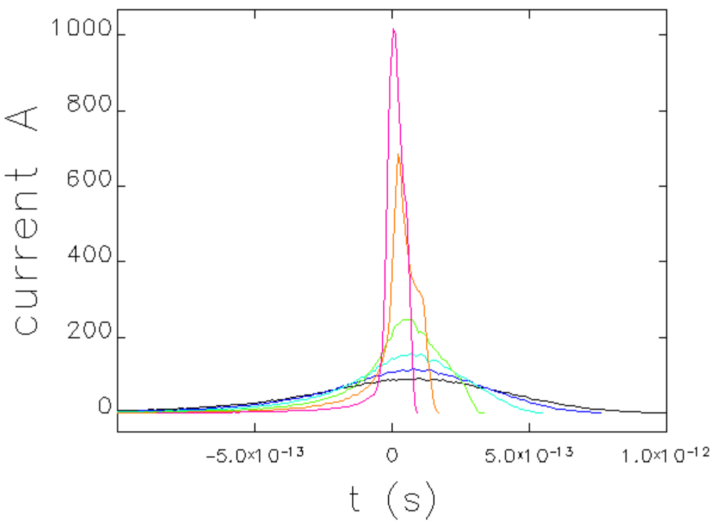
Challenges of future ERL light sources

Conceptual Layout of 4GLS



High average current loop





HACL Bunch Parameter	100 mA Operation	VUV-FEL Operation
Energy at Source	600 MeV	600 MeV
Normalised emittance	2 mm mrad	2 mm mrad
RMS Projected Energy Spread	0.1 %	0.1 %
RMS Bunch Length at Device	100-900 fs in 6straights	100 fs
Bunch Charge	77 pC	77 pC
Bunch Repetition Rate	1.3 GHz	n x 4.33 MHz
Beam Power at 600 MeV	60 MW	n x 200 kW
Injector Energy	10 MeV	~ 10 MeV
Dump Energy	~ 10 MeV	~ 10 MeV

Bunch profiles at each of the ID straights, with CSR.

Challenges: Generation of low emittance beams

- **Photoinjectors**
  - 77pC, 1.3 GHz (100mA) **has never been built before**
    - Even more demanding laser
    - DC version has issues with power supply, high voltages
    - 100 mA photocathode (short pulses)
    - SCRF version has issues with photocathodes
    - Other groups are active: Cornell, BNL & JLab…..
  - 1nC, 1kHz **has never been built before**
    - Demanding laser
    - Thermal problems from RF losses
    - Other groups are active: BESSY/DESY & LBNL ….

Challenges: SCRF Accelerators

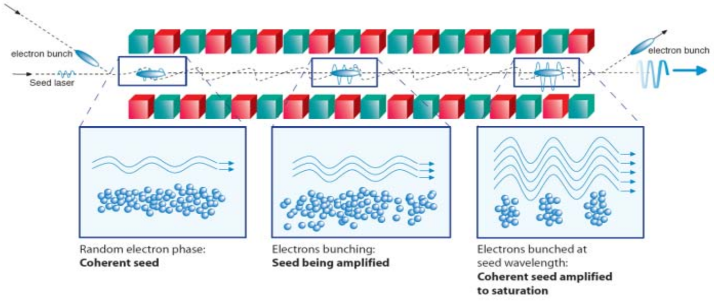
- High input powers (10MeV, 100mA = 1MW)
- Three distinct beams in main linac
- Complex pulse trains
- Beam loading
- Need to minimise HOMs & extract power at correct temperature – Beam Break Up
- Phase and amplitude control: 0.01°, 0.01% :- state of the art
- Large scale cryogenics

Challenges: Electron Beam Transport

- Preservation of small emittance
- Generation of <<ps bunches at the correct locations, longitudinal gymnastics
- Minimisation of instabilities (CSR, wakes, ...) – long bunches!
- Merge and separation of different beams
- Minimise losses
  - Collimation
  - **60 MW beam power –** ILC is 11 MW !
- 1MW Dump
- Diagnostics
- Tuning

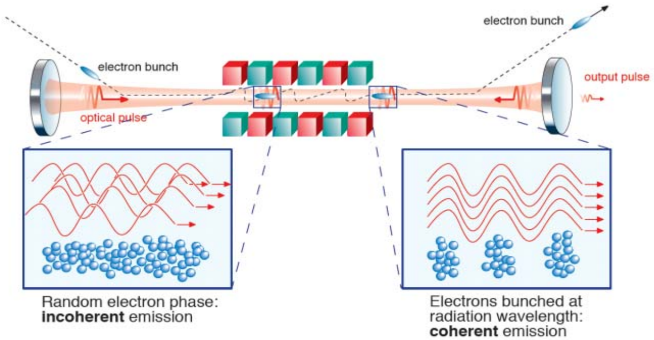
Challenges: FEL design

1



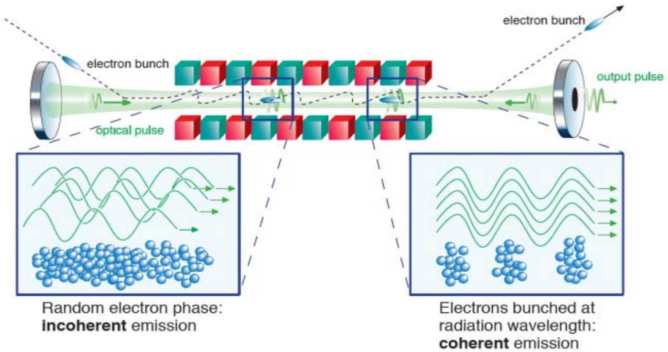
- Single pass seeded amplifier
- eXtreme Ultra Violet Seed laser (state of the art HHG system)
- Undulator tolerances very demanding

2



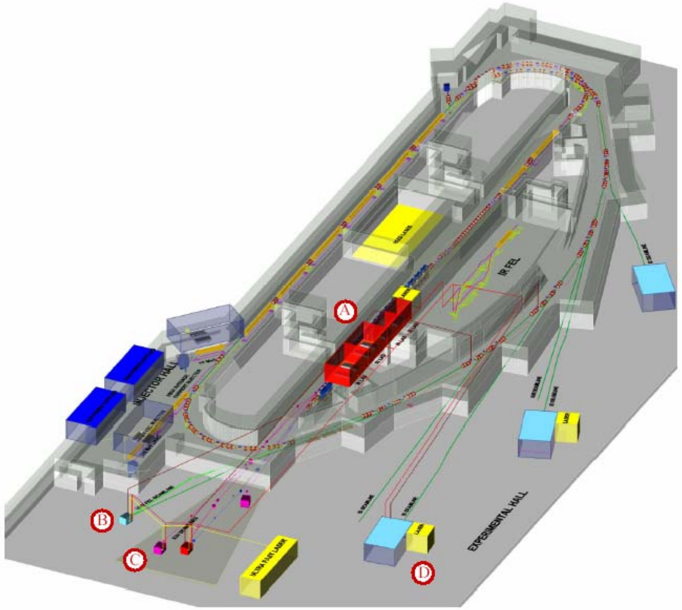
Low Q cavity (Vacuum Ultra Violet)
Mirrors withstand high peak powers

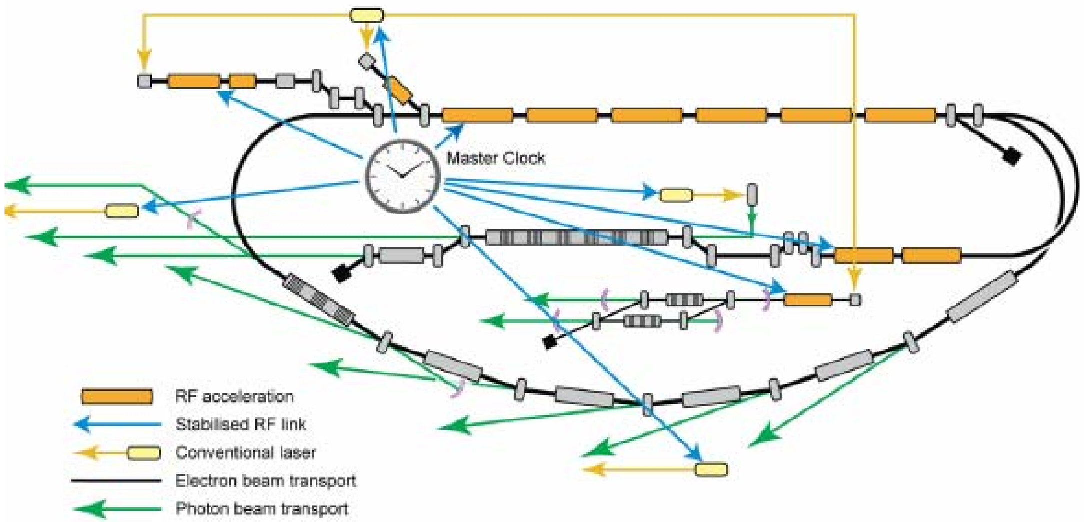
3



High Q cavity (Infra Red)

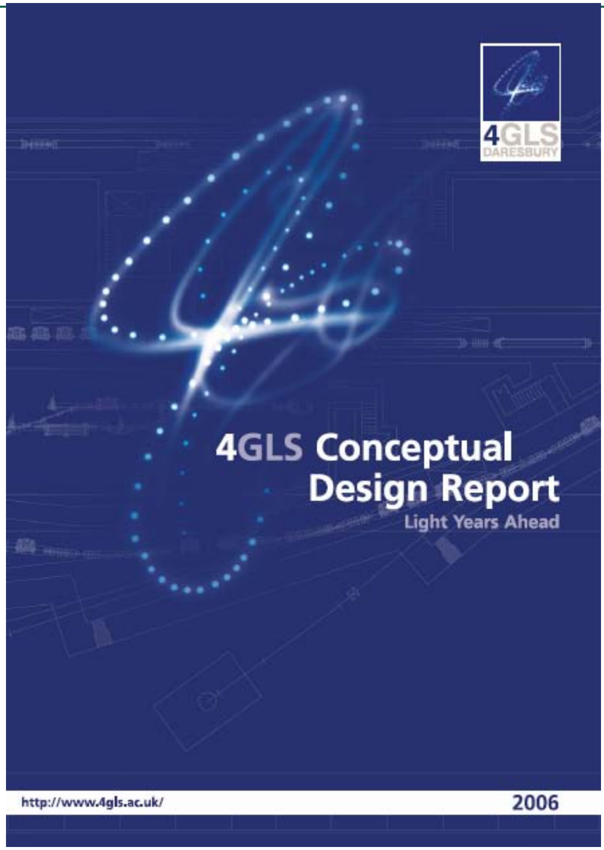
Challenges: Combining Sources



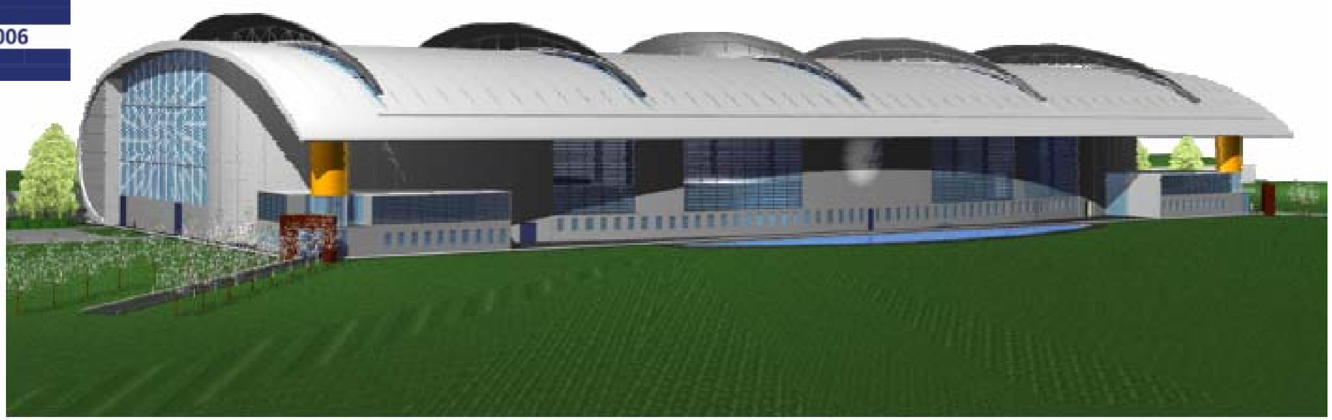


- **Timing & Synchronisation**
  - All combined sources to have synchronisation better than 100fs
  - Particular combinations require 10fs
  - Many sources of jitter
    - Laser
    - RF signals
    - RF acceleration
    - Electron transport
    - Photon transport

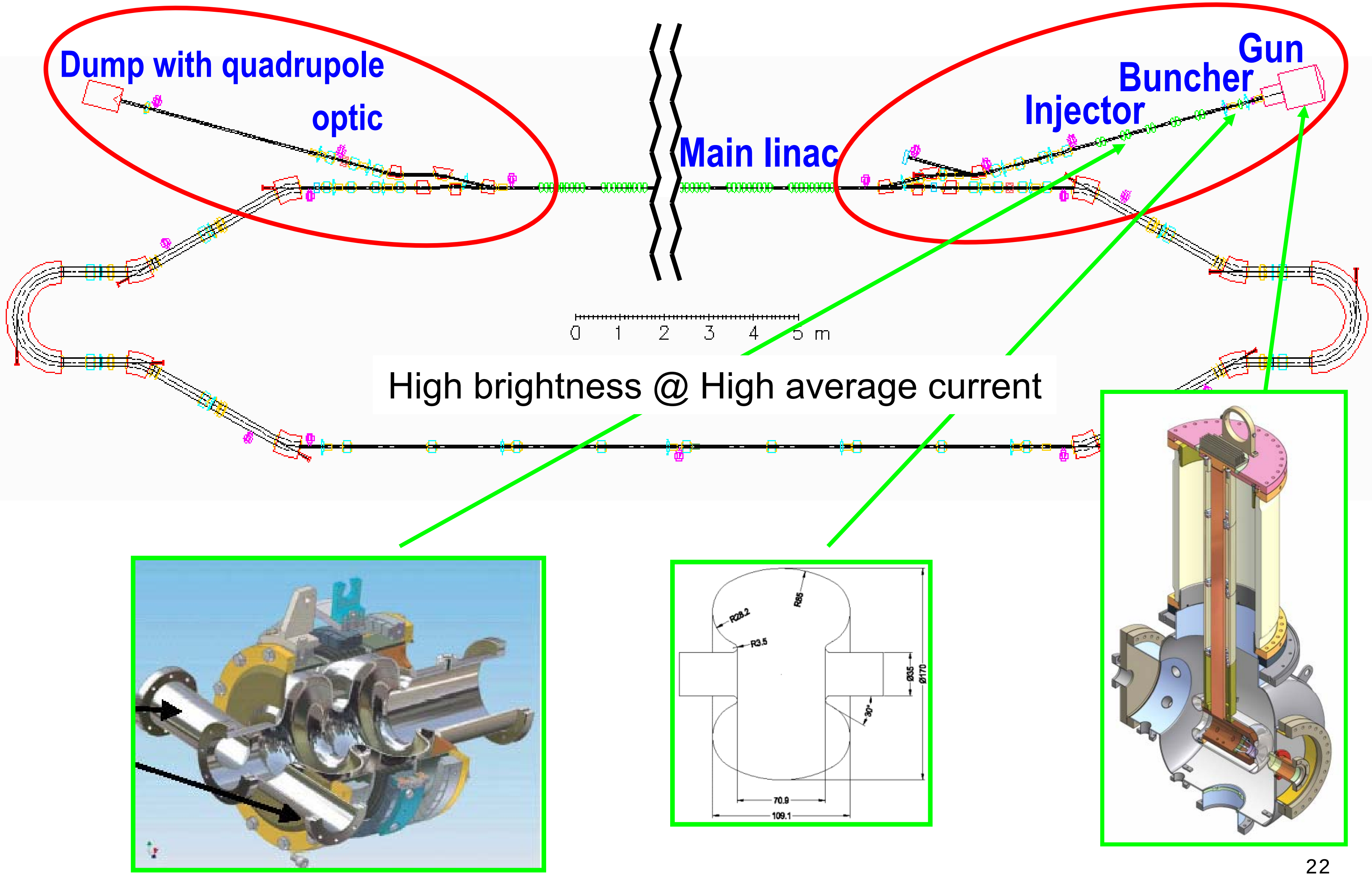
www.4gls.ac.uk



- 2003 Prototype design/build
- ERLP Commissioning (2006-2007)
- 4GLS CDR April 2006 **www.4gls.ac.uk**
- Technical design phase 2007-8
- Prototyping (SCRF, Photoinjector)
- Bid for 4GLS funding 2007/2008
- Construction 2008 – 20012/13



Cornell ERL Injector Prototype Project



High brightness @ High average current

DC Photoinjector

CORNELL UNIVERSITY

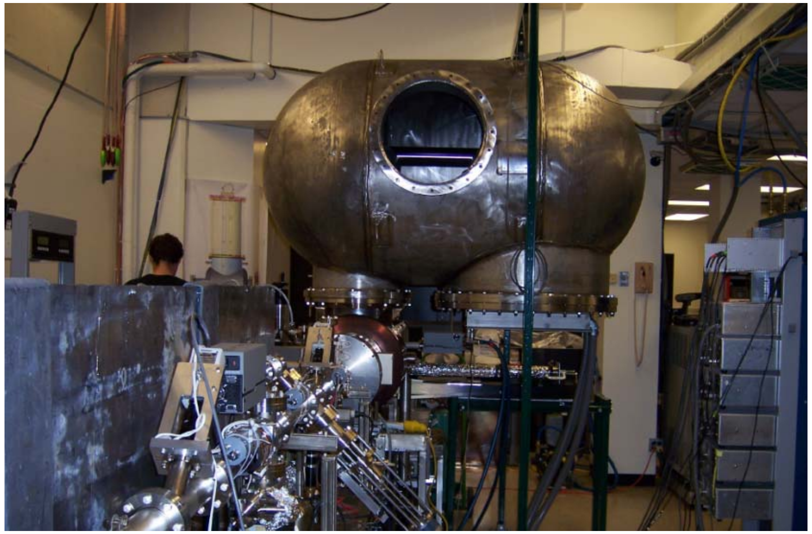
Simulations normalized r.m.s. emittances < 0.1 mm-mrad ,77 pc/bunch, I = 100 mA.

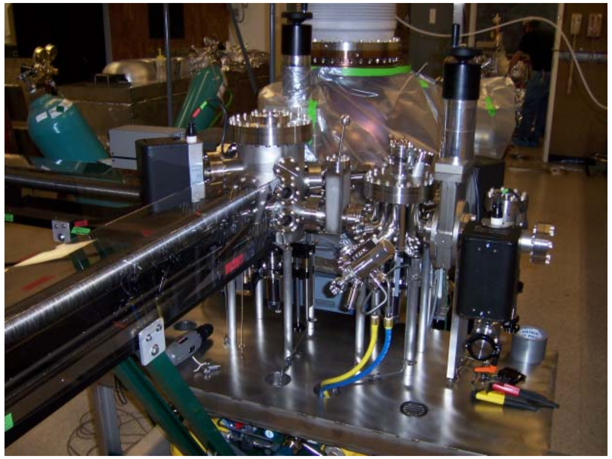
(Bazarov et al., Phys. Rev. ST-AB **8**, 034202 (2005))

Yb fiber laser 100 nJ/micro pulse

750 KeV 100 mA supply in Autumn

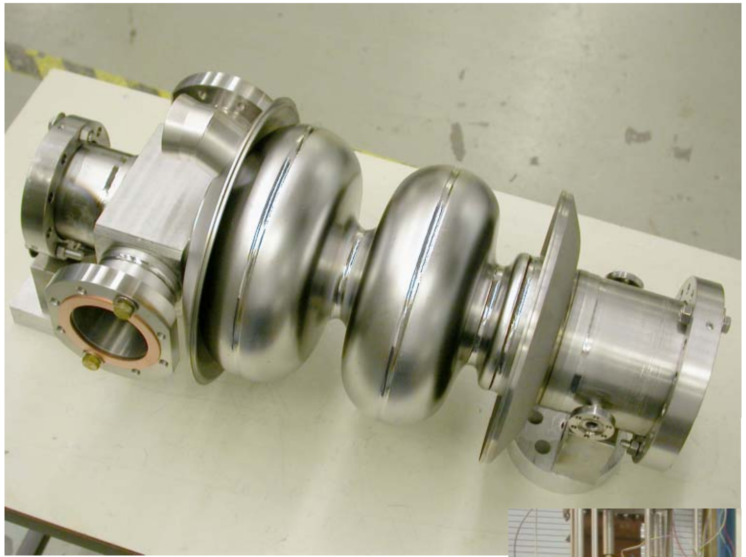
NEA GaAs and GaAsP cathodes >17% QE





The photocathode load lock and preparation system, with translation mechanisms

Two cell SRF cavity



75 kW beam dump constructed

575 kW required for full injector test

Beam diagnostics challenging design are in progress.

>120 kW, e2v klystrons, efficiency >50%, RF testing soon

Two ports, coupler power ~50 kW, two tested soon

1st successful vertical test of 2 cell cavity

Fabrication of five cavities (tests by next year)

Horizontal test of complete assemblies early next year

Cornell ERL Injector Prototype Project

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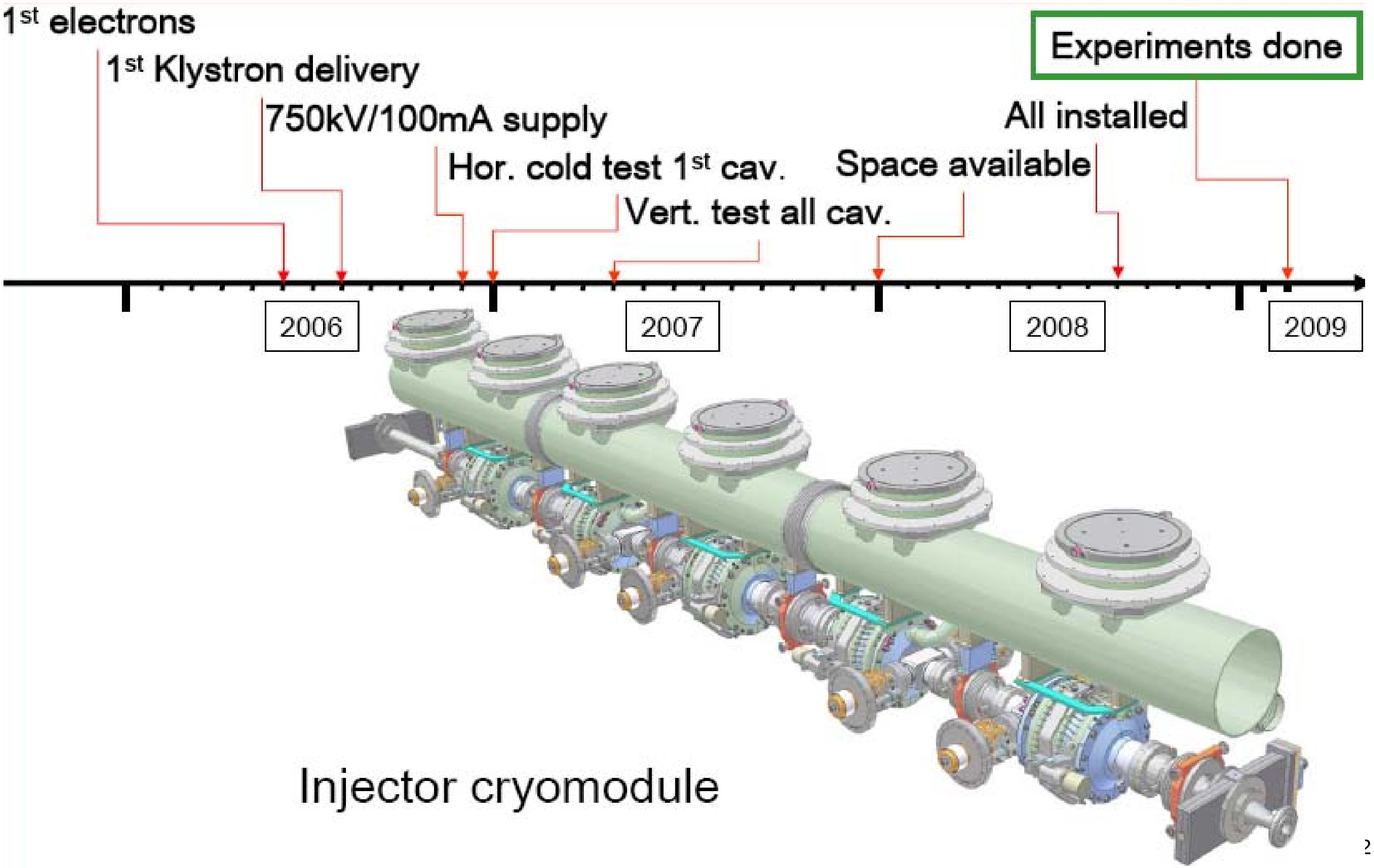
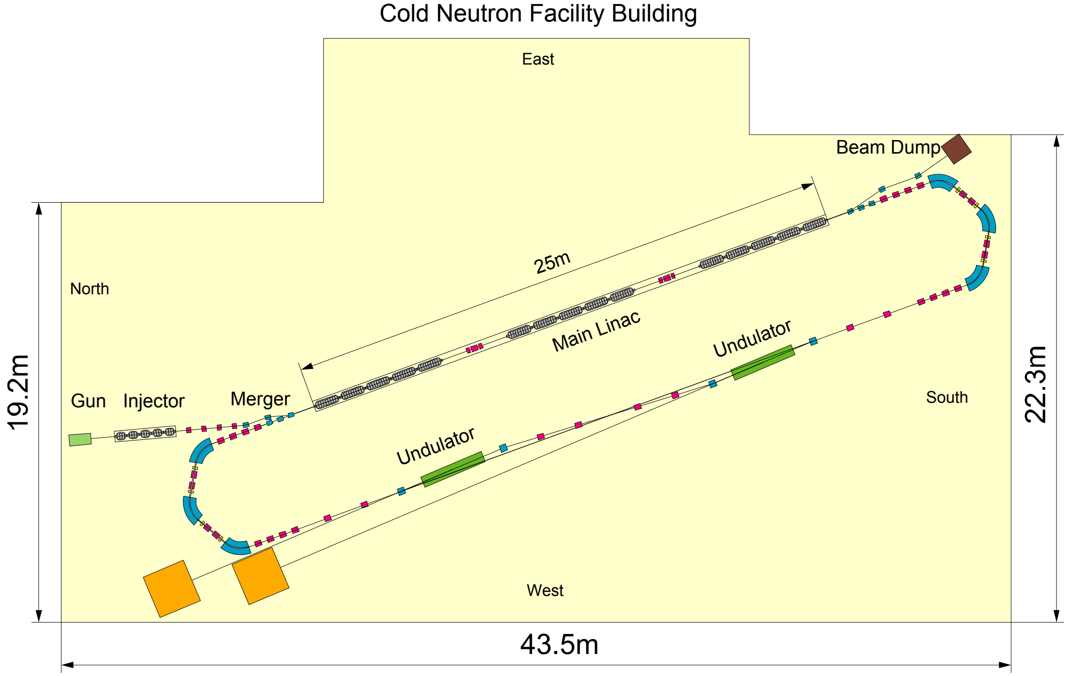
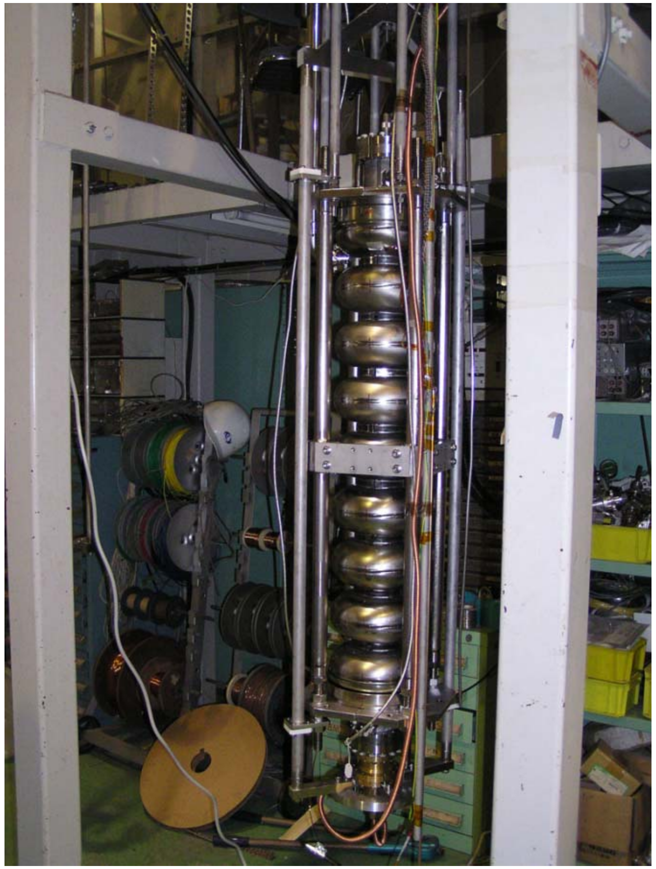


KEK-JAEA Test Facility

Preliminary plan of ERL test facility at KEK





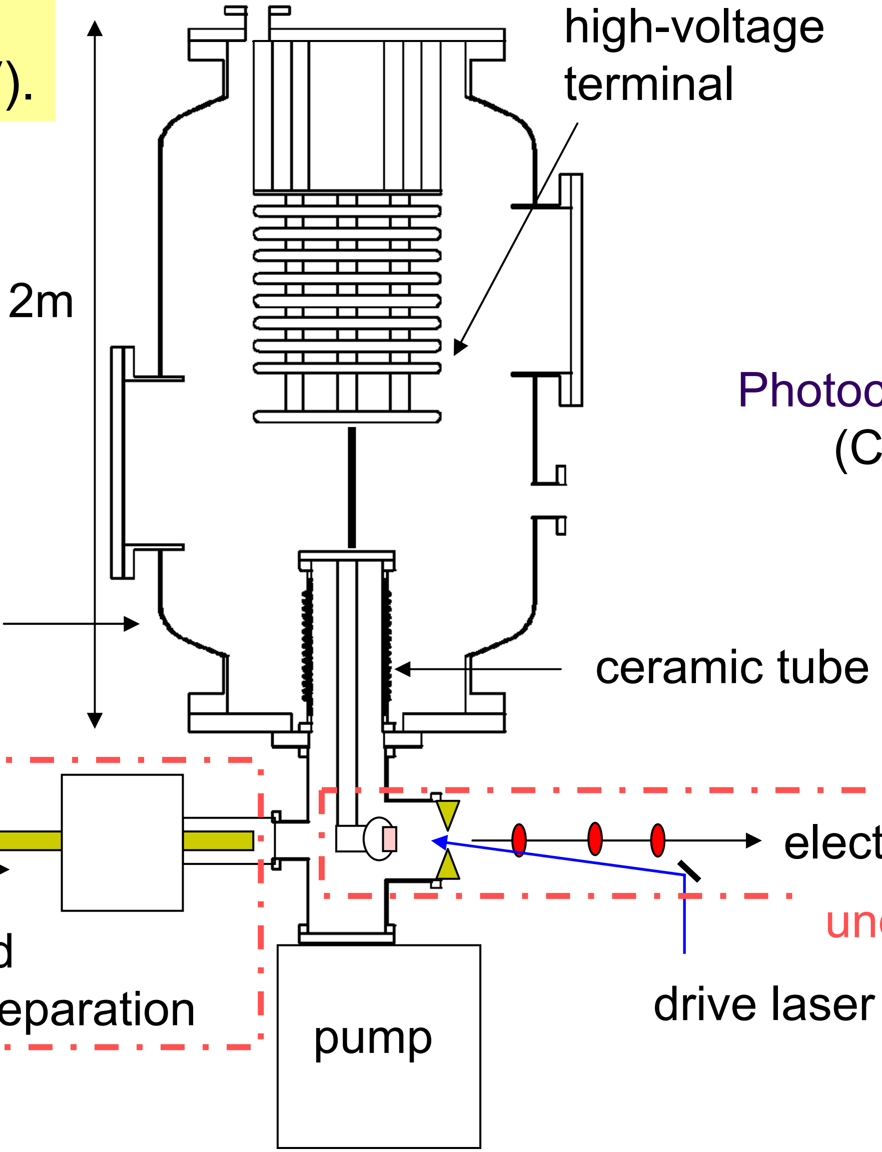
Tentative parameters of the ERL test facility

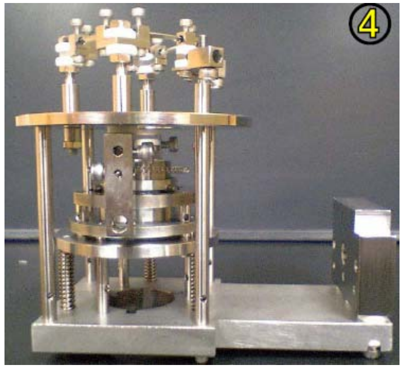
Beam current	100 mA
Injection energy	5 MeV (up to 15 MeV at lower currents)
Beam power at injector	500 kW
Normalized emittance	1 – 0.1 mm·mrad (initially, larger)
Beam energy at main linac	60 – 200 MeV (increase step by step)
Bunch length (rms)	~ 100 fs (short bunch mode)

Close collaboration with Superconducting Test Facility (STF) team at KEK.

Development of a DC gun

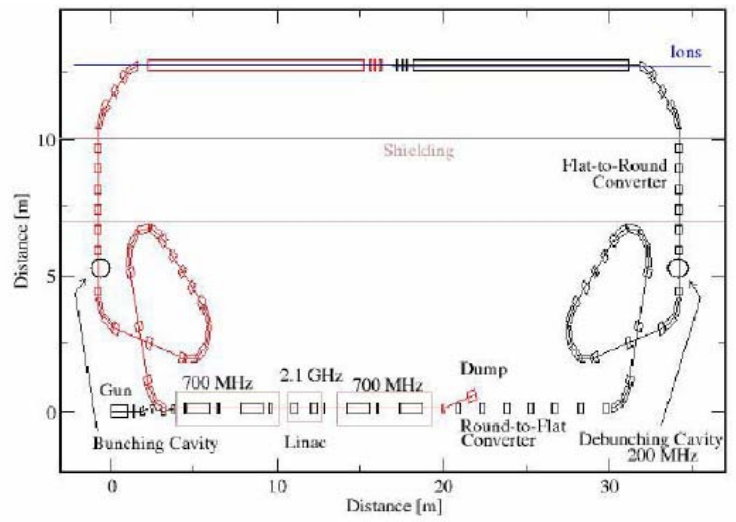
high-voltage test
was completed (245kV).

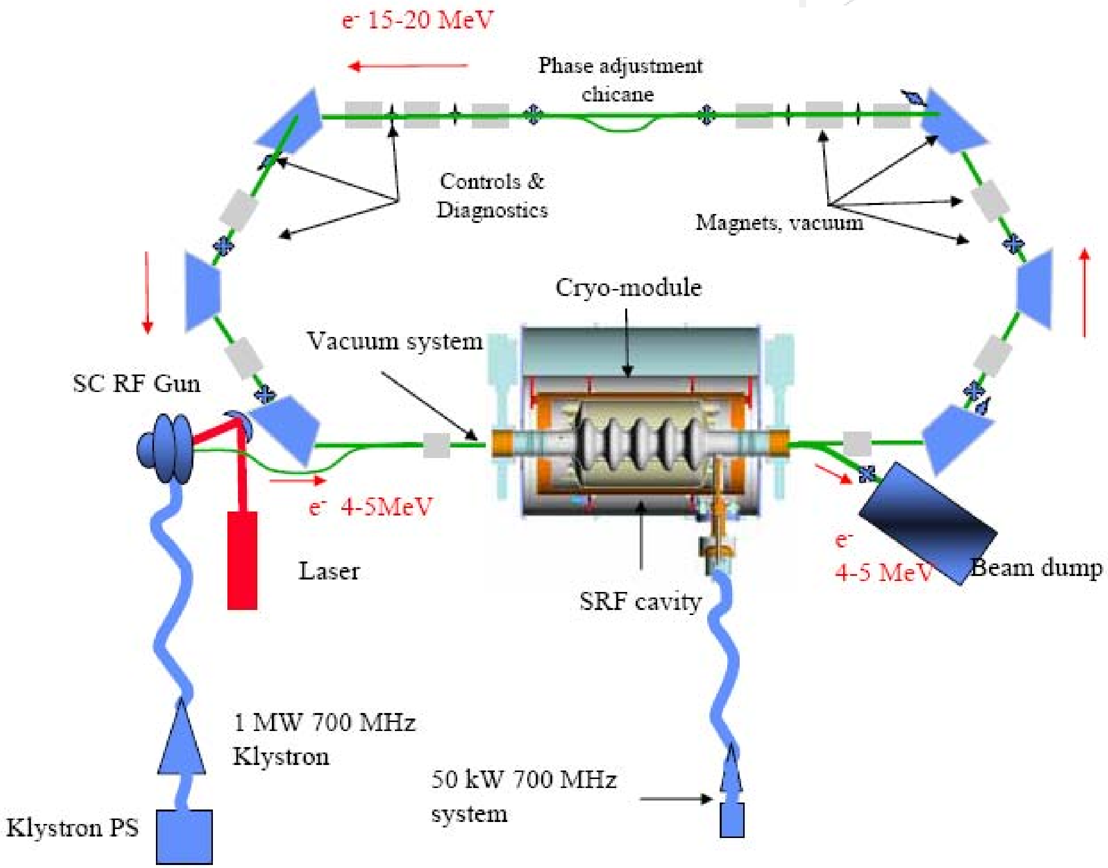




Photocathode Test Bench
(Cathode holder)

BNL Test Facility





RHIC electron cooler is based on a 200 mA, 55 MeV ERL
20 nC per bunch, 9.4 MHz

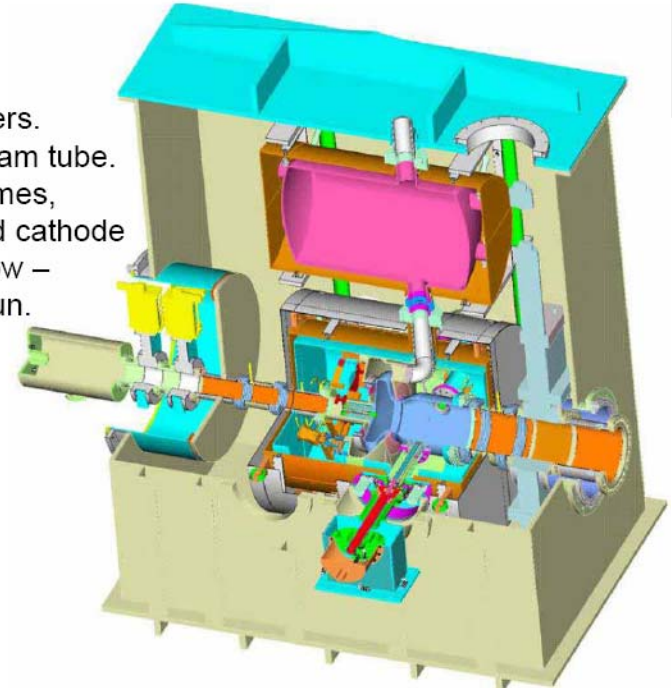
The prototype ERL (20-25 MeV) is still under construction with plan for commissioning in 2008 (linac tests later this year).

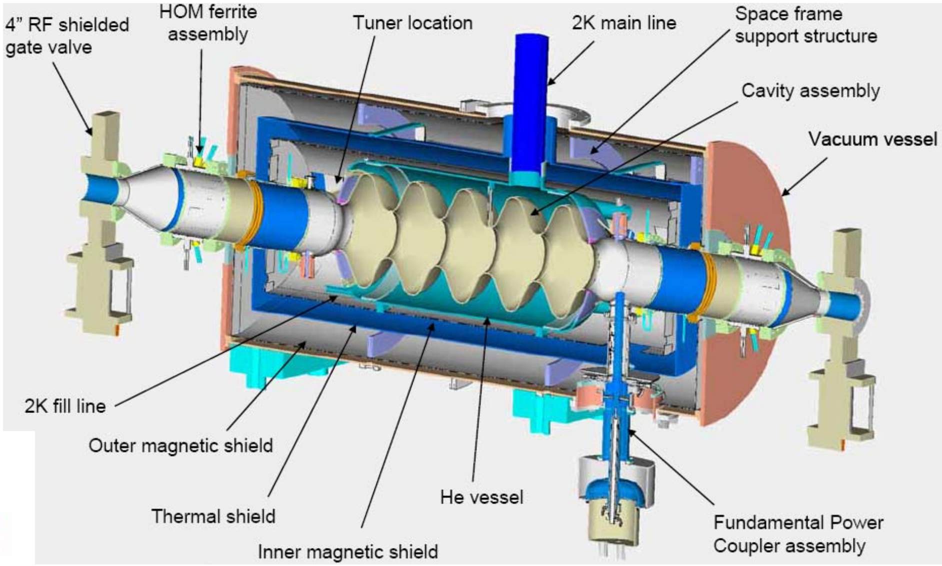
Superconducting RF Photoinjector

RF SC Photo injector

703.75 MHz gun.
2x0.5 MW input couplers.
HOM damping thru beam tube.
Various cathode schemes, including encapsulated cathode behind diamond window – isolation cathode ↔ gun.

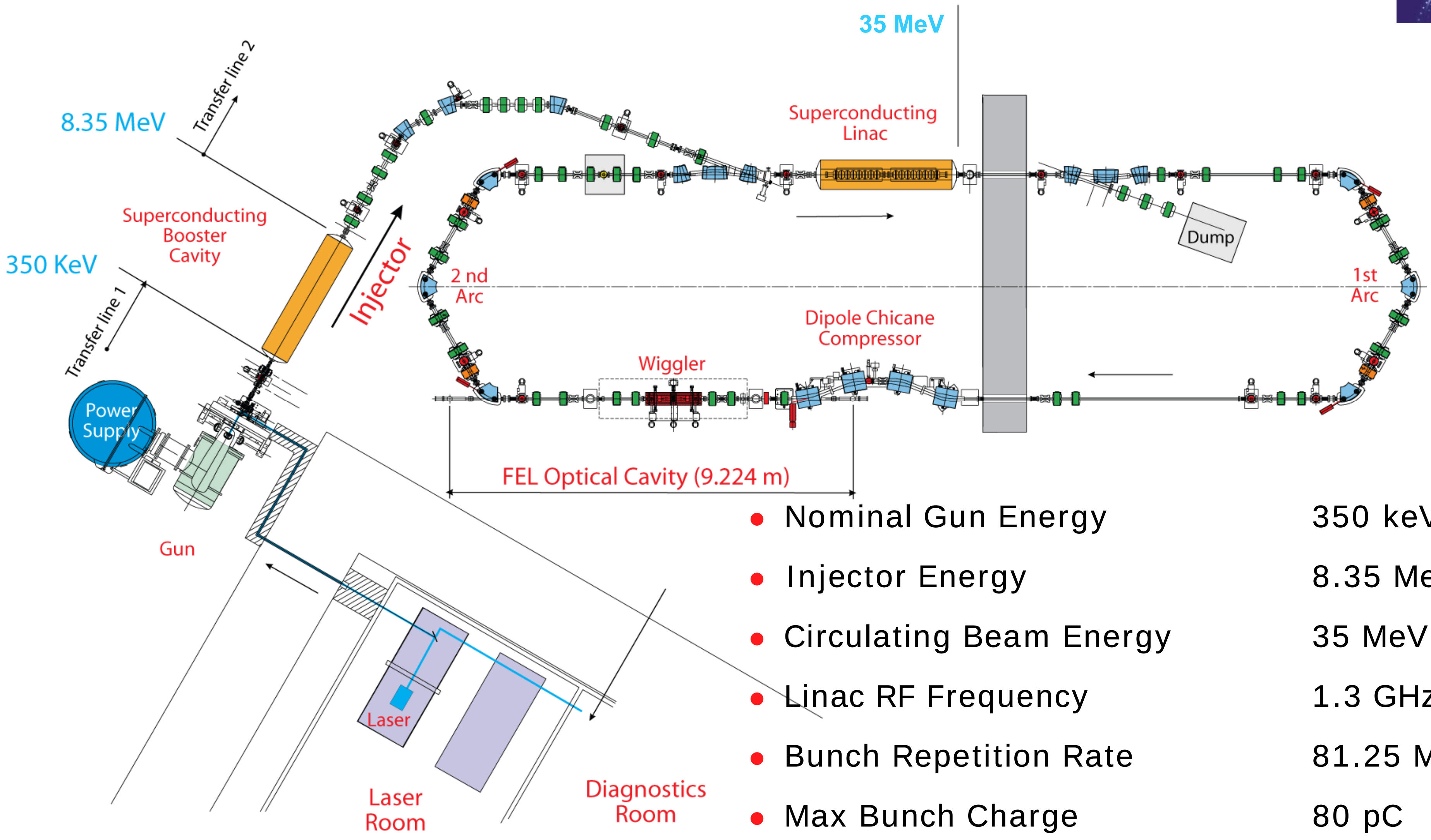
CW performance
0.5 ampere @ 2 MeV.





703.75 MHz Module

Energy Recovery Linac Prototype (ERLP)



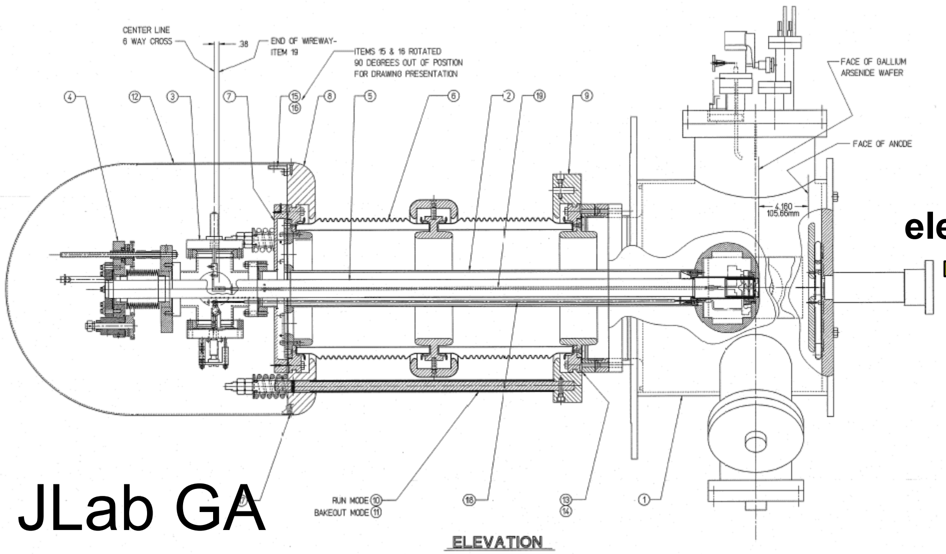
Nominal Gun Energy	350 keV
Injector Energy	8.35 MeV
Circulating Beam Energy	35 MeV
Linac RF Frequency	1.3 GHz
Bunch Repetition Rate	81.25 MHz
Max Bunch Charge	80 pC
Max Average Current	13 μA

Photoinjector Laser

- Wavelength: 1.05µm, multiplied to 0.53µm/0.26µm (NdYvanadate)
- Pulse energy: 80nJ on target
- Pulse duration: 10ps FWHM
- Pulse repetition rate: 81 MHz
- Macropulse duration: 20 ms
- Duty cycle: 0.2%
- Timing jitter: <1ps
- Spatial profile: circular (top hat) on photocathode

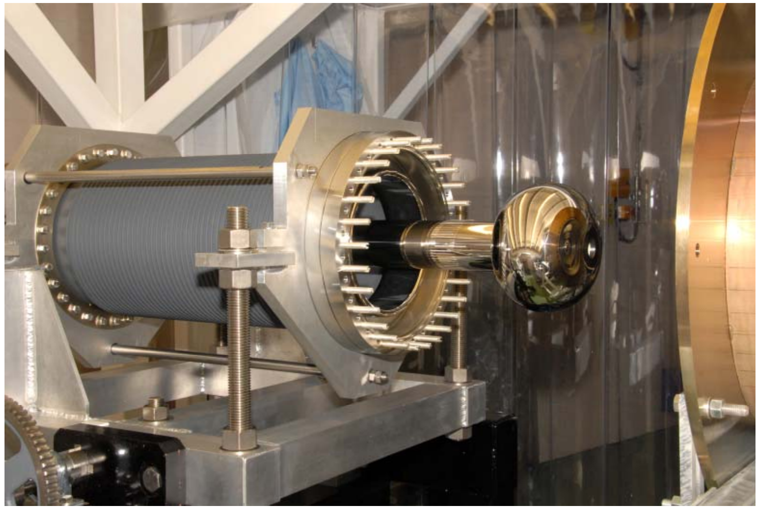
Laser system commissioned 2005

Gun



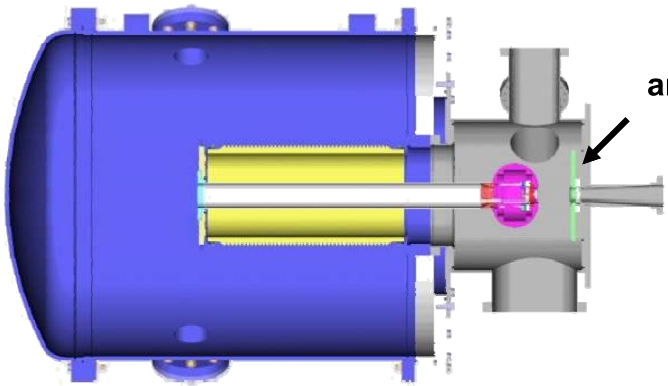
JLab GA

electrons



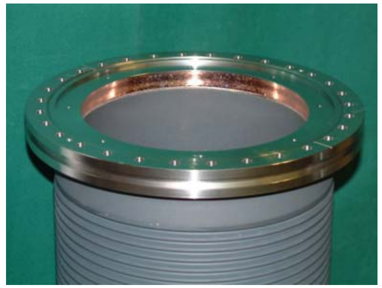
Gun ceramic – major source of delay – at Daresbury (~1 year late)

transverse emittance
~3 mm mrad



anode

electrons

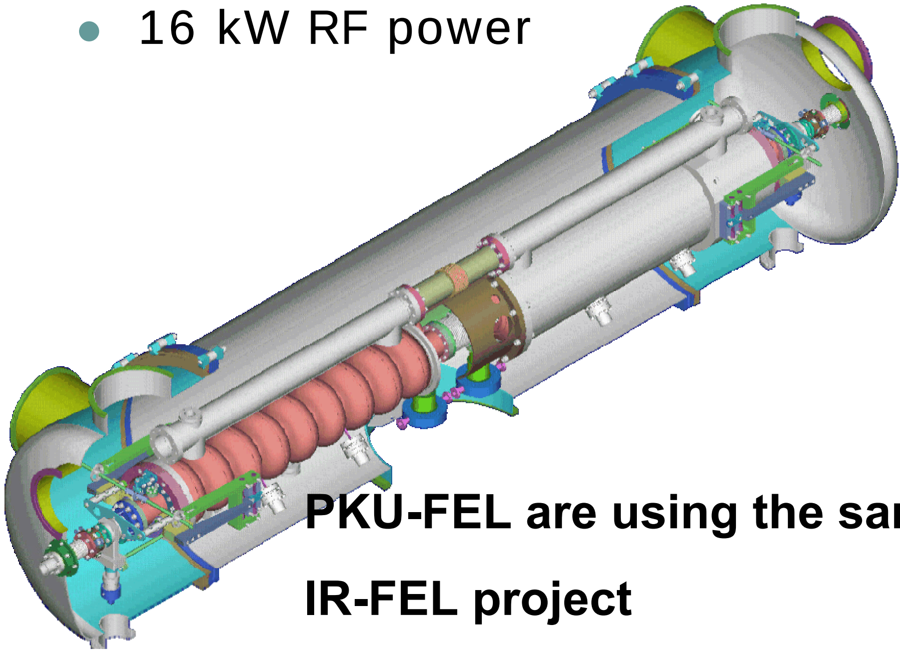


Superconducting Modules

- 2 x Stanford/Rossendorf cryomodules – 1 Booster and 1 Main LINAC.
- Booster module:
  - 4 MV/m gradient
  - ~50 kW RF power
- Main LINAC module:
  - 14 MV/m gradient
  - 16 kW RF power

Delivery April/July 2006 (~7 months late)

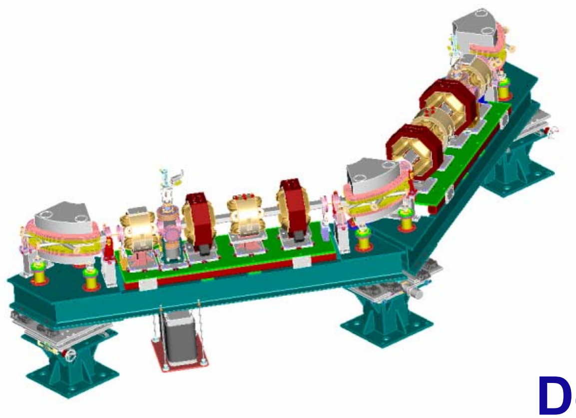
JLab HOM coupler design adopted for the LINAC module



PKU-FEL are using the same modules for their IR-FEL project

Status

Laser system ready
RF power supply under test on site
Gun ceramic – major source of delay – at Daresbury (~1 year late)
Accelerator modules arrive April/July 2006
4 K commissioning May 06
Gun commissioning August-October 06
2K commissioning November 06
Complete machine ready December 06
Energy Recovery Spring 07
Exploitation 2007……



Coming soon

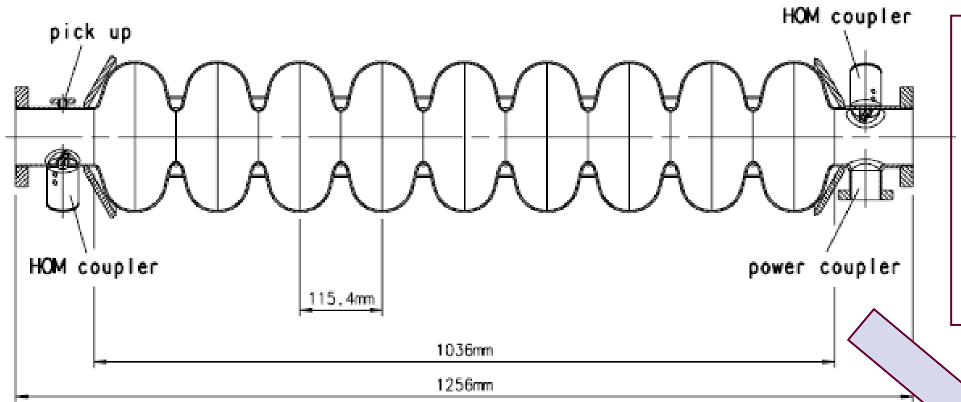
ERLP @ Daresbury

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

ERL Cavity/Cryomodule Collaboration

CCLRC Daresbury. Cornell, LBNL, FRZ Rossendorf

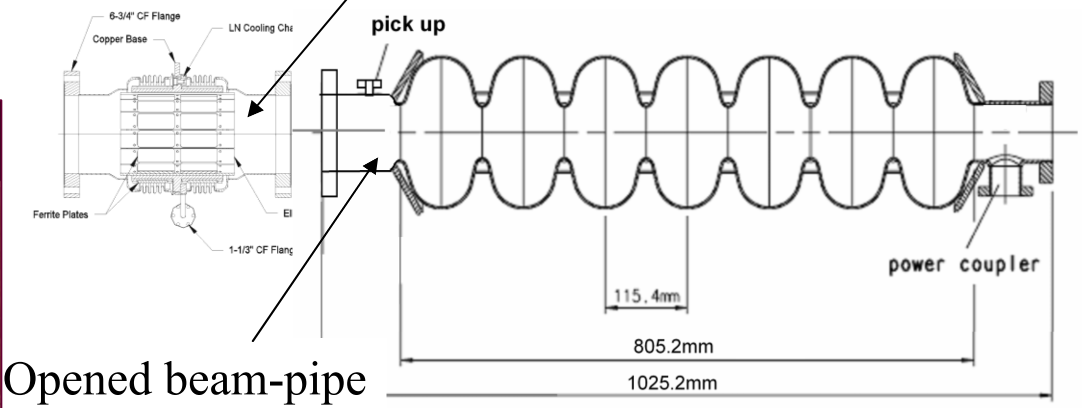
TESLA/TTF 9-cell SRF Cavity



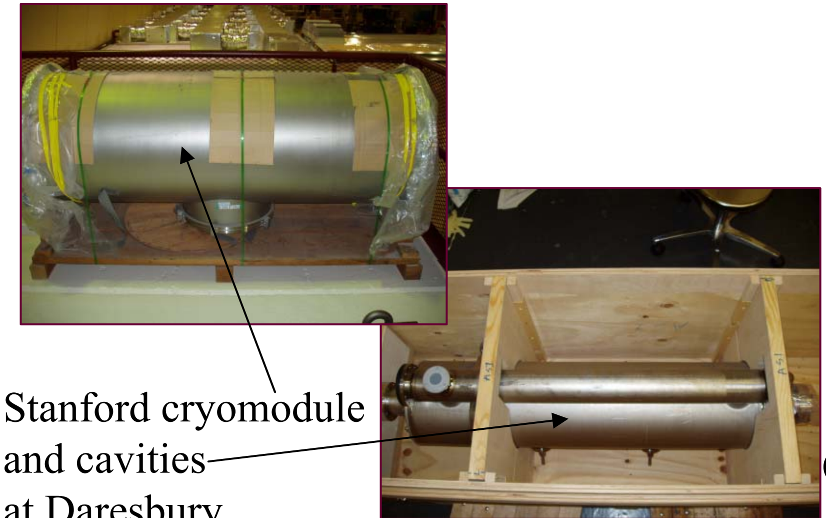
Modified 7-cell SRF Cavity

CW-mode operation ⇒ improved He delivery
Reduced loss factor
Reduced HOM contribution
Larger HOM dissipation capacity
Larger RF power capability

80K HOM absorber



Opened beam-pipe



Stanford cryomodule
and cavities
at Daresbury

Installation on the Daresbury ERLP 2008

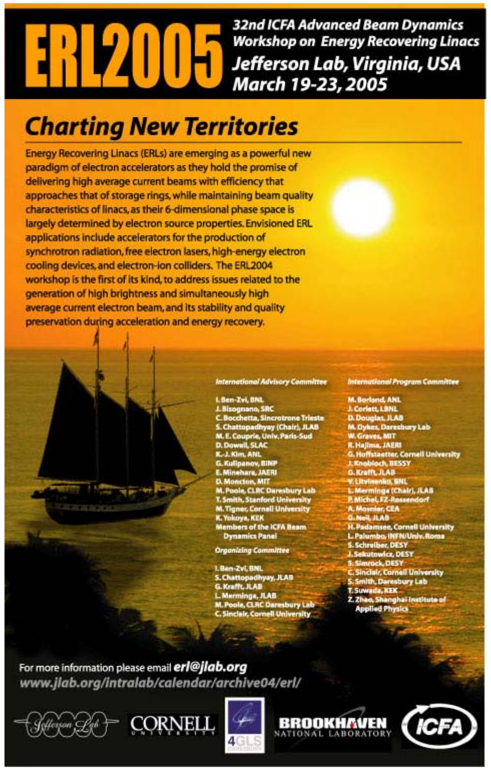
Conclusions /Outlook

- Operating ERL light sources have proven the principle and continue to push the bounds of performance providing valuable experience.
- R&D toward the next generation of ERL light sources is well underway at many accelerator centres and will shortly reach two major milestones
  - ~100 mA, low emittance, photoinjectors
  - ~100 mA, CW SC accelerating modules
- Other ERL issues are under study or planned to be addressed at both existing sources and deadicated prototype facilities
  - Diagnostics, BBU control, high Q cavities, microphonic detuning…
  - Synchronisation, CSR, wakefields, bunch length control, beam loss etc.…

- **Across the globe, the ERL has become the accelerator of choice for a new breed of light sources with an outstanding potential for the delivery of advanced photon science.**

Thanks

Charlie Sinclair, Georg Hoefstatter, George Neil, Gennadiy Kulipanov, Ryoichi Hajima, Vladimir Litvinenko….



The 4GLS Team

&

Our International Collaborators

ERL2007 @ Daresbury