Applications of High Brightness Beams: Energy Recovered Linacs

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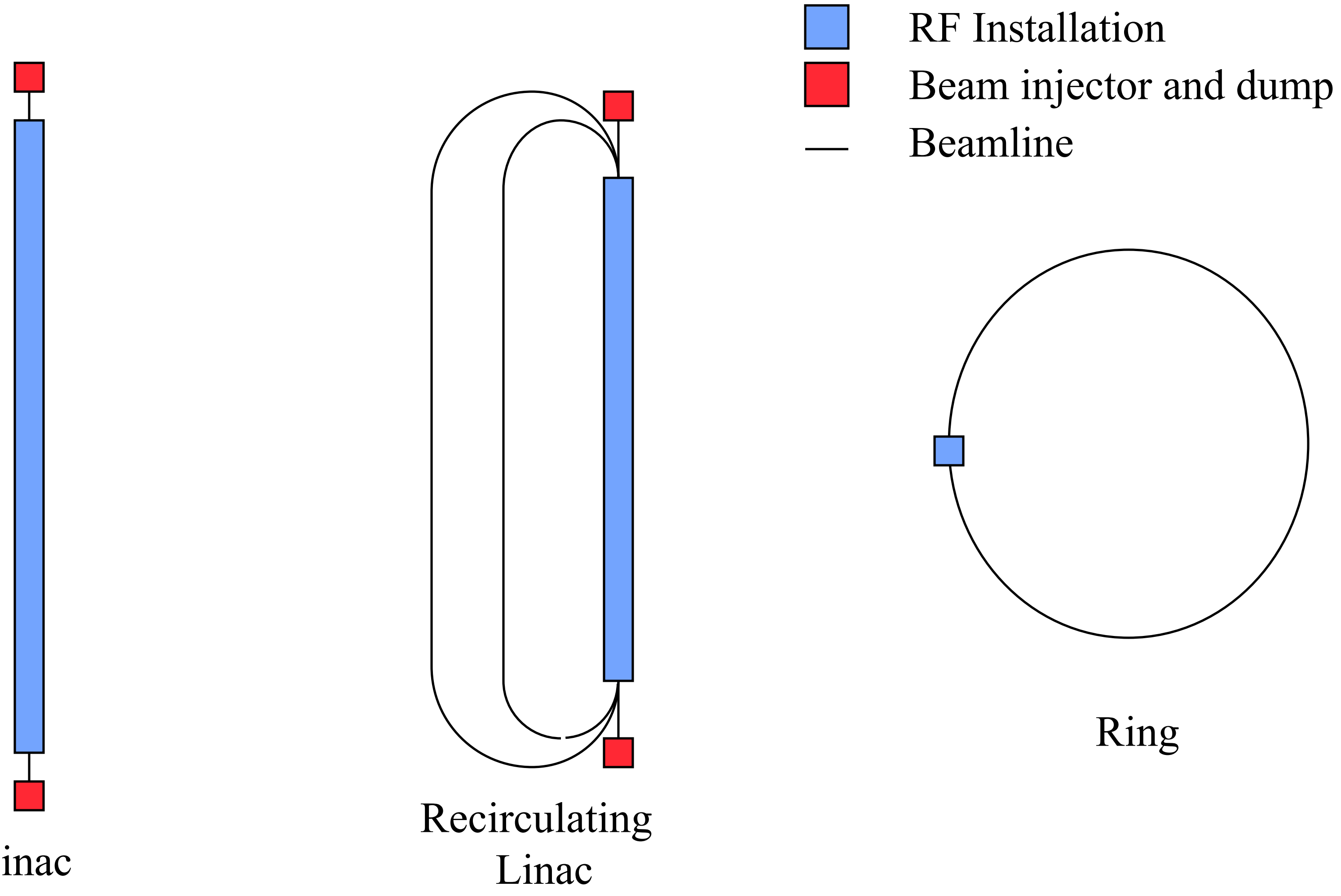
Jefferson Lab

Schematic Representation of Accelerator Types



🟦 RF Installation

🟥 Beam injector and dump

— Beamline

Linac

Recirculating
Linac

Ring

Comparison between Linacs and Storage Rings

- **Advantage Linacs**

Emittance dominated by source emittance and emittance growth down linac

Beam polarization “easily” produced at the source, switched, and preserved

Total transit time is quite short

Beam is easily extracted. Utilizing source control, flexible bunch patterns possible

Long undulaters are a natural addition

Bunch durations can be SMALL (10-100 fsec)

Comparison Linacs and Storage Rings

- **Advantage Storage Rings**

  Up to now, the stored average current is much larger

  Very efficient use of accelerating voltage

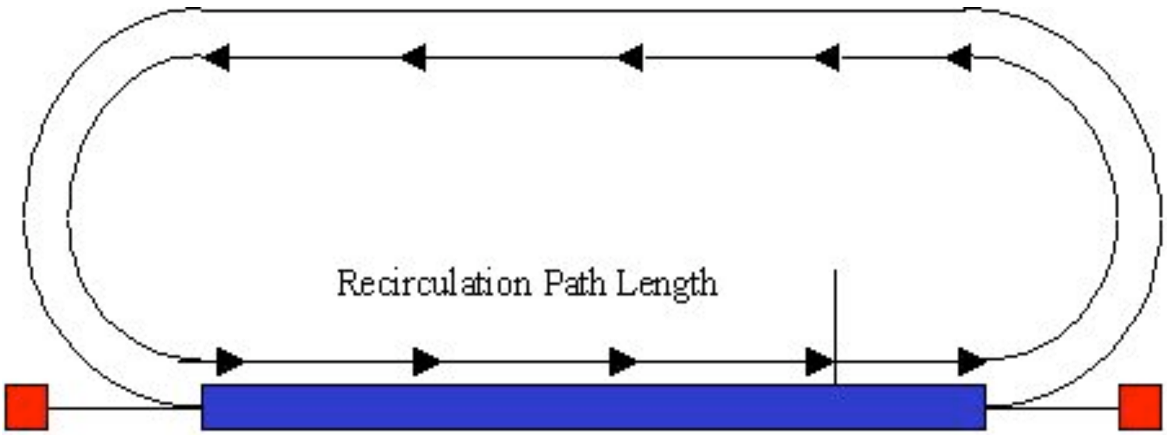
  Technology well developed and mature

- **Disadvantage of Storage Rings**

  Technology well developed and mature (maybe!)

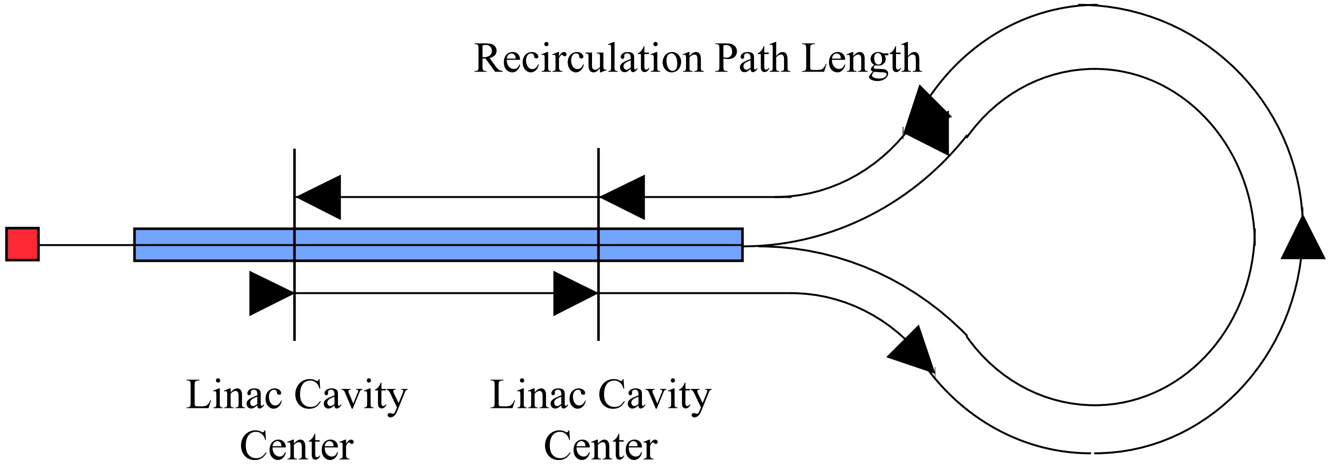
  One cannot eliminate the synchrotron radiation and the emittance and bunch length it generates

Beam Energy Recovery



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

Beam Energy Recovery



Recirculation path length in herring-bone or back-to-front recirculated linac. For energy recovery choose it to be n_{RF}. Note additional complication: path length has to be an integer at each and every different accelerating cavity location in the linac. Beam optics is easier though.

Power Multiplication Factor

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

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

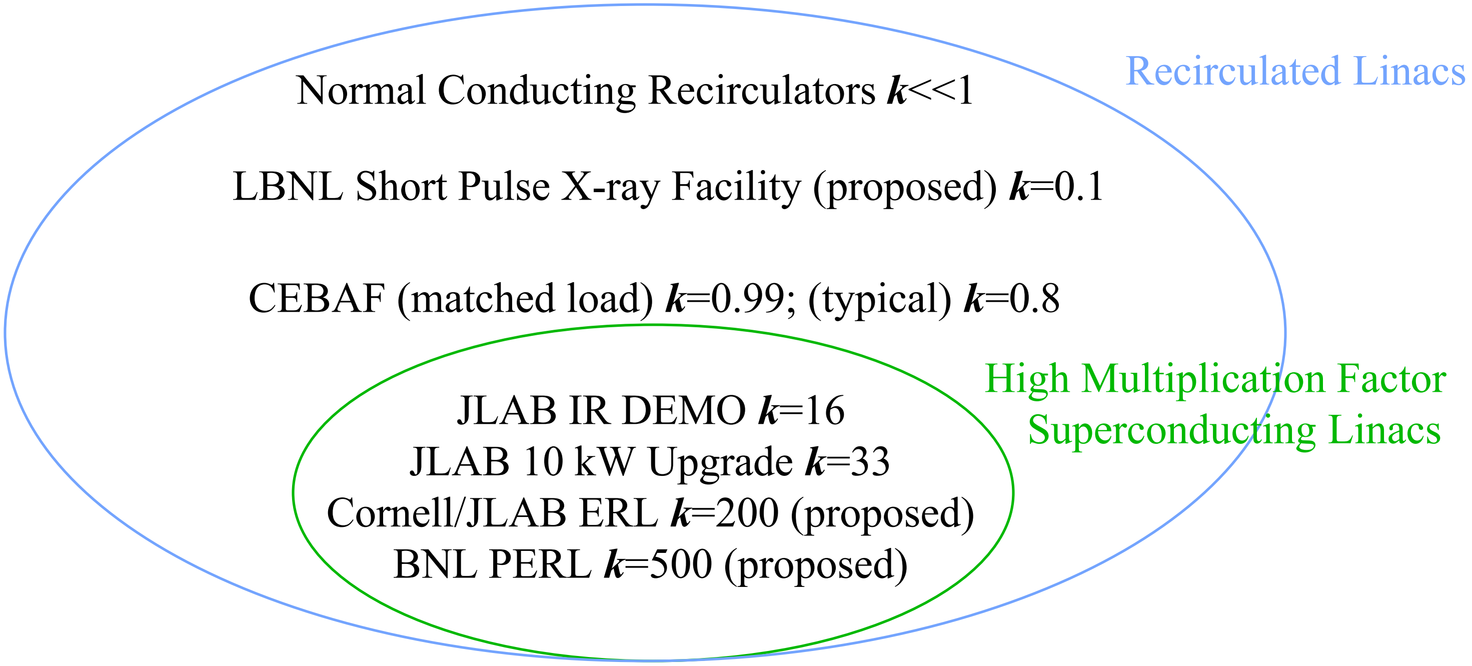
where P_{rf} is the RF power needed to accelerate the beam

- By the first law of thermodynamics (energy conservation!) $k < 1$ 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



Recirculated Linacs

Normal Conducting Recirculators ***k***<<1

LBNL Short Pulse X-ray Facility (proposed) ***k***=0.1

CEBAF (matched load) ***k***=0.99; (typical) ***k***=0.8

High Multiplication Factor Superconducting Linacs

JLAB IR DEMO ***k***=16
JLAB 10 kW Upgrade ***k***=33
Cornell/JLAB ERL ***k***=200 (proposed)
BNL PERL ***k***=500 (proposed)

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

Comparison Accelerator Types

Parameter	High Energy Electron Linac	High *k* Recirculated Superconducting Linac	Ring
Accelerating Gradient[MV/m]	>50	10-20	NA
Duty Factor	<1%	1	1
Average Current[mA]	<1	10 going to 100	1000
Average Beam Power[MW]	0.5	1.0 going to 700	3000
Multiplication Factor	<1	33 going to 200	1000
Normalized Emittance[mm mrad]	1	1	4
Bunch Length	100 fsec	100 fsec	20 psec

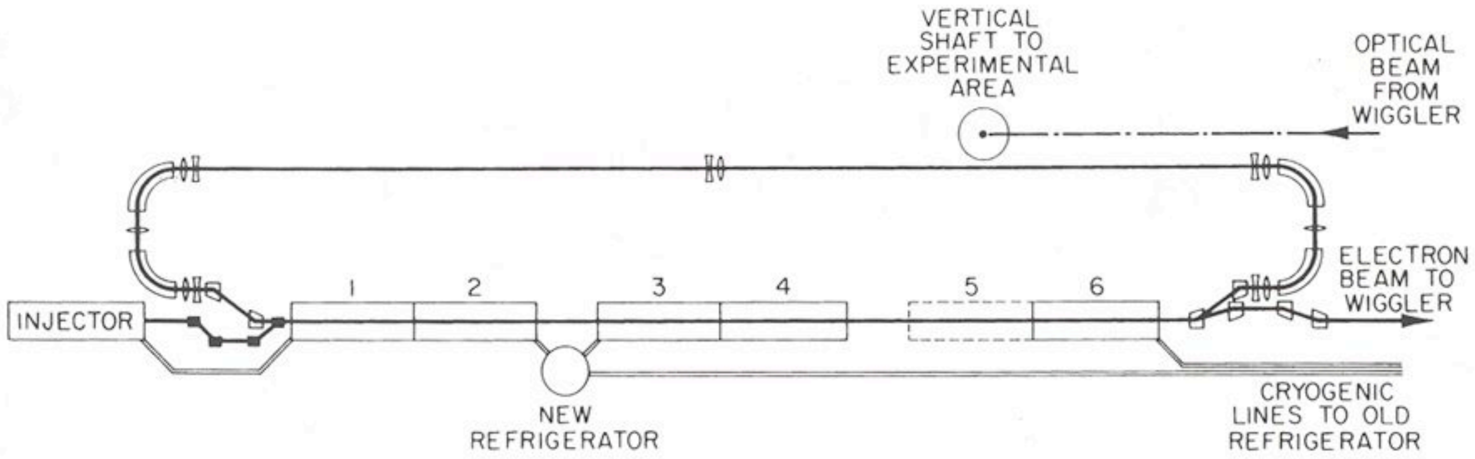
Typical results by accelerator type

Major Challenge for High Current Recirculation

- High average current sources to provide beam
- Applications:
  - High average power free electron lasers
  - Recirculated linac light sources
  - Electron coolers
  - Collider ERL electron sources
- Right now, depending on the applications, looks like several ways to get there including DC photocathode sources and RF photocathode sources, either normal conducting or superconducting

The SCA/FEL Energy Recovery Experiment

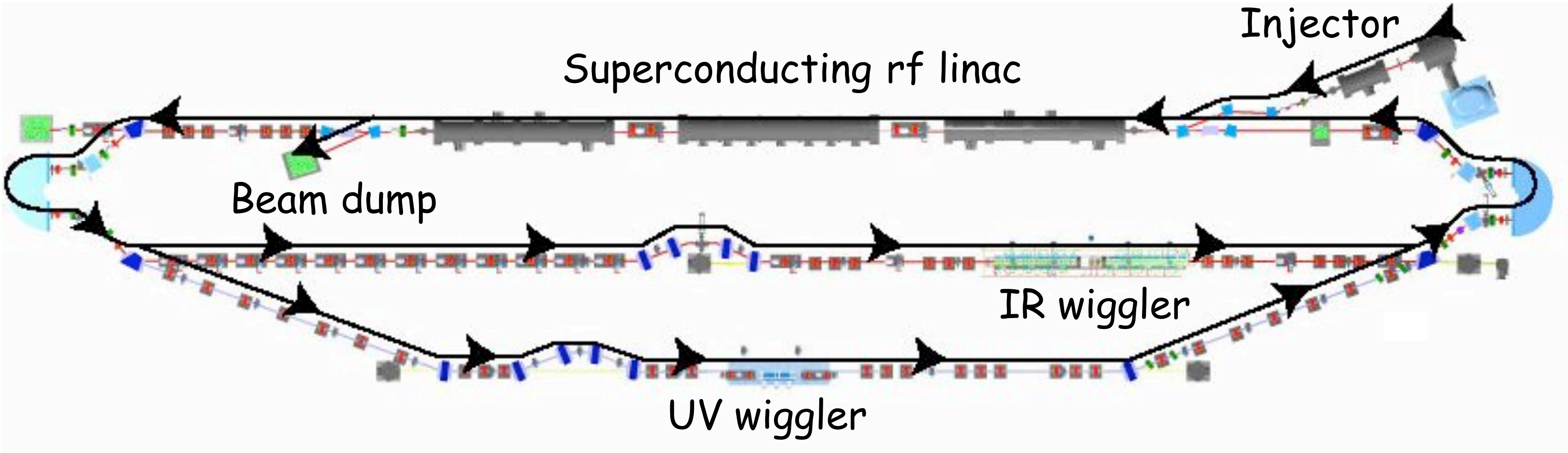
- Same-cell energy recovery was first demonstrated in a superconducting linac at the SCA/FEL in July 1986
- Beam was injected at 5 MeV into a ~50 MeV linac (up to 95 MeV in 2 passes), 150 µA average current (12.5 pC per bunch at 11.8 MHz)
- The Recyclotron beam recirculation system could be not used 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.



Operating ERL-FELs

- Jefferson Lab FEL
- JAERI FEL
- BINP FEL

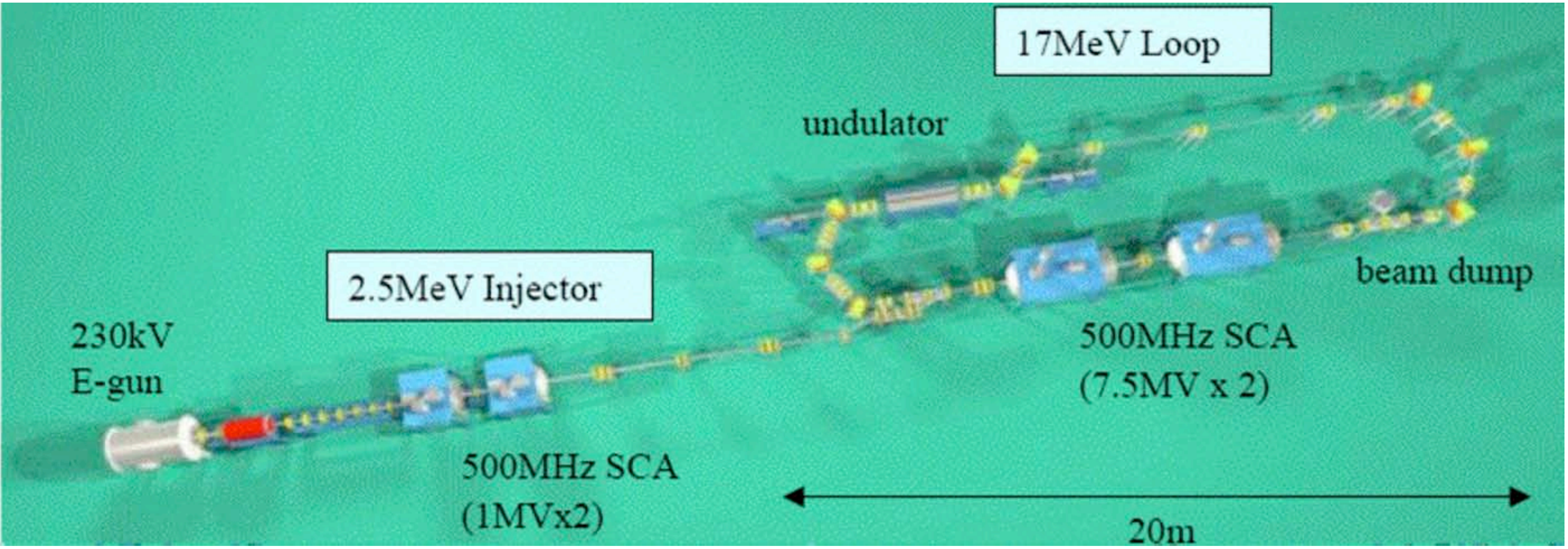
JLab 10kW IR FEL and 1 kW UV FEL



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%

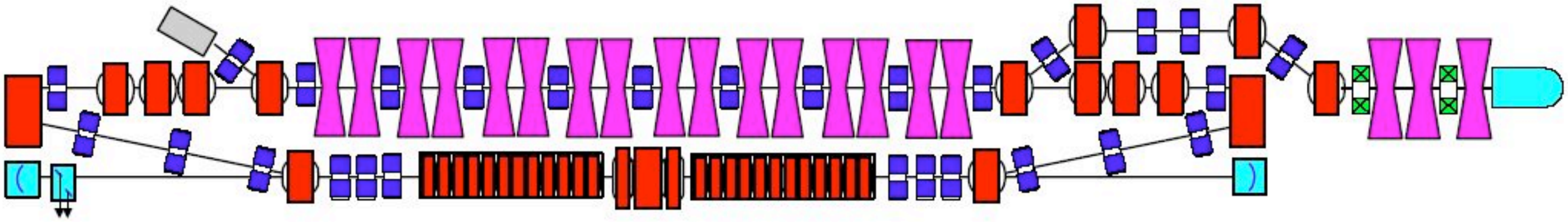
JAERI ERL-FEL



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

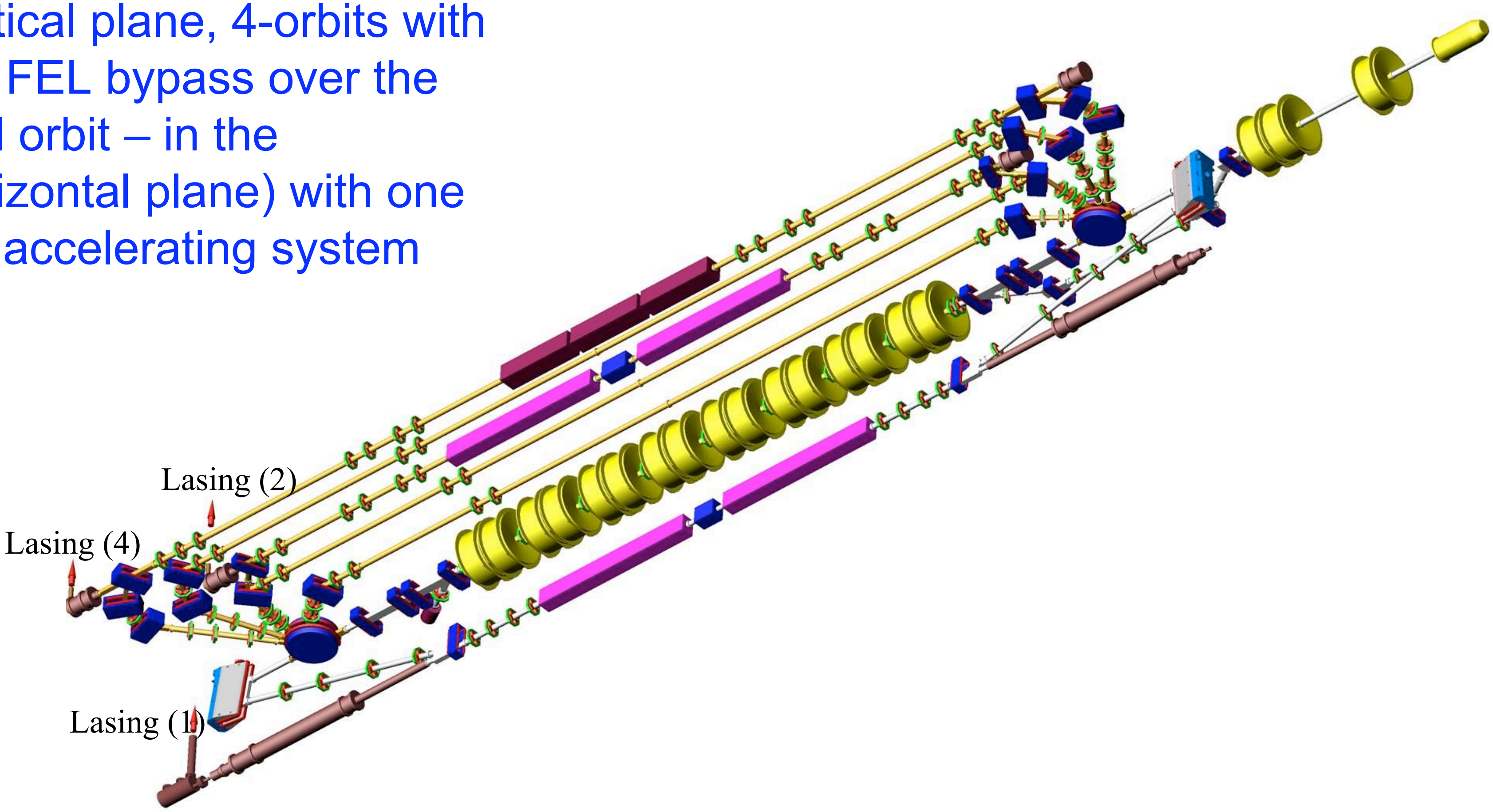
Undulators Buncher Mirrors Outcoupler

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

BINP ERL-FEL

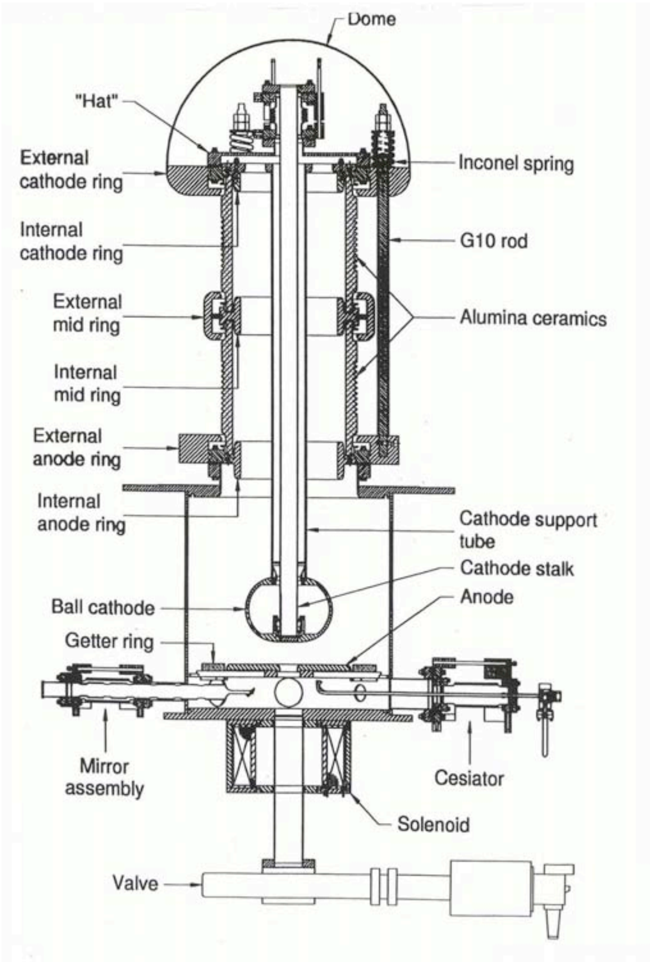
Two ERLs (1-orbit in vertical plane, 4-orbits with the FEL bypass over the 2nd orbit – in the horizontal plane) with one RF accelerating system



DC photoinjectors

State-of-the-art: JLAB FEL gun

- High repetition rate up to 75 MHz
- $\varepsilon_{N,rms}$~ 7-15 mm-mrad for q ~ 60 –135 pC/bunch (measured at the wiggler)
- Average current up to 9 mA
- Cathode voltage: 350 – 500 kV



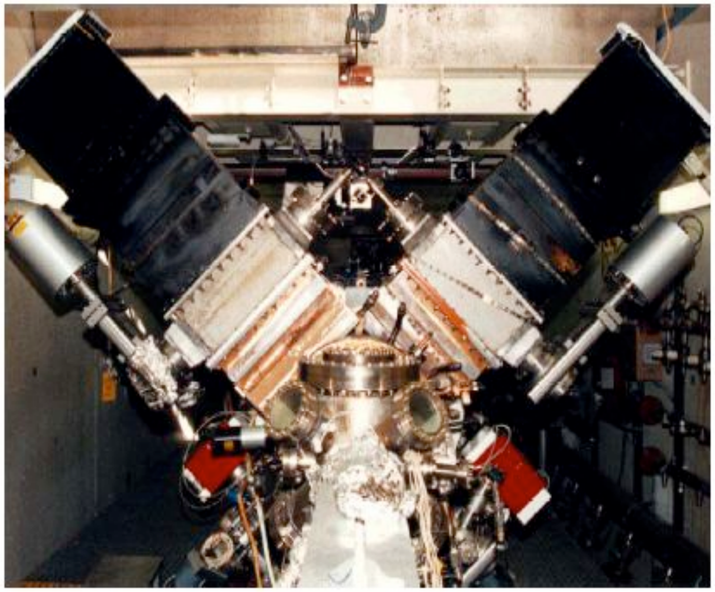
Planned DC Photoinjectors

- **JLab**: 500 kV, 75 MHz, 10 mA
- **JLab/AES**: 750 MHz, 100 mA
- **Daresbury ERLP**: Duplicate of JLab FEL gun, 6.5 mA
- **Cornell**: 500 – 750 kV, 100 mA, 77pC/bunch, 1.3 GHz, $\varepsilon_{N,rms}$~ 0.1 mm-mrad

RF photoinjectors

- To date RF guns have produced best normalized emittances: $\varepsilon_{N,rms} \sim 1\ \mu m$ at $q \sim 0.1 - 1$ nC , but at relatively low rep rate (10-100 Hz)

- Challenge: Balance high gradient (low emittance) with high rep rate (thermal effects)

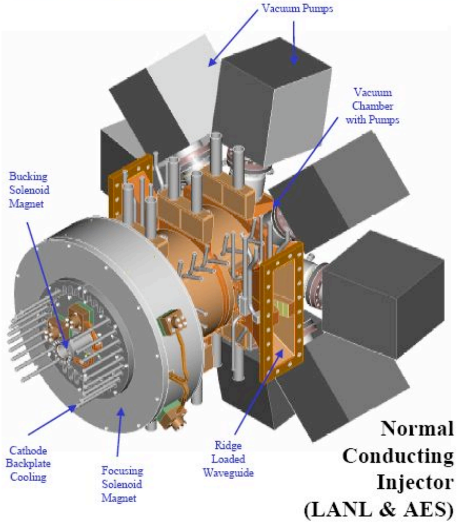


State-of-the-art: Boeing gun

- Repetition rate 433 MHz at 25% DF
- Average current 32 mA

Planned RF Photoinjectors

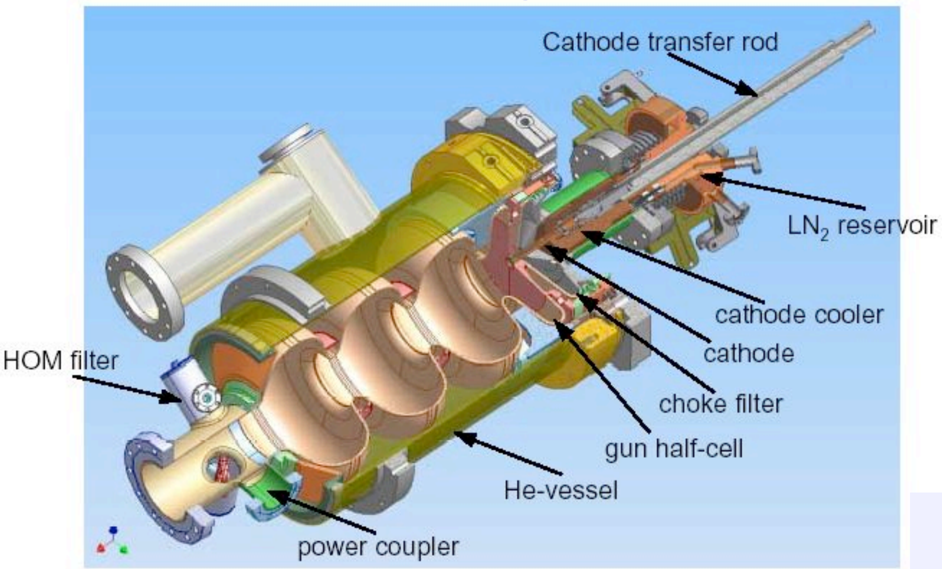
- **LANL/AES:** 700 MHz,100 mA

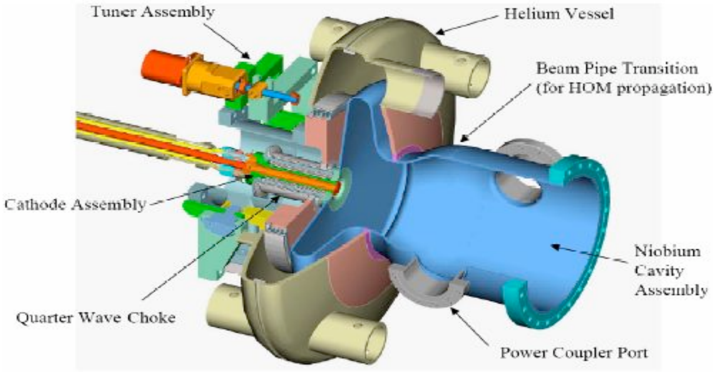


Normal Conducting Injector (LANL & AES)

SRF photoinjectors

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





Rossendorf proof of principle experiment:

1.3 GHz, 10 MeV

77 pC at 13 MHz and 1 nC at < 1 MHz

BNL/AES/JLAB development:

1.3 GHz _-cell Nb cavity at 2K

Test diamond amplified cathode

AES/BNL development:

703.75 MHz _-cell Nb photoinjector

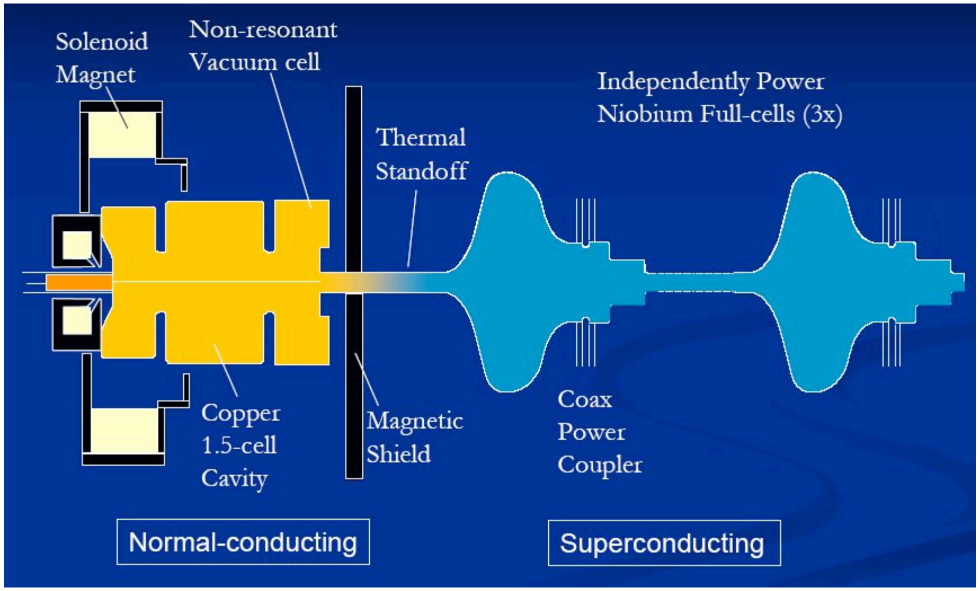
Hybrid Guns

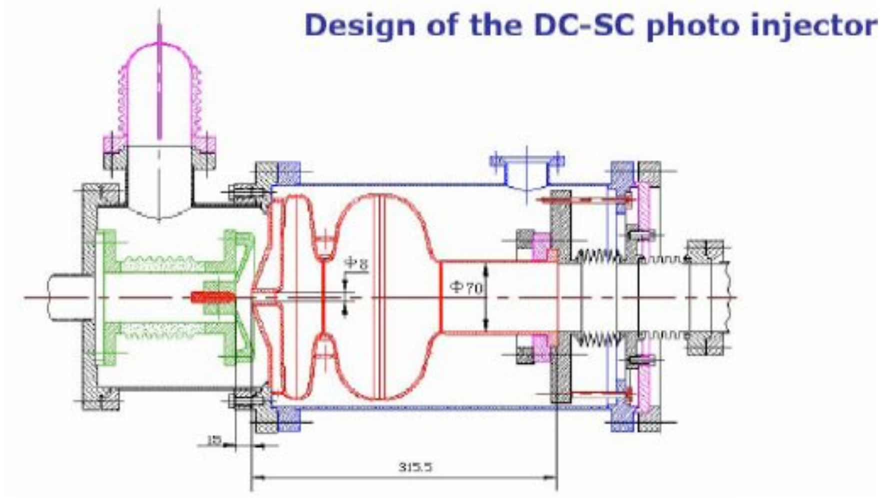
- **LANL**

  NC 1 _-cell + SRF cells

- **University of Peking**

  DC + SRF gun

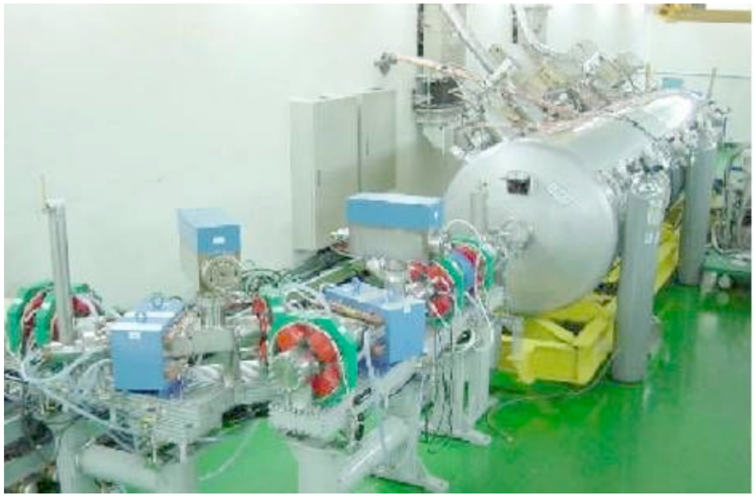


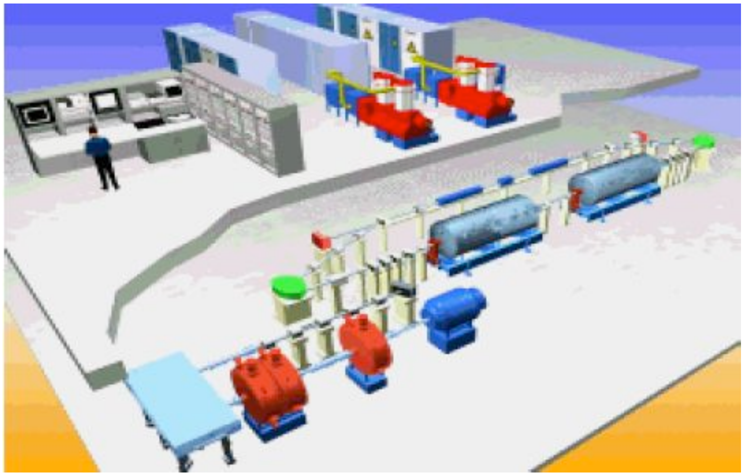


Planned ERL-FELs

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

KAERI FEL



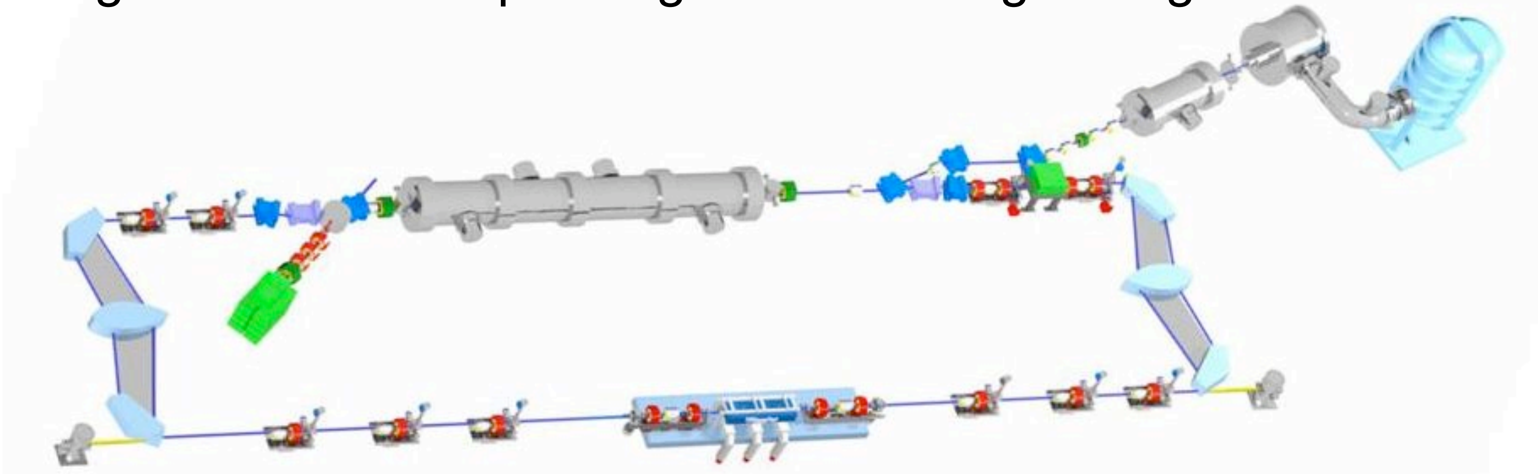


Output Light Parameters	Goal
Wavelength range (microns)	3-20
Bunch Length (FWHM psec)	20-50
Laser power / pulse (mJoules)	50-250
Laser power (kW)	1-5
Rep. Rate (MHz)	22
Macropulse format	CW

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

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 _m.

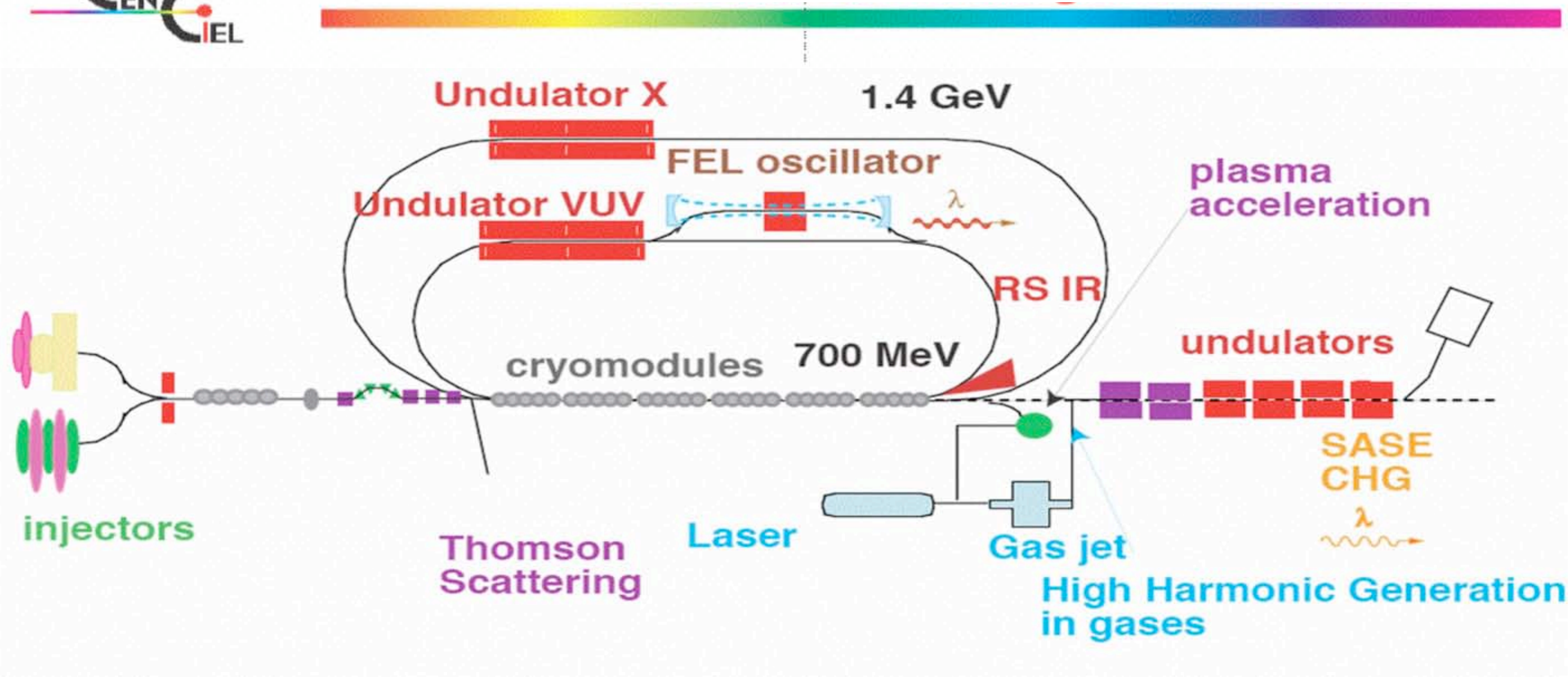


Output Light Parameters	**Goal**
Wavelength range (microns)	2-100
Bunch Length (FWHM psec)	0.5-few
Laser power / pulse (mJoules)	~25
Laser power (kW)	~1
Rep. Rate (MHz)	37.5
Macropulse format	CW

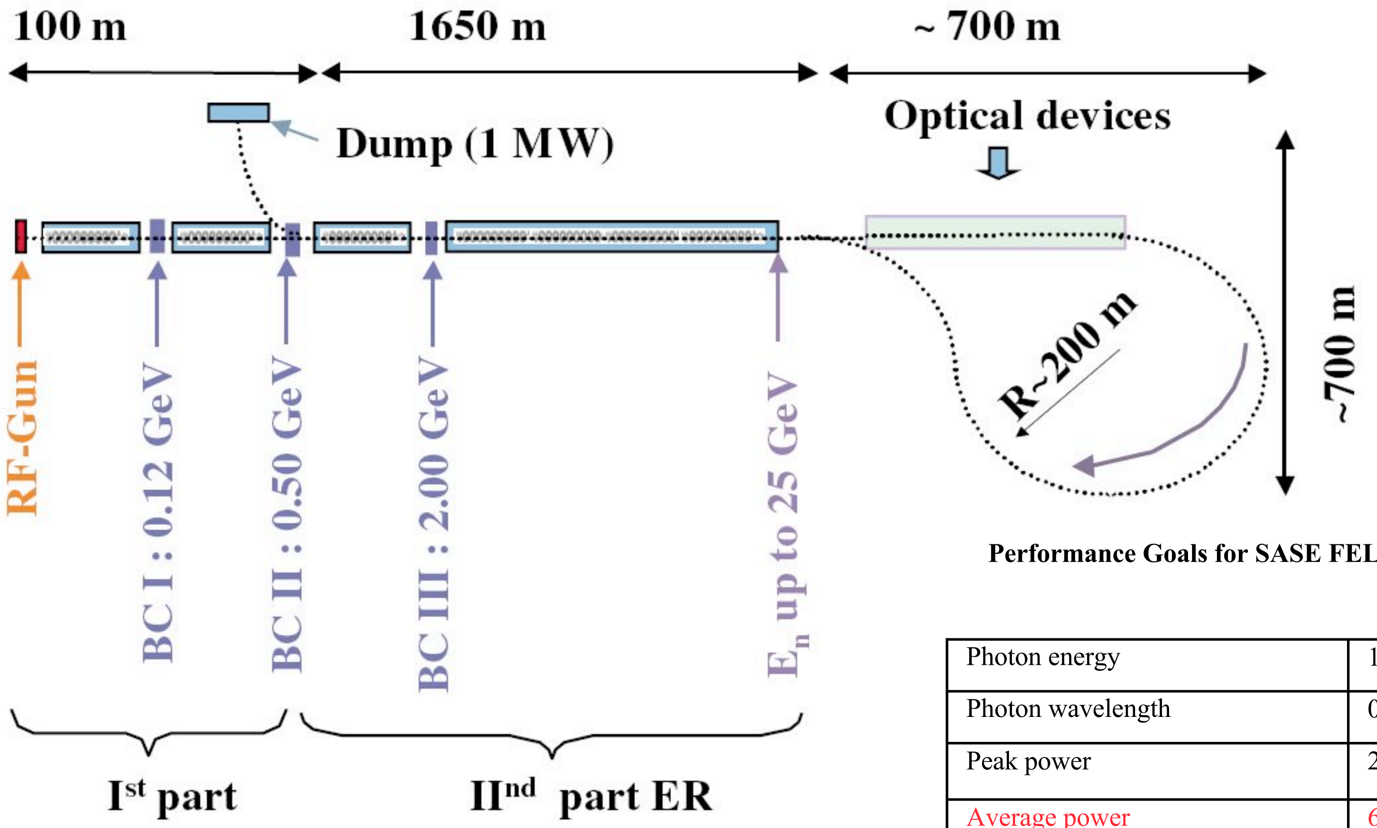
Electron Beam Parameters	**Goal**
Energy (MeV)	60
Accelerator frequency (MHz)	1500
Charge per bunch (pC)	135
Average current (mA)	5
Peak Current (A)	200
Beam Power (kW)	300

ARC-EN-CIEL - SACLAY

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



TESLA XFEL ERL



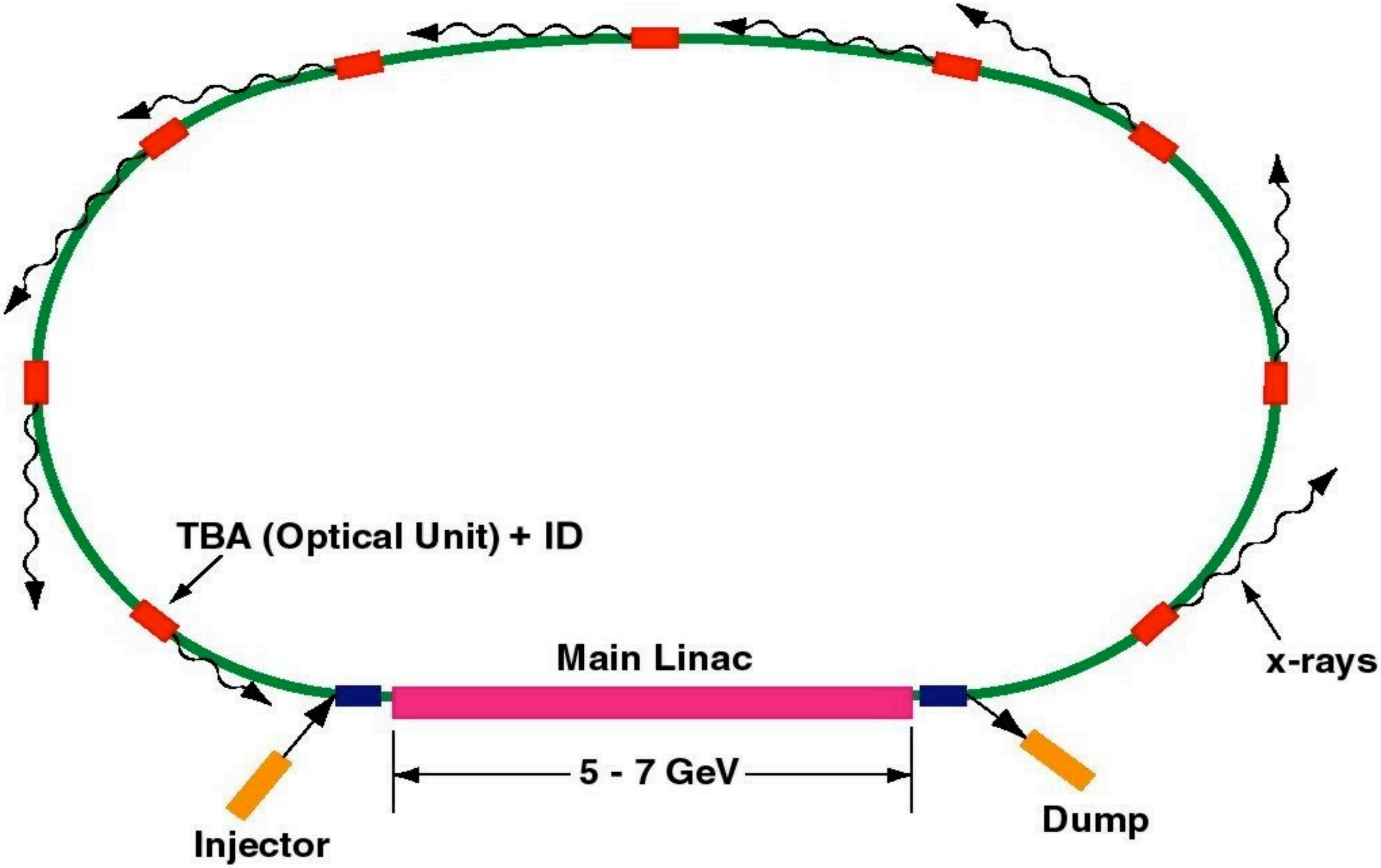
Proposed ER operation would have a rep rate of 1 MHz instead of DESY XFEL rep rate of 10 Hz, increasing the average power and brilliance by a factor of 10^5

Performance Goals for SASE FEL Radiation at the DESY XFEL

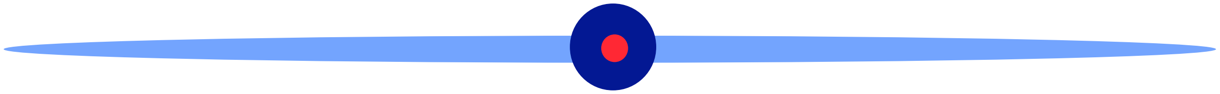
Photon energy	12.4 – 0.2 keV
Photon wavelength	0.1 – 6.4 nm
Peak power	24 – 135 GW
Average power	66 – 800 W
# photons/ pulse	$1 – 430 \times 10^{12}$
Peak brilliance	$5.4 – 0.6 \times 10^{33}$ **
Average brilliance	$1.6 – 0.3 \times 10^{25}$ **
** in units of photons / (s mrad^2 mm^2 0.1% b.w.)	

ERL X-ray Source Conceptual Layout

CORNELL UNIVERSITY
CHESS / LEPP



Why ERLs for X-rays?



ESRF 6 GeV @ 200 mA

_$_x$ = 4 nm mrad

_$_y$ = 0.02 nm mrad

B ~ 10^{20} ph/s/mm^2/mrad^2/0.1%BW

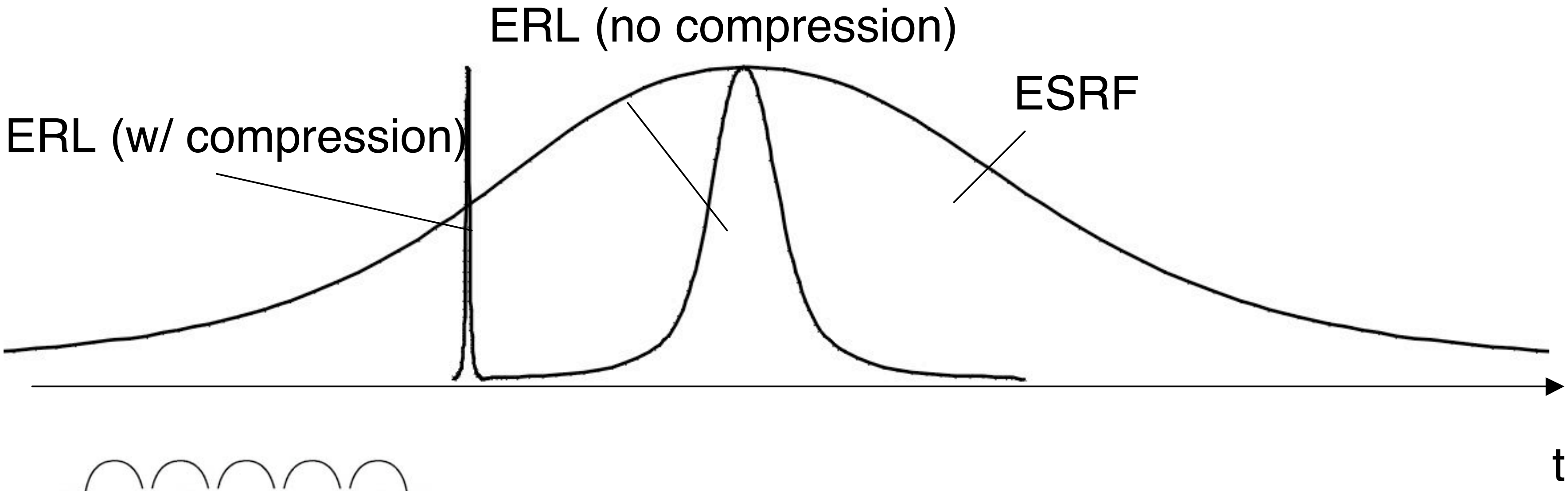
L_{ID} = 5 m

ERL 5 GeV @ 10-100 mA

_$_x$ = _$_y$ → 0.01 nm mrad

B ~ 10^{23} ph/s/mm^2/mrad^2/0.1%BW

L_{ID} = 25 m



Brilliance Scaling and Optimization

- For 8 keV photons, 25 m undulator, and 1 micron normalized emittance, X-ray source brilliance

$$B \propto \frac{I}{\varepsilon^2} = \frac{fQ}{\varepsilon_{th}^2 + AQ^p}$$

- For any power law dependence on charge-per-bunch, *Q*, the optimum is

$$AQ^p \approx \varepsilon_{th}^2 / (p-1)$$

- If the “space charge/wake” generated emittance exceeds the thermal emittance —$_{th}$ from whatever source, you’ve already lost the game!
- BEST BRILLIANCE AT LOW CHARGES, once a given design and bunch length is chosen!
- Unfortunately, best flux at high charge

ERL Source Sample Parameters

Parameter	Value	Unit
Beam Energy	5-7	GeV
Average Current	100 / 10	mA
Fundamental frequency	1.3	GHz
Charge per bunch	77 / 8	pC
Injection Energy	10	MeV
Normalized emittance	2 / 0.2*	_m
Energy spread	0.02-0.3*	%
Bunch length in IDs	0.1-2*	ps
Total radiated power	400	kW

* rms values

ERL X-ray Source Average Brilliance and Flux

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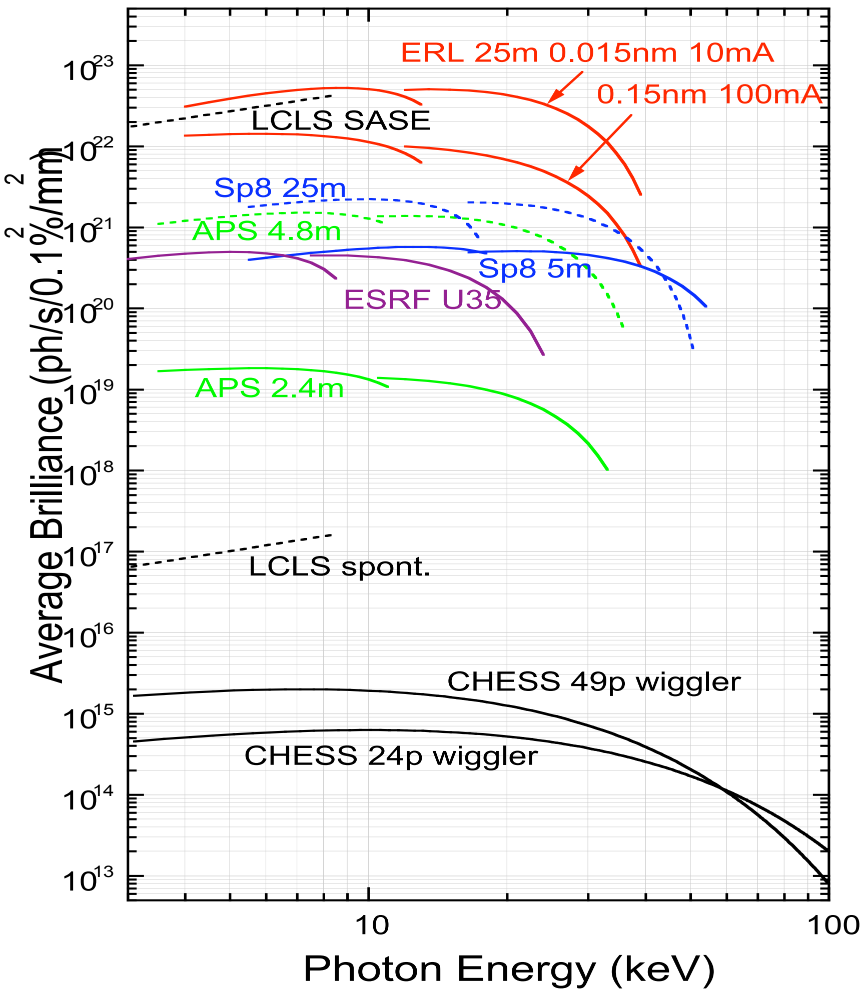
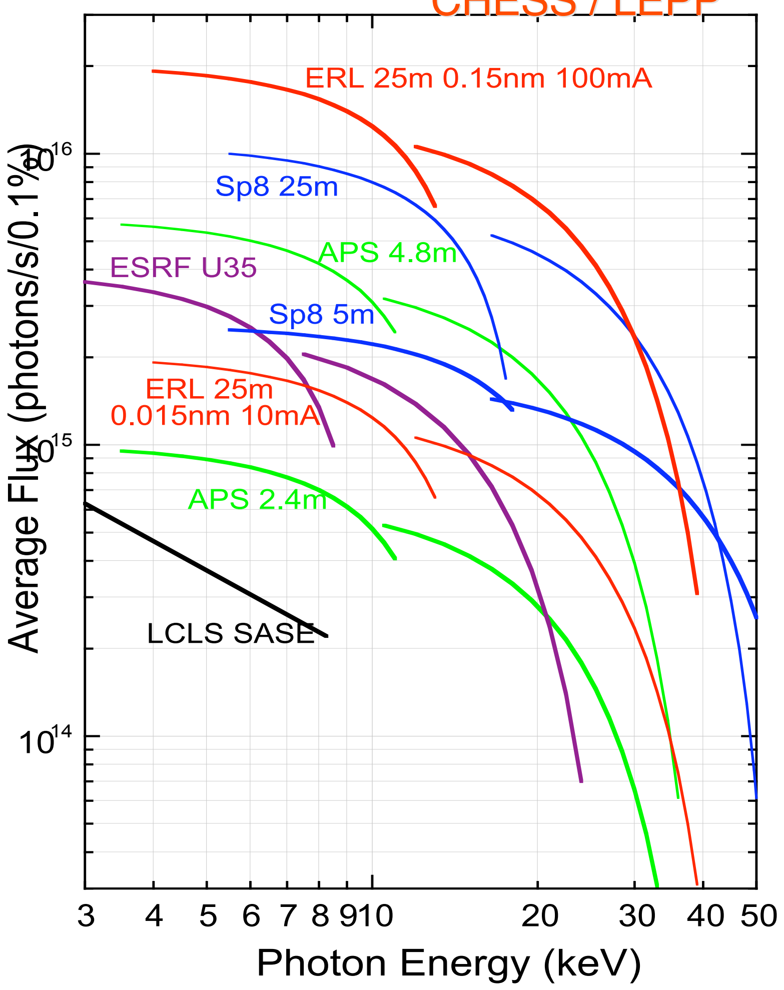
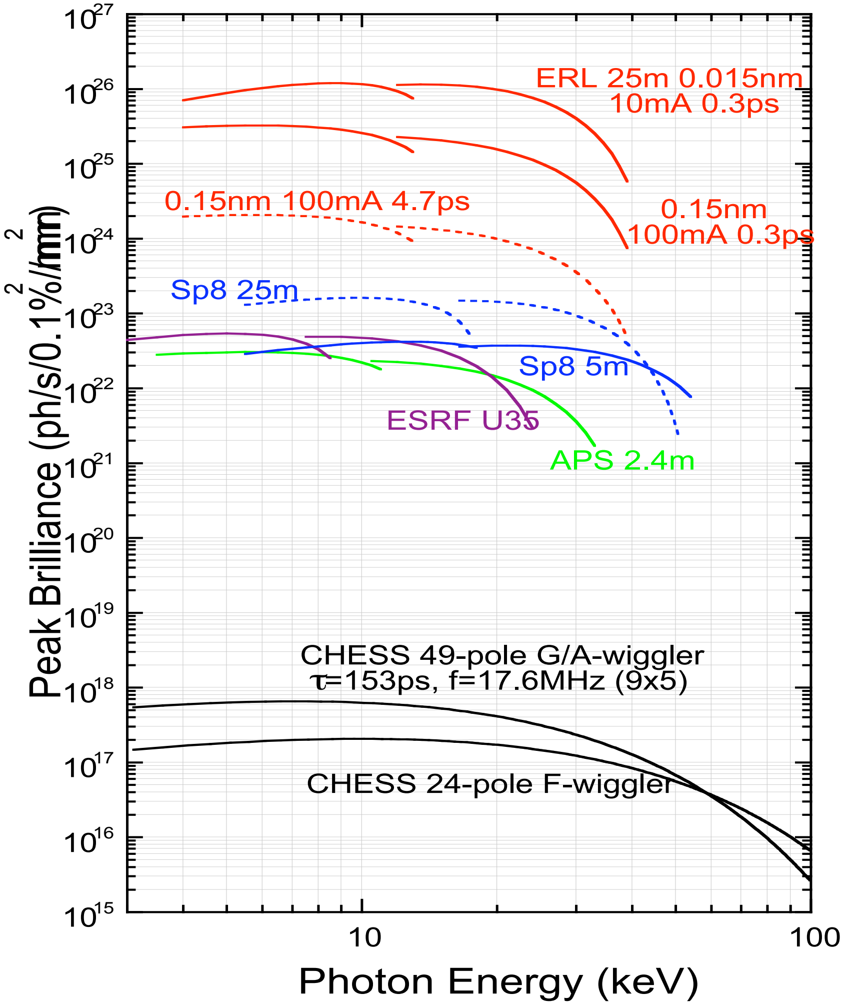


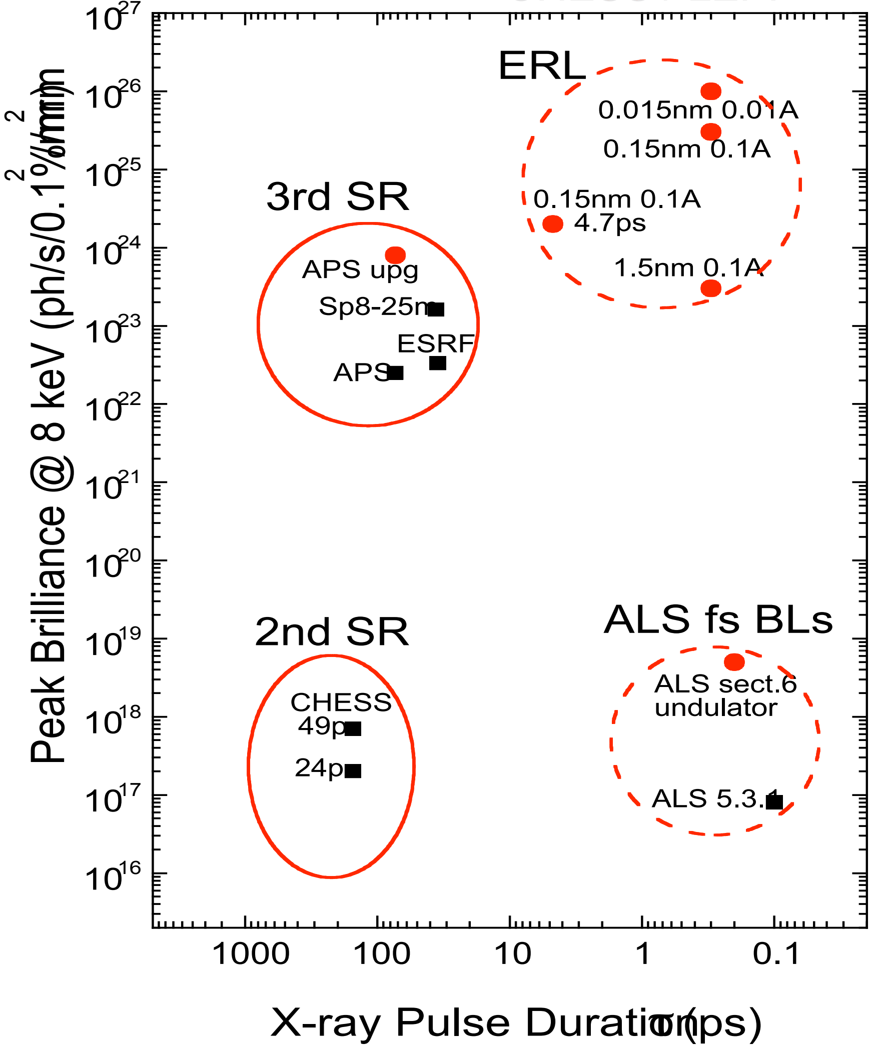


Courtesy: Qun Shen, CHESS Technical Memo 01-002, Cornell University

ERL Peak Brilliance and Ultra-Short Pulses

CHESS / LEPP





Courtesy: Q. Shen, I. Bazarov

Thomas Jefferson National Accelerator Facility

Cornell ERL Phase I: Injector

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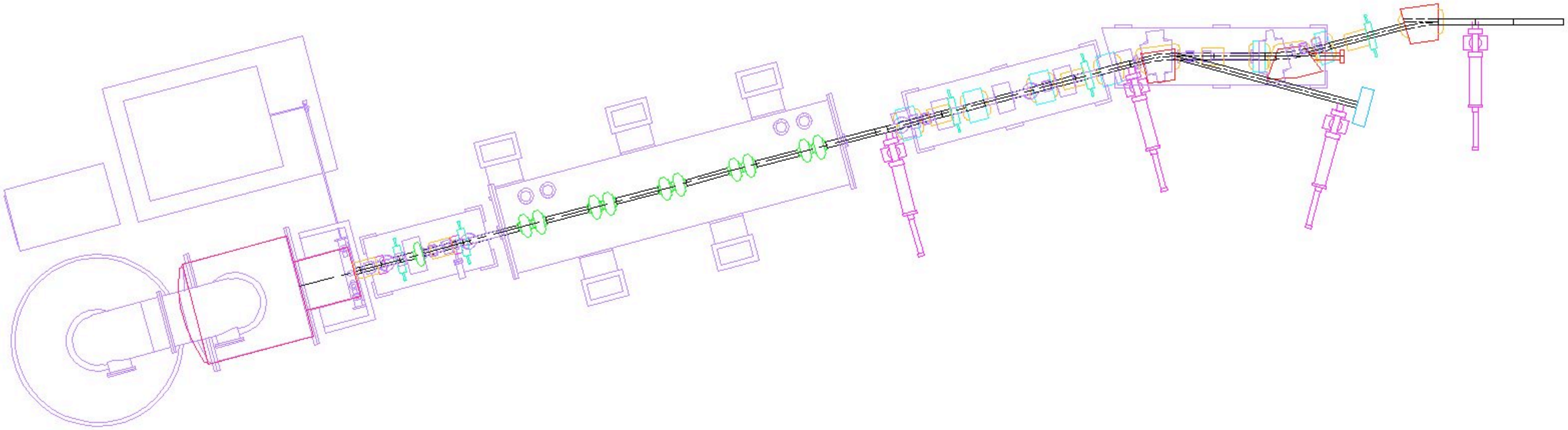

Injector Parameters:

Beam Energy Range	5 – 15[a] MeV
Max Average Beam Current	100 mA
Max Bunch Rep. Rate @ 77 pC	1.3 GHz
Transverse Emittance, rms (norm.)	< 1[b] μm
Bunch Length, rms	2.1 ps
Energy Spread, rms	0.2 %

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[a] at reduced average current

[b] corresponds to 77 pC/bunch

Beyond the space charge limit

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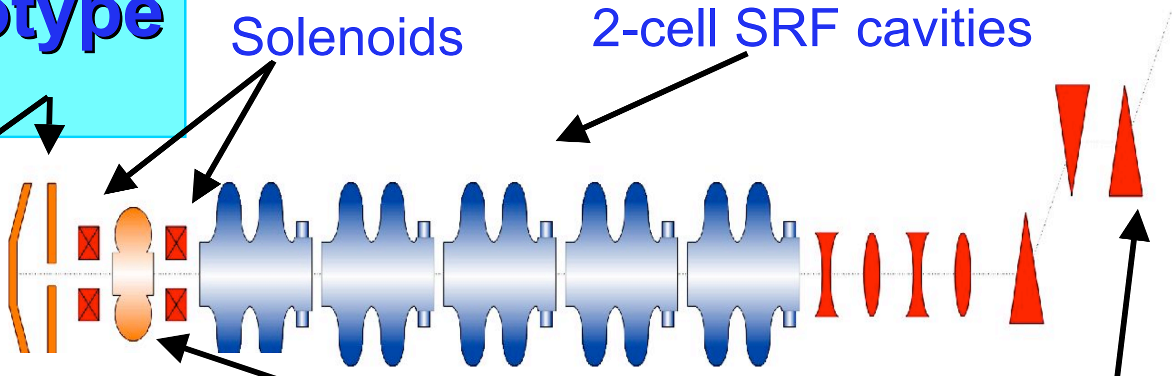
Cornell ERL Prototype Injector Layout



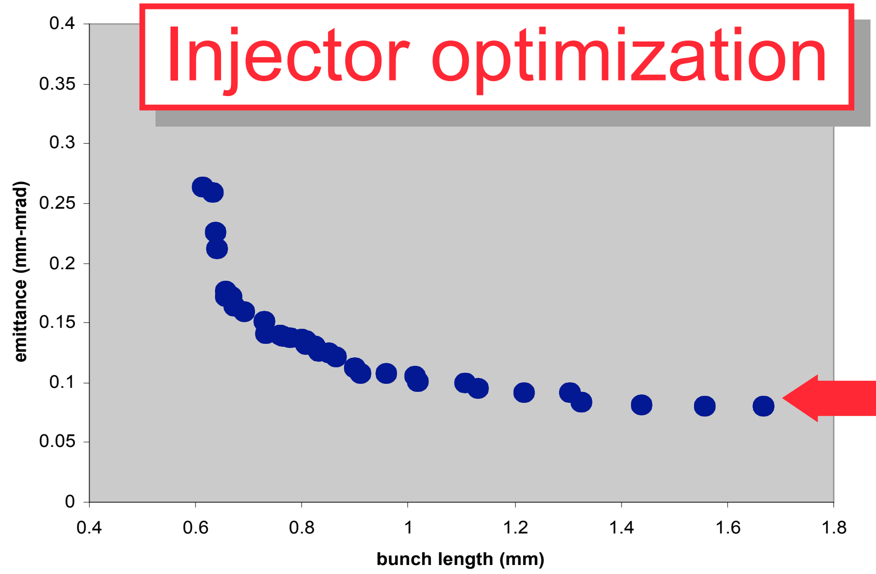
500-750 kV DC Photoemission Gun

Solenoids

2-cell SRF cavities

Buncher

Merger dipoles into ERL linac



Injector optimization

0.1 mm-mrad, 80 pC, 3ps

Courtesy of I. Bazarov

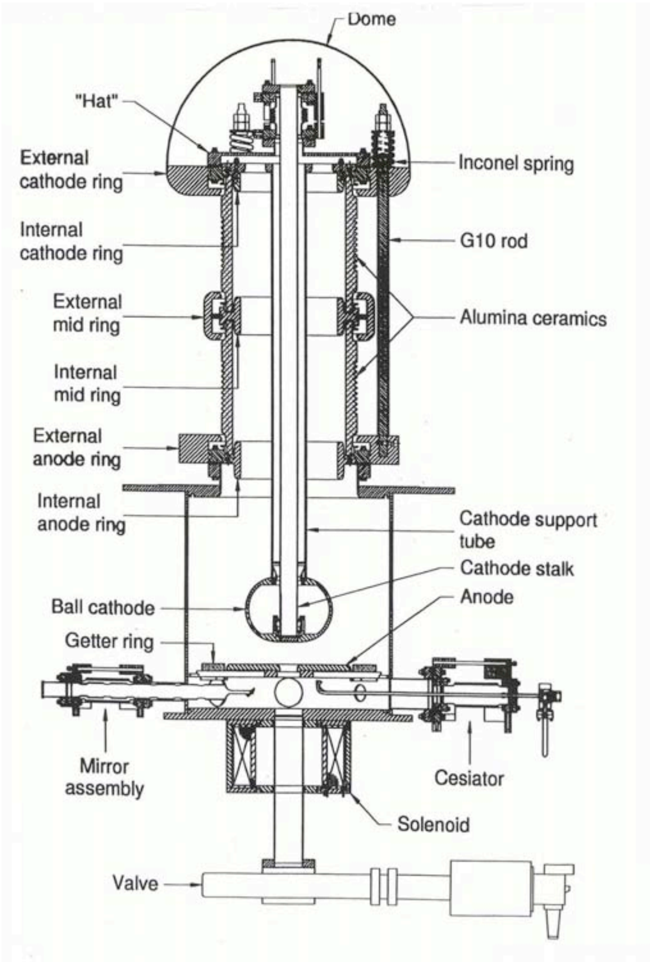
Sinclair Points

- Emittance compensation is effective in reducing the emittance from DC guns too. The computer designs of the Cornell ERL source require its application to achieve the best beam parameters.
- Thermal emittance matters, even at high charge. Starting with the best possible thermal emittance, as may be extracted from GaAs photocathodes (photoelectrons are thermalized before being emitted), may be preferred.
- You don't need infinite voltage or cathode gradient to get decent performance from a DC gun.
- First beam, optimistically, by the end of the year.

DC photoinjectors

State-of-the-art: JLAB FEL gun

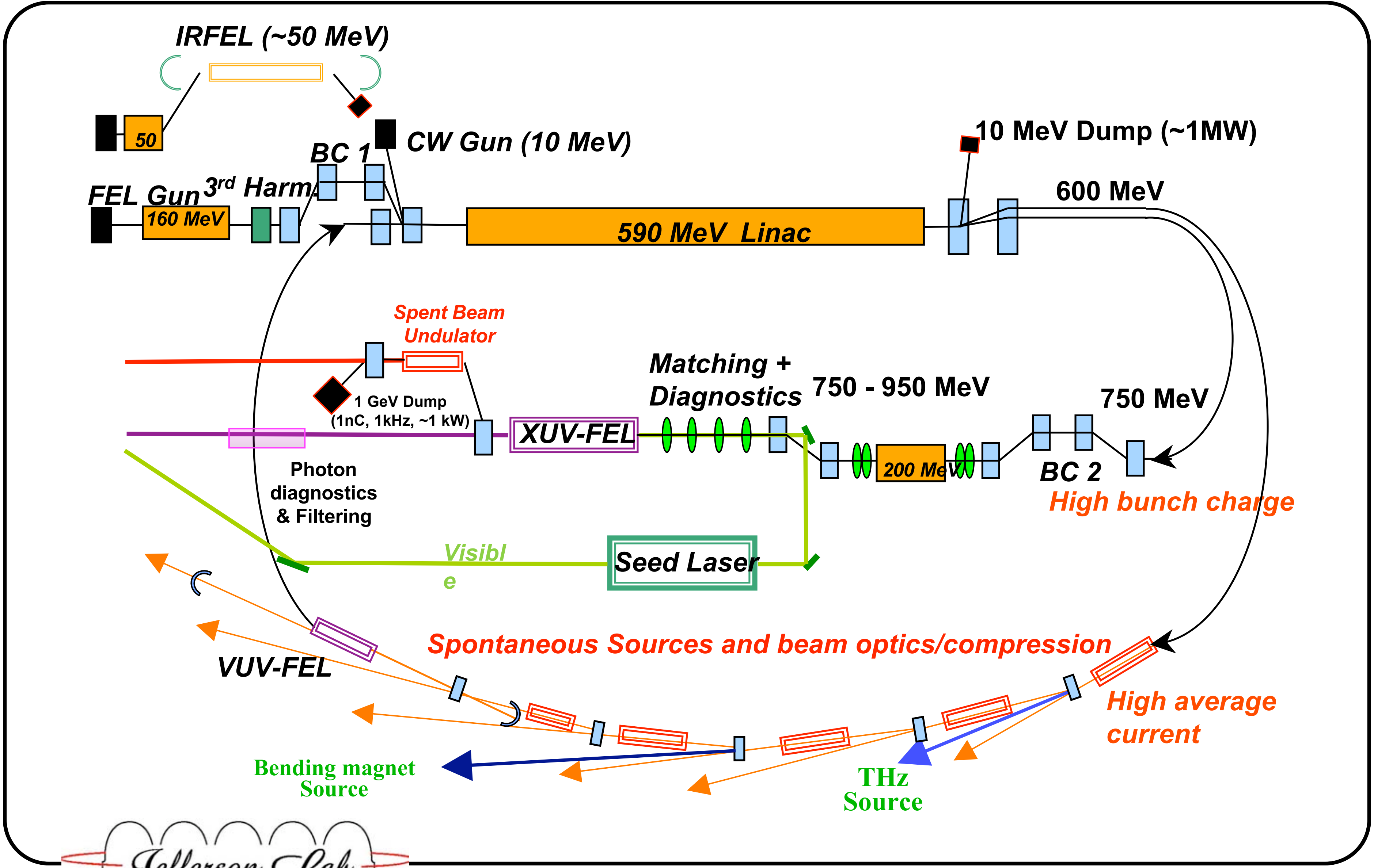
- High repetition rate up to 75 MHz
- $\varepsilon_{N,rms}$~ 7-15 mm-mrad for q ~ 60 –135 pC/bunch (measured at the wiggler)
- Average current up to 9 mA
- Cathode voltage: 350 – 500 kV



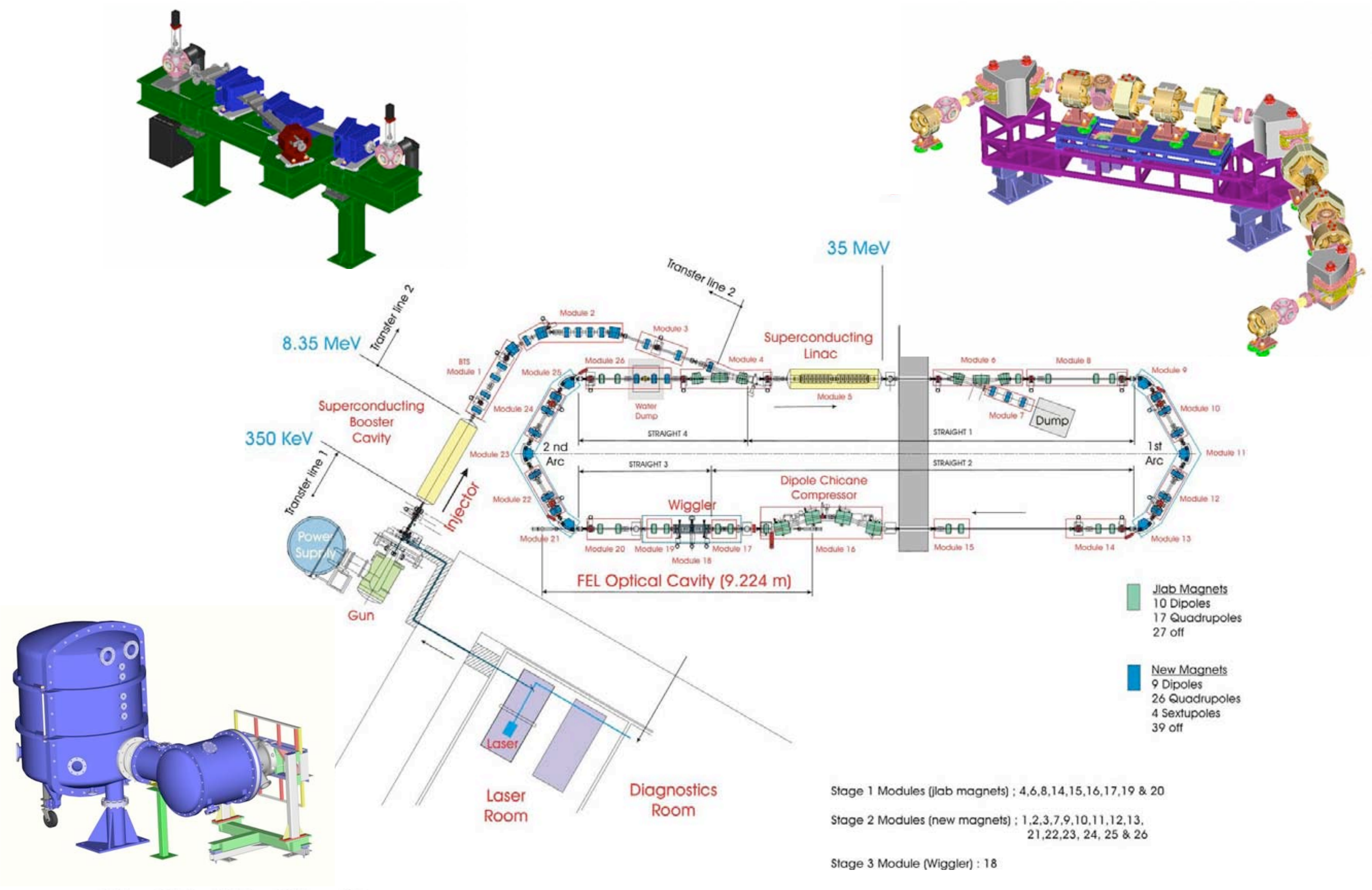
Planned DC Photoinjectors

- **JLab**: 500 kV, 75 MHz, 10 mA
- **JLab/AES**: 750 MHz, 100 mA
- **Daresbury ERLP**: Duplicate of JLab FEL gun, 6.5 mA
- **Cornell**: 500 – 750 kV, 100 mA, 77pC/bunch, 1.3 GHz, $\varepsilon_{N,rms}$~ 0.1 mm-mrad

Conceptual layout of 4GLS



Daresbury: ERL Prototype



🟩 Jlab Magnets
10 Dipoles
17 Quadrupoles
27 off

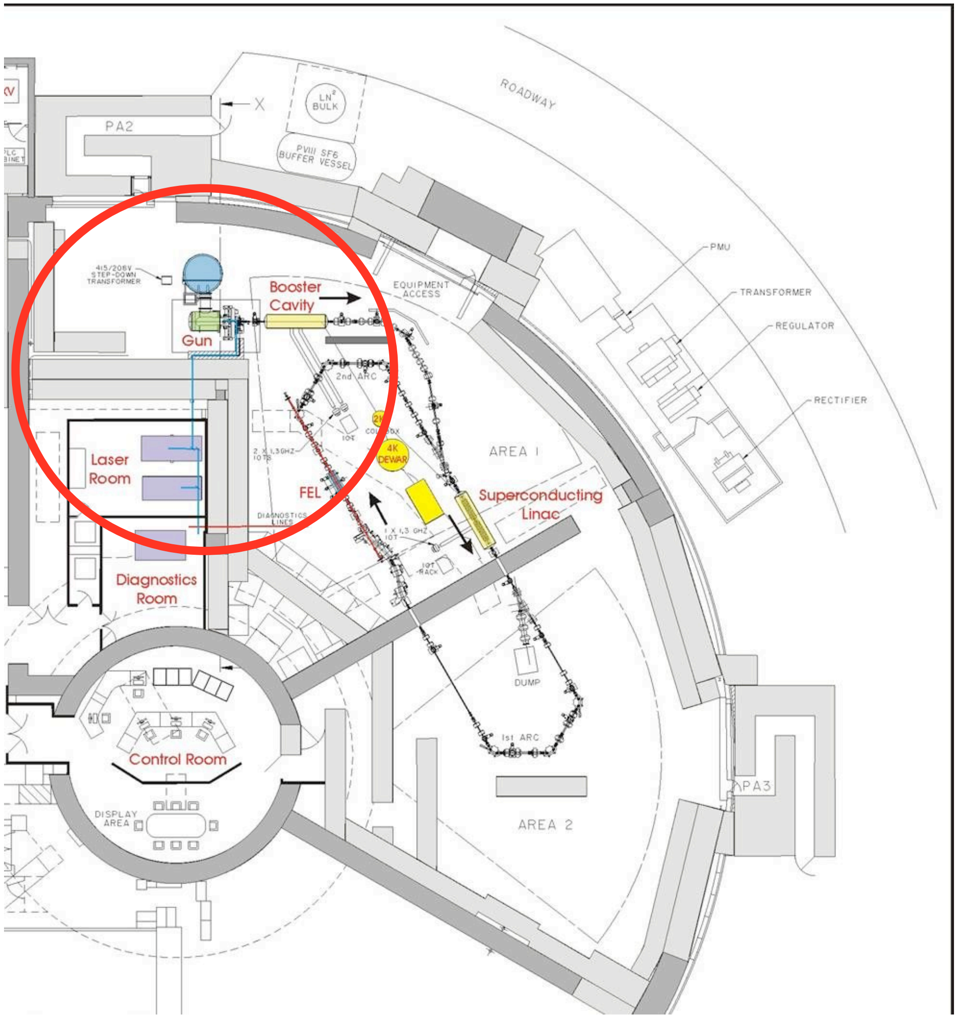
🟦 New Magnets
9 Dipoles
26 Quadrupoles
4 Sextupoles
39 off

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

Daresbury: ERL Prototype



Electron Beam Parameters	**Goal**
Energy (MeV)	30-50
Accelerator frequency (MHz)	1300
Charge per bunch (pC)	>80
Average current (_A)	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 (_ Joules)	9
Macropulse average laser power (kW)	0.7
Rep. Rate (MHz)	81.25
Macropulse length @20 Hz rep rate (_sec)	100

ERLs in High Energy and Nuclear Physics

- Electron cooling of hadron storage rings

The requirements:

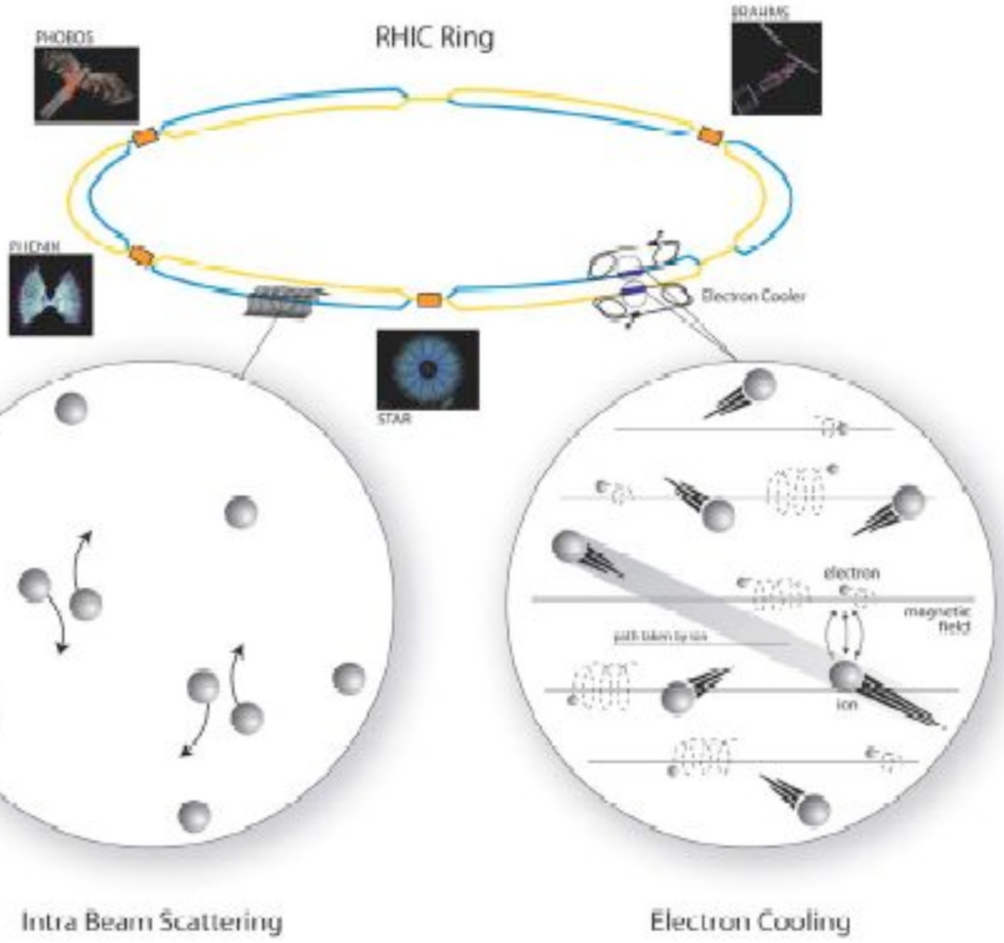
1. Low-energy
2. High brightness
3. High-Charge
4. High-current

- Provide electron beams for high-luminosity colliders.

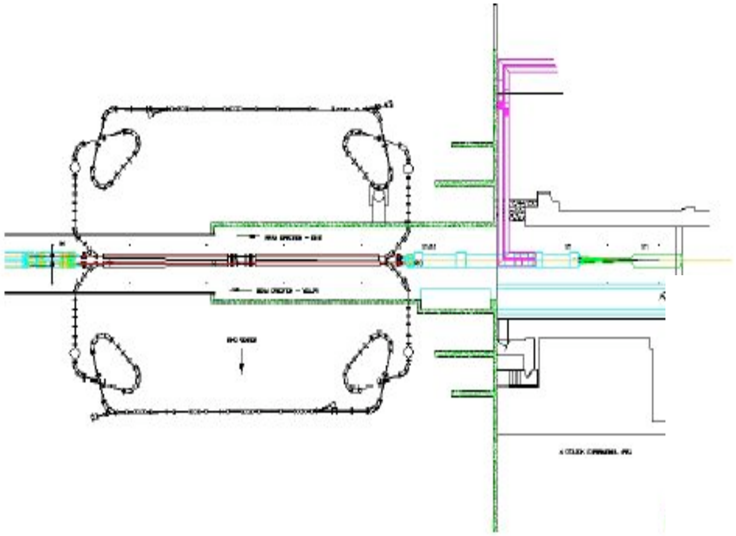
The requirements:

1. High-energy
2. Polarization
3. High-current

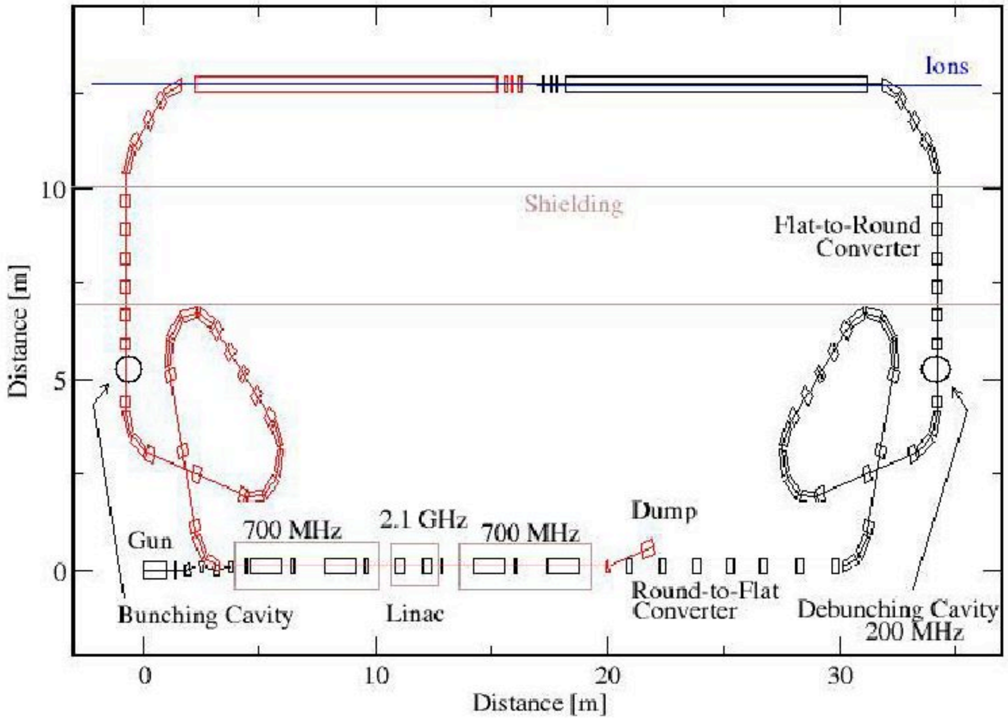
Electron Cooling



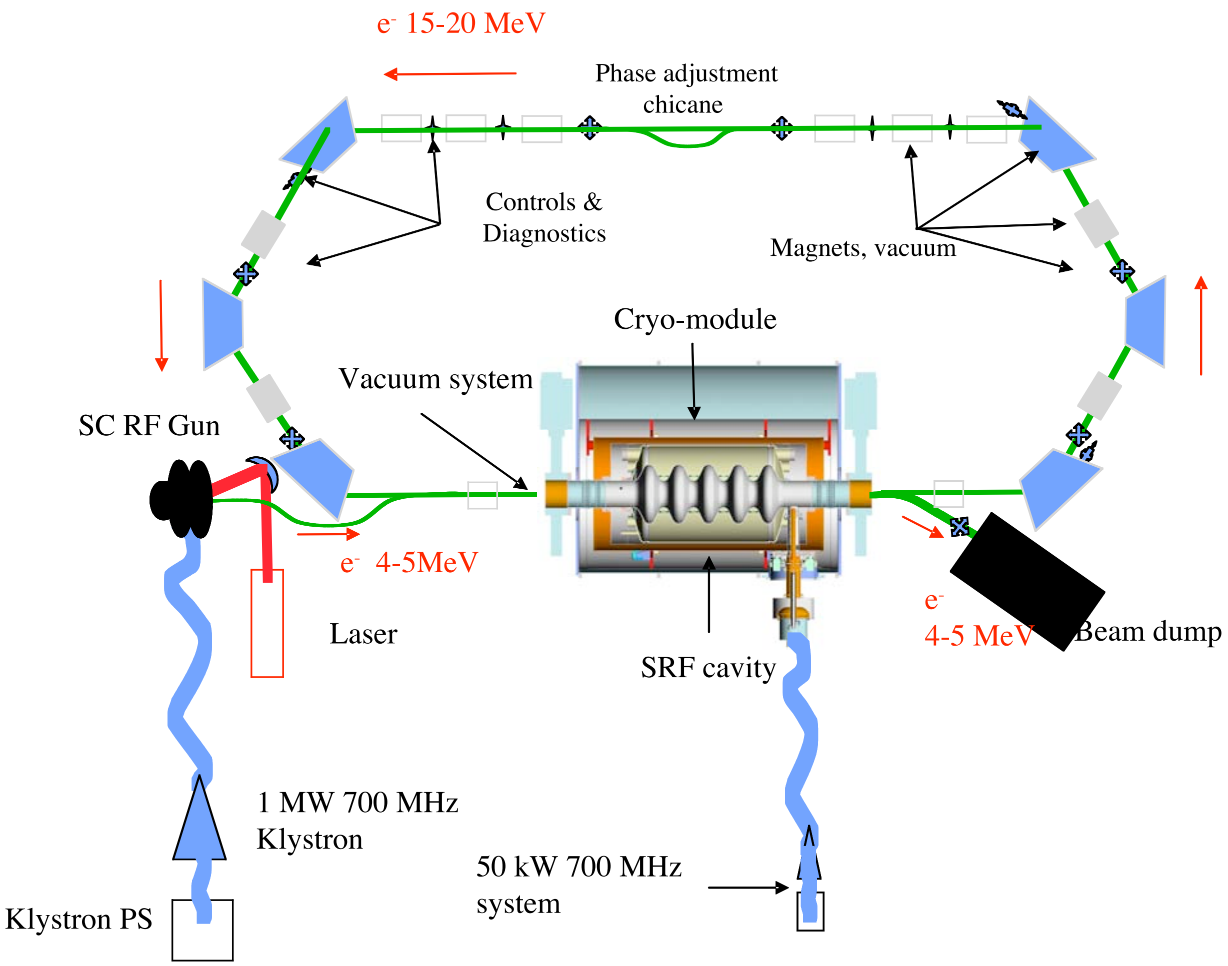
ERL-Based Electron Cooler



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

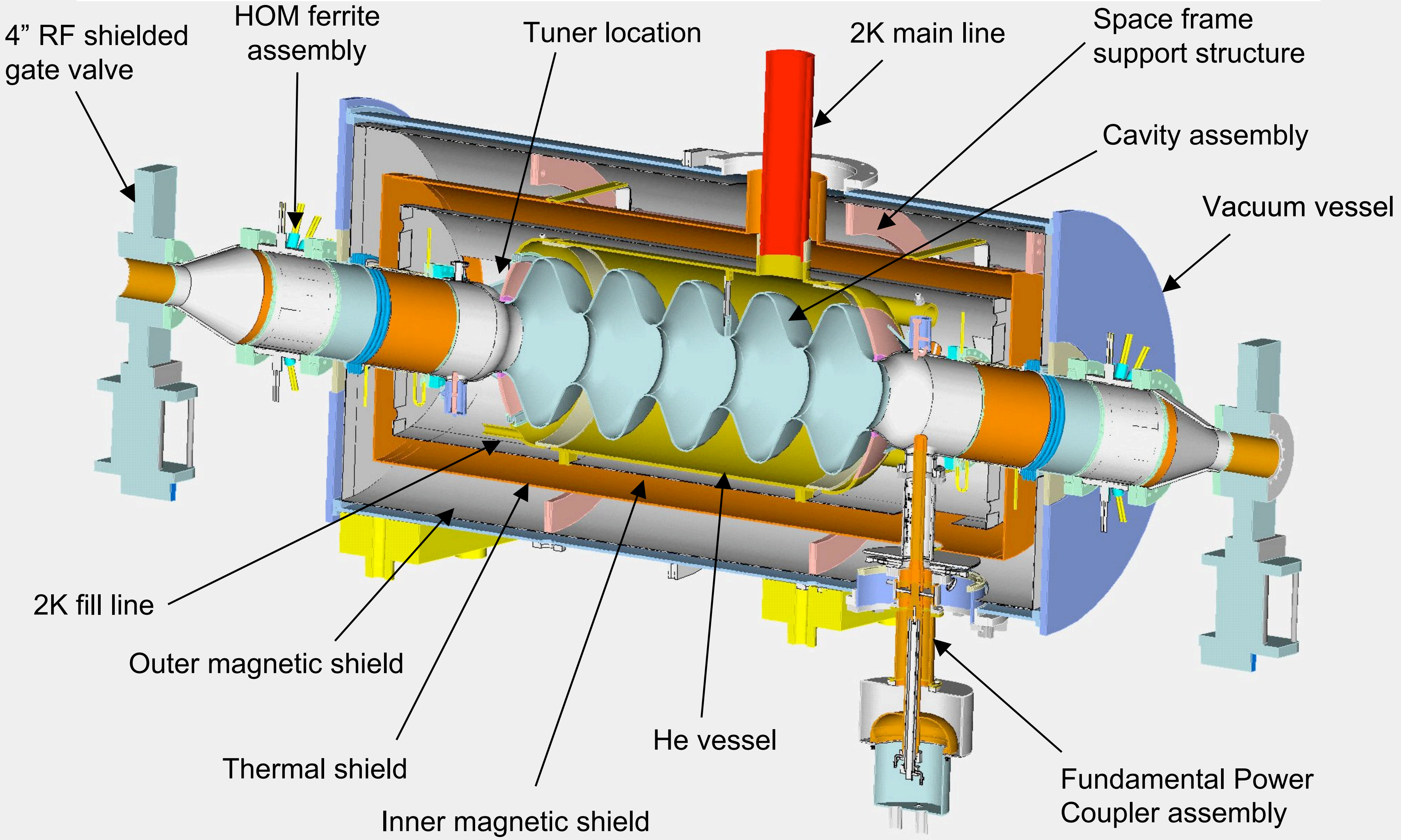


BNL ERL R&D Facility



ERL
Under construction

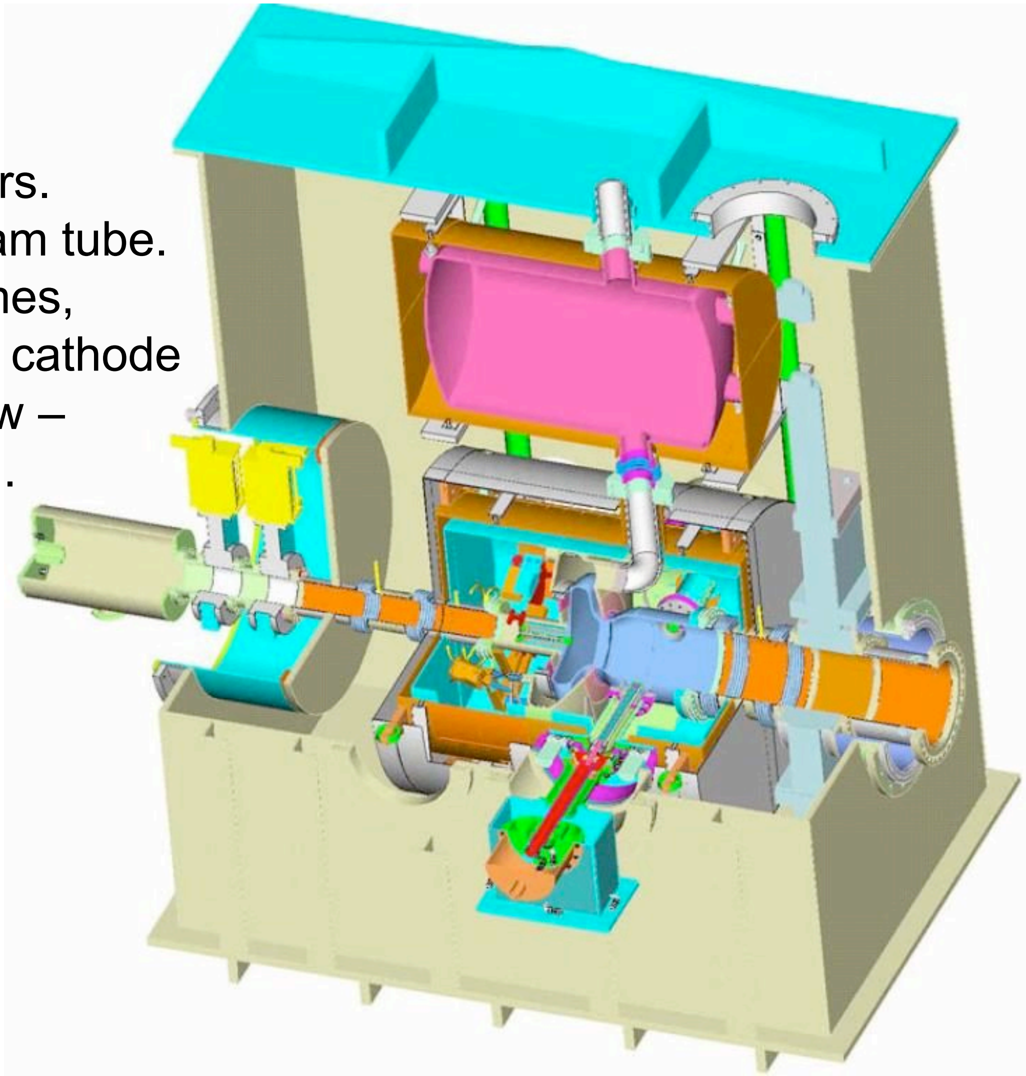
Cryomodule Design



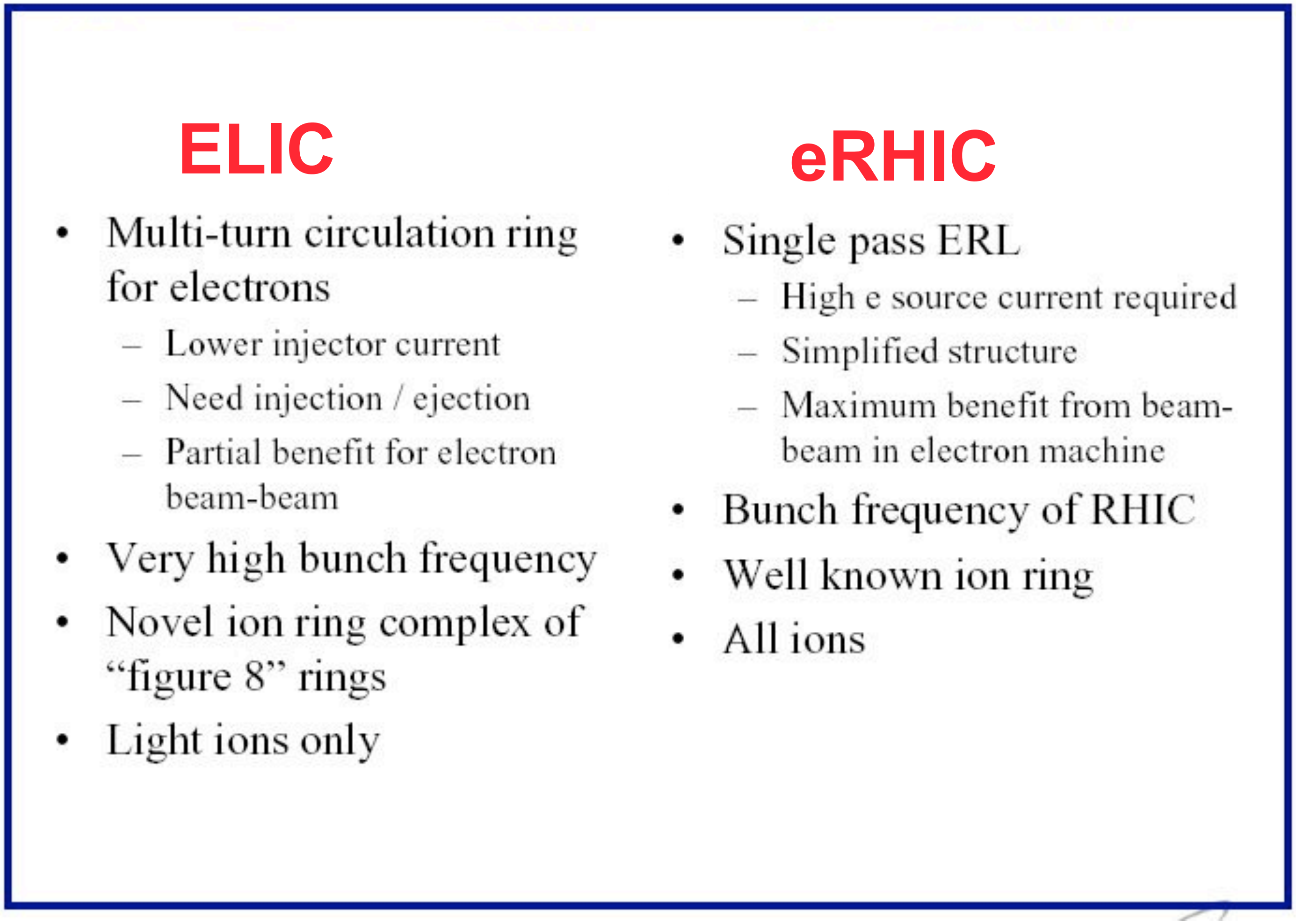
Superconducting RF gun under development

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.



Two Proposed Electron-Ion Colliders



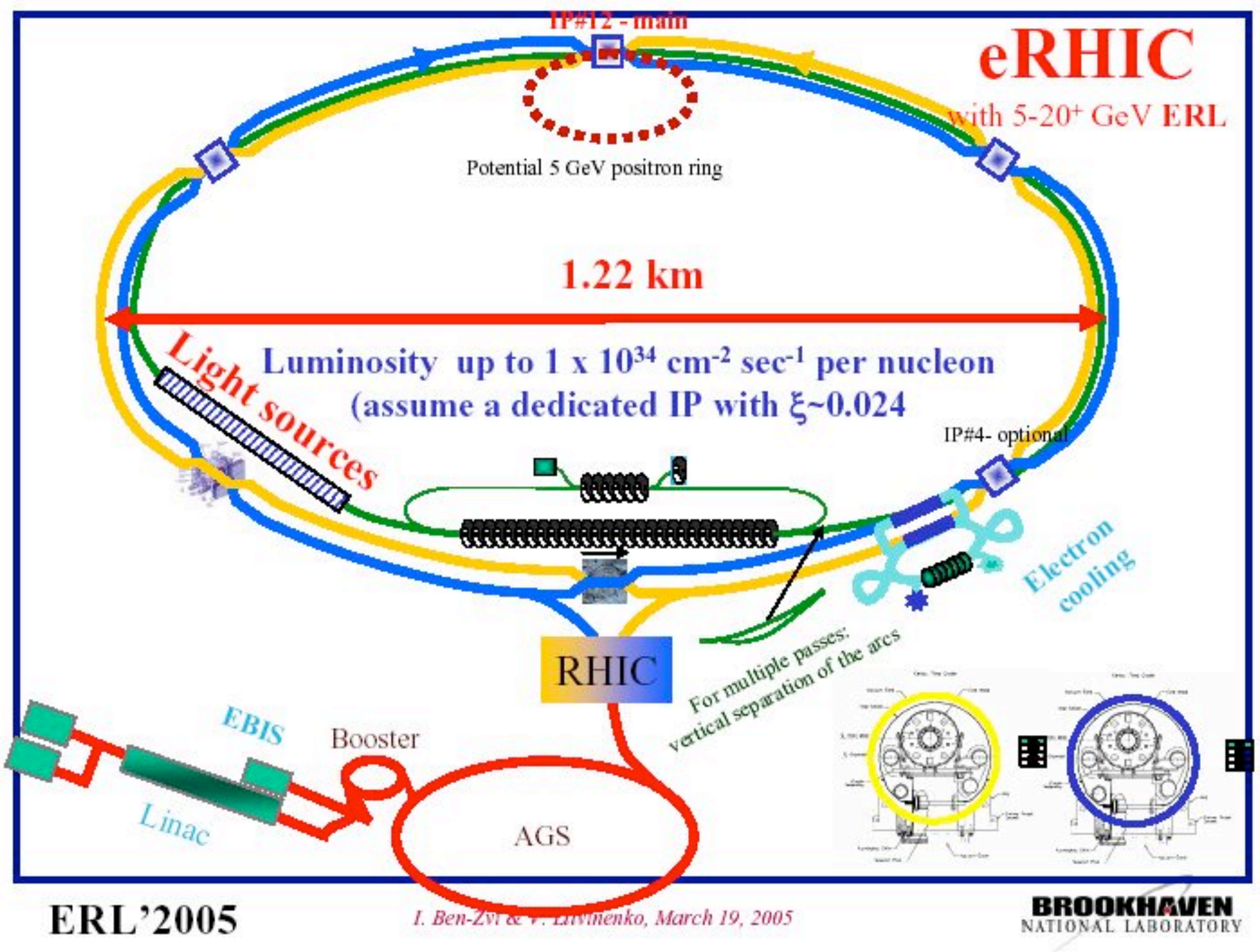
ELIC

- Multi-turn circulation ring for electrons
  - Lower injector current
  - Need injection / ejection
  - Partial benefit for electron beam-beam
- Very high bunch frequency
- Novel ion ring complex of “figure 8” rings
- Light ions only

eRHIC

- Single pass ERL
  - High e source current required
  - Simplified structure
  - Maximum benefit from beam-beam in electron machine
- Bunch frequency of RHIC
- Well known ion ring
- All ions

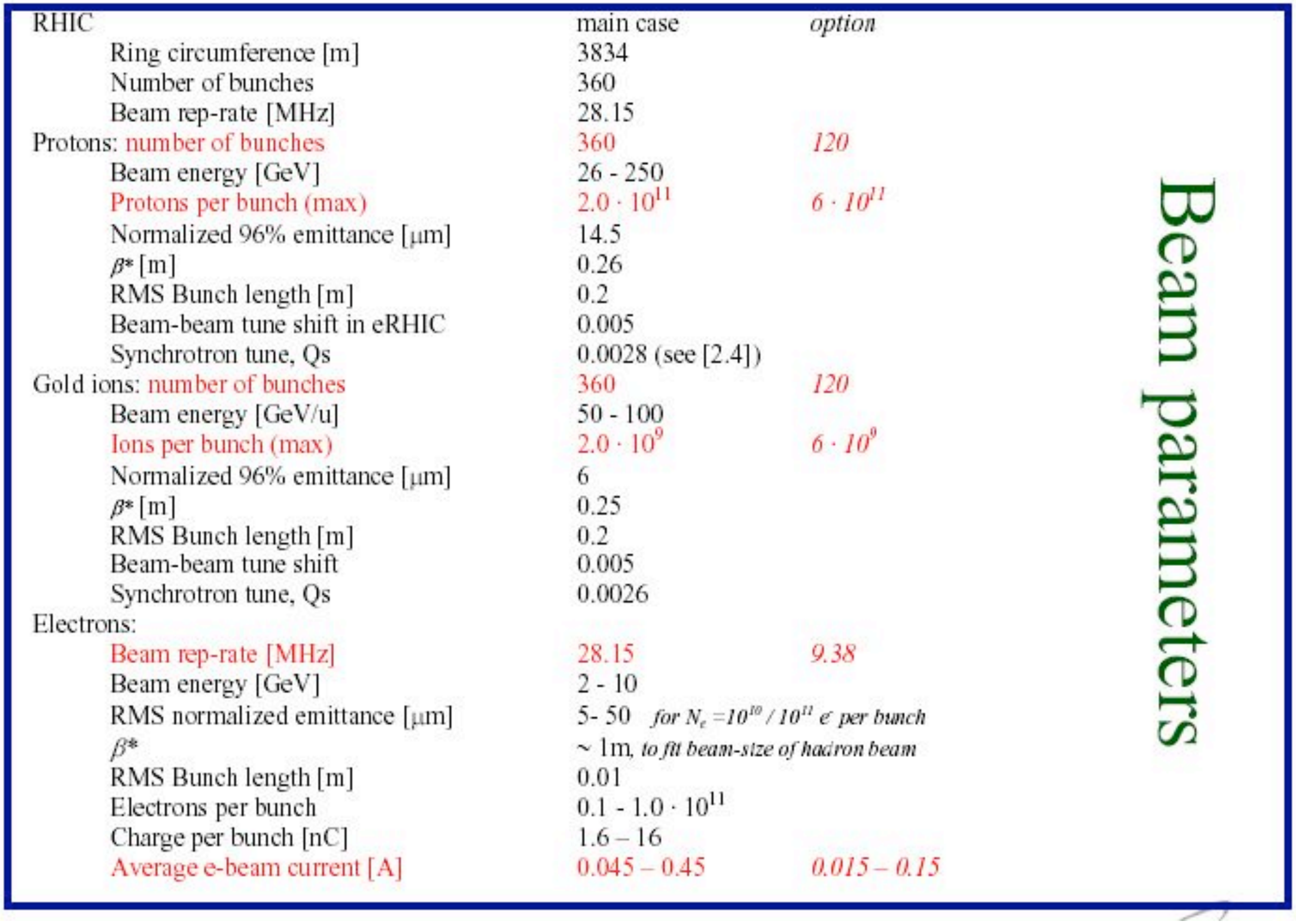
eRHIC



Luminosity up to 1 x 10^{34} cm^{-2} sec^{-1} per nucleon

(assume a dedicated IP with ξ~0.024

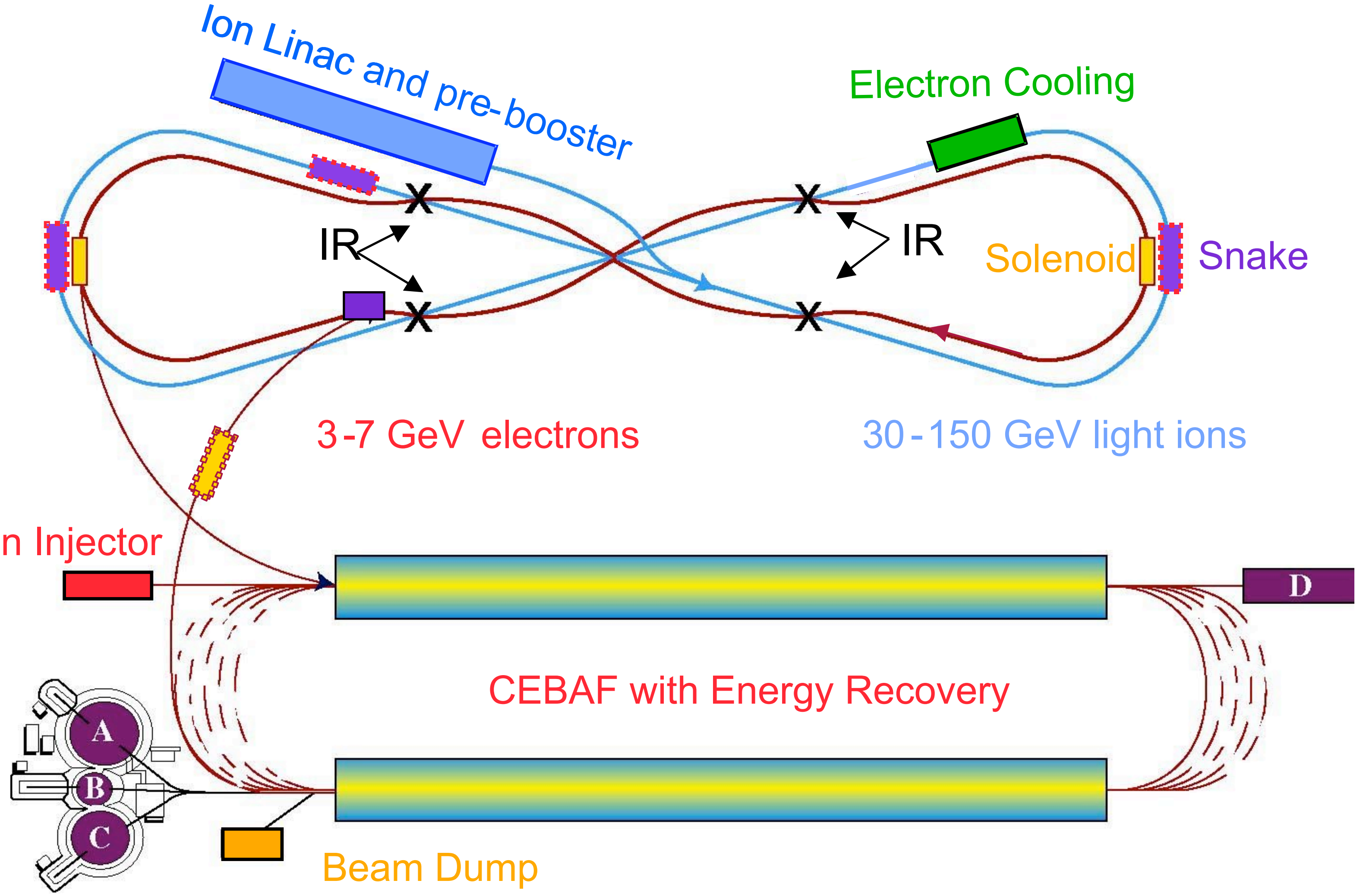
eRHIC Beam Parameters



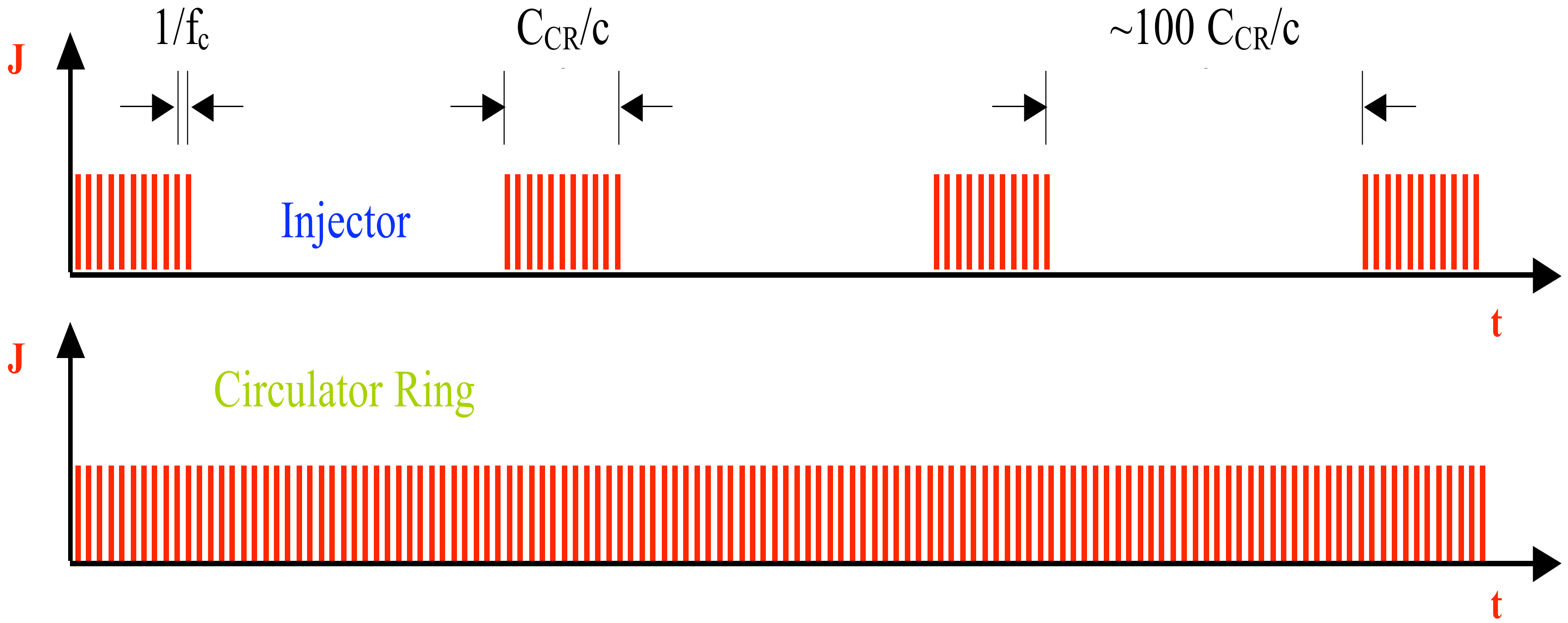
RHIC	main case	*option*
Ring circumference [m]	3834	
Number of bunches	360	
Beam rep-rate [MHz]	28.15	
Protons: number of bunches	360	*120*
Beam energy [GeV]	26 - 250	
Protons per bunch (max)	$2.0 \cdot 10^{11}$	$6 \cdot 10^{11}$
Normalized 96% emittance [μm]	14.5	
β^* [m]	0.26	
RMS Bunch length [m]	0.2	
Beam-beam tune shift in eRHIC	0.005	
Synchrotron tune, Qs	0.0028 (see [2.4])	
Gold ions: number of bunches	360	*120*
Beam energy [GeV/u]	50 - 100	
Ions per bunch (max)	$2.0 \cdot 10^{9}$	$6 \cdot 10^{9}$
Normalized 96% emittance [μm]	6	
β^* [m]	0.25	
RMS Bunch length [m]	0.2	
Beam-beam tune shift	0.005	
Synchrotron tune, Qs	0.0026	
Electrons:		
Beam rep-rate [MHz]	28.15	*9.38*
Beam energy [GeV]	2 - 10	
RMS normalized emittance [μm]	5- 50 *for* $N_e = 10^{10} / 10^{11}$ e^- *per bunch*	
β^*	~ 1m, *to fit beam-size of hadron beam*	
RMS Bunch length [m]	0.01	
Electrons per bunch	$0.1 - 1.0 \cdot 10^{11}$	
Charge per bunch [nC]	1.6 – 16	
Average e-beam current [A]	0.045 – 0.45	*0.015 – 0.15*

Beam parameters

ELIC Design


Ion Linac and pre-booster
Electron Cooling
IR
IR
Solenoid
Snake
3-7 GeV electrons
30-150 GeV light ions
Electron Injector
D
CEBAF with Energy Recovery
A
B
C
Beam Dump

Circulator Ring



ELIC Parameters at different CM energies

Parameter	Unit	Value	Value	Value
Beam energy	**GeV**	**150/7**	**100/5**	**30/3**
Cooling beam energy	**MeV**	**75**	**50**	**15**
Bunch collision rate	**GHz**	**1.5**		
Number of particles/bunch	**10^{10}**	**.4/1.0**	**.4/1.1**	**.12/1.7**
Beam current	**A**	**1/2.4**	**1/2.7**	**.3/4.1**
Cooling beam current	**A**	**2**	**2**	**.6**
Energy spread, rms	**10^{-4}**	**3**		
Bunch length, rms	**mm**	**5**		
Beta-star	**mm**	**5**		
Horizontal emittance, norm	**?m**	**1/100**	**.7/70**	**.2/43**
Vertical emittance, norm	**?m**	**.04/4**	**.06/6**	**.2/43**
Number of interaction points		**4**		
Beam-beam tune shift (vertical) per IP		**.01/.086**	**.01/.073**	**.01/.007**
Space charge tune shift in p-beam		**.015**	**.03**	**.06**
Luminosity per IP*, 10^{34}	**cm^{-2} s^{-1}**	**7.7**	**5.6**	**.8**
Core & luminosity IBS lifetime	**h**	**24**	**24**	**? 24**
Lifetime due to background scattering	**h**	**200**	**? 200**	**? 200**

Luminosity Evolution of ELIC

Parameter	Unit	Value	Value	Value
Beam energy	**GeV**	**150/7**		
Cooling beam energy	**MeV**	**75**		
Bunch collision rate	**GHz**	**.15**	**.5**	**1.5**
Number of particles/bunch	**10^{10}**	**.4/1.0**		
Beam current	**A**	**.1/.24**	**.3/.8**	**1/2.4**
Cooling beam current	**A**	**.2**	**.6**	**2**
Energy spread, rms	**10^{-4}**	**3**		
Bunch length, rms	**mm**	**25/5**	**10/5**	**5/5**
Beta-star	**mm**	**25**	**10**	**5**
Horizontal emittance, norm	**?m**	**1/100**		
Vertical emittance, norm	**?m**	**.04/4**		
Number of interaction points		**4**		
Beam-beam tune shift (vertical) per IP		**.01/.086**	**.01/.086**	**.01/.086**
Space charge tune shift in p-beam		**.003**	**.007**	**.015**
Luminosity per IP *, 10^{34}	**cm^{-2} s^{-1}**	**.15**	**1.2**	**7.7**

Summary

- 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 projects and proposals worldwide promises an exciting next decade as:
  - Three currently operating ERL-FELs will reach higher performance
  - At least five more ERLs are in serious planning stages and will likely be constructed
  - New advanced concepts are being explored; most of the applications need high average brightness beams

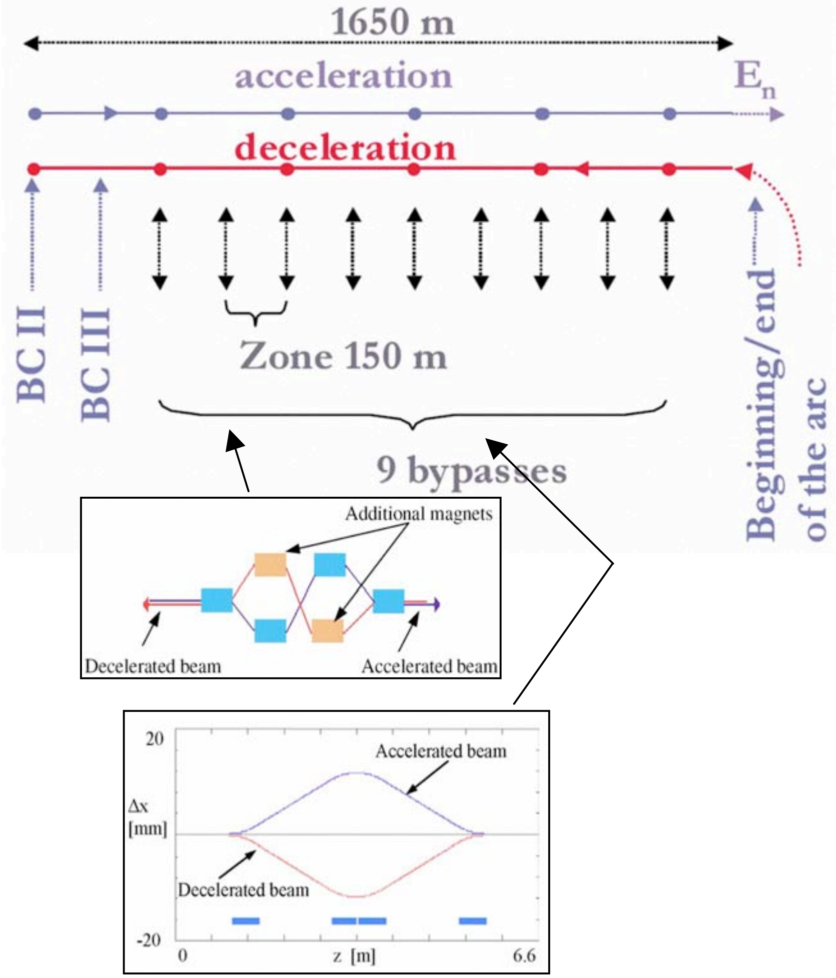
Sources

Many thanks to

- Ivan Bazarov
- Lia Merminga
- Todd Smith
- Ilan Ben-Zvi
- Susan Smith

for providing information/slides for this talk

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



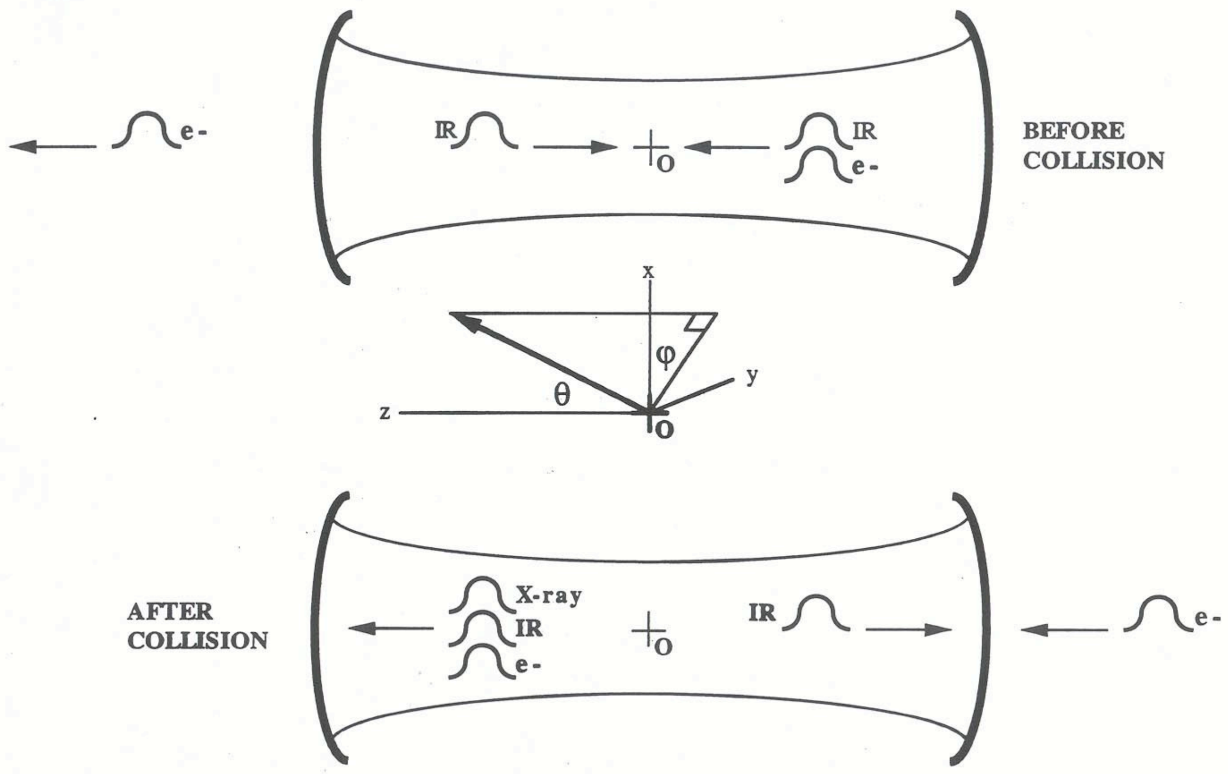
At a 1 MHz rep rate there are 6 bunches in the ERL at a given time, thus 12 collision locations separated by 150 meters.

The proposed solution is to avoid collisions altogether!

Three suggested beam time structures:

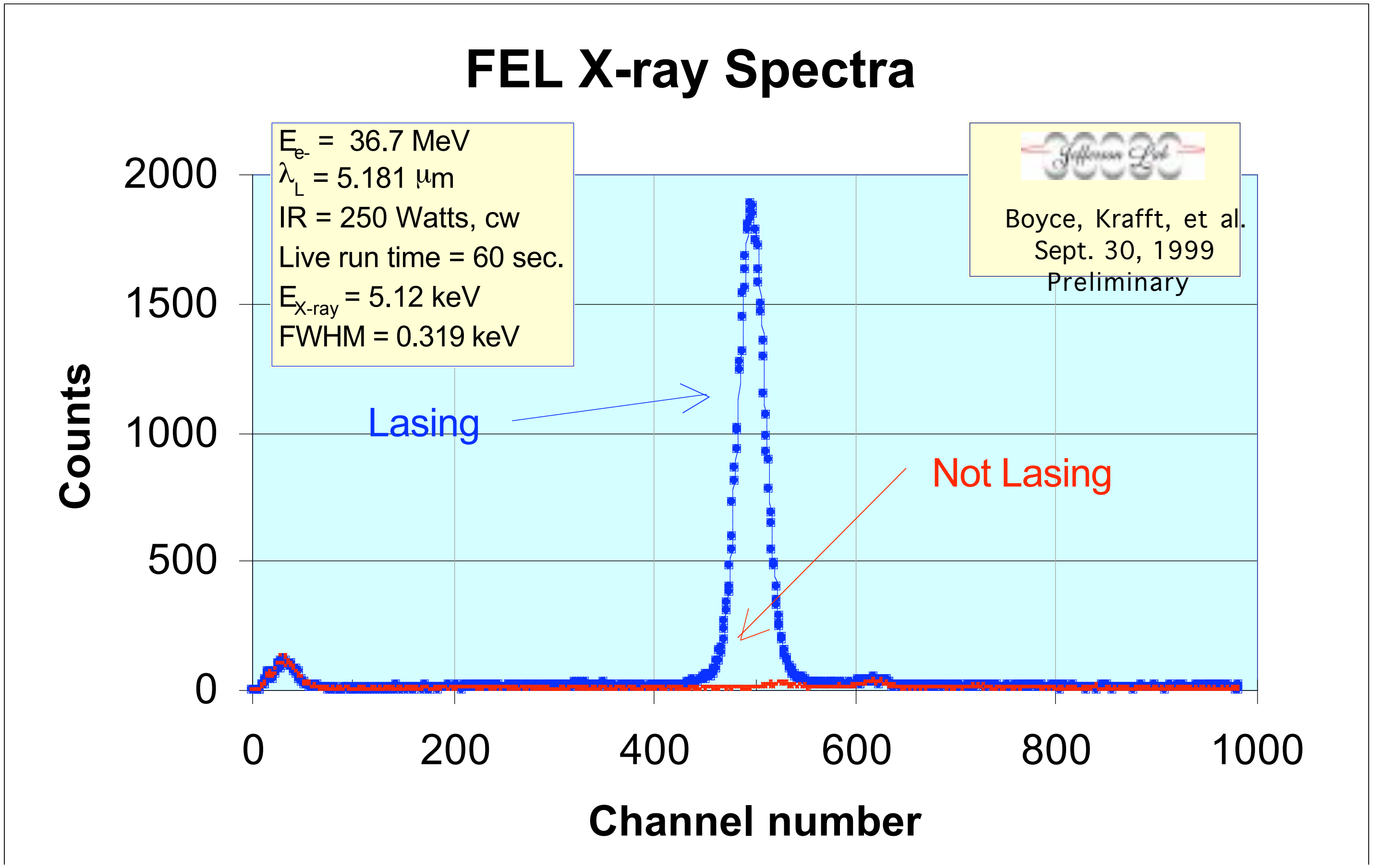
- Nominal beam: 1 μpulse every μs
- Short trains of bunches: The bypass chicanes are about 4.5 m in length. Bunch trains of this length (~20 RF cycles, 15 ns) can repeat every μs without colliding.
- Long trains: The return arc plus the straight section for undulators is about 2000 m long. A 6.7 μ s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

Thomson Source Scattering Geometry



SCATTERING GEOMETRY

60 sec FEL Short-pulse X-ray Spectrum



E_{e-} = 36.7 MeV
λ_L = 5.181 μm
IR = 250 Watts, cw
Live run time = 60 sec.
$E_{X\text{-ray}}$ = 5.12 keV
FWHM = 0.319 keV

Boyce, Krafft, et al.
Sept. 30, 1999
Preliminary