JLab ERL, 802 MHZ cavity design, and Polarized Source

Andrew Hutton

Jefferson Lab

Jefferson Lab IR Demo Free-electron Laser

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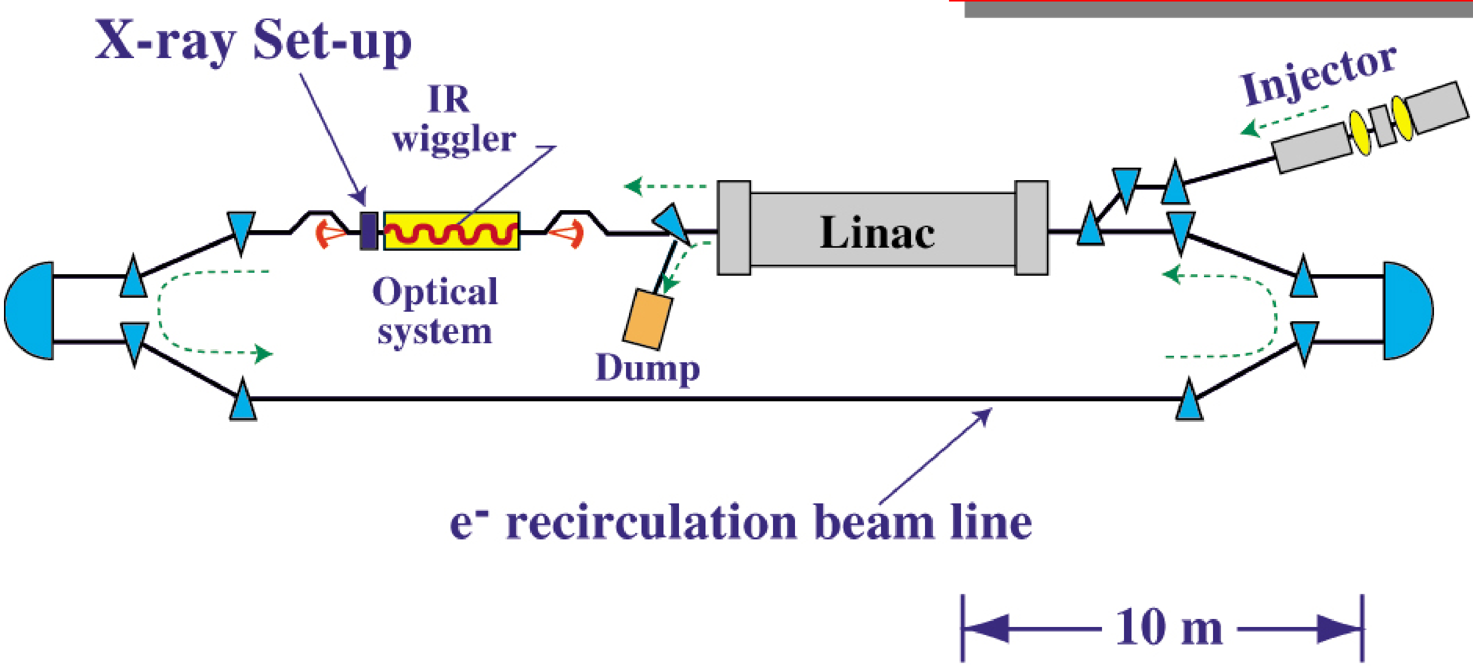
Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery

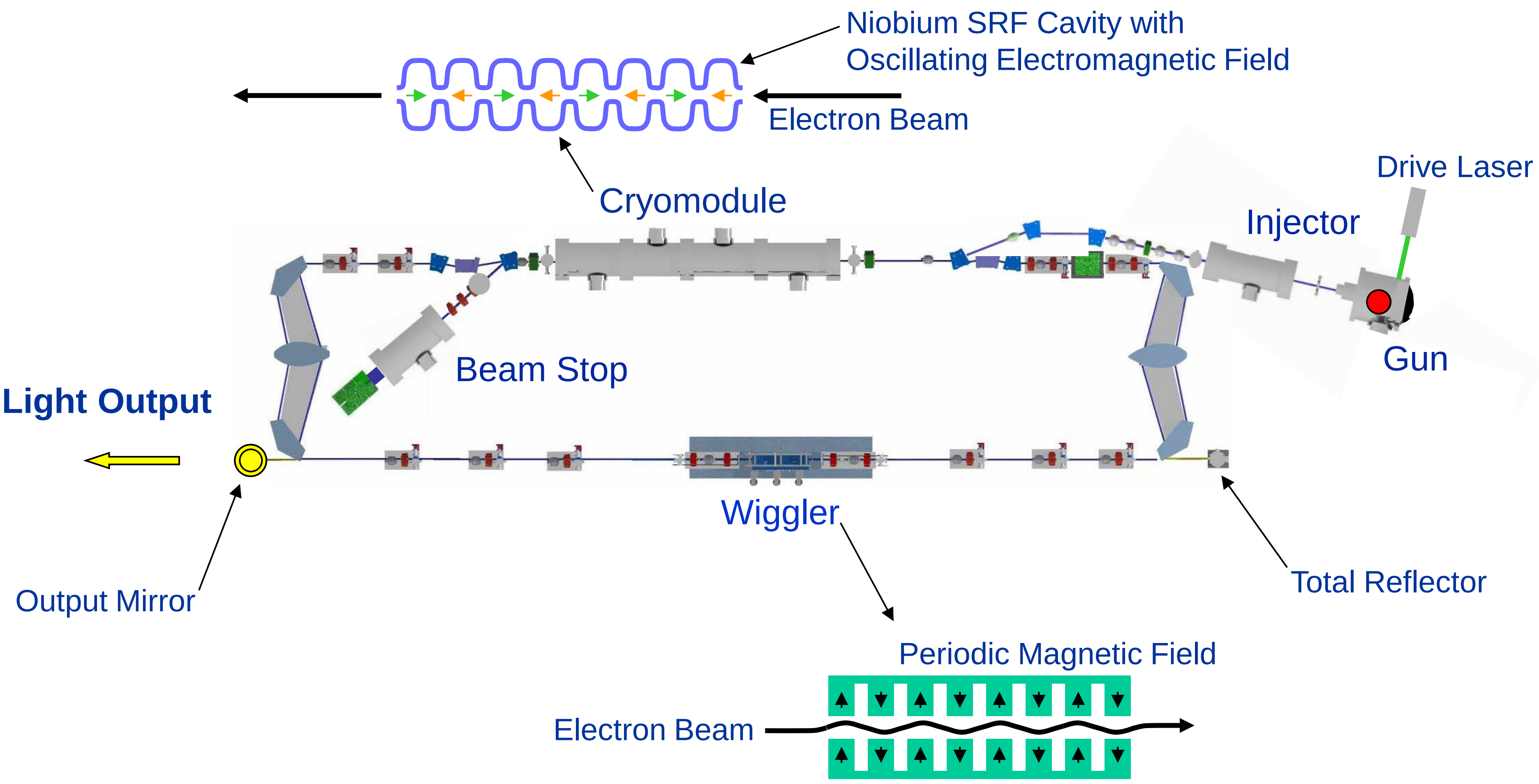
G. R. Neil,* C. L. Bohn, S. V. Benson, G. Biallas, D. Douglas, H. F. Dylla, R. Evans, J. Fugitt, A. Grippo, J. Gubeli, R. Hill, K. Jordan, R. Li, L. Merminga, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn
Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606
(Received 3 September 1999)

FEL Specifications

- 2 – 8 microns at > 1 kW average power
- sub-picosecond pulse length
- up to 75 MHz rep rate
- 3-40 keV sub picosecond x-rays

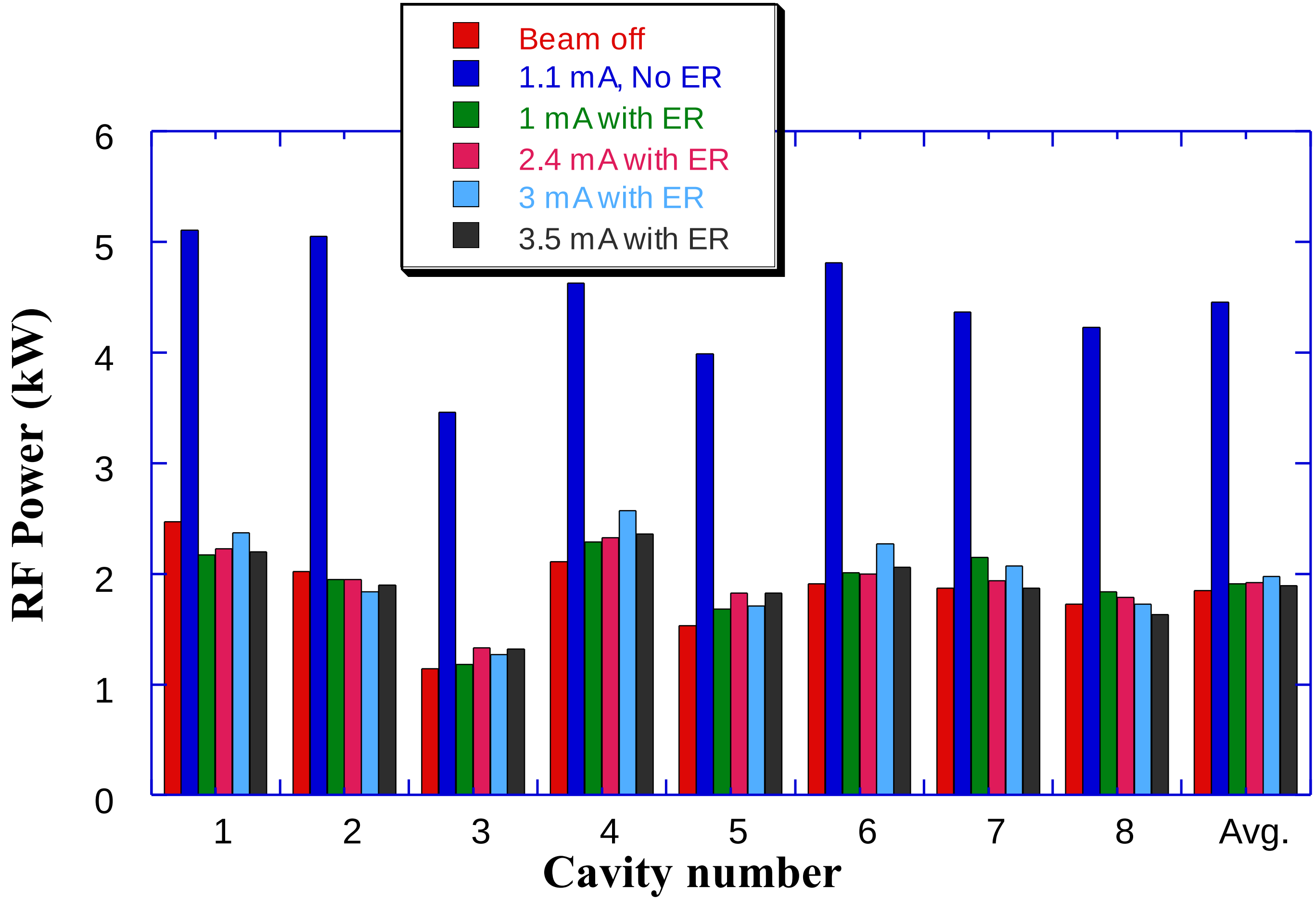


Free Electron Laser Operation in ERL



ENERGY RECOVERY WORKS

- Required RF rises from 14.8 kW with beam off to 15.2 kW with energy recovery at 3.5 mA but rises to 35.7 kW with no recovery at 1.1 mA



Benefits of Energy Recovery

AC Power Draw in IR Upgrade: 10 kW FEL output

Beam 10 mA, 160 MeV

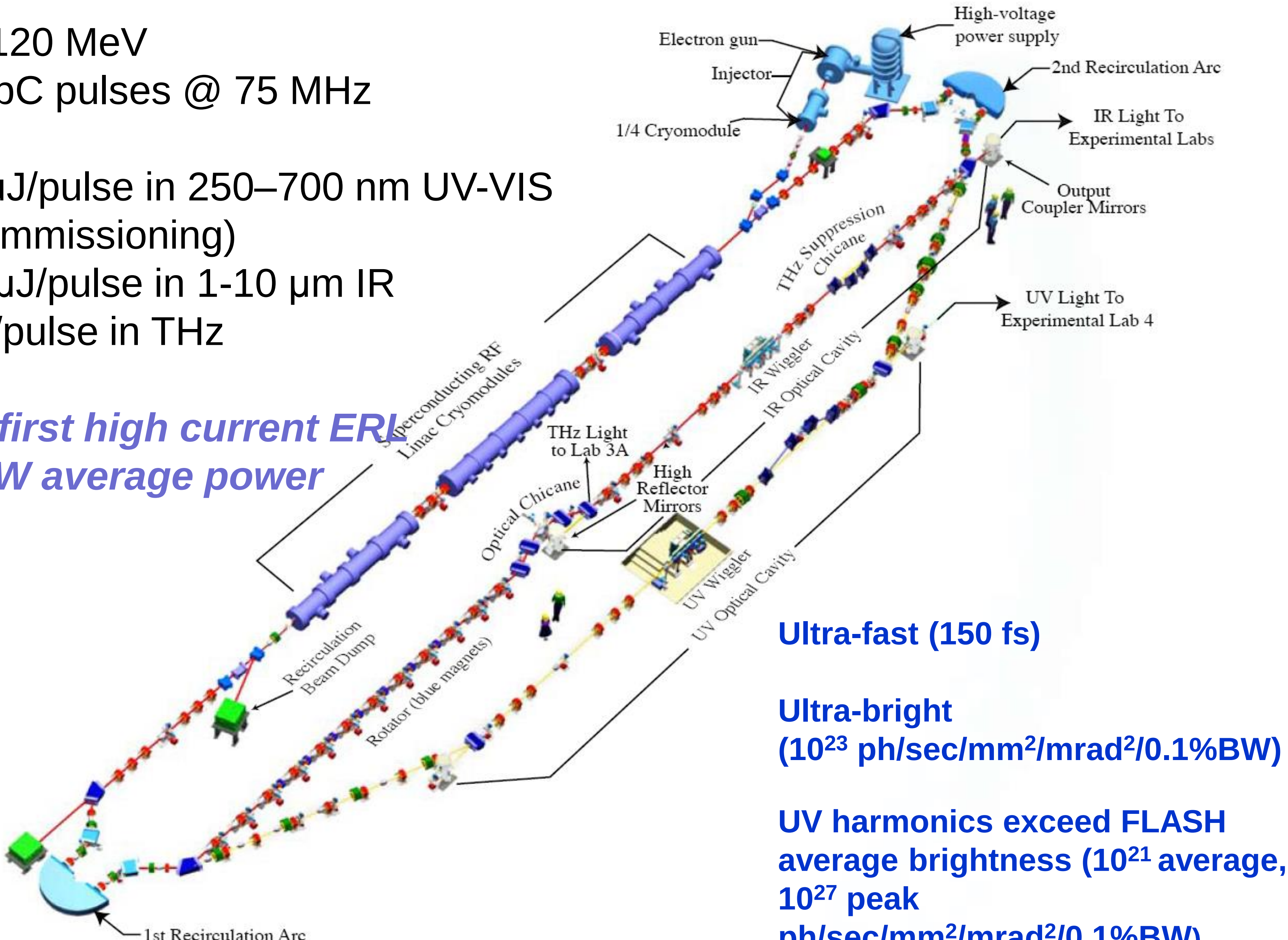
Component	With Energy Recovery	Without Energy Recovery (estimates)	
Injector RF	350 kW	350 kW	
Linac RF	525 kW	4200 kW	
He Refrigerator	100 kW	100 kW	
Magnets, Computers, etc.	100 kW	40 kW	
Total	1075 kW	4690 kW	

Existing JLab 4th Generation IR/UV Light Source

E = 120 MeV
135 pC pulses @ 75 MHz

(20 μJ/pulse in 250–700 nm UV-VIS in commissioning)
120 μJ/pulse in 1-10 μm IR
1 μJ/pulse in THz

The first high current ERL
14 kW average power

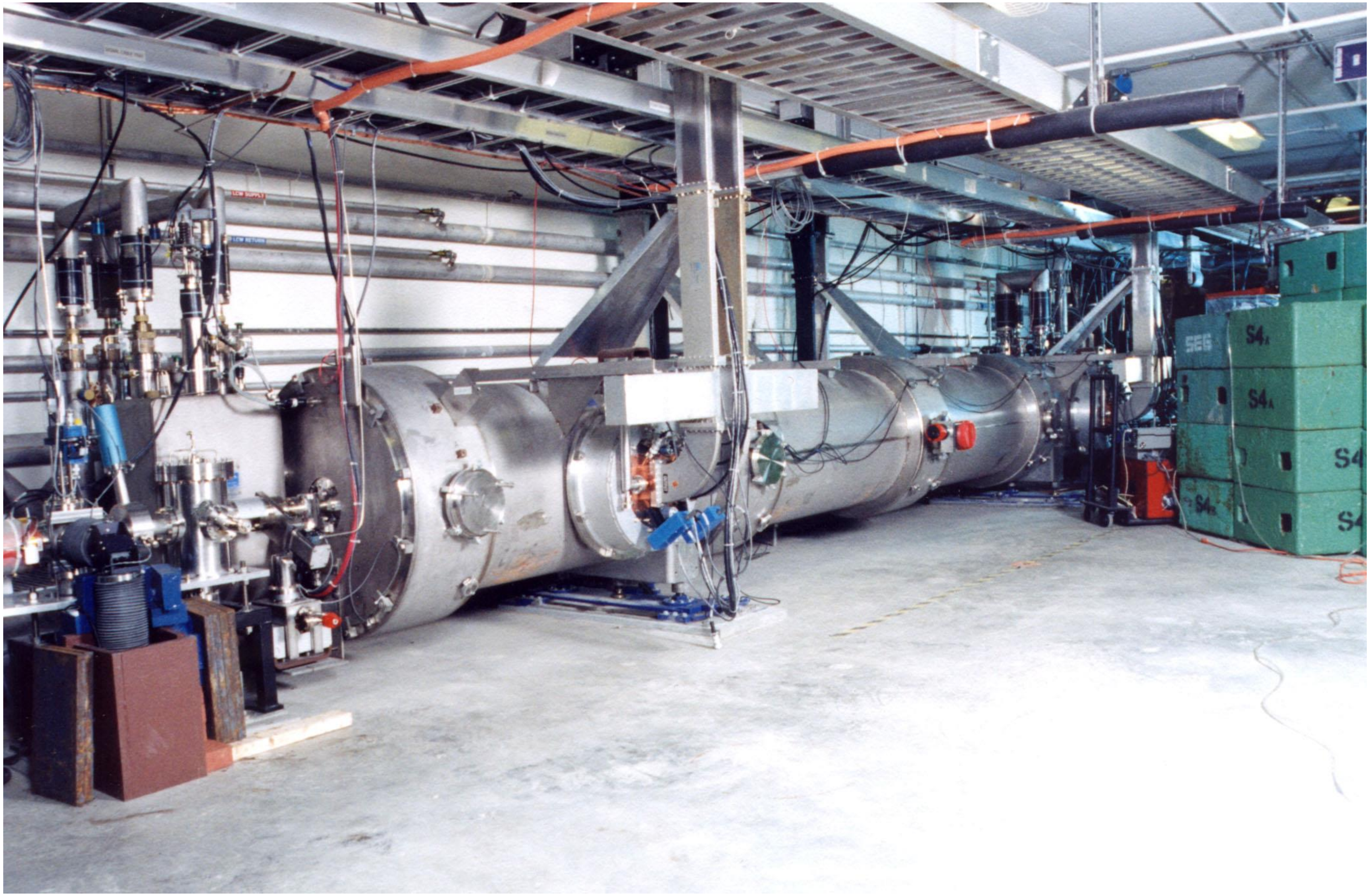


Ultra-fast (150 fs)

Ultra-bright
(10^{23} ph/sec/mm^2/mrad^2/0.1%BW)

UV harmonics exceed FLASH average brightness (10^{21} average, 10^{27} peak ph/sec/mm^2/mrad^2/0.1%BW)

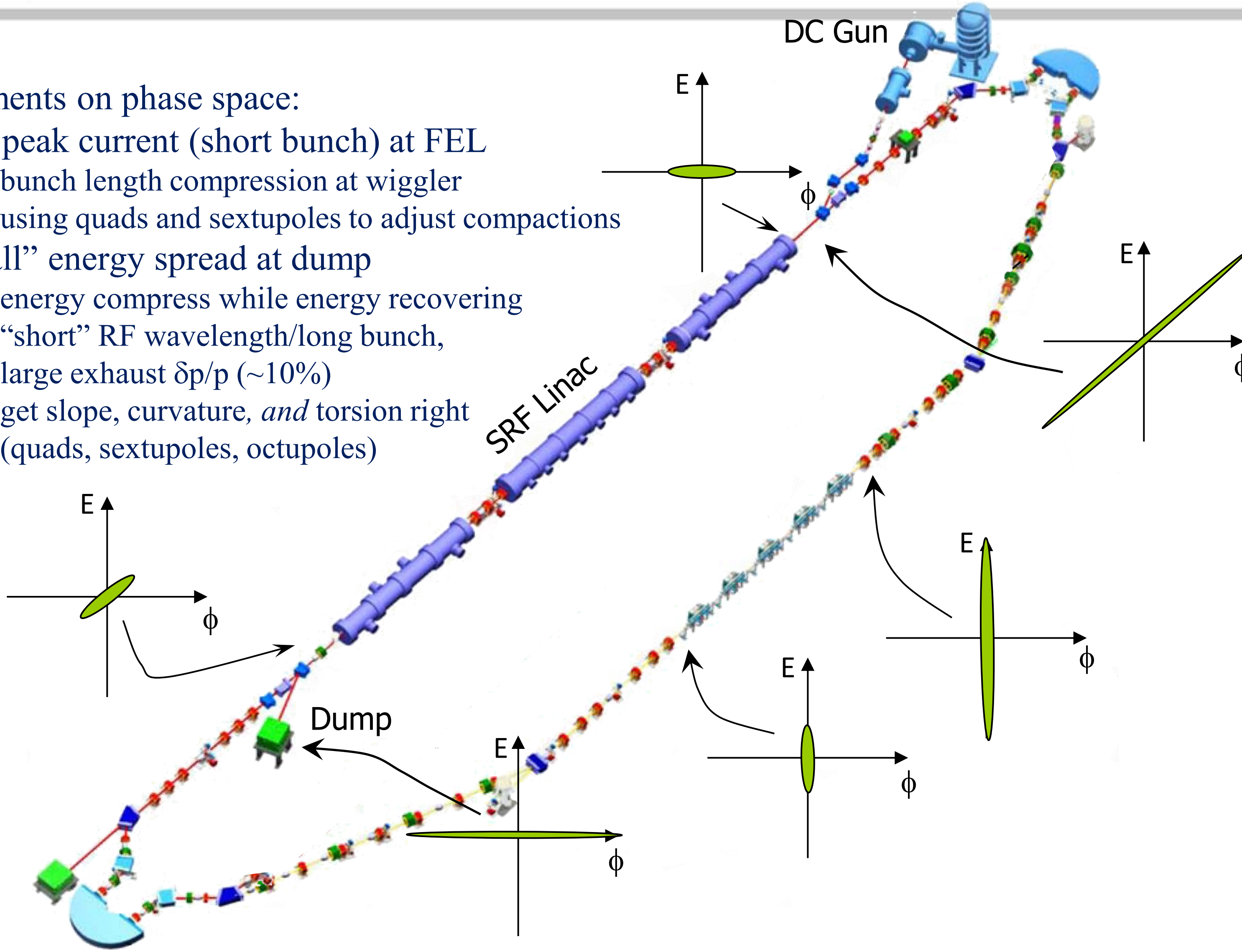
Jefferson Lab FEL Superconducting Linac



Longitudinal Matching Scenario

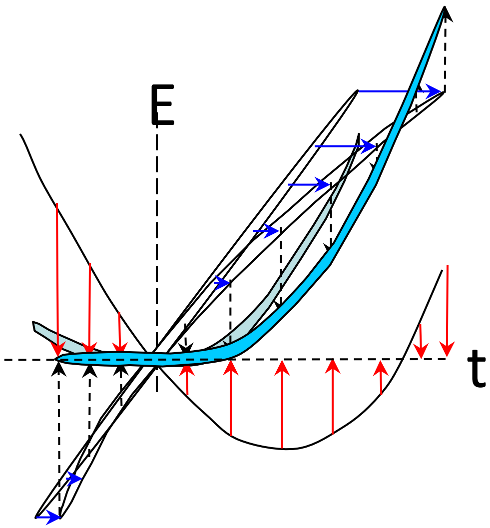
Requirements on phase space:

- high peak current (short bunch) at FEL
  - bunch length compression at wiggler
    using quads and sextupoles to adjust compactions
- "small" energy spread at dump
  - energy compress while energy recovering
  - "short" RF wavelength/long bunch,
    large exhaust $\delta p/p$ (~10%)
  - ⇒ get slope, curvature, *and* torsion right
    (quads, sextupoles, octupoles)



Higher Order Corrections

- Without nonlinear corrections, phase space becomes distorted during deceleration
- Curvature, torsion,… can be compensated by nonlinear adjustments
  - differentially move phase space regions to match gradient required for energy compression
- Required phase bite is $\cos^{-1}(1-\Delta E_{FEL}/E)$; this is >25° at the RF fundamental for 10% exhaust energy spread, >30° for 15%
  - typically need 3rd order corrections (octupoles)
  - also need a few extra degrees for tails, phase errors & drifts, irreproducible & varying path lengths, etc, so that system operates reliably
- In this context, harmonic RF very hard to use…



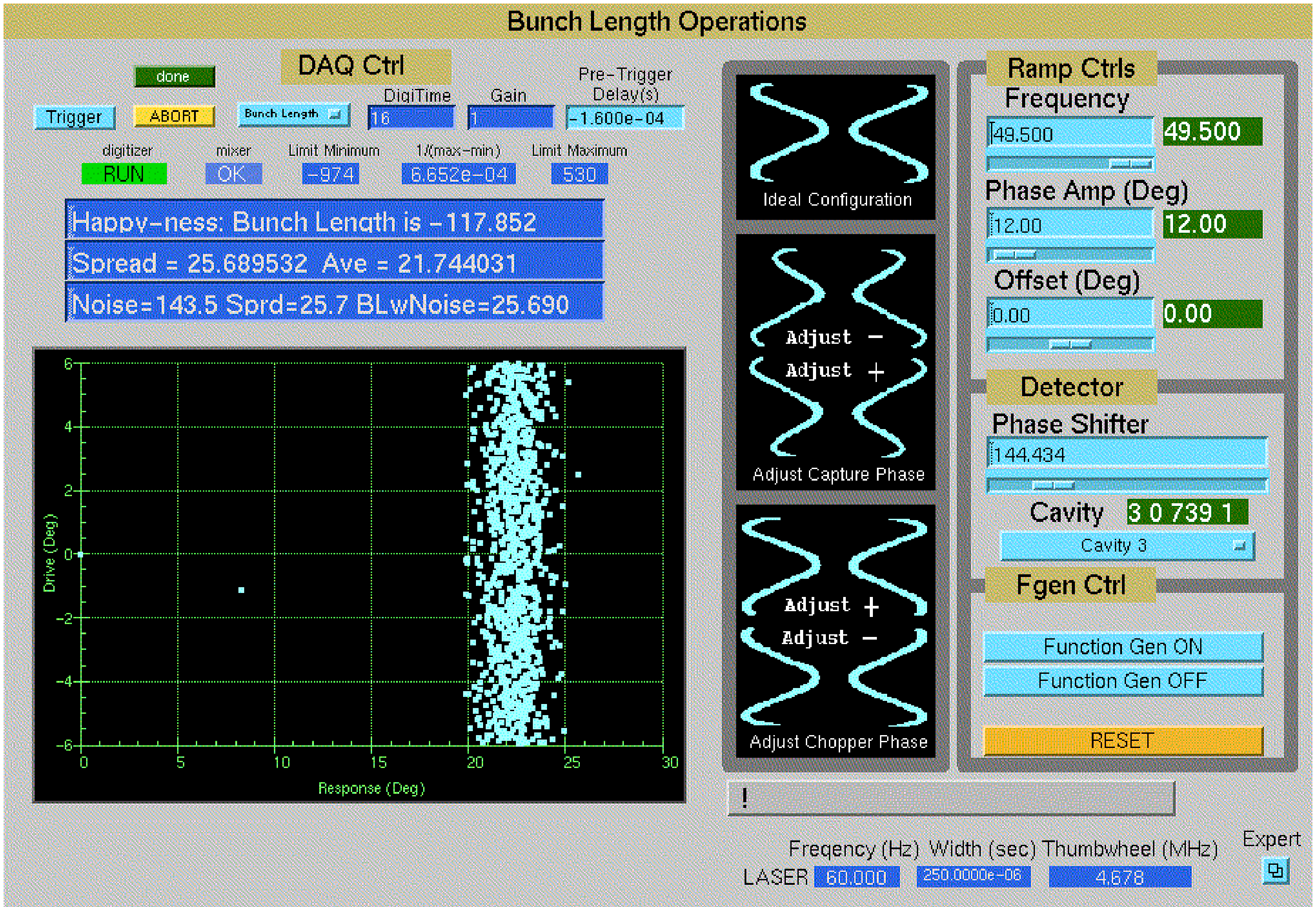
$$M_{56} = -\frac{\lambda_{RF}}{2\pi}\left(\frac{E_0}{E_{linac}}\right)\frac{1}{\sin\phi_0}$$

$$T_{566} = -\frac{1}{2}\left(\frac{2\pi}{\lambda_{RF}}\right)(M_{56})^2\frac{\cos\phi_0}{\sin\phi_0}$$

$$W_{5666} = -\left[\frac{1}{6}+\frac{1}{2}\frac{\cos^2\phi_0}{\sin^2\phi_0}\right]\left(\frac{2\pi}{\lambda_{RF}}\right)^2(M_{56})^3$$

$$U_{56666} \propto \left(\frac{2\pi}{\lambda_{RF}}\right)^3(M_{56})^4, \text{etc.}$$

The M55 cavity system can map out phase response of any of the elements in the injector



Major R&D Efforts Around the World

- Injector, injector, injector! No existing injector delivers required CW brightness. Many groups are working on this: LBNL, Cornell, Wisconsin, JLab, KEK, Daresbury, BNL, PKU…
- Brightness preservation: Solutions to coherent synchrotron radiation (CSR) emittance degradation, longitudinal space charge (LSC) in pulse compression
- Halo control essential for CW – non-Gaussian tails!!! < 1μA local loss allowed
- High order mode & beam breakup control in cavities
- Wakefield and propagating mode damping

High HOM power lost at srf temps?

- Handling sizeable (~ 20 kW! @ 100 mA) THz radiation in bends
- Resistive wall heating in undulators 100W/m at 4mA on JLab IR FEL
- Reducing srf dynamic load to lower refrigerator costs; probably more important than increasing gradient

JLab FEL Accelerator Capabilities

	Near Term Capability	Full Capability	Internal Target (Near Term)
	external target	external target	internal target
E (MeV)	80-320	80-610	80-165
P_{max} (kW)	**100**	**300**	**1650**
I (mA)	0.31-**1.25**	0.5/**3.75**	**10**
f_{bunch} (MHz)	750/75	750/75	750/75
Q_{bunch} (pC)	1.67-0.4/16.7-4	5-0.67/50-6.7	13.5/135
$\varepsilon_{transverse}$ (mm-mrad)	~1/~3	~2/~5	~3/~10
$\varepsilon_{longitudinal}$ (keV-psec)	~5/~15	~10/~25	~15/~50
Polarization	No	**Up to 600 μA**	No
	750 MHz drive laser; single F100	12 GeV RF drive; three F100s	12 GeV RF drive; three F100s

High Dynamic Range Diagnostic Development is Essential

Four sorts of the unwanted beam (beam *halo*)

1. Fraction of the phase space distribution that is far away from the core (due to the beam dynamics)

1. Low charge due to not well attenuated Cathode Laser (ERLs) – but real bunches that have proper timing for acceleration

1. Due to the Cathode Laser but not properly timed (scattered and reflected light)

1. Field emission: Gun (can be DC or RF), Accelerator itself (can be accelerated in both directions)

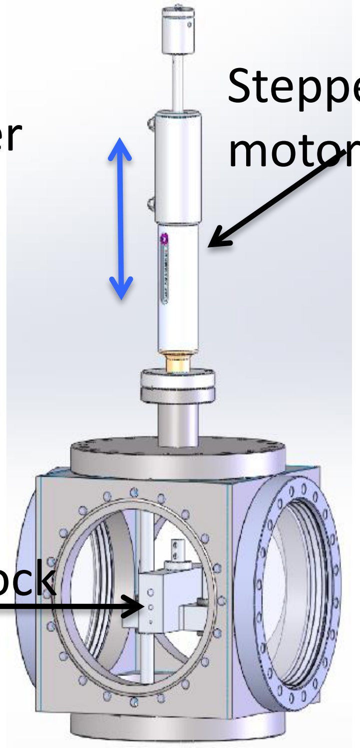
Evtushenko

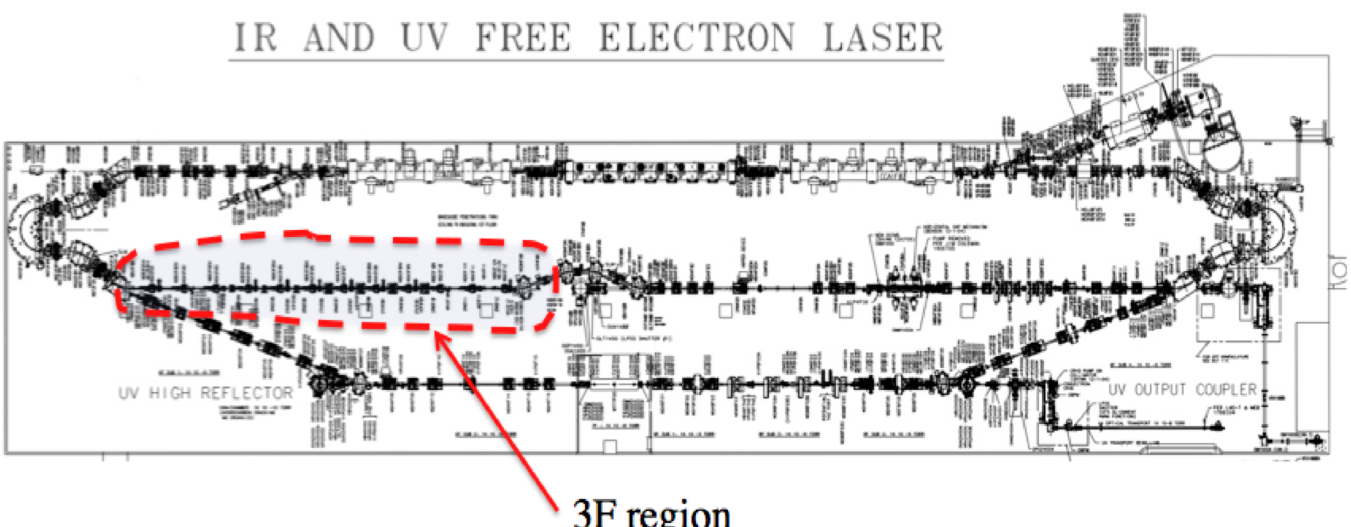
DarkLight Feasibility Test

Goal

Simulate high-power ERL operation with an internal gas-jet target controlling power deposition from beam loss and impedance/wake effects from both beam core and halo components through a 10 cm long small aperture (6, 4, or 2 mm diameter)

i.e., put > 400 kW through a coffee stirrer!

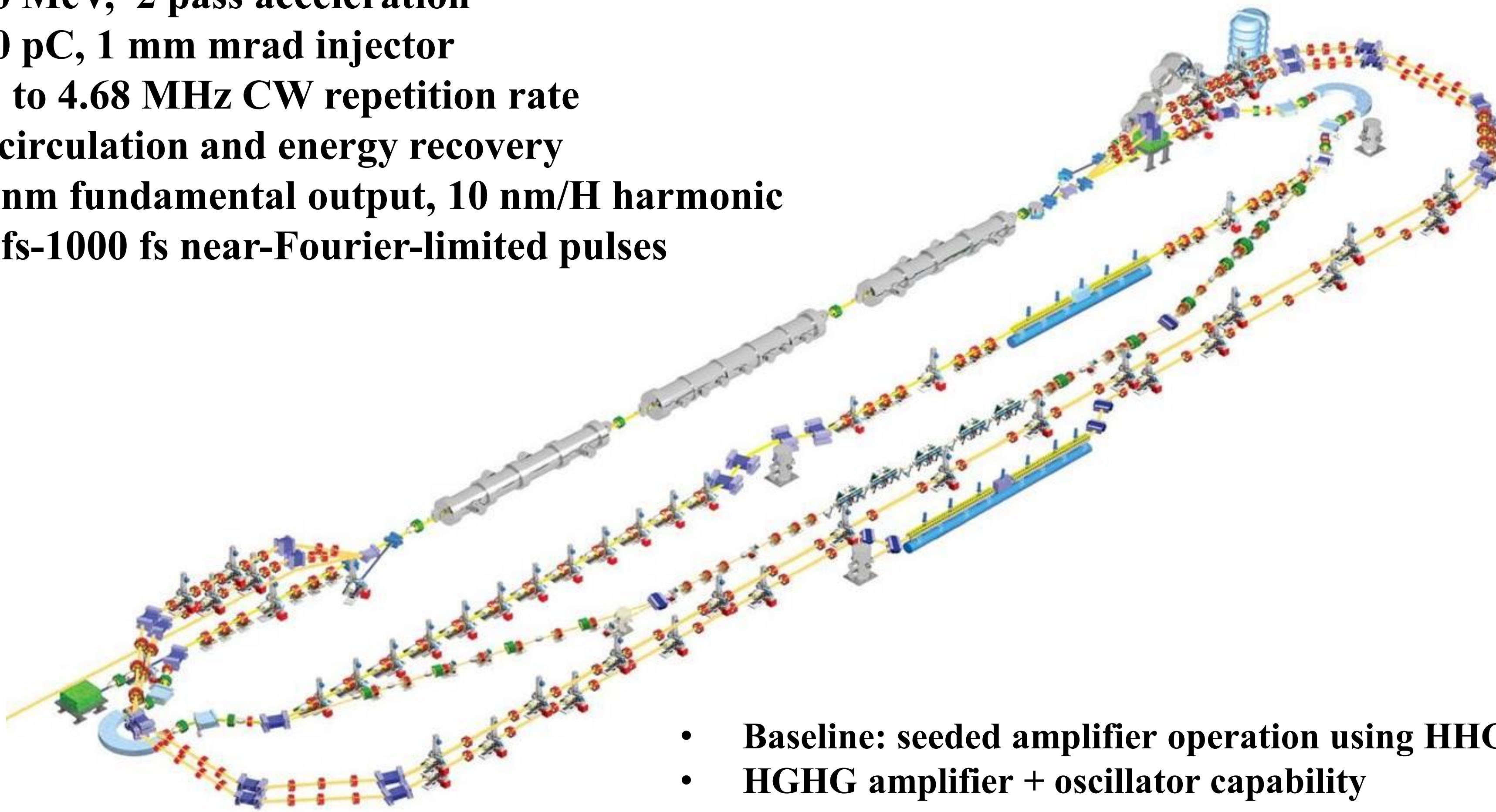




Designed and constructed by MIT-Bates R&E Center in collaboration with JLab FEL staff

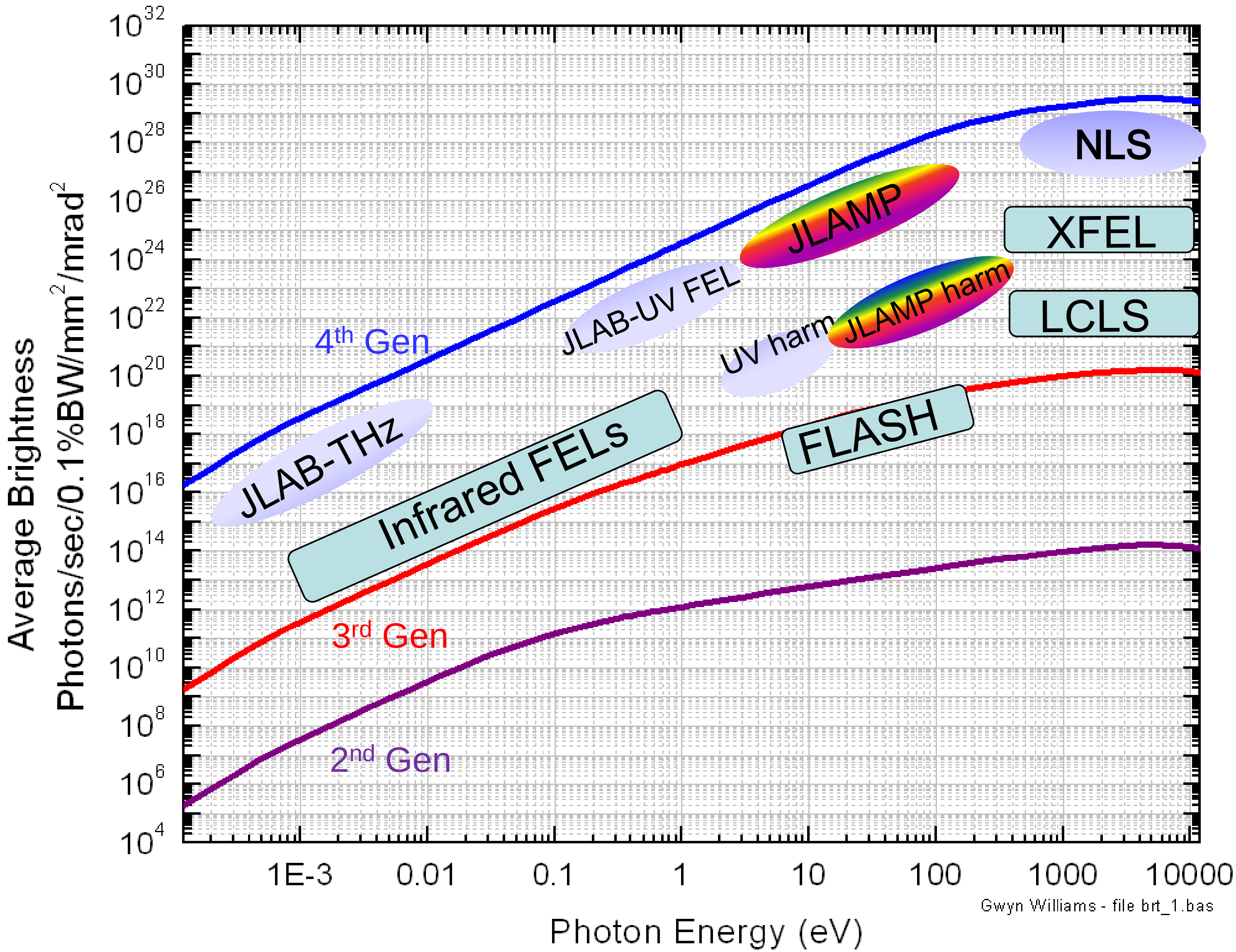
JLAMP FEL designed for unparalleled average brightness of 10-100 eV photons

- 600 MeV, 2 pass acceleration
- 200 pC, 1 mm mrad injector
- Up to 4.68 MHz CW repetition rate
- Recirculation and energy recovery
- 10 nm fundamental output, 10 nm/H harmonic
- 50 fs-1000 fs near-Fourier-limited pulses



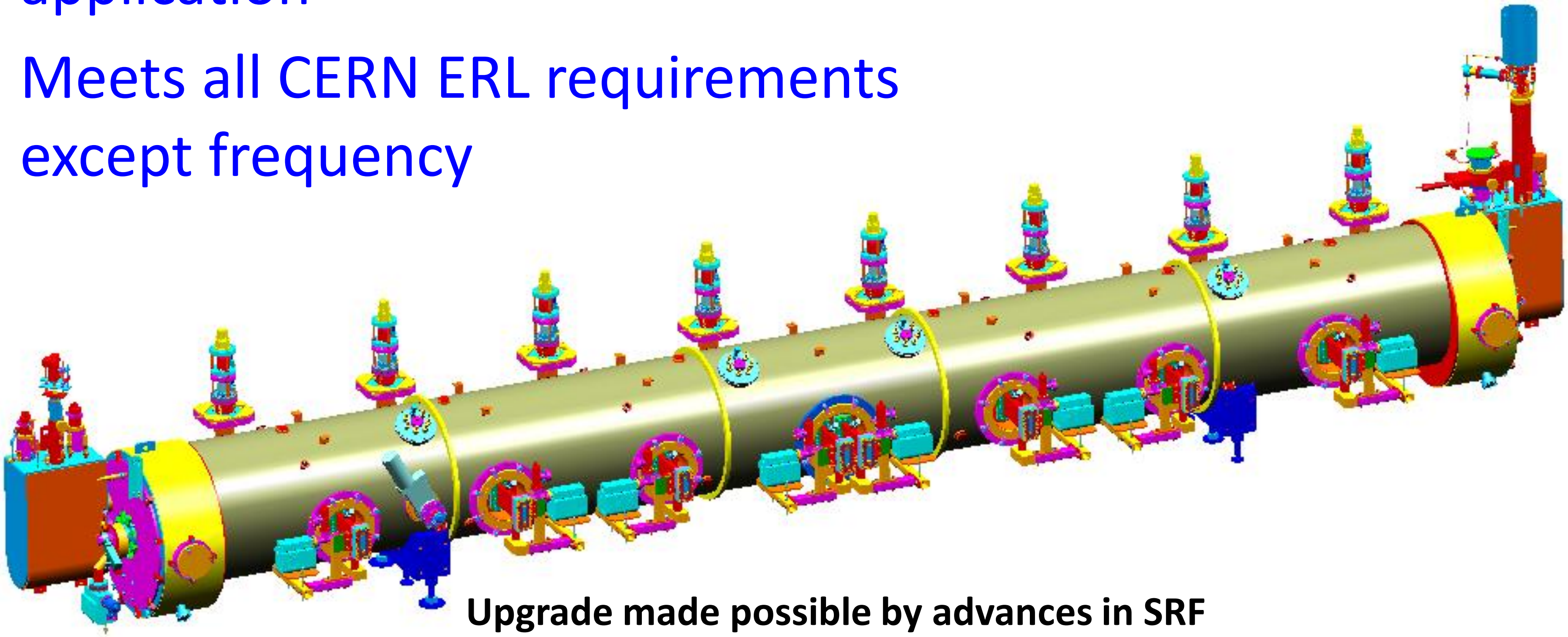
- Baseline: seeded amplifier operation using HHG
- HGHG amplifier + oscillator capability
- THz Wiggler for synchronized pump/probe

CW operation gives high average brightness in both fundamental and harmonics



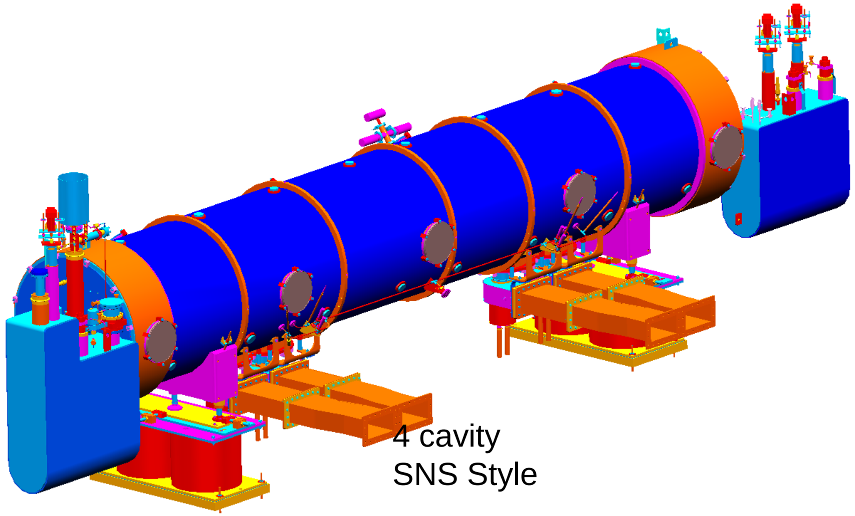
F100 Cryomodule

- 108 MV, 20 MV/m, 7-cell cavities
- 20 MV, 5 MV/m, 5-cell cavities
- HOM Damping increased for FEL application
- Meets all CERN ERL requirements except frequency



Upgrade made possible by advances in SRF

F100 Cavity String December 2013



SRF Cryomodules for LHeC: SNS-Style Conceptual Design

E. Daly, J. Henry, A. Hutton, J. Preble and R. Rimmer
JLab Accelerator Division
20-JAN-2014

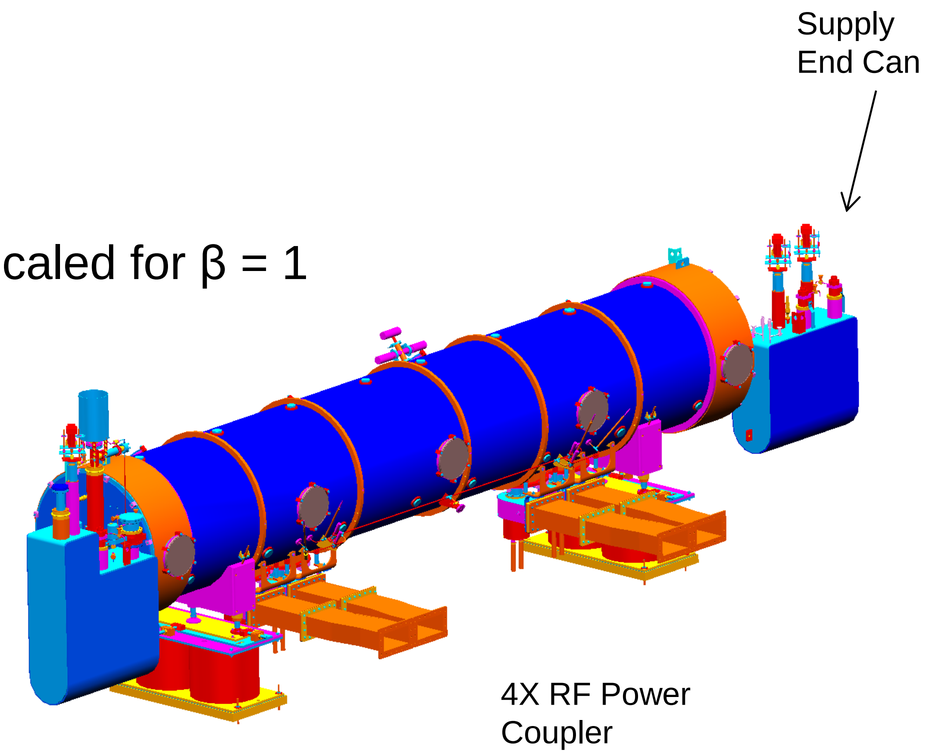
Proposal : SNS-Style Cryomodule
4 cavities per CM, 802.5 MHz

- Based on SNS CM
  - 5-cell Low Loss Shape
  - Coaxial Fundamental Power Coupler
  - Single RF Window
  - DESY-style HOM Couplers
  - Cold Tuner Drive

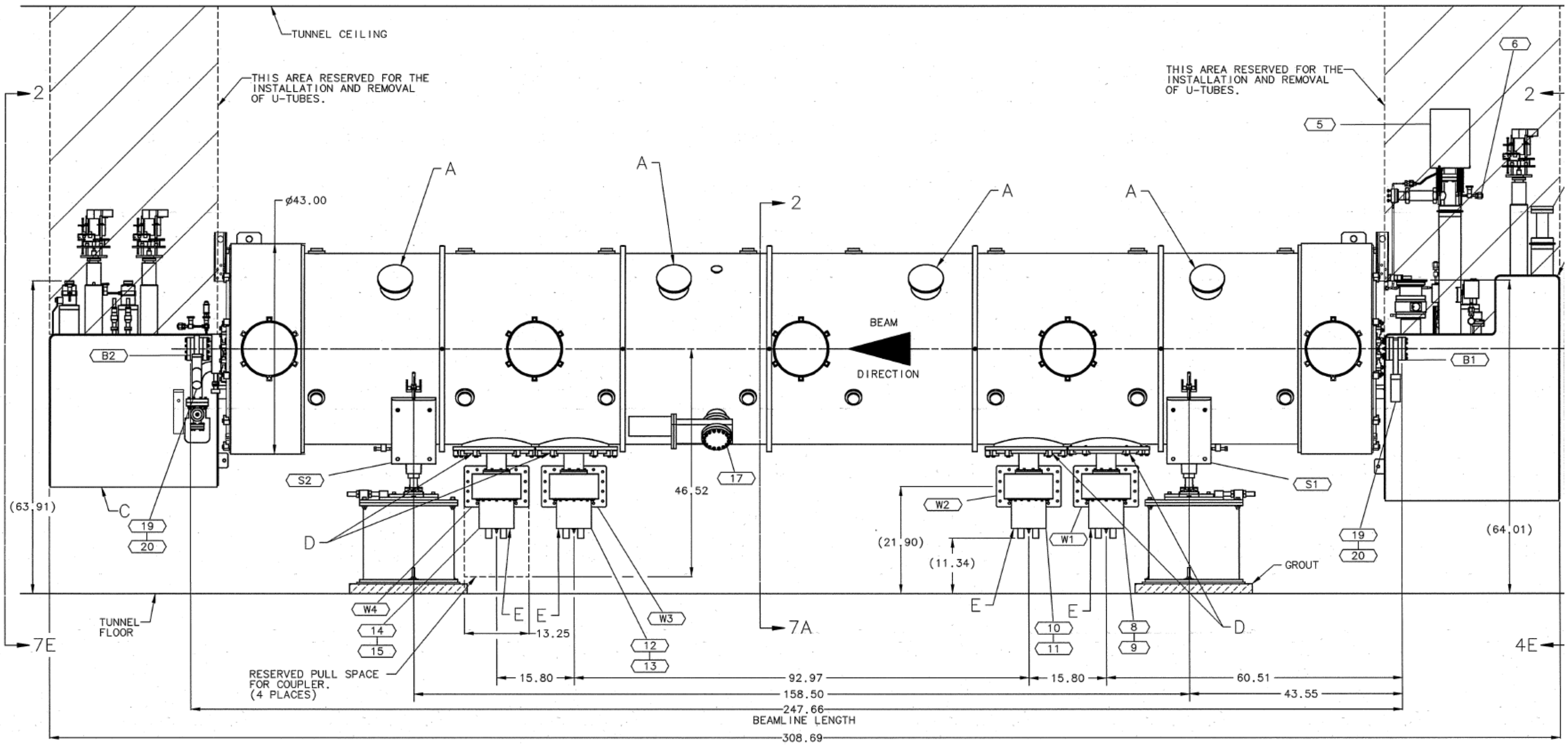
Scaled for $\beta = 1$

- Overall Length – 7.524 m
- Beamline Length – 6.705 m

- End Cans include integral heat exchanger for improved efficiency at 2K operations



SNS High Beta Cryomodule

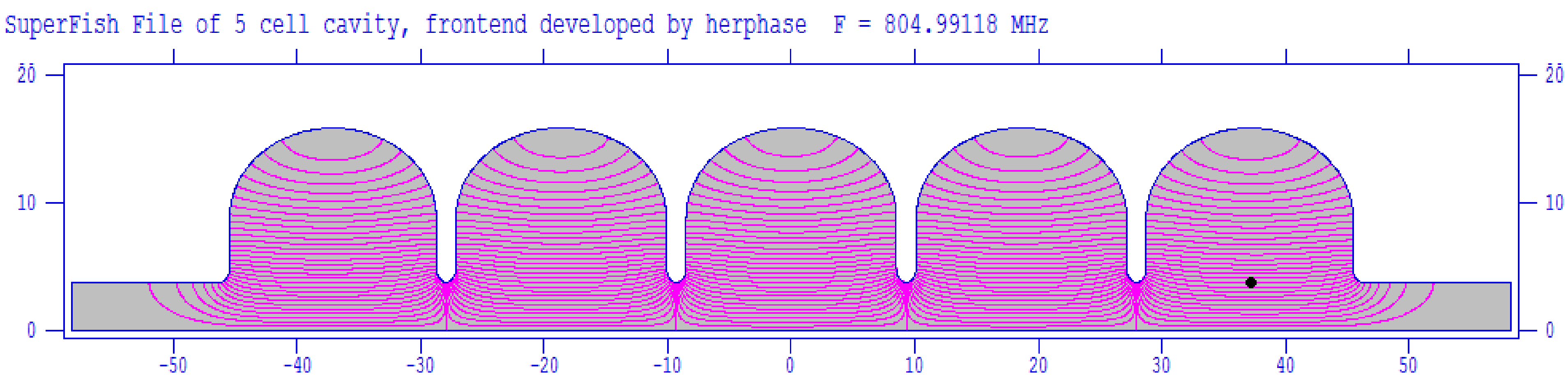


ELEVATION

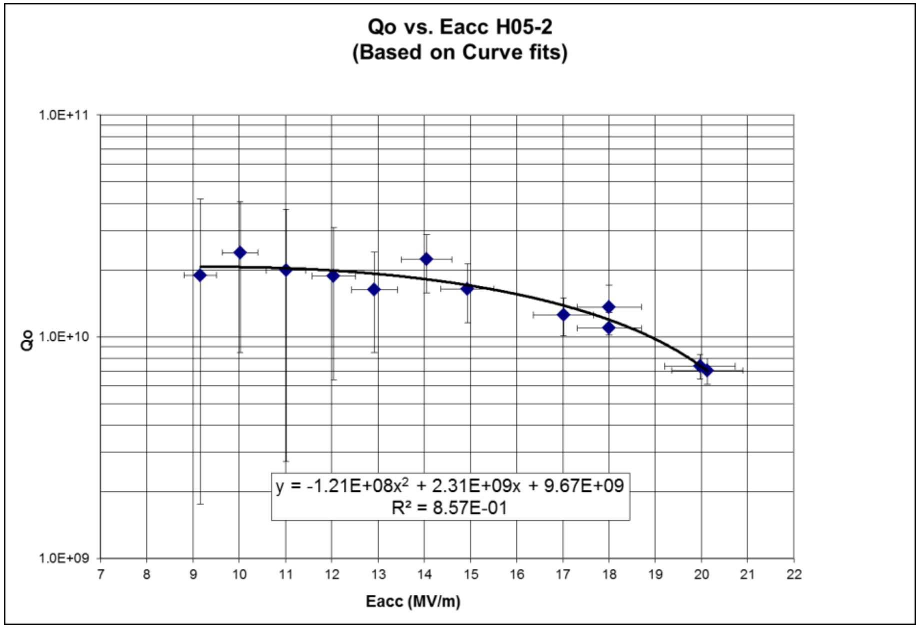
Example of Low-Loss Cavity Parameters (805 MHz) to be modified for 802.5 MHz

- 0 degree wall angle
- Same shape for mid & end cell
- Could use SNS cryomodule
- N^2/k~3000, better than JLab-LL
- Assuming E_a=15MV/m, then E_p=36MV/m, B_p=50mT.
- Assume Rres~10nΩ at 2K, so Q_0~2.0e10, P_{loss}~12.6W at 15MV/m
- MP and HOM NOT investigated

Frequency [MHz]	805
Cavity inner diameter [mm]	316.7
Beam pipe diameter [mm]	75.74
Cavity total length [mm]	1165
Cavity active length [mm]	925.2
Ep/Ea	2.40
Bp/Ea [mT/(MV/m)]	3.34
Geometry factor [Ω]	288
Ra/Q [Ω]	764
Ra*Rs (=G*Ra/Q) [Ω^2]	2.20×10^5
Cell-to-cell coupling k	0.84%



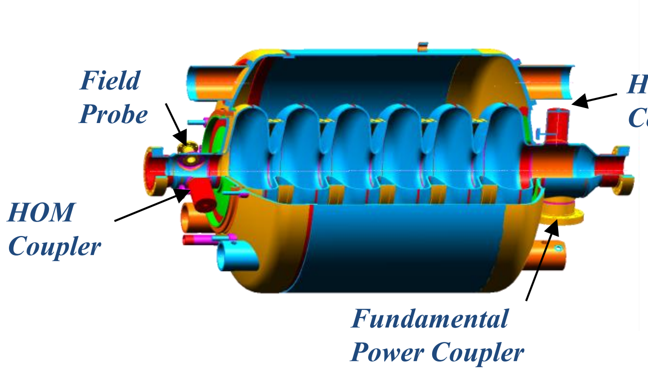
Measured Results for Production SNS High Beta Cavity



- Average Q_o at 10 MV/m = 2.0E10
- Dissipated Power = 8.4 Watts

- Average Q_o at 15 MV/m = 1.64E10
- Dissipated Power = 23.2 W

T = 2.0 K
Sample size = 7 Cavities



- SNS-style CM : 4 cavities at 15 MV/m, 56 MV total
  - $Q_o = 1.64 \times 10^{10}$ ~110 W per Cryomodule
  - $Q_o = 3.0 \times 10^{10}$ ~ 60 W per Cryomodule

Performance/Design Maturity and Cost Considerations

- Design maturity
  - Cryostat design is complete, SNS cryostat and cryogenic connection is a “drop in” design
  - Jefferson Lab has existing 750 MHz and 800 MHz cavity designs
    - Needs HOM coupling design, detail SNS style coupler for this application
    - Can use SNS coupler with minimal changes for CW operations (lower average power in this case, makes the design simpler)
- Production
  - Cryostat and power coupler costs from SNS production (2002) available
    - Costs need to be corrected for small quantity production and escalation
  - Jefferson Lab in-house cavity assembly to control schedule

Engineering and Design Effort

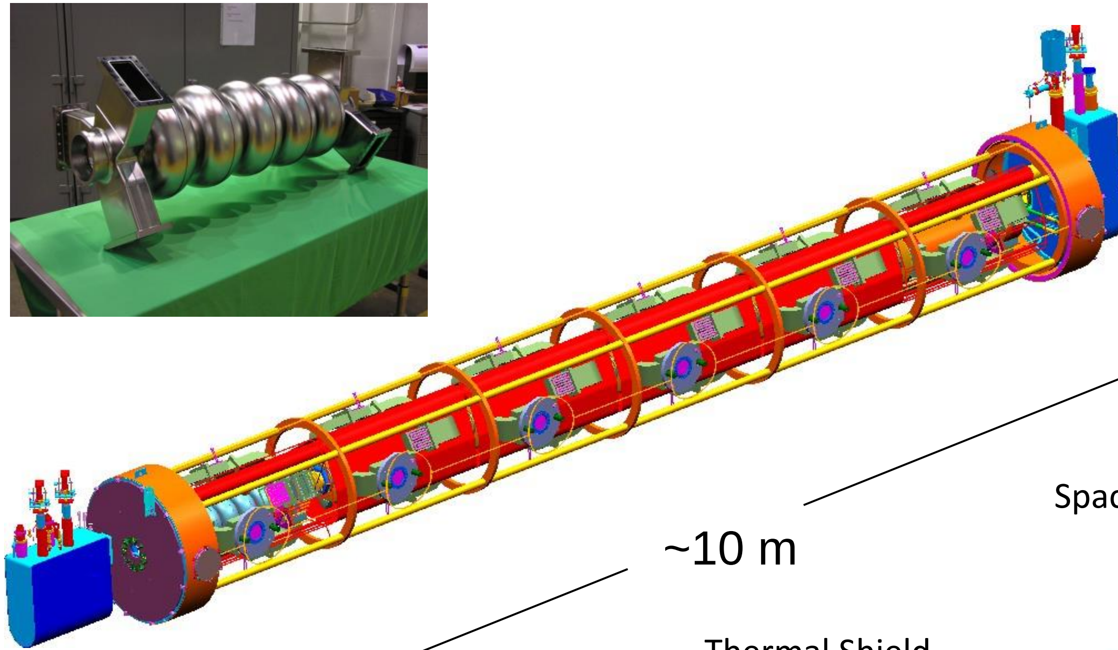
- Table illustrates estimated labor effort for engineering design activities including analysis, design drawings, assembly drawing and technical specifications for a complete engineering design – "Ready for Production"
- Design activities are split into three groups – cavity, helium vessel & tuner and cryostat
- Assumes only incremental changes (scaling) from SNS Designs
- PRELIMINARY costs to be confirmed upon scope agreement
- Documentation generated is sufficient to support procurement and production for JLAB scope of work.
- Option 2b represents one possible split of work
  - JLAB collaborates with CERN on their scope while designing the cryostat components (vacuum vessel, thermal shield, magnetic shield, cryogenic piping, end cans, etc.)
  - CERN designs cavity, helium vessel and tuner

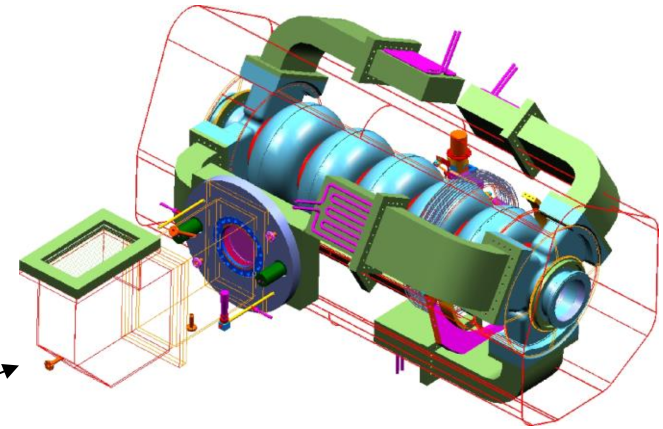
Option	Design Team	Cavity Type	Cavity (weeks)	Helium Vessel & Tuner (weeks)	Cryostat (weeks)	Total (weeks)
2a	JLAB	SNS-Style	43.5	13	71	127.5
2b	JLAB	SNS-Style	4.35	1.3	71	76.65
	CERN		43.5	13	0	56.5

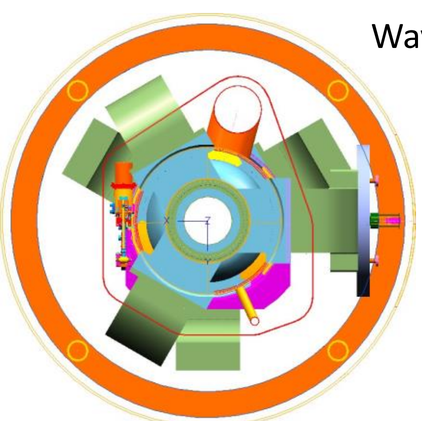
Conclusion

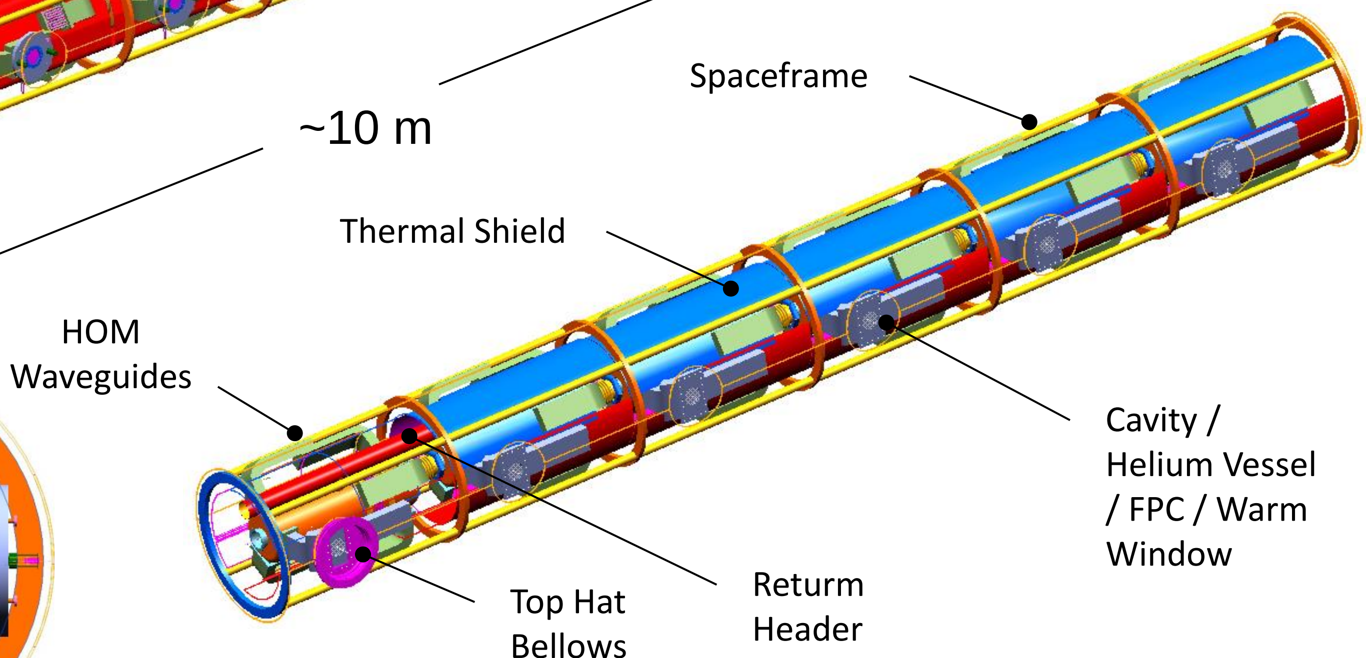
- SNS-Style Cryomodule
  - Design work is primarily the cavities
    - Leverage CERN engineering resources
- CERN participation in engineering and design welcome
- MESA cryomodule could be prototype

JLab 750 MHz FEL Cryomodule Concept









Tank diameter increased to accommodate HOM loads

Polarized Electron Gun

Source Parameter Comparison

Parameter	CEBAF	JLab/FEL	Nuclear Physics at Jlab FEL	Cornell ERL	LHeC	eRHIC	CLIC	ILC
Polarization	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Number electrons/microbunch	2.5×10^6	8.3×10^8	4.4×10^6	4.8×10^8	1×10^9	2.2×10^{10}	6×10^9	3×10^{10}
Number of microbunches	CW	CW	CW	CW	CW	CW	312	3000
Width of microbunch	50 ps	35 ps	35 ps	2 ps	~ 100 ps	~ 100 ps	~ 100 ps	~ 1 ns
Time between microbunches	2 ns	13 ns	0.67 ns	0.77 ns	25 ns	71.4 ns	0.5002 ns	337 ns
Microbunch rep rate	499 MHz	75 MHz	1497 MHz	1300MHz	40MHz	14MHz	1999 MHz	3 MHz
Width of macropulse	-	-	-	-	-	-	156 ns	1 ms
Macropulse repetition rate	-	-	-	-	-	-	50 Hz	5 Hz
Charge per micropulse	0.4 pC	133 pC	0.7 pC	77 pC	160 pC	3.6 nC	0.96 nC	4.8 nC
Charge per macropulse	-	-	-	-	-	-	300 nC	14420 nC
Average current from gun	200 uA	10 mA	1 mA	100 mA	6.5 mA	50 mA	15 uA	72 uA
Average current in macropulse	-	-	-	-	-	-	1.9 A	0.0144 A
Duty Factor	2.5×10^{-2}	2.6×10^{-3}	5.2×10^{-2}	2.6×10^{-3}	4×10^{-3}	1.4×10^{-3}	0.2	3×10^{-3}
Peak current of micropulse	8 mA	3.8 A	19 mA	38.5 A	1.6 A	35.7 A	9.6 A	4.8 A
Current density*	4 A/cm^2	19 A/cm^2	2 A/cm^2	500 A/cm^2	8 A/cm^2	182 A/cm^2	12 A/cm^2	6 A/cm^2
Laser Spot Size*	0.05 cm	0.5 cm	0.1 cm	0.3 cm	0.5 cm	0.5 cm	1 cm	1 cm

* Loose estimates

Existing: CEBAF, JLab/FEL, Nuclear Physics at Jlab FEL

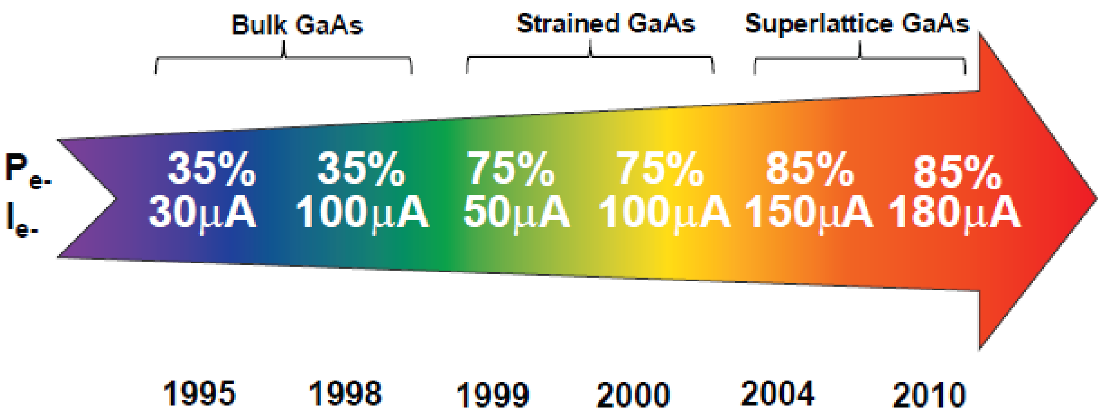
Proposed: Cornell ERL, LHeC, eRHIC, CLIC, ILC

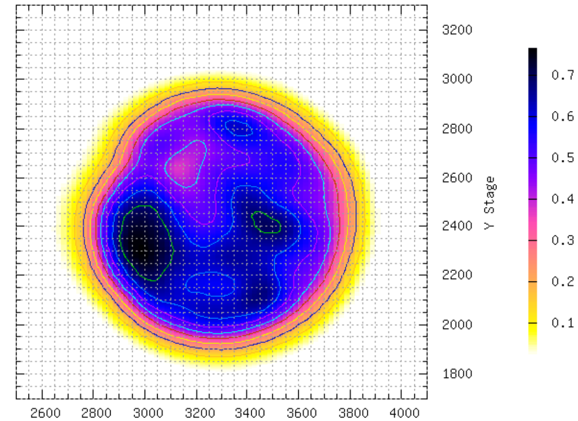
Challenges depend on specific beam requirements

Key Features of a Polarized Photogun

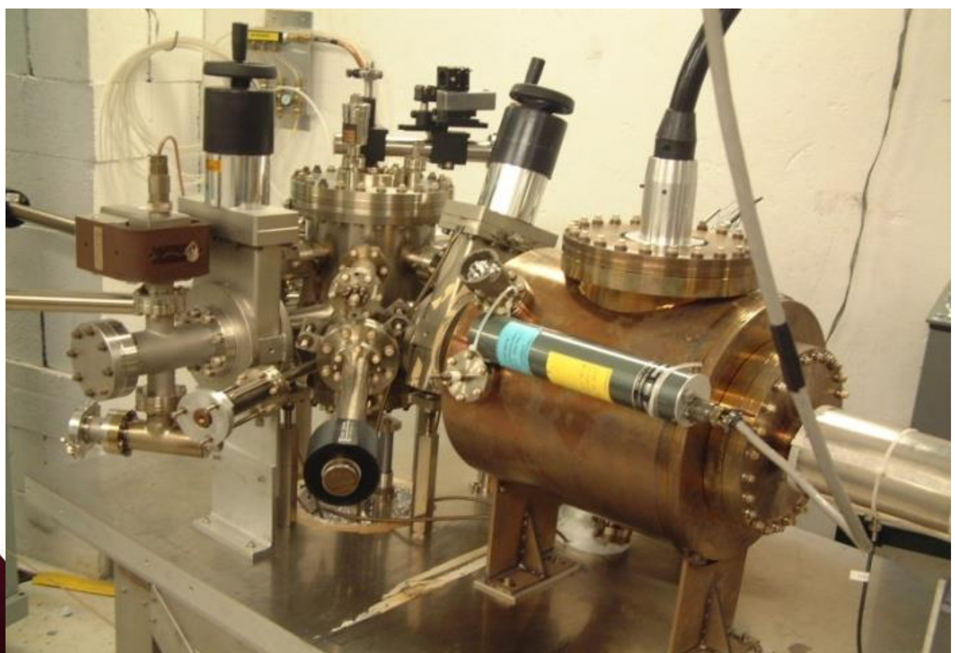
- Vacuum
  - Static Vacuum
  - Dynamic Vacuum
- High Voltage
  - Eliminating field emission
- Drive Laser
  - Reliable, phase locked to machine
  - Adequate Power, Wavelength Tunable?
- Photocathode
  - High Polarization, QE
  - Long Lifetime

Jlab - ILC High Current Polarized Electron Source





R. Suleiman et al., PAC'11, New York (NJ, USA), March 28 – April 1, 2011



Parameter	Value
Laser Rep Rate	1500 MHz
Laser Pulselength	50 ps
Laser Wavelength	780 nm
Laser Spot Size	350 µm FWHM
High-Pol Photocathode	SSL GaAs/GaAsP
Gun Voltage	200 kV DC
CW Beam Current	**4 mA**
Run Duration	**1.4 hr**
Extracted Charge	20 C
1/e Charge Lifetime	85 C
Bunch charge	2.7 pC
Peak current	53 mA
Current density	55 A/cm^2

How Long Can Gun Operate at 6.5 mA?

- 6.5 mA operation, 23 C/hr, 560 C/day.
- Photocathode with 1% initial QE, 2W at 780nm and gun with 80 C charge lifetime
  - Achieved at JLab during 4mA test
- Need initial laser power ~ 1 W to produce 6.5mA
- Should be able to operate at 6.5mA for 2 hours before running out of laser power.
- Imagine a 10W laser and 1000 C charge lifetime. This provides 4 days of operation.
- Message: high current polarized beam applications need photoguns with kilo-Coulomb charge lifetime

Summary

- JLab has over 15 years experience in designing, constructing and operating high-power CW ERLs
  - Facility under-utilized, available for ERL studies
- JLab designed JLamp, a 600 MeV ERL-based light source
  - Many similarities with CERN ERL Test Facility
- JLab has over 25 years of experience with high-power SRF design, production and operation
  - Built over 90 cryomodules, including 805 MHz SNS modules
  - SNS Cryostat can be modified for CERN 802 MHz cavities
- JLab has active polarized source development

We are ready to collaborate