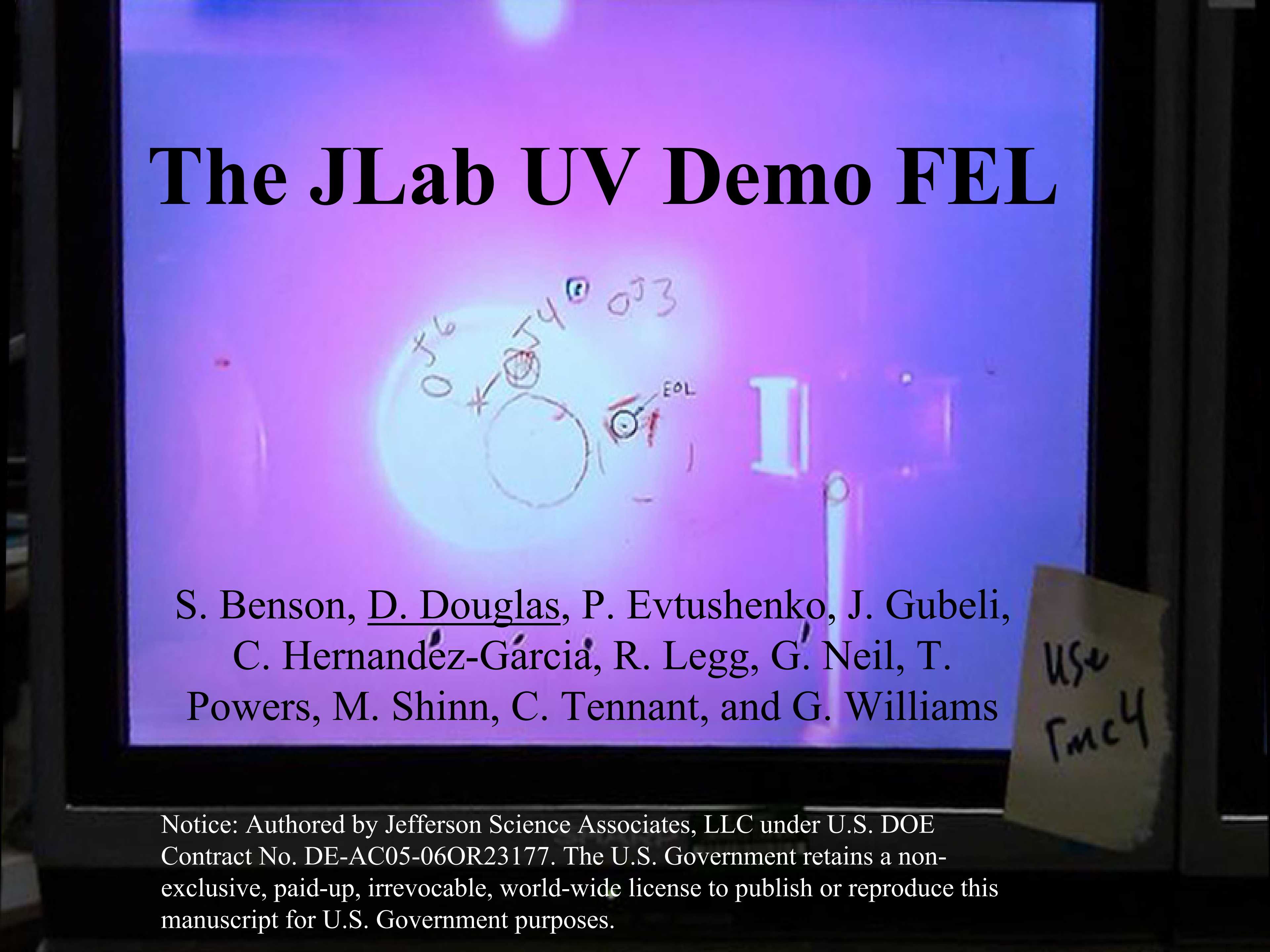


The JLab UV Demo FEL

S. Benson, D. Douglas, P. Evtushenko, J. Gubeli,
C. Hernandez-Garcia, R. Legg, G. Neil, T.
Powers, M. Shinn, C. Tennant, and G. Williams

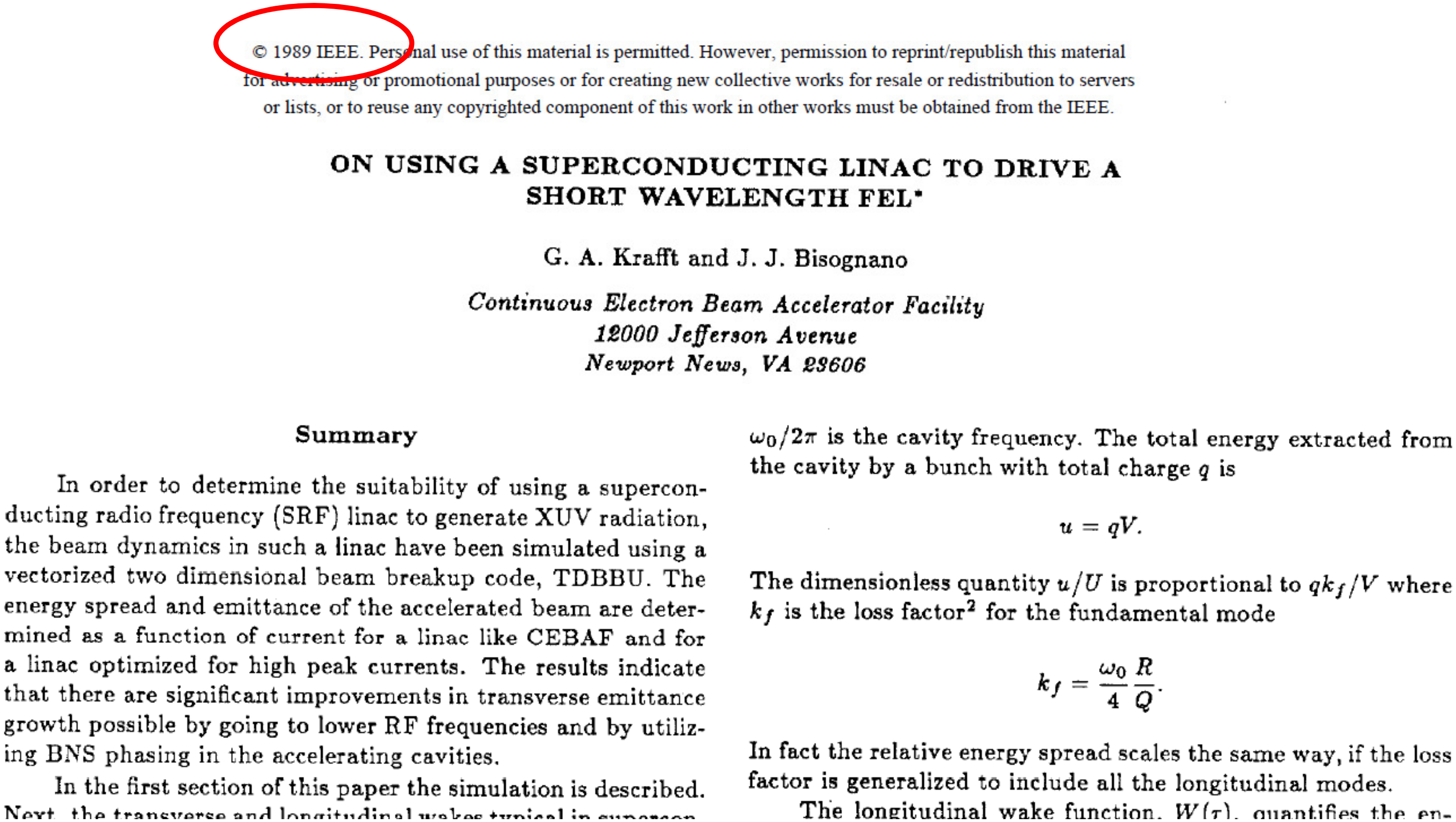
Overview

- History/Context
- FEL Concept & Design
- Driver ERL
- Commissioning
- FEL Performance
- Status/Future

Historical Context

Long-term interest in short-wavelength FELs…

- CEBAF = FEL driver (Bisognano & Krafft, PAC'89)



ON USING A SUPERCONDUCTING LINAC TO DRIVE A SHORT WAVELENGTH FEL*

G. A. Krafft and J. J. Bisognano

Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue
Newport News, VA 23606

Summary

In order to determine the suitability of using a superconducting radio frequency (SRF) linac to generate XUV radiation, the beam dynamics in such a linac have been simulated using a vectorized two dimensional beam breakup code, TDBBU. The energy spread and emittance of the accelerated beam are determined as a function of current for a linac like CEBAF and for a linac optimized for high peak currents. The results indicate that there are significant improvements in transverse emittance growth possible by going to lower RF frequencies and by utilizing BNS phasing in the accelerating cavities.

In the first section of this paper the simulation is described. Next, the transverse and longitudinal wakes typical in supercon-

$\omega_0/2\pi$ is the cavity frequency. The total energy extracted from the cavity by a bunch with total charge q is

$$u = qV.$$

The dimensionless quantity u/U is proportional to qk_f/V where k_f is the loss factor[2] for the fundamental mode

$$k_f = \frac{\omega_0}{4}\frac{R}{Q}.$$

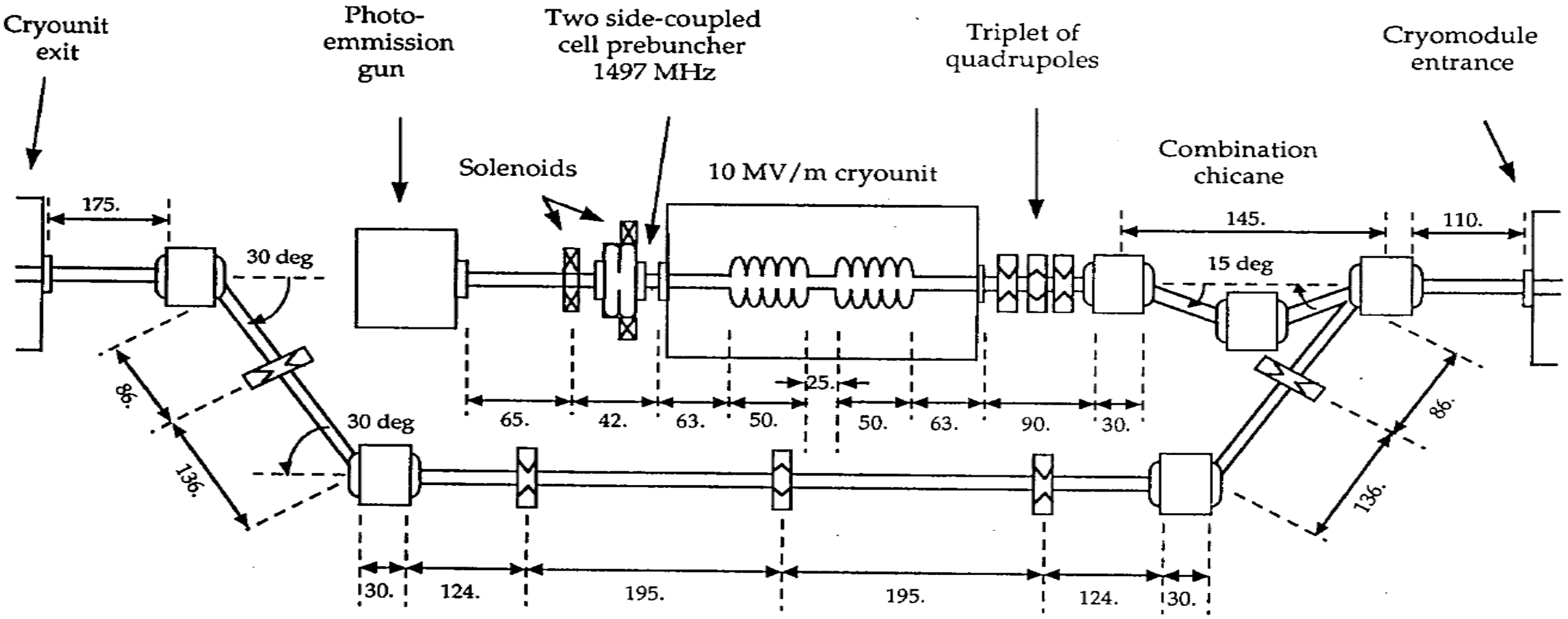
In fact the relative energy spread scales the same way, if the loss factor is generalized to include all the longitudinal modes.

The longitudinal wake function, $W(\tau)$, quantifies the en-

Historical Context

Long-term interest in short-wavelength FELs…

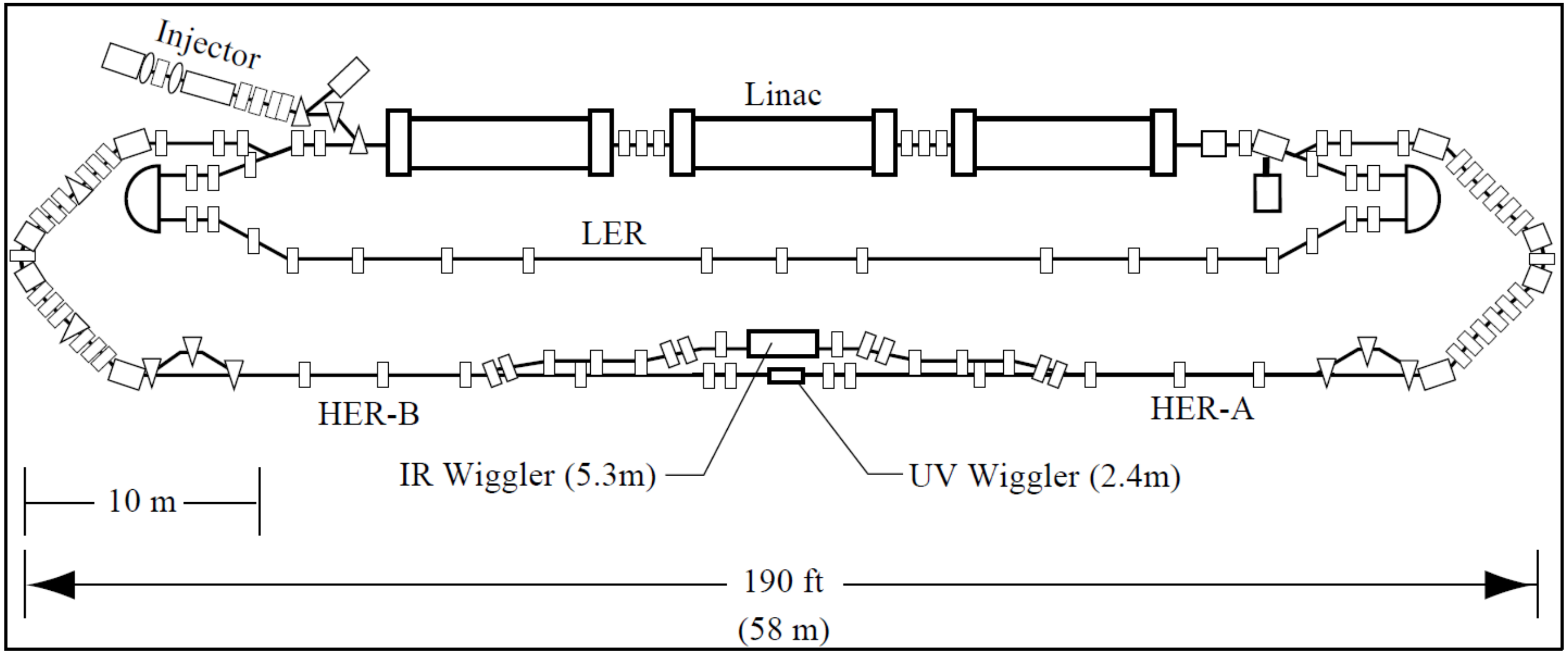
- CEBAF = FEL driver (Bisognano & Krafft, PAC'89)
  - "nuclear physics bypass" + partial injector installation (1993); funding-limited



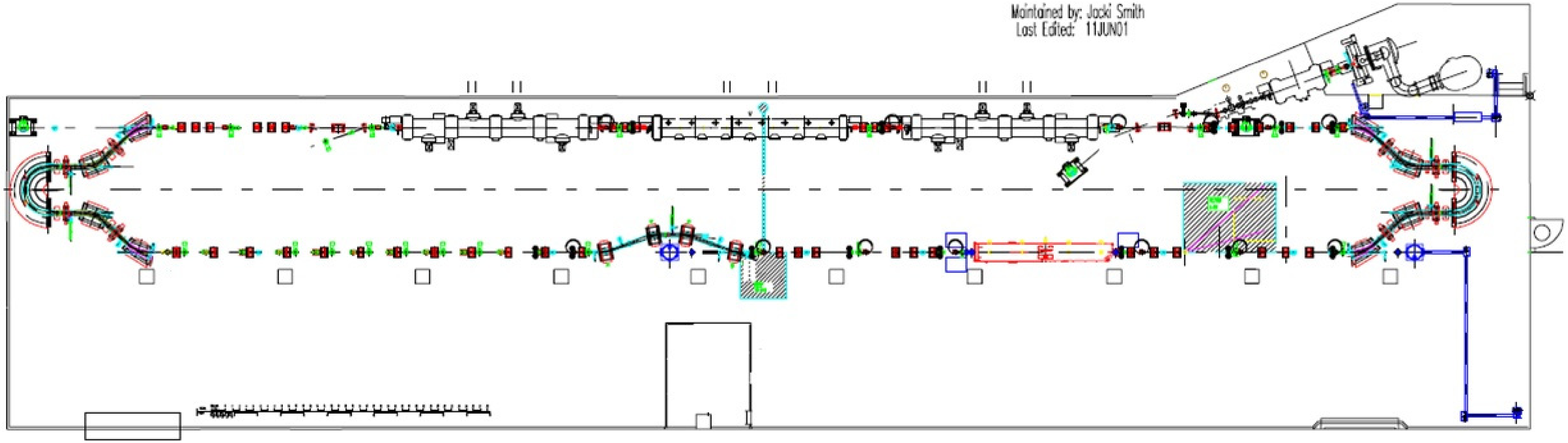
Historical Context

Long-term interest in short-wavelength FELs…

- CEBAF = FEL driver (Bisognano & Krafft, PAC'89)
  - "nuclear physics bypass" + partial injector installation (1993); funding-limited
- Science/technology case evolved; growing user interest motivated 1 kW UV Industrial Demo study – stand-alone system design (1994-5)
  - micromachining applications, materials processing (needed high UV power)
  - stimulated construction funding for facility (Commonwealth of Virginia, 1995)



Historical Context



Defined available footprint

- Circuitous path to UV (via IR) – ONR-funded high-power IR systems: IR Demo (1995-2001), Upgrade (2002-on)
- USAF funding for UV construction in parallel to IR Upgrade (2002-on)
  - UV design integral part of IR Upgrade and optimized for existing facility
  - Shares, re-uses existing SRF accelerator
- UV construction completed ("plus-up"funding) 2008-9, commissioned 2010.

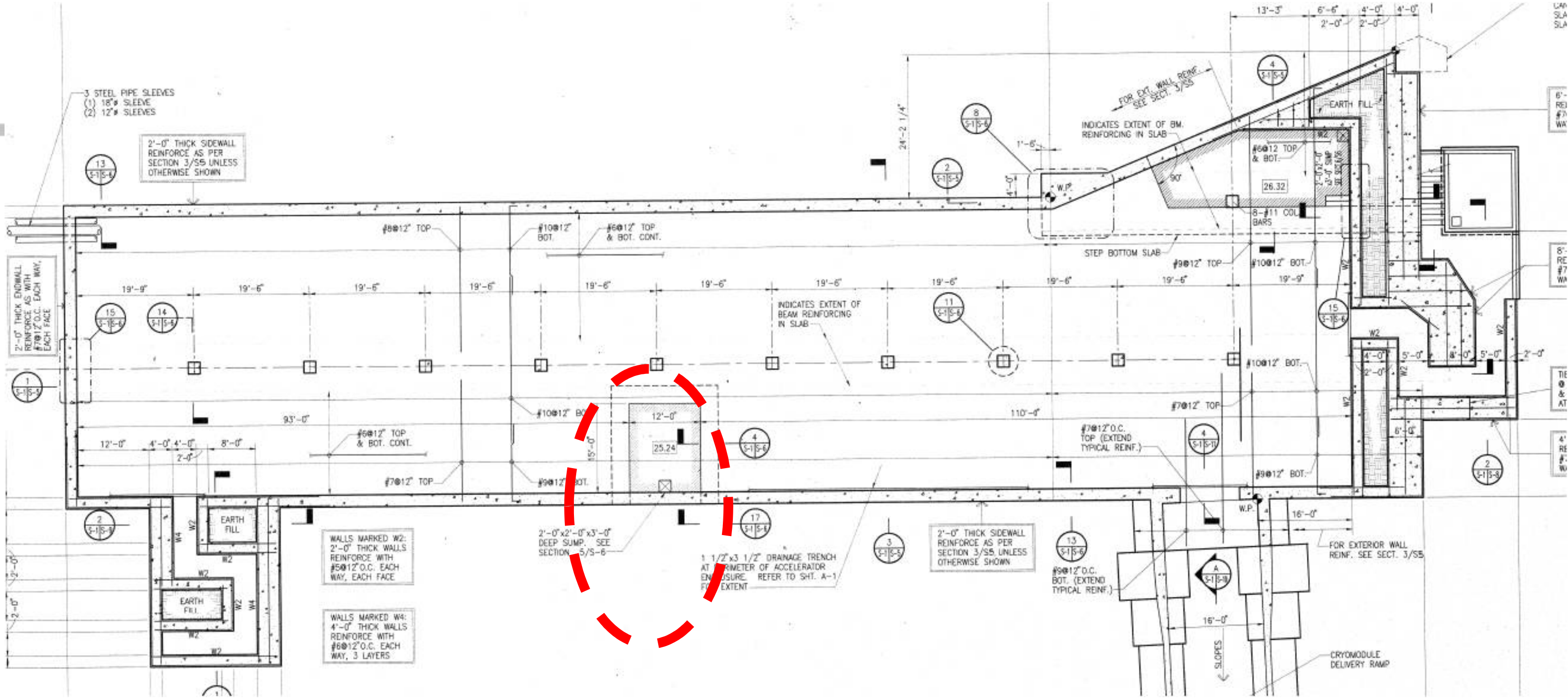
The Grail (& the Quest)

Materials science & (industrial scale) processing

- Tunable UV wavelengths down to ~160 nm
- High average power/high repetition rate (CW)
  - Paradigm: low peak, high average power (PAC'89)
  - Micromachining ⇒ need kW CW power (run time)
- Provide reach into VUV with significant brightness
  - FEL harmonics

FEL Concept & Design

- PAC'95 ⇒ *FEL oscillator driven by CW SRF ERL*
- Legacy concept evolved,
  - informed by operation of two earlier IR systems
    - High I_{peak} at lower Q_{bunch} (better bunch compression)
    - Mirror performance limits (heating)
      - THz management, cryo mirrors
  - constrained by facility and available hardware
    - Vault designed for legacy (PAC'95) system
      - Wiggler location/elevation defined by CEBAF beamline elevation; pit used to lower wiggler centerline
    - SRF performance limits (vacuum event-driven damage)



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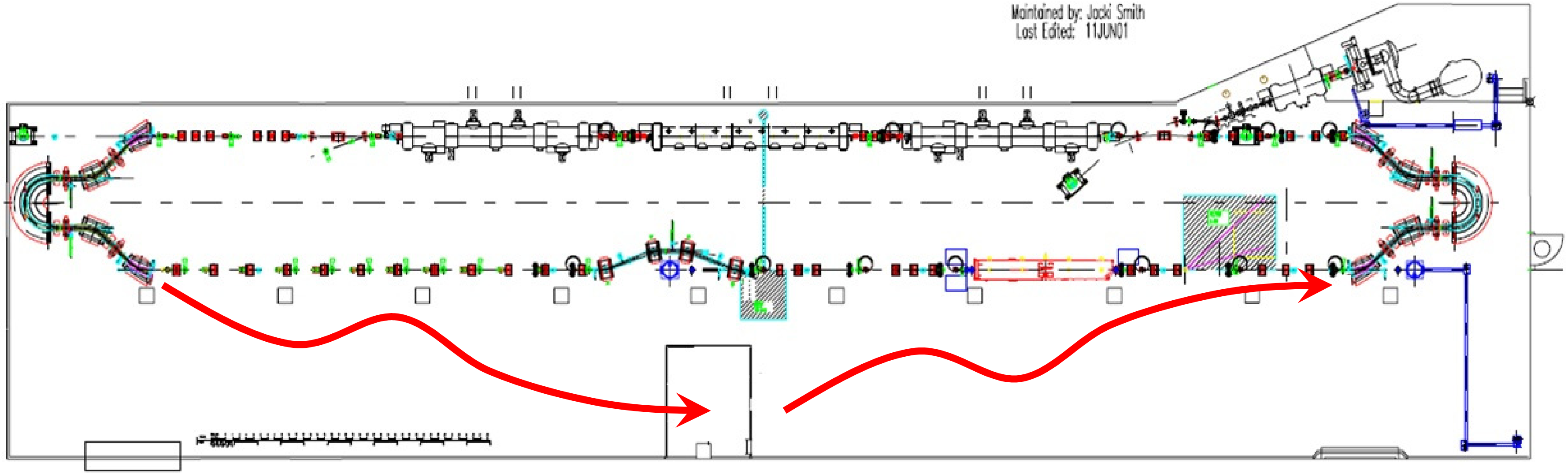

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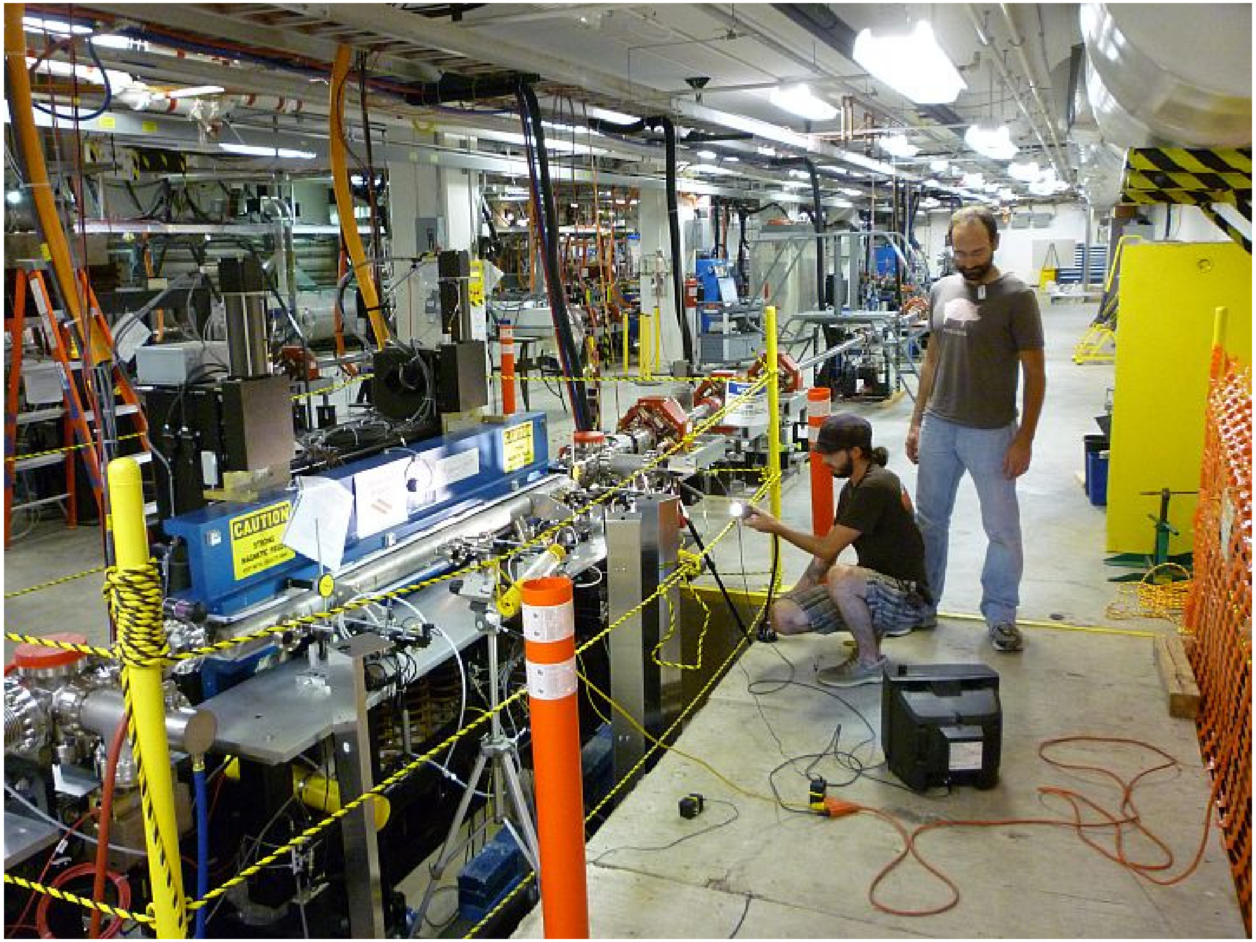
FEL Concept & Design



Legacy/As-Built Comparison

Parameter	Legacy Design (1995)	As Built (2003-9)
e^- beam energy (MeV)	100-200	135
repetition rate (MHz)	2.34-37.43	4.68-74.85
Q_{bunch} (pC)	135	60
σ_z (psec)	0.2	0.11
I_{peak} (A)	270	240
maximum I_{ave} (mA)	5	5
$L_{wiggler}$ (m)	2.376	1.98
L_{period} (cm)	3.3	3.3
N_{period}	72 (APS undulator A)	60 (APS undulator A prototype)
K_{wig}	0.5-1.64	0.5-1.51
gap (mm)	11.5	11.5
L_{cavity} (m)	64.08	32.04

cryomodule performance, wear & tear

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Legacy/As-Built Comparison

operational experience: improved e^- beam brightness (emittance, bunch length) at lower charge

Para		
e^- beam energ		
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APS undulator A prototype loaned by Cornell University

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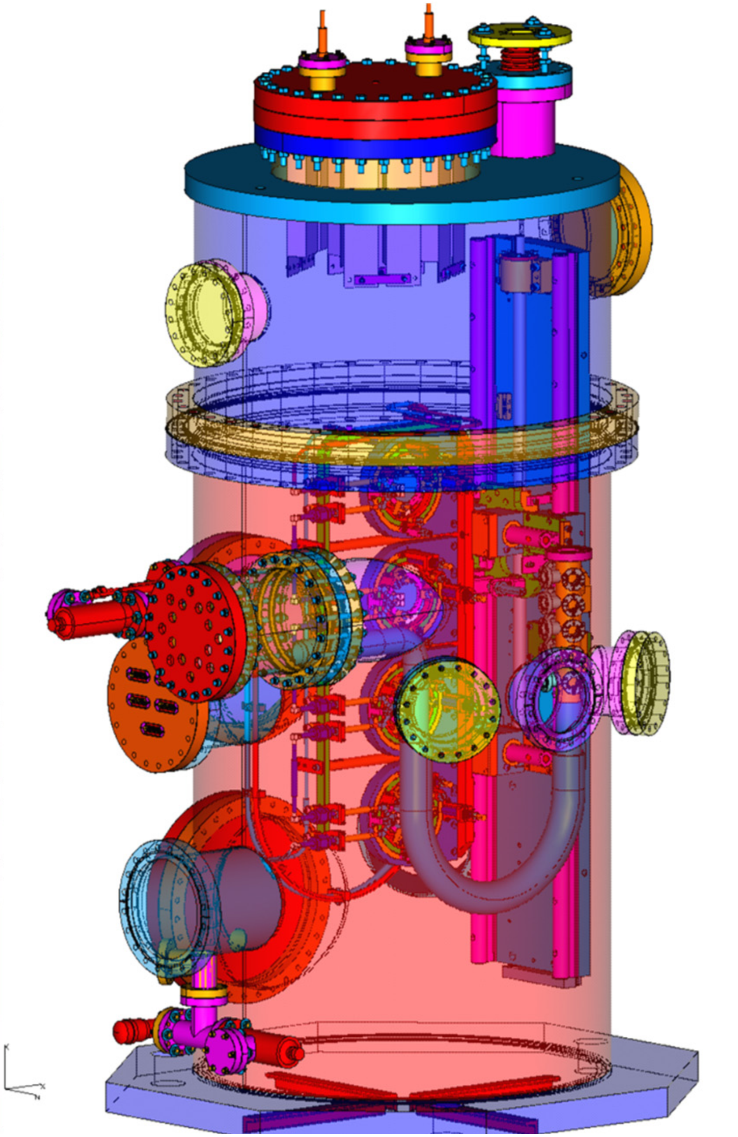
evolved optical cavity design

Comparison



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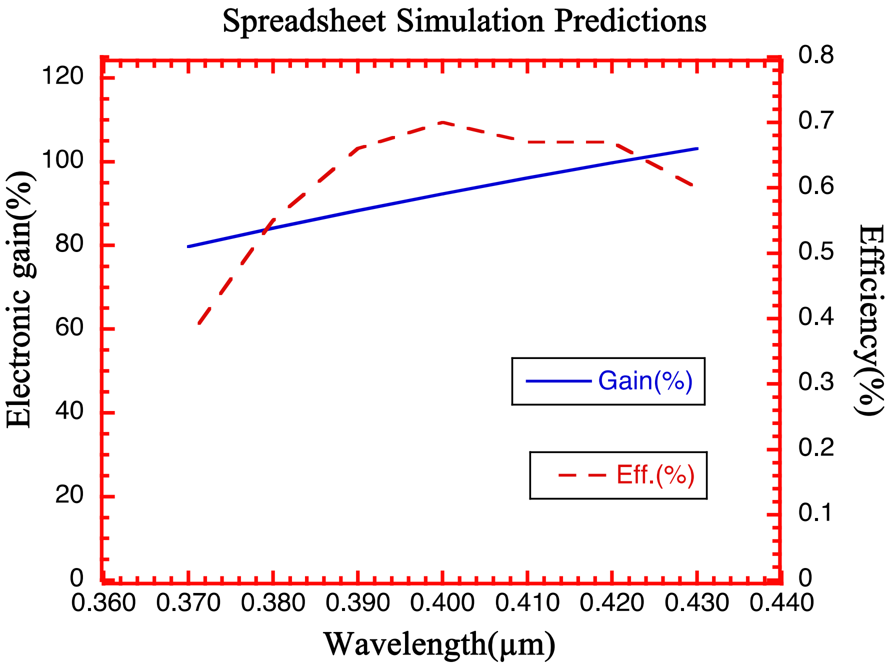
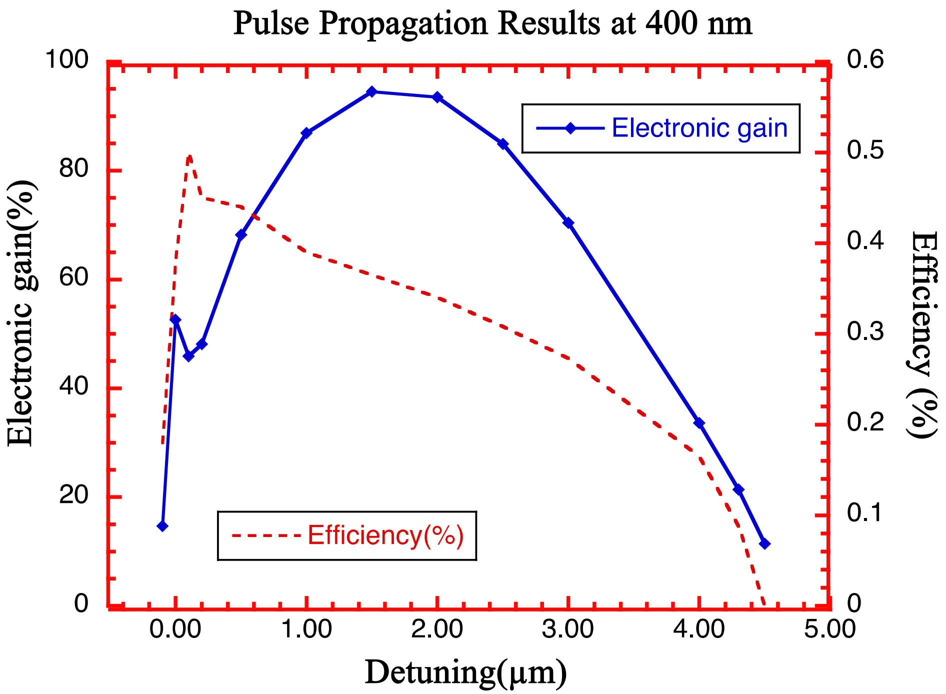
L_{cavity} (m		32.04

- Improved vacuum design
- Cryo mirror capable

Estimates of FEL performance

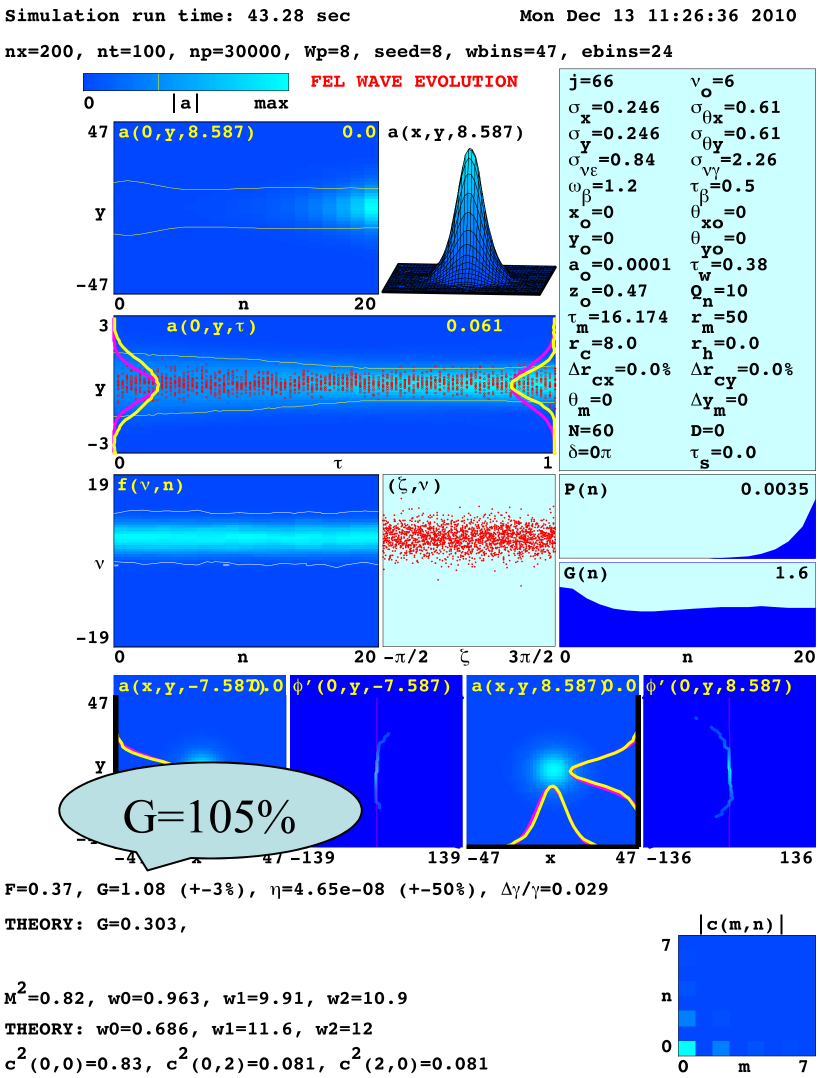
- Both pulse propagation and one-dimensional spreadsheet models are first used to estimate the gain and power.





Note: Both models assume perfect mirrors with a 93 cm Rayleigh range and 10% transmissive output coupling.

Three Dimensional Simulations



Simulation run time: 43.28 sec Mon Dec 13 11:26:36 2010

nx=200, nt=100, np=30000, Wp=8, seed=8, wbins=47, ebins=24

$j=66$ $\nu_o=6$
$\sigma_x=0.246$ $\sigma_{\theta x}=0.61$
$\sigma_y=0.246$ $\sigma_{\theta y}=0.61$
$\sigma_{\nu\varepsilon}=0.84$ $\sigma_{\nu\gamma}=2.26$
$\omega_\beta=1.2$ $\tau_\beta=0.5$
$x_o=0$ $\theta_{xo}=0$
$y_o=0$ $\theta_{yo}=0$
$a_o=0.0001$ $\tau_w=0.38$
$z_o=0.47$ $Q_n=10$
$\tau_m=16.174$ $r_m=50$
$r_c=8.0$ $r_h=0.0$
$\Delta r_{cx}=0.0\%$ $\Delta r_{cy}=0.0\%$
$\theta_m=0$ $\Delta y_m=0$
$N=60$ $D=0$
$\delta=0\pi$ $\tau_s=0.0$

G=105%

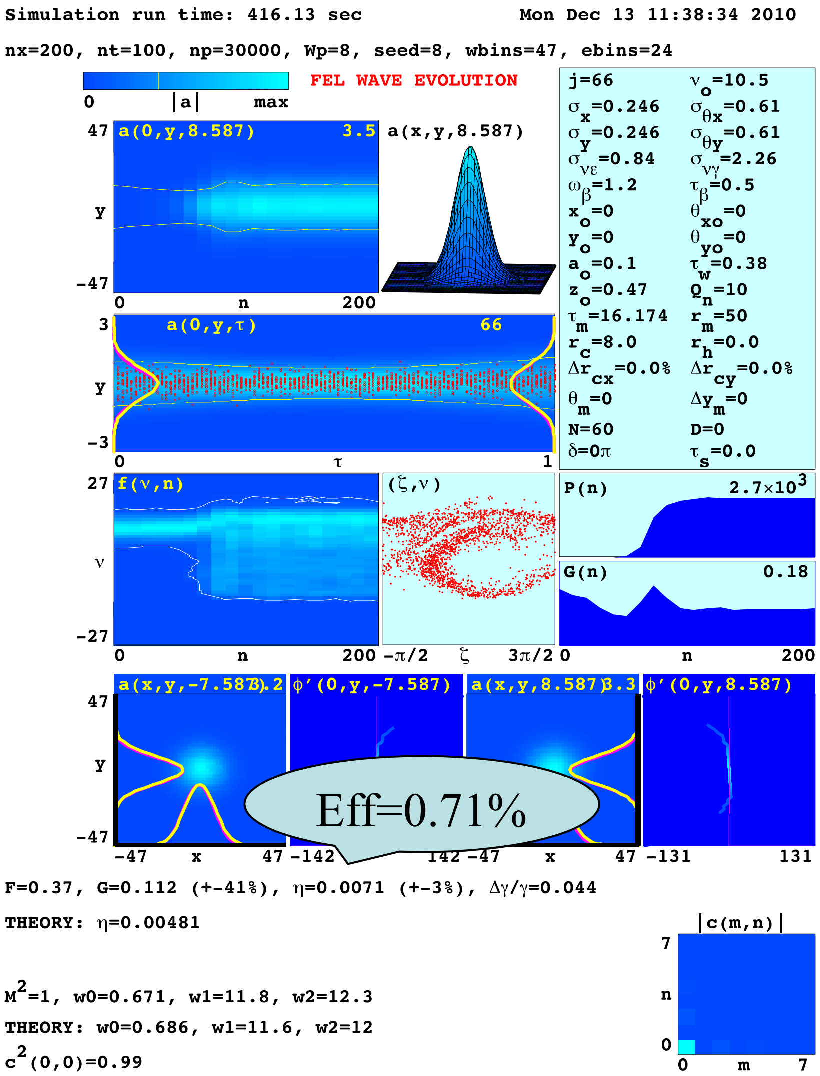
F=0.37, G=1.08 (+-3%), $\eta=4.65\text{e-}08$ (+-50%), $\Delta\gamma/\gamma=0.029$

THEORY: G=0.303,

$M^2=0.82$, w0=0.963, w1=9.91, w2=10.9

THEORY: w0=0.686, w1=11.6, w2=12

$c^2(0,0)=0.83$, $c^2(0,2)=0.081$, $c^2(2,0)=0.081$



Simulation run time: 416.13 sec Mon Dec 13 11:38:34 2010

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$j=66$ $\nu_o=10.5$
$\sigma_x=0.246$ $\sigma_{\theta x}=0.61$
$\sigma_y=0.246$ $\sigma_{\theta y}=0.61$
$\sigma_{\nu\varepsilon}=0.84$ $\sigma_{\nu\gamma}=2.26$
$\omega_\beta=1.2$ $\tau_\beta=0.5$
$x_o=0$ $\theta_{xo}=0$
$y_o=0$ $\theta_{yo}=0$
$a_o=0.1$ $\tau_w=0.38$
$z_o=0.47$ $Q_n=10$
$\tau_m=16.174$ $r_m=50$
$r_c=8.0$ $r_h=0.0$
$\Delta r_{cx}=0.0\%$ $\Delta r_{cy}=0.0\%$
$\theta_m=0$ $\Delta y_m=0$
$N=60$ $D=0$
$\delta=0\pi$ $\tau_s=0.0$

Eff=0.71%

F=0.37, G=0.112 (+-41%), $\eta=0.0071$ (+-3%), $\Delta\gamma/\gamma=0.044$

THEORY: $\eta=0.00481$

$M^2=1$, w0=0.671, w1=11.8, w2=12.3

THEORY: w0=0.686, w1=11.6, w2=12

$c^2(0,0)=0.99$

Performance Projection

Drive Beam Requirements

- $Q_{bunch} \sim 60$ pC
  - $\varepsilon_N \sim 5$ mm-mrad
  - $I_{peak} \sim 250$ A
- $f_{bunch} = N \times 4.68$ MHz (32 m optical cavity fundamental)
- E=135 MeV

Projected Results

- Gain ~100%
- Efficiency ~0.7%

but

- power limited ~100 W (@ 400 nm) by mirror loading (*using room temp mirrors –* cryo mirrors ⇔manage load, ~10× higher power)

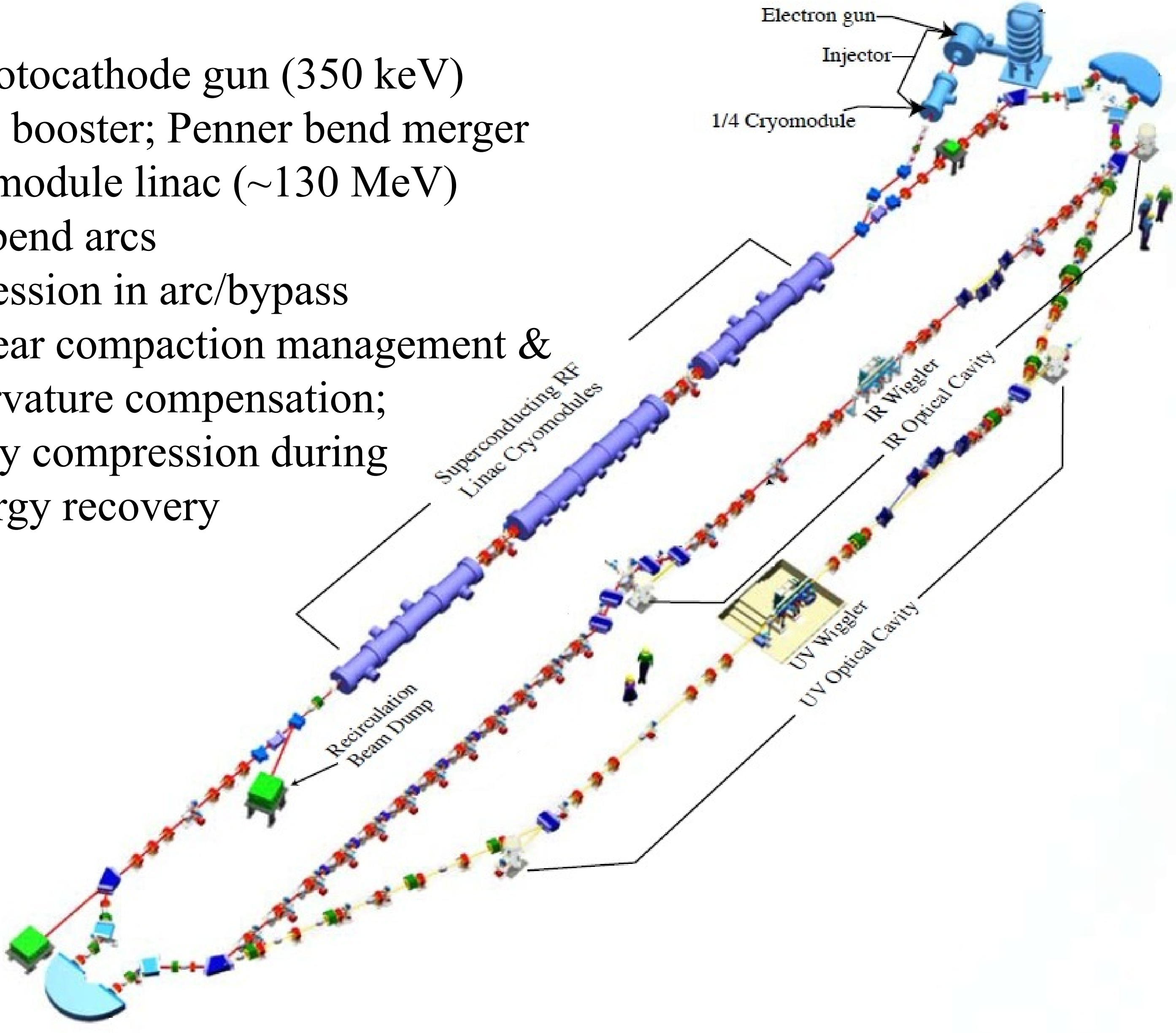
Driver Accelerator Requirements

SRF CW ERL driven FEL oscillator – stable, wall-plug efficient, high power/rep rate, operational flexibility

- e^- to FEL with properly configured phase space
  - Transverse matching to wiggler acceptance
  - Longitudinal match – provide high peak current
- Recover RF power from exhaust beam
  - ERL ⇔ reduce required RF power
  - Manage large FEL exhaust energy spread
- Preserve beam quality & avoid instability
  - Space charge (LSC), CSR, BBU, resistive wall, wakes/impedances,…
- Use available wiggler & facility w/o major reconfiguration
  - Transport drive beam to/from existing wiggler pit
    - Match 1.4 m commercial standard wiggler elevation to 0.7 m CEBAF standard beamline elevation

Driver Accelerator Design

- DC photocathode gun (350 keV)
- 9 MeV booster; Penner bend merger
- 3 cryomodule linac (~130 MeV)
- Bates bend arcs
- compression in arc/bypass
- nonlinear compaction management & RF curvature compensation; energy compression during energy recovery



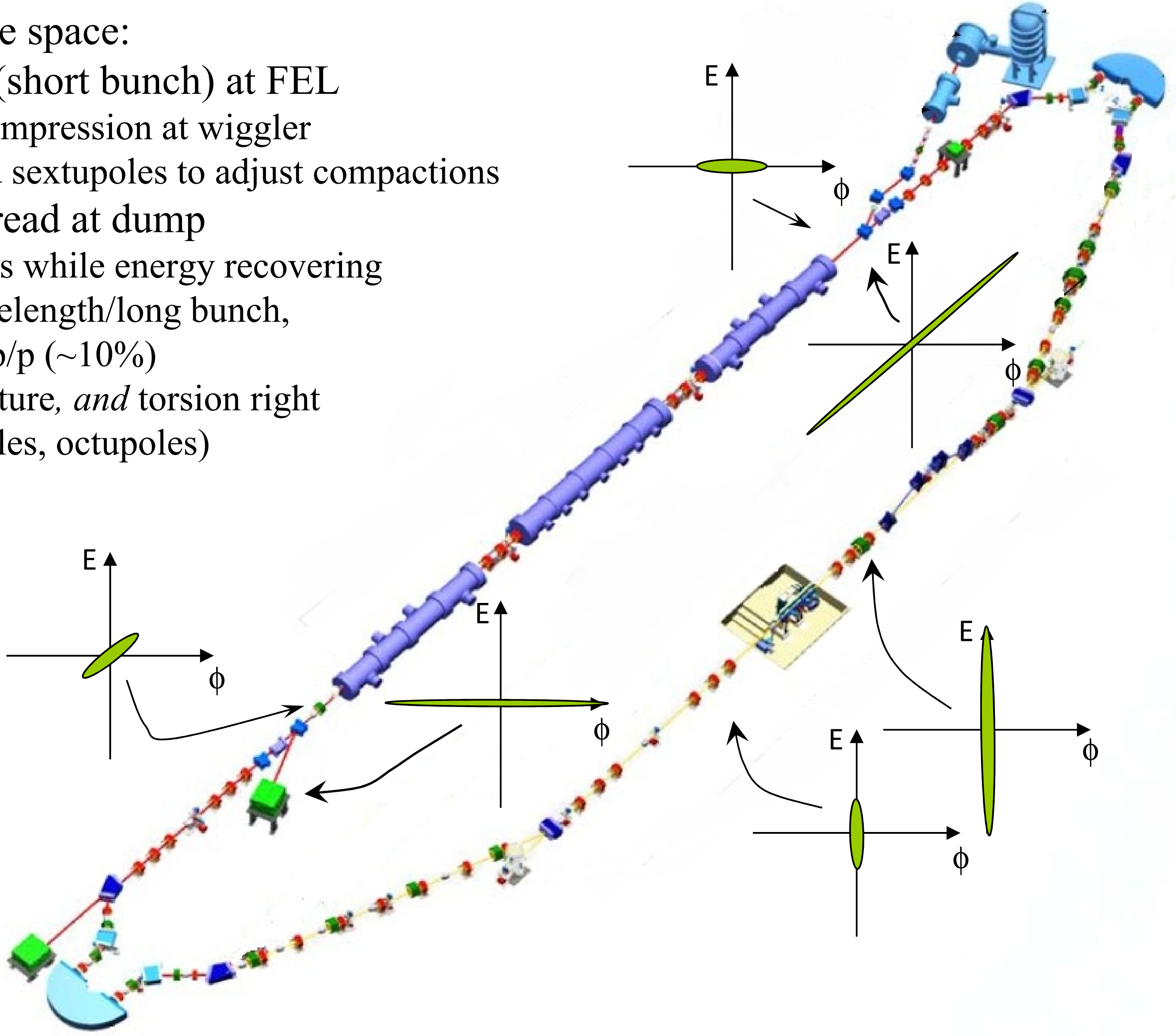
Driver Accelerator Details

- Shares injector, linac with IR Upgrade
  - Reduce charge (135 pC ⇒ 60 pC) to improve beam quality
- ERL "longitudinal match" differs from conventional linac-driven FEL; defines much of design
  - Single stage bunch length compression
  - Single stage energy compression during energy recovery
    - Manage large FEL exhaust $\delta p/p$ & turn on/off energy/phase transient
- ***No chicane*** for compression – use transport compaction
- ***No harmonic RF***
  - curvature correction done in transport system

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 δp/p (~10%)
  - ⇒ get slope, curvature, *and* torsion right (quads, sextupoles, octupoles)

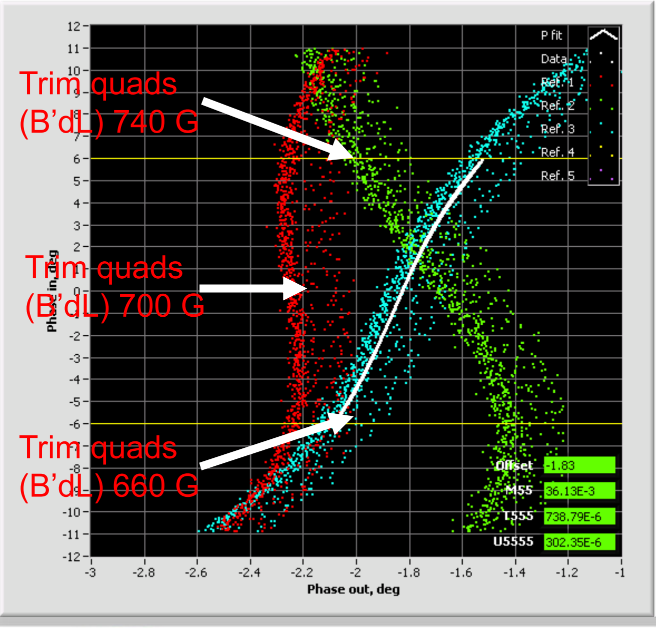


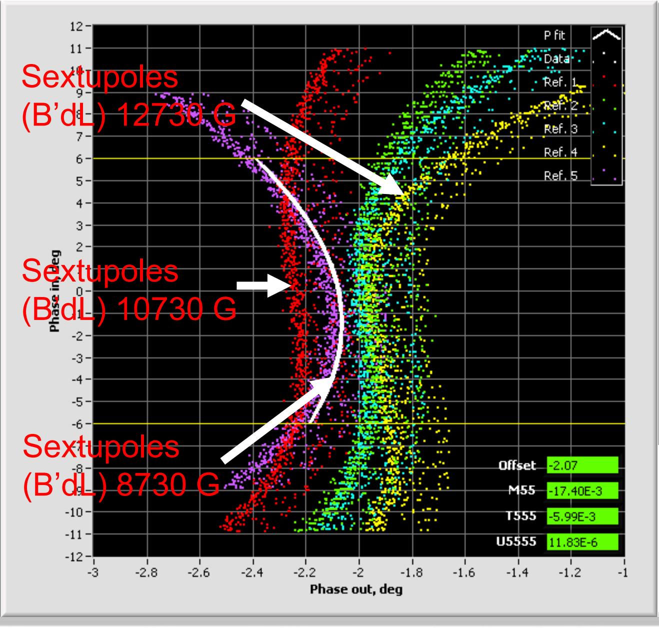
JLab FEL bunch compression and diagnostics

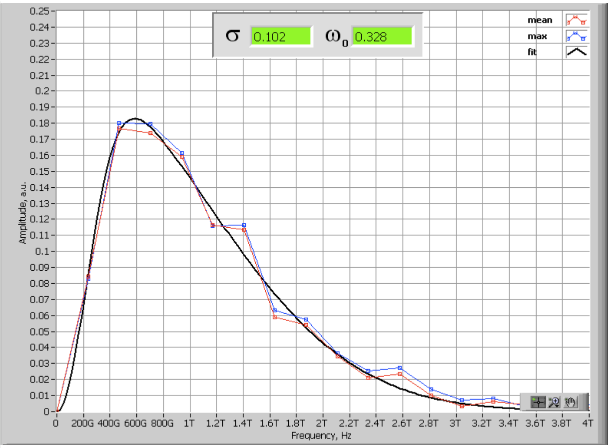
- JLab IR/UV Upgrade FEL operates with bunch compression ration of 90-135 (cathode to wiggler); 17-25 (LINAC entrance to wiggler).
- To achieve this compression ratio nonlinear compression is used – compensating for LINAC RF curvature (up to 2nd order).
- The RF curvature compensation is made with multipoles installed in dispersive locations of 180° Bates bend with separate function magnets - no harmonic RF
- Operationally longitudinal match relies on:
  a. Bunch length measurements at full compression (Martin-Puplett Interferometer)

  b. Longitudinal transfer function measurements R_{55}, T_{555}, U_{5555}

  c. Energy spread measurements in injector and exit of the LINAC







Martin-Puplett Interferometer data in frequency domain – give upper limit on the RMS bunch length

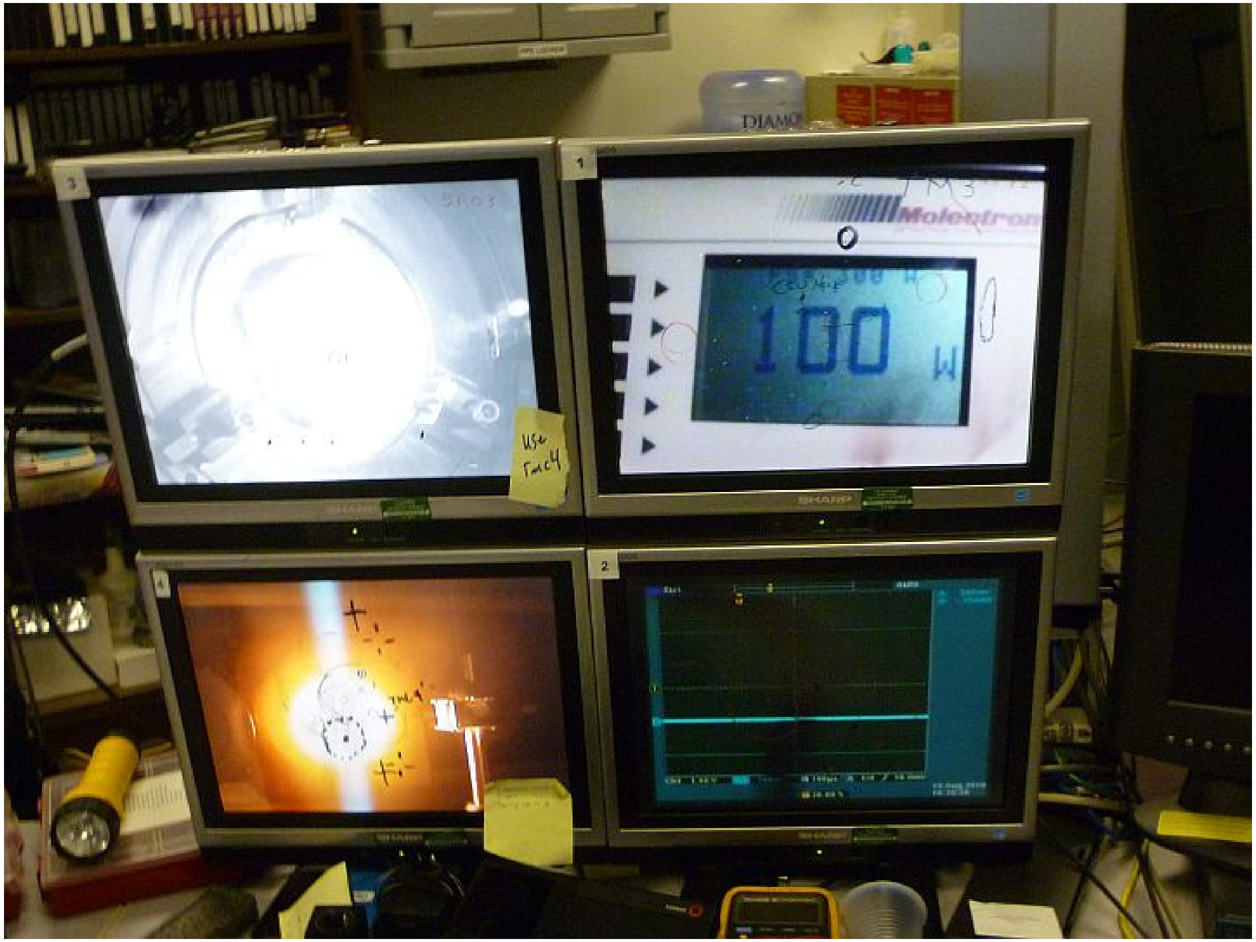
Commissioning

- (Funding-constrained) phased installation/commissioning
  - AF/Aerospace funding: 2004-6
  - Congressional plus-up 2007
  - Final installation & commissioning: 2009-10
- 1st recirculation/recovery (~ 2.5 hrs, no BPMs) Oct'09
- Full-up beam ops summer 2010 – winter 2011
  - ~100 hours beam operations to reach full CW operation, 150 W @ 700 nm
  - <40 additional hours shifts to 104 W @ 400 nm
  - CW 3rd harmonic 10 eV @ high brightness (Dec '10)

ERL Parameters (Achieved)

Parameter	**IR**	**UV**
Energy (MeV)	88-165	135
I_{ave} (mA)	9.1	2
Q_{bunch} (pC)	135	60
ε_N transverse/longitudinal (mm-mrad/keV-psec)	8/75	5/50
$\sigma_{\delta p/p}$, σ_l (fsec)	0.4%, 160	0.4%, 100
I_{peak} (A)	400	250
FEL repetition rate (MHz) (cavity fundamental 4.6875)	0.586-75	1.172-18.75
η_{FEL}	2.5%	0.7%
ΔE_{full} after FEL	~15%	~7%

Images While Lasing

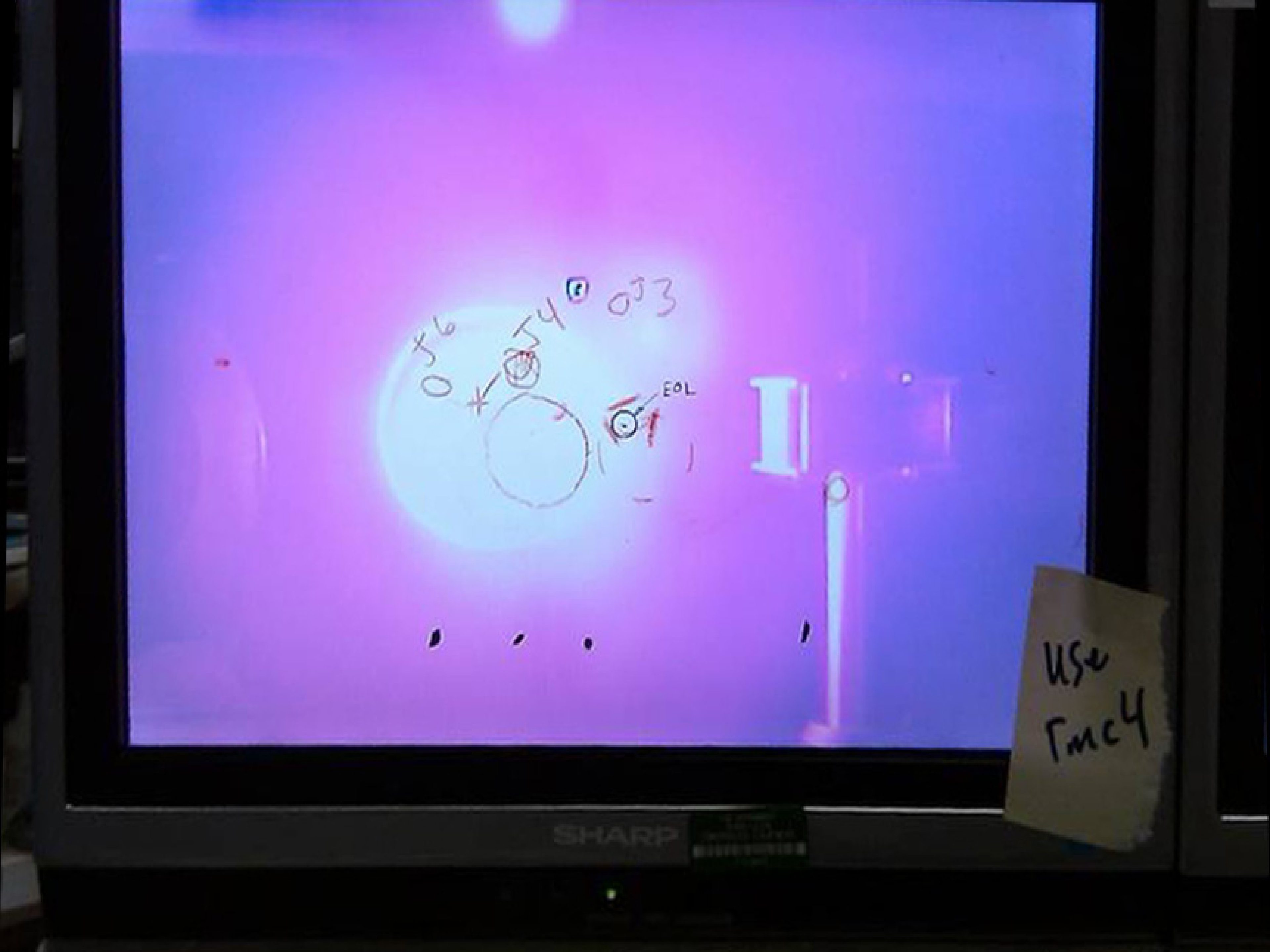


Light scattered from HR mirror

Power meter

Light scattered from power probe

Time dependent diagnostics


OJ6
OJ4
OJ3
EOL
SHARP
Use TMC4

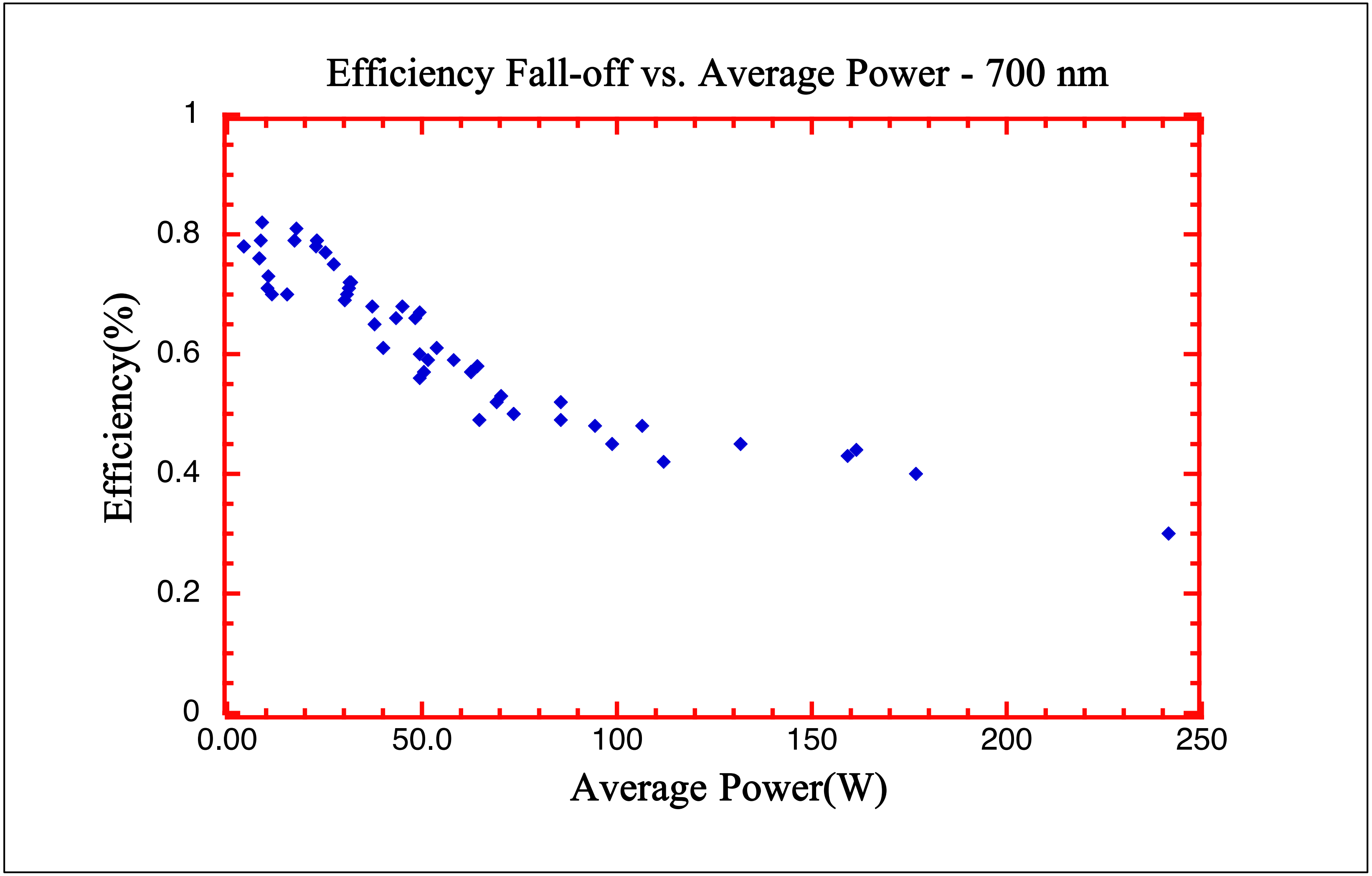
Commissioning/Operational Issues

- Drive laser stability & control
- Gun performance; cathode lifetime
- SRF performance/damage
  - Limited energy
- Magnet field quality
  - ~time-of-flight spectrometer
  - susceptibility to small errors
- DC power/field reproducibility
- Mirror performance
  - loading/heating
  - damage

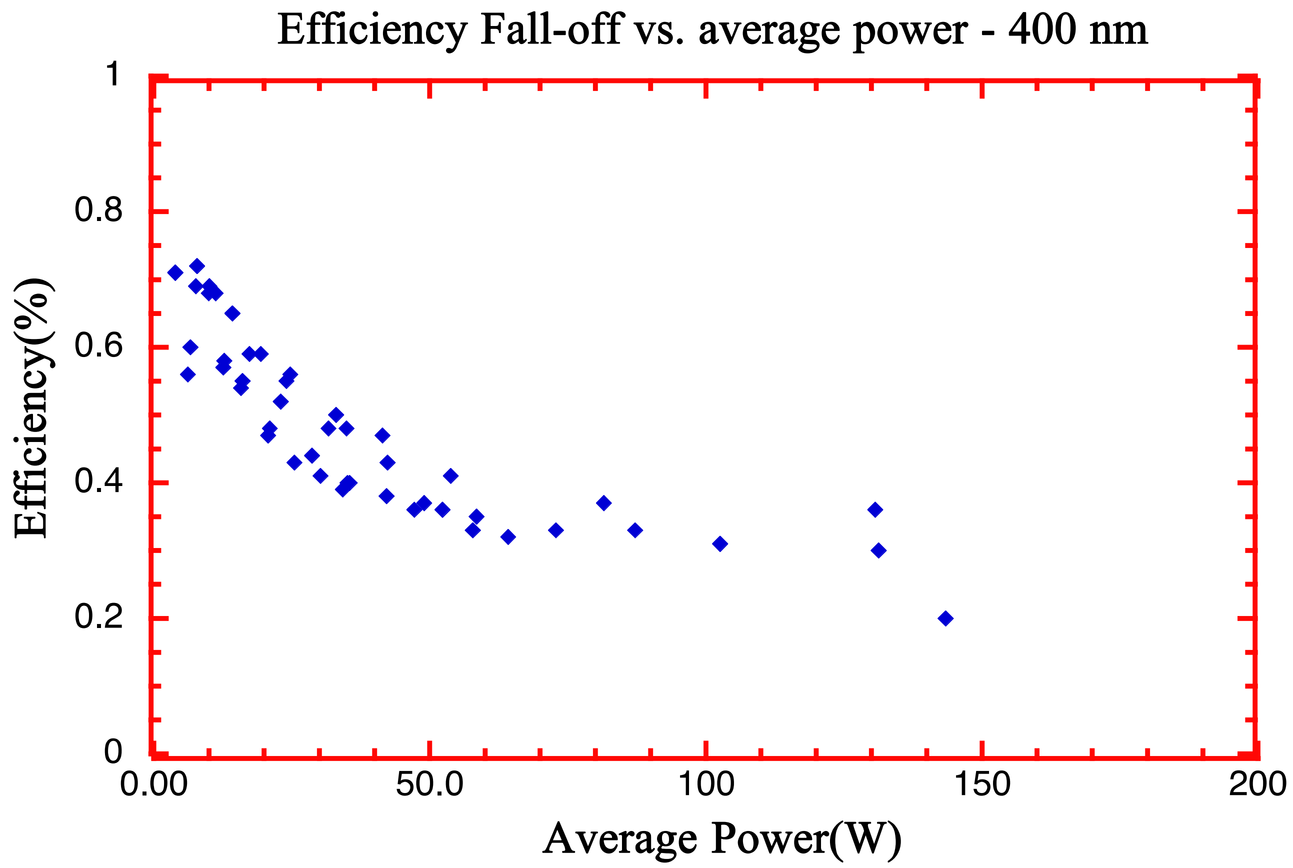
FEL Performance

- Operated at 700 nm, 400 nm (+ coherent harmonics)
- Low power
  - gain >>100%
  - extraction efficiency ~0.7%
  - long detuning curves (700 nm: 12.5 µm)
- High power
  - > 100 W @ both wavelengths
  - efficiency rolls off as mirrors load
- FEL works very well… TOO well, in fact
  - better than the models…

FEL Performance



FEL Performance



Very High Gain @ 400 nm

Data: localhost felscope09 CH2

timed out error

EPICS PV (gain/loss) FELGEN9ai1

Send to PV ● PV initialization ●

Folred: C:\DATA\scope data\9-14-2010

file: logged_at_5-14-33 PM_#1_400nm gain.txt

file # 41

Ch # 2

Y scale Log

Fit function b*exp(t)

A ini 1.79m

B ini 4.00u

τ ini 257.61n

Find ini On

A 1.79m

B 1.57u

τ 236.40n

δτ 3.19494n

Fit to peaks

Tolerance 0.0010

Iterations 1000

Avrg pnts 21

Threshold 12.000m

Width 4

Found # 4

Use peaks 4

Peak find OK ●

Exp. fit OK ●

g 147.0 ± 3.02 %

N 1.106

τ 236.4n sec

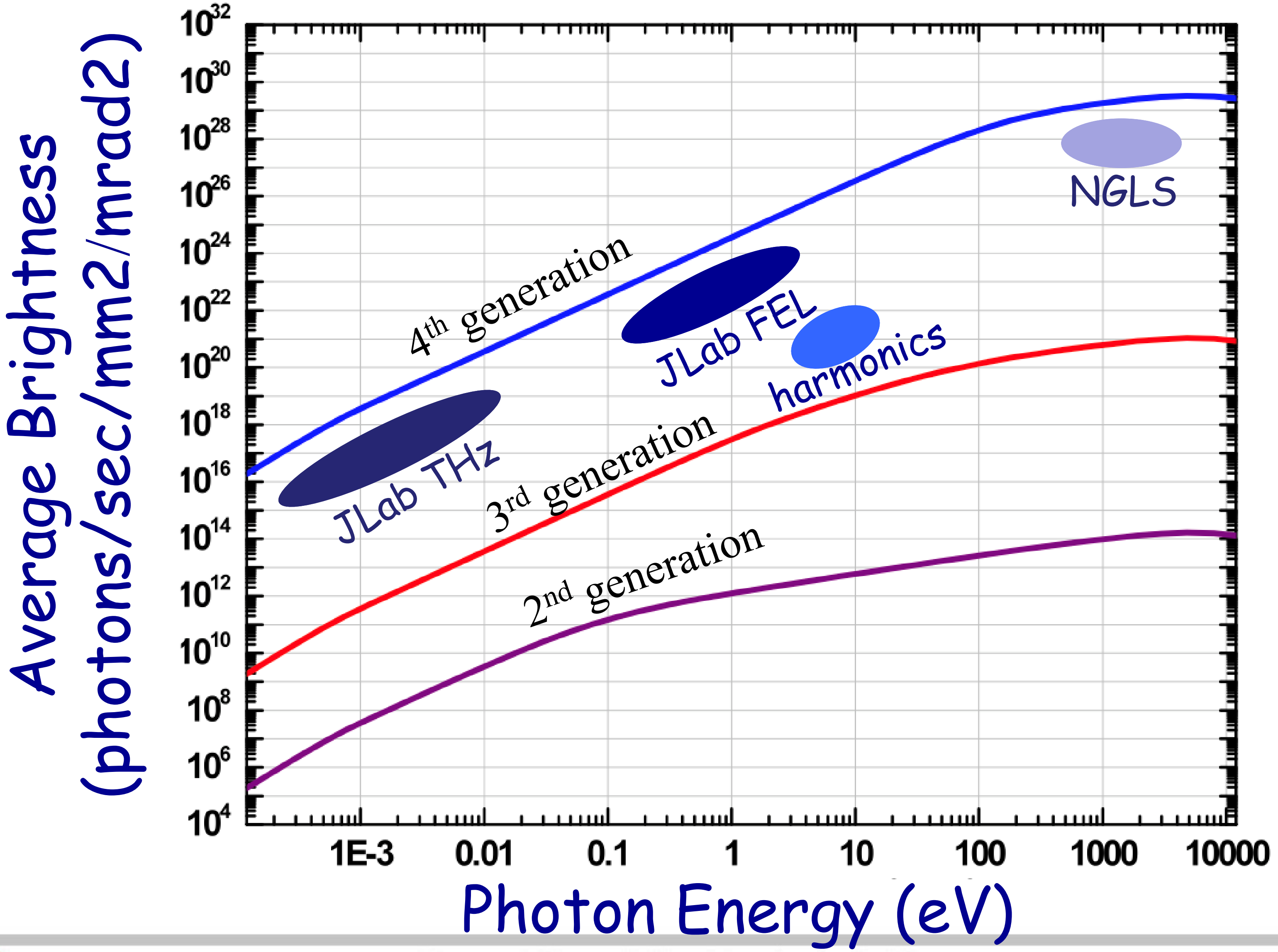
Performance Exceeds 1D and 3D Predictions

Parameter	*Simulations*	*Experiment*
Turn-on time	8.6 µsec.	5 µsec.
Net Gain	~70%	~150%
Detuning curve	4.5 µm	>7 µm
Efficiency	0.5-0.7%	0.73±0.05%

	Net gain (%)	Lasing eff. (%)
JLab spreadsheet	75	0.7
Genesis/OPC (3D)	88	0.67
Wavevnm(NPS-3D)	88	0.72
Medusa/OPC (3D)	168	0.63
Medusa/OPC (4D)	119	0.41
Expt	145±10	0.73±0.05

3D codes are close on efficiency but 4D is low. Medusa 3D, modified by slippage factor is close to experiment.

JLab Coherent Sources



Comparison to other sources

	photons/pulse	photons/sec	average spectral brightness ph/s/mm^2/mrad^2	peak spectral brightness ph/s/mm^2/mrad^2
Advanced Light Source LBL	2.0×10^{6}	1.0×10^{15}	1.0×10^{17}	2.9×10^{18}
High Harmonic Generation	1.6×10^{8}	1.6×10^{11}	4.1×10^{13}	4.1×10^{24}
JLab FEL	6.3×10^{9}	3.0×10^{16}	7.5×10^{18}	4.7×10^{24}

- above table is for 10 eV photon energy, 0.1% bandwidth
- assumes JLab FEL at 4.7 MHz, 230 fs FWHM

Status/Future Directions

- Near term (March-August run)
  - fully funded for FY ‘12 operations
  - multiple accelerator, FEL, & optics experiments
    - Trial VUV user run underway (recovered lasing on 5/10)
- Mid-term (next few years)
  - machine overhaul (partially funded, underway)
    - cryo mirrors ⇒ ~1 kW CW
    - new e^- source ⇒ 500 kV, brighter beam, robust operation
    - SRF refurbishment ⇒ higher energy, shorter wavelength
  - repurposed operation
    - dark matter search with internal target (“DarkLight”)

Long term trend to shorter wavelength (brighter e- source, higher energy); higher power ⇒ expanded user operations

Have significant potential for very high UV performance!

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