Wisconsin FEL Initiative

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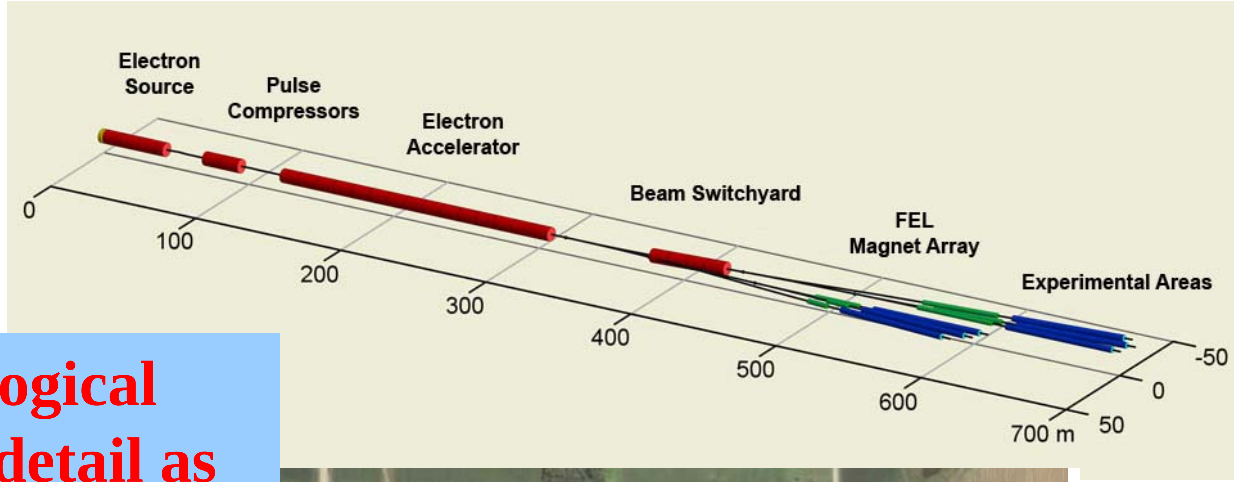
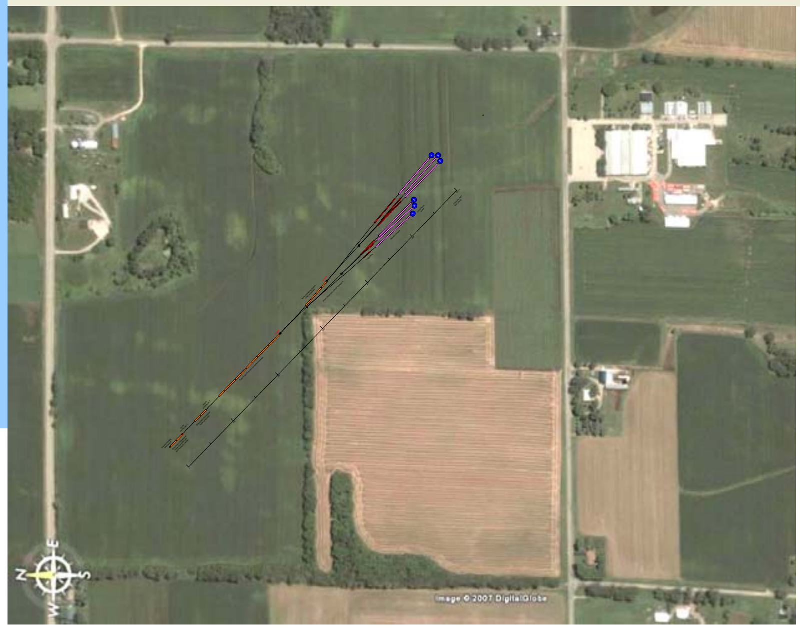
Wisconsin Free Electron Laser (WiFEL)

Next Generation VUV/Soft X-ray Light Source



Physical, chemical, and biological activity can been viewed in detail as they evolve and function on their characteristic temporal, spatial, and energy scales—femtoseconds, nanometers, millivolts



Massachusetts Institute of Technology

WiFEL Facility Goals

- **Transform-limited output** – longitudinal and transverse
- **Short pulses**: 20 fs and maybe shorter
- Enabling resolution of meV or less
- **Many FELs** operating simultaneously and independently

  at up to **~1 MHz repetition frequency** per beamline
- Complete tunability to **900 eV** in first harmonic
- Third harmonic for higher energy
- **Tunable polarization**
- **Peak power** and brilliance much larger than best synchrotrons/ERLs
- **Average flux** and brilliance much larger than best synchrotrons/ERLs

Next Generation VUV/Soft X-ray Sources

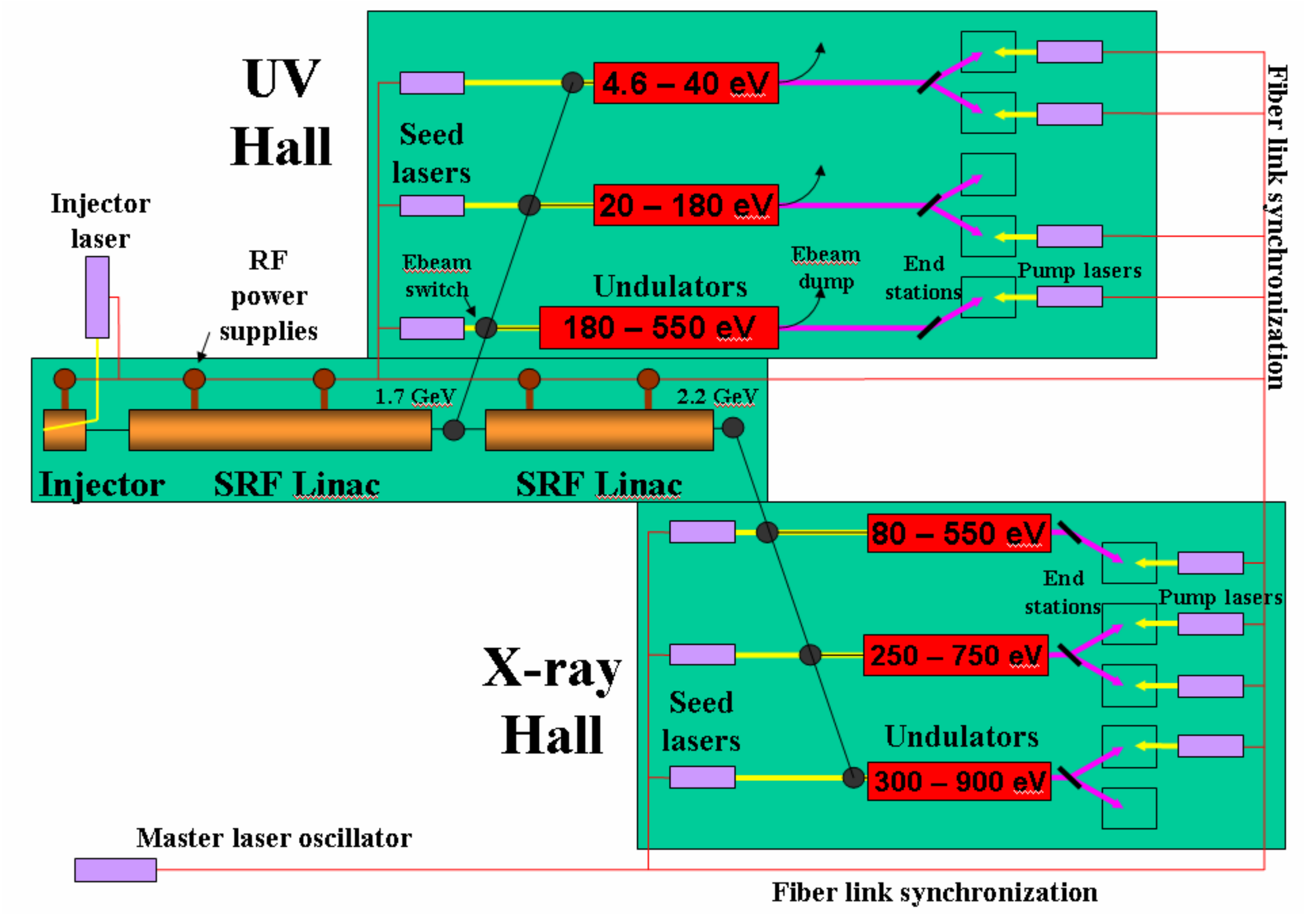
- Possible Sources
  - Relatively large, low energy, low emittance storage ring
  - Energy recovery linac (ERL)
  - Soft X-ray free electron laser, seeded for best performance
- How we converged
  - Storage rings are approaching limits of performance
  - At these lower photon energies, an ERL doesn't offer a big advantage over storage rings since horizontal and vertical ERL emittances vary as 1/Energy
  - ERL time structure problematic for, e.g., pump/probe
  - FELs will be truly transformational in enabling cutting edge science with dynamics as the key word

WiFEL Technical Approach

WiFEL

- 2.2 GeV CW superconducting linac with RF separation for many high-rep-rate beamlines
- Superconducting electron gun injector
- Low charge bunches
- Seeding with High Harmonic Generation sources
  - Stability and clean spectrum
  - < 20 femtosecond pulse length
  - Cascaded harmonic generation without “fresh bunch”
  - Beam energy, configuration, and undulator technology trade-off is “conservative” to establish clear feasibility in a Pre-Conceptual Design

WiFEL Schematic

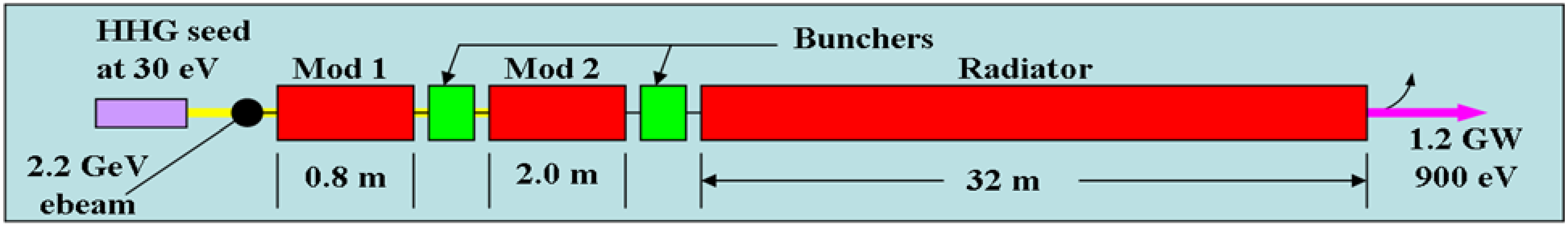


All FELs operate simultaneously at repetition rate up to ~1 MHz each

CW SRF driven facility can have many FELs. Total number of undulators set by budget. <u>Up to 16 not unreasonable</u>

Expansion potential to harder X-rays with additional linac sections

General WiFEL Design Philosophy



- **Modulators in a cascade are kept relatively short with little exponential gain until the final stage.**
- **Number of cascades minimized by HHG seeding at short wavelengths**
- **The short modulators provide a number of advantages**
  - **The “fresh-bunch” technique not needed, since phase space degradation minimized**
  - **Allows the use of a single short, low-charge bunch.**
  - **Lower charge has a major impact on cost/complexity**
    - **For fixed gun/linac-current/RF power, more endstations**
    - **Allows use of “blow out” ellipsoidal bunches with their nice linear fields**

WE5RFP031

Dynamics of Seeded Free Electron Laser Harmonic Cascades

W. Graves (MIT)

Harmonic cascade FELs amplify and upconvert the coherent radiation from a seed laser to a higher photon energy by manipulating electron dynamics in an undulator. There are a variety of ways to achieve this, for example by choosing particular harmonic ratios, by controlling exponential FEL gain in intermediate stages, by different combinations of electron beam energy, undulator period, and field strength parameter, or by using a fresh-bunch approach or not. In this work several of the alternatives are reviewed, and a method is chosen that provides stable output for a large harmonic ratio and low noise amplification while requiring modest electron beam parameters.

WE5RFP032

Design of the Wisconsin FEL Seeded Soft X-Ray FEL Undulator Lines

W. Graves, F. X. Kaertner, D. E. Moncton (MIT) J. Bisognano, M. Bissen, R. A. Bosch, M. A. Green, K. Jacobs, K. J. Kleman, R. A. Legg, R. Reininger (UW-Madison/SRC)

The seeded FEL performance of a number of Wisconsin FEL (WiFEL) undulator lines is described. The experimental design requirements include coverage of a broad wavelength range, rapid wavelength tuning, variable polarization, and variable pulse energy. The beam parameters allow experiments ranging from those requiring low peak power with high average spectral flux to those that need high peak power and short pulse lengths in the femtosecond range. The FELs must also be stable in timing, power, and energy while satisfying constraints on electron beam quality and fluctuations, undulator technologies, and seed laser capabilities. Modeling results are presented that illustrate the design performance over the full wavelength range of the facility.

WE5RFP057

Microbunching Gain of the Wisconsin FEL Beam Spreader

R. A. Bosch, K. J. Kleman (UW-Madison/SRC) J. Wu (SLAC)

The microbunching gain of a free-electron laser (FEL) driver is affected by the beam spreader that distributes bunches to the FEL beam lines. For the Wisconsin FEL (WiFEL), analytic formulas and tracking simulations indicate that a beam spreader design with a low value of R56 has little effect upon the gain.

WE5RFP058

Single-Stage Bunch Compression for the Wisconsin FEL

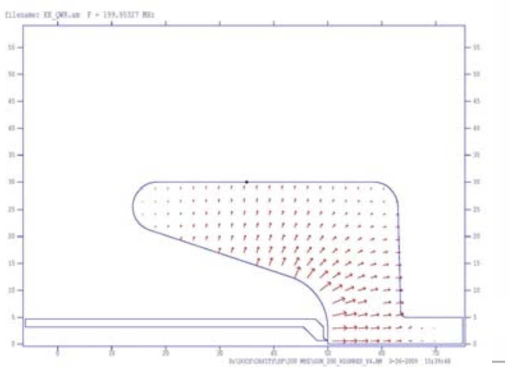
R. A. Bosch, K. J. Kleman (UW-Madison/SRC) J. Wu (SLAC)

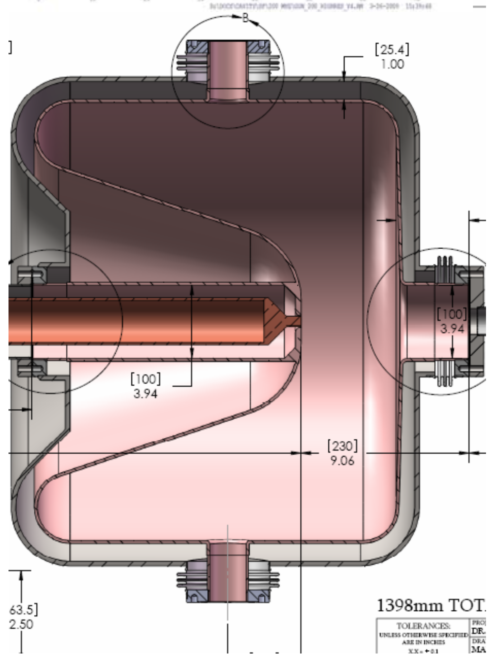
The microbunching gain of the driver for the Wisconsin FEL (WiFEL) is reduced by more than an order of magnitude by using a single-stage bunch compressor rather than a two-stage design. This allows compression of a bunch with lower energy spread for improved FEL performance.

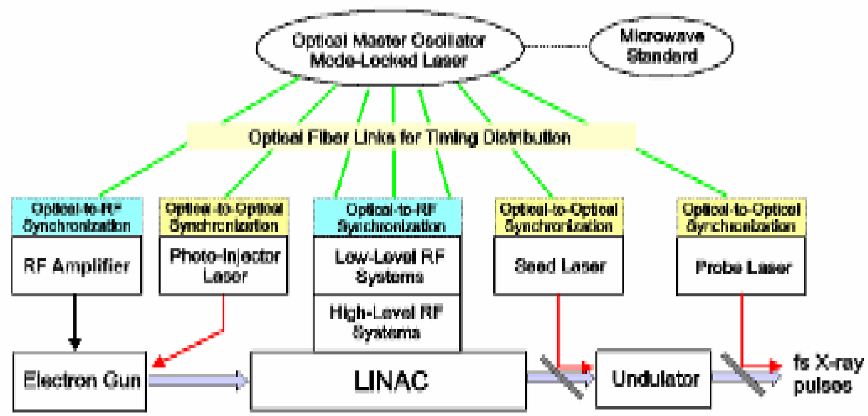
Table 1: Output properties for each beamline tuned to highest photon energy

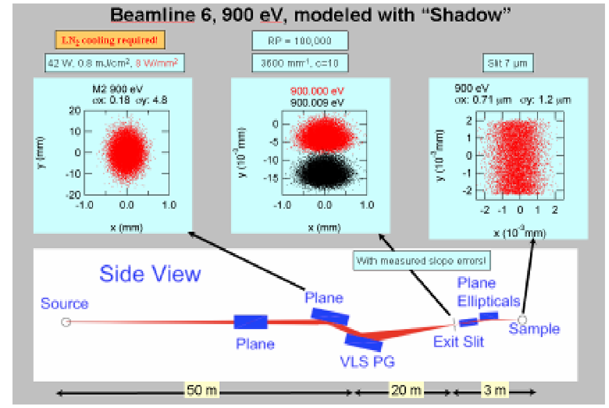
	BL1	BL2	BL3	BL4	BL5	BL6
Highest photon energy (eV)	40	180	550	550	750	900
Wavelength (nm)	31.0	6.9	2.3	2.3	1.65	1.37
Peak power (GW)	3.0	3.0	1.4	2.3	1.6	1.2
Photons per pulse	1.3e13	3.8e12	4.9e11	7.2e11	2.8e11	1.5e11
Pulse energy (μJ)	80	110	43	63	34	22
RMS pulse length (fs)	9.3	11.0	9.0	8.3	7.3	6.4
RMS bandwidth (meV)	43	60	102	93	110	128
Coherence length (fs)	41	35	22	24	19	16
Peak brilliance (p/s/0.1%/ mm^2 mr^2)	3.8e29	5.6e30	3.2e31	5.4e31	5.3e31	4.9e31
Avg brilliance (p/s/0.1%/ $mm^2 mr^2$ at 1 MHz)	3.5e21	6.2e22	2.9e23	4.4e23	3.9e23	3.1e23
Peak flux (photons/s)	5.0e26	1.1e26	2.1e25	3.0e25	1.3e25	8.1e24
Avg. flux (photons/s at 1 MHz)	1.3e19	3.8e18	4.9e17	7.2e17	2.8e17	1.5e17
RMS source size (μm)	85	42	42	44	36	33
RMS diffraction angle (μrad)	44	20	4.7	4.5	3.9	3.6
M^2	1.50	1.56	1.07	1.10	1.07	1.06
Waist location (m from undulator end)	-1.4	-6.7	-8.2	-6.4	-6.8	-7.0
Rayleigh length (m)	2.0	2.1	8.8	9.6	9.2	9.1

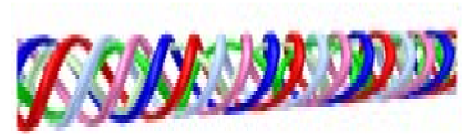
R&D Program

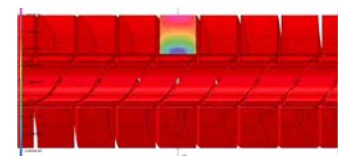


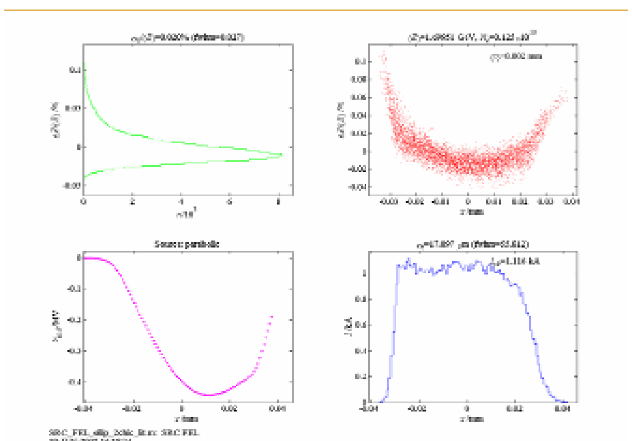








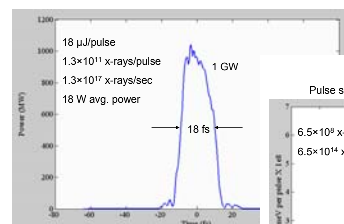




LiTrack simulations

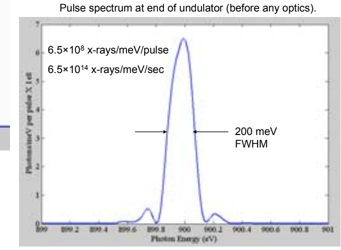
900 eV Time Distribution

Pulse shape at end of undulator (before any optics).



900 eV Spectrum

Pulse spectrum at end of undulator (before any optics).



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FEL Electron Beam Requirements

Repetition frequency	5 MHz
I peak	1000 Amps
Normalized $\varepsilon_{Transverse}$	<1 mm-mrad
Bunch length rms	70 fsec
Charge/bunch (derived)	200 pC
I average (derived)	1 mA

Photoinjector

WiFEL

• Pursue low-frequency (200 MHz) superconducting RF injector operating CW

• Operation in "self inflating" or "blow out" mode to produce elliptical bunches

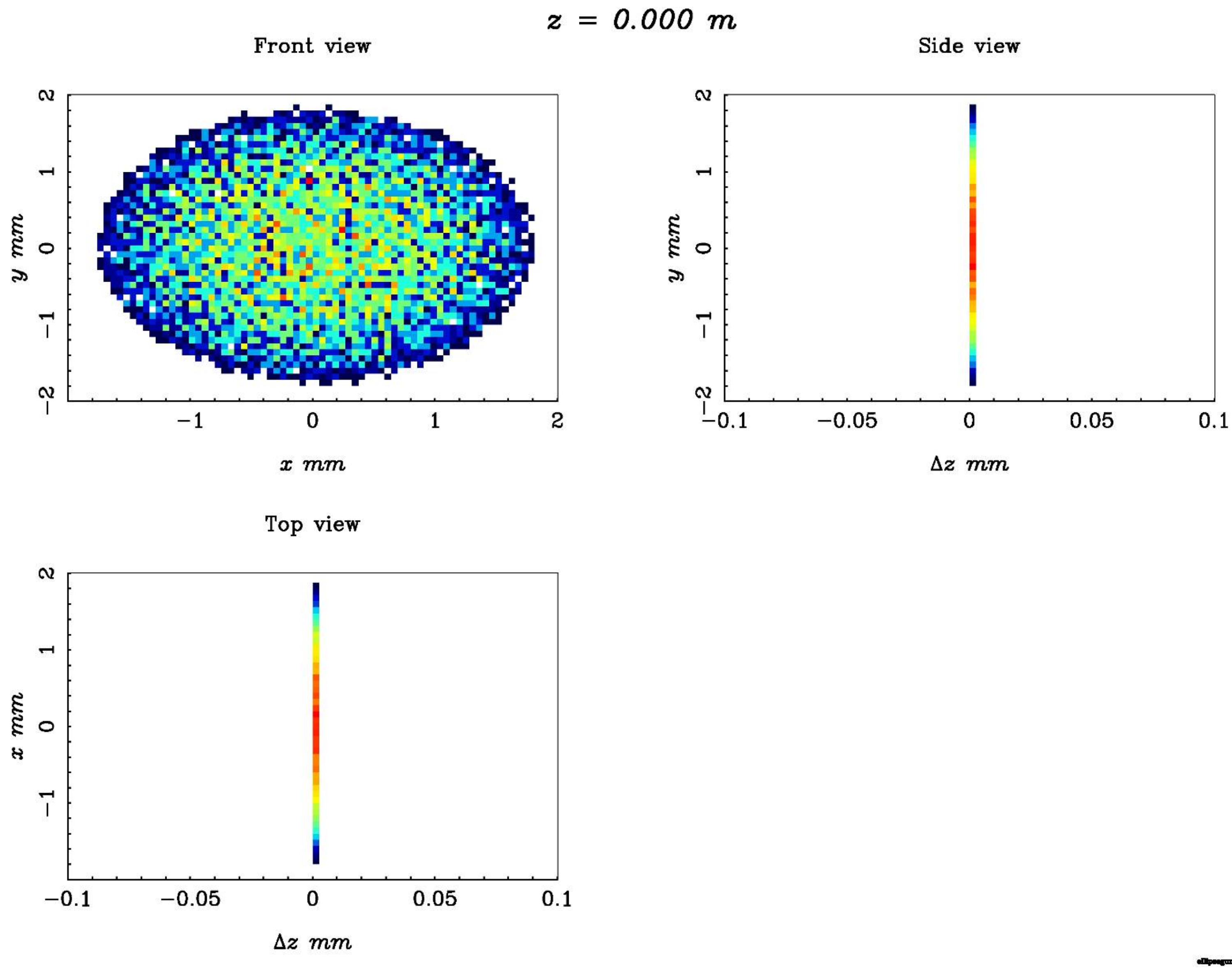
  • Cleaner emittance compensation

  • Smoother for compression

• Photocathode drive laser uses short (~30 fs) UV pulses with transverse shaping. Electron bunch rapidly expands to several picosecond bunchlength with ellipsoidal shape

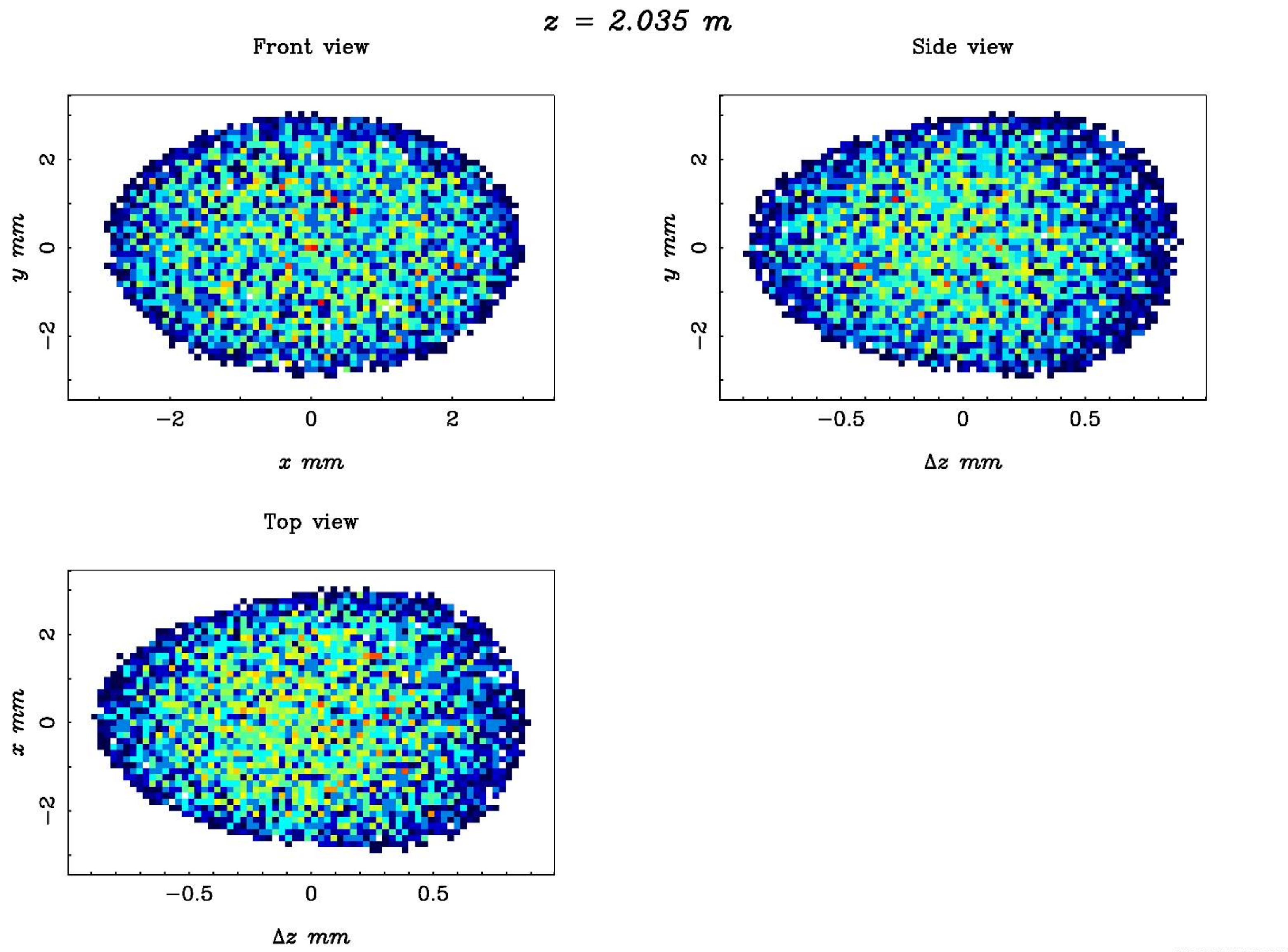
• 1 kA at 1 mm-mrad ε_n and 10^{-4} energy spread

Ellipsoidal bunch expansion



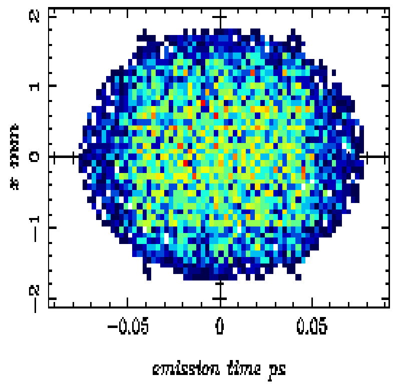
Courtesy Bob Legg

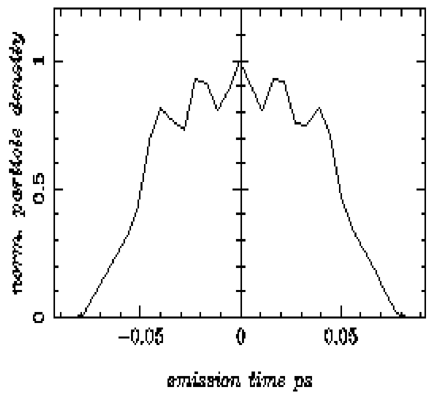
Ellipsoidal bunch expansion



Courtesy Bob Legg

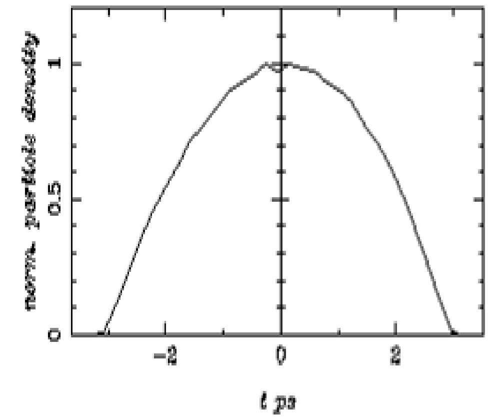
Blow-Out Mode Smooths Initial Distribution Errors



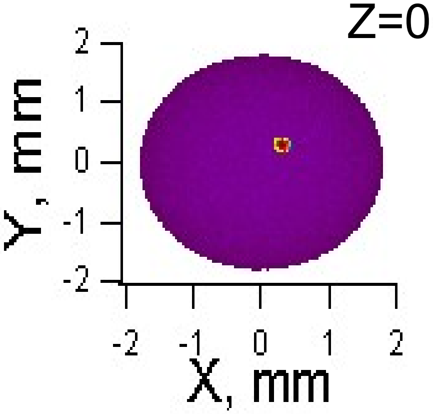


x vs z Z=0

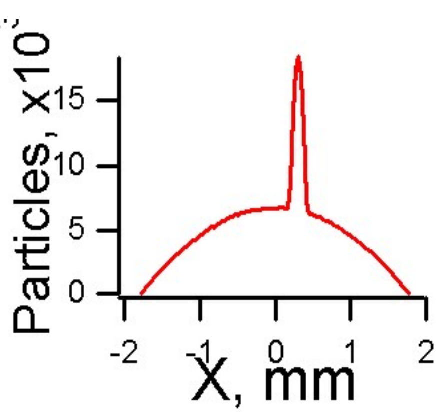
Bunch with Initial Longitudinal Modulation



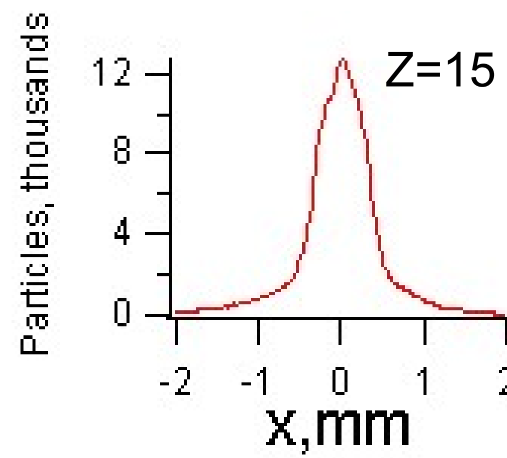
x vs z Z=15 m



Z=0



Bunch with Initial Transverse Modulation



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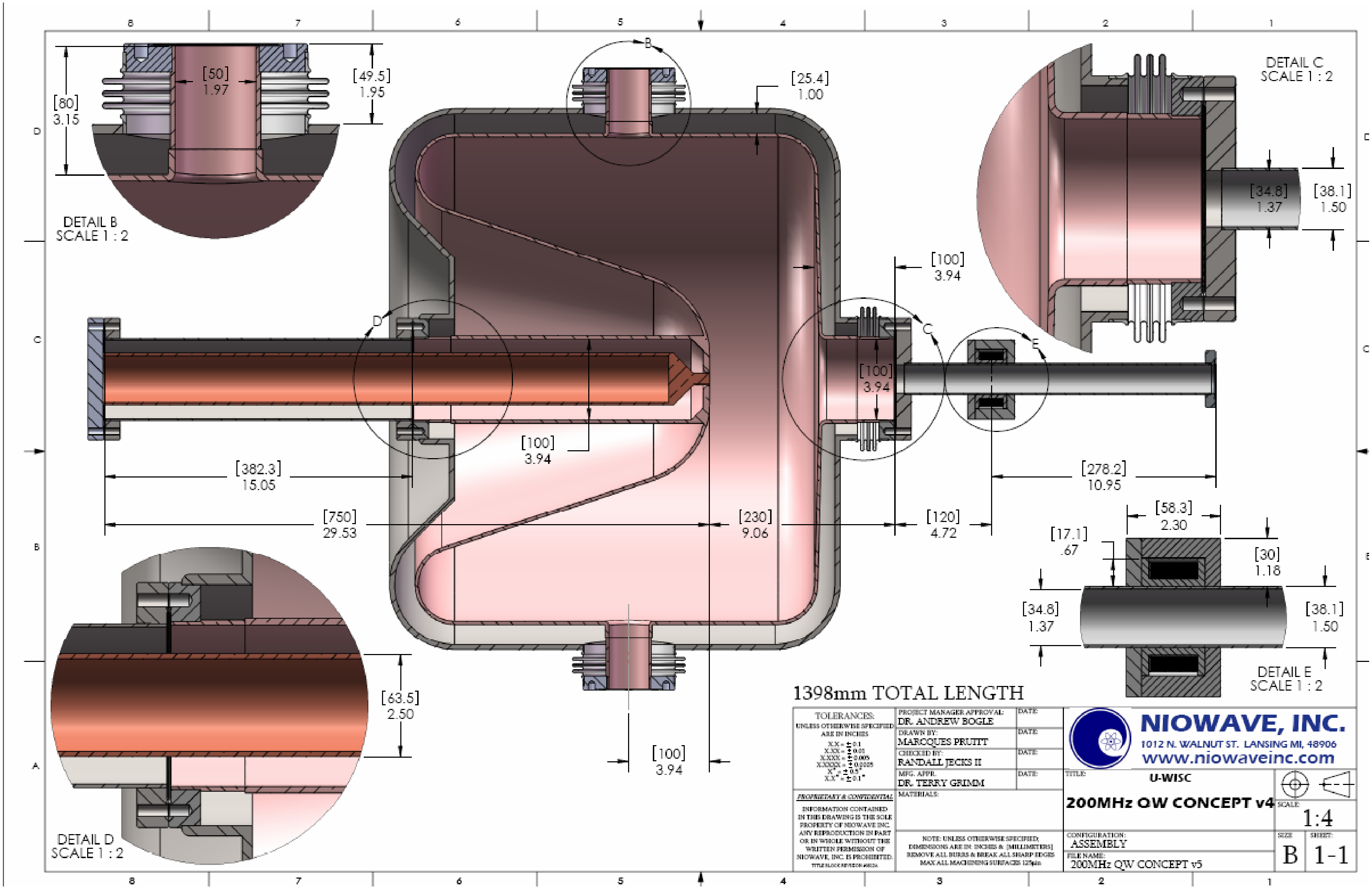
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1.18
DETAIL E
SCALE 1 : 2
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2.50
DETAIL D
SCALE 1 : 2
1398mm TOTAL LENGTH
TOLERANCES:
UNLESS OTHERWISE SPECIFIED ARE IN INCHES
PROPRIETARY & CONFIDENTIAL
PROJECT MANAGER APPROVAL:
DR. ANDREW BOGLE
DRAWN BY:
MARCQUES PRUITT
CHECKED BY:
RANDALL JECKS II
MFG. APPR.
DR. TERRY GRIMM
MATERIALS:
DATE:
NIOWAVE, INC.
1012 N. WALNUT ST. LANSING MI, 48906
www.niowaveinc.com
TITLE:
U-WISC
200MHz QW CONCEPT v4
SCALE:
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CONFIGURATION:
ASSEMBLY
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SIZE
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SHEET:
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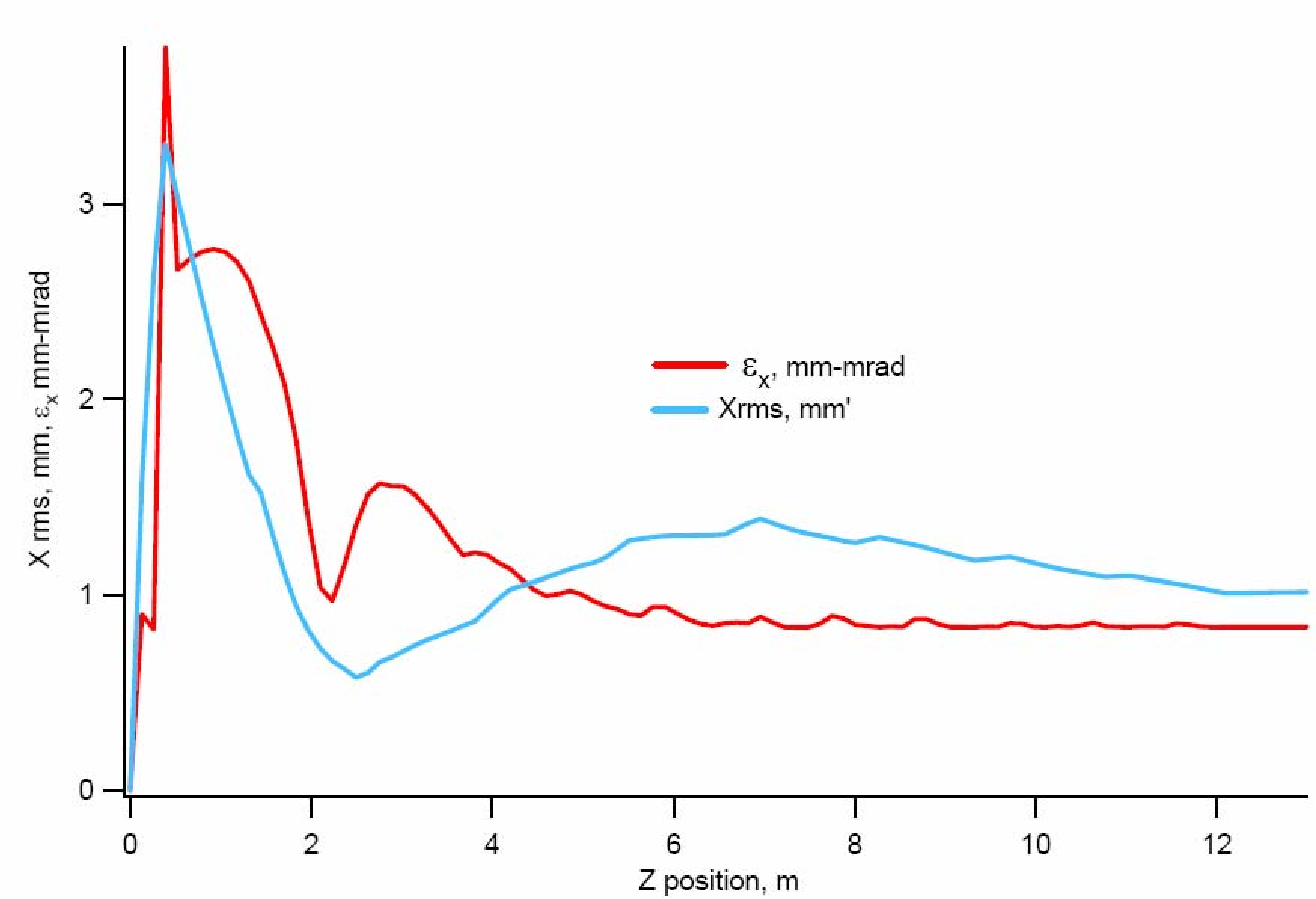
εx, mm-mrad
Xrms, mm'
X rms, mm, εx mm-mrad
Z position, m
0
1
2
3
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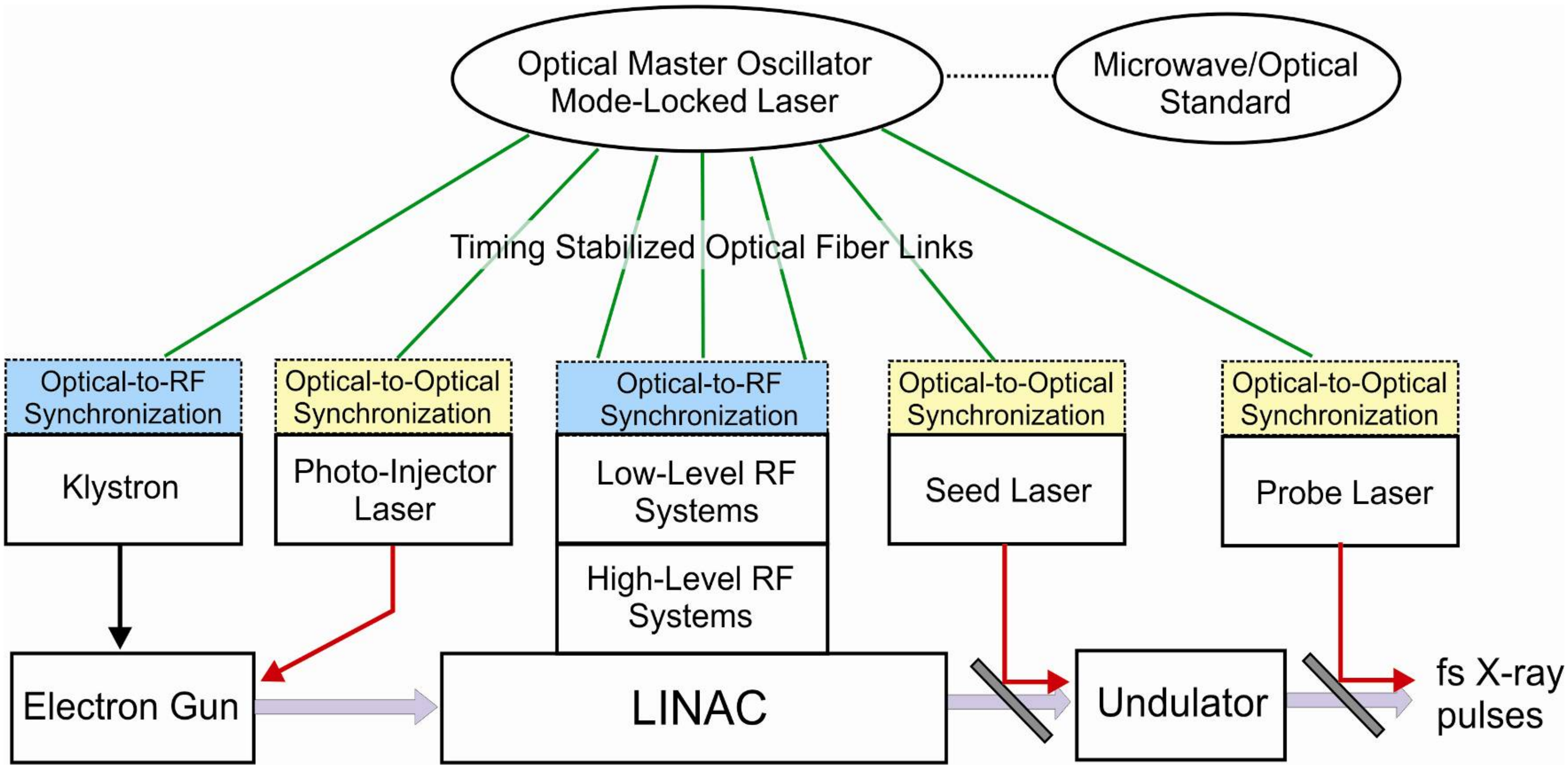
4
6
8
10
12

"Conventional" Laser Systems at WiFEL



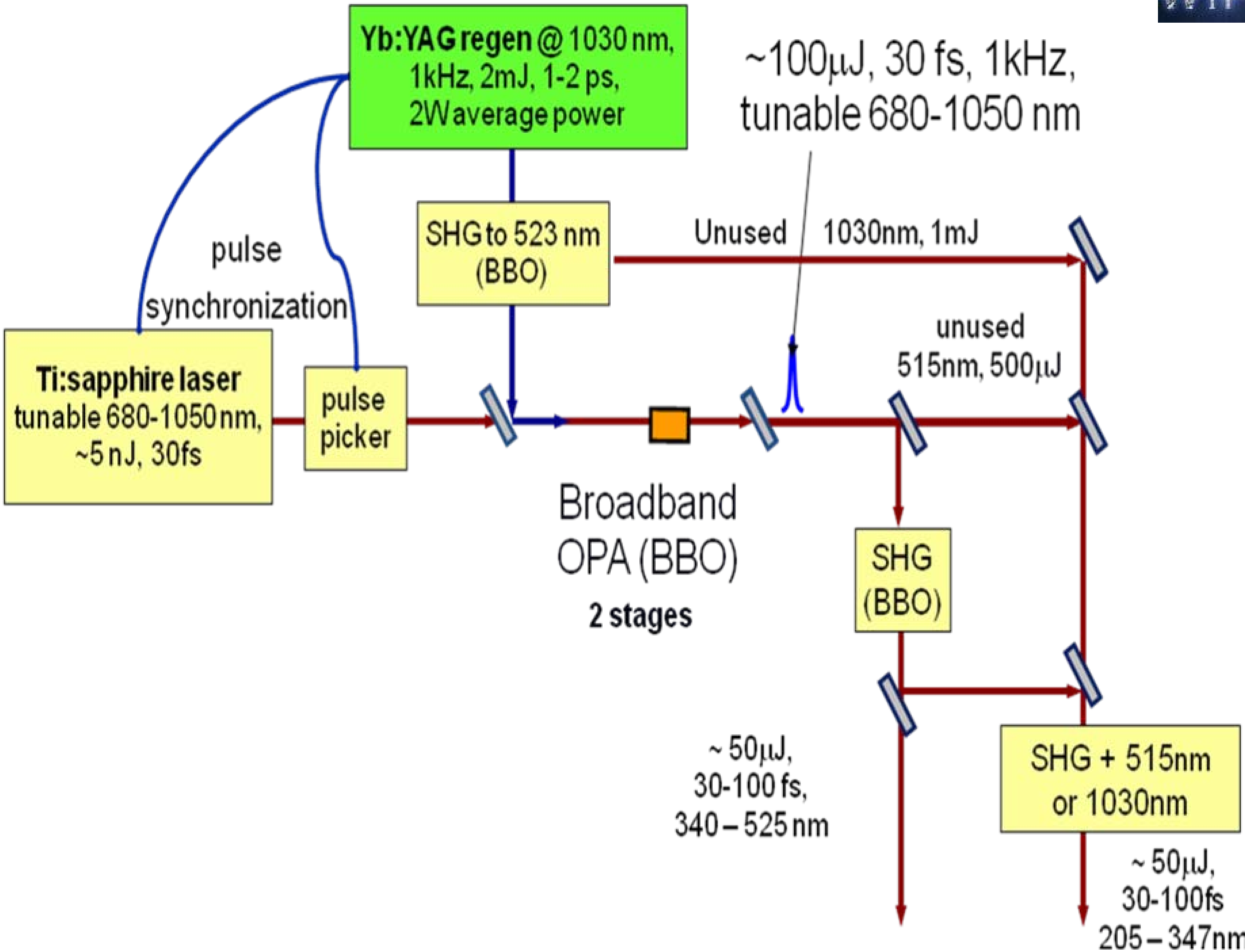
Sub-10 fs performance already demonstrated by Kim et al.: Nature Photonics, Published online: 2 November 2008; doi:10.1038/nphoton.2008.225

Primary Laser R &D

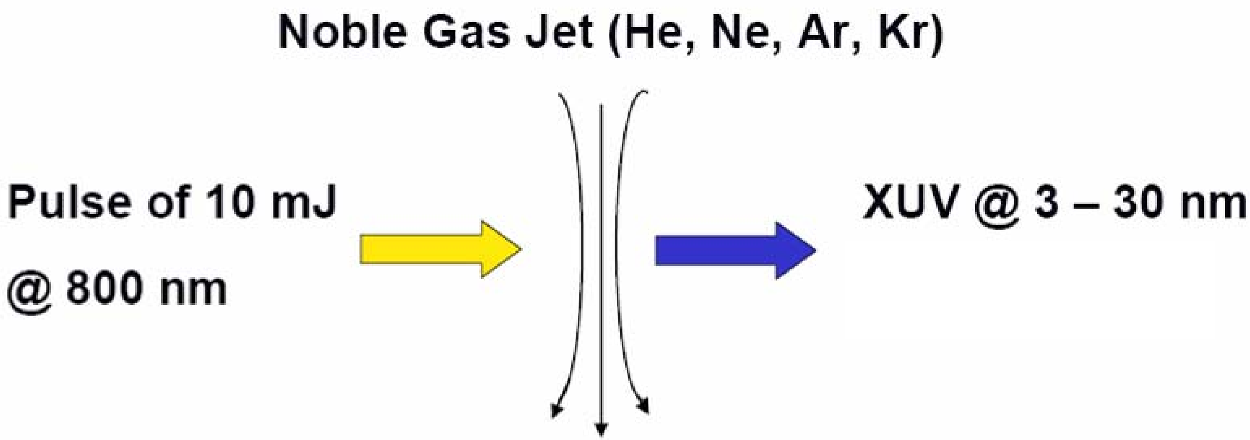
- UV seed laser
  - Required pulse energy for UV seeding is available commercially today at kilohertz rep rates
  - Cryogenically cooled nonlinear crystals to go from kHz to MHz for UV
  - Cryogenically cooled Yb:YAG amplifiers up to even three times higher average power levels than needed currently developed at MIT Lincoln Lab

- XUV seed laser
  - Required infrared pulse energy to produce the XUV pulse is available today commercially at kilohertz rep rates
  - To extend to MHz repetition rates, a key laser development effort is to show the application of cryogenic cooling to Yb:YLF and/or Yb:Y2SiO5
  - Goal is to demonstrate such a laser system at the 100W power level with scalablility to the multi-kW level

- Robust tunability of HHG source by pulse shaping of the driver


Yb:YAG regen @ 1030 nm,
1kHz, 2mJ, 1-2 ps,
2W average power
~100µJ, 30 fs, 1kHz,
tunable 680-1050 nm
SHG to 523 nm
(BBO)
Unused
1030nm, 1mJ
pulse
synchronization
unused
515nm, 500µJ
Ti:sapphire laser
tunable 680-1050 nm,
~5 nJ, 30fs
pulse
picker
Broadband
OPA (BBO)
2 stages
SHG
(BBO)
~ 50µJ,
30-100 fs,
340 – 525 nm
SHG + 515nm
or 1030nm
~ 50µJ,
30-100fs
205 – 347nm

High-Harmonic Generation



When gaseous atoms are exposed to an intense femtosecond laser field, the periodic modulation of the electron motion produces high-order harmonics of the laser frequency.

Courtesy Franz Kaertner, MIT

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Massachusetts Institute of Technology

High Repetition Rate XUV-Seed Laser

Necessary
XUV-Seed energy:
300nJ

HHG Efficiency
@ 40 nm: $\eta = 10^{-4}$
3mJ pulse energy

Average power
1kHz: 3W
1MHz: 3kW

Yb:YLF or Yb:Y_2SiO_5: novel broadband laser materials emitting at 1μm

Research plan is to demonstrate cryogenic operation at 100 W level with scalability to 3 kW

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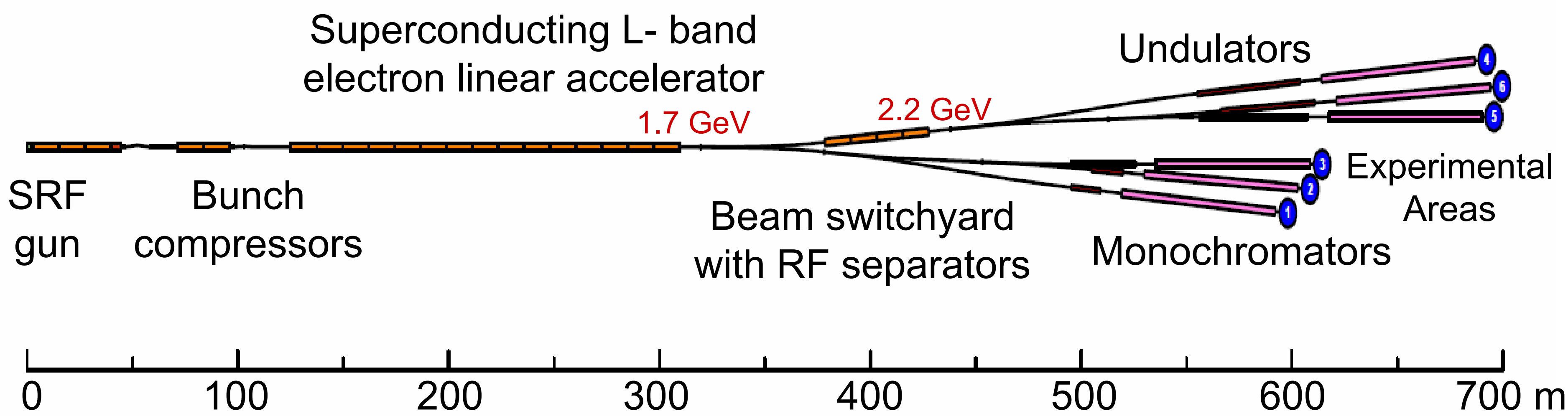
Wisconsin FEL



Details www.wifel.wisc.edu

Contains Pre-conceptual design, Science Case, R&D program, Papers, and Workshops