Design of a VUV/Soft X-ray FEL Facility and R&D on Critical Technologies

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Building a Seeded FEL Facility

- The facility we envision will:
  - Produce fully coherent light up to 900 eV
  - With ~0.1% of the power in the third harmonic
  - Tunable in energy and polarization
  - Enabling resolution to a meV or less
  - With pulses of 20 fs and ultimately less
  - With extremely high flux when needed
  - Which will also enable non-linear studies
  - And coherent control
  - With timing systems synchronized to 10fs
  - To enable two color pump-probe,
  - Maybe even two FEL colors

- In the following , I'll present a pre-conceptual design concept based on reasonable extrapolations of current technologies

- **We believe there is a clear path of R&D and design that makes a construction start early in the next decade truly realizable**

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Technical Approach

- 2.2 GeV CW superconducting linac
- Superconducting electron gun injector operating in "blow out" mode
- Seeding with High Harmonic Generation
  - 30 femtosecond pulse length
  - Megahertz repetition rates
  - Cascaded harmonic generation, but with short, low amplification modulators to avoid fresh bunches
- Beam energy and undulator technology trade-off is "conservative" to establish clear feasibility

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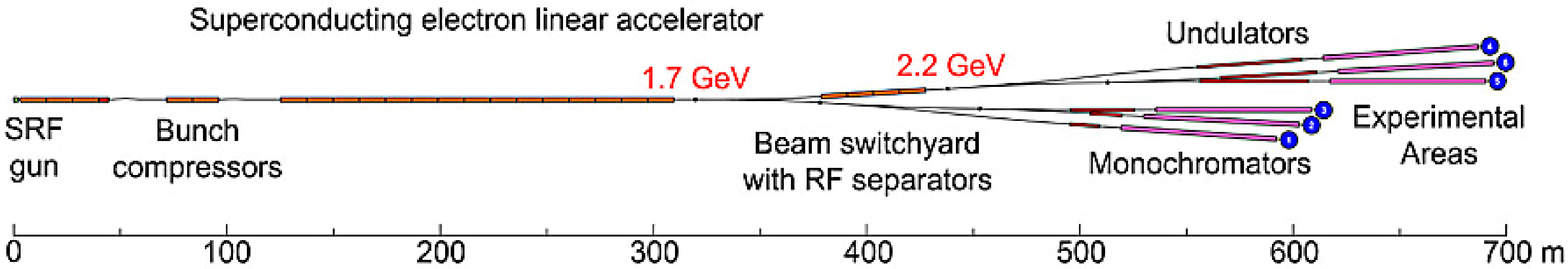
Wisconsin FEL Physical Layout



Details in R&D proposal submitted to NSF at

www.wifel.wisc.edu

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

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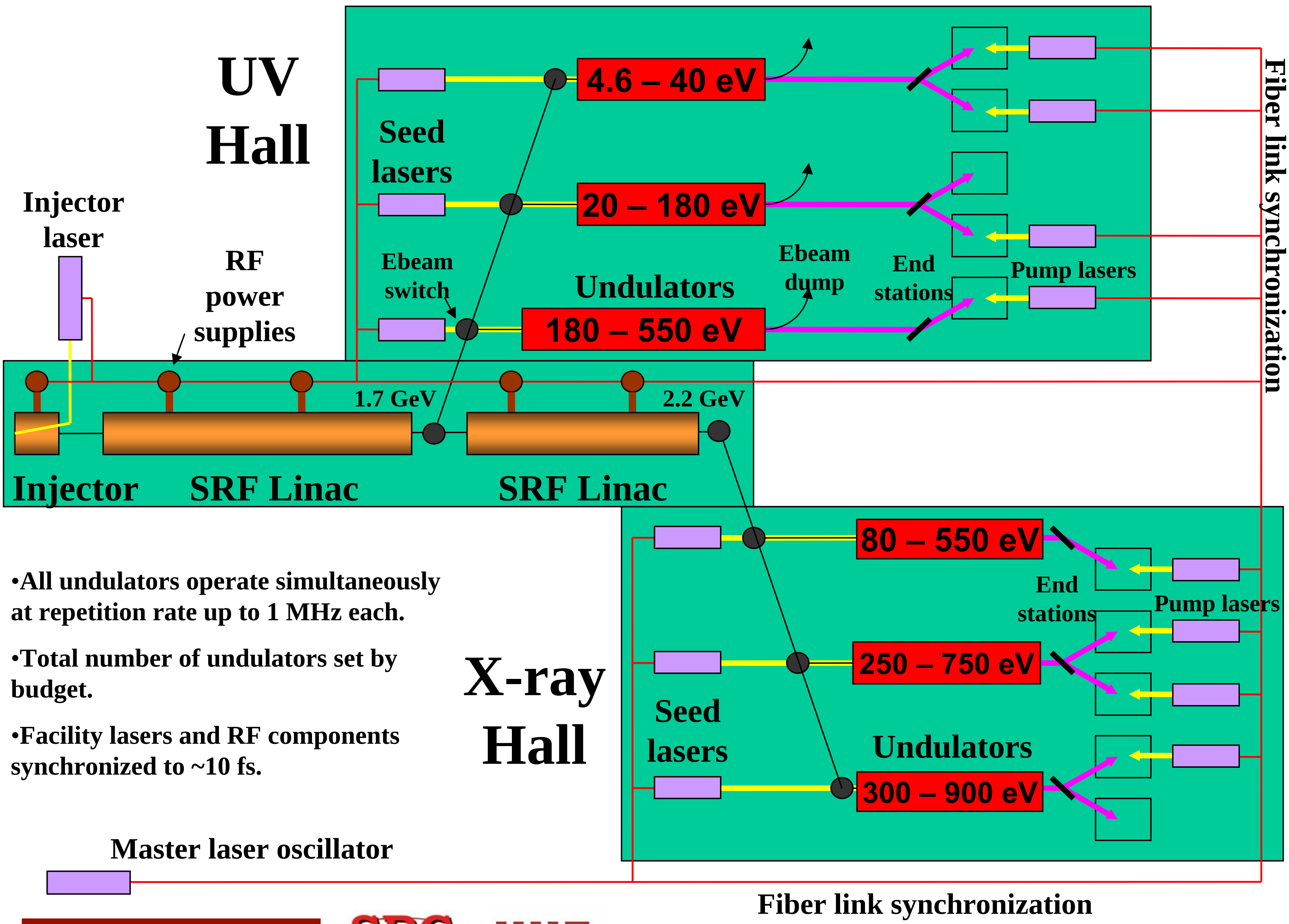
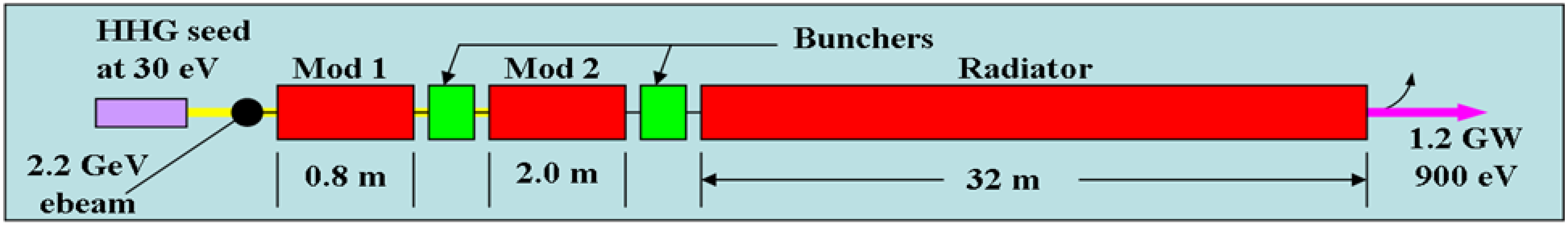
UWFEL Layout



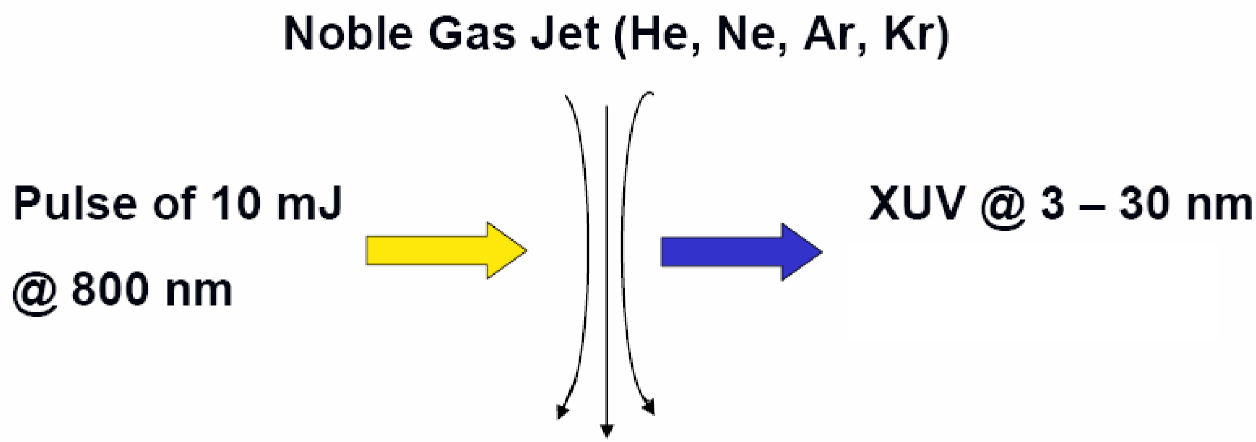
- All undulators operate simultaneously at repetition rate up to 1 MHz each.
- Total number of undulators set by budget.
- Facility lasers and RF components synchronized to ~10 fs.

General FEL Design Philosophy



- **Each of the modulators in a cascade is kept relatively short with little exponential gain until the final stage.**
- **The next undulator may be**
  - **A long radiator as designed for beamlines 1 and 2**
  - **Another short modulator to further up-convert the beam in a harmonic cascade as in beamlines 3 – 6**
- **Number of cascades minimized by HHG seeding at short wavelengths**
- **The short modulators provide a number of advantages**
  - **The modulation depth in each stage is modest, allowing the use of a single short, low-charge bunch.**
  - **The “fresh-bunch” technique not needed.**
  - **Lower charge has a major impact on cost/complexity**
    - **Allows, for fixed gun/linac-current/RF power, more endstations**
    - **Allows use of “blow out” ellipsoidal bunches with their nice linear fields**

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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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

Simulations

- Same electron bunch for all beamlines
- Electron beam properties:
  - **Normalized emittance: = 1 μm**
  - **Peak current: = 1000 A**
  - **RMS slice energy spread: = 200 keV**
- HHG Seed properties: 10 MW, 30 fs up to 30 eV

FEL codes:

- GENESIS 1.3; Sven Reiche (SLAC)
- GINGER; Bill Fawley (LBL)

Both are well-established, good physics models with many comparisons against experiment and theory.

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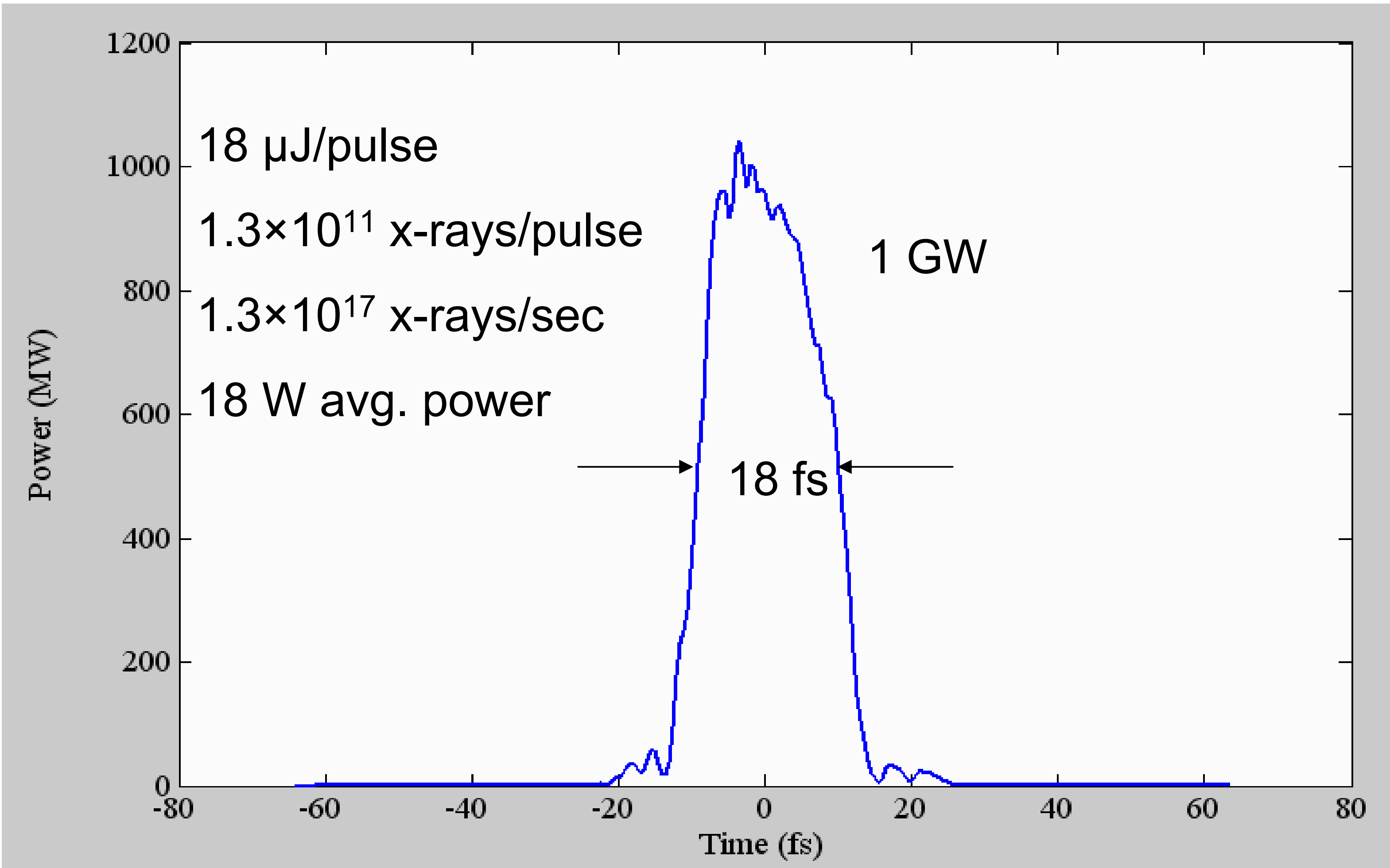
900 eV Time Distribution

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



Courtesy Bill Graves

R&D Program

- **To realize this vision:** four-year R&D plan proposed for the most critical aspects of the accelerator technology, the free electron laser systems, the conventional laser subsystems, and the photon beamline optics to optimize performance, reduce risk, and minimize costs.

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Key R&D Areas

- CW superconducting RF injector
- Superconducting accelerating structures and low level RF targeted to FEL needs
- Conventional laser systems for the master oscillator, photoinjector, FEL seeding, and timing
- Monochromator design, with particular attention to demonstrating heat load solutions
- Prototype advanced, small gap undulators for optimal FEL cost and performance
- Refined electron-beam and FEL dynamics simulation and theory
- Experimental techniques suited to FEL characteristics and prototype experiments

Photoinjector

- Pursue superconducting RF injector operating CW
- Major component of R&D program
- Desire for low charge (200 pC), ellipsoidal bunches.
- Photocathode drive laser use short (~30 fs) UV pulses with transverse shaping. Electron bunch rapidly expands to several picosecond bunchlength with ellipsoidal shape.
- Low energy spread and emittance are critical.

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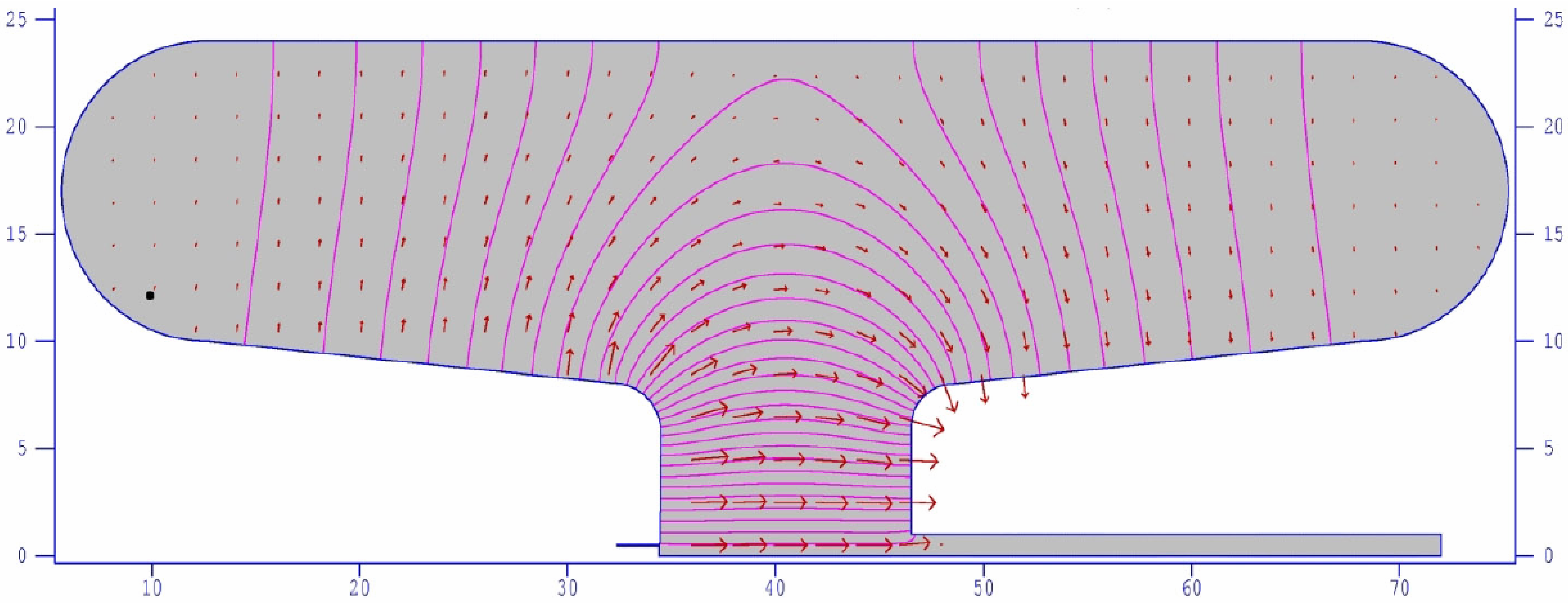
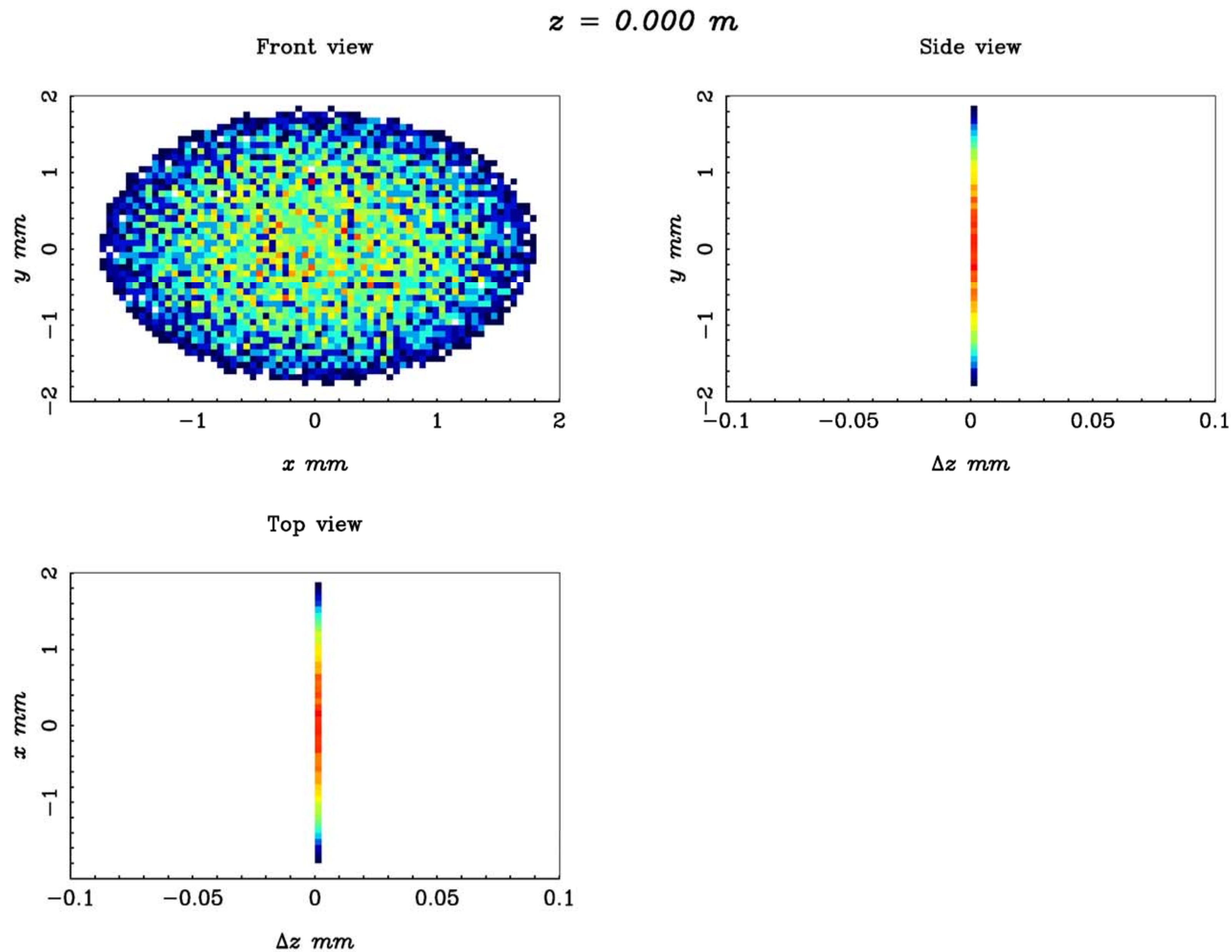


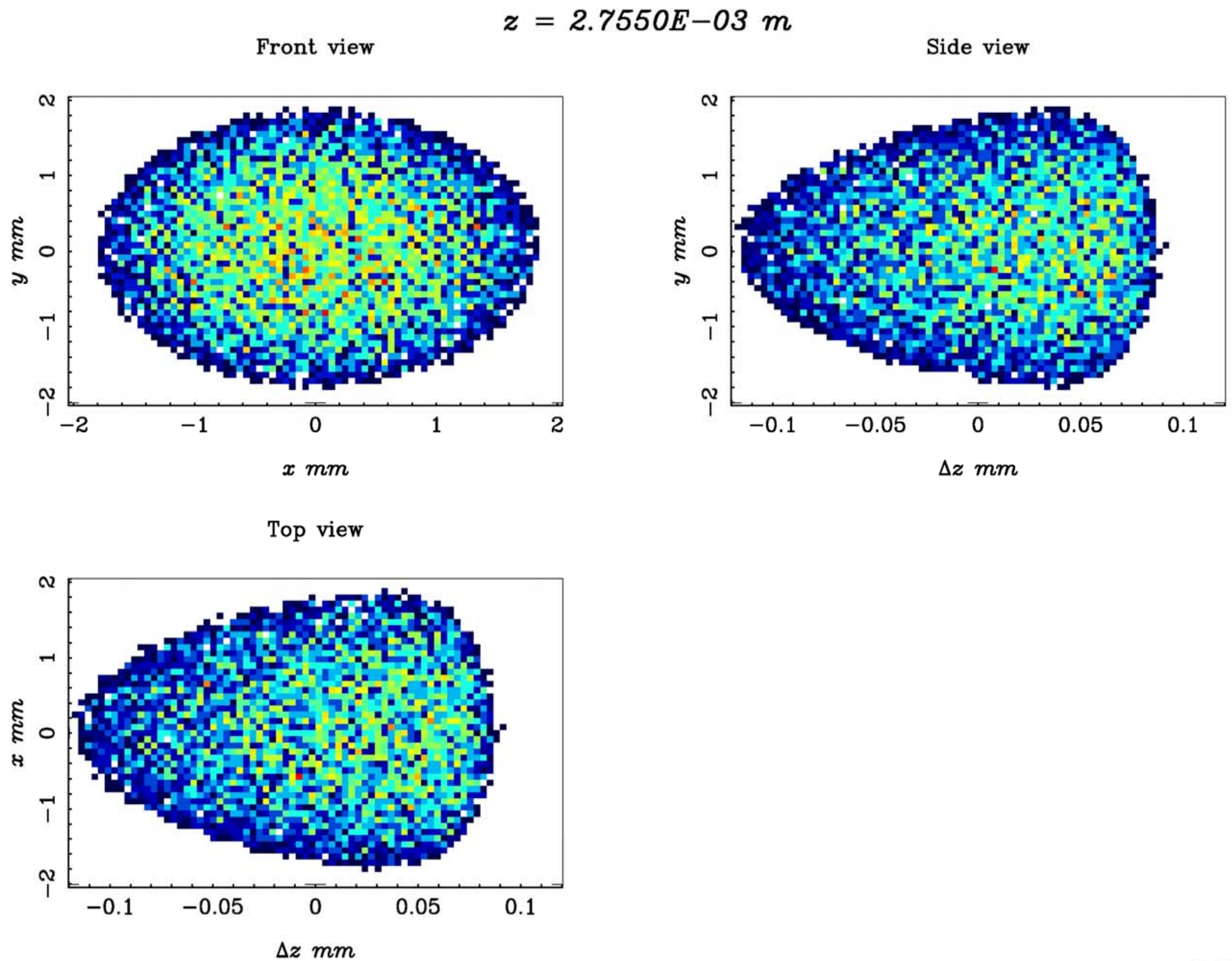
Figure 4: Superfish model of half-wave gun structure

Ellipsoidal bunch expansion (1 of 4)



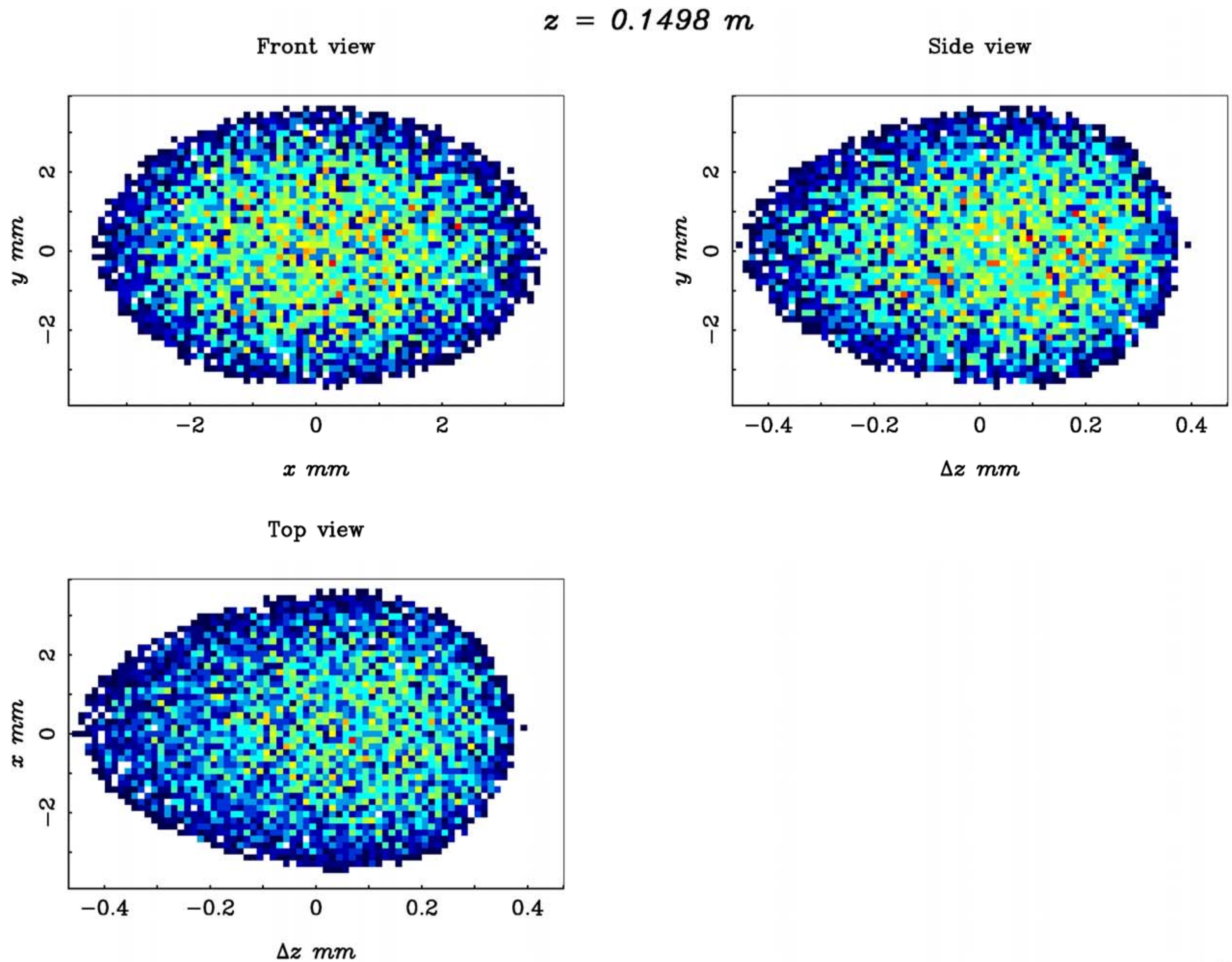
Courtesy Bob Legg

Ellipsoidal bunch expansion (2 of 4)



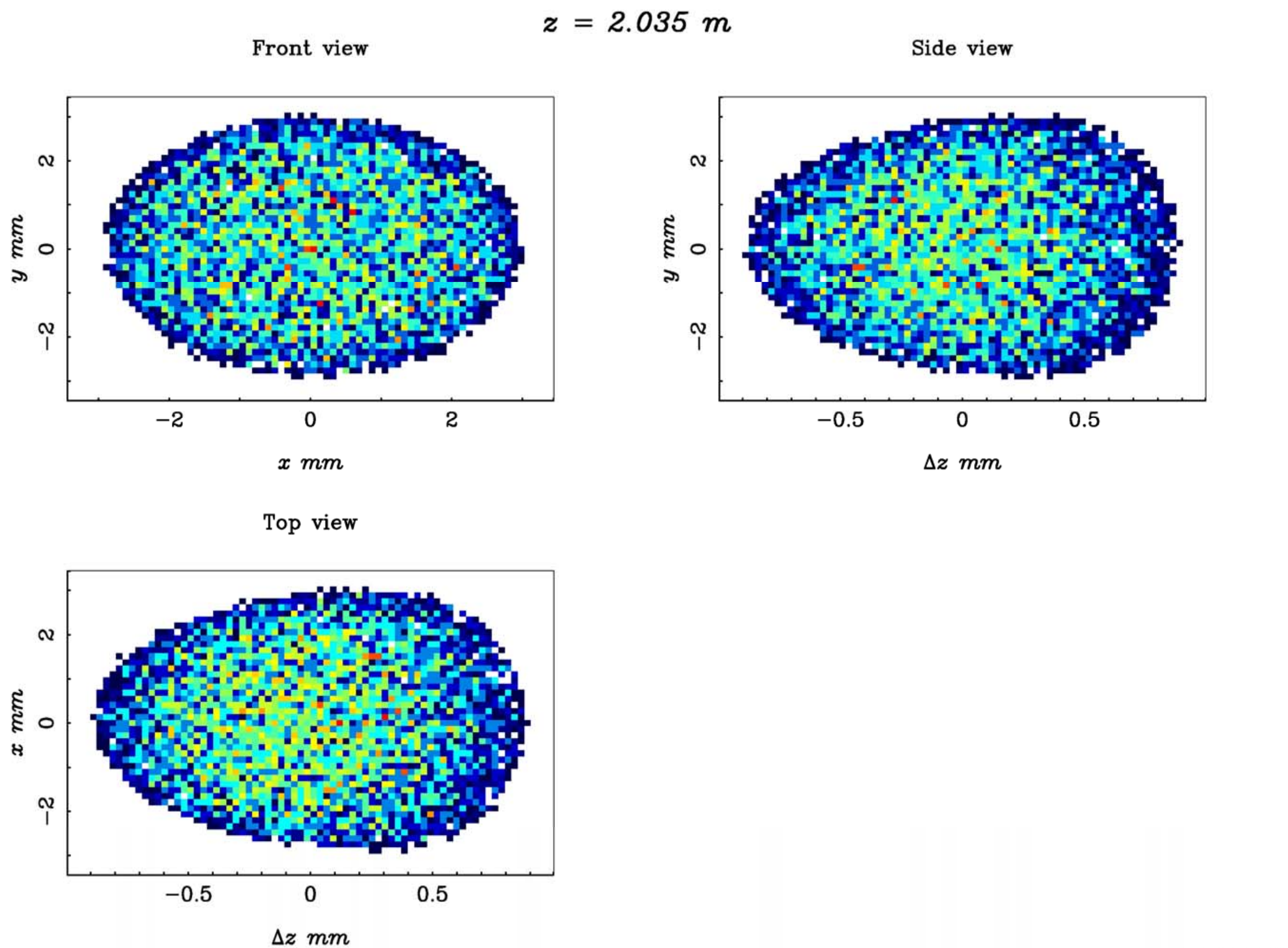
Courtesy Bob Legg

Ellipsoidal bunch expansion (3 of 4)



Courtesy Bob Legg

Ellipsoidal bunch expansion (4 of 4)



Courtesy Bob Legg

Injector Program

- Design, manufacture, and commission 200 MHz, half-wave resonator superconducting RF gun
- Verify performance meeting the requirements for WiFEL
- Benchmark simulation codes and models to provide predictive tools for further development.

Modeling

- Seamless start-to-end model where the input for each stage uses the output of the previous stage finally resulting in the most complete and accurate performance estimates possible

- Refine understanding of microbunching instability and how it arises from shot noise

- Understanding and calculation of the spectrum and growth of noise in the initial seed laser and electron beam, and its correct scaling through the FEL harmonic generation cascade

- Time dependent phase and amplitude of an HHG seed pulse and its noise characteristics

Accelerator Requirements

- CW 2.2 GeV SRF linac, L-band at ~15 MV/m, Q~10^{10}
- SRF Gun, Half Wave 200 MHz
- ~1mA current, RF separated to several FEL lines
- Amplitude control of ~0.02 %, phase control ~0.03°
- Jefferson Lab 12-GeV upgrade cavities, e.g., meet the needs
- RF control within factor of two of today; easier than Euro XFEL specs

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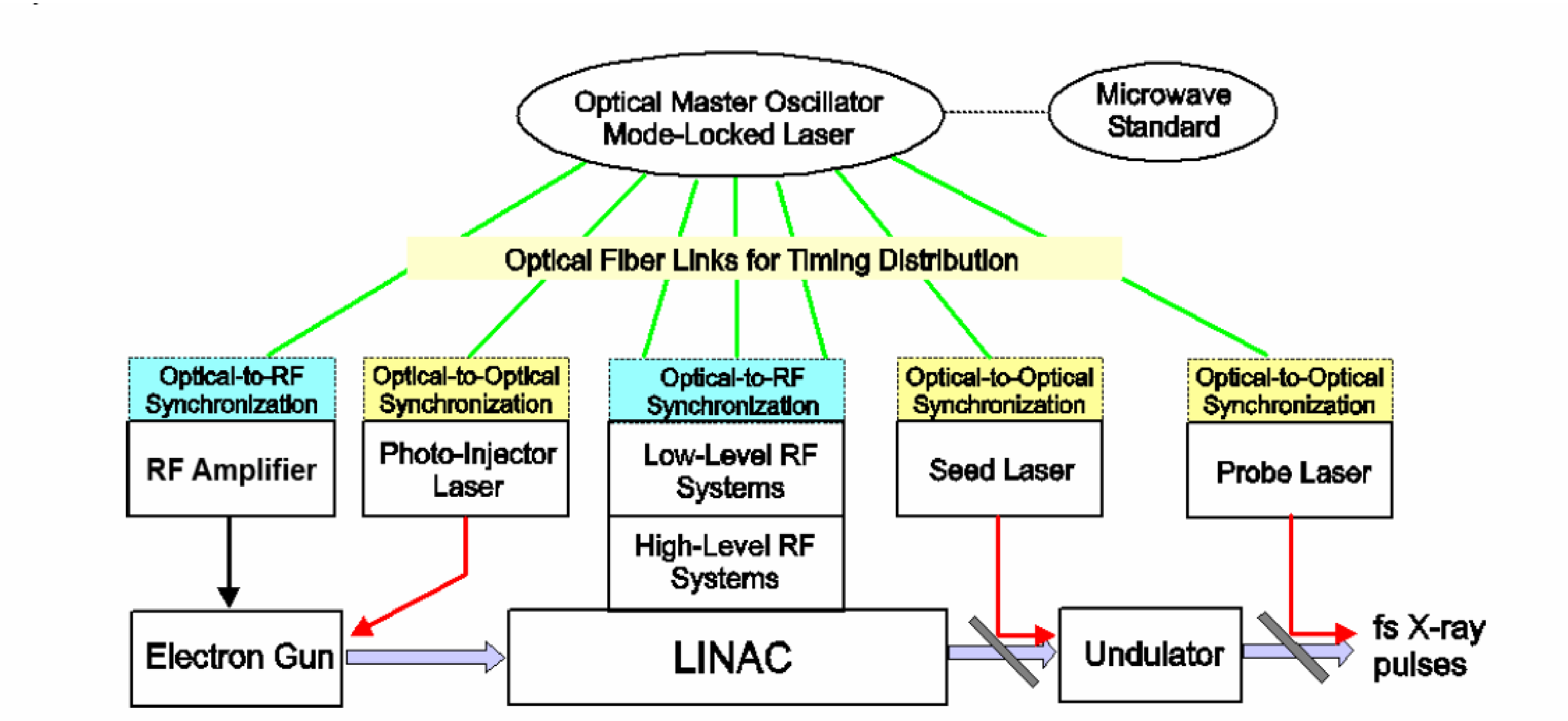
WiFEL Requires an Array of Femtosecond Lasers and Femtosecond Synchronization



R&D program provides a clear path to necessary performance based on proven achievements of MIT laser team

Primary Laser R &D

- Jitter
  - Noise characterization of master oscillator and syncrhonization at femtosecond time scale; aiming at < 10 fs jitter from 10’s of femtoseconds today
  - Stabilized fiber links: 10 fs demonstrated at DESY over 12 hours
- 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:Y_2SiO_5 and
  - 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 demonstrated pulse shaping of the driver

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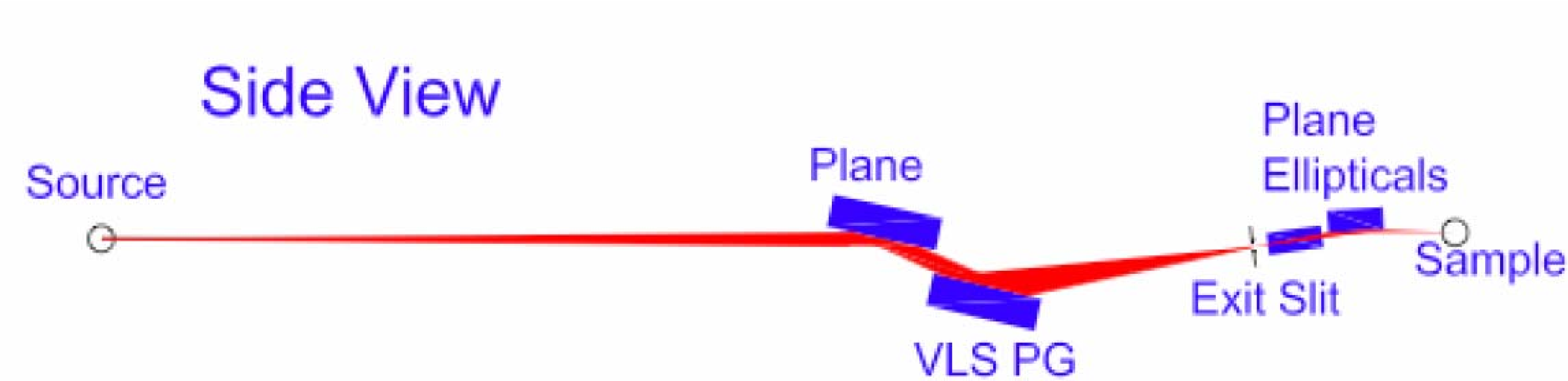
High Resolution Beamlines

Preliminary calculations with monochromator designs achieving a resolving power of 10^5 between 5 and 900 eV for the various FEL beamlines.

By way of comparison, an XUV beamline on a third generation storage ring can deliver at best three orders of magnitude less flux at the same resolving power



Beamline Optics Heat Loads

- High repetition rates of the FELs significantly aggravate the head load problem on the optics

- This power density is comparable to the highest values encountered at third generation hard x-ray facilities

- Liquid nitrogen cooling will be used to prevent thermal

- Studies would be carried out at SRC to
  - Establish design of cryogenic mirror assemblies
  - Measure figure errors, characterizing materials and overall efficacy in reducing figure errors
  - Assess surface contamination
  - Develop and benchmark wave propagation codes for understanding effects of errors and correction with other optical elements

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Undulator R&D

- Pre-conceptual design utilizes “conservative” assumptions; e.g., gaps and fields similar to LCLS
- The peak linac energy, hence the linac length and cost, is directly related to the peak magnetic field of the final elliptically-polarizing undulator radiator in the highest energy beamline
- More generally, all beamlines could benefit from higher magnetic fields either in that undulator vacuum gaps could be increased or beamline tuning ranges extended
- Two approaches
  - Update the APPLE design by incorporating both in-vacuum and cryo-cooling
  - Develop a fully variable polarization superconducting undulator

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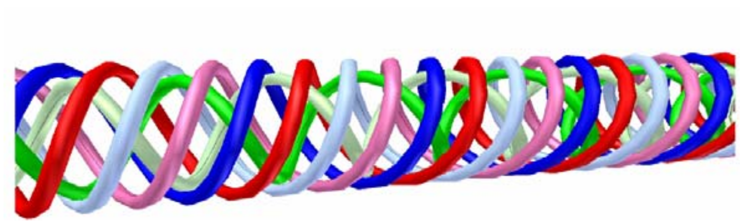

New Experimental Techniques and Prototype Experiments

- As part of our scientific workshops, ideas were generated for experimental approaches that could make best use of FEL properties
- Some illustrative examples
  - TOF detectors for improved time/energy resolution and data throughput
  - Optical schemes and phase retrieval methods for fast image reconstruction
  - Optical delay instrumentations for pump-probe experiments
  - Specialized ZPAL patterning tools
  - Autocorrelator for EUV/soft x-ray pulses for multiphoton processes
  - Two-time correlation measurement at FLASH, including development of synthetically labeled materials
- Further concepts would be solicited from user community
- Best ideas would move forward to prepare for FEL turn-on

Summary

- A pre-conceptual design has been developed for a seeded UV / soft x-ray FEL.
- Necessary R&D has been identified which should allow a construction start early in the next decade
- We believe that a VUV/Soft-X-ray seeded free electron laser facility is technologically achievable and that the scientific potential is both compelling and essential for the US to maintain it scientific leadership.

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