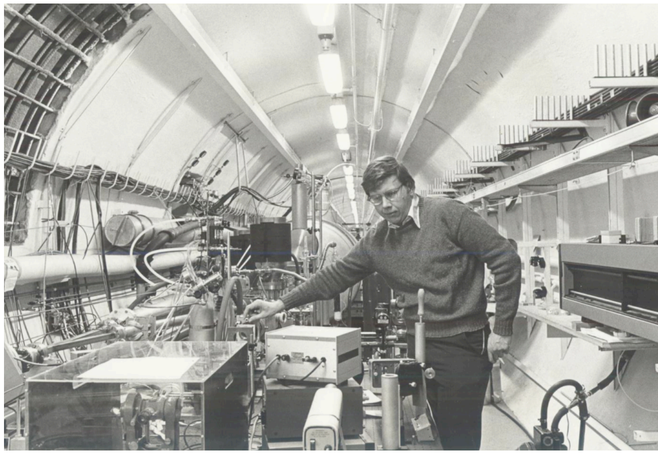

NPS
PRAESTANTIA PER SCIENTIAM
1909

Evolution of Free Electron Lasers

Bill Colson

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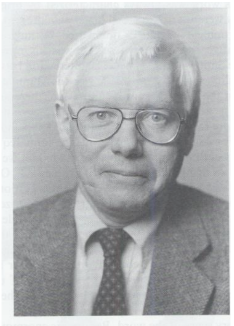
Berlin FEL Conference, August 28, 2006

Acknowledgements:

John Madey, Mike Poole, Lex van der Meer, Todd Smith, Nicolay Vinokurov, Dave Dowell, Dinh Nguyen, John Lewellen, and Joe Blau

Klaus Halbach



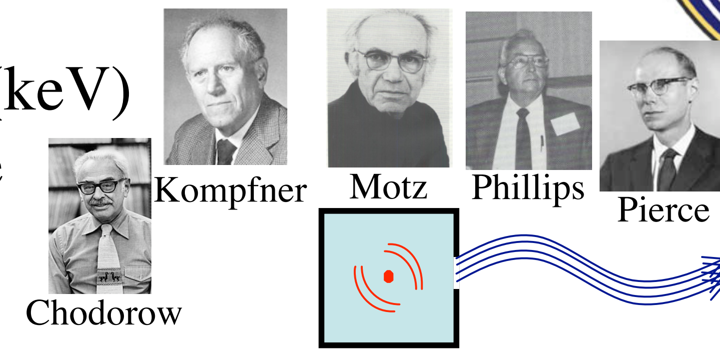
John Walsh

- Focus on evolution of concepts, not reciting history
- Influenced by perceptions, experiences and discussions
- Evolution of general history, specific connections, early developments, injectors, undulators, theory, configurations, applications, …

FEL General History

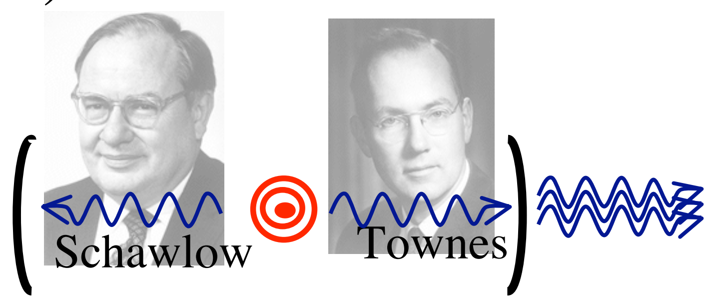
- Microwave Tubes (1930's)
  - free nonrelativistic electrons (keV)
  - microwave cavity, waveguide

  ⇒ long wavelengths & efficient



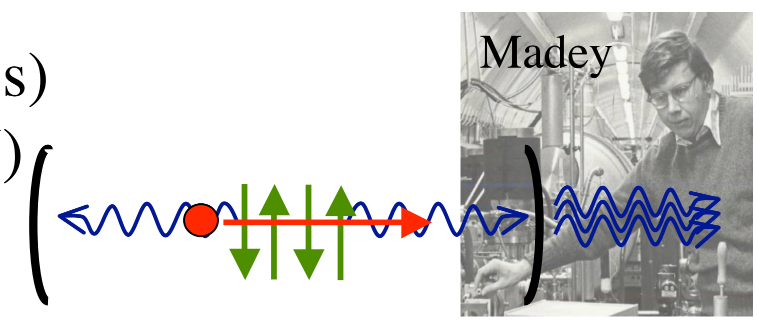
- Atomic and Molecular Lasers (1960's)
  - bound electrons (eV)
  - open optical resonator

  ⇒ short wavelengths, not tunable, not efficient, Noble Prize



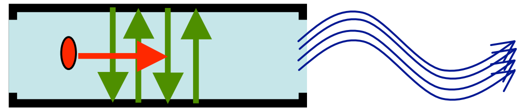
- Free Electron Laser (Madey 1970's)
  - free relativistic electrons (MeV)
  - open optical resonator

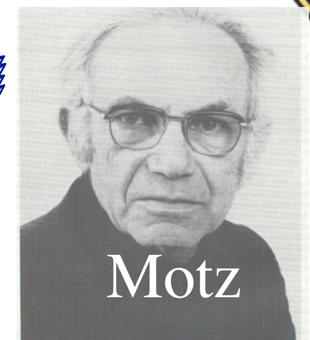
  ⇒ short wavelengths, tunable, efficient



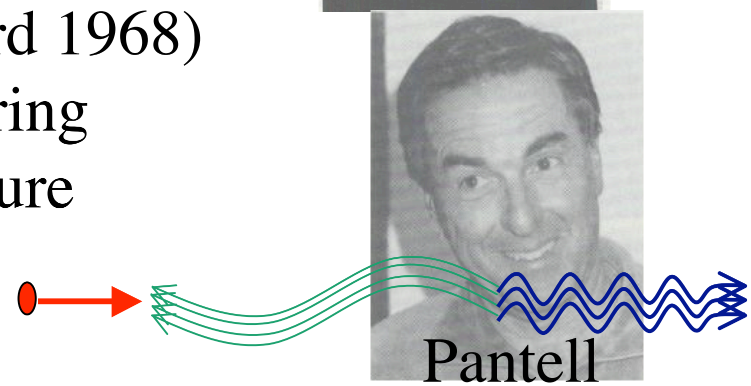
Specific Connections

- Motz (Stanford 1951)
  - Undulator, waveguide
  - traveling wave tube, $\gamma \approx 3$, $\lambda \approx$ mm

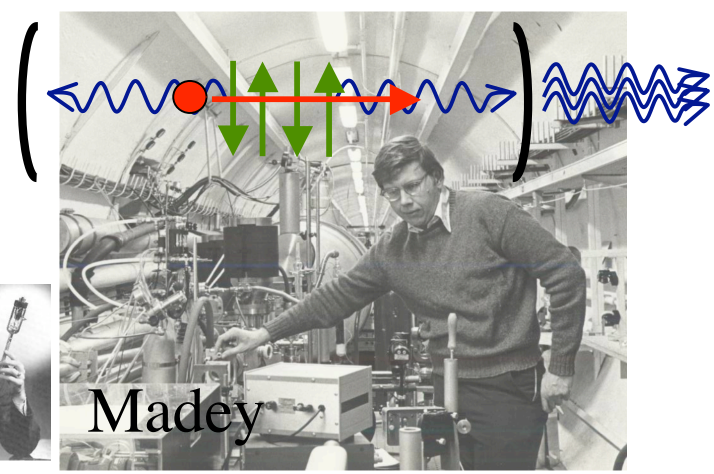




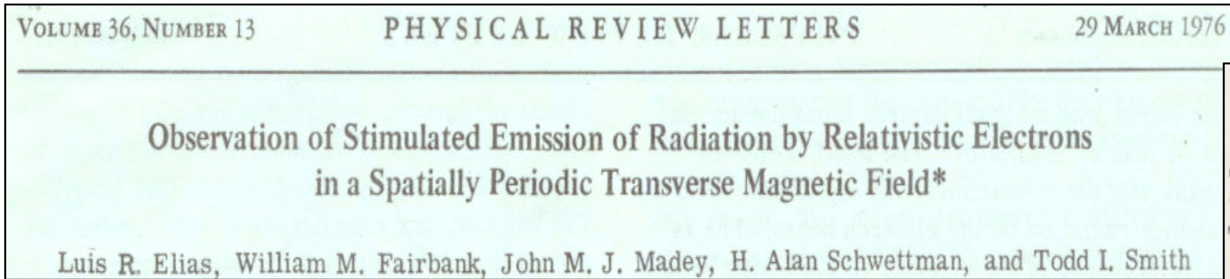
- Pantell, Soncini and Putoff (Stanford 1968)
  - Stimulated Compton backscattering
  - Self-bunching, waveguide in figure
  - $\gamma \approx 10$, $\lambda \approx 0.1$ mm



- Madey (Stanford 1972)
  - undulator & optical resonator
  - $\gamma \approx 100$, $\lambda \approx 0.001$mm
  - "If guys like Pierce couldn't do it (<mm), need something new"



First Experiment: Measure 7% Gain, '76



VOLUME 36, NUMBER 13 PHYSICAL REVIEW LETTERS 29 MARCH 1976

Observation of Stimulated Emission of Radiation by Relativistic Electrons in a Spatially Periodic Transverse Magnetic Field*

Luis R. Elias, William M. Fairbank, John M. J. Madey, H. Alan Schwettman, and Todd I. Smith

$\lambda \approx 10\mu m$

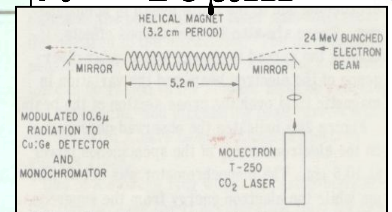
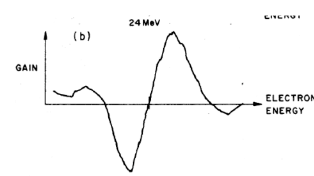


FIG. 1. Experimental setup. The electron beam was magnetically deflected around the optical components on the axis of the helical magnet.

- Madey '72 → experiment on Stanford's SCA
- Stanford skeptics → my thesis beginning in '74
- Madey used Compton "estimate" of gain
- Quantum vs Classical mechanism discussion
- Ted Hansch (NP) at Stanford:

  "If it is a laser, it is classical".



quantum (Madey) →

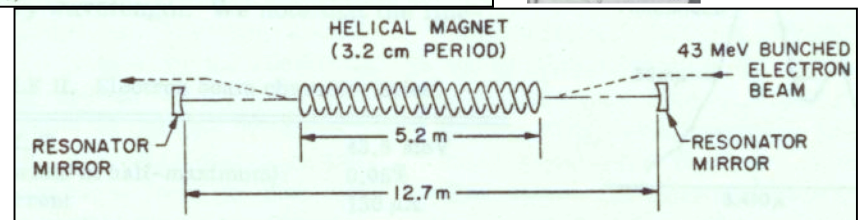
- **Classical - Maxwell-Lorentz**
- Quantum Electrodynamics
- Plasma theory (many)
- Laser theory (Scully)

2nd Experiment '77: 1st FEL Oscillator

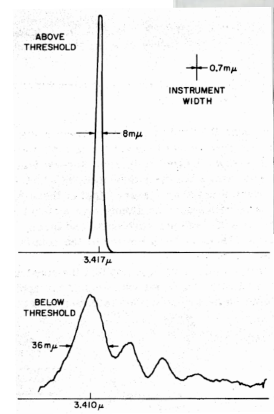
VOLUME 38, NUMBER 16 PHYSICAL REVIEW LETTERS 18 APRIL 1977

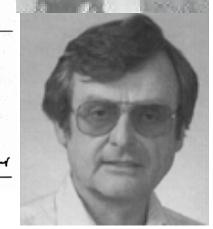
First Operation of a Free-Electron Laser* $\lambda \approx 3\mu m$

D. A. G. Deacon,† L. R. Elias, J. M. J. Madey, G. J. Ramian, H. A. Schwettman, and T. I. Smith
High Energy Physics Laboratory, Stanford University, Stanford, California 94305
(Received 17 February 1977)



- "Epoxy" motivated FEL
- Self-bunching, no waveguide
- Synchronism understood, but not "lethargy"
- Synchrotron radiation undulators & wigglers
- Theory begins solid development
- Storage ring FEL → xrays (Claudio)

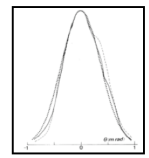


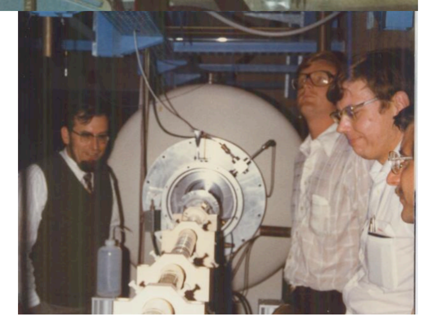


Beam physics
Plasma physics
Laser physics
→ **FEL Physics**

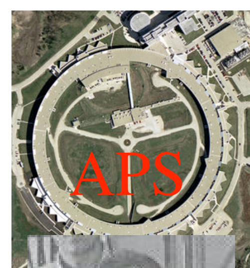
Second FEL: Orsay, France '81

- First Storage Ring FEL - $\lambda \approx 0.65\mu m$
- Farge, Petroff motivated FEL as addition to synchrotron facilites
- Dave Deacon, Orsay group →
- Renieri limited power < spontaneous
- Single transverse mode observed →
- Storage ring FELs → xrays (?)



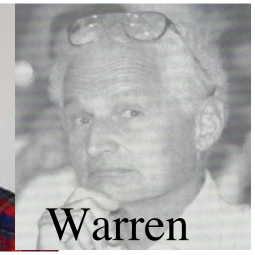


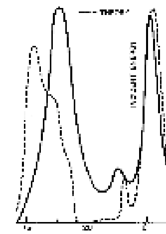
- **Synchrotron Sources:**
- Concurrent with FELs (late '70s)
- Undulators & wigglers → xrays
- Several $1B facilities around the world
- ~ 2000 scientists @ each facility / year
- Amazingly successful BIG science
- Some synchrotron facilities have FELs



Couprie Ortega Elleume

Third FEL: LANL'83, 1st Tapered



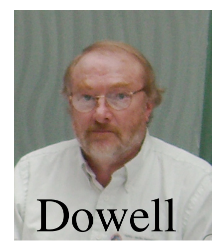


- Room Temp linac, $\lambda \approx 10\mu m$
- Initial amplifier experiments
- Observed $\eta \approx 4\%$ extraction
- Many important experiments (mode guiding, inverse taper)
- FEL tapered oscillator, electron beam recirculation '86

NH publications

- **"Star Wars" (SDIO)** started in '80s
- Induction linac, 1st high-gain FEL (ELF, $\lambda \approx 0.8cm$, waveguide)
- First high-gain tapered FEL, large extraction
- Competition: <u>Boeing-LANL</u> vs TRW-LLNL
- RF linac oscillator vs Induction linac amplifier
- BIG $, focused goals, BIG FELs
- Poor electron beam quality limits output
- Rest of the world developing scientific FELs

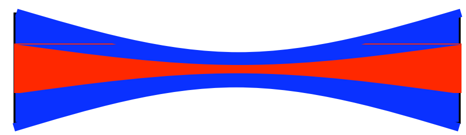

Scharleman Prosnitz



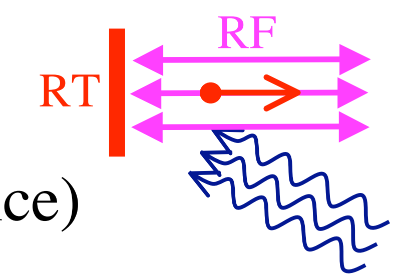
FEL Injector Evolution

- o Four Injectors: Cathode (RT - SC) with Fields (DC - RF)

- o Stanford SCA - thermionic injector (RT-DC) in 1st FEL
  (emittance: $\varepsilon_n \approx 10\mu m$ after throwing away 90% of beam)
- o FEL success tied to electron beam quality (derived early 80s)
- o Emittance: $\varepsilon_n < \gamma\lambda/4\pi \approx 10\mu m$ to fit mode



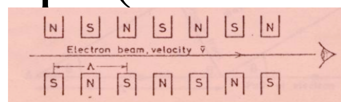
- o **SDIO** (no high power) $\rightarrow$ photo-injector
- o high charge & low emittance, high "brightness"

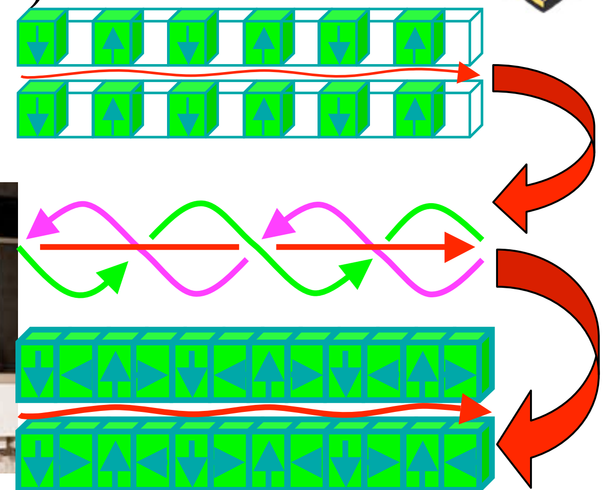


- o Steady improvement since '85 (US, Japan, France)
- o Achieve: 1nC with $\varepsilon_n \approx 2\mu m$
- o Now ('90s): linac beam has better quality than storage ring
- o AES successfully builds injectors for FELs
- o All 4 types are still used: SC-RF if hopeful
- o "Further improvements likely" $\rightarrow$ **xrays !!**

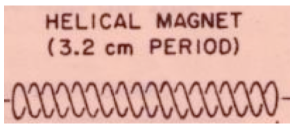
Undulator Evolution

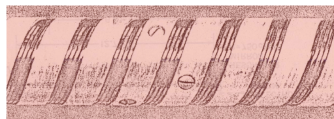
- Hans Motz and Bob Phillips (UBITRON) undulators:



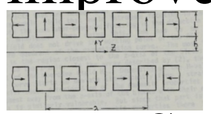


- First FEL @ Stanford SC helical coils





- Klaus Halbach improves

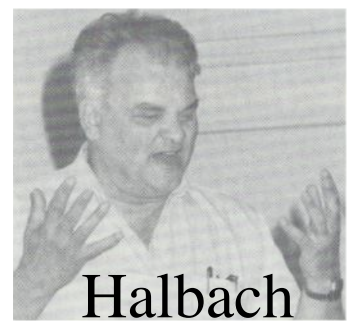


- Mature part of FEL, STI has made thousands


Robinson

STI OPTRONICS
(World wide business)

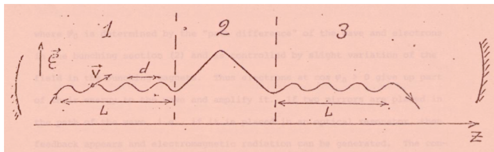
- New materials (SmCo, NdFeB, …)
- New hybrid designs, …


Halbach

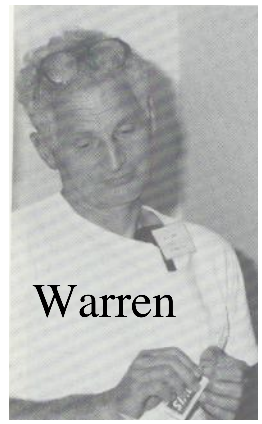
undulator
→ Halbach, hybrids, polarization
→ SmCb, NdFeB, … new materials
⇢ E & M coils (less often, …)

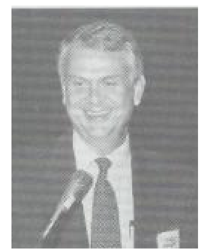
Undulator Interaction Designs

- Nicolay Vinokurov: FEL klystron undulator
  - Enhances gain in weak optical fields

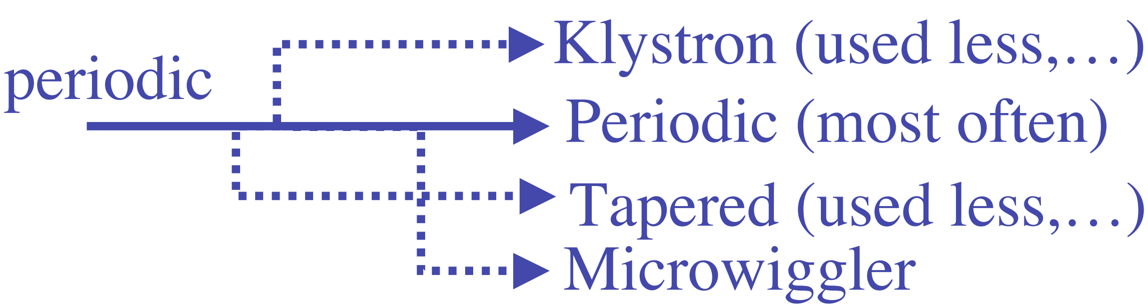


- "Microwiggler" ($\lambda_0 < 1$cm)
  - ("Dodge" Warren)



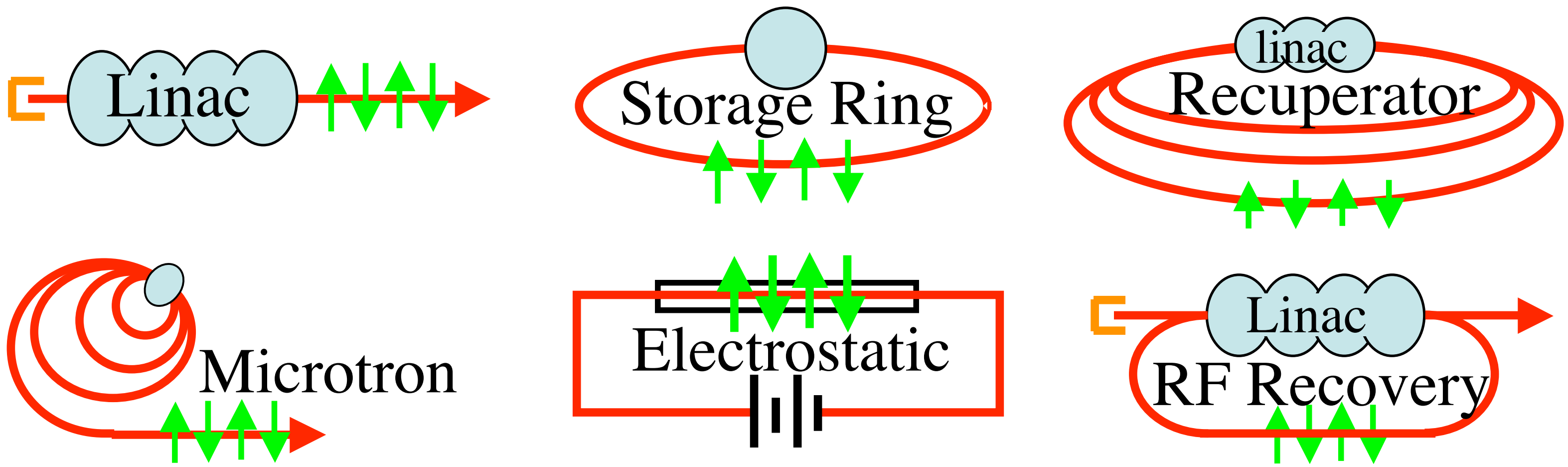


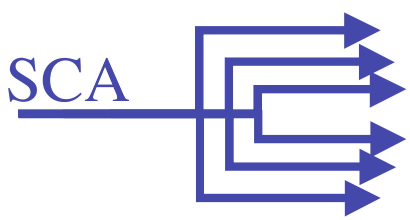
- Phil Sprangle: tapered undulator
  - Enhances extraction in strong optical fields



Accelerator Evolution

- Early tubes were non-relativisitic (Motz, Phillips)
- RF accelerators, Stanford's SC linac
- All FEL accelerators need high beam quality
- RF cavities can be room temperature, or superconducting

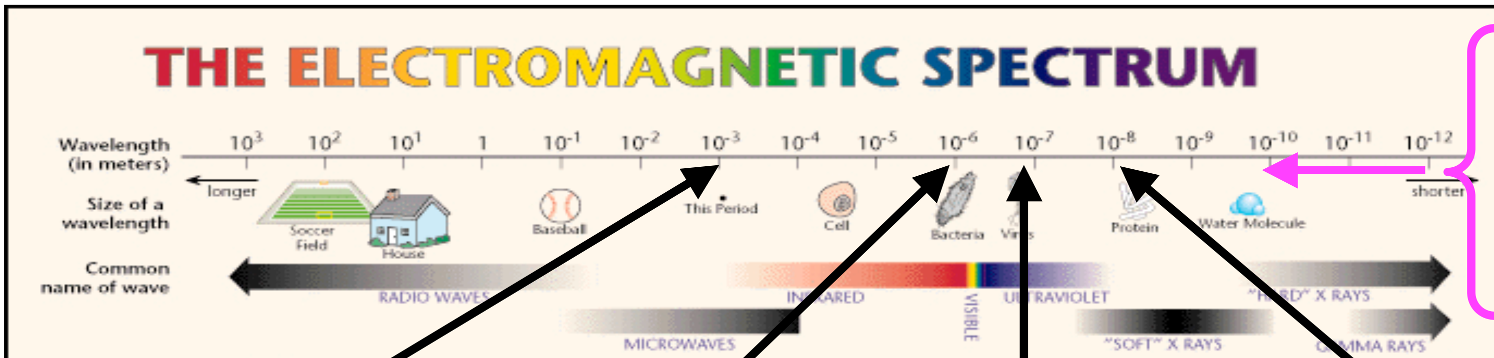




- All accelerator types now active
- Most FELs are RF linacs with resonator
- Superconducting Energy Recovering Linac !!!

Wavelength λ Evolution

- Evolution to shorter λ relies on higher beam energy (γmc^2)
- Electron beam quality must increase as well ($\varepsilon_n < \lambda$)



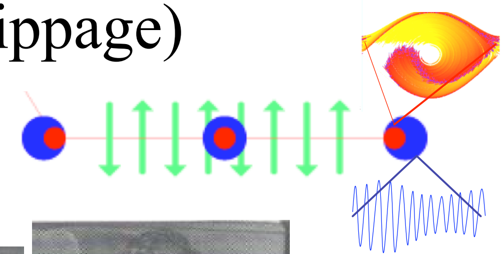
λ→xrays
DESY
LCLS
Korea
MIT

Motz, Phillips	Madey	Duke	DESY
1950s	1970s	1990s	2000s
(waveguide)	(resonator)	(storage ring)	(SC linac)

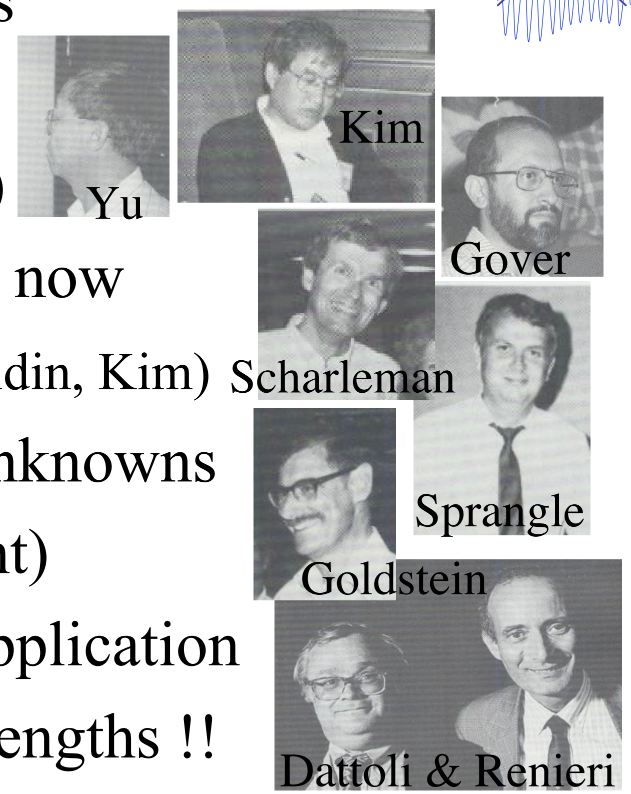
- FELs at λ ≈ 0.1mm (Italy, UCSB, Novosibirsk, Korea)
- Many FELs (≈ 30) in range 0.3μm < λ < 0.1mm
- FELs at λ≈0.1μm (Orsay,Osaka,Tsukuba,Italy,Duke,ANL,DESY)
- SLAC, DESY, MIT, Korea → 0.1nm FELs - **real xray lasers !!**

Theory Evolution

- Madey's concept correct - '72 paper difficult & limited
- Plasma, laser, & quantum theories → Maxwell-Lorentz theory
- Pendulum equation & SVAP wave equation (slippage)
- Theory & experiment ('80s): Eckstein, LANL



- Clarify science of lasers: no energy levels
- Short pulses (lethargy) & harmonics
- High gain (Shih), optical guiding (Moore)
- Transverse modes & coherence simulated now
- SASE(Pellegrini, Fawley, Bonifacio, Reiche, Saldin, Kim)
- Only limitations are experimental input unknowns
- Start-to-end simulations (cathode → light)
- FEL theory now reliable, wide range of application
- FEL theory works from cm to xray wavelengths !!



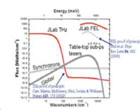
Geographical Evolution and Distribution in 2006

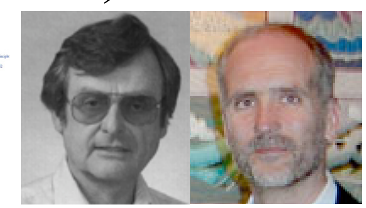
(All FELs at ≈40° Latitude !?)

- =RF,H(1)
- =RF,O(26)
- =SR,O(7)
- =EA,O(2)
- =RF,S(3)
- =M,O(1)
- =RF,A(3)

Application Evolution

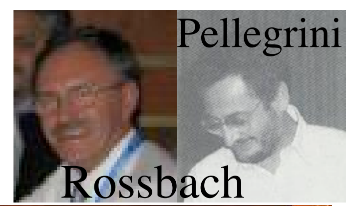
- Early applications: “avoid conventional lasers”
- FEL size and cost too big, so needs big applications
- Clarify science of lasers: no energy levels
- Storage rings & military applications are early goals (‘80s)
- Infrared user facilities developed (many countries ‘90s)
  (FOM, SPring-8, Jlab,
  Stanford, Orsay, UCSB, …)





Schwettman van der Meer

- Fourth Generation Light Sources (‘00s): FELs
- SASE process, single ⊥ mode, coherent || modes
- soft x-rays, and soon to hard x-rays
- High average power (‘00s)
  - Industrial & military
  - THz sources



Litvinenko Hama

Future Directions

- Infrared Facilities continue (FOM - 60 scientists/yr/beam)
  (successful synchrotrons - 2000 scientists/year/100beams)
- High power military & industrial applications (Jefferson Lab)
- THz sources facilities & compact (really) THz sources
- Japanese FEL effort are inspirational to us all (let's go!)
  (many universities and industries working together)
- Several "new lasings" each year at FEL conference !
- Steady ~250 participants/year (Google hits = 242,000 ↑)
- Xray FELs will give exciting, new physics !!
- University positions in FELs & coherent radiation sources
- Our FEL community is one of our best products

⇒ **We have done well, best is yet to come !**