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FREE ELECTRON LASERS DRIVEN BY LINEAR INDUCTION ACCELERATORS - HIGH POWER RADIATION SOURCES

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This talk will address the technology of FELs and LIAs

- Fundamentals of FELs
- Basic concepts of linear induction accelerators
- The Electron Laser Facility — a microwave FEL
- PALADIN — an infrared FEL
- Magnetic switching
- 'IMP'
- Future directions — relativistic klystron

The Free Electron Laser under development at LLNL is based on a single pass amplifier design

- The electron beam is generated by a Linear Induction Accelerator:

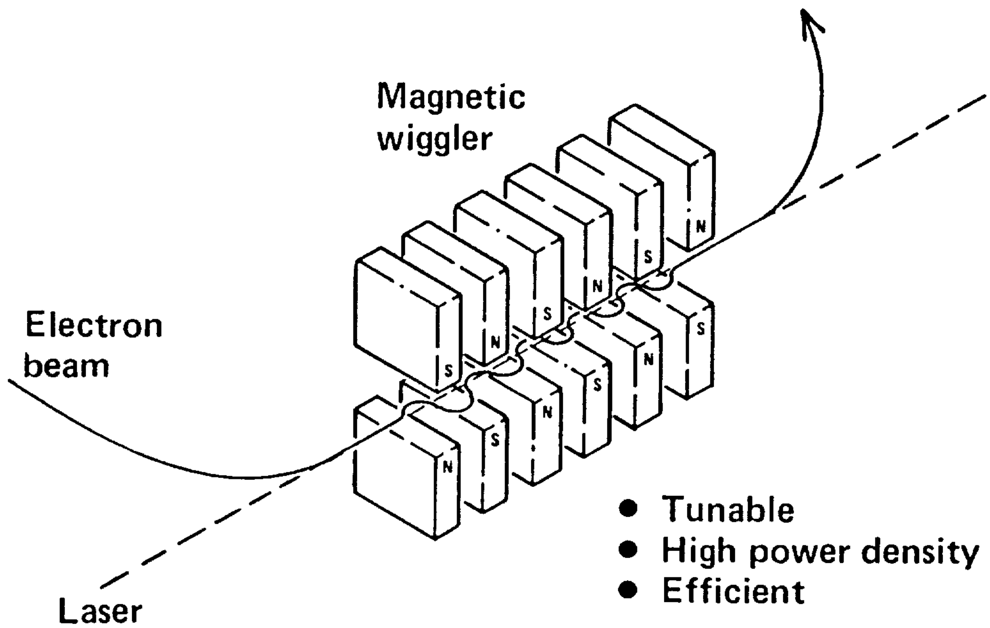
  $E_b \approx$ several MeV
  $I_b \approx$ few kA
  $P_b \approx 10^{10}$ W

  $\tau_p \approx 50$ nsec
  prf $\approx$ few kHz
  duty factory $\approx 10^{-4}$
  $P_b \approx 10^6$ W

- In the FEL amplifier, an injected signal grows exponentially, trapping a significant fraction of the electron beam. Proper design of the wiggler fields leads to a large fraction of the beam energy being converted to radiation energy ($\approx$ 40%)

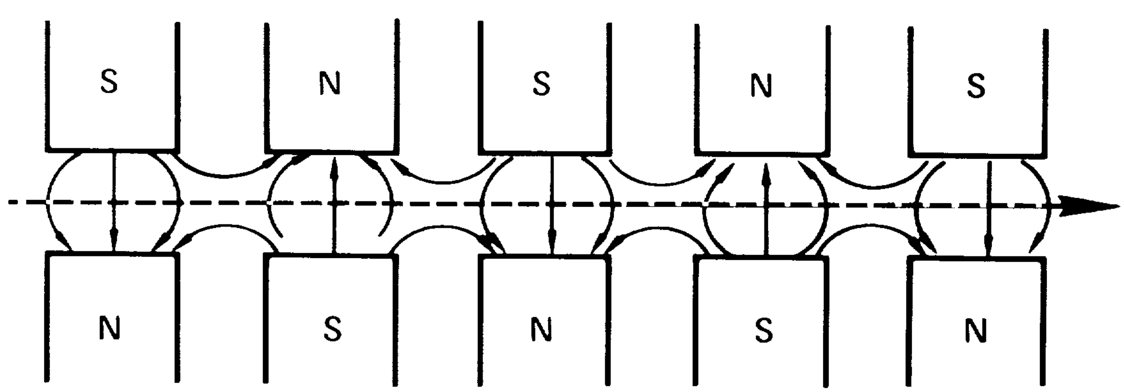
A free-electron laser converts the kinetic energy of a relativistic electron beam into coherent radiation. The electrons are given transverse momentum in a device called a wiggler. This transverse momentum can now couple to the transverse electric field of a co-propagating electromagnetic wave.

Free Electron Laser



- Tunable
- High power density
- Efficient

The wiggler-a periodic, vertical magnetic field



---- Electron beam

——— Magnetic field lines

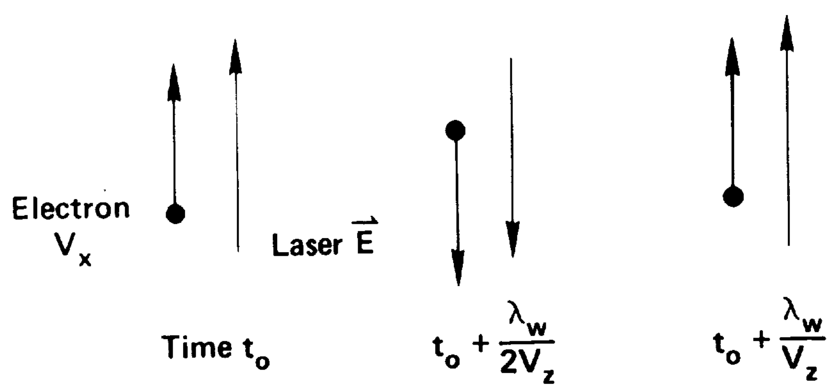
On midplane $\vec{B} = B_{yo} \cos k_w z \quad k_w = 2\pi/\lambda_w$

In resonance, the electromagnetic wave travels one wiggler period plus one radiation wavelength in the time the electron has traveled one wiggler period. This "slippage" keeps the electron's transverse velocity always in the same direction as the electronic field of the radiation. Thus

$$\int v_\perp \cdot E_{rf} \, dz \neq 0 \quad .$$

Electron-laser coupling

- **Moving with the average motion of an electron**



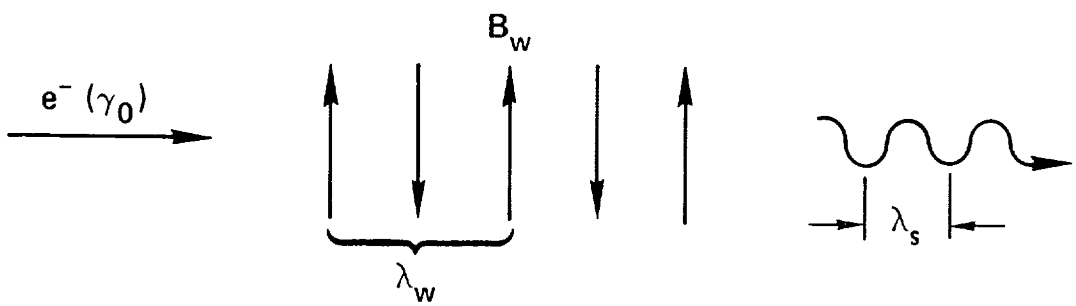
- **$\vec{V} \cdot \vec{E}$ always greater than zero ⇒ steady energy <u>loss</u> of electron ⇒ steady energy <u>gain</u> of laser**

The resonance condition depends on the beam energy

$$\gamma \equiv 1 + \frac{eV}{mc^2} \quad ,$$

λ_w (wiggler period) and B_w (wiggler magnetic field).

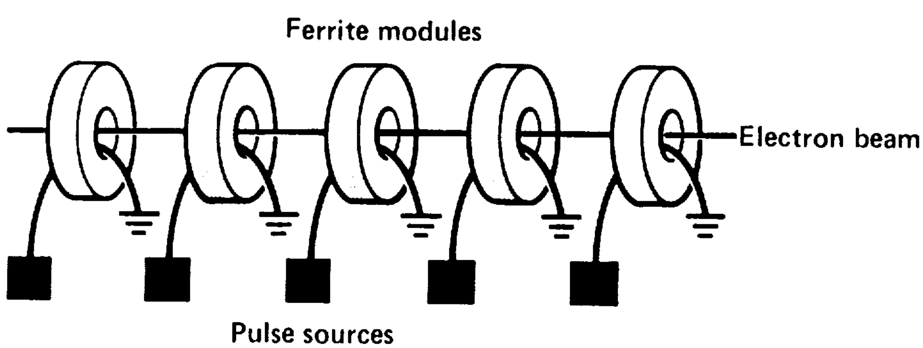
Wavelength scaling



The output frequency of the FEL is the result of a Lorentz contraction (of the wiggler period) followed by a Doppler shift.

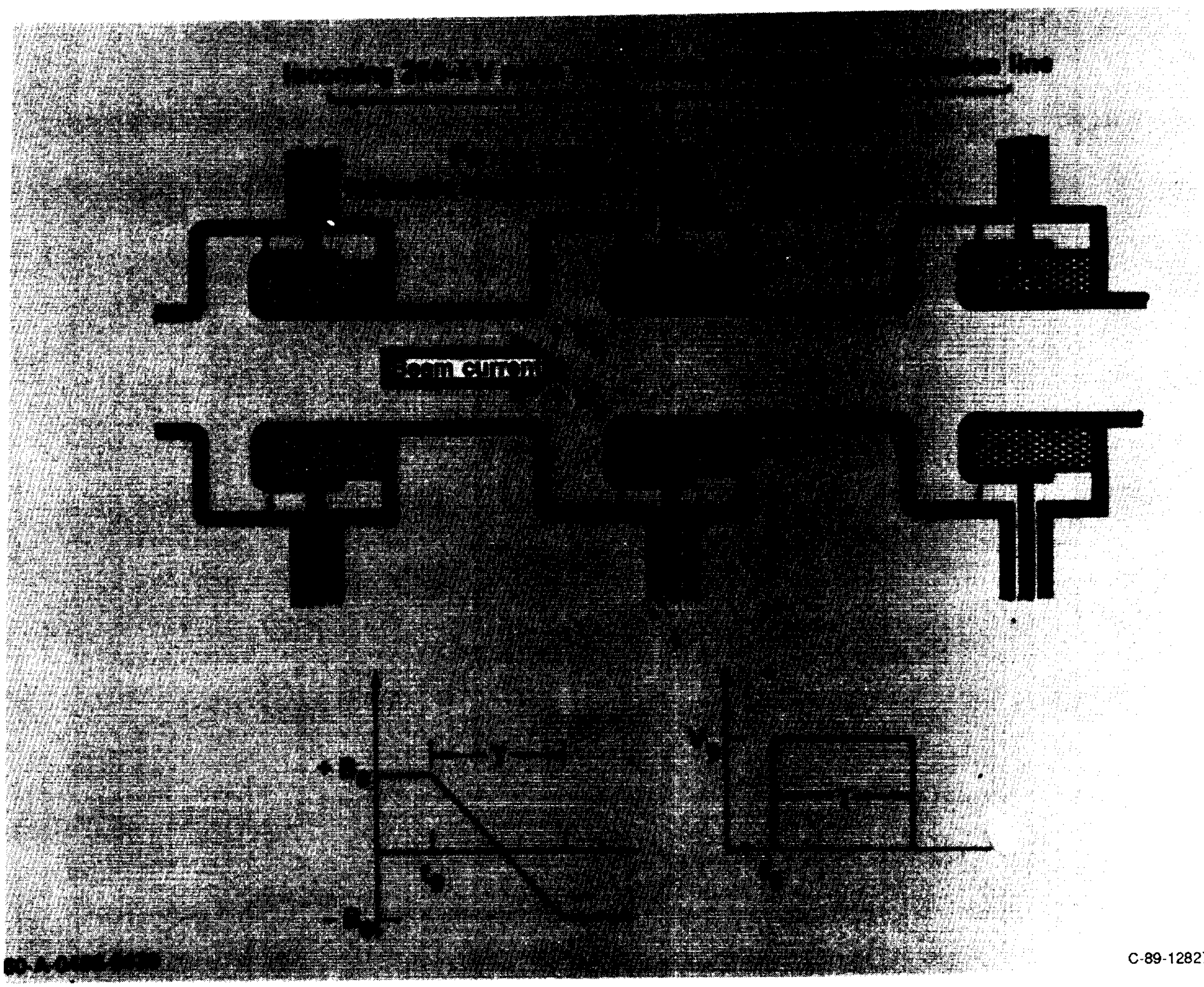
$$\lambda_s = \frac{\lambda_w}{2\gamma_{\|}^2} = \frac{\lambda_w}{2\gamma_0^2}\left[1 + \frac{1}{2}\left(\frac{e B_w \lambda_w}{2\pi mc}\right)^2\right]$$

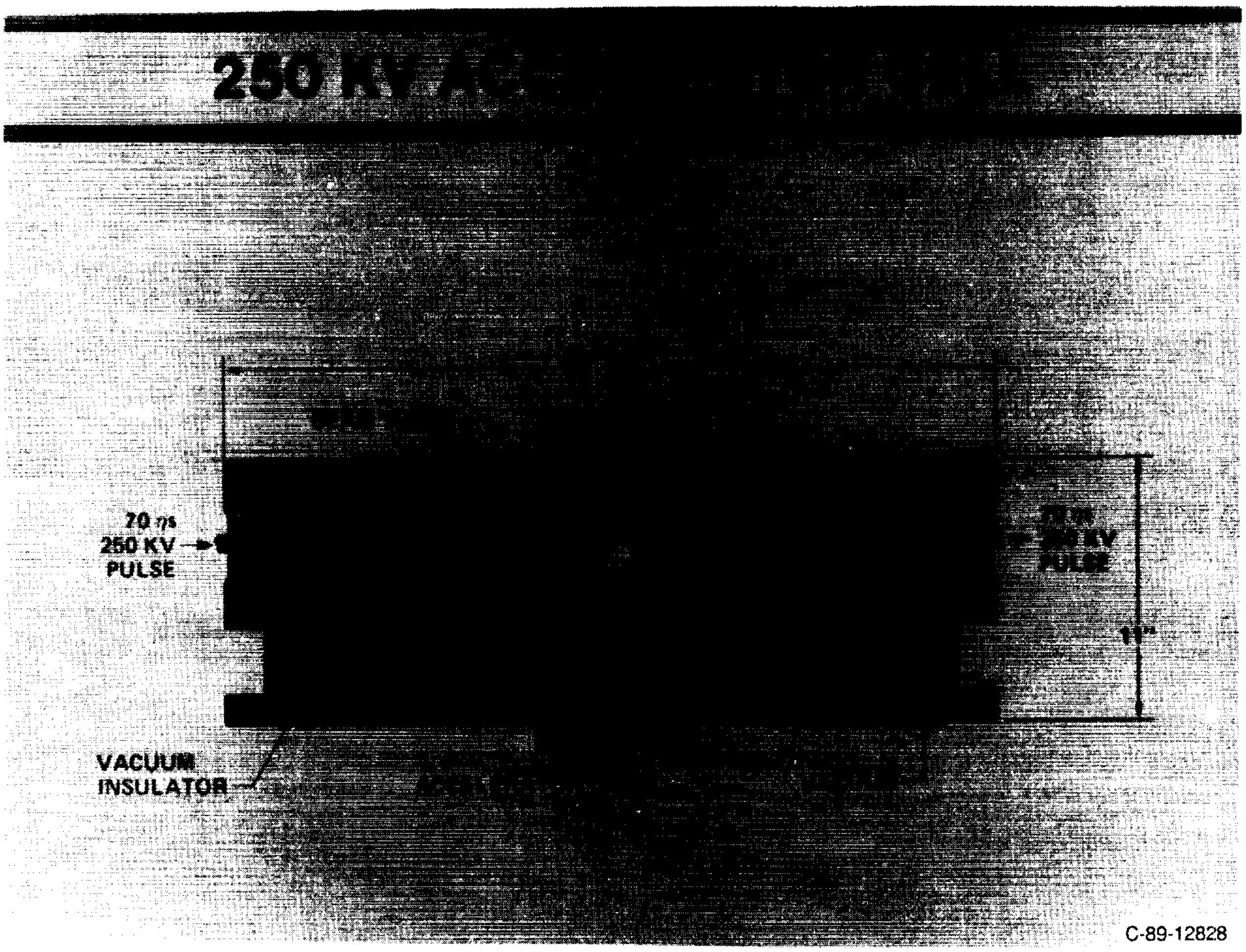
LIA concept



- An induction linac works as a series of 1:1 pulse transformers threaded by the electron beam
- Each module generates an increment of beam acceleration

The accelerating voltage is impressed across the accelerating gap. The accelerating voltage and pulse length are determined by the amount of ferrite (volts-seconds) in the accelerator cell.




250 KV
70 ηs
250 KV
PULSE
11"
VACUUM
INSULATOR
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Picture of 2.5-MeV (ten cells) section of ATA. The ten-cell block is about 3-meters long.

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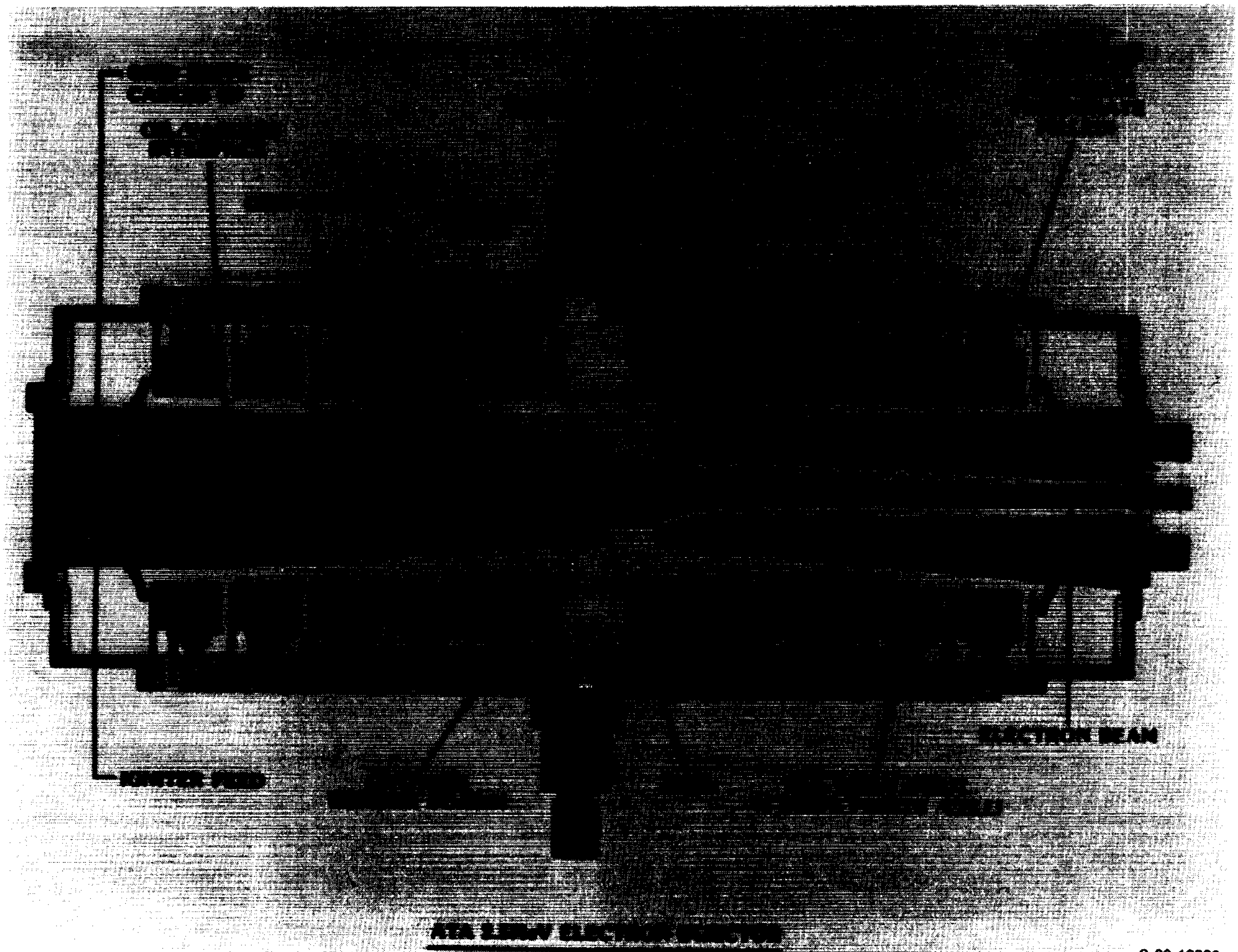
The source of the electron beam, called an injector or gun, is a diode driven by ten inductive cells connected in series.



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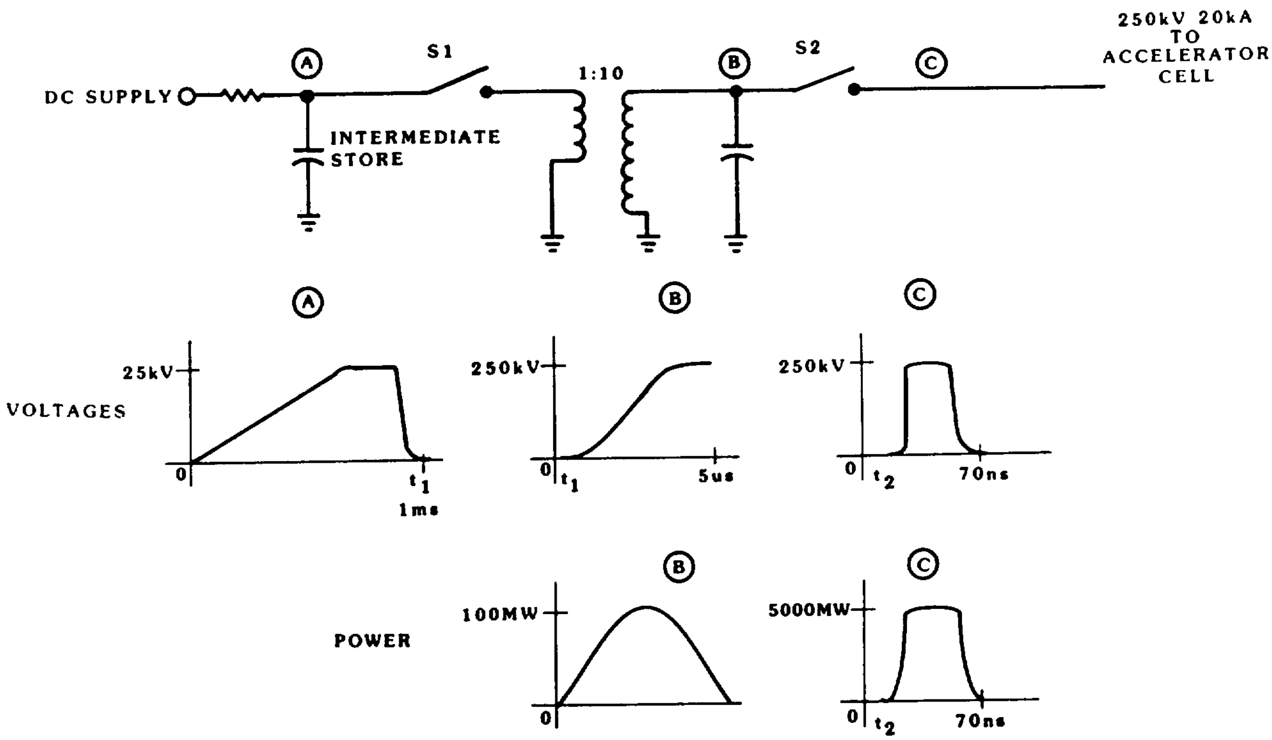
Conventional pulse drive for induction linacs.

S_1 = thyratron

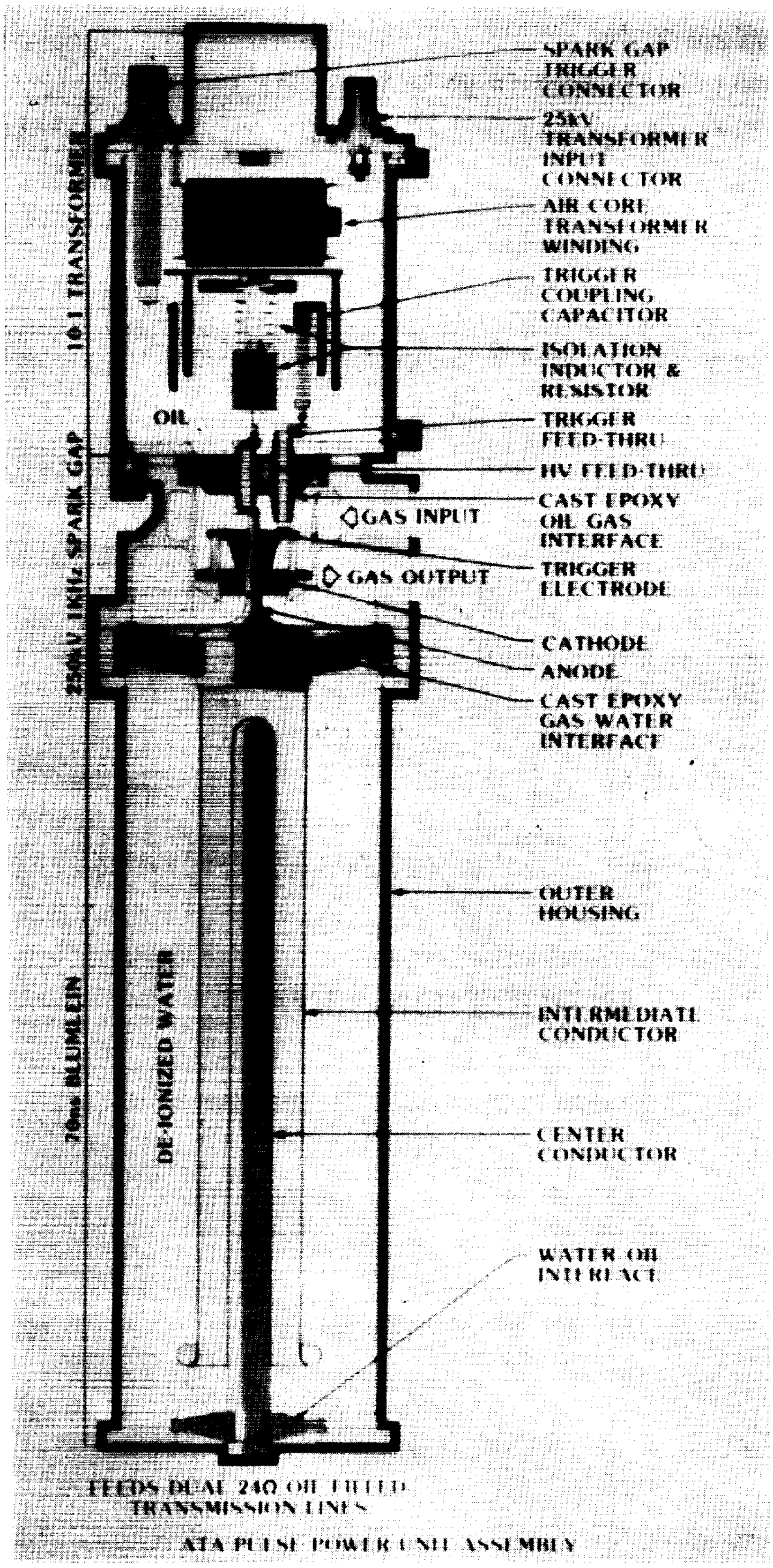
S_2 = pressurized spark gap

The spark gap must be replaced to go to high duty factor.



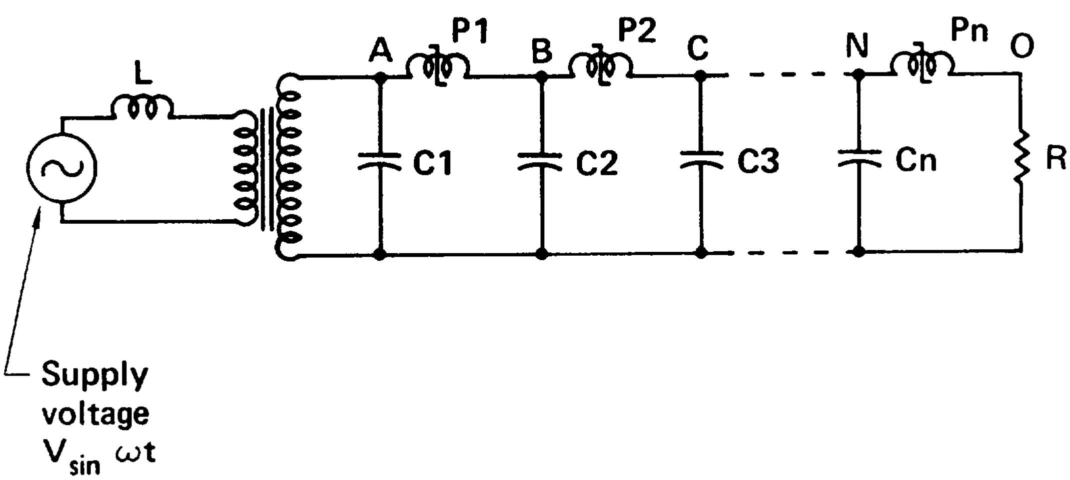
INDUCTION LINAC

Schematic of conventional pulsed power unit.

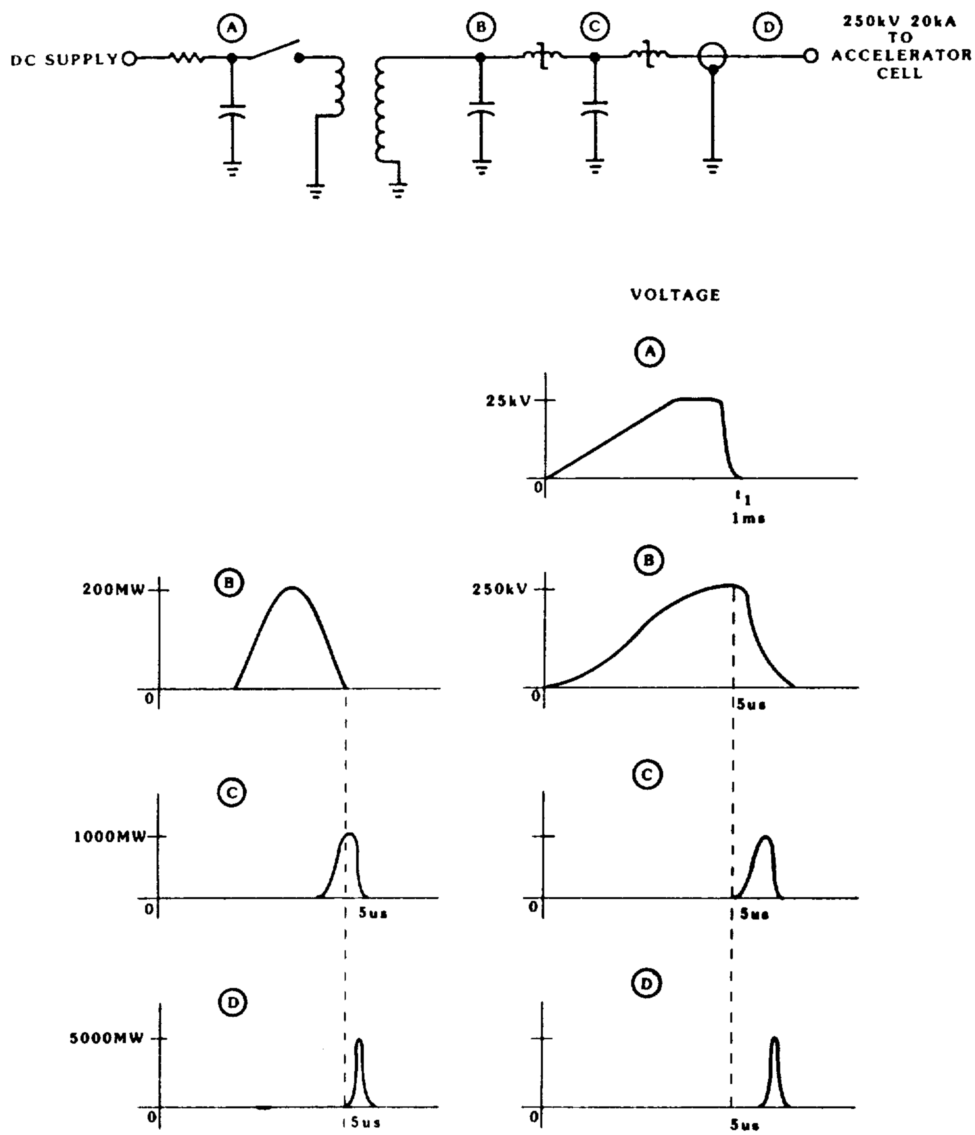


Magnetic pulse compressor concept. P_1, P_2... are saturable reactors. During the initial charge phase of C_n, P_n is a high-impedance shunt with only a small leakage current passing through it. When it saturates, it is a low impedance path and C_n dumps into C_{n+1}. Proper design of the circuit results in pulse compression.

Simplified schematic of a magnetic pulse compressor



Induction linac drive based on saturable reactors.



INDUCTION LINAC NONLINEAR MAGNETIC DRIVE

The Electron Laser Facility (ELF) serves a threefold purpose:

1. Study basic physics of Free Electron Lasers
2. Serve as a test bed for the physical models used in the design of other FEL amplifiers
3. Provide a source of high power microwave radiation

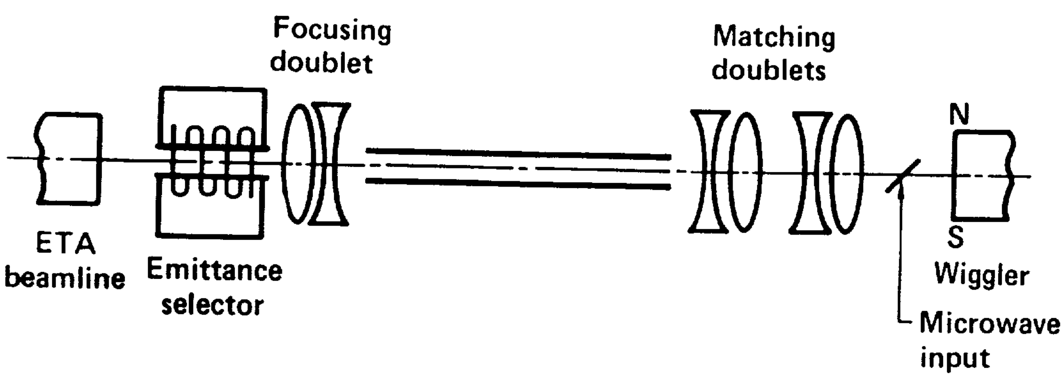
Principal features of ELF

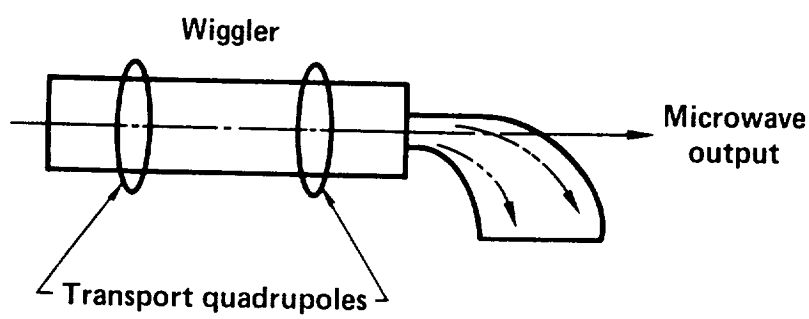
- Operates in an amplifier mode
  - $\lambda_s = 8.6$ mm
  - $P_{in} \leqslant 50$ kw
- Pulsed electromagnetic wiggler
  - $\lambda_w = 9.8$ cm
  - $L_w = 3$ m
  - $B_{w,max} = 5$ kG
  - Linearly polarized
  - No axial magnetic guide field (horizontal focusing provided by external, horizontally focusing quadrupoles)
  - Each two periods independently controlled
- Interaction region
  - Oversized waveguide (3 cm $\times$ 10 cm)
  - Fundamental excitation mode: TE_{01}

Electron beam characteristics

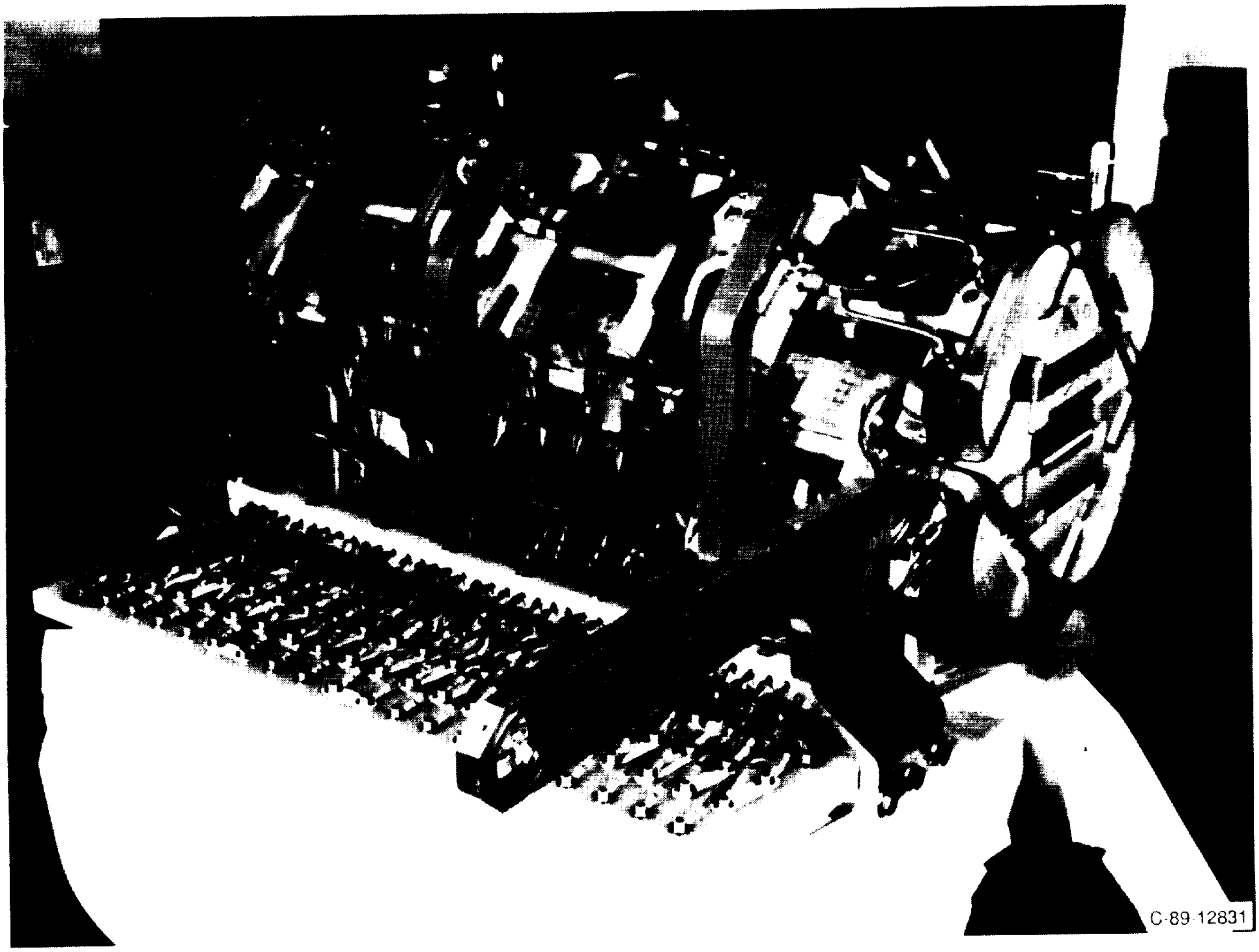
- Beam energy $\simeq$ 3.5 MeV
- Field emission cathode
- 30 ns pulse length
- 1 Hz prf
- ~4 kA accelerated current
- $\mathcal{J} = 2 \times 10^4$ amps/cm^2 -rad^2

ELF Beamline





One-meter section of ELF wiggler.



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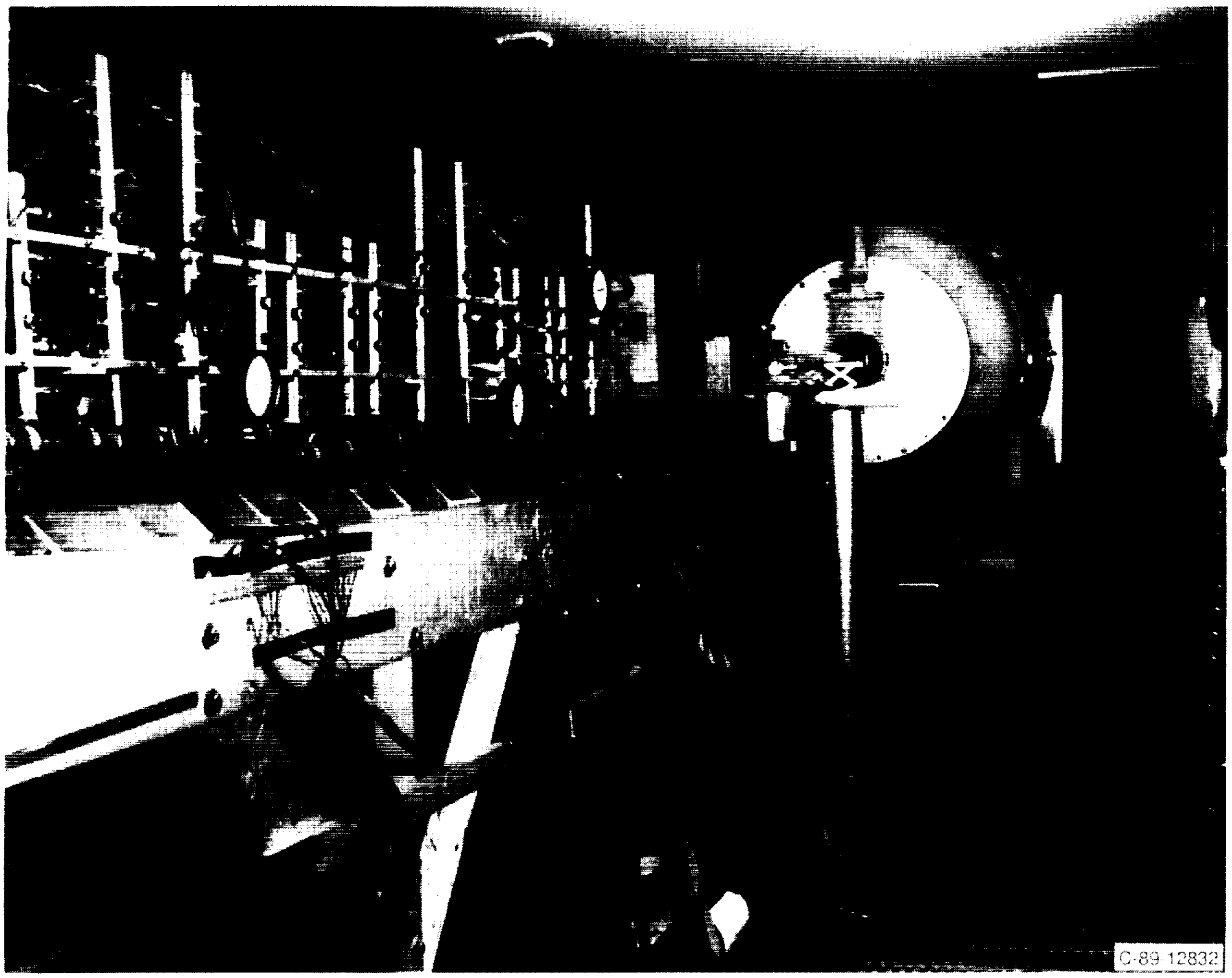
Picture of ELF experiment. On the left is the wiggler magnet. Right of center is a large vacuum diffraction tank which eliminated the problem of air breakdown.



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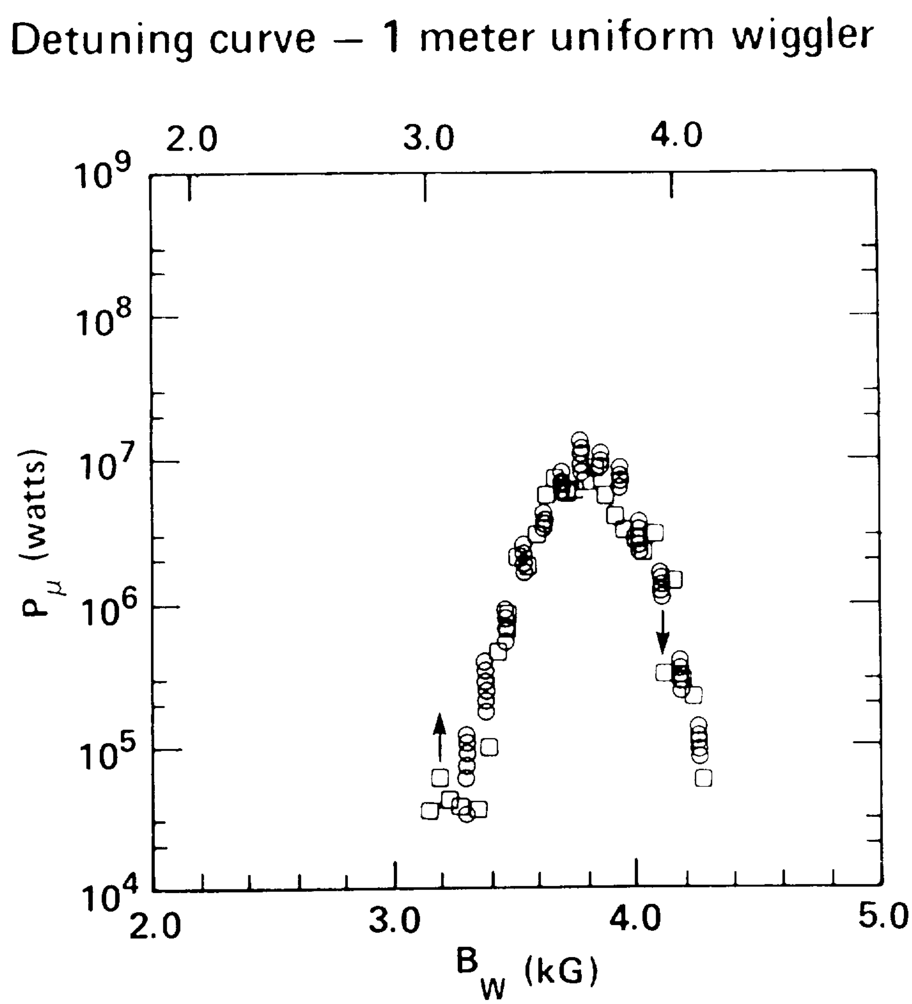
Power output as a function of wiggler magnetic field. Circles are experimental data while squares are the result of numerical simulation.

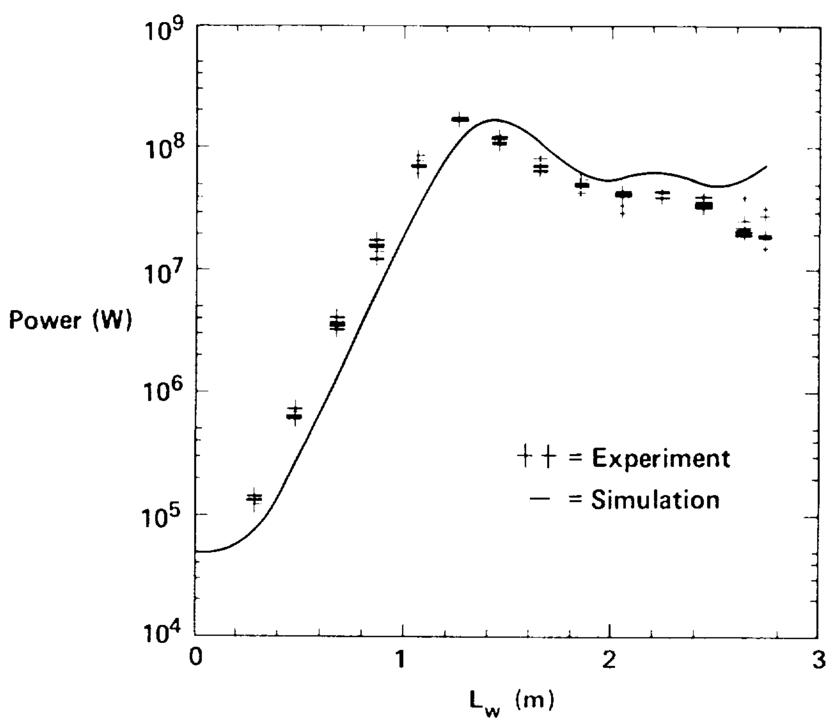


Power output as a function of wiggler length. The device saturates at about 1.2 meters. Sufficient energy (~7%) has gone from e-beam to radiation to violate resonance condition (see "wavelength scaling" viewgraph)

$$\gamma \equiv 1 + \frac{eV}{m_e c^2}$$

where eV is the beam energy, $M_e c^2$ is the electron rest mass energy. The solid line is the result of a numerical simulation.

Microwave power vs wiggler length: uniform wiggler—B_W=3.72 kG



Prescription for tapering the wiggler fields

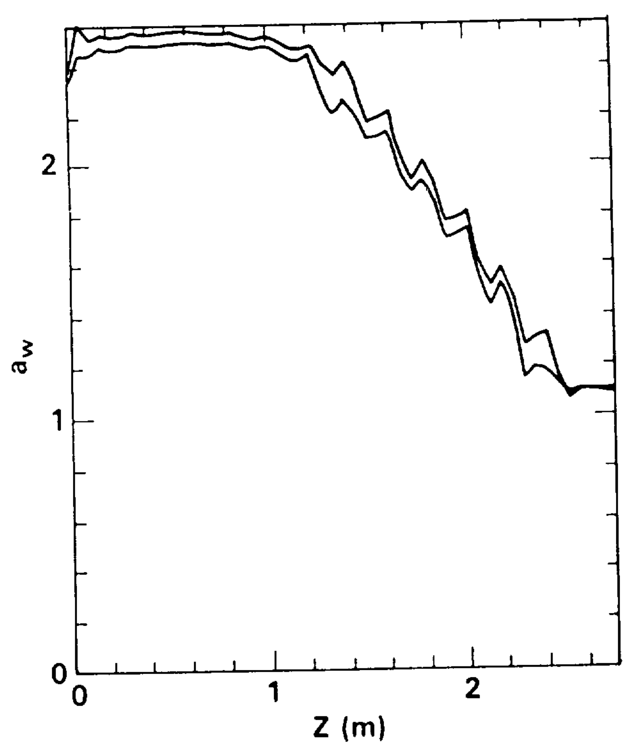
- Use a uniform wiggler on resonance almost out to saturation. Keep the remaining wiggler well below resonance ($B_w = 0.4 \times B_{w,res}$).

- Tune each subsequent power supply (2 period segments) to maximize the output power.

Tapering the wiggler magnet (changing the wiggler magnetic field and/or period) allows the resonance condition to be maintained throughout the length of the device.

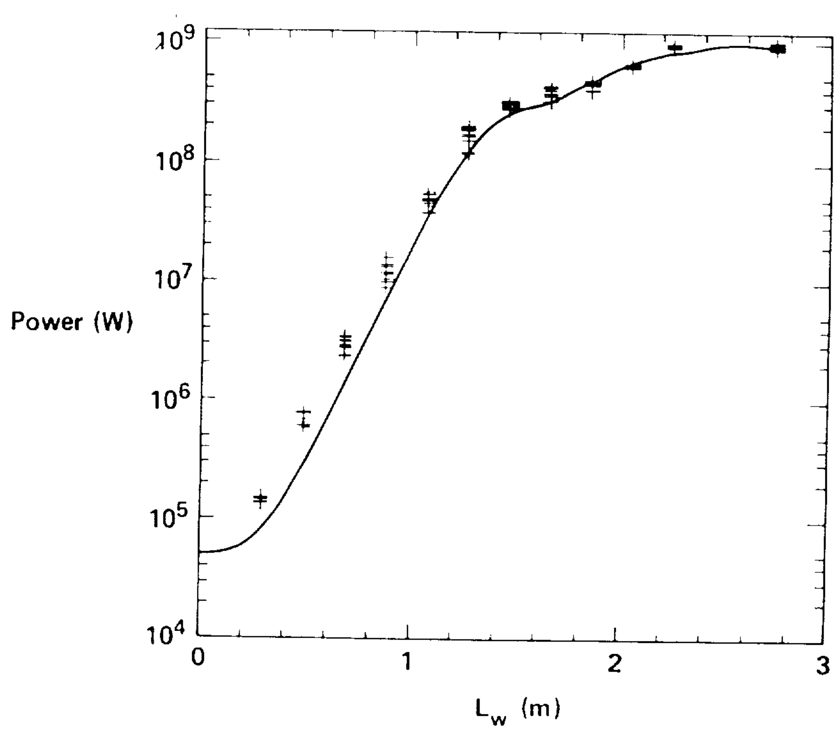
$$a_w = \frac{eB_w\lambda_w}{\sqrt{8}\ \pi\ m_e c} \qquad \text{(in MKS units)}$$

Optimized tapered wiggler field (computed)



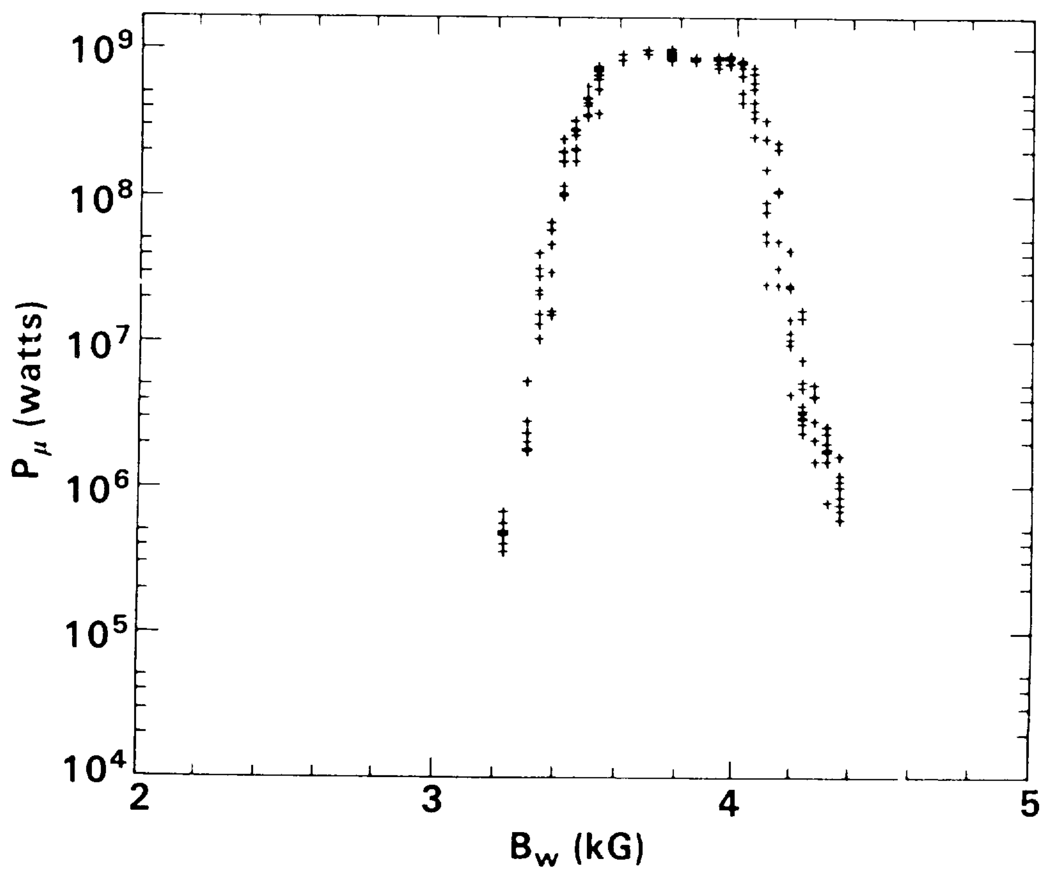
Results for output power versus wiggler length using the wiggler profile on the previous viewgraph. The solid line is the result of a numerical simulation.

Microwave power vs wiggler length: tapered wiggler-B_w = 3.72 kG

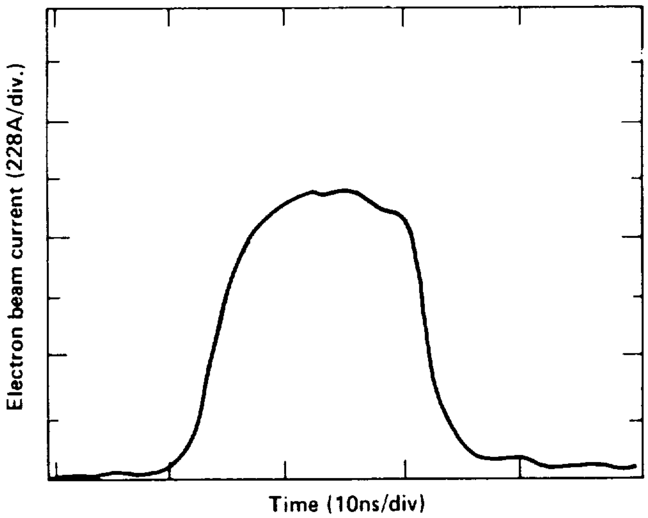


Power output as a function of wiggler magnetic field for a tapered wiggler. Compare this with the "detuning" curve shown previously for a one-meter wiggler. Note the increased bandwidth of the resonance.

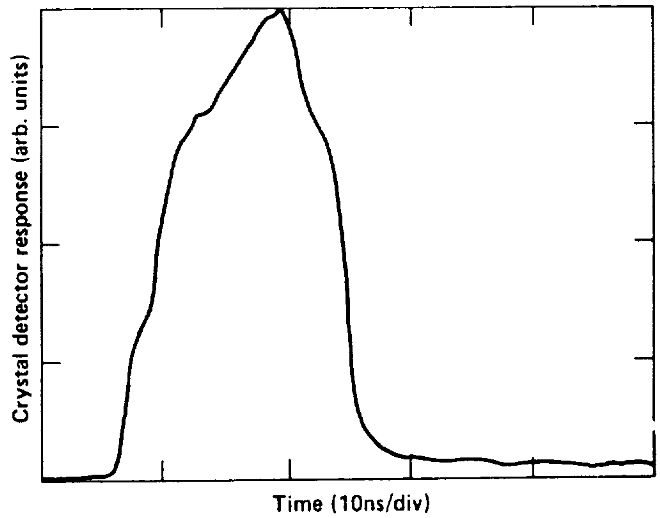
Detuning curve: 3-m tapered wiggler



Experimental data indicate efficiencies in excess of 40%

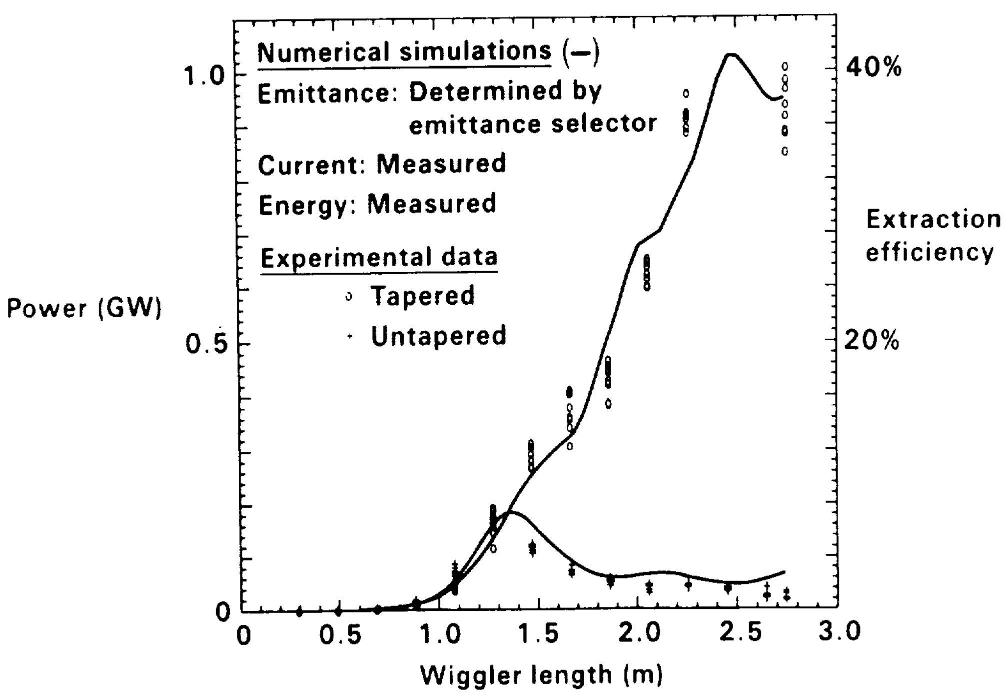


Electron beam energy = 3.5 MeV
Electron beam current = 1090 A
Electron beam power = 3.8 GW



Microwave power: 1.82 GW peak

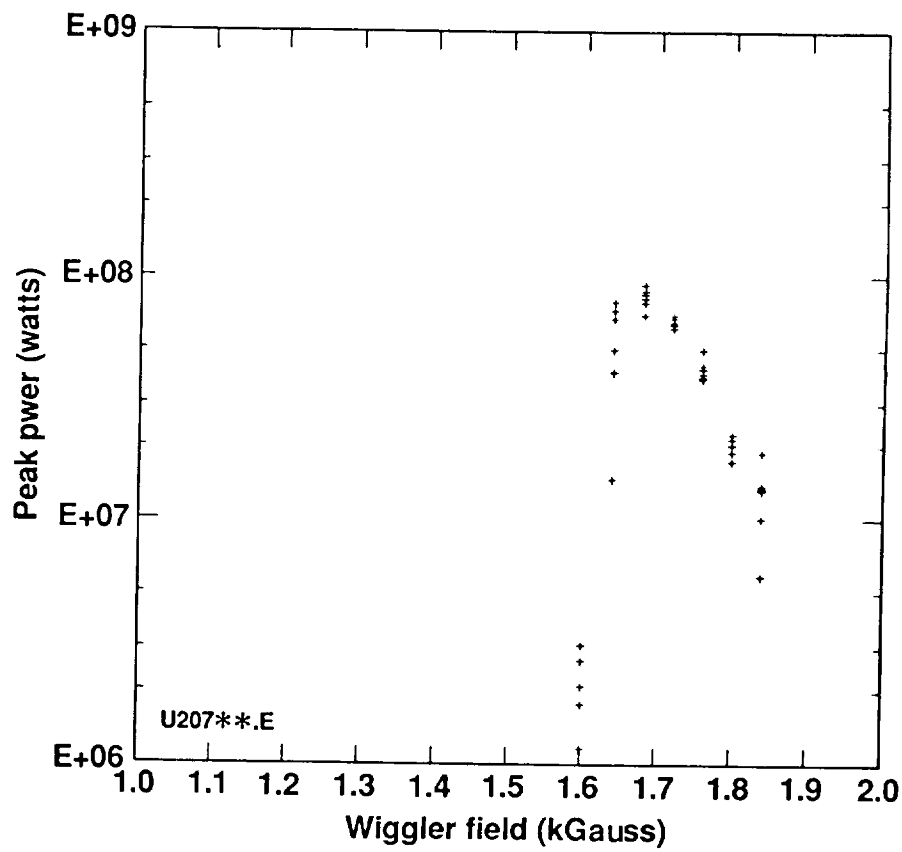
ELF clearly demonstrates the advantage of tapered wigglers



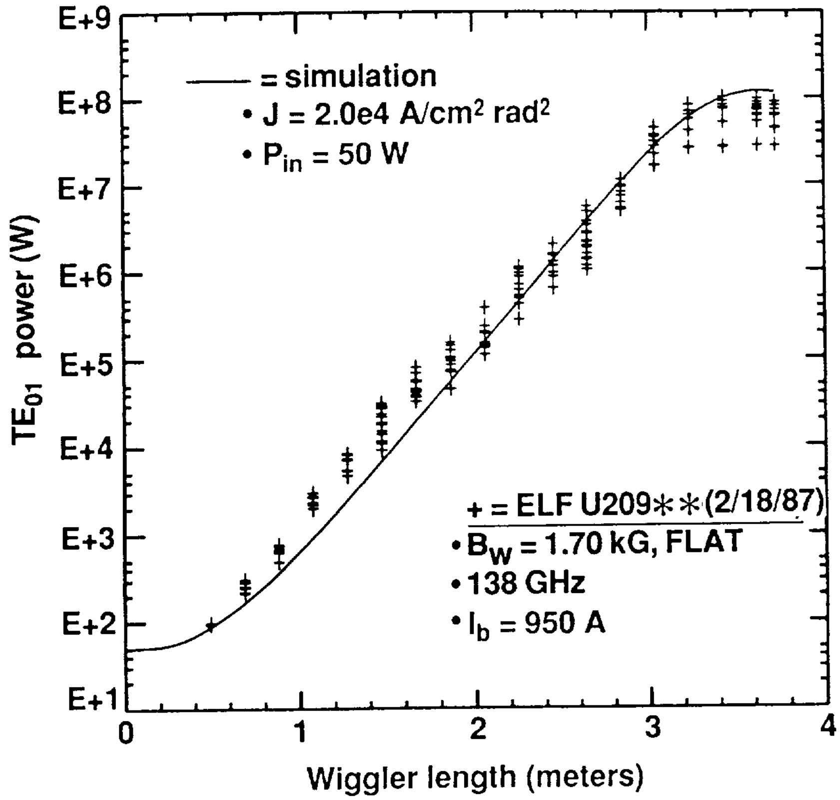
ELF operates as a 2mm amplifier

- 50 watt signal (f = 140 GHZ) injected into ELF interaction region
- Signal grows at 20 dB/m
- Signal saturates at $P_S \sim 70$ MW 3.2m into the interaction region

ELF detuning curve at 138 GHz — 4-meter flat wiggler



FRED simulations agree well with ELF results at 140 GHz



IMP is an integral part of a magnetic fusion experiment

- The ALCATOR tokamak is currently being reassembled at LLNL

- The microwave radiation from IMP will heat the tokamak plasma

Parameters for a 250 GHz FEL driven by an LIA operating at 5 kHz with 50 nanosecond pulse width.

IMP is designed to deliver high peak and high average power radiation

IMP design parameters:

E_{beam}	10 MeV
I_{beam}	3 kA
f_{μ}	250 GHz
P_{μ}(peak)	12 GW
% extraction	40%
P_{μ}(ave)	2 MW

IMP wiggler

L_W	5 m
λ_W	0.1 m
B_W (max)	4.5 kG

PALADIN is an optical FEL operating at 10.6 microns. The current operating parameters are listed on the following viewgraph.

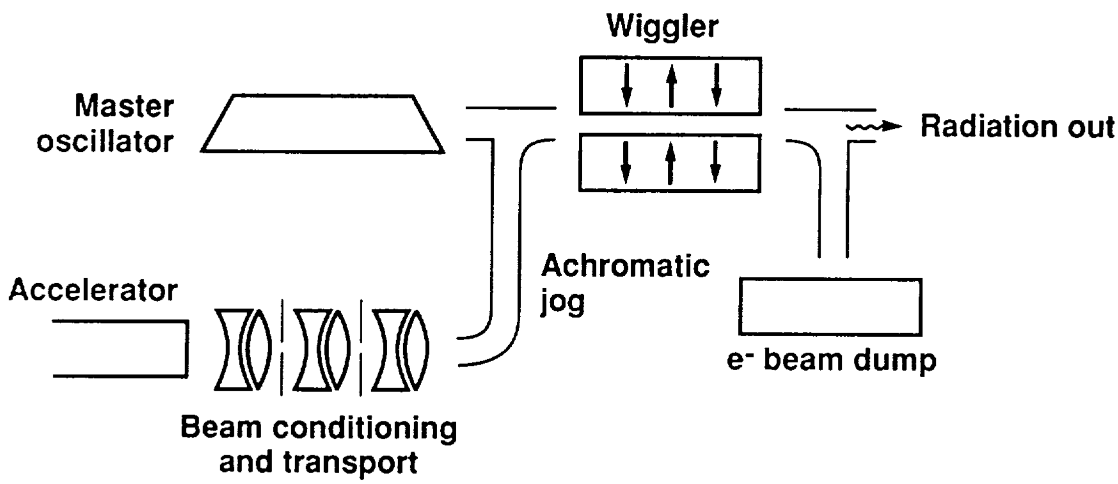
PALADIN Phase III experimental parameters

Wavelength	10.6 μ
Input signal	14 kW - 5 MW
Wiggler period	8 cm
Wiggler length	15 m
Raleigh range	5 m
Beam energy	45 MeV
Beam current	600-700 A
Beam brightness*	Mid-10^7 A/(rad-m)^2

*Assuming uniformly filled acceptance of quadrupole emittance selector

Schematic of the PALADIN beamline.

Principle components of a free electron laser amplifier



PALADIN Wiggler – General Specifications

Laser wavelength	10.6 μm
Electron beam energy	50 MeV
Nominal wiggle field	2.5 kG
Period	8.0 cm
Pole-to-pole gap	3.0 cm
Overall length	5–25 m

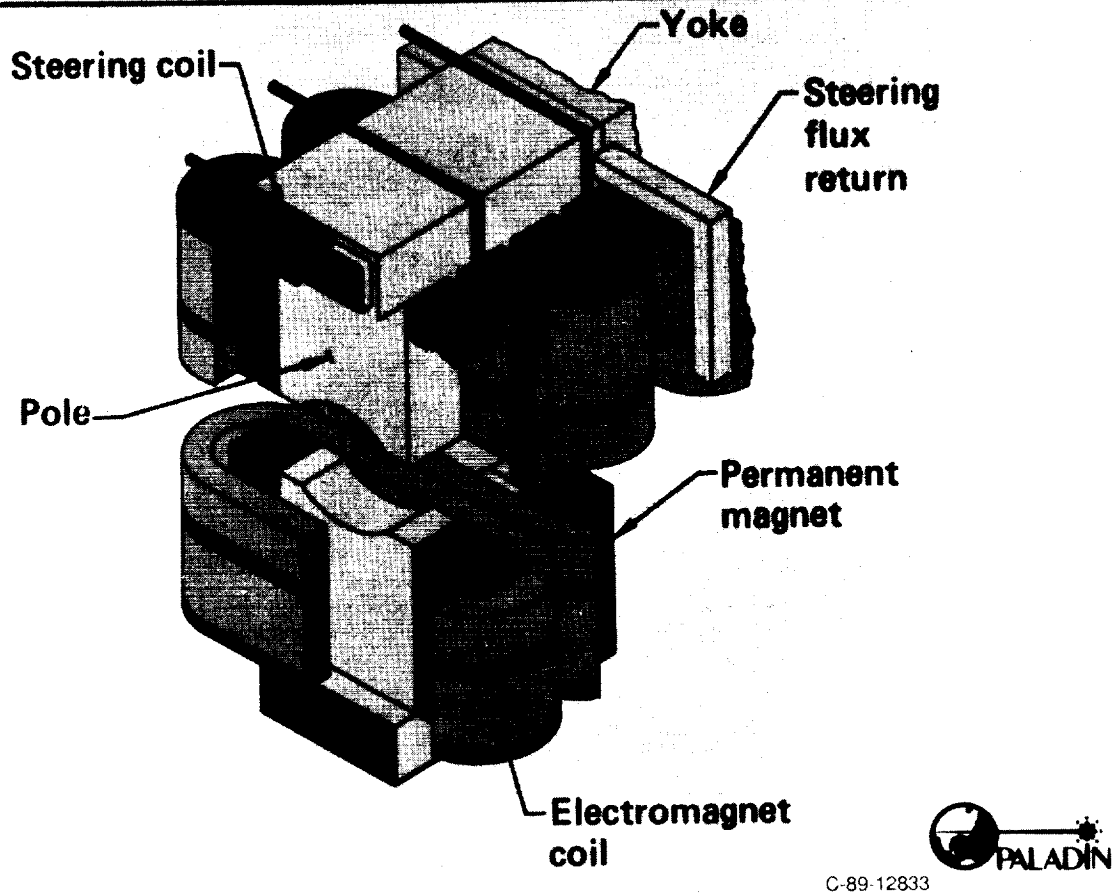
Desired field profile:

$$B_y = B_0 \cosh(k_0 x)\cosh(k_0 y)\cos(k_w z)$$

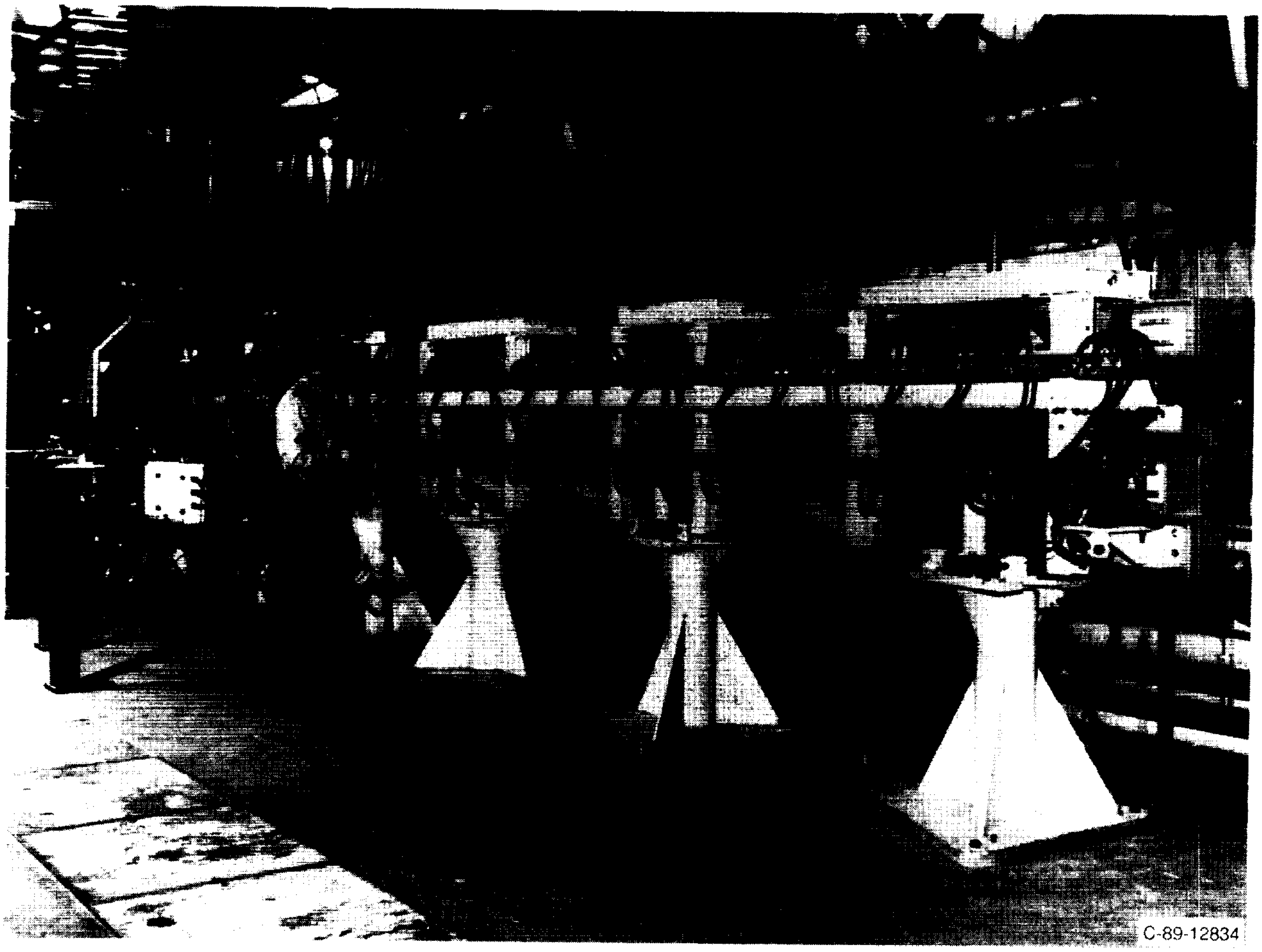
C'2

Schematic of one period of PALADIN wiggler. The iron core wiggler operates in a continuous mode. The specially shaped iron pole piece provides horizontal (wiggle plane) focusing.

PALADIN Wiggler Schematic



Ten meters of the PALADIN wiggler during installation.



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Spatial profile at output of wiggler for three different gain conditions. (The medium and high gain cases are appropriately attenuated.) The high gain keeps the signal at a waist at the end of the wiggler. This is an excellent example of gain guiding.

The accelerator and pulsed power are the major cost items of a free-electon laser system.

Element cost breakdown indicates pulse power is major item