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Technical and Physics Issues for Future High Energy Accelerators

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What physics questions motivate the next Linear Collider?

Linear collider at first step of E_{cm} = 500 GeV

Direct attack on EWSB

Driving element

- Higgs or Higgs surrogate should be accessible;
  ⇒ elucidate model and mechanism
- TeV-scale supersymmetry? ⇒ Likely to see and measure at least neutralinos/charginos, sleptons; model-independent determination of SUSY parameters
- Strong-coupling symmetry breaking?
  ⇒ Precision measurements of *W*, *Z*, and top quark; more energy for W^+W^- scattering
- Other new particles connected with EWSB, extra dimensions, etc.

Other important physics

Strengthen case

- Precision top quark measurements
- Precision W/Z boson measurements
- QCD studies
- Search for and characterize new particles not connected with symmetry-breaking

Rick Van Kooten, Indiana Univ., FNAL Users Meeting, HEPAP Session, June 27, 2000

What is required of future LCs?

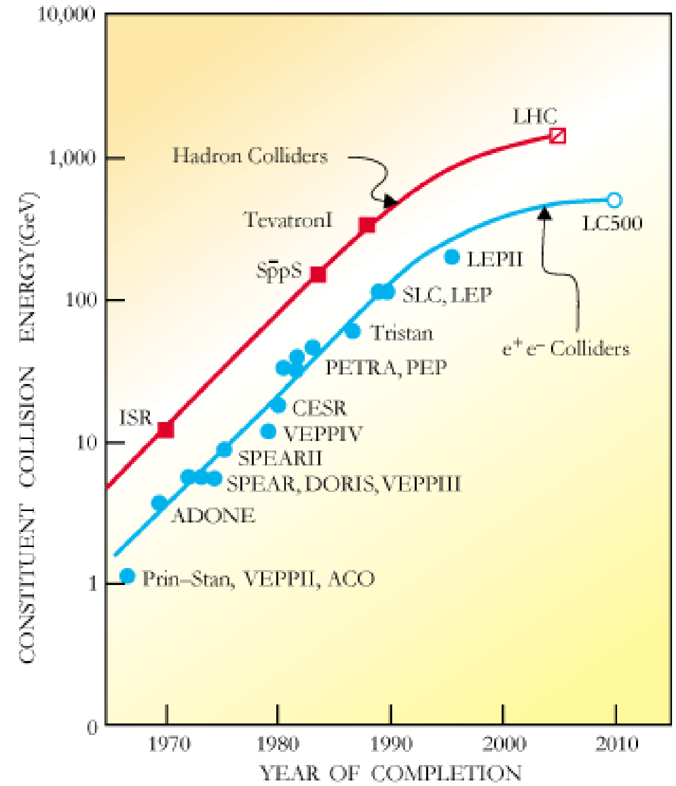
- Center-of-mass energy 0.5 TeV
  - Readily extensible to 1 TeV, 5 TeV,…
- Luminosity $>10^{34}$ cm^{-2} s^{-1} near-term
  - Increasing with γ^2 long-term

Progress in collision energies has slowed considerably in the last decade.

- •Progress in accelerating gradient has slowed
- •Beam quality demands have become steadily more stringent

M. Tigner, "Does Accelerator-Based Particle Physics Have a Future?", in Physics Today, January, 2001.

Figure 2



Effective constituent collision energy of hadron colliders (top curve) and electronpositron colliders (bottom curve), plotted against completion date. Because electrons and positrons are point particles, the effective collision energy of each e^+e^- collider is simply the sum of its colliding beam energies. But protons are composite particles. Each constituent quark carries, on average, only $^1/_6$ of the proton's momentum, and one is looking, primarily, for quarkquark collisions. For the hadron colliders, therefore, the constituent collision energy is taken to be $^1/_6$ the sum of the beam energies. Construction of the Large Hadron Collider (LHC) is just beginning at CERN, and LC500, the proposed 500-GeV linear e^+e^- collider, is still in the planning stage.

What are the Key Issues for Next Generation Linear Colliders?

- Improving acceleration gradient
- Developing e^+/e^- sources matched to the accelerator technique used
- Developing diagnostics for very short, low charge, low emittance beams
- Mitigating emittance dilution from wakefields, static & dynamic misalignments
- Developing a more compact final focus

What does a 5 TeV Accelerator look like now?

- TESLA-5000 (1.3 GHz, superconducting, discrete klystron)
  - Gradient: 25 MeV/m (40 MeV/m?)
  - Length: 2 x 150 km (2 x 94 km) [1.8 million cavities]
- ILC (5.7 or 11.4 GHz, normal conducting, discrete klystron)
  - Gradient: 65 MeV/m (87 MeV/m?)
  - Length: 2 x 50 km (2 x 37 km) [9.7 million cavities]
- VLEPP (14 GHz, normal conducting, discrete klystron)
  - Gradient: 100 MeV/m
  - Length: 2 x 30 km [7.1 million cavities]
- CLIC (30 GHz, two-beam accelerator)
  - Gradient: 125 MV/m (200 MeV/m?)
  - Length: 2 x 23 km (2 x 15 km) [13 million cavities]

What are the Serious Difficulties Limiting Accelerating Gradient?

- Direct:
  - Single- vs. Multi-cell structure breakdown thresholds
    - Surface and near-surface material properties
    - Geometry
  - Field emission, breakdown, plasma erosion
    - Surface cleanliness, subsurface particles, grain-boundary inclusions
    - Material yield strength
  - Obtaining high energy densities
    - Transient surface heating of structures
    - High frequency sources
      - Severe wakefields
  - Power source capabilities

Added complications for microwave accelerators…

- Indirect:
  - Power sources (klystrons, beams) have limited markets outside defense, aviation, and accelerator physics
  - Accelerating structures are made by manufacturing techniques that exhibit few economies of scale
  - It is the extension of older technology
  - The technology is not attracting bright young minds

What gradient is possible in a normal-conducting microwave cavity?

Some hints of the answer:

- Single-Cell Test Results (copper)
  - Matsumoto *et al*, 1993: 0.33 GV/m in single 2.8 GHz cavity
  - Laurent *et al*, 2000: 0.35 GV/m in TM_{020} 11.4 GHz cavity
  - Wuensch *et al*, 2000: 0.53 GV/m in single 30 GHz cavity
- Multi-Cell Test Results (copper)
  - Haimson *et al*, 2000: 0.055-0.07 GV/m, at 17.1 GHz
  - Lowen *et al*, 2000: 0.067 GV/m, 206 cells, at 11.4 GHz
  - CLIC, 1999: 0.125 GV/m, 150 cells, at 30 GHz

→ Factor-of-6 Discrepancy

How can the gradient be improved?

- Material Science
  - Superconducting RF gradients have improved dramatically over the last decade due to rigorous:
    - Impurity control (RRR)
    - Process control (chemistry, vacuum firing)
    - Cleanliness (Cl. 100- Cl. 10)
- Geometry
  - Traveling vs. Standing wave structures

Achieving Higher Gradients Efficiently

- Higher energy density in structures
  - Higher fluence sources $E/(t_p \lambda^2)$
  - Higher Q structures (metallic resonators: $\sim\lambda^{0.5}$)

But, higher frequencies imply:

- More severe wakefield effects $\sim\lambda^{-1}$ to λ^{-2}
  - Lower bunch charge
    - Higher pulse repetition rates $f_{rep} \sim \lambda^{-1}$ to λ^{-2}
    - HOM-free structures
  - Tighter alignment tolerances
    - more exotic fabrication and positioning

Also, finding appropriate power sources is not easy…

Evaluating Power Sources: By Efficiency

- Microwave Tubes
  - Modulators: →70%
  - Klystrons: →65%
  - Pulse compressors: →85%

NET: ~40%

WALL-PLUG TO PHOTONS

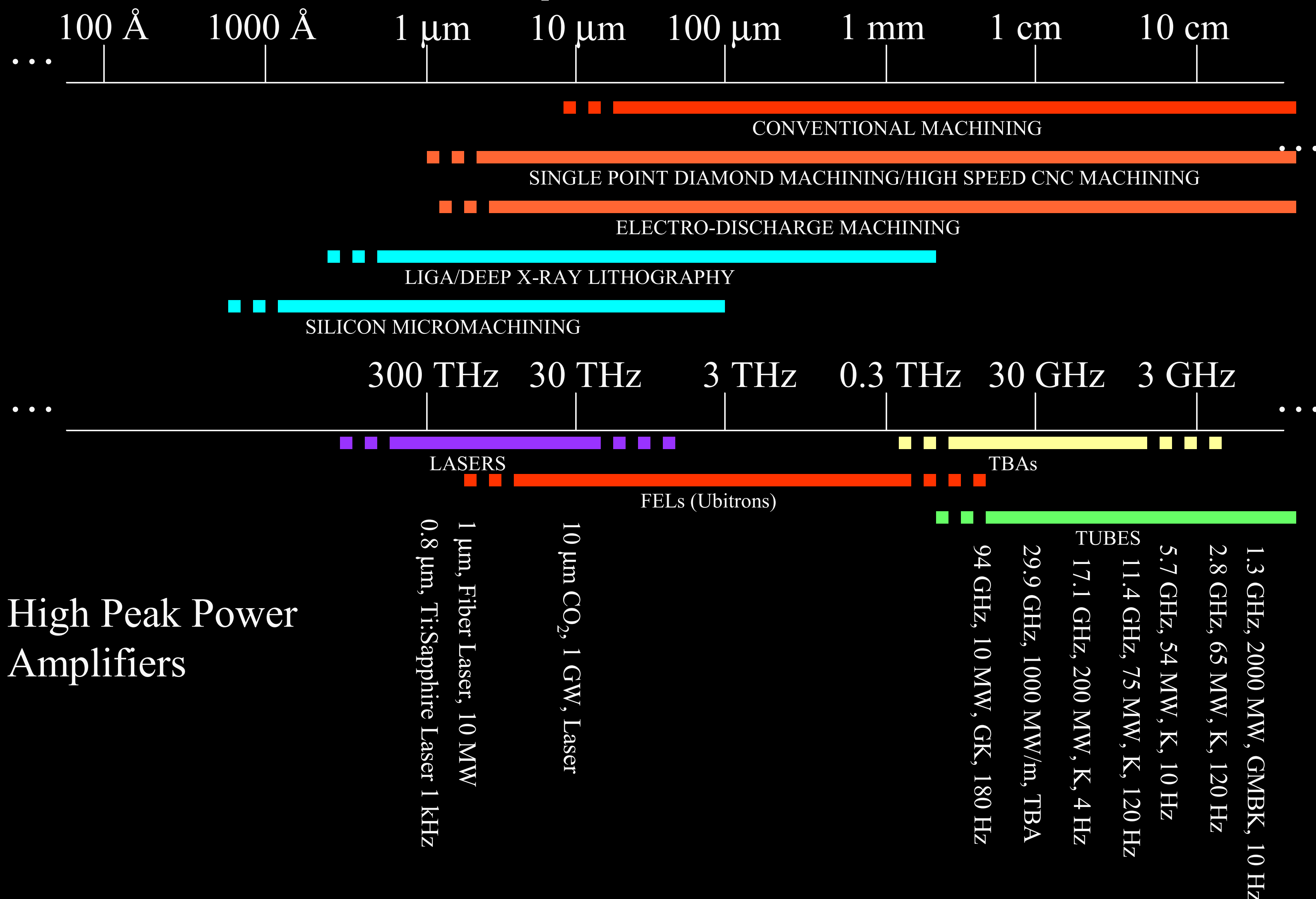
- Lasers
  - CO_2 , Ti:Sapphire: 1-2%
  - DPSS/Nd:YVO_4: 4-6%
  - Yb-Fiber: 7%
  - ZnTe:Se →20% (at 1-2 μm)

WALL-PLUG TO PHOTONS

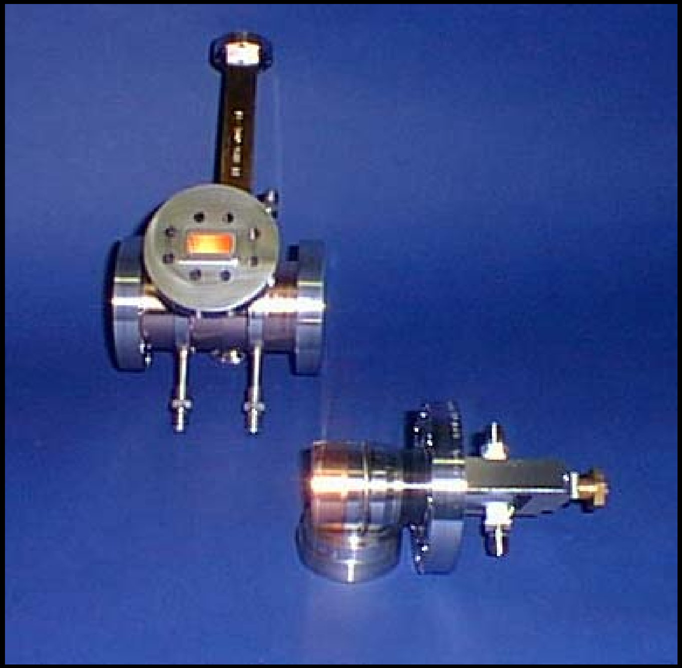
Power Sources

Source	Units	SLAC	SLAC	Mitsubishi	SLAC	Haimson	CLIC	UMD/CCR	LLNL	C02 Laser	Ti:Sapphire	Fiber	Units
Source Type		MBK	K	K	K	K	TBA	GK	Ub	Laser	Laser	Laser	
Frequency	[GHz]	1.3	2.856	5.712	11.424	17.136	30	94	140	29979.2458	374740.573	299792.458	[GHz]
Wavelength	[mm]	230.609583	104.969348	52.484674	26.242337	17.4948913	9.99308193	3.18928147	2.1413747	0.01	0.0008	0.001	[mm]
Peak Power	[MW]	2000	65	54	75	200	1000	10	2000	1000000	1000000	10000	[MW]
Pulse Length	[ns]	1000	6000	6000	2000	500	130	100	1	0.001	0.0001	0.0001	[ns]
Efficiency	[%]	50			65			30				20	[%]
Rep Rate	[Hz]	10	120	50	120	4	100	180	10	10	1000	300000000	[Hz]
Fluence	[TW/cm^2]	3.8E-12	5.9E-13	2.0E-12	1.1E-11	6.5E-11	1.0E-09	9.8E-11	4.4E-08	1.0E+00	1.6E+02	1.0E+00	[TW/cm^2]
Buckets per pulse		1.3E+03	1.7E+04	3.4E+04	2.3E+04	8.6E+03	3.9E+03	9.4E+03	1.4E+02	3.0E+01	3.7E+01	3.0E+01	
Buckets*Fluence	[TW/cm^2]	4.9E-08	1.2E-06	3.4E-06	3.0E-05	2.2E-06	3.9E-04	1.7E-04	6.1E-05	3.0E+02	5.9E+06	9.0E+09	[TW/cm^2]
PUNITIVE SCALING $Q \sim \lambda^2$ (Charge reduced to compensate for reduced RF bucket size AND to hold wakefields constant)													
Bunch Charge	[nC]	4.8E+00	**1.0E+00**	2.5E-01	6.3E-02	2.8E-02	9.1E-03	9.2E-04	4.2E-04	9.1E-09	5.8E-11	9.1E-11	[nC]
Emittance Product	[micron2]	2.0E+01	**0.22**	5.5E-02	1.4E-02	6.1E-03	2.0E-03	2.0E-04	9.2E-05	2.0E-09	1.3E-11	2.0E-11	[micron2]
"Luminosity"	[cm^-2 s^-1]	6.6E+33	3.2E+34	1.7E+33	5.1E+32	5.0E+30	2.3E+31	1.4E+30	2.3E+28	2.3E+21	1.2E+20	7.0E+25	[cm^-2 s^-1]
Luminosity Ratio		0.20	1.00	0.05	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
BETTER SCALING $Q \sim \lambda^1$ (Charge reduced to compensate for reduced RF bucket size ONLY)													
Bunch Charge	[nC]	2.2E+00	**1.0E+00**	5.0E-01	2.5E-01	1.7E-01	9.5E-02	3.0E-02	2.0E-02	9.5E-05	7.6E-06	9.5E-06	[nC]
Emittance Product	[micron2]	4.8E-01	**0.22**	1.1E-01	5.5E-02	3.7E-02	2.1E-02	6.7E-03	4.5E-03	2.1E-05	1.7E-06	2.1E-06	[micron2]
"Luminosity"	[cm^-2 s^-1]	8.8E+33	3.2E+34	4.8E+33	4.0E+33	7.3E+31	7.9E+32	2.6E+32	7.9E+30	2.5E+27	5.7E+27	2.4E+33	[cm^-2 s^-1]
Lum Ratio		1.00	4.91	0.72	0.61	0.01	0.12	0.04	0.00	0.00	0.00	0.36	

Manufacturability



Pulsed Heating



X-band TE_{011} Test Cavity showing removed end cap. (SLAC)

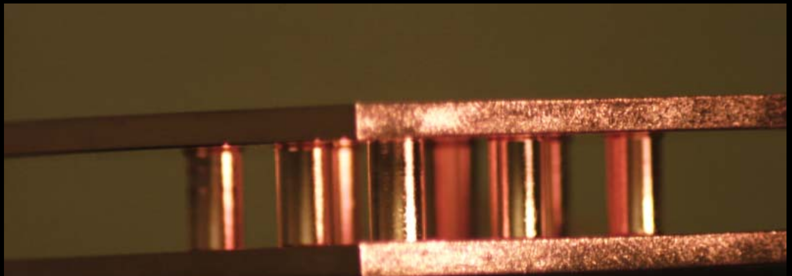
Close up of end cap after $\Delta T \sim 120$ K 55×10^6 pulses

Coupling Mechanisms

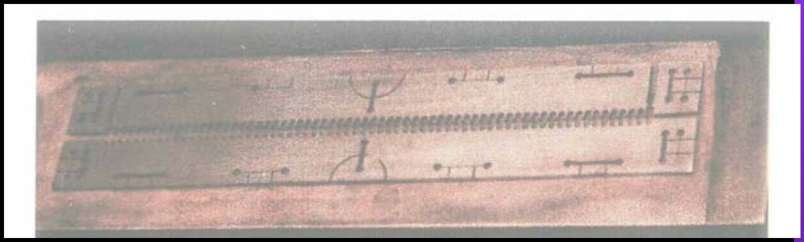
- Copper and dielectric microwave structures
- Plasma wakefield acceleration
- Vacuum laser acceleration structures
- Active structures

Other Structures

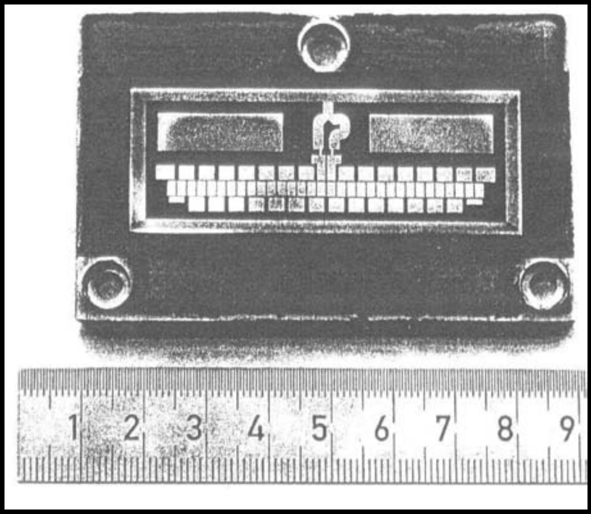
W-band “Zipper” Structure (EDM)
UCSD/SLAC



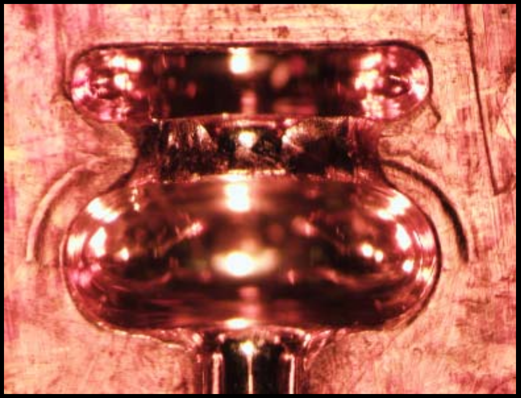
X-band Photonic Band Gap Structure
UCSD/SLAC



W-band 108 Cell Constant Gradient Structure (LIGA), Argonne National Lab



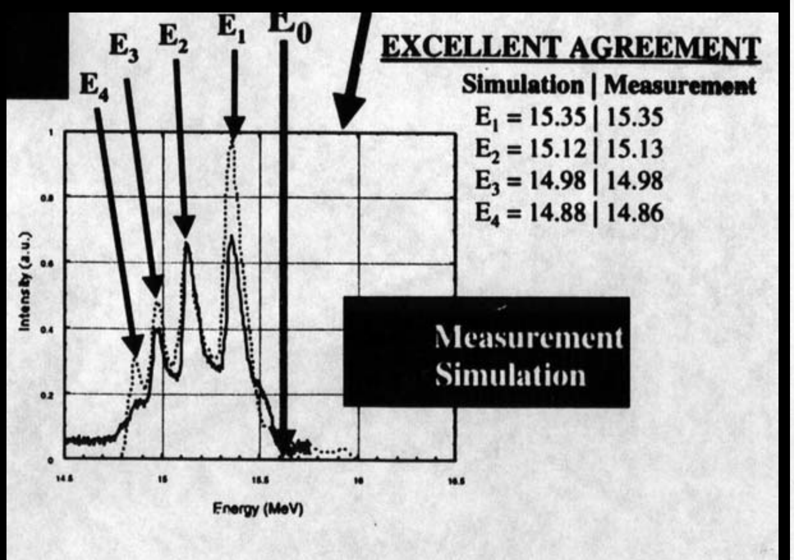
W-Band Side-Coupled π/2 Structure (LIGA) T.U. Berlin



Adiabatically Stamped
W-band RF Gun (half)
SLAC

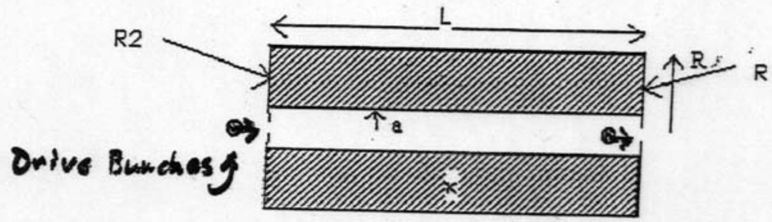
Dielectric Structures

J. Power et al, “Multimode Dielectric Wakefield Experiment”, in Proc. AAC2000, Santa Fe, NM, (2000).



The Wake Field “Resonator”

Here is a finite length section of cylindrical waveguide, lined with an alumina annulus. On each end are reflecting surfaces, so this becomes a TM_{0nq} resonator. Drive bunches pass through this resonator, and excite wake fields, which bounce back and forth inside.



Marshall, Fang, Hirshfield, Park, “The Wake Field Resonator”, in proc. AAC2000, Santa Fe, NM, (2000).