X-band Design + R&D Report

For teams from SLAC, KEK, LBNL, LLNL, BINP, IHEP...

ICFA Seminar '99 FNAL

Nobu Toge
(KEK, Accelerator Lab)

In this talk I will present the status of R&D efforts towards linear collider designs that are based on the X-band RF technology for the main linacs.

This work is pursued mainly by SLAC (US) and KEK (Japan) with a number of collaborating institutes around the world (LBNL, LLNL, BINP, IHEP, [illegible] - - -

Partnership in the form of "International Study Group" (ISG) exists between SLAC and KEK, and the majority of the work presented here has been done in this context, if not all.

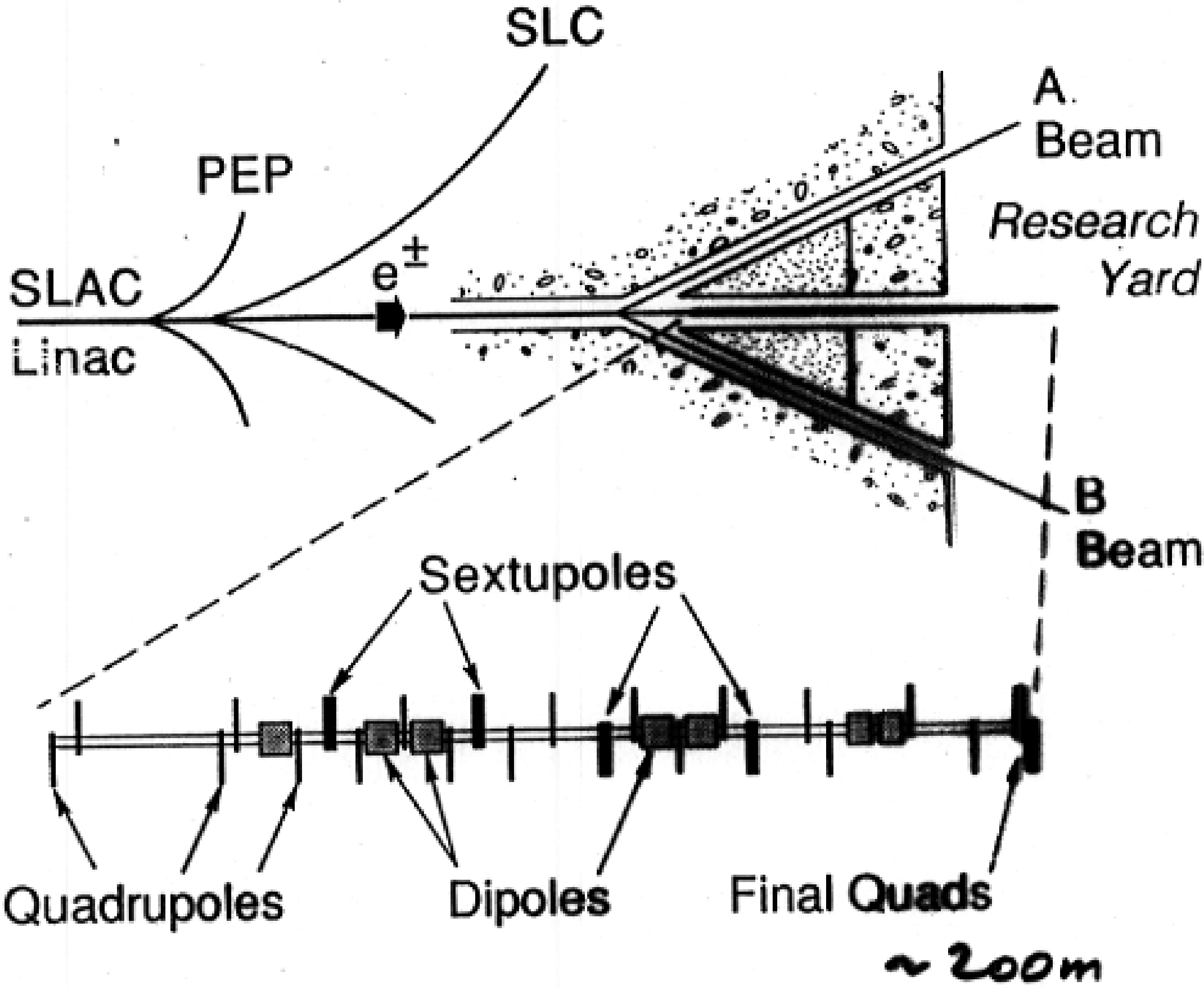
I will visit the topics as follows:

- SLAC-KEK ISG, Background
- Introduction to the X-band Linac Design
- Technology development status
  - Klystron modulators
  - Klystrons
  - Power Distribution System
  - Accelerating Structure
- Prospects and conclusions

SLAC-KEK ISG and its Background

- Long-standing history of cooperation (since '80s)
- LC concepts with similar technology basis.
- MoU between the lab directors in early 1998 for: Joint efforts of certain pre-(conceptual) design work.
  - Common design parameters.
  - Common or mutually-compatible hardware schemes.
  - Information sharing within the US-Japan HEP collab protocol.
  - Periodic general meetings (twice a year)
  - Prepare status report by early 2000.
- Many labs and Univs involved besides KEK and SLAC.
- Long-term future of ISG is pending negotiations between the KEK and SLAC lab directors, based on –
  - ISG status report
  - Community discussions

FFTB



8-90 Final Focus Test Beam 6700A2

$\gamma \epsilon_y \sim 2 \times 10^{-6}$ m in FFTB

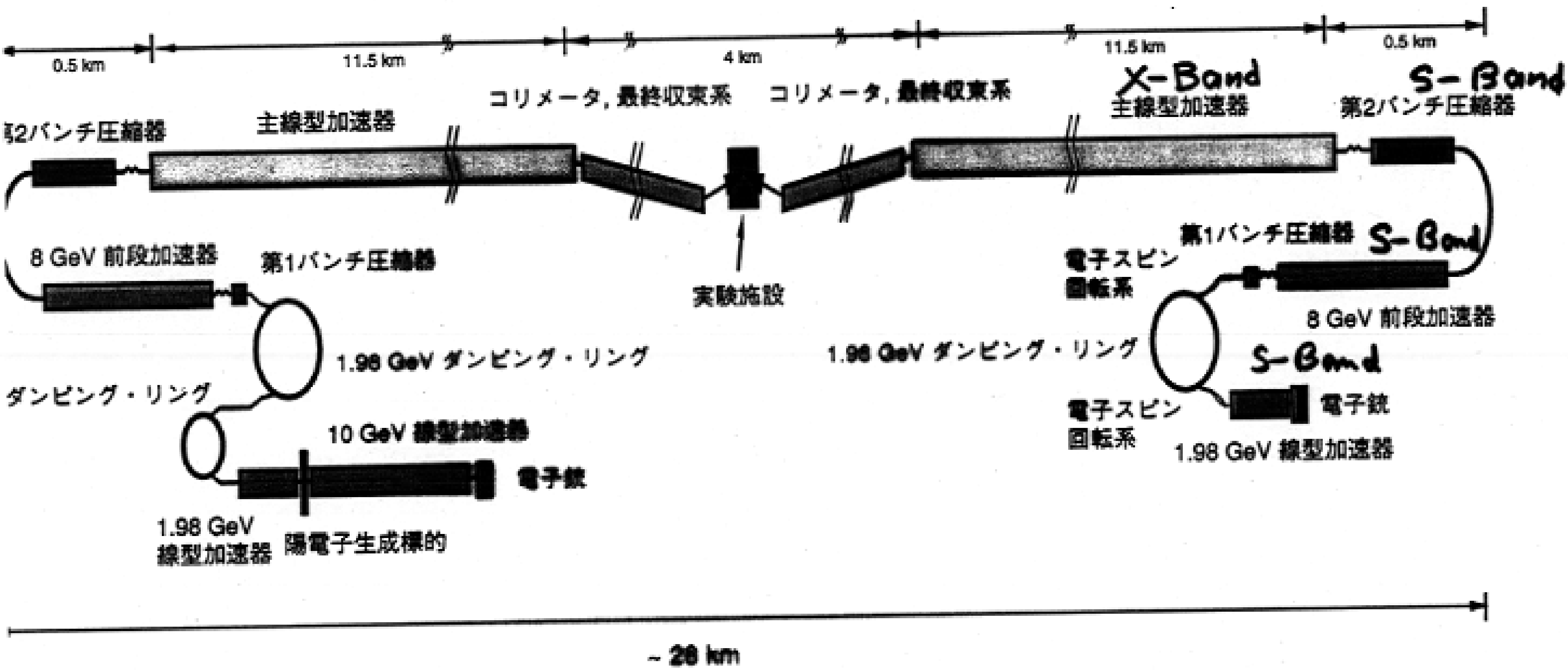
$n = 6.5 \times 10^{9}$

$\sigma_E / E = 0.05 \sim 0.1\%$

if $\beta^* = 0.13$ mm $\Rightarrow \sigma_y^* \simeq 52$ nm

電子・陽電子リニア・コライダー　JLC

重心系エネルギー：E_{CM} = 500 GeV JLC-I → $E_{CM} \gtrsim$ 1 TeV JLC-II



1.0 TeV 構成時

X-band Linac Design

11.424 GHz

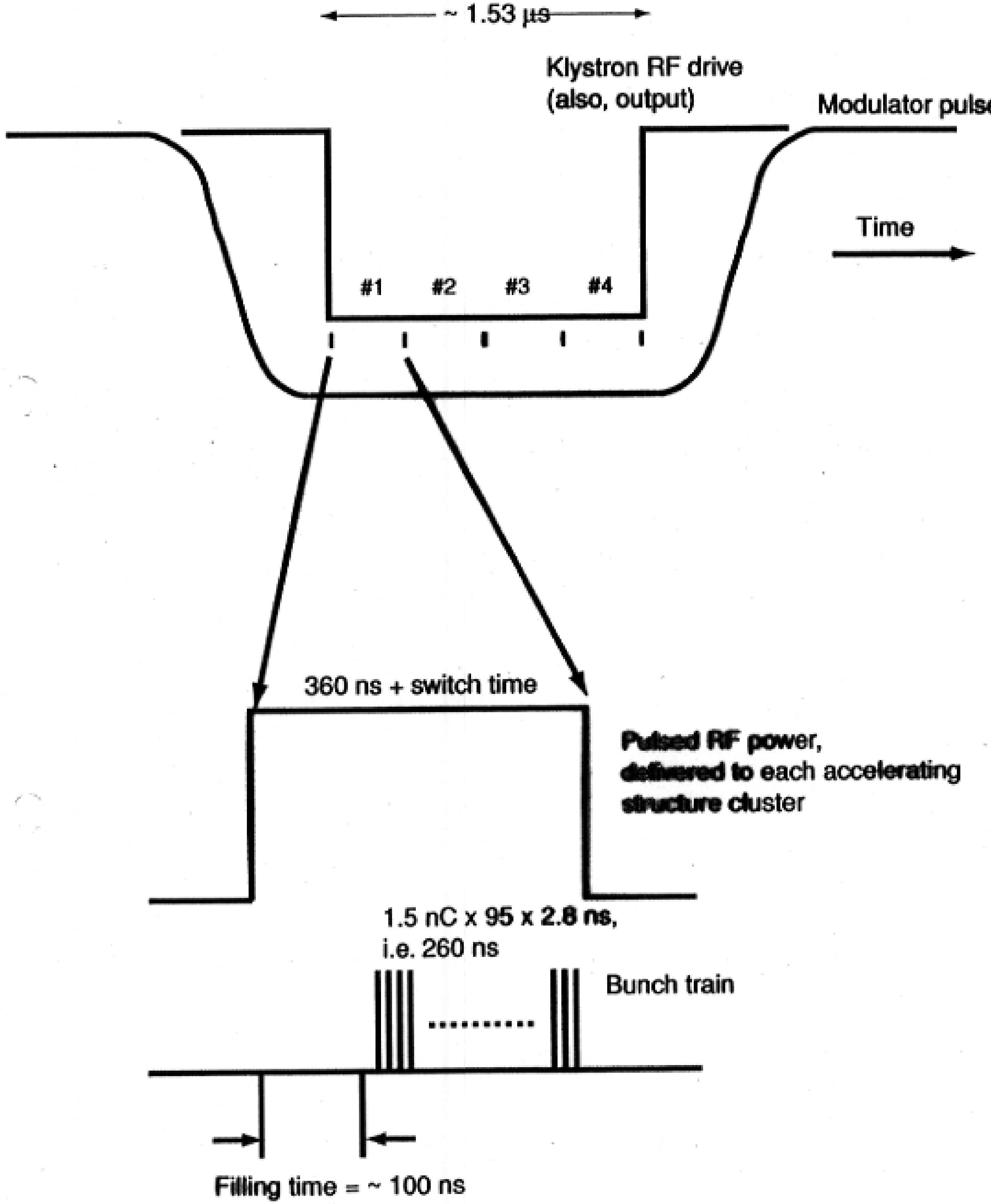
- Considerations on the design parameters have been already covered in Tor Raubenheimer's talk (NLC and JLC share common basic parameters)

- 500 GeV --> 1 TeV adiabatic upgrade with the same RF system: 55 MV/m loaded acc. gradient, which is realized by:
  - Conventional or solid-state-switch based modulator.
  - 75 MW, 1.53 μs X-band klystron with permanent-magnet focusing.
  - Highly efficient power distribution with DLDS (delay-line distribution system) concept.
  - Damped-Detuned Structure with Rounded corners (RDDS), 1.8 m-long each for accelerating trains of bunches (95 x 1.1E10 elec/bunch, 2.8 ns apart)

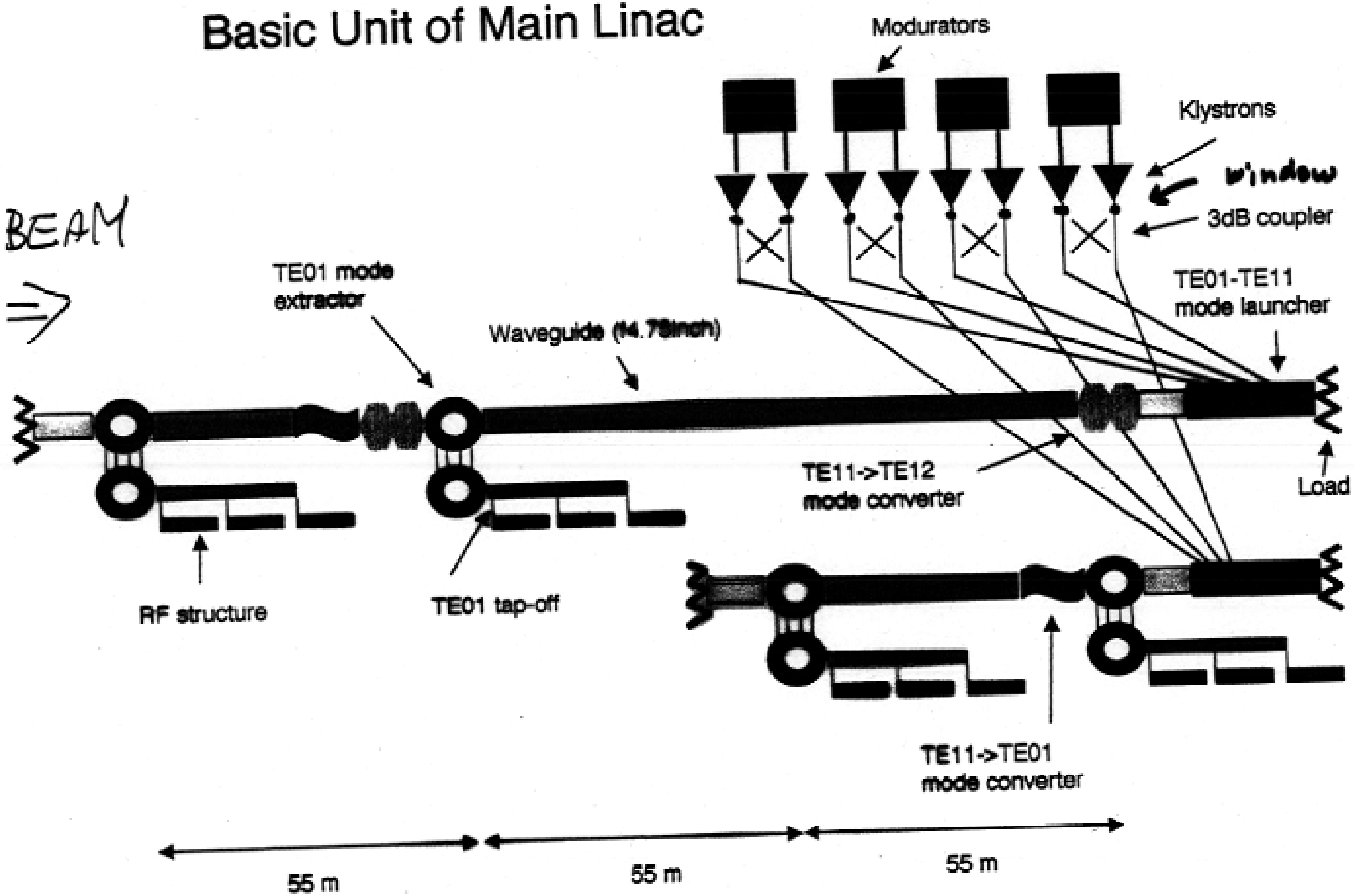
- We are yet to demonstrate beam acceleration with ultimate emittance preservation in a full-fledged, complete RF system above; but we have made good progress in recent component R&D.

- Also, we have operated small / medium-scale systems at NLCTA (SLAC) and ATF Linac (KEK) for demonstrating certain aspects of technology that are needed at X-band linacs.

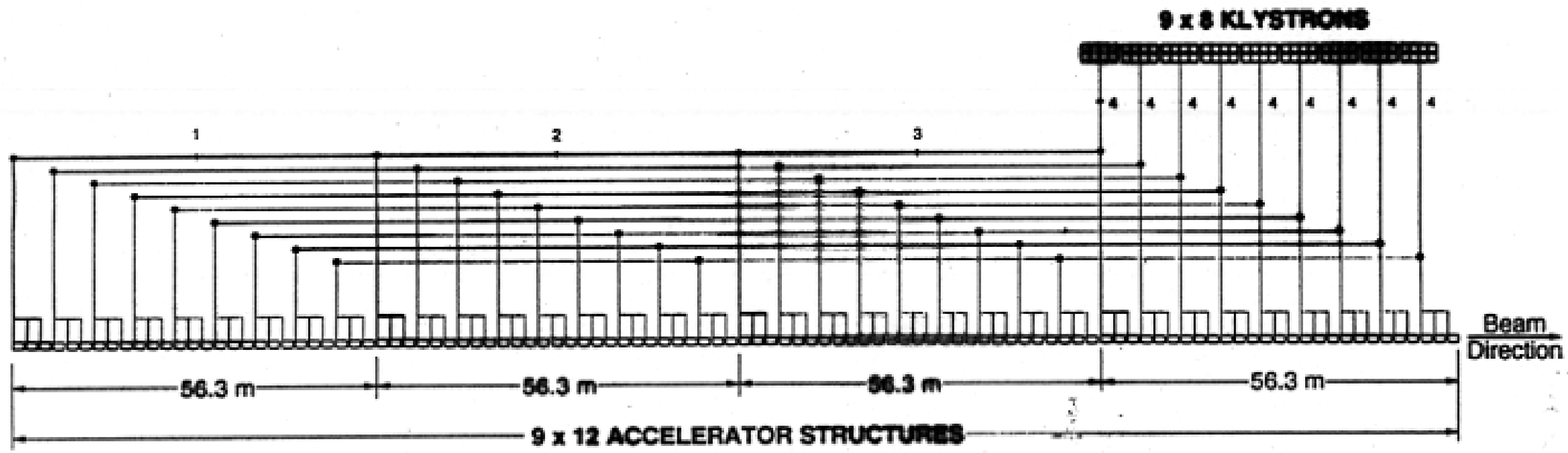
Relationship between the RF Power and Bunch Train



Basic Unit of Main Linac



LINAC SECTOR - DLDS NONET



Active / Actual Length = 9 x 12 x 1.8 / 225.2 = 86%

Table of Paremters for the X-band Main Linacs

<table>
<tr><th></th><th>Phase-1</th><th>Phase-2</th></tr>
<tr><td>Final Energy / linac</td><td>250 GeV</td><td>500 GeV</td></tr>
<tr><td>Particles / bunch</td><td colspan="2">0.7 - 1.1 E10</td></tr>
<tr><td>Bunch Spacing</td><td colspan="2">2.8 ns</td></tr>
<tr><td>Bunches / pulse</td><td colspan="2">95</td></tr>
<tr><td>Pulse repetition rate</td><td colspan="2">120 (- 150?) Hz</td></tr>
<tr><td>Effective gradient</td><td colspan="2">55 MV/m</td></tr>
<tr><td>Klystron Power</td><td colspan="2">75 MW</td></tr>
<tr><td>Klystrons / linac</td><td>1600</td><td>3200</td></tr>
<tr><td>Structures / linac</td><td>2400</td><td>4800</td></tr>
</table>

■ **Decisions made in 1997 - 1998 thru SLAC-KEK discussions:**

- **Same** RF system through **Phase-1 and** 2.
- Increased bunch spacing to 2.8 ns (was 1.4 ns)
  - Beam-loading reduction: 28% --> 16 %
  - Reduction of unloaded gradient: 85 --> 74 MV/m
- Increased klystron pulse width (was 0.96 μs)
- Adoption of DLDS scheme
  ... leading to reduction of #klystron by 1/3.
- Adoption of RDDS cell design
  ... leading to increased RF -> Beam efficienty (up 6%)

Technology Development – Klystron Modulators

- What do we need?

  500 kV, 530 A, 2.0μs output
  1.5 μs flat-top width
  Energy efficienty goal: 75 %

  800 units/linac if adopt "2-pack" implementation

- Where are we?

  Proven conventional technology exists, in principle.

  Issues exist in -

  Efficiency improvement.
  Reduction of cost for fabrication and maintenance.
  modular construct for easy assy + maint.

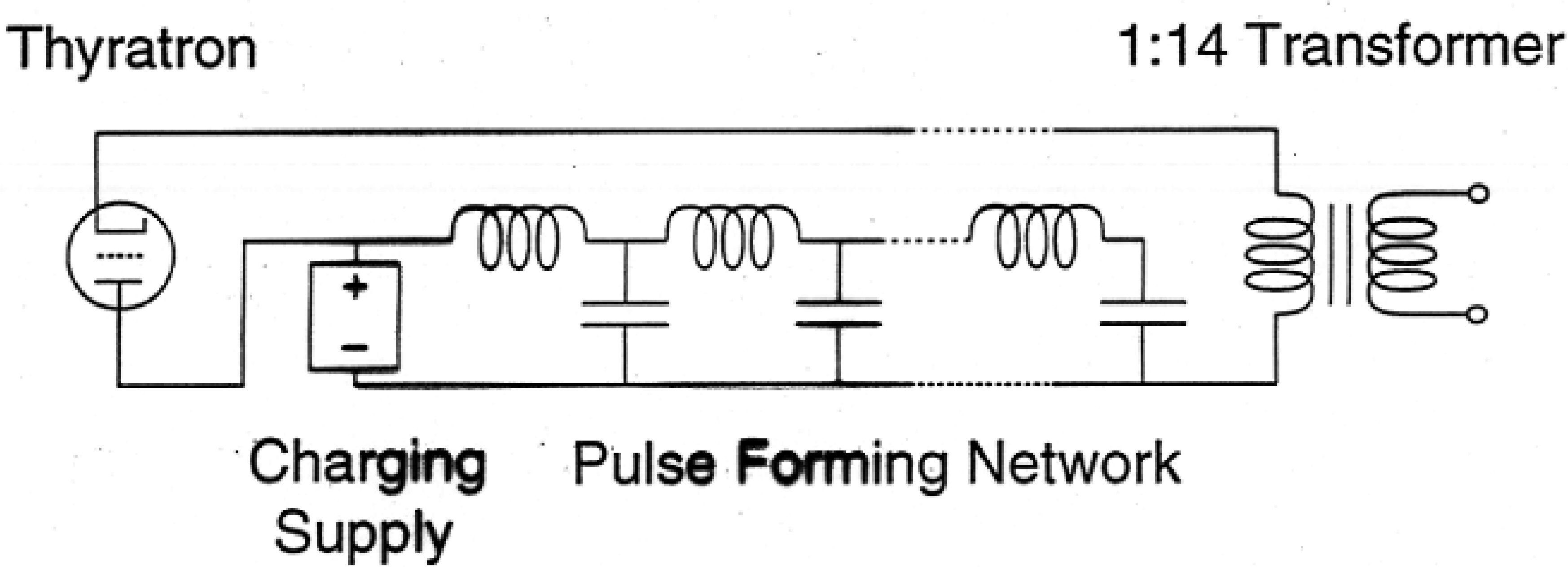
- What are we doing?

  Operation and construction of conventional thyratron-PFN modulators with attention to a lot of details.
  stray inductance ↓ mismatch ↓

  Removal of thyratrons and/or PFN by using :

  IGBT switches --> induction modulator or
  SI-thrystor stack switch or...

  (It will take some time and resources)


Thyratron
1:14 Transformer
+
−
Charging
Supply
Pulse Forming Network

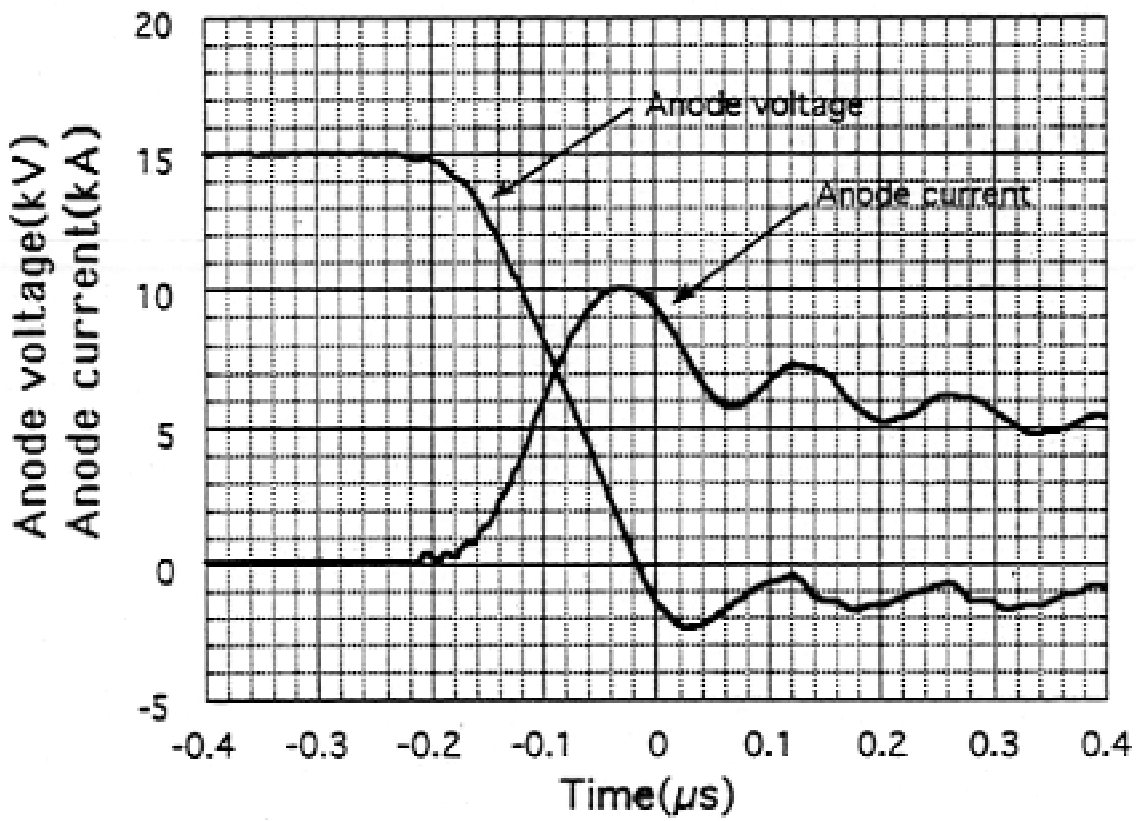
KEK-NGK Si-thyristor switch

45 KV, 10 kA peak current ← 15-STACK
di/dt ~ 110 kA/μs

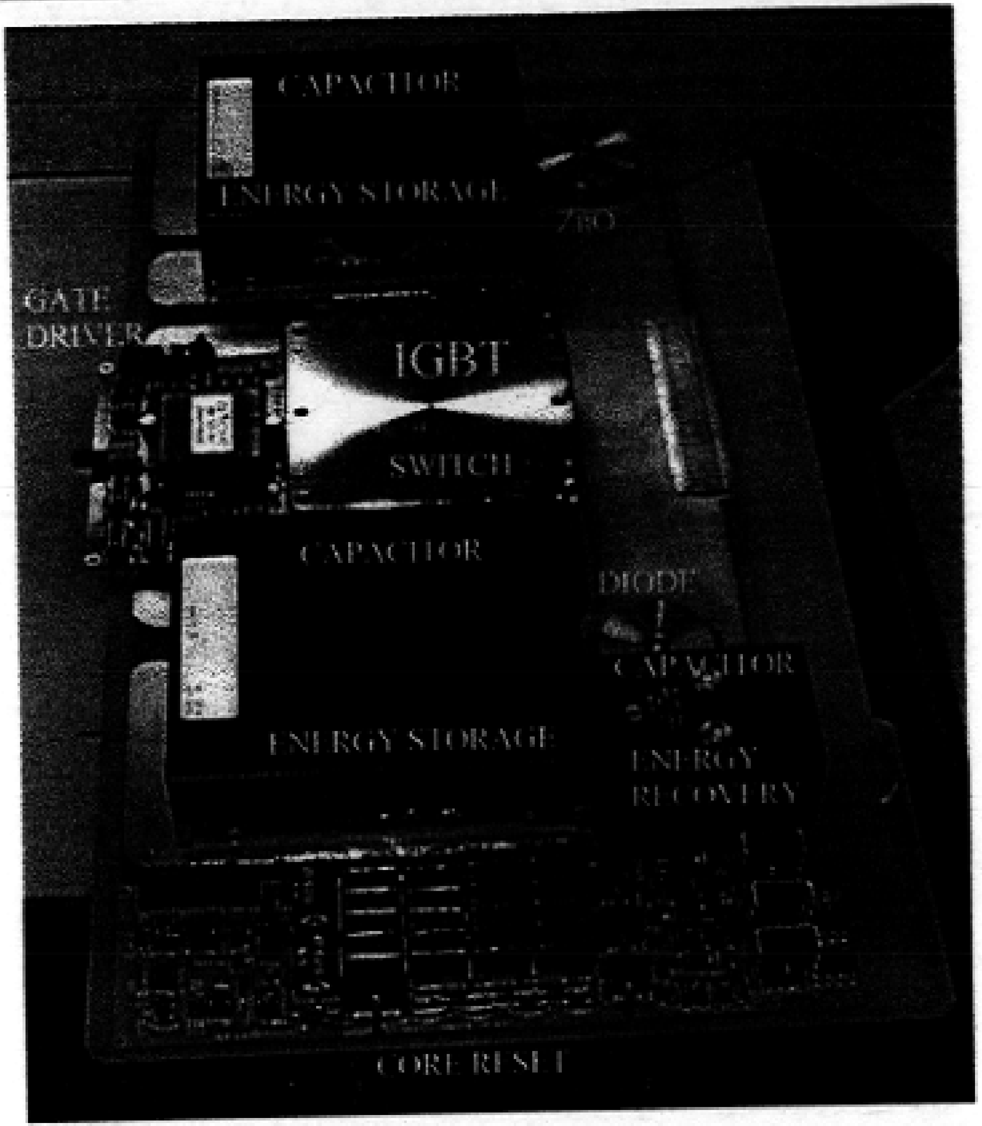
1 UNIT : 5 KV, 10 kA

Typical anode voltage and current waveforms

Test results from 5-stack

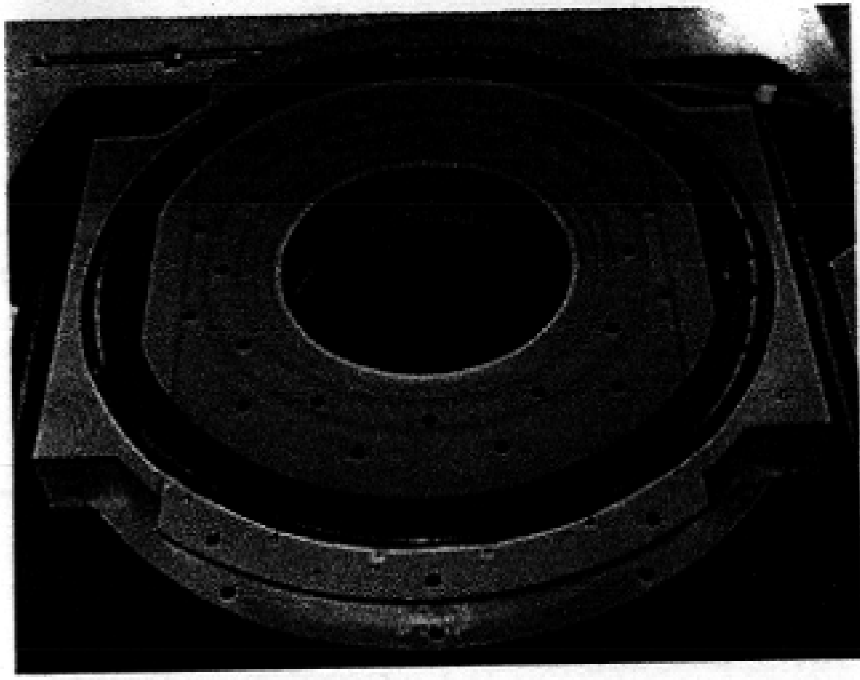


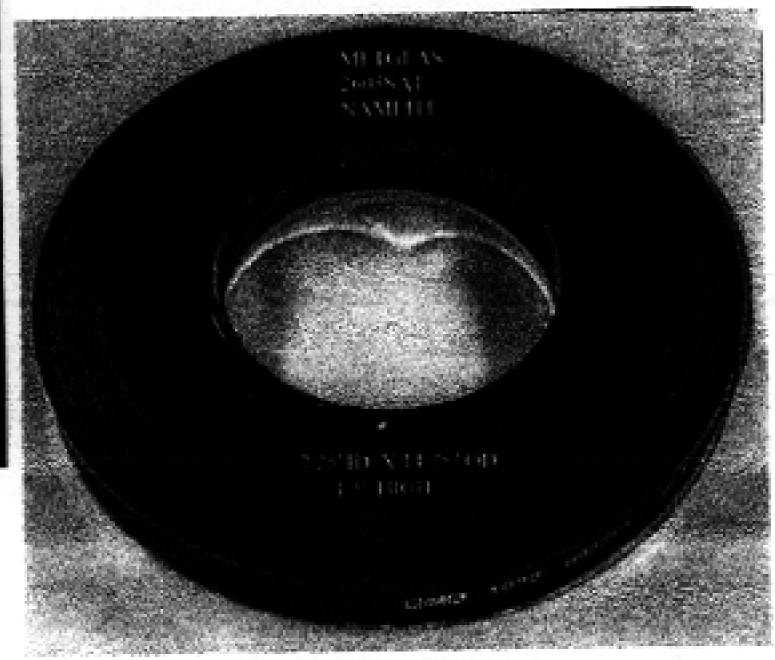
Drive PC Board



- 2.5 kV pulse
- 2 kA 3uSec.
- 25 ufd 5kV Cap
- 120 A core reset

Modulator Core & Case

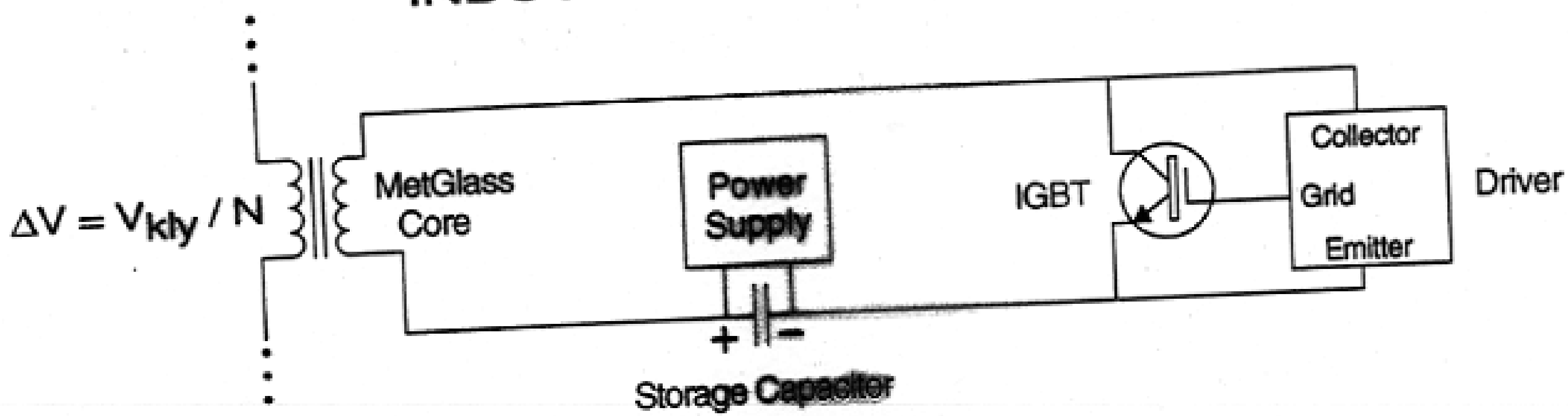


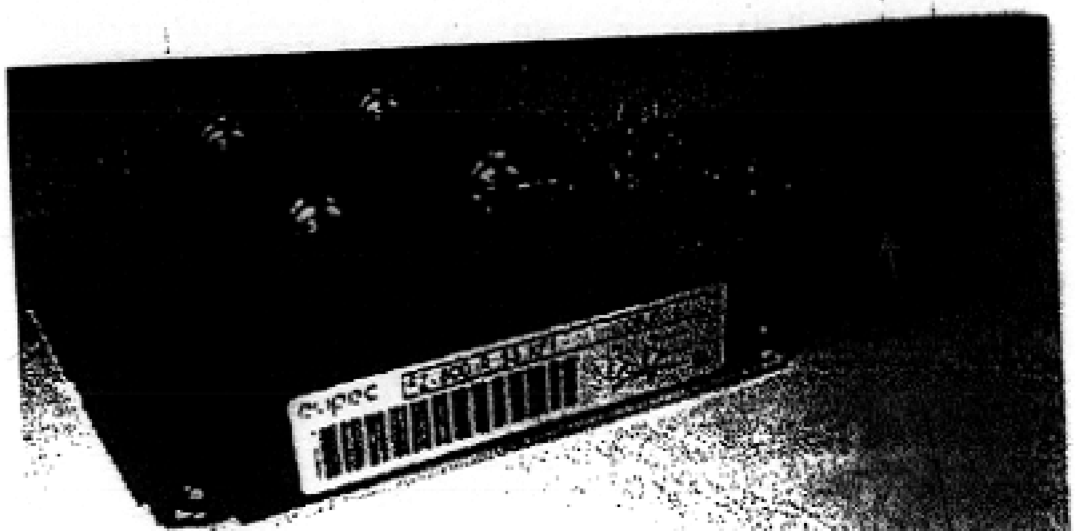


- 6.5" ID double ended drive core
- 0.006 Volt-Sec core
- 4kV 1.5uSec 0.5 Joules loss

SUM MANY LOW VOLTAGE SOURCES INDUCTIVELY

INDUCTION CIRCUIT (1 OF N)





10 CM

Dr Circuit

Isolated Gate Bipolar Transistor

Rated: 3.3 kV @ 0.8 kA (DC)

Tested: 2.0 kV @ 1.5 kA (Pulsed)

Future: 5.0 kV @ 2.0 kA (Pulsed)

Technology Development – Klystrons

- What do we need?

  75 MW peak power
  1.53 μs output pulse
  120 (-150) Hz rep. rate

  For E_{CM} = 500 GeV
  1600 units/linac

  High efficiency, reliable, low-manufacturing cost, low-maintenance cost, low-operation cost...

  → High η, PPM tubes

- Where are we?

  We have clearly met the R&D goal a few times.

  Very good simulation codes at hand. Pretty good understanding if the subject is a 2-dim problem. 3-dim code exists and in use, too, although very CPU intensive work.

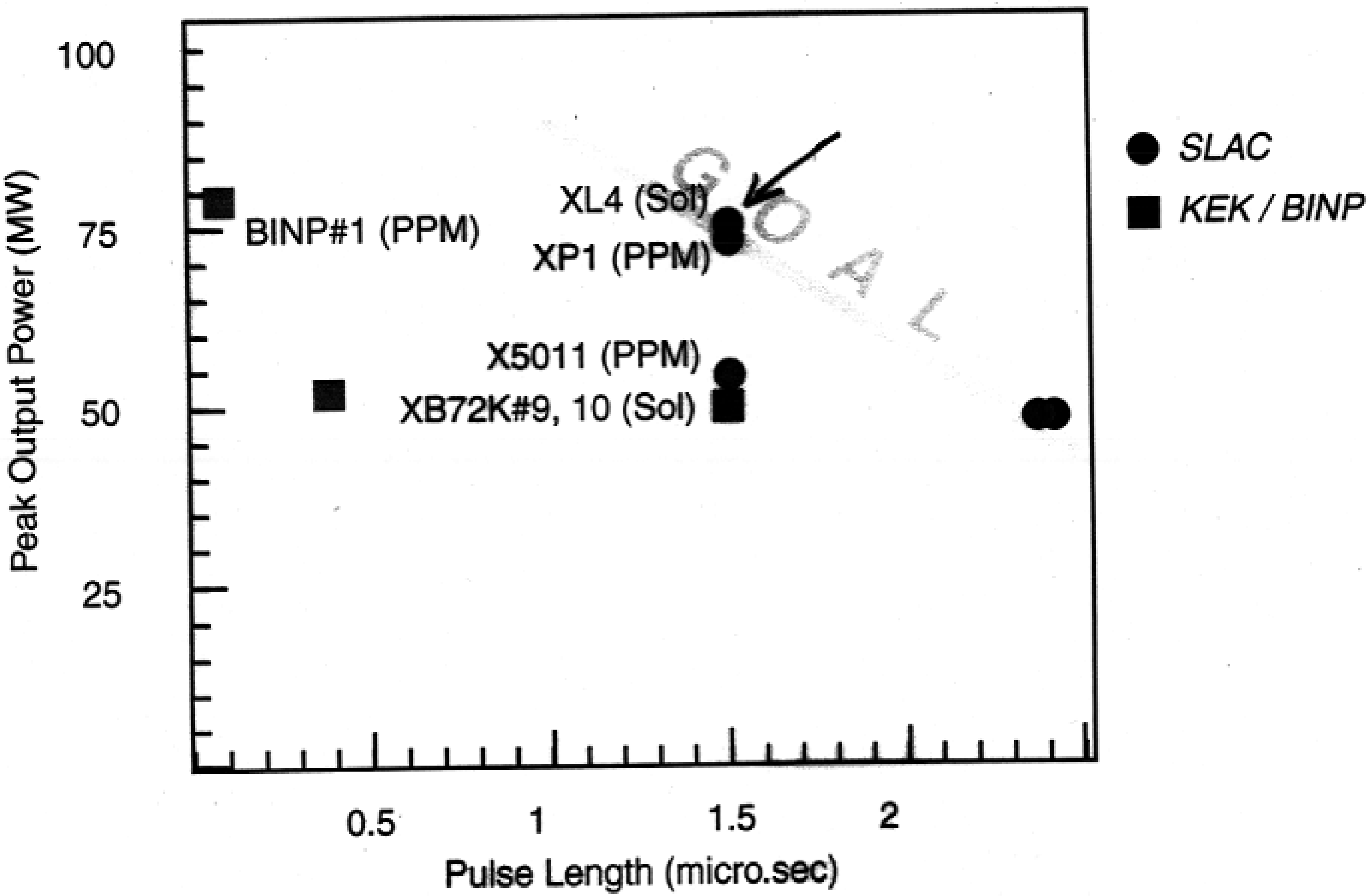
  Reliability of XL4 (SLAC, solenoid-focusing) model has been excellent. Need to do the same with PPM tubes.

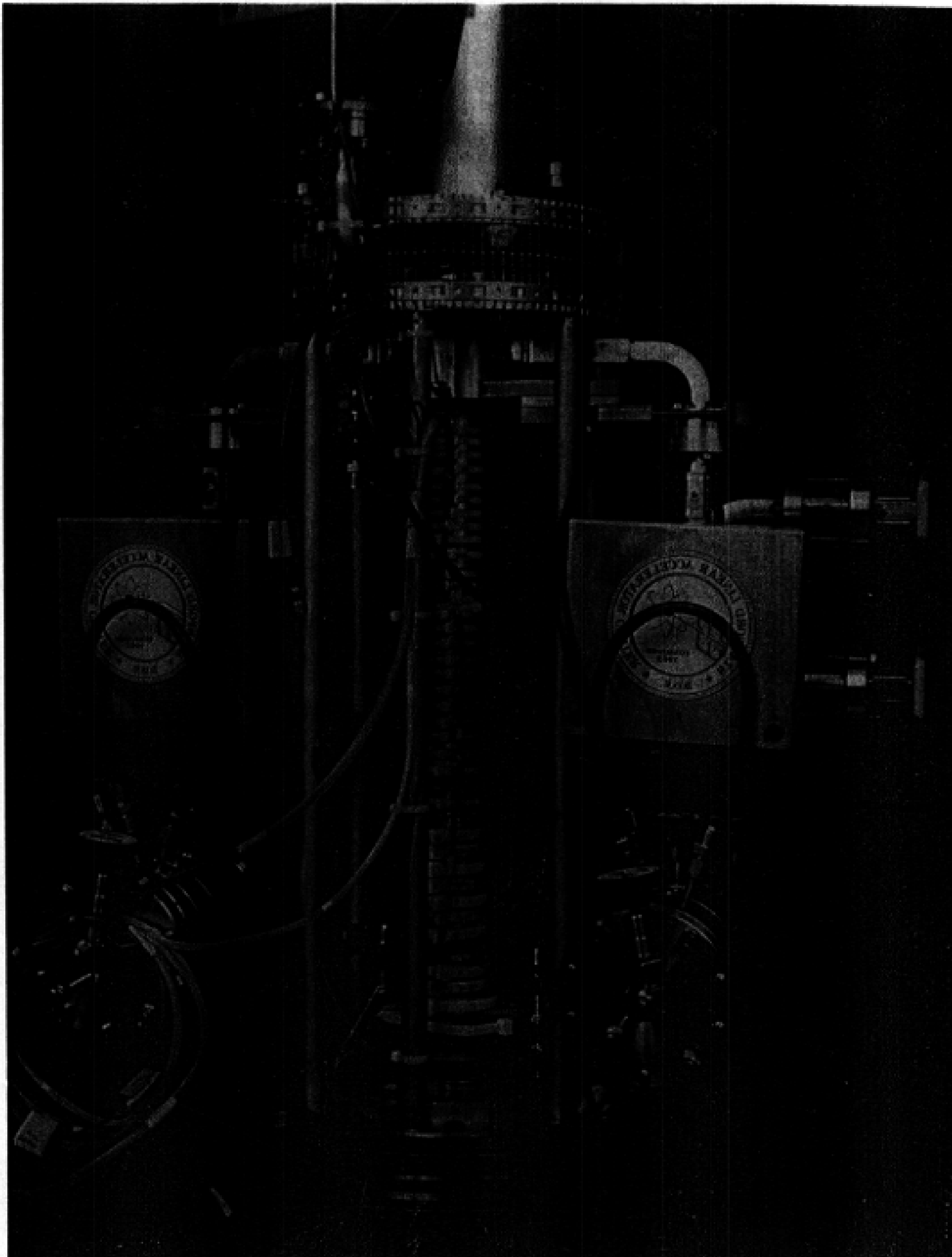
  However, in general, technology of PPM (permanent-magnet focusing) klystron still has to be established.

- What are we doing?

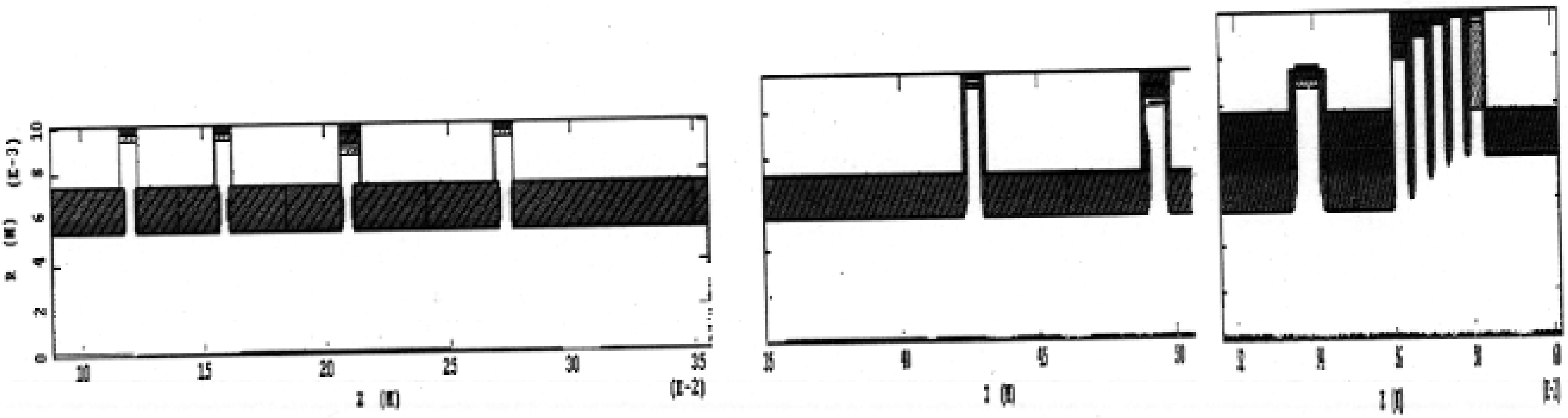
  Testing and design of XP1, XP3 (SLAC) models, KEK-BINP #2, KEK PPM#1 models. Approx. 1 - 2 tubes/year at each lab.

Performance of Recent X-band Klystron Prototypes



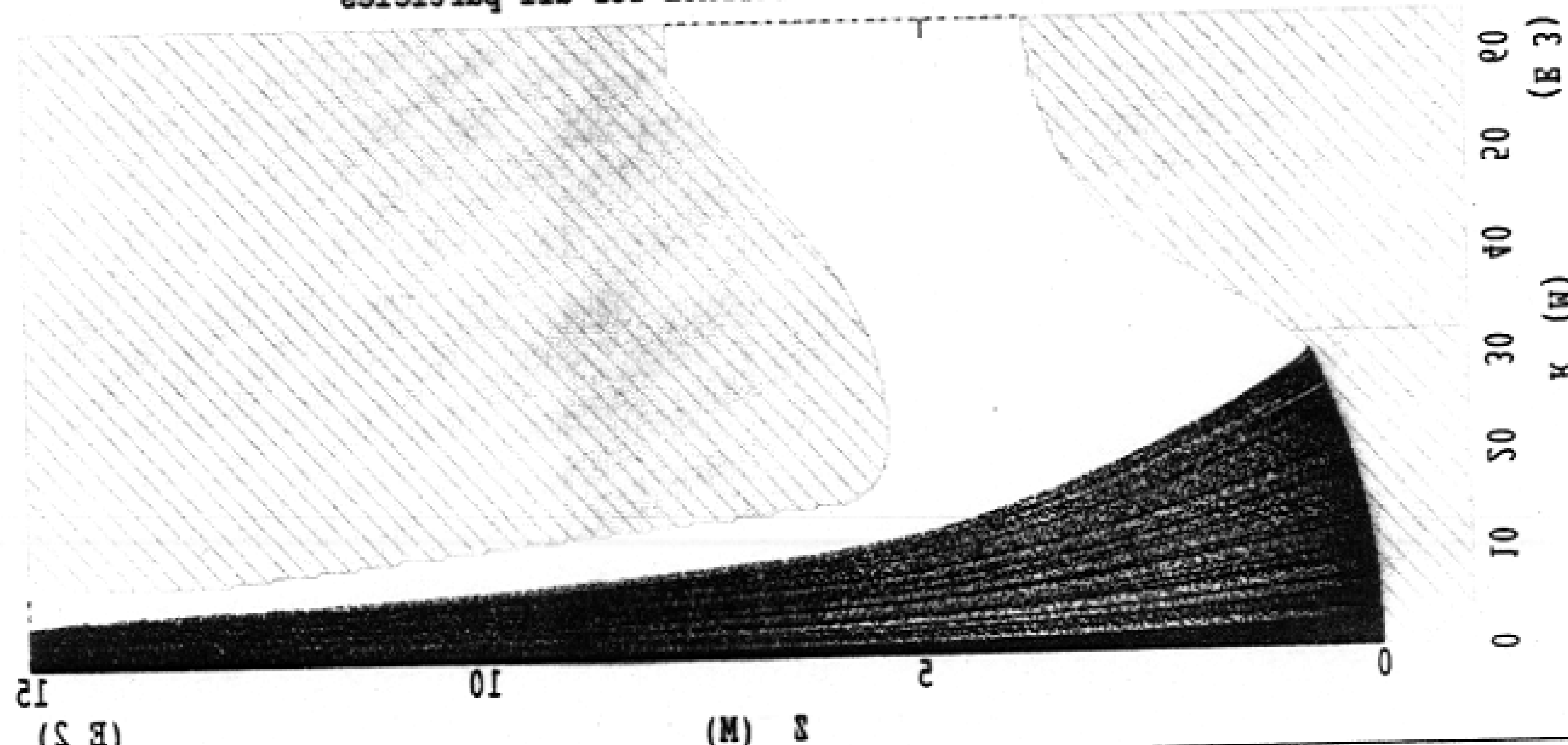


MAGIC Results



Beam voltage=490KV, Beam current=275A
Drive power=300Watts,
Output power=84MW, Efficiency=62.7%

Time 13.980 ns: PHASESPACE for all particles

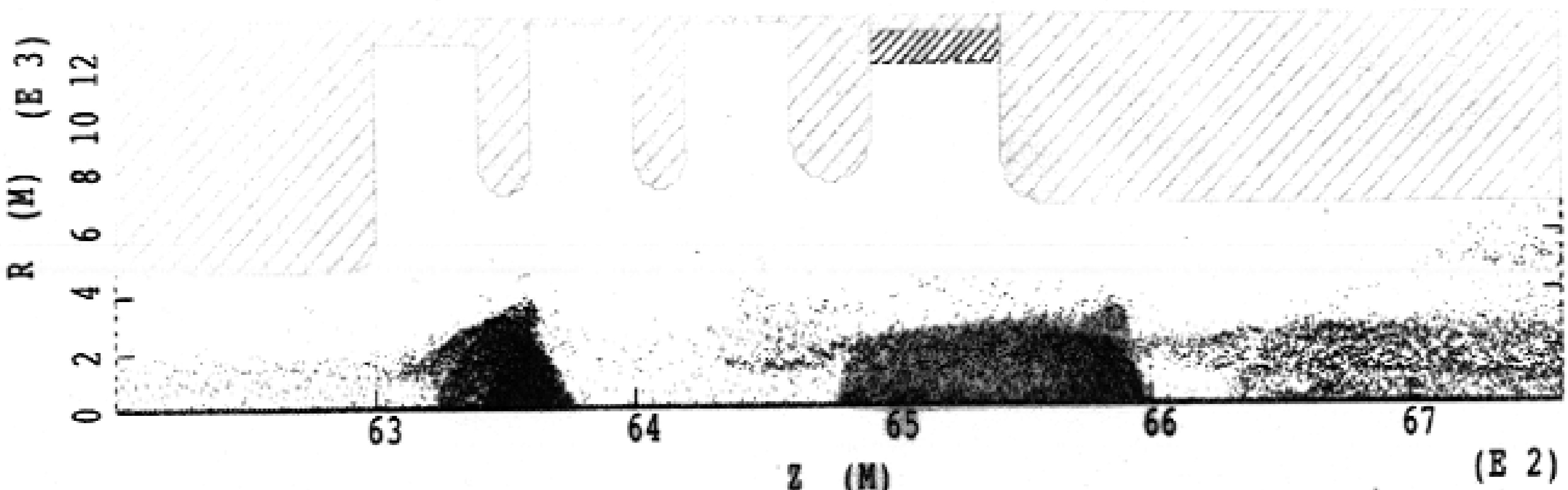


PHASESPACE Plot 1
Remarks: Fine Mesh to z 24mm. Ideal Pierce Gun
Mag Larionov/ 3900AT /300A, Bc 14.5Gs.

Device: T ppm X band Klystro
Run No: *
File: Tx.mgc
Author: S.M.
Organization: KEK

MAGIC2D Version: March 1999 Date: Sep 02,1999 Time: 13:04 Page: 16

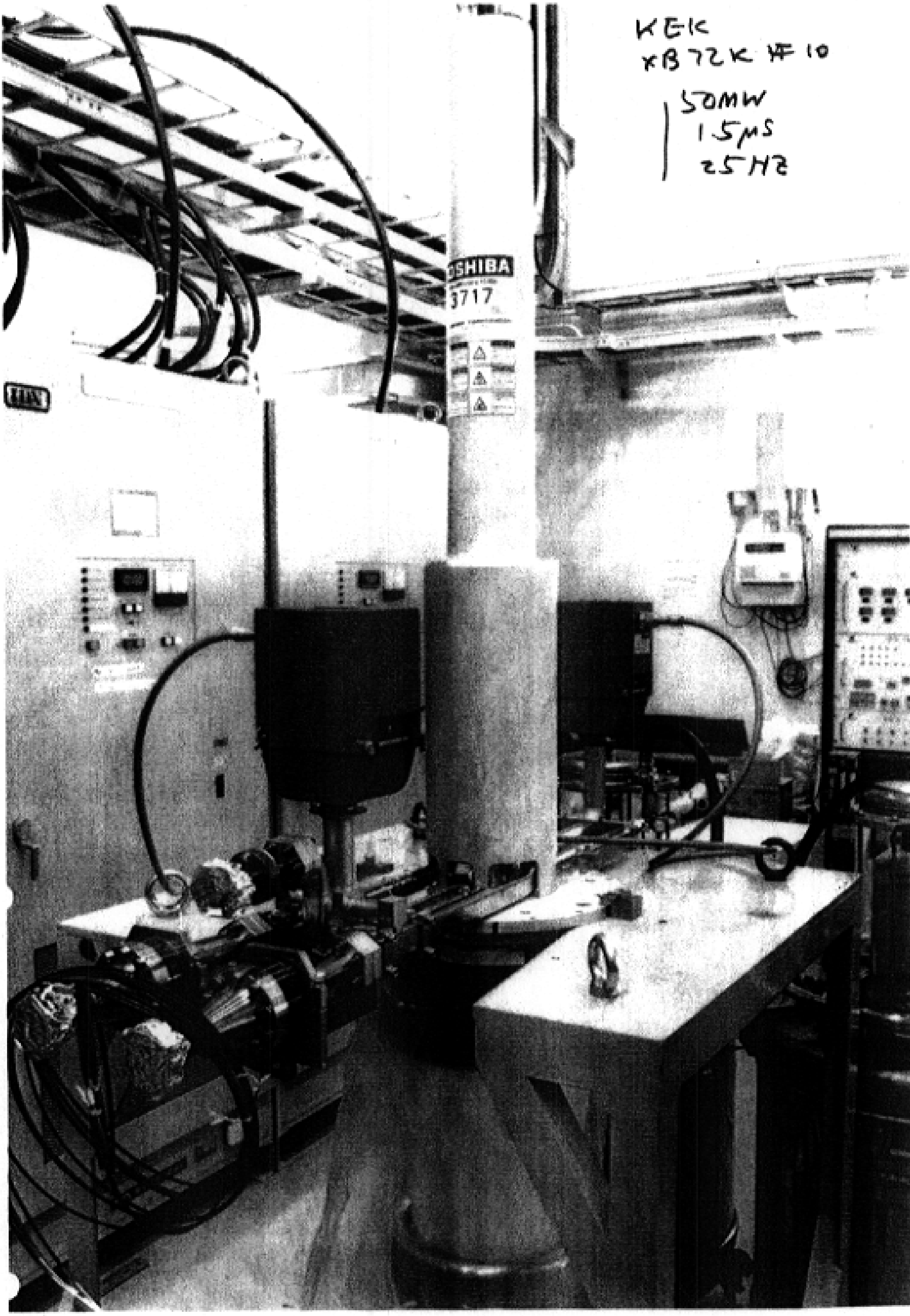
Time 8.754 ns: PHASESPACE for all particles



HASESPACE Plot 1 emarks: XO#105 |s11|=0.8,arg(s11)=71.72deg.	Device: Toshiba ppm Run No: 1 File: xo106.mgc Author: H. Tsutsui/ S.M. Organization: KEK

AGIC2D Version: March 1999 Date: Sep 21,1999 Time: 21:48 Page: 40

KEK
XB72K #10
50MW
1.5μs
25Hz



Technology Development – RF Power Distribution

200 DLDS "Ensembles" per Linac @ E_{cm} = 500 GeV

- What do we need?

  Design and demonstrate DLDS (Delay-Line Distribution System).

  Several design variants are possible. The first task was to see if we can/should continue pursuing what we-call 2x2 DLDS. Three issues need to be looked at.

  1. Feasibility of RF switching components.
  2. Transport of X-band RF through delay lines.
  3. Check-out of the two subjects above in low-power and high-power RF testing

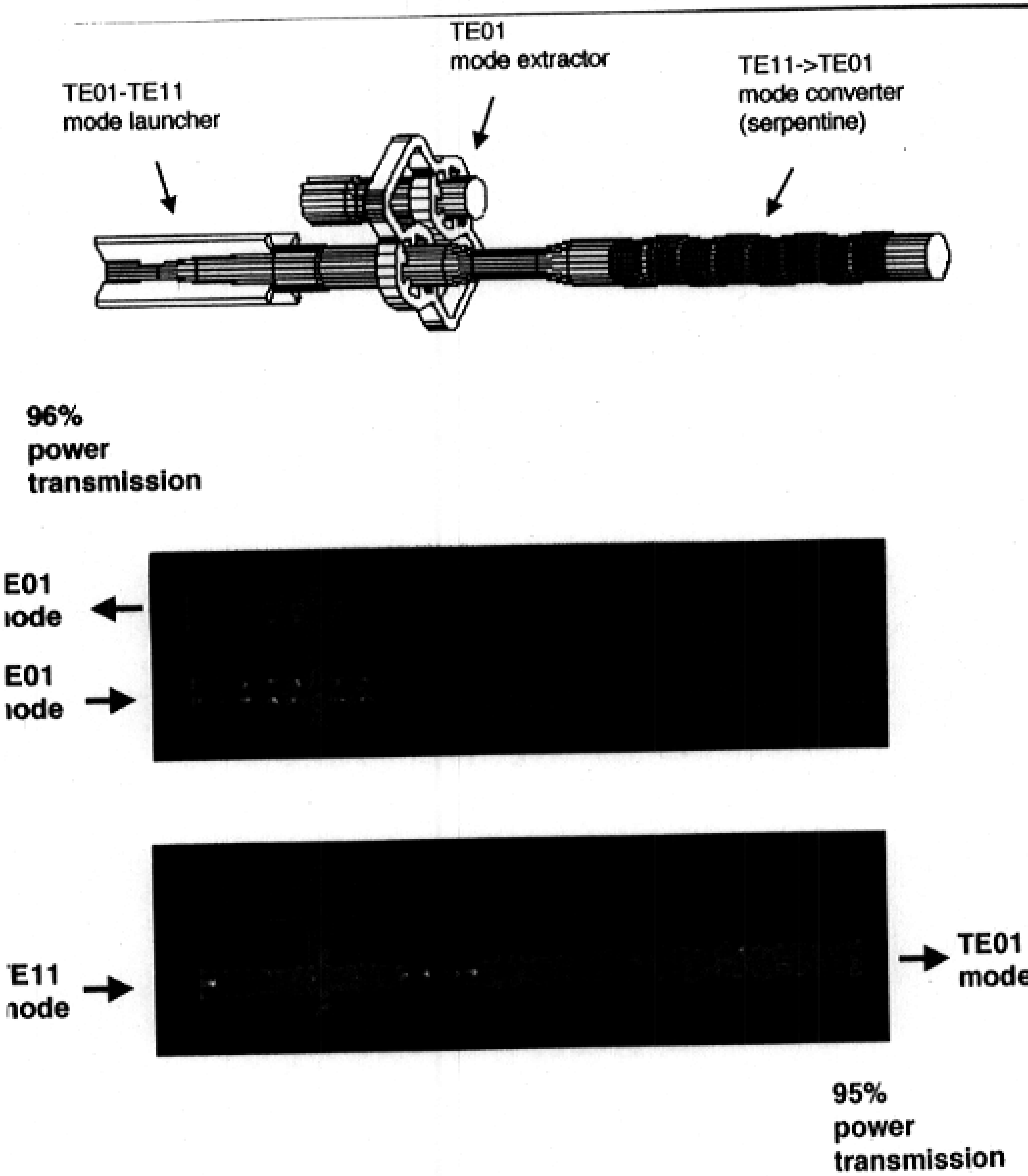
- Where are we?

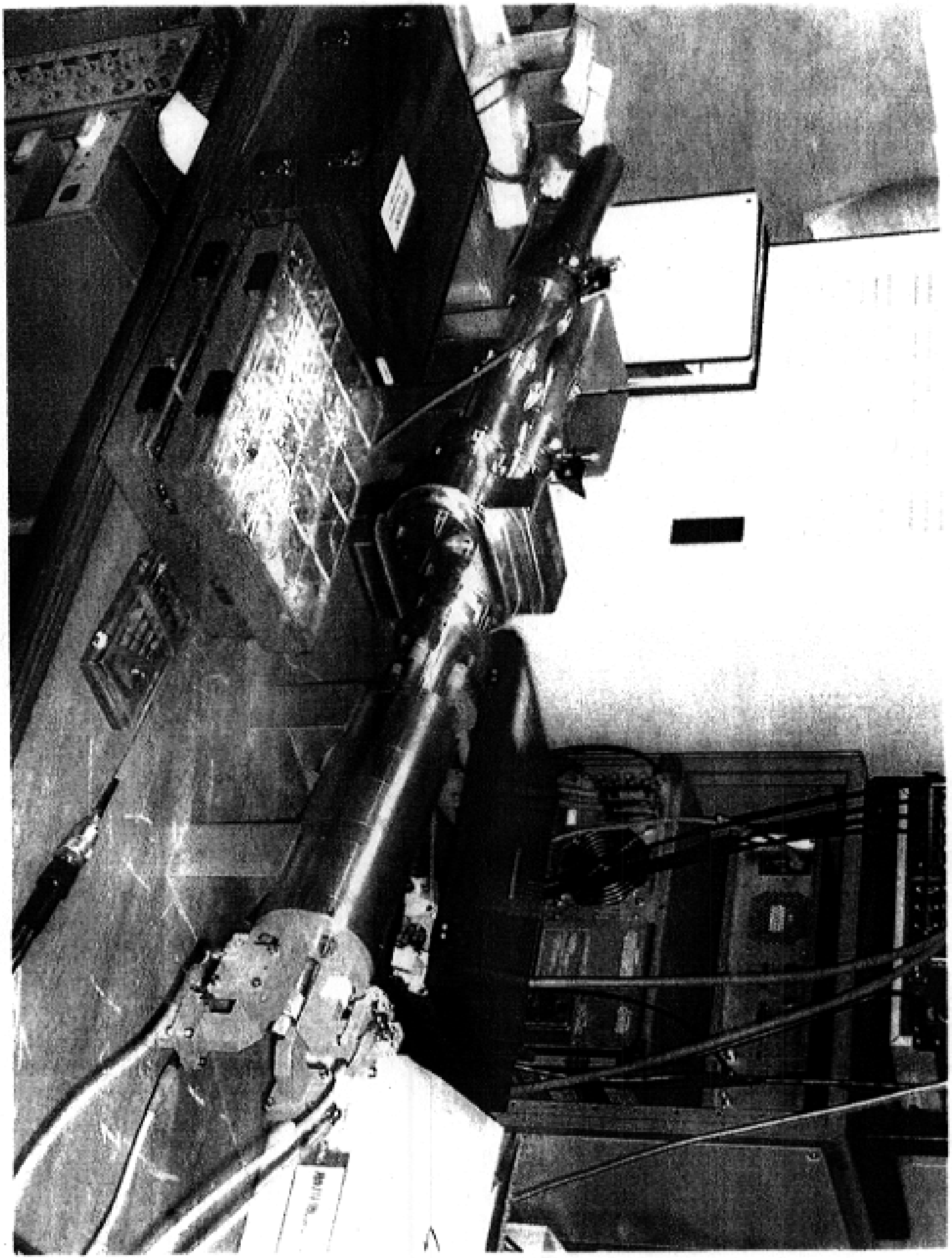
  Low-power testing of RF switching components showed satisfactory results.

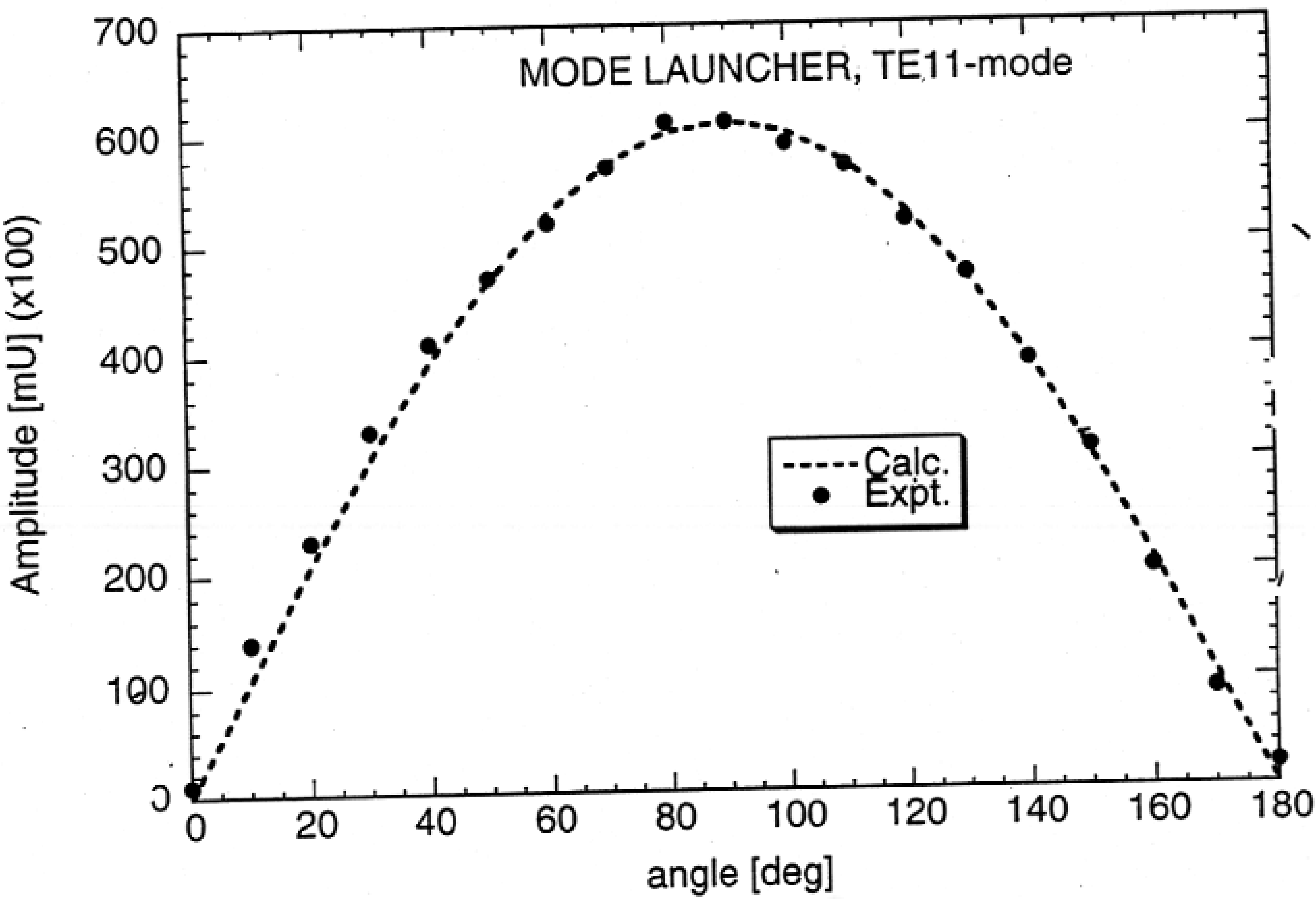
  Low-power testing of X-band RF transport (TE12-mode over 55 m) showed no traces of mode degredation / mixing / rotation.

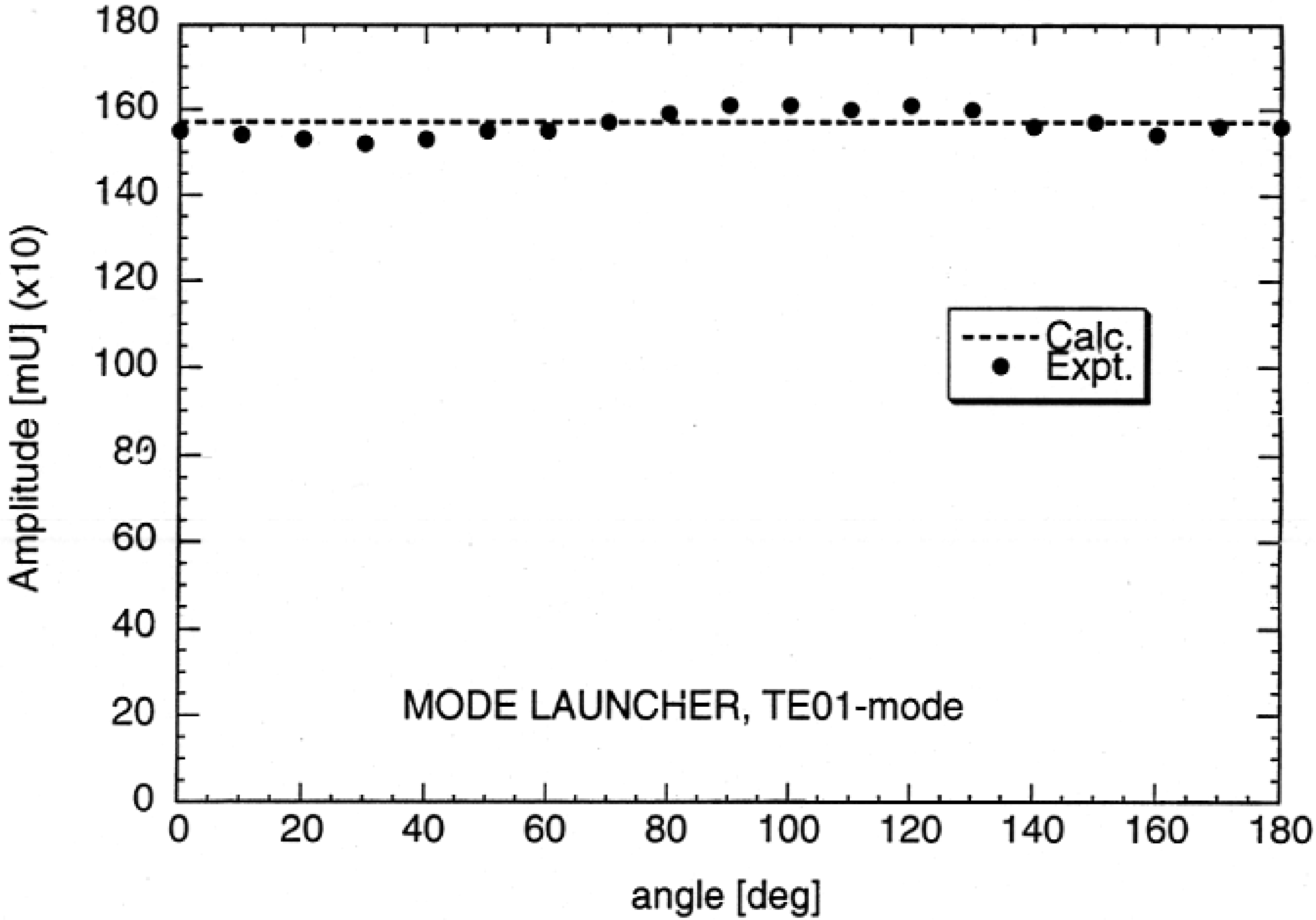
  So we intend to move on to high-power RF component design and testing in yr 2000.

− 30 dB admixture
< 1° TE12 rotation

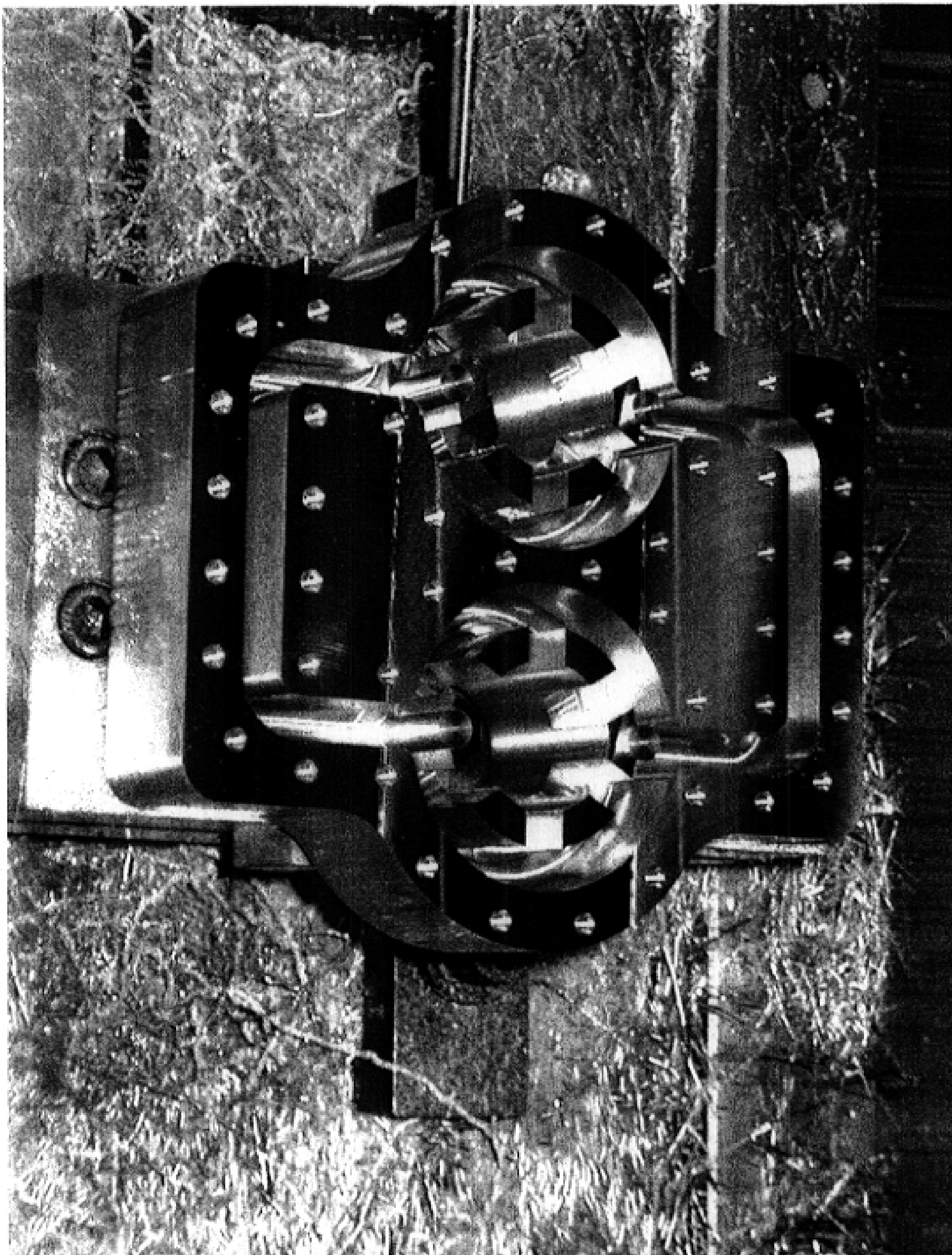

TE01
mode extractor
TE01-TE11
mode launcher
TE11->TE01
mode converter
(serpentine)
96%
power
transmission
E01
ıode
E01
ıode
'E11
ıode
TE01
mode
95%
power
transmission

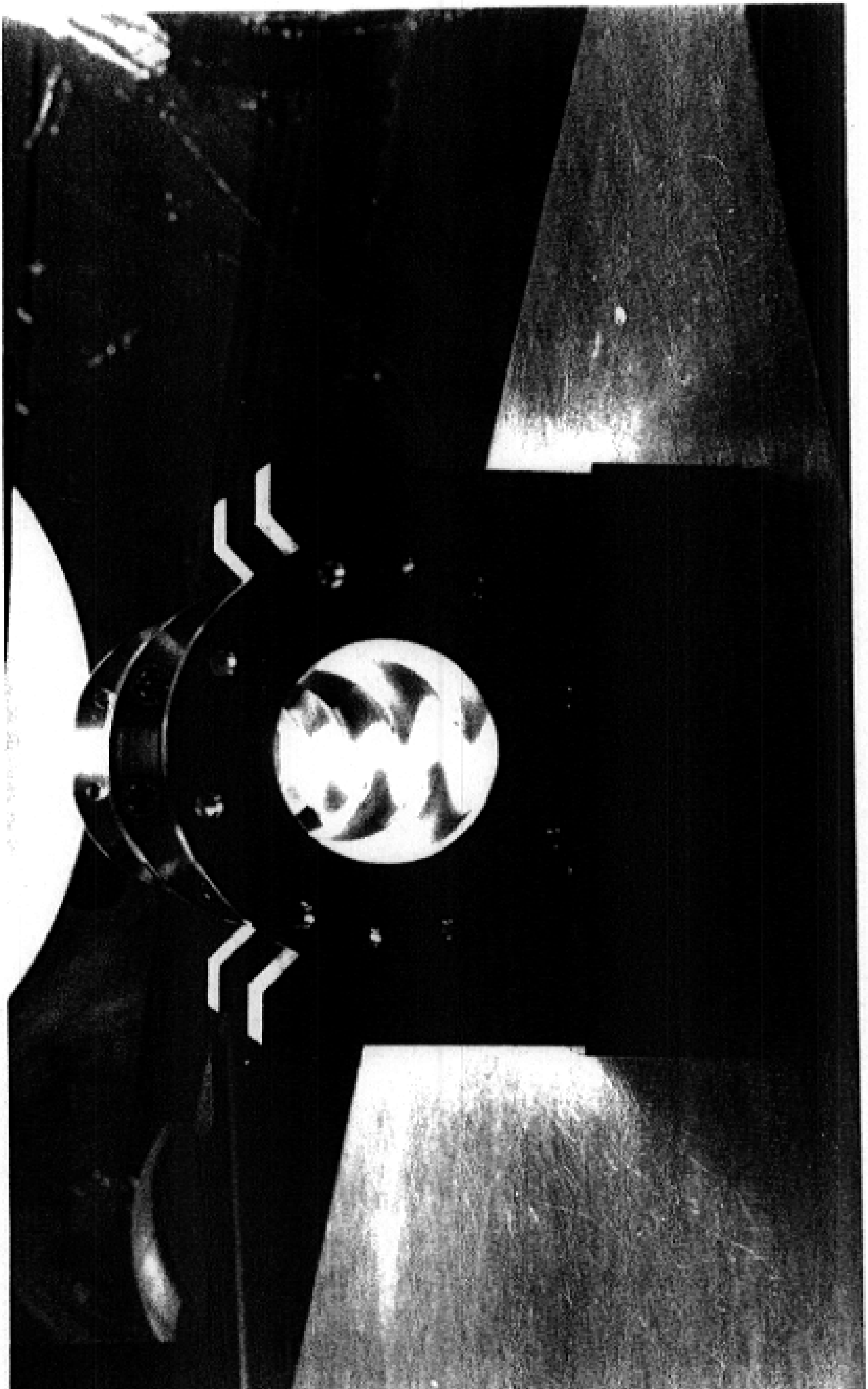


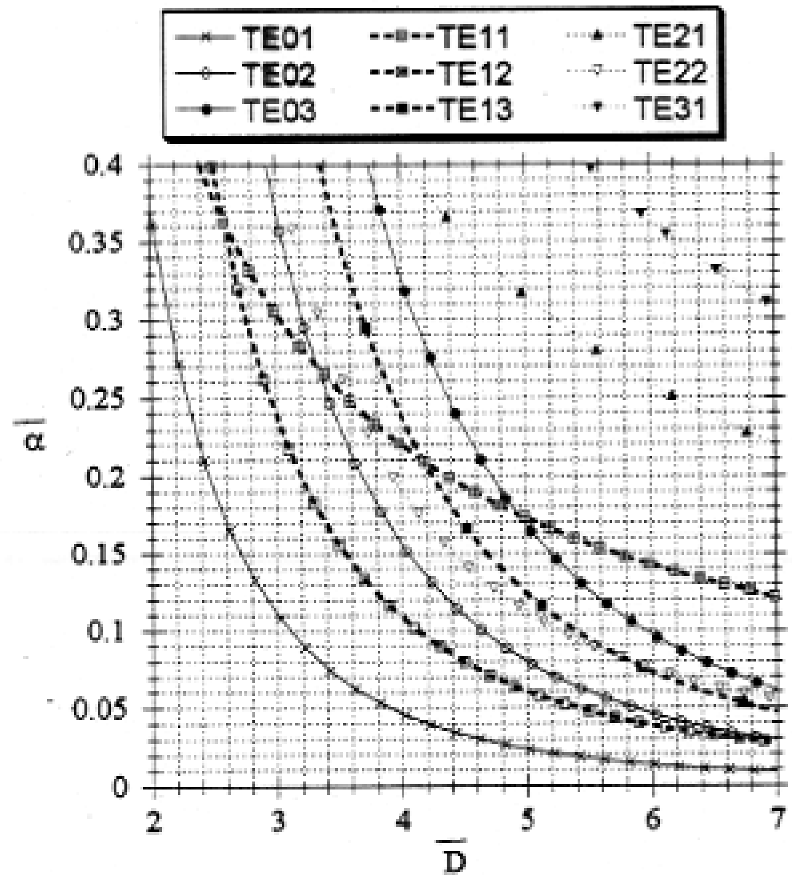

MODE LAUNCHER, TE11-mode
Amplitude [mU] (x100)
angle [deg]
Calc.
Expt.
0
100
200
300
400
500
600
700
0
20
40
60
80
100
120
140
160
180



Amplitude [mU] (x10)
angle [deg]
Calc.
Expt.
MODE LAUNCHER, TE01-mode

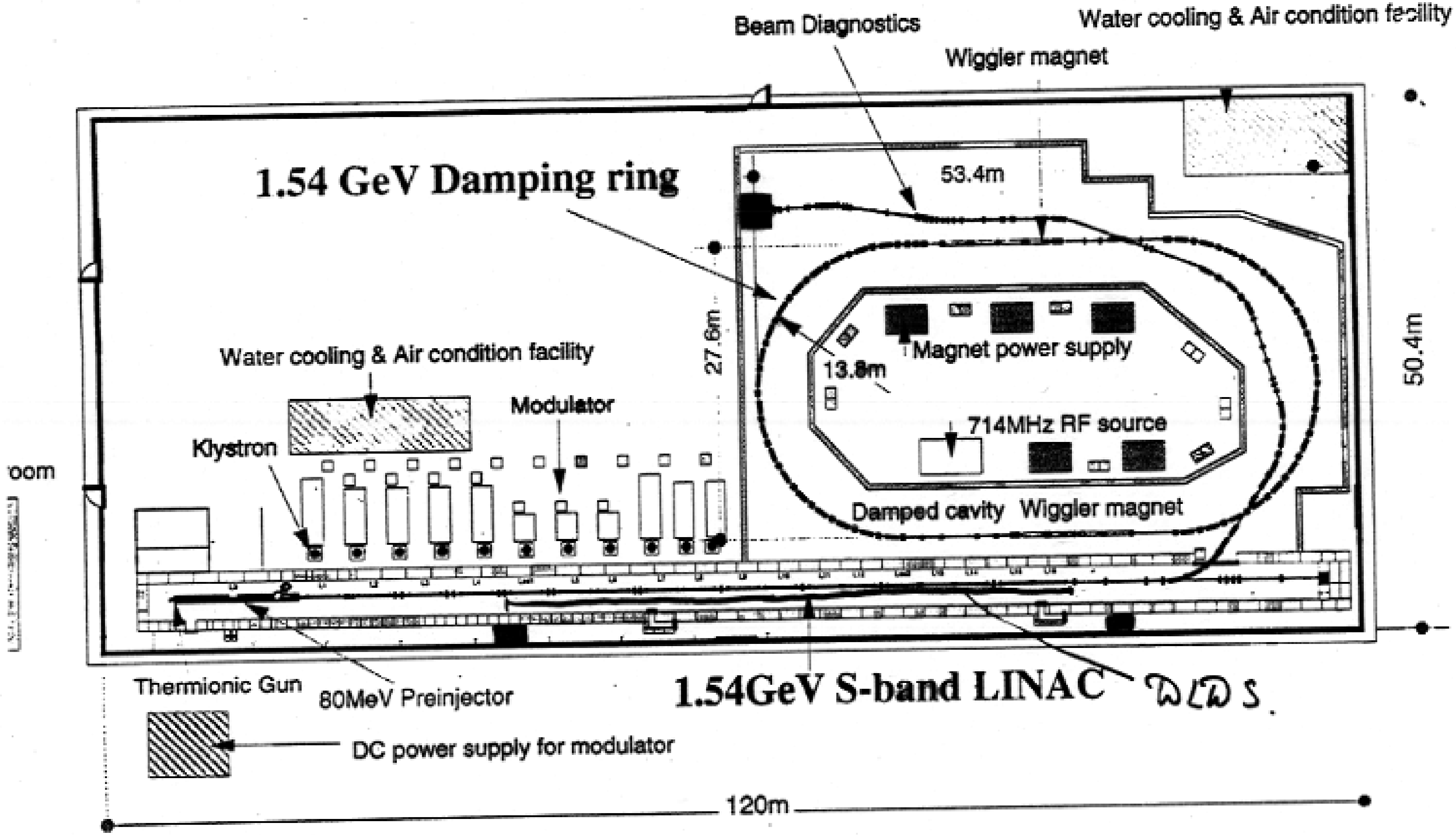


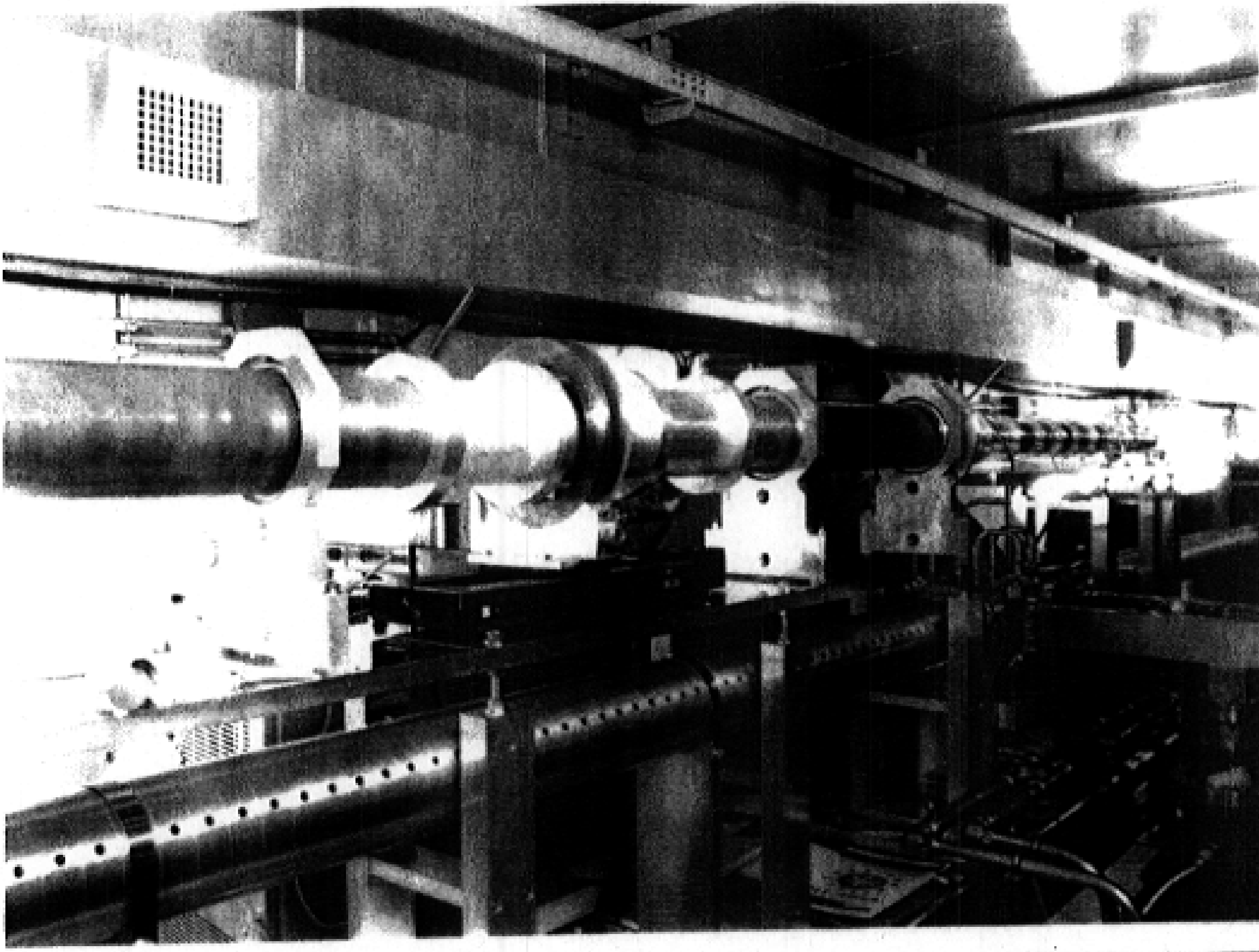


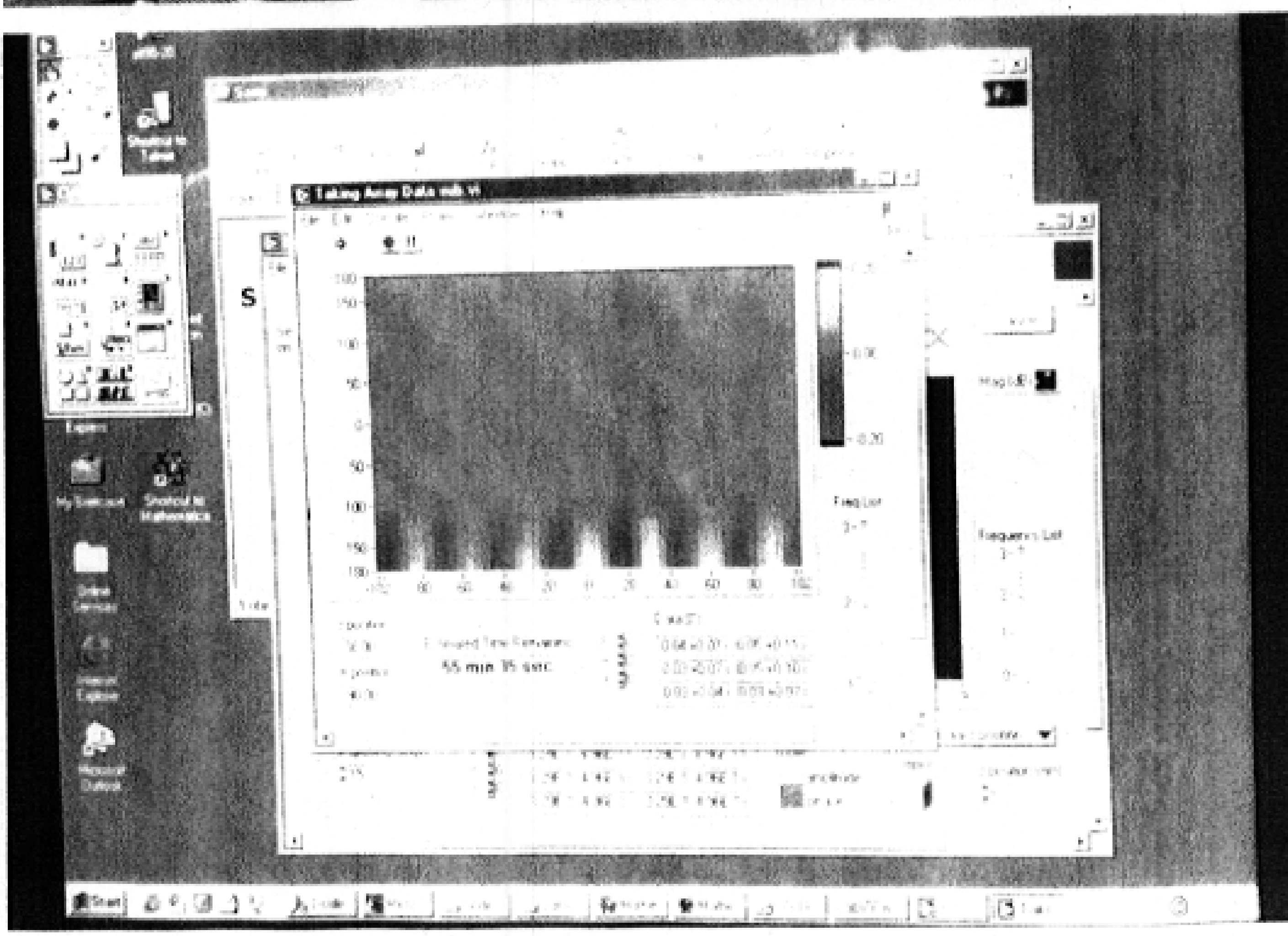


Relative attenuation of different modes per unit time in circular waveguide versus the normalized diameter of the waveguide.

Accelerator Test Facility for JLC







Technology Development – Accelerating Structure

2400 units / linac
@ E_{CM} = 500 GeV

■ What do we need?

$a/\lambda = 0.18$

2/3-π mode, damped-detuned structure with rounded corners. 1.8m-long., which can take 70MV/m if not loaded with beam.

Reduction of wakefield in the multi-bunch environment has to give

Wake amplitude < 1 V / pC / m / mm

Which means,

Disk fabrication tolerance < O(μm)
Disk assembly tolerance < O(a few ~ 10 μm) for smoothness
Structure alignment tolerance < O(a few 10μm)

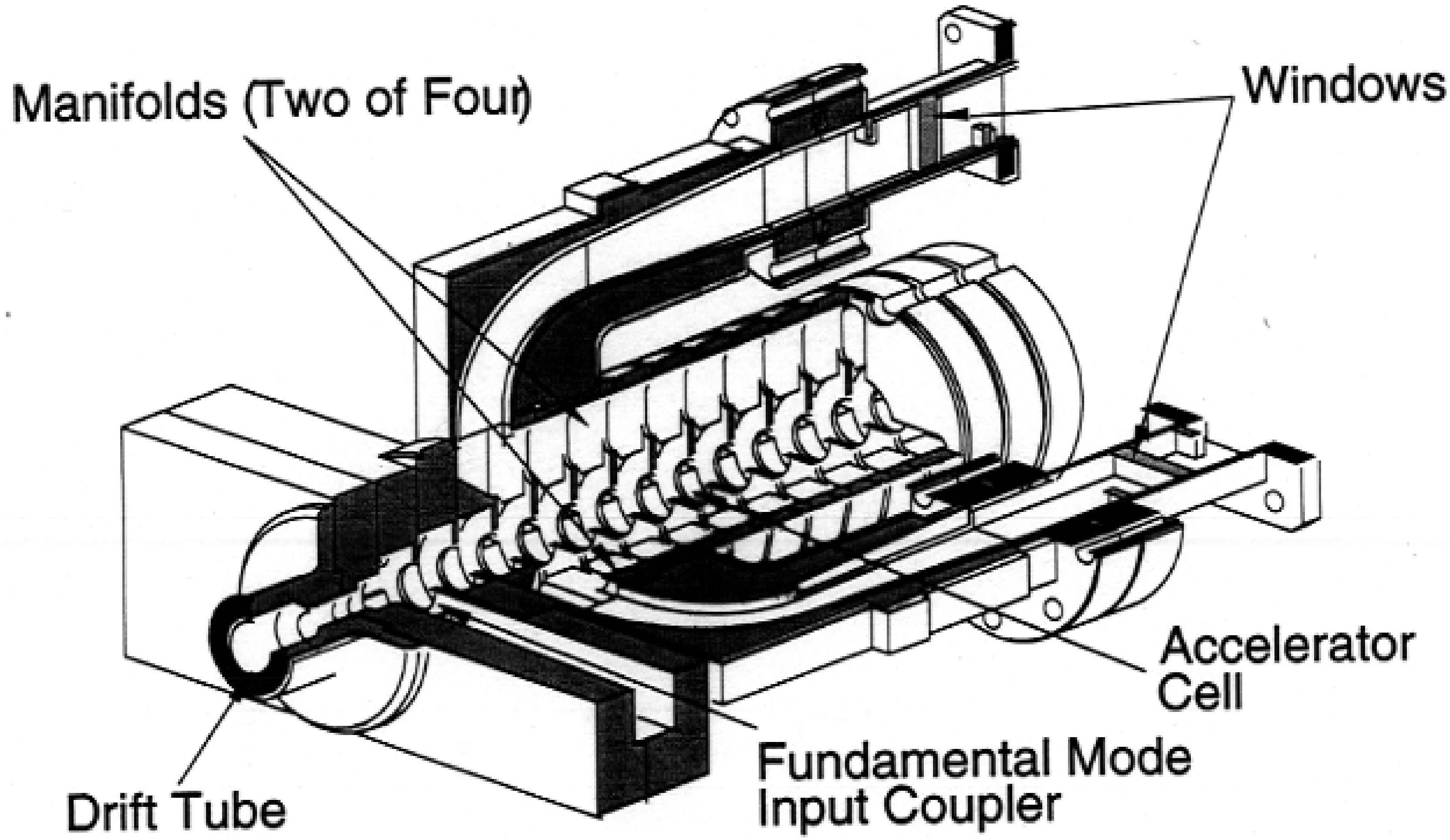
■ Where are we?

Experiences of several successful structure prototypes in the past. Without rounded-corners, we saw good calc-exp agreement on wake damping, HOM signal at ASSET experiments (SLAC).

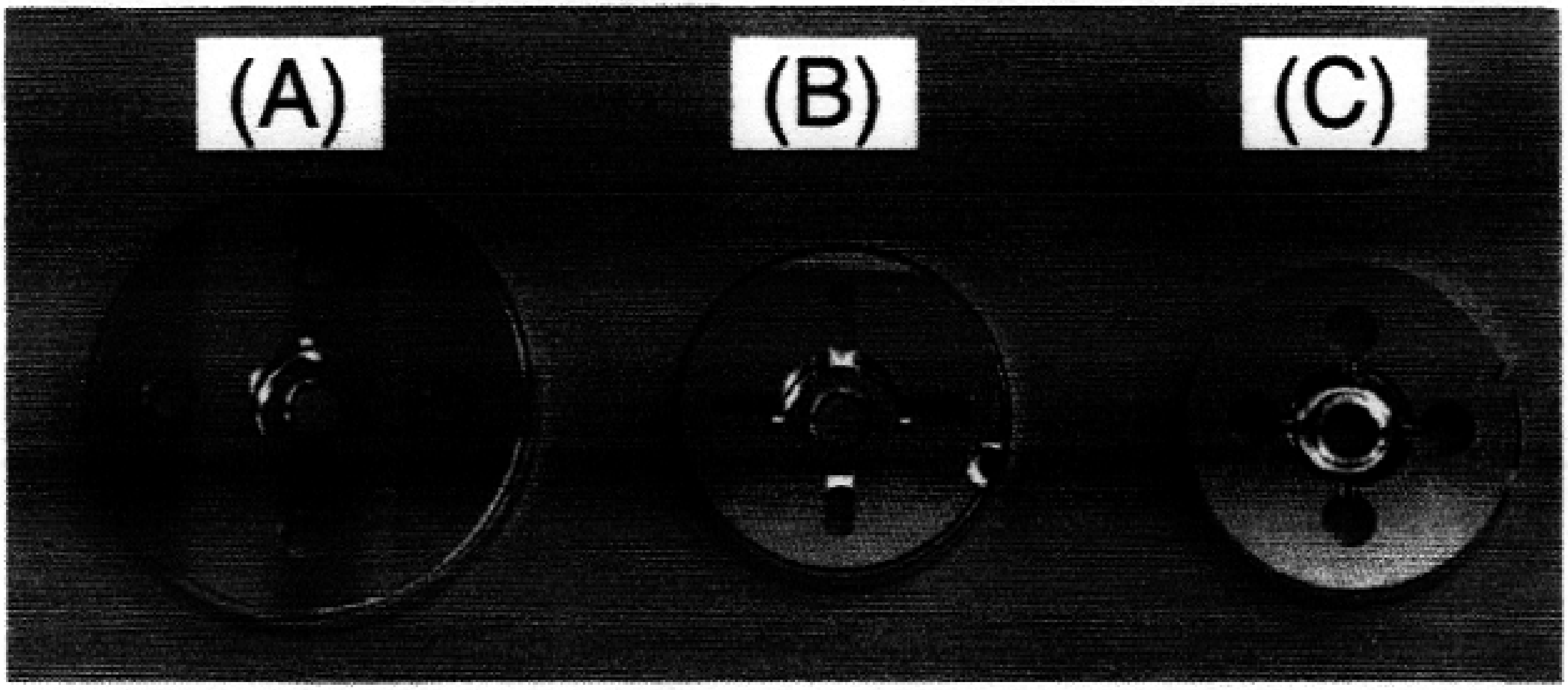
RF processing of a prototype structure (1.3m-long) up to 85MV/m has been successful, though we need more studies.

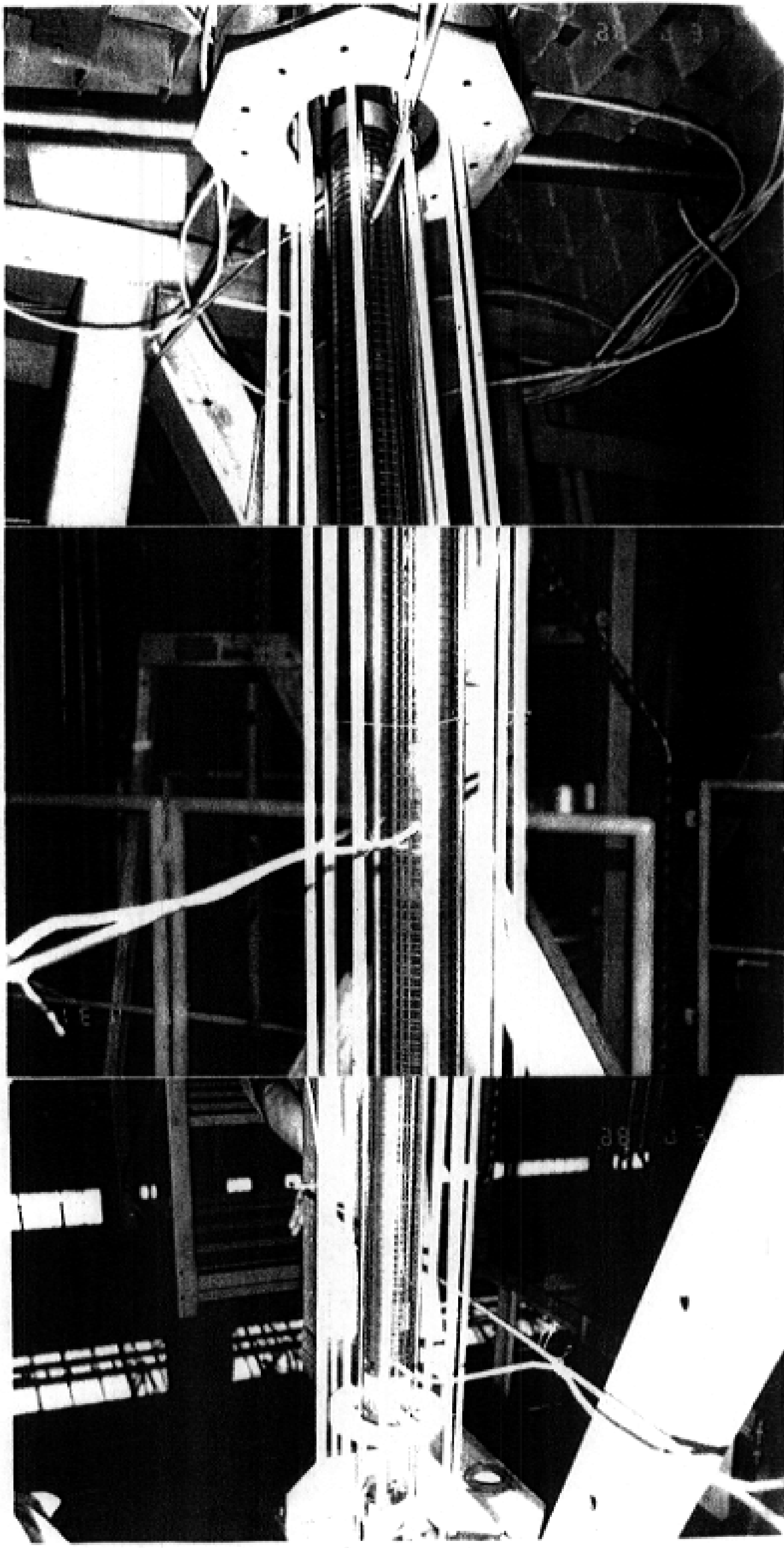
Electrical design of first RDDS prototype well at hand.

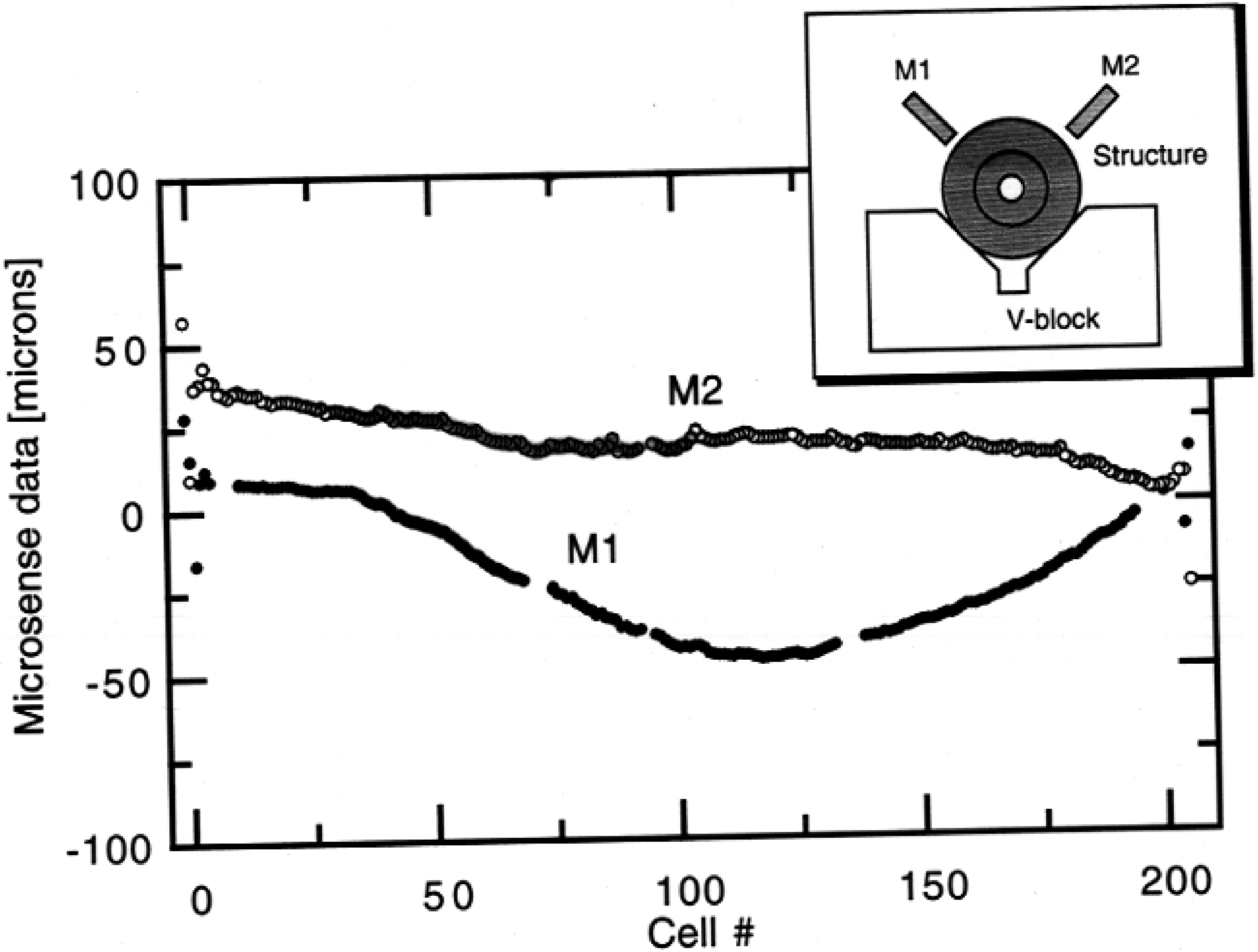
Fab and assembly technologies for DDS/RDDS are in good control at lab level, while their industrialization is a big subject yet to be fully established.



Cutaway view of the upstream end of DDS3.

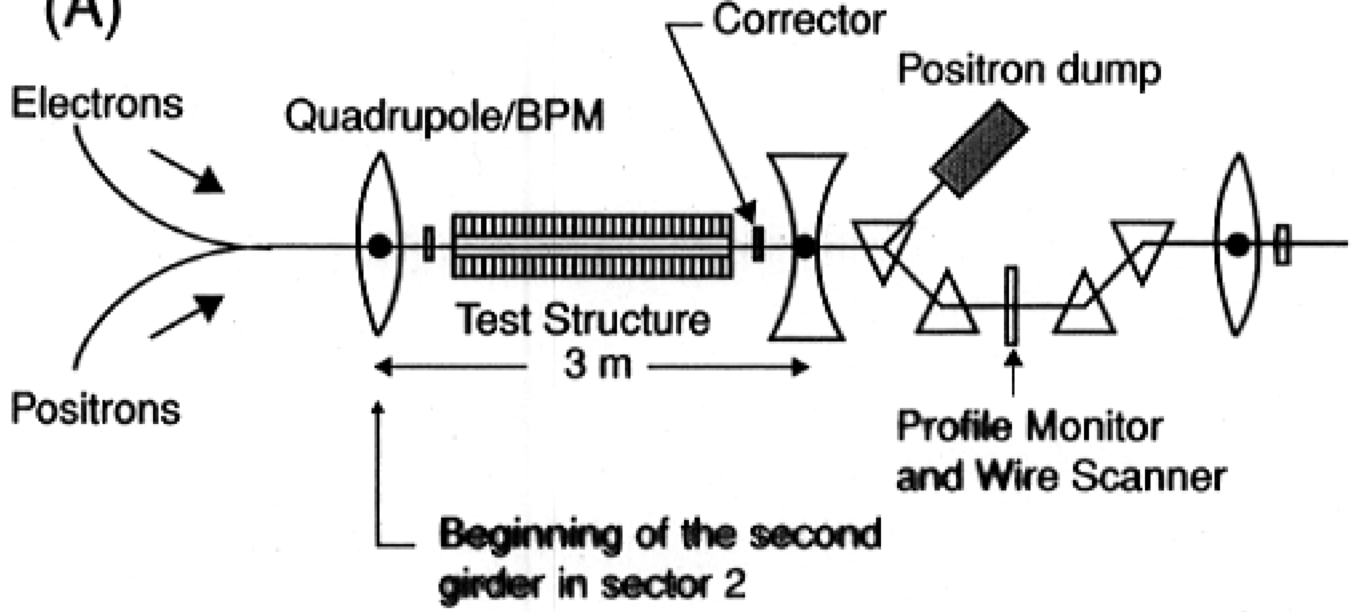

(A)
(B)
(C)




M1
M2
Structure
V-block
Microsense data [microns]
100
50
0
-50
-100
0
50
100
150
200
Cell #

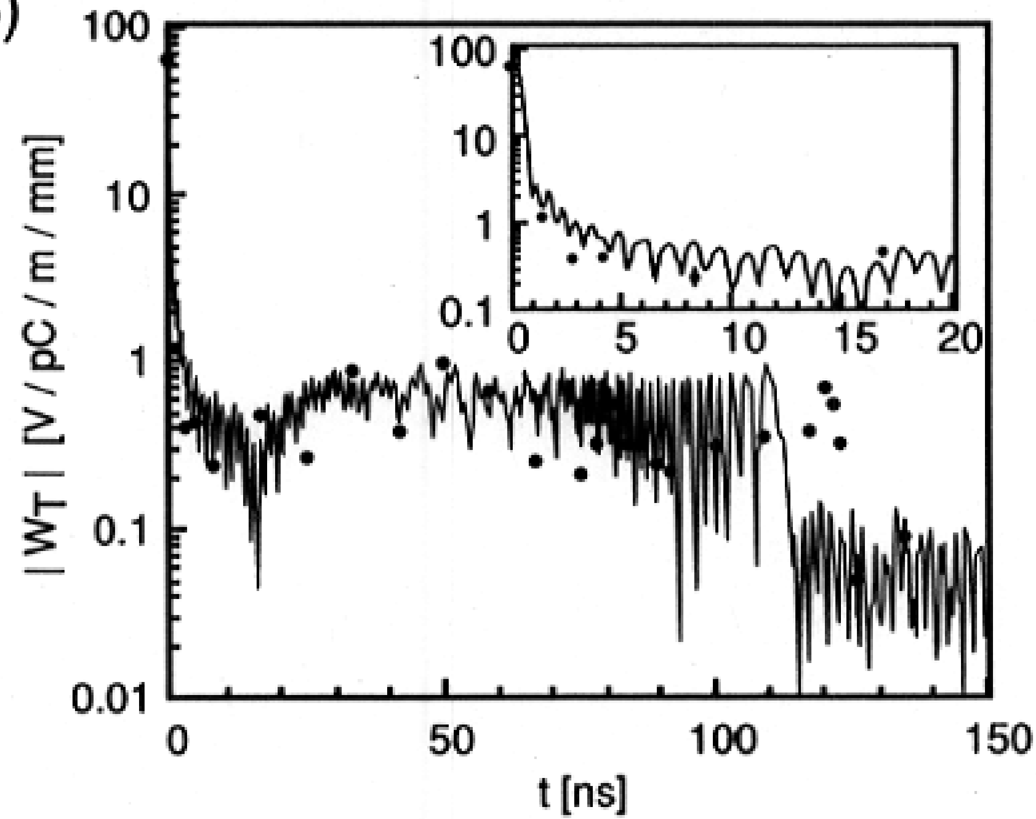
ASSET (SLAC)

(A)



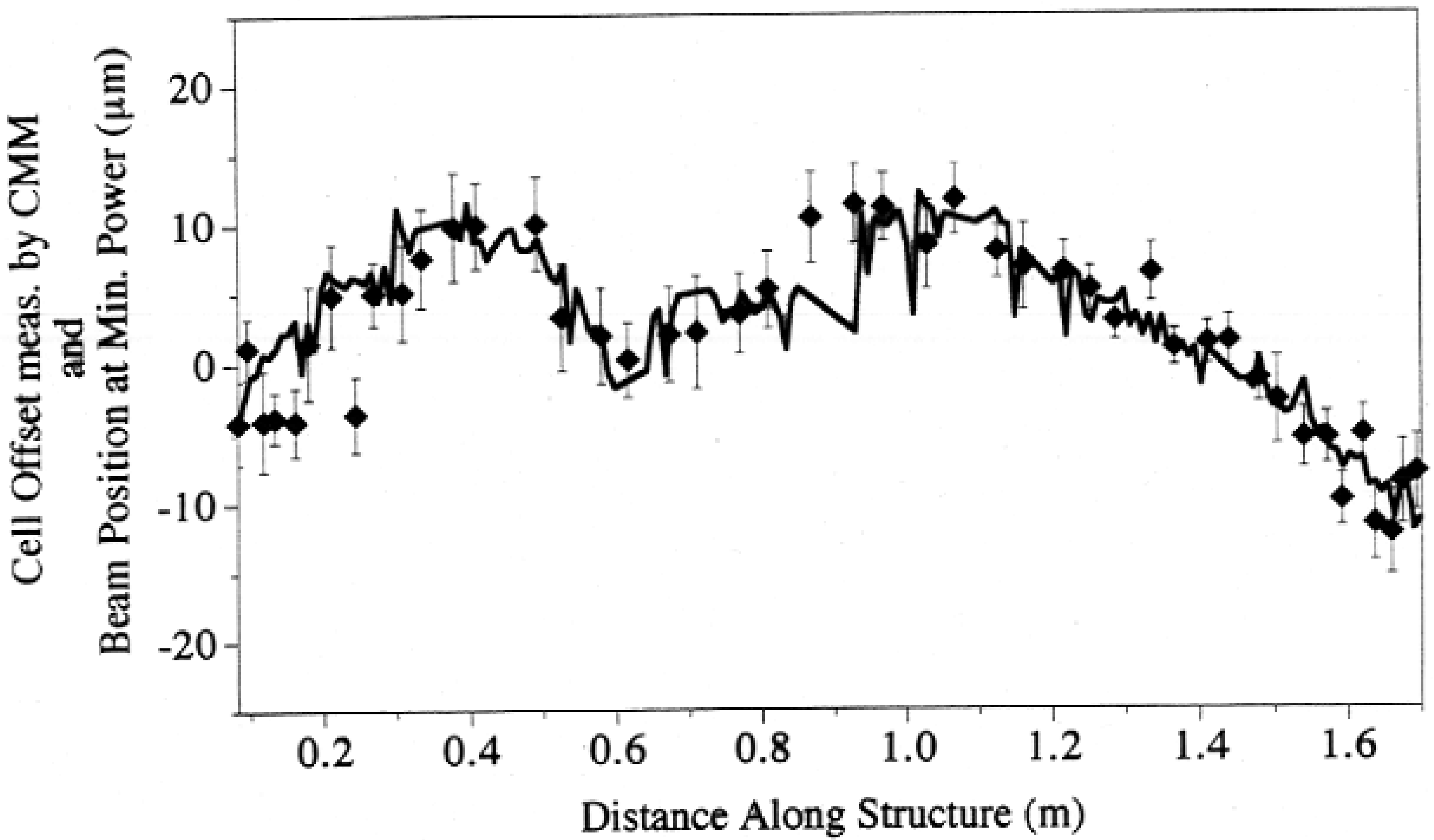
DDS-1

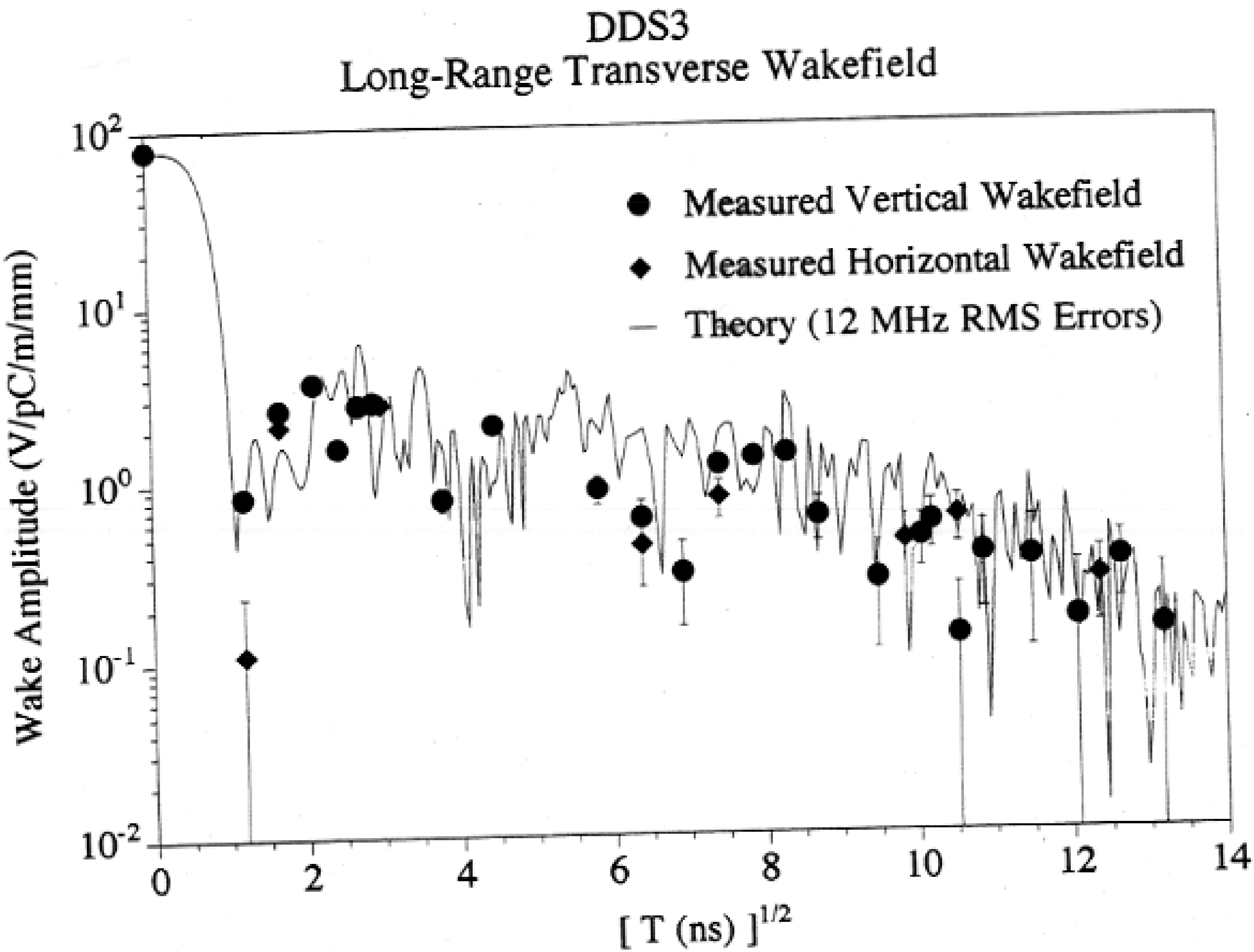
(B)

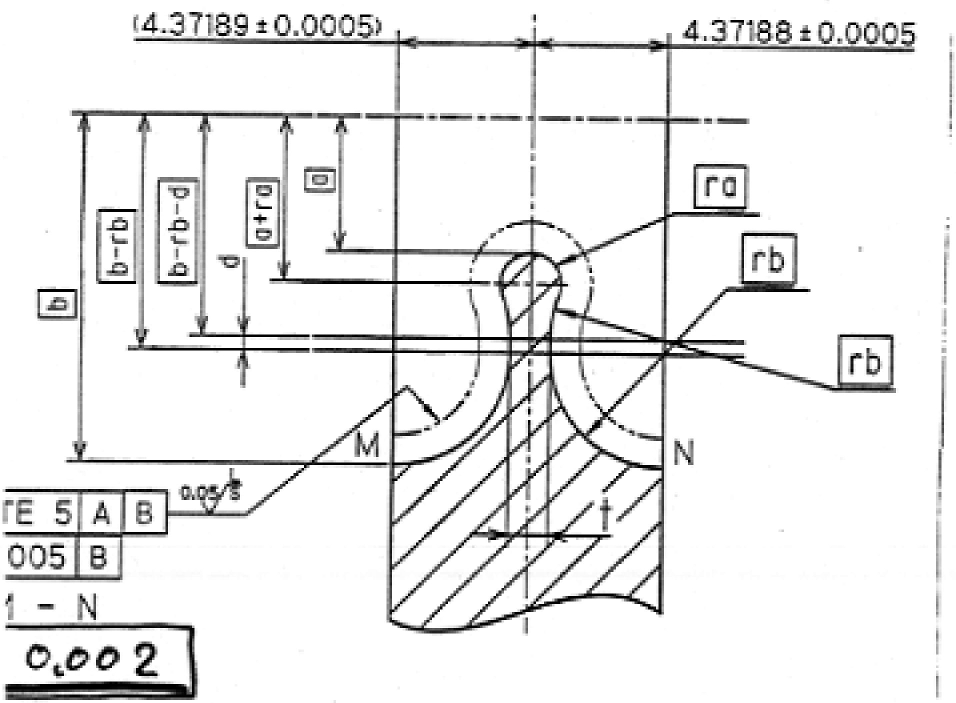


DDS3 Structure Straightness

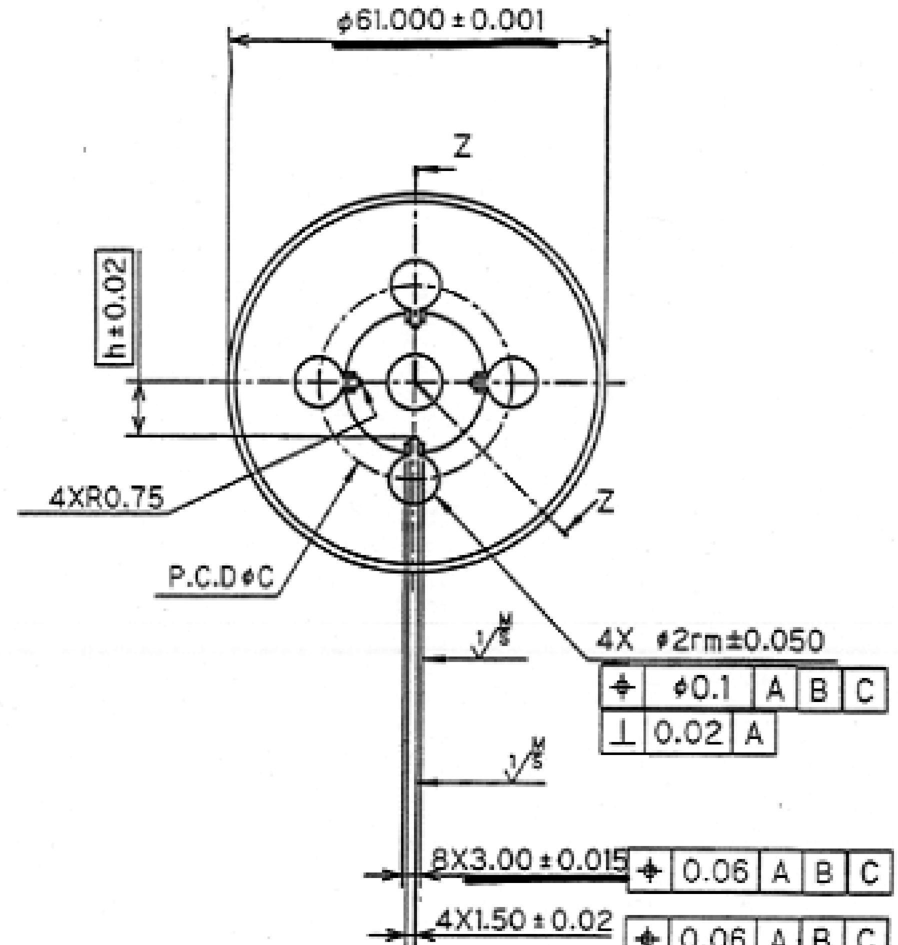
Horizontal CMM Data (Solid Line) and Beam X Positions at Minimum Dipole Signal Power (Diamonds)



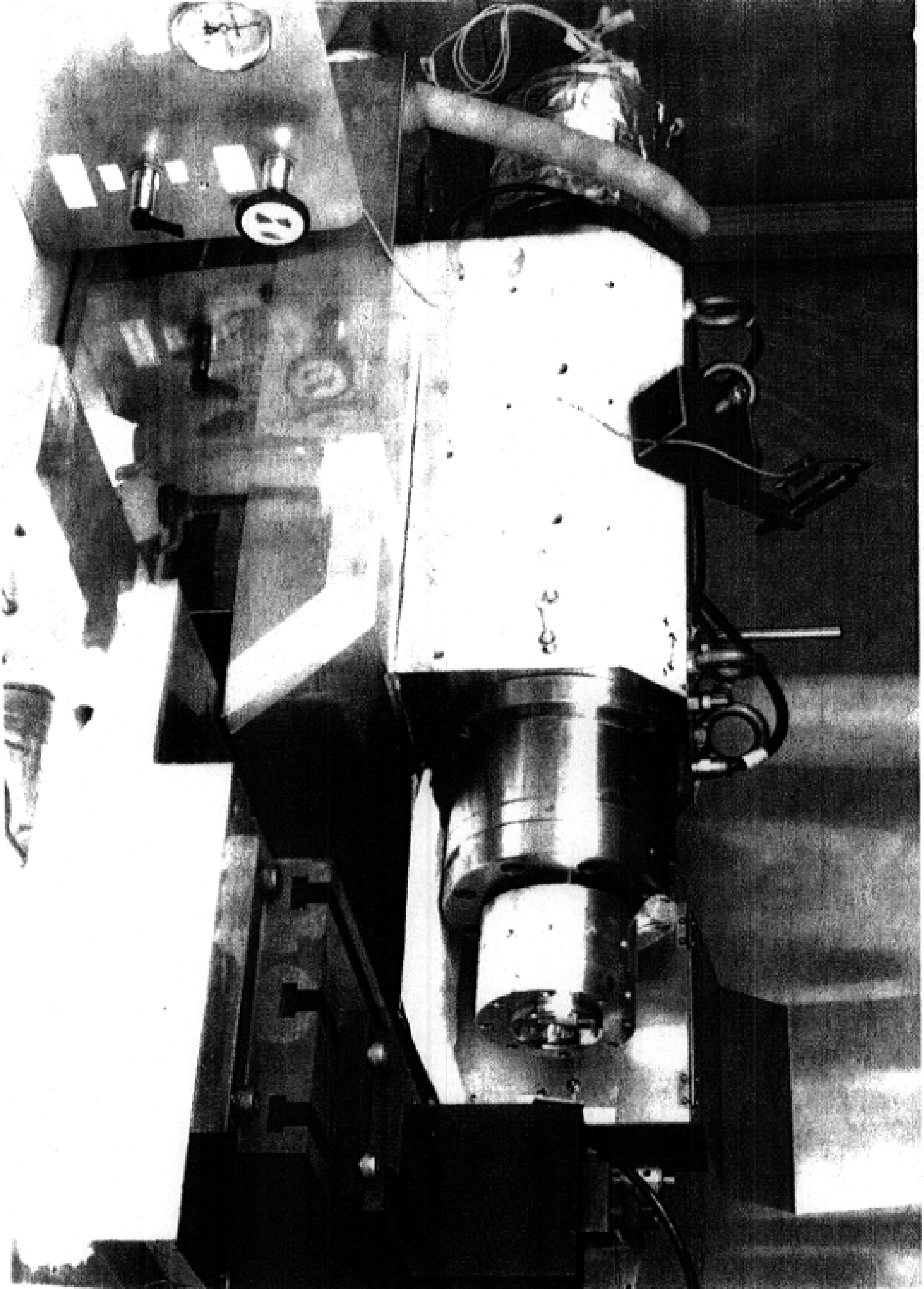

DDS3
Long-Range Transverse Wakefield
Measured Vertical Wakefield
Measured Horizontal Wakefield
Theory (12 MHz RMS Errors)
Wake Amplitude (V/pC/m/mm)
10^2
10^1
10^0
10^{-1}
10^{-2}
0
2
4
6
8
10
12
14
$[\,T\,(ns)\,]^{1/2}$

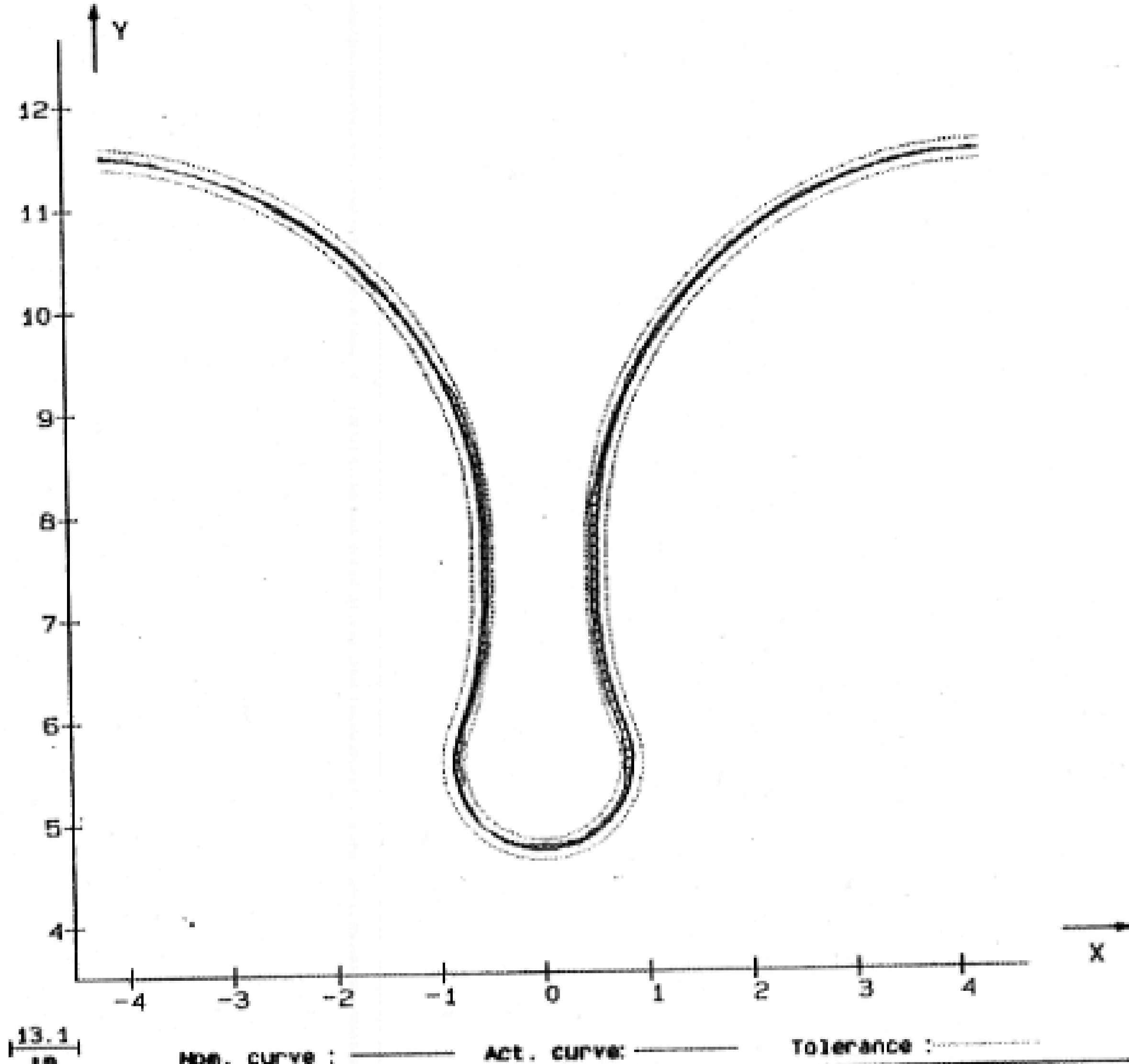


(4.37189 ± 0.0005)
4.37188 ± 0.0005
b
b-rb
b-rb-d
d
a+ra
a
ra
rb
rb
M
N
t
0.05
TE 5 A B
005 B
1 - N
0.002



ϕ61.000 ± 0.001
Z
Z
h ± 0.02
4XR0.75
P.C.Dϕ C
4X ϕ2rm±0.050
ϕ0.1 A B C
⊥ 0.02 A
8X3.00 ± 0.015
0.06 A B C
4X1.50 ± 0.02
0.06 A B C





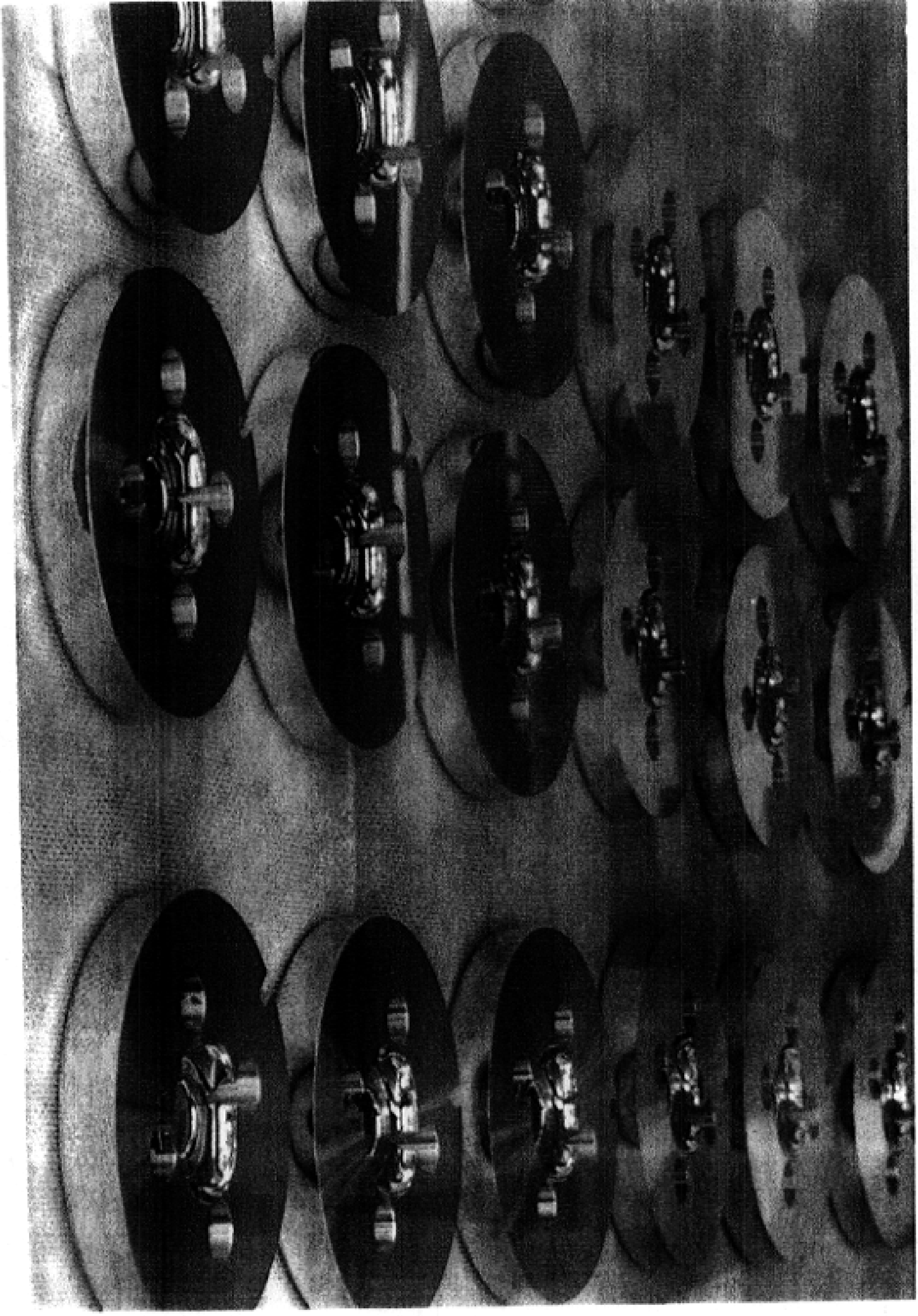
Dscrption:
Ser. No. :
Customer :

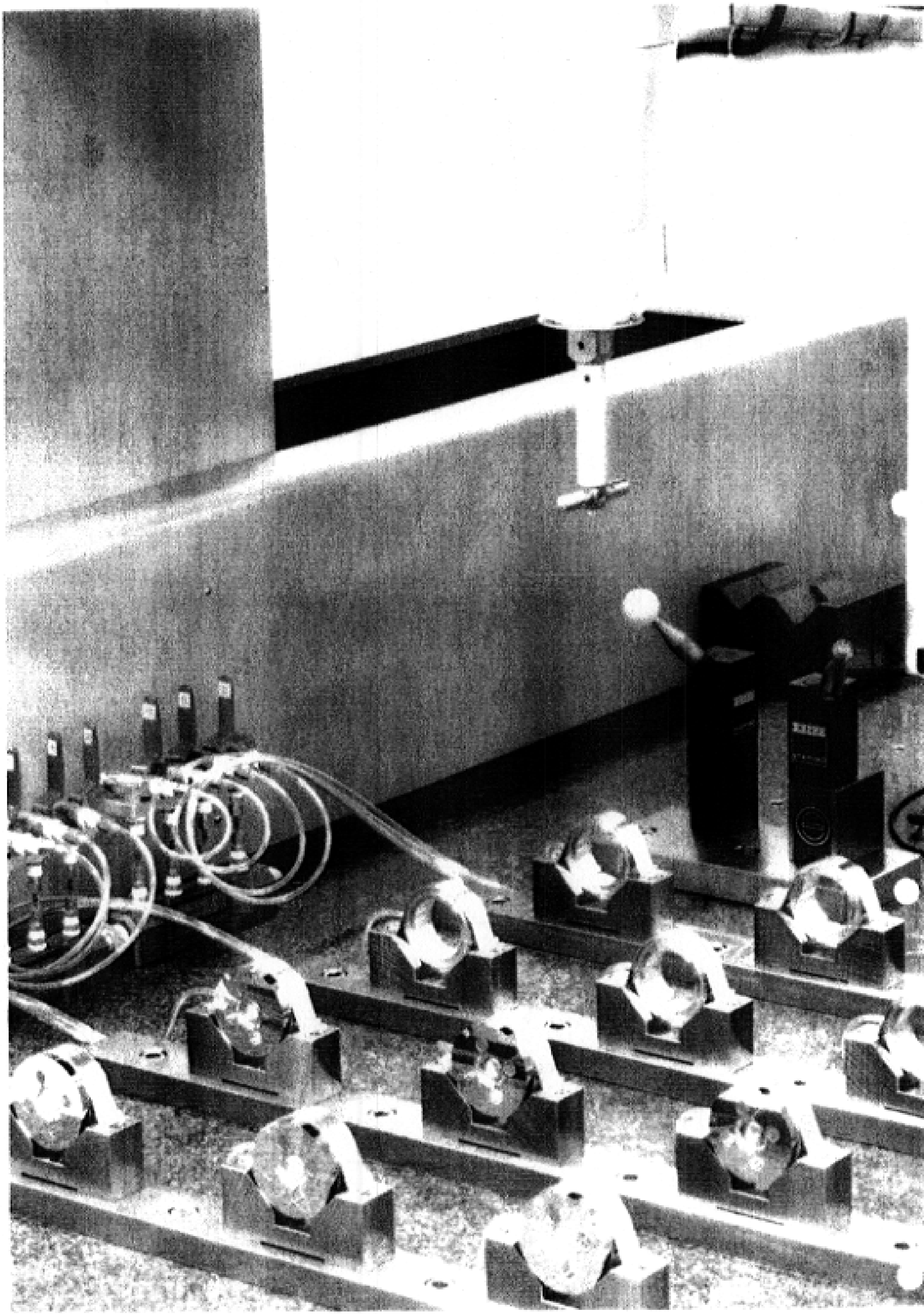
File No. :
Draw. No.:

Element : PROFILE_CURV (2)
Department: MET-06Q

			X	Y	Z	Nr.
Form ....: 0.00192	Min. Deviat.:	-0.00142	0.858	5.489	0.000	82
Lower Toler. :-0.00200	Max. Deviat.:	0.00050	-2.462	10.983	0.000	170
Upper Toler. : 0.00200						
Error Magnif.: 50						
No. of points: 188						

SLAC MET Inspection Department - 06Q - Established 1962	2D - CONTOUR	Inspector.: Date .....: 12-MAR-98 Time .....: 10:28:45





Other Work Worth Mentioning

- ATF Linac (KEK)

  1.5 GeV S-band linac with ~ 30MV/m gradient as injector for ATF dampring ring prototype.

  Demonstration of beam-loading compensation with Δf scheme.

  ±1.428 MHz out of 2856 MHz

- NLCTA (SLAC)

  Construct and reliably operate an engineered model of a section of the NLC high-gradient X-band linac, as of ZDR design (two-pack klystron drive, XL4, SLED-II, DDS, etc)

  Testing of beam dynamics issues coupled to acceleration.

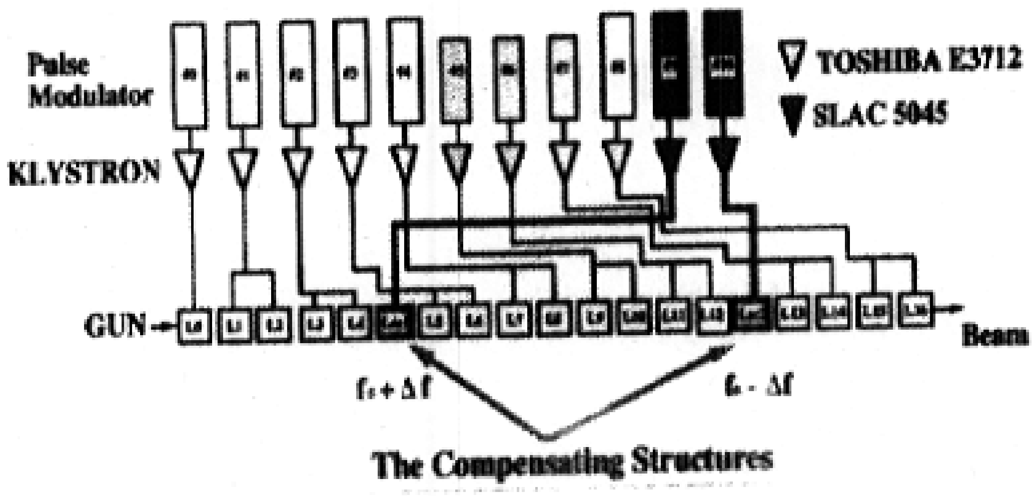
  Successfully conducted beam-loading compensation with phase-amplitude modulation of SLED-II / klystron drives.

Unloaded gradient:	37 - 47 MV/m
%loading:	17 - 14 %

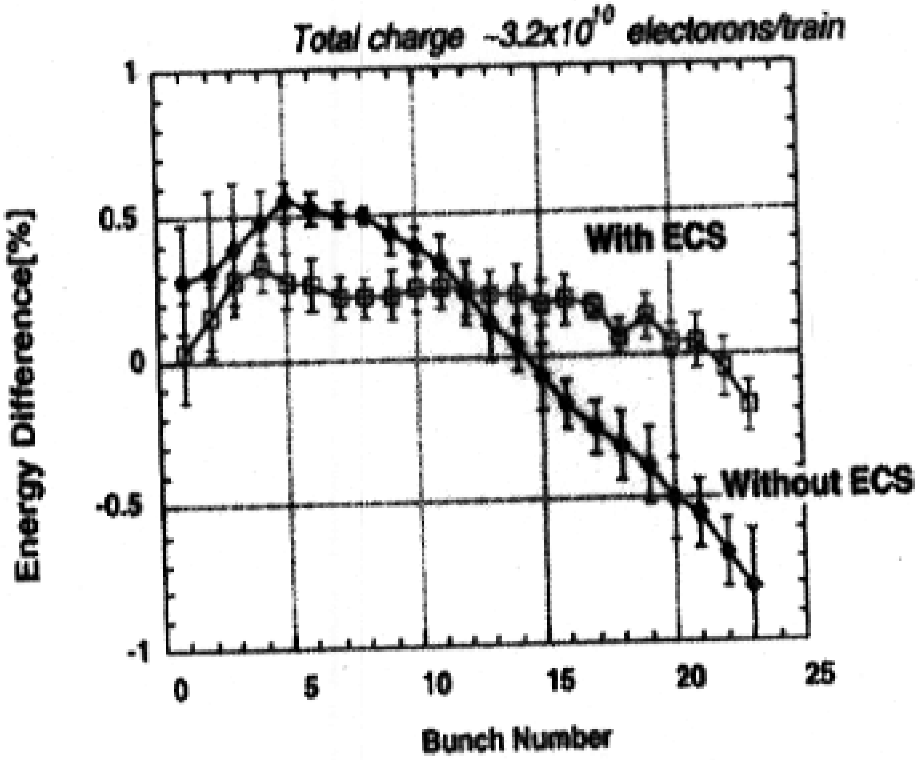
- So what?

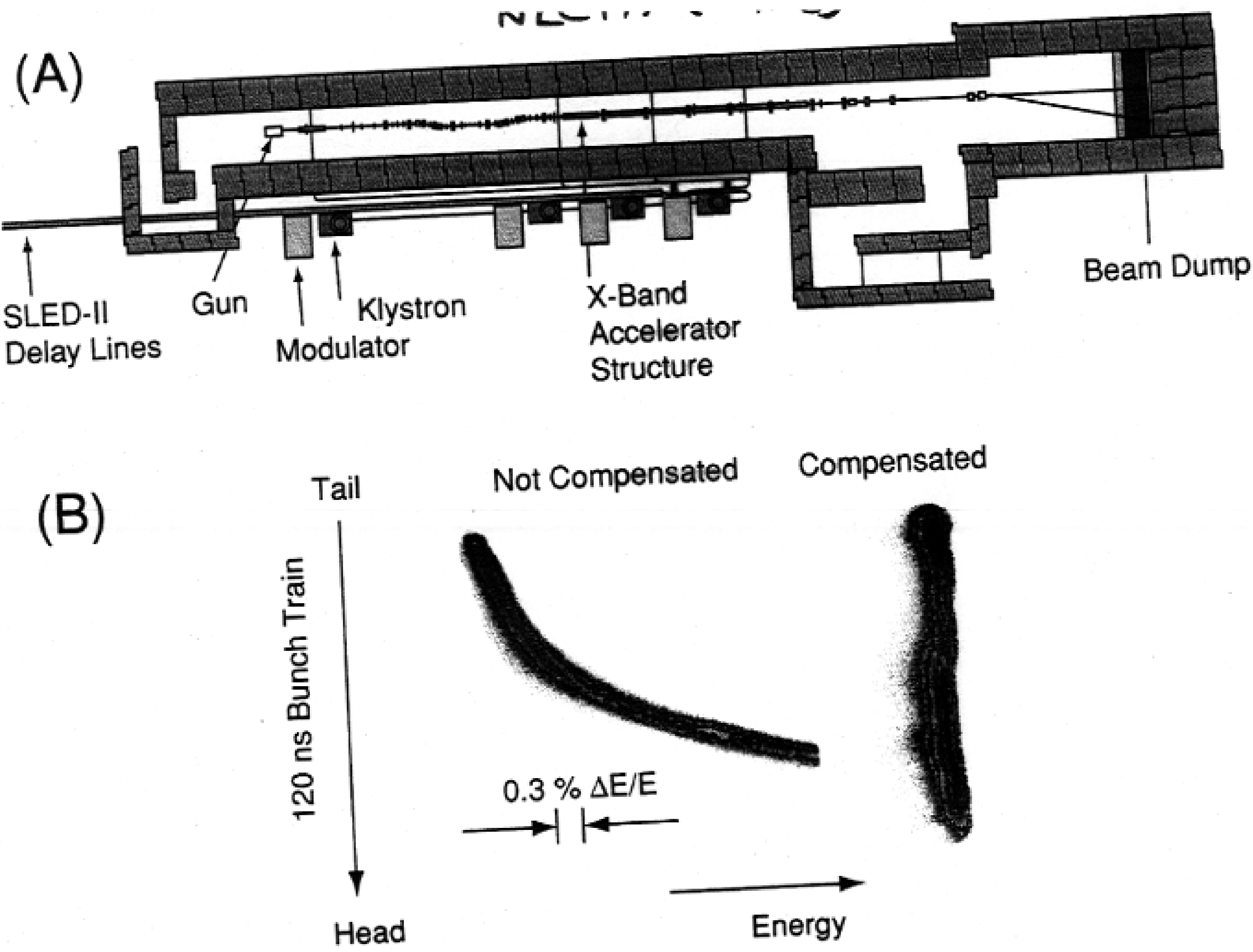
  They were encouraging, but
  We should do something similar with the latest X-band main linac scheme. also: i.e. new modulators, PPM tubes, DLDS, RDDS.

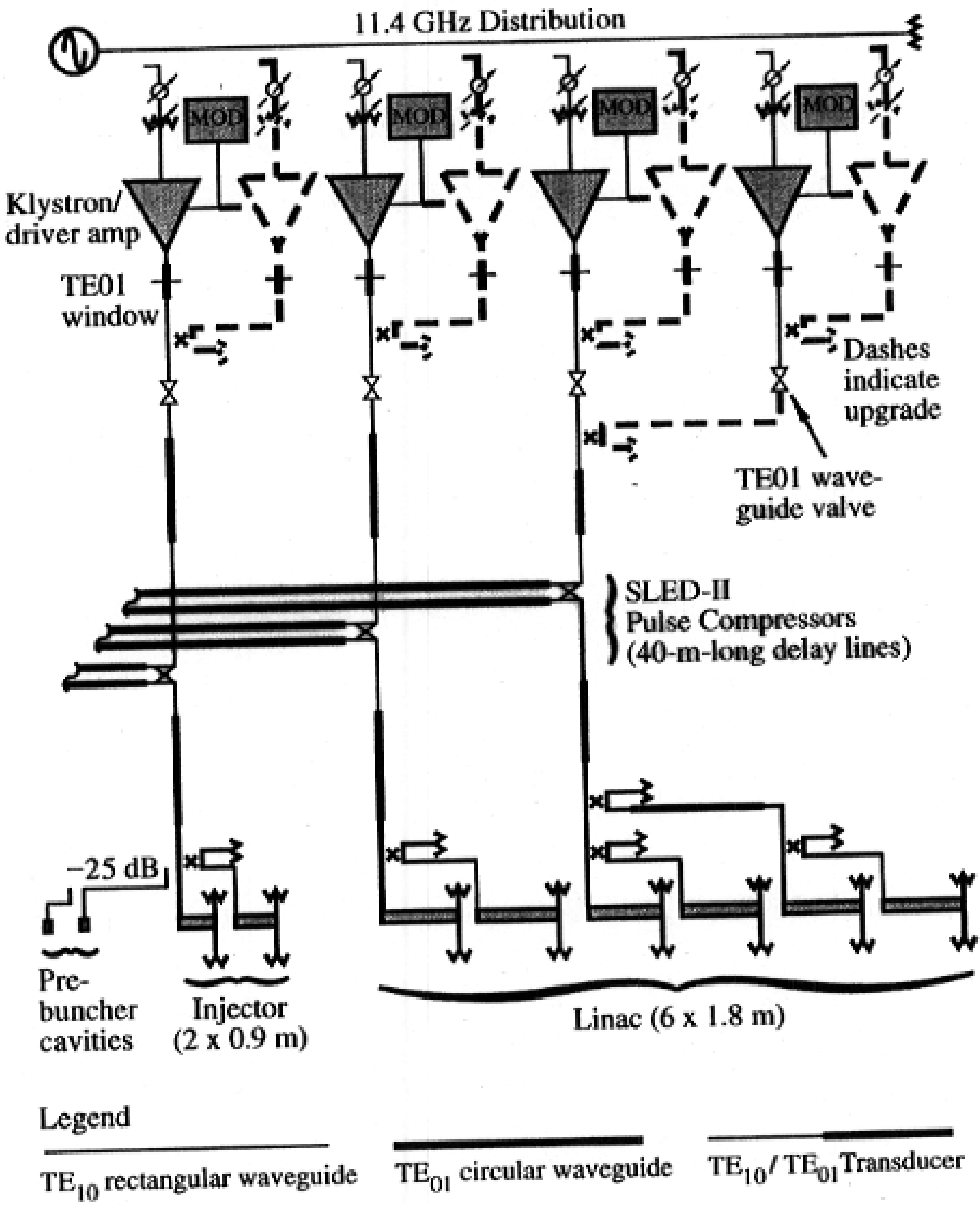
(A)


Pulse Modulator
KLYSTRON
TOSHIBA E3712
SLAC 5045
GUN
Beam
The Compensating Structures

(B)


Total charge ~3.2x10^10 electorons/train
With ECS
Without ECS
Energy Difference[%]
Bunch Number
1
0.5
0
-0.5
-1
0
5
10
15
20
25


(A)
SLED-II
Delay Lines
Gun
Modulator
Klystron
X-Band
Accelerator
Structure
Beam Dump
(B)
Tail
120 ns Bunch Train
Head
Not Compensated
Compensated
0.3 % ΔE/E
Energy



11.4 GHz Distribution
MOD
MOD
MOD
MOD
Klystron/
driver amp
TE01
window
Dashes
indicate
upgrade
TE01 wave-
guide valve
SLED-II
Pulse Compressors
(40-m-long delay lines)
–25 dB
Pre-
buncher
cavities
Injector
(2 x 0.9 m)
Linac (6 x 1.8 m)
Legend
TE10 rectangular waveguide
TE01 circular waveguide
TE10/ TE01 Transducer

7-96

8196A1

Concluding Remarks

- ISG framework helped a lot in accelerating the X-band R&D.

  Progress Report will be submited to KEK/SLAC directors in early yr 2000:
  for their review;
  for their R&D policy making for the future,
  in consutation with HEP communities.

- Concerning industrialization issues during the R&D:

  Some aspects of R&D are already done in collab with industry. Gradual increase of industry involvement is important for:

  Building-up confidence in the manufacurability of components and thus, "do-ability" of LC projects.

  Building-up confidence in cost estimates.

- Test projects such as

  8 klystrons + 12 structures + 1 DLDS "leg"

  and others would reveal many "hidden" technical issues, *and* production / industrialization issues. So, we should do them.

- We recognize that these pre-project R&D activities on LC will take substantial human + funding resources. We need HEP community's wide-range understanding and support.