Review of Linear Colliders
In the Framework of Future World Accelerators

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Talk Outline

World Family of HEP Accelerators

e^+e^- Colliders

Linear Colliders: The Big Issues

Luminosity, Emittance, Energy

Test Facilities and Hardware Development

Ground Motion, Tuning and Sites

The Future

Present and Future HEP Accelerators

In Operation:

- DAΦNE
- VEPP4
- BEPC I
- SLAC LINAC
- CESR, KEK B, PEP II
- KEK 12 GeV PS
- JINR NUCLOTRON
- 10 GeV ITEP PS
- 70 GeV SERPUKHOV PS
- YEREVAN SYNCHROTRON
- CERN PS and SPS
- PETRA, HERA
- AGS, RHIC
- TEVATRON

Under Construction:

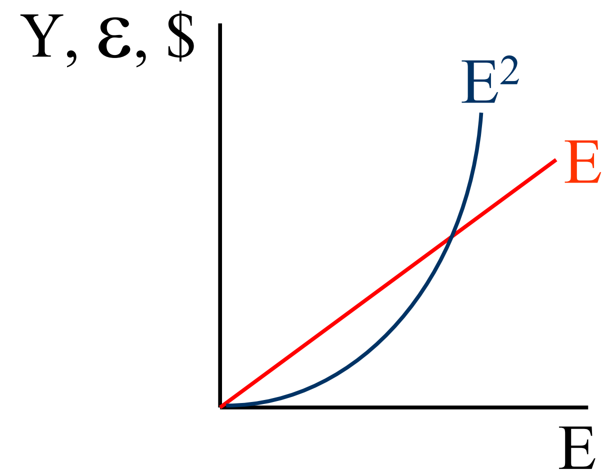
- VEPP 2000 (2003)
- JHF (2007)
- LHC (2007)

Under Proposal, Design or Study:

- BEPC II (recently funded)
- CESR-c

- TESLA, JLC/NLC, CLIC
- SUPER *B* FACTORIES
- MUON RINGS/NEUTRINO FACTORIES
- VLHC, VLLC
- EIC, HIP
- FUTURE TECHNOLOGIES

Cost of e^+e^- Colliders



Circular $C = K_C E^2$

Linear $C = K_L E$

Assumes Costs proportional to Length and Power are equalized [not always the case]

Ignores Fixed costs [Injectors, Beam Delivery, Detectors, etc.]

"LEP 1000"

2 TeV in Center-of-Mass

Diameter ≈ 900 km

Linear Collider at 50 MeV/m

Length = 40 km →-←

Why LEP 1000 gave way to the idea of linear colliders

International Collaboration and Competition on R&D Toward LC

A Brief History

1965	First suggestion of Clashing Linacs by M. Tigner
1979	B. Richter proposes SLC, completed in 1988
1983	First papers on large linear collider
1987	B. Richter proposes international collaboration on next e+e- linear collider, biannual LC Workshops are started
1994	Formal International Collaboration Council meets in London and creates Technical Review Committee (TRC)
1995	Publication of first TRC Report
2001	ICFA orders second TRC Report at its February 8-9 meeting at DESY

1995 Options

TESLA

SBLC†

JLC (C)

JLC (X)

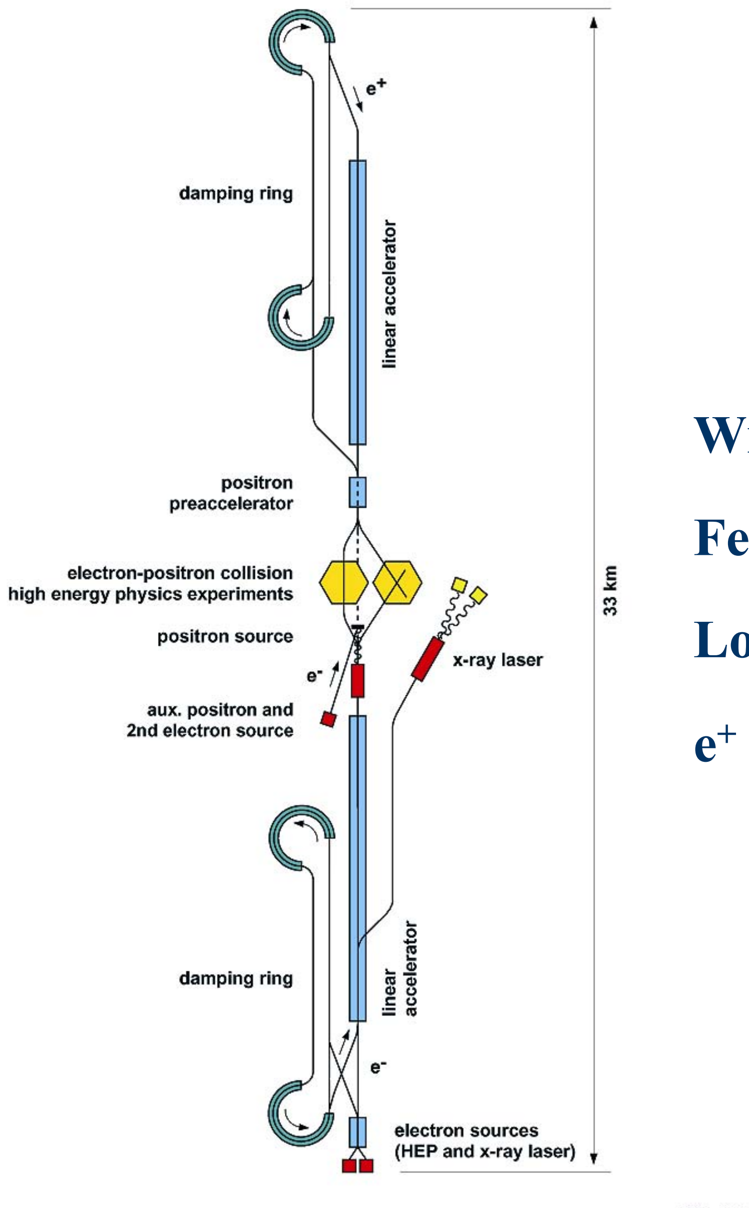
NLC (X)

VLEPP†

CLIC

† Abandoned subsequently

TESLA Layout



Wide Bunch Spacing

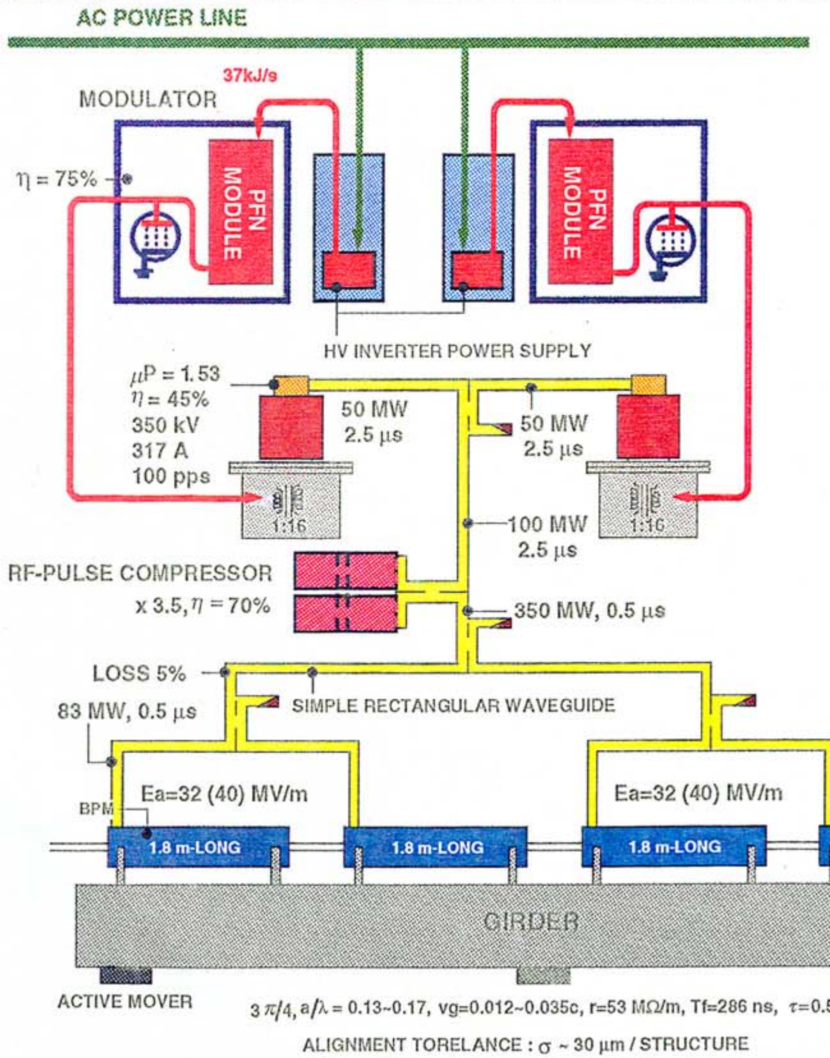
Feedback Possible between Bunches

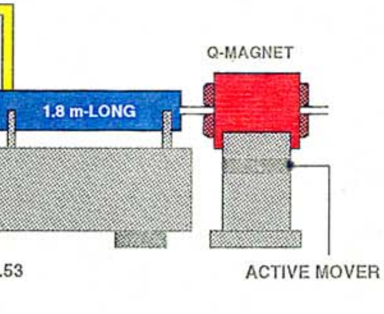
Long Dog Bone DR's

e^+ from e^-/γ

C-band LC

MAIN LINAC RF-SYSTEM C-band LINEAR COLLIDER

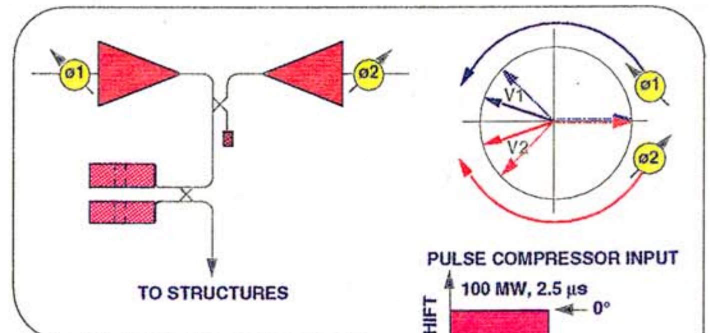


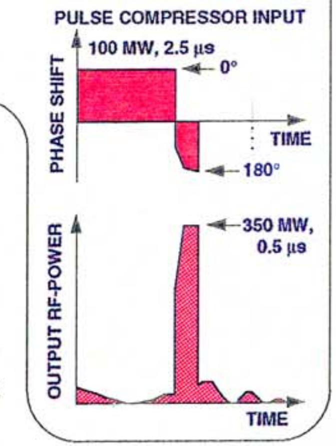


5712 MHz, $\sqrt{S}$ =500 GeV FOR TWO LINACS

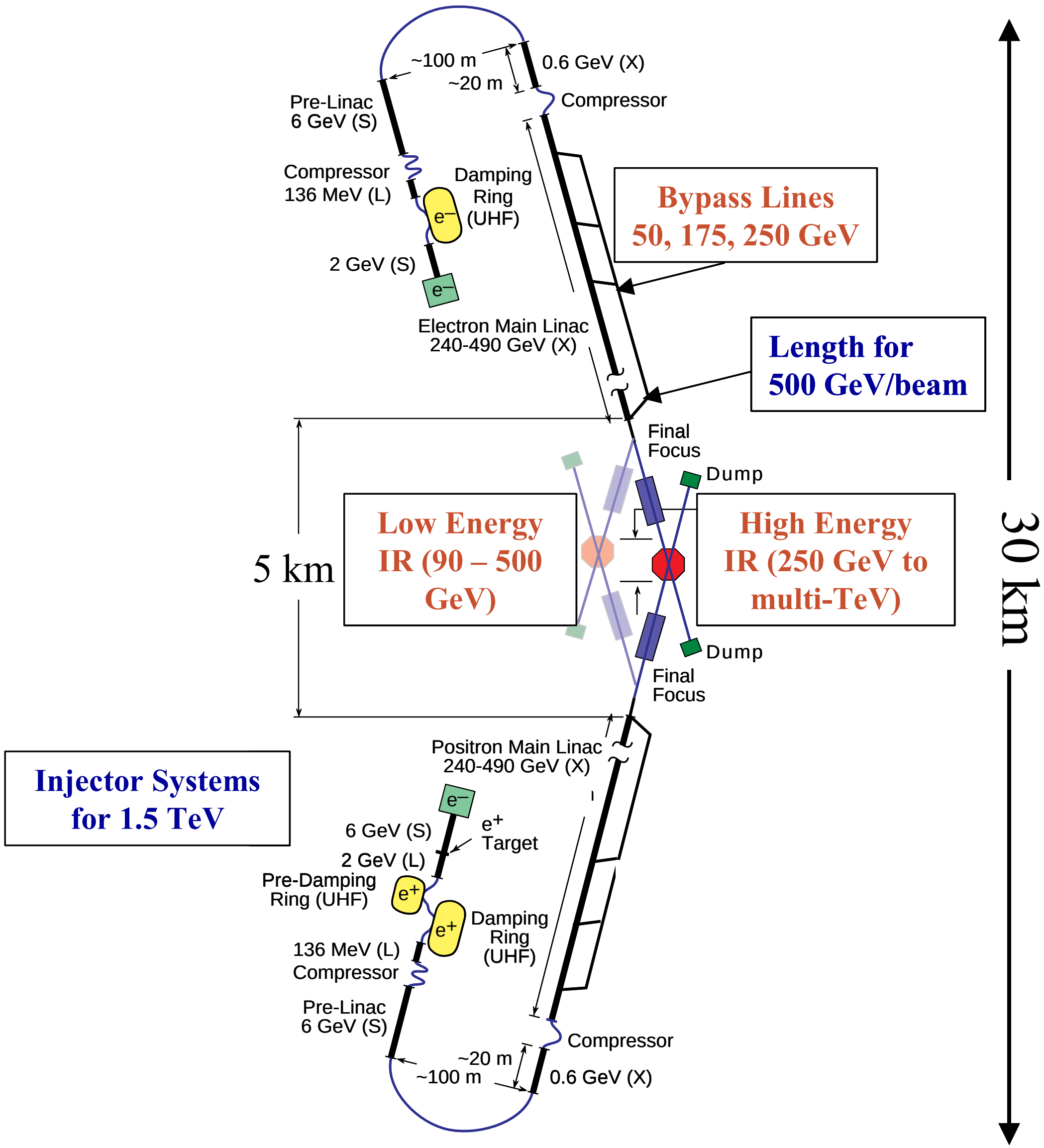
RF-SYSTEM	: 2040 UNITS
MODULATORS	: 4080
KLYSTRONS	: 4080
ACC. STRUCTURES	: 8160
ACTIVE LENGTH	: 14.7 KM
WALL-PLUG POWER	: 150 MW

BEAM LOADING COMPENSATION USING PHASE -TO-AMPLITUDE MODULATION

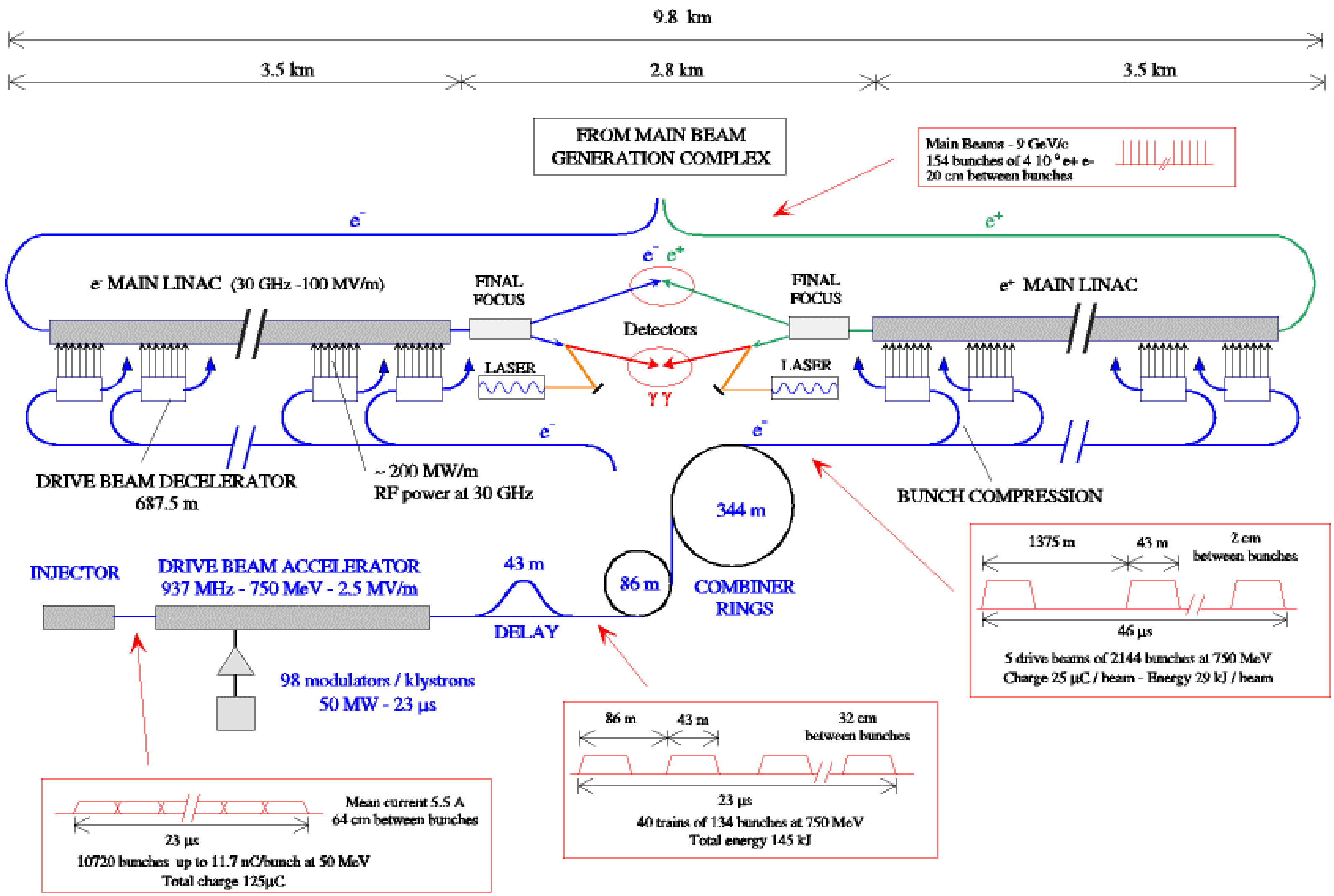




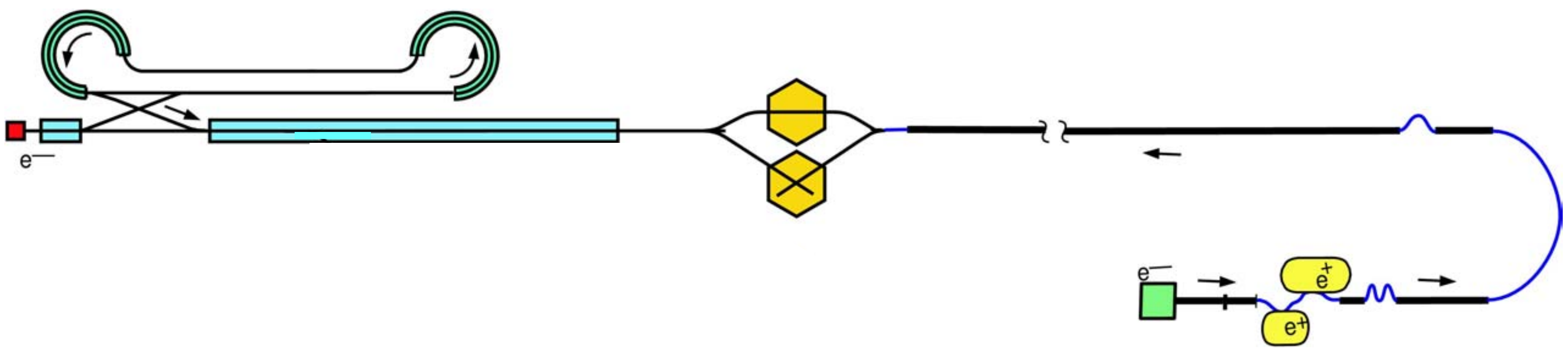
The JLC/NLC Configuration



Overall Layout of the CLIC Complex at 500 GeV C.M.



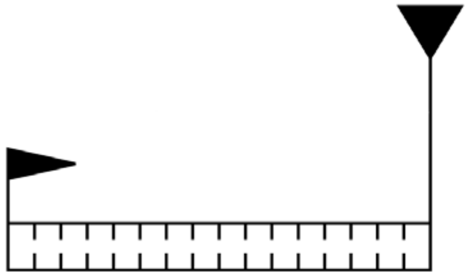
The Combined Hybrid Linear Collider
A great idea that doesn't work



RF Power Source

5 Hz

RF Power Source



120 Hz

The Big Issues

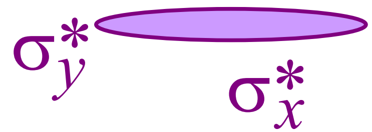
Robust sources and Pre-linacs	**Polarized e^-**
	e^+ (possibly polarized)
Low Emittance Generation	**Damping Rings**
	Jitters
	Construction tolerances
	BPM's
Low Emittance Preservation	**Alignment**
	Ground motion
	Feedbacks
Linear Accelerators	**RF Systems, vacuum, supports, cryogenics**

Collimation, Beam Delivery, Machine/Detector Interface
Final Focus, Beam-Beam Effects
Reliability, Availability, Tunability
Machine Protection
Energy Upgradeability

Luminosity

$$L = f_{\text{rep}}\, n_{\text{b}} \frac{N^2}{4\pi\sigma_x^*\sigma_y^*} H_{\text{D}}$$

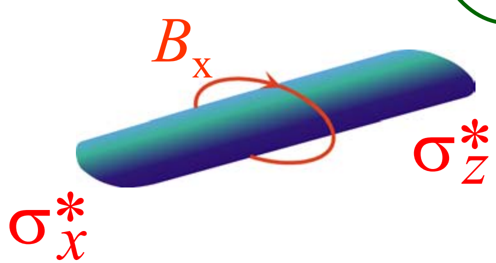
Pinch
Hour Glass
Crossing Angle



$$L = \frac{1}{4\pi E} \frac{N}{\sigma_x^*} \frac{\boxed{f_{\text{rep}} n_{\text{b}} N E}}{\sigma_y^*}$$

Single
Beam Power

Damping Rings
Emittance Control



Ampere's Law

$$\sim B_x\, \sigma_z^* \sim \frac{N}{\sigma_x^*} \sim \frac{n_\gamma}{2 r_{\text{e}}\, \alpha}$$

Luminosity, Emittance Generation and Preservation

$$L = f_{rep} n_b \frac{N^2}{4\pi\sigma_x^* \sigma_y^*} H_D$$

$$\sigma_x^* = \sqrt{\beta_x^* \in_x^*} \qquad \sigma_y^* = \sqrt{\beta_y^* \in_y^*}$$

LC 500 GeV	**TESLA**	**JLC/NLC**	**CLIC**
DR Extraction $\gamma \in_x^* / \gamma \in_y^*\ 10^{-6}\ m.rad$	**8/0.02**	**3/0.02**	**1.6/0.003**
IP $\gamma \in_x^* / \gamma \in_y^*\ 10^{-6}\ m.rad$	**10/0.03**	**3.6/0.04**	**2/0.02**
$\beta_x^* / \beta_y^* (mm)$	**15/0.4**	**8/0.11**	**10/0.15**
$\sigma_x^* / \sigma_y^* (nm)$ *at IP*	**554/5.0**	**243/3.0**	**202/2.5**
$P / Beam(MW)$	**11.3**	**8.7/6.9**	**4.9**
H_D	**2.1**	**1.5**	**1.8**
$L(10^{33} cm^{-2} s^{-1})$	**34**	**25/20**	**14.1**

Energy and RF Structures

Energy gain in
Structure of length L
(steady state)

$$V = K_1\sqrt{P\, r\, L}\; - K_2\, i\, r\, L$$

Structure
input power

Shunt impedance

Beam loading

Superconducting

Cryogenic losses $\sim \omega^2$

Shunt impedance $\sim \omega^{-1}$

[Cost of Niobium $\sim \omega^{-1}$]

Room Temperature

Shunt impedance $\sim \omega^{\frac{1}{2}}$
Filling time $\sim \omega^{-\frac{3}{2}}$
Energy stored $\sim \omega^{-2}$
Power/feed $\sim \omega^{-2}$
Breakdown gradient $\sim \omega^{\frac{1}{2}}$ (not sure)

Dark current capture gradient $\sim \omega$

Push to low ω

Push to high ω

But transverse wakefields $\sim \omega^3$

Tolerances harder $\longrightarrow$

RF Parameters and Upgrade Strategies

$$\text{Gradient} = K_1 \sqrt{\frac{P\,r}{L}} - K_2\, i r$$

LC Gev	TESLA 500	TESLA 800	JLC/NLC 500	JLC/NLC 800	CLIC 500	CLIC 3000
Unloaded/Loaded Gradient	23.4/23.4	35/35	70/55		172/150	
$P_K^{(MW)}/N_{Klystrons}$	9.7/572	9.7/572	75/1872 *	75/3744 *	50/332	50/364
RF Compression Gain	1		8		32×4	32x22
$N_{Sections}$	20592	21816	11232	22464	7400	42940
Total AC Power for Linacs	95	160	140	230	100	300

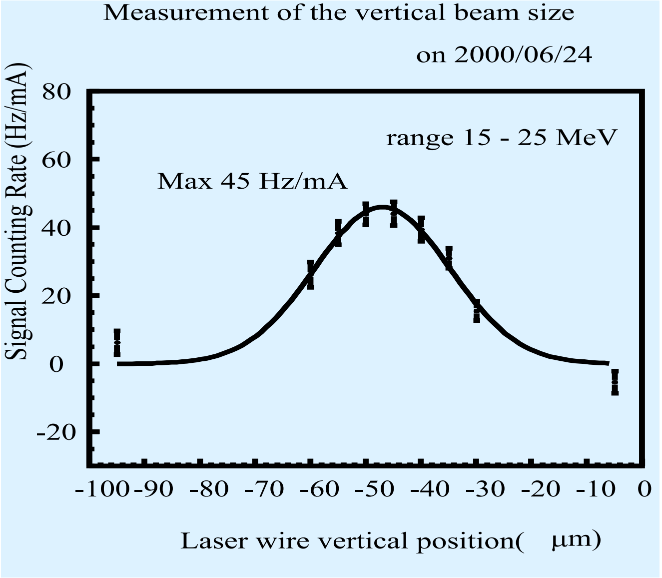
* Numbers are for NLC; numbers for JLC are double

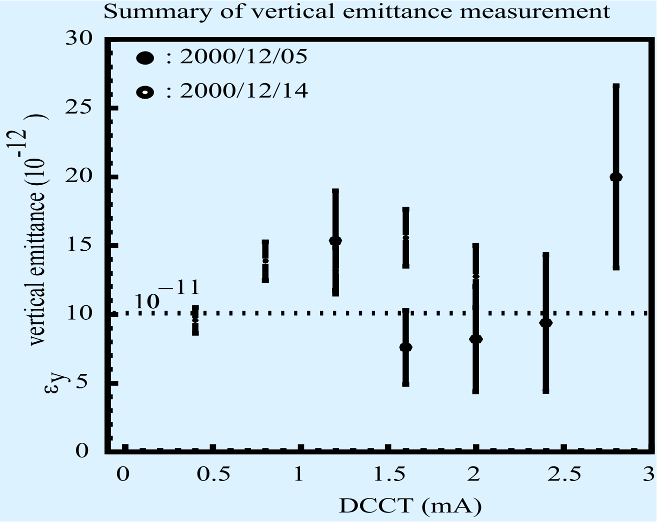
Test Facilities, etc.

TTF I	**Two modules (sixteen 9-cell structures) ~ 25 MV/m** **Electropolished 9-cell structure reaches 35 MV/m (March 2002)** **Test of superstructure this September** **Tests conclude in Fall 2002**
TTF II	**Commissioning starts summer 2003**
C-Band	**Tests proceed at KEK and towards FEL construction at SPRING-8 (next three years)**
ATF (KEK)	**DR testing for next three years**
NLCTA (SLAC)	**X-Band structure tests and 8-pack tests continue for next three years**
ASSET (SLAC)	**Ongoing collimator and structure tests**
CTF-2	**Ends operation in Fall 2002**
CTF-3	**Tests will start in late 2004 and continue for 3-5 years**

ATF Damping Ring at KEK

Vertical emittance 3.5×10^{-8} measured with laser wire (~2 x NLC spec)

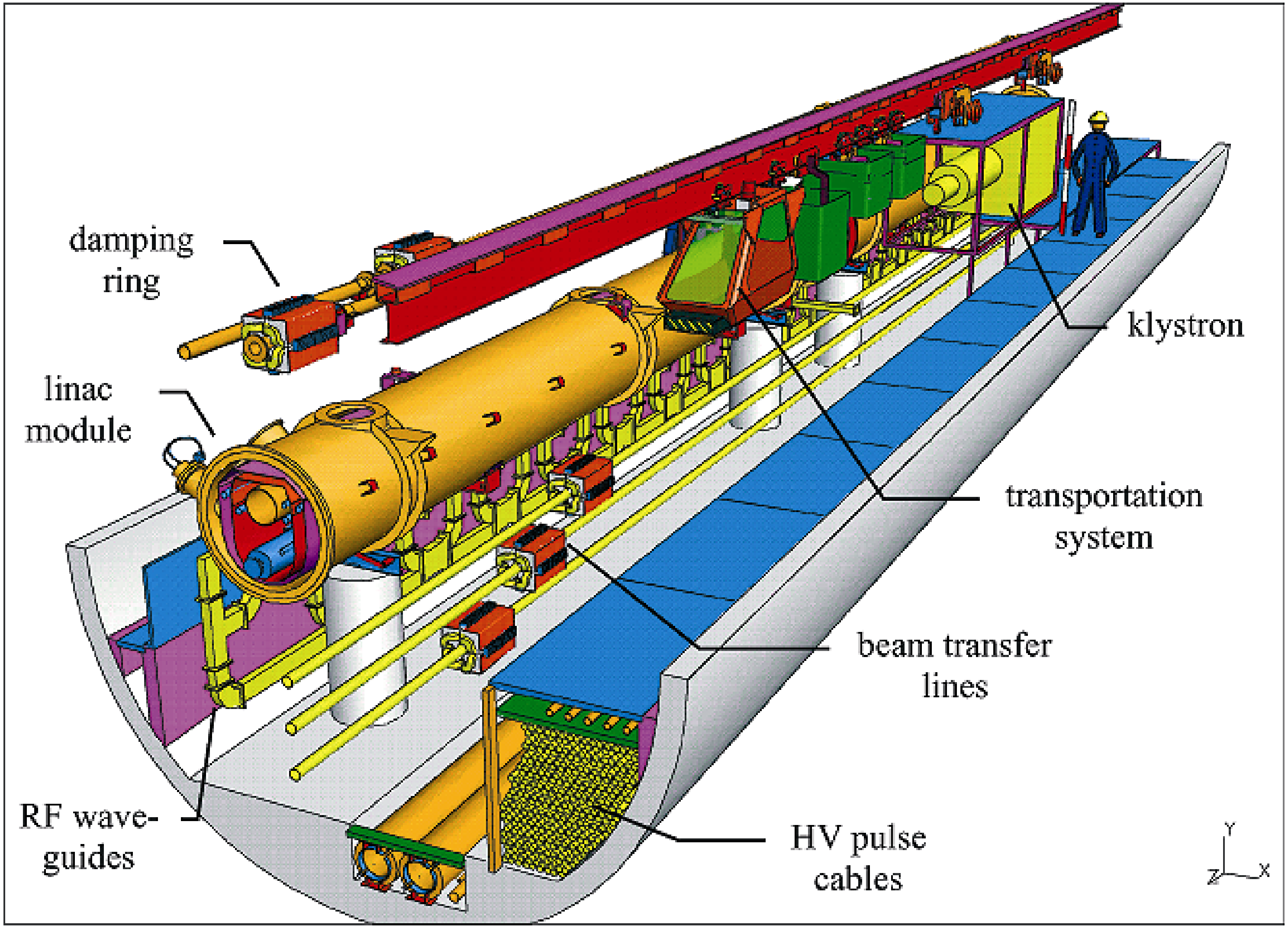




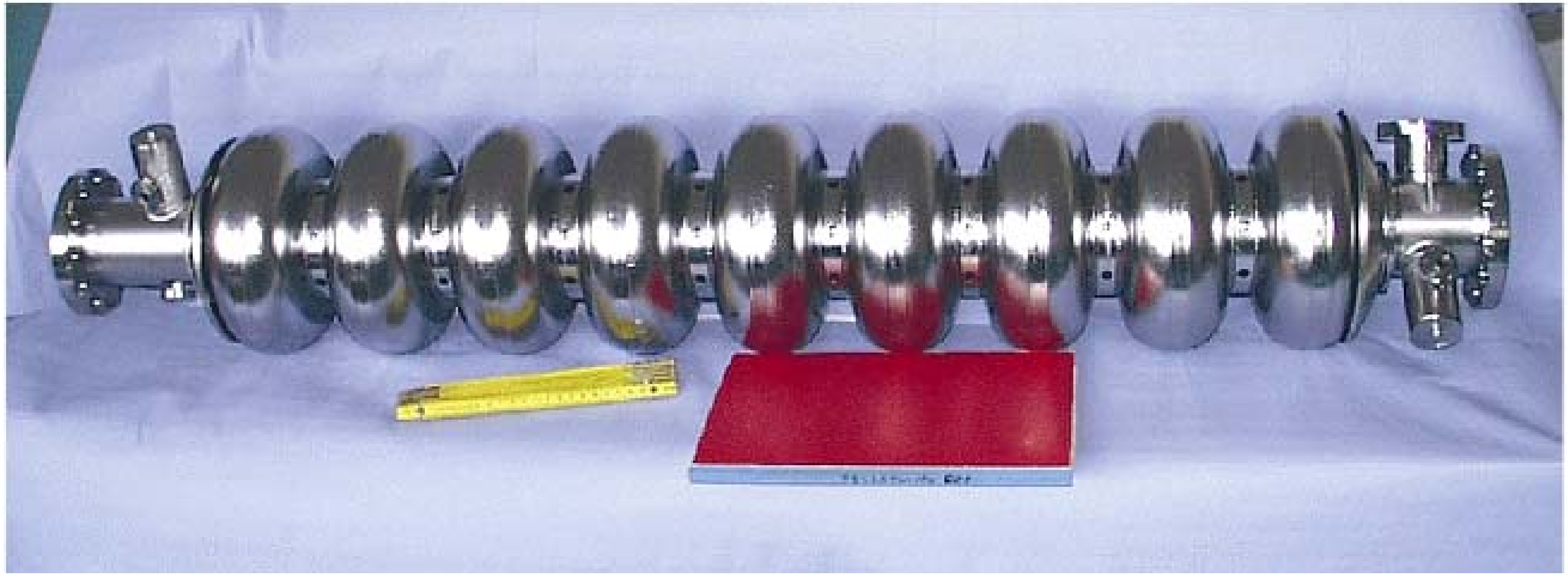
Challenges for Damping Rings

- Damping Rings push the performance limits of electron storage rings
  - required vertical beam size typically ~ 5 μm
  - rapid damping rate from large radiation energy loss per turn (0.4% in TESLA)
  - injection efficiency close to 100% required, for tolerable radiation loads
- There are demanding requirements for many systems and components
  - < 100 μm alignment tolerances for initial survey on major components
  - effective coupling correction requires BPM resolution less than 1 μm
  - diagnostics must be developed for fast, non-invasive beam-size measurements with necessary precision
  - lattice must have large acceptance for injected beam (large dynamic and physical aperture, and momentum acceptance)
  - injection and extraction kickers need fast rise times (20 ns for TESLA)
  - damping wiggler must have minimal impact on dynamical stability
  - electron cloud instability could be a serious problem in the positron rings
  - high bunch charge density can lead to instability through space-charge effects (in TESLA) or emittance growth from intra-beam scattering (in NLC)
  - fast ion instability could require vacuum much better than 1 nTorr

Sketch of the 5m diameter TESLA linac tunnel



The 9-cell niobium cavity for TESLA

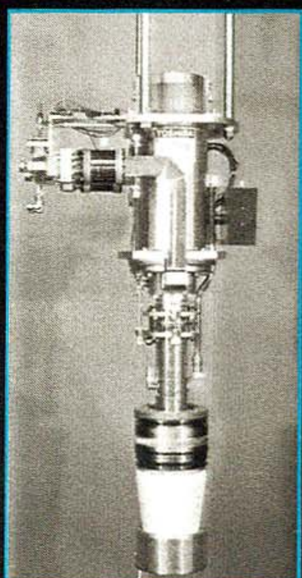
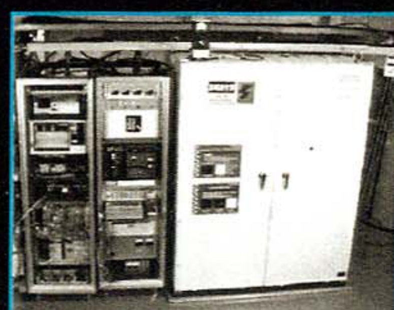
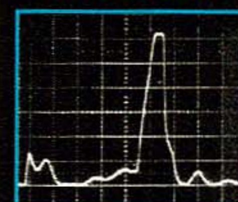
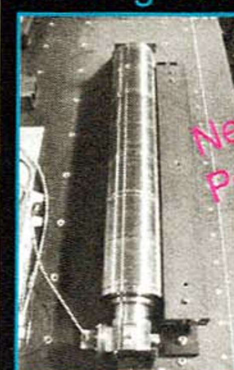
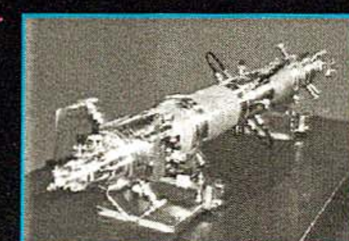


24 MV/m achieved in TTF I and 35 MV/m achieved in single test
+ Superstructure soon to be tested

Figure 1.1.3: *Assembly of a string of eight 9-cell cavities in the clean room at TTF.*

Clean Rooms
Chemical Treatment
High Temperature Treatment
High Pressure Water Rinsing
Electropolishing
Test Stands, CW, Pulsed Processing

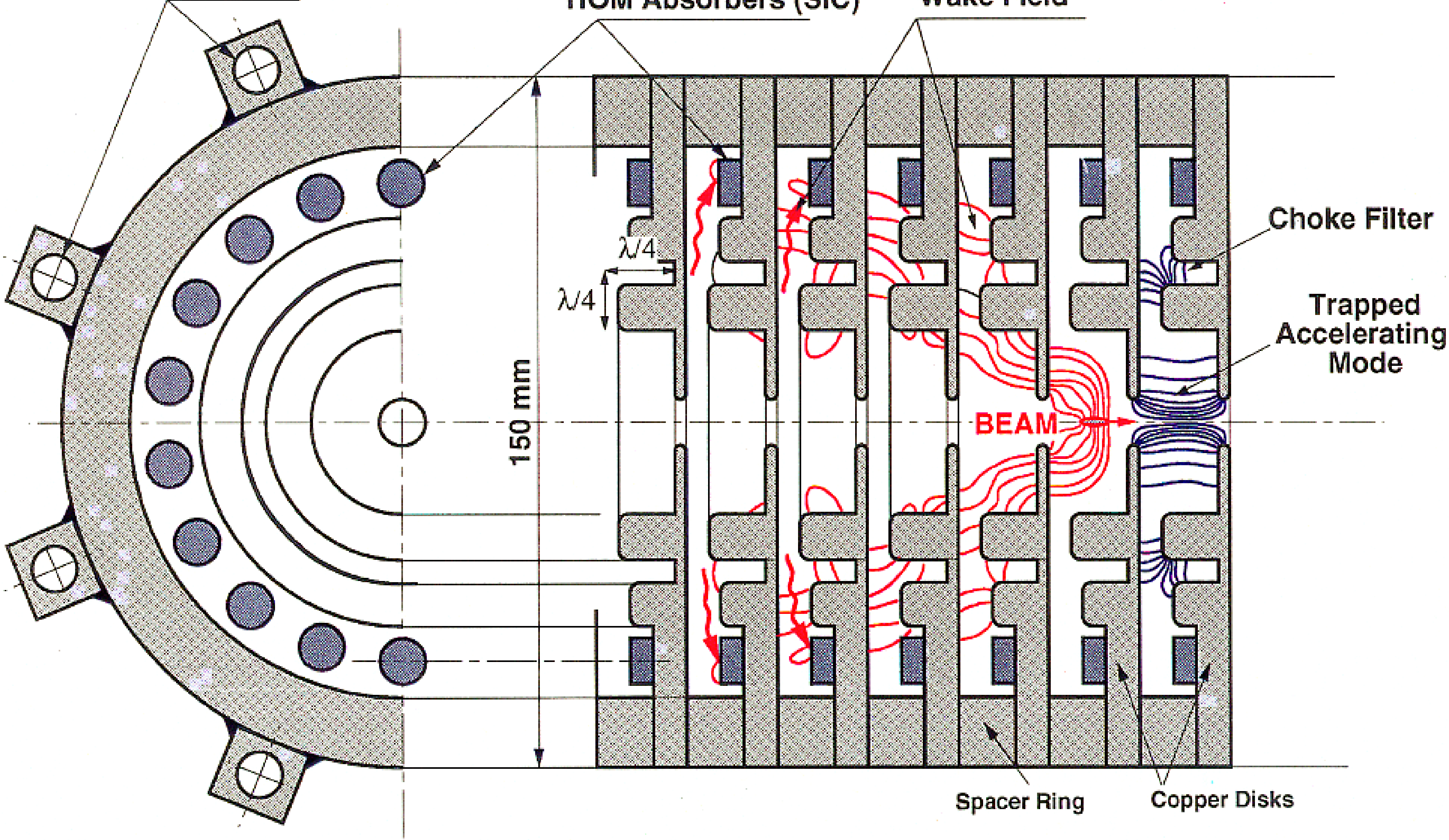
Phase-I R&D Summary

C-band Klystron	Klystron Modulator	RF Pulse Compressor	Accelerating Structure
50 MW, OK 2.5 sec, 47 %	110 MW OK 100 pps	Flat Pulse Gain 3.3	1.8 m OK Choke-Mode
Life test >5000 hour, OK. 	Smart modulator using inverter HV charger. Running for klystron life test. 	Three-cell cavity.  1 m long cold model.  Need High Power Test	Beam acceleration at 50 MV/m was done at ATF-KEK, with S-band model. HOM damping performance was proved by ASSET-SLAC test, 1998. 

HOM-Free Linear Accelerating Structure

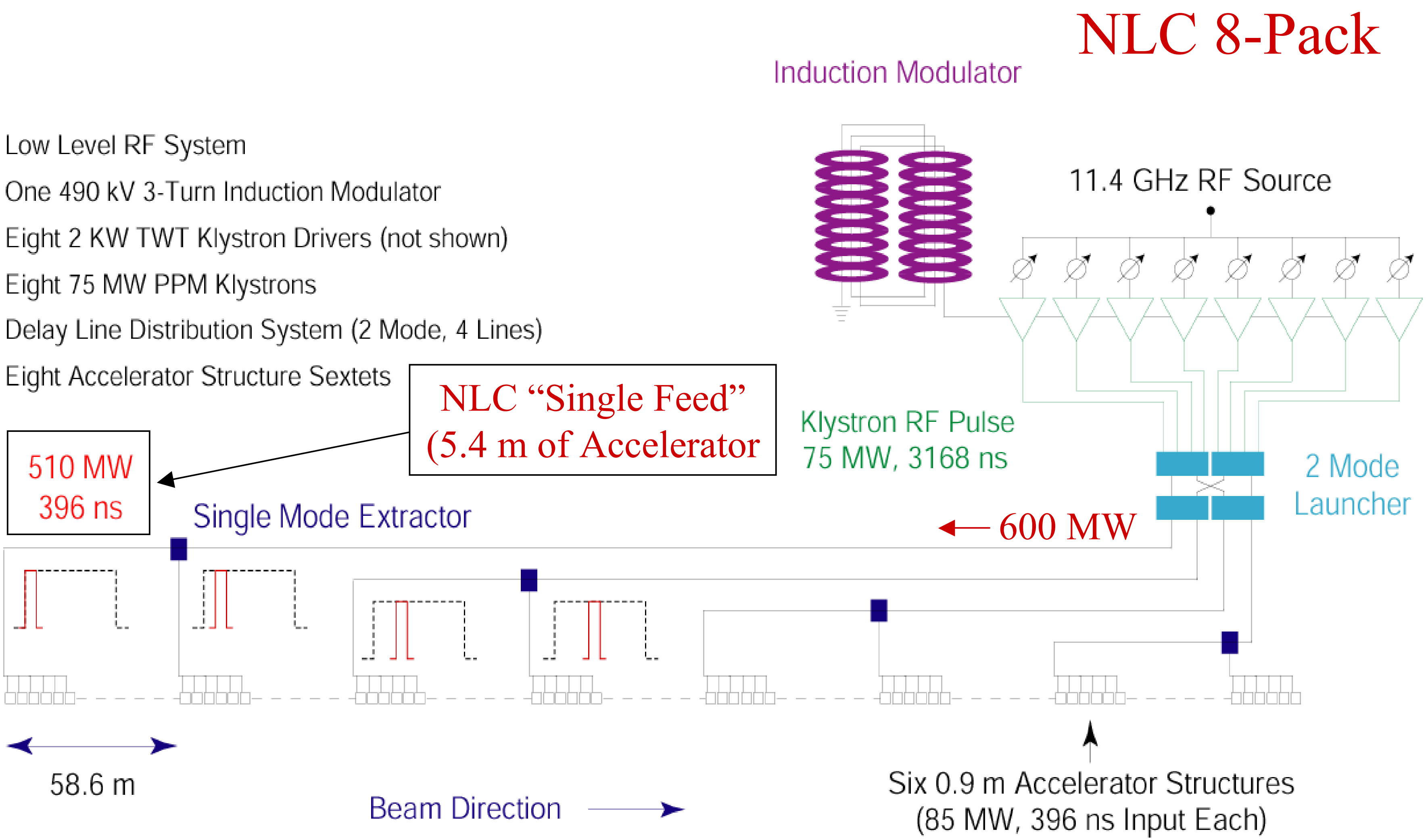
C-band LC

"Choke-Mode Cavity"
T. Shintake 1992



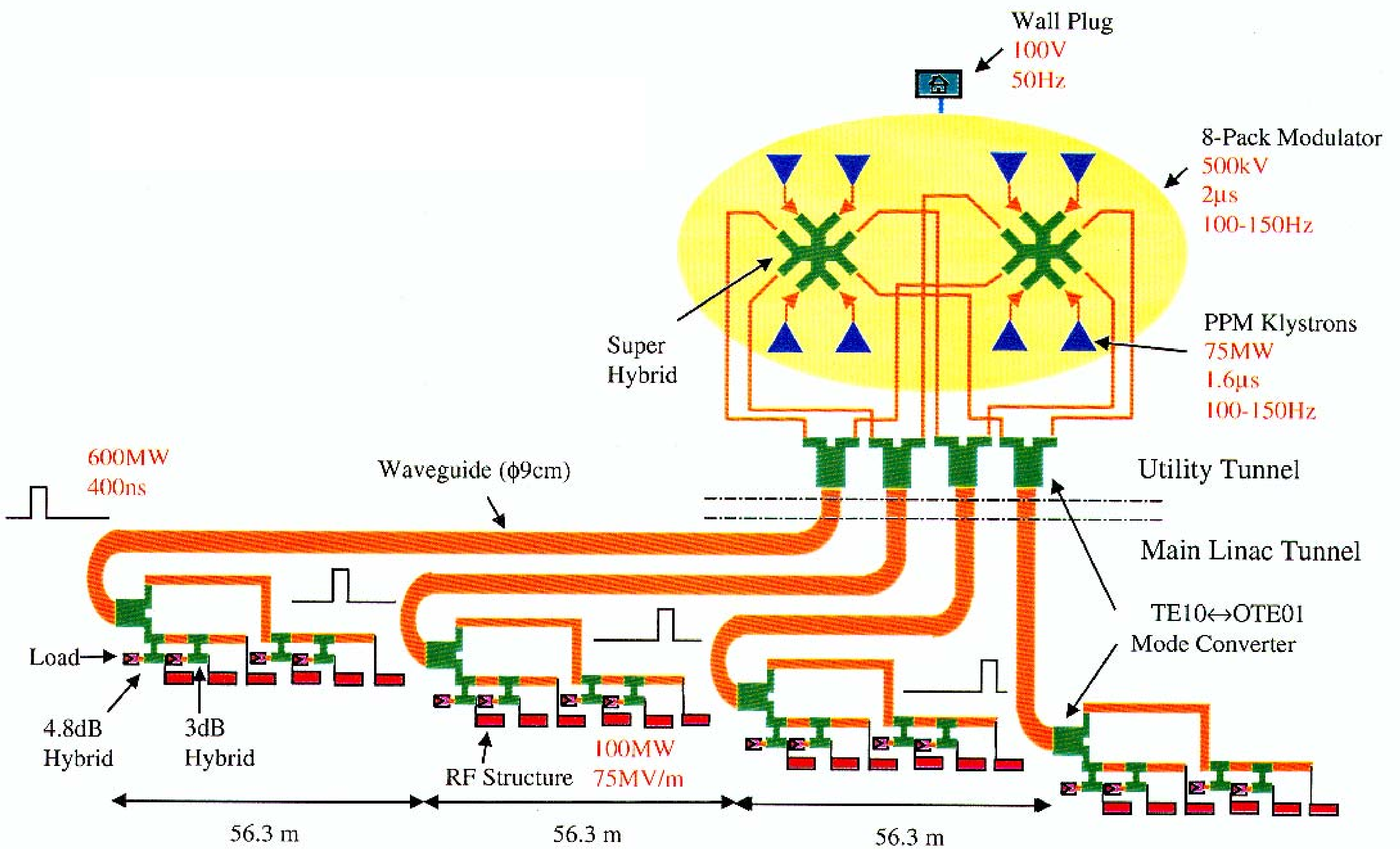
NLC Main Linac RF System

Low Level RF System
One 490 kV 3-Turn Induction Modulator
Eight 2 KW TWT Klystron Drivers (not shown)
Eight 75 MW PPM Klystrons
Delay Line Distribution System (2 Mode, 4 Lines)
Eight Accelerator Structure Sextets



GOAL 70 MV/m (unloaded)

JLC X-Band Main Linac Unit



8-Pack Phase-I (SLED-II System)

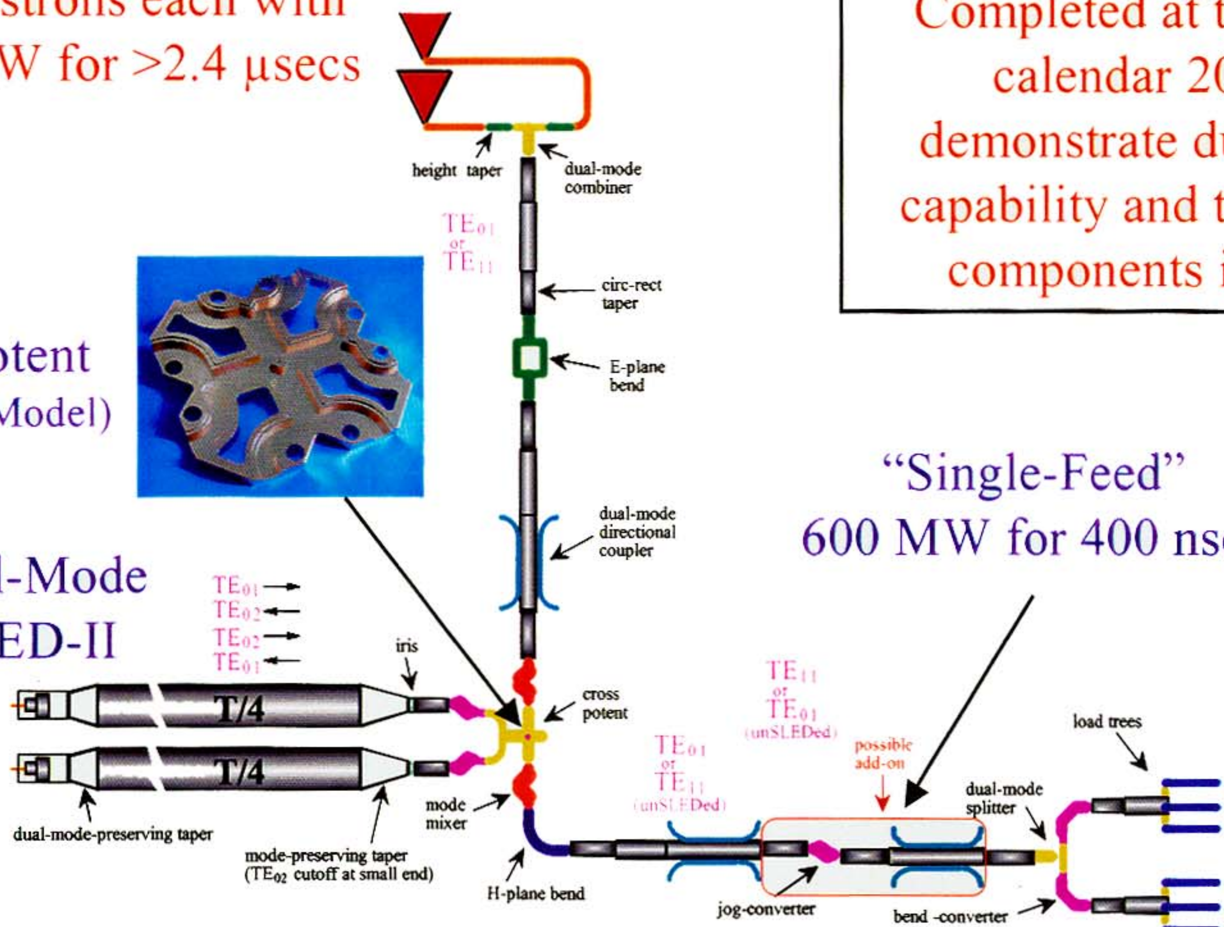
2 Klystrons each with
75 MW for >2.4 μsecs

Completed at the end of calendar 2002 to demonstrate dual-mode capability and test DLDS components in 2003.

Cross-Potent
(Cold Test Model)

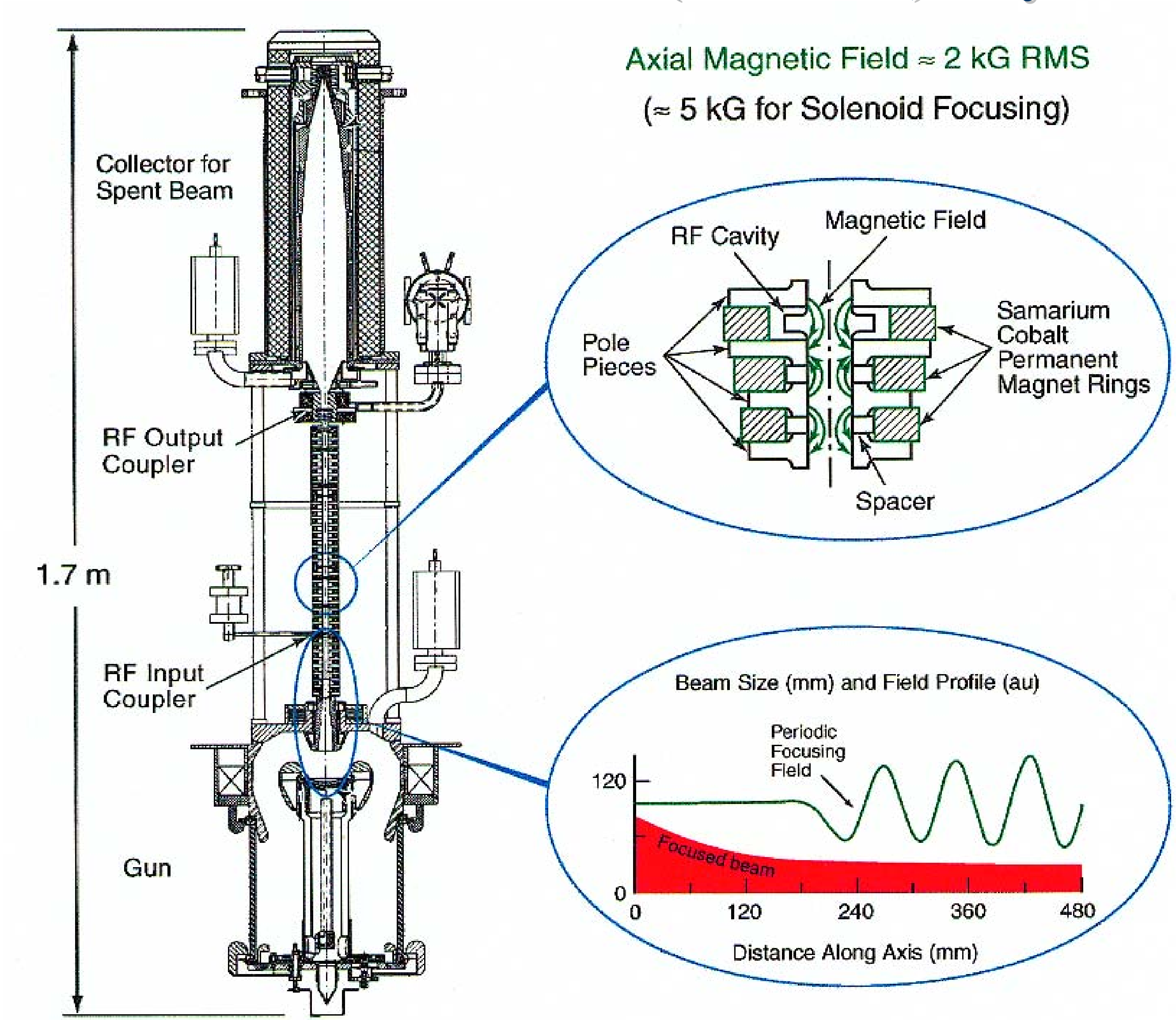
Dual-Mode
SLED-II

“Single-Feed”
600 MW for 400 nsec



600 MW
400 ns

Periodic Permanent Magnet (PPM) Focused X-Band (1.4 GHz) Klystrons

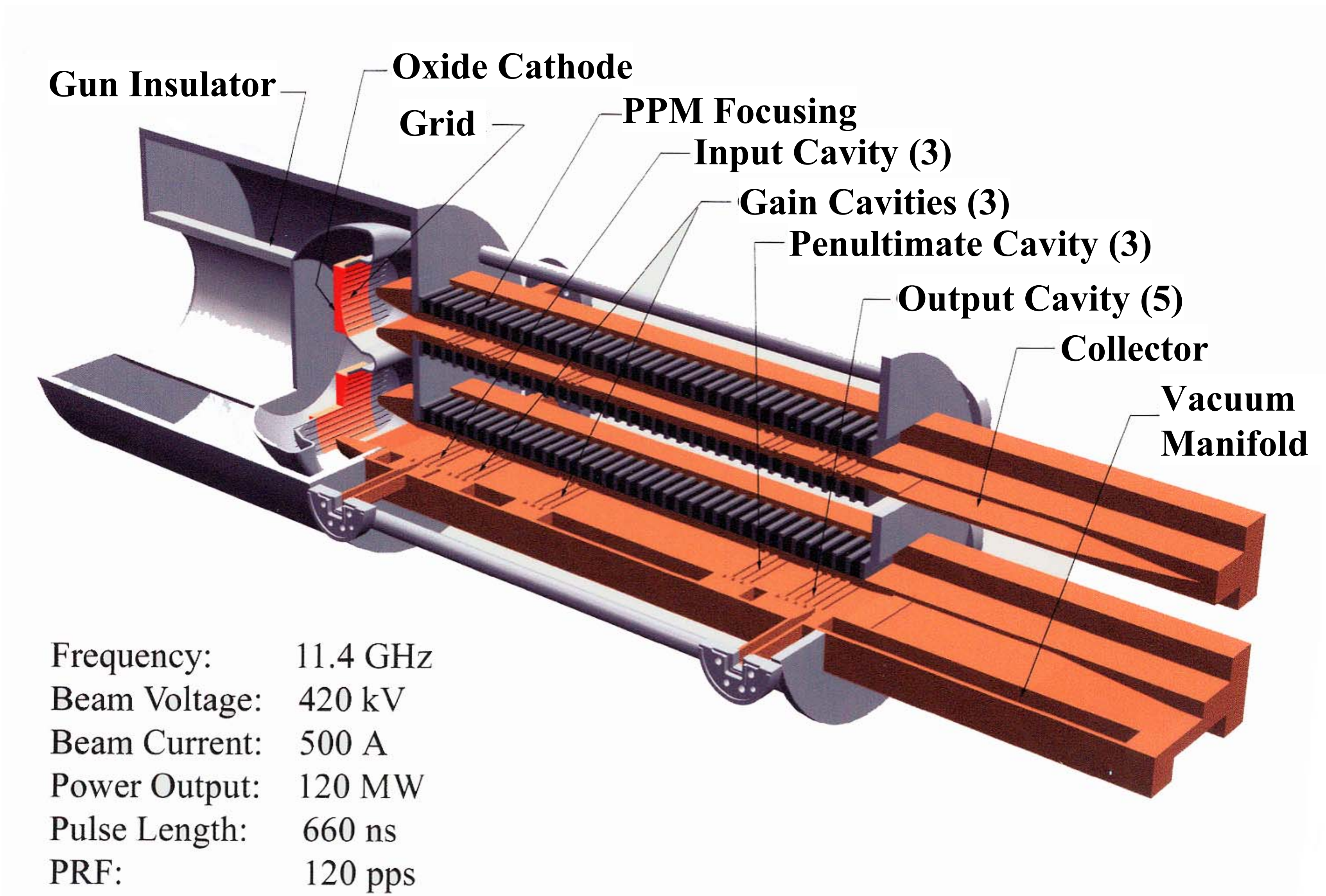


50 MW/2.4 μs achieved with SLED II yielding 35 MV/m loaded gradient in NLCTA

75 MW/3.2 μs still in R&D at SLAC

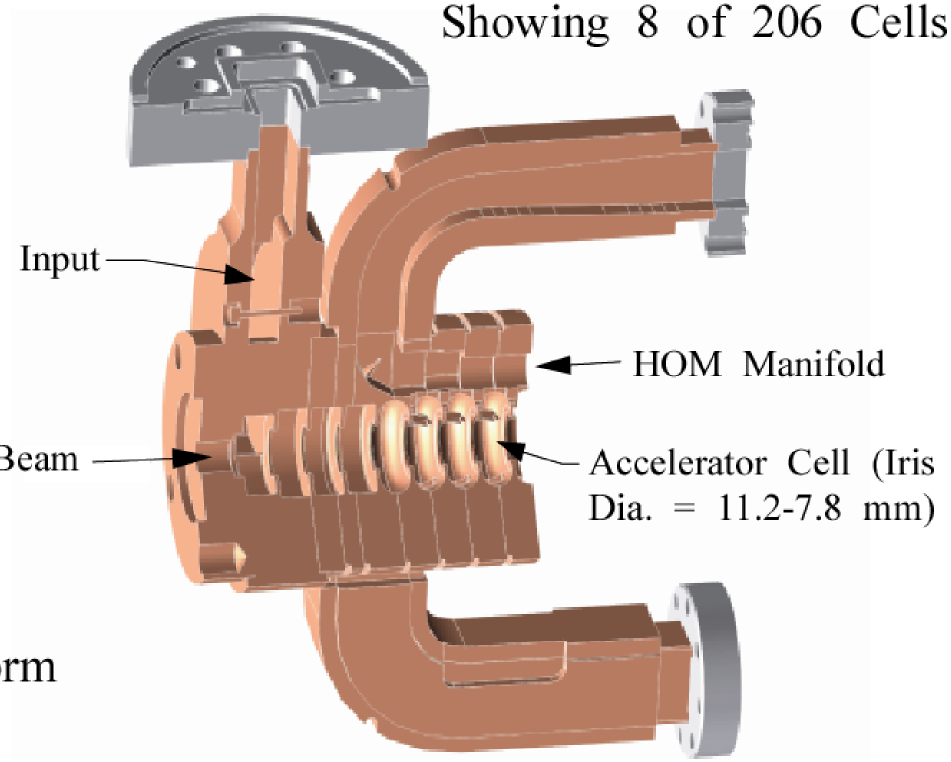
75 MW/1.6 μs achieved at KEK/Toshiba

Double Sheet Beam Klystron

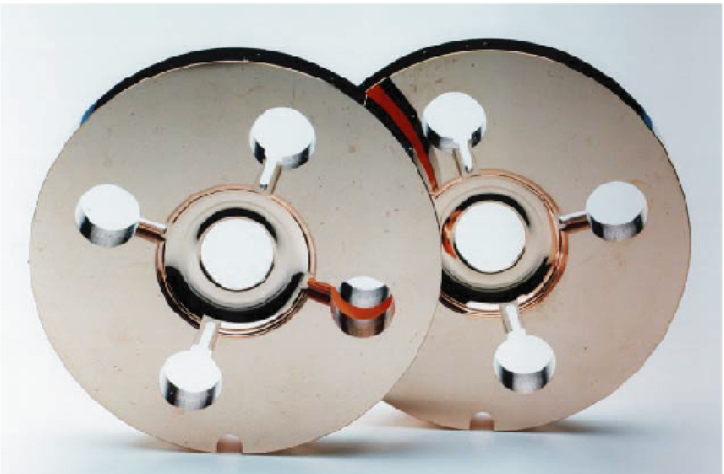


NLC/JLC Rounded Damped-Detuned Structure (RDDS)

RDDS Cutaway View Showing 8 of 206 Cells



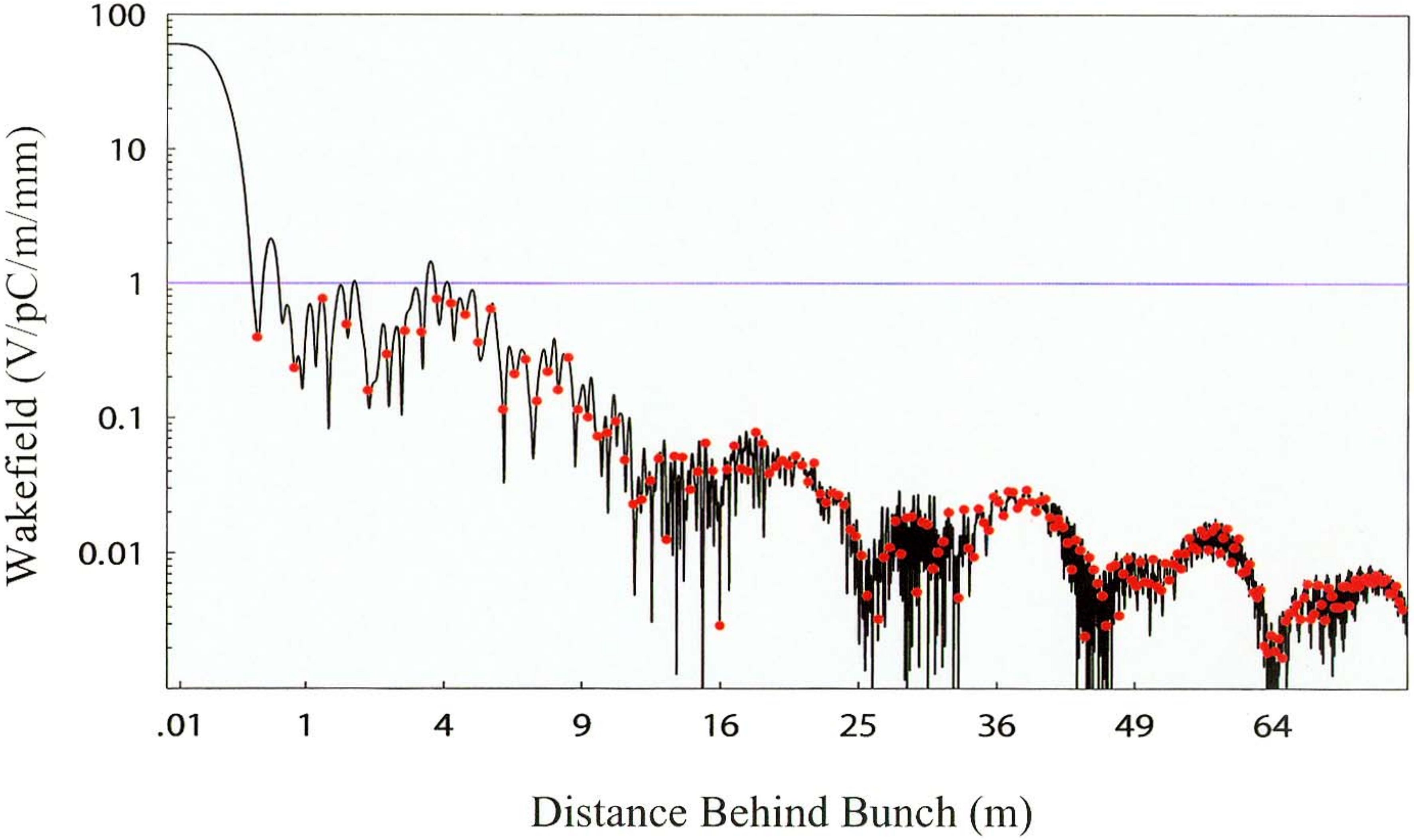
- Made with Class 1 OFE Copper.
- Cells are Precision Machined (Few µm Tolerances) and Diffusion Bonded to Form Structures.
- 1.8 m Length Chosen so Fill Time ≈ Attenuation Time ≈ 100 ns.
- Operated at 45 °C with Water Cooling. RF Losses are about 3 kW/m.
- RF Ramped During Fill to Compensate Beam Loading (21%). In Steady State, 50% of the 170 MW Input Power goes into the Beam.



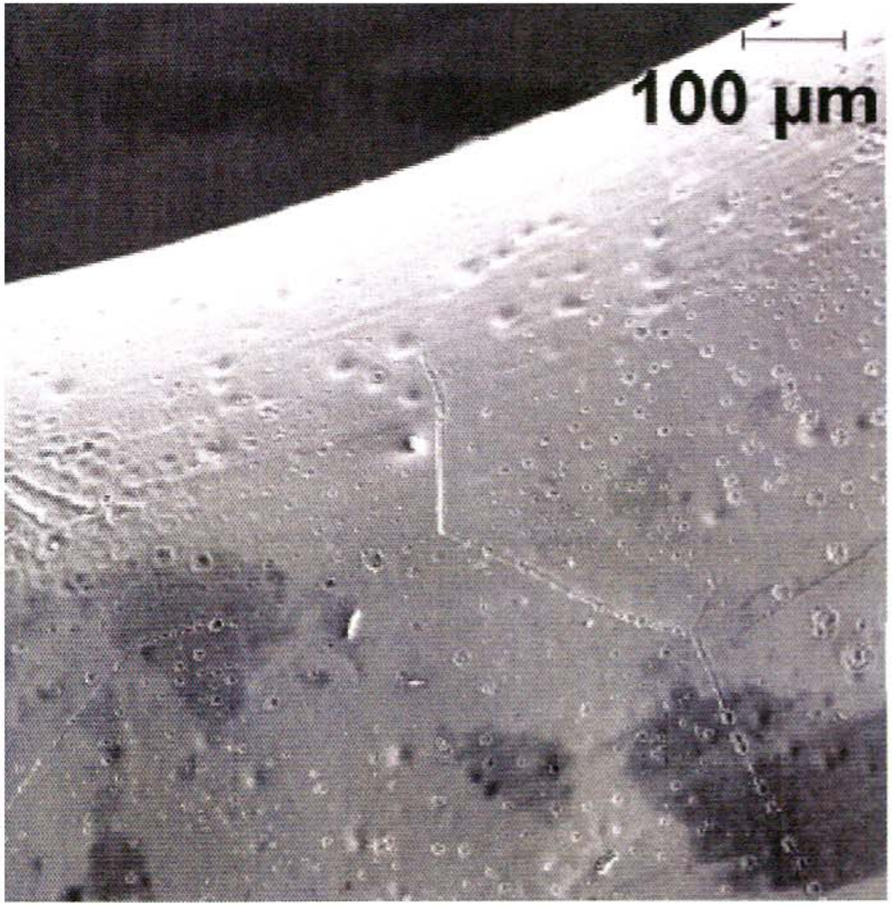
Two RDDS Cells

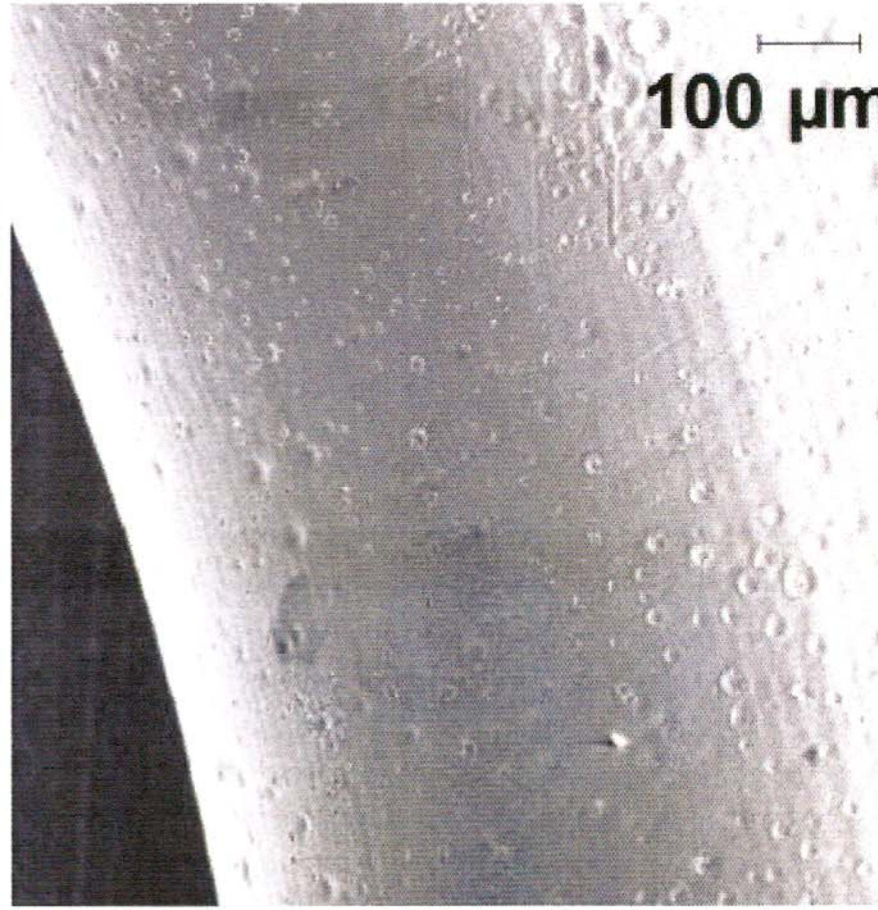
Example of Long-Range Transverse Wakefield for H60VG3 with Manifold Damping and Three-Fold Interleaving

(Red = Subsequent Bunch Locations)



Pitting on the T53VG3R Input Coupler Iris



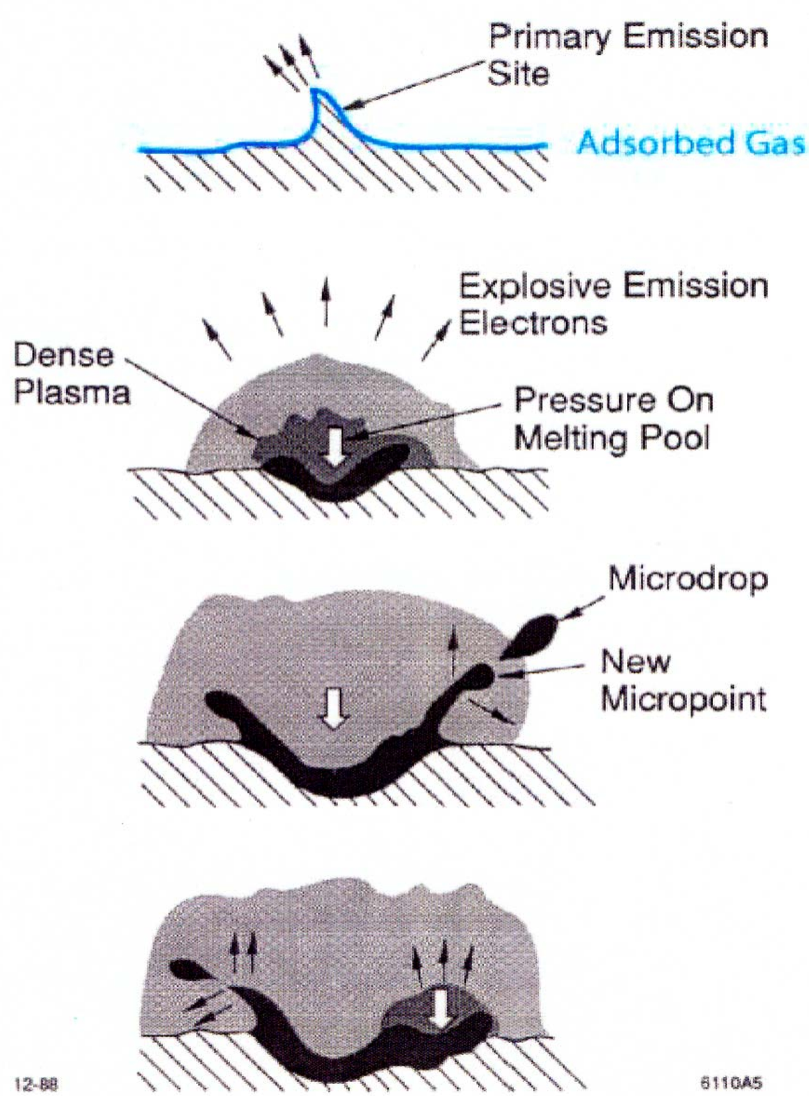


Rough Estimate of Number of Pits on Iris = 30,000

Number of Coupler Breakdown Events = 1500

Number of Pits per Breakdown = 20

Breakdown through Electron Emission and Damage

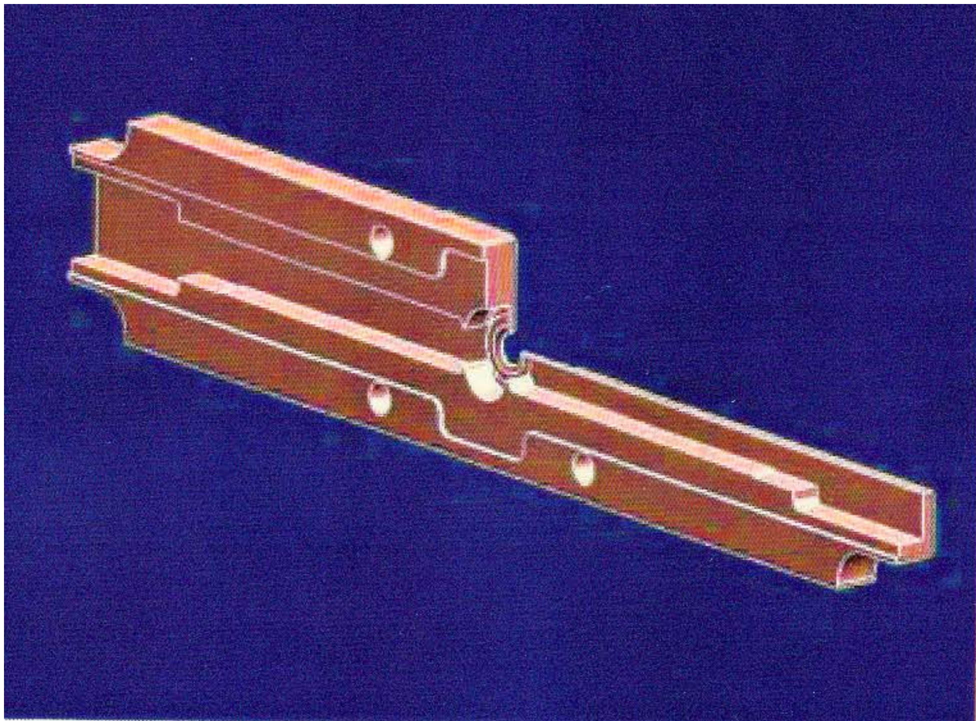


$E_{ACC} \sim 100$ MV/m

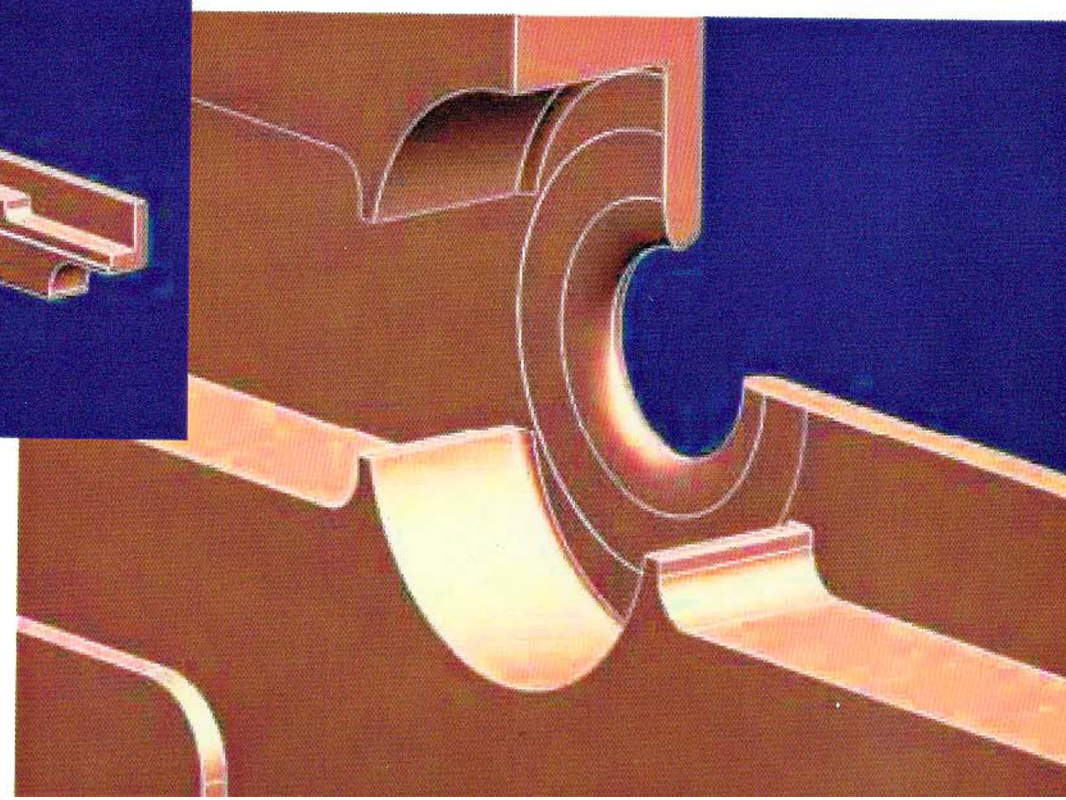
$E_{FLAT\ SURFACE} \sim 200$ MV/m

$E_{PROTRUSION\ IMPURITY} \sim 1.5$ GV/m

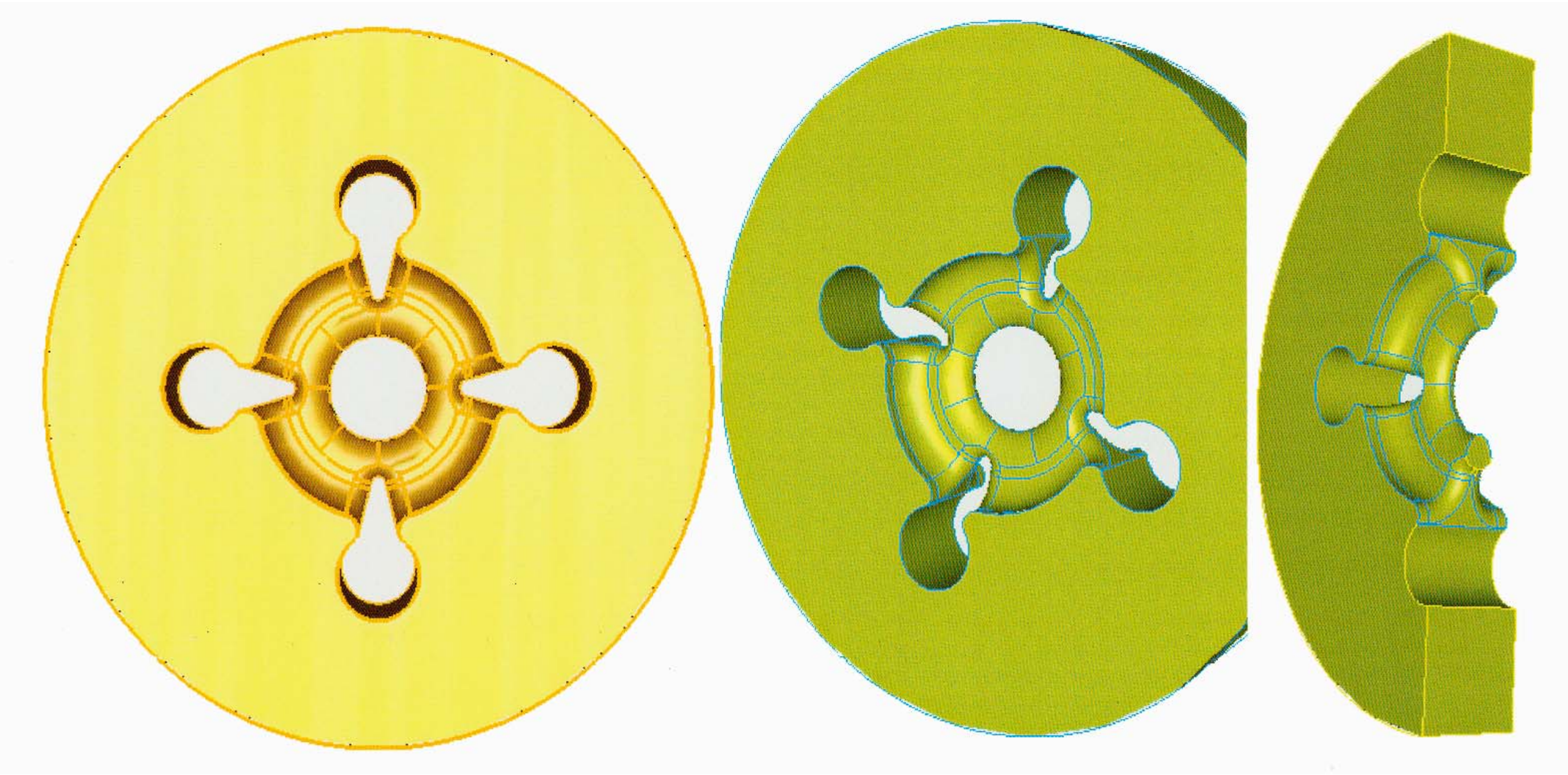
T53VG3RA Input Coupler



Pulse Heating

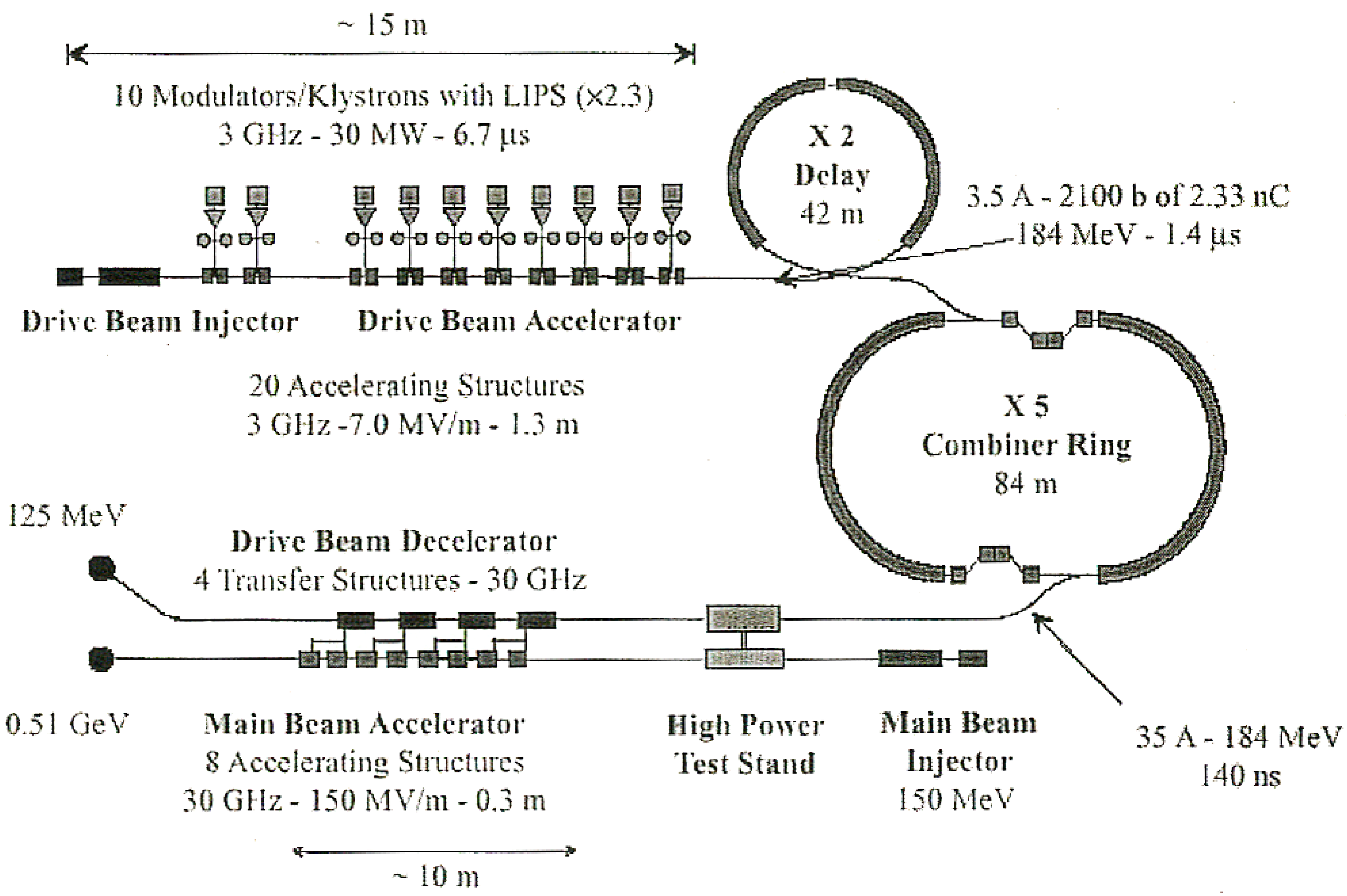


PIE-shaped Slot — rounded cell

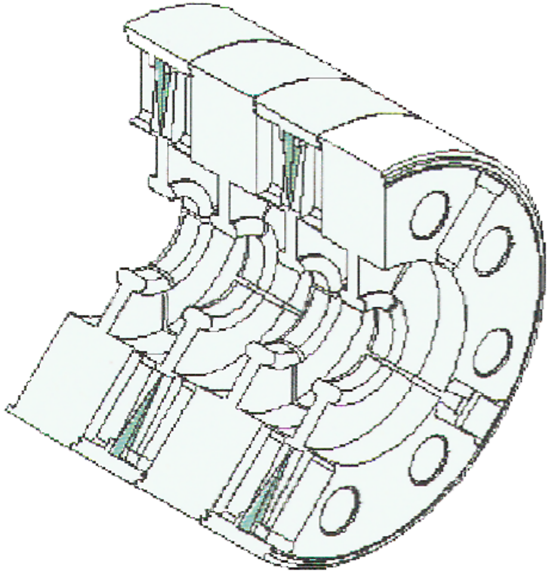


Overall Layout

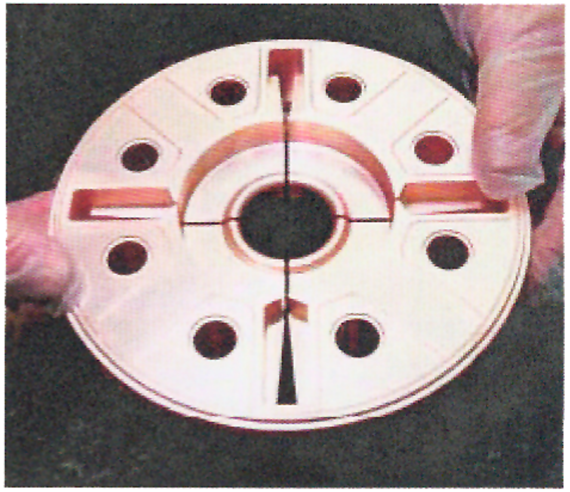
CLIC Test Facility CTF3



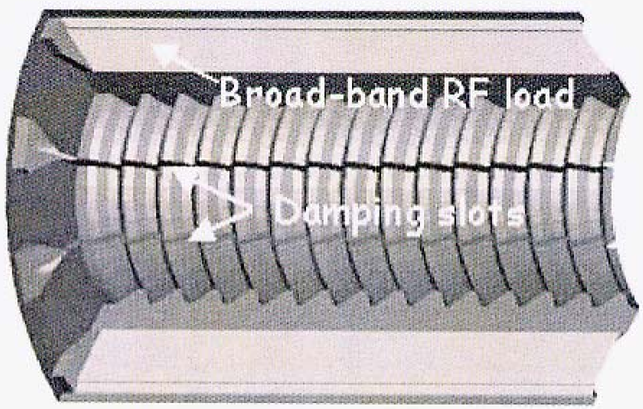
SICA Accelerating Structure



Conceptual view of the SICA accelerating structure



Machined disc of the 3 GHz version of the SICA structure



A quarter geometry of the C-PETS with 12 damping slots and SiC loads

Future Technologies

Lasers, Plasmas, Wakefields

Goal for Gradients ~ 1 GV/m

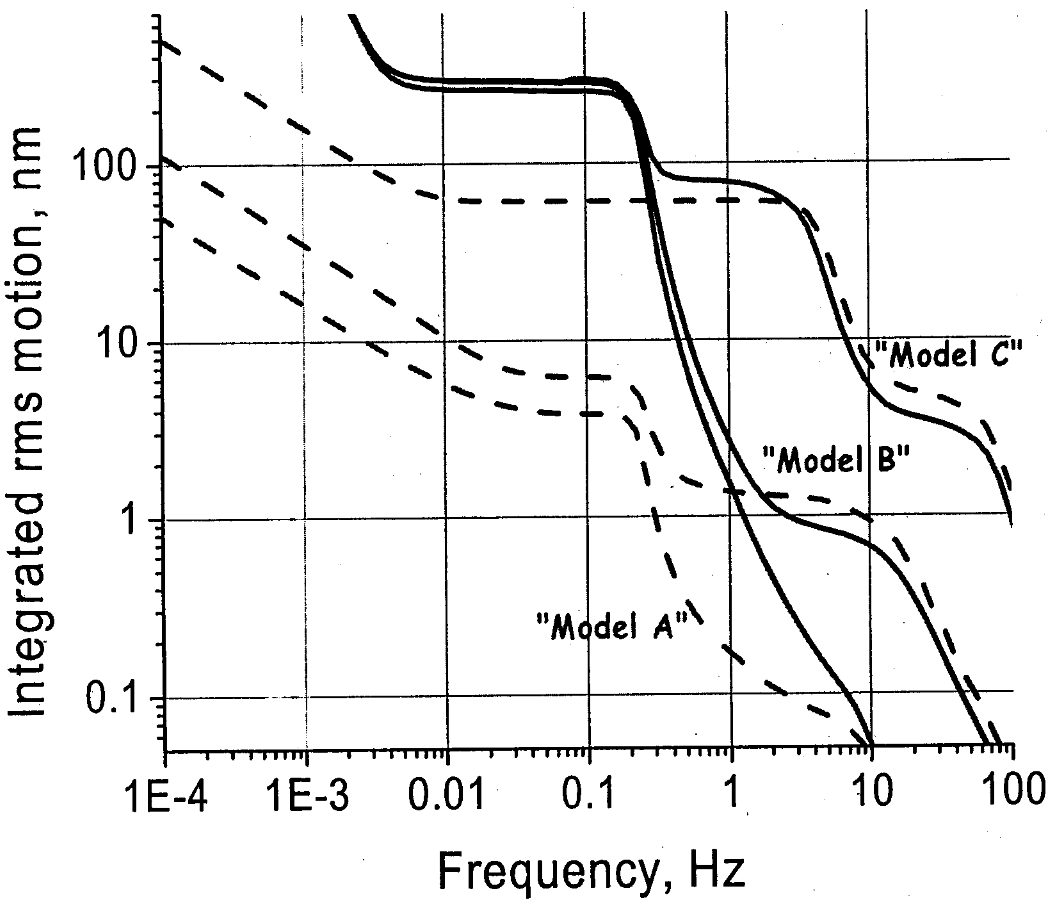
Compare with the CLIC 3 TeV goals

Gradient	172/150 MV/m
N	4×10^9
Bunches/sec	15400
$\gamma\varepsilon_x / \gamma\varepsilon_y$	$0.7/0.02 \times 10^{-6}$ m.rad
β_x / β_y	8/0.15 mm
$\sigma_x \sigma_y$	43/1 nm
δ_B	30.5%
Upsilon	8.3
AC to RF EFF.	40%
Luminosity	0^{35}cm^{-2}sec^{-1}

Challenges for Future Technologies:

- Can staging be achieved?
- Can similar N, bunches/sec be achieved?
- Can low emittances survive acceleration process?
- Can accelerating efficiency be achieved?

Ground Motion Models



3 models used for simulations

A - quiet

B - medium

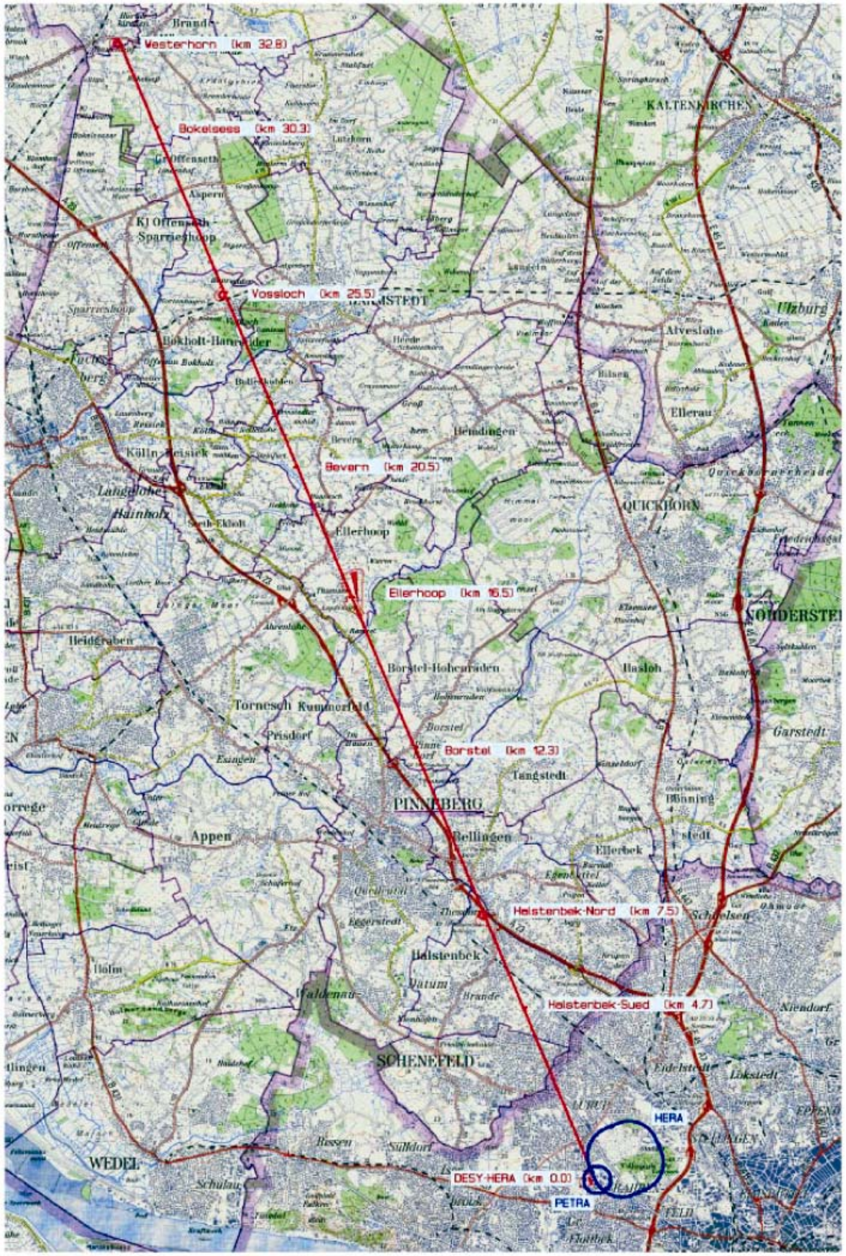
C - noisy

Based on data from various accelerators

Machine Tuning Simulations Sequence

1. Start with a perfect machine and calculate luminosity
2. Introduce errors likely to exist upon installation
3. Make corrections using Beam Based Alignment (BBA) and Beam Bumps, and tuning of the longitudinal phase space (bunch length, energy spread,energy)
4. Now include magnet jitter and ground motion

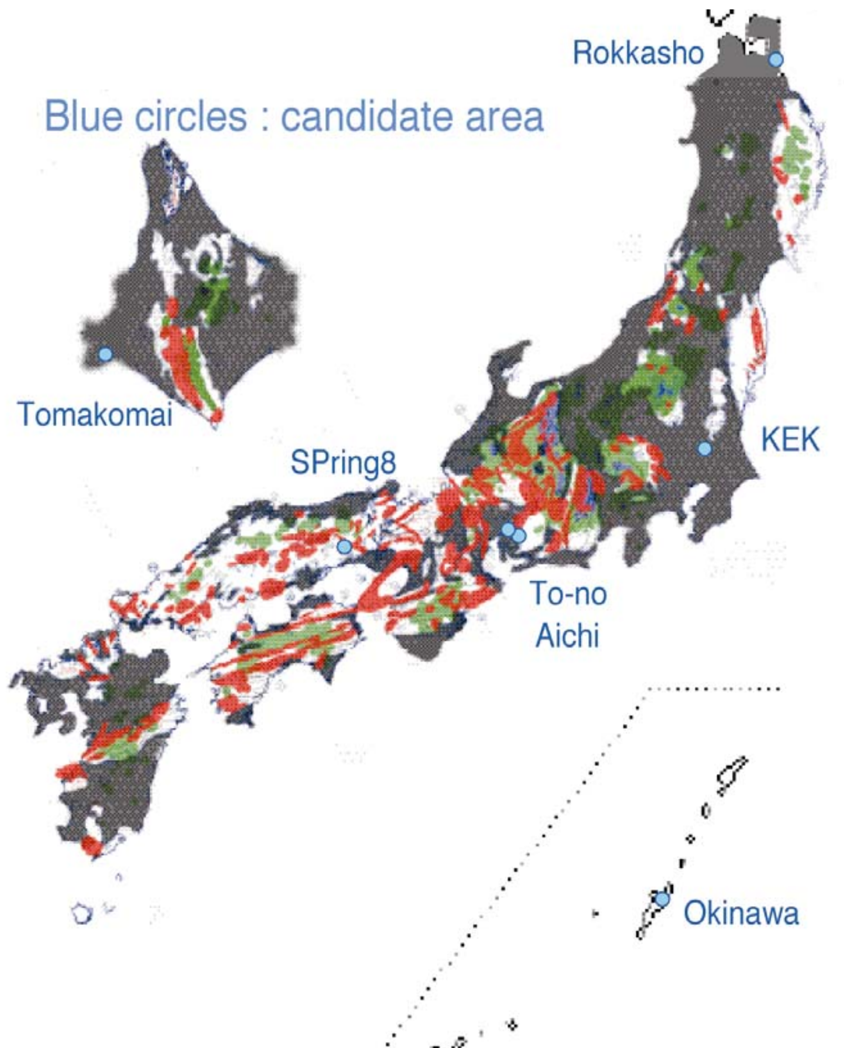
   assumptions along with energy jitter and changing klystron populations
5. Verify that beam-based feedbacks stabilize the beam and maintain luminosity over short-term
6. Repeat BBA and emittance tuning – verify that BBA and tuning algorithms converge in the presence of jitter (try to model realistic diagnostic performance)
7. Unfortunately, steps 3 and 5 will take several months to complete; hence steps 4 and 6 must proceed in parallel on the basis of guessed assumptions for the effectiveness of the BBA and beam tuning



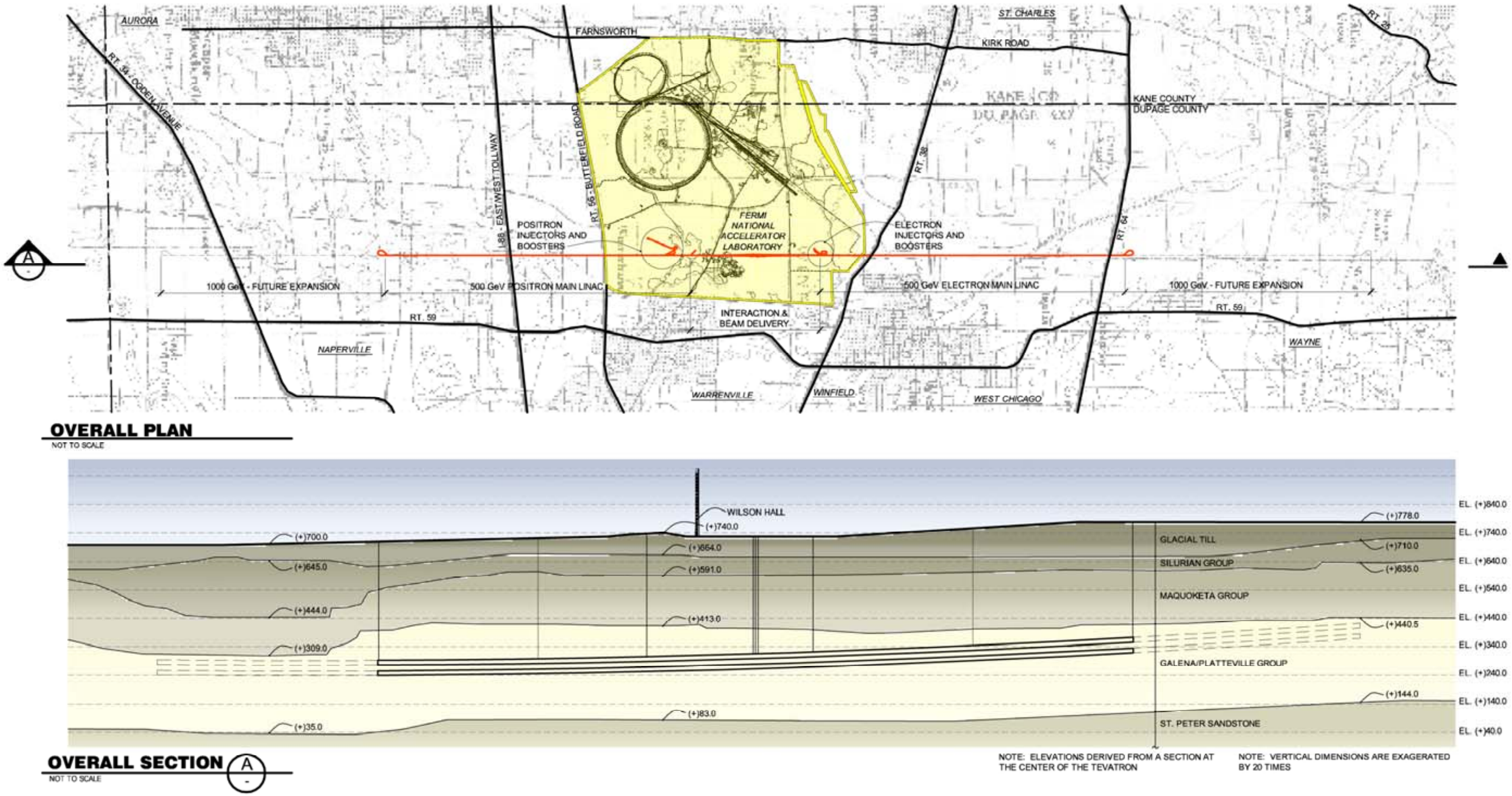
TESLA the region to the north-west of the DESY-Laboratory

Japanese Candidate Sites

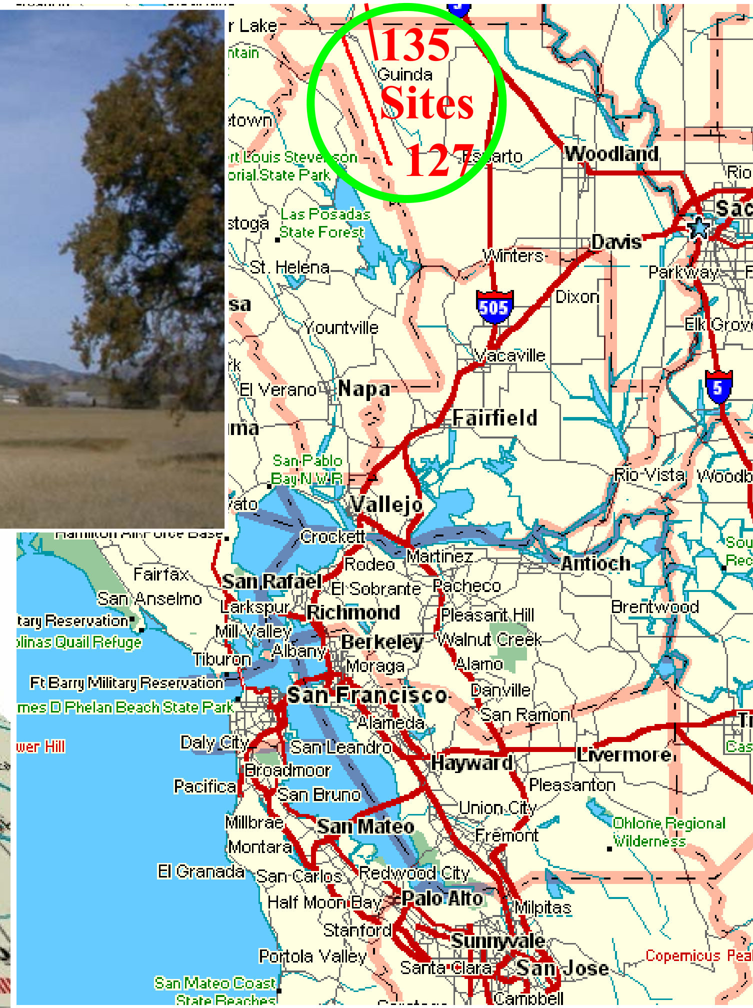
Close to existing National Science Centers



Illinois N-S Site



NLC representative sites in CA
(deep tunnel site 127 & cut and cover site135)



Second ILC-TRC Report
Future Milestones

July 30, 2002	Interim report to ICFA in Amsterdam
September 9-12, 2002	Fourth review (DESY)
October 9, 2002	Report to ICFA at CERN
December 2002	Publication of main report
Early 2003	Possible publication of Addenda

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