Positron Production for Linear Colliders

- **Linear Colliders**
- **Conventional Positron Production**
- **Undulator Based Positron Production**

Vinod Bharadwaj

Ronkonkoma, Sep 9, 2003

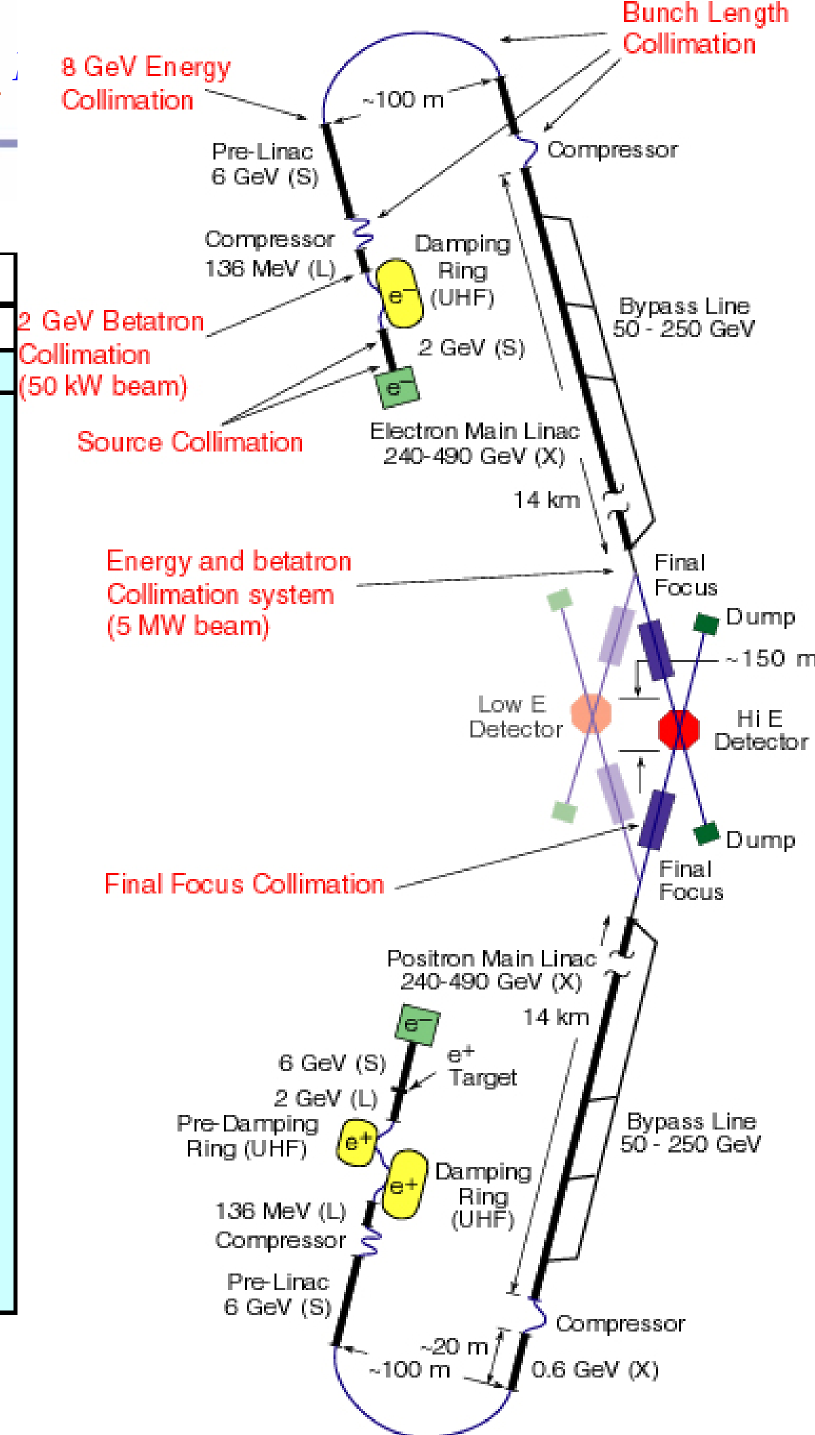
Linear Colliders

- Linear colliders are high energy electron-positron colliders
  - Synchrotron radiation limits the c.m.s. energies that can be achieved in a circular machines
  - Use two separate linacs to accelerate electron and positrons to very high energies and then collide the beams
- Multi-billion dollar devices
- The nominal beam energies are 250 GeV on 250 GeV
- Plans exist to run linear colliders from the Z mass and up to 1 TeV c.m.s. or even higher
- Different projects, very large international collaborations
  - NLC , effort led by SLAC (base of experience with the SLC)
  - GLC, formerly the JLC , effort led by KEK, Japan
  - TESLA, effort led by DESY
- Different technologies
  - X-band warm linacs
  - L-band super-conducting linacs
- Machines complementary to the high energy hadron colliders
- Potential to discover the Higgs, SUSY …

NLC/GLC Parameters &Layout

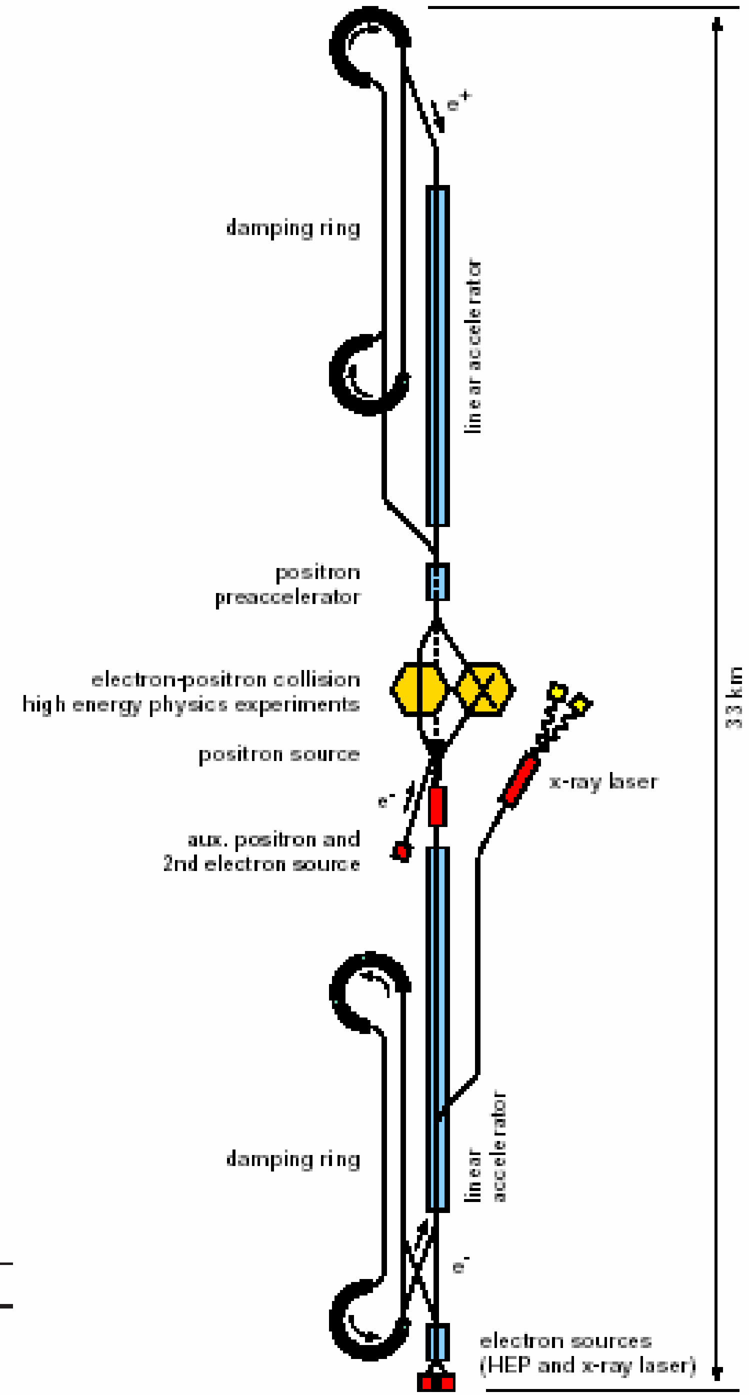
High Energy IP Parameters

	Stage 1		Stage 2	
CMS Energy (GeV)	500		1000	
Site	US	Japan	US	Japan
Luminosity (10^{33})	**20**	**25**	**30**	**25**
Repetition Rate (Hz)	120	150	120	100
Bunch Charge (10^{10})	**0.75**		**0.75**	
Bunches/RF Pulse	192		192	
Bunch Separation (ns)	1.4		1.4	
Loaded Gradient (MV/m)	**50**		**50**	
Injected $\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ (10^{-8})	300 / 2		300 / 2	
$\gamma\varepsilon_x$ at IP (10^{-8} m-rad)	360		360	
$\gamma\varepsilon_y$ at IP (10^{-8} m-rad)	**4**		**4**	
β_x / β_y at IP (mm)	8 / 0.11		13 / 0.11	
σ_x / σ_y at IP (nm)	**243 / 3.0**		**219 / 2.1**	
θ_x / θ_y at IP (nm)	**32 / 28**		**17 / 20**	
σ_z at IP (um)	110		110	
Υ_{ave}	0.14		0.29	
Pinch Enhancement	1.51		1.47	
Beamstrahlung δB (%)	5.4		8.9	
Photons per e+/e-	1.3		1.3	
Two Linac Length (km)	13.8		27.6	



Tesla : Parameters & Layout

Accelerating gradient	E_{acc} [MV/m]	23.4
RF-frequency	f_{RF} [GHz]	1.3
Fill factor		0.747
Total site length	L_{tot} [km]	33
Active length	[km]	21.8
No. of accelerator structures		21024
No. of klystrons		584
Klystron peak power	[MW]	9.5
Repetition rate	f_{rep} [Hz]	5
Beam pulse length	T_P [μs]	950
RF-pulse length	T_{RF} [μs]	1370
No. of bunches per pulse	n_b	2820
Bunch spacing	Δt_b [ns]	337
Charge per bunch	N_e [10^{10}]	2
Emittance at IP	$\gamma\varepsilon_{x,y}$ [10^{-6}m]	10, 0.03
Beta at IP	$\beta^*_{x,y}$ [mm]	15, 0.4
Beam size at IP	$\sigma^*_{x,y}$ [nm]	553, 5
Bunch length at IP	σ_z [mm]	0.3
Beamstrahlung	δ_E [%]	3.2
Luminosity	L_{e+e-} [10^{34}cm^{-2}s^{-1}]	3.4
Power per beam	$P_b/2$ [MW]	11.3
Two-linac primary electric power (main linac RF and cryogenic systems)	P_{AC} [MW]	97
e^-e^- collision mode:		
Beamstrahlung	$\delta_{E,e-e-}$ [%]	2.0
Luminosity	L_{e-e-} [10^{34}cm^{-2}s^{-1}]	0.47



Positron Sources

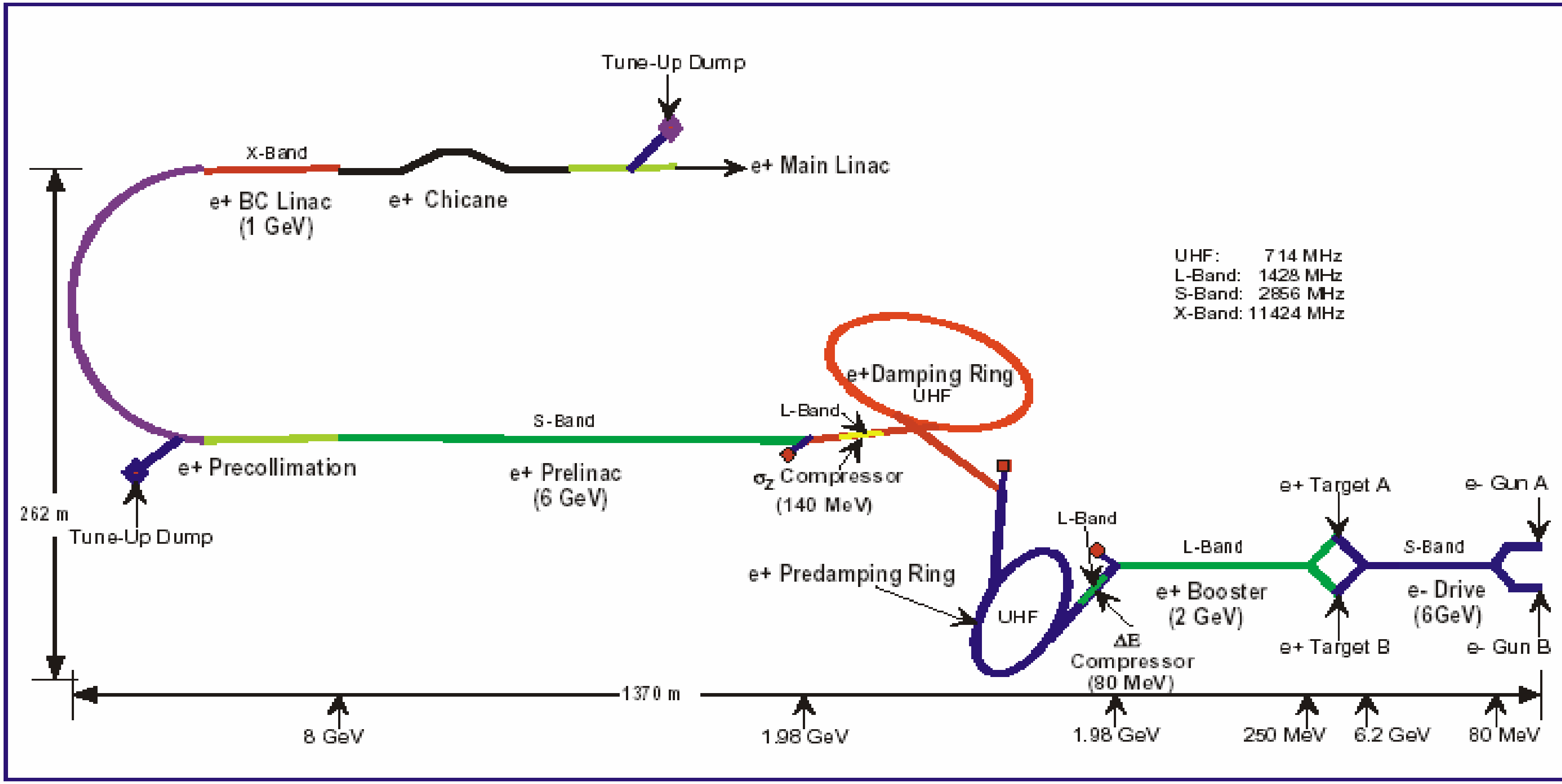
- Positron Production
  - Conventional
    - Target high energy electron beam onto a few radiation lengths of a target made of a high-z , high density material
    - This was the technique used at the SLAC Linear Collider
  - Undulator-Based
    - Use a very high energy beam to make multi-MeV photons in an undulator
    - Target these photons onto a thin target to make positrons
    - If the undulator is helical, the photons will be circularily polarized and hence the positrons will be polarized
  - Compton backscattering
    - Backscattering a high optical laser beam high produced high energy polarized photons that can then produce positron in a thin target
- The systems for capturing the produced positrons and producing usable beams are fairly independent of the method of positrons production
  - e.g. in the NLC, the target is followed by SLC-like matching device (6-7 T flux concentrator). The positrons are then captured in a L-band RF system and accelerated to 250 MeV, focused by high-gradient solenoids and then accelerated to the damping ring energy (1.98 GeV) in an L-band accelerator. The beam is then damped in a series of two damping rings

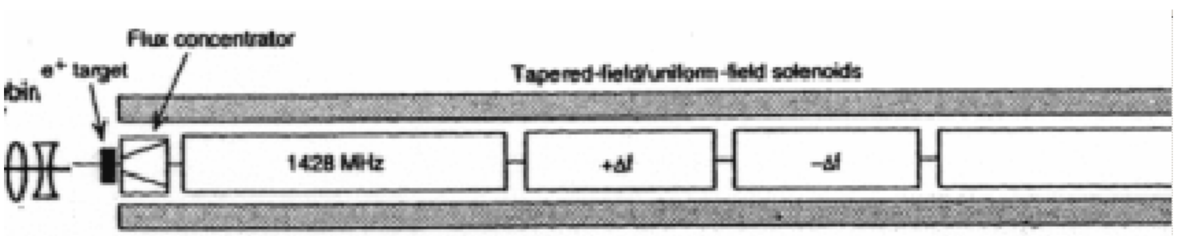
CONVENTIONAL: NLC Positron Source Parameters

(beam delivered to positron pre-damping ring)

Parameter Name	Symbol	Injector Output		Units
Bunch Spacing	T_b	2.8	1.4	ns
Energy	E	1.98	1.98	GeV
Energy Adjustability	ΔE	±5	±5	%
Bunch Energy Variation	$\delta E/E$	1	1	% Full Width
Single Bunch Energy Spread	σ_E/E	2	2	% Full Width
Emittance (norm. edge)	$\gamma\varepsilon_{x,y}$	.03	.03	m-rad
Bunch Length	σ_Z	<10	<10	mm
Particles/Bunch	n_B	1.8	0.9	10^{10} particles
Train Population Uniformity	$\Delta n_T/n_T$	1	1	% Full Width
Bunch-to-Bunch Pop. Uniformity	$\Delta n_B/n_B$	2	2	% rms
Number of Bunches	N_b	96	192	#
Repetition Rate	f	120	120	Hz
Horizontal Beam Jitter	$\Delta\gamma J_x$	.015	.015	m-rad
Vertical Beam Jitter	$\Delta\gamma J_y$	.015	.015	m-rad
Beam Power	P_b	65	65	kW

NLC Positron Injector





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Ronkonkoma Sep 9, 2003

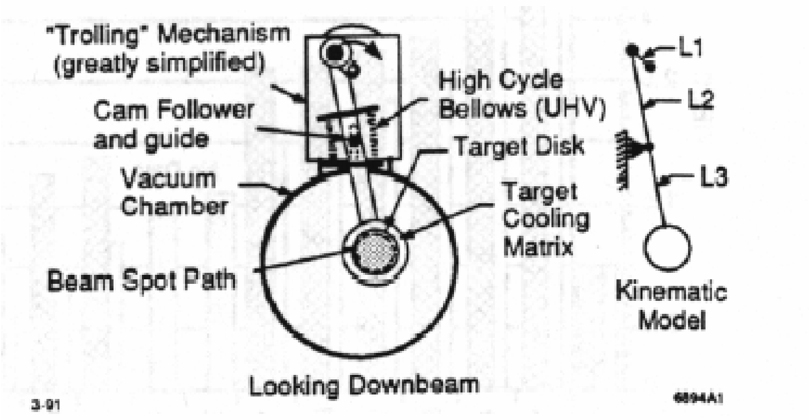
Electron Drive Linac Parameters

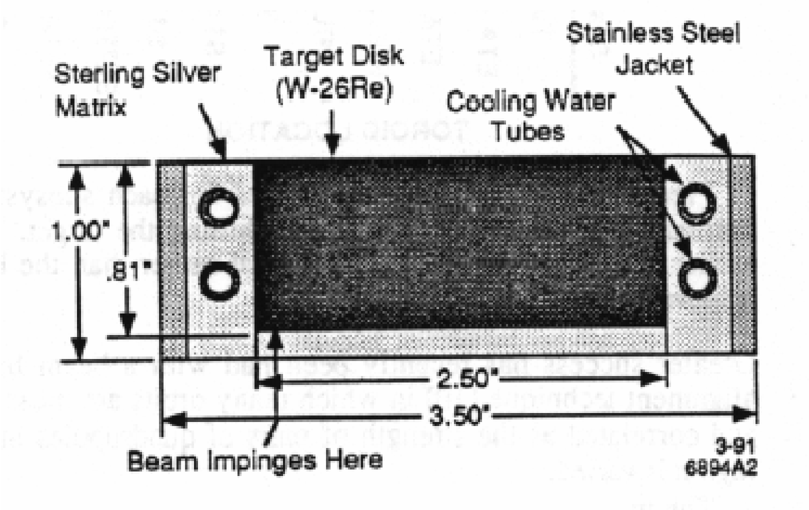
(for the NLC Positron Source)

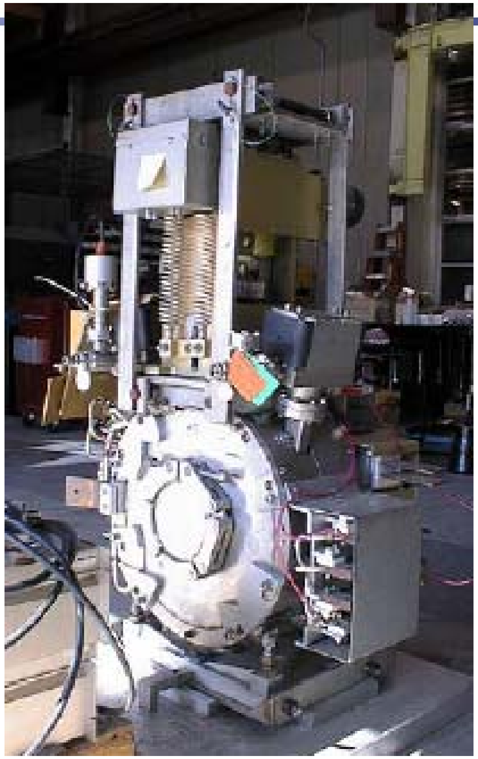
Drive Linac Electron Beam Parameters:

Parameter Name	Symbol	Output		Units
Bunch Spacing	T_b	2.8	1.4	ns
Energy	E	6.2	6.2	GeV
Bunch Energy Variation	$\delta E/E$	1	1	% Full Width
Single Bunch Energy Spread	σ_E/E	1	1	% Full Width
Emittance (norm. rms)	$\gamma\varepsilon_{x,y}$	100.0	100.0	10^{-6} m-rad
Bunch Length	σ_Z	1.6	1.6	microns
Particles/Bunch	n_B	3.0	1.5	10^{10} particles Yuri's Yield=0.6
Train Population Uniformity	$\Delta n_T/n_T$	1	1	% Full Width
Bunch-to-Bunch Pop. Uniformity	$\Delta n_B/n_B$	2	2	% rms
Number of Bunches	N_b	96	192	#
Repetition Rate	f	120	120	Hz
Horizontal Beam Jitter	$X_{/}\sigma_x$	10	10	%
Vertical Beam Jitter	$Y_{/}\sigma_y$	10	10	%
Beam Power	P_b	339	339	kW

SLC Positron Target







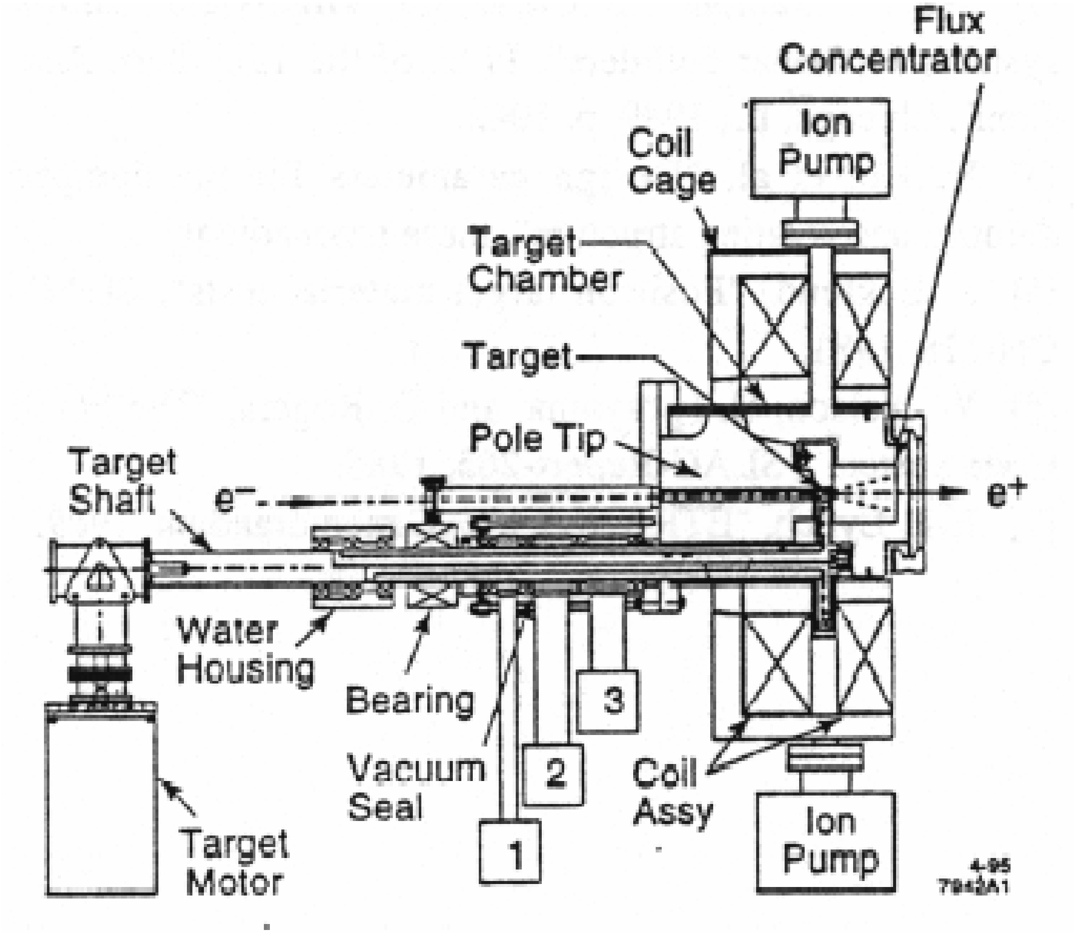
The NLC target design uses the operational experience gained from the SLC.

SLC positron target made of 6 r.l. W-Re. "Trolling target". Was made so that average heating would not damage the target

SLC drive beam is 30 GeV, 4 x 10^{10} e^-/bunch, 1 bunch/pulse, 120 pulses/sec, 24 kW

NLC Positron Target

NLC positron target design – extrapolated from the SLC positron target



NLC spinning target design.

20 cm. dia. W Re target ring. 23 kW deposited

Oscillating at 1/2 Hz.

Beam rate is 120 Hz.

Spinning shaft with water and vacuum seals.

Extrapolation to NLC Drive Beam Power

- NLC target made bigger to allow for greater average beam power (340 kW as compared with 24 kW)
- The energy deposition for a single pulse in the NLC target is calculated to be below the level that will damage the target material.
- The SLC was thought to be a factor of two below damage threshold
- BUT
  - The SLC positron target failed (after 5 years of operation)
  - Failure lead to a detailed analysis of materials properties: radiation damage, shock and stress, fatigue, etc.

Positron target damage threshold analysis

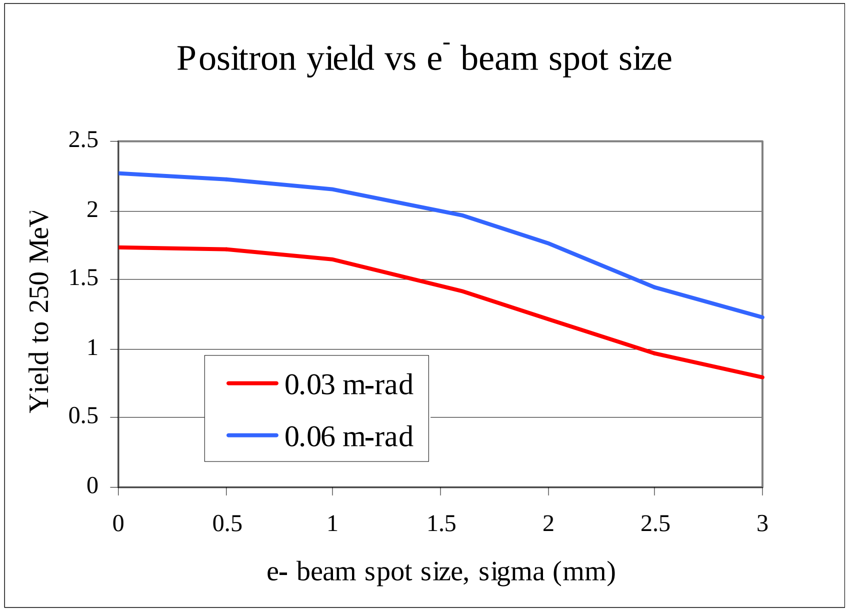
- R&D Effort – How best to design our way around this problem
  - SLC target materials analysis at LANL (L. Waters, S. Maloy, M. James, *et al*)
  - Shock & dynamic stress and radiation damage analysis at LLNL (W. Stein *et al*)
    - Old NLC baseline design has stresses in excess of fresh target strength
  - Analysis of coupon tests to validate analyses at LLNL (A. Sun-Woo)
  - Design of improved W Re target material at LLNL (A. Sun-Woo)
  - Yield simulations to determine electron beam power (Y. Batygin)
  - Investigations of other target materials; Cu, Ni (as at FNAL pbar source) & liquid metal (Pb) targets at BINP (G. Silvesterov, *et al*)
  - Beam tests of the target design at SLAC

- Analysis leads to new e^+ source designs
  1. Divide the bunch train into lower power trains
  2. Spread the beam in time to alleviate instantaneous shock stress

Positron system yield calculations

Start–to–End simulation of yield (e^+/e^-), from e^+ out of target (from EGS)to pre-DR

Allows optimization of
- spot size
- collection
- RF phasing
- energy compression
- target material: WRe, Cu, Ni, …

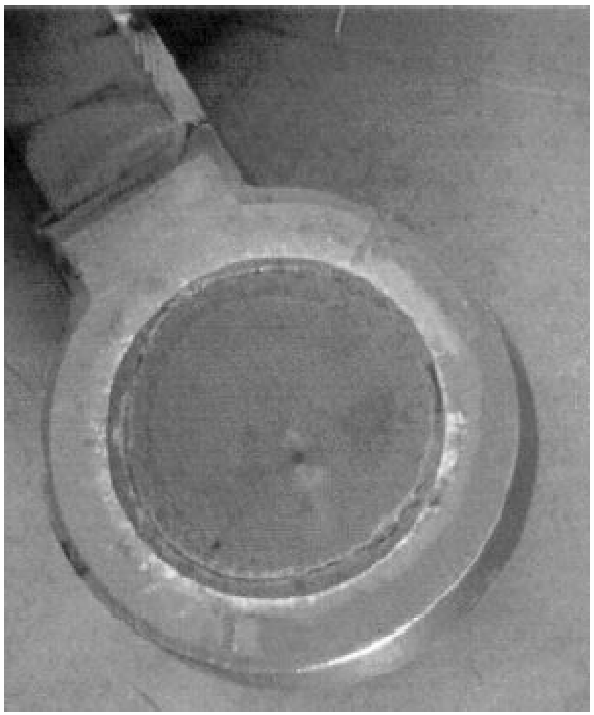


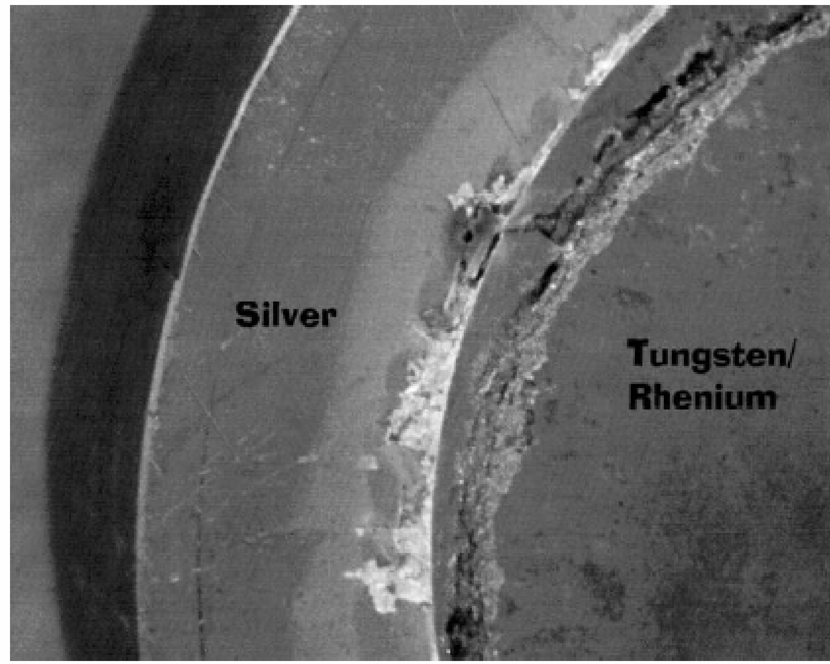
- Yield of 0.76 e^+/e^- gives:

NLC	4RL $W_{25}Re$	6.2 GeV	190 x 1.2 $x10^{10}$	1.6 mm	125 J/g
SLC	6RL $W_{25}Re$	33 GeV	1 x $4x10^{10}$	0.8 mm	28 J/g

EGS results for maximum energy deposition

SLAC Target Damage

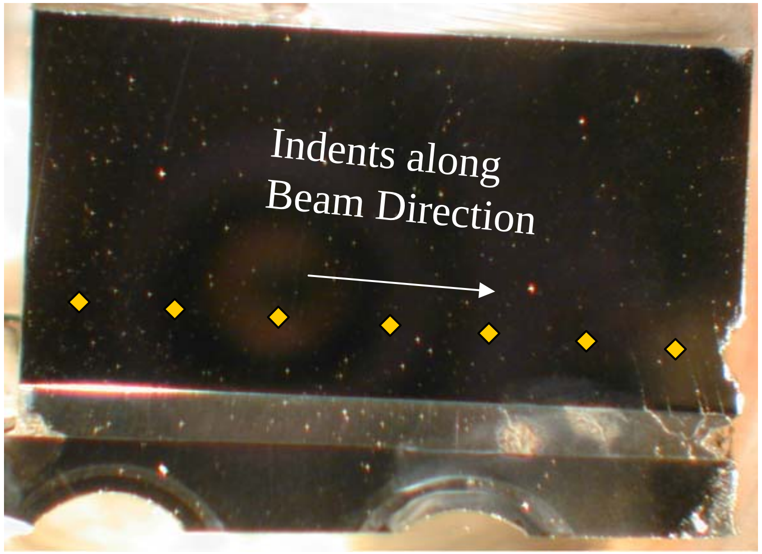


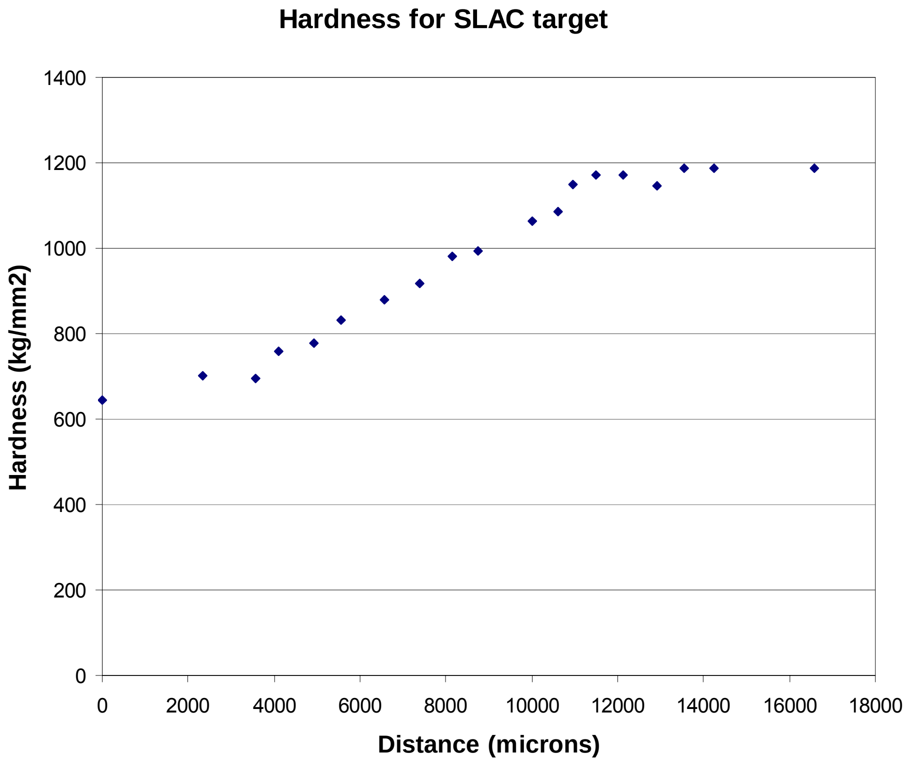


SLC target damage studies were done at LANL. Results show evidence of cracks, spalling of target material and aging effects.

SLC target materials analysis at LANL

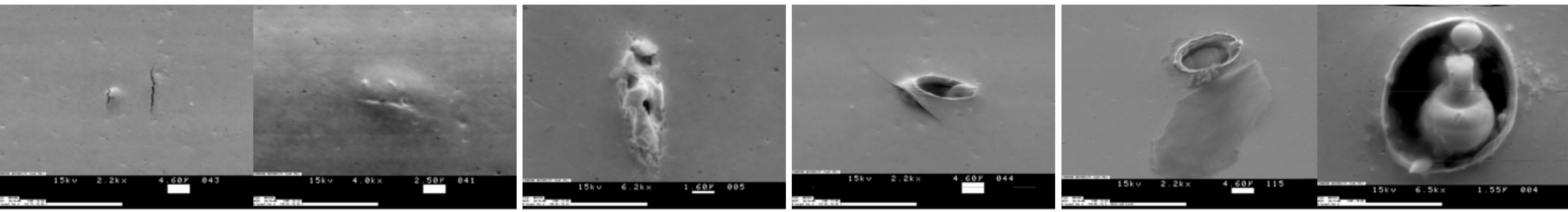
The SLC positron target was cut into pieces and metalographic studies done to examine level of deterioration of material properties due to radiation exposure.





Radiation damage, work hardening, or temperature cycling?

Coupon Tests of Target Material in SLAC BEAM



263 J/g 319 J/g 344 J/g 420 J/g 770 J/g 2101 J/g

Results from irradiating W-Re at different energy depositions using SLAC beam focused down to small spots (1 x 10^{10} electrons , 45 GeV, focused to small spots)

Tests done with Ti, Cu, GlidCop, Ni, Ta, W and W-Re

Pictures show that target material melts before showing obvious evidence of shock/stress effects. Results not completely understood.

Shock & Stress Calculations

- Calculations done at LLNL
  - Shock, stress, thermal heating effects investigated
- Conclusions
  - SLC target should have been fine
  - However target aging could have reduced tensile strength of material and cracks in target may cause local heating
  - Shock and stress effects have timescales of about a microsecond, so spreading out beam in time may help
- PAC2001 Paper

THERMAL SHOCK STRUCTURAL ANALYSES OF A POSITRON TARGET

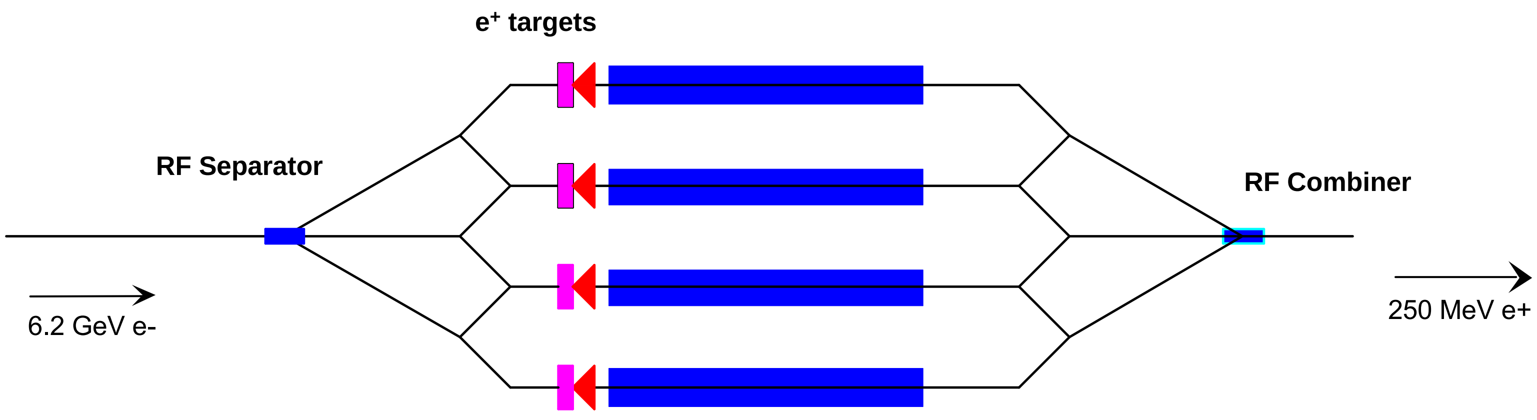
W. Stein, A. Sunwoo, LLNL,* Livermore, CA, USA
V.K. Bharadwaj, D.C. Schultz, J.C. Sheppard, SLAC,* Stanford, CA, USA

Positron target – multiple stations

Do not feel comfortable with energy depositions beyond SLC, therefore NLC baseline changed to incorporate multiple targets.

An RF multiplexed e^+ source system

- The 192 bunches in a train are sequentially dealt to N targets
- Each target sees 1/N the shock & stress & heating
- NLC baselines has three targets stations (and one spare)



3 out of 4 target system schematic

RF multiplexed positron source

Transverse layout

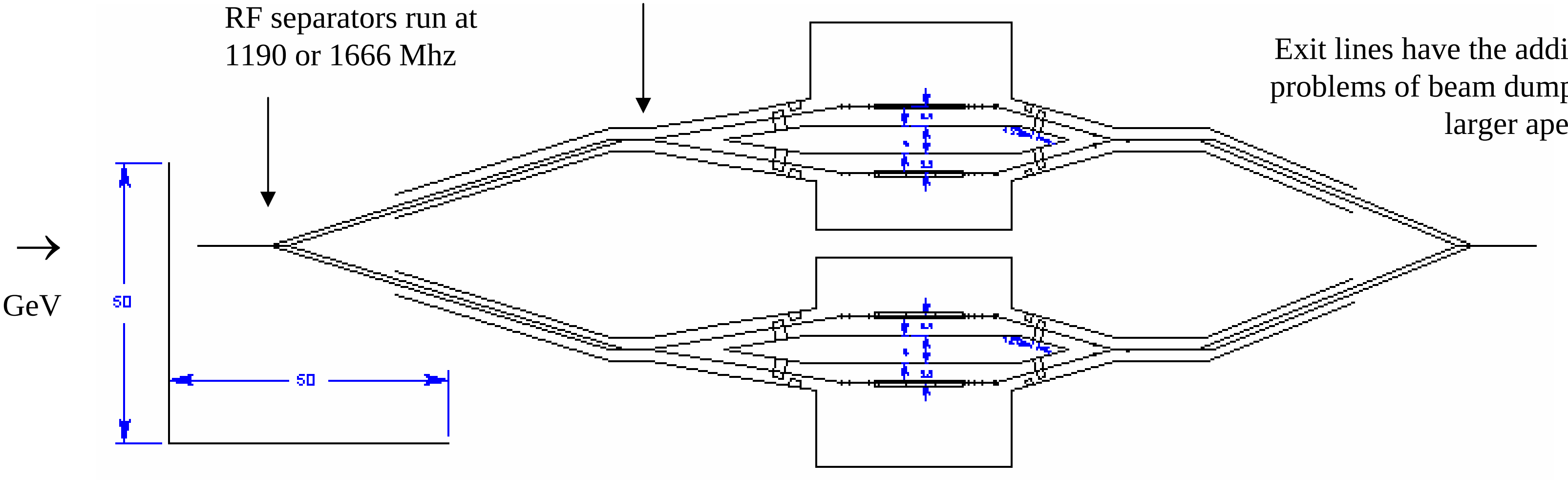
- 4 targets: 3 operating, 1 spare/repair
- Access and 5m shielding between vaults sets scale
- Detailed design needed

Chicane makes up for small difference in path lengths, correcting for exit line length differences as well.

RF separators run at 1190 or 1666 Mhz

Exit lines have the additional problems of beam dumps and larger apertures

e^- in at 6 – 8 GeV



NLC Source Parameters – 3 target stations

PARAMETER NAME	SYMBOL	VALUE	UNITS
Bunch Spacing	T_B	1.4 (2.8)	ns
TARGET			
Drive Beam Energy	E	6.2	GeV
Drive Beam Energy Spread	ΔE	1	% full width
Electrons/Bunch on Target	n_B	1.5 (3)	10^{10} particles
e^- Bunch-to-Bunch Pop. Uni.	$\Delta n_B/n_B$	<0.5	% rms
Number of Bunches	N_B	63 (32)	#
Incident Beam Radius	σ_r	1.6	mm rms
Repetition Rate	f	120	Hz
Drive	P_b	113	kW
Target Material		$W_{75}Re_{25}$	
Target Thickness	L_T	4	Rad. Length
Peak Energy Deposition	$\Delta E/\Delta vol$	35	J/g
Absorbed Target Power	P_T	16	kW
POSITRON CAPTURE			
RF Frequency	f_{rf}	1428	MHz
Bunch Length	ΔT	60	ps full width
Capture Energy	E_C	250	MeV
Capture Emittance (norm. edge)	$\gamma\varepsilon_{x,y}$	0.03	m-rad
Pre-DR Acceptance (norm.)	γA	0.045	m-rad
Yield@ 250 MeV	Y_C	1.4	e^+/e^-
Yield@ 1.98 GeV into γA = 0.03 m-rad	Y_{PDR}	1.0	e^+/e^-

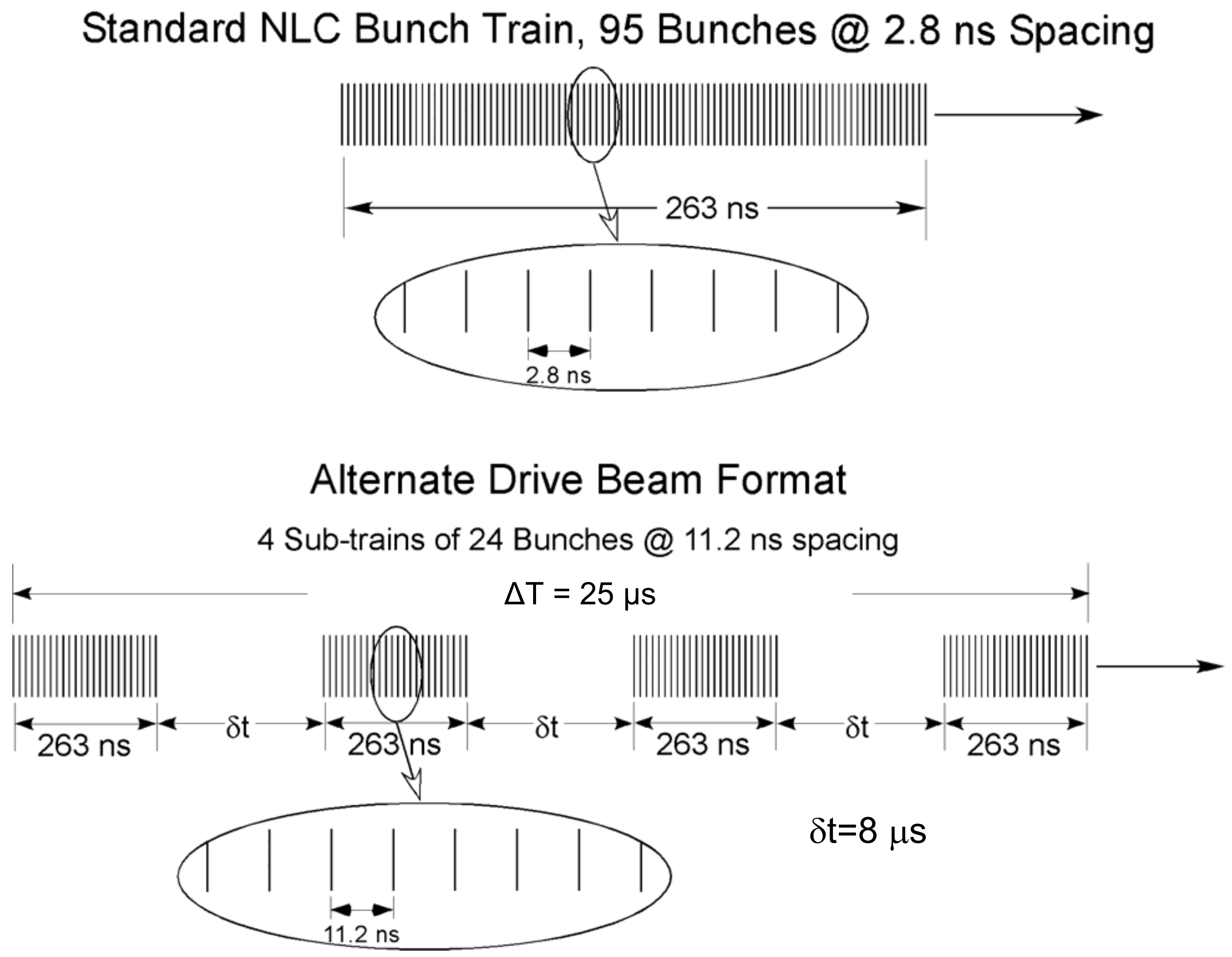
Stretched pulse positron source scheme

Basic Idea

- Timescales
  - Instantaneous shock timescale is microseconds.
  - Temperature dissipation timescales are ~ 0.1 seconds
    - stress levels due to temperature gradient (500 °C) are lower than instantaneous shock
- Consider spreading out the NLC drive beam
  - In time (to 25 μs)… to reduce instantaneous shock
    - The concept comes out of the LLNL analysis
  - In space … to reduce local temperature rise
    - Spin the target at 4000 RPM to get temperature gradient ~200 °C

Stretched pulse positron source scheme

Drive Beam Format



Undulator-Based Positron Sources

- The undulator based sources are advantageous because
  - Conventional targets many radiation lengths, need to use high density, high-z materials to avoid emittance blowup of the produced beam
  - Undulator-based positron targets are fractions of a radiation length
  - Can use stronger materials such as Ti-alloys
- The original TESLA linear collider design always had undulator based positron production
  - The very high energy electron beam that is needed to produced the multi-MeV photons in the undulator is in fact the “spent” electron beam after the collider collision point.
  - This scheme places limits on collision energy because the electron beam has to have enough energy to be able to produced the needed multi-MeV photons in the undulator
  - The positron sources performance is affected by the need to tune the collision energy which in affects the positron yield, positron system tuning.
  - The TESLA undulator for making the multi-MeV photons is planar. Planar undulator are straightforward to make, but cannot produce polarized photons and hence polarized positrons. Also helical undulators can be a factor of 2 shorter
- US Linear Collider Group (USLCG) has adopted undulator-based positron sources in its base line

USLCG: Undulator-Based Positron Systems

US LC physics requirements specified by the USLCSG Physics/detector Subcommittee

- initial energy 500 GeV c.m.
- upgrade energy: at least 1000 GeV c.m.
- electron beam polarization > 80%
- an upgrade option for positron polarization
- integrated luminosity 500 fb^{-1} within the first 4 yrs of physics running, corresponding to a peak luminosity of $2x10^{34}cm^{-2}s^{-1}$.
- beamstralung energy spread comparable to initial state radiation.
- site consistent with two experimental halls and a crossing angle.
- ability to run at 90-500 GeV c.m. with luminosity scaling with E_{cm}

G. Dugan, NLC Coll. 6/17/03

USLCG: Undulator-Based Positron Systems

Warm option reference design

New features of 2003 NLC configuration:

- SLED-II pulse compression
- 2-pack modulator
- 60 cm, 3% v_g HDS structures
- EM quads in linac
- Improved damping ring design
- Improved positron source
- BNL-style SC final focus doublet
- "Low-energy" IR reach improved to 1.3 TeV

Differences between the warm option reference design and the 2003 NLC design:

• The use of an undulator based positron source, utilizing the high energy electron beam at 150 GeV, instead of the conventional positron source

• At the subsystem and component level, specification changes to facilitate comparison with the cold LC option.

G. Dugan, NLC Coll. 6/17/03

USLCG: Undulator-Based Positron Systems

Cold option reference design

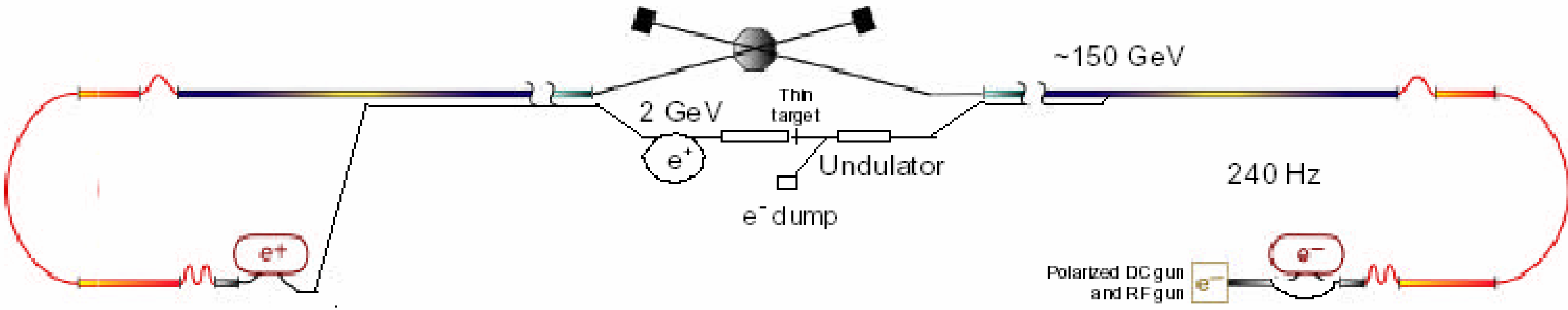
The major changes to be made to the TESLA design are:

- An increase in the upgrade energy to 1 TeV (c.m.), with a tunnel of sufficient length to accommodate this in the initial baseline.
- Use of the same injector beam parameters for the 1 TeV (c.m.) upgrade as for 500 GeV (c.m.) operation
- The choice of 28 MV/m as the initial main linac design gradient for the 500 GeV (c.m.) machine.
- The use of a two-tunnel architecture for the linac facilities.
- An expansion of the spares allocation in the main linac.
- A re-positioning of the positron source undulator to make use of the 150 GeV electron beam, facilitating operation over a wide range of collision energies from 91 to 500 GeV
- The adoption of an NLC-style beam delivery system with superconducting final focus quadrupoles, which accommodates both a crossing angle and collision energy variation.
- At the subsystem and component level, specification changes to facilitate comparison with the warm LC option.

G. Dugan, NLC Coll. 6/17/03

Generic Undulator-Based Collider

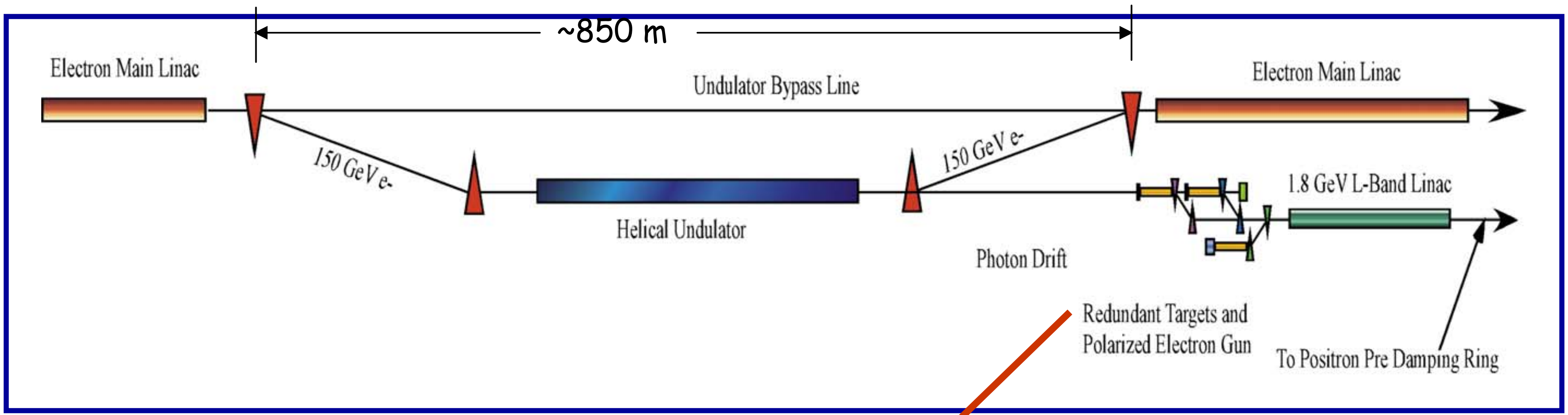
- Produce multi-MeV gammas using a long undulator and >150 GeV electron beam
- Multi-MeV gammas pair produce in a thin (0.2 RL) converter
- Positron are collected by flux concentrator/L-band rf/solenoid system
- Use of high strength titanium alloys mitigates target damage problems
  - Use extracted beam from part of electron linac instead of the spent beam after collisions
  - If helical undulator, then circularly polarized gammas and polarized positrons
  - Two target stations for redundancy/reliability



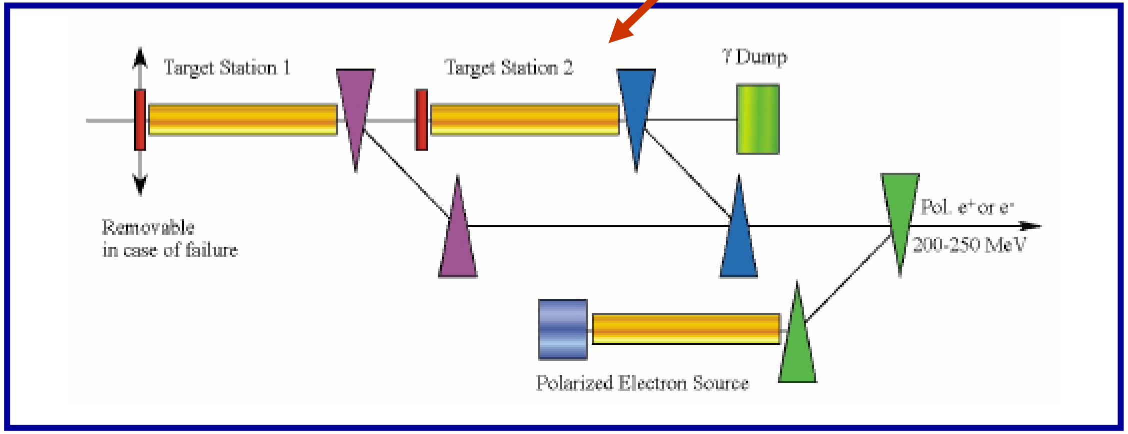
USLCG Positron Source Parameters

	TESLA TDR	Unpolarized	Polarized	Conventional
Drive Beam Energy [GeV]	250	153	153	6.2
Beam Energy Loss [GeV]	3.0	4.9	6.5	-
Beam Energy Spread In [%]	0.05	0.50	0.50	-
Beam Energy Spread Out [%]	0.10	0.46	0.46	-
Additional Linac Length [m]	120	95	126	230
Undulator Length [m]	100	150	200	-
Undulator Insertion Length [m]	340	790	850	-
Positron Source Length [m]	400	450	450	450
Photon Energy [MeV]	28.0	10.7	10.7	-
Undulator type	K=1; Planar	K=1; helical	K=1; helical	-
Undulator Field [T]	0.75	1.07	1.07	
Undulator Period [cm]	1.4	1.0	1.0	-
Undulator Full Gap [mm]	5	6	6	-
Pulse Energy on Target [kJ]	26.9	1.1	1.1	0.7
Average Power on Target [kW]	135	136	126	85
Spot Size on Target [mm]	0.75	0.75	0.75	1.6
Target Material	Ti-alloy	Ti-alloy	Ti-alloy	W74-Re26
Target Thickness [r.l.]	0.4	0.4	0.4	4.0
Target Energy Adsorption [%]	4	9	8	14
Beam Polarization [%]	0	0	59	0
Positron Yield	2.0	1.4	1.5	1.5

USLCG Positron Production Schematic – Undulator Based

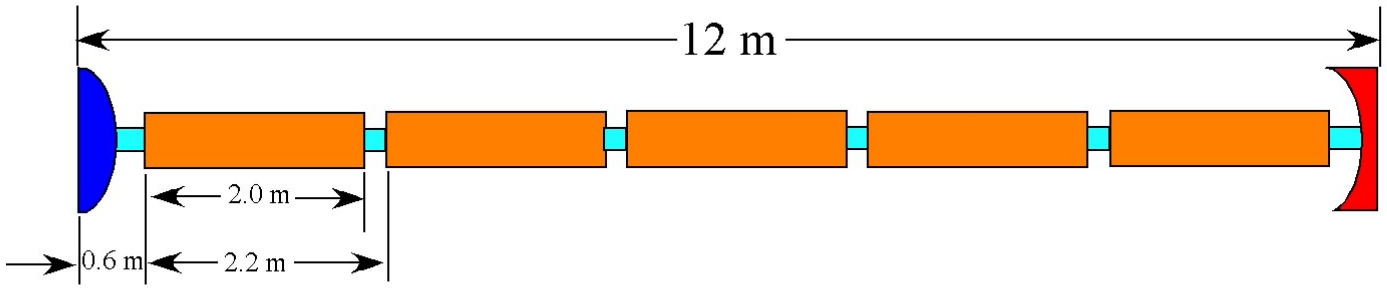


2 Target assembles for redundancy



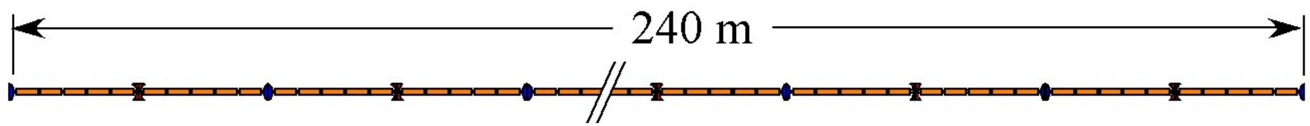
NLC/USLCSG Polarized Positron System Layout

Undulator Lattice Half Cell



[Undulator Module Parameters: Helical, K=1, λ_u=1 cm (B_0=1.07 T), ID=6-7 mm, L_u=2.0 m]

Undulator Lattice, 10 FODO Cells

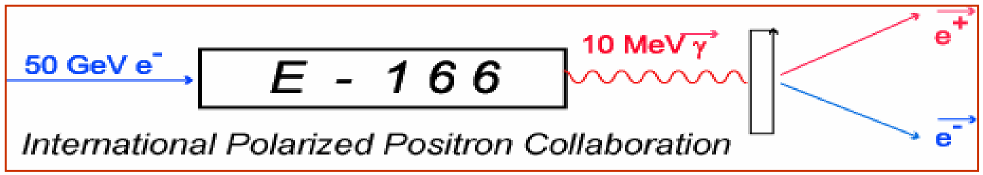


Undulator-based positron system is described in USLCSG Cold Reference Design Document

USLCG Positron Target Parameters

	TESLA TDR	Unpolarized	Polarized	Conventional
Pulse Energy on Target [kJ]	26.9	1.1	1.1	0.7
Average Power on Target [kW]	135	136	126	85
Spot Size on Target [mm]	0.75	0.75	0.75	1.6
Target Material	*Ti*-alloy	*Ti*-alloy	*Ti*-alloy	W74-Re26
Target Thickness [r.l.]	0.4	0.4	0.4	4.0
Target Energy Adsorption [%]	4	9	8	14
Target Radius [m]	0.400	0.125	0.125	0.125
Revolution Rate [rpm]	1200	46	46	46
Pulsed Temperature Rise [deg	420	530	530	200
Number of Targets/Spares	1/0	1/1	1/1	3/1

E-166 Update



E-166

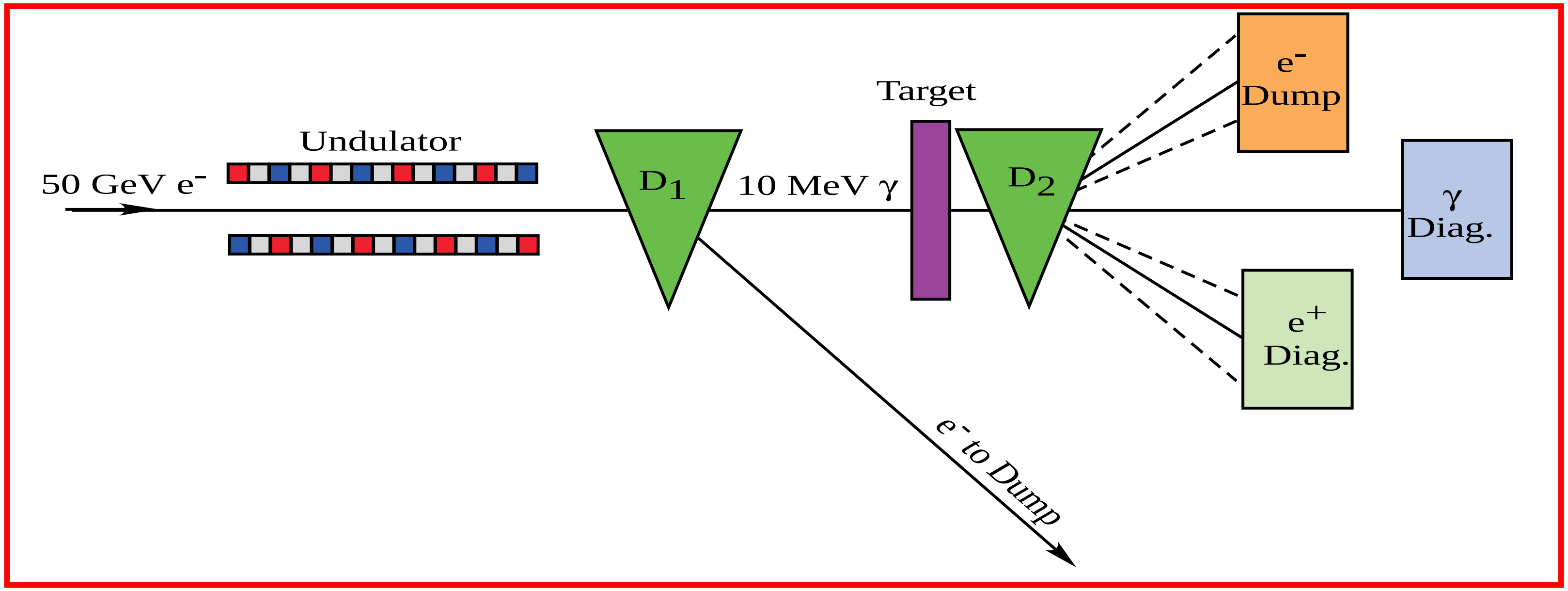
Undulator-Based Production of Polarized Positrons

A proposal for the 50 GeV Beam in the FFTB

K.T. McDonald and J.C. Sheppard, co-spokesmen

E-166 Experiment

E-166 is a demonstration of undulator-based polarized positron production for linear colliders



- E-166 uses the 50 GeV SLAC beam in conjunction with 1 m-long, helical undulator to make polarized photons in the FFTB.
- These photons are converted in a ~0.5 rad. len. thick target into polarized positrons (and electrons).
- The polarization of the positrons and photons will be measured.

"What are we interested in"

- Material damage thresholds
  - How do the thresholds change as a function of time in the beam
- How good are calculations
  - Fatigue due to both thermal and radiation effects
  - Comparisons with experiments, what has been done and what can be done
- High radiation environments
  - Design of stations
  - Maintenance of target stations
  - Does one fix broken targets or just put new ones in
  - Remote handling and robotics
- Superconducting adiabatic matching device ("flux concentrator")

Summary

- Target for linear collider positron production have high thermal, shock and stress parameters
- Solutions exist for producing needed positron beams for linear colliders
- Conventional systems require multiple target stations
- Might be able to spread beam out in time and get away with only one operating target station
- Undulator-based system are very promising, not only because the target thermal, shock and stress problems are alleviated, but also because the possibility exists for polarized positron beams
- Need to understand radiation damage in Ti-alloys
- E166 experiment approved to demonstrate polarized positron production feasibility