DISPERSION MANAGED SOLITONS
and
DENSE WDM

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Commercial Development

LambdaXtreme of Lucent Technologies:

“Dense WDM” system, developed ~2001, offering:

Up to 128 channels at 10 Gbit/s each

“Reach” of > 4000 km without electronic regeneration

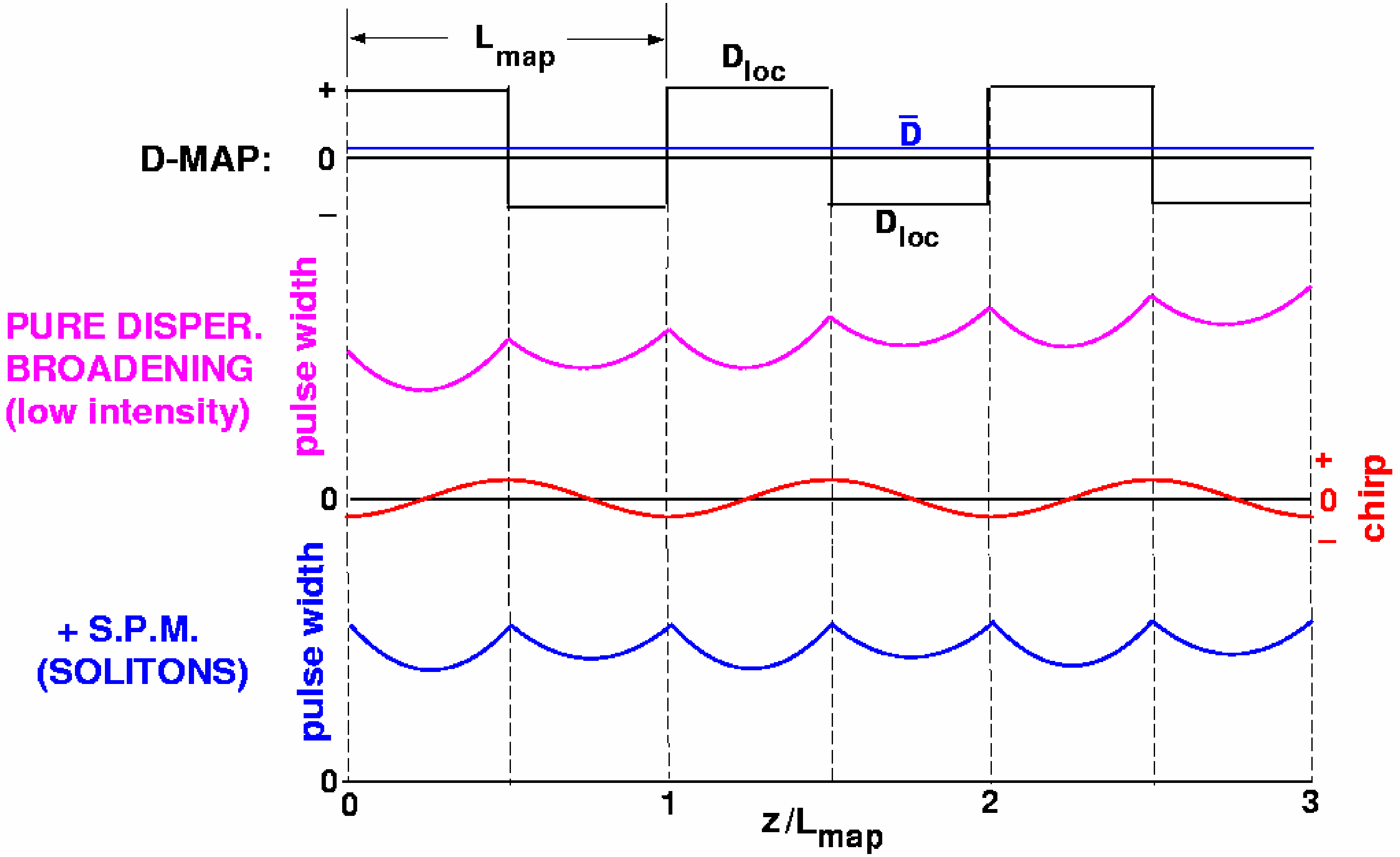
First customers:

Verizon (~$100 million) Installed as of early 2005   ~20,000 km

Qwest   (> $100 million)

Deutsche Telekom

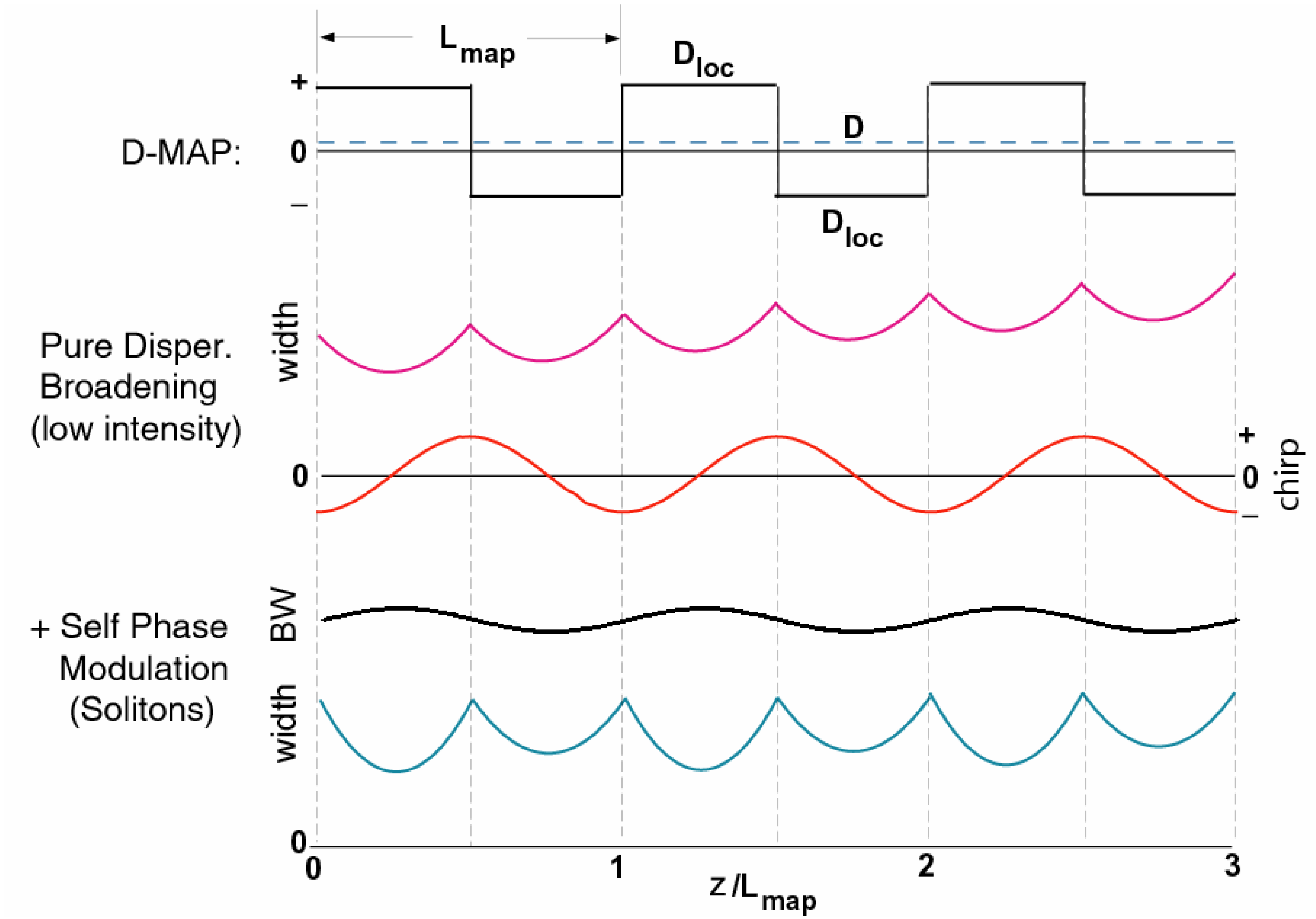
DISPERSION-MANAGED SOLITONS IN A NUTSHELL



Path-av. SPM and $\bar{D}$ cancel each other's effects exactly over each L_{map}.

Pulse shape, however, is largely determined by D_{loc} (the dominant term). Thus, pulse shape tends to be Gaussian.

DISPERSION-MANAGED SOLITONS IN A NUTSHELL



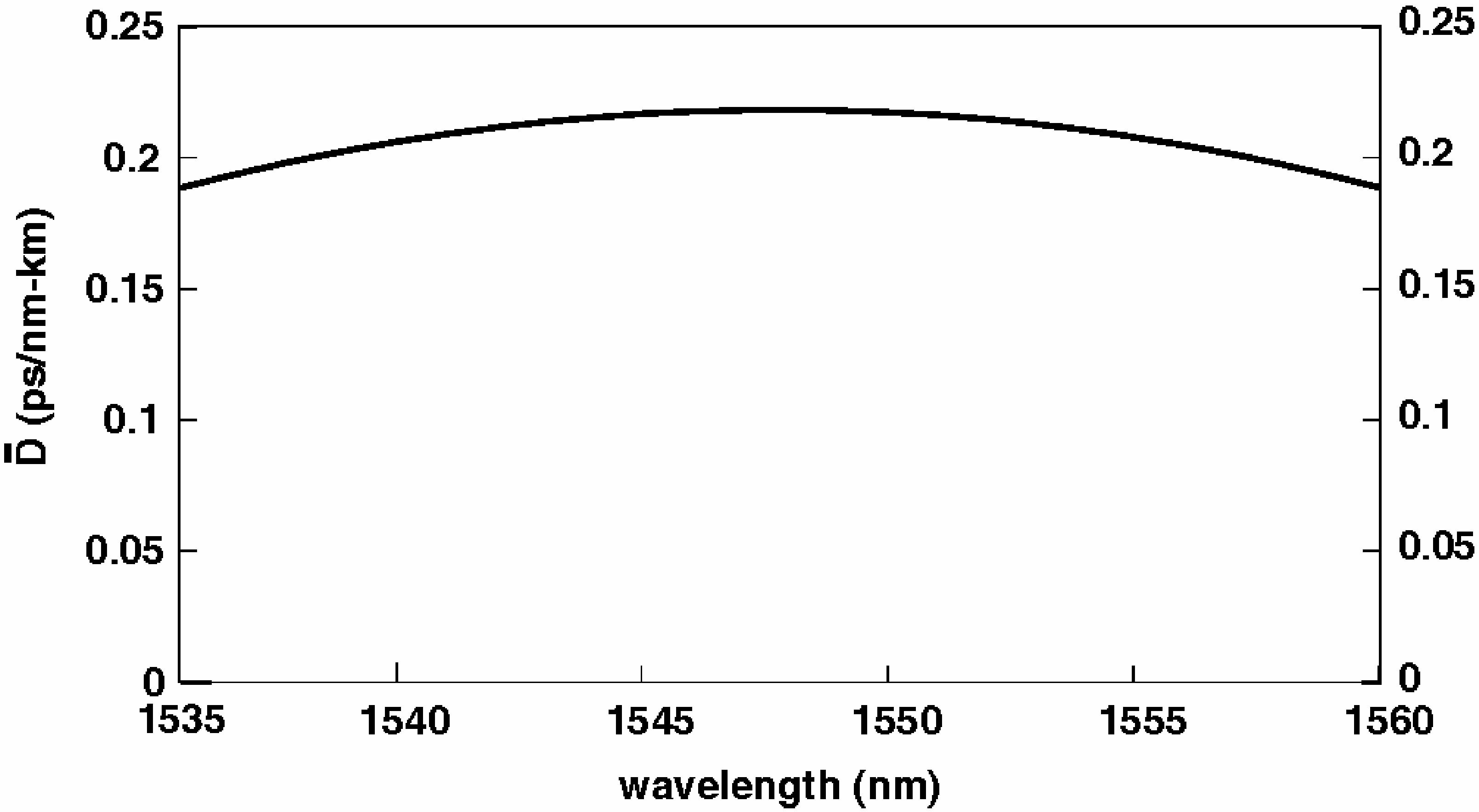
Phase shift from dispersive term scales as D x $(BW)^2$, and not just as D. Therefore, small variation in BW makes large change in net phase shift.

PROPERTIES OF SOME COMMERCIAL FIBERS

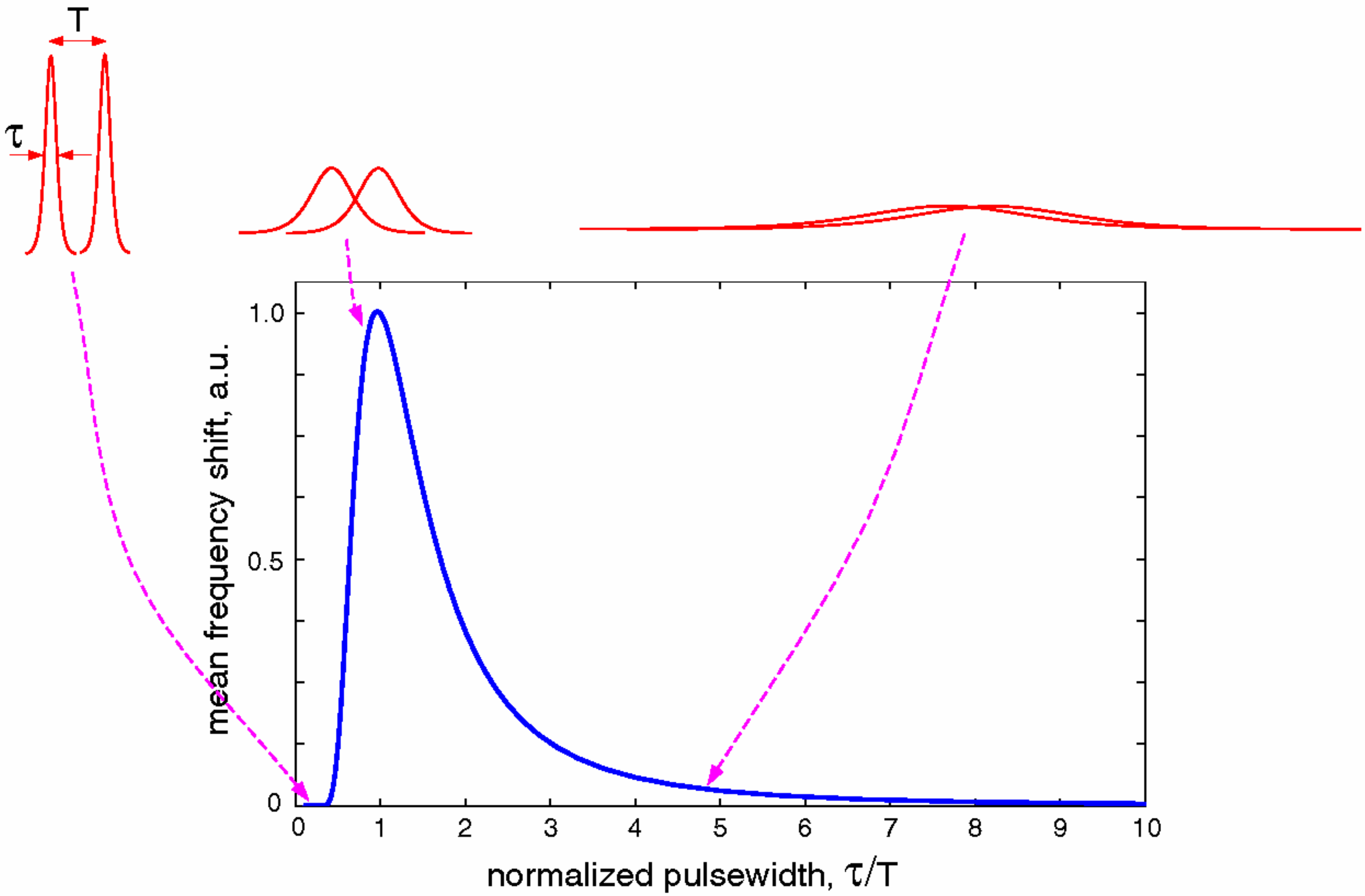
TYPE	D(ps/nm-km) (@ 1555 nm)	S(ps/nm2-km)	D/S (nm)	Aeff(µm2)
Standard	+16.7	+0.056	298	80
low-slope DS (Lucent TWRS)	+6.6	+0.045	147	50
IDF	-17.7	-0.057	310	35
hi-slope DCF	- 105	-0.35	300	20
ultra-slope DCF	-115	-0.78	147	18

NB: The combinations Std. + IDF, Std. + hi-slope DCF, and TWRS + ultra-slope DCF all yield essentially zero slope to the net dispersion.

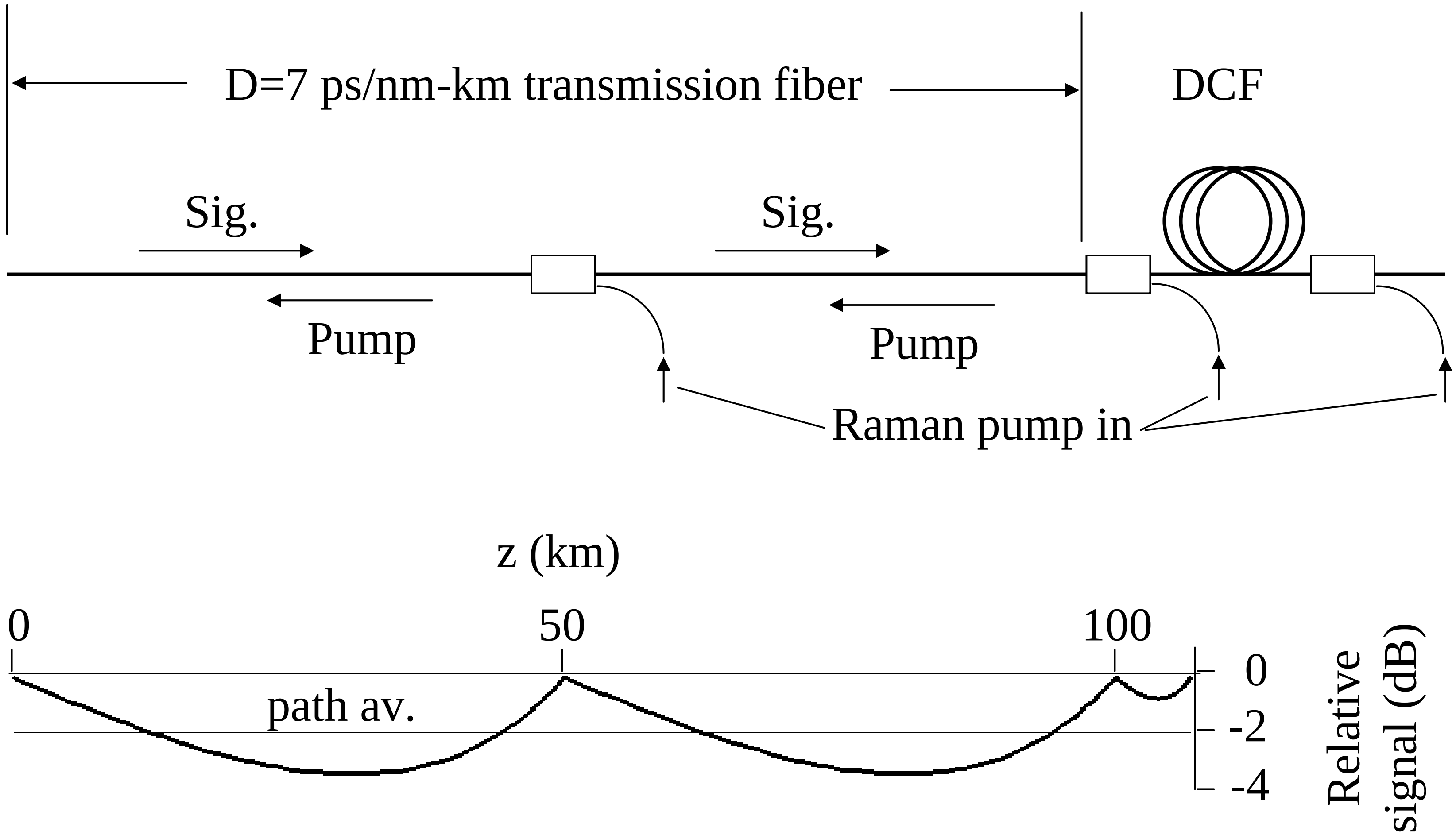
Dbar OF TWRS SPANS + ULTRA-SLOPE DCF
(FROM RELATIVE TIME-OF-FLIGHT MEASUREMENTS)



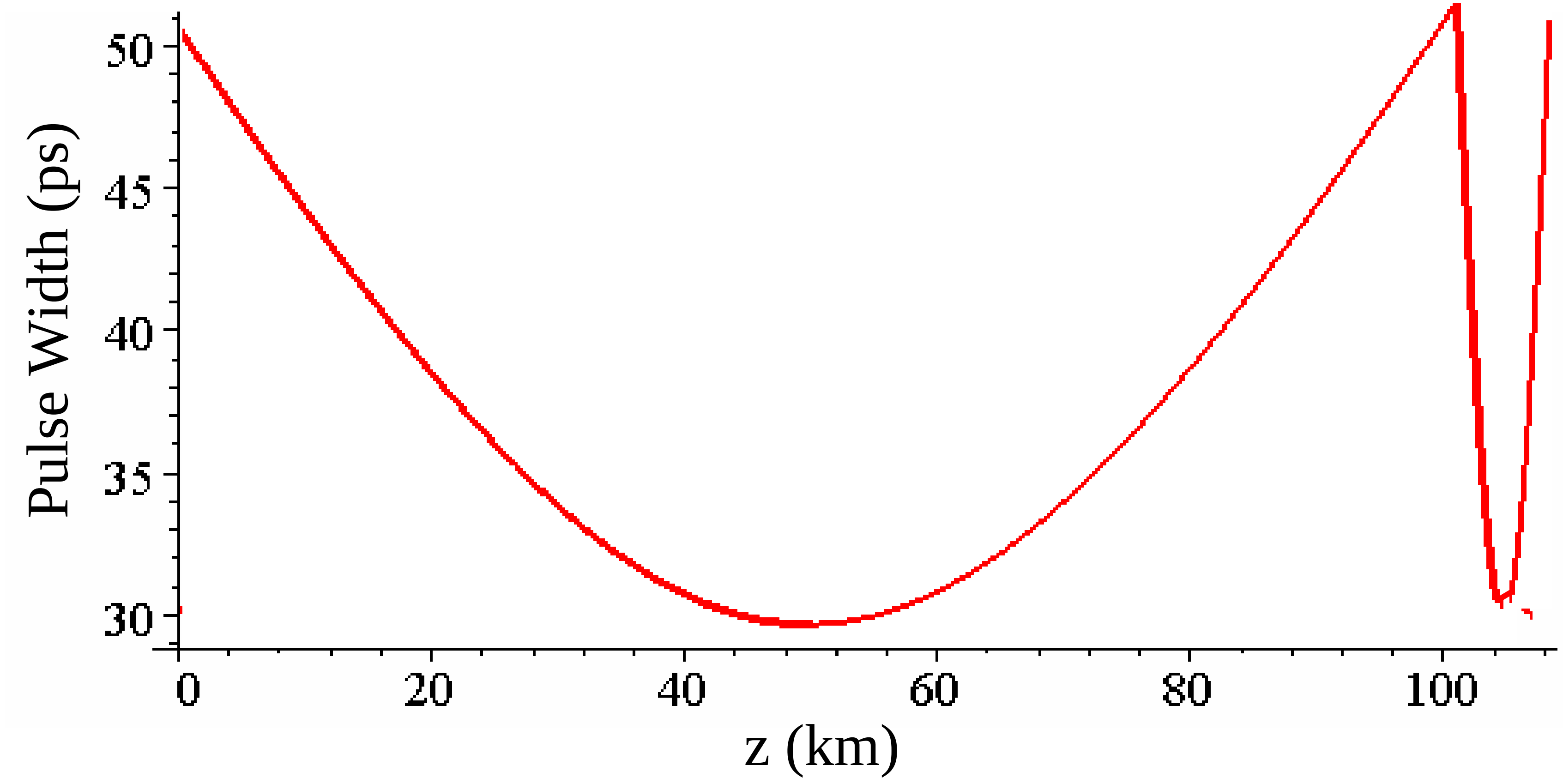
XPM-INDUCED ADJACENT PULSE INTERACTION



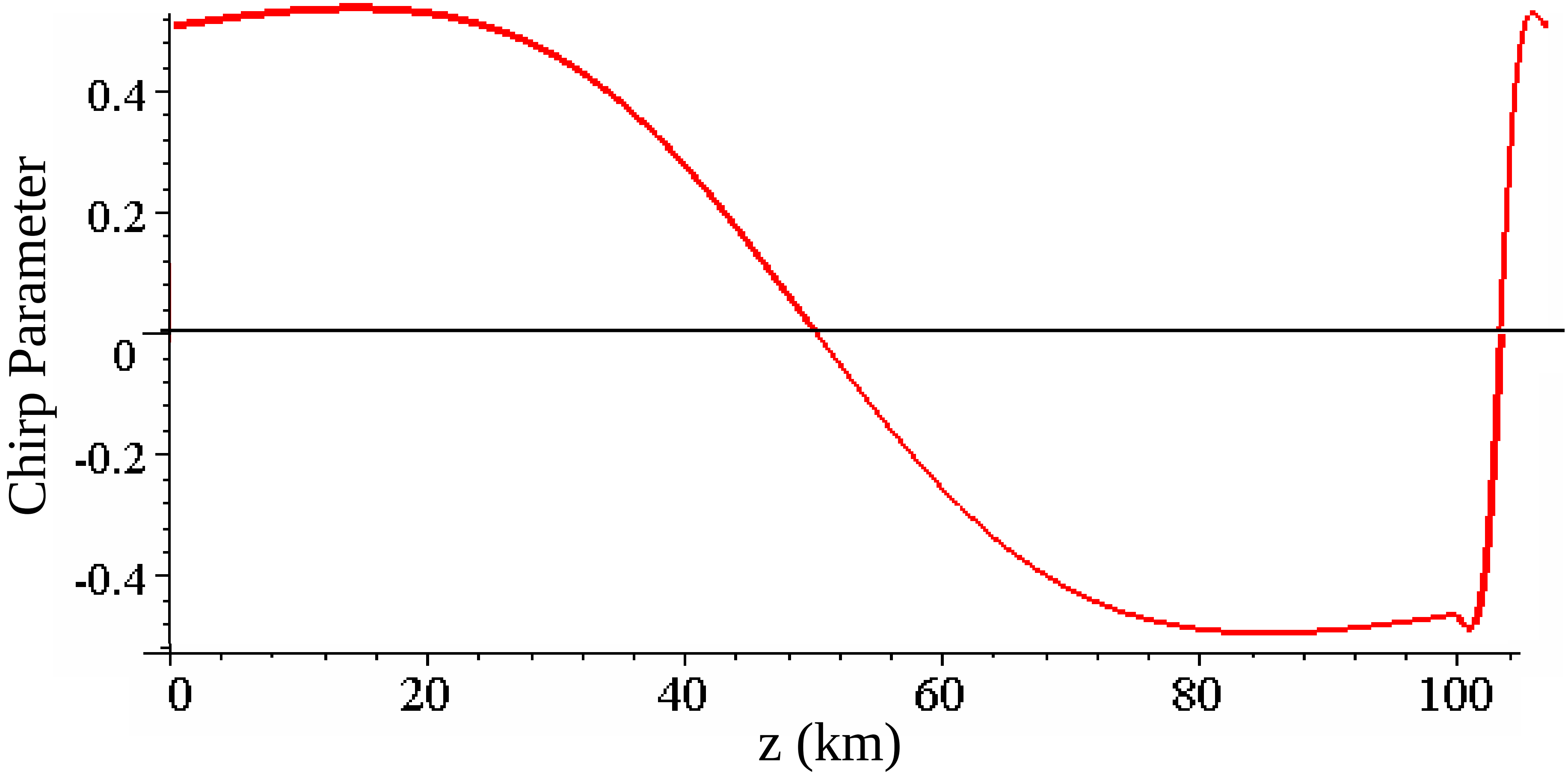
A Real-World Example of a Dispersion Map for DMS



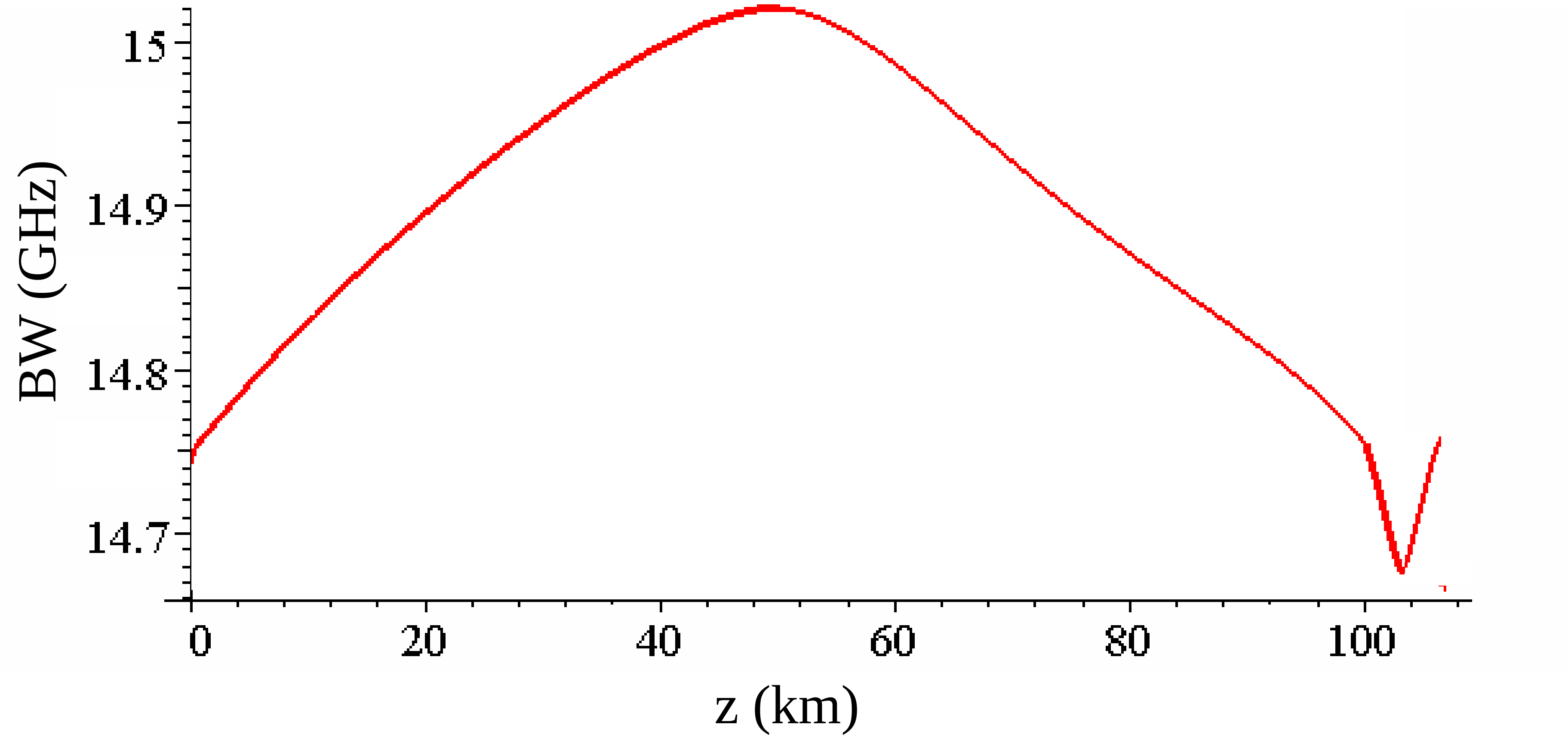
Pulse Width vs Distance of DMS in Map using 7ps/nm-km Fiber and Dbar = 0.15 ps/nm-km Mid-span backward Raman pumping



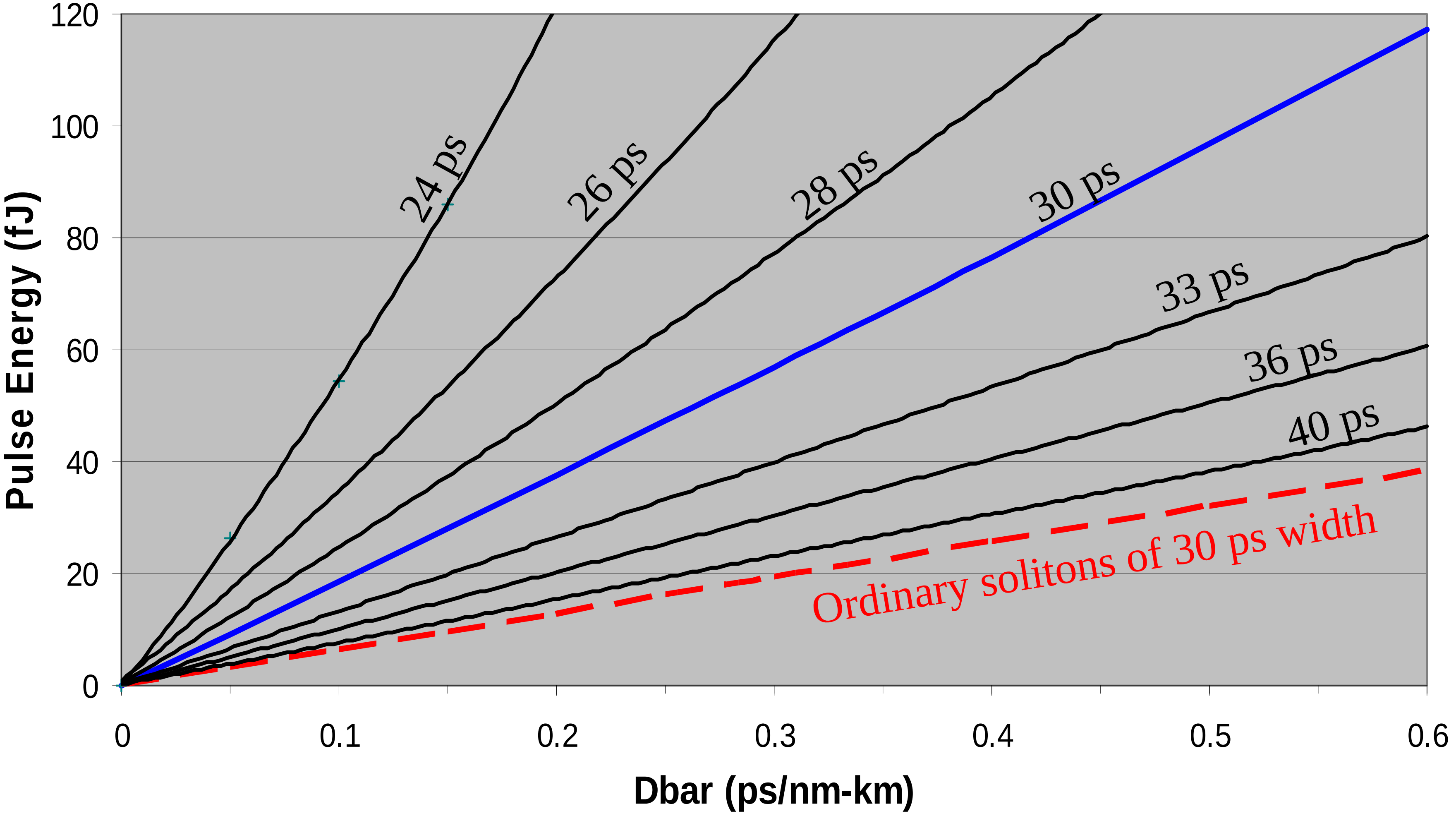
Normalized Chip Parameter vs Distance of DMS in Map using 7ps/nm-km Fiber and Dbar = 0.15 ps/nm-km Mid-span backward Raman pumping



Pulse Band Width vs Distance of DMS in Map using 7ps/nm-km Fiber and Dbar = 0.15 ps/nm-km Mid-span backward Raman pumping



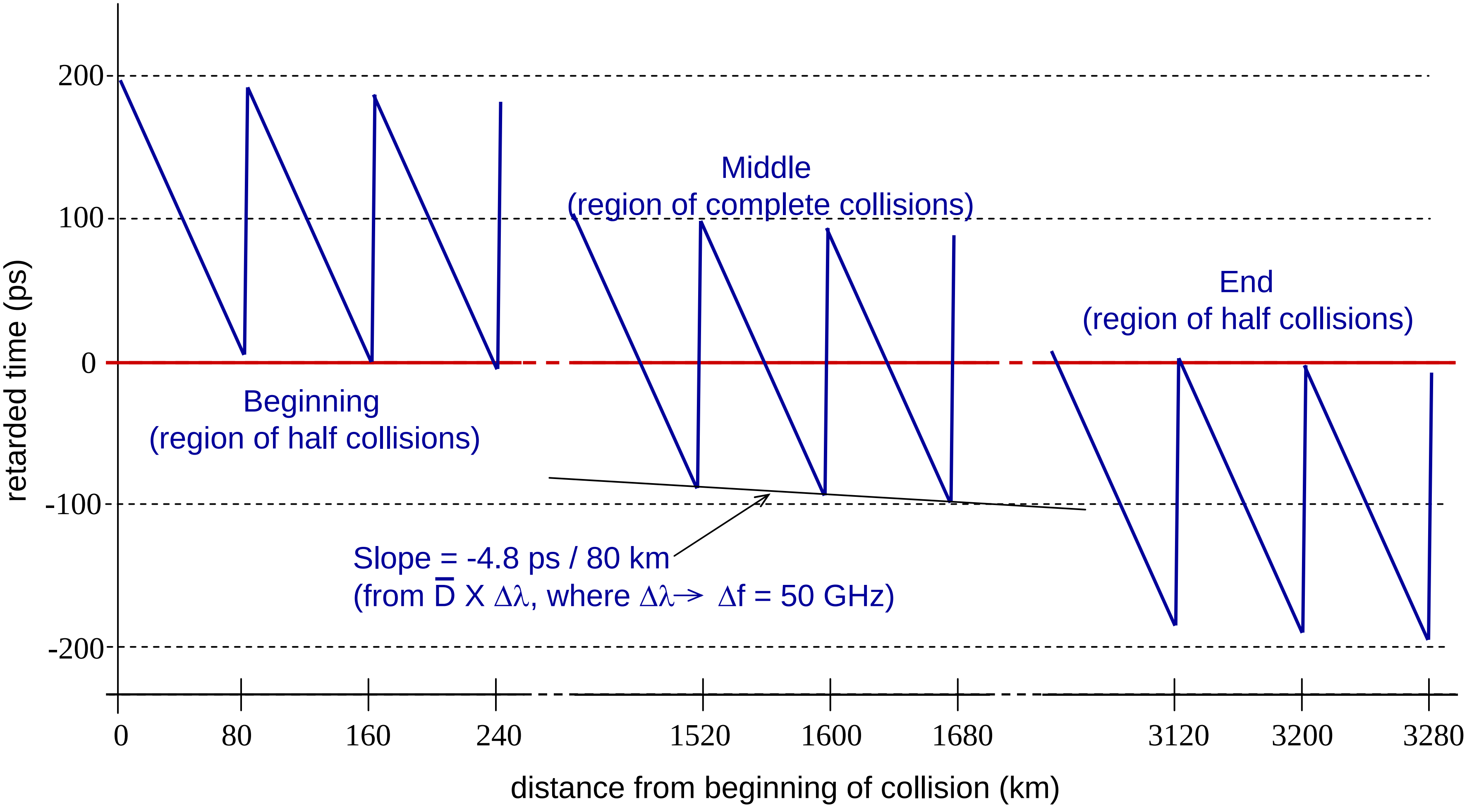
Pulse Energy vs Dbar for DMS in Map using 7ps/nm-km Fiber



RELATIVE MOTION IN RETARDED TIME OF COLLIDING, DISPERSION-MANAGED SOLITONS

Blue line shows motion of higher-frequency (+50 GHz) pulse
relative to lower-frequency pulse (fixed at t = 0).

D-map = 80 km of D = +6 ps/nm-km + DCF; $\bar{D}$ = +0.15 ps/nm-km.

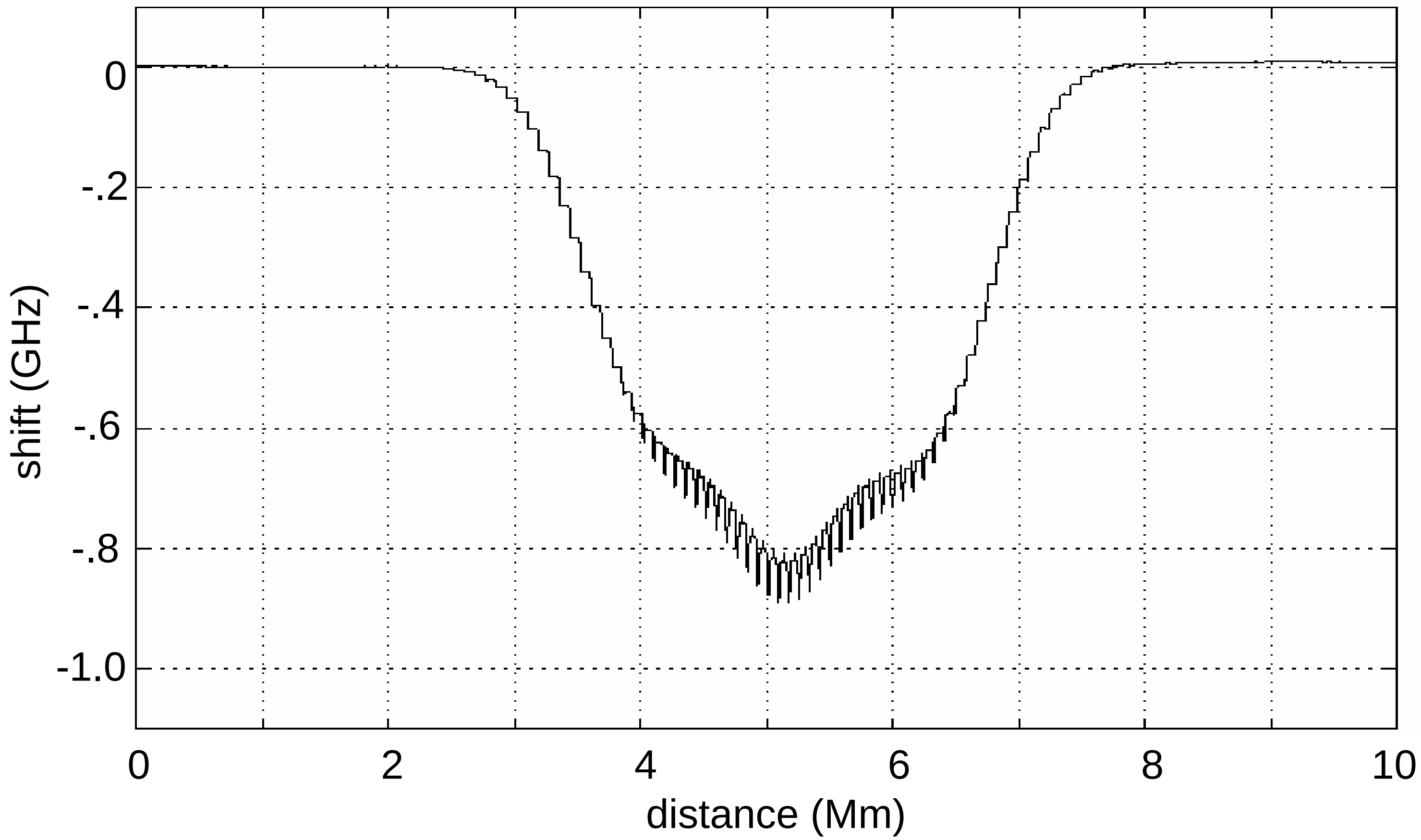


FREQUENCY SHIFT OF THE LOWER-FREQUENCY ONE OF TWO COLLIDING, DISPERSION-MANAGED SOLITONS

Solitons separated by 50 GHz and orthog. polarized

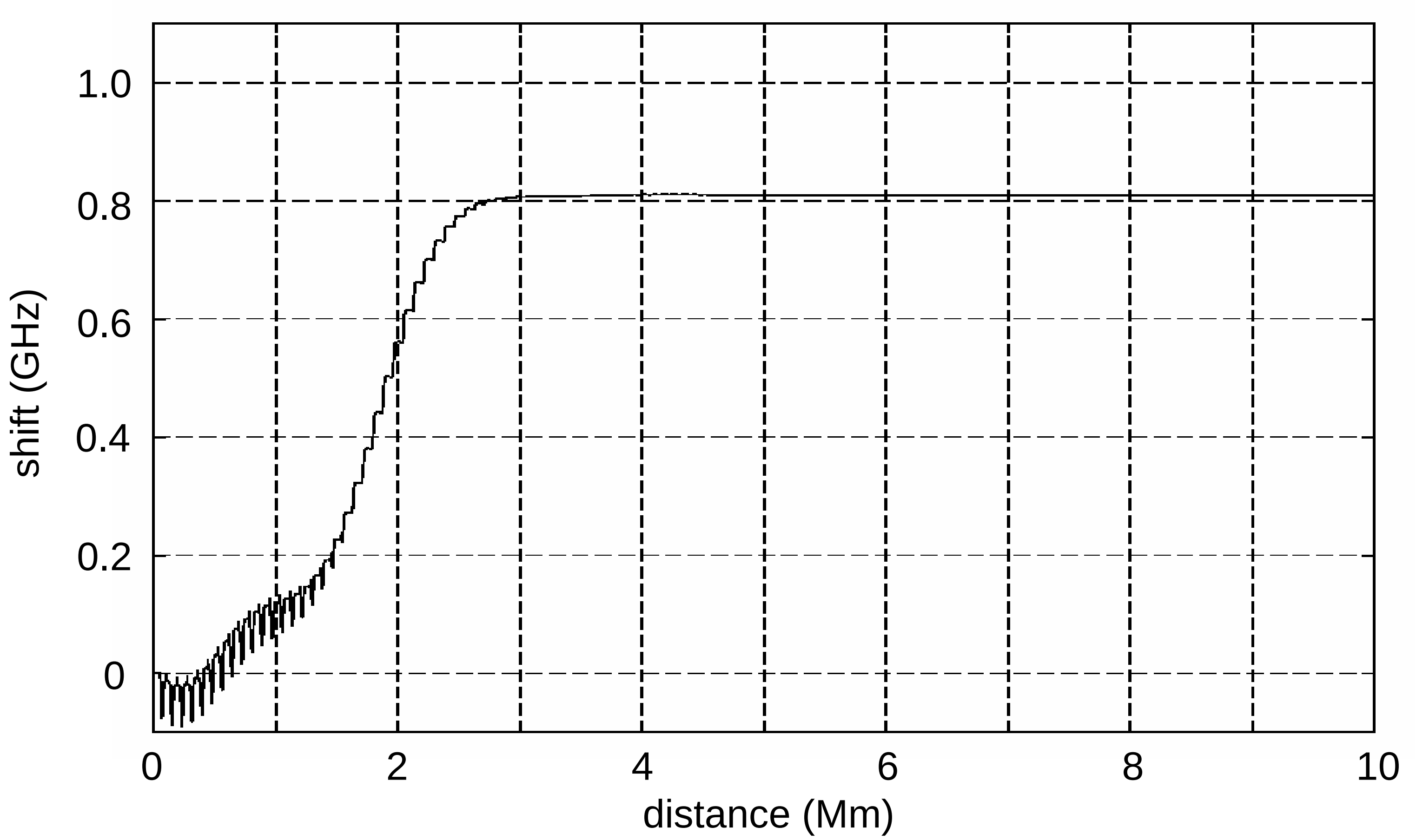
D-map = 80 km of D = +6.0 ps/nm-km + DCF; D = +0.15 ps/nm-km.

Backward Raman pumped at end and at mid-span; DCF at end.



PARTIAL COLLISION AT SYSTEM INPUT
(Part of the complete collision shown on a previous slide)

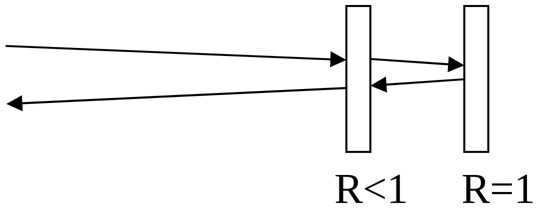
Note the change in sign and the permanent nature of the shift produced.

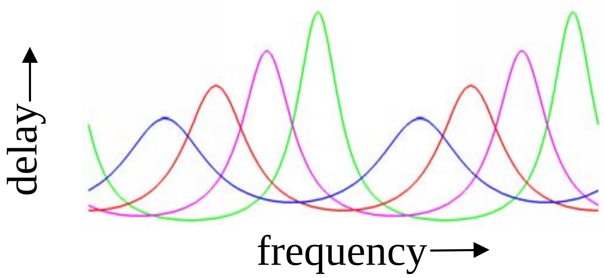


REDUCTION IN THE COLLISION-INDUCED TIMING JITTER BY THE USE OF PERIODIC GROUP DELAY COMPENSATORS

Recently, periodic group delay (PGD) dispersion compensators have become available commercially. In the next few slides, we shall show how the use of these devices to compensate a modest fraction of the span dispersion can effect a drastic reduction in the collision-induced timing jitter.

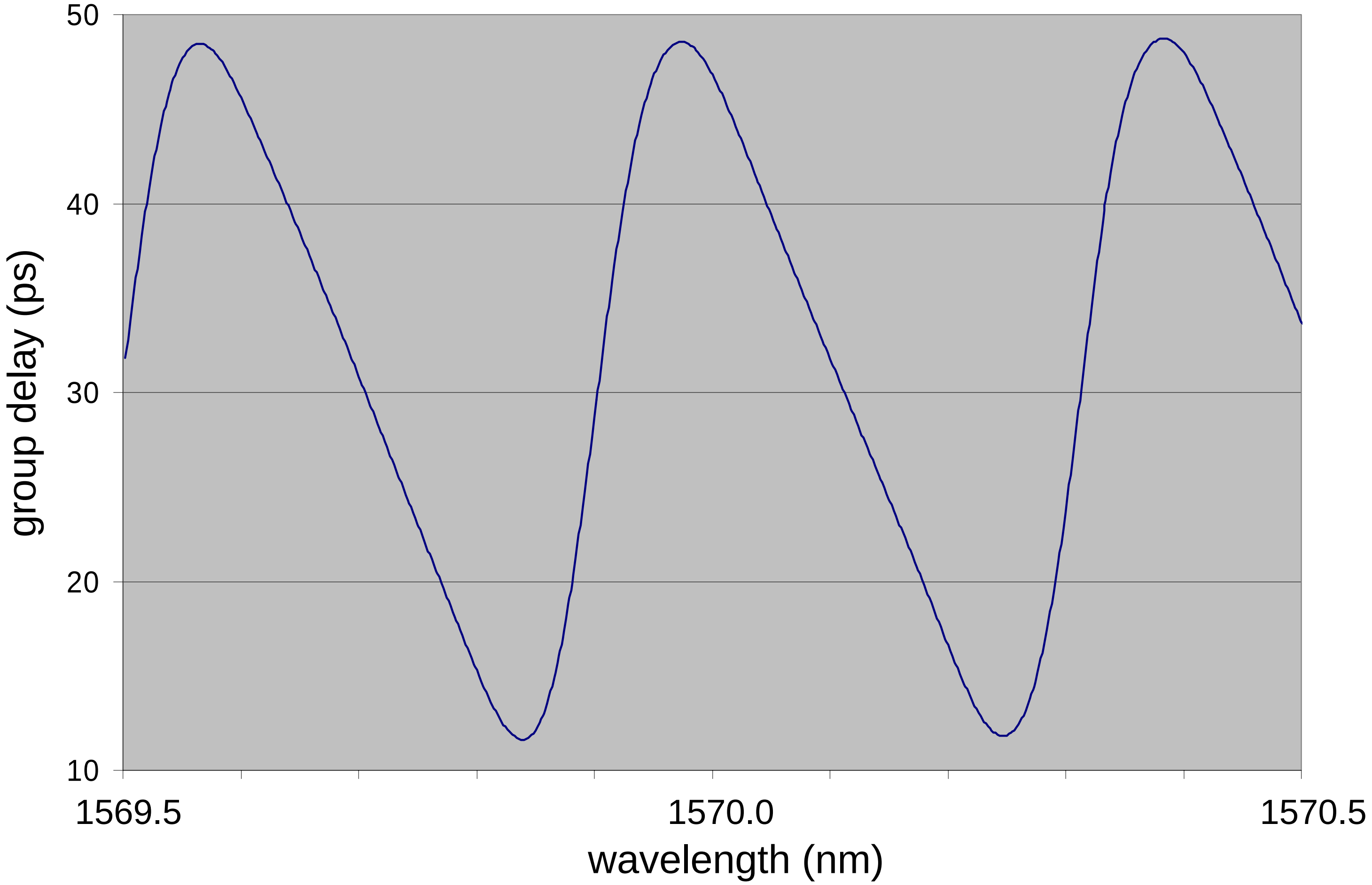
The most successful of the PGD devices are based on a cascade of Gires-Tournois etalons:





Note that these act as “all pass” filters, i.e., they are 100% reflective for all wavelengths, but that the effective delay time varies with frequency, and that the peak delay depends on the reflectivity of the front mirror. A number of these devices, cascaded together, can provide a low insertion loss element whose delay characteristics tend to look like the ideal on the next slide.

MEASURED GROUP DELAY OF PGD MODULE*

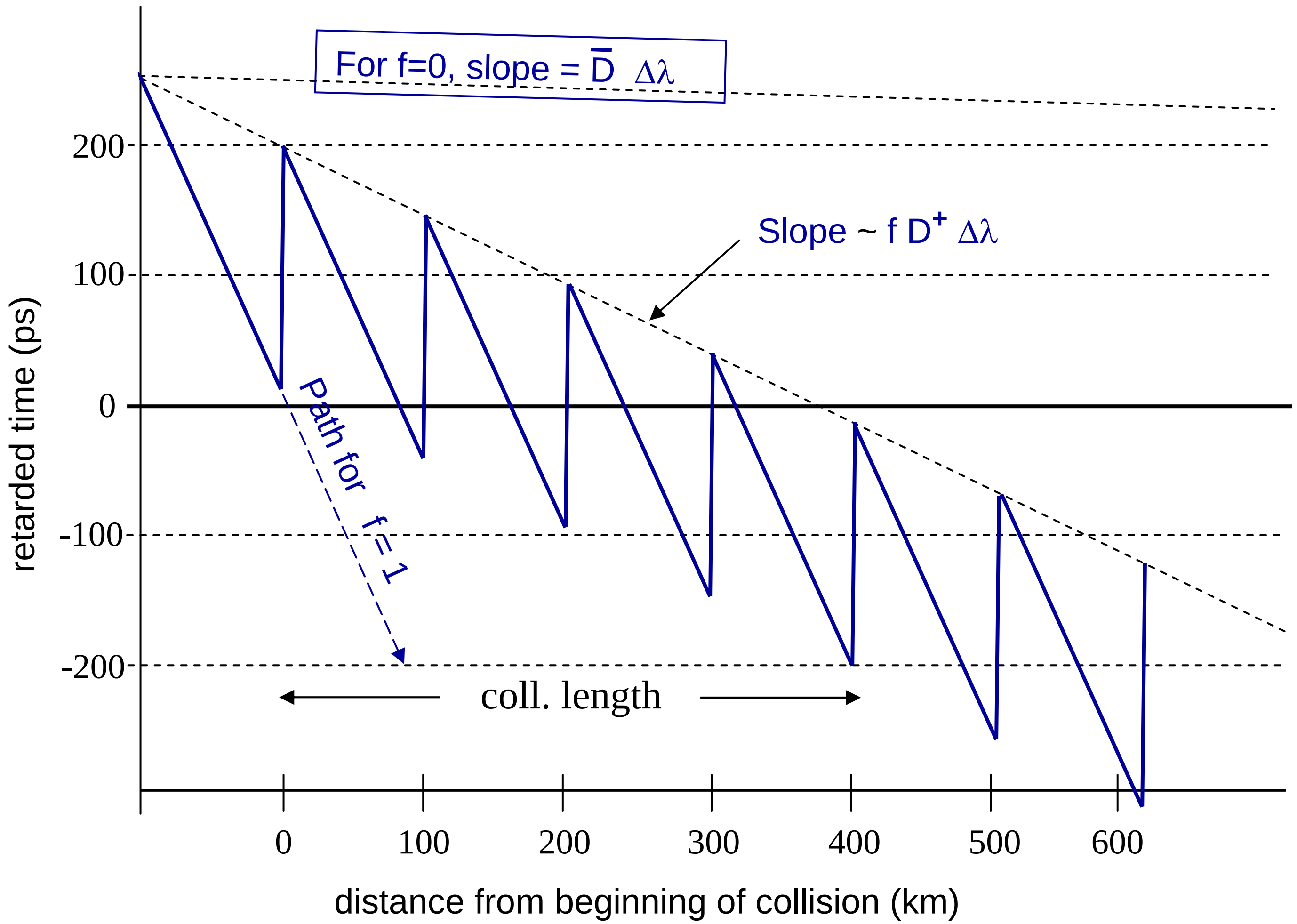


Note that the mean group delay is the same for all channels.

***Avanex “power-shaper”**

RELATIVE MOTION IN RETARDED TIME OF COLLIDING, DISPERSION-MANAGED SOLITONS

D-map = 100 km of D = +6 ps/nm-km, with fraction (1-f) of its dispersion compensated by DCF and fraction f compensated by a PGD-device

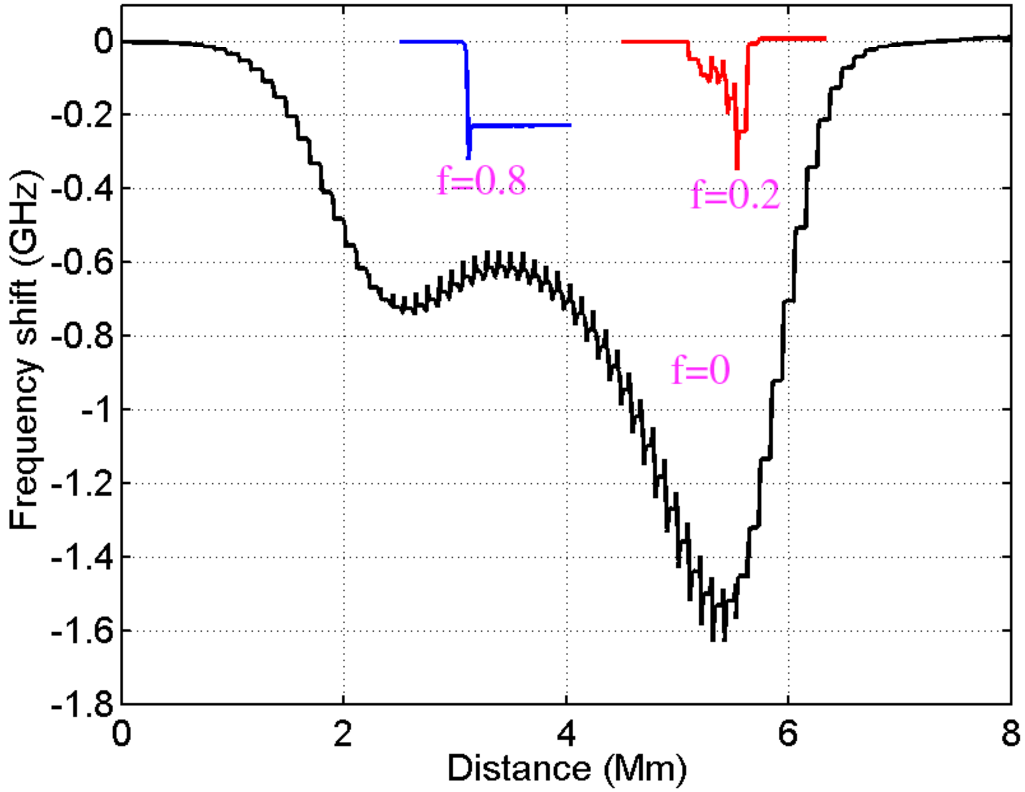


FREQUENCY SHIFT OF THE LOWER-FREQUENCY ONE OF TWO COLLIDING, DISPERSION-MANAGED SOLITONS

for different values of the parameter f

Solitons separated by 50 GHz and co-pol.

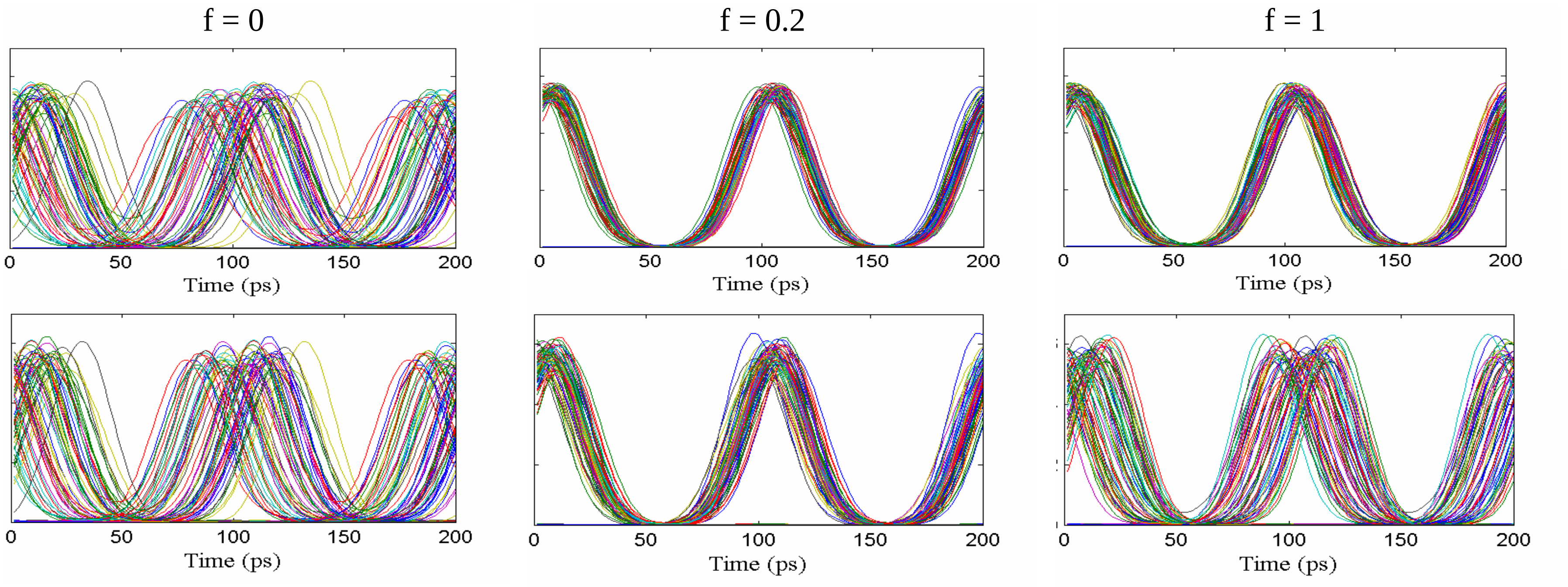
D-map = 100 km of D = +6.0 ps/nm-km + DCF; D = +0.15 ps/nm-km.
Backward Raman pumped at end only; DCF at end.



Note that for f=0.2, (just as for f=0), the collision is “frequency preserving”, i.e., the freq. shift returns essentially to zero after the collision, but that this is not so for f=0.8

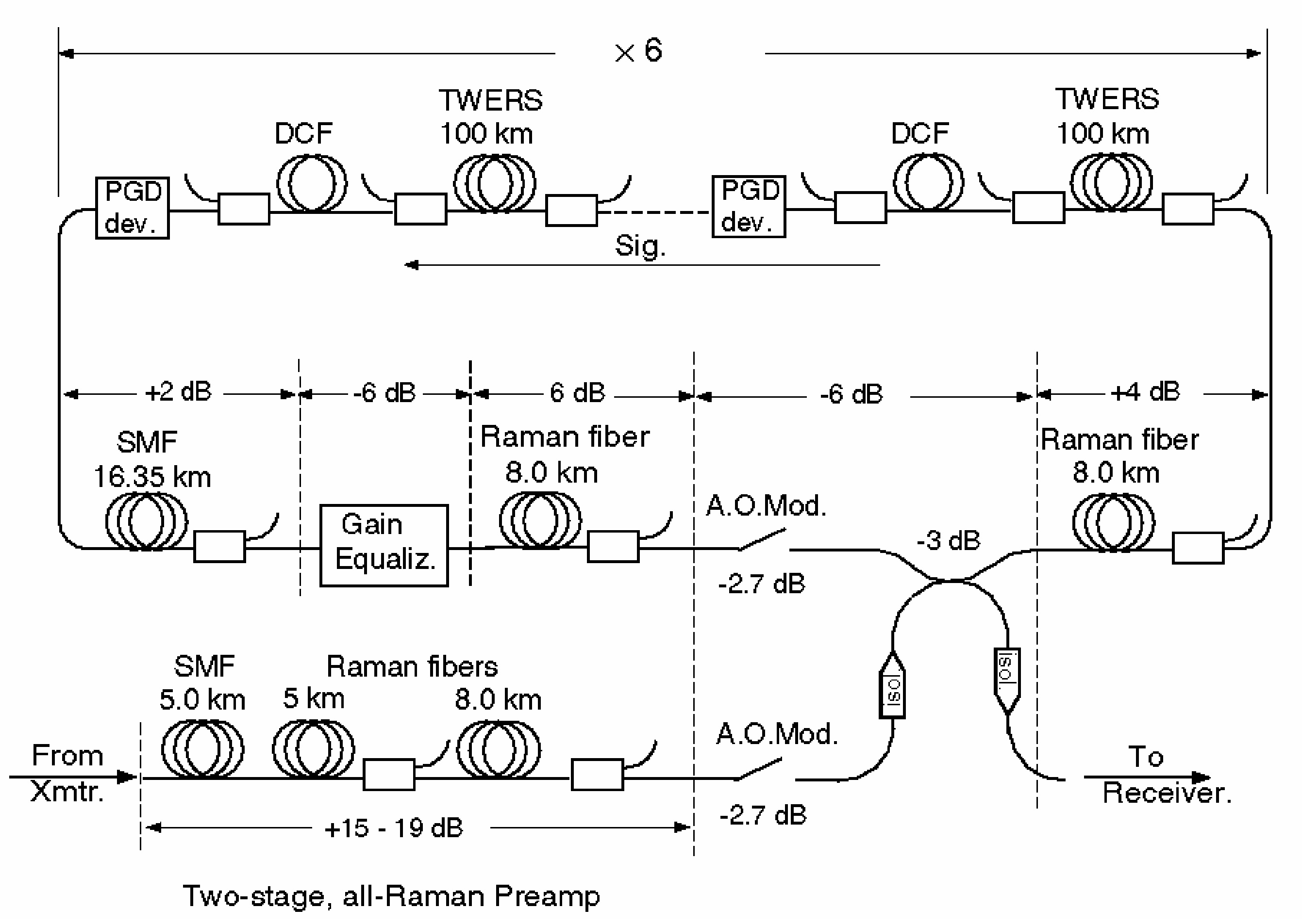
OPTICAL EYES AT 8000 km FOR DIFFERENT VALUES OF f

Above: Case of uniform gain
Below: With 25%/75% fwd/bkwd Raman Pumping



Note how very good these look in the f = 0.2 column! Conclusion: That range of f that yields the shortest Lcoll consistent with frequency preservation effects a large reduction in jitter that is almost independent of Raman pumping conditions.

RECIRCULATING LOOP CONFIGURATION



RECIRCULATING LOOP PARAMETERS

- Net loss around the loop (all connecting hardware included) = 213 dB
  Thus, effective loss/ 100 km span = 213/6 = 35.5 dB
- Measured ASE noise (equipartition energy*) increases at 0.0135 fJ/Mm, when guiding filters are removed.
- Main span dispersion parameter $D \cong 7\,\mathrm{ps/nm-km},\ \mathrm{A}_{\mathrm{eff}} = 50\ \mu\mathrm{m}^2$
- Measured loop average PMD parameter = 0.05 ps/ $\sqrt{\mathrm{km}}$
- Measured PDL = 0.5 dB/600 km.

*****Expected value of the noise energy in unit time (the bit period), in the corresponding unit BW (10 GHz) and in one polarization.

SOME IMPORTANT EXPERIMENTAL DETAILS:

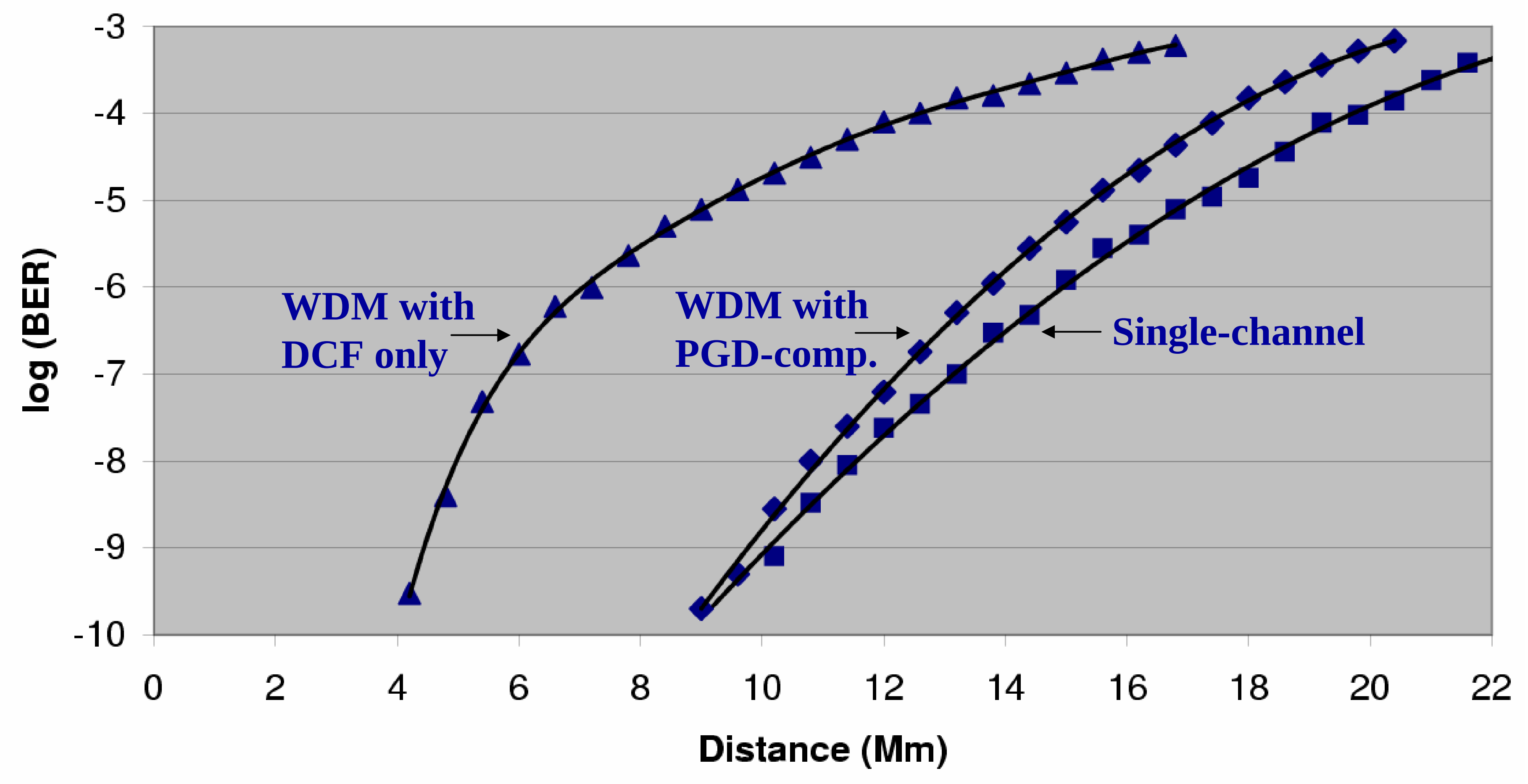
To provide for the most sensitive measure of the WDM penalty,
we have promoted the greatest possible single-channel distance,
as follows:

- Have used one mild (fixed-frequency) guiding filter every 300 km. (Reduces Gordon-Haus jitter and a weak adjacent-pulse interaction.)
- Have used mid-span backward Raman pumping instead of the more usual forward/backward pumping. (Gains about 1 dB noise advantage.)
- Have used temporal lens immediately ahead of the detector, to remove residual timing jitter from collisions and from the Gordon-Haus effect.

- The 600 km recirculating loop contains a polarization scrambler driven simultaneously at two frequencies in the neighborhood of ~1 MHz.

MEASURED BER vs DISTANCE FOR “TYPICAL” WDM CHANNEL

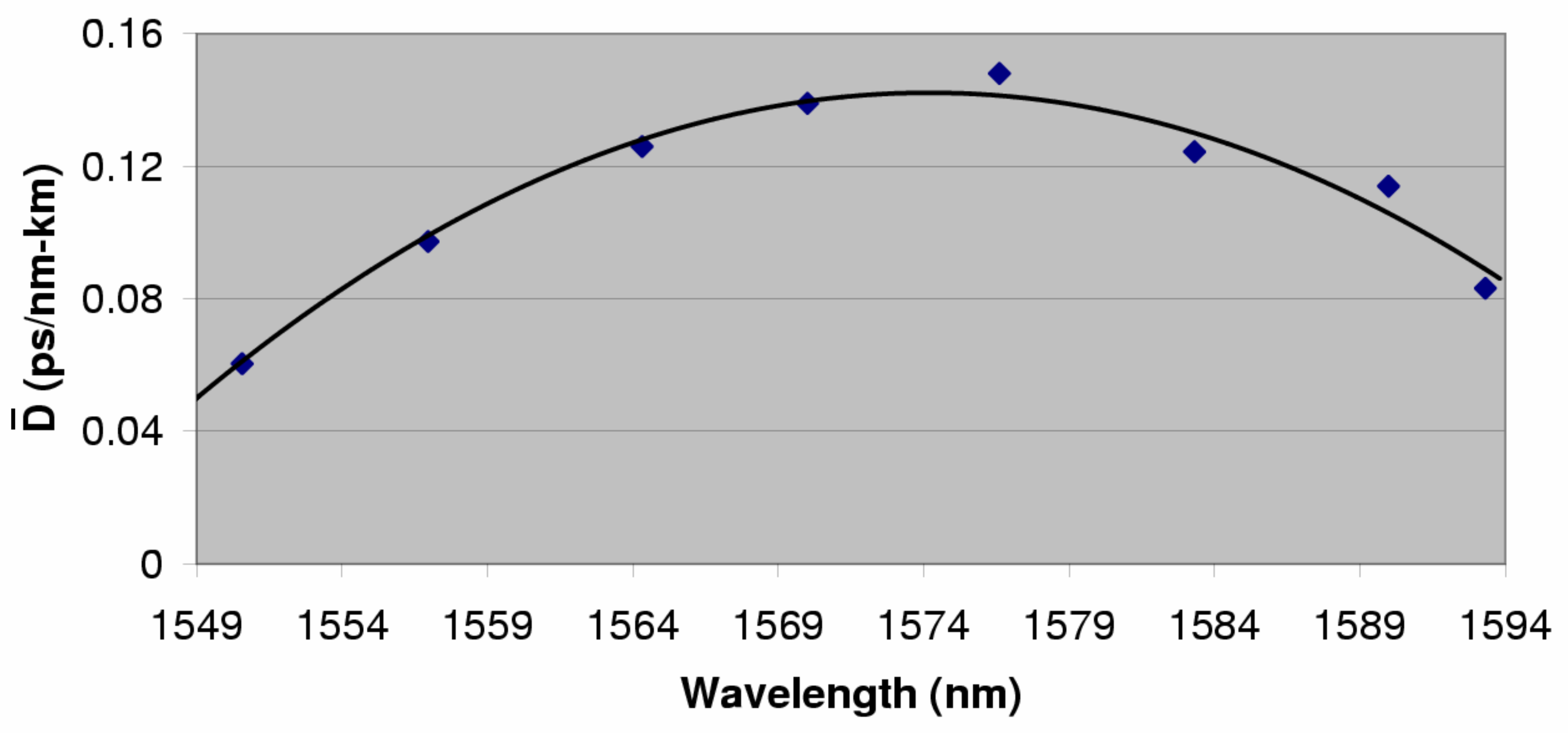
50 GHz Channel Spacing



(Temporal lens, guiding filters, and pol. scrambler used for all 3 measurements.)

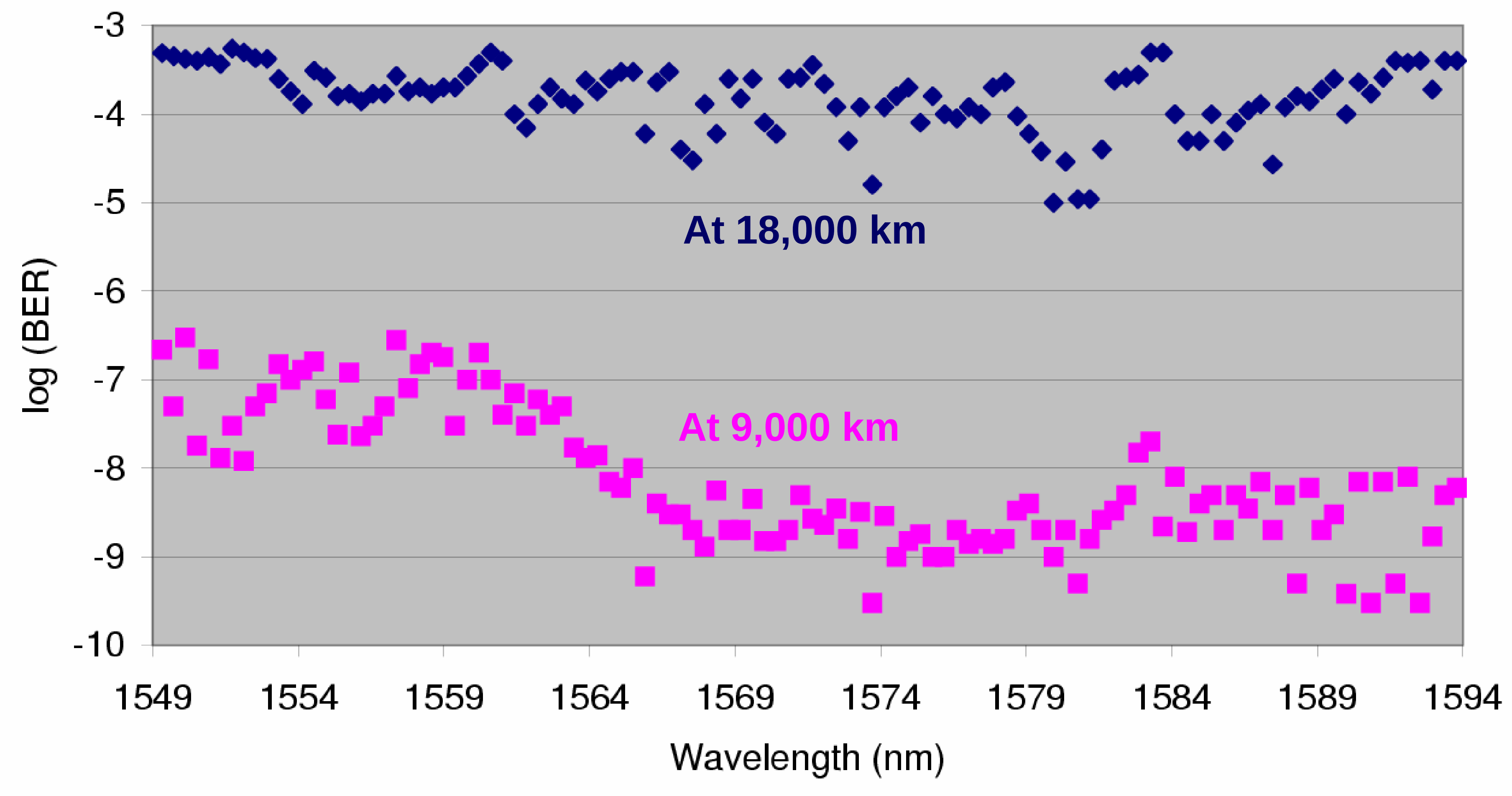
EXPERIMENTAL DETAILS (CONTINUED):

Measured path-average intra-channel dispersion parameter:

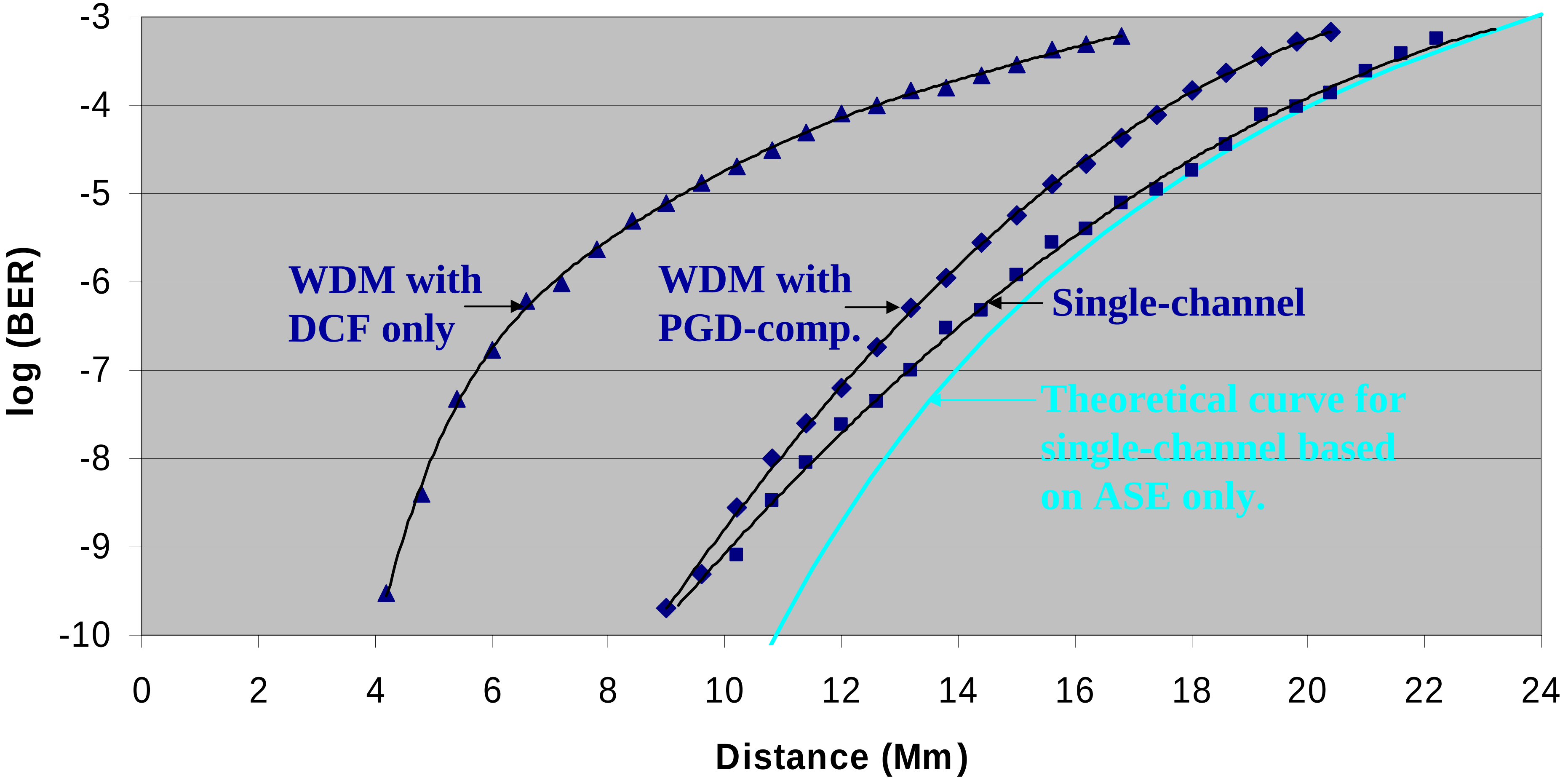


We added small coils of SMF once every 600 km, as needed, to maintain ("pin") the above average dispersion at or near the ideal of 0.15 ps/nm-km.

BER vs WAVELENGTH for 109- CHANNEL (1.09 Tbit/s) WDM



MEASURED BER vs DISTANCE
FOR “TYPICAL” WDM CHANNEL
Single channel result shown matched to pure ASE limit.



NB: The difference between the theoretical and experimental single-channel curves at low bit rates can be largely ascribed to the effects of PMD and PDL.

Nonlinear vs. “Linear” Transmission

	D-M Solitons	“Linear” Trans.
nonlin. phase shift	large (>>1 rad.)	as small as possible (~1 rad.)
pulse behaviour	periodic, limited breathing	aperiodic, extended breathing
nonlin. penalties	With PGD-technique, all negligible or very small.	Intra-channel effects are serious.
dispersion comp.	simple, distance-independent.	complex, highly distance-dependent.
needs large area fiber for best performance?	no	yes
potential for self regen.	yes!	no!
ultra-long-haul distance	several × > “linear”	limited

NB: All items under solitons are made possible (either directly or indirectly) by SPM!