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Design and Radiation Assessment of Optoelectronic Transceiver Circuits for ITER

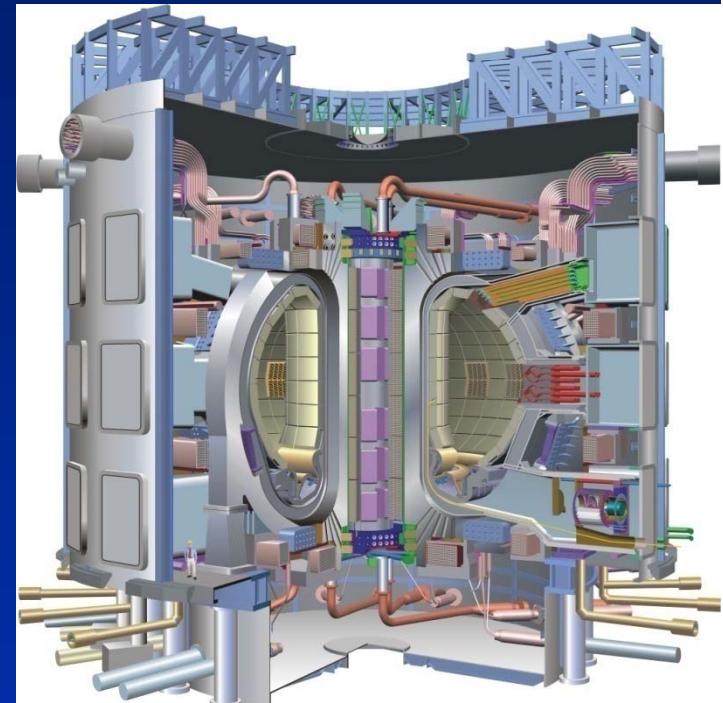
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M. Van Uffelen², M. Steyaert³

Outline

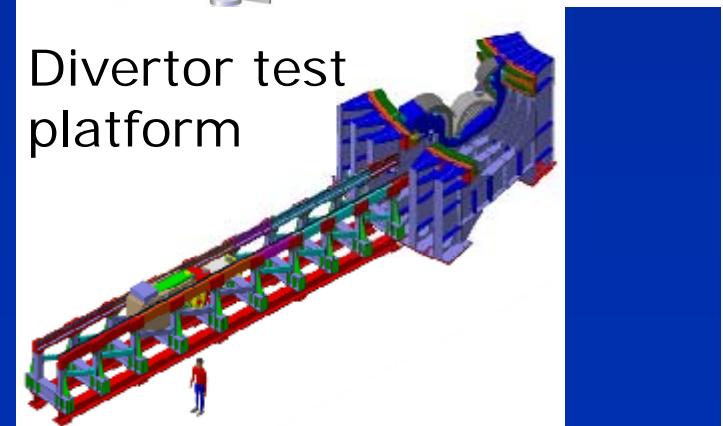
- Context
- SiGe HBT model
- Transmitter circuit: VCSEL driver
- Receiver circuits: transimpedance and post-amplifier
- Summary and conclusions

Context: Thermonuclear fusion (ITER)

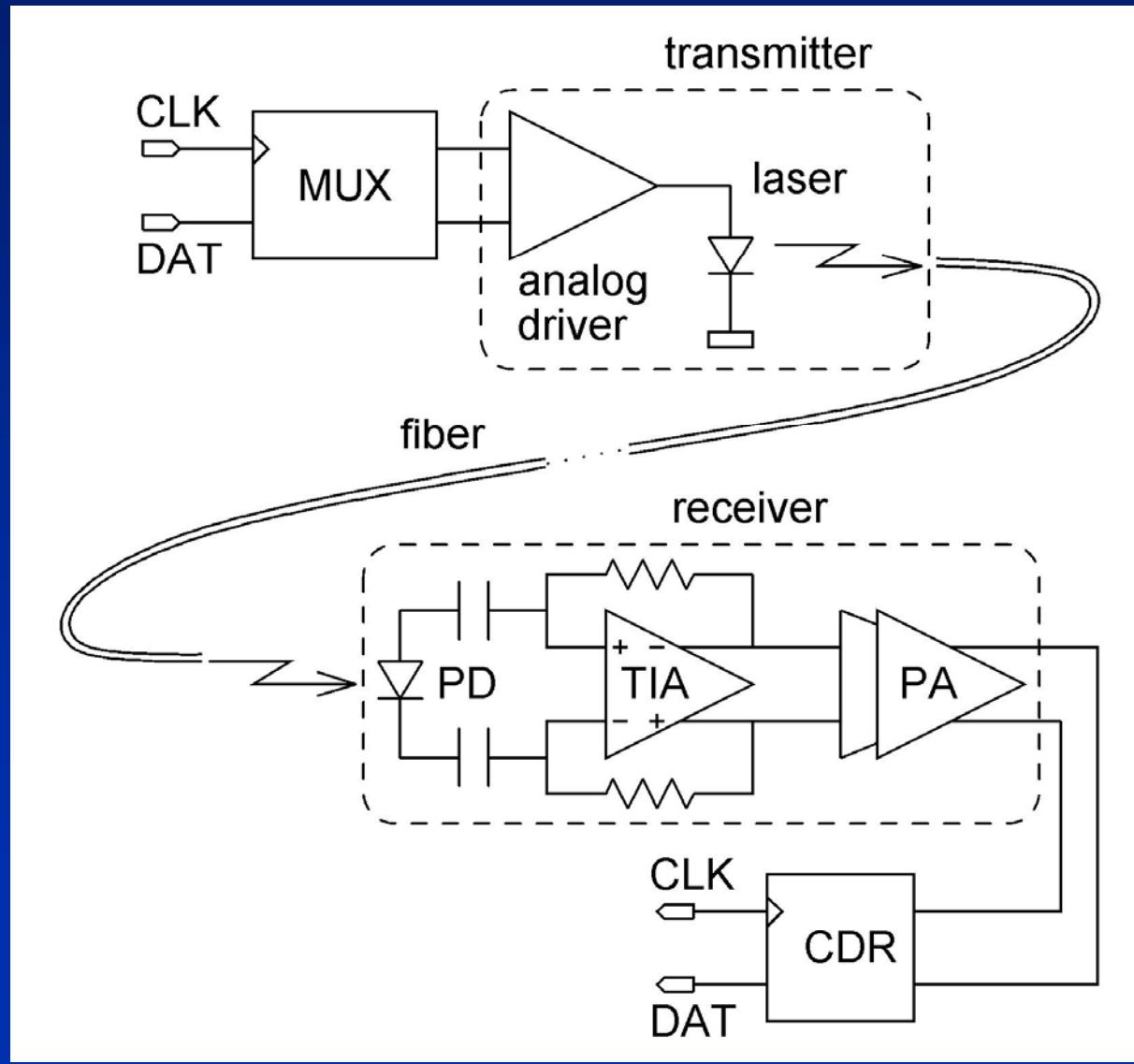
- Robotics for maintenance tasks (MGy dose levels, $25^{\circ}\text{C} < T < 150^{\circ}\text{C}$) : e.g. divertor region
- Fiber-optic umbilical link between reactor and control room
- Radiation effects on fiber-optic components (VCSELs, ...)
- Radiation tolerant transmit and receive electronics



Divertor test platform



Context: Optical communication link



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SiGe HBT model: Base current and SRH recombination

Assumptions:

- ↳ Bulk recombination in the base can be neglected
- ↳ Collector-base reverse leakage current can be neglected

Collector current

$$I_C \approx I_{F0} \left(e^{\frac{V_{BE}}{V_t}} - 1 \right)$$
$$\approx I_{F0} e^{\frac{V_{BE}}{V_t}}$$

Electron injection
from the emitter

Base current

$$I_B \approx I_{BF0} \left(e^{\frac{V_{BE}}{V_t}} - 1 \right) + I_{rec,EB}$$
$$\approx I_{BF0} \cdot e^{\frac{V_{BE}}{V_t}} + I_{rec,0} \cdot e^{\frac{V_{BE}}{2V_t}}$$

Hole injection
from the base

Recombination
in the EB space
charge region

SiGe HBT model: Base current and Ideality factor n

$$I_B \propto I_C^n$$

- Good ideality factor:

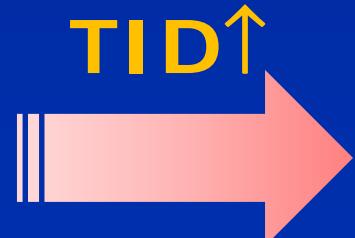
$$n \rightarrow 1$$

forward hole injection
current dominant
(independent of TID)

- Not so good ideality factor: $n \rightarrow 0.5$

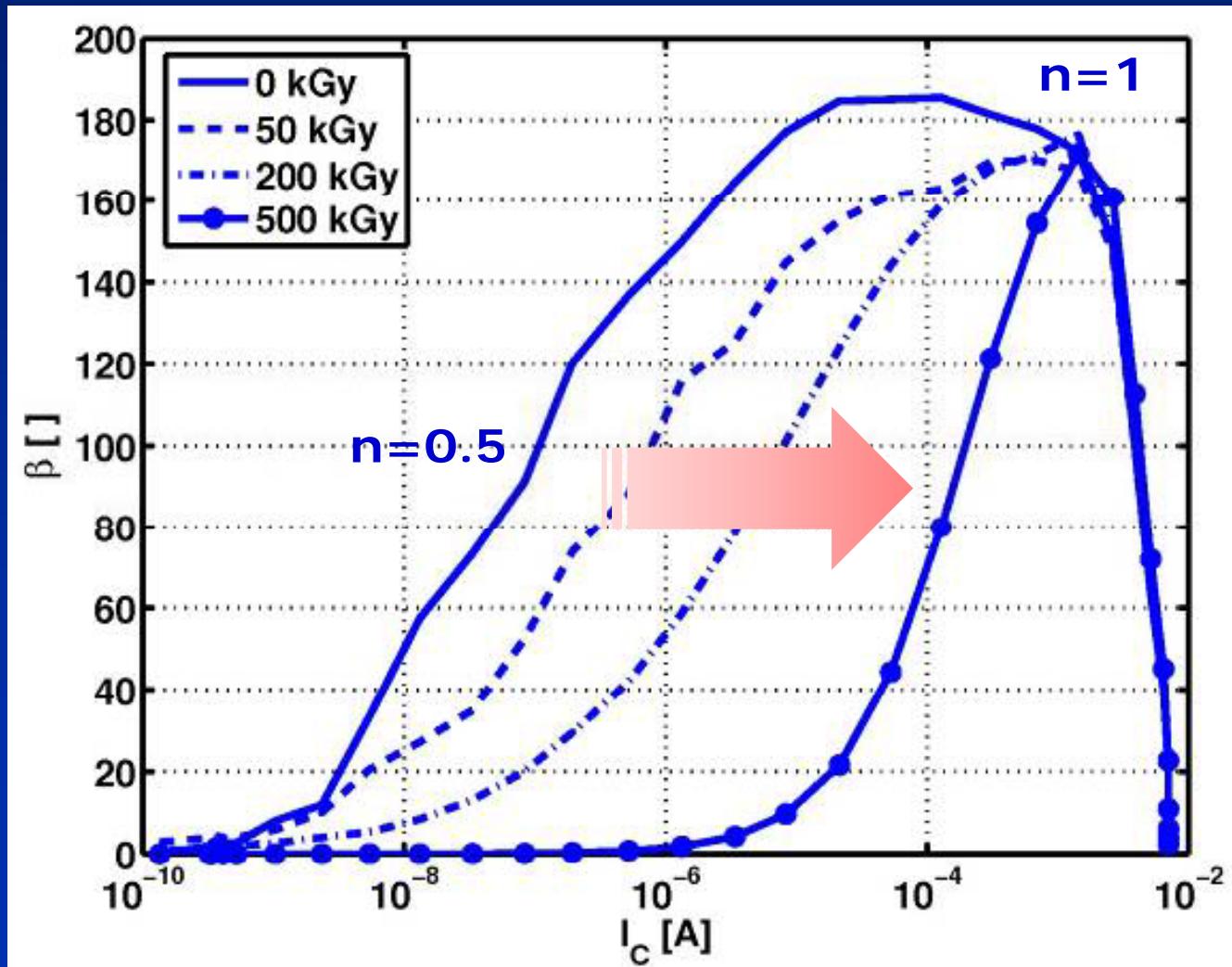
SRH recombination
current dominant
(dependent on TID)

$$I_B \approx I_{BF0} \cdot e^{\frac{V_{BE}}{V_t}}$$



$$I_B \approx I_{rec,0} \cdot e^{\frac{V_{BE}}{2V_t}}$$

SiGe HBT model: Current gain degradation for increasing TID

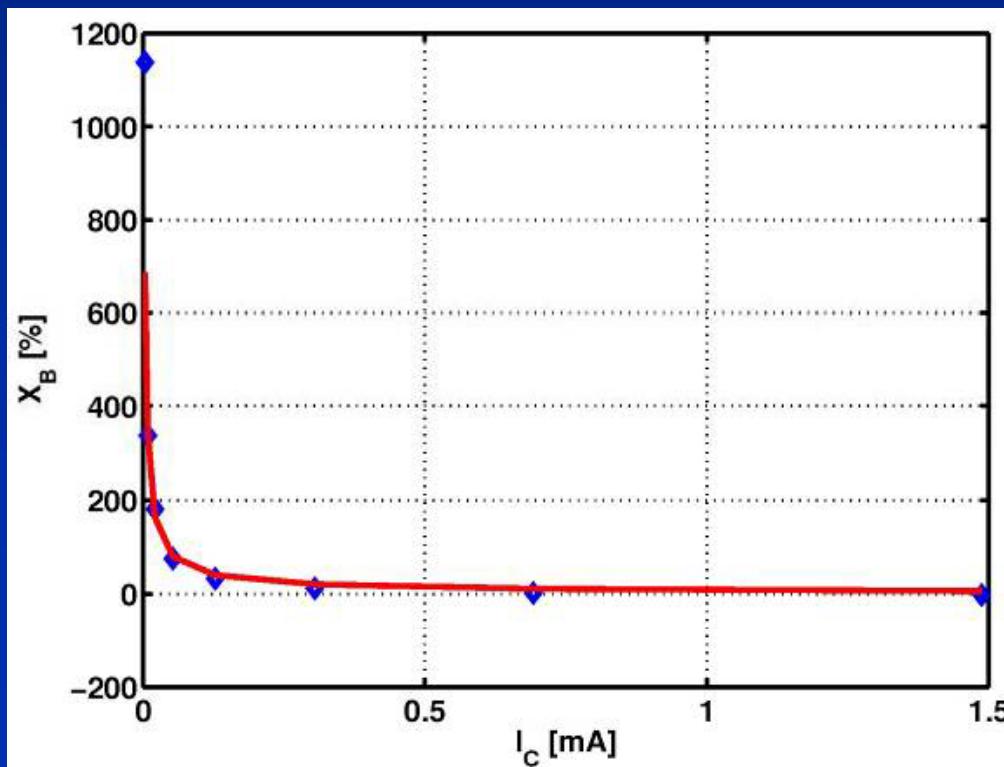


SiGe HBT model: Relative increase in base current

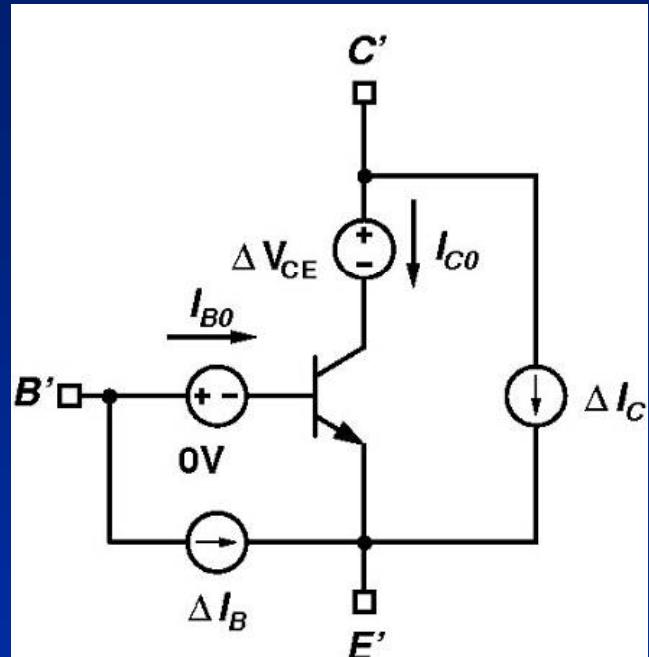
Definition: $X_B(D) = \frac{I_B(D) - I_B(0)}{I_B(0)} = \frac{\Delta I_B(D)}{I_B(0)}$

Observation:

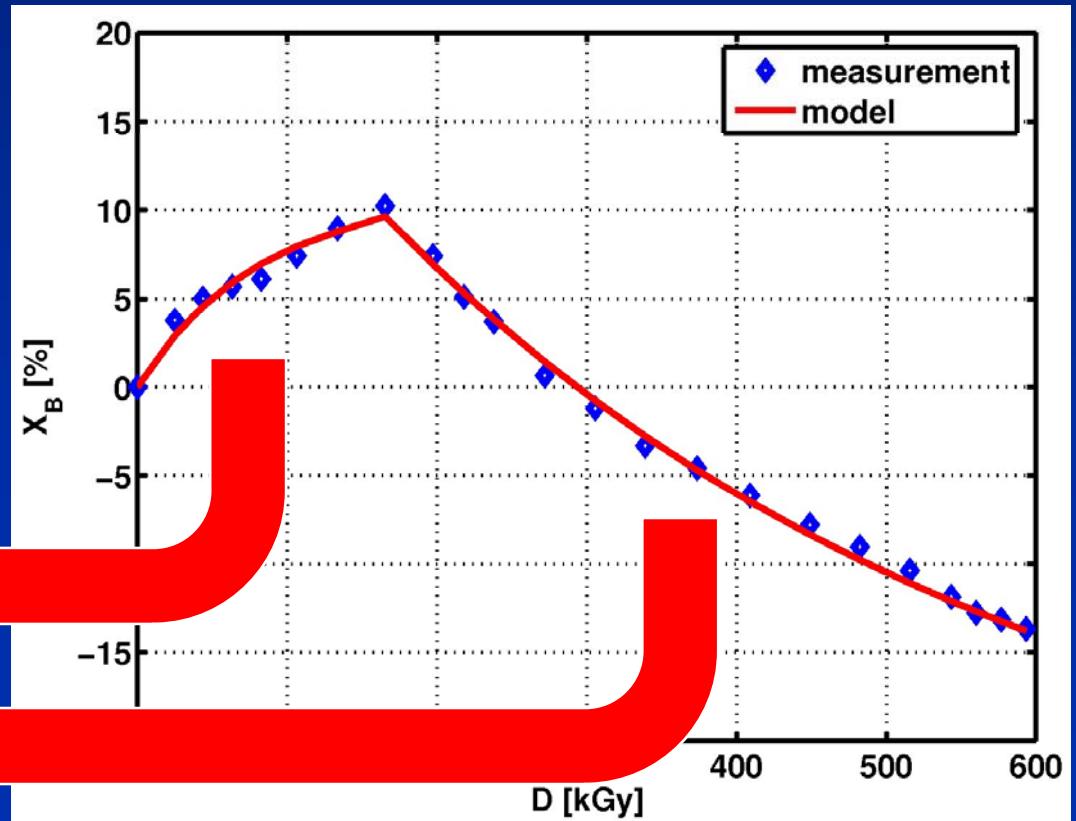
$$X_B(D) \approx \frac{a_1(D)}{I_C^\alpha(D)} \text{ with } \alpha \approx 0.5$$



SiGe HBT model: SPICE implementation



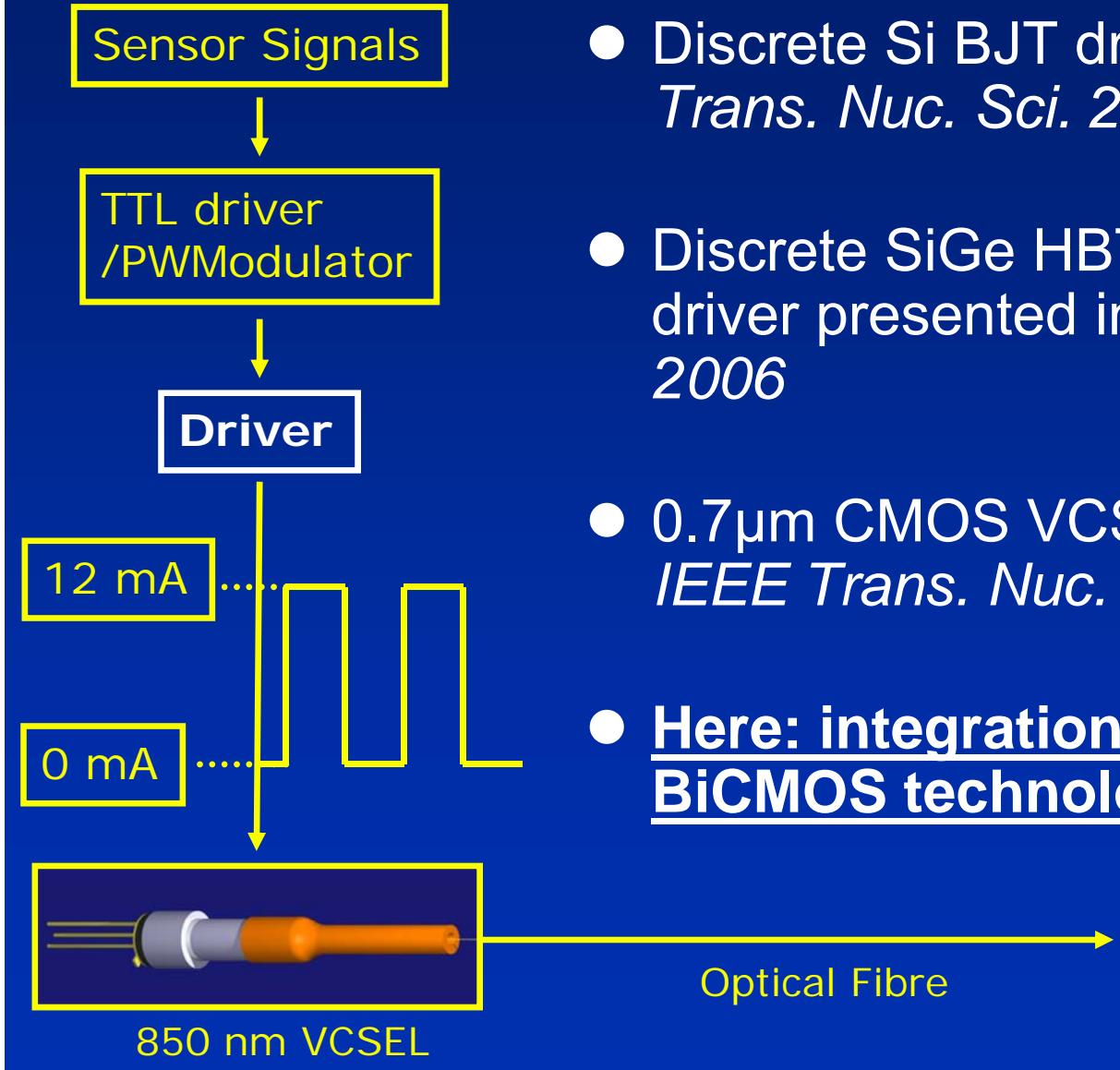
- 2 negative exponentials
 - Initial degradation
 - In-situ recovery



Outline

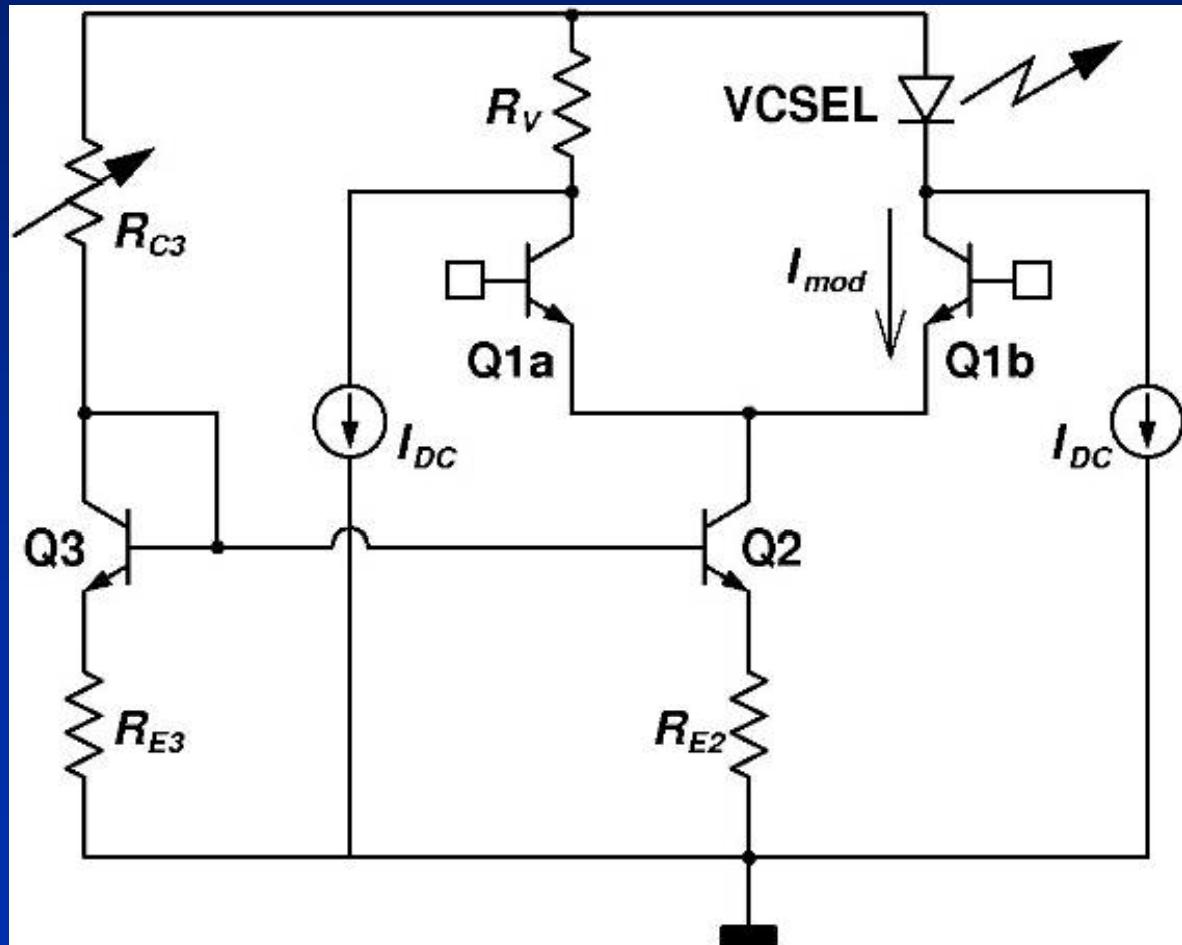
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VCSEL driver: Situation and history

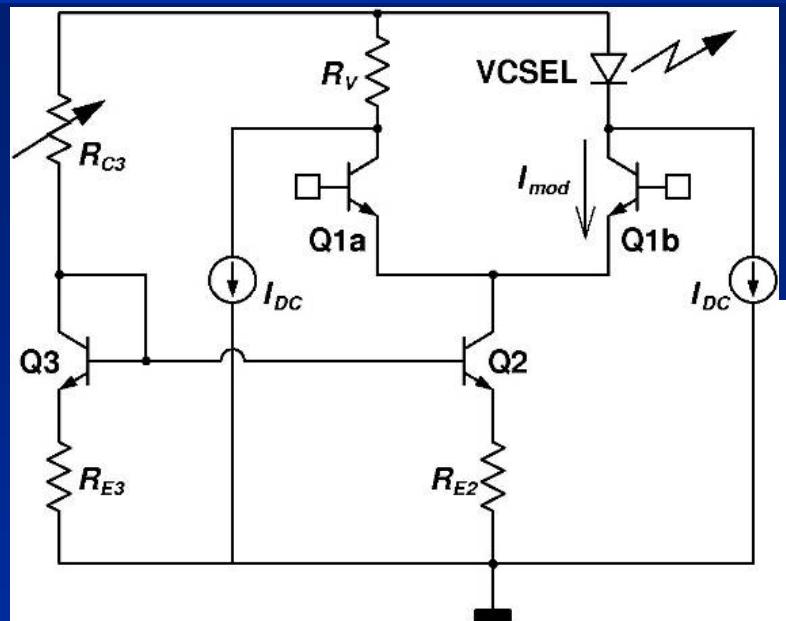


- Discrete Si BJT driver presented in *IEEE Trans. Nuc. Sci. 2002*
- Discrete SiGe HBT (BFP640) VCSEL driver presented in *IEEE Trans. Nuc. Sci. 2006*
- 0.7 μ m CMOS VCSEL driver presented in *IEEE Trans. Nuc. Sci. 2007*
- **Here: integration in a 0.35 μ m SiGe BiCMOS technology**

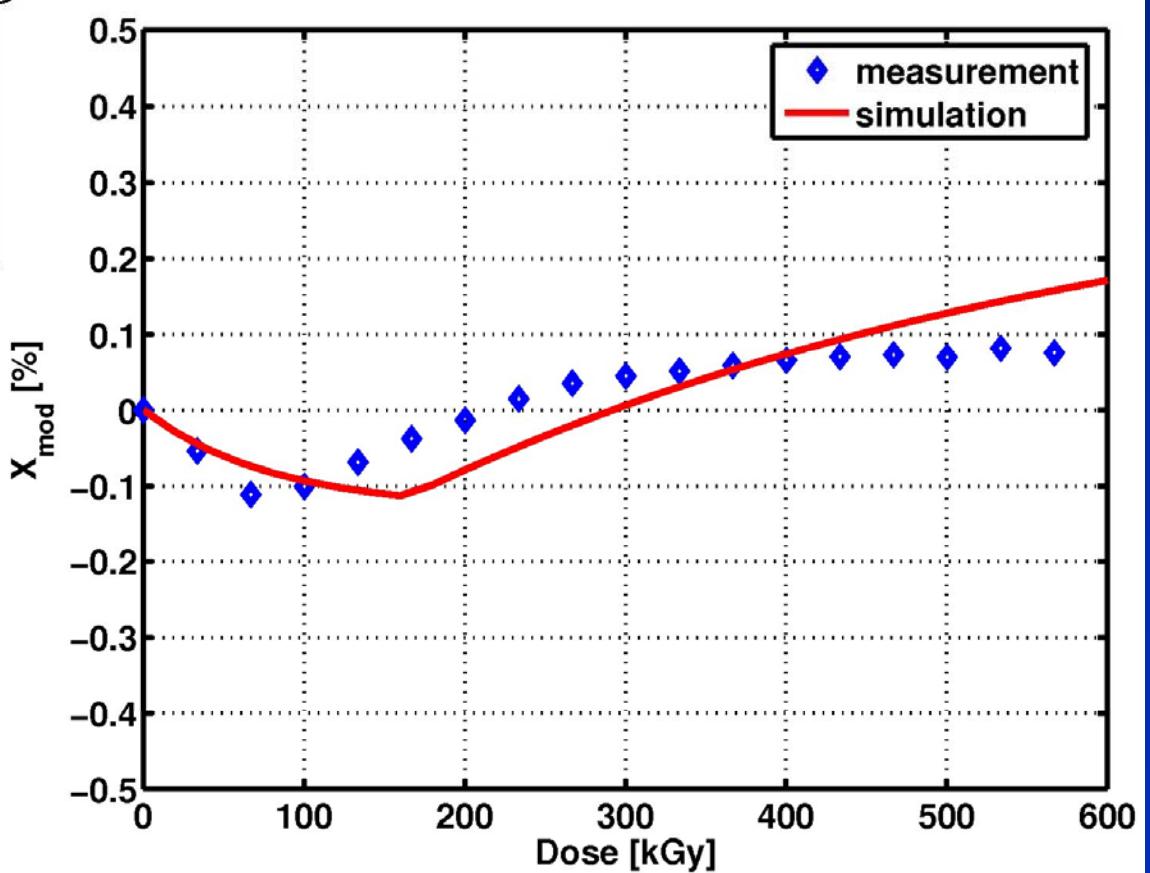
VCSEL driver: Circuit schematic



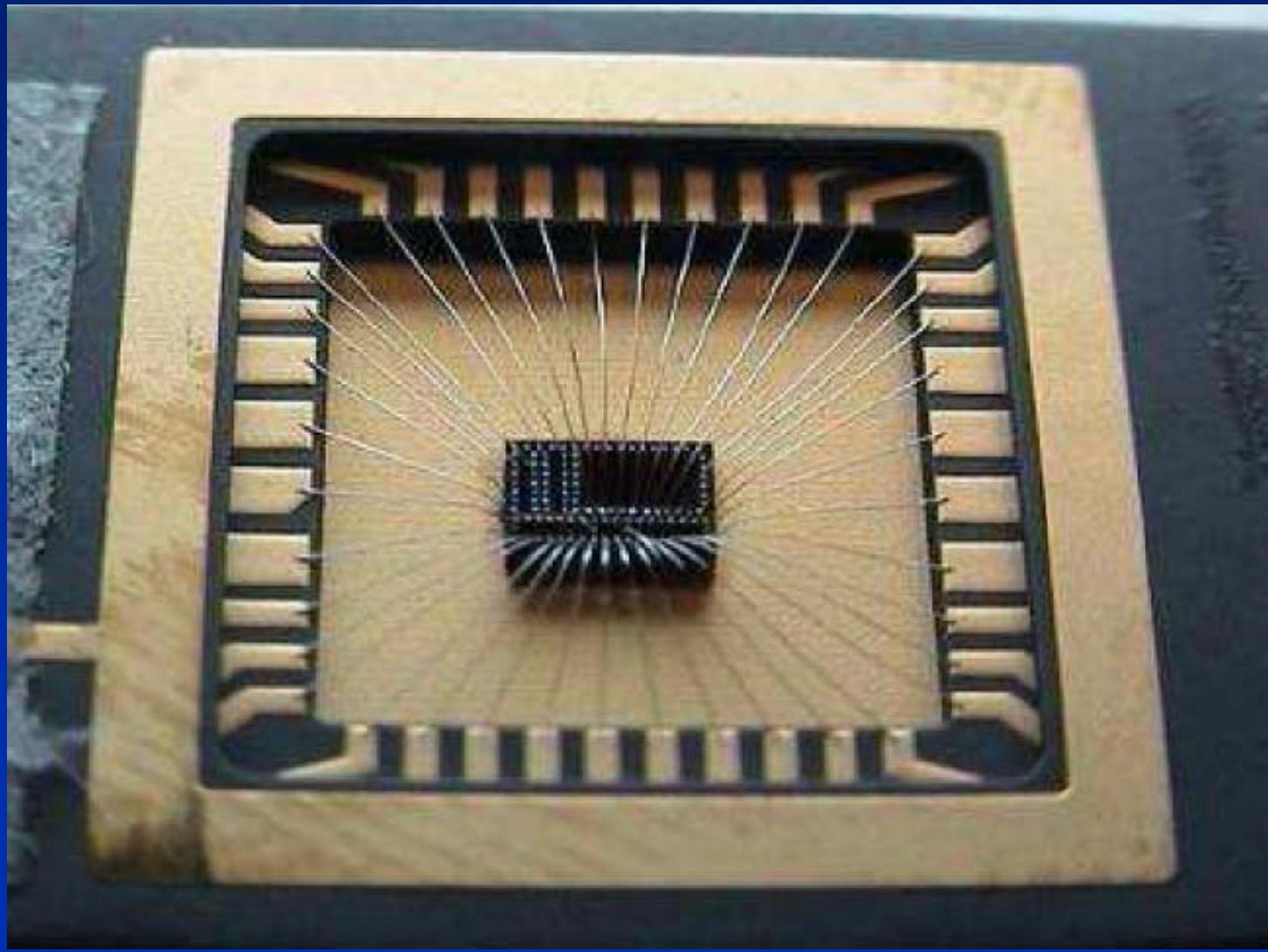
VCSEL driver: DC response to gamma irradiation



$$X_{\text{mod}}(D) = \frac{\Delta I_{\text{mod}}(D)}{I_{\text{mod}}(0)}$$



VCSEL driver: IC in DIL40 package



VCSEL driver: Irradiation experiment overview

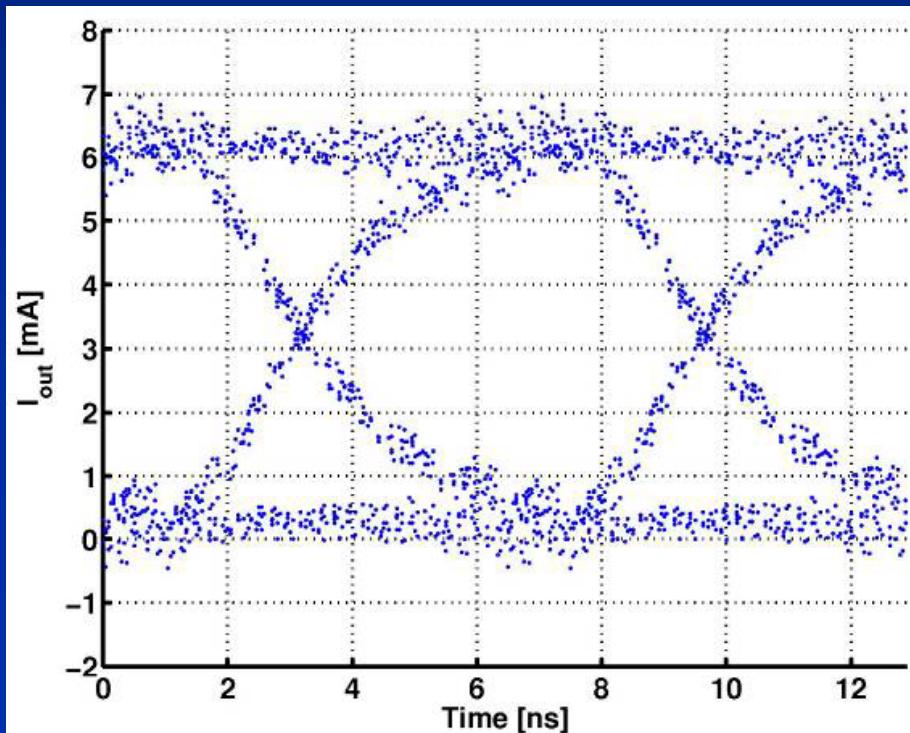
- Irradiation of driver and separate device
 - ↳ up to 600 kGy
 - ↳ in-situ DC measurements
- Irradiation up to 100 kGy
 - ↳ Circuit grounded
 - ↳ Dynamic measurements before and after irradiation
- Irradiation up to 1.6 Mrad
 - ↳ Circuit grounded
 - ↳ Dynamic measurements before and after irradiation



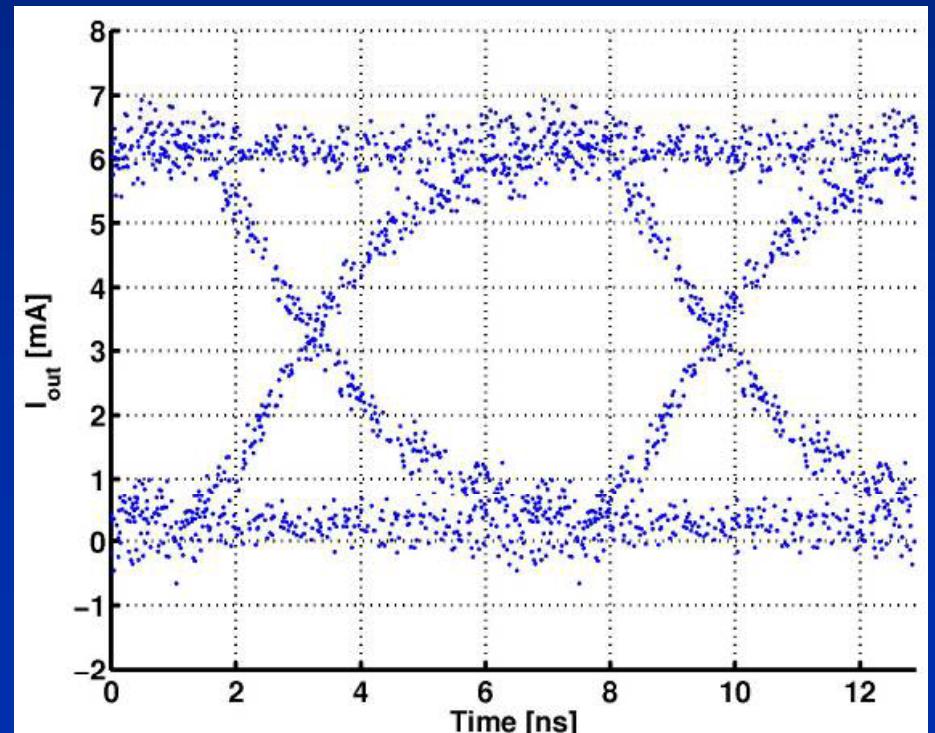
VCSEL driver Dynamic measurements after 100 kGy

155 Mbps, 2⁷-1 PRBS

Before irradiation

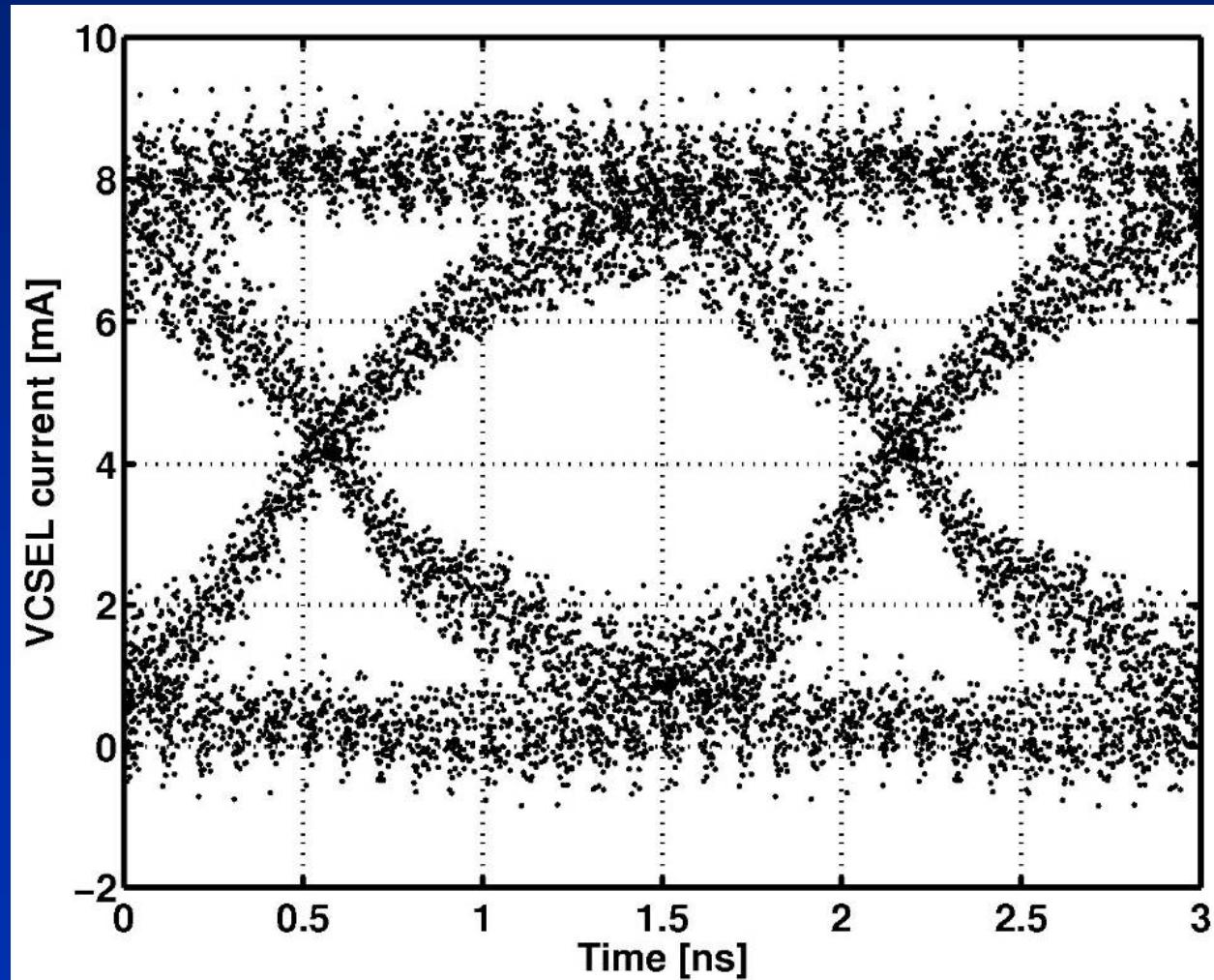


After 100 kGy



VCSEL driver: Dynamic measurements after 1.6 MGy

622 Mbps, $2^7\text{-}1$ PRBS

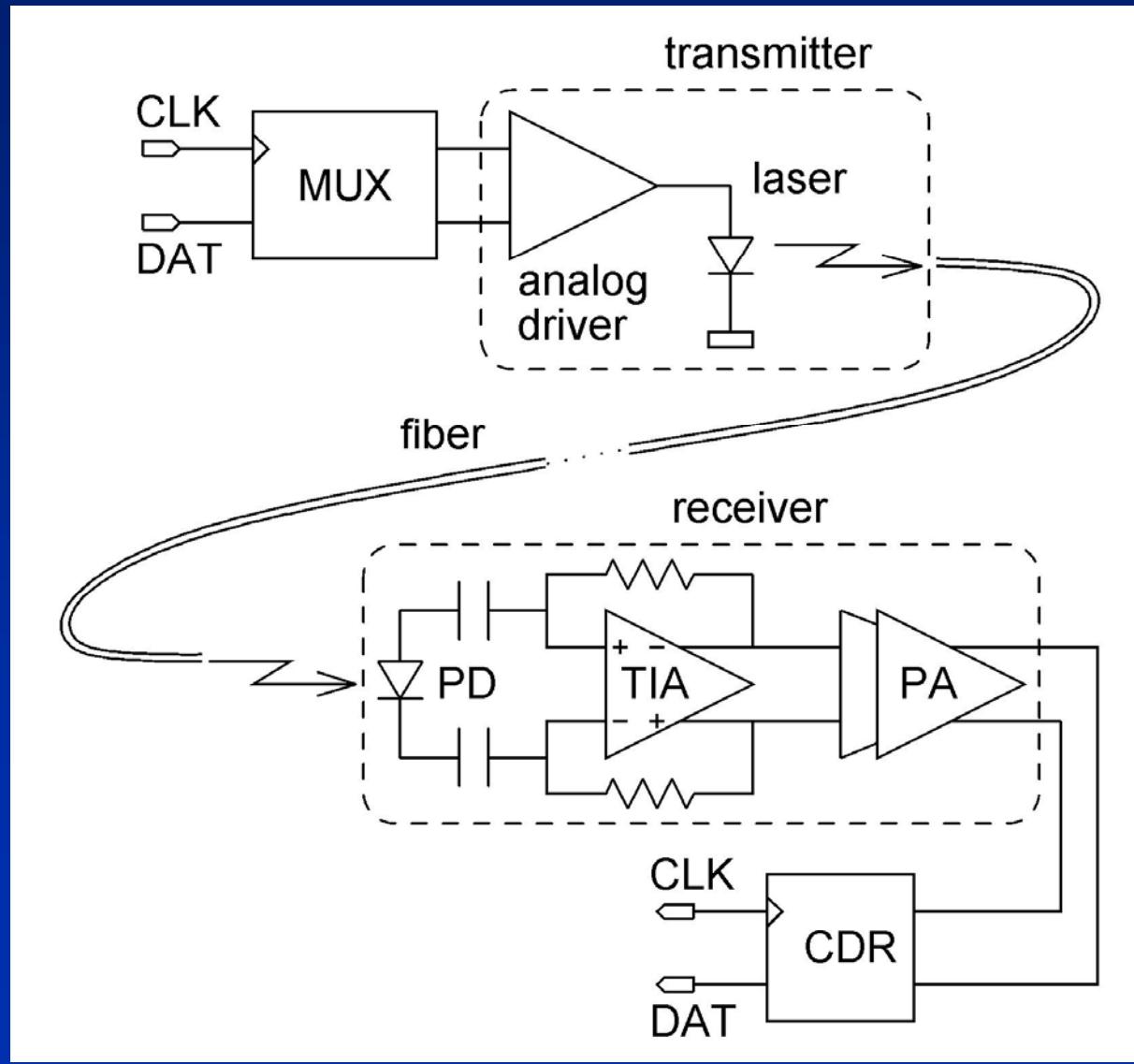


Outline

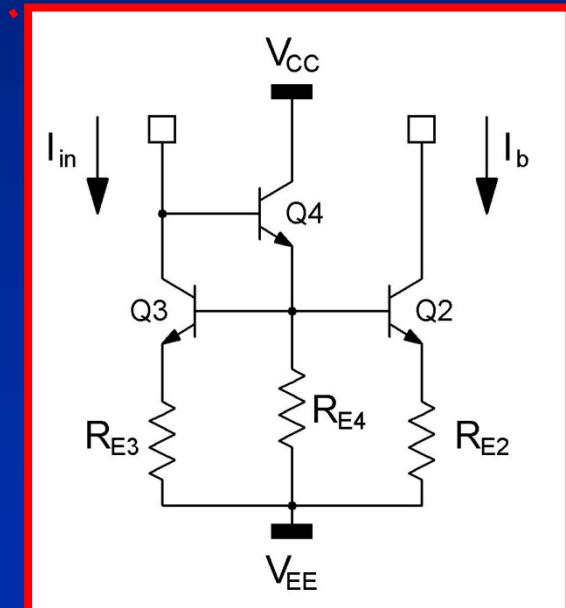
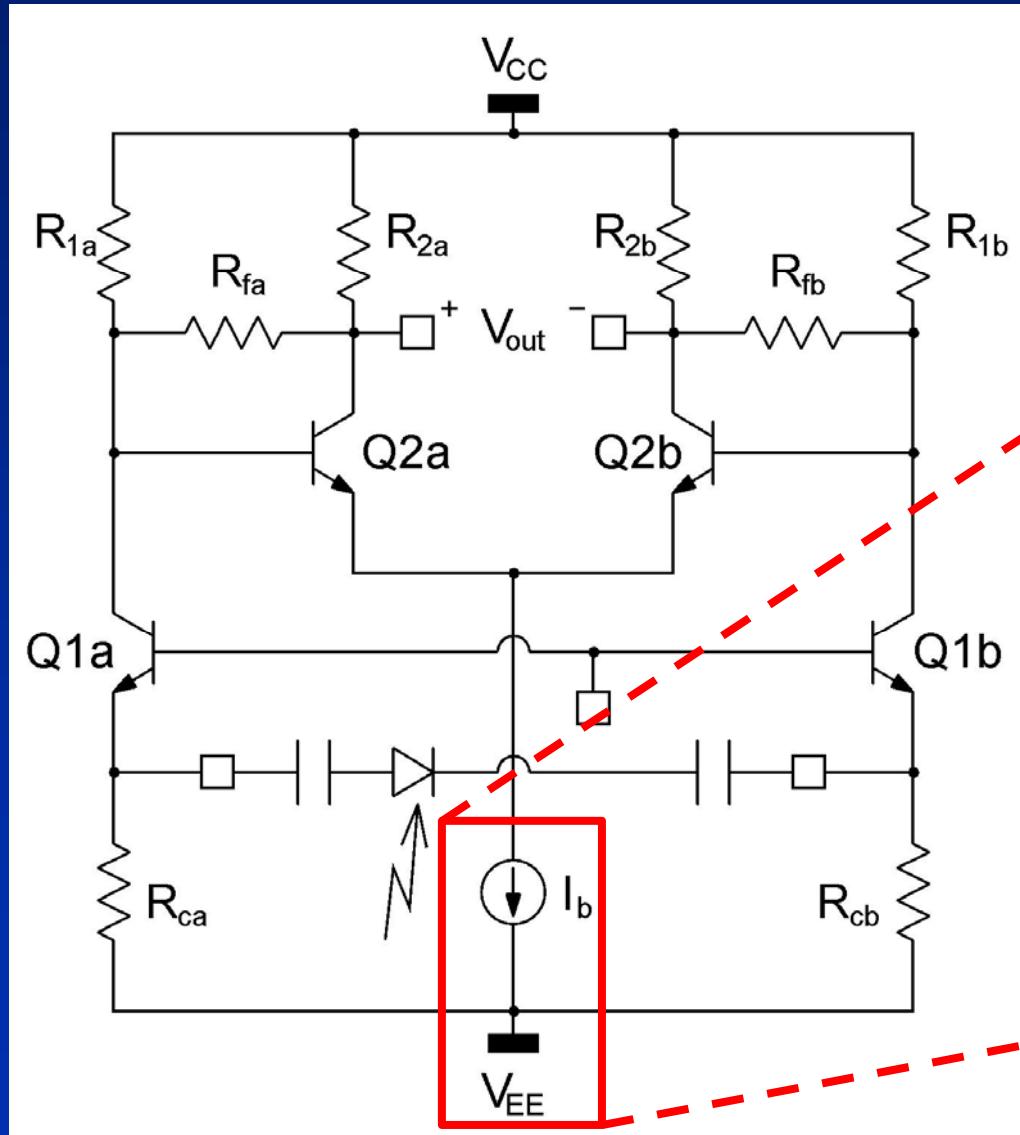
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Context

Optical communication link



Transimpedance amplifier Circuit schematic



Transimpedance amplifier Design equations

- Gain:

$$R_{TIA} = 2R_f = 4\text{k}\Omega$$

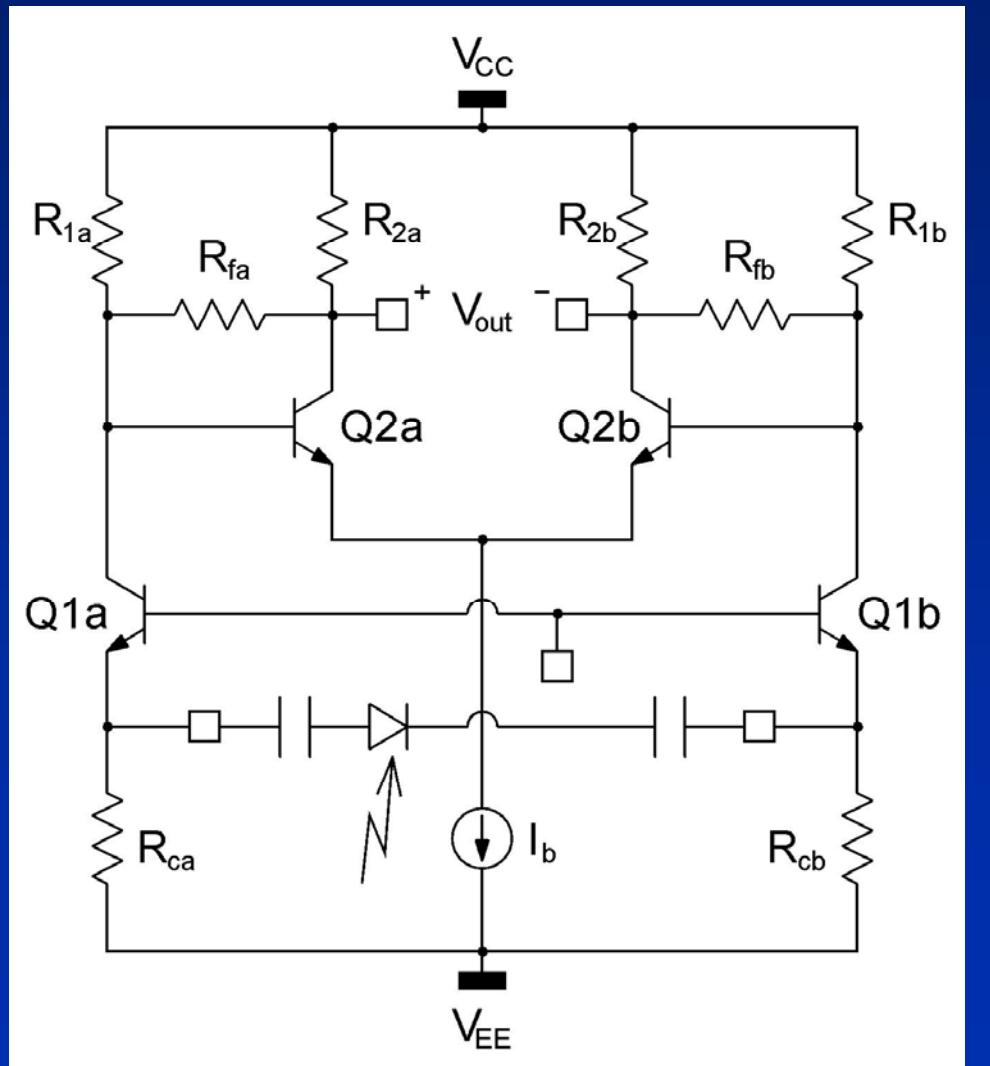
- Bandwidth:

$$BW_{TIA} = \frac{g_{m2}R_2 + 1}{2\pi C_{b2}(R_f \square R_l)} = 1\text{GHz}$$

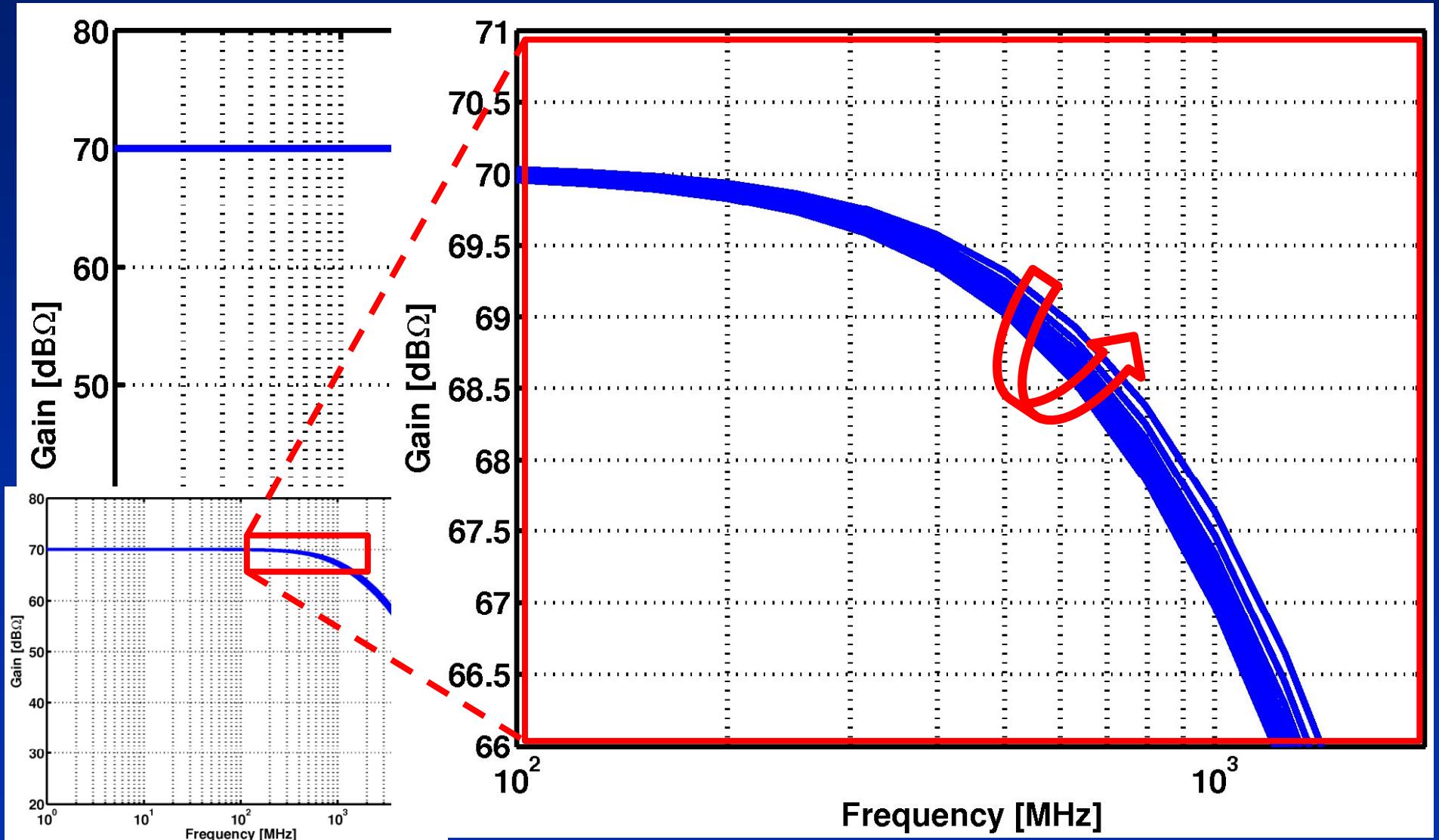
- Noise:

$$\overline{i_{n,in}^2} = 2kT\Delta f \cdot \left(\frac{1}{R_c} + \frac{1}{R_l} + \frac{1}{R_f} + \frac{r_{b1}}{R_c^2} \right)$$

- Stability of the loop!



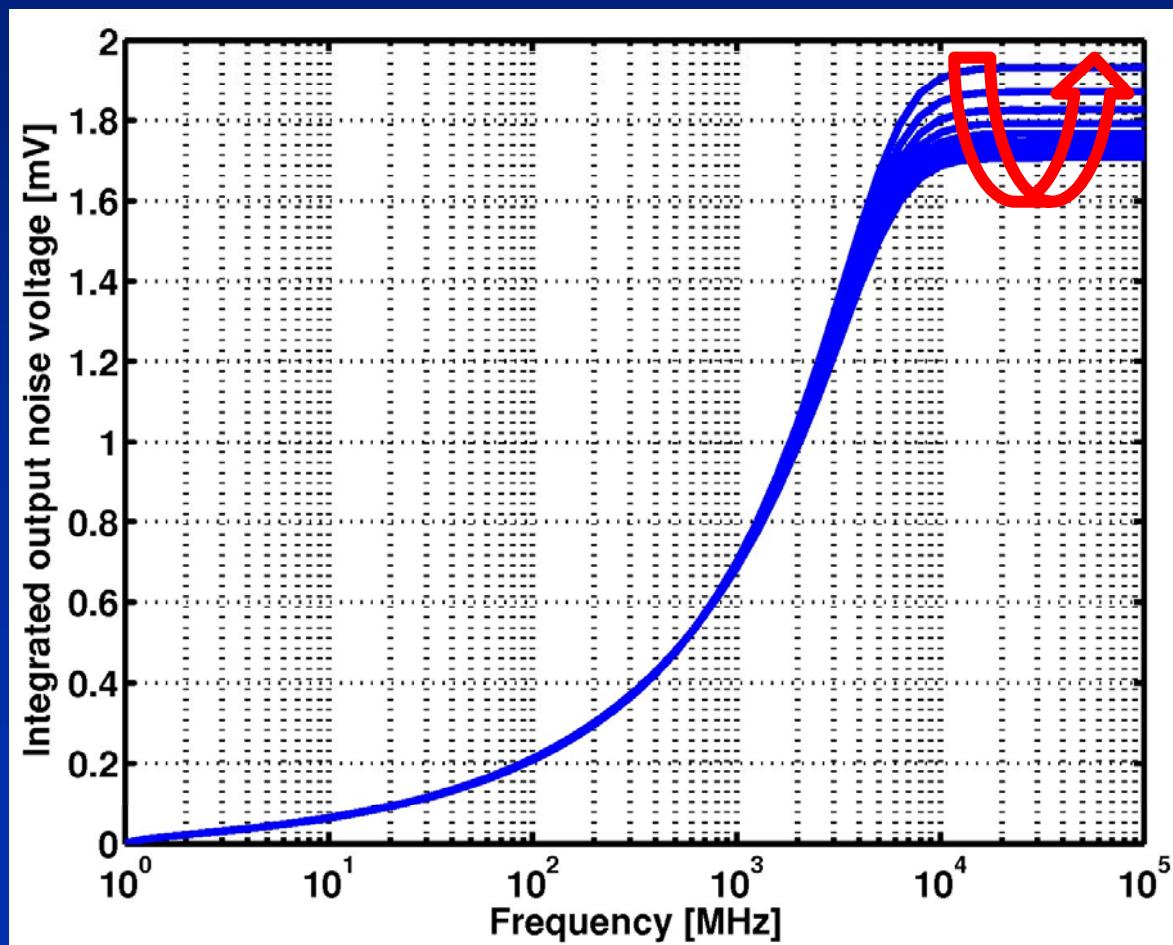
Transimpedance amplifier AC-behavior



Transimpedance amplifier Noise-behavior

Input current sensitivity:

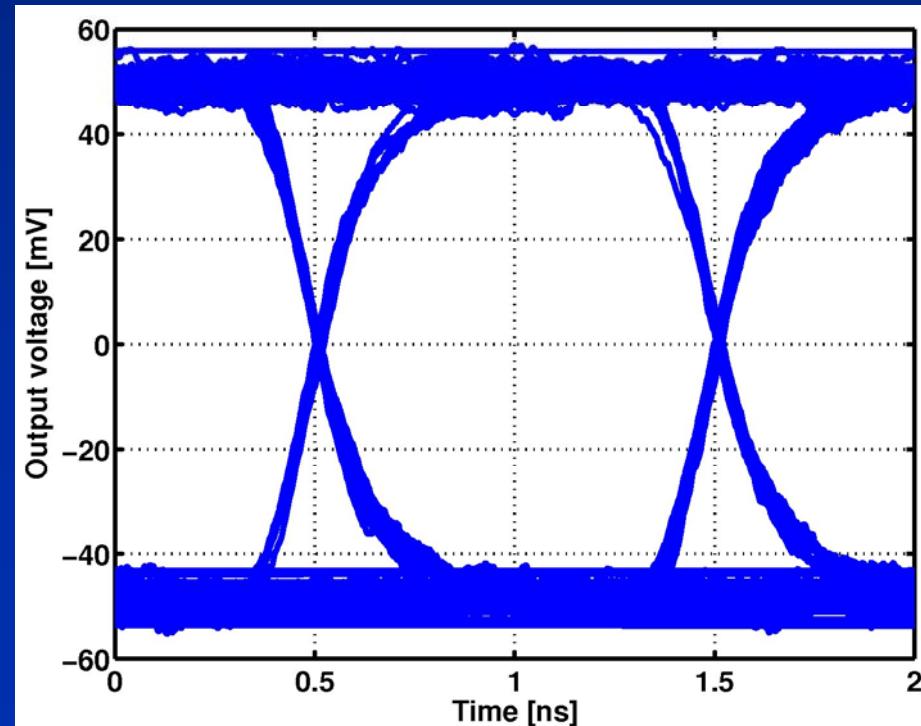
$$i_{\min} = \frac{SNR_{\min} \cdot v_{n,out,rms}}{R_{TIA}}$$
$$= \frac{10 \cdot 1.8 \cdot 10^{-3}}{3 \cdot 10^3} = 6 \mu A$$



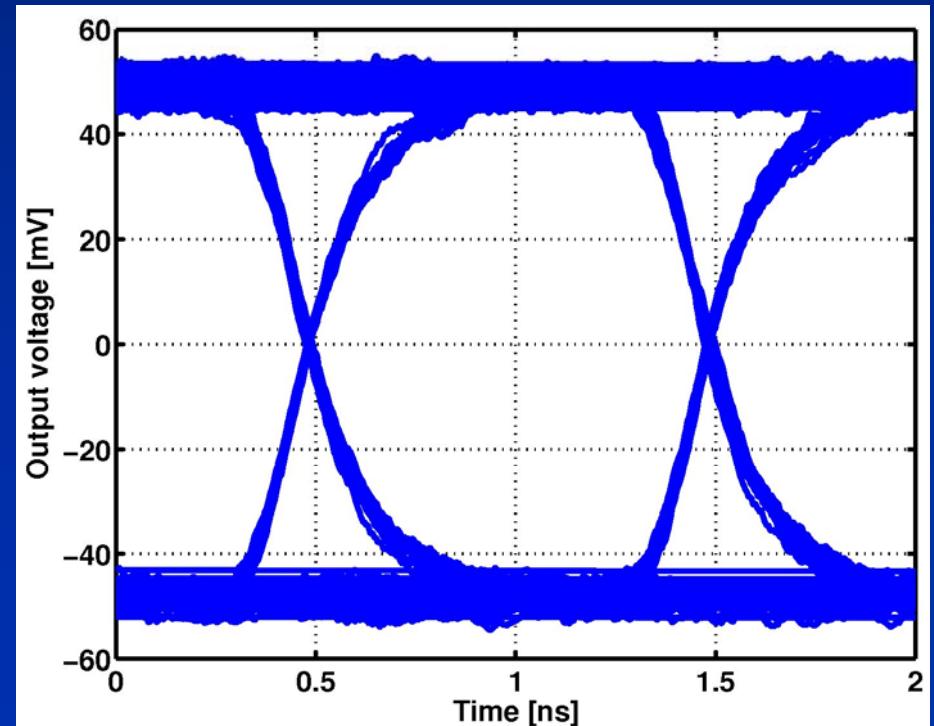
Transimpedance amplifier Signal + noise transient behavior

1 Gbps, 2⁷-1 PRBS, $i_d = 30\mu A$

Before irradiation



After 200 kGy



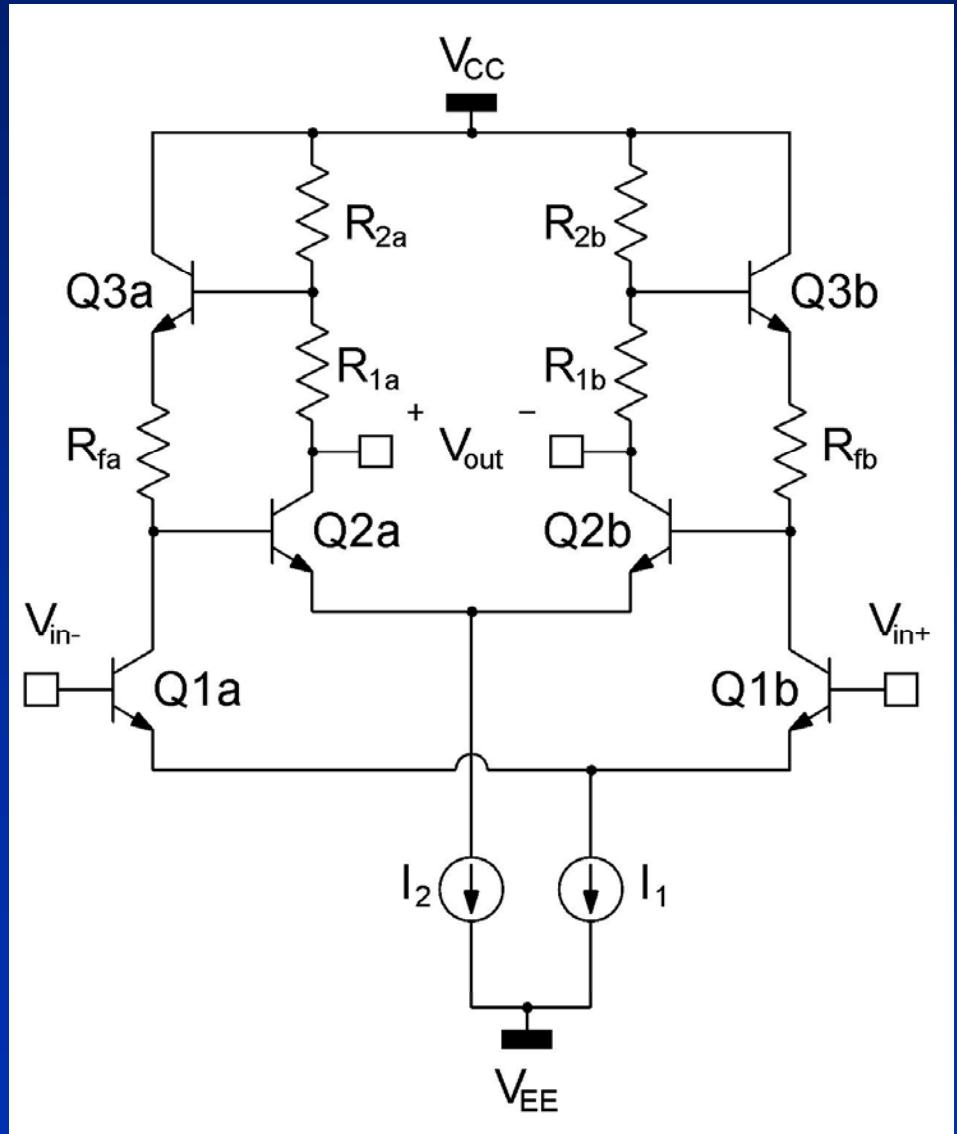
Cherry-Hooper amplifier Circuit schematic

Cherry-Hooper amplifier =

- # → Q1

followed by

- transimpedance stage
→ Q2 with feedback via Q3
and R_f



Cherry-Hooper amplifier Design equations

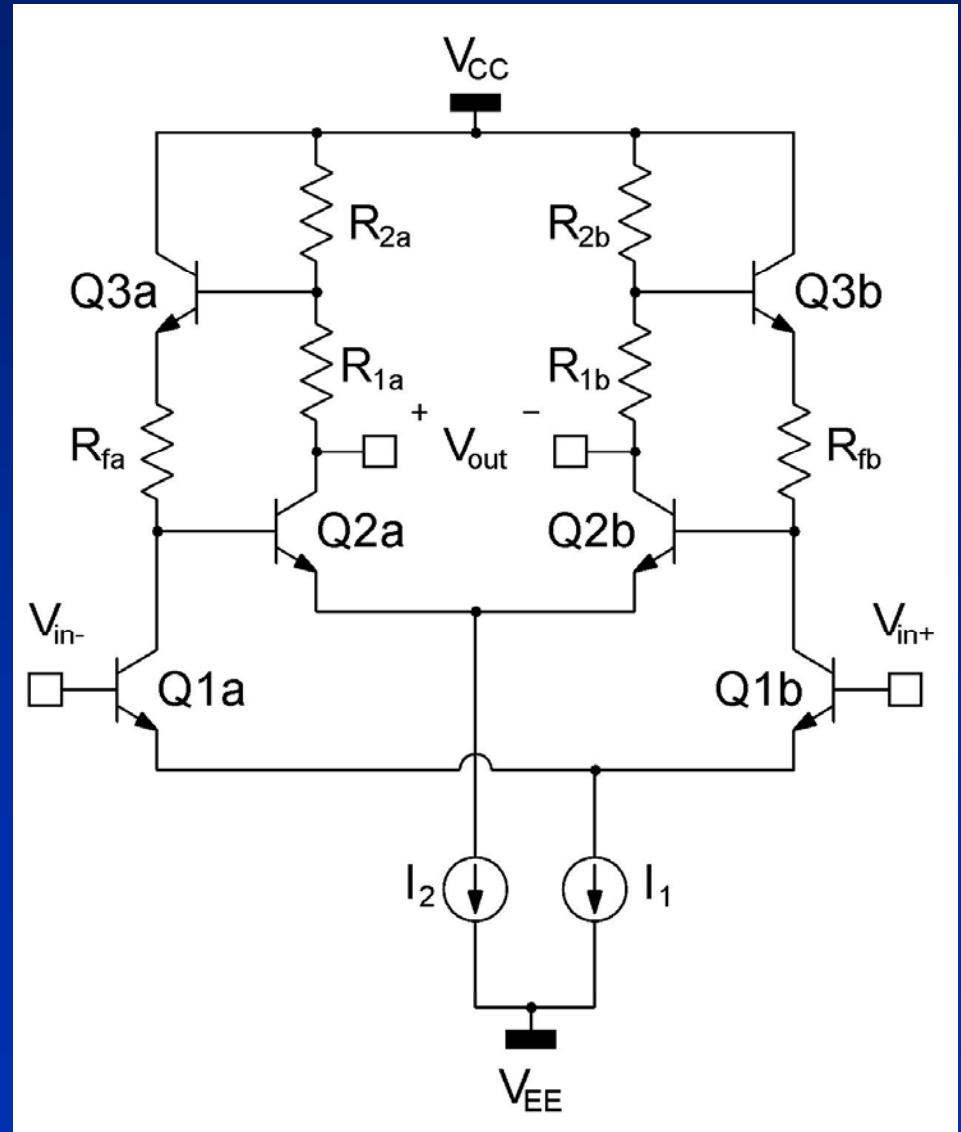
- Gain:

$$A_v = g_m R_f \cdot \left(1 + \frac{R_1}{R_2} \right) = 15$$

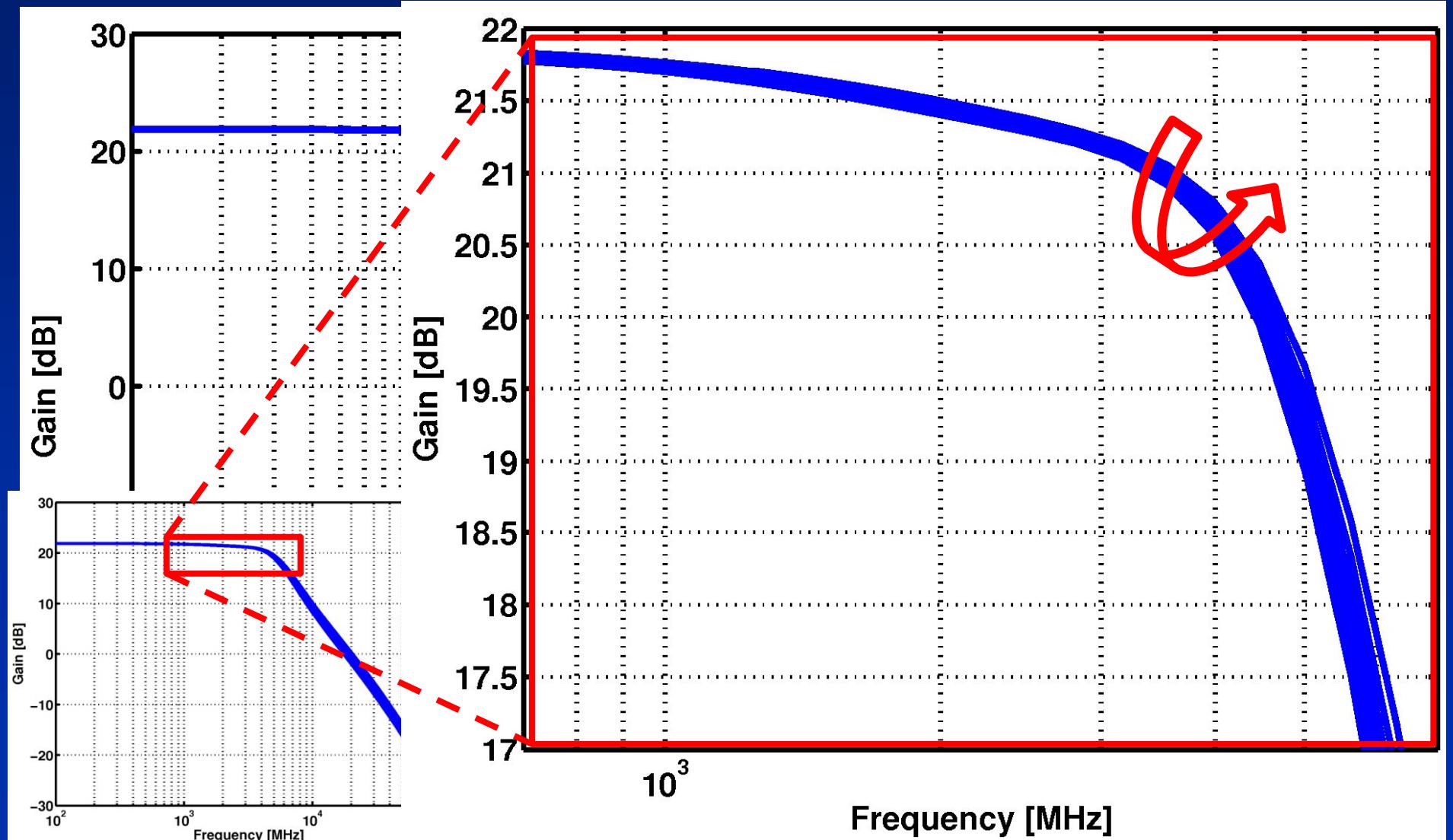
- Bandwidth:

$$BW = \frac{g_m R_2 + 1}{2\pi C_{b2} R_f} = 5\text{GHz}$$

- Stability!



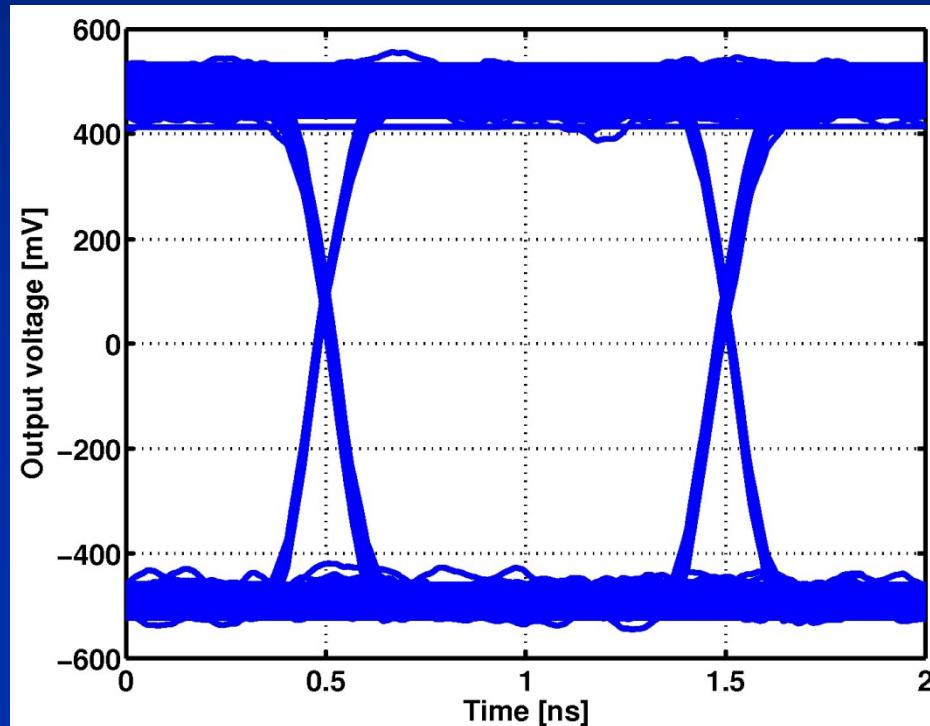
Transimpedance amplifier AC-behavior



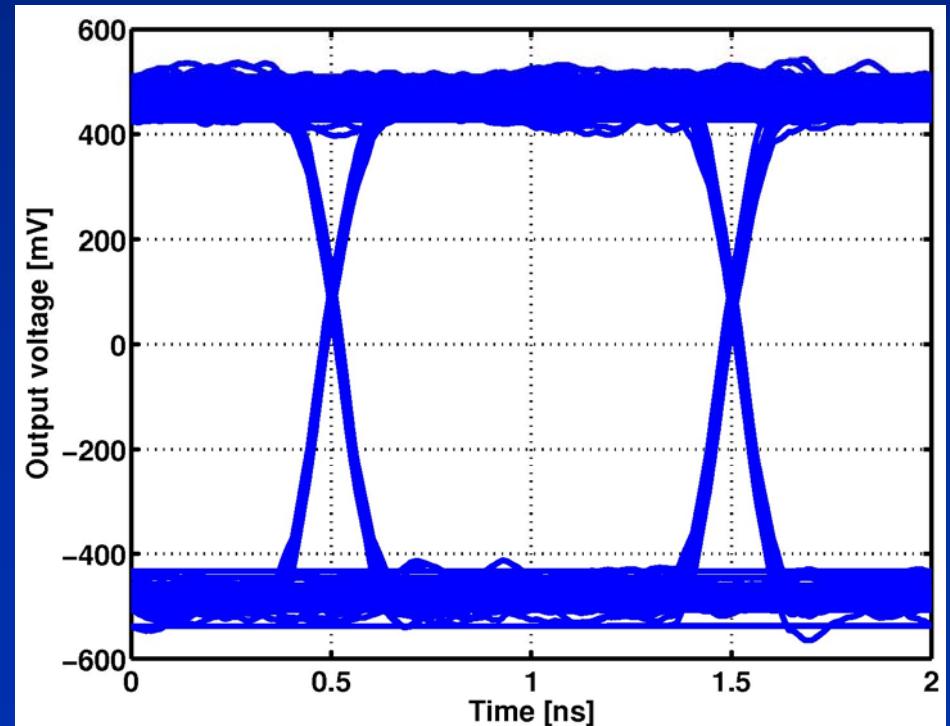
Transimpedance + Cherry Hooper amplifier Signal + noise transient behavior

1 Gbps, 2⁷-1 PRBS, $i_d = 30\mu A$

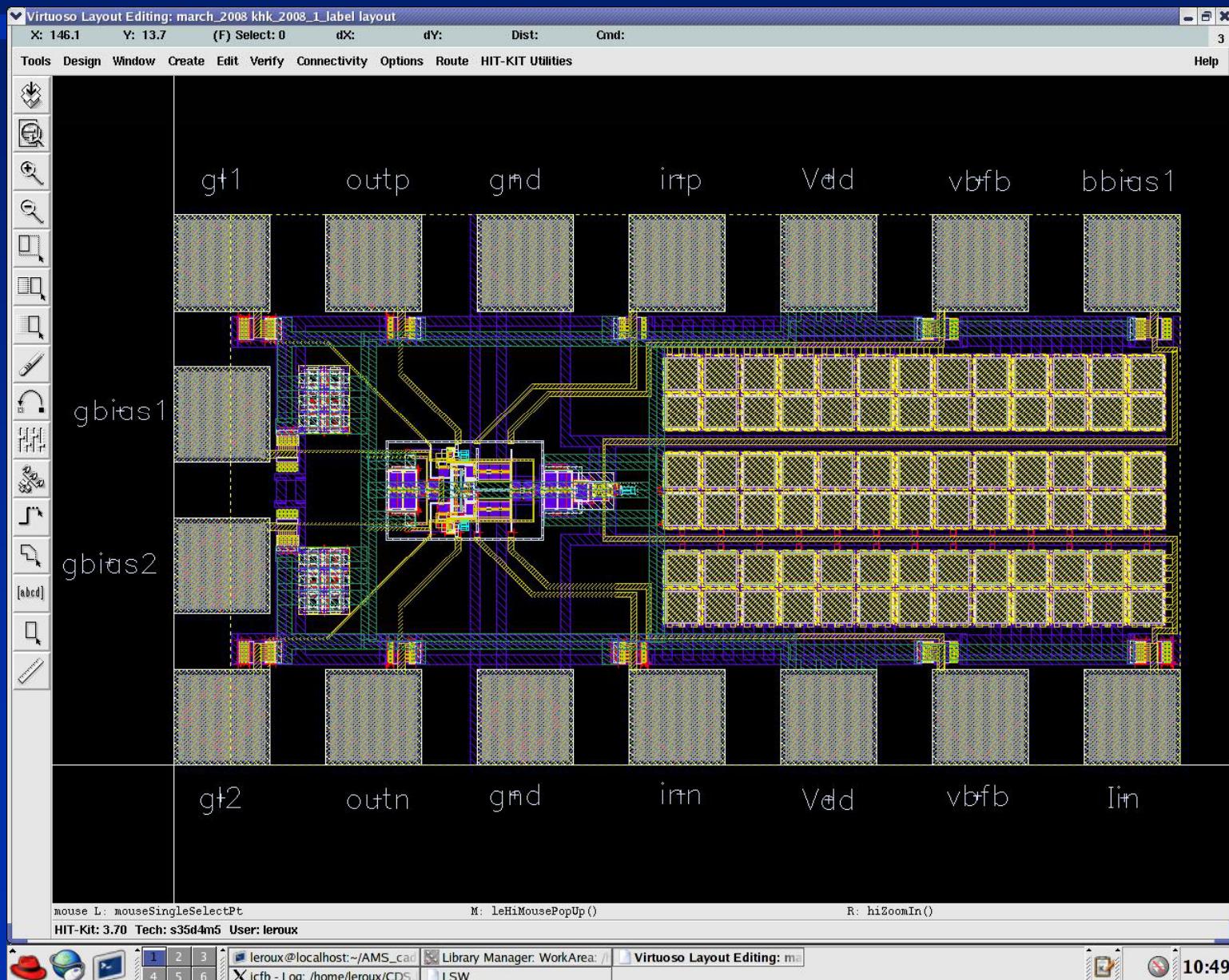
Before irradiation



After 200 kGy



Layout of receiver circuit



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Summary and conclusions

- We measured and modeled the radiation induced gain degradation for the SiGe HBT in a $0.35\mu\text{m}$ BiCMOS technology
- Assessment of an integrated $0.4\mu\text{m}$ SiGe HBT VCSEL driver
 - ↳ Static results up to 600kGy: less than 0.2% degradation in amplitude of the modulation current
 - ↳ Dynamic results up to 1.6 MGy: no significant degradation in the eye diagram of the output signal at 622Mbps
- Design of integrated receiver circuits
 - ↳ $3\text{k}\Omega$, 1GHz transimpedance amplifier
 - ↳ 20dB, 5GHz Cherry-Hooper amplifier
- Promising results for optical communication in harsh radiation environments like ITER

Dharskiyois!?

