Design and Development of Radiation Hardened Application-Specific Integrated Circuit for the ATHENA Mission

APC PhD Day - November 15, 2017

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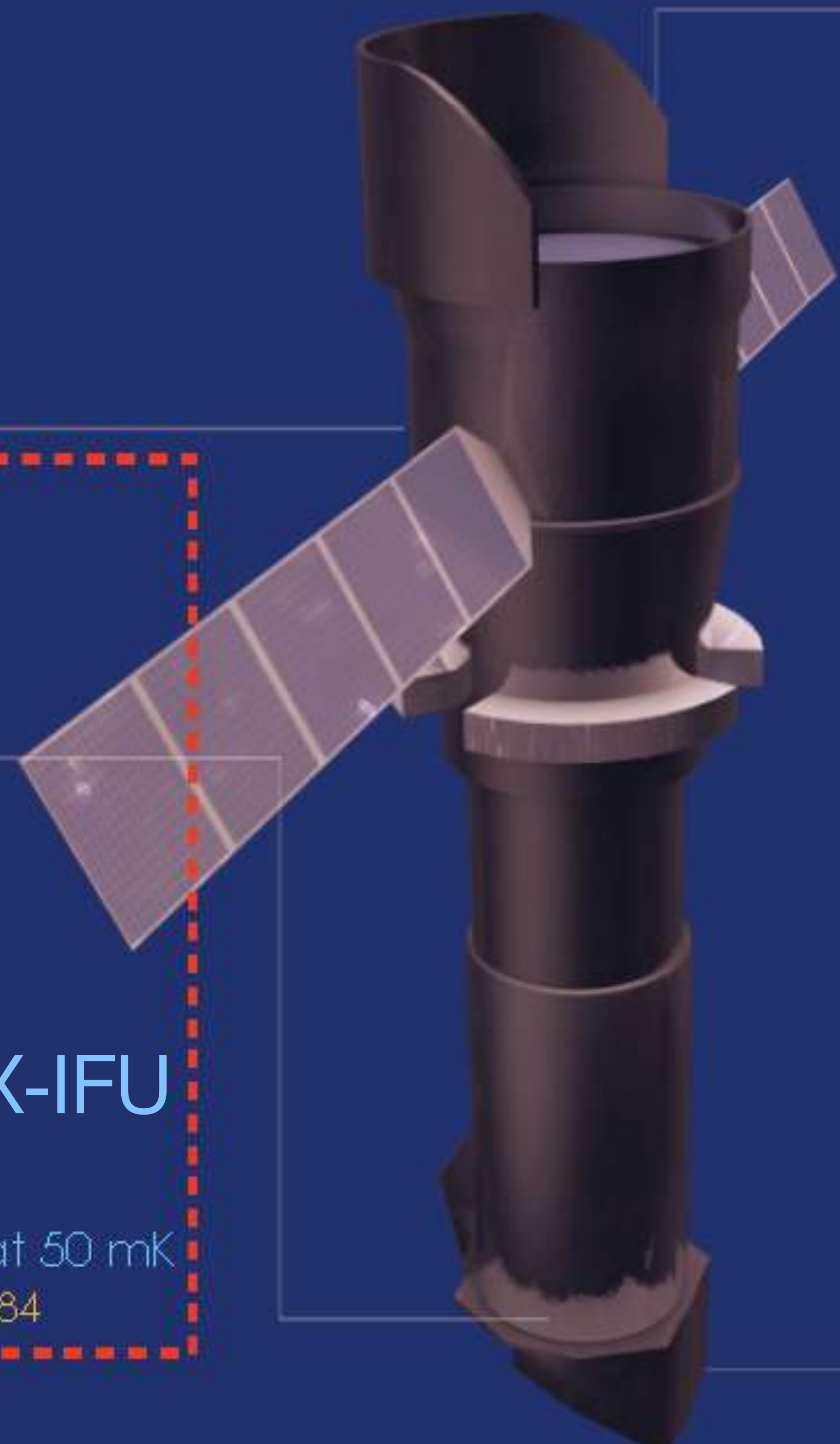
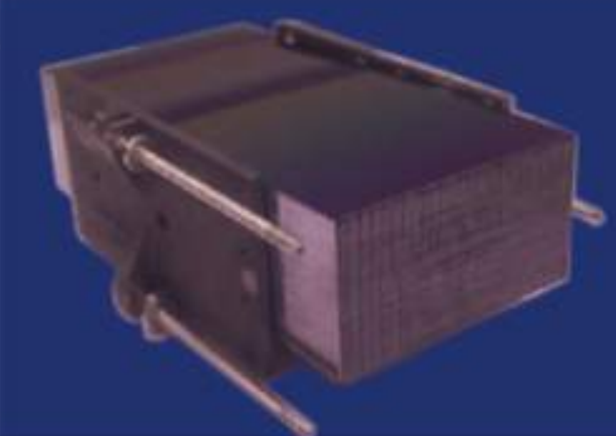
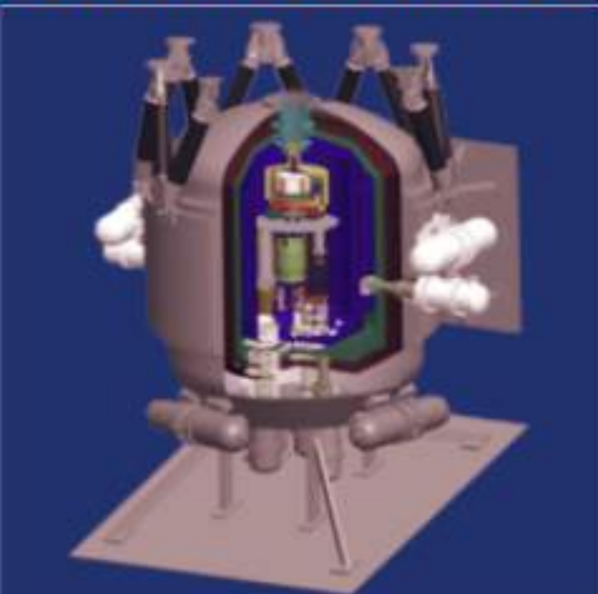
Next Generation **X-Ray** Space **Observatory** of ESA

Ariane V class launcher
Satellite mass ~ 5500 kg
Power ~5600 W
Focal length: 12 m
Lifetime: 5 years (10 years)

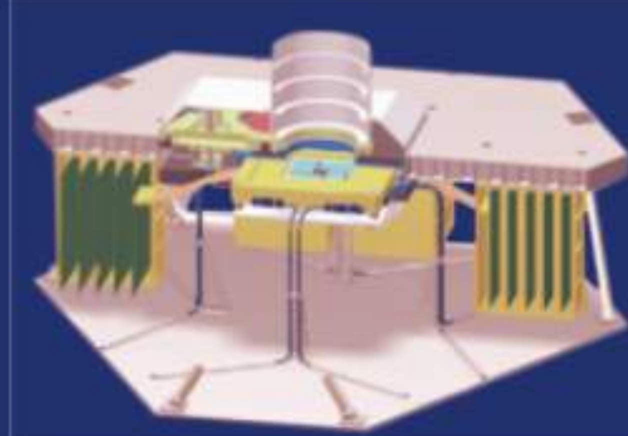




Silicon Pore Optics:
Effective area: 2m² @ 1 keV
PSF (HEW): 5''
Willingale et al. 2013 arXiv1308.6785



X-ray Integral Field Unit: X-IFU
ΔE: 2.5 eV
Field of view: 5 arcmin
Large array of TES cooled at 50 mK
Barret et al. 2013 arXiv:1308.6784

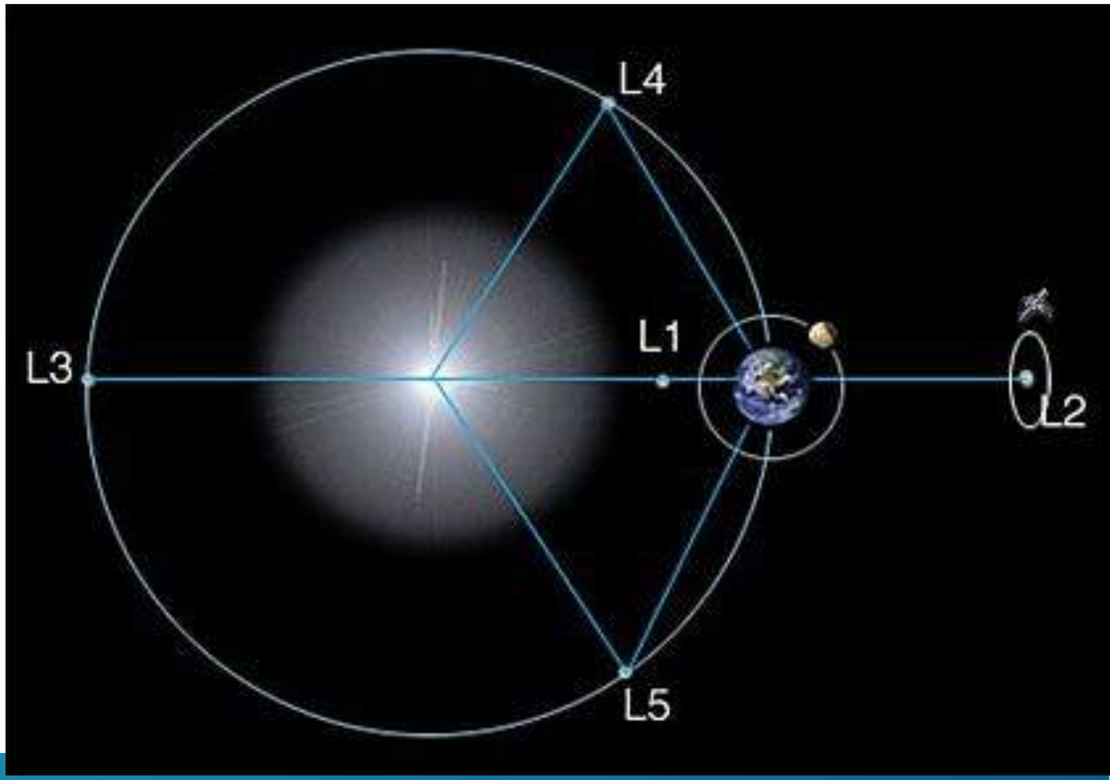


Wide Field Imager: WFI
ΔE: 125 eV
Field of view: 40' x 40'
Rau et al. 2013 arXiv1307.1709

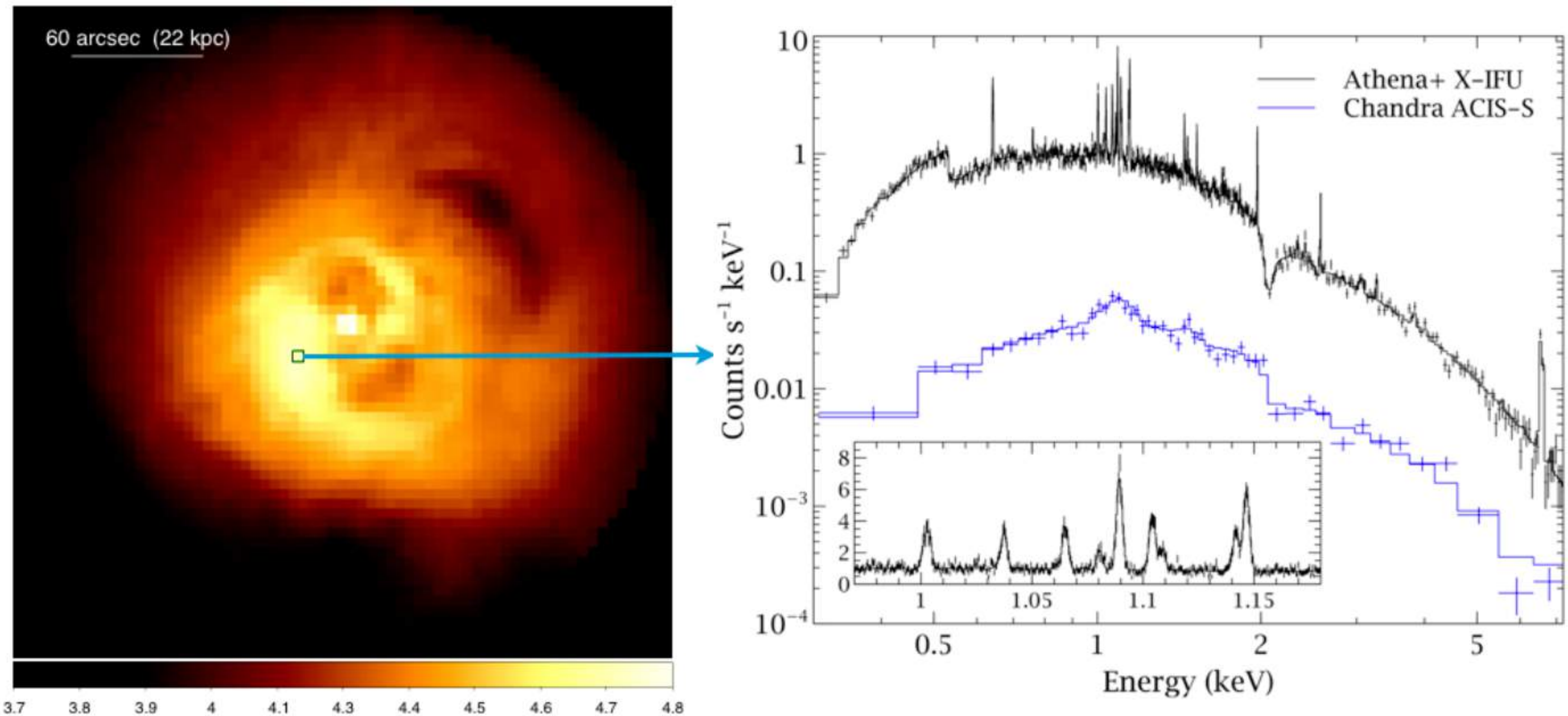
ATHENA Mission

- « Hot and Energetic Universe science » theme
  - How does ordinary matter assemble into the large-scale structures we see in the Universe today?
  - How do black holes grow and shape the Universe?

- 0.5-12keV range
- L-class mission , 5 years lifetime, Launch date: 2028-2030
- Halo orbit around Lagrange point L2,



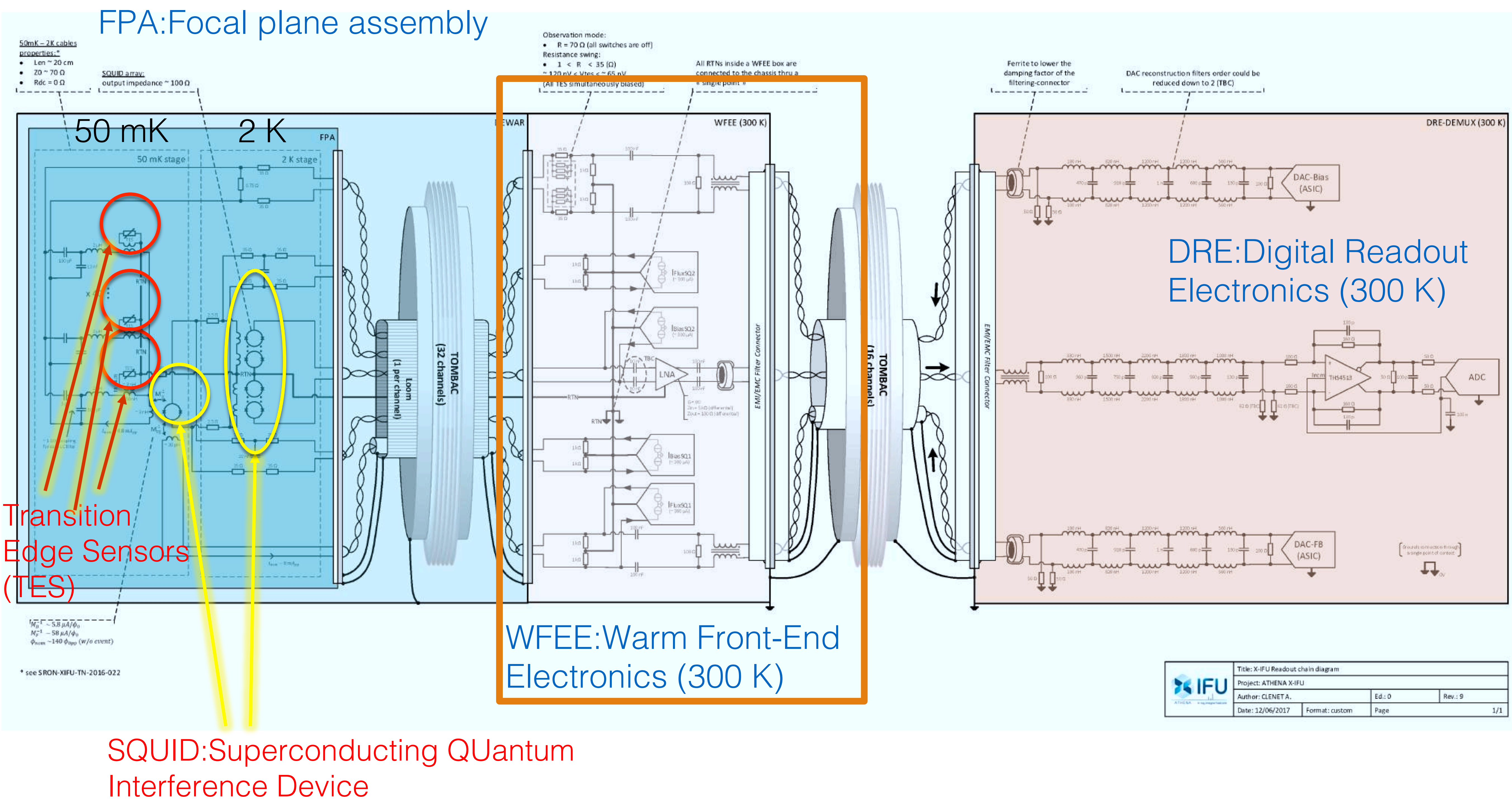
- Simulation of a 50 ks X-IFU exposure of the Perseus cluster



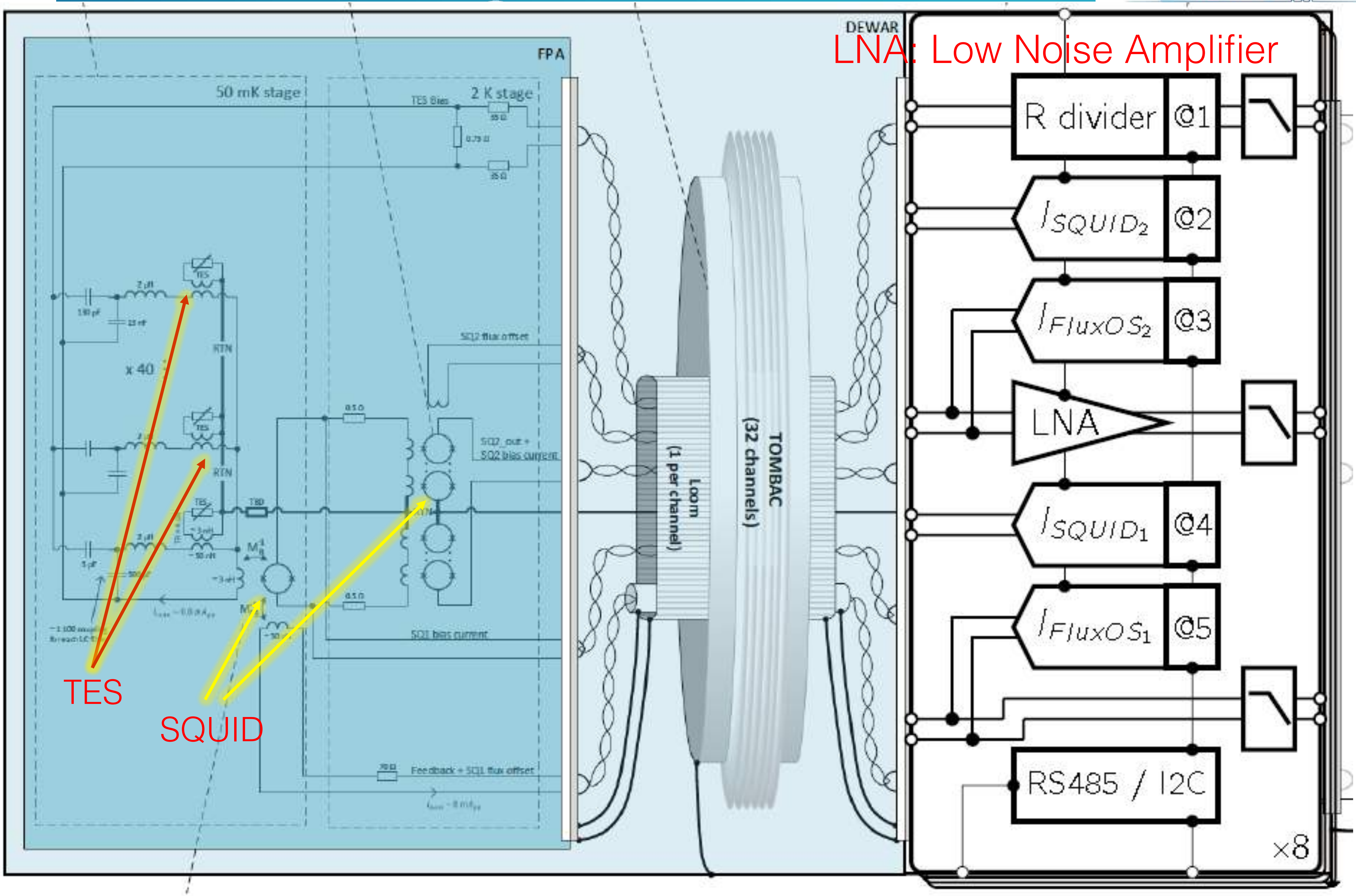
Croston, Sanders et al. (2013, Athena+ Supporting Paper)

X-IFU Electronic Readout chain

- Frequency-Division Multiplexing(FDM) 1-6 MHz, factor 40
- Matrix of 3840 TES /40 = 96 readout channels

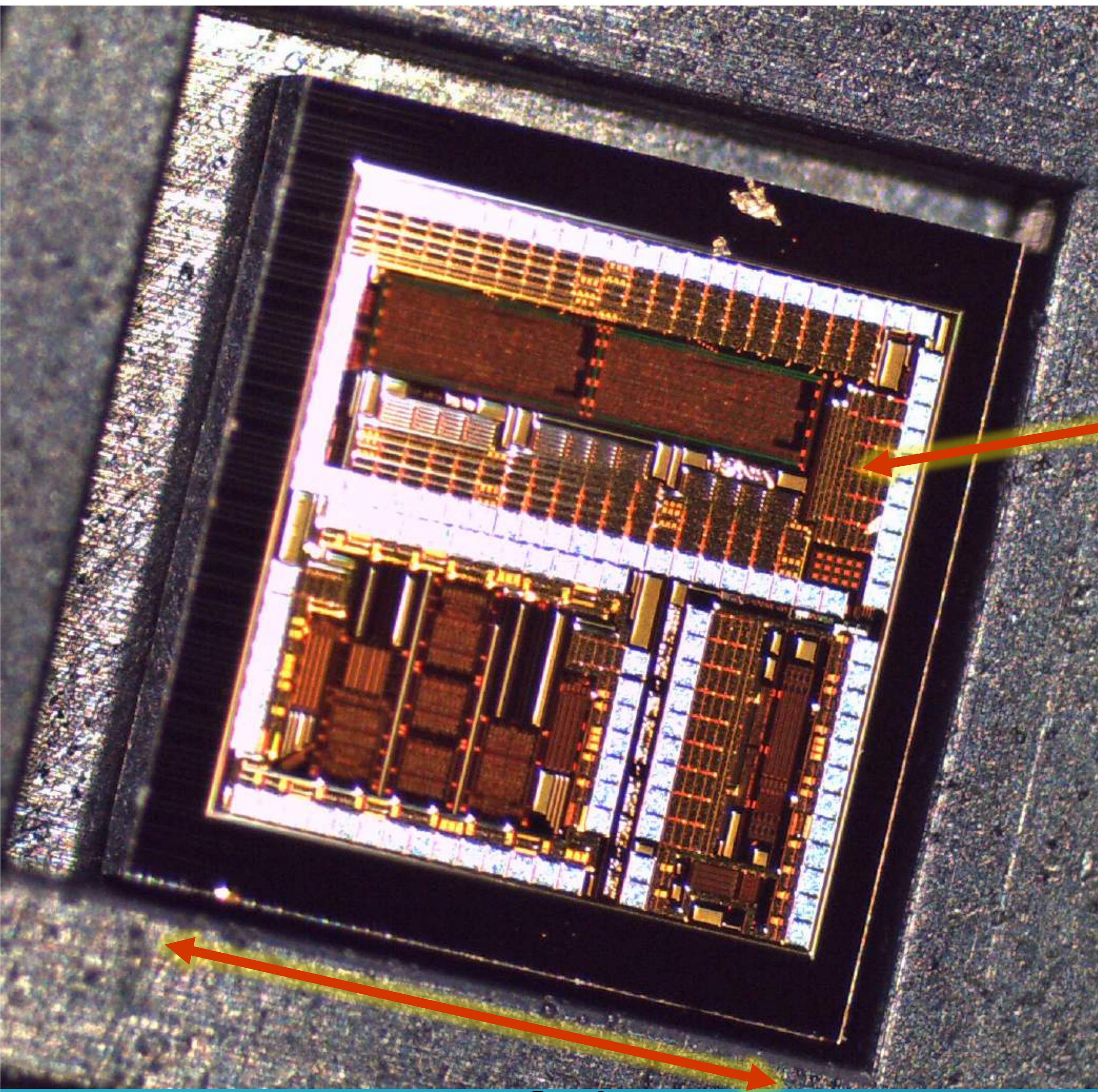


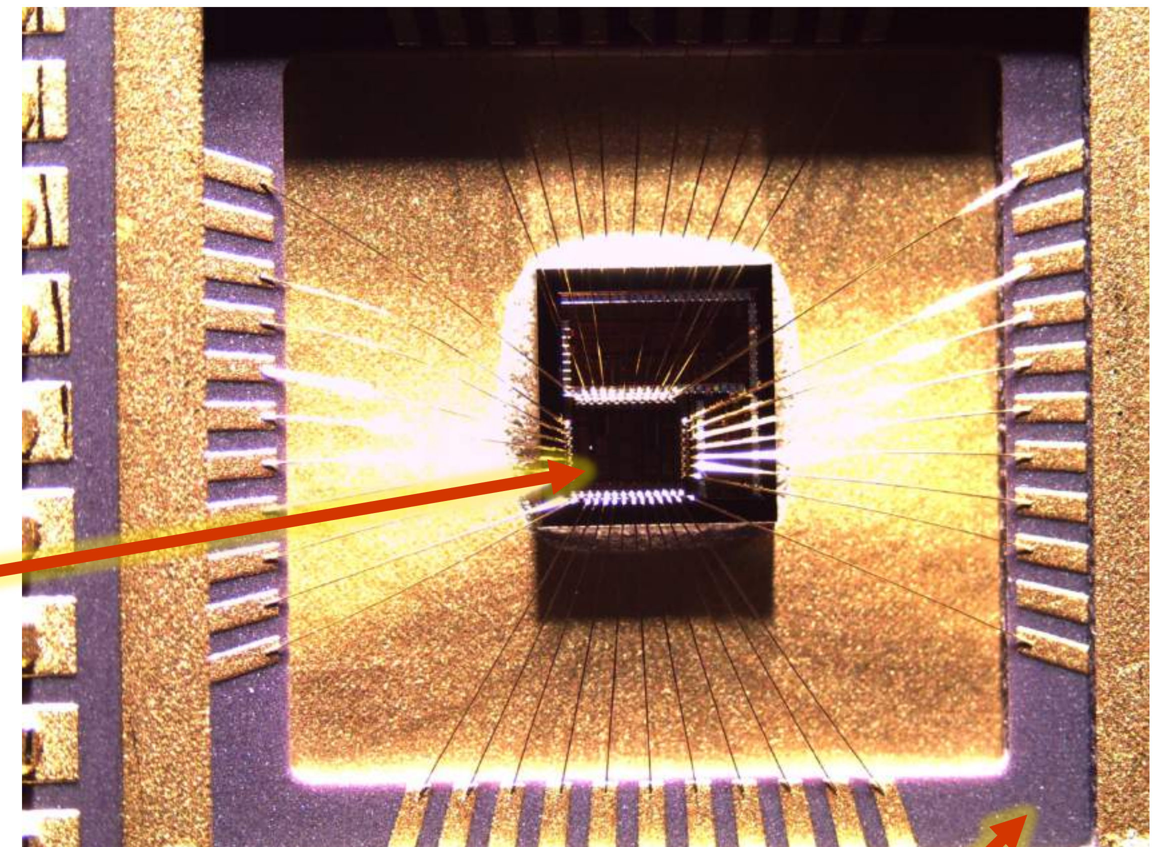
Warm Front-End Electronics (WFEE)

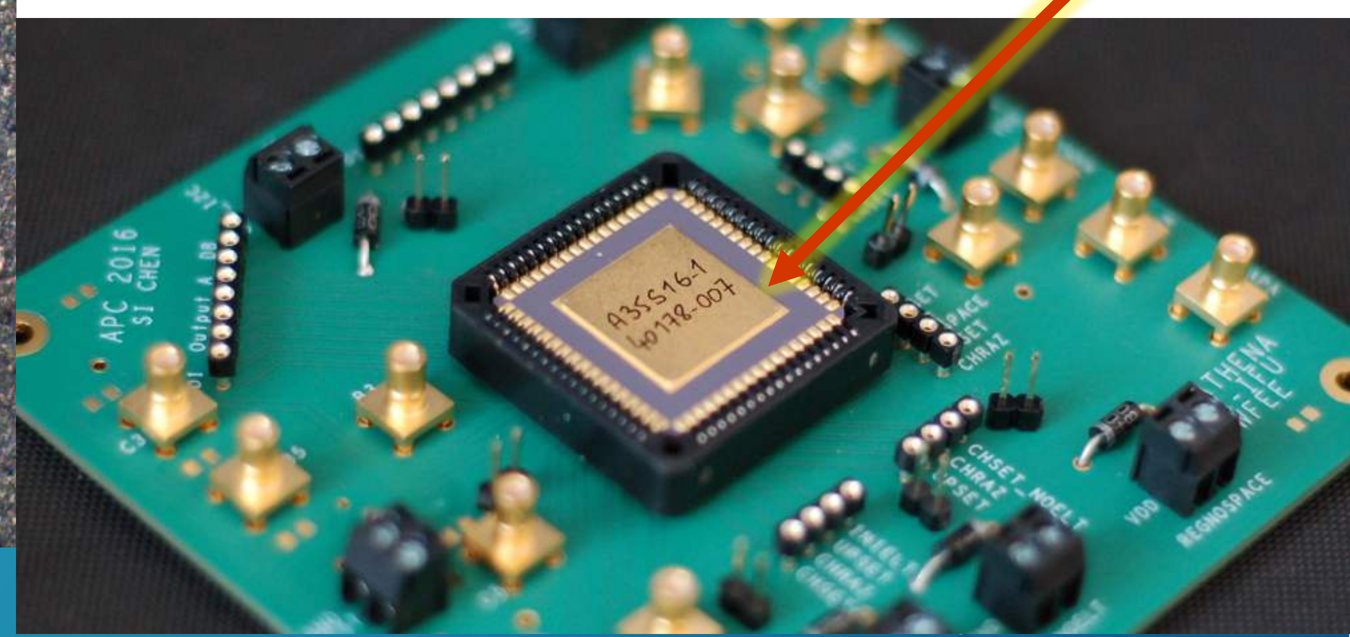


First ASIC AwaXe_V1 dedicated to WFEE

- AMS 350nm BiCMOS SiGe technology: BJT+MOS, good TID (Total Ionizing Dose) tolerance, widely used in space instrmentation, reliable
- ASIC: **Application-specific integrated circuit**





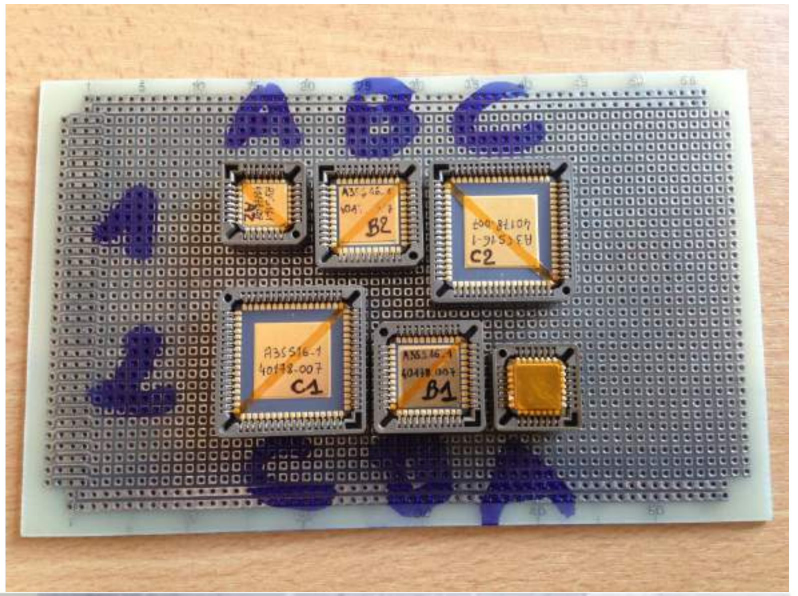


$\approx 2.4mm$

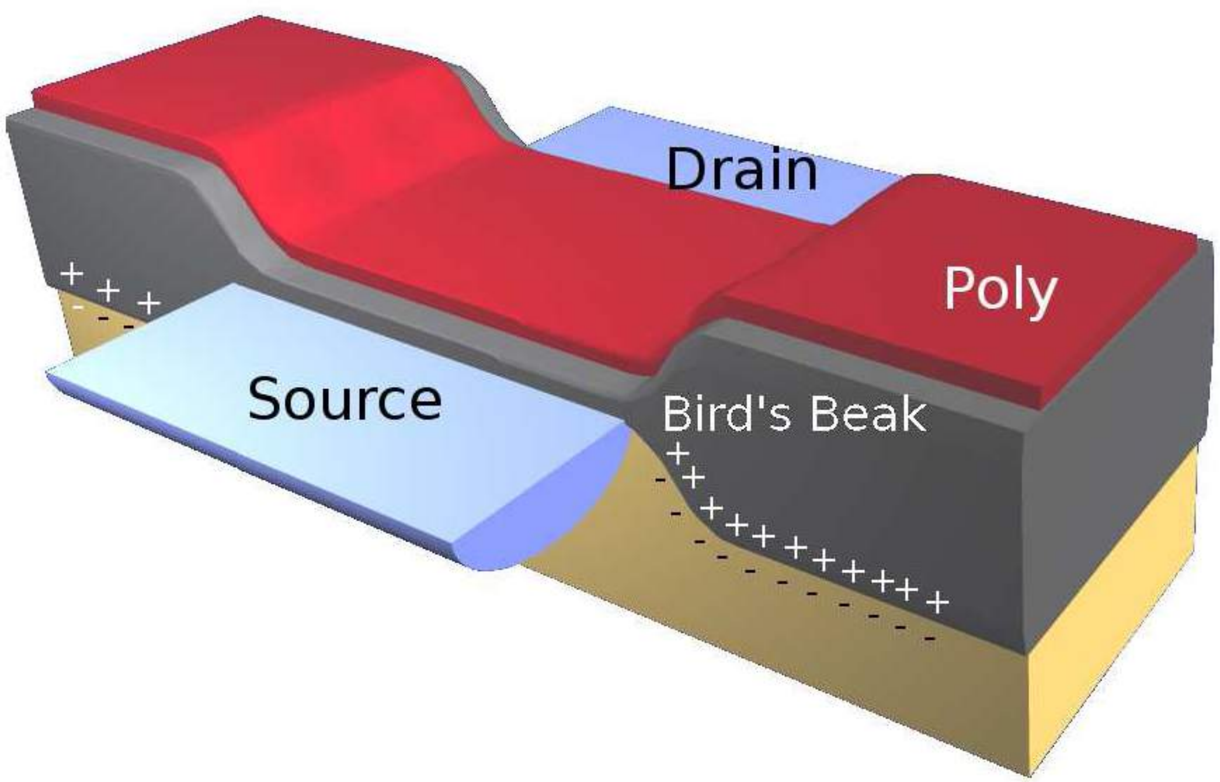
Radiation tests - TID

- TID(Total Ionizing Dose): accumulative effect
- γsource Cobalt 60 with 1.25 MeV, COCASE, CEA-Saclay, >1 months
- 1.4–7 krad during the 5 years lifetime of ATHENA at L2 point

Pack 1	0 rad	1.7 krad	6 krad	8 krad	10 krad
Pack 2	0 krad	6 krad	12 krad	**100 krad**	

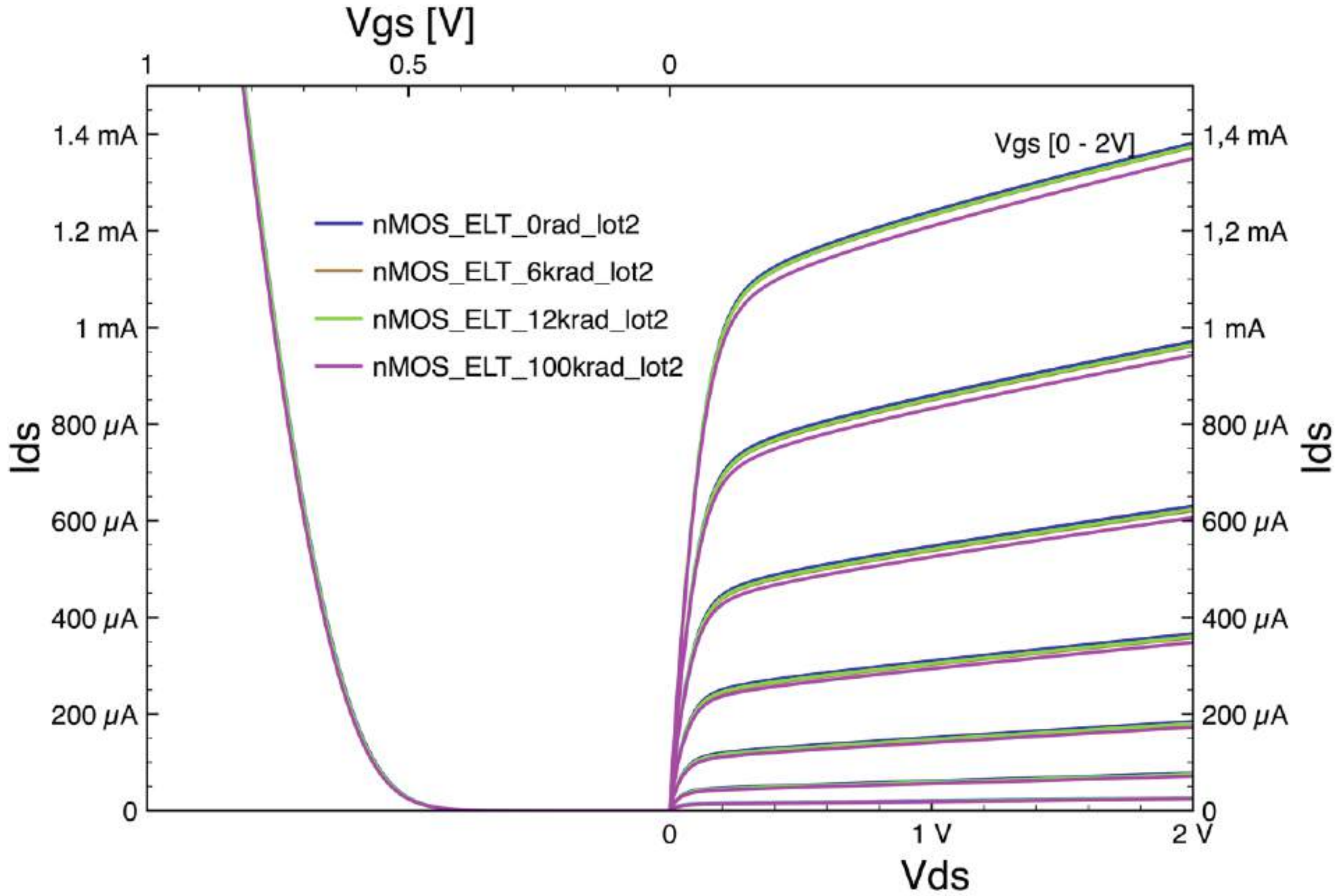


- Positive charged particles trapped in oxide may cause a noticeable leakage current between drain and source, thus change the DC characteristics of MOS

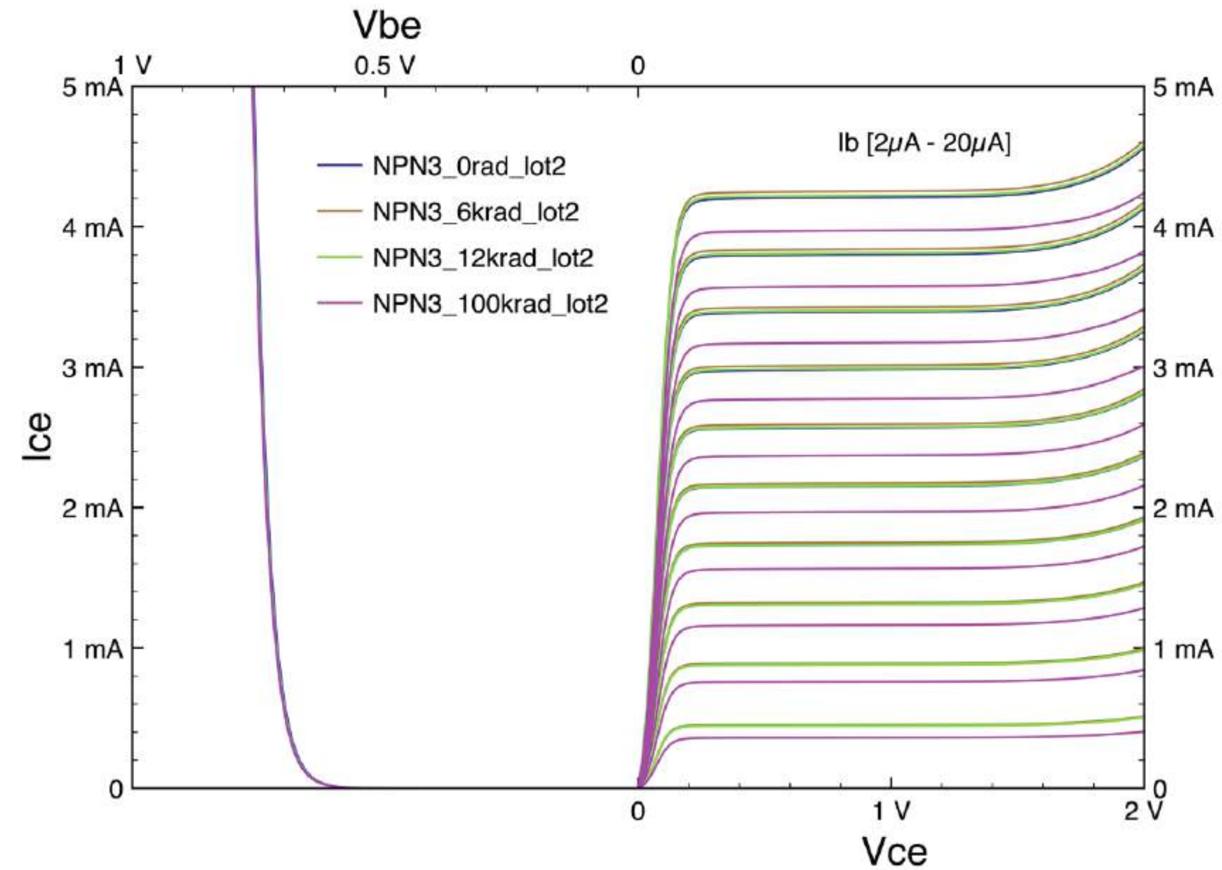


Radiation tests - TID

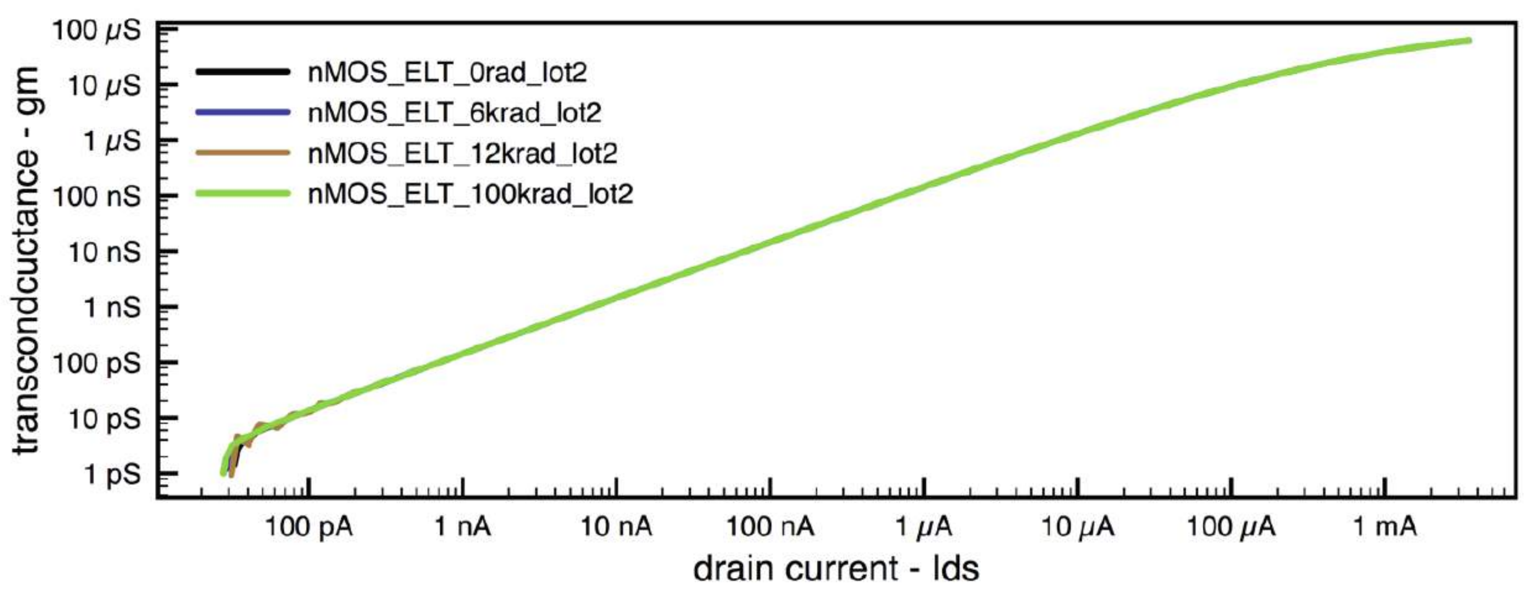
NMOS ELT Ids(Vgs) & Ids(Vds)



npn BJT Ice(Vbe) & Ice(Vce)

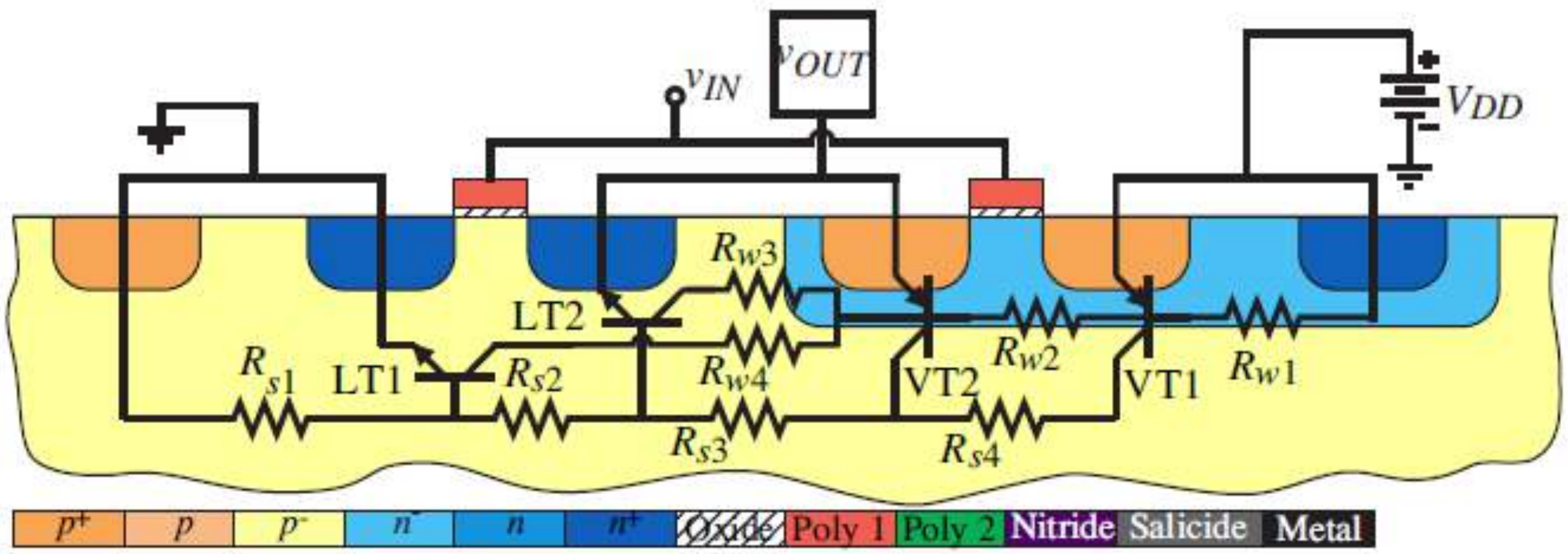


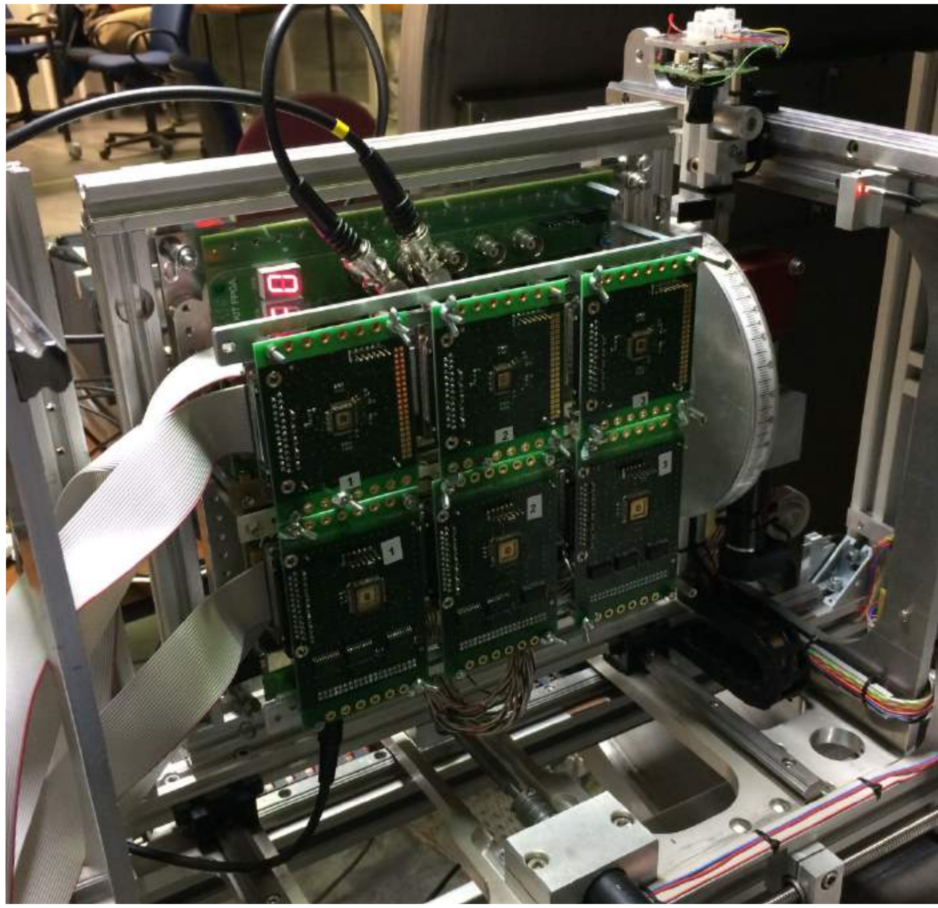
NMOS ELT transconductance gm = dIds/dVgs



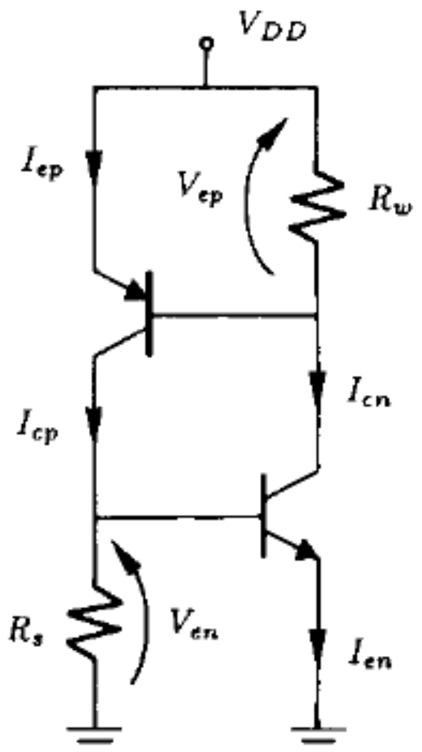
Radiation tests - SEL

- SEL(Single Event Latch-up): caused by heavy ions or protons from cosmic rays or solar flares

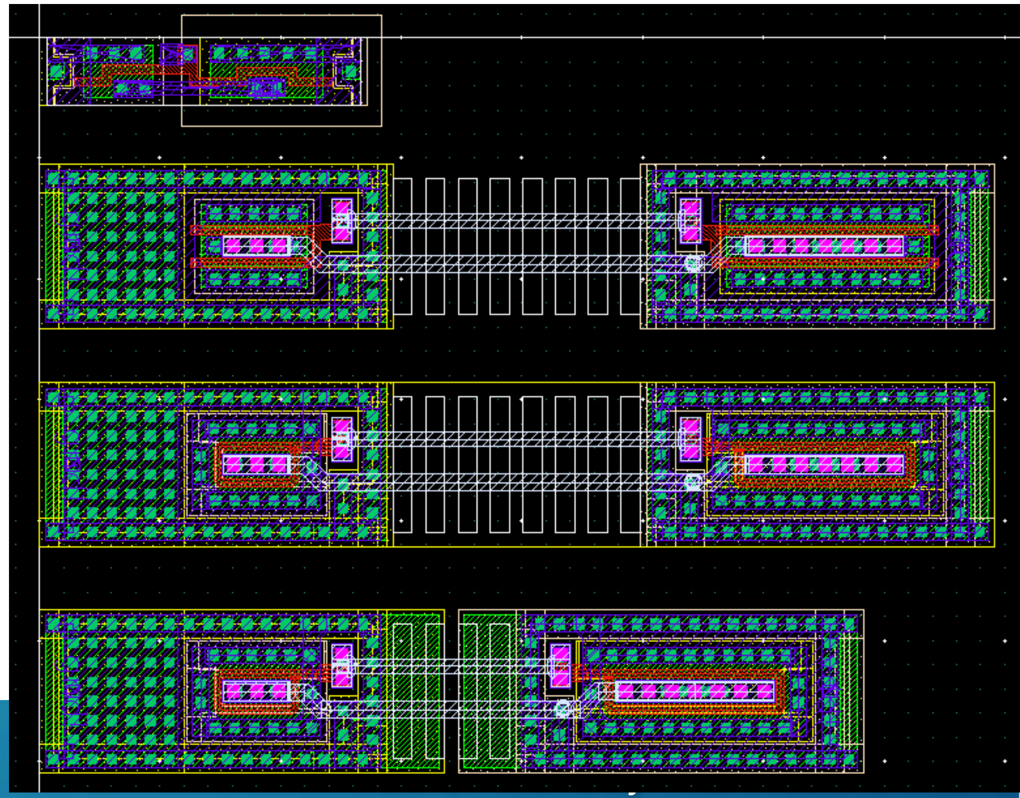




- "Cause I'm the one who's gonna make you **burn**"



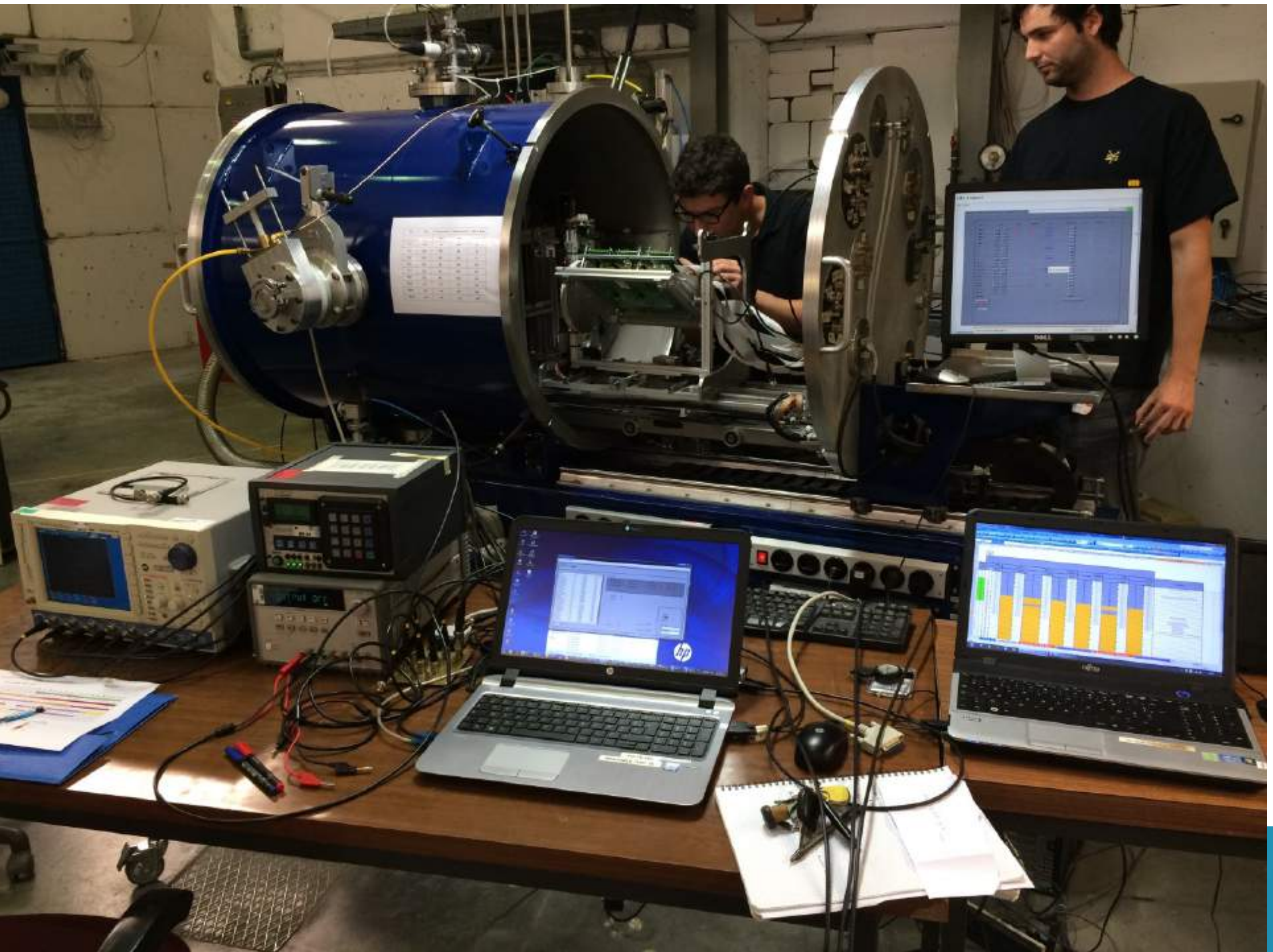
"thyristor"

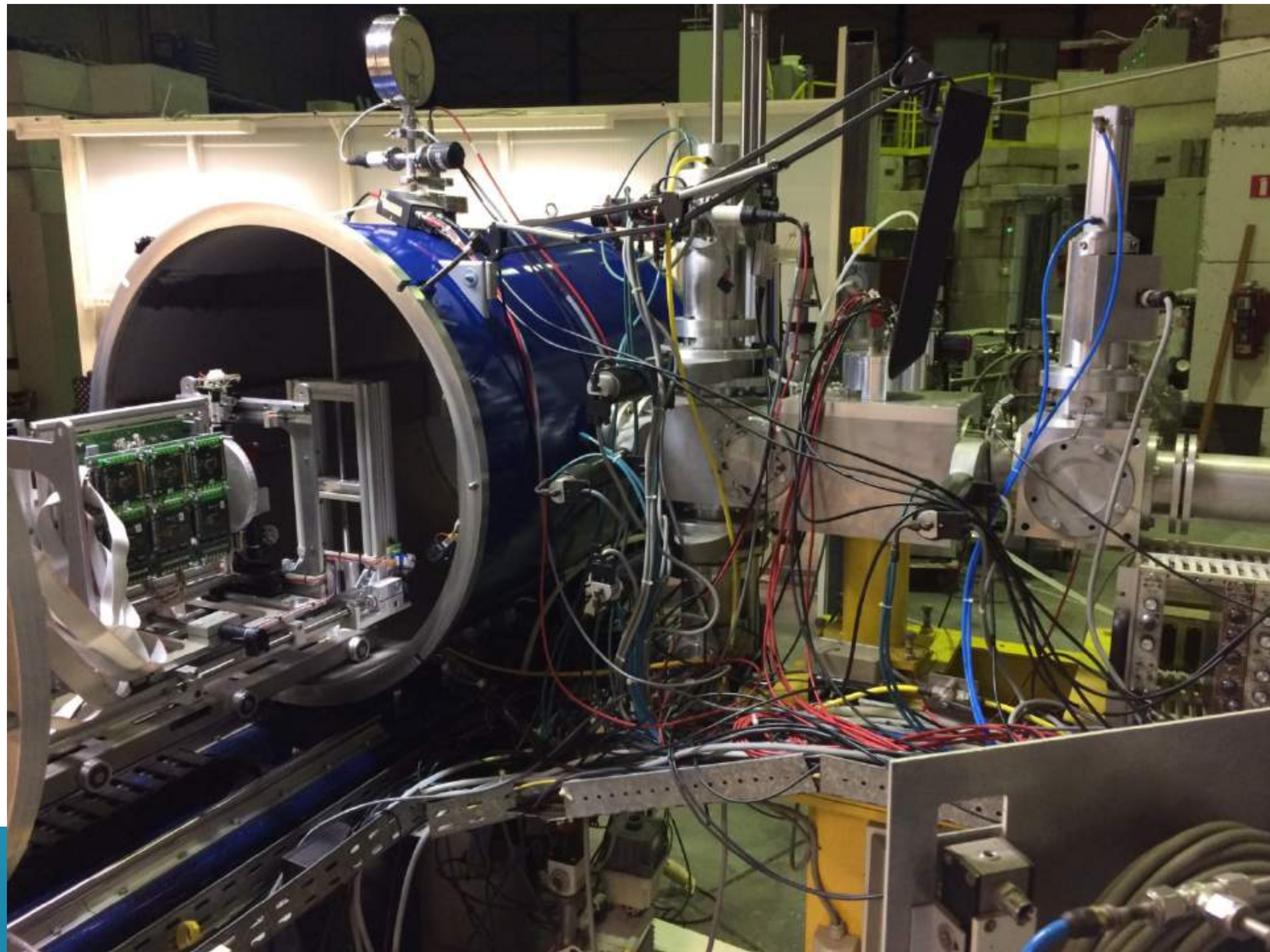


Radiation tests - SEL

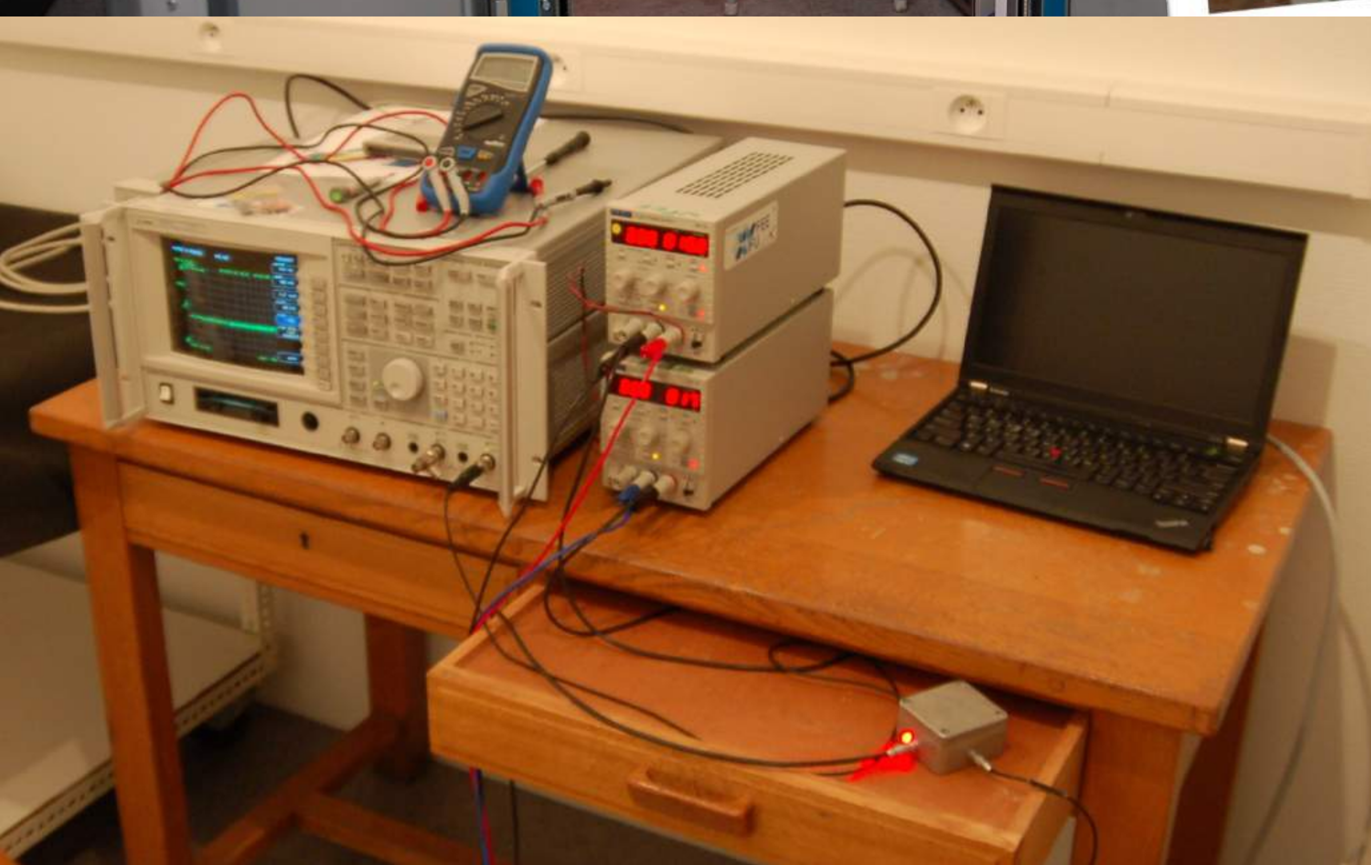
- Cyclotron, Universite Catholique de Louvain, Belgium

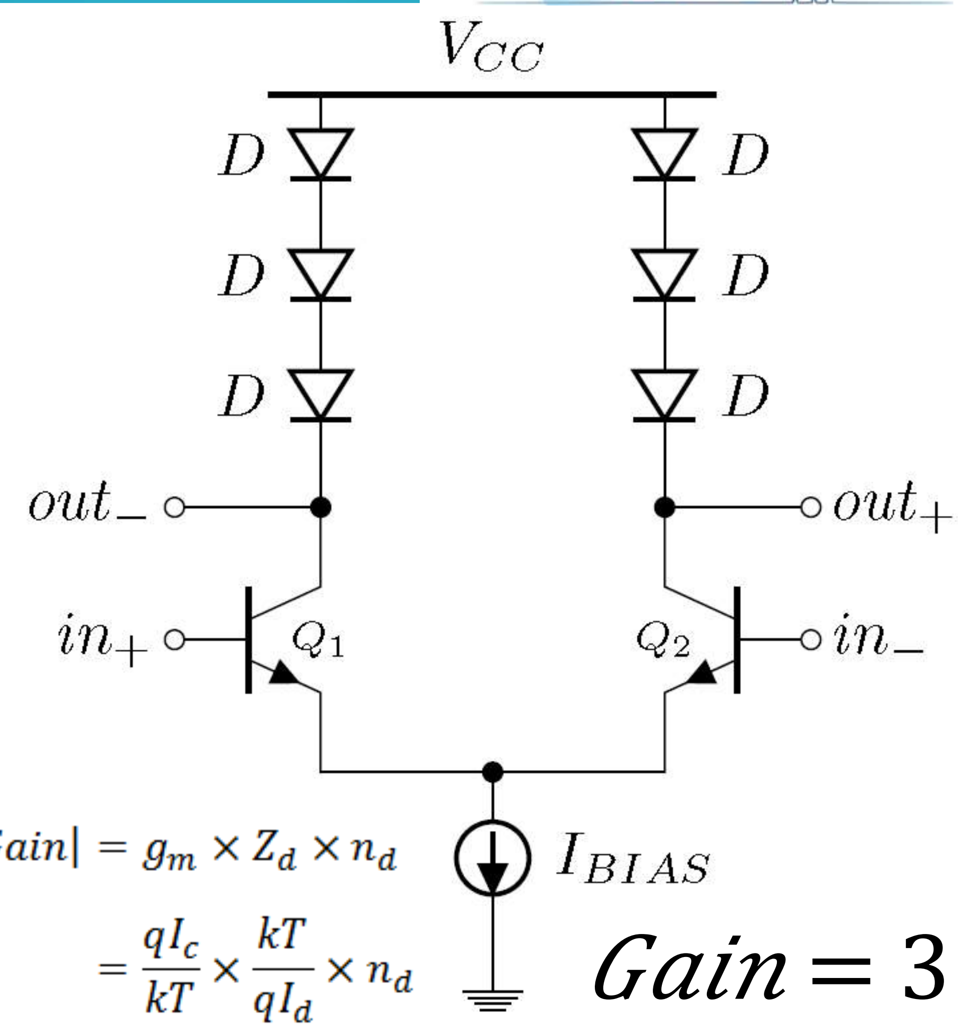
Ion		M/Q	DUT energy [Mev]	Range [µm Si]	LET [MeV/mg/cm^2]
Carbon	$^{13}C^{4+}$	3.25	131	269.3	1.3
Neon	$^{22}Ne^{7+}$	3.14	238	202.0	3.3
Aluminium	$^{27}Al^{8+}$	3.37	250	131.2	5.7
Argon	$^{40}Ar^{12+}$	3.33	379	120.5	10.0
Chromium	$^{53}Cr^{16+}$	3.31	513	107.6	16.0
Nickel	$^{58}Ni^{18+}$	3.218	582	100.5	20.4
Krypton	$^{84}Kr^{25+}$	3.35	769	94.2	32.4
Rhodium	$^{103}Rh^{31+}$	3.32	972	88.7	45.8
Xenon	$^{124}Xe^{35+}$	3.54	995	73.1	62.5





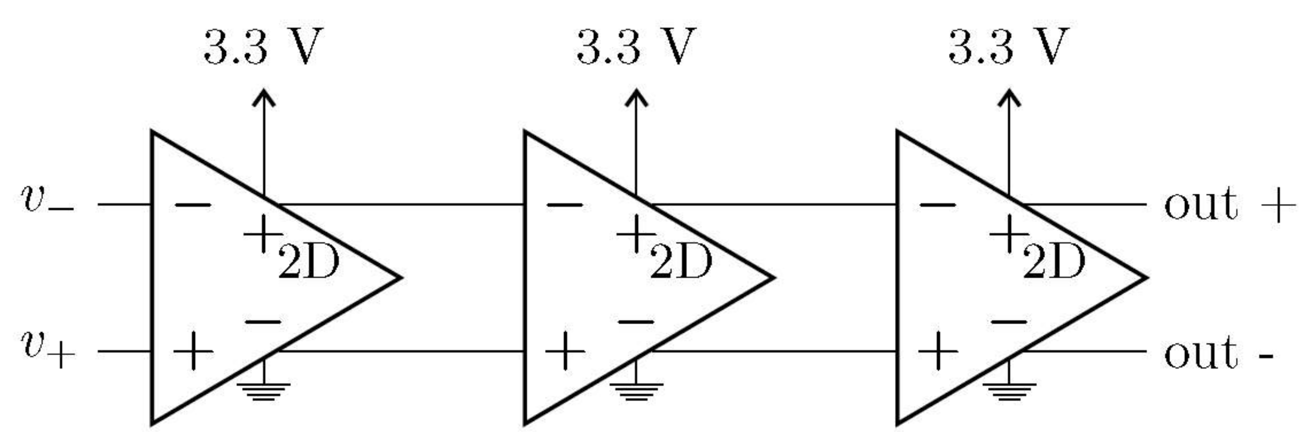
Functional Tests of LNA





$$
\begin{aligned}
|Gain| &= g_m \times Z_d \times n_d \\
&= \frac{qI_c}{kT} \times \frac{kT}{qI_d} \times n_d \\
&= n_d
\end{aligned}
$$

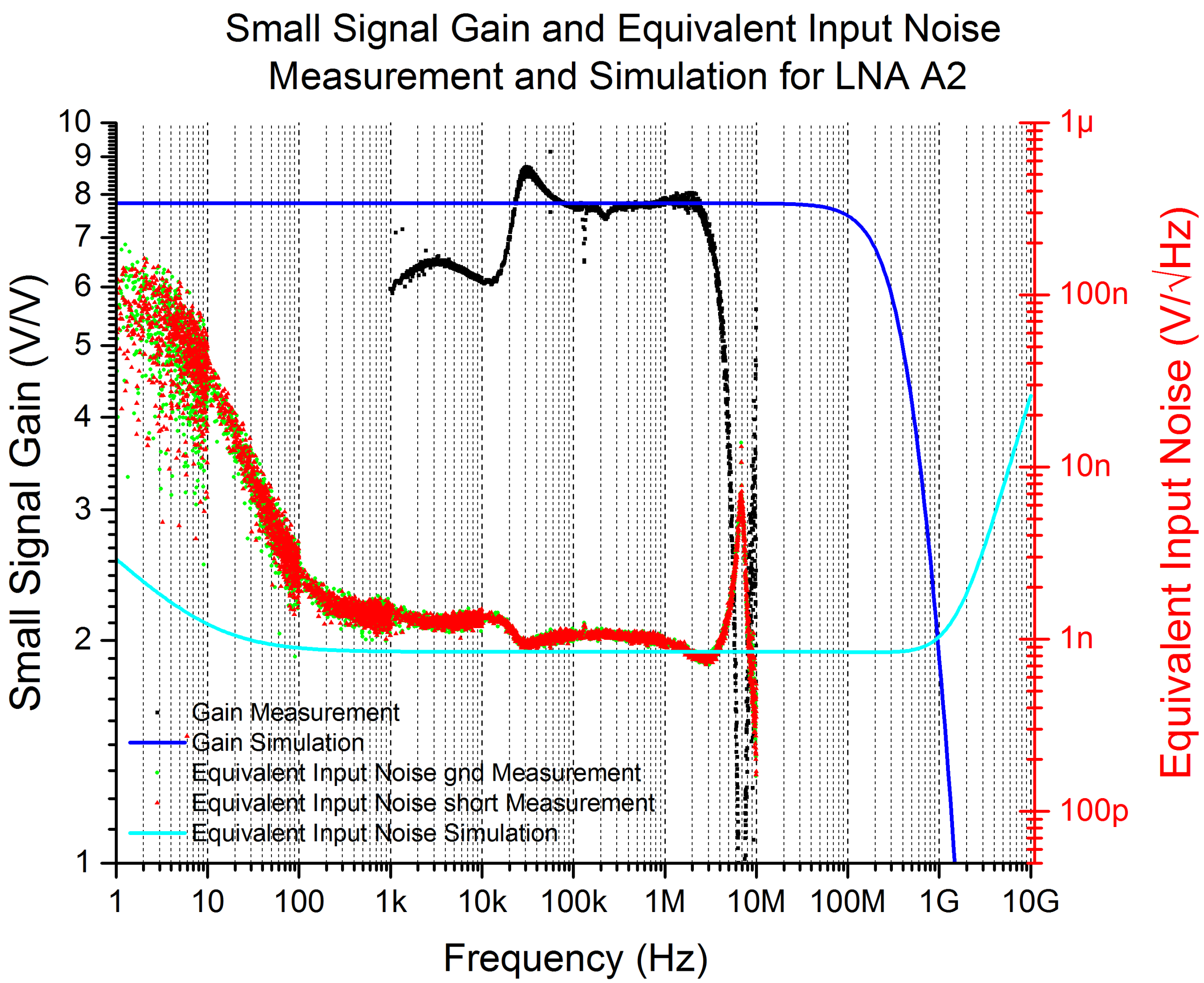
$Gain = 3$

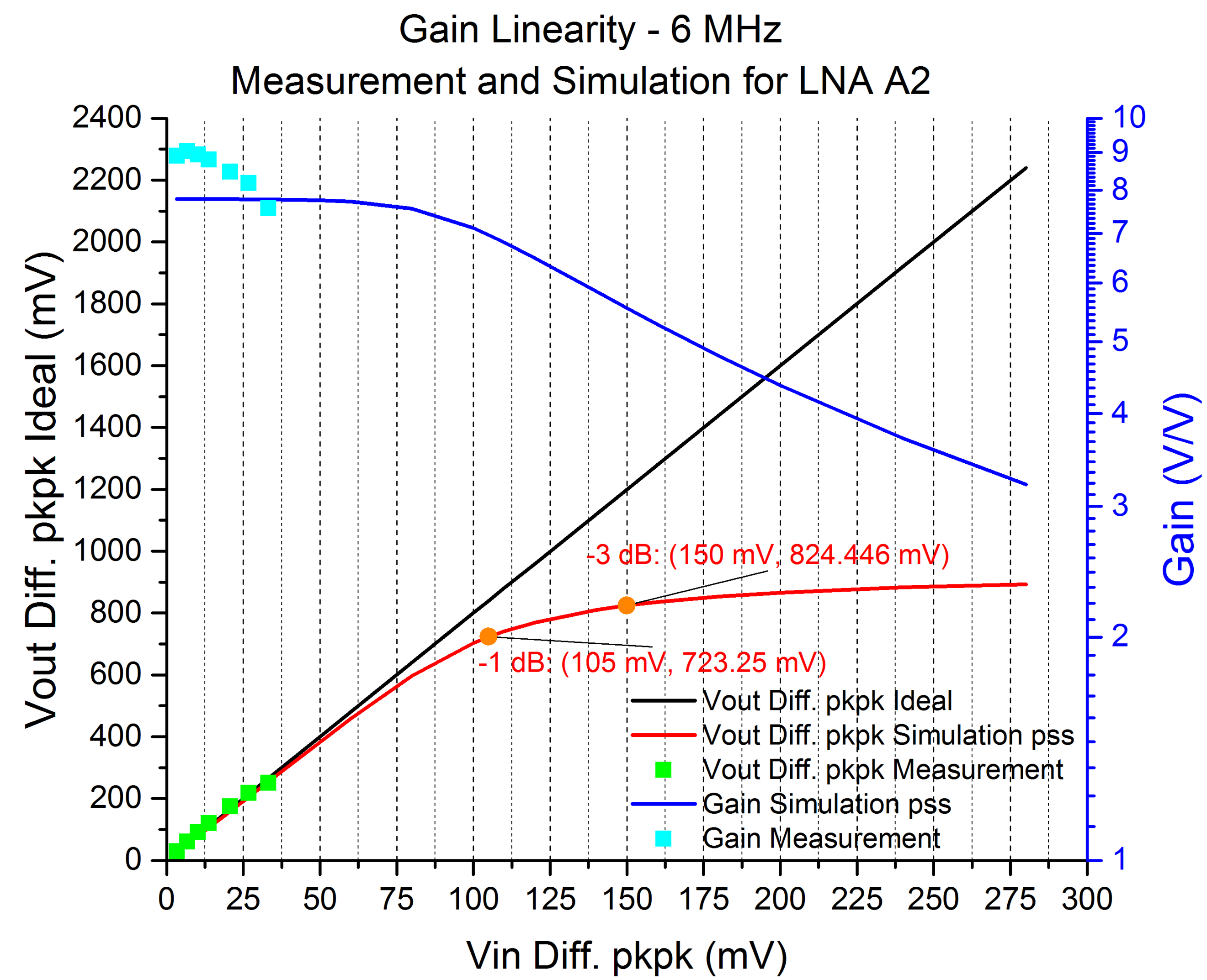


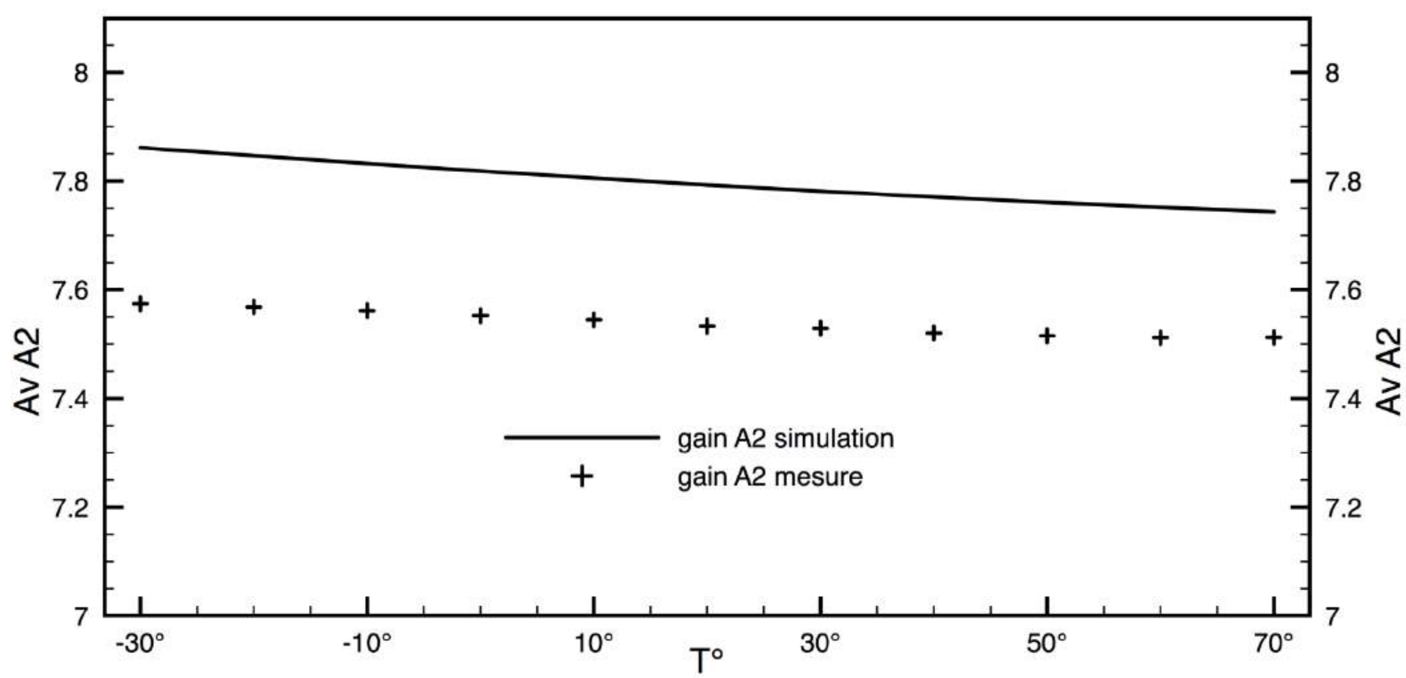
Gain = 2*2*2 = 8

Functional Tests of LNA

- Gain ≈ 8
- Noise ≈ 1 nV/√Hz







WFEE identified Specifications

	Identified spec	ASICv1 measure	ASICv2 goal
Gain	80 V/V	3, 8, 24 V/V	
Noise	$1\ nV/\sqrt{Hz}$	$\approx 1\ nV/\sqrt{Hz}$	
BW	1-6 MHz	DC-10 MHz*	
Linearity	1% on 1 Vpp	1% on 0.2 Vpp	
Drift	$17\ \mu V/V$ x10	≈200 ppm/K	
Serial link	RS 485	I2C	
TID	1.7 - 14 krad	100 krad	
LET	10 $MeV/mg/cm^2$	120 $MeV/mg/cm^2$	

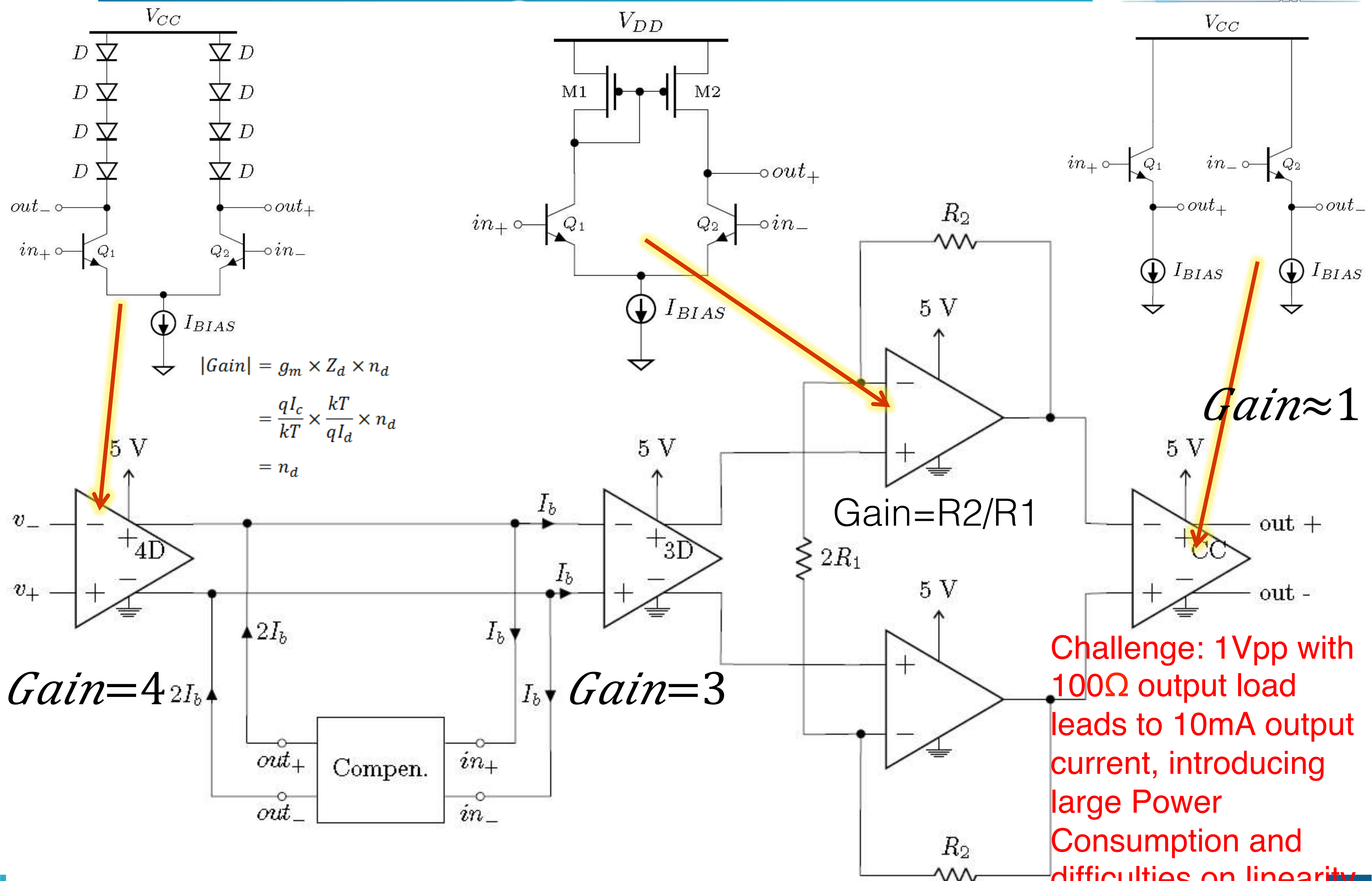
* Small signal

WFEE identified Specifications

	Identified spec	ASICv1 measure	ASICv2 goal
Gain	80 V/V	3, 8, 24 V/V	80 V/V
Noise	$1\ nV/\sqrt{Hz}$	$\approx 1\ nV/\sqrt{Hz}$	$< 1\ nV/\sqrt{Hz}$
BW	1-6 MHz	DC-10 MHz*	DC-6 MHz**
Linearity	1% on 1 Vpp	1% on 0.2 Vpp	1% on 1 Vpp
Drift	$17\ \mu V/V$ x10	≈200 ppm/K	< 300 ppm/K
Serial link	RS 485	I2C	$I2C_{in}/RS485_{out}$
TID	1.7 - 14 krad	100 krad	-
LET	10 $MeV/mg/cm^2$	120 $MeV/mg/cm^2$	-

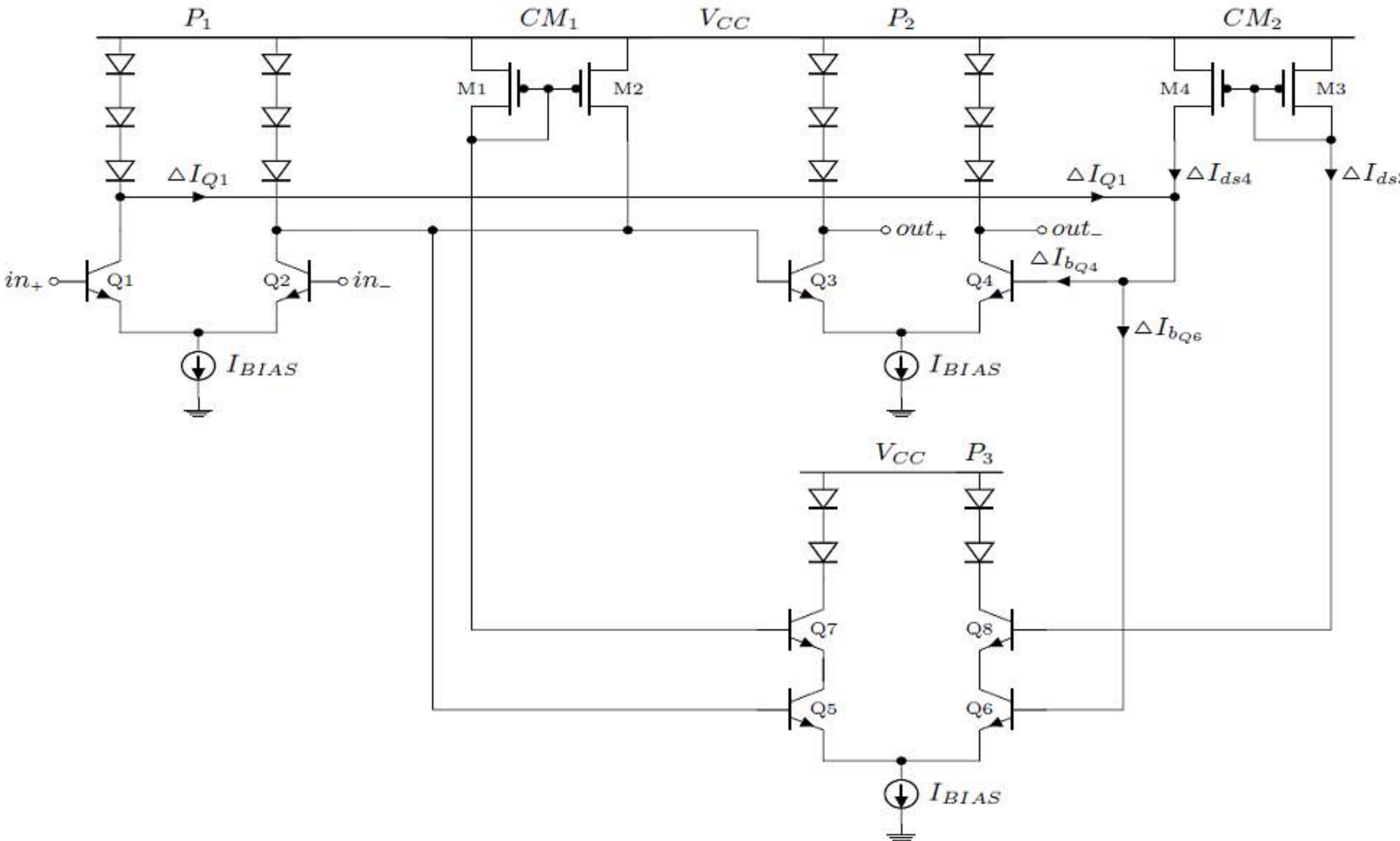
* Small signal
** Small and full dynamic (slew rate)

LNA design for ASIC V2

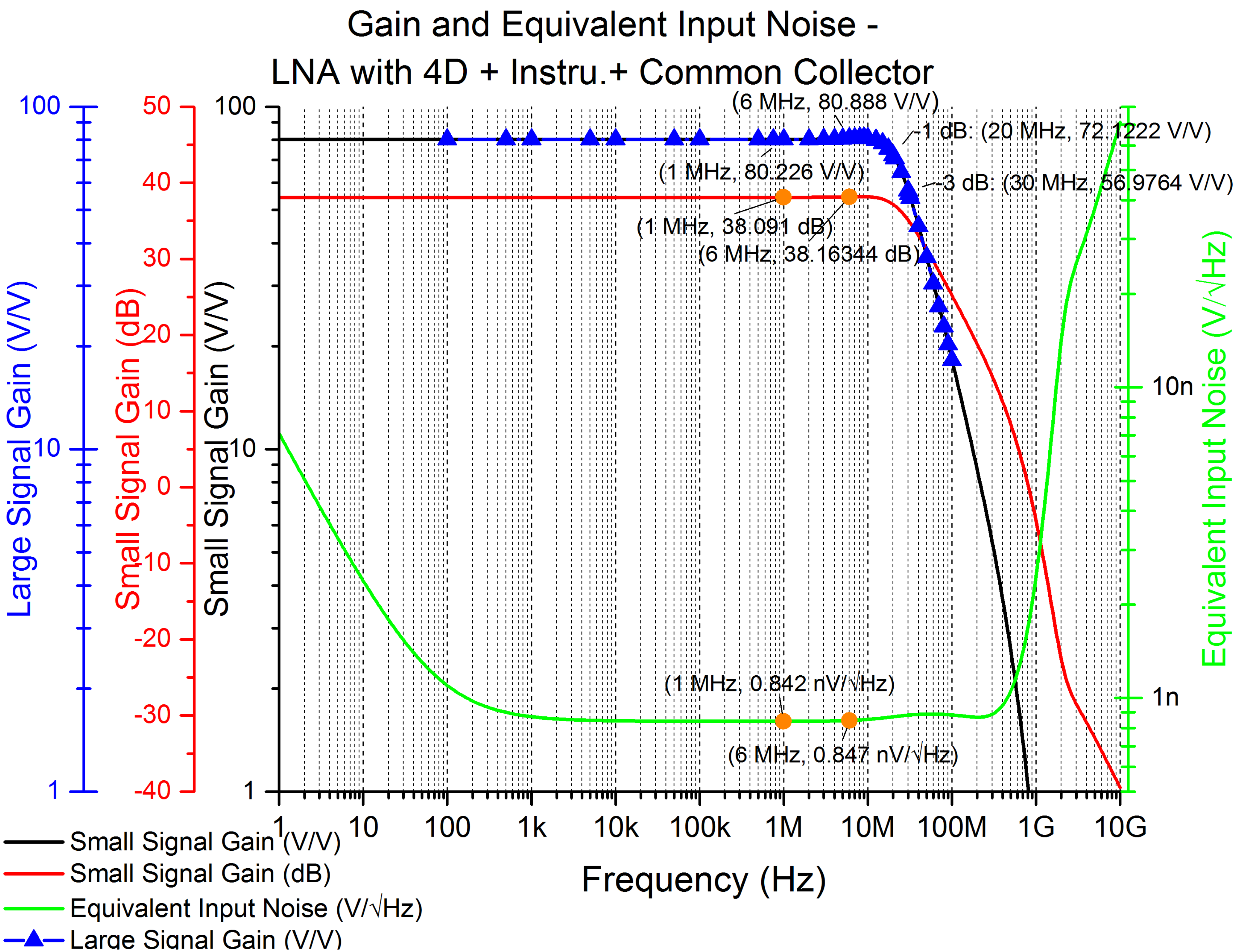


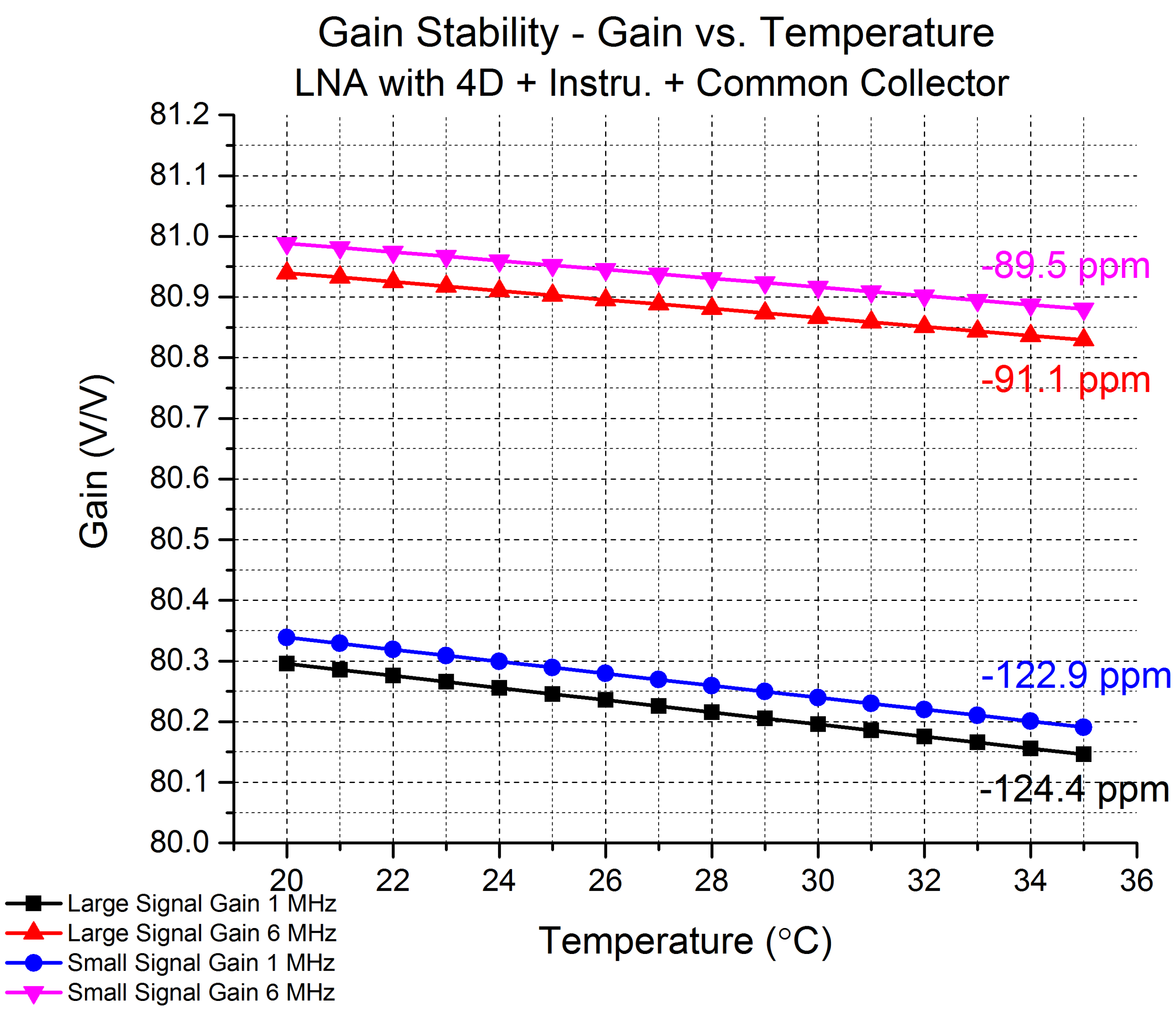
Challenge: 1Vpp with 100Ω output load leads to 10mA output current, introducing large Power Consumption and difficulties on linearity

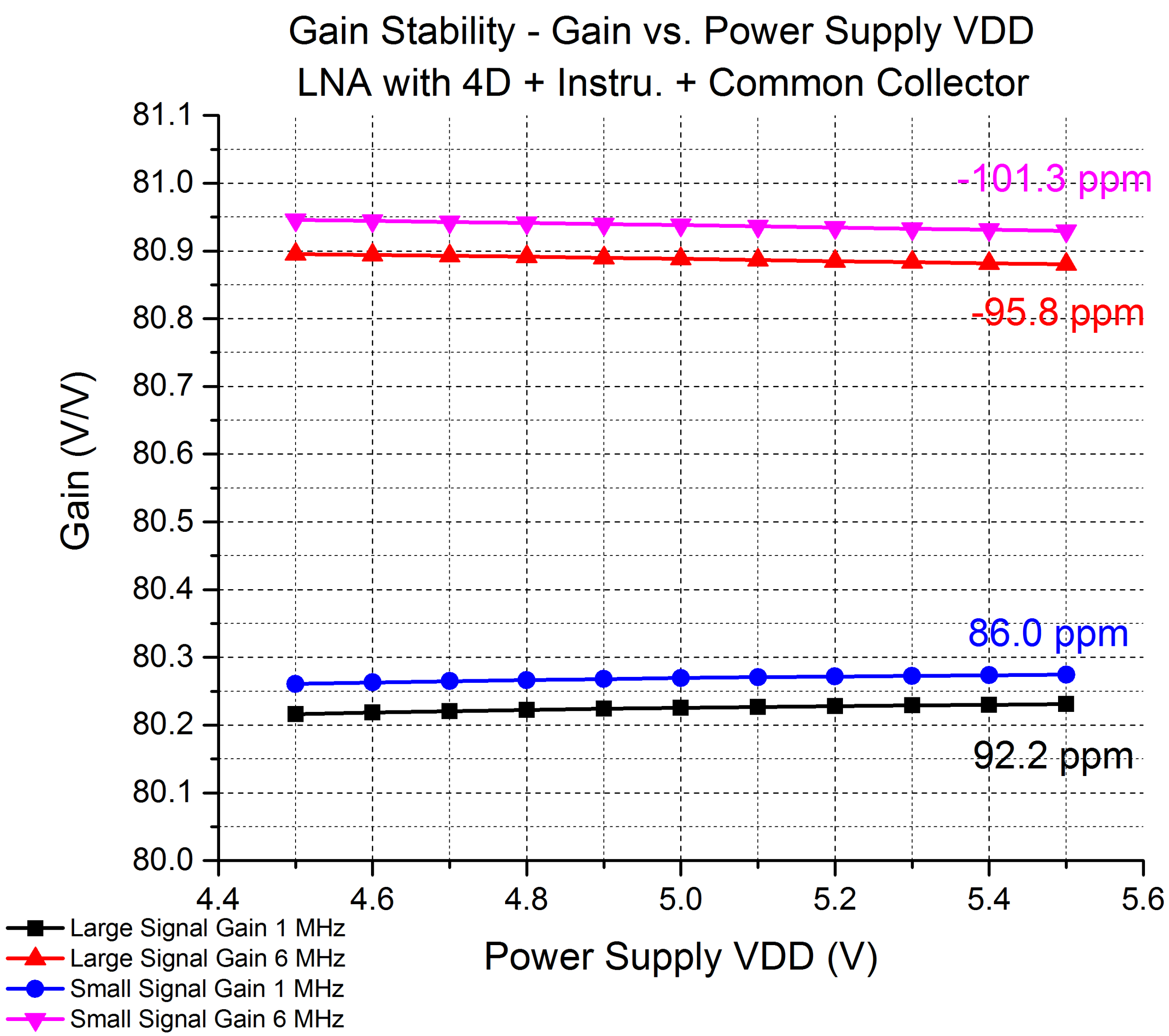
Compensation system of Base current of npn bipoar transistor



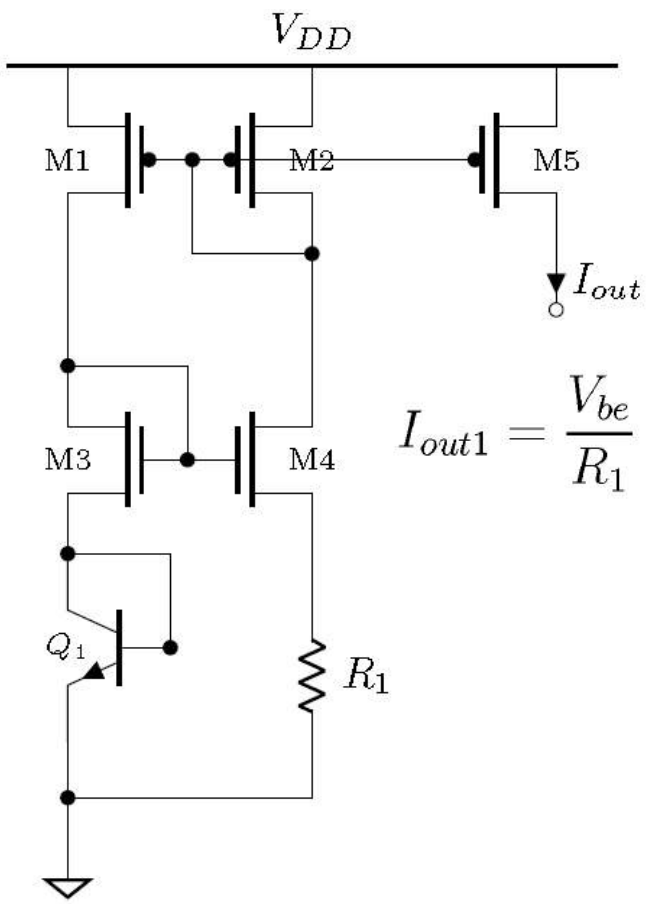
LNA design for ASIC V2 -Simulation results




Gain Stability - Gain vs. Temperature
LNA with 4D + Instru. + Common Collector
Gain (V/V)
Temperature (°C)
-89.5 ppm
-91.1 ppm
-122.9 ppm
-124.4 ppm
Large Signal Gain 1 MHz
Large Signal Gain 6 MHz
Small Signal Gain 1 MHz
Small Signal Gain 6 MHz

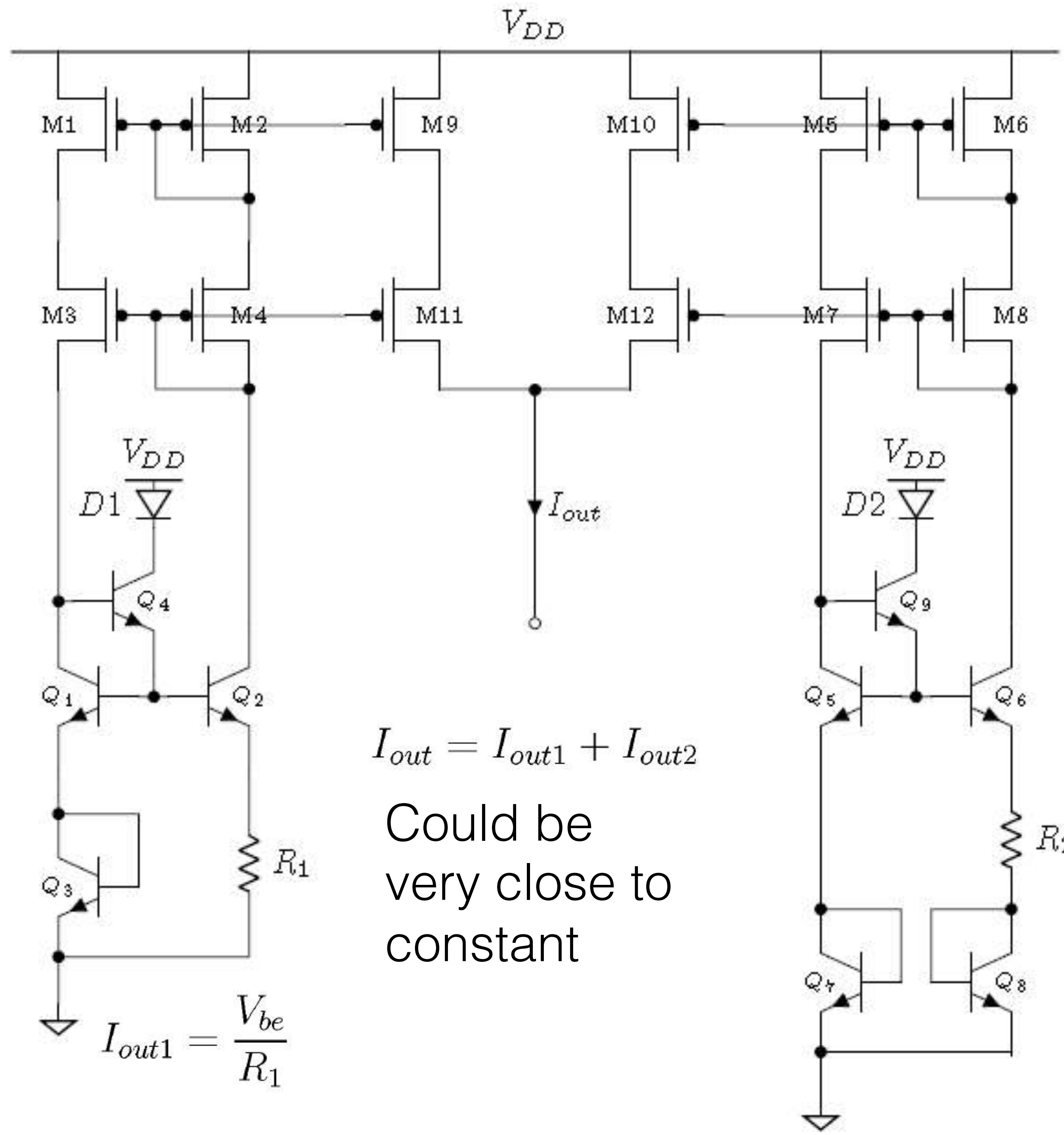

Gain Stability - Gain vs. Power Supply VDD
LNA with 4D + Instru. + Common Collector
Gain (V/V)
Power Supply VDD (V)
-101.3 ppm
-95.8 ppm
86.0 ppm
92.2 ppm
Large Signal Gain 1 MHz
Large Signal Gain 6 MHz
Small Signal Gain 1 MHz
Small Signal Gain 6 MHz

Current Source



$$I_{out1} = \frac{V_{be}}{R_1}$$

Negative temperature coefficient



$$I_{out} = I_{out1} + I_{out2}$$

Could be very close to constant

$$I_{out1} = \frac{V_{be}}{R_1}$$

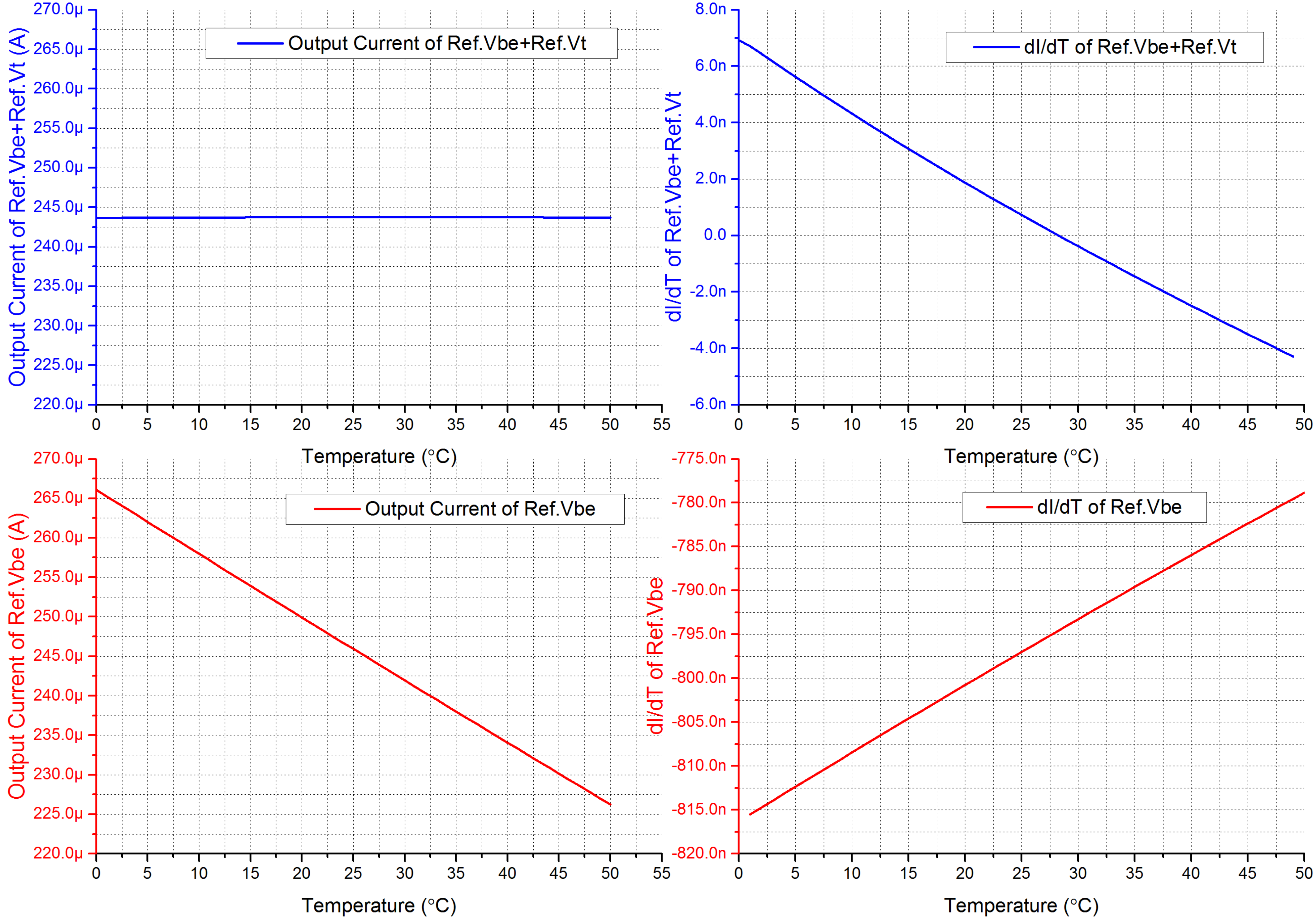
Negative temperature coefficient

Positive temperature coefficient

$$I_{out2} = \frac{\Delta V_{be}}{R_2} = \frac{V_{be7} - V_{be8}}{R_2} = \frac{V_T ln\frac{I_0}{I_s} - V_T ln\frac{I_0}{mI_s}}{R_2} = \frac{V_T ln m}{R_2}$$

Current Source – Simulation results

Output Current vs. Temperature
for Current Source with Ref.Vt+Ref.Vbe and Current Source only with Ref.Vbe



Future work

- Simulations, Layout, Post-simulation (before 03/2018)
- Measurements (07/2018 -)

	Identified spec	ASICv1 measure	ASICv2 goal
Gain	80 V/V	3, 8, 24 V/V	80 V/V
Noise	$1\ nV/\sqrt{Hz}$	$\approx 1\ nV/\sqrt{Hz}$	$< 1\ nV/\sqrt{Hz}$
BW	1-6 MHz	DC-10 MHz*	DC-6 MHz**
Linearity	1% on 1 Vpp	1% on 0.2 Vpp	1% on 1 Vpp
Drift	$17\ \mu V/V$ x10	≈200 ppm/K	< 300 ppm/K
Serial link	RS 485	I2C	$I2C_{in}/RS485_{out}$
TID	1.7 - 14 krad	100 krad	-
LET	10 $MeV/mg/cm^2$	120 $MeV/mg/cm^2$	-

* Small signal
** Small and full dynamic (slew rate)

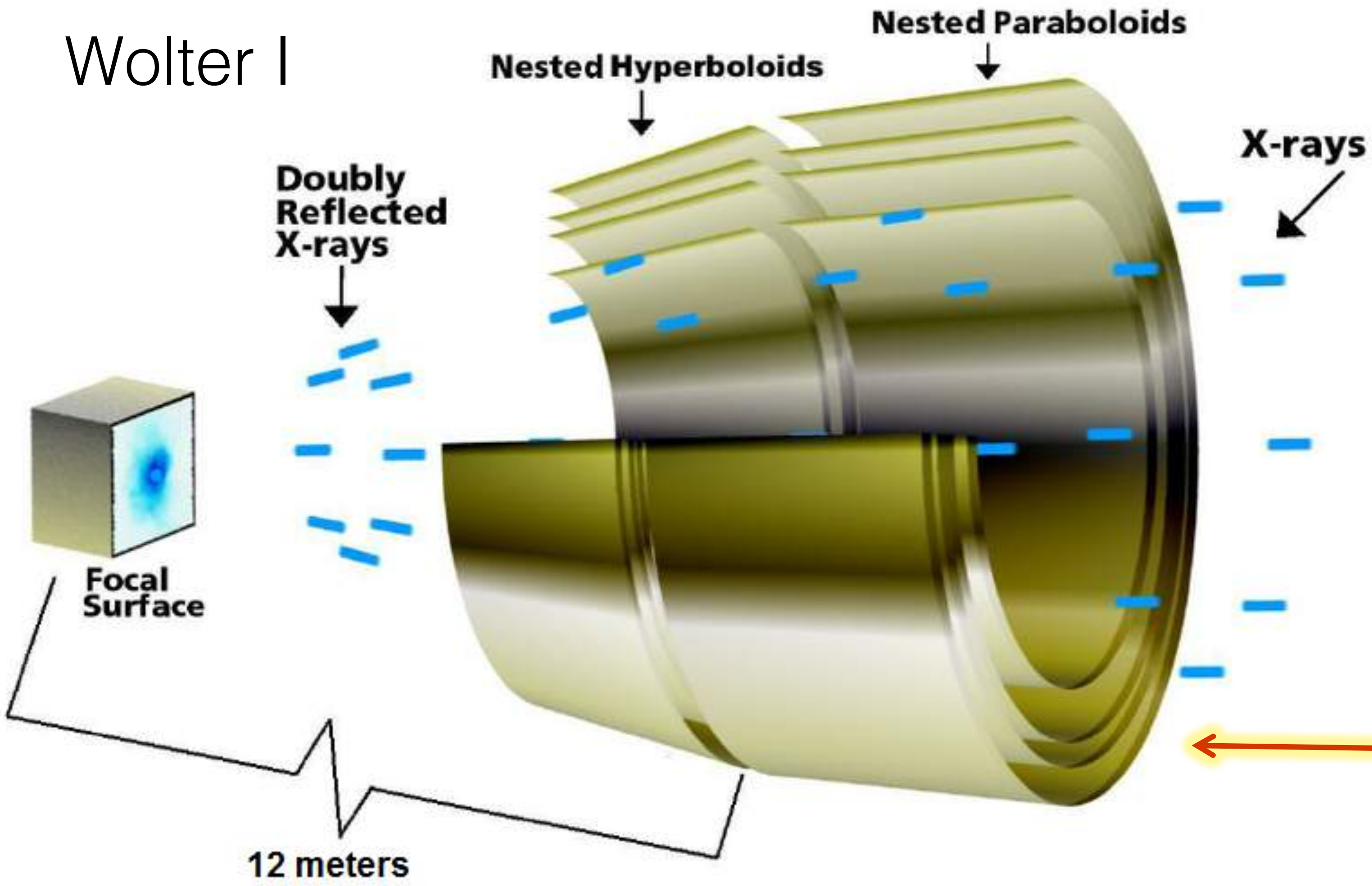

Merci!

Key parameters and requirements of the Athena+ mission

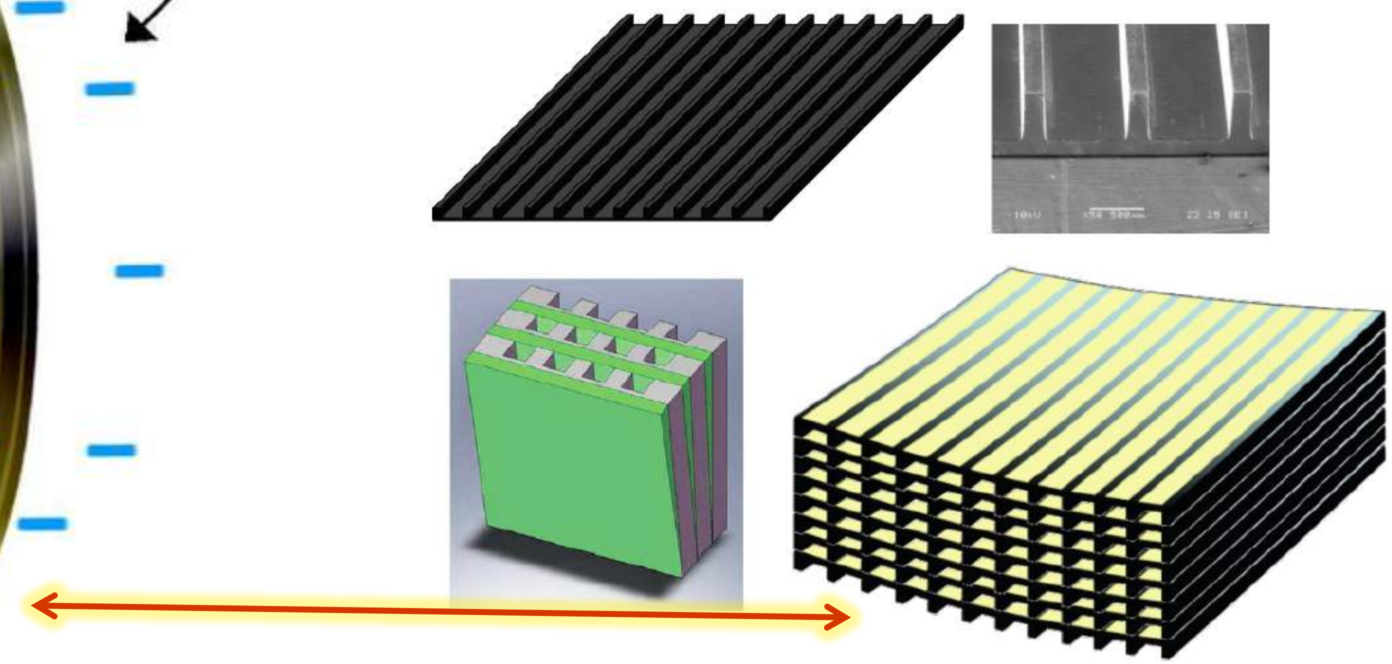
Parameter	Requirements	Enabling technology/comments
Effective Area	2 m² @ 1 keV (goal 2.5 m²) 0.25 m² @ 6 keV (goal 0.3 m²)	Silicon Pore Optics developed by ESA. Single telescope: 3 m outer diameter, 12 m fixed focal length.
Angular Resolution	5" (goal 3") on-axis 10" at 25' radius	*Detailed analysis of error budget confirms that a performance of 5" HEW is feasible.*
Energy Range	0.3-12 keV	Grazing incidence optics & detectors.
Instrument Field of View	*Wide-Field Imager:* (**WFI**): 40' (goal 50')	Large area DEPFET Active Pixel Sensors.
	X-ray Integral Field Unit: (**X-IFU**): 5' (goal 7')	Large array of multiplexed Transition Edge Sensors (TES) with 250 micron pixels.
Spectral Resolution	**WFI**: <150 eV @ 6 keV	Large area DEPFET Active Pixel Sensors.
	X-IFU: 2.5 eV @ 6 keV (goal 1.5 eV @ 1 keV)	*Inner array (10"x10") optimized for goal resolution at low energy (50 micron pixels).*
Count Rate Capability	> 1 Crab[1] (**WFI**)	*Central chip for high count rates without pile-up and with micro-second time resolution.*
	1 mCrab, point source (X-IFU) with 90% of high-resolution events	*Filters and beam diffuser enable higher count rate capability with reduced spectral resolution.*
Target of Opportunity Response	4 hours (goal 2 hours) for 50% of time	*Slew times <2 hours feasible; total response time dependent on ground system issues.*

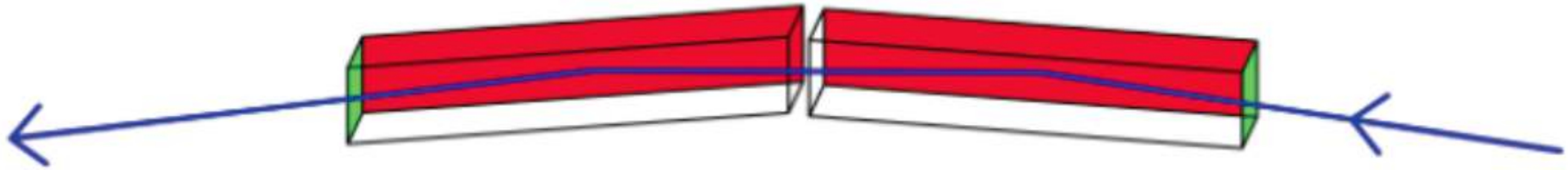
ATHENA Payloads

- 3 key components:
- 1) X-Ray telescope – 12m focal length, an effective area about 2 m² at 1 keV



ESA's Silicon Pore Optics (SPO) technology

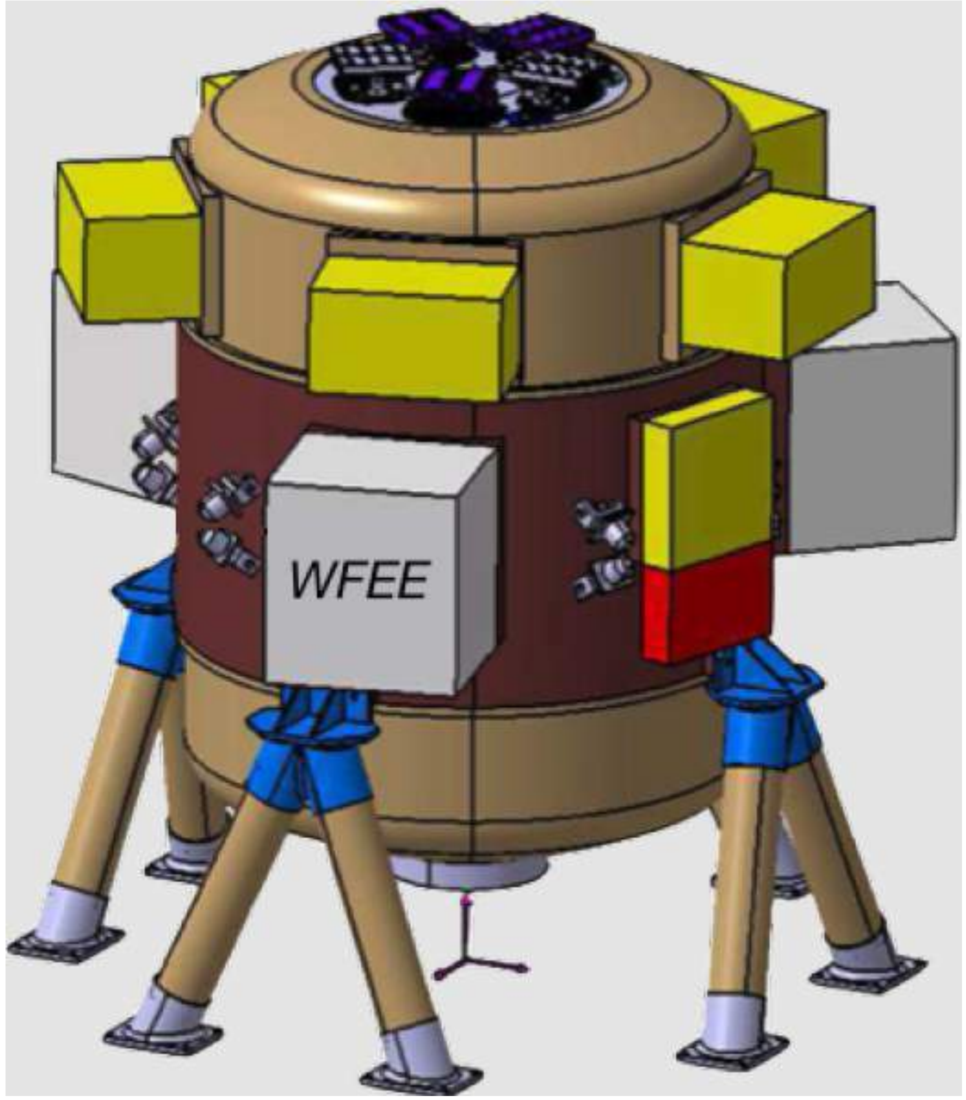


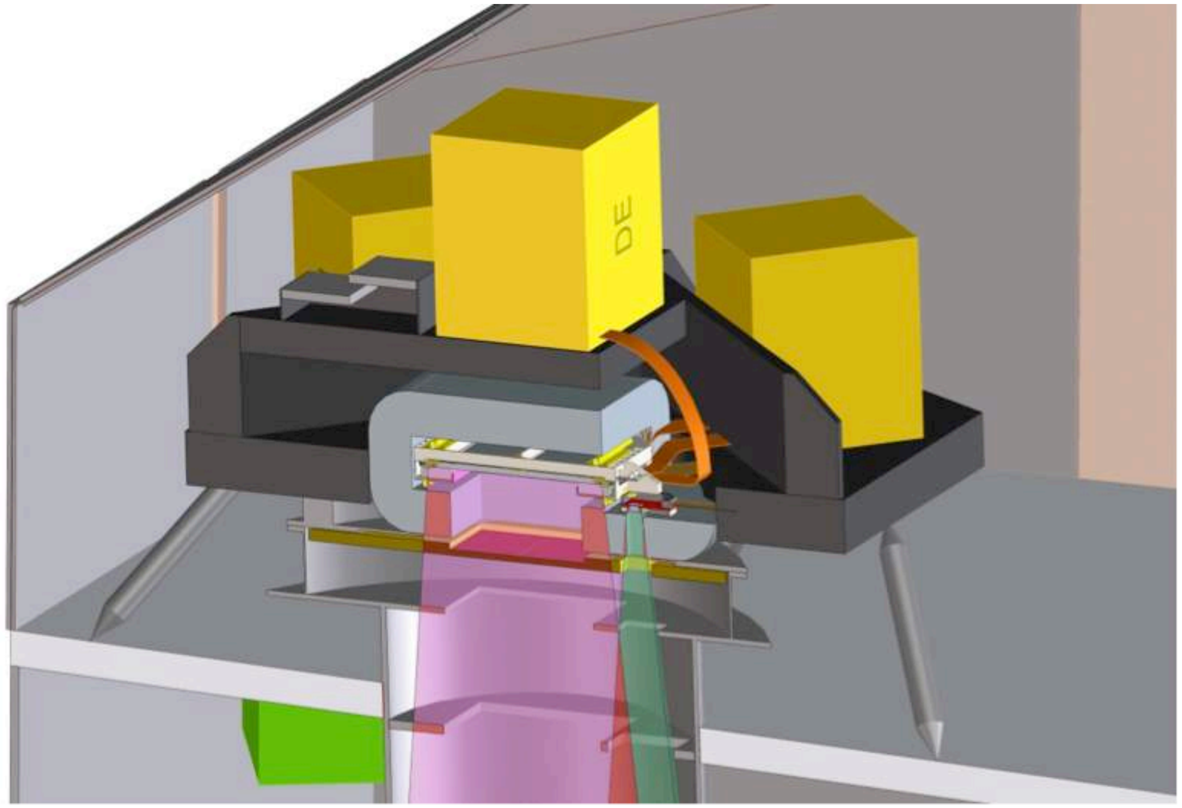


ATHENA Payloads

- 2)X-IFU (X-ray Integral Field Unit) : Transition Edge Sensors (TES), 2.5 eV high spectral resolution: E < 7 keV
- 5"pixels, field of view 5 arc minutes

- 3)WFI (Wide Field Imager) for high count rate, large field of view, 0.2-15 keV energy band
- Silicon-based detector using DEPFET Active Pixel Sensor (APS) technology





Tests of the I²C decoder