RF System Stability Issues for NSLS-II

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- Machine and RF System Overview
- RF field phase and amplitude requirements derived from User experiments
- Hardware issues impacting RF field purity

- Ion-Clearing-Gap-Induced Bunch Profiles,
  Cavity and beam transfer functions, and Coupled-Bunch Modes (Nathan)

X-RAY Ring Parameters

Beam Property	Required Baseline	Full Capability
Beam Energy	3 GeV	3Gev option to 3.5GeV
Stored Current	500 mA	700 mA
Horizontal emittance	1 nm	0.6nm
Vertical emitance	0.010 nm	0.008 nm
Energy Loss per turn	1 MeV	2 MeV
Momentum acceptance	3%	>3%
ID Straights for undulators	>21	>25
Electron Beam Stability	1 μm	< 1 μm
Top-off Injection Current stability (Δt > 2 min.)	< 1%	< 0.1%
Momentum Compaction	0.00037	0.00037

NSLS-II RF VOLTAGE, POWER REQUIREMENTS

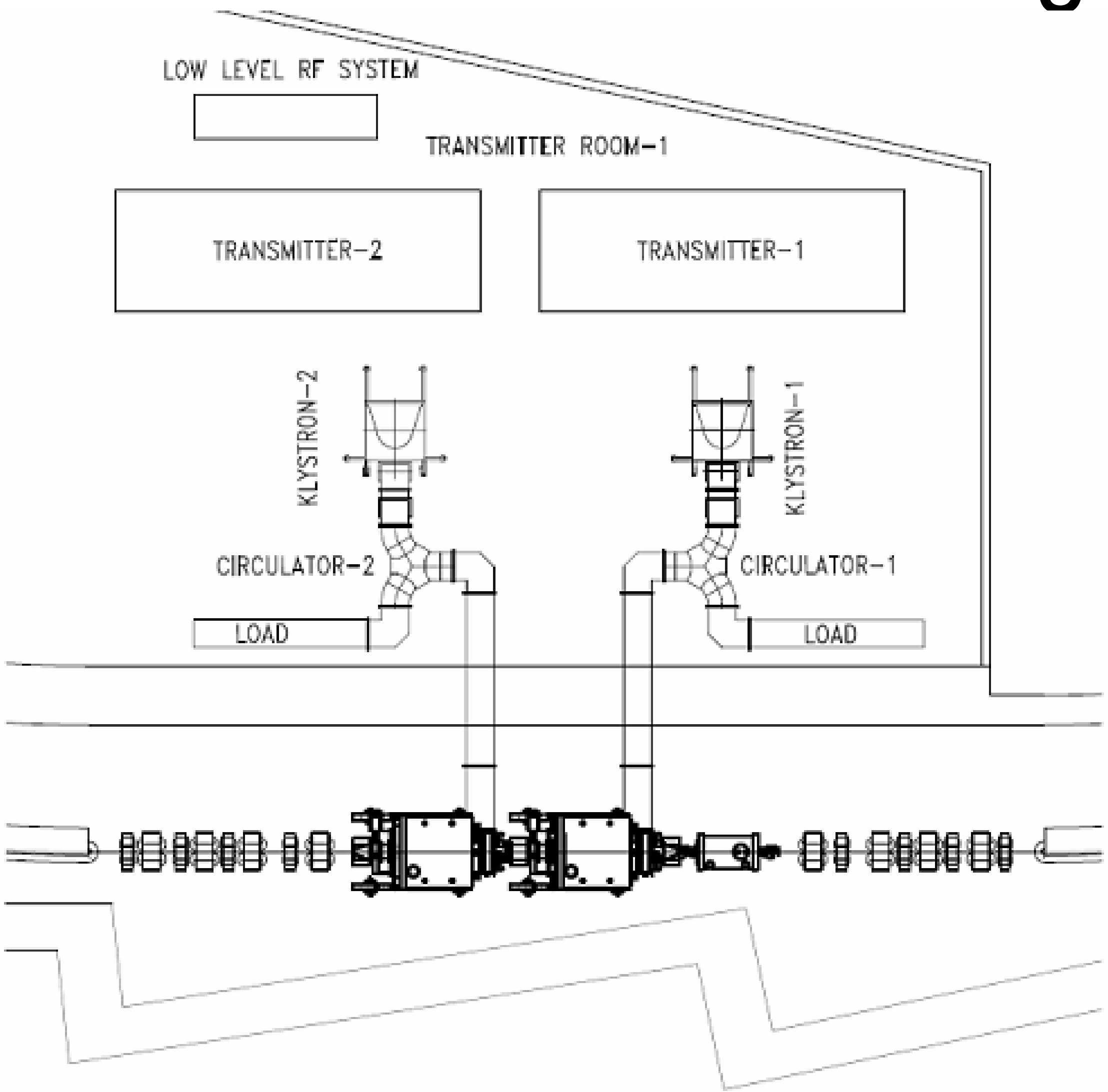
	Baseline Capability with 2 RF Cavity Systems Required Voltage 3.3 MV		Fully Build-out Capability with 4 RF Cavity Systems Required Voltage 5 MV	
	#	P(kW)	#	P(kW)
Dipole	60	144	60	144
Damping wiggler	3 (21 m)	259	8 (56m)	517
Cryogenic-PMU	3	76	6	127
EPU	2	33	4	66
Additional devices	~7	120	~10	200
TOTAL		529		1003
Available RF Power		540		1080

NSLS-II RF System Conceptual Design

Ring RF system

- CESR-B SCRF cavities chosen for ring RF
  - low impedance better for beam stability
  - higher AC power efficiency
  - Reliability and costs well established
- KEK-B SCRF cavity as option
  - Higher power per coupler attractive
  - minimal impact on conceptual design
- 310 kW Klystron amplifiers chosen for baseline:
  - Well established at other LS facilities
  - Reliability and costs well established
  - Combined IOT's as option
- Passive SCRF Landau cavity
  - Demonstrated performance at SLS, ELLETRA

NSLS-II RF Straight layout

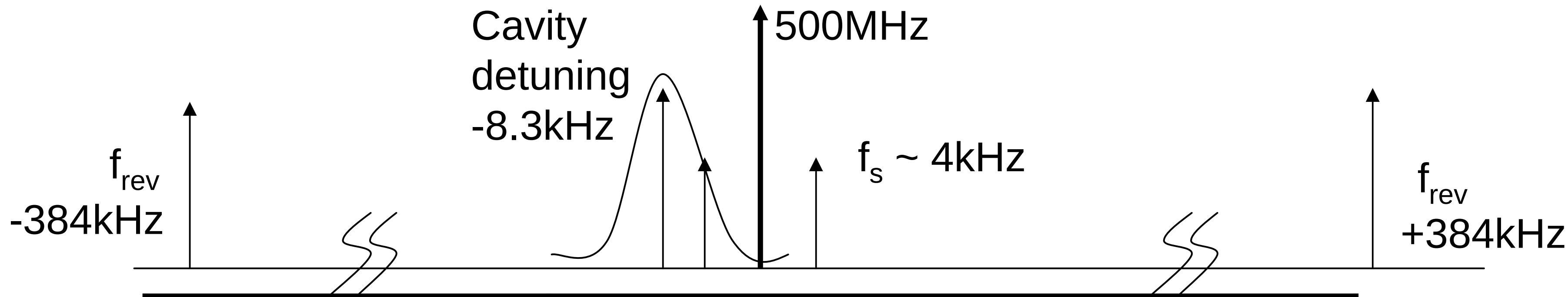


Two 500 MHz cavities
+ one 1500 MHz passive harmonic cavity fit in one 8m straight: meets initial power requirements

Second straight reserved for third , possible fourth 500 MHz and
second 1500MHz cavities as additional user insertion devices increase RF power requirement

Klystrons located in adjacent RF building to minimize loop delays in feedback systems

Beam Loading parameters



	Baseline	Fully Built Out
R/Q	44.5	44.5
Q_0	$5*10^8$	$5*10^8$
Revolution Frequency	384 kHz	384 kHz
Total V	3.3 M	4.9 MV
Synchrotron Frequency	3 kHz	4 kHz
Number of cavities	2	4
Q_L*	$1.2*10^5$	$6.7*10^4$
Bandwidth (FWHM)	4 kHz	7.4 kHz
Frequency detuning	-6.4 kHz	-8.3 kHz
* Q_L ~ 86k for minimum reflected power over all phases (preliminary)		

RF system Parameters for Beam stability

The stability criteria for heavily beam loaded systems can be written as

$$P_{beam} < (1+\beta) P_{cav} \frac{\sin(2\phi_s)}{\sin|2\psi|}$$

The beam is marginally stable since to match to a heavily beam loaded cavity

$\beta \sim P_{beam}/P_{cav}$ and $\boldsymbol{\psi \sim \phi_s}$ although

$-\psi/\phi s$ <1 by small amount

We can increase the stability margin by detuning the cavity by some angle χ ($o \leqq \chi \leqq \phi_s$) at the cost of some reflected power, then we obtain a current limit

$$I_o < \frac{2V_{cav}(1+\beta)\sin\phi_s}{R_a \sin[2(\phi_s - \chi]}$$

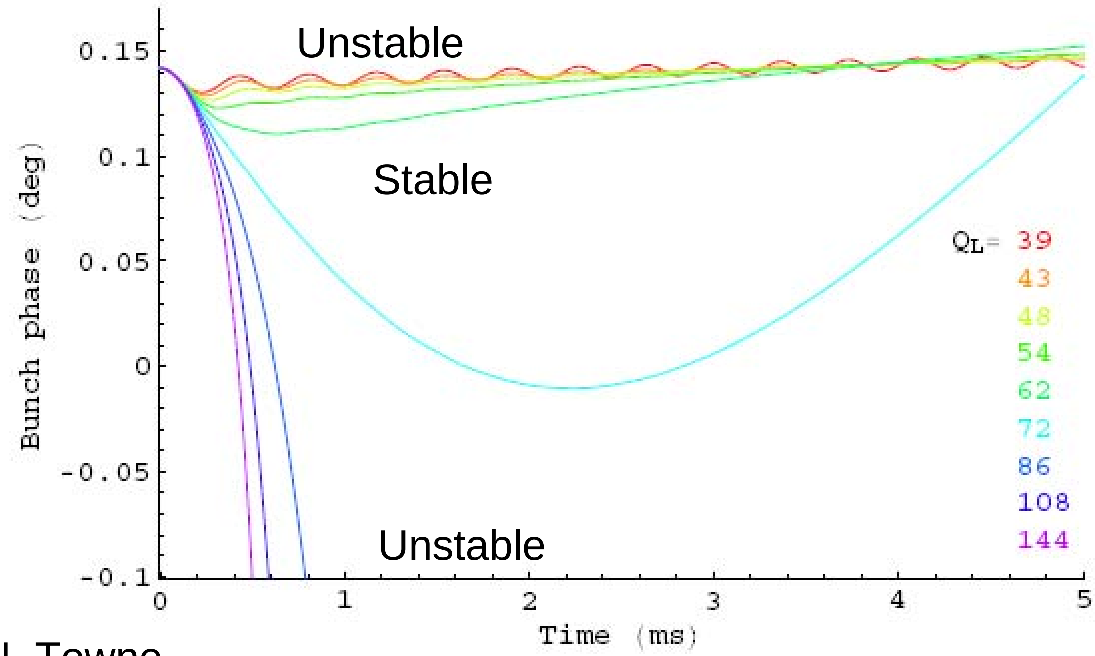
Where $\psi = -\phi_s + \chi$

For $\chi = 0$, $I_0 = 501.3$ mA, small margin !

Alternatively, we can manipulate the impedance R_a with feedback. Feedback is the primary choice for obtaining stability, since there is no additional power required.

We retain each of these options, plus feedback around the beam/RF system for NSLS-II

Vlasov equation solutions for stretched bunches for different QL



N. Towne

FIG. 1: Bunch phase as a function of time of stretched bunchs with varying main-cavity impedance. Traces correspond to the main-cavity loaded quality factors Q_L shown in the legend. Machine parameters are those for the three-cavity commissioning stage of Table II. The impedance-matched quality factor (no rf feedback) is 86,500 for the three-cavity commissioning phase.

- **Need to find coupling which will provide best operation over the phased Installation of ID's, RF cavities**
- **For matched coupling, either further detuning or (preferably) feedback is required to provide adequate stability margin, however intra-beam modes limit gain**

(k)

Summary of RF field Tolerances

	Phase Jitter (°)	Momentum jitter $\Delta p/p$ (%)
Timing-dependent experiments	0.1	0.005
Vertical divergence (from momentum jitter)	1.2	0.04
10% increase in $\sigma\delta$ due to filamentation	1.8	0.065
Vertical centroid	0.82	0.03

Effect of RF jitter on the beam:

Amplitude modulation of the RF fields leads to momentum deviations of the beam, Likewise phase modulations translate into amplitude modulations again leading to momentum deviations. The momentum errors affect beam size and orbit jitter as follows:

The beam size in the center of the 5 m straight is given by

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y} + \left(\eta_{x,y}\sigma_\delta\right)^2}$$

Since the dispersion is near zero (~1mm) and the natural energy spread is <0.001 the second term is negligible and the beam size becomes

$$\sigma_{x,y} = 40\mu m,\ 2.4\ \mu m$$

Orbit jitter is given as $\sigma_{x,y} = \sigma_\delta \cdot \eta_{x,y}$, $\sigma_{x',y'} = \sigma_\delta \cdot \eta_{x',y'}$

•Because of the near zero dispersion in the ID straights, this is not the limiting factor in determining the RF tolerances

Timing experiments in IR beamlines impose limit of phase variations to be <5% of bunch length: Phase error limit of +/- 0.12 degrees and 0.005% Δp/p

Vertical Divergence from momentum jitter for ID higher harmonic users

The vertical photon beam divergence for a experiment using a higher harmonic of an Insertion Device (ID) is given by[1]

$$\sigma_{y'}^2 = \frac{\lambda_n}{2L}\sqrt{1+16n^2 N_w^2 \sigma_\delta^2} + \varepsilon_y / \beta_y$$

Where *n* is the harmonic of the ID being used, N the number of periods, L the length of the ID, $\sigma\delta$ the momentum deviation, εy the vertical emittance of the electron beam and βy the vertical beta function of the lattice at the insertion device location. For NSLS-II εy ~8 x 10-3 nm·Rad and βy ~ 1m at the ID straights, L ~3m, N~100. Because of the n^2 dependence, the worst case is for n >> 3 where the two terms on the right hand side of equation (1) are comparable.

Thus for a 10 % increase in beam size the momentum jitter must be 40% of the inherent momentum spread, or equivalently a phase jitter of 1.2 degrees.

Emittance growth from filamentation due to energy jitter

$$\sigma_\delta = \sqrt{\frac{1}{2}\left(\frac{\Delta p}{p}\right)^2 + \sigma_{\delta,0}^2} = \sqrt{1 + \frac{1}{2} f^2}\,\sigma_{\delta,0}$$

where f = (Δp/p)/σδ is the relative kick factor.

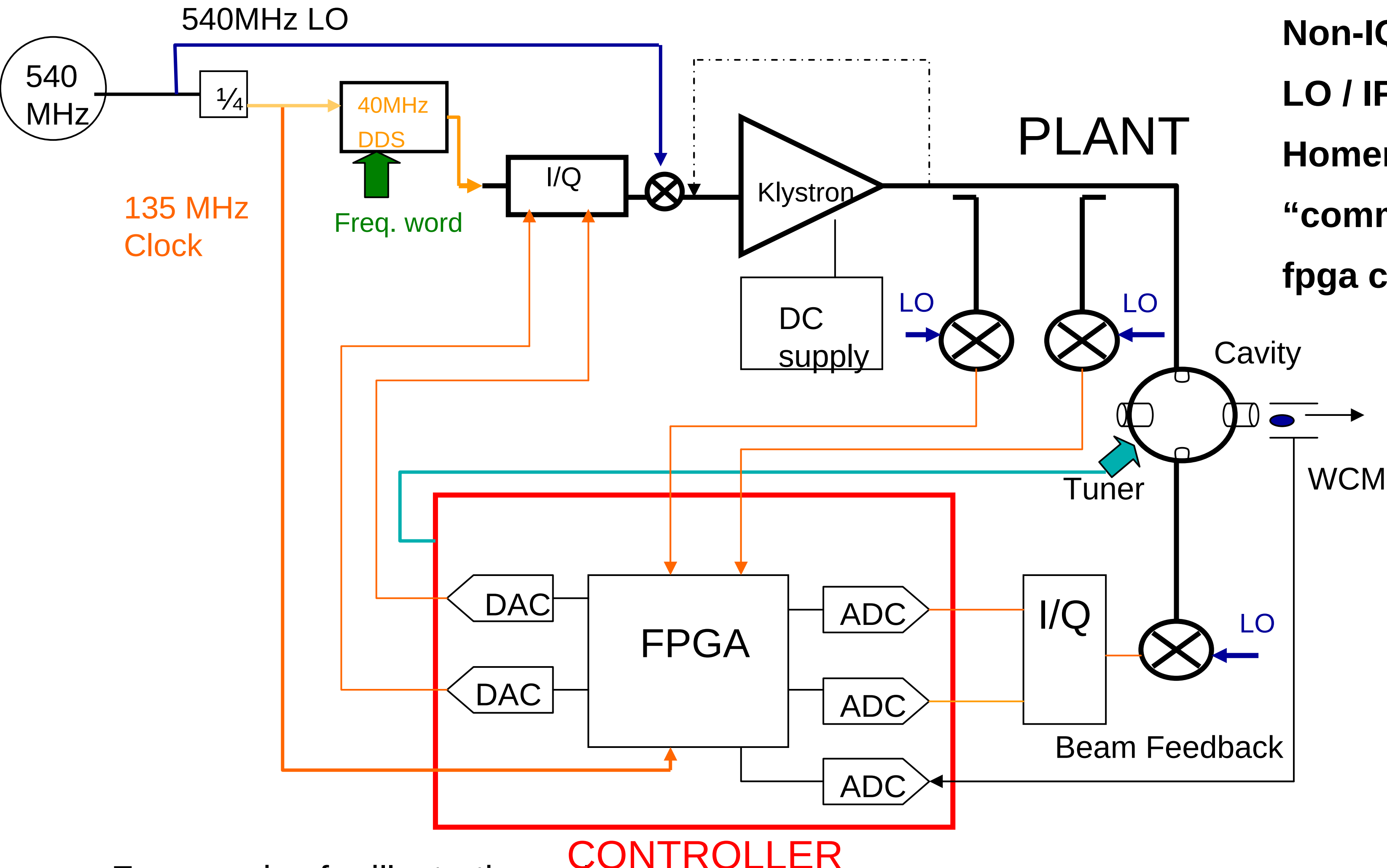
For a 10% increase in σ_δ, f ~ 0.65 or $\Delta_{p/p} = 6.5 \times 10^{-4}$.

The corresponding phase jitter is given by

$$\Delta\phi = \frac{h\alpha_c}{\upsilon_s} \Delta p / p$$

where h is the harmonic number (1300), α_c is the momentum compaction factor = .00037 and ν_s ~0.01, $\Delta\phi$ = 1.8 degrees.

Generic RF System Architecture



Non-IQ sampling?

LO / IF frequency?

Homemade vs. "commercial" fpga card?

Frequencies for illustration only

Klystron RF Feedback Loop

- Klystron RF stability vs. DC supply:
  - RF phase variation vs. beam voltage (constant mod. Anode voltage) 12 degrees/%
  - RF power vs. beam voltage 0.2dB/%
- PSM power supply typical performance (54kV,12A)
  - Full range < 1% pk-pk
  - 75V from 1kHz-2kHz (0.1%) = 1.2 degrees (for freq $<<1/\tau_{cav}$)
  - 15V from 2kHz-4kHz
  - 3V from 4kHz-12kHz
  - 50V for >12kHz

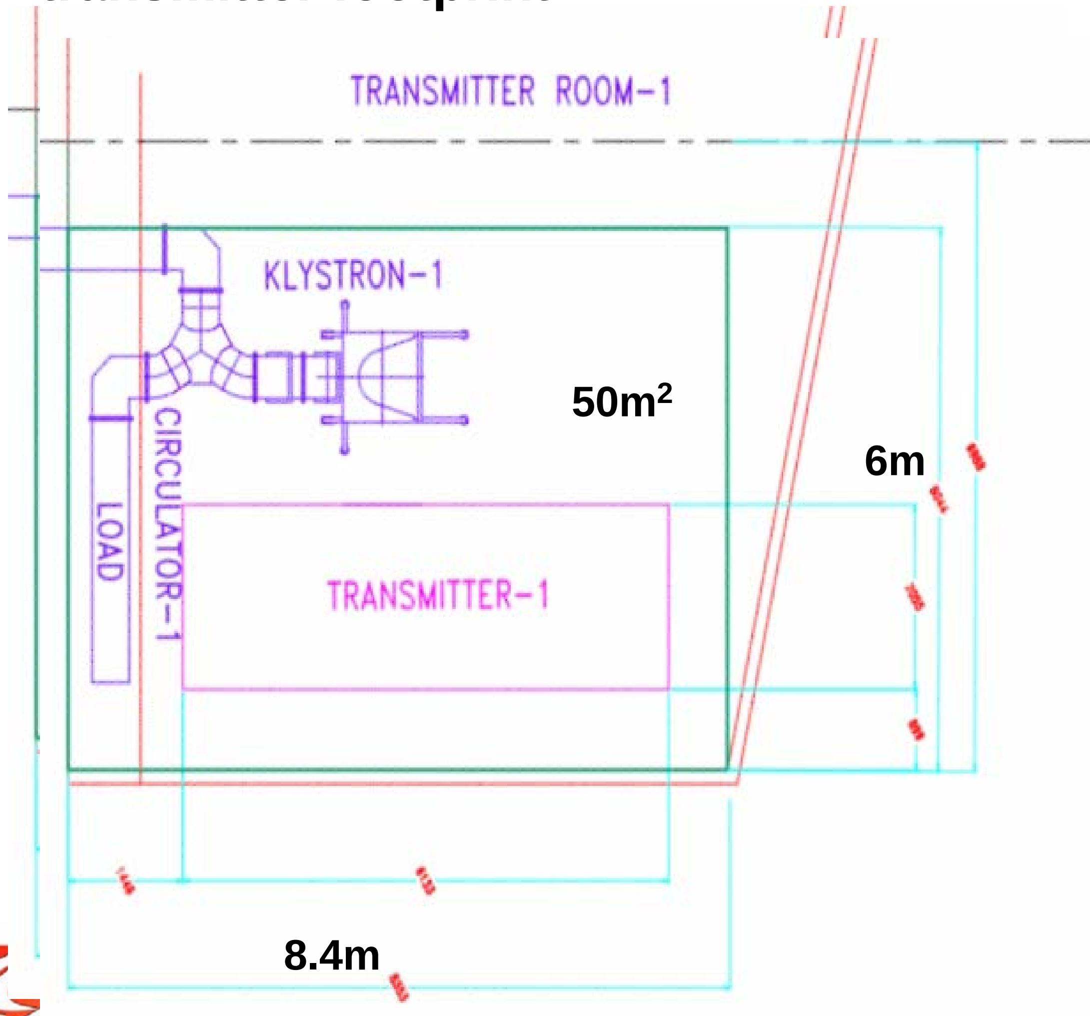
This is limiting factor in APS, ~1 degree phase jitter after feedback using mod-anode

Need Feedback!

BACKUP SLIDES

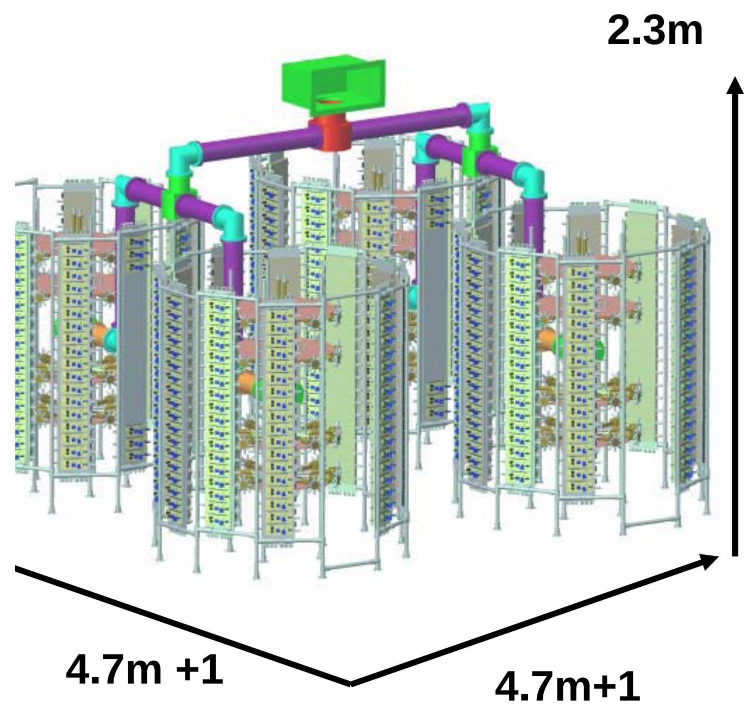
- Radial loop implementation (e.g., APS) sampling of dispersion
- Choice of harmonic number for main ring
- Choice of power amplifier: obsolescence of kystrons vs. silicon
- LLRF: volatility of discrete fpga's, programming tools

Thales 310 kW klystron transmitter footprint



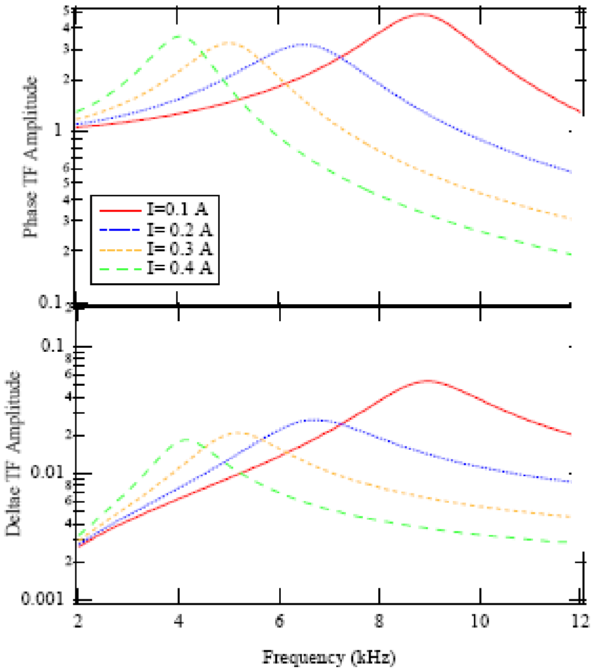
190kW SOLEIL SS transmitter

32.5m^2 (x2 plus DC supply ~2m^2

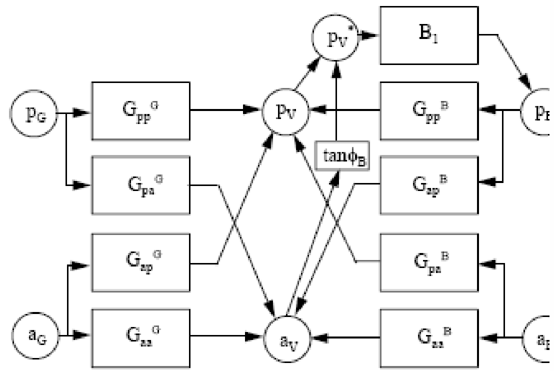


Phase Noise contributions to beam stability

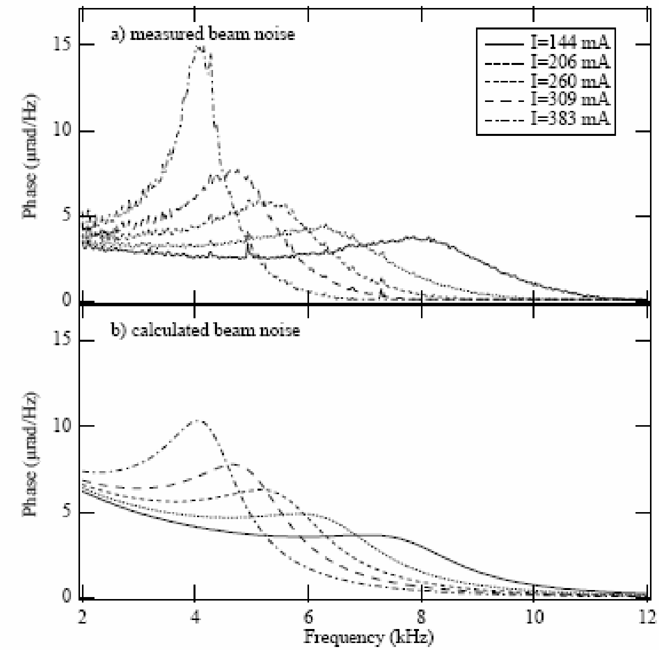
Beam Transfer Function

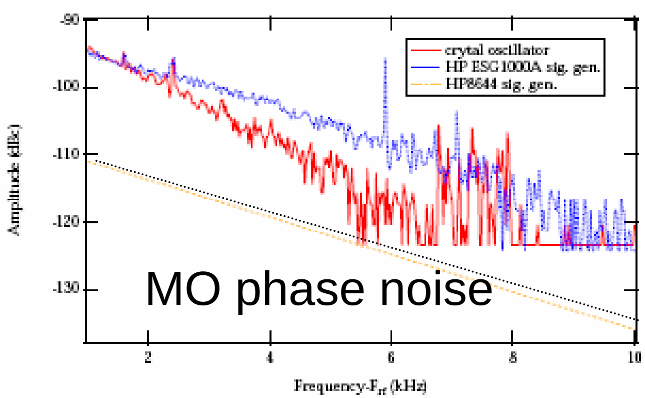


Boussard Model



Beam Phase Noise





MO phase noise

Byrd, "Effects of phase noise in heavily beam loaded storage rings" PAC99

Improvement with HP8644B