CONCEPTUAL DESIGN OF THE NSLS-II RF SYSTEM

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Abstract

RF system requirements are derived from machine parameters and beam stability specifications. The conceptual design of the RF system for NSLS-II to meet these requirements is presented, consisting of 500 MHz superconducting main cavities, 1500 MHz pasive SCRF harmonic cavities for bunch lengthening, and the RF power and cryogenic systems..

INTRODUCTION

The NSLS-II is a proposed third generation light source at Brookhaven laboratory that will enable experiments with spatial resolution of 1 nm and energy resolution down to 0.1 meV with the sensitivity required to perform spectroscopy on a single atom The basic machine parameters are given in Table 1. The design approach to achieve the requisite electron beam parameters is to use damping wigglers combined with soft (ρ=25m) dipole bends to reduce the bare lattice emittance of 2nm-rad to the required 0.5nm-rad [1].The ~ 2 hour electron beam lifetime for NSLS-II is anticipated to be dominated by Touschek scattering with significant contributions from the non-linear dynamics of the lattice and the 5mm vertical aperture of the small gap undulators results in a short beam lifetime of ~2 hours, dominated by Touschek scattering. To mitigate this short lifetime a third harmonic Landau cavity for stretching bunches longitudinally to increase the lifetime to ≥3 hours is proposed.

Table 1: NSLS-II Reference parameters

Parameter	Value	Unit
Energy	3	GeV
Average current	500	mA
Emmitance (ε_x, ε_y)	0.5, 0.01	nm-rad
RF acceptance Δp/p	3	%
Circumference	791.9	m
RF Voltage (initial/upgrade)	3.3 / 5	MV
Momentum compaction α	3.68×10^{-4}	
Lifetime (bare lattice)	2	hours

RF SYSTEM REQUIREMENTS

Table 2 outlines the power requirements for the two phases of the project with a proposed selection of user insertion devices. The actual selection of user ID's is in progress for the baseline machine. The wiggler dominated beam power allows for a phased installation of RF power where the baseline machine has 3 damping wigglers that achieves a 1 nm-rad beam emittance.

The 500kW baseline requirement can be met with existing RF power coupler design by two cavities fed with 300kW RF transmitters. As the facility matures five additional damping wigglers are added to bring the emittance down to 0.5 nm. This increases the beam power up to 1000kW and requires two additional RF cavities and transmitters. Klystron amplifiers are the reference design choice for the 300kW transmitters, with combined IOT and solid state systems being studied during the preliminary design.

Table 2: RF Power losses in dipoles and ID's for baseline project and full build-out as a mature facility.

	Baseline Design		Mature Facility	
Device	#	P (kW)	#	P (kW)
Dipoles	60	144	60	144
Damping wigglers	3	194	8	517
Cryo-PMU's	3	38	6	76
EPU's	2	33	4	66
Additional devices	~7	120	~10	200
Total		529		1003
Available Power		540		1080

Beam Stability Requirements

The user photon beam jitter and beam-size requirements determine the specifications of the electron beam stability and in turn the RF field amplitude and phase specification. Full details are discussed in Ref [2]. The timing-dependent experiments, such as pump-probe, are the most demanding, with jitter specification of a tenth of a degree. Preliminary design studies have calculated the residual jitter of the klystron due to anode power supply voltage regulation tolerances to be 1.2 degrees. A phase loop around the klystron is required to bring this value within tolerance. Detailed analysis of the RF field requirements determined by beam stability as a function of time and frequency is ongoing.

Table 3: Beam stability requirements and their origin.

	Phase Jitter (°)	Momentum Jitter (Δp/p)
Vertical divergence from momentum jitter	2.4	0.009
10% increase in σδ due to filamentation	1.8	0.00065
Vertical Centroid	0.82	0.0003
Timing-dependent experiments	0.14	0.00005
Dipole beamlines	0.27	.0001

CAVITY CHOICE FOR 500 MHZ SYSTEM

The 500mA beam combined with the voltage and power requirements of 5MV and 1000kW respectively led

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us to explore the use of existing HOM-damped cavity designs for B-factories and light sources. A detailed technical and cost study comparing the CESR-B[3], KEK-B[4], PEP-II [5] and BESSY-"Willy Wien ring"[6] HOM damped cavities was undertaken. Each of the systems could meet the requirements. Due to the different voltage and power coupler capabilities of the systems it would require 3 KEK-B cavities, 4 CESR-B, 6 PEP-II and 10 BESSY cavities to meet the requirements of 5MV and 1000 kW in the fully built out machine. The difference in numbers of NCRF systems required offsets the higher costs associated with the SCRF systems. It should be pointed out that the figure of merit is a function ratio of voltage to power required, and a similar cost comparison for ESRF came out in favor of NC cavities [7]. Although the capital costs are higher for SCRF the lower operating costs of the SCRF systems make it the lowest total cost after 5-10 years of operation.

Table 4: Comparison of capital and operating costs for normal conducting and superconducting RF systems. SC landau cavity is assumed in both cases.

	PEP-II	CESR-B
RF cavities + RF power	$13.41M (6)	$13.58M (4)
Cryo-plant cost *	$2M (150W@4.5 K)*	$5.3M (700W@4.5 K)
Water System * (no separate cost yet)	1626 kW RF + 78kW Cryo*	693kW RF + 364kW Cryo*
Capital subtotal	$15.410M	$18.880M
RF AC power	$1.793M/year	$1.159M/year
Cryo-plant AC power *	$39k/year	$170k/year
Water system AC power	$199k/year	$124k/year
RF klystron tubes	$225k/year	$150k/year
Cryogenic gases *	$5k/year	$15k/year
Total capital + 30 year ops	$84.24M	$68.42M
* Includes Harmonic cavity operation		

The technical comparison of SCRF vs. NCRF systems show clear advantages for SCRF. The ion gap in the bunch train causes a phase shift of the bunches away from the nominal synchronous phase. This phase shift, of up to 20-30 degrees, is sufficient to limit the voltage induced in the harmonic cavity as the cavity is tuned towards resonance. The lower fundamental R/Q of the 500MHz cavities combined with the higher voltage achieved per cavity means that the total impedance of the fundamental cavities installed in the ring is a factor of 3-5 lower for SCRF. The lower R/Q of the SCRF results in a ~40% increase in bunch lengthening vs. that achieved by NCRF systems, with corresponding increase in beam lifetime. The effect is a function of the length of the ion gap. In Figures 1 and 2 the average bunch length is plotted as a function of cavity detuning for a ion clearing channel of 20% of the circumference divided into one, two or four gaps.

The lower R/Q of the superconducting cavities combined with the flexibility to design open structures with large beam-tubes to leak HOM modes to on axis dampers results in lower HOM impedances as well. Longitudinal and transverse impedances and coupled bunch instability thresholds were calculated [8,9] and compared for the CESR-B,

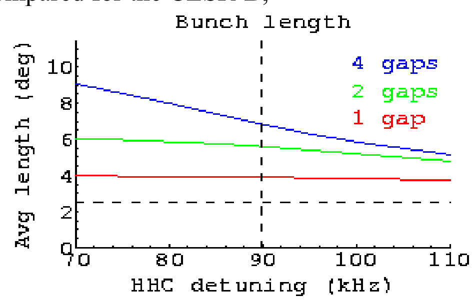

Figure 1" Average bunch length as function of harmonic cavity detuning for SCRF cavities. Total gap is 20% of circumference in each case. Dotted H. line is natural bunch length, V-line optimum short-bunch driven field.

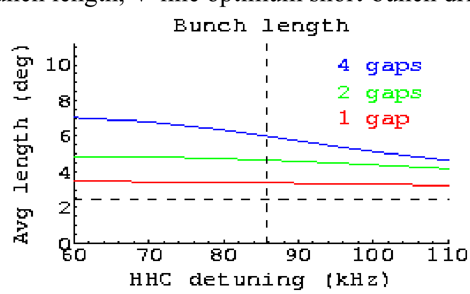

Figure 2: Average bunch length as function of harmonic cavity detuning for NCRF cavities. Total gap is 20% of circumference in each case. Dotted H. line is natural bunch length, V-line optimum short-bunch driven field.

PEP-II and BESSY cavities. Results from ZAP [10] calculations of the longitudinal growth times for both the bare lattice and with 8 damping wigglers installed are shown in Table 5 for the case of un-stretched bunches.

Table 5: Longitudinal coupled bunch instability growth times for NSLS-II. Damping time is 27ms bare lattice, 6 ms fully built-out-8DW.

	Growth time for 500mA in un-stretched bunches
CESR-B (4 cavities)	99ms bare / 121ms-8DW
PEP-II (6 cavities)	13.5ms(bare) /16ms-8DW
BESSY-II (10 cavities)	3.4ms(bare) /4.1ms-8DW

The addition of the Landau cavity to stretch the bunches to increase beam lifetime means that simplified calculations for growth rates assuming Gaussian or parabolic bunch shapes no longer apply. A self-consistent treatment of stretched bunches in a dual RF system was performed using a Vlasov equation integrator [11].

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Results for a system of 4 CESR-B cavities and three 3rd harmonic cells are shown in Figure 3 compared with a simple analytical solution. The HOM impedance threshold for the stretched case is far above that achieved with any of the HOM damped cavities, and no HOM driven coupled bunch instabilities are foreseen. The situation is reversed if the third harmonic cavity is used to shorten the bunches. In this case the lower HOM impedances of the SCRF cavities as compared to NC cavities is still a benefit.

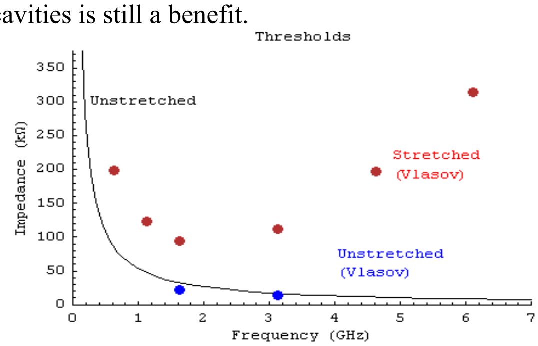

Figure 3: Calculated longitudinal impedance thresholds for stretched and un-stretched bunches.

LANDAU CAVITIES

In order to reduce the frequency and duration of top-off injections a third harmonic cavity is required to increase beam lifetime. Studies have concluded that a passive, superconducting harmonic cavity is the best choice for NSLS-II. Advantages are the simplicity of a passive system, and the nearly ideal phase due to the low cavity losses. 1500 MHz SCRF cavities can provide approximately 500 kV per cell economically. The two cell SUPER3HC cavity in operation at both SLS and Trieste.[12] can meet the baseline requirement of ~1 MV in a length of 1.5 m. An additional cavity is required for the fully built out machine, resulting in two identical RF straights. One straight is built up as part of the baseline project with two 500 MHz cavities and a two cell 1500 MHz cavity. A second identical straight will be added when additional damping wigglers and user ID's are installed.

SYSTEM LAYOUT

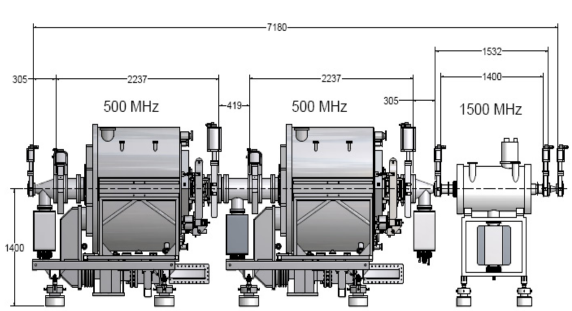

Figure 4: The layout of the RF straight with two fundamental and a single two cell harmonic cavity

A layout of a single RF straight is shown in figure 4. Two 500MHz cavities and a Super3HC cavity fit within a single long straight of the NSLS-II lattice. A second long straight is reserved for an identical installation for the full build out of the facility.

CRYOGENIC SYSTEM

A near turn-key 700 watts at 4.5 K helium closed-cycle cryogenic system will provide liquid helium to all super-conducting RF cavities. To enhance reliability, the refrigerator is sized to operate at 60% of its peak cooling capacity and two sets of helium compressors, one serving as hot standby. A near fully automated control system is planned to ensure continuous operation under various modes

BOOSTER RF

The booster requires 1.2 MV per turn for a 0.91% bucket height, [13]. In order to meet the injection rate of 7.5 nC per minute in a single booster cycle with sufficient margin to account for injection losses a goal of 15 nC per booster cycle has been assumed. With a beam current in the booster of 28 mA and an energy loss per turn of 628 keV, the beam power is 17.6 kW. The 5 cell $\pi/2$ "PETRA" cavity [14] has been selected for the baseline design. With a shunt impedance of ~14.5 MΩ, 50 kW is required to reach 1.2 MV, for a total of 68 kW of RF power. An 80 kW IOT transmitter is specified which will provide a 15% headroom on RF power.

LINAC

In order to inject single bunches and long bunch trains 'bunch-to-bucket' into the 499.68 MHz booster the linac frequency will be 2998MHz, the six harmonic of the rings. A sub-harmonic buncher at 499.68 MHz will be incorporated to increase capture efficiency. Details are given in Ref. [15].

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