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A NEW ULTRA-STABLE VARIABLE PROJECTION MICROSCOPE FOR THE APS UPGRADE OF 32-ID*

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Abstract

A new nano-computed tomography projection microscope (n-CT) is being designed as part the Advanced Photon Source Upgrade (APS-U) beamline enhancement at sector 32-ID. The n-CT will take advantage of the APS-U source and provide new capabilities to the imaging program at 32-ID. A Kirkpatrick and Baez (KB) mirror-based nanofocusing optics [1, 2] will be implemented in this design. To meet the n-CT imaging goals, it is the desire to have sub 10 nanometer vibrational and thermal drift stability over 10-minute measurement durations between the optic and the sample. In addition to the stability requirements, it is desired to have a variable length sample projection axis of up to 450 mm. Such stability and motion requirements are challenging to accomplish simultaneously due to performance limitations of traditional motion mechanics and present a significant engineering challenge. To overcome these limitations, the proposed n-CT design incorporates granite air bearing concepts initially used in the Velociprobe [3]. These types of granite stages have been incorporated into many designs at APS [4] and at other synchrotron facilities [5]. Utilizing the granite air bearing concept, in tandem with other design aspects in the instrument, the requirements become reachable. A novel multi-degree of freedom wedge configuration is also incorporated to overcome space limitations. The design of this instrument is described in this paper.

INTRODUCTION

The new n-CT instrument will exploit the new APS-U source characteristics by implementing projection x-ray imaging for the high-speed imaging program at APS. A throughput gain is achieved as the temporal resolution of the nano-imaging tomography instrument goes from 500 ms to tens of µs. A unique advantage of the instrument geometry allows zooming capability that fills the gap in terms of resolution and field of view between the currently available µ-computed tomography (µ-CT) and the transmission x-ray microscopy (TXM) based nano-computed tomography (n-CT). Another unique advantage of the instrument geometry allows the multi-modality measurement capability coming from the simplicity of using the focused beam as a probe for XRF measurement.

The variable projection microscope at 32-ID will be a combination of a KB mirror system and a high precision sample rotation and nano positioning stack on a common support structure with separate granite air bearing coarse positioning axes. A separate camera and detector system will be integrated just downstream of the instrument. A visualization of the instrument is shown in Fig. 1.

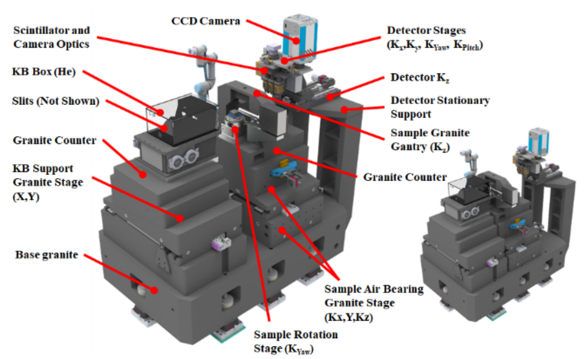

Figure 1: Rending [6] of the n-CT instrument design, labeling major components. Largest working distance (left) and probing stage (bottom right).

It is the desire to have sub 10 nm vibration and thermal drift stability over the course of 10-minute measurements. Because of the long variable zoom axis of this instrument, it is difficult to implement relative optic to sample metrology to correct thermal drifts. It is the design of the coarse granite stage positioning system and support that enables this relative stability. The instrument design and these details are discussed in subsequent sections.

N-CT CONFIGURATION METHODOLOGY

The following numbered items represent the most critical requirements of design and configuration for this instrument:

1. A stable, helium isolated KB optics environment is required to achieve the nanofocusing of the KB's along with extending their lifetime.
2. Optics to sample stability is required. This is both when considering contributions of vibrations and thermal drifts.
3. Variable projection zoom axis of 450 mm must be implemented in the design. Stability cannot be compromised with variable zoom.
4. Various sample environments must be accommodated with >360 rotation capability. Voltage biasing and fluid feedthroughs must be integrated into the design

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5. The ability to mount multimodal detection strategies must be facilitated by the design. An example is the ability to mount a fluorescence detector in the future.

N-CT CONFIGURATION AND PARAMETERS

Figure 2 depicts the optical configuration of the n-CT instrument. The defining characteristic of this instrument is the variable projection zoom axis K, which moves along the kicked beam of the KB mirror to change magnification. The key performance parameters of the instrument are shown Table 1.

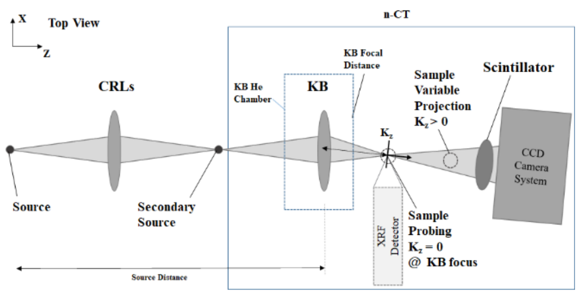

Figure 2: Schematic showing the optical layout and detection of the n-CT instrument. The n-CT works with a secondary source created by a CRL system upstream in the beamline. The new directions KX, KY, and KZ are noted as the “kicked” axes of the beam by the KB mirror pair.

Table 1: Characteristic Parameters of the n-CT Instrument

n-CT Characteristic Parameters Specifications		
Specification	Value	Unit
Simultaneous Measurement Methods	FFnCT, XRFnCT*	
Variable Projection Zoom (K_z) Total Range	450	mm
Selectable Scan Axis	Sample X, Y, Sample θ_y	
Rotational Scan Range	>360	deg
MIM for rotation step	150	μrad
Sample K_y Scan Range	≥ 50	μm
Sample K_x' Scan Range	≥ 100	μm
MIM for planar scan	≤ 2	μm
Relative Sample to Optic Positioning Resolution	≤ 10	nm
Relative Sample to Optic Stability	≤ 10, 10 minutes	nm
Optic Focal Spot Size (KB)	20	nm
Optical Working Distance	60	mm
Working Energy	25	keV
Detector Pixels	4000 x 4000	
Largest Volume of Interest	80 x 80 x 80	μm
Target Imaging Resolution	15	nm

GRANITE SUPPORT AND MOTION DESIGN

The granite air bearing concept is to float and position dynamic pieces of granite with air pressure and then to set them back down (air off) thus again creating a monolithic structure.

The n-CT incorporates 6 such dynamic granite pieces, resulting in 4 degrees of freedom (DOF) for the sample stack, and 2 for the KB system. The sample stack granite configuration is shown in Fig. 3. The KB has almost identical form factor and components, however just X and Y motions. The KB motions are expected to only be used during initial commissioning, while the sample motions are expected to be used frequently during user experiments. A new 2 DOF wedge design has been incorporated in this instrument such that pieces 2 and 3 of Fig. 3 provide both X and Y motion with two independent drives. The drive for the following wedge is shown in Fig. 4. By incorporating transverse motion in the follower, one less air bearing interface is needed in the motion stack.

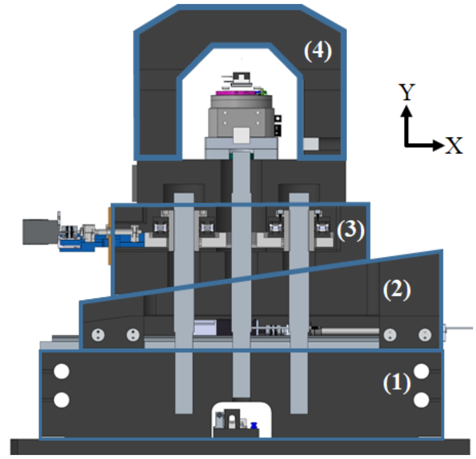

Figure 3: n-CT granite stage stack with motion granite components highlighted. 1- granite Z motion (KZ for sample), 2- X driving wedge that creates Y follower motion, 3- Two degree of freedom Y follower wedge with X motion, 4-Z motion granite gantry for sample environments and detector mounting. Pieces 1, 2 and 3 are nearly identical for supporting the KB system.

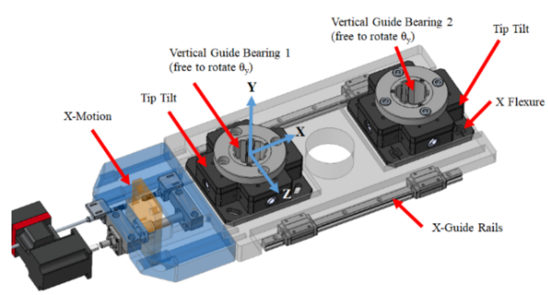

Figure 4: n-CT following wedge guide/drive design. This drive allows the follower wedge to be guided vertically by two posts but be driven transversely.

KB SYSTEM

A set of KB mirrors and stages are configured inside a helium enclosure, shown in Fig. 5. A set of highly stable and repeatable nanopositioning stages are configured to give all the DOF required to align the system to the beam. The specification of the KB mirrors is given in Table 2. The performance of the KB system is not discussed in this paper, but the reader is encouraged to read the referenced papers pertaining to the KB nanopositioning system [1, 2].

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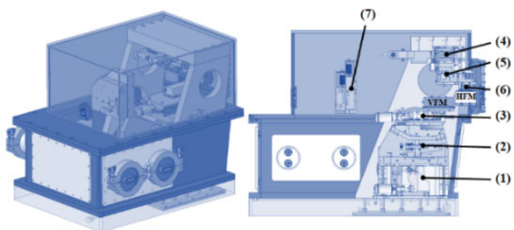

Figure 5: n-CT KB system. VFM – vertically focusing mirror, HFM – horizontally focusing mirror, 1- Vertical stage, 2-Rotation X stage, 3- Tranlsation Z stage, 4-Rotation stage Y, 5-Translation X stage, 6- Rotation Z stage (manual), 7-Clean up slits upstream of the KB mirror.

Table 2: Characteristic Parameters of n-CT KB Mirrors

KB Mirror Specification Table				
Specification	VFM	HFM	Unit	Comment
Substrate material	Silicon	Silicon		
Mirror Shape	Elliptic	Elliptic		
Useful length	60	40	mm	
Useful width	3	3	mm	
Mirror Length	65	45	mm	
Roughness (at 50x)	0.2	0.2	nm rms	
Tangential Slope error	0.1	0.1	µrad rms	
Tangential figure error (PV)	1	1	nm	
Incidence angle	20	20	mrad	at mirror center
Object distance	33	33.057	m	at mirror center. Secondary source (BDA) is at 41 m.
Image distance	0.13950	0.08250	m	at mirror center
Gap between mirrors	2		mm	
Working Distance	60		mm	
Coating	None	None		Multilayer coating will be deposited in-house

SAMPLE STACK

A compact continues rotation samples stack has been designed for the n-CT and is shown in Fig. 6. The union and slip ring are buried in the granite plate this stage stack is interfaced with. The option to choose piezo scanning (load limited) or a kinematic mounting interface has been incorporated to increase user flexibility.

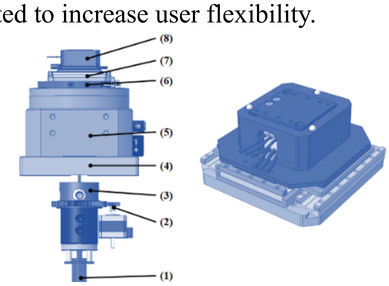

Figure 6: n-CT sample stack. 1-Electrical slip ring, 2-Rotary union separate rotation mechanics, 3- rotary union, 4- base plate, 5-rotation stage, 6- feedthrough manifold, 7-XZ nanopositioner, 8- optional scanning mount or stationary kinematic mount (right picture).

DETUNING CONSIDERATIONS

The worst parasitic error for this instrument is rotational detuning of the sample rotation axis about the X direction of the kicked KB beam (K_X). In relation to the pixel size and working distance, it is desired to keep this number below 1000 µrad. Parasitic errors are contributed to by granite guiding mechanics and form for positional repeatability. Considering all the errors it is expected a worst-case detuning of 173 µrad can occur (non-quadrature).

MODAL ANALYSIS

A modal analysis was performed on the instrument support and staging to determine the natural frequency is sufficiently above the cultural noise floor of 30Hz at APS [7]. The n-CT preloaded jack stiffness used to define the 8 floor interfaces is given in Table 3. Modal analysis results are shown in Fig. 7. The supporting structure and granite stages are sufficiently stiff to not amplify vibrations.

Table 3: Jack stiffness matrix. Z – beam direction, Y – vertical direction. Empirical tested values obtained at APS.

n-CT Jack Stiffness						
Load (N)	K_{XX} (N/m)	K_{YY} (N/m)	K_{ZZ} (N/m)	$K_{\theta X}$ (Nm/rad)	$K_{\theta Y}$ (Nm/rad)	$K_{\theta Z}$ (Nm/rad)
60,000	1.14E9	2.31E9	1.15E9	2.32E6	4.79E6	5.42E6

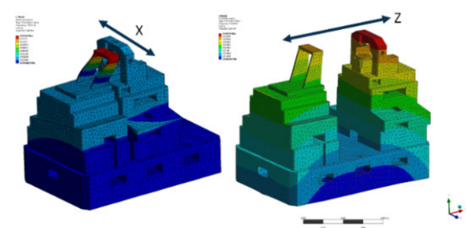

Figure 7: Modal analysis [8] results. The first mode is a KB frame motion (~158 HZ) and is not a rigid body motion of the support structure or granite stages. In the probing (left) and farthest projection position (right), the second natural frequency is ~179 Hz and ~172 Hz respectively for rigid body the rigid body modes. The direction of rigid body motion induced by rocking is shown in the figure.

THERMAL CONSIDERATIONS

The KB optics and sample stack are mounted on nearly identical granite stage platforms. Both granite stage stacks should respond the same to environmental change. The KB system is inside a helium enclosure. The sample environment is exposed to air. It is expected that the largest thermal drift is the relative response of these two systems, where the KB tank is more invariant to temperature change. It is estimated currently that the thermal response time of the sample stack given a 0.2 degC change to respond 10 nm is ~6 minutes from simplified lumped thermal calculations. It is expected after incorporating more resistance to convection to the sample stack exposed areas (Lexan panels) that this instrument will not respond more than 10 nm over 10-minute timescales.

CONCLUSIONS

The stability requirements for this instrument are very demanding. By incorporating a granite coarse positioning design along with stiff KB nanopositioning, the stability goals at both projection extremes can be met. This instrument provides the right combination of flexibility and motion for user experiments, without sacrificing stability performance.

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