Status of LN-Cooled Monochromator Efforts at SSRL

Thomas Rabedeau & Andy Ringwall
with Michael Holmes, Gan Li, Bill Nolan, James Peck, Michael Rowen, and Plamen Velikov

ESRF Double Crystal Monochromator Workshop
May 13-14, 2014

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

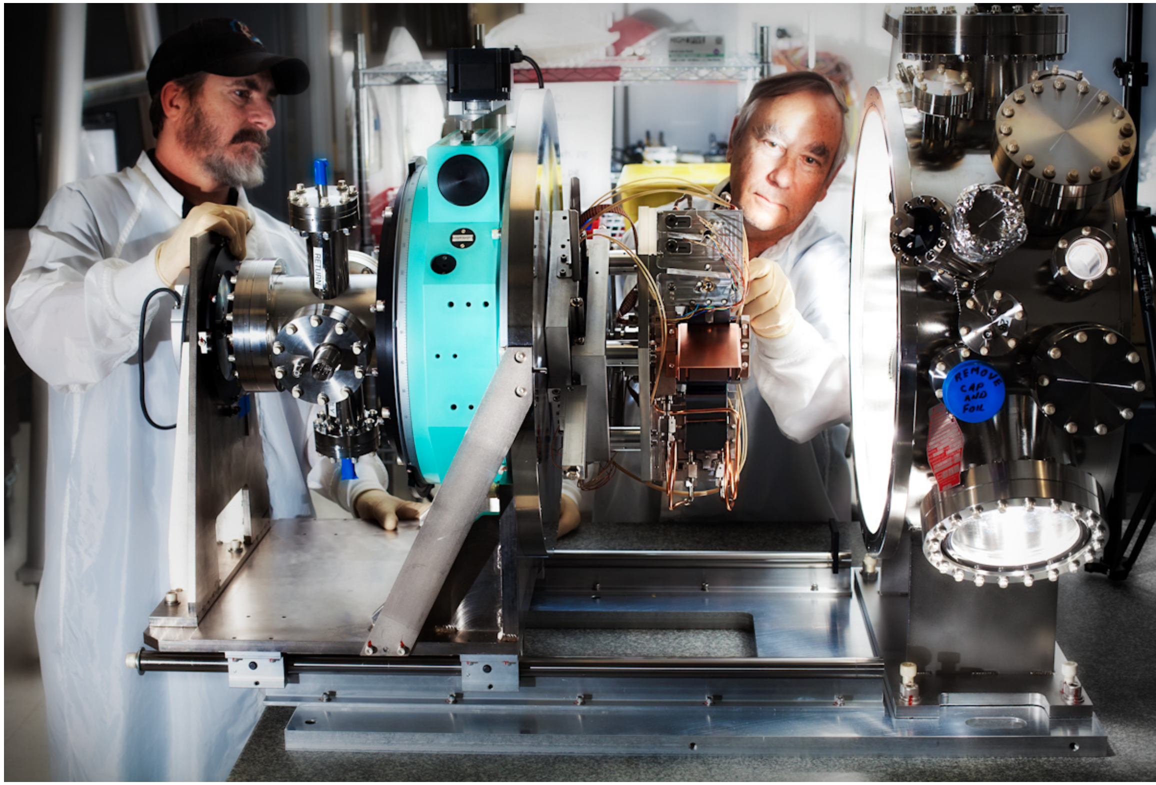
Presentation Overview

First half – overview of SSRL LN-cooled monochromator

- notable design constraints and features
- performance

Second half – FEA studies of approaches to maintain diffraction volume at temperature of minimal strain

- LN flow hence wet wall coefficient control
- Weak thermal link with Joule heating

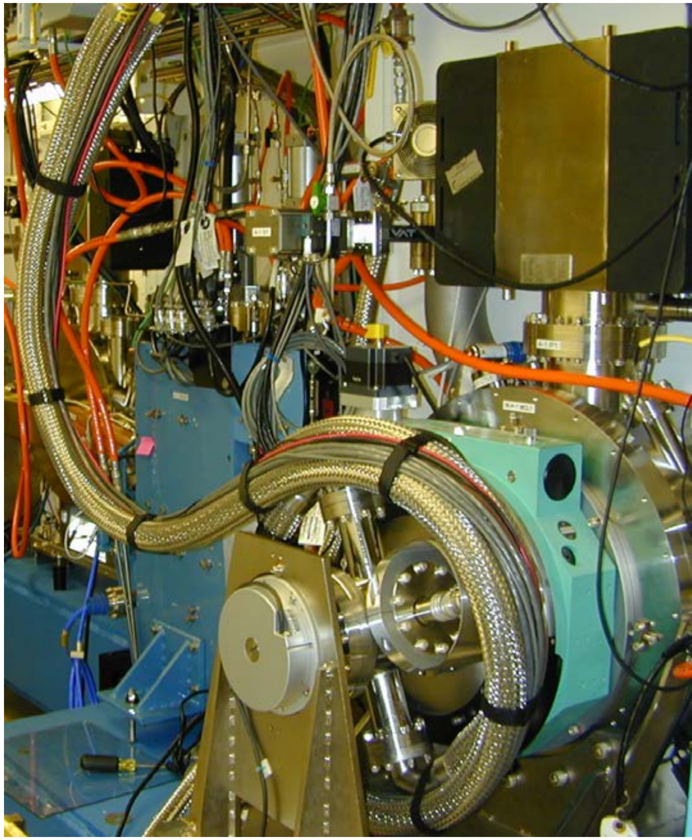


SSRL LN-Cooled Monochromator

Installed Base

SSRL design and fabricated LN-cooled, double crystal monochromators are installed on 13 wiggler and IVU BLs:

- 11 monos feature two crystal sets each (nine at SSRL and two at CLS); conservative design circa 2000 with fixed 6.5-8.5mm crystal channel, worm drive turn table, ferro-fluid vacuum seal, etc.
- one mono features a Si(111) crystal pair and a MoB4C multilayer pair (SSRL)
- one sagittal focusing mono includes two pairs of crystals (SSRL)



A further two fixed exit / fixed channel (selectable) LN-cooled double crystal monochromators are in fabrication for installation on IVU BL at SSRL

SSRL LN-Cooled Monochromator

Design Constraints

CLS installation

(1) Compatible with wiggler (300-1000W) and IVU power loading (50-100W and up to ~50W/mm^2) for 3GeV/500mA SPEAR3

(2) Must contain at least two pairs of crystals for remote resolution changes and/or glitch avoidance, yet lateral footprint must be consistent with use on wiggler side stations.

(3) The monochromator must provide adequate stability and reproducibility for spectroscopy applications.

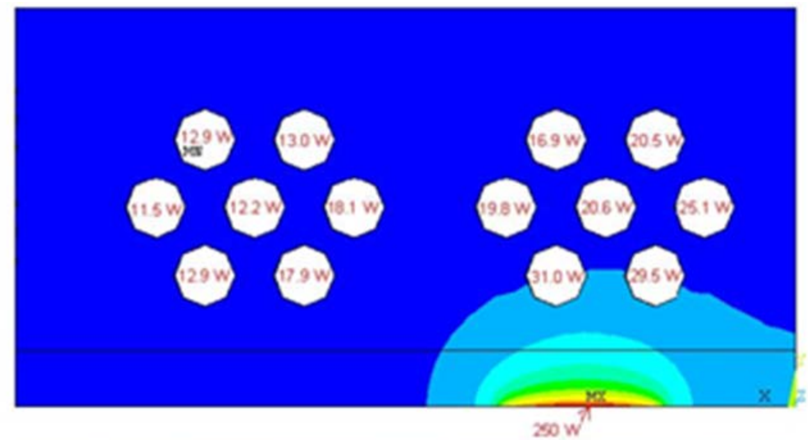
SSRL LN-Cooled Monochromator

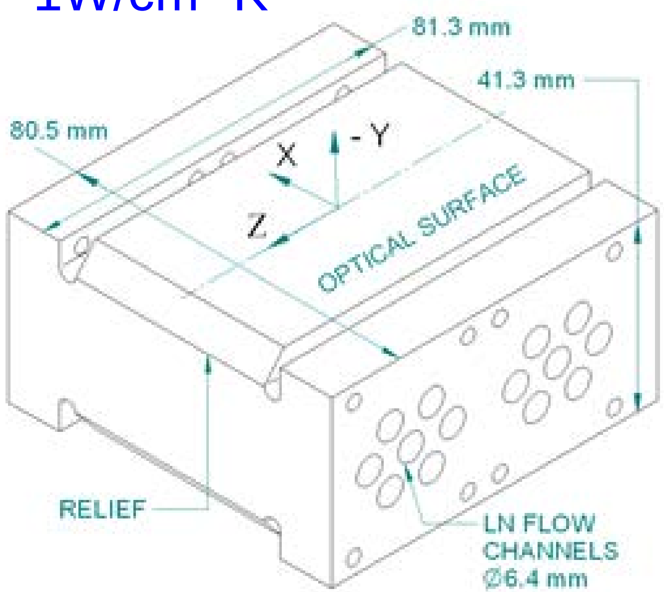
Internal Cooling Ducts

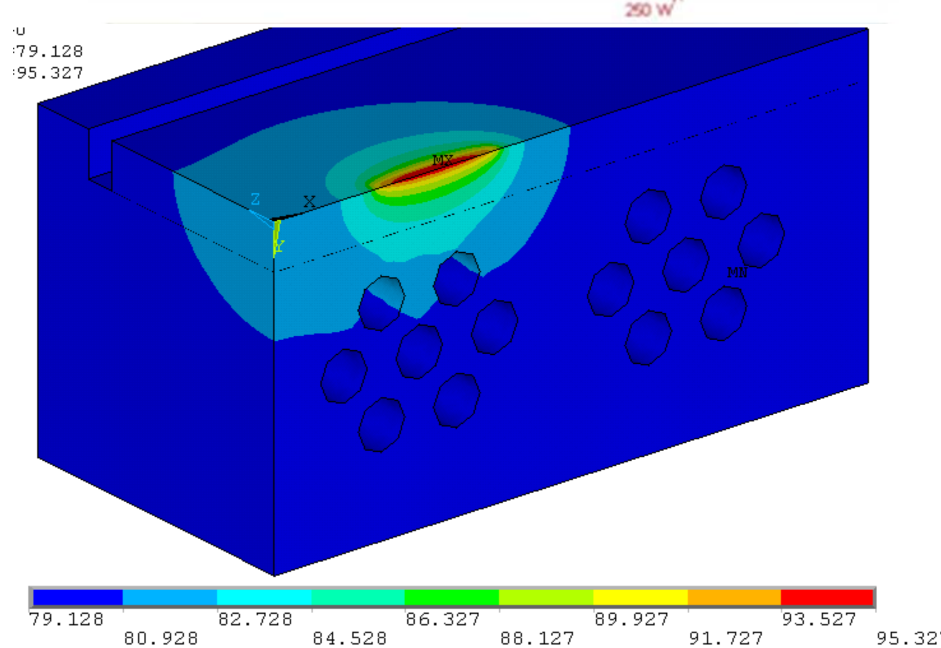
SLAC

High total power load associated with the wiggler application dictates internal cooling:

- Two bundles of 7 each 6.35mm diameter cooling ducts oriented transverse to the scattering plane
- Typical flow rates 250-400 lit/hr (~600 lit/hr maximum) for typical $h_c \sim 1 W/cm^2 K$





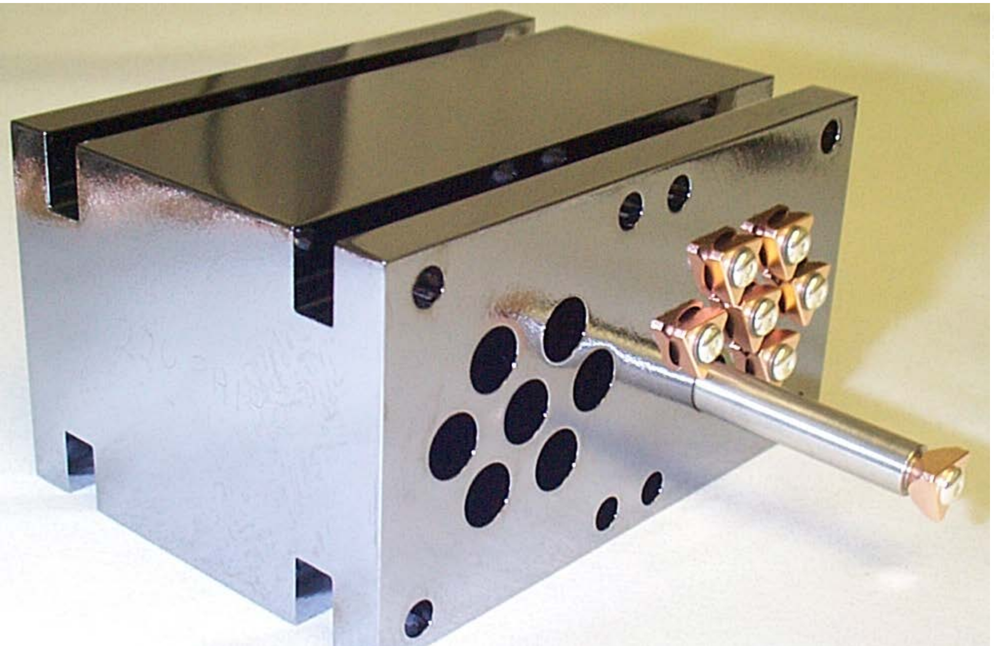


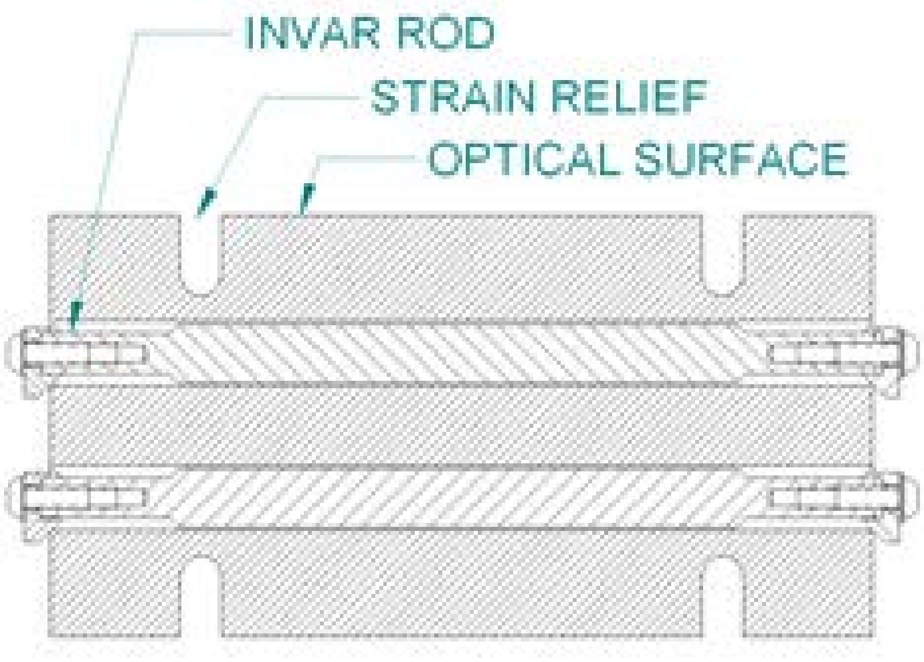
SSRL LN-Cooled Monochromator

Internal Cooling - Inserts

Cooling ducts back filled with invar rods restricting flow to 0.25mm annuli:

- Enhanced wet wall heat transfer coefficient for given flow
- Reduced mass flow in ducts and perhaps more importantly in the supply and return manifolds

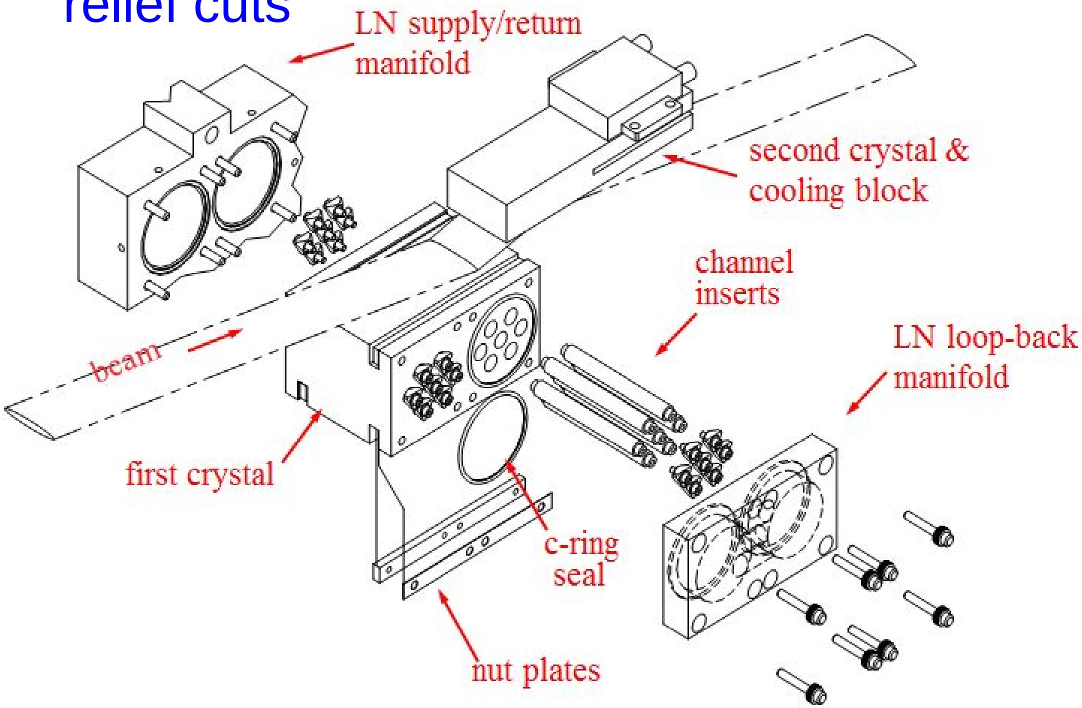


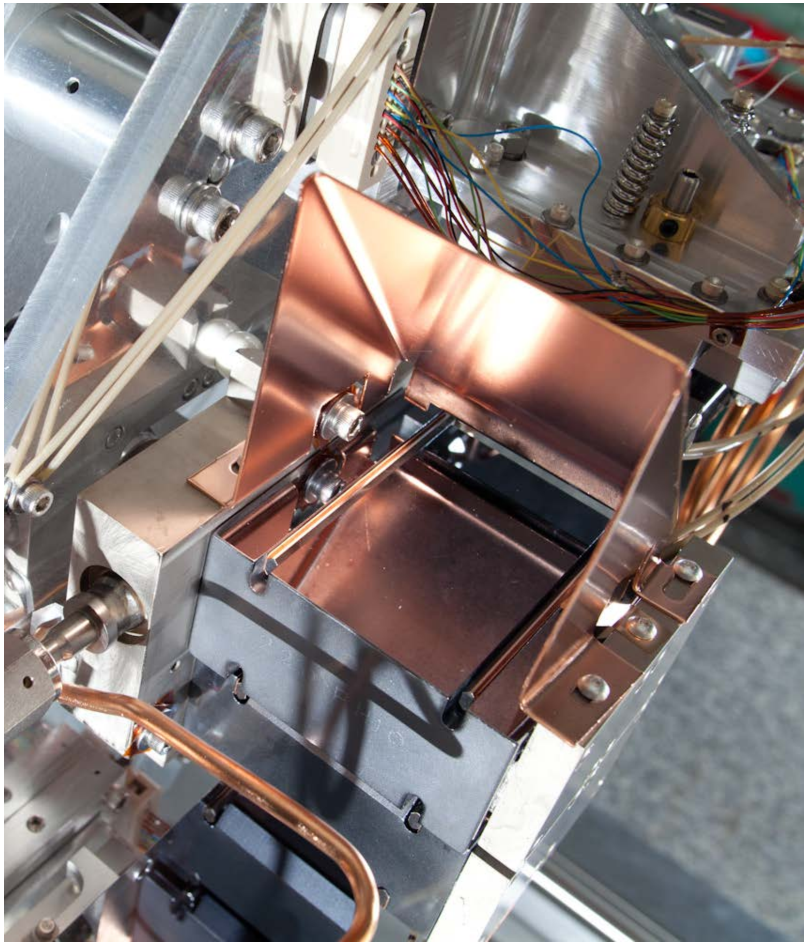


SSRL LN-Cooled Monochromator

Internal Cooling – Seals & Manifolds

- Invar manifolds with indium coated C-ring seals adapted from APS capable of 10 bar LN pressure and 2-6 thermal cycles
- C-ring seal clamp and sealing pressure orthogonal to scattering plane and isolated from crystal scattering volume by strain relief cuts



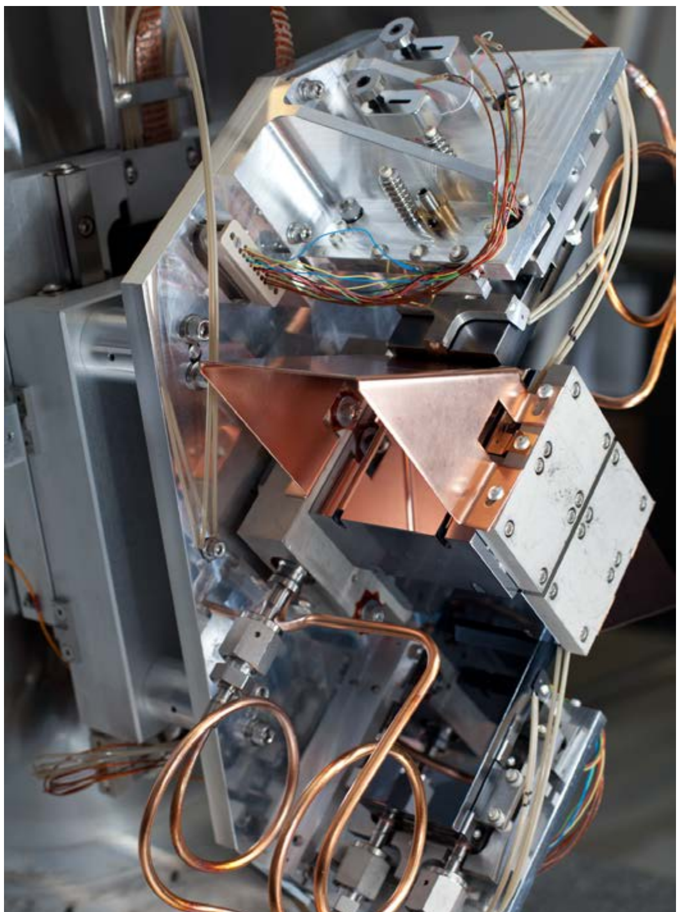


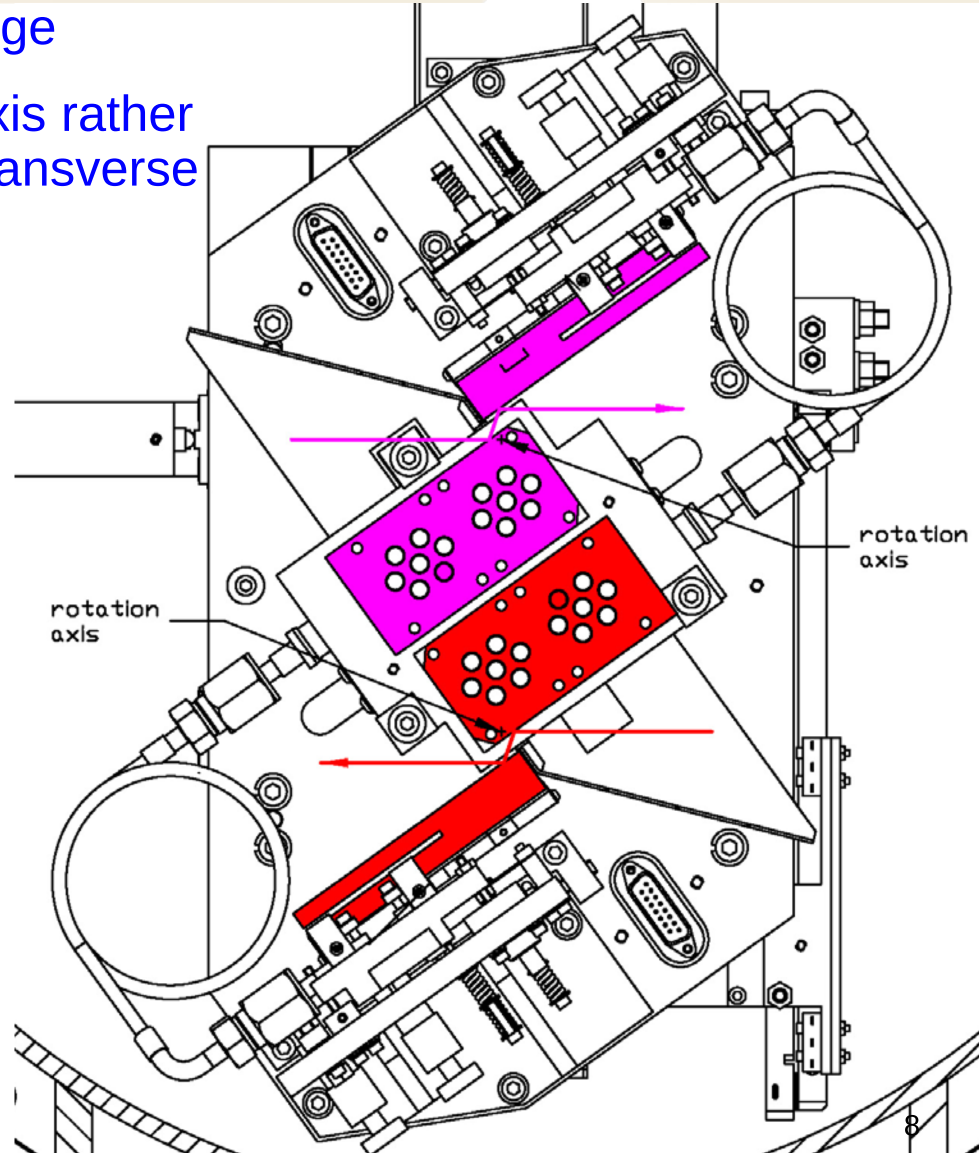
SSRL LN-Cooled Monochromator

Crystal Exchange

SLAC

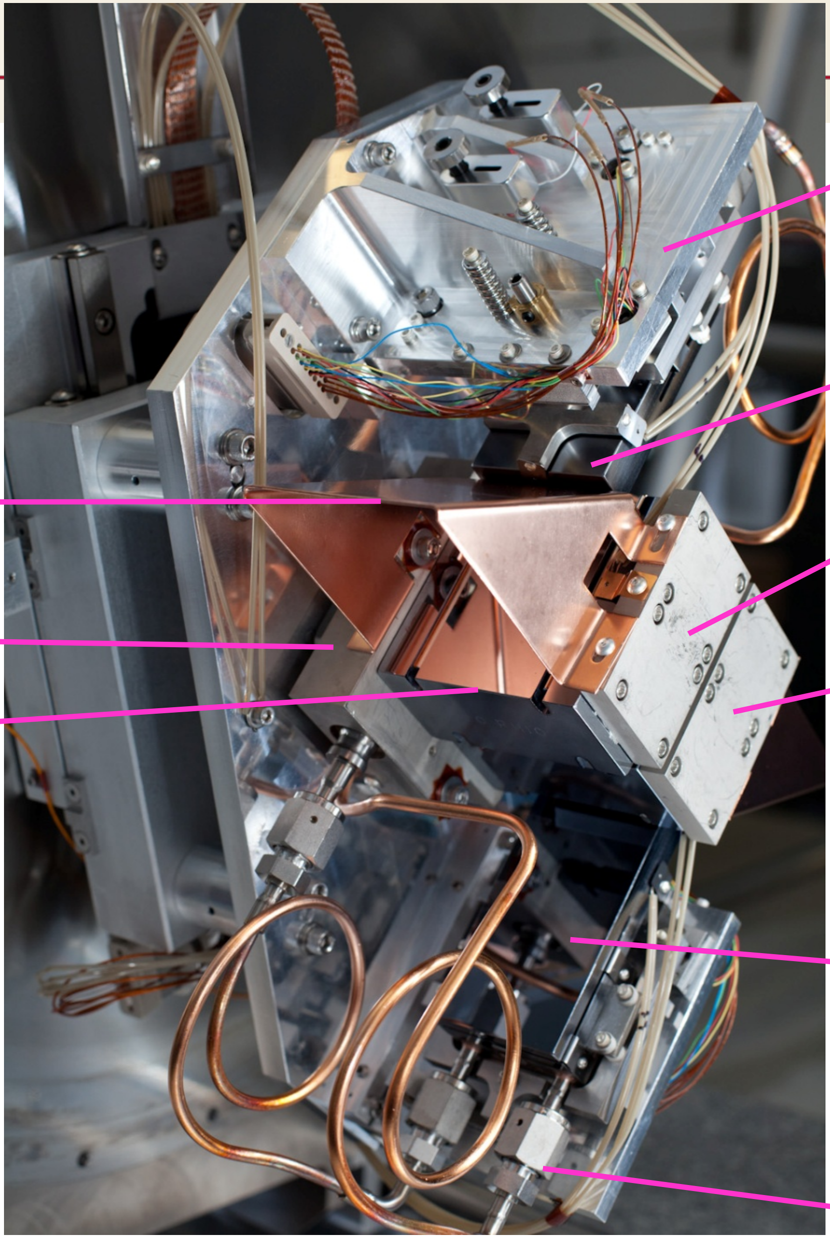
- Two crystal sets with remote exchange
- Exchange via rotation about theta axis rather than lateral translation for minimal transverse width to mono





SSRL LN-Cooled Monochromator

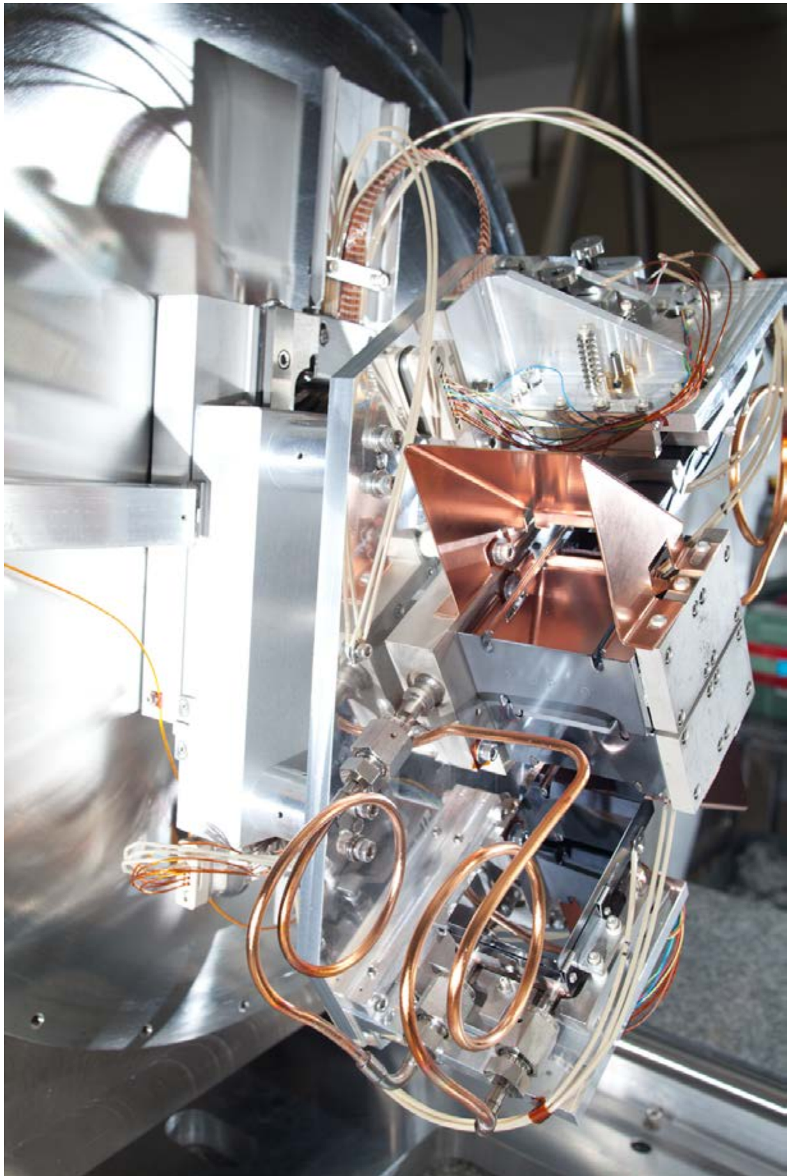
Other Features



SSRL LN-Cooled Monochromator

Other Features

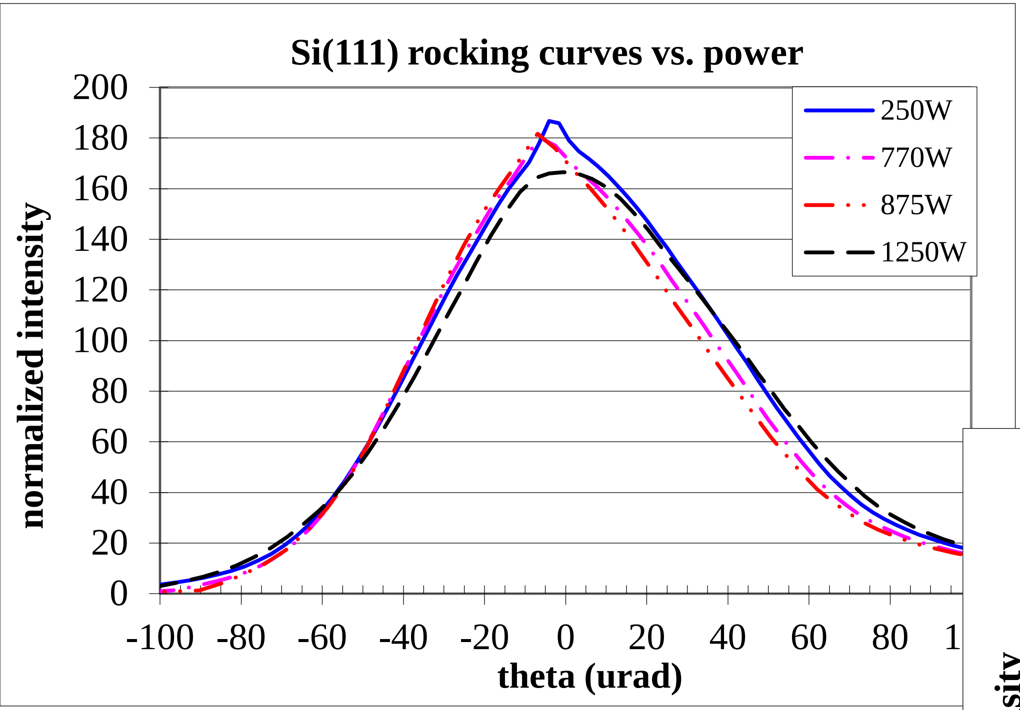
- Main LN supply and return lines parallel to theta axis thus minimize moments induced about theta
- No bellows inside mono is exposed to LN flow (nozzle-cup flex joint enclosed by bellows)
- First crystals rigidly (kinematic) mounted to support plate with thermal standoff
- Second crystal fixture very light and stiff for high resonant frequency (kinematic mount with pico-motors augmented by flexure force multipliers for pitch/roll … no piezo servos)
- Crystal exchange translation includes piezo "parking brake" (gib lock).
- Compton shields minimize diffuse power illumination of second crystal fixture
- Theta spindle employs 142.5mm diameter ferro-fluidic seal with 12.7mm spindle wall thickness for minimal torsional flex



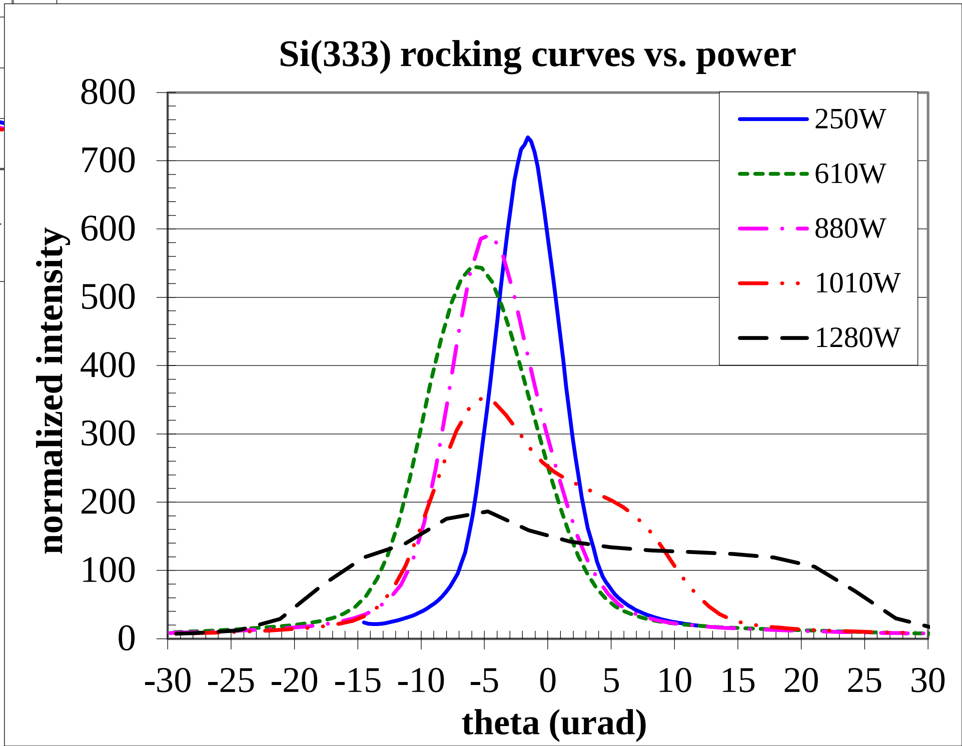
SSRL LN-Cooled Monochromator

Thermal Performance – Wiggler Power Deposition

SLAC



Wiggler beam S(111) at 5keV and Si(333) at 15keV rocking curves at various ring currents and mono horizontal acceptances (data from first two 500mA SPEAR3 shifts circa 2005)

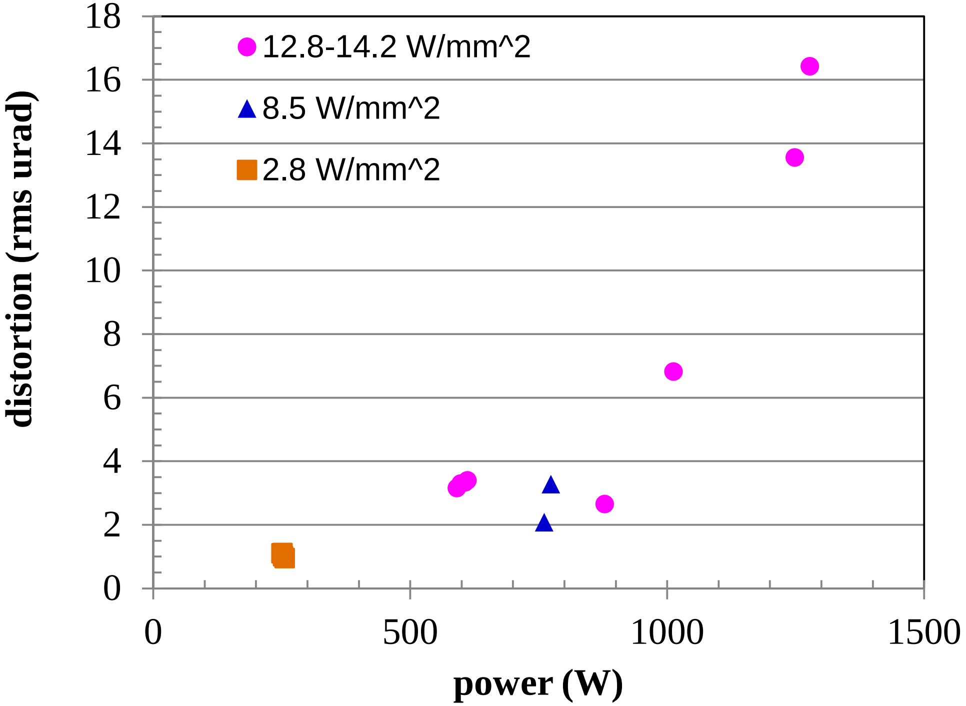


Powers calculated not measured hence somewhat over estimated owing to Compton, etc

SSRL LN-Cooled Monochromator

Thermal Performance – Wiggler Power Deposition

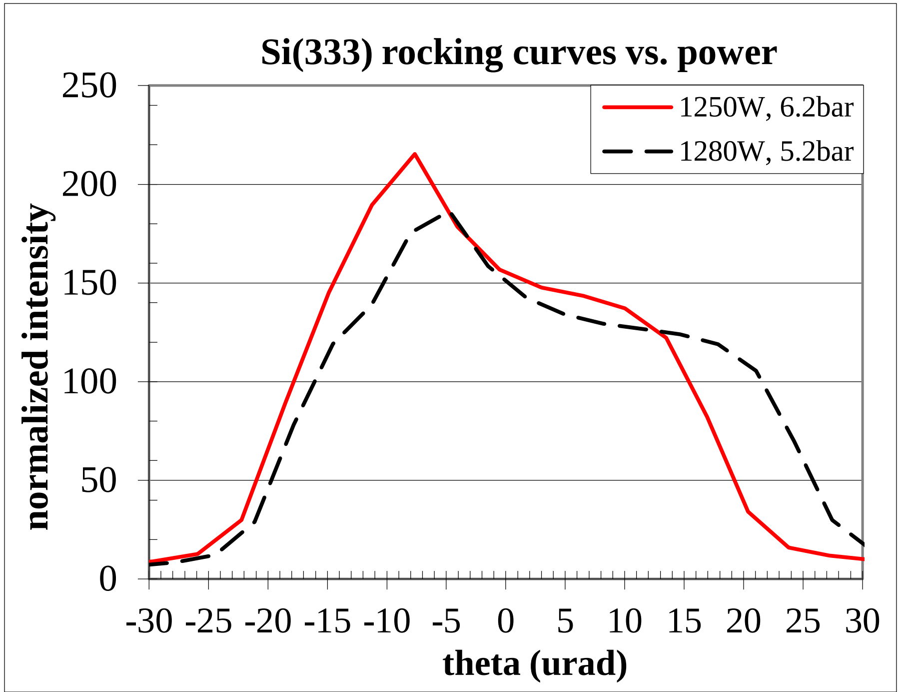
SLAC



Distortion calculated from Si(333) rocking width less Darwin width (quadrature subtraction)

Indication of distortion local minimum near ~800-900W

Pronounced broadening for power >1000W owes to wet wall boiling



LN-Cooled Crystal Concepts

Distortion Control – FEA Calculations

Shift gears to discuss FEA studies of distortion control at the "thermal sweet spot"

per Zhang, et al, J. Synchrotron Rad. 2003 and more recent publications

LN-Cooled Crystal Concepts
Ideal Thermal Servo System Characteristics

What are the ideal characteristics of a thermal servo system which would maintain the diffraction volume at the optimal temperature for minimal distortion?

1) Simple yet reliable feed forward system based on stored current, insertion device k, filters, and monochromator acceptance.
2) Minimize the thermal gradient in the vicinity of the diffracting volume (i.e., isothermal crystal approximation).
3) Avoid influencing the optics acceptance as part of the servo scheme (i.e., avoid introducing resolution changes or, for diffraction limited beams, acceptance truncation effects).

→ Introduce a controlled temperature gradient between the crystal and the thermal ground: (a) variable thermal impedance or (b) variable heat load with a fixed but “remote” thermal impedance.

LN-Cooled Crystal Concepts

Variable Thermal Impedance

SLAC

Employ feed forward control of LN flow hence wet wall thermal transfer coefficient to tailor temperature drop across wet wall.

FEA results for 1.7mm x 7.05mm footprint

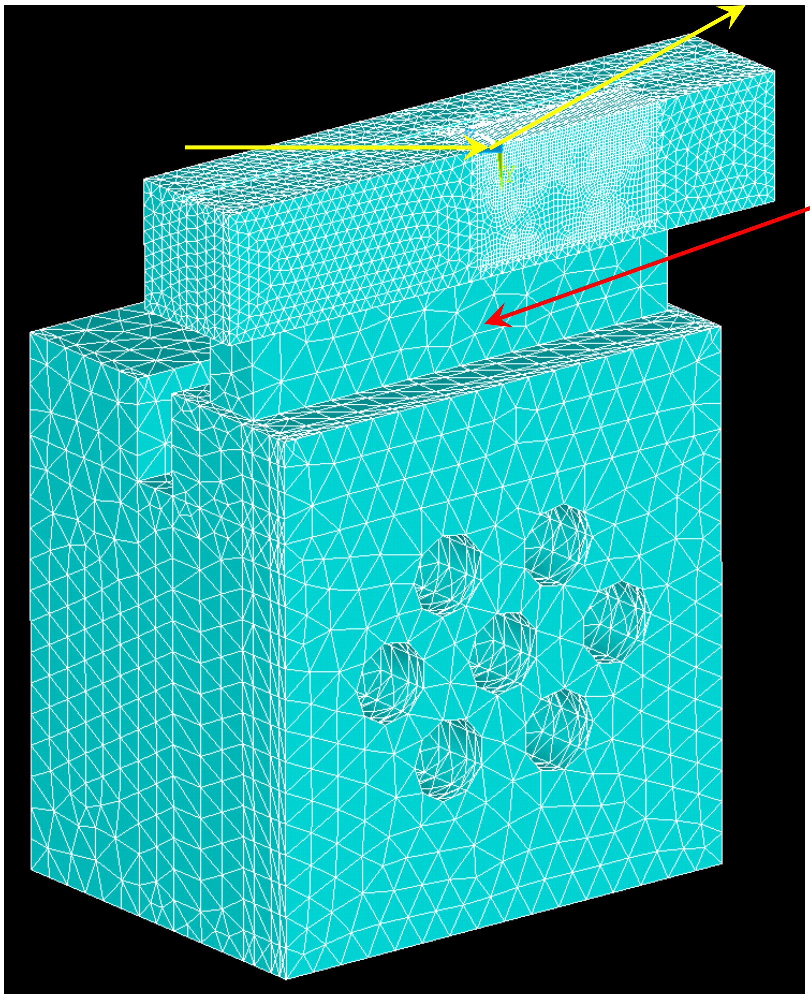
Power (W, W/mm^2)	h_c (W/cm^2 K)	T_{hot} (K)	T_{wet} (K)	distortion (rms µrad)
310, 25.9	1	125.0	81.5	4.9
	0.125	152.3	95.0	1.9
	0.1	167.0	98.7	1.2
220, 18.4	1.0	105.0	80.7	3.7
	0.05	153.0	105.6	0.40
120, 10.0	1.0	91.4	79.5	1.9
	0.02	138.5	113.0	0.21

Impractical → High wet wall temperatures require high LN pressure to prevent boiling (e.g., >11bar at 105K and >16bar at 113 K).

LN-Cooled Crystal Concepts

Weak Thermal Link with Heater

Introduce a thermal impedance between the crystal diffracting volume and the thermal ground and add a heater to compensate for beam power changes.



weak thermal link (rib)

- Half section model depicted
- Size rib (weak thermal link) such that at maximum deposited beam power or power density the diffracting volume is just below the ideal temperature for minimal distortion
- Joule heat rib for lower power conditions such that diffracting volume maintains the ideal temperature for minimal distortion

LN-Cooled Crystal Concepts

Weak Thermal Link with Heater

4m CPMU18 on a 6.0GeV/200mA/130pmx3pm ring:

CPMU18	P_density	Power
k	(kW/mrad^2)	(30.0x13.5ur)
2.0	747	300
1.5	553	223
1.0	359	144
0.6	195	77
0.5	151	59

Let's use this totally arbitrary source to illustrate this concept for a Si(111) monochromator located 50m from the source with 300W maximum accepted power at k=2.0 (ie., ~3σ' x 3σ' at 6.4keV (1st) and ~4.5σ' x 4.5σ' at 19.2keV (3rd)).

LN-Cooled Crystal Concepts

Weak Thermal Link with Heater

- Start by sizing side legs such that the diffracting volume is just under the ideal T for minimal distortion at 300W.
- We should have started with the first harmonic, but because it touched bases with prior FEA, we “designed” the side legs for 300W on the 3rd at 19.2keV.

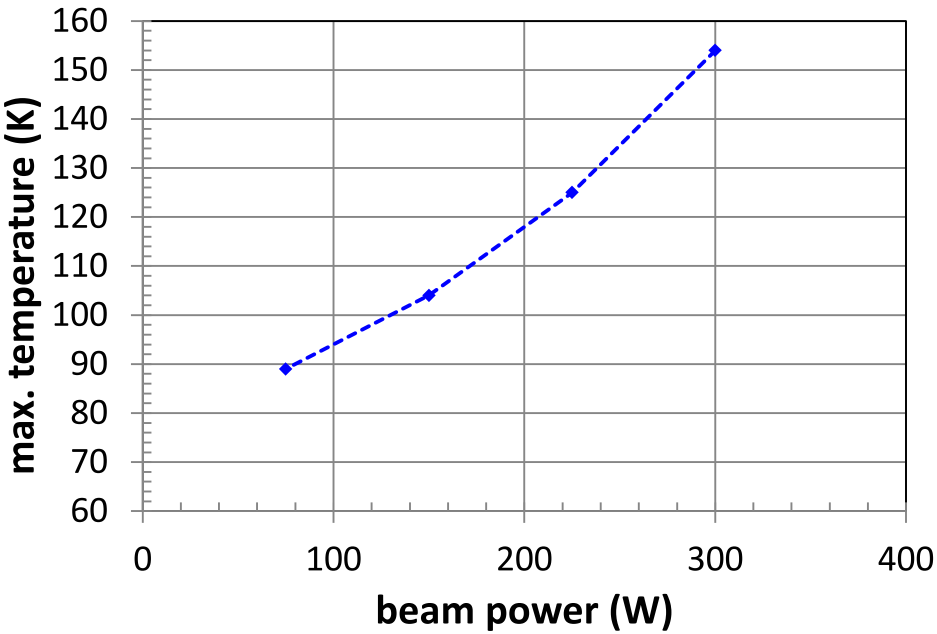
38 mm x 5mm x h side legs		
h	T_hot	distortion
(mm)	(K)	(μrad rms)
6.5	149	0.68
8.5	154	0.35
10.0	158.5	0.31
8.5*	159	0.31
* 30W heater power		

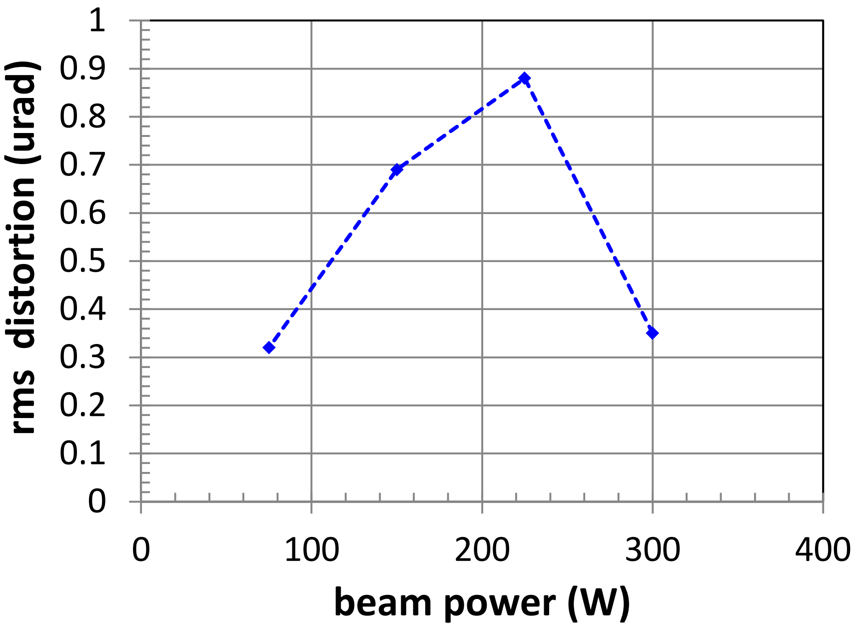
Relatively modest changes in the side leg geometry tune the temperature in the diffracting volume through the “sweet spot.”

LN-Cooled Crystal Concepts

Weak Thermal Link with Heater

What happens when we change the power loading without compensating with heater power in the side leg?

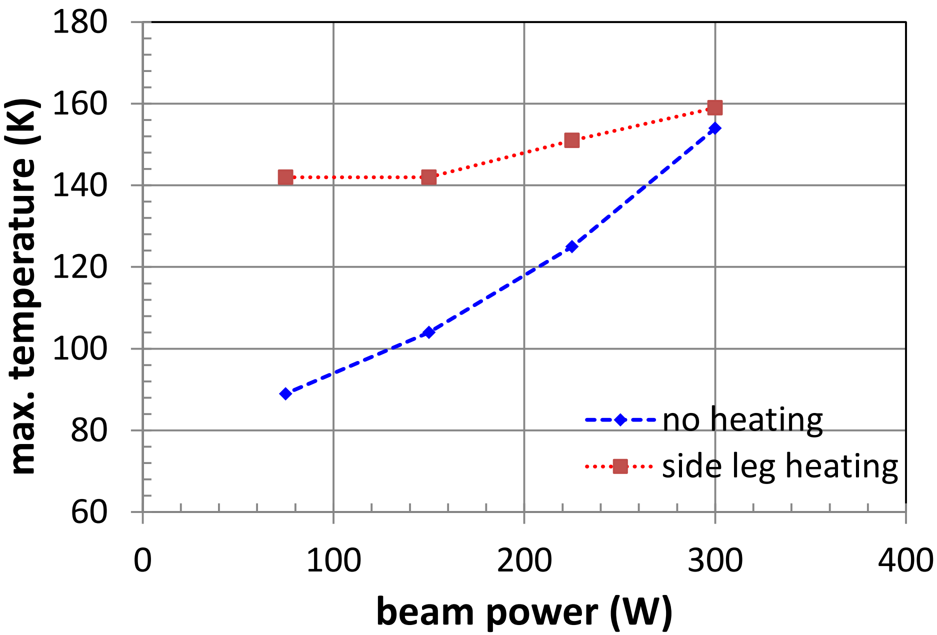


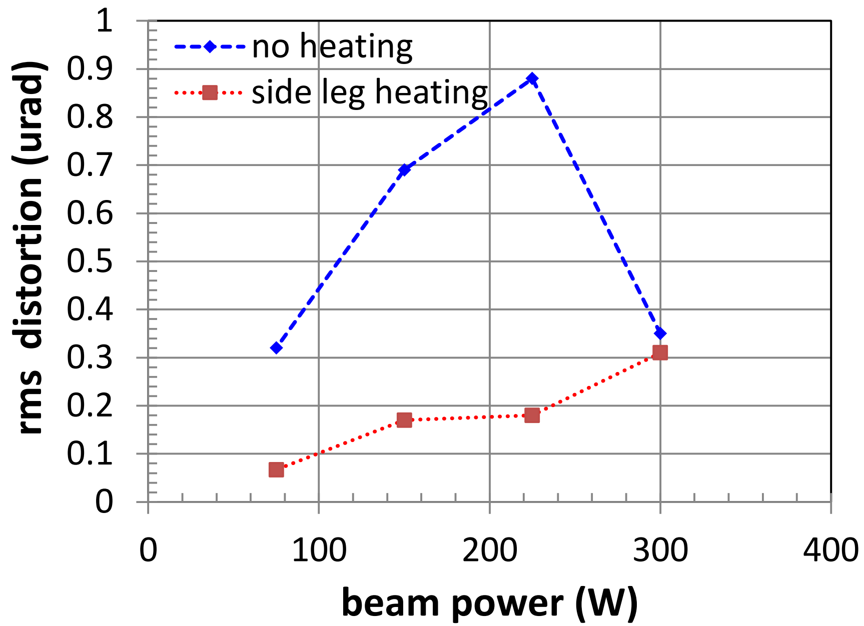


LN-Cooled Crystal Concepts

Weak Thermal Link with Heater

What happens when we change the power loading and try compensating with heater power in the side leg?





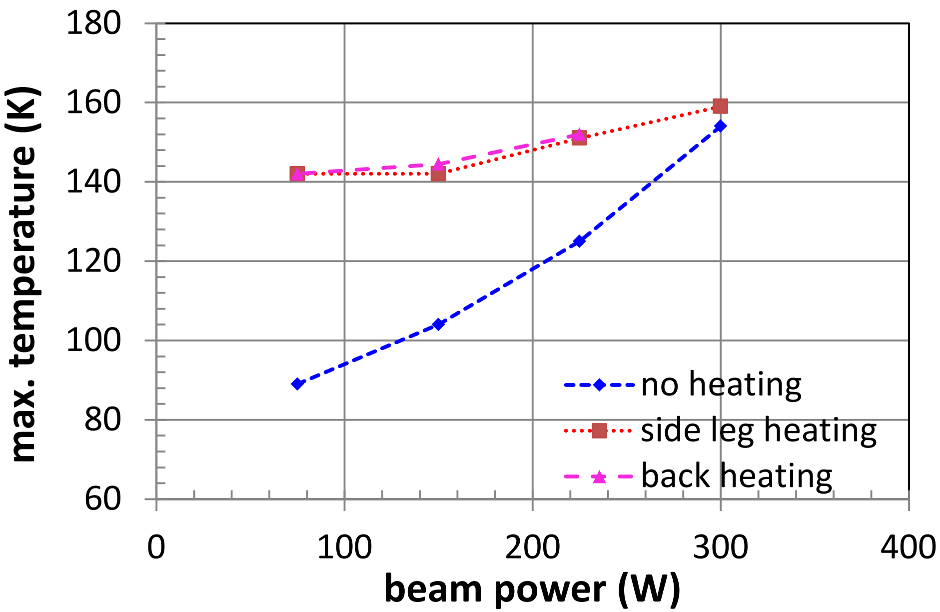
		T_hot		rms distortion		heater power	
power	power density	H=0W	H_side	H=0W	H_side	H=0W	H_side
300	30.8	154	159	0.35	0.31	0	30
225	23.1	125	151	0.88	0.18	0	270
150	15.4	104	142	0.69	0.17	0	500
75	7.7	89	142	0.32	0.067	0	800

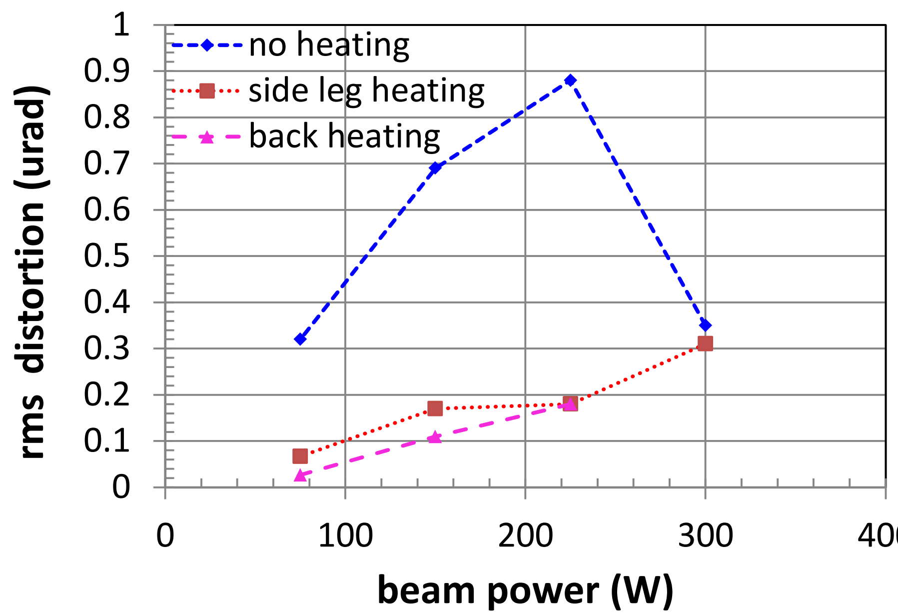
LN-Cooled Crystal Concepts

Weak Thermal Link with Heater

SLAC

How about heating the back of the diffracting crystal?



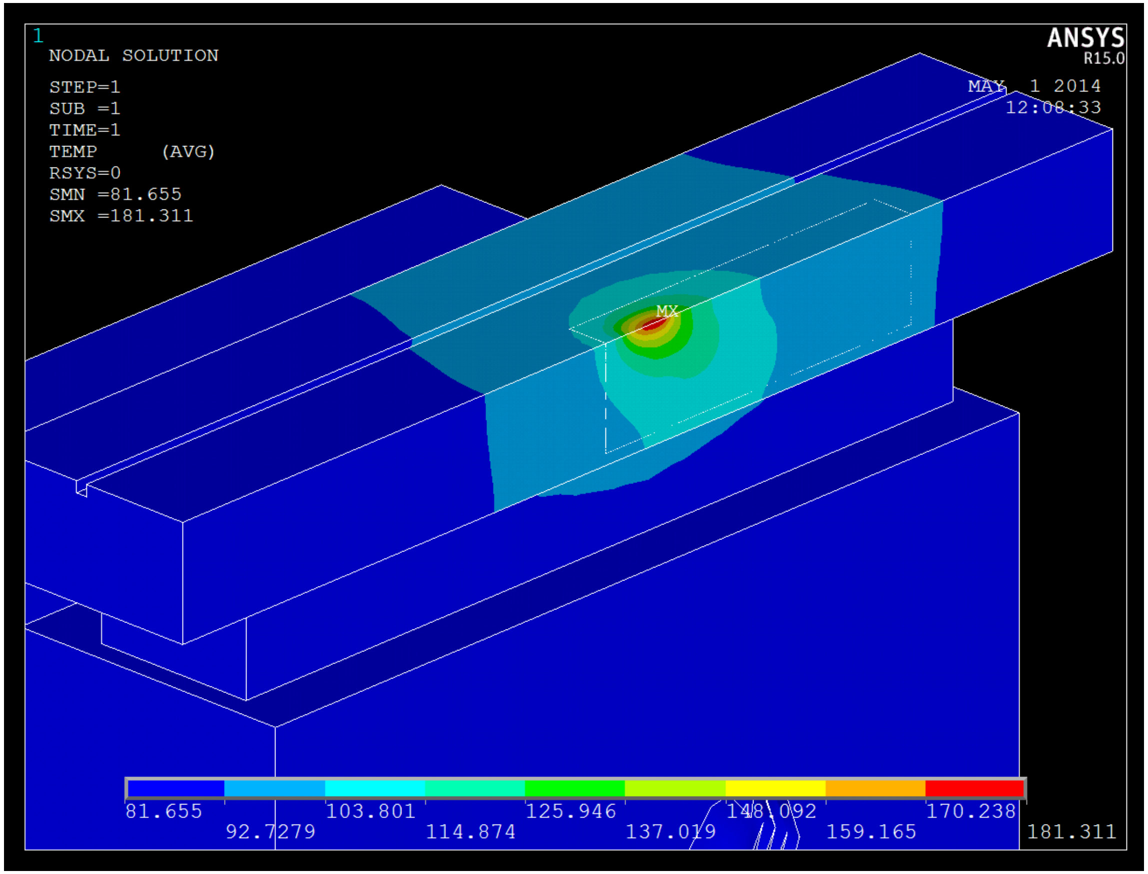


		T_hot			rms distortion			heater power		
power	power density	H=0W	H_side	H_back	H=0W	H_side	H_back	H=0W	H_side	H_back
300	30.8	154	159		0.35	0.31		0	30	
225	23.1	125	151	152	0.88	0.18	0.18	0	270	200
150	15.4	104	142	144.5	0.69	0.17	0.11	0	500	300
75	7.7	89	142	142	0.32	0.067	0.027	0	800	560

LN-Cooled Crystal Concepts

Weak Thermal Link with Heater

So far we have discussed a Si(111) crystal that was tuned to the sweet spot for 300W acceptance at k=2 on the third harmonic (ie., 19keV). Now what happens when one takes the same 300W tuned to the fundamental at 6.4keV?



It gets harder owing to the higher power density! Need to redesign the weak thermal link to improve the conductivity to thermal ground.

LN-Cooled Crystal Concepts

Weak Thermal Link with Heater

SLAC

The best we could manage at the 6.4keV fundamental without changing weak link design the was ~200W for <1.2urad distortion.

			T_hot			rms distortion			heater power		
Energy	power	power density	H=0W	H_side	H_back	H=0W	H_side	H_back	H=0W	H_side	H_back
19.2 keV	300	30.8	154	159		0.35	0.31		0	30	
	225	23.1	125	151	152	0.88	0.18	0.18	0	270	200
	150	15.4	104	142	144.5	0.69	0.17	0.11	0	500	300
	75	7.7	89	142	142	0.32	0.067	0.027	0	800	560
6.4 keV	200	64.0	152			1.17			0		
	175	56.0	136	147	147	1.69	0.82	0.82	0	100	70
	75	24.0	96	137	136	1.41	0.17	0.21	0	600	420

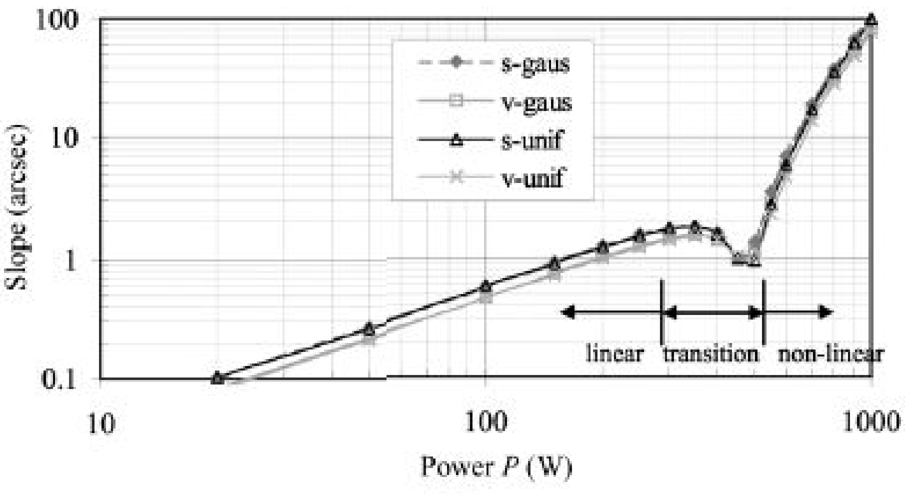
Moral of the story, start the weak link design with the worst case.

Summary

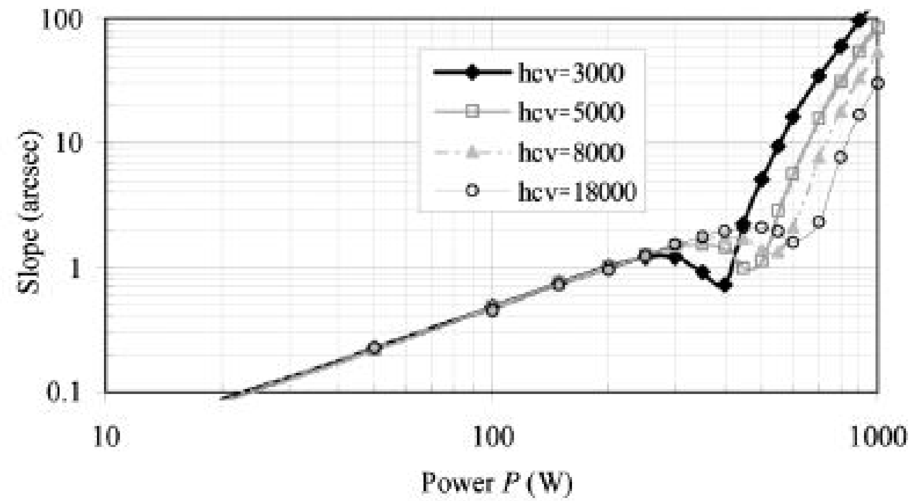
- The SSRL standard LN-cooled monochromator design is strongly influenced by the high total power of wiggler applications as manifest by the internal cooling and small footprint crystal exchange concept.
- The monochromator performs acceptably in IVU applications and at up to ~1000W in wiggler applications.
- An initial “proof of concept” FEA exploration indicates utilization of a properly designed weak thermal link between the diffraction volume and the thermal ground coupled with Joule heating can maintain the diffraction volume at the “sweet spot temperature” for minimal diffraction volume distortion.

LN-Cooled Crystal Concepts

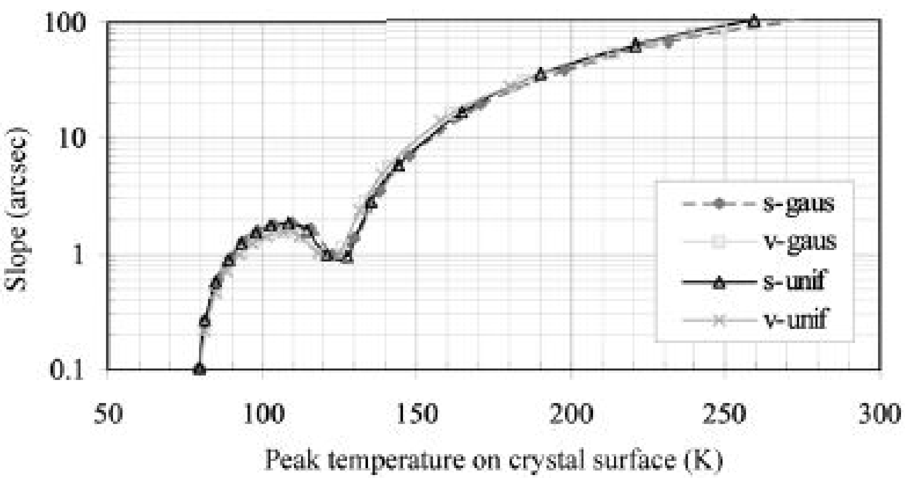
Distortion Control – FEA Calculations



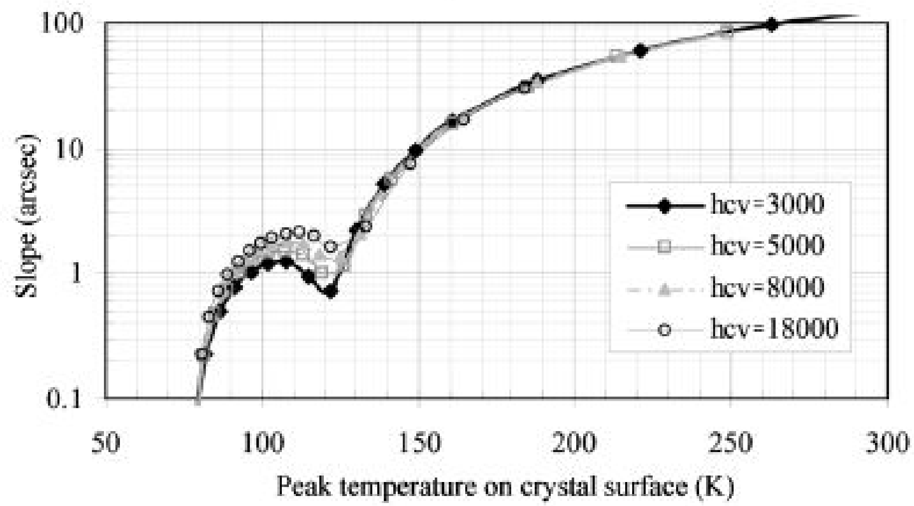
(a)



(a)



(b)

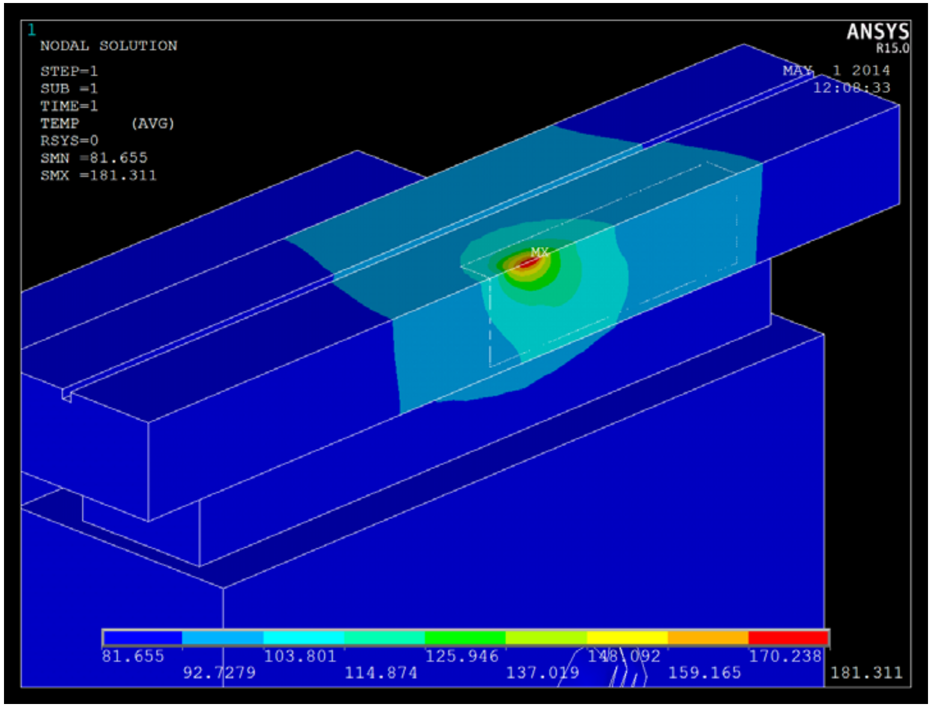


Zhang, et al, J. Synchrotron Rad. 2003 and more recent publications

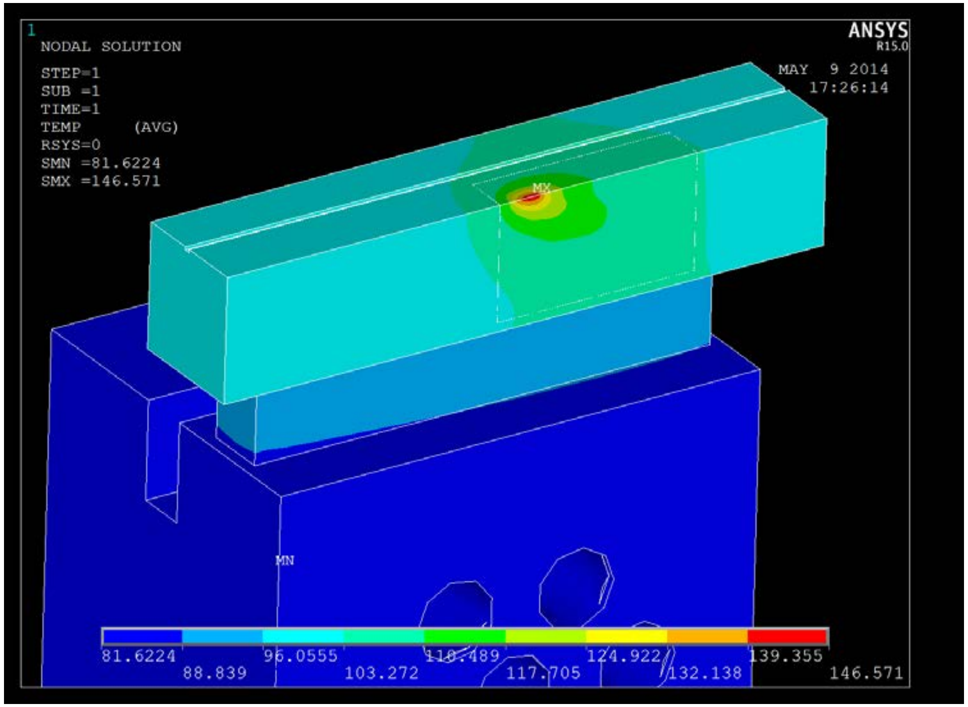
LN-Cooled Crystal Concepts

Weak Thermal Link with Heater

Si(111) crystal tuned for 6.4keV with 300W and 175W beam power in 1.25mm x 2.5mm footprint.



300W with no heater power

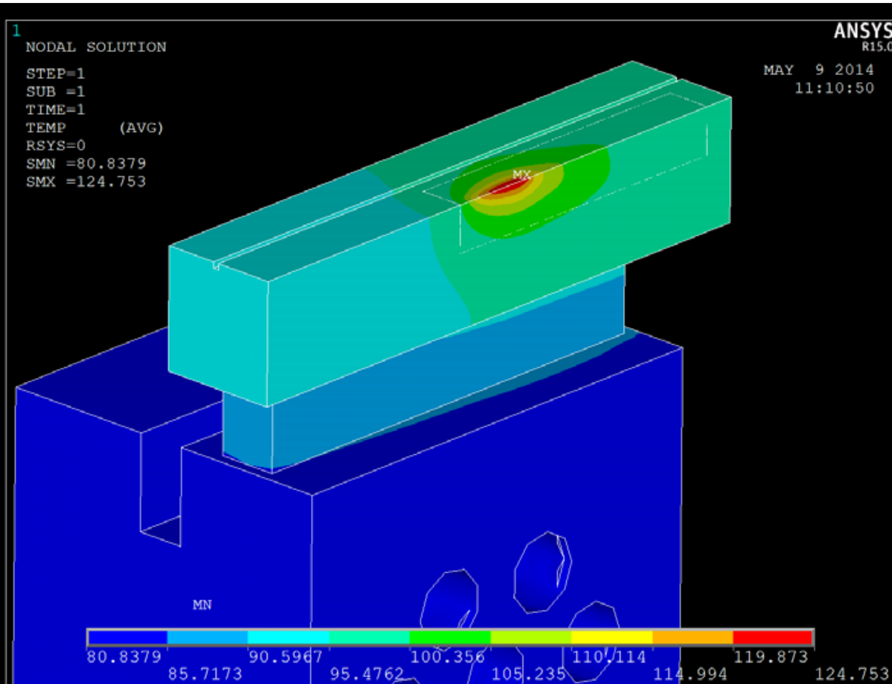


175W with 70W backside heater power

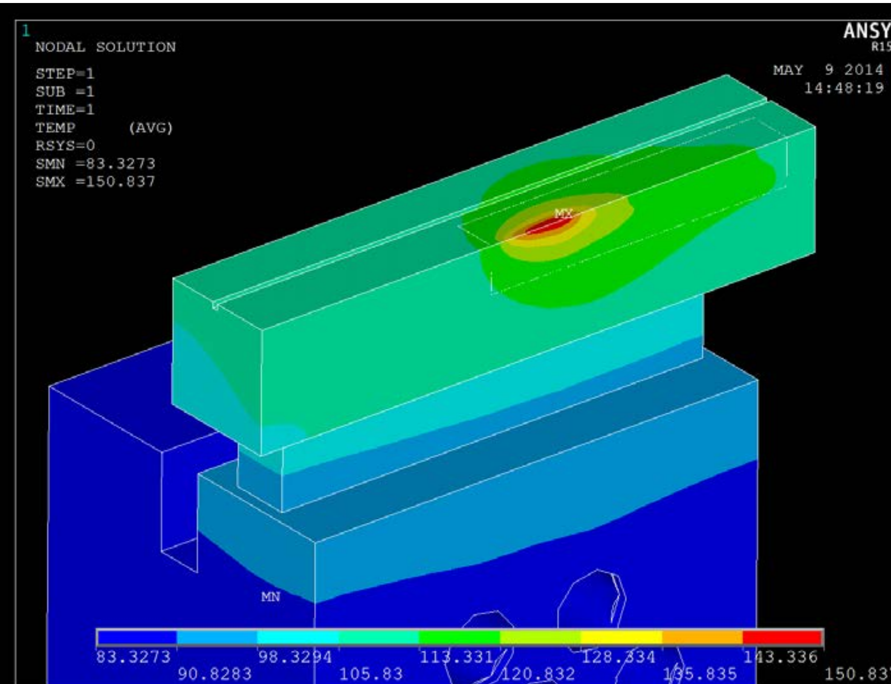
LN-Cooled Crystal Concepts

Weak Thermal Link with Heater

Si(111) crystal tuned for 19.2keV with 225W beam power in 1.5mm x 6.5mm footprint.



225W with no heater power



225W with 270W side leg heater power