The Flexible Taper Transitions for an In-Vacuum Undulator

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Abstract

In a joint project between SPring-8 and PSI, an in-vacuum undulator U24 was installed in the SLS storage ring during 2001. In this frame, cooled flexible taper transitions were developed. Tests performed on a numerically optimized shape of the tapers have proven the validity of the adopted concept.
In a further development step, a family of in-vacuum undulators is currently being designed. These will require an upgrade of the flexible tapers allowing a longitudinal degree of freedom based on a parallel spring translator mechanism.
In this work the results the optimized design of the taper assembly will be presented. A short description of the foreseen set-up being developed for the respective fatigue tests will follow. Depending on the outcome of the experimental assessment, the same concept could then be adopted also for a scraper device.

Keywords: In-Vacuum Undulator, Flexible Taper, FEM Analysis, Fatigue Tests

1. Introduction

In a joint project between SPring-8 and PSI an in-vacuum undulator U24 built by the Japanese company Sumitomo was installed at the new Swiss Light Source (SLS) facility. In this frame, cooled flexible taper transitions (FTT) were developed to provide a smooth transition between the vertical aperture of the adjacent fixed taper sections and the magnet beams of the undulator, thus minimizing any impedance discontinuity.

The original conceptual design was characterized by localized stress concentrations that limited the lifetime of the FTT to a few hundred cycles. An effort was thus performed to optimize the shape of the transition via numerical modeling, resulting in a device characterized by evenly distributed stresses. The experimental assessment of the fatigue lifetime on the resulting mechanism manufactured via electro-discharge machining from a beryllium-copper plate has proven the validity of the adopted concept. Nevertheless, during the installation of the U24 device and the performed bake-out, it became evident that, because of the rigid fixation of the FTT constraining its longitudinal expansion coupled with the differential thermal expansion of the magnet beams with respect the ultra-high vacuum chamber, an axial-stresses-induced plastic deformation of the FTT can occur.

A need to improve this situation in the framework of the design of a new series of in-vacuum undulators for SLS, resulted thus into a design where not only the shape of the

FTT was further optimized via non-linear FEM analysis, but the longitudinal compliance of the device was assured by employing a parallel spring translator.

In this work the results of a non-linear finite element optimization of the resulting flexible taper assembly will be presented, together with the set-up being developed for the fatigue tests of the whole structure.

2. Original Design

Flexible upstream and downstream tapering transition sections have been foreseen to smoothly connect the end of the magnet carrying beams and the adjacent vacuum duct in the U24 in-vacuum insertion device installed at the SLS in a framework of a collaboration with SPring-8. One end of the flexible taper is clamped to the vacuum tank, while the other is fixed to the in-vacuum magnet carrying beams therefore following the ID gap movements. The resulting shape is similar to a ribbon cellular radiator with water-cooled tubing press-fit into the grooves.

The conceptual design phase of the FTT resulted with a flexible beryllium-copper (CuBe) structure cooled with a spiral Cu tube. In fact, among the considered vacuum-compatible spring materials, CuBe is characterized by the highest figure of merit defined as the ratio of the material yield strength to its Young's modulus ($\sigma_{0.2}/E$). Moreover, CuBe has also a favorable fatigue lifetime characteristics (Fig. 1).

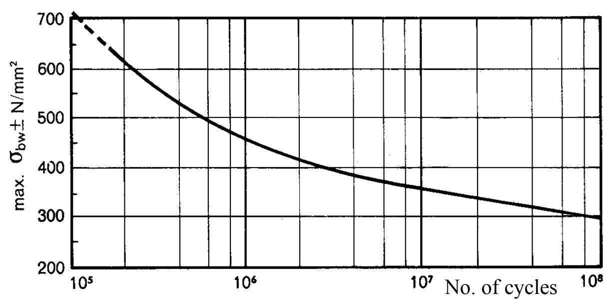
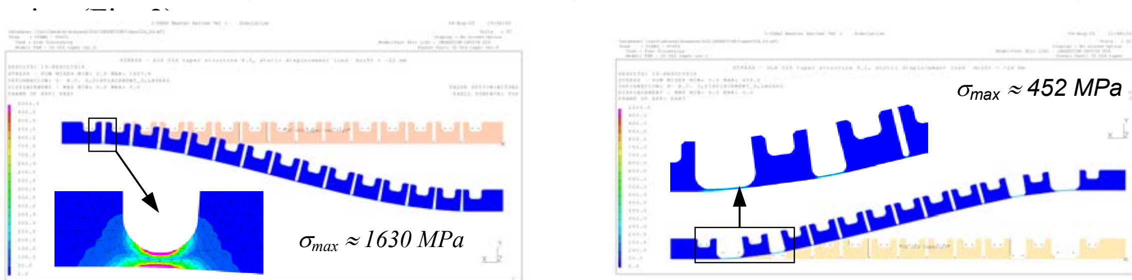


Fig. 1: Woehler-curve of CuBe25.

The results of preliminary fatigue experiments on a 150x105x8 mm^3 test specimen produced by employing Electro-Discharge-Machining (EDM) showed, however, that the stress concentrations in the structure were so high to induce the rupture of the device already after <10^3 cycles. A numerical optimization of the structure via linear numerical analysis was thus performed, allowing to optimize its shape and thus lower the stresses by a factor of >3, allowing to increase the lifetime to the $3 \cdot 10^4$ cycles r



(a) (b)

Fig. 2: Original (a) and improved (b) shape of the FTT.

However, during the installation and the bake-out procedures of the ultra high vacuum (UHV) chamber, other thermo-mechanical and kinematic problems associated with the thus produced FTT (Fig. 3) emerged because of its rigid fixation at both ends constraining the longitudinal expansion as well as the rotational degrees of freedom. In fact, due to the differential thermal expansion of the magnet beams with respect the UHV chamber during bake-out, an axial-stresses-induced plastic deformation of the FTT on one side of the UHV chamber was observed. The deformed FTT was still however capable of withstanding a cyclic test of up to 10^4 cycles. Also, the proper handling of the bake-out procedures, together with a careful choice of the in-vacuum beams fixation points during the bake-out has allowed avoiding the occurrence of the stresses exceeding the yield point.

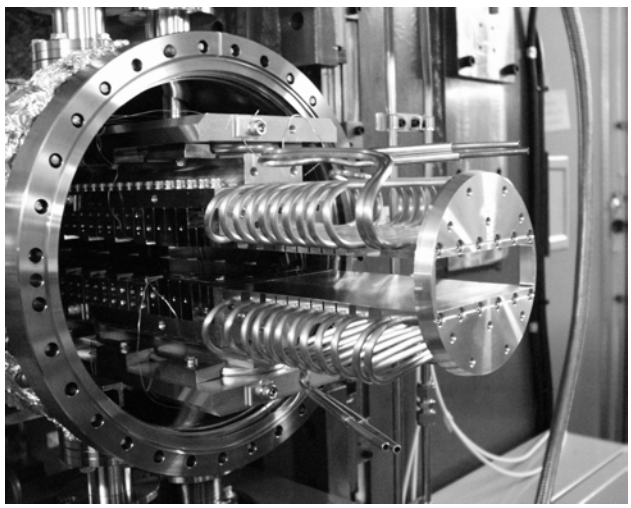


Fig. 3: Flexible taper installed at the U24.

3. Optimized Design

The request to minimize the risk of axial-stresses-induced deformations and increased lifetime requirements in the framework of the development of a new series of 3 in-vacuum U19 undulators covering an energy range 5-18 keV and with a gap range of 4-40 mm was specified. This required a further optimization of the shape of the taper via non-linear numerical modeling, as well as an upgrade of its fixation allowing a longitudinal degree of freedom based on a parallel spring translator mechanism. The considered concept for the newly developed FTT is shown in Fig. 4:

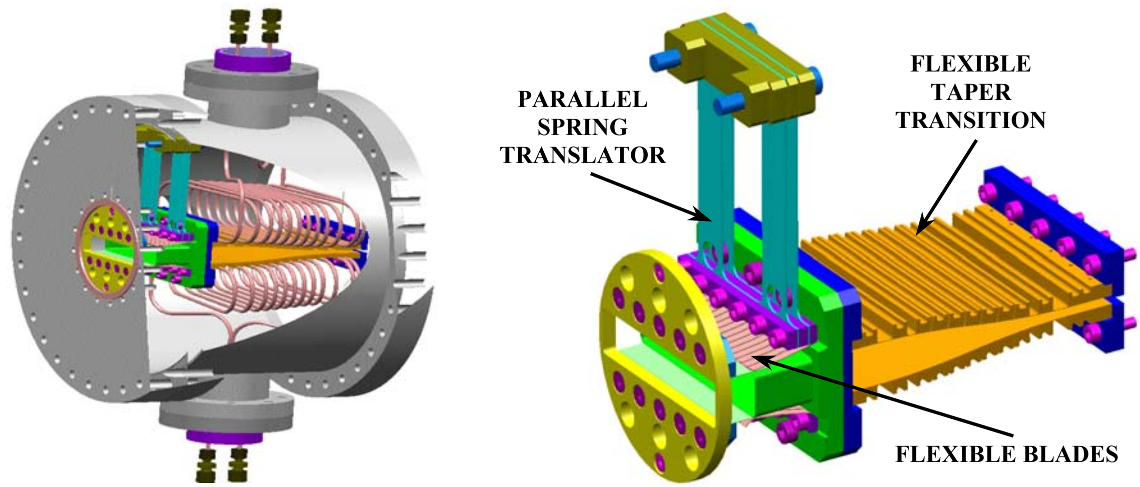


Fig. 4: Innovative flexible taper transition.

A 2-D finite element model (Fig. 5) was used for the optimization of the structure. Based on the evaluation of the worst-case operating conditions, 3 load cases (Table 1) were defined and investigated with linear and non-linear finite element analyses (FEA); the considered material properties are outlined in Table 2.

Table 1: Load Cases Considered in the FE Analysis

Nr	Load Case	Δx Displacement	Δy Displacement
1	Max vertical displacement Maximum tapering		±10 mm
2	Thermal expansion during bake-out Combined vertical and horizontal displacement	+ 3mm	±10 mm
3	Thermal expansion during bake-out Combined vertical and horizontal displacement	- 3 mm	±10 mm

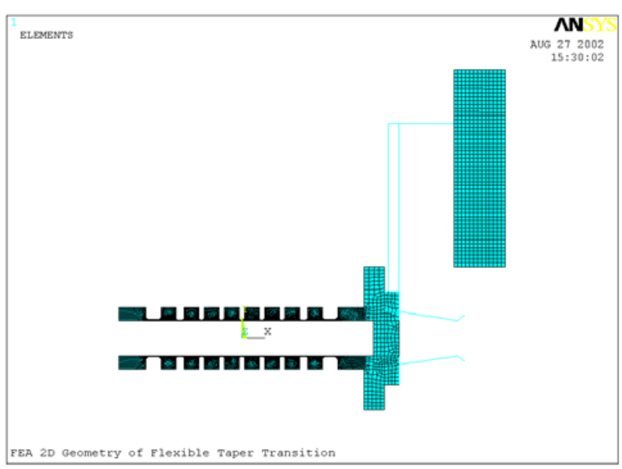


Fig. 5: A 2D FEM model of the optimized FTT device.

Table 2: Material Properties Taken into Account in the FEA

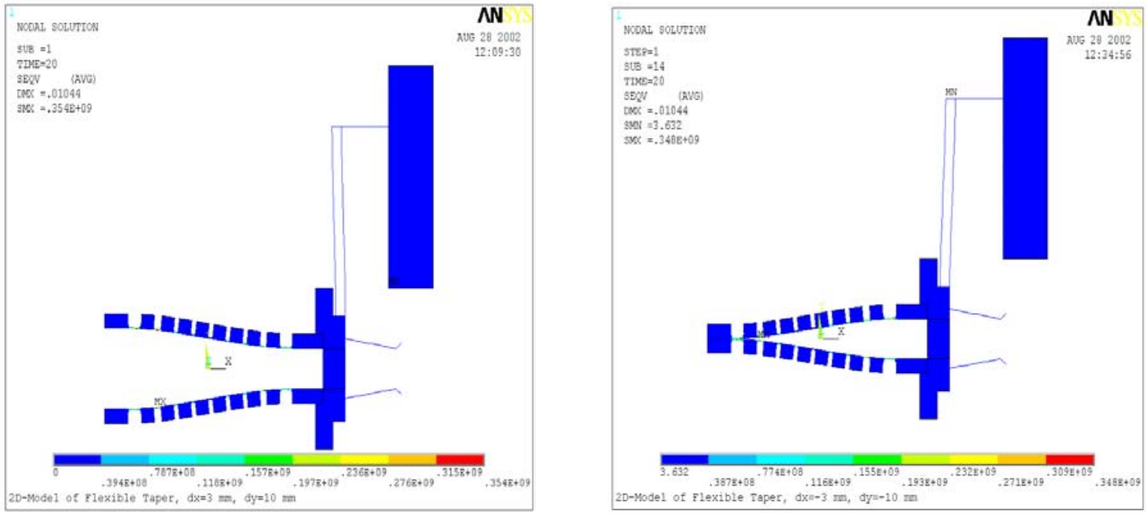
Component	Material	Mechanical Properties
Flexible Taper	CuBe20C	E=135 GPa σ_y =1.15 GPa $\sigma_{0,2}$ = 1 GPa
Parallel Spring Translator	CuBe25	E=135 GPa σ_y = 1.31 GPa $\sigma_{0,2}$ = 690 MPa
Cooling Pipes	Cu-DHP	E=125 GPa σ_y = 200 MPa $\sigma_{0,2}$ = 40-80 MPa
Other Parts	AISI 316LN	E=195 GPa σ_y = 520 MPa $\sigma_{0,2}$ = 220 MPa

The shape optimization process included the choice of the number and thickness of the notch transitions. This process resulted in a structure with 9 notch transitions of different length (the longest ones being next to the ends of the FTT) and of a thickness varying between 0.3 and 0.4 mm. The respective von Mises stresses obtained for the load cases outlined in Table 1 are in the 280-350 MPa range (see Table 3 and Fig. 6). Contrary to the case when the FTT is longitudinally constrained, where the axial loads can induce very high stresses already for small axial displacements, as well as buckling related yielding of the structure, on the device including the parallel spring translator even with the greatest foreseen longitudinal displacements there is no danger that either the FTT or the spring-strips may plastically deform or buckle.

Table 3: Resulting von Mises Stresses for the Considered Load Cases

Load case Nr.	Ux [mm]	Uy [mm]	Max von Mises Stress - Linear Static Analysis [MPa]	Max von Mises Stress – Nonlinear Static Analysis [MPa]	Buckling
1	0	±10	~354	~352	none
2	+3	±10	~354	~354	none
3	-3	±10	~354	~354	none

The vertically arranged suspension spring-strips have therefore proved their suitability for the foreseen application reducing significantly the mechanical stresses. The usage of the parallel spring translator does induce a small asymmetry in the behavior of the lower and upper FTT halves, due to a parasitic vertical displacement of the ends of the springs in the μm range (typically < 5 μm). This effect has, however, a negligible influence on the stress-strain behavior of the FTT.



(a) (b)

Fig. 6: von Mises stresses for load case 2 (a) and load case 3 (b).

During the gap scans with the FTT and during the bake-out procedure, the flexible blades assuring the smooth transition between the FTT and the vacuum flange are also slightly deformed, but the resulting stress levels are negligible.

A check of the whole device via a 3D FE model (Fig. 7) was also performed yielding approximately the same results.

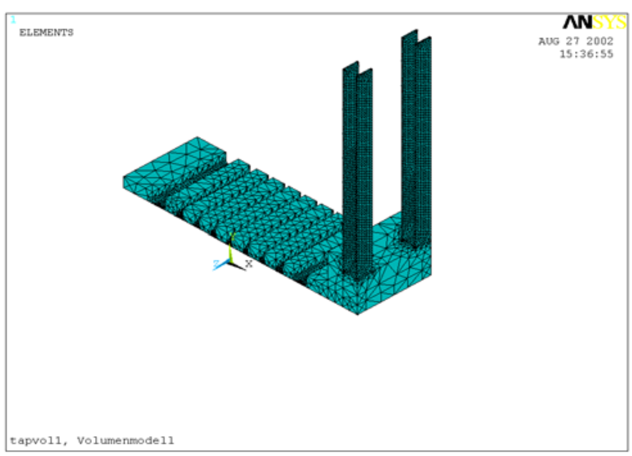


Fig. 7: 3D model of the FTT device.

4. Fatigue Tests

To validate the numerical results, a campaign of fatigue tests is foreseen. A full test specimen of the FTT device including the parallel spring translator and the flexible blades is therefore being produced and assembled at the PSI premises. The experimental set-up is concurrently being prepared at the Swiss Material Research Institute (EMPA).

The motion of the FTT will be imposed via a shaker coupled to a cycle counting electronics. The experimental set-up will not only allow to test the lifetime achievable with the new design, but also to evaluate the potential occurrence of wear at the spring translator-to-FTT connection or at the surface of the flexible blades.

Depending on the outcome of the experimental assessment, the concepts developed in the framework of the FTT design could then be adopted also for a scraper device.

5. Conclusions

The non-linear finite element analysis of the modified FTT design resulted in a design characterized by considerable stress minimization, while concurrently guaranteeing a broad range of displacement degrees of freedom. The resulting von Mises stresses are, in fact, < 350 MPa assuring a lifetime of 10^5 cycles with a safety factor of 2.

Foreseen fatigue tests will be carried out to investigate not only the lifetime of the device but also the respective wear properties. Other effects that could not be taken into account during the numerical optimization (e.g. effects induced due to the fabrication and heat treatment procedures) will also be evaluated.