REPORT FROM THE LANL SPOKE CAVITY WORKSHOP IN OCTOBER 2002

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Abstract

In the past few years spoke resonators have become serious candidates as accelerating structures for low velocity proton and ion beams. Starting from the early work by Jean Delayen [1] and colleagues, various designs at different frequencies and betas have been demonstrated in low-power tests. With the consideration of these resonators in recent linac designs the next steps must be taken to demonstrate their usefulness on real accelerators.

At a workshop sponsored by Los Alamos Laboratory (LANL) in October of 2002 the community working in this field gathered to review their approaches and develop ideas to advance the field. The presentation will give a summary of the discussions and report on first successes resulting from implementation of workshop findings.

INTRODUCTION

Spoke resonators have become an essential component of many recent proton linac concepts in Europe and the US. In support of these concepts new spoke resonators have been built and tested [2], [3], [4]. To advance beyond these proof-of-principle tests, a workshop was held to report and compare approaches and discuss paths to more praxis oriented experiments.

The complete active international community (USA, Germany, France and Italy) participated with 37 members from 11 laboratories and universities and 3 companies. The resulting proceedings (642 pages) [5] represent a good snapshot of the field at the end of 2002.

λ/2 RESONATORS

History

For the acceleration of protons or ions the RF-resonators have to cover a wide range of particle velocities during acceleration. This dictates a number of different resonators. For low beam velocities, v (1-10% of the speed of light, c) low frequency resonators have to be employed, as the active length of a structure is proportional to the wavelength λ, times β=v/c. The first structures used in the velocity range were quarter-wave structures that provide the smallest transverse dimensions for the longest accelerating gaps. The structures however are susceptible to mechanical vibrations and they cannot easily be extended to generate multi-gap structures for a higher real-estate gradient.

Coaxial λ/2-resonators can address the mechanical vibration issue, but do not provide a solution to the low real-estate gradients. Jean Delayen first investigated spoke resonators as a variant of a half-wave structure [1] at the end of the 1980s, these have a potential to produce high real-estate gradients.

Types of Half-Wave Resonators

Figures 1 and 2 show the coaxial and spoke resonators and the two options to extend them for multi-gap operation.

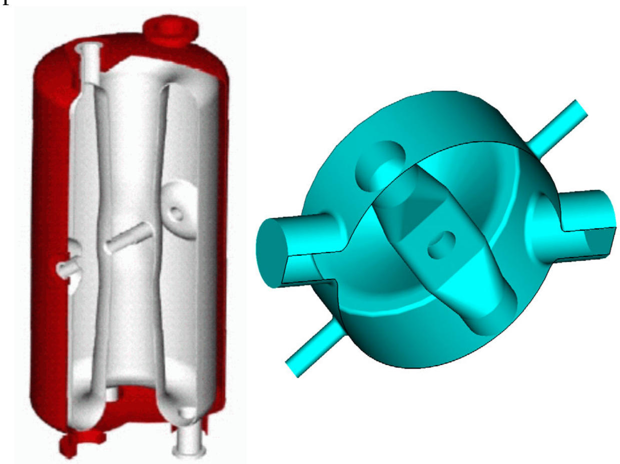

Figure 1: Simple coaxial (left, Argonne National Lab (ANL)) and spoke-type λ/2 resonators (right, LANL)

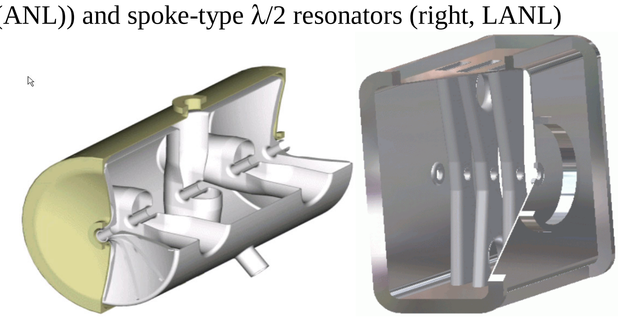

Figure 2: Multi-gap spoke resonators with cross- (left, ANL) and parallel (right, INFN-Legnaro) aligned spokes.

Advantages of Spoke Resonators

Spoke resonators are well suited for bridging the gap between very low β structures (< 0.1) and βs where elliptical resonators become useful (approx. 0.5). As multi-gap structures they exhibit a very stable field profile due to the high cell-to-cell coupling (10-20 %). They are mechanically more stable than λ/4 or elliptical resonators. Due to the large number of degrees of freedom they show low peak surface fields for structures in this β-range. As a consequence they achieve fairly high gradients.

As there is no clear-cut transition energy from spoke resonators to elliptical ones, spokes can be used to make structures more compact if needed, as for the same

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frequency they are half the diameter of an elliptical cavity. Or for the same size they operate at half the frequency of elliptical resonators, which in many cases allows operation at 4K instead of requiring a more complex 2K cryogenic system.

Spectrum of Spoke Resonators

Figures 1 and 2 already indicate the breadth of proposed spoke resonator solutions. The reason for so many different solutions lies in the larger number of degrees of freedom in the structure parameters, the still small experience base for what works best, and the different emphasis on the importance of criteria, dependent on the application. Last but not least the designer needs to make a tradeoff between the degree of optimization and the need to keep the cost acceptable. Figure 3 shows two more examples of potential solutions.

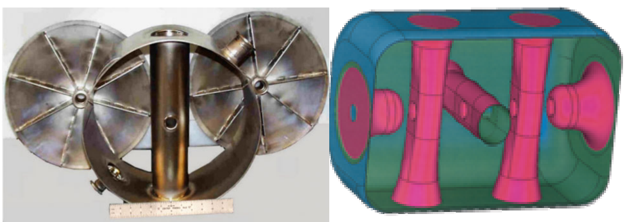

Figure 3: The spoke on the left is a simple design from ANL with a straight cylindrical spoke; the right resonator is a design from FZ Jülich with a rectangular cavity body.

The simple spoke shape (Fig. 3-left) was sufficient for the proof-of-principle purpose. The achieved gradient was almost as good as that for further optimized spoke shapes. This geometry also shows a different end-cap design from e.g. the LANL and IPN Orsay designs. The latter use a re-entrant end-cap as opposed to the designs by Ken Shepard from Argonne that use a dish-shaped end-cap. The rectangular resonator on the right could be a candidate for higher gradient operation due to its lower peak magnetic field values.

DESIGN PRESENTATIONS

RF-Design

There were five presentations on the design of spoke resonators. ANL presented work related to the Radioactive Ion Accelerator (RIA) project [2], [6]. Their emphasis was to show the advantages of using multi-gap spoke resonators (4-gaps, β=0.5 and 0.62) instead of elliptical resonators (6-gap, β=0.47 and 0.61) in the medium-β range of the accelerator.

The group from IPN Orsay presented their design work on a β=0.35, 2-gap resonator [3]. Their main emphasis was on showing optimization strategies for low peak surface fields that lead to varying cross-sections along the length of a spoke.

FZ Jülich presented a wide range of different $\lambda/2$ geometries [7]. Their main contribution to the field is the introduction of a rectangular cavity cross-section. This leads to lower peak magnetic fields in spoke resonators. The performance gain still has to be demonstrated.

LANL showed the design of a spoke resonator for high current applications [4]. The usefulness of tools for an integrated mechanical and RF-design as well as the integration of coupler and cavity issues was demonstrated.

INFN-Legnaro showed the design work on a parallel spoke arrangement (called a ladder-structure) in a multi-gap structure. The main advantages are the applicability at very low βs and the good access to the cavity for cleaning, an important issue for achieving high gradients [8].

Mechanical Design

The mechanical design presentations showed two different stiffening schemes for the end-caps of spoke resonators. ANL and IPN Orsay have solutions with radial rib stiffeners, while the LANL and INFN-Legnaro designs use ring stiffeners. Both solutions provide sufficient stiffness and reasonable tuning stresses. The ANL design that integrates the mechanical issues of the cavity and helium vessel has the nice feature that the net effect of deformations during cool-down does not change the resonator frequency. LANL showed the tools for the integrated mechanical and RF-designs. Common surface nodes of the shell-mesh for the mechanical design and the volume mesh for the RF-design allow calculation of the effects of 3D deformations on the RF-properties with high accuracy.

Other Design Related Topics

The design related presentations included a discussion on tuners. FZ Jülich presented an adaptation of the INFN/DESY tuner to long spoke resonators. For the RIA project the prospects of using a Voltage Controlled Reactance (VCX) fast tuner was evaluated. 350 MHz seems to be the limiting frequency for this type of tuner, the cost savings of fast active tuning compared to tuning compensation by over-coupling have been shown to be substantial [9]. LANL plans to use a PZT tuner incorporated into the actuator of the slow tuning mechanism.

Related to fabrication all presenters reported good cooperation with industry while procuring either parts or entire spoke resonators from them. The LANL experience of receiving 2 complete prototype resonators from industry within 10 month was particularly impressive.

Cryomodule designs presented also showed a breadth of different solutions that reflected the local experience of the different laboratories. Notably, ANL is using a design based on ATLAS, but avoiding the common beam-line and cryostat vacuum. This seems to be prudent in view of the significantly higher gradients compared to ATLAS. The LANL cryo-module design is driven by the high-power application. The emphases in the design are on the use of the power coupler as the main cavity support element and on the use of a thermo-syphon to impose a significant flow for minimizing potential vapor-trapping, particularly in the spoke, that is a consequence of large dissipative loads from CW operation [10].

An important issue in partially beam-loaded structures is microphonics. Jean Delayen provided a microphonics overview and initial ANL measurements for their β=0.4 spoke were also presented. A noteworthy result is that the measurements clearly showed the ATLAS refrigeration system as a source of mechanical excitations. This type of results can be used to specify requirements on the cryogenic system to lift some burden from stiffening structures or from complex low-level RF-controls.

The reports on power coupler designs reflected the spectrum of applications from 500W-20 kW for RIA to more than 200 kW for LANL's Accelerator Transmutation of Waste (ATW) proposal. While the ANL RIA design proposes the standard magnetic loop type of coupler [11], the LANL design introduced electric coupling, the simplicity of which is required for the thermal management of the much higher transmitted power [12].

As unresolved issues multipacting simulations and determination of the importance of higher order modes (HOM) have been identified. To study multipacting in these structures, reliable full 3D simulation software is needed. At the time of the workshop none has been identified as being sufficient. Preliminary results with the MULTP code [13] have been presented, however. The issue of HOMs needs attention, as beam-pipes in spoke resonators are smaller than in elliptical resonators, thus HOM extraction from the beam pipes might not be sufficiently effective. Coupling from the cavity body was not seen as an issue by most participants. It was also pointed out that due to the strong magnetic coupling trapped modes seem unlikely to occur.

TEST RELATED PRESENTATIONS

Cavity Processing

Implemented pre-test cavity processing procedures were presented by two groups. ANL has the unique possibility to electropolish (EP) parts of their spoke resonators before the final external welds are done. To maintain the quality of surfaces, only a light Buffered Chemical Polish (BCP) is done after welding. The cavities are also High-Pressure Rinsed (HPR) before the final assembly. LANL uses a BCP system optimized for their spoke geometry; the cavities are filled with acid from the bottom. Five of the other ports are used to remove the acid from the cavity volume. This avoids the stagnation of the BCP solution at the ports. They also do HPR and bake the cavity at 110^{O} C while under vacuum.

Test Results Reported at the Workshop

The same groups also presented their most recent cavity test results.

Figure 4 shows several results at 4.2K for the ANL β=0.4, 2-gap spoke resonator. These results indicate the importance of surface treatment and cleaning to achieve high accelerating gradients. The ANL spoke resonator tests also included a long-term (1 month) test, where the tested resonator was held at a constant field gradient of 7 MV/m without any degradation of the system. The peak gradient that has been achieved in this resonator is 11.5 MV/m at a Q_0 of approximately 5E8.

Figure 5 shows 2K and 4K results for a LANL β=0.175, 2-gap spoke resonator. The LANL resonators showed more electron activity due to multipacting than the ANL resonators. To achieve optimal performance helium processing to further clean the surfaces was required. The peak accelerating gradient in this structure reached 13.5 MV/m at a Q_0 of 3E8 for the better of two identical resonators. The LANL report also included preliminary results of a Q-disease study at 350 MHz indicating that fast cool-down for an operation in an accelerator will not be required.

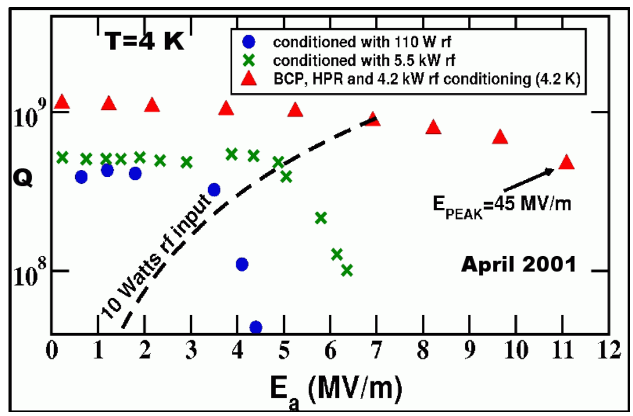

Figure 4: 4.2 K test results for the ANL β=0.4, 2-gap spoke resonator.

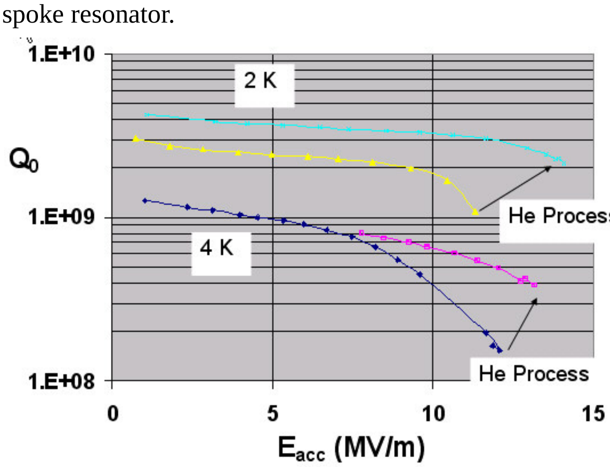

Figure 5: Test results for the LANL β=0.175, 2-gap spoke resonator.

Recent Results/Recent Progress

Since the workshop was held, some additional noteworthy results have been achieved. IPN Orsay has tested their β=0.35, 2-gap spoke resonator with excellent results [14]. They were also able to improve their resonator performance through helium-processing. ANL tested the first 3-gap spoke resonator ever built. This was also the first resonator that processed with the above mentioned electropolishing and BCP procedures. The performance of this resonator was better than their previously tested 2-gap resonators, which indicates that with more experience and better surface preparation further increases in spoke resonator performance can be expected [15]. LANL finished their Q-disease study confirming that at 350 MHz spoke resonators can be held at 100 K for 24 hours without any Q-degradation [16]. With Michigan State University (MSU) a new group entered the field since the workshop. They successfully built and tested a coaxial half-wave resonator advanced as an alternate proposal for the RIA accelerator [17]. Table 1 summarizes the best test results for the groups that are actively working in the field right now.

Table 1: Spoke Resonator Performance Summary

Institute	**ANL**	**ANL**	**ANL**	**IPN**	**LANL**
$^{\&}f_0$	340	345	345	359	350
β	0.30	0.40	0.40	0.35	0.175
Gaps	2	2	3	2	2
Q_0 (4K)	2.0E9	1.0E9	1.3E9	1.1E9	1.74E9
Q_0 (2K)	8.8E9	1.3E9	-	-	7.0E9
$^{*}E_{amax}$	12.5	11.5	11.5	12.2	13.5
$^{*}E_{pmax}$	52.5	46.0	39.9	37.3	38.1
$^{\#}B_{pmax}$	113.8	123.1	79.4	101.0	99.6
Limit	Quench	Quench	Quench	Power	Quench

& In MHz, * In MV/m, # In mT/MV/m

THE NEXT GENERATION

The discussion on the future developments showed a clear trend towards multi-gap spoke resonators. In addition to the higher real-estate gradient, the new motivation behind this is the potential to replace elliptical resonators that become challenging at or below moderate β around 0.5. Spoke resonators at half the frequency of elliptical resonators with similar β in general allow operation at 4K, which is less complex; they have a better longitudinal beam acceptance and for a similar number of gaps a larger active length. The only obvious disadvantage is a smaller transverse acceptance due to the smaller beam pipe apertures. This limit is not seen as an issue for moderate beam currents. Figure 6 shows candidate designs for the ANL RIA design and the LANL design of an Accelerator Driven System (ADS).

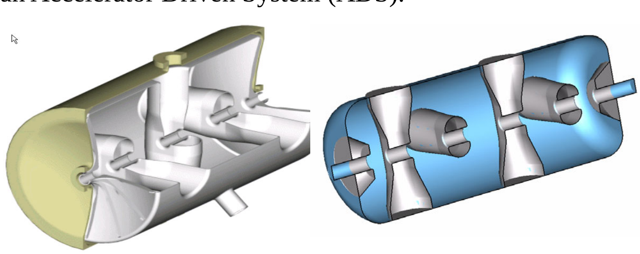

Figure 6: An ANL 4-gap spoke resonator at β=0.62 (left) and a 5-gap, β=0.48 spoke resonator from LANL. Both are investigated for their potential to replace similar elliptical resonators.

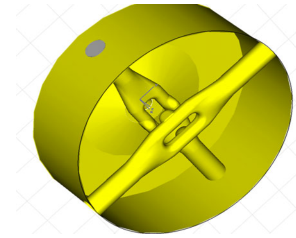

Figure 7: A LANL designed β=0.125 3-gap spoke resonator with RF-focusing in the center-gap.

LANL also presented the investigation of a low-β spoke resonator that incorporated RF-focusing between adjacent spokes (see Figure 7). Beam-dynamics studies show that this resonator could be used immediately behind the ATW RFQ. The RF-focusing in the center gap is sufficient to replace external focusing elements [18].

ALTERNATE DESIGN CONCEPTS

In the velocity range, where spoke resonators are useful, other resonator types are also being considered. To allow comparison, some of these concepts were also presented during the workshop. INFN-Legnaro presented their single cell re-entrant resonator concept [19]. These structures are more compact than spokes for very low β. Multi-gap solutions for this approach are not in sight yet. However, these structures might have a good potential for beam-capture right behind a Radio-Frequency Quadrupole (RFQ), where spoke resonators might be less efficient. More studies are needed to answer this question. The University of Frankfurt presented their concept for a CH-structure, a superconducting variant of the IH structure [20]. A complex geometry and focusing arrangement allow very long structures that could be used for low βs around 0.1.

WORKSHOP SUMMARY

All groups active in the field presented their work and shared their approaches on the details of the spoke resonator design process and related issues. The open technical discussion provided a good understanding of the details. A lot of ‘’do’s and don’ts’’ that normally are not published were shared. All the information presented is also available on the web at http://laacg1.lanl.gov/spokewk/ .

There was general agreement that the recent successes by all groups were clearly related to the introduction of high cleaning standards like EP, BCP and HPR. While the importance of multi-gap structures has been acknowledged, their benefit for the lowest βs might be limited, if failure tolerance is an issue. One of the advantages of independently driven short segments is that single failing resonators do not require a shut-down of the machine. Re-phrasing the neighboring resonators would allow continuation of the accelerator operation. LANL beam-dynamics simulations for ATW have already shown that for 2 and 3-gap structures the accelerator can not tolerate a failure of any of the first few superconducting few resonators [21].

OUTLOOK TO THE FUTURE

The workshop showed that the process of spoke resonator design is well enough understood to make different solutions work with comparable performance. Thus proof-of-principle experiments would only add new information, if a significant increase in achievable gradient could be shown. Still missing are a high power demonstration and a demonstration of a spoke resonator operating with beam.

A number of other issues have been identified that have not been addressed sufficiently. These are high power coupling for large beam currents and HOMs especially in multi-gap spoke resonators. Also a reliable tool for 3D multipacting simulations still needs to be identified or written. Finally, the limits, if any, of spoke-resonator beam-velocity boundaries must be identified.

ACKNOWLEDGEMENTS

I would like to thank Jean Delayen and Ken Shepard for the constant support in advancing the understanding of low-β structures. All presenters and participants of the workshop should get credit for openly sharing their knowledge for the benefit of the accelerator community. I also wish to thank Ken Shepard, Jean Delayen, Brian Rusnak, Dale Schrage and Tsuyoshi Tajima for helping me in structuring the workshop to cover all that is important on this matter.

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