DEVELOPMENT OF ANNULAR COUPLED STRUCTURE

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Abstract

A $\pi/2$-mode standing-wave linac of an Annular Coupled Structure (ACS) has been developed for the 1-GeV proton linac of the Japanese Hadron Project (JHP). This ACS has four coupling slots between accelerating and coupling cells in order to overcome difficulties in putting the ACS to practical use. Two prototypes of a four-slot ACS (f=1296MHz, $\beta=v/c$=0.8) have been constructed and tested: one with a staggered slot-orientation from cell to cell; and the other with a uniform one. The staggered configuration has the following advantages over the uniform one: the former gives a larger coupling constant and a larger shunt impedance than the latter with the same size of coupling slot. Both models have been conditioned up to the design input RF power. Concerning distortion of the accelerating field caused by the coupling slots, the four-slot ACS gives a distortion-free accelerating field around the beam axis, while a Side-Coupled Structure (SCS) cavity gives an accelerating field mixed with a TE111-like mode.

Introduction

We have been carrying out the R&D on a four-slot ACS [1,2] as a promising candidate for the high-β coupled-cavity structure of the JHP 1-GeV proton linac. In an ACS linac, accelerating cells and non-excited annular coupling cells are alternately located. It is the annular coupling cell that typifies the RF properties of the ACS. An annular cavity has higher order modes (HOM's), such as TM110 and TM210, near the coupling mode, TM010. It makes the coupling mode of ACS easily affected by breakdown of the axial symmetry caused by opening coupling slots. This RF property had prevented the ACS from being put to practical use.

First, we studied on two-slot ACS cavities with the computer code MAFIA. Two-slot ACS cavities have the following problems [1,3-5]:

• For the uniform slot-orientation from cell to cell, the TM110 mode of the annular coupling cell comes close to the TM010 coupling mode as the coupling constant becomes larger, and finally enters the accelerating passband.

• For the staggered slot-orientation, the $\pi/2$ accelerating mode excites a TM210-like mode in the coupling cell, which reduces the shunt impedance.

Both problems arise from an axial asymmetry caused by opening two slots. One way to restore the axial symmetry is to increase the number of slots and to reduce the individual slot size. In order to study the possibility of a multi-slot ACS, we made four-slot and eight-slot cold models at S-band and measured their RF properties. We obtained the following results [1]:

• With the four-slot configuration, the axial symmetry can be sufficiently restored to suppress mode mixing between the coupling mode and the TM110 or TM210 mode.

• With the eight-slot configuration, no improvements were found, compared with the four-slot configuration.

• The total arc length of the slots, which is defined by the arc length of the individual slot multiplied by the number of slots, increases when the number of coupling slots increases from four to eight.

The structural strength and thermal conductivity of the ACS became poor as the total arc length of slots was increased. Therefore, the four-slot configuration was a practical choice to develop a high-power model of the ACS as the next step.

It should be noted that the side-coupled structure (SCS) [6] is well known as an efficient $\pi/2$ coupled-cavity structure and has been used in several linacs. The shunt impedance of the SCS is higher than that of the four-slot ACS by about 5%. Why should we develop the ACS while an efficient SCS is already available? Is it only for an academic interest? No. The reason is as follows: For future high-brightness linacs, we need an accelerating structure that never deteriorates the beam quality and has reasonable efficiency. For example, a HOM-free accelerating structure will be necessary for a linear collider operated with multiple bunches and heavy individual bunch loading. On the other hand, the distortion of the accelerating field, itself, due to coupling slots or coupler ports becomes a serious problem in high-brightness linacs [7]. The accelerating mode mixed with a dipole mode would kick the beam in a transverse direction. Recently, we have found by numerical simulations that the ordinary slot configuration of the SCS tilts the axis of the TM010 accelerating field from the beam axis. This kind of field distortion may affect the beam quality in an SCS linac. Therefore, developing another coupled-cavity structure with a distortion-free accelerating field is indispensable for future high-brightness linacs. That motivated us to carry out the R&D of the four-slot ACS.

High-Power Models of ACS

__Structure and RF Properties__ Two types of four-slot ACS cavities were constructed for high-power tests: one had the staggered slot-orientation (S type [2]) from cell to cell to reduce the second nearest-neighbor coupling between accelerating cells; the other had the uniform slot-orientation (U type). Table 1 gives the design parameters for the high-power model.

Figure 1 is a cutaway view showing the four-slot ACS cavity of type-S, where the slot-orientation is rotated 45 degrees from segment to segment. The shape of the accelerating cell was optimized to give a high shunt impedance, and the cross section of the annular cavity like a ridged waveguide is also optimized to make the outer diameter of the ACS cavity as small as possible. Four coupling slots were bored at the wall between the accelerating and coupling cells. The edge at each side of the coupling slot was tapered so as to increase the magnetic coupling. From Table 1, the average power dissipation per accelerating cell amounts to about 800 W. In order to reduce the thermal detunig during high-duty operation, cooling-water circuits (Fig. 1) were adopted, by which the

TABLE 1
Design Parameters for the ACS high-power models

frequency	1296 MHz
β (=v/c)	0.78
accelerating gradient (E_0T)	3.6 MV/m
shunt impedance (ZT^2)	80% of 54 MΩ/m
peak RF power	27 kW / accelerating cell
RF pulse width	600 μs
repetition rate	50 Hz

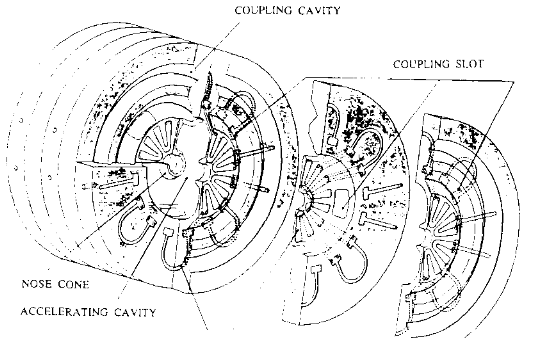

Fig. 1 A Cutaway view of the four-slot ACS of type-S. The slot-orientation is rotated 45 degrees from segment to segment.

nosecone region can be directly cooled [8]. The segments were machined from oxygen-free copper (OFC) using a super-precision lathe and a milling machine. Before brazing, individual cells were tuned to the design frequency within ±100 kHz by fine machining. After all of the machining was completed, the segments were stacked and brazed together in a vacuum furnace to form the ACS cavity.

Table 2 gives a few RF parameters of the $\pi/2$ accelerating mode measured for the S-type ACS cavity, together with the theoretical values calculated using SUPERFISH. The shunt impedance is reduced by 22% compared with the theoretical value. This reduction 22% consists of two parts: a reduction of 4% coming from surface imperfections of the cavity wall; the remaining 18% is due to the coupling slots. For the U-type ACS cavity, the measured Q value was 1.8×10^4. This value is 75% of the theoretical value and lower by 4% than the Q value of the S-type cavity.

Table 3 gives the coupling constants k and k_A for the S-type and U-type cavities, the slot sizes of which are the same. The parameter k is the nearest-neighbor coupling, and k_A is the second nearest-neighbor coupling between accelerating cells. As expected from the staggered slot-orientation, the S-type cavity gives a smaller value of k_A than the U-type cavity does. For the nearest-neighbor coupling, the S-type cavity gives a larger value.

From the results of the RF measurements, the staggered slot-orientation is preferable to the uniform one.

TABLE 2
RF Parameters of the $\pi/2$ Accelerating Mode for the S-type ACS

	measured	theoretical
Q	1.9×10^4	2.4×10^4
R (ZT^2)	42 MΩ/m	54 MΩ/m

TABLE 3
Coupling Constants for the S-type and U-type ACS Cavities

	k	k_A
type S	5.6×10^{-2}	4.4×10^{-4}
type U	4.5×10^{-2}	-6.7×10^{-3}

k : the nearest-neighbor coupling
k_A : the second nearest-neighbor coupling between accelerating cells

<u>High-power Tests</u> Figure 2 is a picture of the setup for high-power tests. A schematic drawing of the setup is shown in Fig. 3. Two five-cell ACS cavities are coupled by a bridge coupler with a disk-loaded structure [9]. The bridge coupler has an iris port at the central cell, through which RF power is fed, and is also equipped with three tuning plungers to perform cavity tuning.

A series of high-power tests were carried out with two setups: a pair of S-type ACS cavities coupled by the bridge coupler (setup SS) and a combination of S-type and U-type ACS cavities (setup SU).

The first high-power test was performed with setup SS at a low duty factor of 0.2% (200 μs, 10 Hz) [2]. The cavity was conditioned up to the design peak power of 300 kW in about 10 hours without experiencing any problems.

The second high-power test was carried out with the same setup in the following way:
(1) At a duty factor of 1.5% (300 μs, 50 Hz), the cavity was conditioned up to a peak power of 500 kW. The cavity was then continuously operated at 450 kW for 18 hours.
(2) At a low duty factor of 0.1% (100 μs, 10 Hz), the cavity was conditioned up to a peak power of 600 kW and continuously operated at this power level for 12 hours.
Figure 4 shows the data concerning the thermal detuning vs. the input RF peak power, measured from the tuner position during test (1). The data shows good agreement with a thermal-analysis prediction (solid line) [8] using the computer code ISAS2. After test (2), the field-emission current from the nosecone regions was noticeably reduced to about one third.

The third high-power test was performed with setup SU. That was the first test for the U-type ACS cavity. The cavity was conditioned up to a peak power of 600 kW at a low duty factor of 0.2% (200 μs, 10 Hz) without experiencing any problems. After this test, the Pulse Forming Network (PFN) of the klystron modulator was upgraded so that RF pulses with a flat top of 500 μs became available at 50 Hz. Then, the final high-power test was carried out at a duty factor of 2.5% (500 μs, 50 Hz) up to the design peak power of 300 kW.

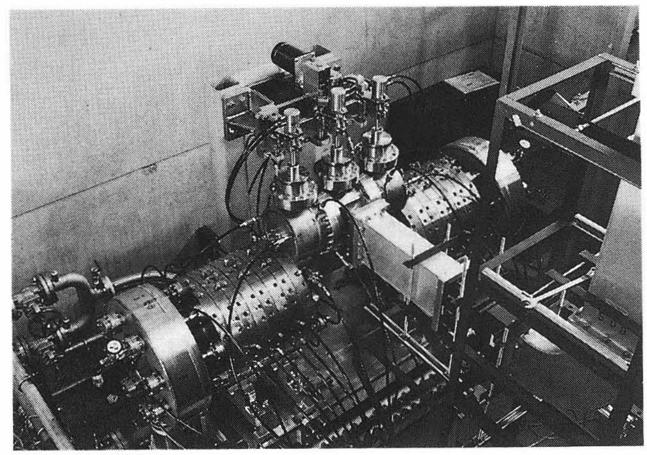

Fig. 2 A photo of the setup for high-power tests.

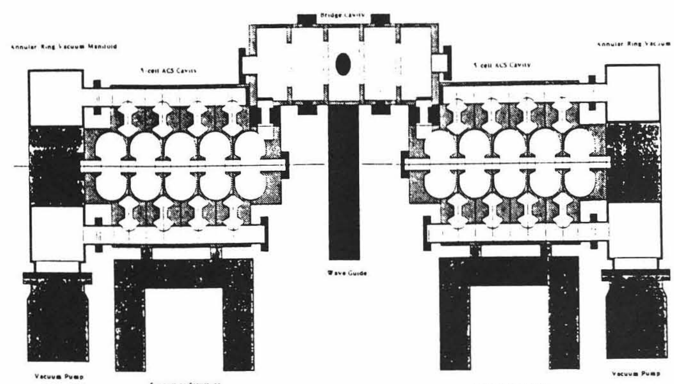

Fig. 3 A schematic drawing of the setup for high-power tests.

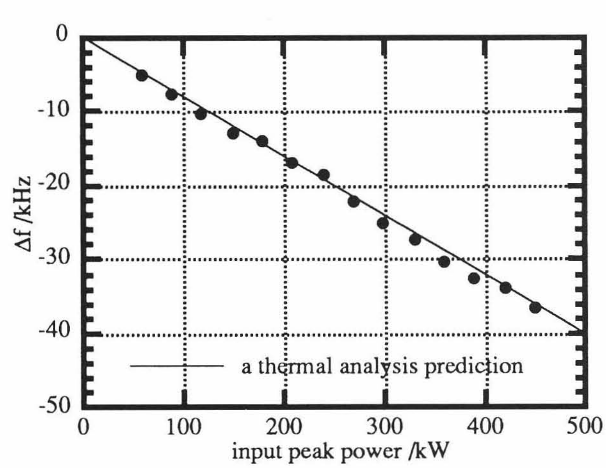

Fig. 4 Measured thermal detuning vs. the input RF peak power.

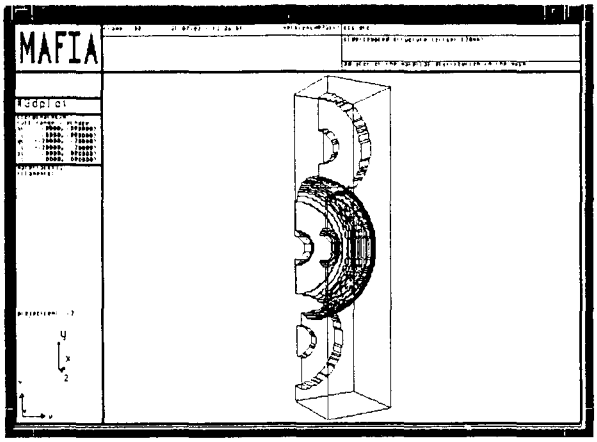

Fig. 5 A three-dimensional geometry of an SCS cavity

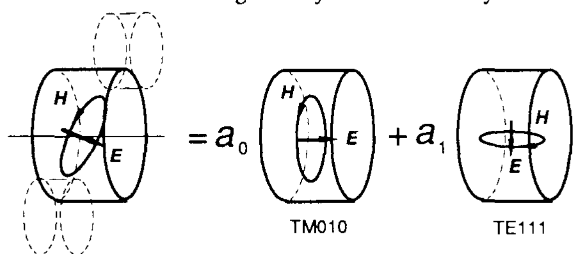

Fig. 6 A schematic drawing showing how the accelerating field is distorted in an SCS cavity.

Field Distortion of Accelerating Mode

We have analyzed the distortion of the accelerating field caused by coupling slots for an SCS cavity and a four-slot ACS cavity with a staggered slot-orientation. The analyses were carried out using MAFIA in the following way:

- First, the electromagnetic fields of the accelerating mode were calculated for a coupled-cavity structure.
- Second, the electromagnetic fields of the accelerating mode were calculated for an axially symmetric single cell without coupling slots.
- Finally, the field distortion was obtained by subtracting the electromagnetic-field data for the single cell from those for the coupled-cavity structure.

From the numerical simulations, we have found that the slot configuration of the SCS causes the axis of the TM010 accelerating mode to tilt from the beam axis. In an ordinary SCS linac, an accelerating cell has an adjacent coupling cell mounted on the top and another coupling cell attached to the bottom, as shown in Fig. 5. This slot configuration is asymmetric with respect to the horizontal plane including the beam axis. The field distortion is caused by the way that the TM010 mode is mixed with a TE-dipole mode (TE111). That is schematically shown in Fig. 6. We calculated how much the tilted accelerating field in the SCS kicks the beam in a transverse direction during the period in which the beam goes through an accelerating cell. Figure 7 shows the ratio of the transverse kick to the longitudinal acceleration as a function of the coupling constant (k). The data point at $k = 0$ is for the axially symmetric single cell without slots. It can be considered that a non-zero value of ~$5x10^{-4}$ at $k = 0$ comes from numerical errors. At $k = 0.05$, the ratio becomes $8x10^{-3}$, which is not negligible. Fortunately, the direction of the transverse kick is reversed when the beam goes through the next accelerating cell. Therefore, the transverse kicks are canceled out if the number of accelerating cells in the SCS linac is an even number. However, we should notice that this counterbalance is assured only when there are no errors in the field amplitude or phase and the beam dynamics remains linear.

For the four-slot ACS of type-S, the accelerating mode is distorted in the way that the TM010 mode is mixed with a TE-octupole mode. The field strength of the octupole component is negligibly small around the beam axis. Figure 7 shows that the amount of the transverse kick in an ACS cavity with a coupling constant of 0.045 is almost equal to zero within the accuracy of the numerical simulation.

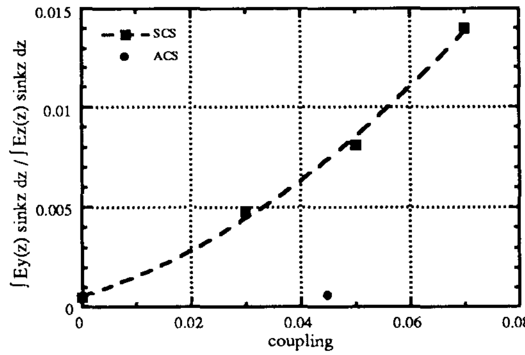

Fig. 7 The ratio of the transverse kick to the longitudinal acceleration for each accelerating cell in an SCS linac is plotted as a function of the coupling constat k, compared with that in a four-slot ACS (type-S) linac.

Conclusion

Two prototype four-slot ACS's have been constructed and tested: type-S with a staggered slot-orientation and type-U with a uniform one. Both types have been conditioned at a duty factor of 2.5% (500μs, 50Hz) up to the design RF peak power, and at a low duty factor of 0.2% (200μs, 10Hz) up to a peak power twice as large as the design value. Concerning the π/2 accelerating mode, type-S gives a larger coupling constant by about 25%, and a larger shunt impedance by about 4%, compared with type-U with the same size of coupling slot.

Numerical simulations using MAFIA were carried out for SCS and ACS cavities to analyze distortion of the accelerating field caused by coupling slots:

- The ordinary slot-configuration of the SCS causes the accelerating field to tilt from the beam axis. In an SCS cavity with a coupling constant of 0.05, the ratio of the transverse kick to the longitudinal acceleration amounts to $8x10^{-3}$.
- On the other hand, a four-slot ACS cavity (type-S) with a coupling constat of 0.045 gives an distortion-free accelerating field that is almost axially symmetric around the beam axis.

The four-slot ACS that has reasonable efficiency is promising as an accelerating structure for high-brightness linacs.

References

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