200 MHz FAST PHASE SHIFTERS and PHASE DETECTION for a RAMPING ENERGY

JP. Auclair, PA. Chamouard, JL. Lemaire,
Laboratoire National Saturne
C.E.N. Saclay, France.

Summary

Injection using a ramped energy is required at Saturne. The mean energy is linearly increased during the 400 μs of injection by means of two rf cavities (ramping cavity and debuncher). The phase of each cavity is shifted relative to the linac phase. A set of fast phase shifters using strip-line techniques have been developed, which are presently in operation.

Introduction

The multiturn injection at Saturne is performed by a linear increase of the mean energy of the beam, to follow the linear increase of the electromagnetic field ($\dot{B} = 4.2$ T/s) in the main ring. This is obtained by means of a ramping cavity, which is located just at the end of the linac. As a consequence, the phase of the debuncher must be shifted to deal with the variation of the mean energy. The phase-shifting of these two cavities is achieved using two ferrite phase shifters, which operate between the rf linac feeder and each cavity (Fig. 1).

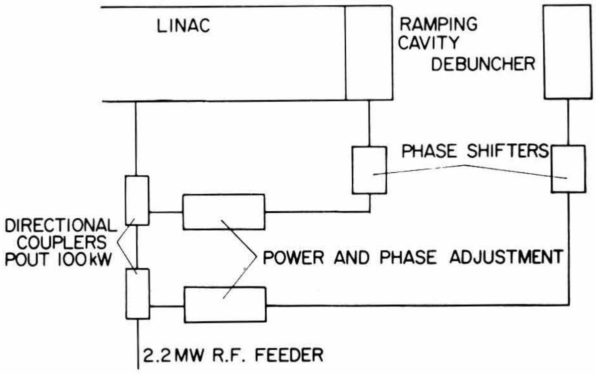

Fig. 1 Block diagram of rf power system

Description of a Phase Shifter

The phase shifter consists of an rf transmission line whose dielectric material is an rf ferrite having a dielectric constant $\varepsilon = \varepsilon' - j\varepsilon''$ and magnetic permeability $\mu = \mu' - j\mu''$. The propagation vector is then given by

$$\gamma = j \cdot \frac{2\pi\ell}{\lambda} \sqrt{\varepsilon\mu} ,$$

where ℓ is the length of the transmission line and λ is the wave length.

When a magnetic field is applied to the ferrite, the phase shift decreases due to the variation of the magnetic permeability, reaching a minimum value when the ferrite is saturated.

The transmission line is strip-line, in which the inner conductor has a notched shape. The line operates like a delay line to avoid prohibitive length of the device and to limit losses in the dielectric material. The driving magnetic field is provided by 19 coiled ferrite toroids of rectangular cross-section. Additional permanent magnets are placed on each side of the strip-line (Fig. 2) and are used, along with a steady current in the coils, to minimize the attenuation when no driving current is applied. The strip-line is 1-m long, 6-cm wide and 2-cm thick.[1] The overall load connected to the current generator is: L = 1.7 mH, R = .3Ω, and the permanent magnets give a 330 Oe magnetic field.

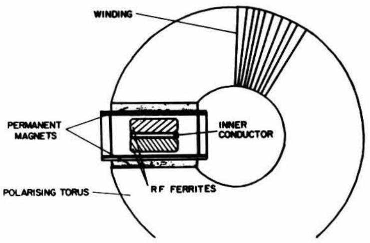

Fig. 2 Cross section of the phase-shifter

The line is made of printed circuit materials in order to reduce eddy-currents. As the transmitted power may reach 100 kW, the whole apparatus is housed inside a pressurized tank filled with SF_6 at a pressure of 2 bars, to avoid sparking.

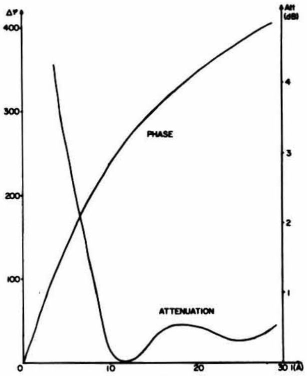

Fig. 3 Static response

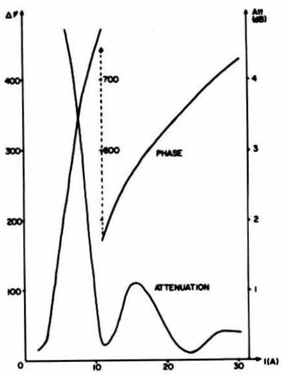

Fig. 4 Static response

Figures 3 and 4 show power attenuation and phase shift versus a dc applied current for two different types of rf ferrite. Figure 5 shows the driving current and phase shapes versus the duration of an applied rectangular voltage.[2]

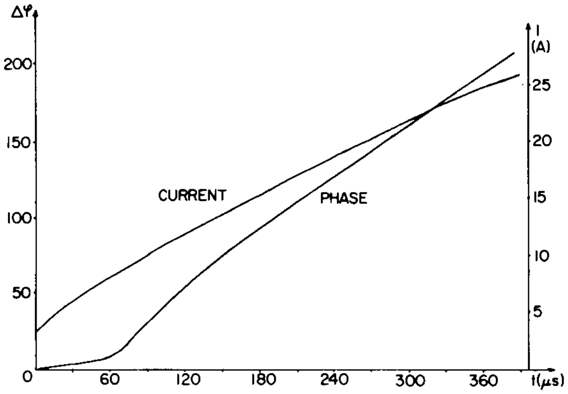

Fig. 5 Dynamic response vs duration of the excitation

Calculation of the Phase Laws

Theoretical considerations

a) Ramping cavity

Let W be the mean kinetic energy of an ion having a charge-to-mass ratio $\varepsilon = z/A$. The duration of injection is then $T_{inj} = \frac{X}{Rg} \frac{(B\rho)}{\rho \dot{B}}$.

X is the useful aperture in the main ring and g the local chromatic function.

Since the rigidity $(B\rho)$ is the same for all particles, one has for the kinetic energy ramp:

$$\dot{W} = \frac{e^2}{m_o} A \varepsilon^2 B \rho^2 \dot{B}$$

Therefore, the maximum variation given by the ramping cavity has to be:

$$\Delta W = \frac{e^2}{m_o} \frac{A \varepsilon^2}{Rg} (B\rho)^2 X$$

Because the energy ramp must be as linear as possible, the phase shift of the ramping cavity must be from -45° to + 45°.

b) Debuncher

The shifting rate is going to be larger for the debuncher due to the time-of-flight between the two cavities.[3] Let D be the distance, then:

$$\Delta \emptyset = - \frac{2\pi D}{\lambda} \left(\frac{m_o c}{e}\right) \frac{X}{Rg} \frac{1}{\varepsilon (B\rho)}$$

$$\dot{\emptyset} = - \frac{2\pi D}{\lambda} \frac{m_o c}{e} \frac{1}{\varepsilon} \frac{\rho \dot{B}}{(B\rho)^2}$$

c) Numerical Results

The main parameters are the following :
$\dot{B} = 4.2$ T/s $Rg = 6.5$ $\rho = 6.34$ m $D = 8.4$ m

The results are given in Table I:

Table I

	p (20 MeV)	ions (5MeV/A)	$\vec{p}$
T_{inj} (μs)	400	400	200
$\dot{W}_{rc}$ (keV/μs)	1.65	0.825	0.825
$\dot{\Phi}_{rc}$ (°/μs)	0.22	0.22	0.22
$\Delta \emptyset_d$ (°)	166	332	332
$\dot{\emptyset}_d$ (°/μs)	0.42	0.84	1.68

Driving Generators

To get good working conditions, the attenuations of the phase shifters must be smaller than 2 db and 0.8 db during the phase shifting time. Therefore, the biasing current is greater than 7 A or 9 A, respectively (see Figs. 3 and 4). A dc power supply provides the bias current needed to operate the transmission line at close to 1 db attenuation and a pulsed generator, which is schematically represented in Fig. 6, provides a rectangular voltage shape delivering a sawtooth-like current. The tune is then easily obtained by properly adjusting the level of the voltage.

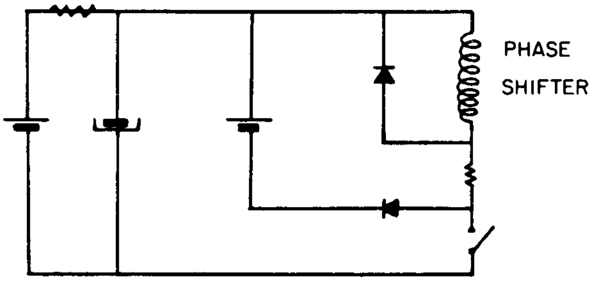

Fig. 6 Schematic of the ramping cavity driving generator

As far as the debuncher phase shifter is concerned, the problem is a bit more complicated because of the larger spread of the phase variation. Non-linear regions occur requiring an additional inductance in series with the transmission line. Consequently the linearity of the current sawtooth can be adjusted by shortcircuiting this inductance at a given time in the pulse (Figs. 7 and 8).

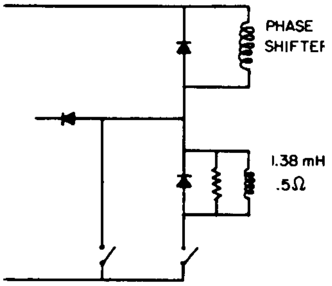

Fig. 7 Schematic of the debuncher driving generator

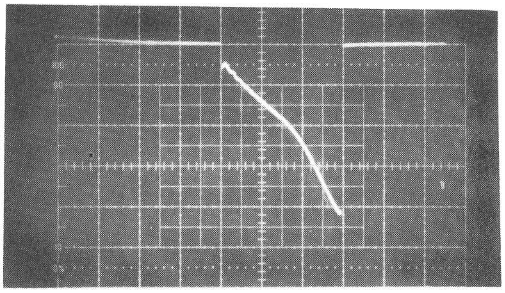

Fig. 8 Driving current shape using the additional inductance
100 μs/cm 20 A/cm

Phase Detection

The phase shifting is measured with a phase comparator. This device detects both sine and cosine of any phase between two rf inputs. Let X and Y be the output voltages, then $X = A \sin \phi$ and $Y = B \cos \phi$. The two coefficients are amplitude dependant on the input signals. Fortunately, they show a good linearity if the amplitude of the input voltages varies within a range of 5 db. The phase shifting is then given by: $\phi = \text{Arctg}\ c\,\frac{X}{Y}$, with $c=\frac{B}{A}$, obtained by calibration of the phase comparator.

The dynamic phase shifting can be observed on both computer display and X-Y scope display. The former is done using a JCAM 10 microprocessor, which gives the phase shifting versus time (30 measurements spaced by 15 μs) while the later directly shows ϕ using polar coordinates.[4]

The dotted line is obtained by chopping the electron beam. This method gives an idea of the linearity of the phase shifting (Figs. 9 and 10).

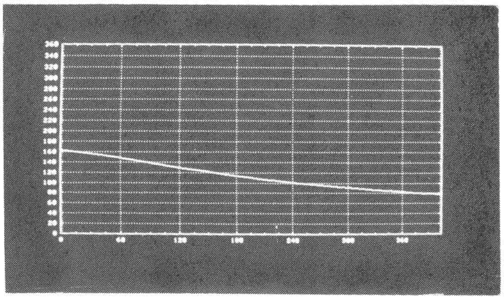

Fig. 9 Computer display of the phase shifting

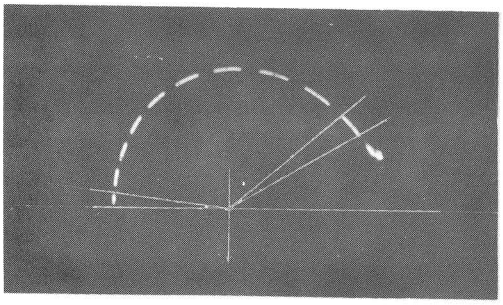

Fig. 10 X-Y scope display of the phase shifting

Conclusion

The 200-MHz phase shifters have been used for 7 years at Saturne 1 with operating $\dot{\phi}$ values from 0.15°/μs to 0.5°/μs, using n° 6311 ferrites. Due to the $\dot{B}$ increasing from 1.8 T/s to 4.2 T/s, the Saturne 2 injection method required $\dot{\phi}$ be raised to 0.84°/μs, which exceeds the range of the old phase shifters. So new devices were developed using a new type of ferrite (n° 6912) from L.T.T. Company. These are able to reach a $\dot{\phi}$-value up to 1.1°/μs. This is good enough even for heavy ion acceleration but is still under the required performances as far as polarized protons are concerned (1.68°/μs). For this use it was decided to run two-phase shifters in series, which are presently under construction.

Acknowledgments

The authors would like to thank JM. Lagniel who contributed to the first measurements of dynamic phase shifting.

References

1 - Etude et réalisation de déphaseurs à ferrite,
LTT Report

2 - Mesures sur le déphaseur à ferrite,
JP. Crenn, Internal Report

3 - Caractéristiques de l'injecteur pour diverses particules,
PA. Chamouard, Internal Report

4 - Mesure de phase dynamique,
JP. Auclair, PA. Chamouard,
Internal Report.