# DAΦNE HARMONIC CAVITY UPDATE AND BUNCH SHORTENING STUDIES

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# Summary

- 1 Cavity design and measurements;
- 2 Parked cavity option;
- 3 Bunch lengthening;
- 4 Bunch shortening (in progress);
- 5 Multi-Bucket option.

### 1 – Cavity Design and Measurements

The installation of a passive third harmonic cavity in both the e+ and e- rings of the Frascati Phi-factory DAFNE has been decided to improve the Touschek lifetime by lengthening the bunches and to weaken the coherent instabilities by increasing the Landau damping due to the non-linearity of the longitudinal potential well. Since the machine runs in the bunch lengthening regime, the actual DAFNE bunch length depends on the single bunch current and the present operating conditions are  $\sigma_z = 2.8$ cm (@ I<sub>b</sub> = 20mA, V<sub>RF</sub> = 120kV). The implementation of a high harmonic RF system will allow to approach a bunch length value  $\sigma_z = 3$ cm also increasing the RF voltage up to 200kV.

A passive harmonic cavity seems to be the most effective and simplest choice for DAFNE because of its low RF voltage and high beam current. Moreover the harmonic number 3 ( $f_{harm}$ =1104.9MHz) is a compromise between beam dynamics requirements and constraints related to the space available for the cavity installation.

The implications of the RF harmonic system on the beam dynamics, in particular the shift of the frequency of the coupled bunch coherent motion and the effects related to the gap in the bunch filling pattern, have been carefully studied by means of analytical and numerical tools.

The harmonic voltage can be almost completely switched-off by tuning the cavity as far as possible from the harmonic 3h (h=120). In order to minimize the coherent effects, it is worth tuning the cavity at  $(3h+n+0.5)f_{rev}$ , with the integer n as high as the the tuning system allows. This is a useful option to recover the operating conditions before the cavity installation. In our case n can be chosen in the range from –1 to 2.

#### Cavity body with tapered transition

•Single rounded cell connected, at one end, to a tapered enlargement of the beam tube to fit the damper diameter.

•Like a high pass filter, the tapered section rejects the fundamental mode (TM010) of the cavity and allows the higher frequency modes to propagate down the coaxial region.

•Tuning plunger insertion on the cell top.

•Small RF probes (3) inserted in the structure to measure the beam induced field for low-level control and diagnostics.

### HOM damper with ferrite bonded on the inner wall

•Ferrite ring (IB-004), bonded on a flanged stainless steel support with the Hot Isostatic Pressure (HIP) method.

•Damper designed and fabricated for the superconducting cavities of KEK B-factory and KEK laboratory.

#### Coaxial shielding of ferrite

•An inner tube (having the same section of the beam pipe) shields the ferrite respect to the beam image current. Broadband impedance degradation and ferrite damages are prevented.



### DAMPING OF THE HIGH ORDER MODES





#### TM010 mode (fundamental)

freq.: 1.104 GHz

The e.m. fields are evanescent in the tapered transition and only a negligible amount of them can reach the damper.

# **Generic HOM** (picture refers to M4) freq.: 1.65 GHz

The cut-off frequency of the transition tube is lower than the HOM resonance frequency. The e.m. fields can propagate towards the ferrite load.

#### **CAVITY TUNABILITY RANGE vs. TUNER POSITION**



#### SIMULATION RESULTS

An eigenmode solution of the cavity model has been performed using both MAFIA and HFSS simulation codes in order to find all the monopoles and dipoles trapped into the structure and to evaluate the relative contribution to the longitudinal and transverse impedance of the machine.

HFSS 3D simulations give also the transmission response (see figs.) between two small antennas inserted into the cell like a Network Analyzer measurement of the real device.





frequency [GHz]

The frequency response measured between two probe ports is sketched below. Some modes calculated with simulations where not measurable on the prototype. The low Q value of these modes and the presence of high polarity modes (quadrupoles, sextupoles, etc.) are possible explanations for this lack.

Longitudinal and transverse impedance measurements based on the wire method have been also performed. The fundamental mode shunt impedance is about 0.5 M $\Omega$ .

mode	simulations			measurements		
	f [GHz]	Q	R/Q [Ω]	f [GHz]	Q	R/Q [Ω]
M1	1.105	23000	26	1.105	18500	21.4
M2	1.335	12	16			
M3	1.600	27	6			
M4	1.650	55	2	1.650	168	16.8
M5	1.899	52	4			
M6	2 <mark>.0</mark> 94	115	7	2.100	22 <mark>4</mark>	
M7	2 <mark>.270</mark>	117	9	2.289	6 <mark>0</mark>	
M8	2.495	167	3	2.466	140	
M9	2.524	226	10	2.507	278	
<b>0</b> (	4 ==0	10000		4 505		0 /0 0*
Q1	1.559	10000	0/0.59*	1.585	11300	0/0.3*
	simulations			measurements		
mode		simulatior	ns	me	easuremer	nts
mode	f [GHz]	simulatior Q	ns R/Q [Ω/m]	f [GHz]	easuremer Q	nts R/Q [Ω/m]
mode D1	f [GHz] 1.089	simulatior Q 438	ns R/Q [Ω/m] 66	me f [GHz] 1.070	easuremer Q 450	nts R/Q [Ω/m] 146
mode D1 D2	f [GHz] 1.089 1.244	simulatior Q 438 35	ns R/Q [Ω/m] 66 26	me f [GHz] 1.070	easuremer Q 450	nts R/Q [Ω/m] 146
mode D1 D2 D3	f [GHz] 1.089 1.244 1.445	simulation Q 438 35 158	ns R/Q [Ω/m] 66 26 22	me f [GHz] 1.070 1.400	easuremer Q 450 139	nts R/Q [Ω/m] 146 29
mode D1 D2 D3 D4	f [GHz] 1.089 1.244 1.445 1.618	simulation Q 438 35 158 158	ns R/Q [Ω/m] 66 26 22 29	me f [GHz] 1.070 1.400 1.560	easuremer Q 450 139 175	nts R/Q [Ω/m] 146 29
mode D1 D2 D3 D4 D5	f [GHz] 1.089 1.244 1.445 1.618 1.797	simulation Q 438 35 158 158 266	ns R/Q [Ω/m] 66 26 22 29 37	me f [GHz] 1.070 1.400 1.560 1.725	easuremer Q 450 139 175 163	nts R/Q [Ω/m] 146 29
mode D1 D2 D3 D4 D5 D6	f [GHz] 1.089 1.244 1.445 1.618 1.797 1.886	simulation Q 438 35 158 158 266 283	ns R/Q [Ω/m] 66 26 22 29 37 24	me f [GHz] 1.070 1.400 1.560 1.725 1.865	easuremer Q 450 139 175 163 190	nts R/Q [Ω/m] 146 29 74

A quadrupolar mode (Q1) shows a measurable impedance when the tuner is deeply inserted

\*Tuned / parked cavity

The prototype measurements have pointed out the presence of one not damped (high Q) resonance with an impedance value depending on the deepness of the tuner insertion into the cell.

3D HFSS simulations show that the tuner strongly perturbs the field configuration of the first quadrupole (Q1) cavity mode. The longitudinal component of the E-field is no more zero, giving rise to a measurable both longitudinal and transverse impedance. In any case, even with the tuner fully inserted (parked cavity option), the mode R/Q is low enough to keep negligible the impedance values.



Longitudinal component of the E-field for mode Q1 (above:tuner out; below: tuner inserted).



The maximum power delivered by the beam to the cavity HOMs is about  $P_{HOM} \approx 3.5$ kW (@ I=1.5A into 60 bunches). This power is mainly dissipated in the ferrite damper that is already provided with cooling coils.

The power needed to substain the required harmonic voltage (57kV) is about 3.5kW. This power has to be dissipated on the cavity walls.

Starting from the power density distribution on the cavity surface calculated with HFSS, the water cooling system has been dimensioned for an overrated RF dissipation of 5kW. Ten coils (internal diameter size 6mm, 0.025 liter/s each), wrapped around the cavity body, assure an adequate temperature distribution.

Separeted water circuit has been foreseen for the tuner and the tube connecting the tuner port to the cell.





Cavity profile, dissipated RF power  $(kW/m^2)$  and power on water per tube (kW).







# POSITRON RING LAYOUT





# ELECTRON RING LAYOUT





### 2 - Parked cavity option

Back-up procedure consisting in tuning the harmonic cavity between two revolution harmonics sufficiently far from the 3h line.



1-Analysis of the coherent frequency shifts and growth rates of the CB Modes (without gap, analitycal formulae)

2-Synchronous phase spread (with gap, M.B. tracking code)

<u>1-Analysis of the coherent frequency shifts</u> and growth rates

a) uniform filling pattern

b)  $f_H = 3f_{RF} + 2.5f_0$ 

#### <u>2-Sinchronous phase spread for different</u> parking options:

a) I<sub>TOT</sub>=1.6 A

b) 47 bunches over 60 (or 94 over 120)





### App. 1: M.B. Tracking code

- a) The bunches are modeled as macroparticles
- *b) The code can simulate:*

-an arbitrary bunch pattern
-the beam loading in the main RF cavity
-the feedback system (FIR filter)
-resonant impedances in the ring

c) The harmonic Cavity is simulated as a peculiar resonant impedance

## 3 - Bunch lengthening

a) The harmonic voltage allows to reduce the RF slope at the bunch center. It is possible, therefore, to increase the main RF voltage (energy acceptance) increasing (or preserving) the bunch length. This can give an increase of the lifetime due to the Touschek scattering;

b) The non-linearities induced by the 3<sup>rd</sup> harmonic voltage increases the Landau damping (Landau cavity);

#### **Beam dynamics studies**

1 uniform filling pattern:

-S.B.: tracking code -M.B.: analytical approach

2 with a gap in the filling pattern:

-M.B.: tracking code -S.B.: tracking code

3 Touschek lifetime calculation

#### Harmonic system working point

	Concrent neq. bi
Main RF voltage (V <sub>RF</sub> )	200 [KV]
Main cavity shunt impedance (R)	1.9 [MΩ]
<b>Main cavity Q-factor</b> (Q <sub>0</sub> )	31500
Main cavity input coupling factor $(\beta)$	~4.6
Detuning of the main cavity at I=0 $(Q_L \delta_0)$	1.2
<b>RF harmonic frequency</b> $(f_{RFH}=3 f_{RF})$	1104.87 [MHz]
<b>RF harmonic voltage</b> $(V_{RFH})$	56 [KV]
Harmonic cavity shunt impedance $(R_{\rm H})$	0.48 [MΩ]
Harmonic cavity Q-factor $(Q_{0H})$	18500
Natural bunch length ( $\sigma_{z0}$ )	~2.5 [cm]
Bunch length in the lengthening regime $(\sigma_z)$	-2.9 [cm] with $I_b=17 \text{ mA}$ -3.1 [cm] with $I_b=34 \text{ mA}$
<b>RF</b> acceptance $(\epsilon_{RF}/E_0)$	0.7%

Coherent freq. Shift CB MODE 0

Uniform filling pattern

#### **B.D.** with uniform filling pattern



Multi-bunch





$$\left(\frac{\omega_{c}}{\omega_{i}}\right)_{n}^{2} = 1 + \frac{I\alpha_{c}\omega_{0}^{2}}{\omega_{i}^{2}2\pi E/e} \sum_{\substack{p=iN_{b}\pm n\pm\frac{\omega_{c}}{\omega_{0}}} pZ_{i} (p\omega_{0})e^{-(p\omega_{0}\sigma_{i})^{2}}$$
$$\omega_{i}^{2} = \omega_{RF}^{2}\alpha_{c} \frac{V_{RF}\sin\varphi_{s} + 3V_{H}\cos(3\varphi_{s} + \varphi_{H})}{2\pi h E/e}$$
$$V_{Tot}(t) = V_{RF}\cos(\omega_{RF}t) - V_{H}\sin(3\omega_{RF}t + \varphi_{H})$$

### App. 2: S.B. Tracking code

- a) The *bunch* is modeled with a set of macroparticles ( $\sim 10^5$ )
- b) The *main and harmonic voltages* are simulated as pure sine-waves
- c) The effects of *short range wakefields* is taken into account. The wake function is substituted with the wake potential of 2.5 mm gaussian bunch.

z, m

0.08

0.04

0.06

$$V(z_{i}^{n}) = V_{RF} \cos\left(\phi_{s} - \frac{2\pi h}{L_{0}} z_{i}^{n}\right) + V_{H} \cos\left(3\left(\phi_{s} - \frac{2\pi h}{L_{0}} z_{i}^{n}\right) + \phi_{H}\right)$$

$$\begin{cases} z_{i}^{n} = z_{i}^{n-1} - L_{0}\alpha_{c} \frac{\varepsilon_{i}^{n-1}}{E_{0}} \\ \varepsilon_{i}^{n} = \varepsilon_{i}^{n-1} + \epsilon \left(V(z_{i}^{n}) + V'(z_{i}^{n})\right) - U_{0} - D\varepsilon_{i}^{n-1} - \sigma_{\varepsilon 0}R\sqrt{2D} \\ V'(z_{i}^{n}) = -\frac{eN_{p}}{N_{s}} \sum_{z_{j}^{n} > z_{i}^{n}}^{j=1,N_{s}} w_{z}(z_{j}^{n} - z_{i}^{n}) \end{cases}$$

#### **B.D.** with a gap in the filling pattern

2.5

2.5

2.5

x 10

45





#### Single bunch





### 4 Bunch shortening

In this case the harmonic voltage is used to increase the total RF slope at the bunch center.

#### **Beam dynamics studies**

1 effect of the short range wakefields in the SB dynamics: -S.B.: tracking code

2 *MB coherent frequency shifts and growth rates:* -M.B.: analytical approach

#### Effect of the short range wakefields in the SB dynamics



The tracking in the SB case can be performed with different  $\alpha_c$  and with different initial conditions for the bunch.



 $\alpha_c = 0.034$   $V_{RF} = 350 \text{ KV}$   $V_H = 0 \text{ KV}$   $\sigma_{z \text{ in}} = 1.2 \text{ cm}$ Damping time=17.8 msec  $10^5$  macroparticles 100 bin160000 turns





5

-0.015

<z> [m]

10

turn

15

x 10<sup>4</sup>

 $\alpha_c = 0.034$   $V_{RF} = 200 \text{ KV}$   $V_H = 50 \text{ KV}$   $\sigma_{z \text{ in}} = 1.2 \text{ cm}$ Damping time=17.8 msec  $10^5$  macroparticles 100 bin160000 turns





 $\alpha_c = 0.034$   $V_{RF} = 150 \text{ KV}$   $V_H = 66 \text{ KV}$   $\sigma_{z \text{ in}} = 1.2 \text{ cm}$ Damping time=17.8 msec  $10^5$  macroparticles 100 bin 320000 turns







0.03 0.025 0.02 0.015 0.01 ~1.8 cm 0.005 0 -0.005σ<sub>z</sub> [m] -0.01 <z> [m] -0.015 -0.02 0 5 10 15 turn x 10<sup>4</sup>  $\alpha_c = 0.034$   $V_{RF} = 150 \text{ KV}$   $V_H = 66 \text{ KV}$   $\sigma_{z \text{ in}} = 2.8 \text{ cm}$ Damping time=17.8 msec  $10^5$  macroparticles 100 bin320000 turns







 $\alpha_c = 0.02$   $V_{RF} = 150 \text{ KV}$   $V_H = 66 \text{ KV}$   $\sigma_{z \text{ in}} = 2.4 \text{ cm}$ Damping time=17.8 msec  $10^5$  macroparticles 100 bin160000 turns





 $\begin{array}{c} 0.03 \\ 0.02 \\ 0.01 \\ 0 \\ -0.01 \\ -0.02 \\ -0.03 \\ 0 \\ 5 \\ turn \\ x 10^4 \end{array}$ 

 $\alpha_c = 0.02$   $V_{RF} = 350 \text{ KV}$   $V_H = 0 \text{ KV}$   $\sigma_{z \text{ in}} = 0.7 \text{ cm}$ Damping time=17.8 msec  $10^5$  macroparticles 100 bin160000 turns



#### **MB** coherent frequency shifts and growth rates





# **The Multi-Bucket Option**

 Is it possible to excite the passive harmonic cavity to such an extent allowing the creation of new stable buckets?

 Is it possible to de-couple the beam energy supply task (to be attributed to the main RF system ) from the bunch longitudinal focusing (mainly reserved to the harmonic cavity)?



# **Putting Charge in the New Buckets: Self-Consistent Solution**

The total voltage may be written as:

 $V_{Tot}(\omega_{RF}t) = V_{RF}\cos(\omega_{RF}t) - V_H\sin(3\omega_{RF}t + \phi_H)$ 

but the phase  $\phi_H$  depends on the bunch synchronous phases  $\phi_0$ ,  $\phi_1$ ,  $\phi_2$  so that a nonlinear equation system has to be solved self-consistently:

$$V_{Tot}(\phi_k) = V_{RF} \cos(\phi_k) - V_H \sin(3\phi_k + \phi_H) = V_{r_0}; \quad \frac{dV_{Tot}}{d\phi}(\phi_k) < 0; \quad k = 0, \ 1, \ 2$$
  
$$I_{360} = \frac{2}{T_{RF}} \sum_{k=0}^{2} q_k \exp(-j3\phi_k);$$
  
$$Z_H(3\omega_{RF}) = \frac{R_H}{1 + jQ_H} \delta \quad \text{where} \quad \delta = 3\omega_{RF}/\omega_H - \omega_H/3\omega_{RF};$$

 $V_H = |I_{360}| \cdot |Z_H| \quad ;$ 

 $\phi_H = \angle I_{360} + \angle Z_H + \pi/2 = \angle I_{360} + \arctan(1/Q_H\delta)$ 

# **Energy Balance**

The non-linear system can be solved starting from energy considerations. The energy to the beam can be only supplied by the main RF systems interacting with the RF harmonic of the beam spectrum:

Left-hand and right-hand sides of the equation can be compared at any possible value of  $\phi_H$ . When they are equal, then there is a self-consistent solution.

However, if the filling in the 3 buckets is uniform  $(q_0 = q_1 = q_2 = q_{Tot}/3)$  and being the three synchronous phases almost regularly spaced  $(\phi_k \approx k \ 2\pi/3)$ , the right-hand side is nearly 0 and the energy balance condition can't be fulfilled. To satisfy the energy balance a *substantial asymmetry in the charge filling* is required.

### **Charge Distribution and Energy Balance**







ANSYS 5.7.1 DEC 16 2002 14:00:13 NODAL SOLUTION STEP=1 SUB = 1TIME=1 TEMP (AVG) RSYS=0 PowerGraphics EFACET=1 AVRES=Mat SMN =54.132 SMX =79.68 54.132 56.97 59.809 62.648 65.486 68.325 71.164 74.002 76.841 79.68

# (Temporary) CONCLUSIONS

A mathematical solution for storing bunches in new buckets generated by a large harmonic voltage exist, provided that the charge is unevenly distributed. Anyway:

- Zero-order technological problems arise. About 15 kW have to be dissipated in the harmonic cavity, and the expected temperature rising is  $\Delta T \approx 45$  °C.
- The longitudinal focusing is given by self-generated voltages, and is expected to be *ineffective* in case of *coherent motion* (barycentric oscillations).
- The impact on the LFB operation is *extreme*. In the very most optimistic scenario the LFB could only control *half of the bunches*, while both the synchrotron frequency and the synchronous phases change during the injection.
- Understanding of the dynamics aspects (including those related to the LFB system) could benefit a *dedicated study* based on *macro-particle tracking*. The code we normally use requires some modifications to include the extra-bunches.