RF Deflectors for Combiner and Damping Rings

FABIO MARCELLINI AND DAVID ALESINI

- MAIN FEATURES OF TRAVELING WAVE AND STANDING WAVE STRUCTURES AS RF DEFLECTORS

- CTF3 COMBINER RING RF DEFLECTOR:
  - STUDY,
  - DESIGN,
  - REALIZATION,
  - MEASUREMENTS,
  - TEST WITH THE BEAM,
  - THE BEAM LOADING EFFECTS ON THE TRANSVERSE BEAM DYNAMICS.

- CTF3 DELAY LOOP RF DEFLECTOR:
  - STUDY,
  - DESIGN,
  - THE BEAM LOADING EFFECTS ON THE TRANSVERSE BEAM DYNAMICS.

- PROPOSAL FOR THE TESLA COMBINER RING RF DEFLECTOR:
  - STUDY,
  - DESIGN,
  - OVERVIEW OF POSSIBLE INJECTION/EXTRACTION SCHEMES USING 2 OR 3 DIFFERENT RF FREQUENCIES.

STANDING WAVE STRUCTURES

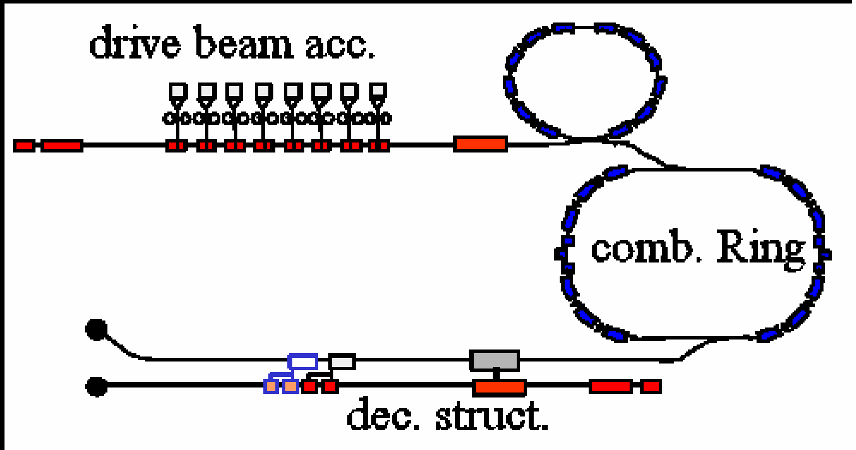
- **HIGH EFFICENCY (DEFLECTION VS. RF POWER) PER UNIT LENGTH.**
- **FILLING TIME PROPORTIONAL TO THE QUALITY FACTOR: GENERALLY SLOW.**
- **DEFLECTING FIELDS SCALES AS $\sqrt{n}$ ($n \equiv$ NUMBER OF CELLS).**
- **STRUCTURES WITH A LARGE n (MORE THAN 9) ARE DIFFICULT TO TUNE DUE TO THE MODE OVERLAPPING.**
- **IN CASE OF PULSED REGIME A CIRCULATOR IS GENERALLY NEEDED TO PROTECT THE KLYSTRON FROM REFLECTED POWER.**
- **NECESSITY OF AN AUTOMATIC TUNING SYSTEM OR OF A VERY GOOD TEMPERATURE STABILIZATION TO MAINTAIN THE CAVITY ON RESONANCE DURING OPERATION.**

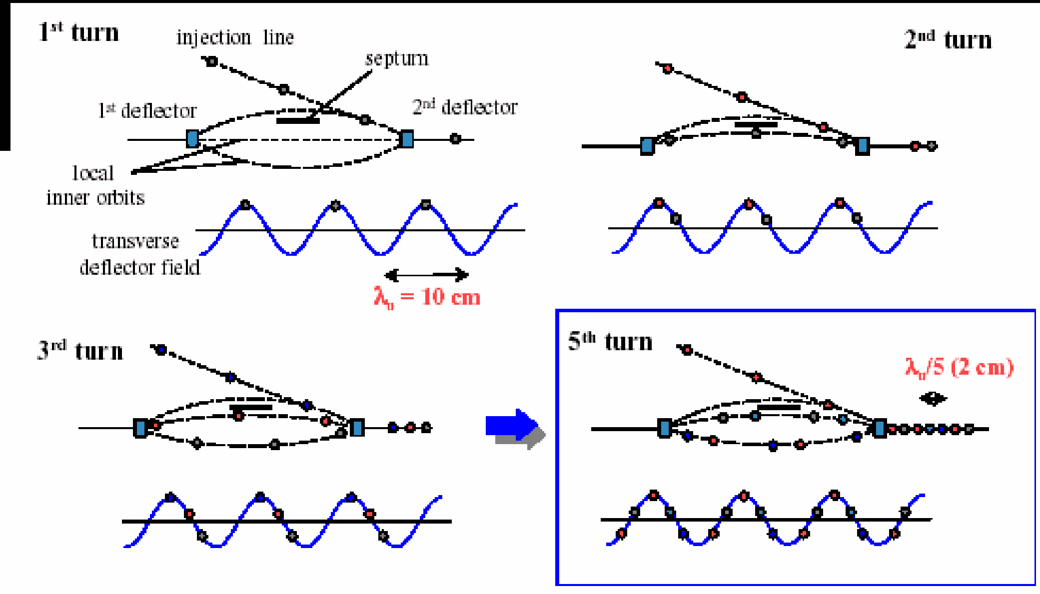
TRAVELING WAVE STRUCTURES

- **LOW EFFICENCY (DEFLECTION VS. RF POWER) PER UNIT LENGTH.**
- **FILLING TIME PROPORTIONAL TO THE GROUP VELOCITY AND THE STRUCTURE LENGTH: GENERALLY FAST.**
- **DEFLECTING FIELDS SCALES AS n.**
- **CIRCULATOR NOT NECESSARY.**
- **LESS TEMPERATURE SENSITIVITY.**

ALL THESE CHARACTERISTICS ARE A CONSEQUENCE OF THE DIFFERENT BANDWIDTH

CTF3 COMBINER RING



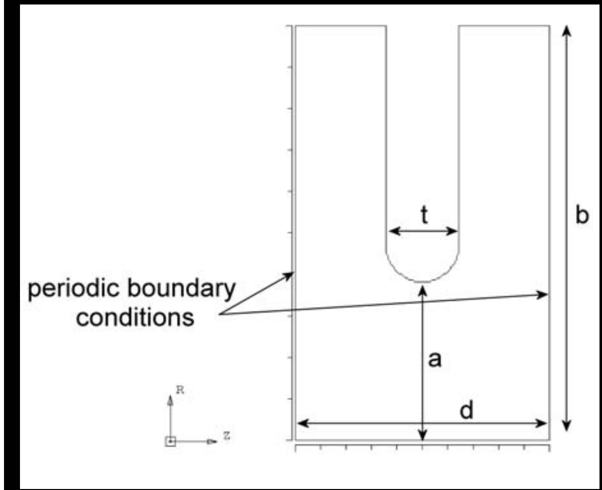


SCALING RESULTS OBTAINED BY LENGELER FOR 2.855GHz T.W. DEFLECTING STRUCTURES

CTF3 RF DEFLECTOR PARAMETERS

Nom. Energy E_n	150 [MeV]
Max Energy E_{max}	300 [MeV]
Frequency f	2.99855 [GHz]
Number of cell	10
De-phasing/cell	$2\pi/3$
Cell length d	33.33 [cm]
Group velocity v_g/c	-0.0244
Phase velocity v_{ph}/c	1
RF power P_{RF}	~1.5 [MW] (@ E_n)
Deflection ϕ	5 [mrad]
$R/Q=v_g/\omega\cdot(F_\perp/e)^2/P_{RF}$	1380 [Ω/m]

HFSS AND MAFIA E.M. SIMULATIONS OF THE DEFLECTOR

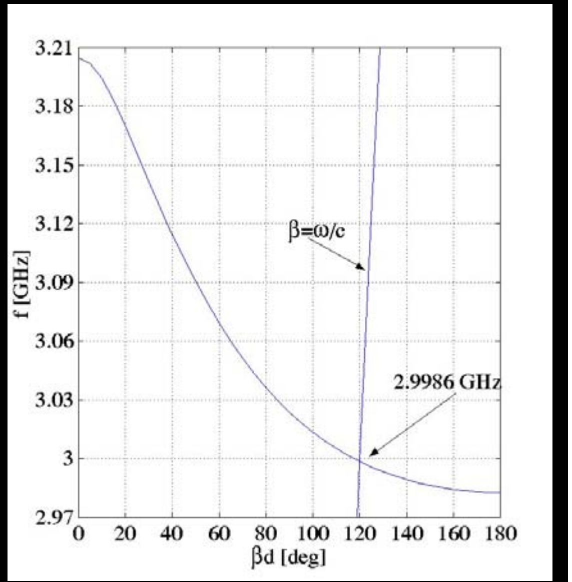


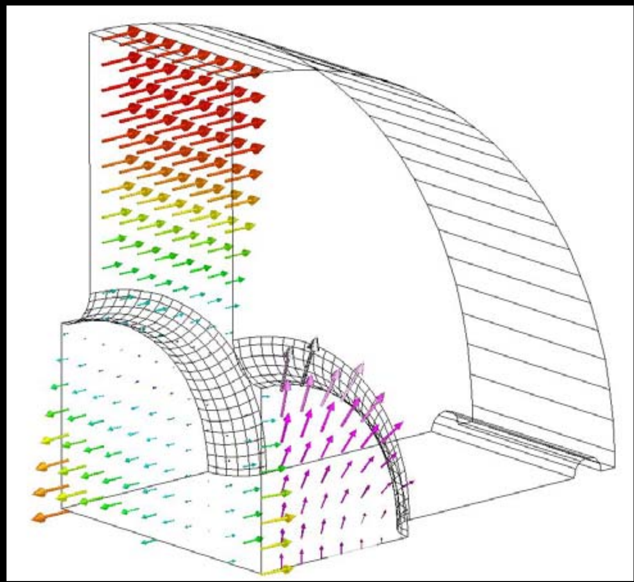
FINAL DIMENSIONS OF THE CELL AND RF DEFLECTORS PARAMETERS OBTAINED BY SIMULATIONS

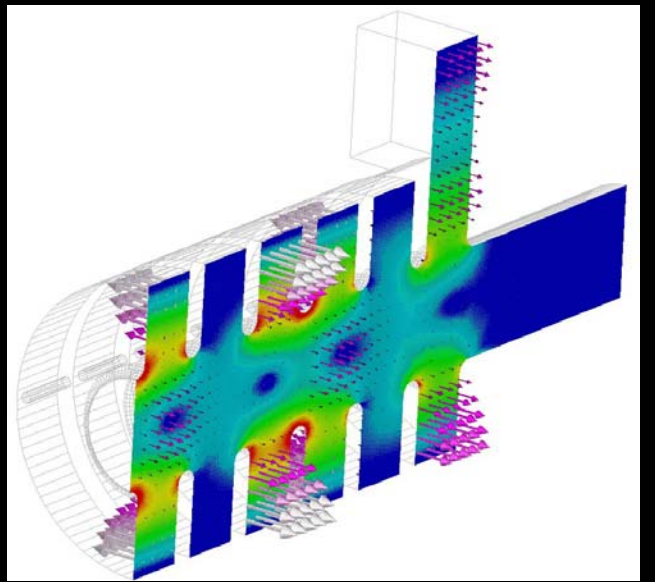
Final dimensions of the cell	a = 21.43 mm
	b = 56.01 mm
	d = 33.33 mm
	t = 9.53 mm
RF deflector parameters (HFSS and MAFIA)	f=2.9986 [GHz] (MAFIA)
	f=2.9983 [GHz] (HFSS)
	v_g=-0.0237*c (MAFIA)
	R/Q=1460 [Ω/m] (HFSS)

LOCAL SENSITIVITY OF THE DEFLECTING MODE FREQUENCY VS. CELL DIMENSIONS

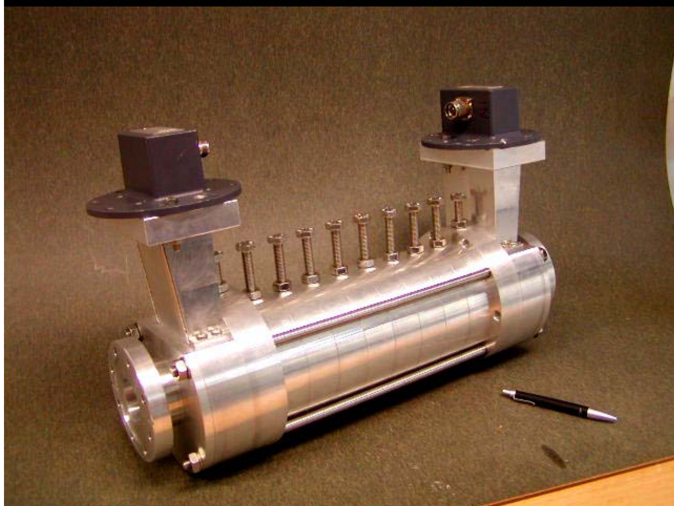
Dimension	Sensitivity
a	$\partial f/\partial a$=-13.2 MHz/mm
b	$\partial f/\partial b$ =-49.7 MHz/mm
t	$\partial f/\partial t$ = 2.9 MHz/mm
d	$\partial f/\partial d$ =1.2 MHz/mm

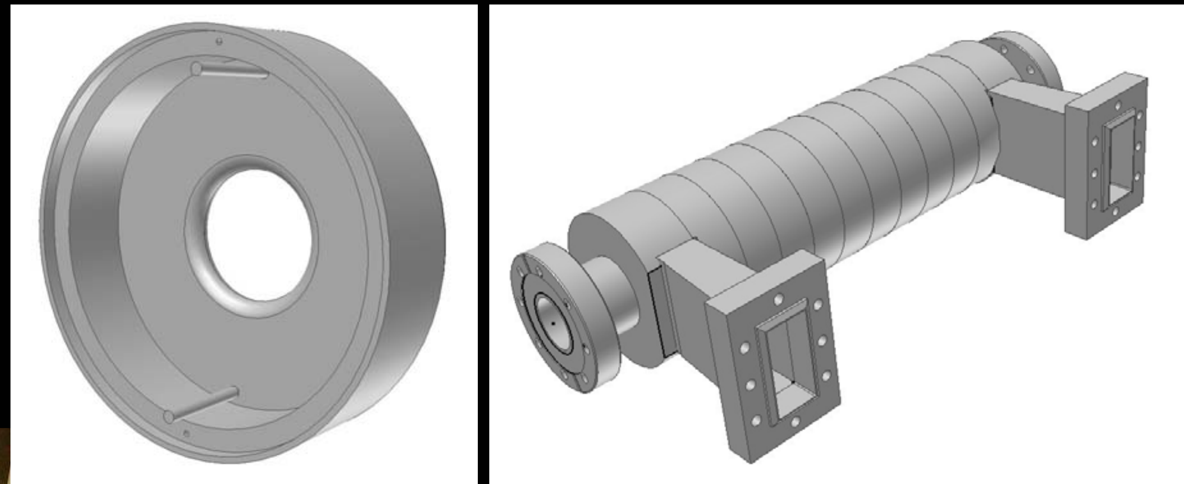






ALUMINIUM PROTOTYPE



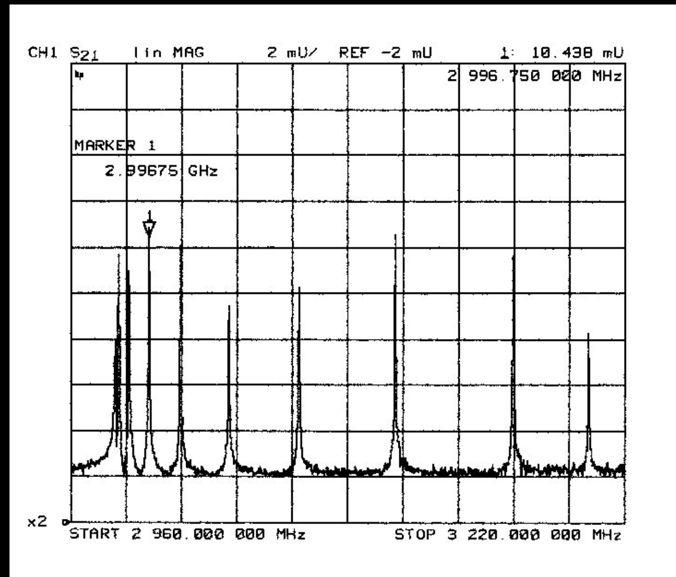


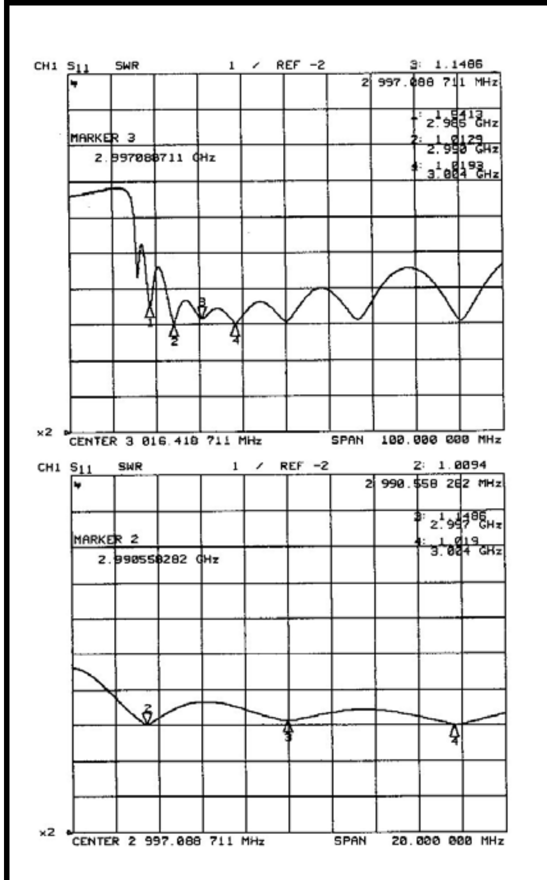
MECHANICAL DRAWING

FABRICATION STEPS

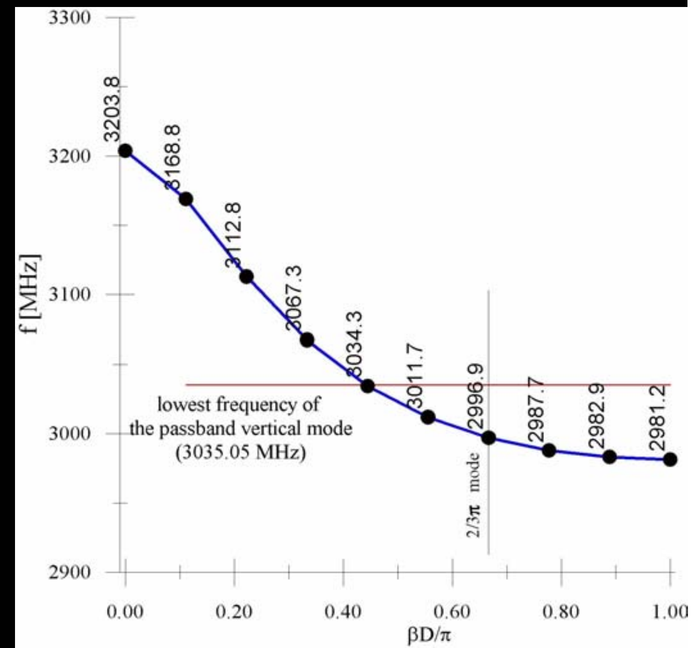
RF MEASUREMENTS

RESONANCE FREQUENCIES OF THE
10 CELLS SHORTENED STRUCTURE

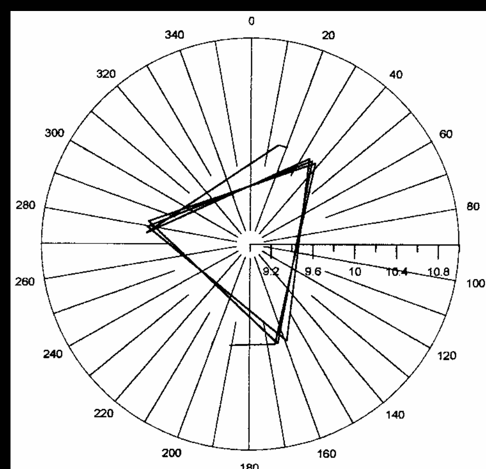




INPUT REFLECTION RESP

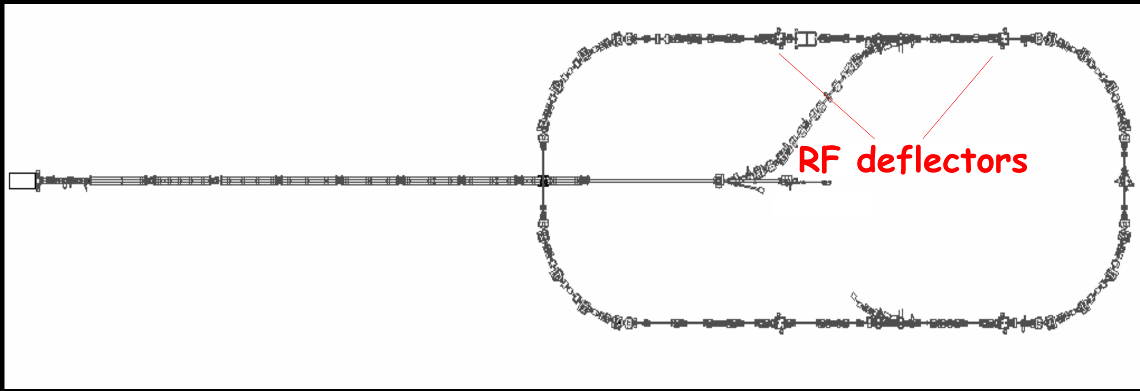


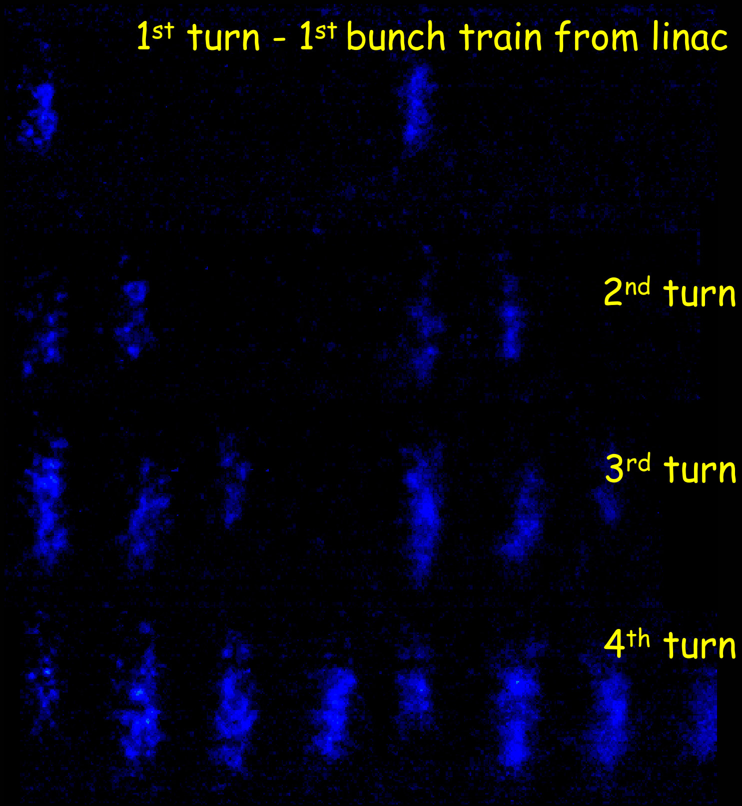
MEASURED DISPERSION CURVE
OF THE TM11-LIKE MODE



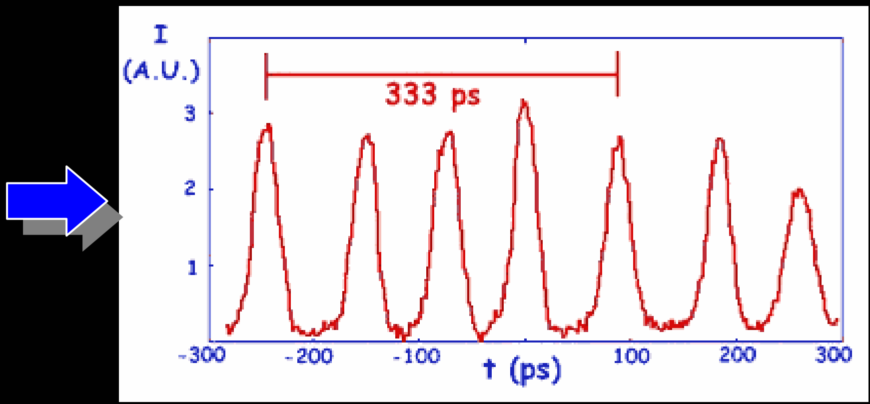
CELL TO CELL
PHASE ADVANCE

DEFLECTORS HAVE BEEN USED IN CTF3 PRELIMINARY PHASE



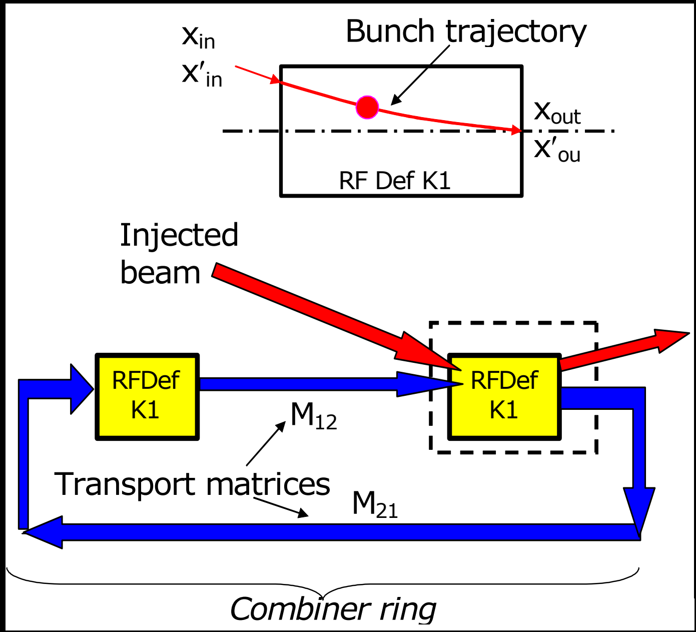


LOW-CHARGE DEMONSTRATION OF THE ELECTRON PULSE COMPRESSION AND FREQUENCY MULTIPLICATION



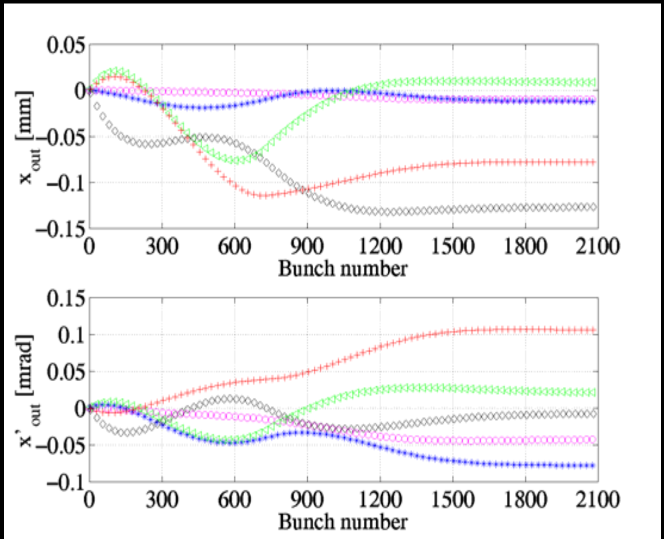
BEAM LOADING IN THE RF DEFLECTOR OF CTF3 COMBINER RING

STARTING FROM A GENERAL EXPRESSION FOR THE SINGLE PASSAGE WAKE FIELD, A DEDICATED TRACKING CODE HAS BEEN WRITTEN TO STUDY THE MULTIBUNCH MULTITURN EFFECTS ON THE TRANSVERSE BEAM DYNAMICS. BOTH THE ON AXIS INJECTION AND THE INJECTION WITH ERRORS IN POSITION OR ANGLE HAVE BEEN CONSIDERED. THE EFFECTS RELATED TO THE FINITE BUNCH LENGTH HAS BEEN EVALUATED AS WELL.



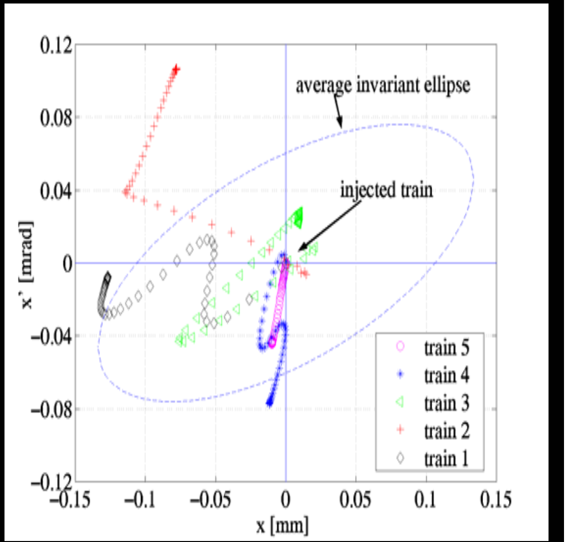
THE TRACKING CODE SCHEME.

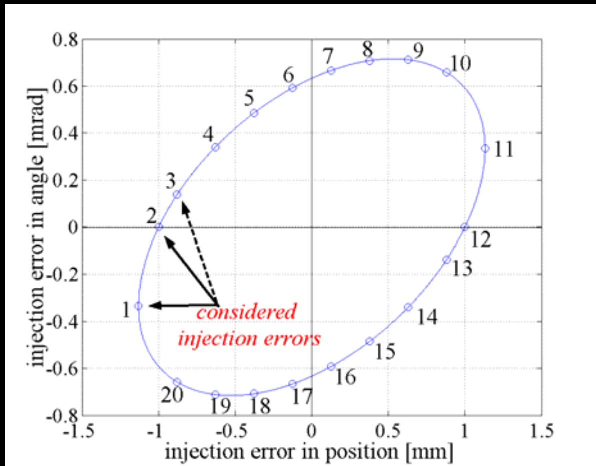
POSITIONS, ANGLES AND COURANT-SNYDER INVARIANTS OF THE BUNCHES AFTER RECOMBINATION ARE CALCULATED AT THE EXIT OF THE DEFLECTOR K1.



INJECTION WITHOUT ERRORS

POSITION AND ANGLE DEVIATIONS FROM THE NOMINAL ORBIT OF EACH BUNCH ALONG THE TRAIN ARE DUE ONLY TO THE EFFECT OF WAKE FIELDS. THE BEAM EMITTANCE GROWTH DUE TO THE WAKE FIELD IN THE RF DEFLECTORS IS NEGLIGIBLE

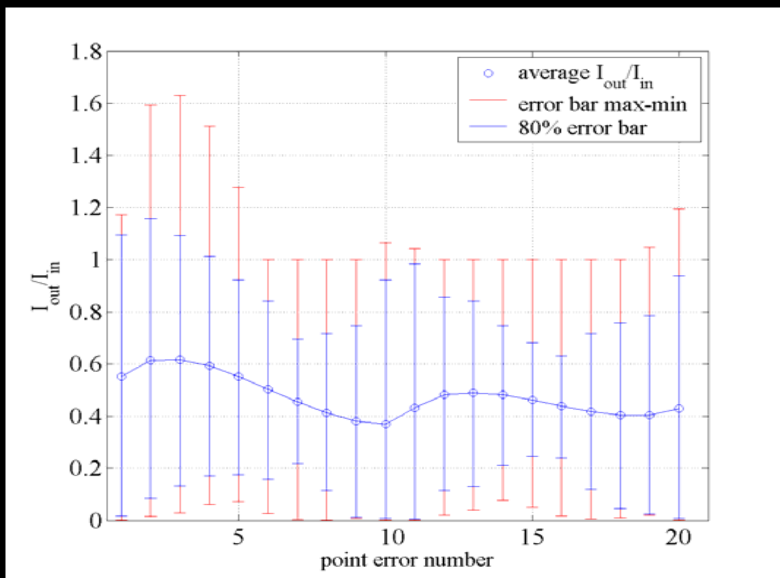




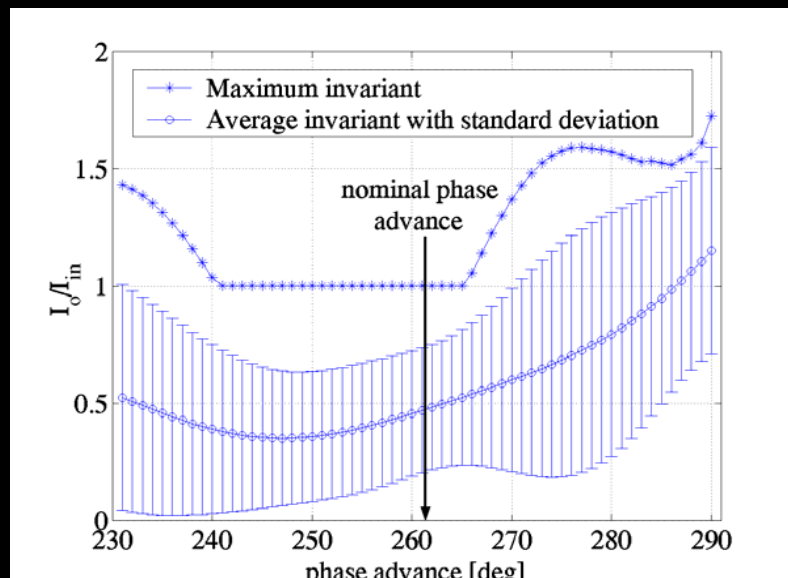
Possible injection errors considered in the horizontal input phase space

INJECTION WITH ERRORS

IN CASE OF INJECTION ERRORS THE FINAL EMITTANCE GROWTH DEPENDS STRONGLY ON THE BETATRON PHASE ADVANCE BETWEEN THE RF DEFLECTORS. FOR THE WORST PHASE ADVANCE VALUES THE EMITTANCE MAGNIFICATION FACTOR MAY EXCEED 100. INSTEAD, FOR THE NOMINAL PHASE ADVANCE OF THE EMITTANCE GROWTH IS CLOSE TO ITS MINIMUM



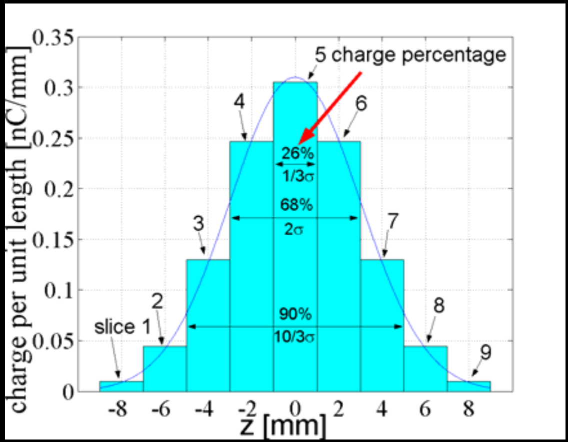
injection errors scan (nominal tune)



tune dependence (fixed injection error)

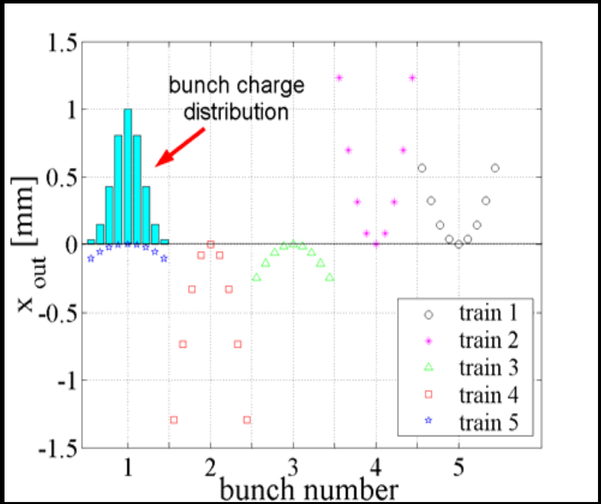
FINITE BUNCH LENGTH

FOR THE CENTRAL PART OF THE BUNCHES THE SCENARIO IS THE SAME THAN IN THE CASE OF ZERO BUNCH LENGTH. HOWEVER, FOR SOME PARTICULAR INJECTION ERRORS, THE BUNCH TAILS CAN CONTRIBUTE TO INCREASE THE TOTAL TRANSVERSE BUNCH EMITTANCES.



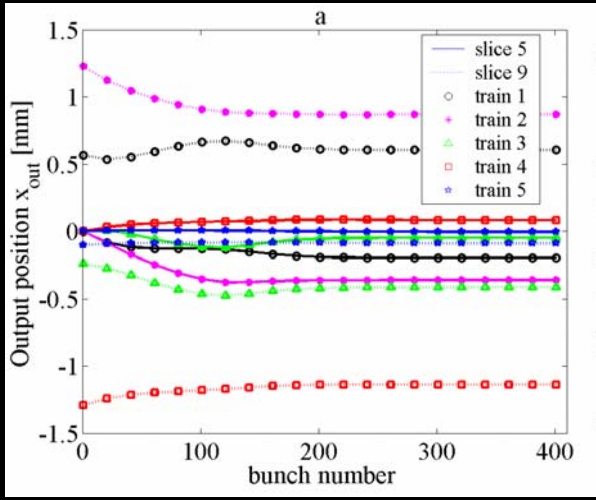
Discretization of the bunch in a finite number of slices

NO BEAM LOADING NO INJECTION ERRORS JUST RF CURVATURE



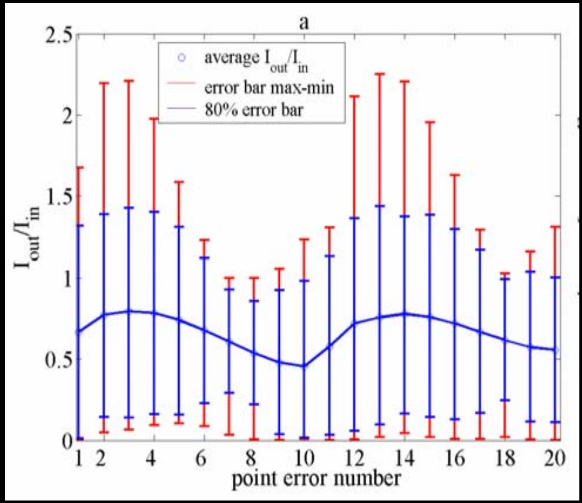
output positions of the bunch slices

BEAM LOADING NO INJECTION ERRORS



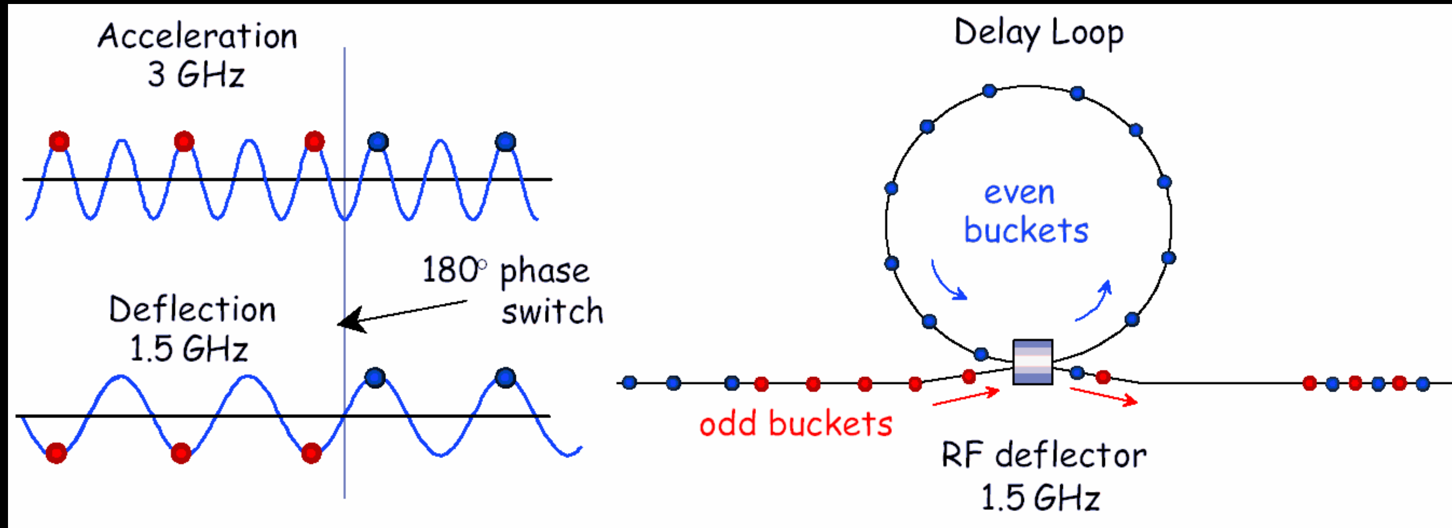
output position of the slices as a function of the bunch number

BEAM LOADING + INJECTION ERRORS



output invariants for the central slices of bunches for any possible injection error

CTF3 DELAY LOOP

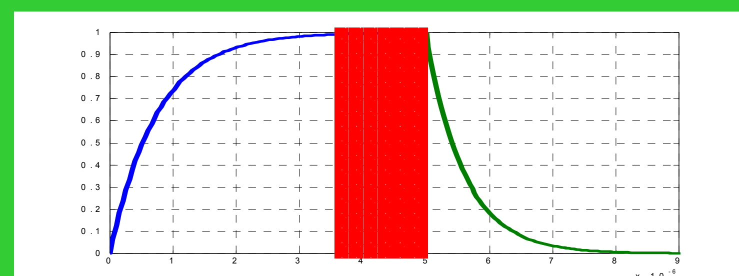


RF PULSE LENGTH = 5μs

REQUIRED DEFLECTING ANGLE = 15mrad
AVAILABLE KLY RF OUTPUT POWER = 20MW
@ beam energy = 300MeV

STANDING WAVE STRUCTURE
T.W. DEFLECTOR SHOULD BE **1.5** METER LONG

CAVITY FILLING TIME HAS TO BE LOWERED, TO REDUCE THE SPREAD OF DEFLECTION ANGLE ALONG THE BUNCHES OF A SINGLE TRAIN



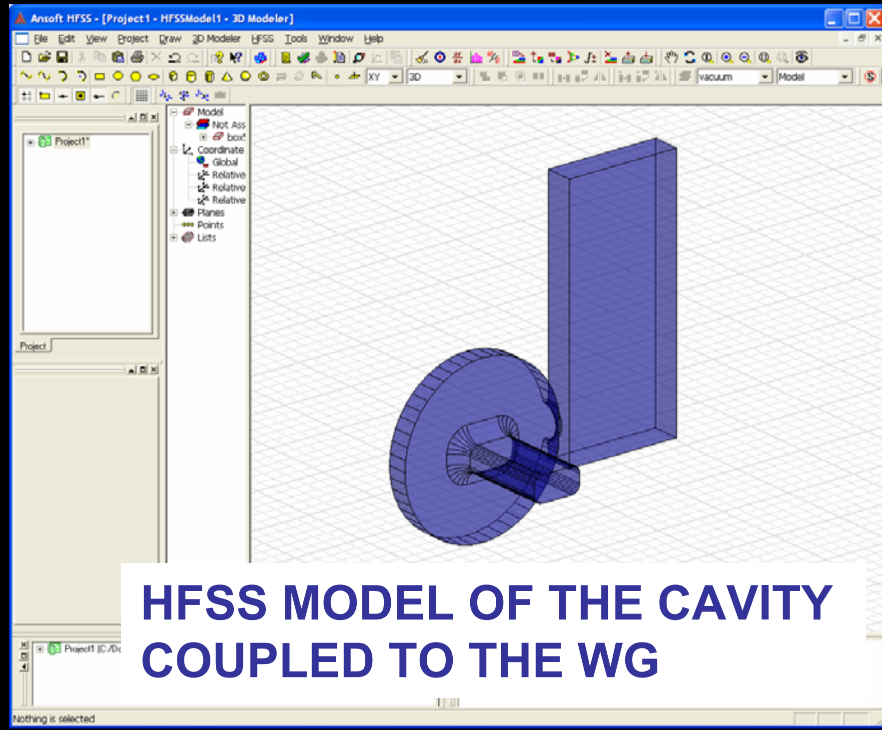
THE CAVITY IS COUPLED THROUGH A HOLE TO THE RECTANGULAR WAVEGUIDE (WR650).

THE INPUT COUPLING COEFFICIENT β IS CHOSEN TO HAVE THE CAVITY LOADED Q:

a) SUFFICIENTLY LOW TO INCRESE AS MUCH AS POSSIBLE THE FILLING TIME

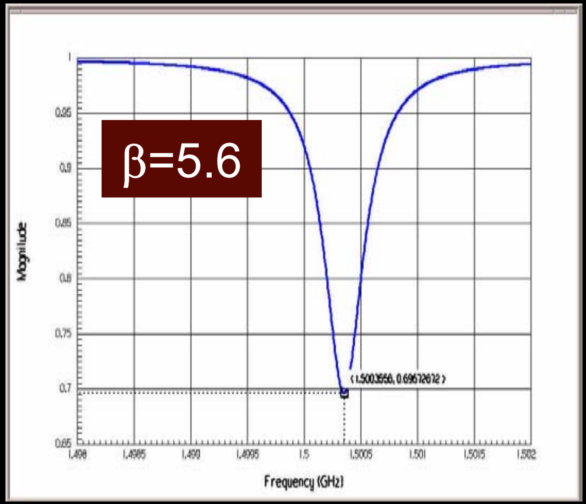
BUT

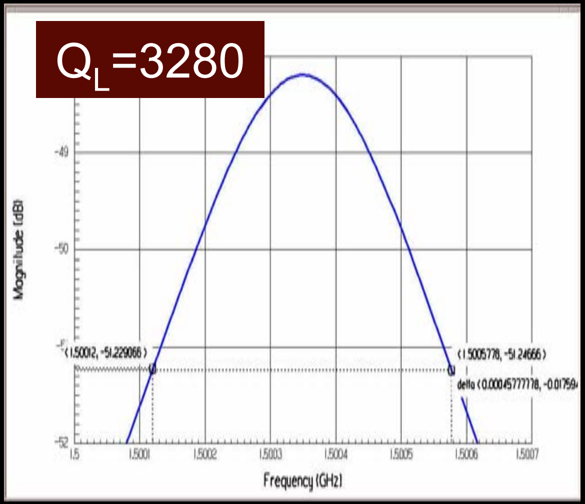
b) SUFFICIENTLY HIGH TO HAVE ENOUGH SHUNT IMPEDANCE TO GET THE REQUIRED KICK

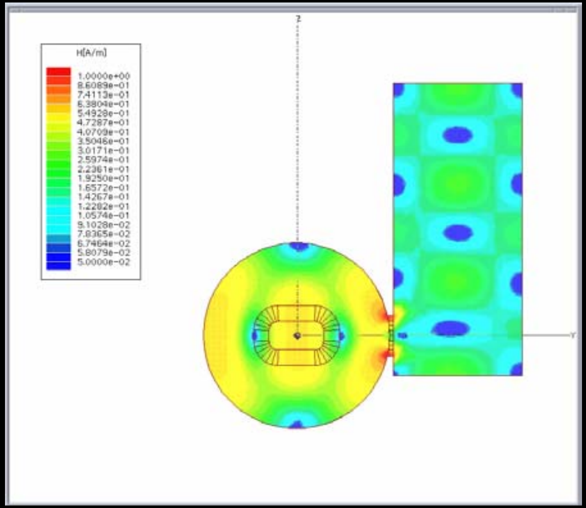


HFSS MODEL OF THE CAVITY COUPLED TO THE WG

REFLECTION AND TRANSMISSION FREQUENCY RESP

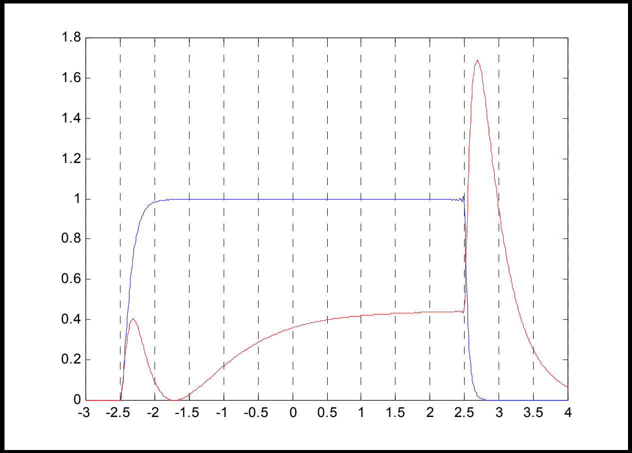


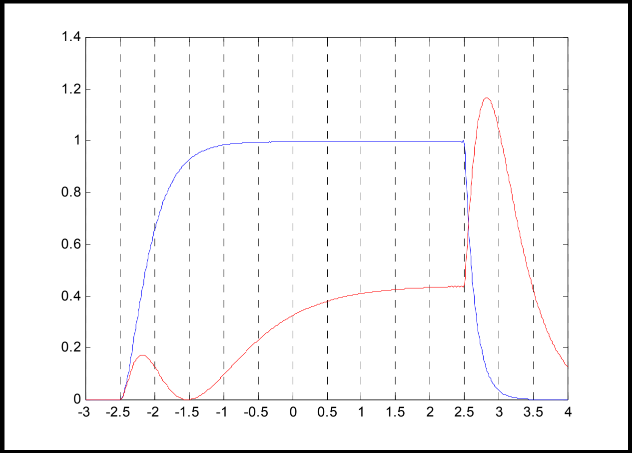




TYPICAL TIME REPONSES OF AN OVERCOUPLED CAVITY TO A PULSED INPUT.
THE AMOUNT OF REFLECTED POWER DEPENDS ON THE β AND ON THE PULSE RISE TIME

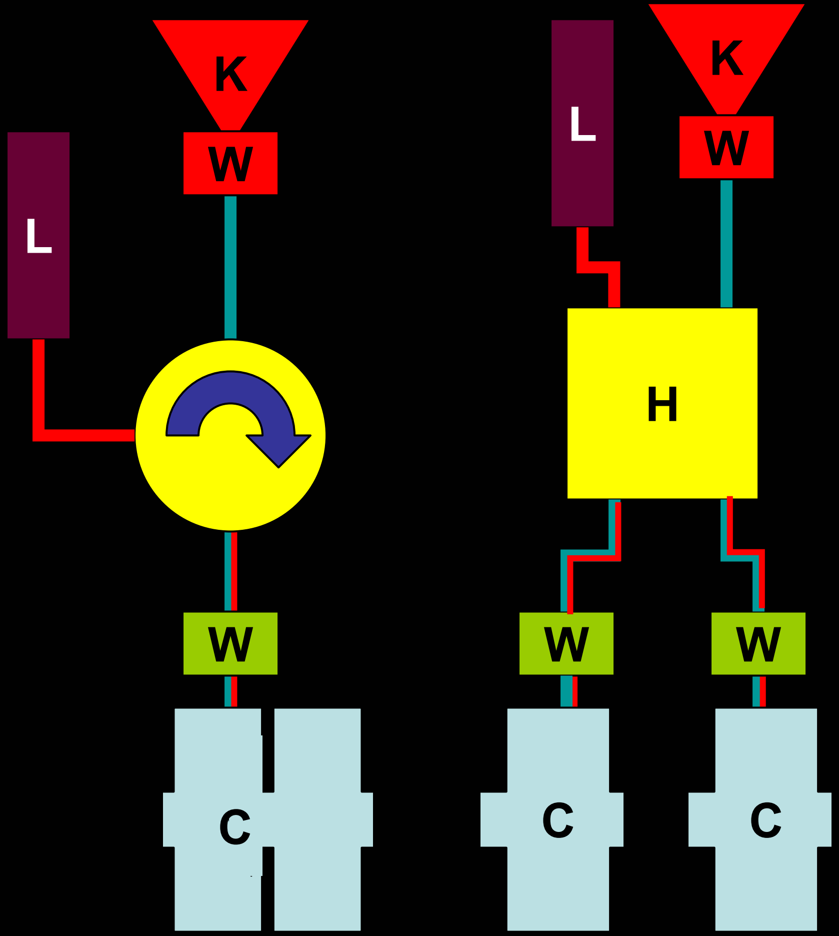
BLUE→ RF INPUT PULSE
RED→ CAVITY REFLECTED POWER



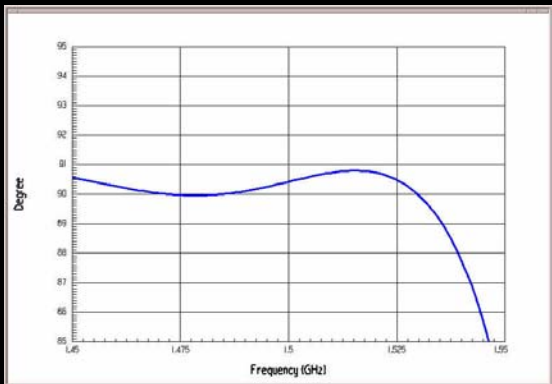


TO PROTECT THE KLYSTRON FROM THE REFLECTED POWER, A CIRCULATOR IS GENERALLY NEEDED

INSTEAD OF CIRCULATOR A HYBRID COUPLER CAN BE USED

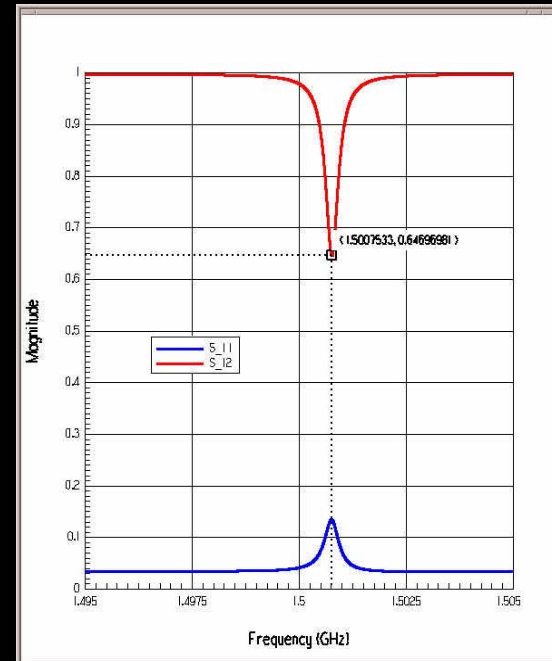


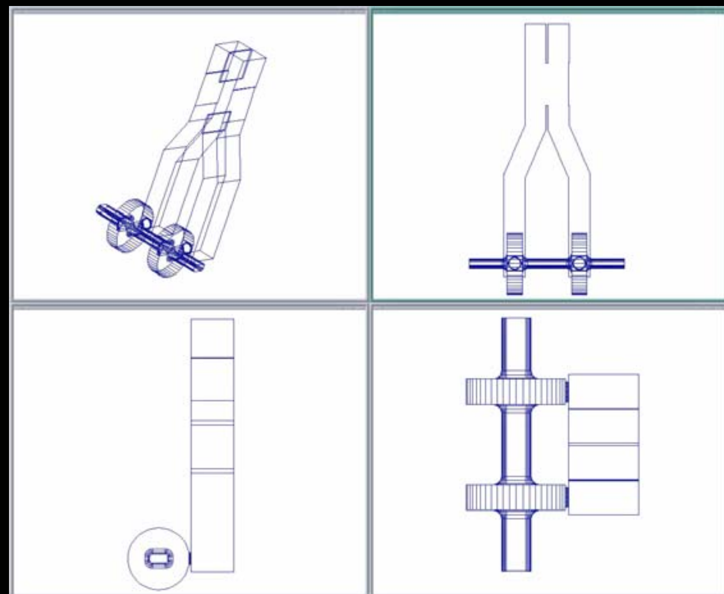
PHASE DIFFERENCE BETWEEN SIGNALS OF THE CAVITY SIDE PORTS WHEN THE DEVICE IS FED FROM KLYSTRON PORT.



SIMULATION RESULTS

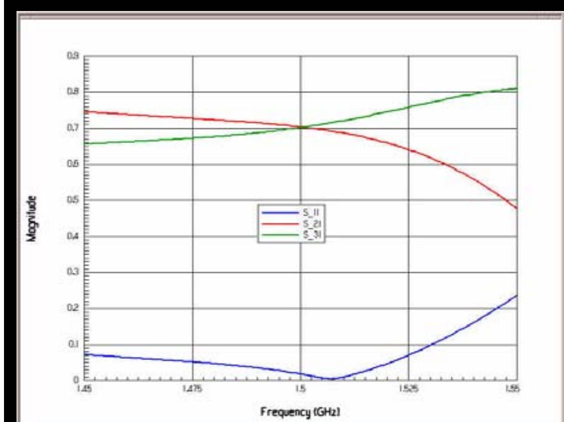
TRANSMISSION BETWEEN INPUT AND OUTPUT PORT (RED) AND REFLECTION AT THE INPUT PORT (BLUE)



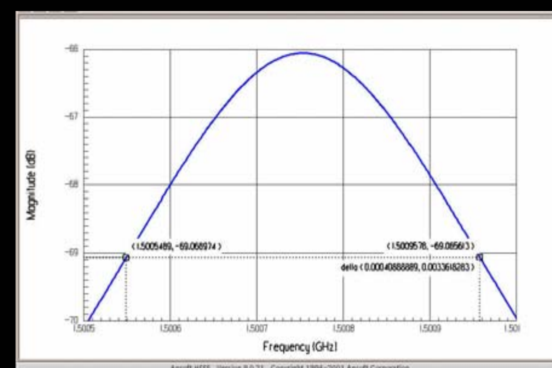


INPUT MODEL FOR SIMULATION

MAGNITUDE OF CAVITY SIDE PORT SIGNALS (GREEN AND RED), AND REFLECTED SIGNAL AT KLYSTRON PORT (BLUE). LEVEL OF OUTPUT SIGNALS ARE BALANCED AT 1.5 GHz.



BANDWIDTH OF THE SYSTEM



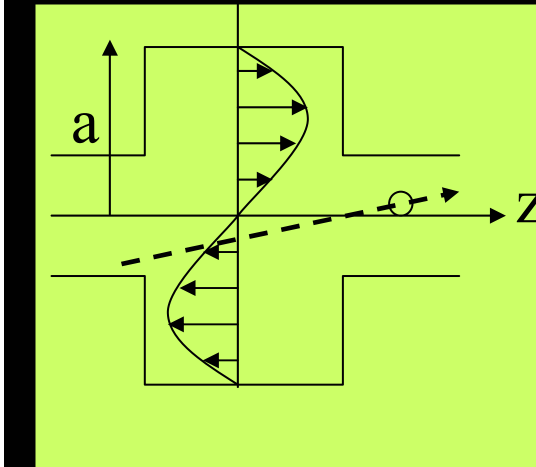
THE BEAM LOADING IN THE DELAY LOOP

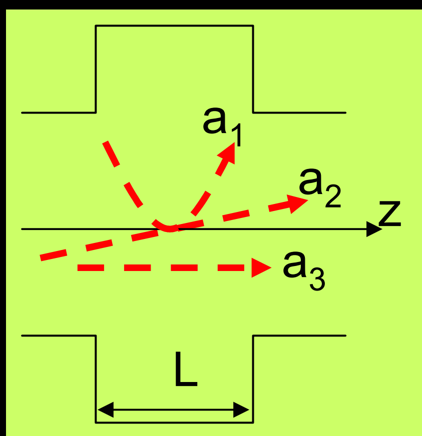
ANALITYCAL APPROACH FOR THE BEAM LOADING CALCULATIONS HAS BEEN USED TO DEVELOP THE TRACKING CODE

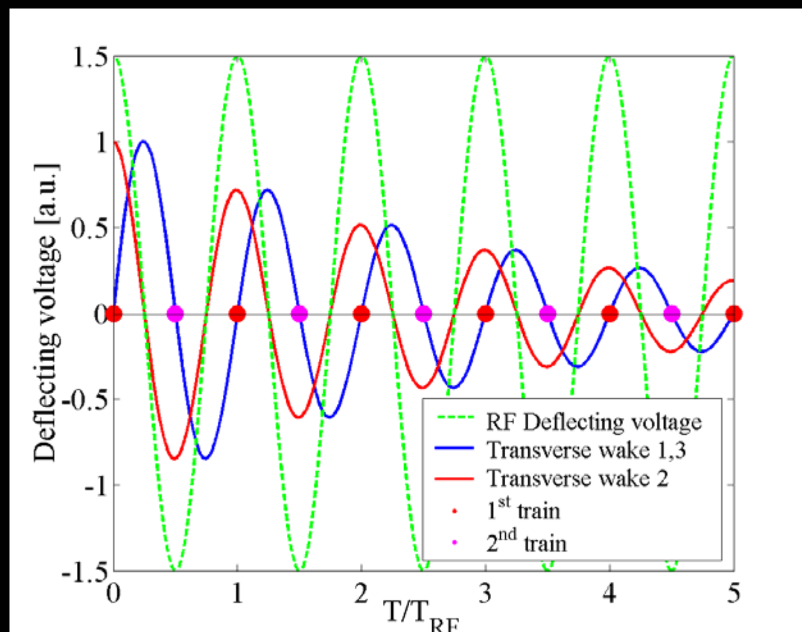
$$\underline{E}_D \begin{cases} E_{D_z} = E_0 J_1\left(\dfrac{p_{11} r}{a}\right)\cos(\vartheta) e^{j\omega t} \\ E_{D_r} = 0 \\ E_{D_\vartheta} = 0 \end{cases}$$

$$\underline{B}_D \begin{cases} B_{D_z} = 0 \\ B_{D_r} = -j\omega \dfrac{a^2}{p_{11}^2 c^2 r} E_0 J_1\left(\dfrac{p_{11} r}{a}\right)\sin(\vartheta) e^{j\omega t} \\ B_{D\vartheta} = -j\omega \dfrac{a}{p_{11} c^2} E_0 J_1'\left(\dfrac{p_{11} r}{a}\right)\cos(\vartheta) e^{j\omega t} \end{cases}$$

Deflecting field

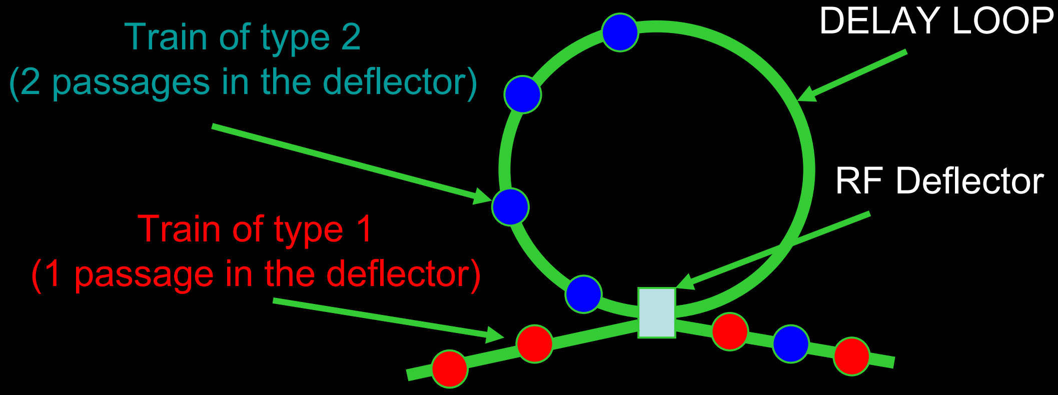


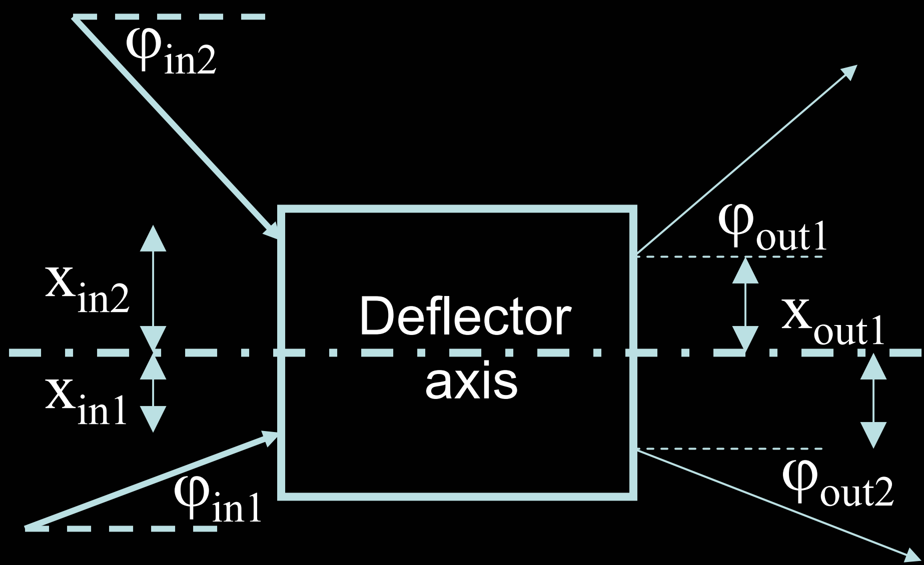




EVERY GENERIC TRAJECTORY INSIDE THE DEFLECTOR CAN BE RECONSTRUCTED FROM THE BASIS OF THE THREE BEAM TRAJECTORIES a1, a2, a3. THE CORRESPONDING WAKE FIELD HAS BEEN CALCULATED.

TRACKING CODE SCHEME AND RESULTS

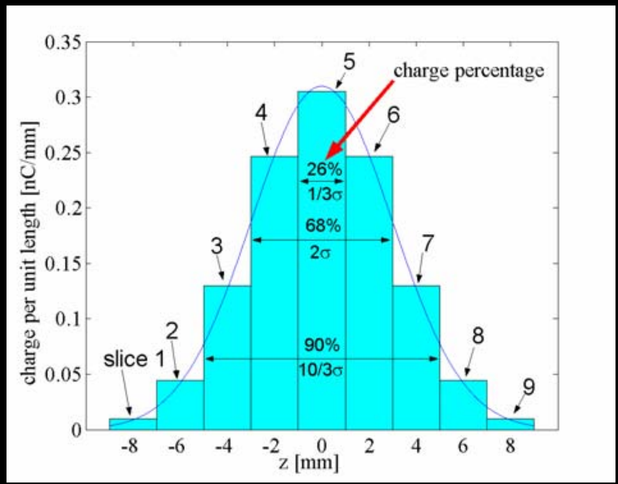




The main effects in terms of final positions and angles of the bunches are given by the finite filling time of the structure. From this point of view two cavities deflectors gives better results.

Effect of different DL phase advances have been investigated showing that DL phases advances near 180 deg can partially cancel the beam loading effects.

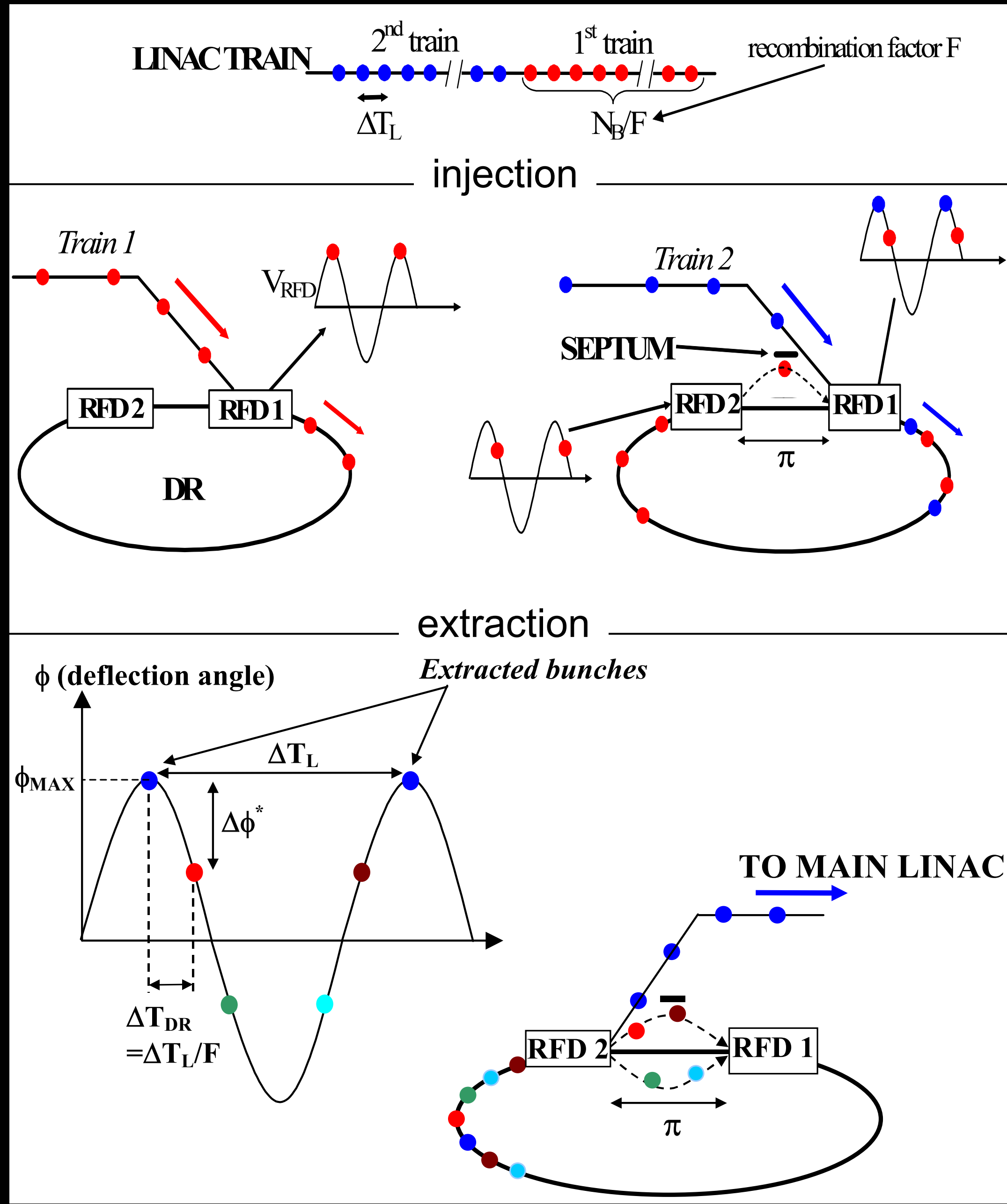
Effect of injection errors in position have been investigated showing that the beam loading effects do not increase the initial errors.



Discretization of the bunch in a finite number of slices

TESLA DAMPING RING

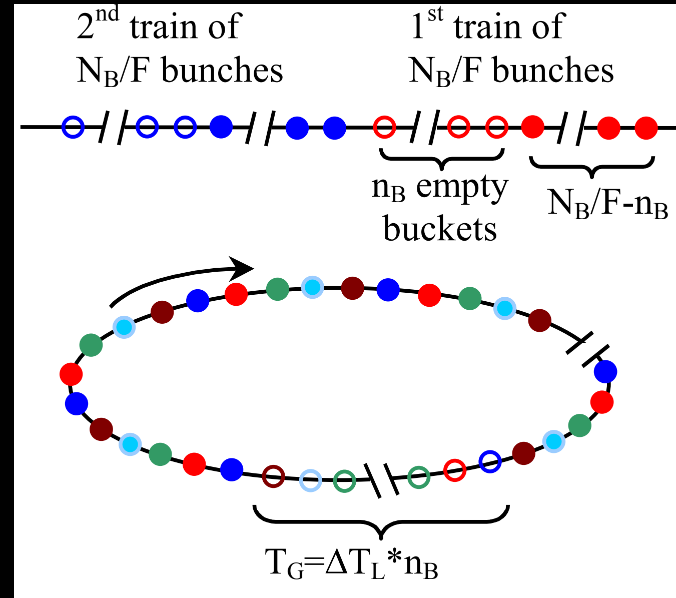
THE PROPOSED INJECTION AND EXTRACTION SCHEMES ALLOW TO REDUCE THE RING LENGTH BY A FACTOR F WITH RESPECT TO THE LINAC TRAIN LENGTH. LIKE IN THE CTF3 COMBINER RING THE FIRST GROUP OF RF DEFLECTORS ALLOWS TO INJECT OR TO EXTRACT THE BUNCHES AND THE SECOND GROUP CLOSES THE ORBIT BUMP DUE TO THE RESIDUAL KICK.



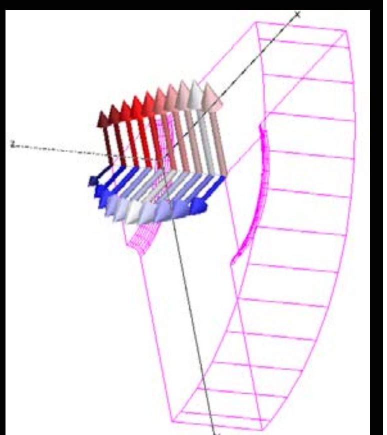
	QUANTITY	SYMBOL	VALUE
LINAC	Number of bunches	N_B	2820
	Bunch spacing	ΔT_L	337 ns
	Total length of train	$L_B = N_B * \Delta L_L$	~285 km
DR	Recombination factor	$\mathbf{F}$	**20**
	Total length	$L_{DR} = L_B/F \pm \Delta L_L/F$	~14 km
	Bunch spacing	$\mathbf{\Delta T_{DR} = \Delta T_L/F}$	**16.85 ns**
RF DEFLECTOR	Number	N_D	4 (2 inj. + 2 extr.)
	Frequency	$\mathbf{f_{RF} = n*1/\Delta T_L}$	**~1.3 GHz (= 438*1/ ΔT_L)**
	Delta deflection	$\Delta\phi^*$	0.6 mrad (@5 GeV)
	deflection	$\mathbf{\phi_{MAX} = \Delta\phi/ [1-\cos(2\pi/F)]}$	**≥12 mrad!! ($\Delta\phi/\phi_{MAX} \cong$ 5%)**

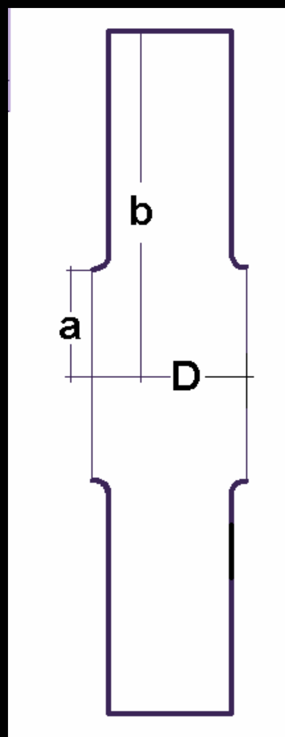
$\tau_F \leq$ 16.85 ns!

1) GAP IN THE RING BUNCH FILLING
2) T.W. SRUCTURE

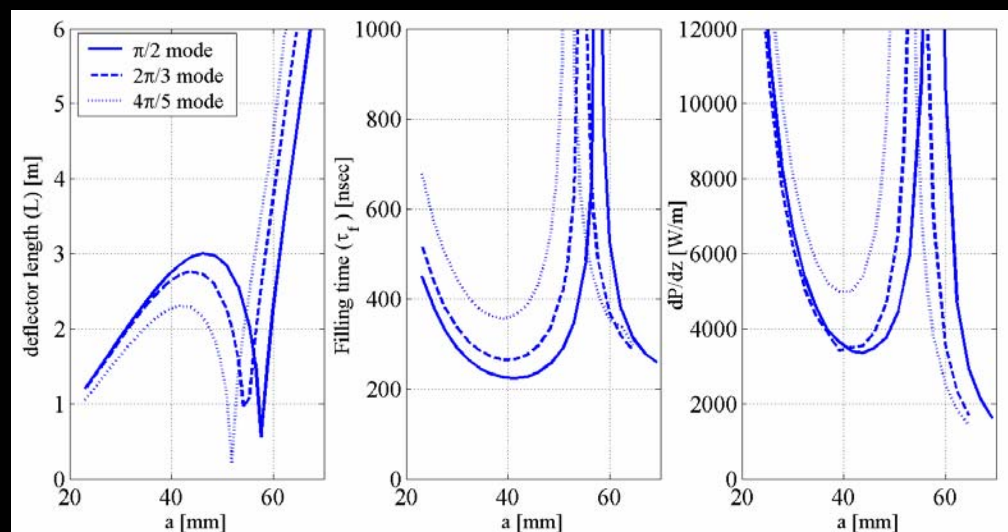


π/2 MODE	
a [mm]	41.80
b [mm]	133.00
d [mm]	58.06





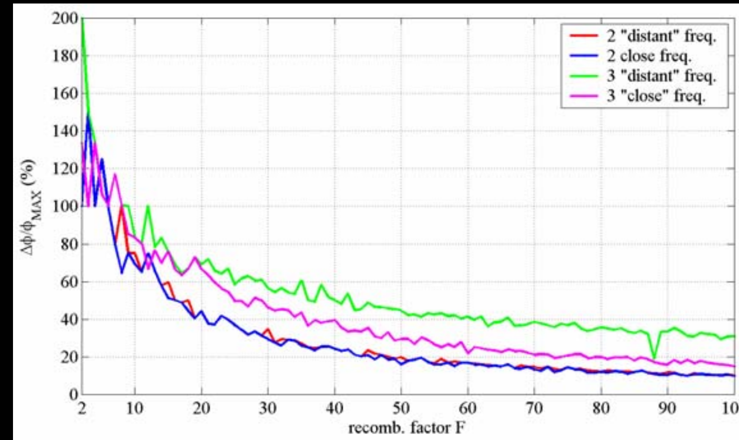
Scaling laws have been applied to investigate the RF deflector properties in term of length, filling time and dissipated power as a function of the iris diameter. Two optimized cells operating on the $\pi/2$ and $\pi/3$ modes can be adopted.



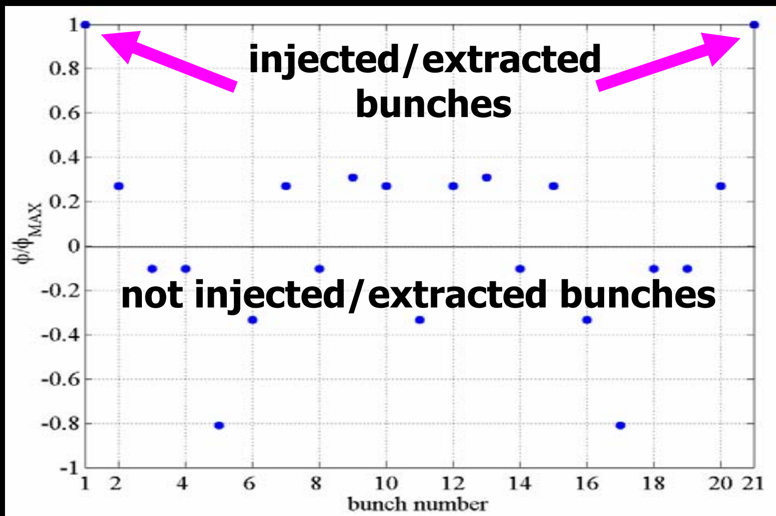
@ ϕ_{MAX} = 1 mrad , P_{RF}=5 MW

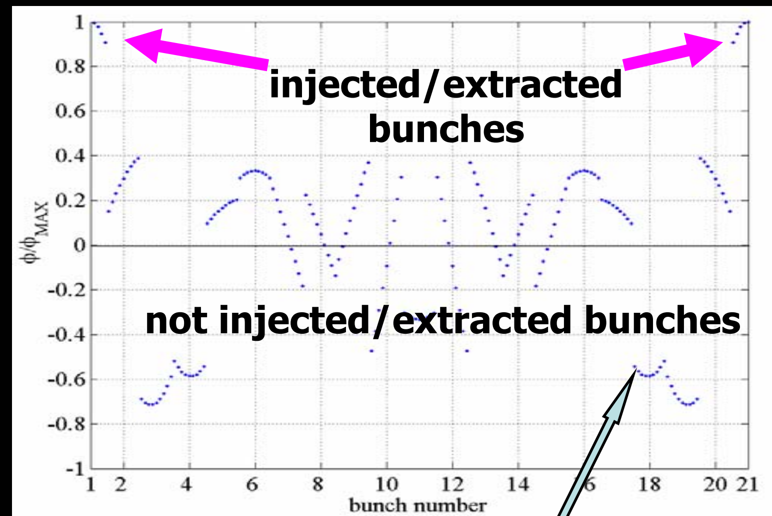
INJECTION/EXTRACTION WITH 2 OR MORE RF FREQUENCIES NEAR 1.3 GHZ

For a given value of ϕ_{MAX}, this technique allows to greatly increase the ratio $\Delta\phi/\phi_{MAX}$.

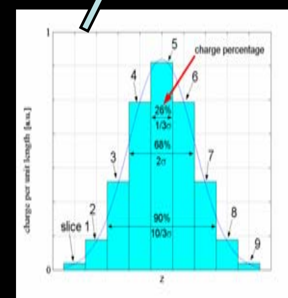


3 frequencies case, F=20

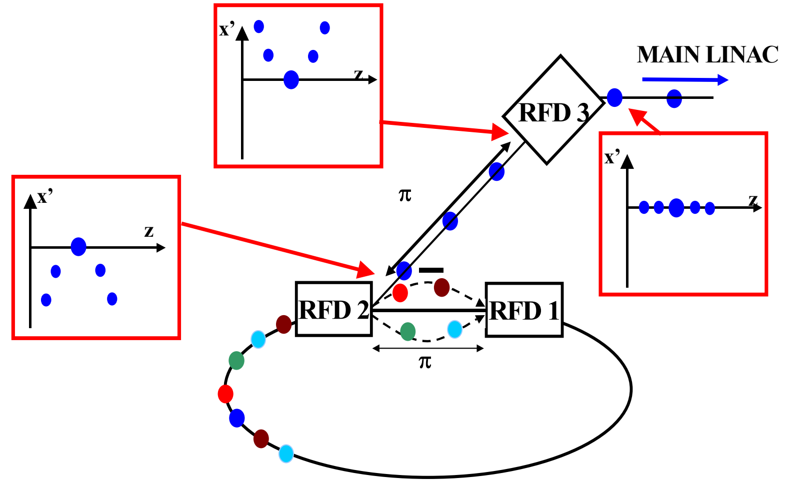




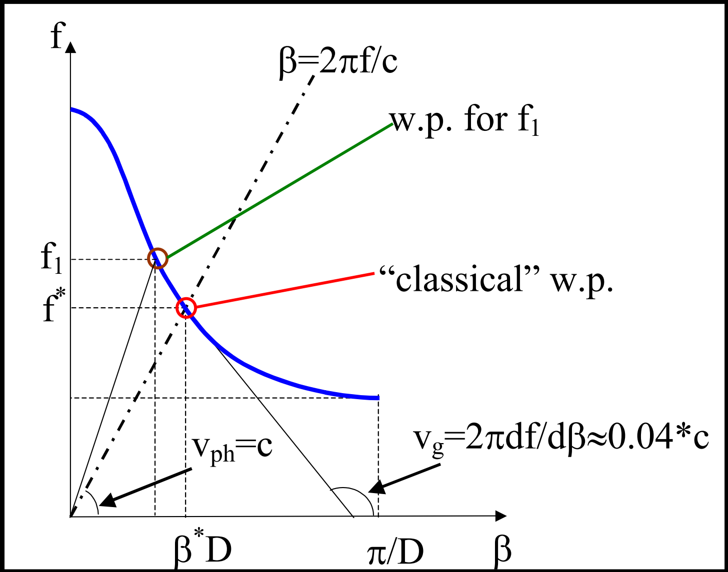
F=20, 3 RF frequencies, σ_z=6mm					
P_{RF} [MW]	Number of Deflectors	fRF [GHz]	RFD length [m]	Filling time [ns]	$\Delta\phi/\phi_{MAX}$
9	**6 inj. + 6 extr**	**f_{RF1}=1317.5** **f_{RF2}=1296.7** **f_{RF3}=1290.8**	**0.78**	**58**	**57%**



Compensation of RF curvature effect within the bunch after extraction.



Two or three "closer" RF frequencies can also be used. In this case we could feed just a single RF deflector with two (or three) frequencies. Looking at the typical dispersion curve of a TW RF deflector we can excite the structure at the frequency (f_1) near the nominal one (f^*).



Effects of errors have been analized to determine the tolerances on the stability of the magnets power supplies and the acceptable RF amplitude and phase jitter.