RF deflector-based sub-ps beam diagnostics: application to FELs and advanced accelerators

David Alesini

(LNF-INFN, Frascati, Rome)

ERICE, October 9-14, 2005

OUTLINE

1) Bunch length
2) Longitudinal phase space measurements
3) Slice emittance measurements
4) Beam manipulation: ultra-short bunch generation
5) Diagnostics with a circular polarized RF deflector

Diagnostics & Manipulation

1) Traveling wave deflectors
2) Standing wave deflectors

RF Deflecting structures

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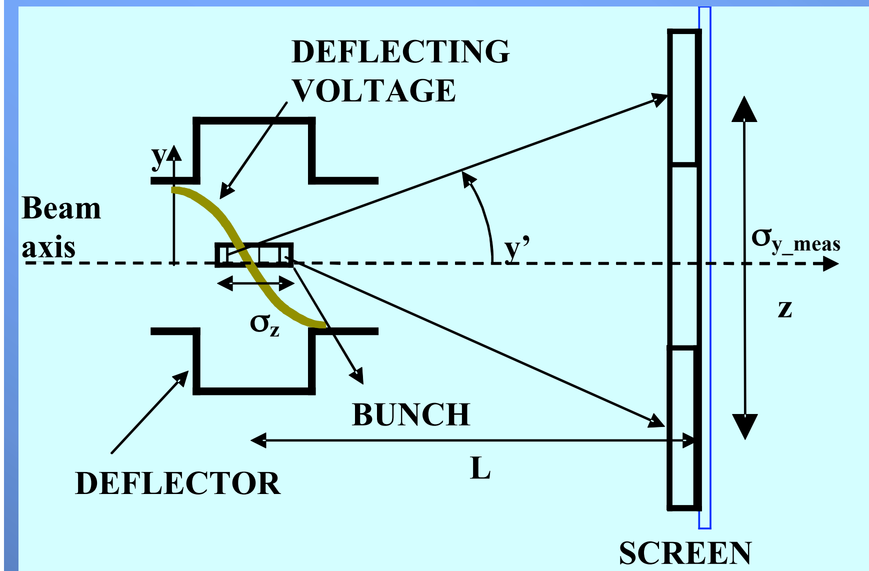
1) Bunch length measurements: ideal case

[G. A. Loew, SLAC-PUB 135,1965]

PRINCIPLE



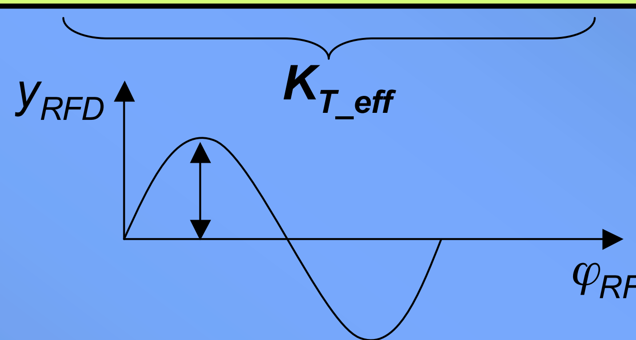
In the ideal case the y-z correlation on the screen is given by the deflector voltage and optical functions.

φ_{RF} is the RF phase (at zero-crossing $\varphi_{RF}=0$)

$$\sigma_{y\_RFD} = \underbrace{\sigma_z \frac{\omega_{RF}}{c} \cos\varphi_{RF}}_{RFD} \underbrace{\frac{V_T}{E/e} \underbrace{\sqrt{\beta_D \beta_S}\,\sin(\Delta\Phi)}_{Opt.}}_{L}$$

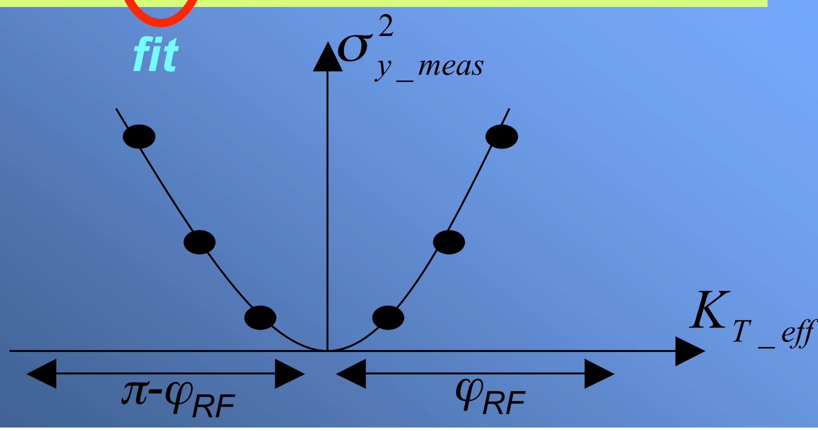
CALIBRATION

$$y_{RFD} = \underbrace{\left[\frac{V_T}{E/e} \sqrt{\beta_D \beta_S}\,\sin(\Delta\Phi) \right]}_{K_{T\_eff}} \sin\varphi_{RF}$$



IDEAL MEASUREMENT

$$\sigma^2_{y\_meas} = \sigma^2_{y\_RFD} = \sigma^2_z \left[\omega^2_{RF} (\cos\varphi_{RF})^2 / c^2 \right] K^2_{T\_eff}$$



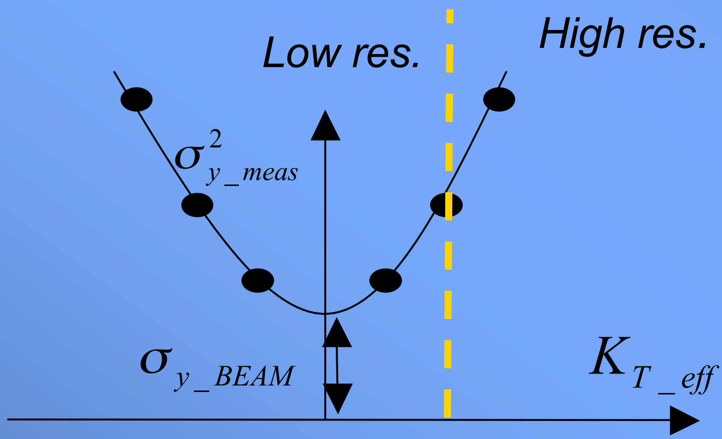
1) Bunch length measurements: sources of errors (1/2)

a) ***Vertical beam size***

$$\sigma_{y\_BEAM} = \sqrt{\beta_S \varepsilon} \Rightarrow \sigma_{y\_meas} = \sqrt{\sigma^2_{y\_RFD} + \sigma^2_{y\_BEAM}} \Rightarrow$$

$$V_T \omega_{RF} \sqrt{\beta_D} \sin(\Delta\Phi) \geq \frac{c(E/e)\sqrt{\varepsilon}}{\sigma_z}$$

$$\sigma_{z\_RES} = \frac{c(E/e)\sqrt{\varepsilon}}{V_T \omega_{RF} \sqrt{\beta_D} \sin(\Delta\Phi)}$$



b) ***Bunch energy spread:***

[P.Emma, et al. LCLS,TN-00-12,2000]

e.g. energy variation along the bunch linearly correlated in time $E=E_0(1+\sigma_E/\sigma_z z)$

$$\sigma_{y\_ES} = \sigma_E \frac{V_T \sin\varphi_{RF}}{E/e} \sqrt{\beta_D \beta_S} \sin(\Delta\Phi)$$

$$\sigma_{y\_meas} = \left|\sigma_{y\_RFD} + \sigma_{y\_ES}\right|$$

$\varphi_{RF} = 0$ requires an **on-axis screen**

measure the spot size for two phases $\varphi=\varphi_0$ and $\varphi=\varphi_0+\pi$ and **average the two**

1) Bunch length measurements: sources of errors (2/2)

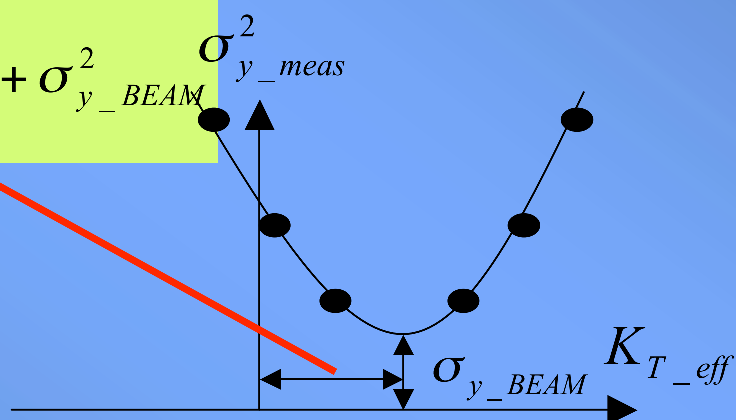
c) *Transverse wakefields*: induced upstream of the deflector by the accelerating structures or (especially with an off-axis kick) between the deflector and the screen. They can cause:

[P.Emma, et al. LCLS,TN-00-12,2000]

1) **a linearly correlated energy spread** within the bunch ⇨ See previous case for correction

2) **linear correlation between y and z** ($y=\sigma_y/\sigma_z z$)

$$\sigma^2_{y\_meas} = \sigma_z^2 \omega_{RF}^2 \cos^2\varphi_{RF}\left(K_{T\_eff} + \frac{\sigma_y}{\sigma_z}\frac{c}{\omega_{RF}\cos\varphi_{RF}}\right)^2 + \sigma^2_{y\_BEAM}$$



In this case the transverse cavity can be used not only as a bunch length diagnostic but also as a tool for measuring transverse wakefield effects and possibly correcting them with orbit bumps

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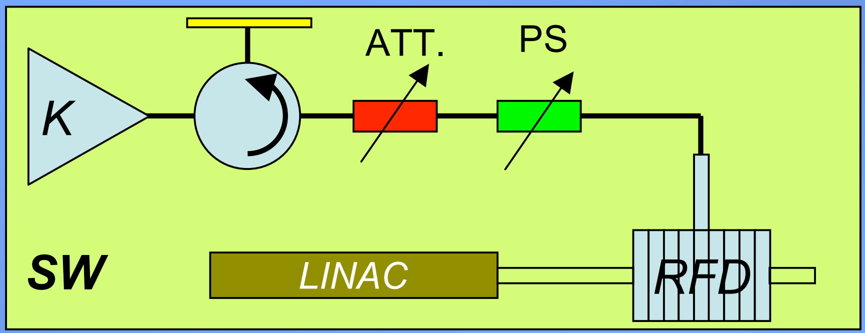
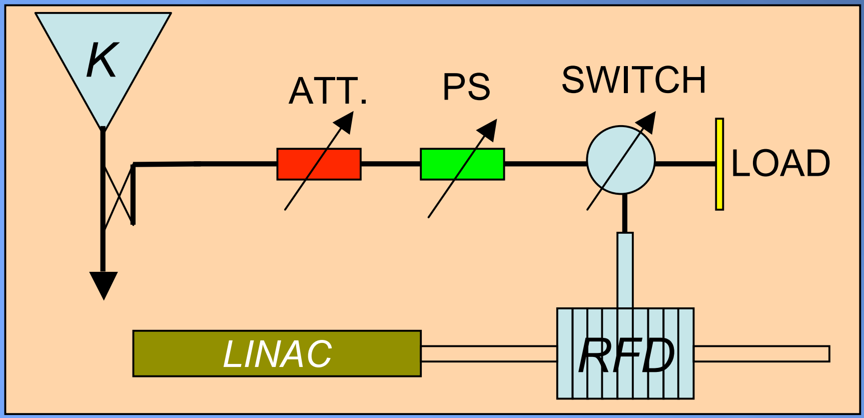
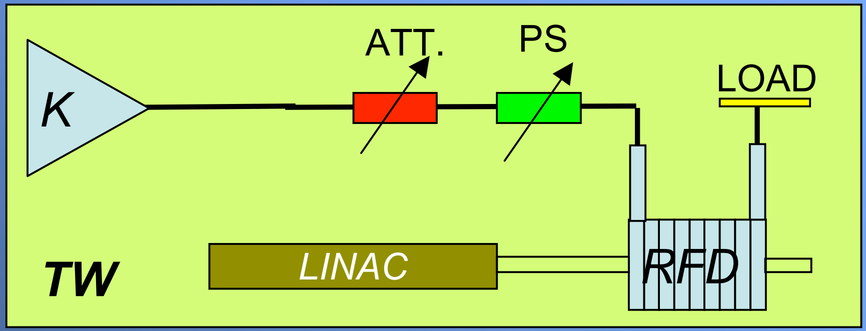
1) Bunch length measurements: power schemes (e.g.)







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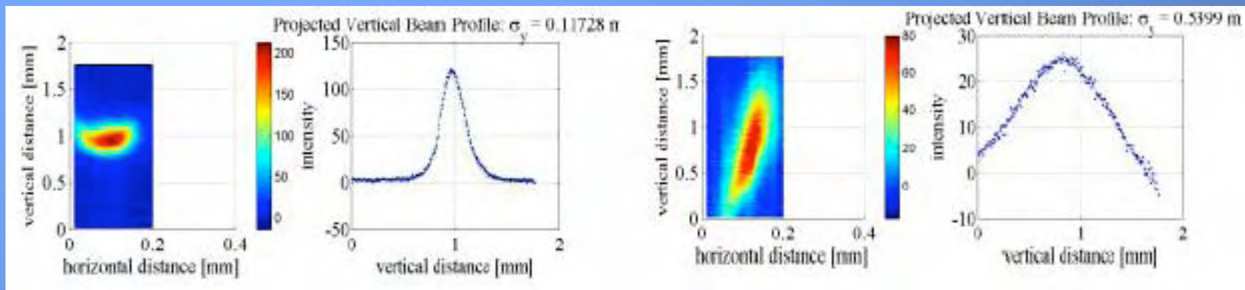
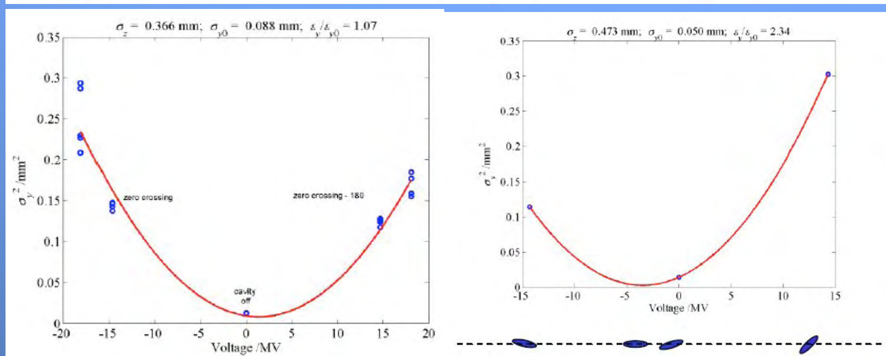
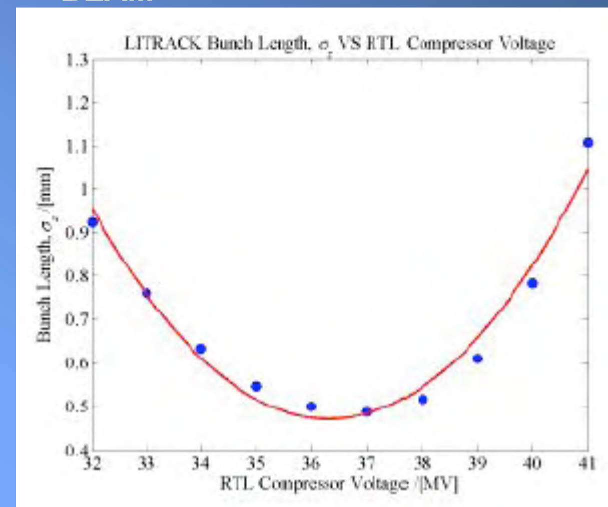
1) Bunch length measurements: experimental results

a) SLAC LINAC *[P. Emma et al., EPAC 2002]*





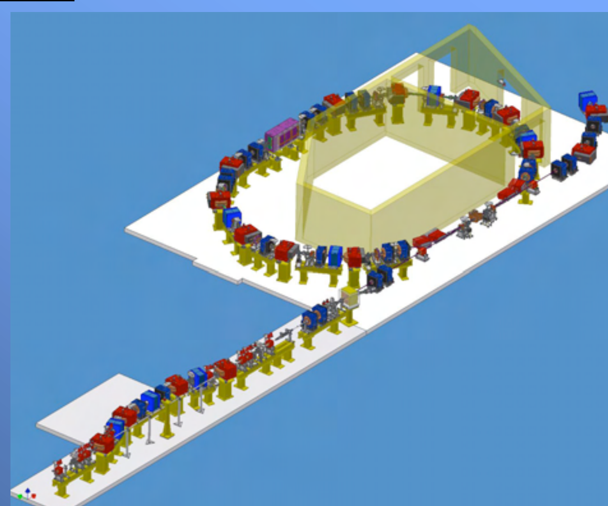
2.44 m TW RFD;
P_{IN_MAX}=20 MW;
E_{BEAM}=28GeV.

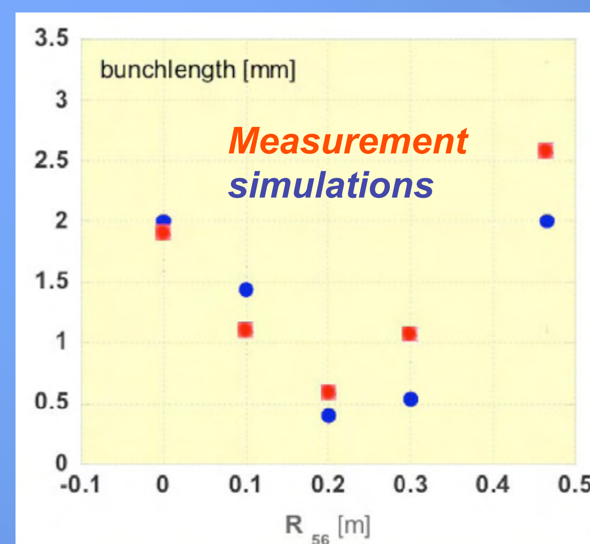


b) CTF3 (CERN) INJECTOR *[A. Ghigo et al., PAC 2005]*

0.4 m TW RFD
E_{BEAM}=100 MeV
n. bunches>600

Possibility of a triggered CAMERA for single bunch beam image





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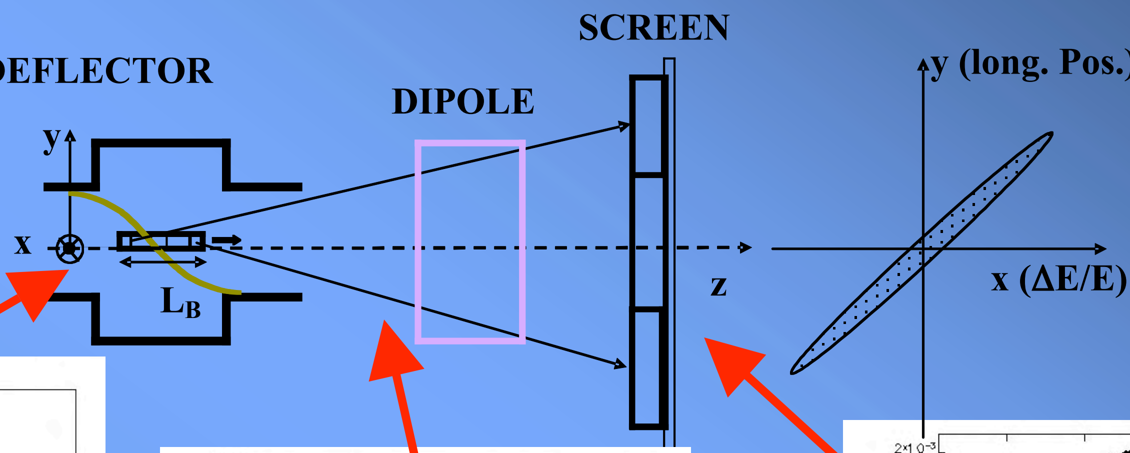
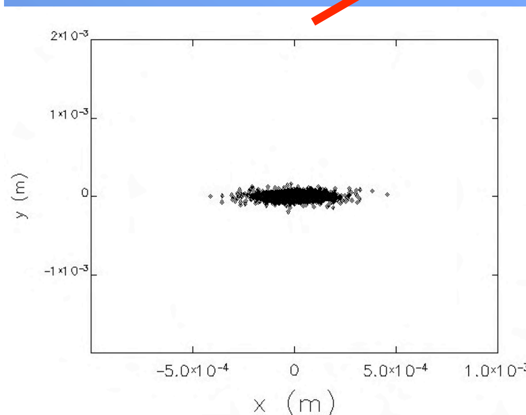
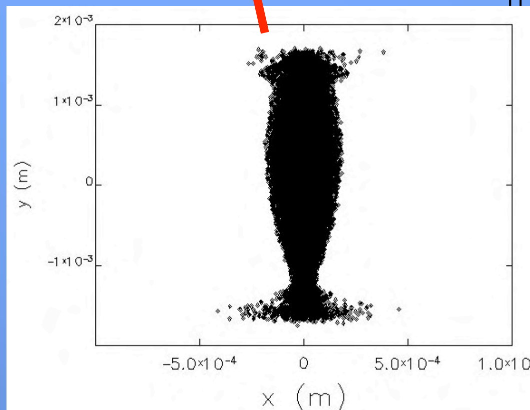
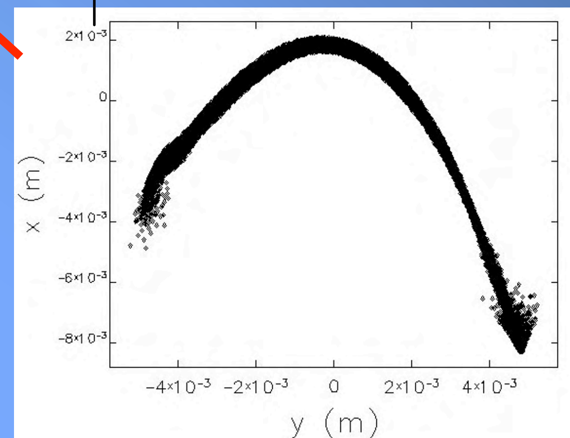
2) Longitudinal phase space measurements



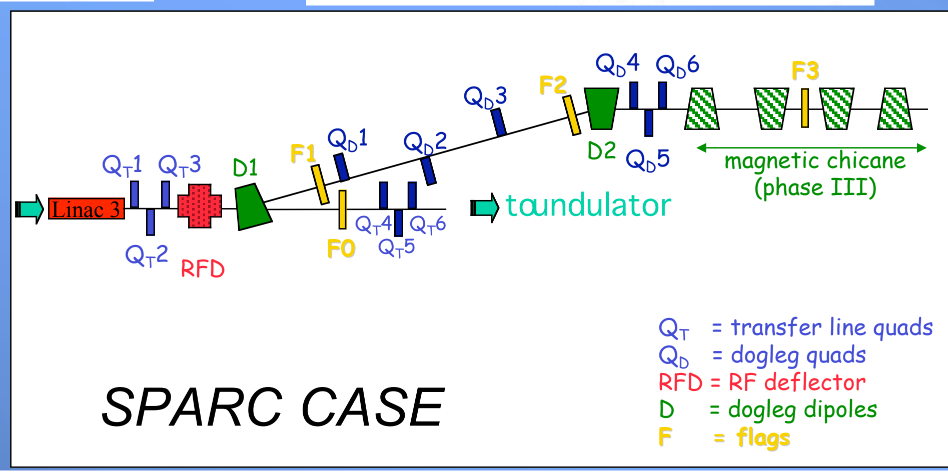
$$\left.\frac{\Delta E}{E}\right|_{res} = \frac{\sqrt{\varepsilon \beta_{H\_S}}}{D_S}$$



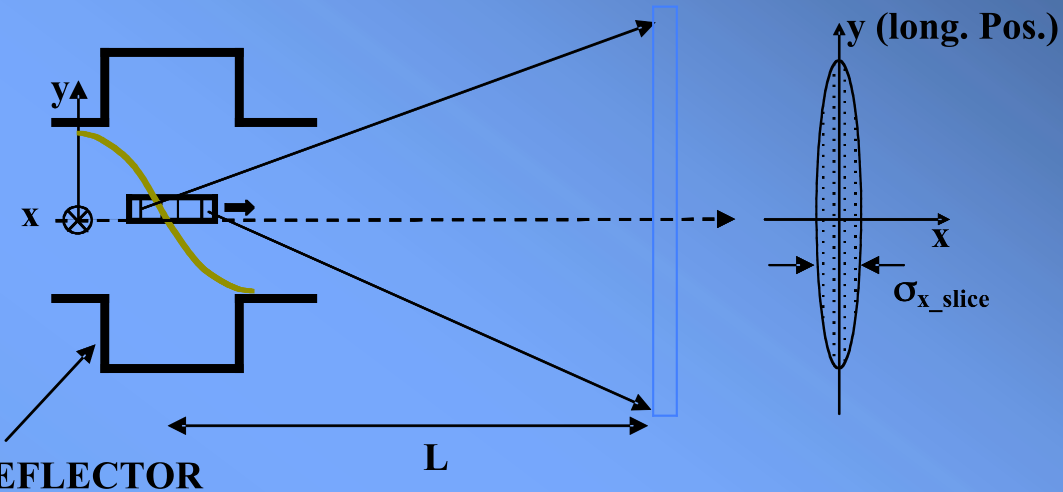


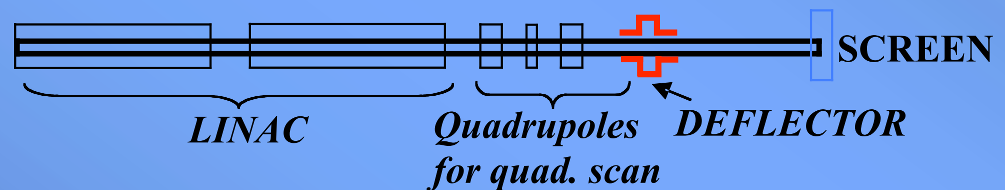


Simulations (C. Vaccarezza, LNF)



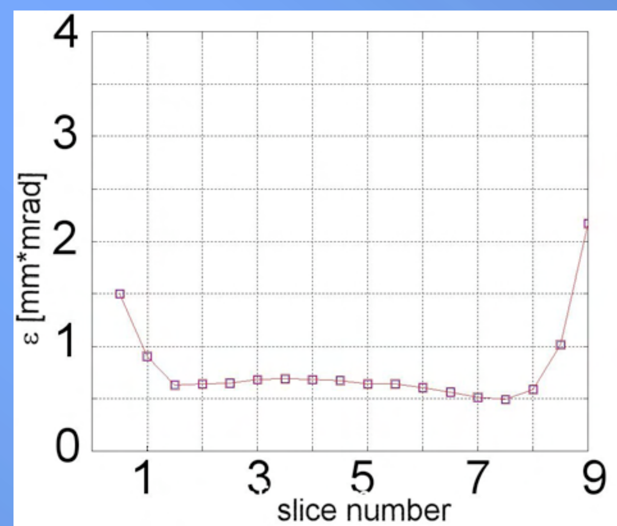
3) Beam slice emittance

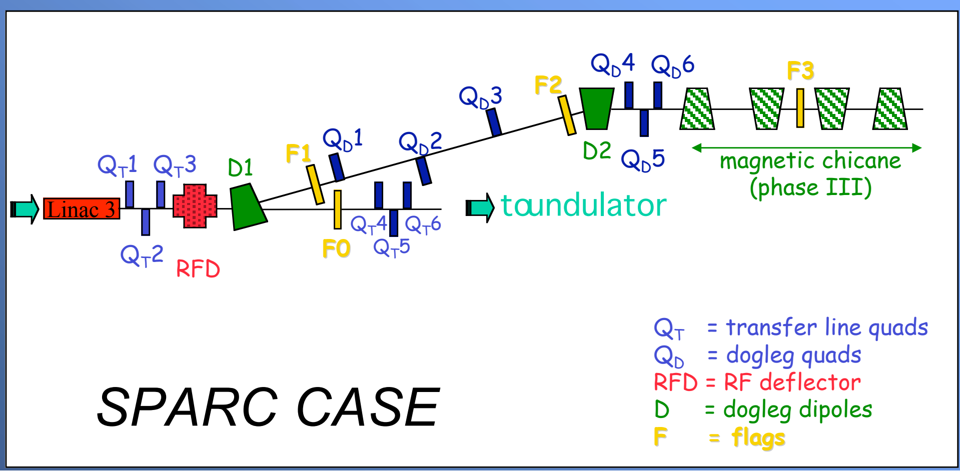




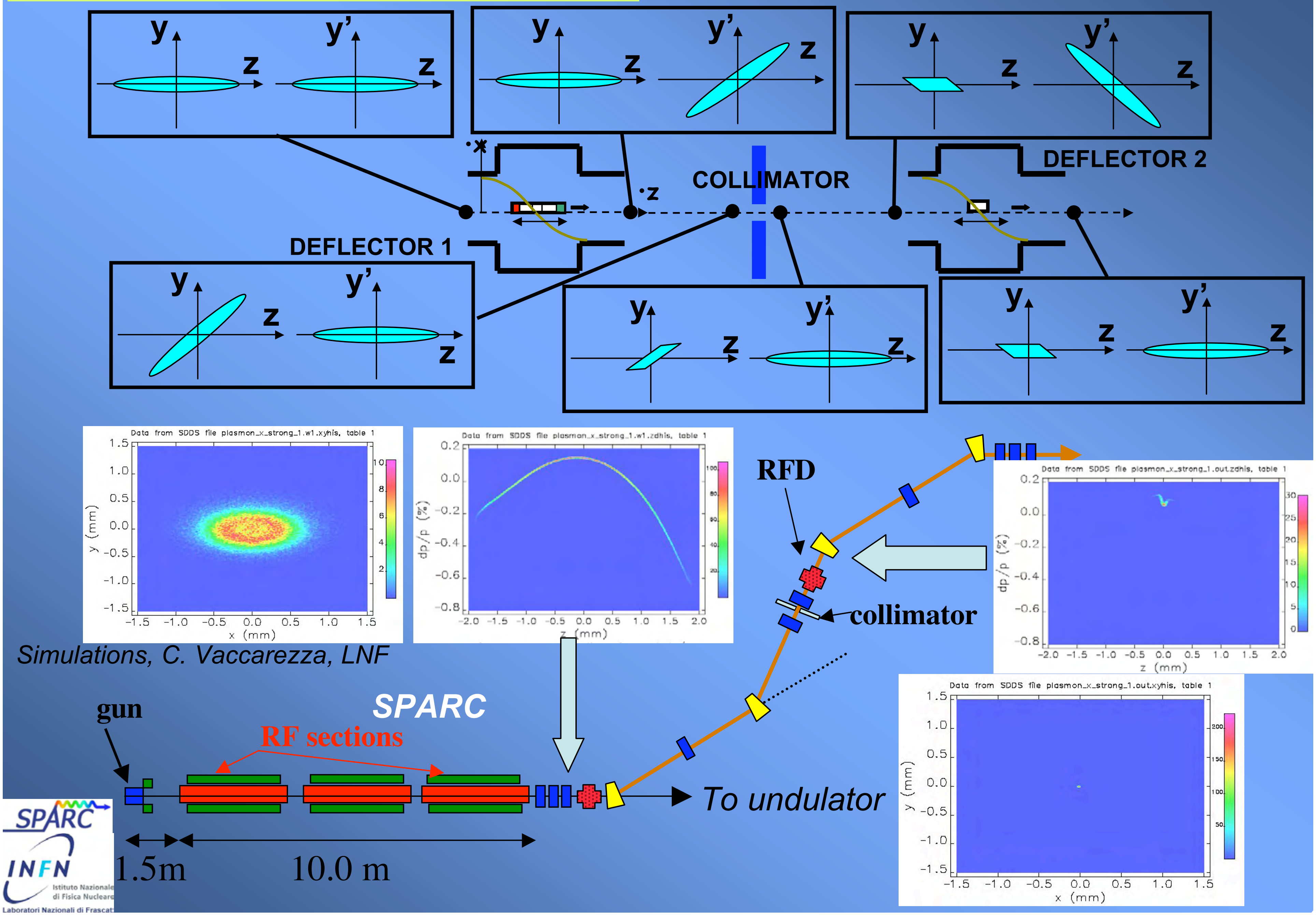
Preliminary experimental results at VUV-FEL, DESY, K. Honkavaara, WG2

Simulations (C. Vaccarezza, LNF)





4) Ultra-short bunch generation



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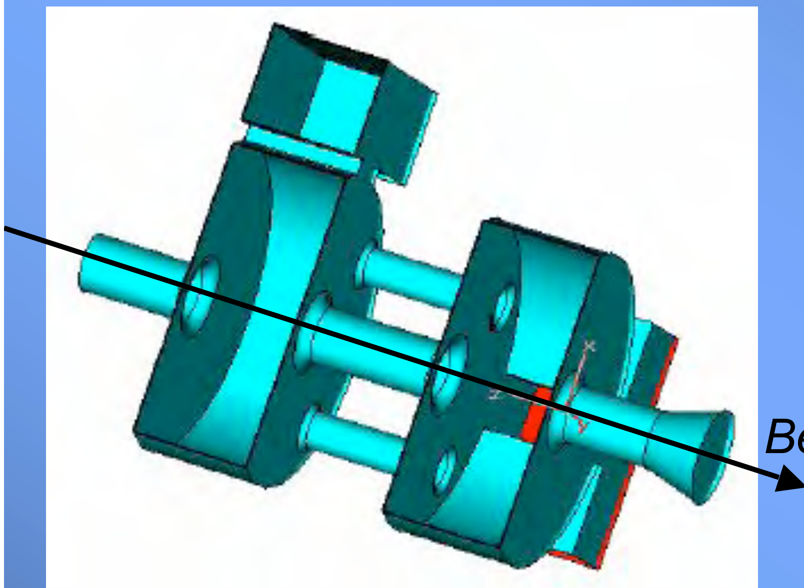
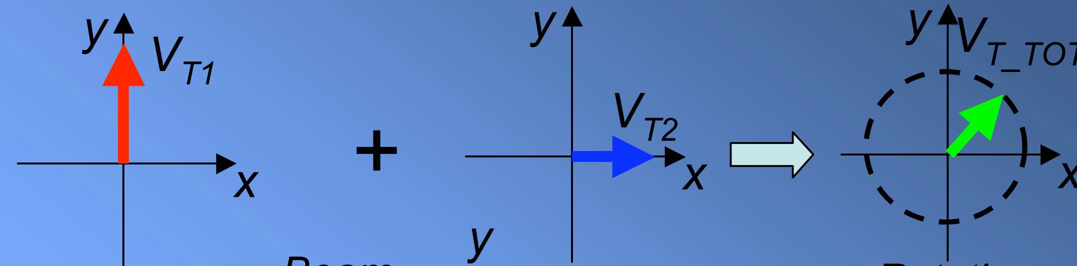
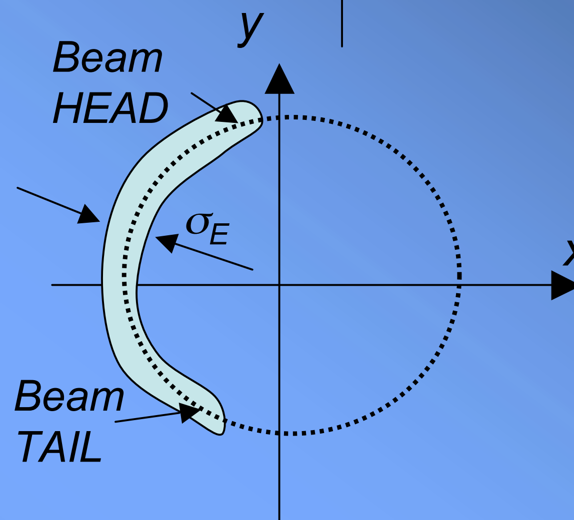
5) Diagnostics with a circular polarized RF deflector

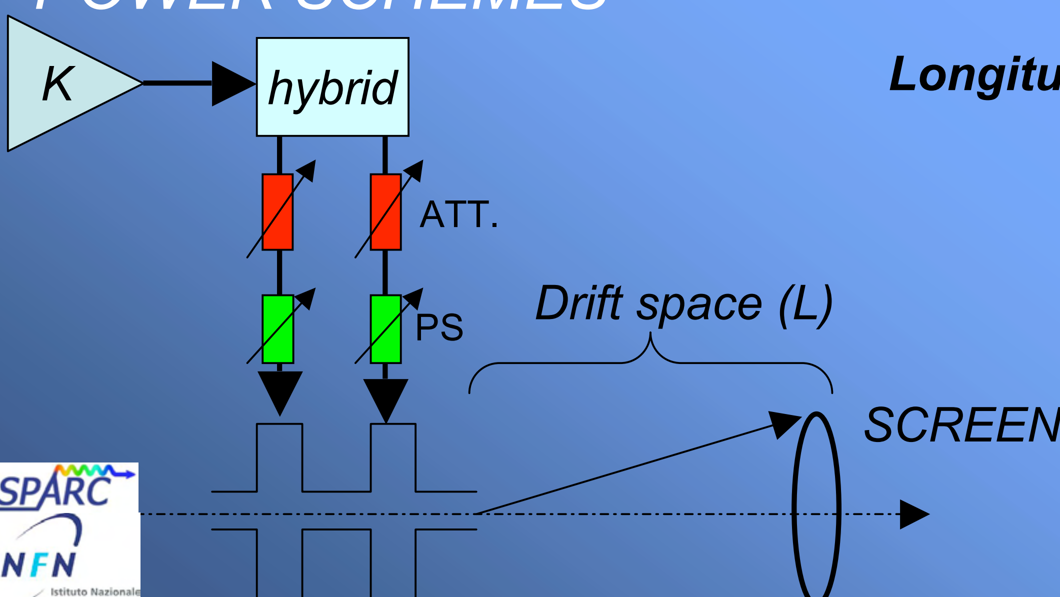
[Haimson et al, AIP, 647, 2002]







POWER SCHEMES



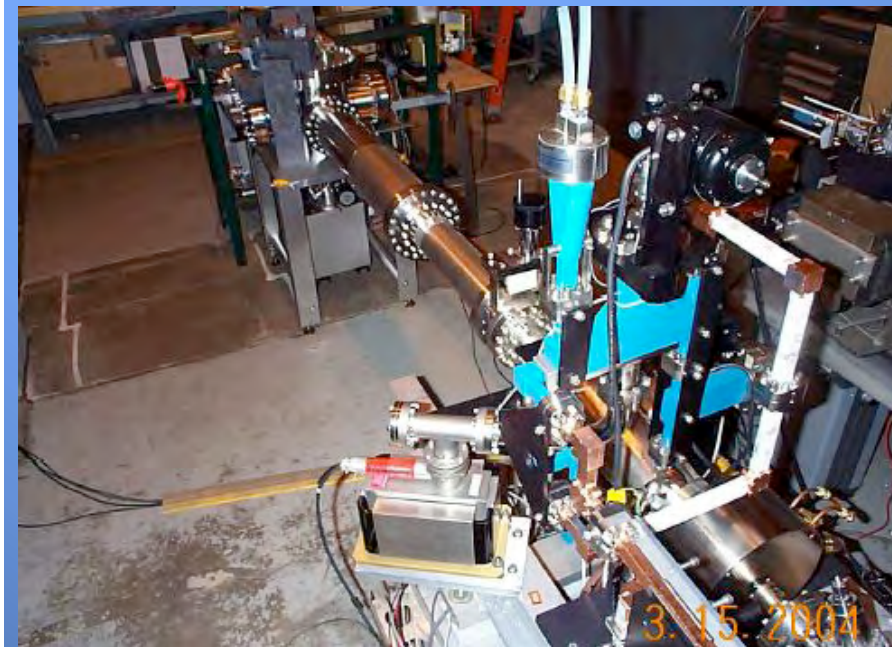
Longitudinal and energy spread resolutions

$$\sigma_{z\_RES} = \frac{c(E/e)\sqrt{\varepsilon}}{V_T \omega_{RF} \sqrt{\beta_D}}$$

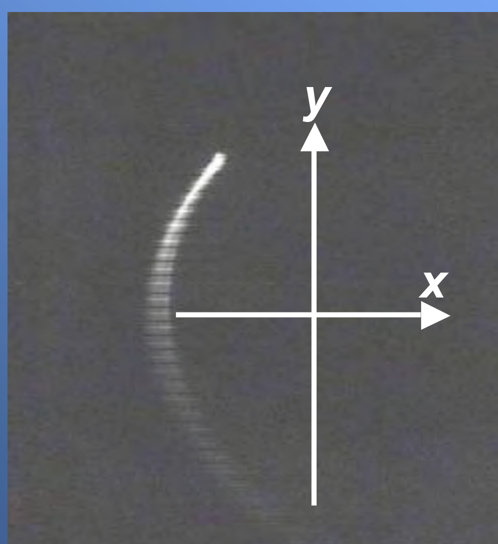
$$\left.\frac{\Delta E}{E}\right|_{RES} = \frac{(E/e)\sqrt{\varepsilon}}{V_T \sqrt{\beta_D}}$$

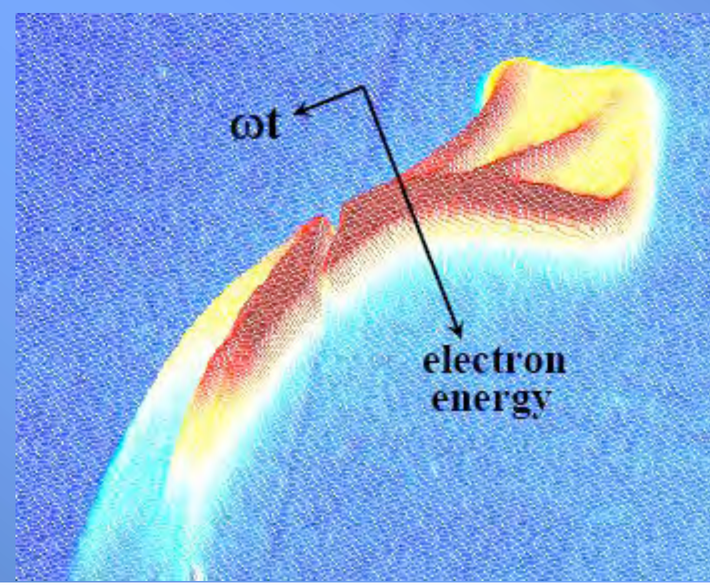
5) Diagnostics with a circular polarized RF deflector: exp. results

[J. Haimson et al, AIP, 737, 2004]



Number of Cavities	2
Operating Frequency	**~17 GHz**
Nominal Beam Energy	15 MeV
RF Deflection Angle	~27 mradian
Drift Distance	2 m
Beam Deflection @ Screen	57 mm
Peak RF Input Power	734 kW
Normalized Emittance	2.8π mm.mrad
Longitudinal resolution	~100 fs
Bunch length	~5 mm





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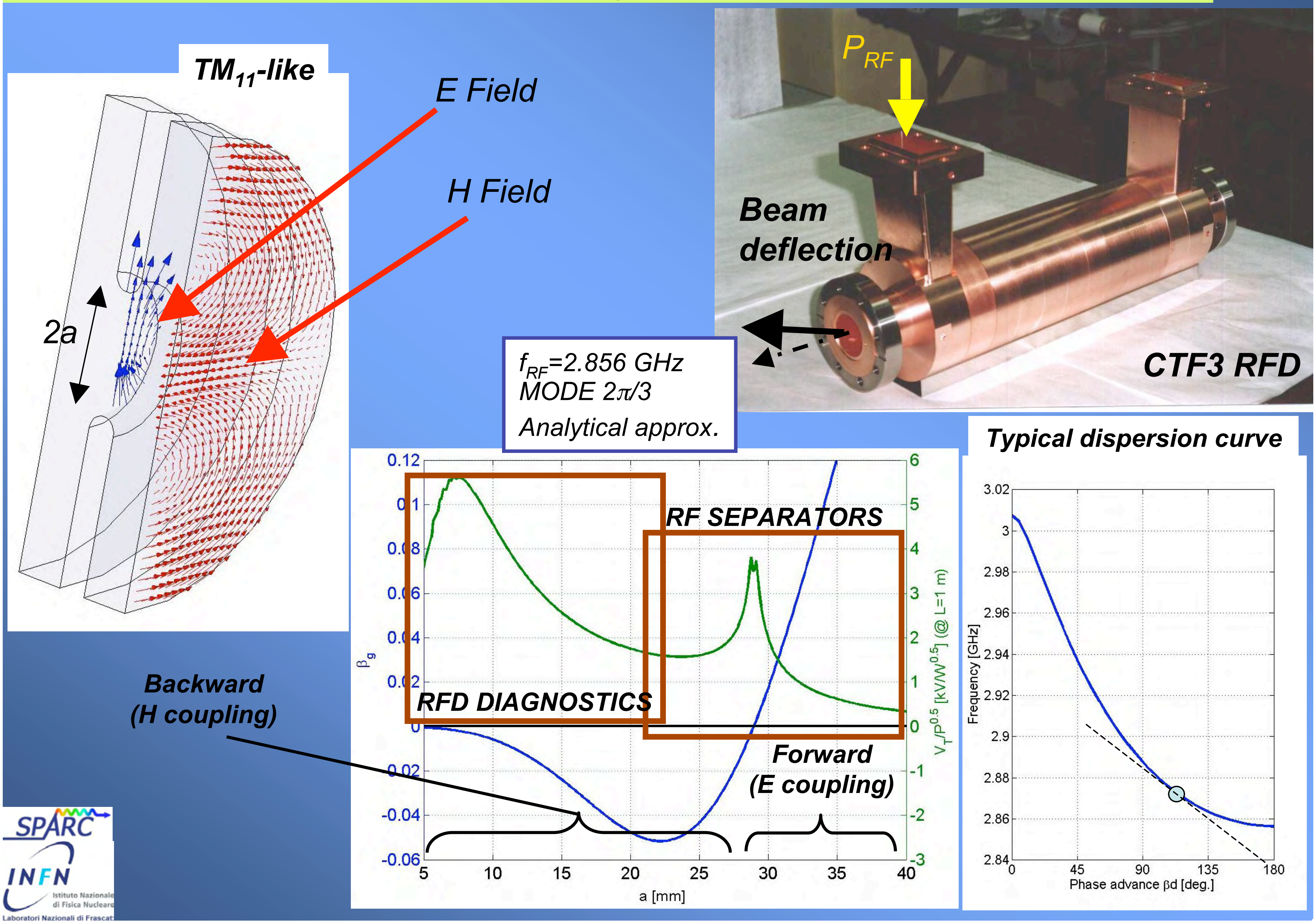
6) Traveling wave deflectors: β_g, efficiency, dispersion curve



6) Traveling wave deflectors: deflecting field

Analytical approx.

$$E_r = E_0\left(k^2a^2 + k^2r^2\right)\cos(\vartheta)e^{-j\beta z}$$

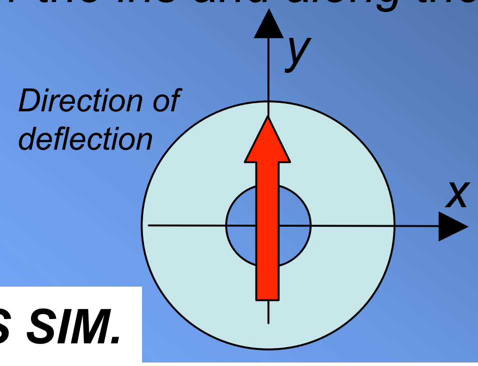
$$E_\vartheta = -E_0\left(k^2a^2 - k^2r^2\right)\sin(\vartheta)e^{-j\beta z}$$

$$cB_r = E_0\left(k^2a^2 - k^2r^2 - 4\right)\sin(\vartheta)e^{-j\beta z}$$

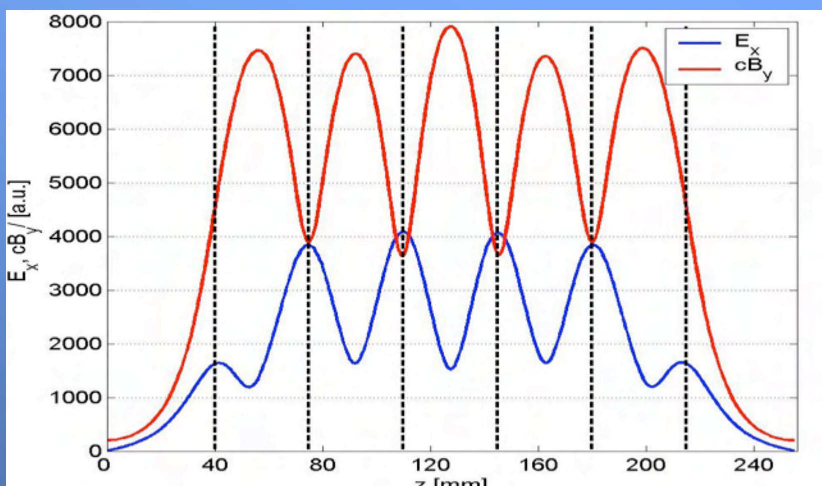
$$cB_\vartheta = E_0\left(k^2a^2 + k^2r^2 - 4\right)\cos(\vartheta)e^{-j\beta z}$$

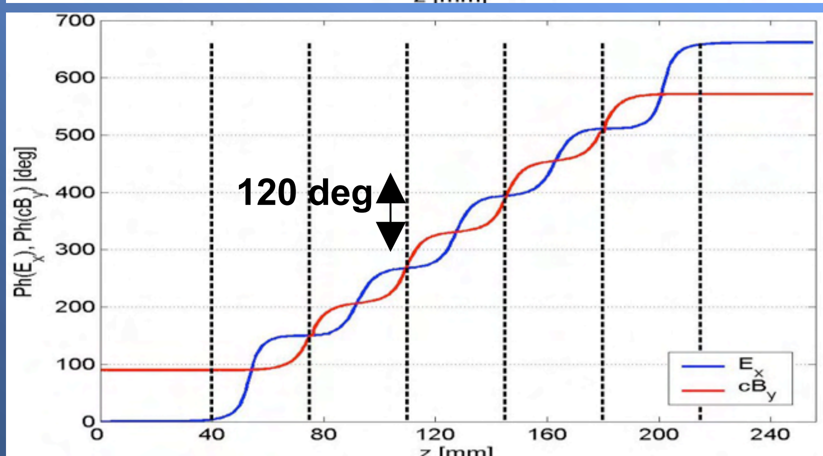
$F_y = const$

Over the iris and along the deflector

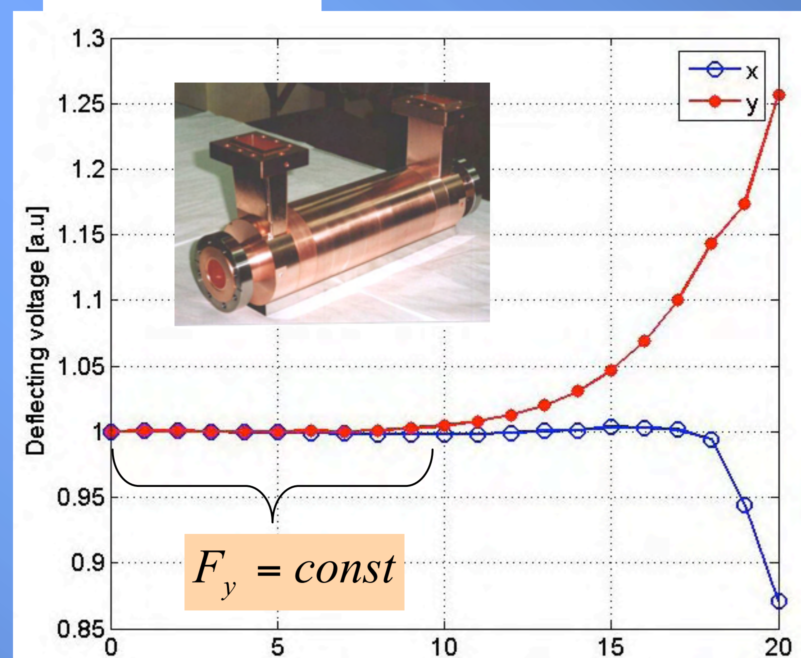


(e.g. 5 cells)



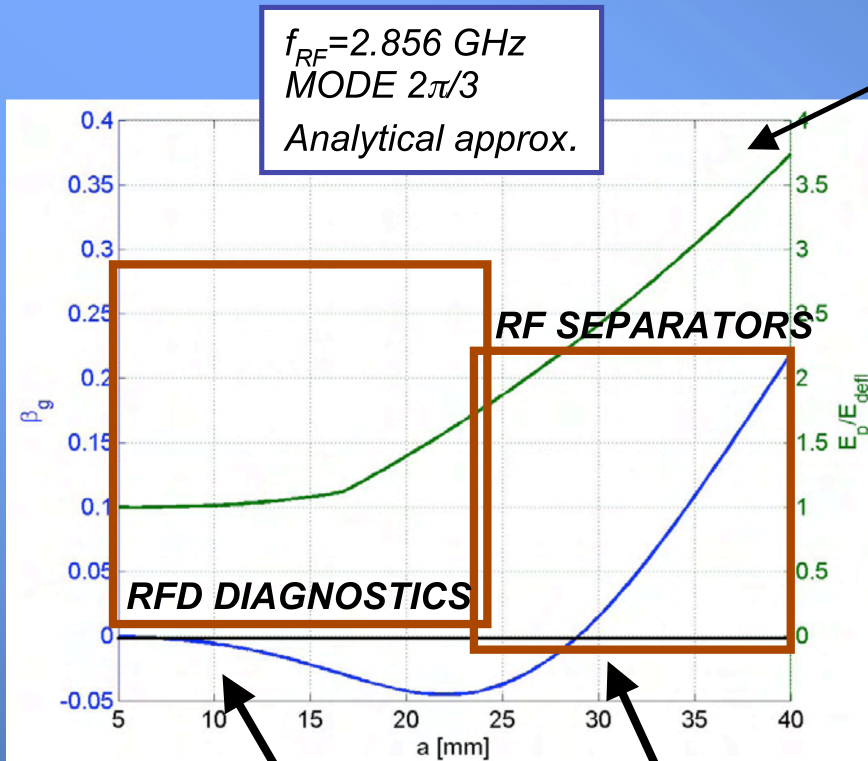


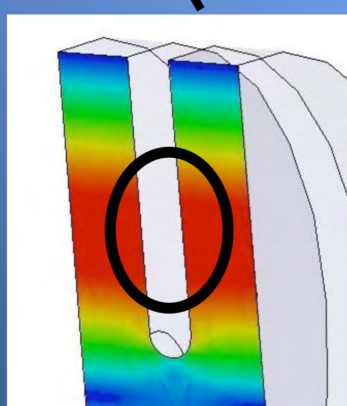
HFSS SIM.

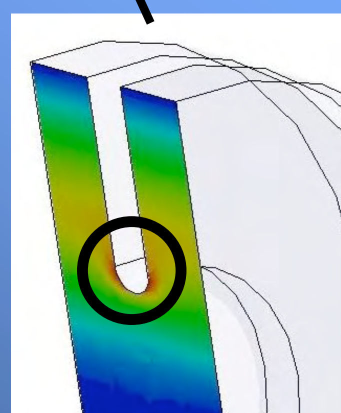


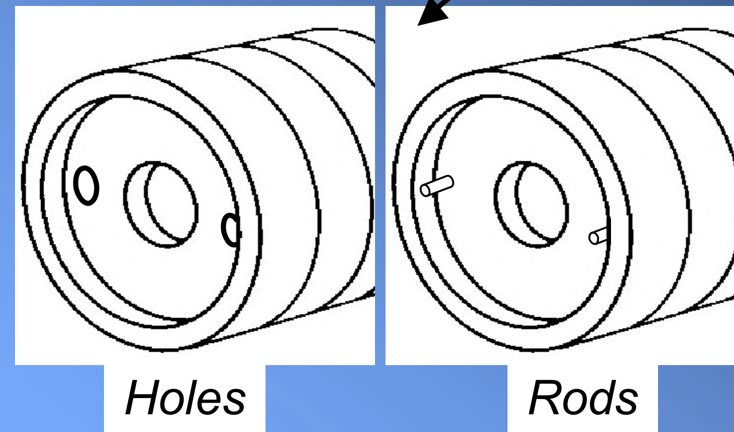
Transverse position along the iris [mm]

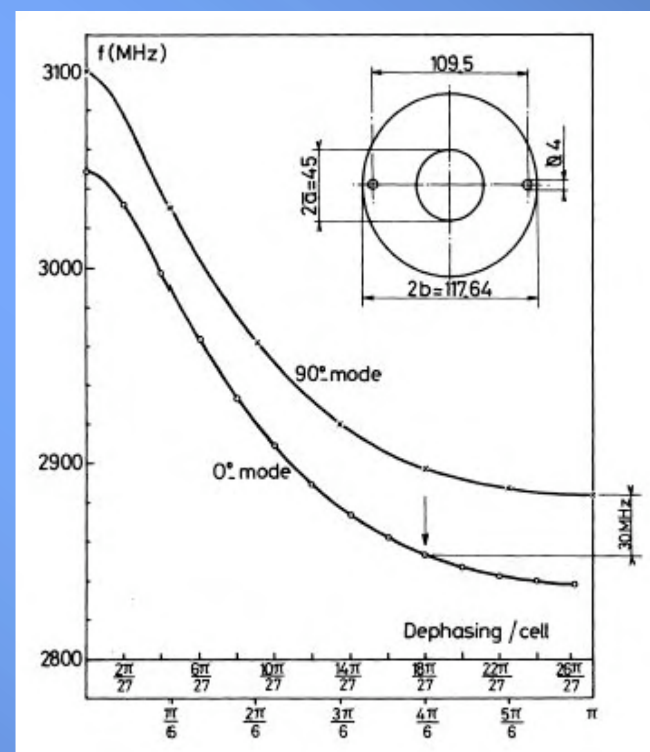
6) Traveling wave deflectors: peak of E-field and tilted polarity





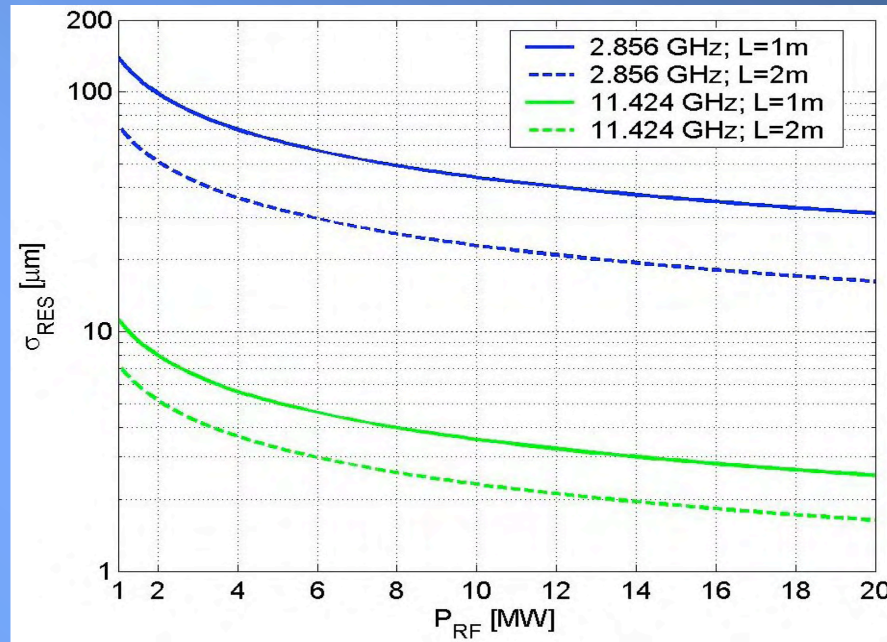


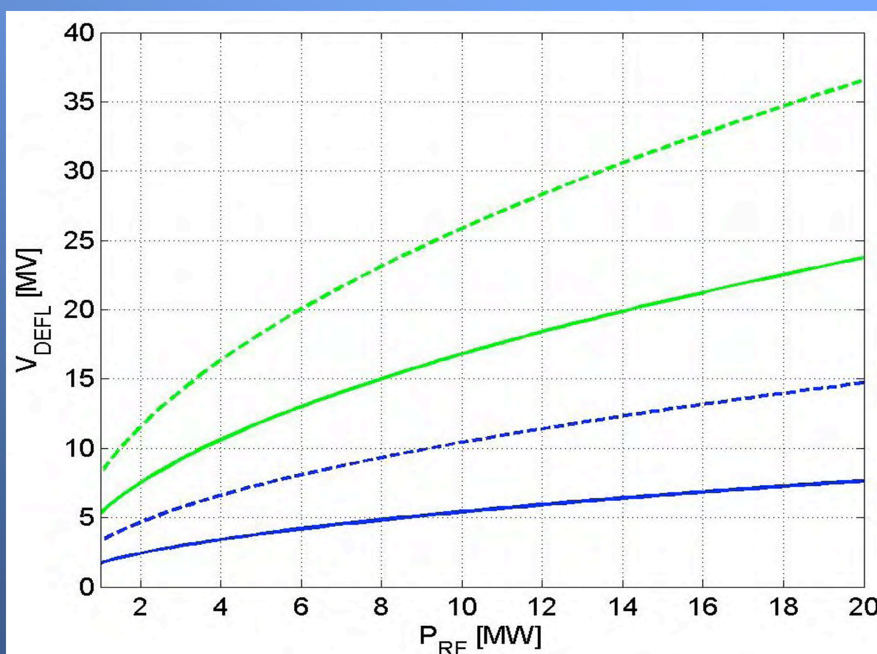


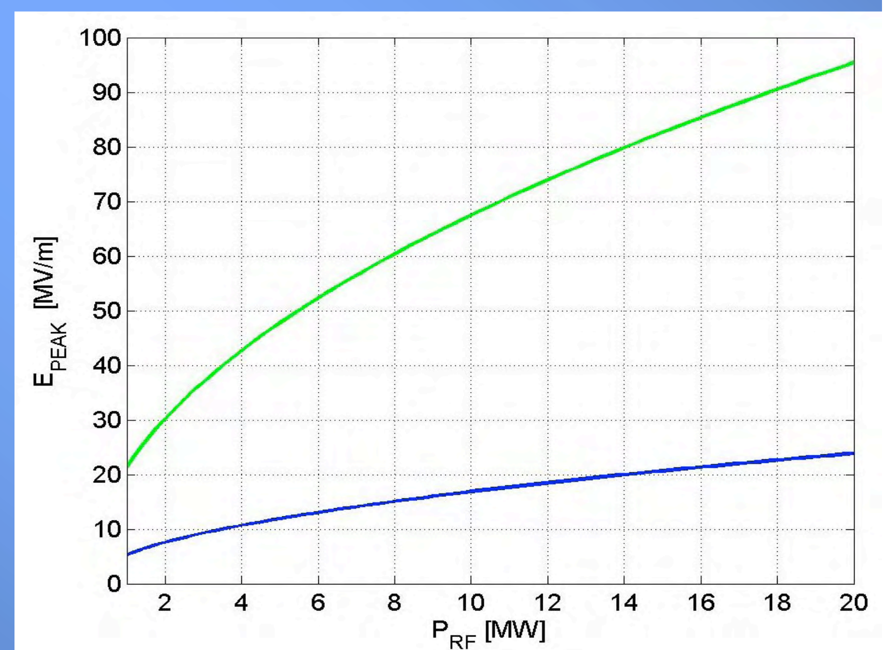


6) Traveling wave deflectors: performances

E_B= 2 GeV;
ε=2 mm mrad;
a=20 mm @ 2.856 GHz;
a=5 mm @ 11.424 GHz;
β_D=20 m; $\Delta\phi$=90 deg;







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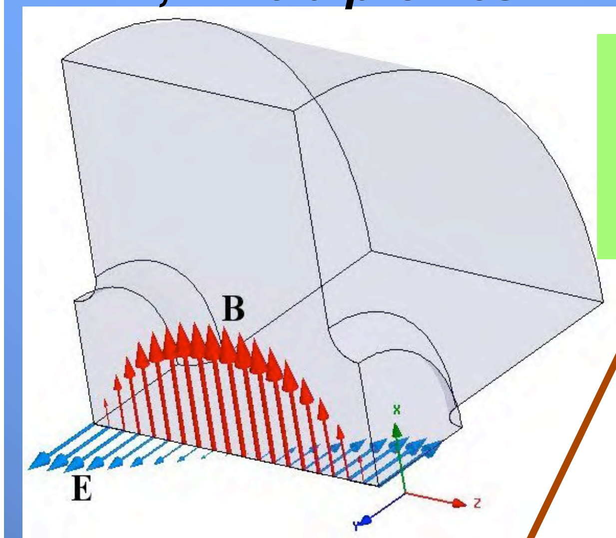
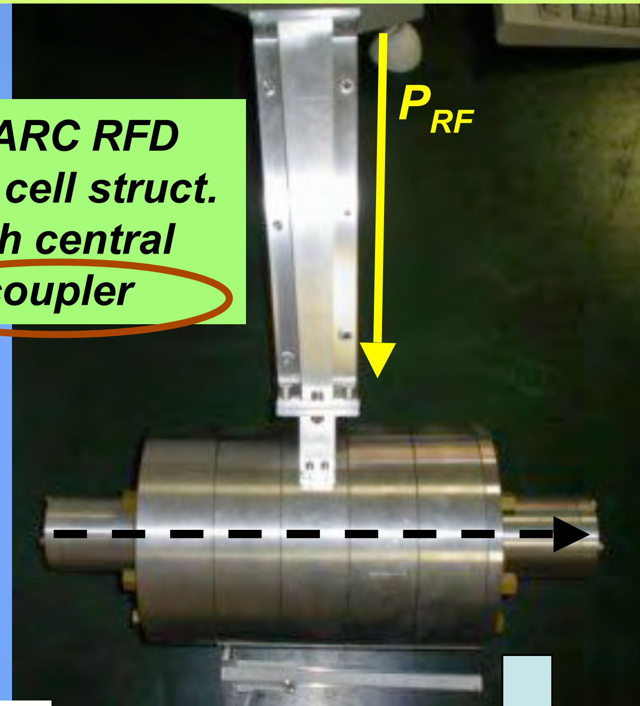
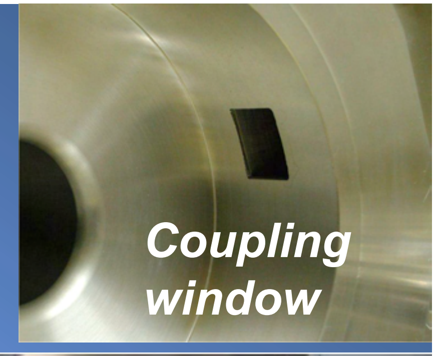
5) Standing wave deflectors: general properties

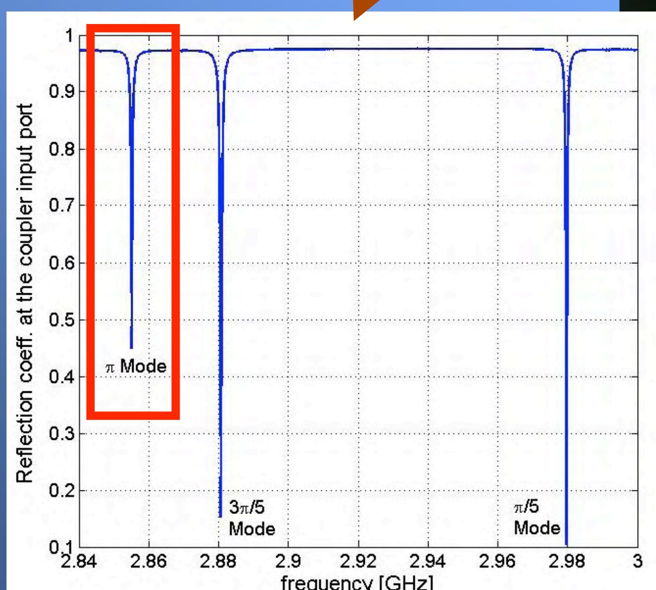
E, B field profiles

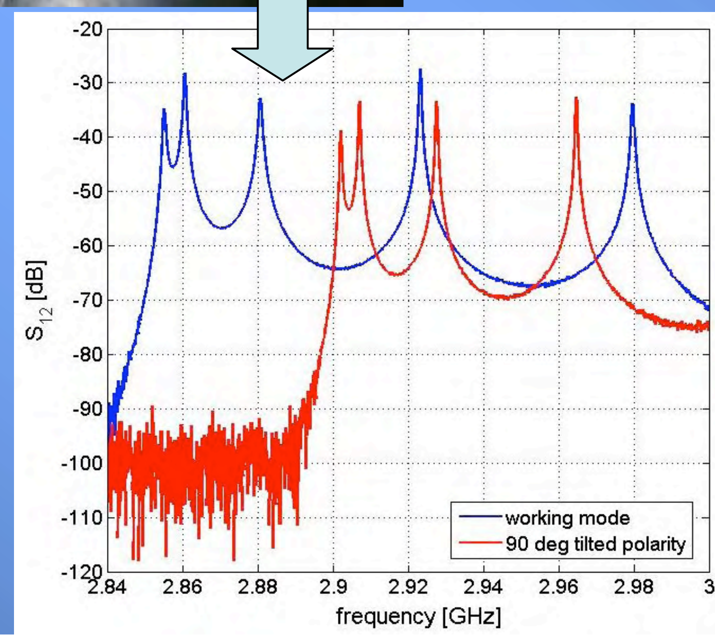


SPARC RFD Multi cell struct. with central coupler



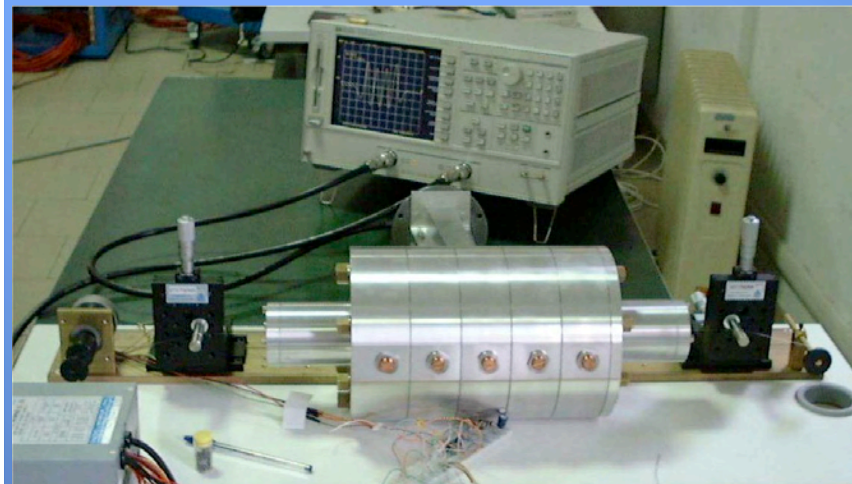


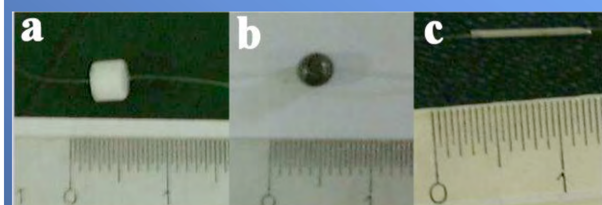




5) Standing wave deflectors: RF measurements

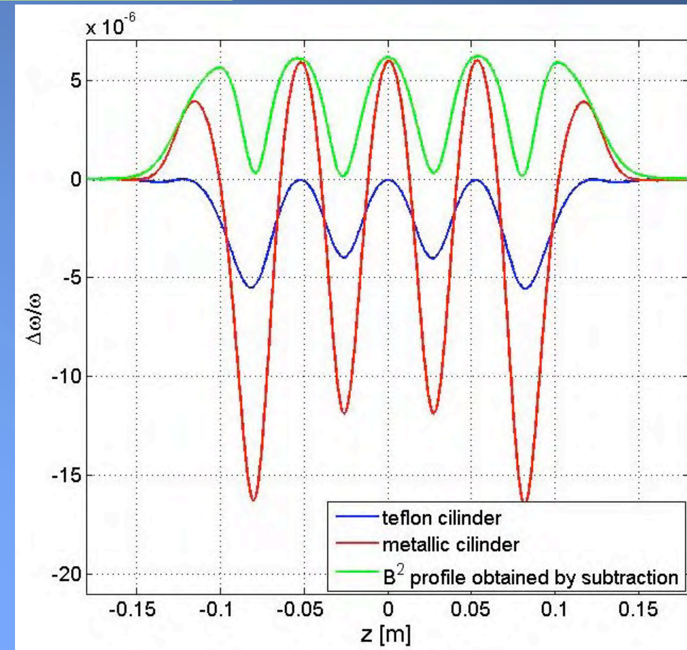
@ Univ. “La Sapienza”, Rome



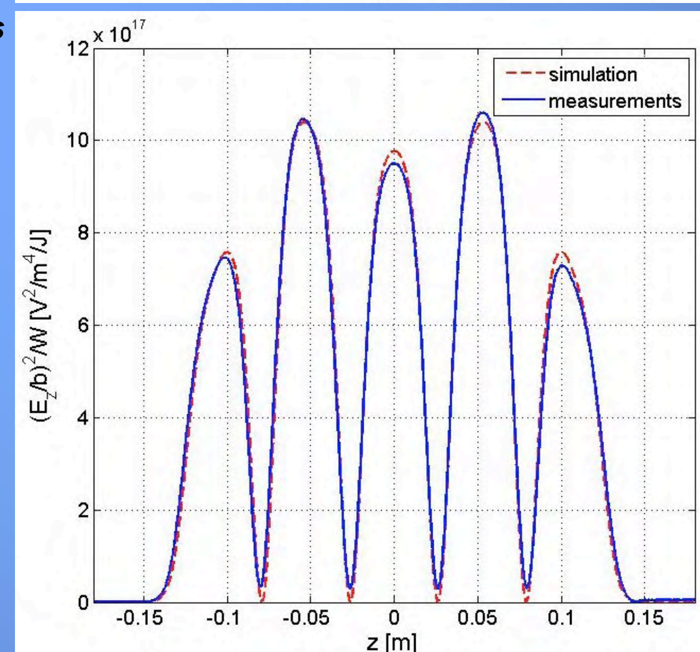


Perturbing objects

B, E components dielectric and metallic objects



Ez component off axis metallic needle (Panofsky-Wenzel Theorem)



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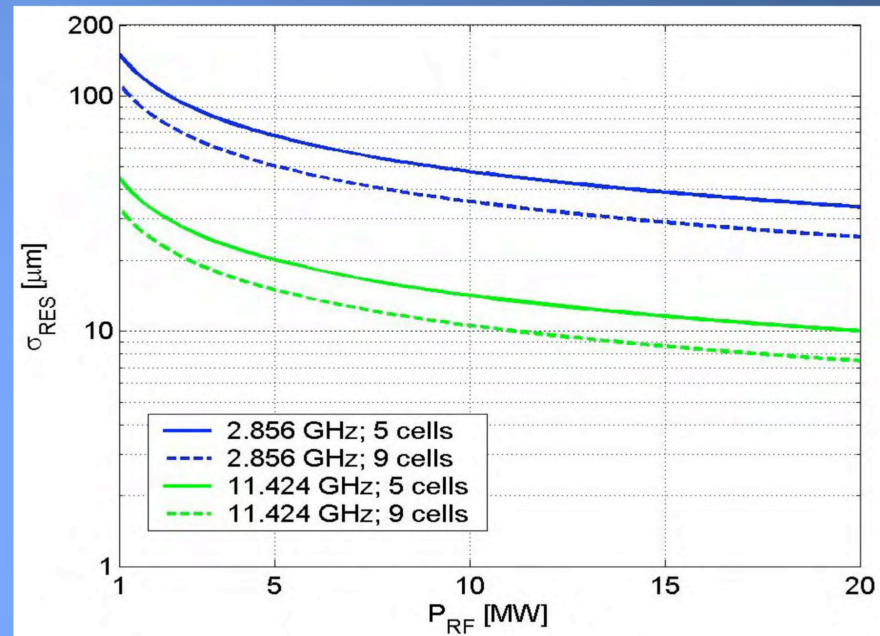
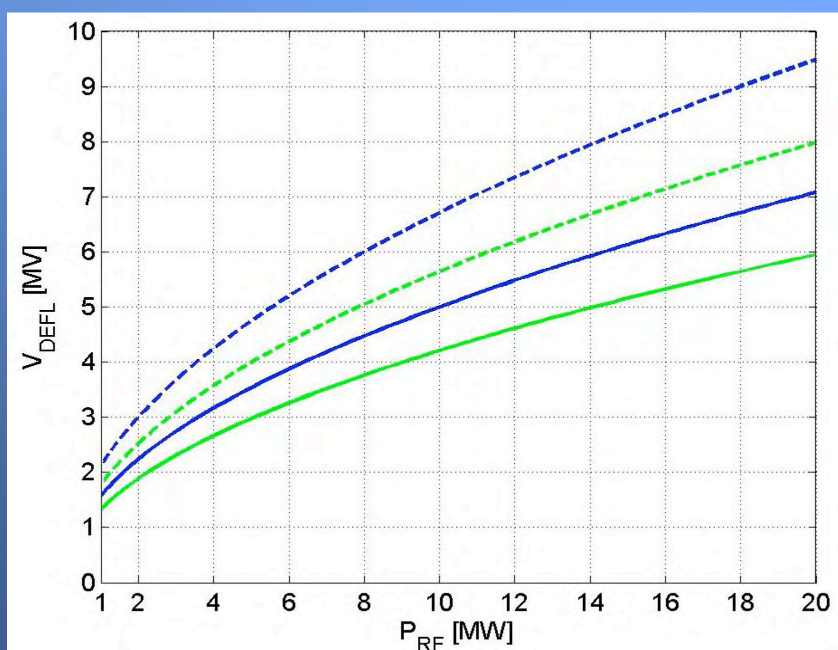
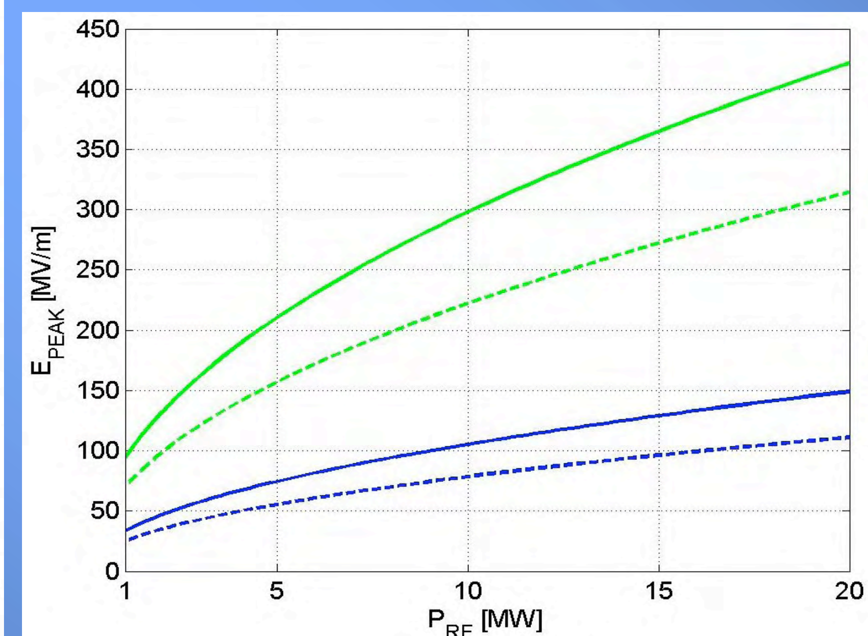
6) Standing wave deflectors: performances

E_B= 2 GeV;
ε=2 mm mrad;
a=20 mm @ 2.856 GHz;
a=5 mm @ 11.424 GHz;
β_D=20 m; $\Delta\phi$=90 deg;







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COMPARE RFD SW-TW

	SW	TW
Efficiency per unit length	High	Low
Filling time	Proportional to the quality factor:generally slow (~μs @ 2.856 GHz)	Proportional to the group velocity and length: generally fast (~0.1 μs @ L=1m)
Maximum number of cells	The maximum number of cells is limited to about 10 because of mode overlapping	After L=2÷3/α the deflecting field decreases
Deflecting field vs. #of cells N	$N^{1/2}$	$(1-e^{-\alpha N})/\alpha$
Power system	A circulator is generally needed to protect the klystron	Circulator not necessary.
E_{PEAK}	It can limit the maximum input power	Not a big constraint
Temperature sensitivity	Necessity of an automatic tuning system or of a very good temperature stabilization	Less temperature sensityvity
Beam impact	low	High
Resolution vs. freq.	$1/f^{3/4}$ (N fixed)	$1/f^{2}$ (L fixed, small dissipation)

Compact device (space)
Low input power
Long pulse length
Circulator

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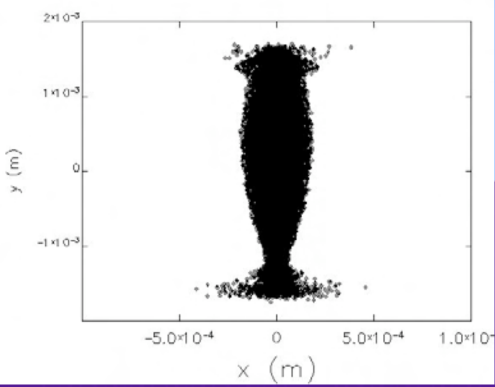
SW RFD Applications

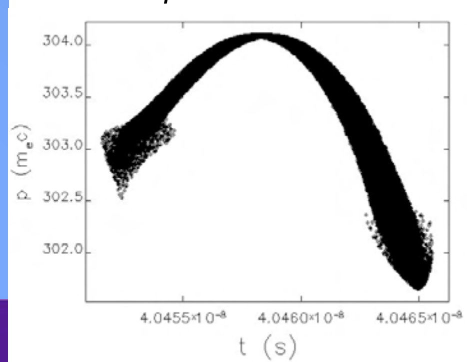
1) SPARC (LNF-Frascati)

Electron Beam energy [MeV]	155
RMS normalized transverse emittance @ linac exit [mm mrad]	<2
RMS bunch length @ LINAC exit [mm]	1

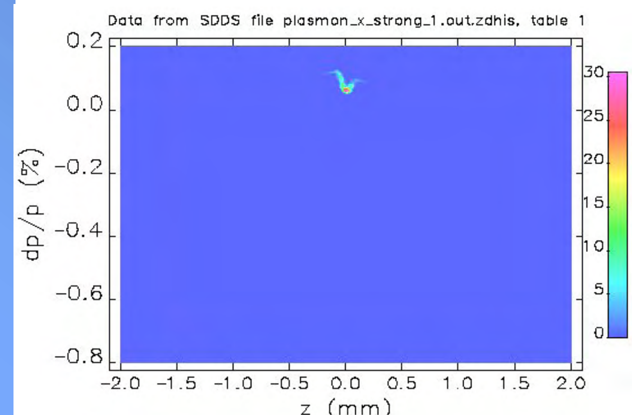
Bunch length measurement (σ_{RES}=20μm)

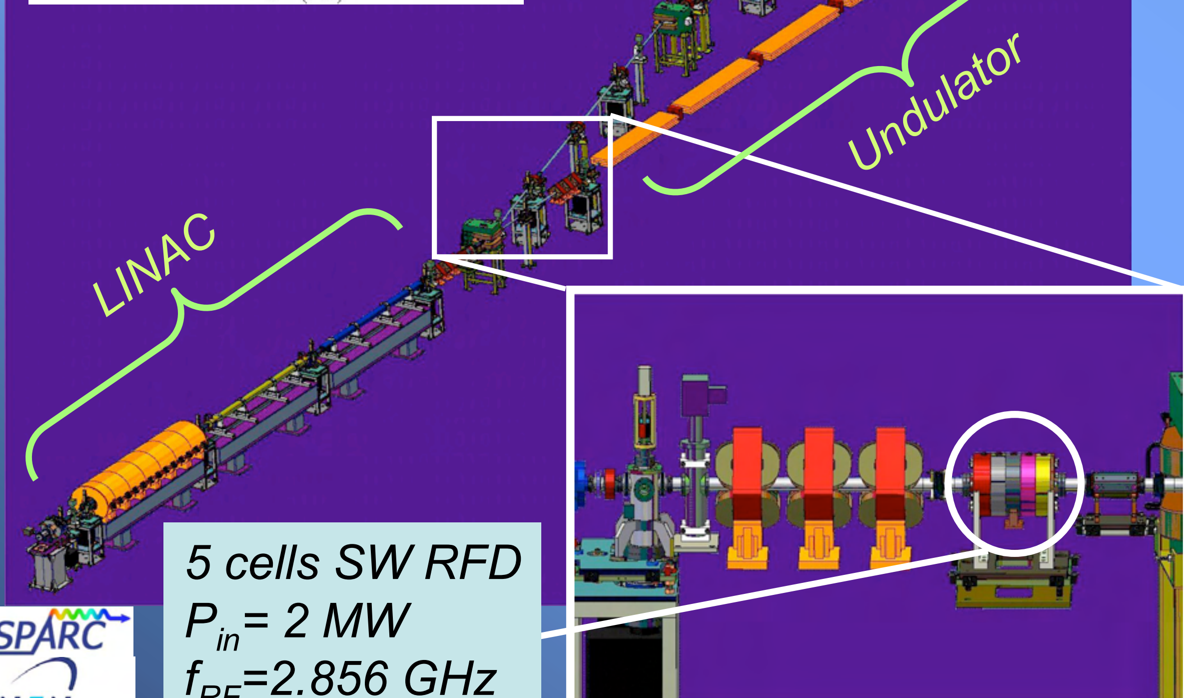


Phase space measurement

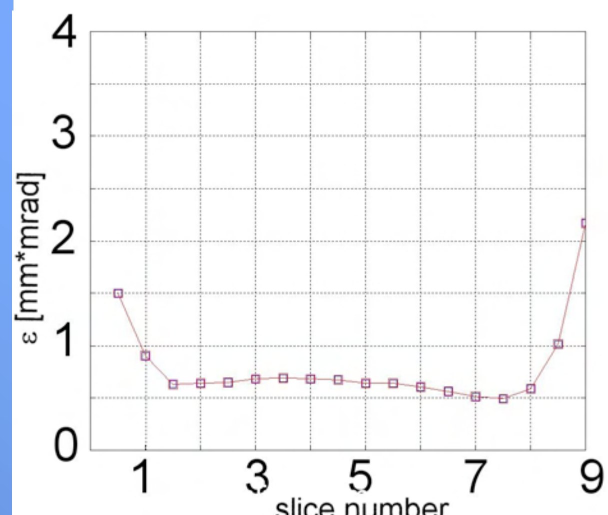


Ultra short bunch generation using 2 RFD: (200-500μm)





Slice emittance measurement

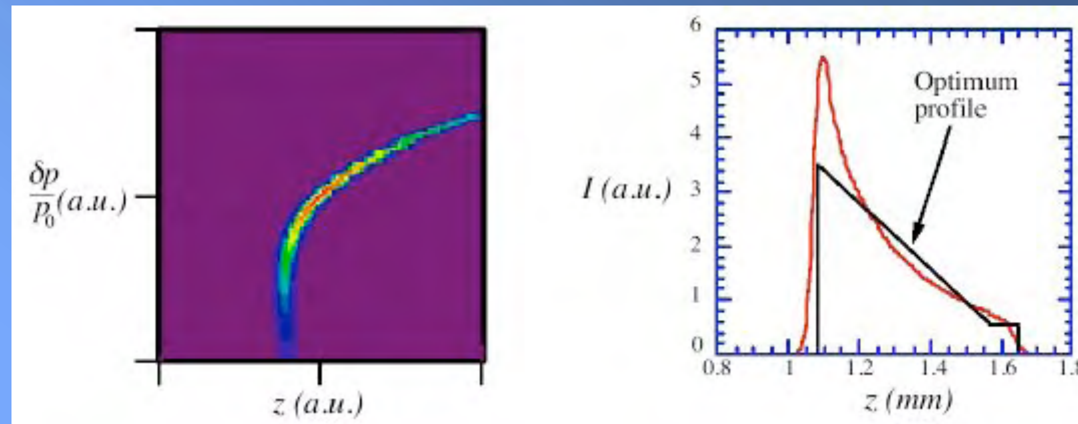


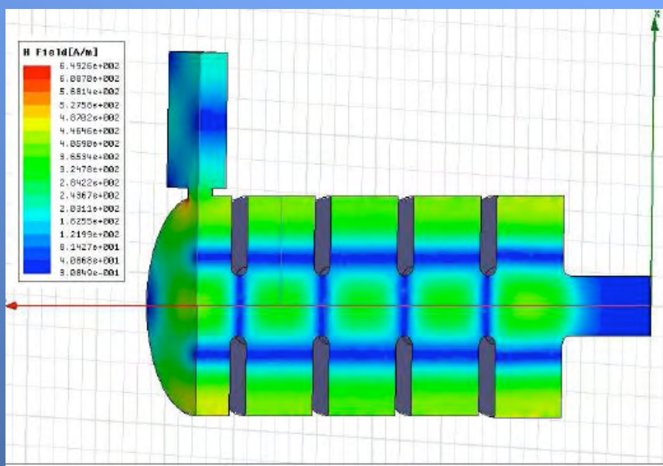
5 cells SW RFD
P_{in}= 2 MW
f_{RF}=2.856 GHz
σ_{RES}=25μm

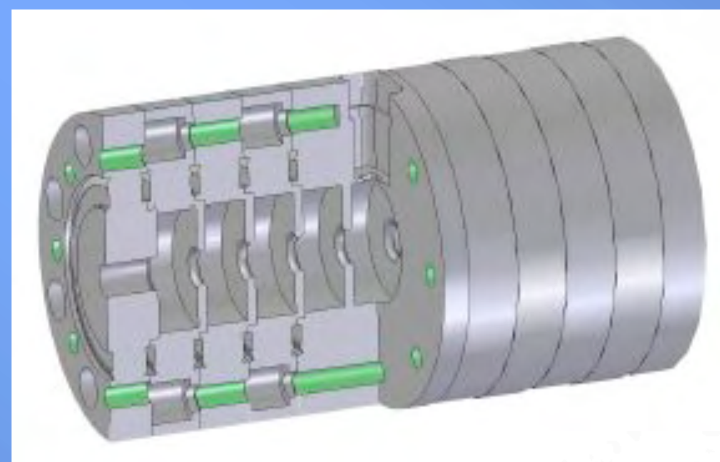
2) NEPTUNE (UCLA-PBPL, Los Angeles)

([J. England et al., PAC05])

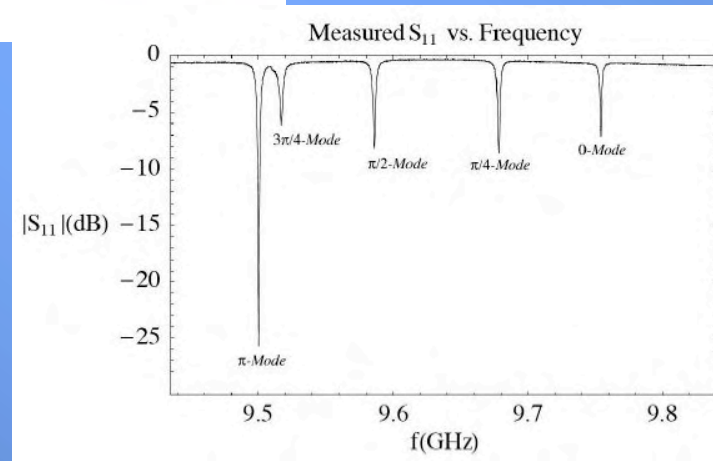
-bunch-shaping experiments (plasma wakefield acceleration)







Electron Beam energy [MeV]	14
P_{RF}	**50kW**
f_{RF}	**9.6 GHz**
Number of cells	9
σ_{RES}	15µm



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CONCLUSIONS

<u>Diagnostics & Manipulation</u>:

1) **Simple principle applicable to different type linear injector;**
2) **Theory of measurement: resolution and source of errors;**
3) **Longitudinal and transverse phase space characterization;**
4) **Short bunch generation;**
5) **Circular polarized concept;**
6) **Experimental results already available (CTF3, SLAC, DESY, …);**

<u>RF Deflecting structures</u>:

1) **TW and SW deflectors design criteria;**
2) **Compare and peculiarities of TW and SW devices;**
3) **SW devices to be installed (SPARC, UCLA);**

THANKS TO…

A. Mostacci, L. Ficcadenti, L. Palumbo, C. Vaccarezza, G. Di Pirro, B. Spataro, J. Rosenzweig, J. England, J. Haimson.