RF Deflecting Structures for Bunch Length Monitoring

D. Alesini

(LNF-INFN, Frascati, Rome)

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Cockcroft Institute, UK on July 12th/13th 2010

OUTLINE

- **Bunch Length Monitoring by RFD: principle and calibration**

- **RF Deflecting structures:**

  TW and SW

  Performances

- **General measurement setup:**

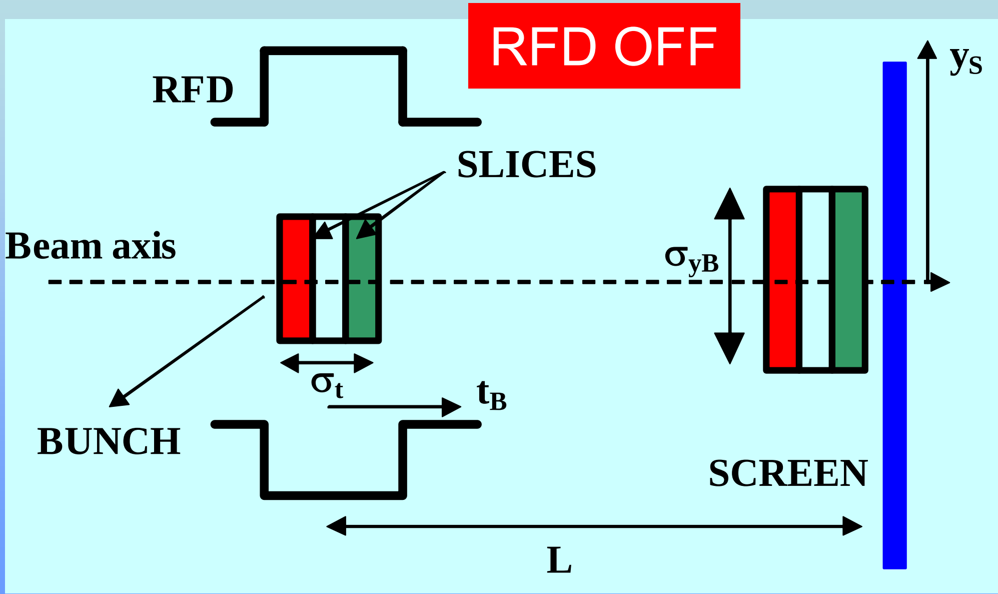
  beam profile and long. phase space meas.

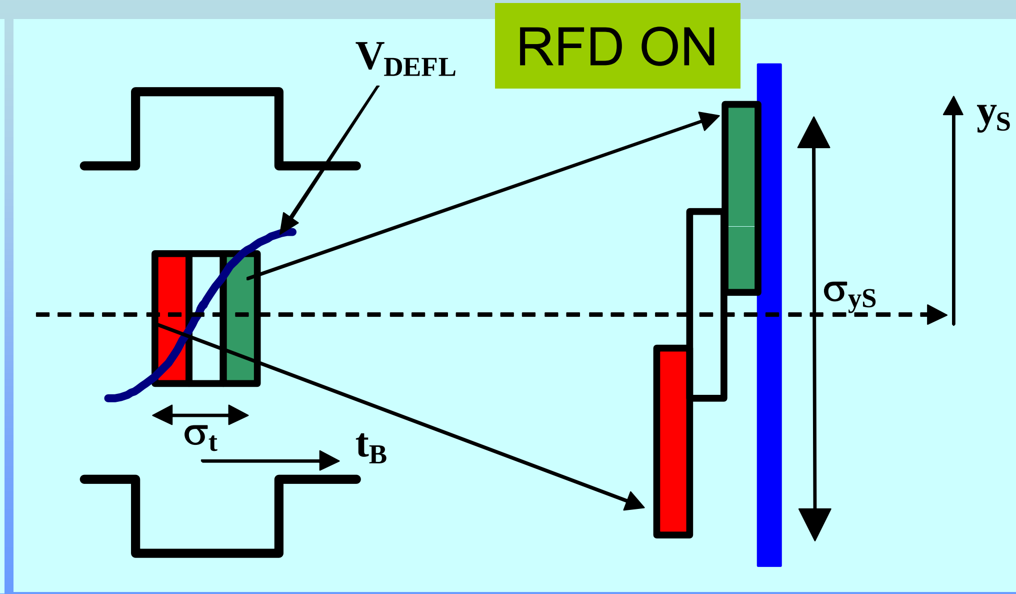
  effects of RFD structures

- **Examples:**

  SPARC
  LCLS
  FLASH

Slice parameter measurements by RFD: principle



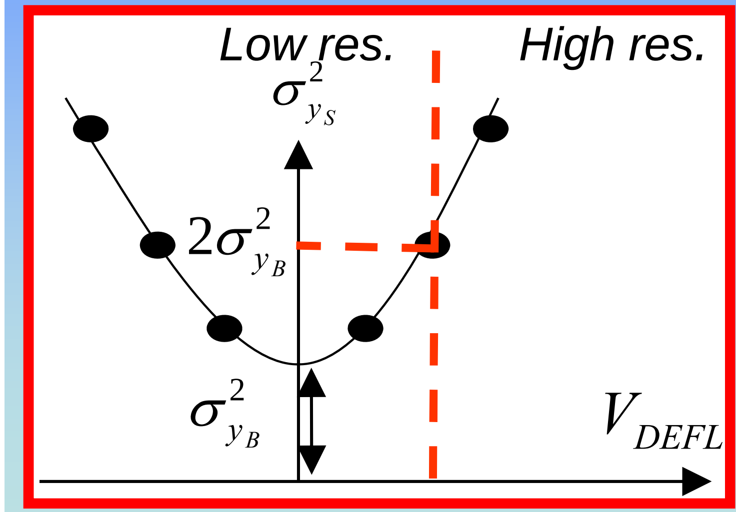


The different types of measurements that can be done with RFDs are based on the property of the transverse voltage (V_{DEFL}) to introduce a **linear correlation between the longitudinal coordinate of the bunch (t_B) and the transverse one** (vertical, in general) at the screen position (y_S).

$$y_S \cong \left(\frac{V_{DEFL}}{E/e}\omega_{RF} L\right)\left(t_B + \frac{\Delta\phi_{RF}}{\omega_{RF}}\right)$$

K_{cal}

$$R_{34} = \sqrt{\beta_S \beta_{defl}} \sin \Phi_{s\_defl}$$



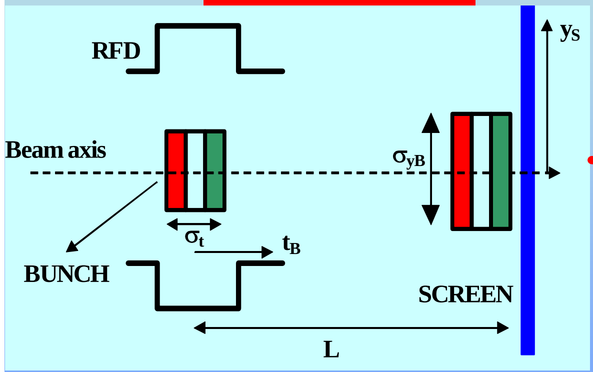
resolution

$$\sigma_{y_S}^2 \cong K_{cal}^2 \sigma_{t_B}^2 + \sigma_{y_B}^2$$

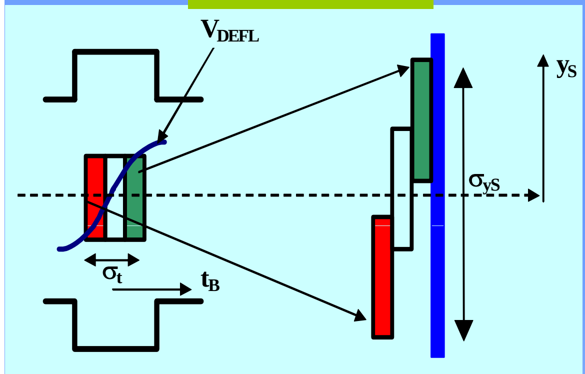
$$\sigma_{t_B\_RES} = \frac{\sigma_{y_B}}{K_{cal}} = \frac{\sqrt{\varepsilon_y \beta_S}}{K_{cal}}$$

Calibration: measurements @ SPARC

RFD OFF



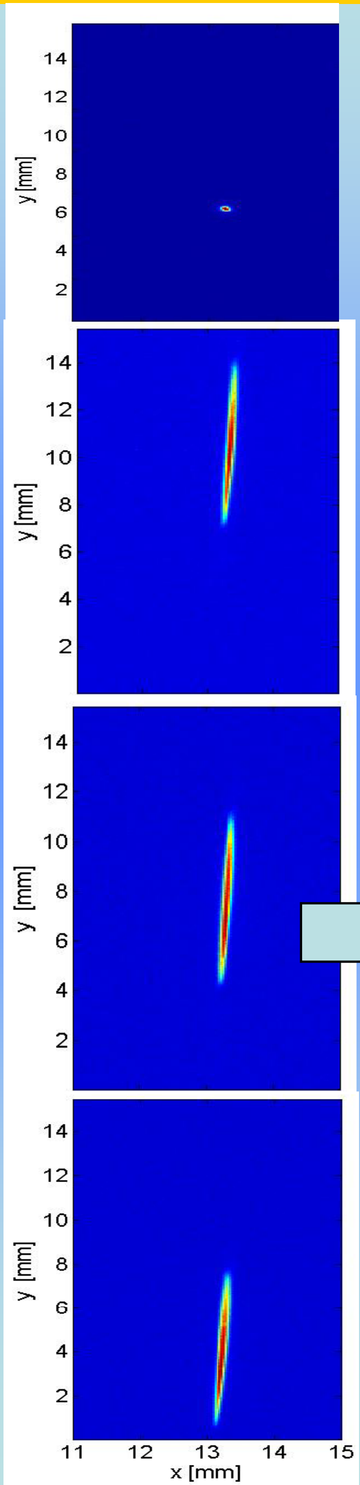
RFD ON



$$K_{cal} \cong \omega_{RF} \frac{\langle y_S \rangle|_{meas\_1} - \langle y_S \rangle|_{meas\_2}}{\Delta\phi|_{meas\_1} - \Delta\phi|_{meas\_2}}$$

Self calibrated meas.

The coefficient K_{cal} can be directly calculated measuring the bunch centroid position on the screen for different values of the RFD phase



$\sigma_{y_B} \cong 100\mu m$

$V_{DEFL} \cong 1.5MV$

$E \cong 150MeV$

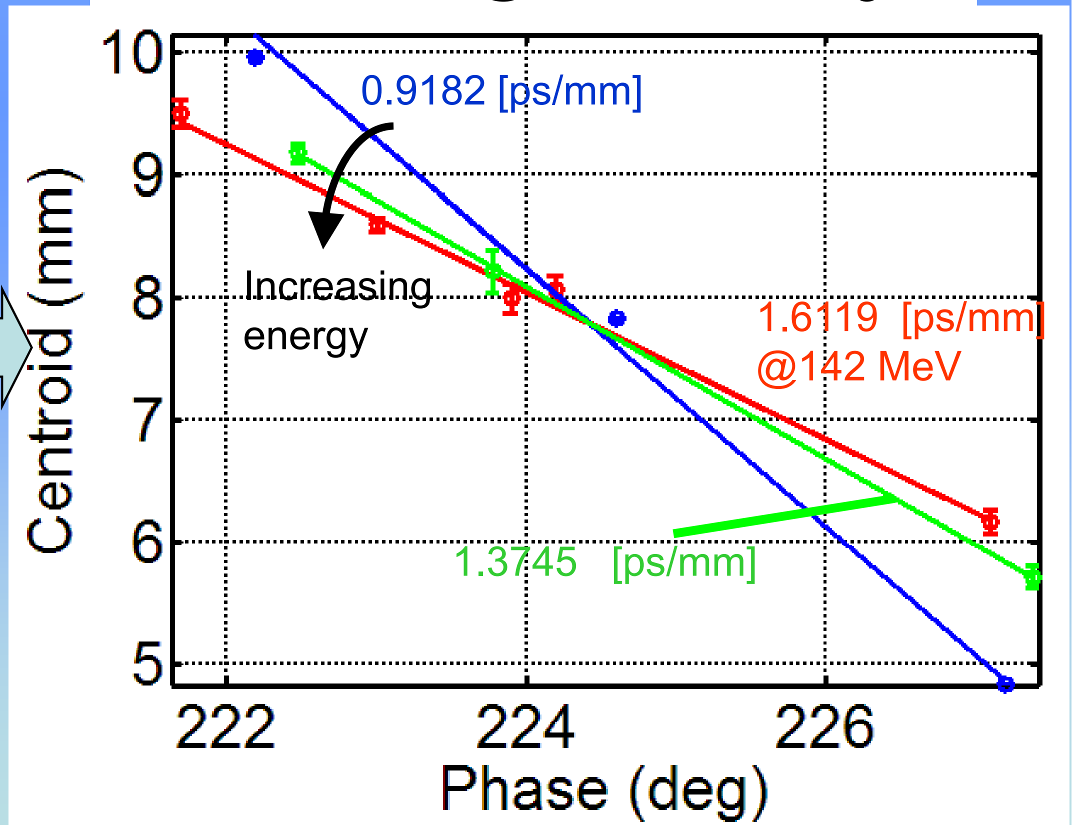
$f_{RF} \cong 2.856GHz$

$L \cong 4m$

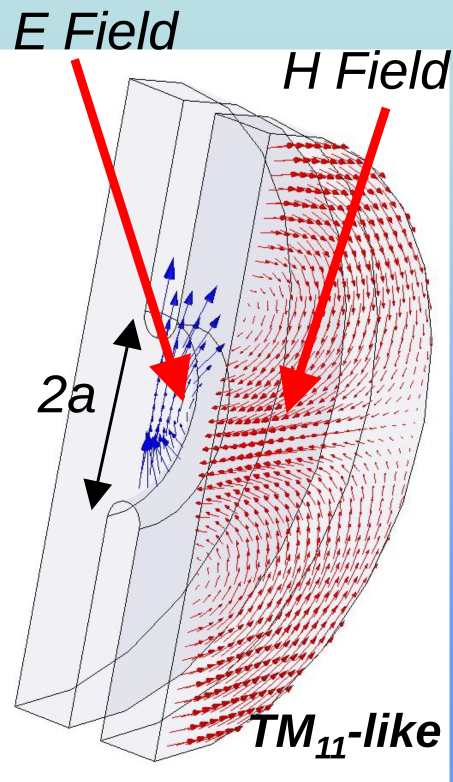
Typical SPARC parameters

$$\sigma_{t_B\_RES} = \frac{\sigma_{y_B}}{\frac{V_{DEFL}}{E/e}\omega_{RF} L} \cong 130 fs$$

SPARC results @ different energies



RF Deflecting structures: TW case

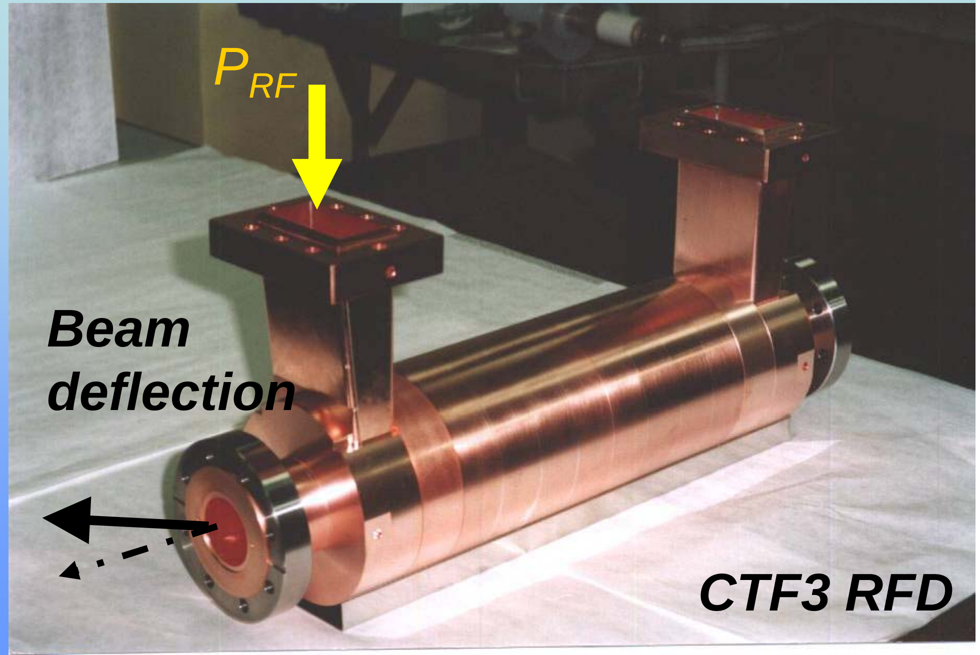


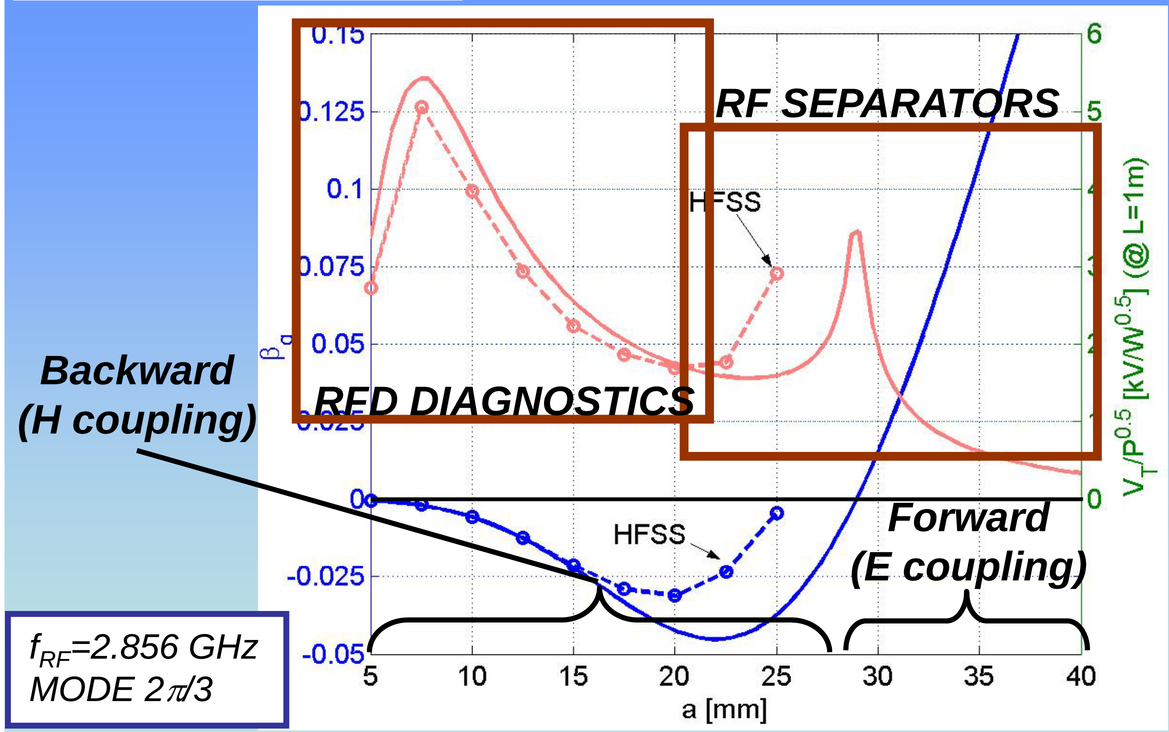
As in the case of accelerating sections, we have **TW and SW cavities**. In general RFDs are multi-cell devices working on the TM_{11}-like mode.

Both the **E and the B** field contribute to the total deflection.

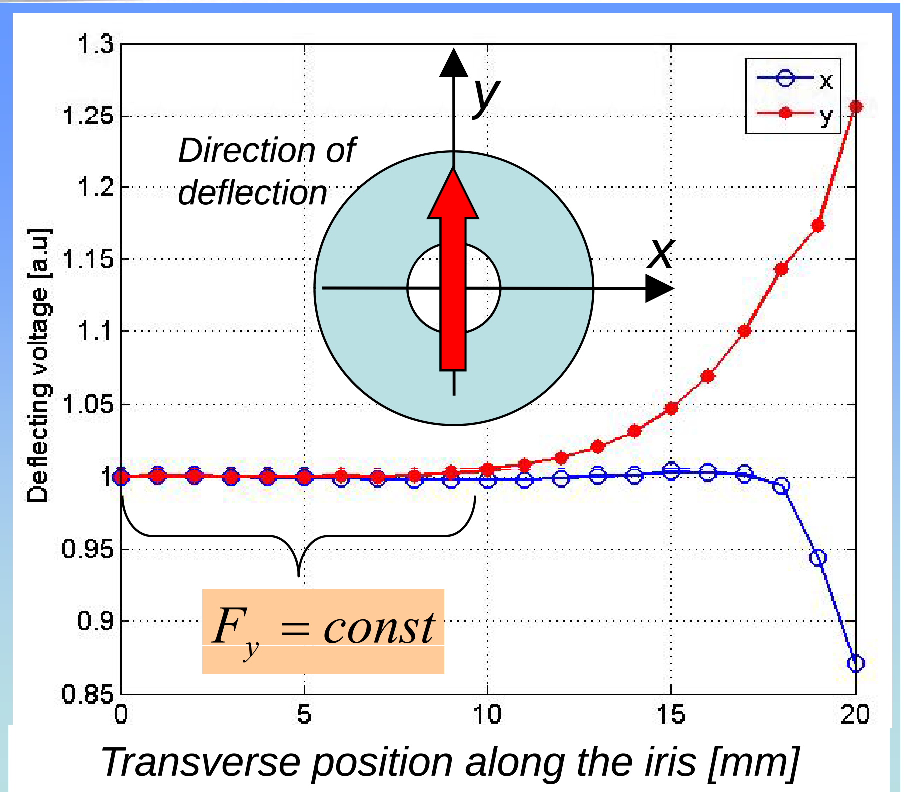
The **transverse force is uniform** over a wide region inside the iris aperture

In TW devices the **iris aperture (a)** is the most important parameter to fix the deflection efficiency and group velocity

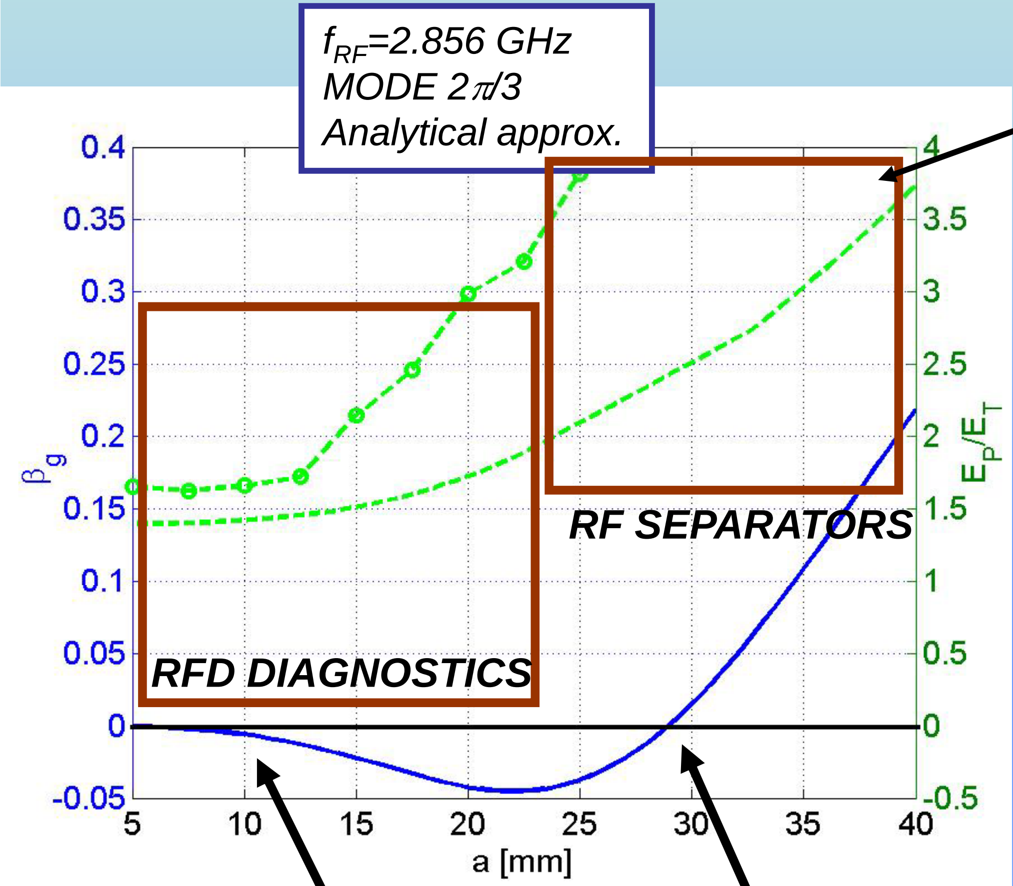


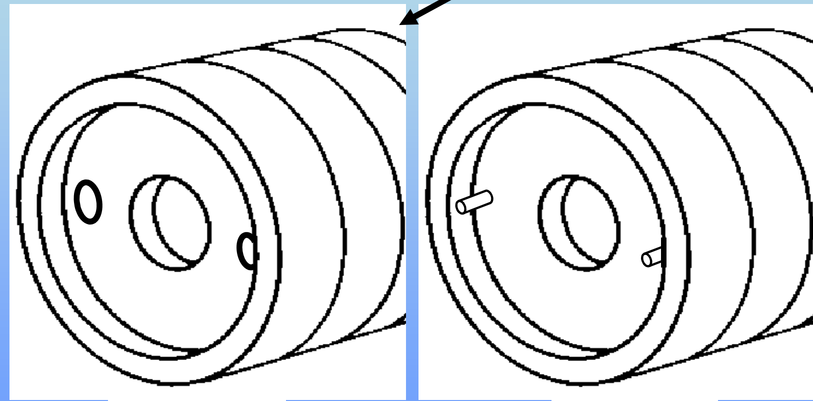


f_{RF}=2.856 GHz
MODE 2π/3

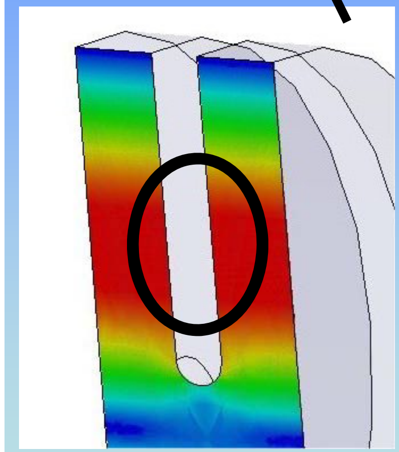


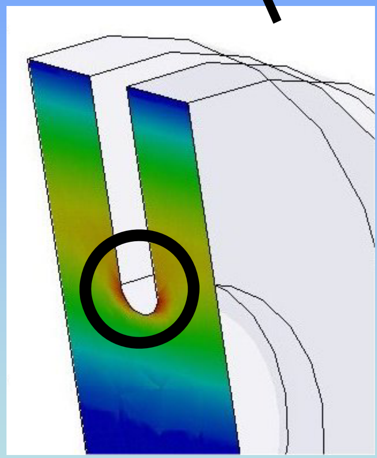
RF Deflecting structures: peak E field and polarization

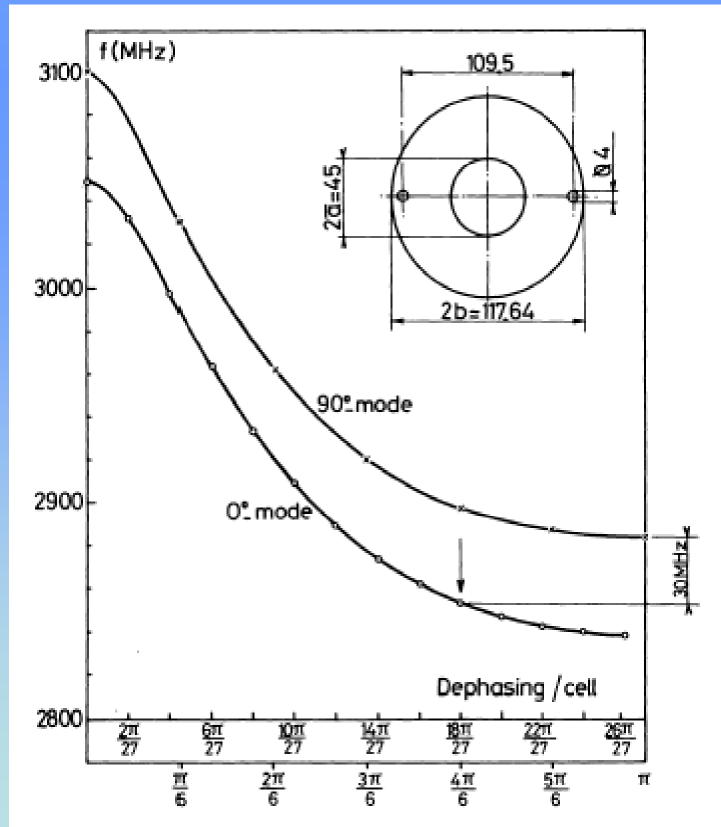




Holes Rods



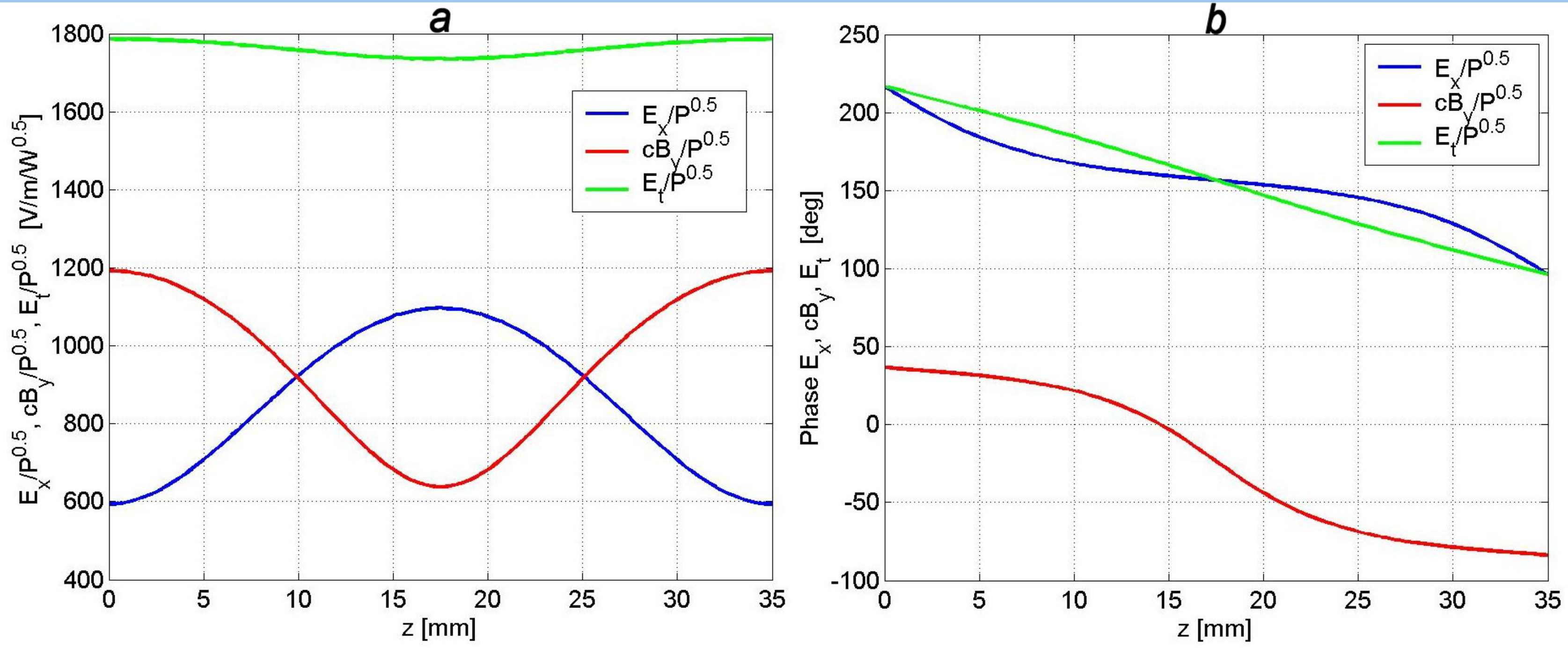




Since there are two possible polarities of the deflecting field, **polarizing rod or holes** are, in general, foreseen to introduce an **azimuthal asymmetry** in the structure fixing the working polarity itself

RF Deflecting structures: E and B field components

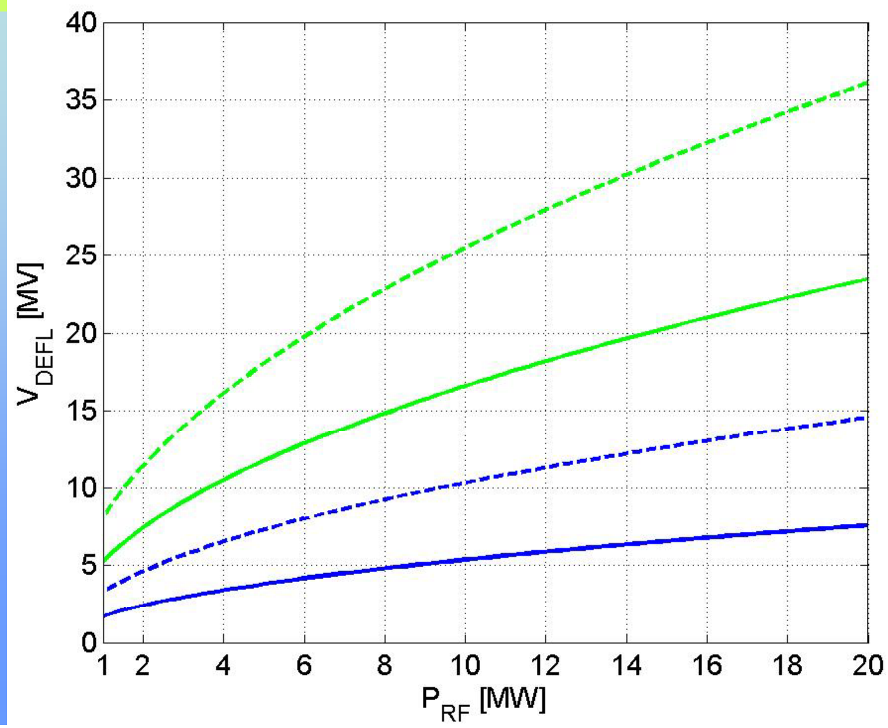
f_{RF}=2.856 GHz
MODE $2\pi/3$
Analytical approx.
a=20mm, t=10mm

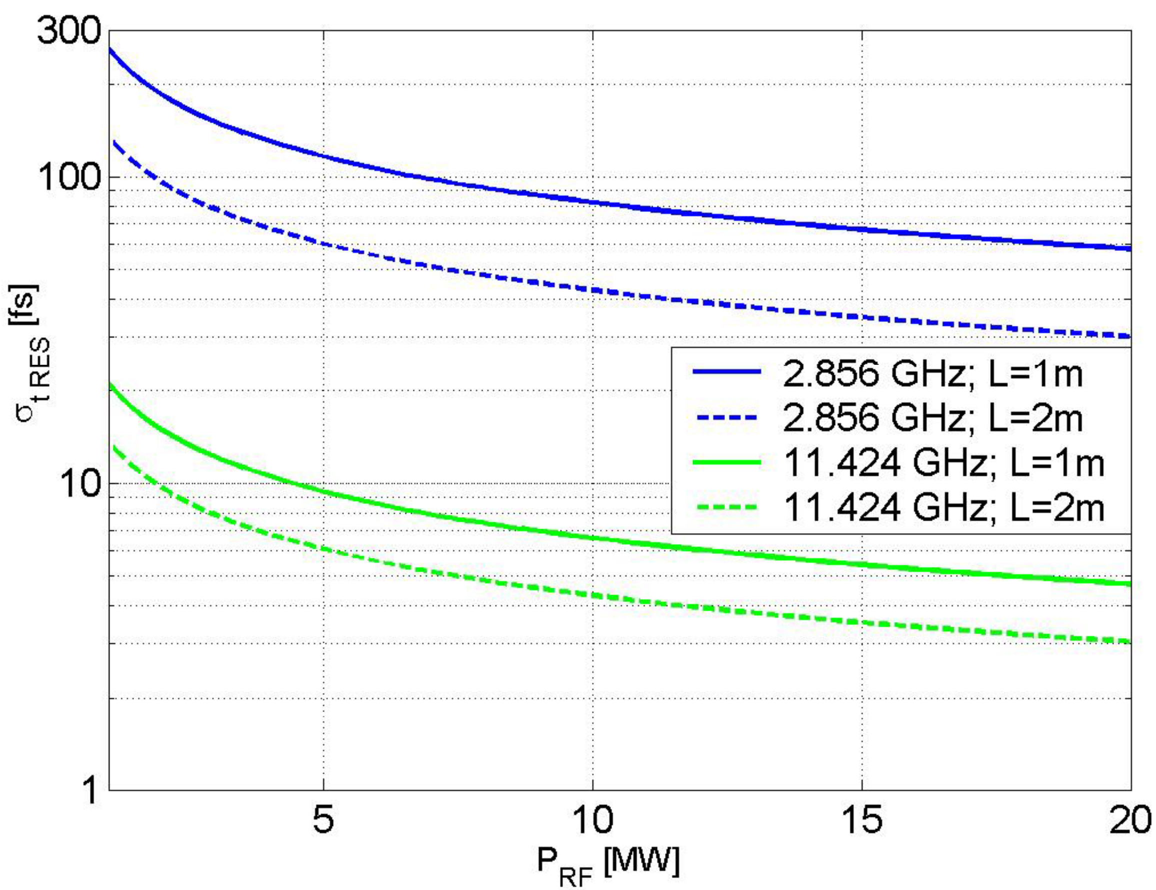


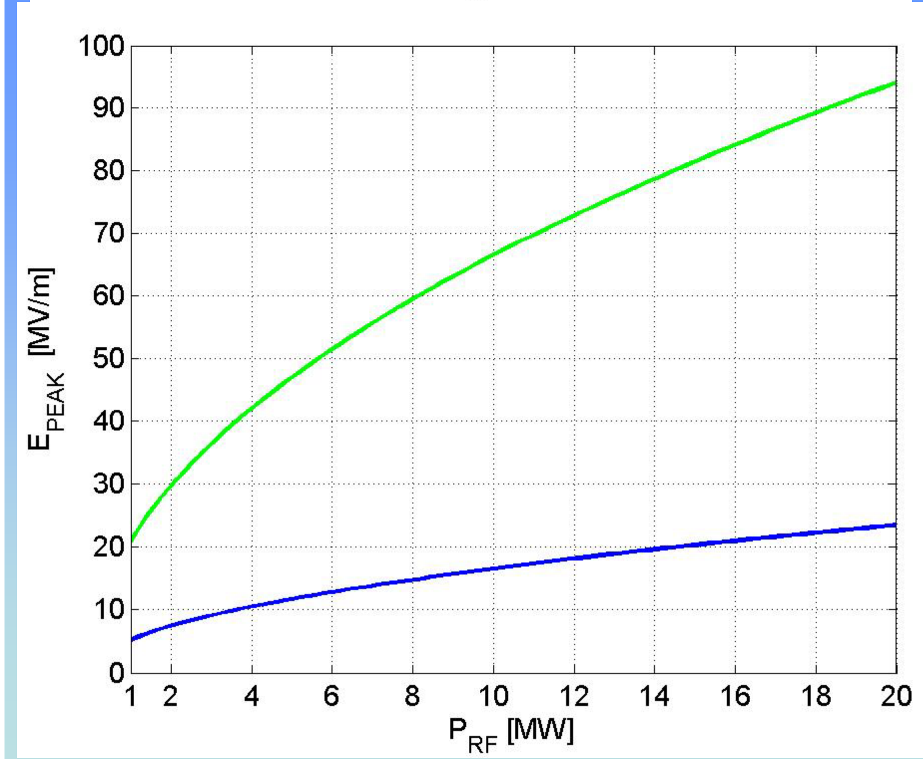
The ratio between the magnetic and the electric deflection depends on the iris diameter. For small irises the deflection is magnetic but for usual TW structures also the E field contrbute to the deflection.
Both *E* and *B* field have a longitudinal modulation given by the irises periodicity but the total deflecting field has a smaller modulation due to the partial compensation between the two *E* and *B* contributions.
Also the phase has almost a linear phase advance.

Traveling wave deflectors: performances

E_B= 2 GeV;
ε=1 mm mrad;
a=20 mm @ 2.856 GHz;
a=5 mm @ 11.424 GHz;
β_S=1 m;
L=4 m

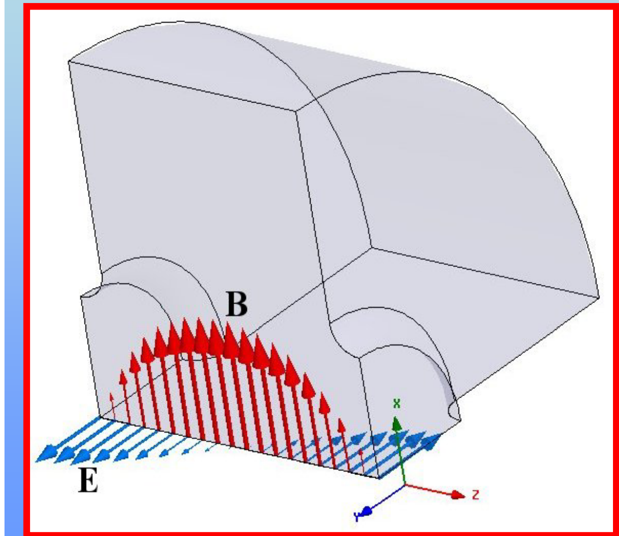




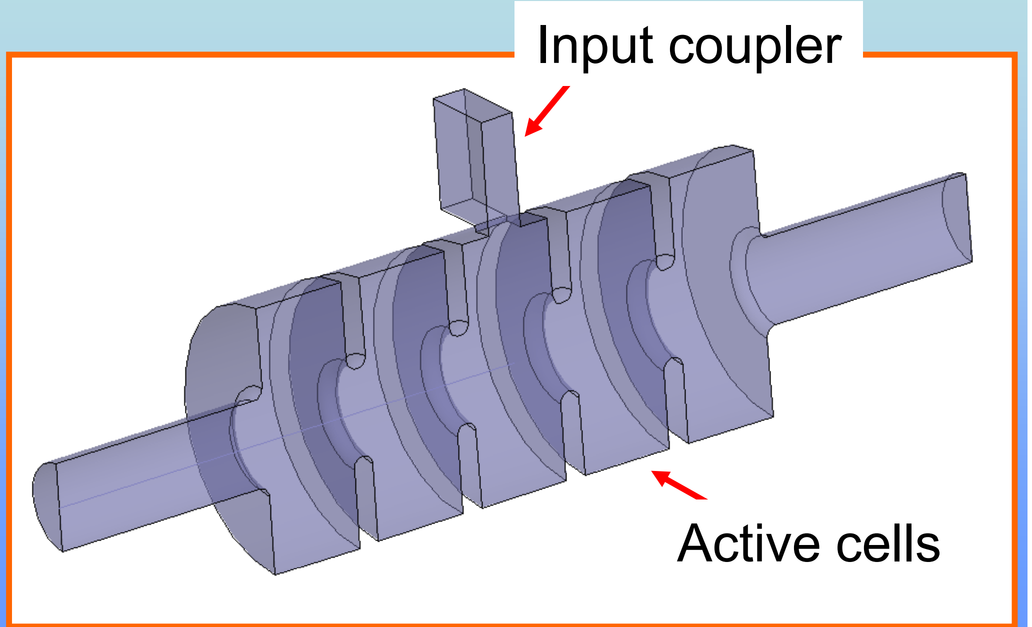


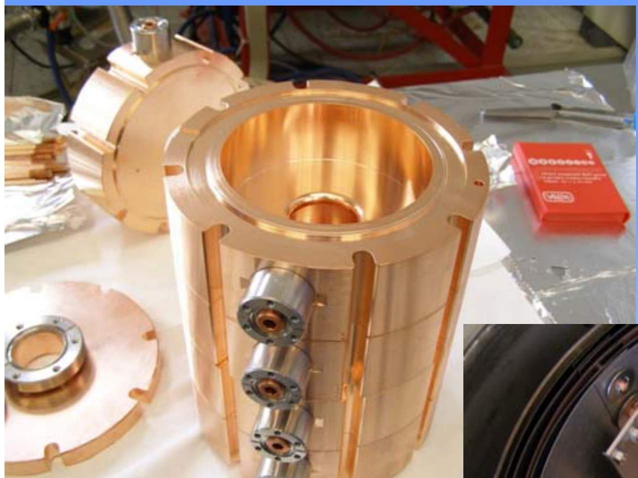
RF Deflecting structures: SW case (SPARC RFD)

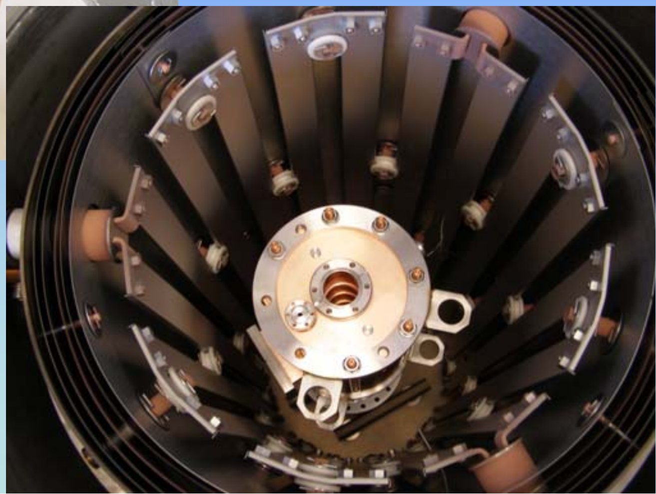
E, B field profiles



SW structures are multi cell devices working, for example, on the π-mode. Theses structures have, in general a **higher efficiency per unit length** with respect to the TW ones but the maximum number of cells is limited to few tens because of mode overlapping. They requires **circulators** to protect the RF source from reflections.

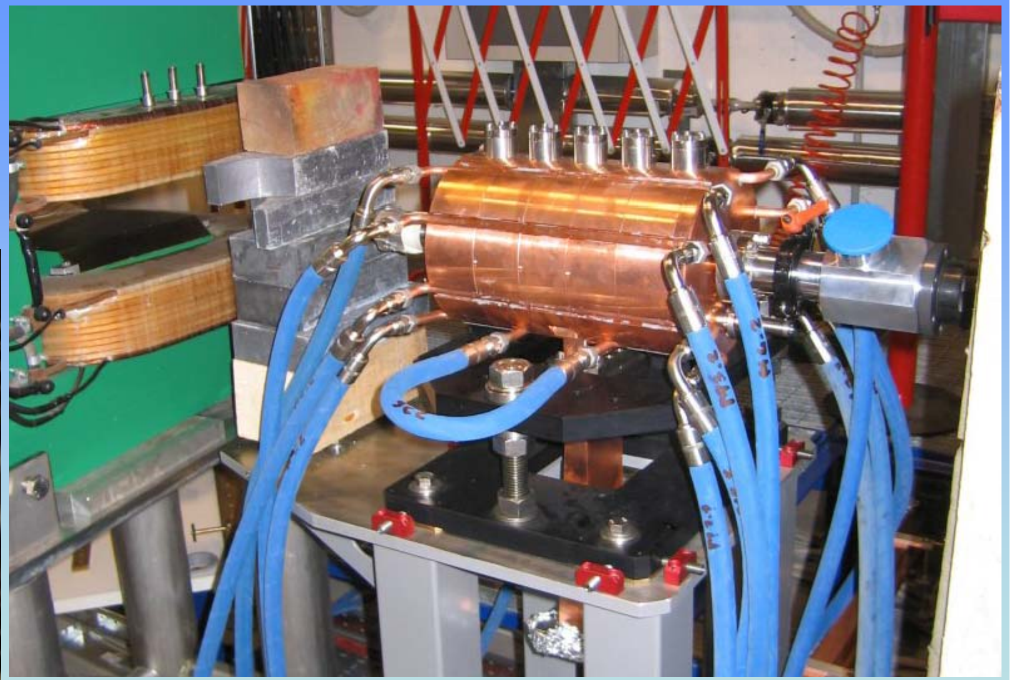






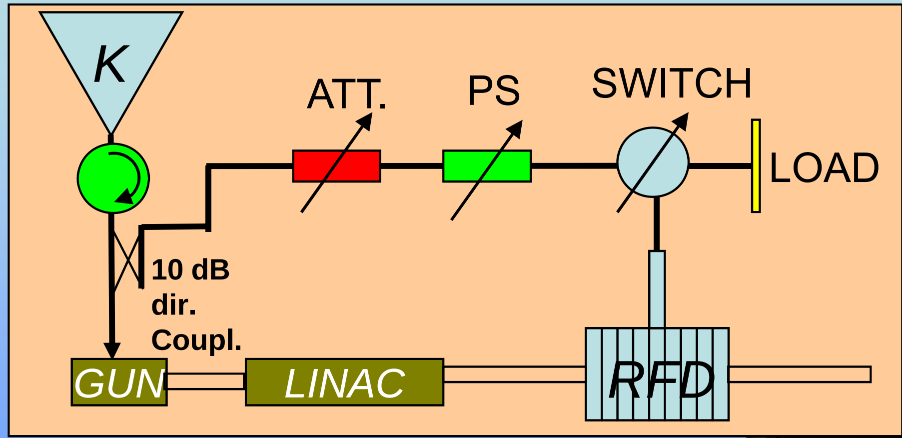
RFD in the LNF oven

RFD installed in SPARC

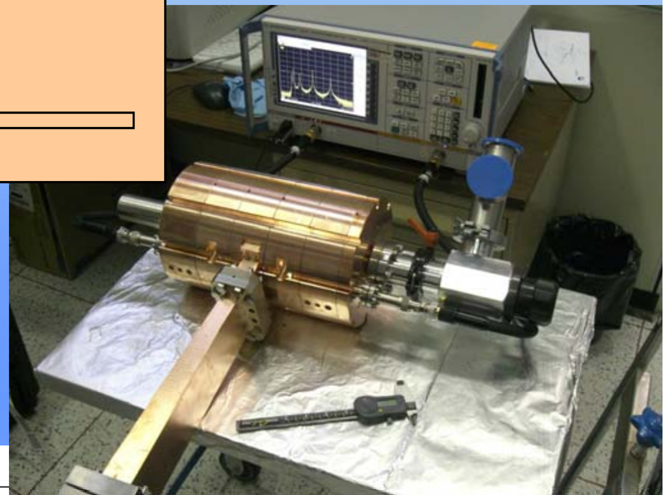


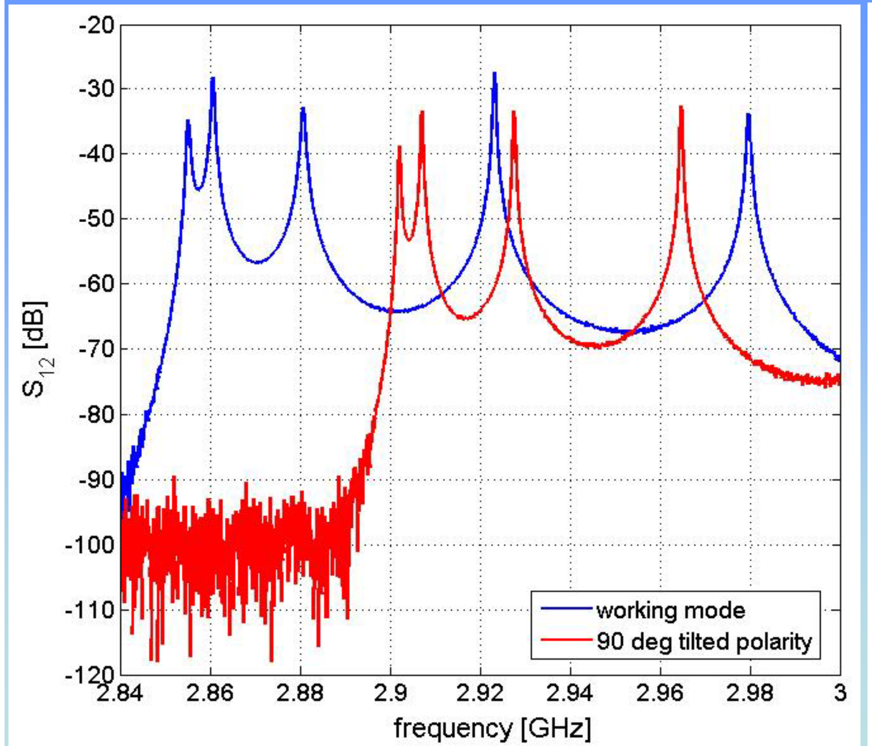
SPARC RF Deflector

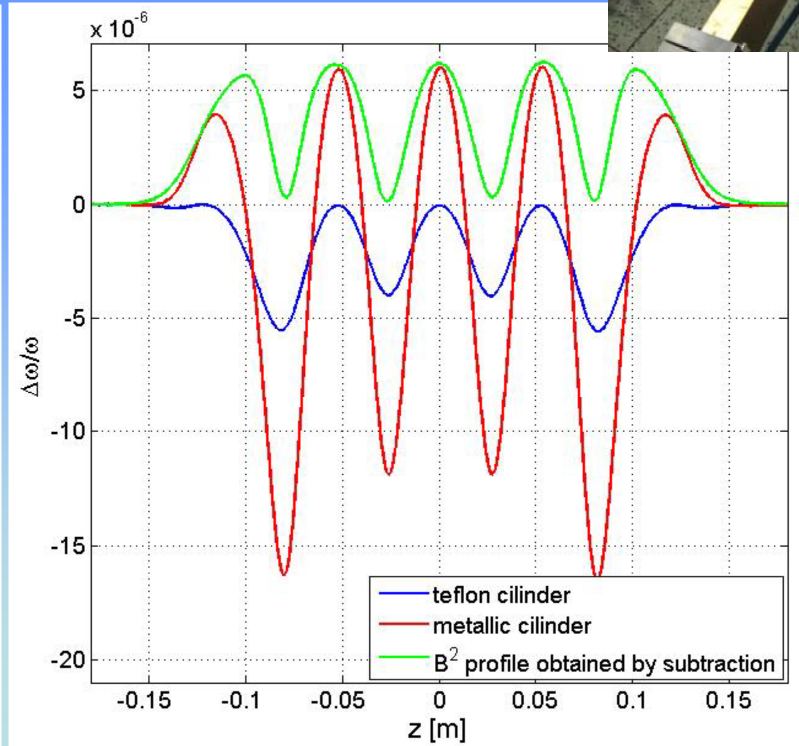
PARAMETERS	
Deflecting mode	SW, π
Number of cells	5
Frequency	2.856 GHz
Quality factor (Q_0)	16000
Coupling coefficient (β)	1
Max. input power (P_{RF_MAX})	2 MW
Transv. shunt imp. (R_T)	2.4 MΩ
Defl. voltage @ P_{RF_MAX} (V_T)	3 MV
Max. surf. E field (E_{PEAK})	50 MV/m



An example of SW structure is the SPARC RFD. It is a 5 cells SW structure working on the π-mode at 2.856 GHz and fed by a central coupler with coupling coefficient equal to 1.







RF Deflecting structures: SW vs TW performances

ε_N=1 [mm*mrad]

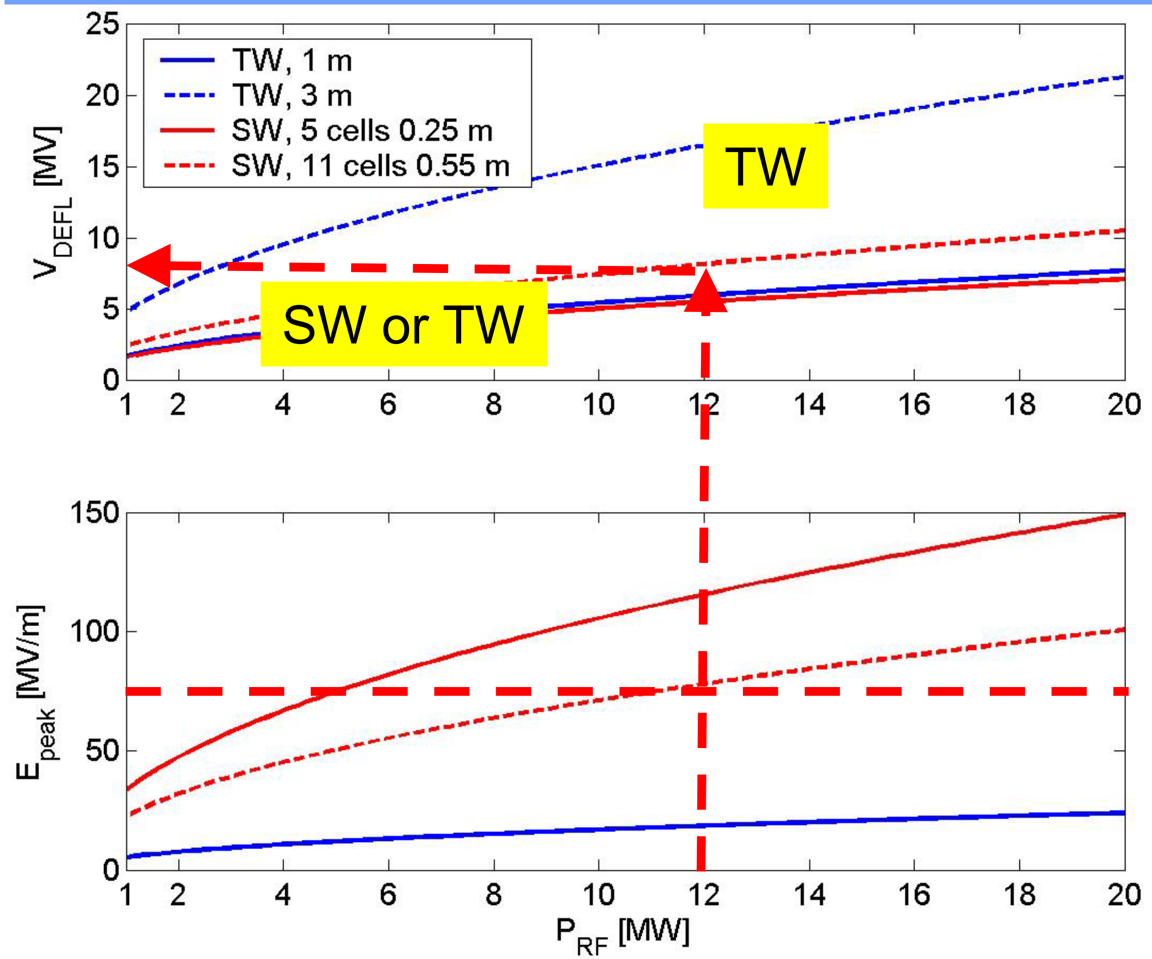
f_{RF}=2.856 [GHz]

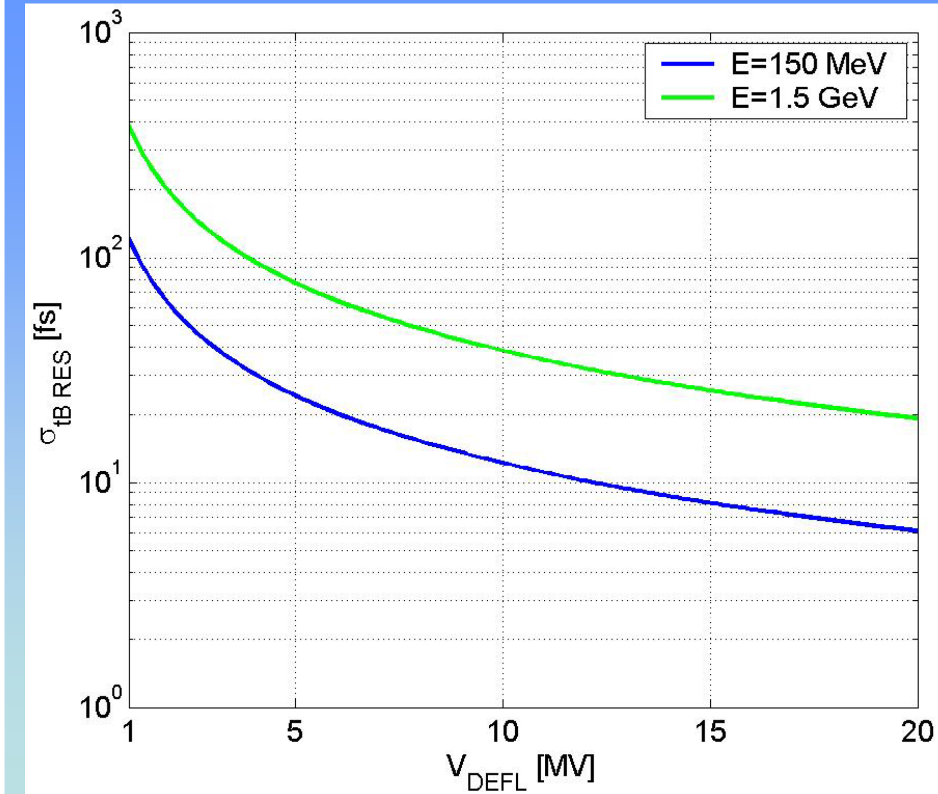
β_S=1 m
⇒ σ_{yB}≅18 μm (@1.5 GeV)
⇒ σ_{yB}≅58 μm (@150 MeV)
$L_{Defl\text{-}Screen}$=4 m

$$\sigma_{t_B\_RES} = \frac{\sigma_{y_B}}{\frac{V_T}{E/e}\omega_{RF}L} = \sqrt{E/E_0}\,\frac{\sqrt{\varepsilon\beta_S}}{V_T\omega_{RF}L}$$

Because of the higher surface electric field, SW multi-cell devices can be used with input power below 10 MW giving V_{DEFL}<7 MV

	SW	TW
Efficiency per unit length	High	Low
Filling time	slow	fast
Maximum number of cells	15	3-4 m
Circulator	yes	not
E_{PEAK}	high	low
Beam impact	low	High

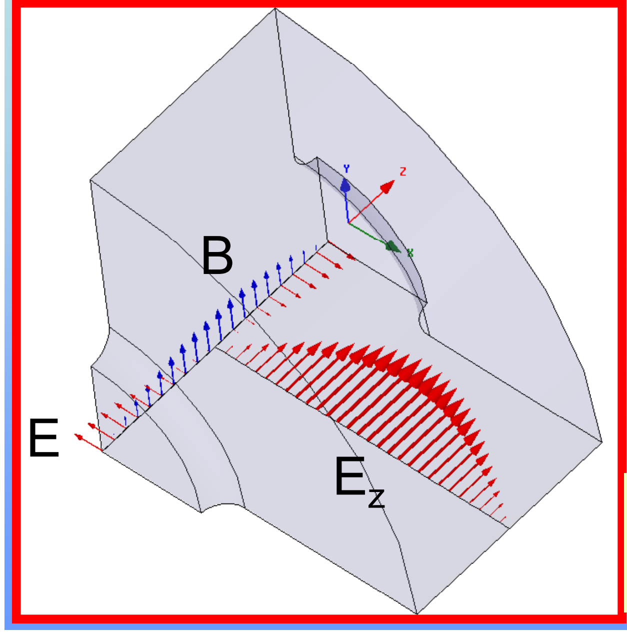




RF Deflecting structures: SW vs TW other characteristics

	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 15 because of mode overlapping	L up to 3 m in S band
Deflecting field vs. #of cells N for a given $P_{RF\ in}$	$N^{1/2}$	$(1-e^{-\alpha N})/\alpha$
Power system	A circulator is generally needed to protect the klystron	Circulator not necessary.
Temperature sensitivity	Necessity of an automatic tuning system or of a very good temperature stabilization	Less temperature sensitivity
Beam impact	low	High
Resolution vs. freq.	$1/f^{3/4}$ (N fixed)	$1/f^2$ (L fixed, small dissipation)

RF Deflecting structures: induced energy spread

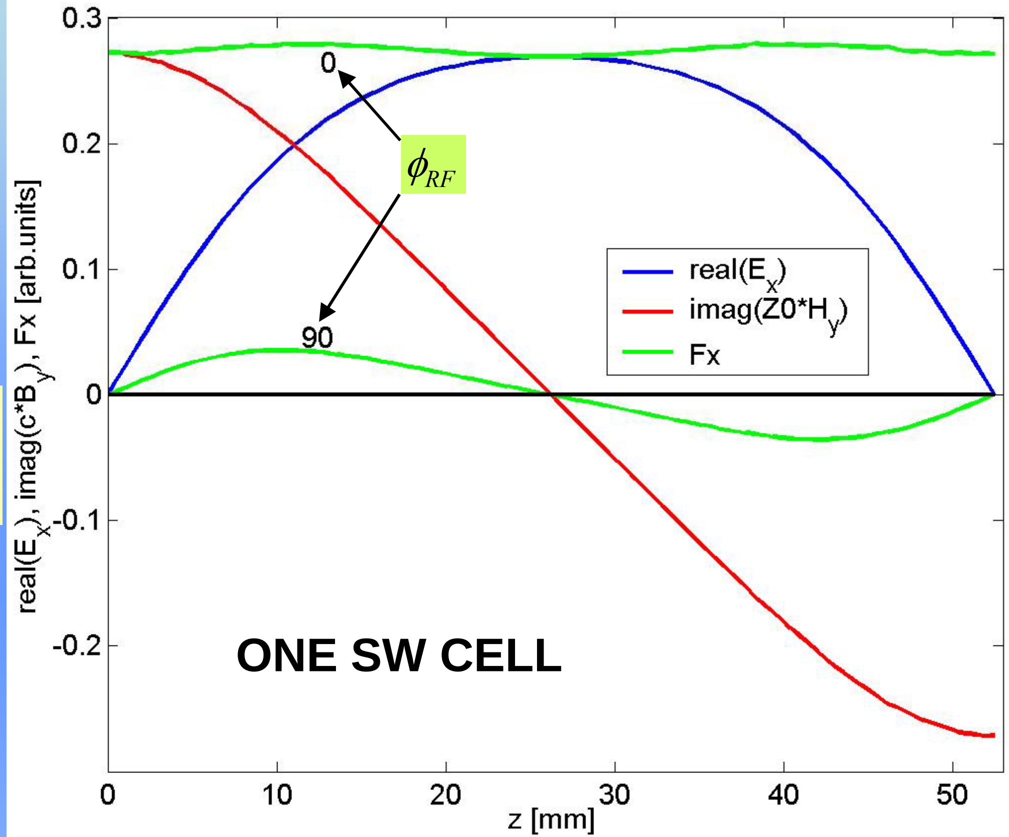


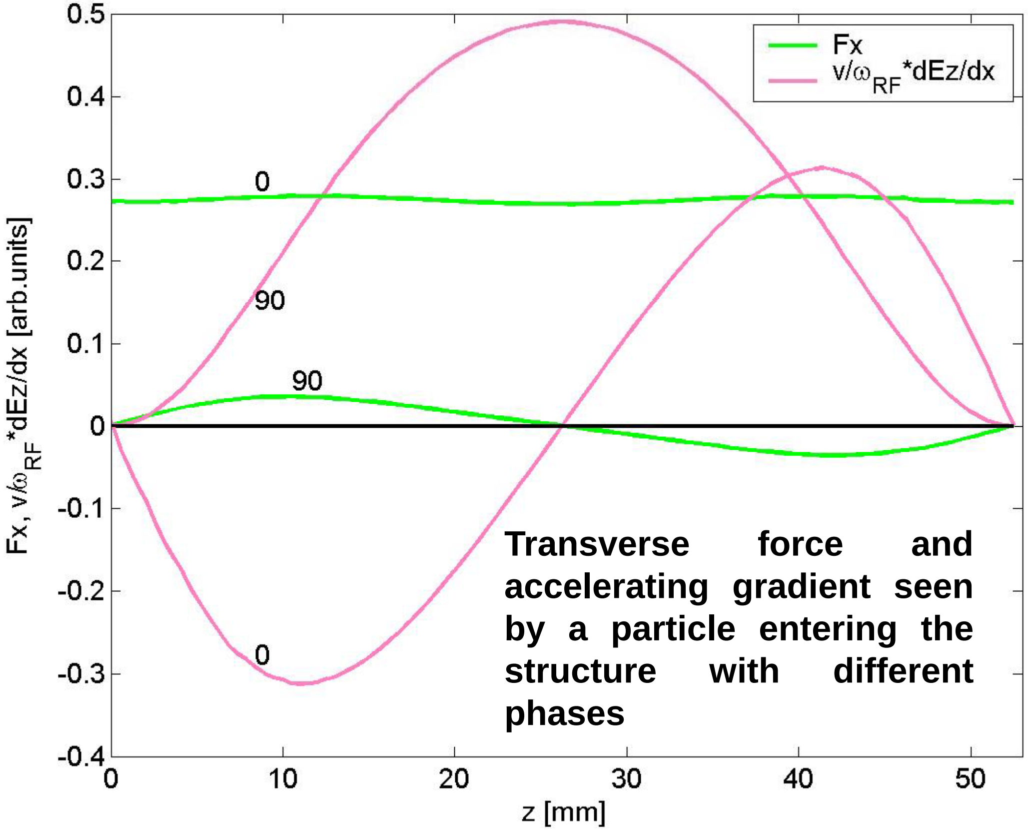
a) The ***Panofsky-Wenzel*** theorem relates the RFD transverse deflecting voltage and the ***longitudinal electric field gradient***;

b) The transverse deflecting voltage and the longitudinal one are ***90 deg out-of-phase***

$$\tilde{V}_{y\_RFD} = j \frac{c}{\omega_{RF}} \nabla_y \tilde{V}_{z\_RFD}$$

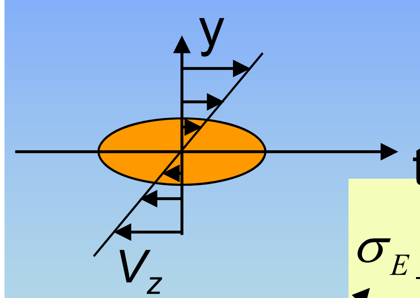
Transverse force and deflecting field components





Transverse force and accelerating gradient seen by a particle entering the structure with different phases

FIRST ORDER ESTIMATION



$$\sigma_{E\_RFD} \cong \frac{\omega_{RF}}{c} \hat{V}_{DEFL} \sigma_{yB\_RFD} \quad [eV]$$

RFD Induced energy spread

Average transverse beam dimension at the deflector

RF Deflecting structures: transport matrix of a single cell

RFD Correlation t_B-(y_{OUT}, y'_{OUT}) allowing long. Profile measurements

$$B = -\frac{E_{defl}\omega_{RF}}{E_B}\sin(\phi_{RF}) \qquad E_{defl} = \frac{V_{defl}}{L_{RFD}}$$

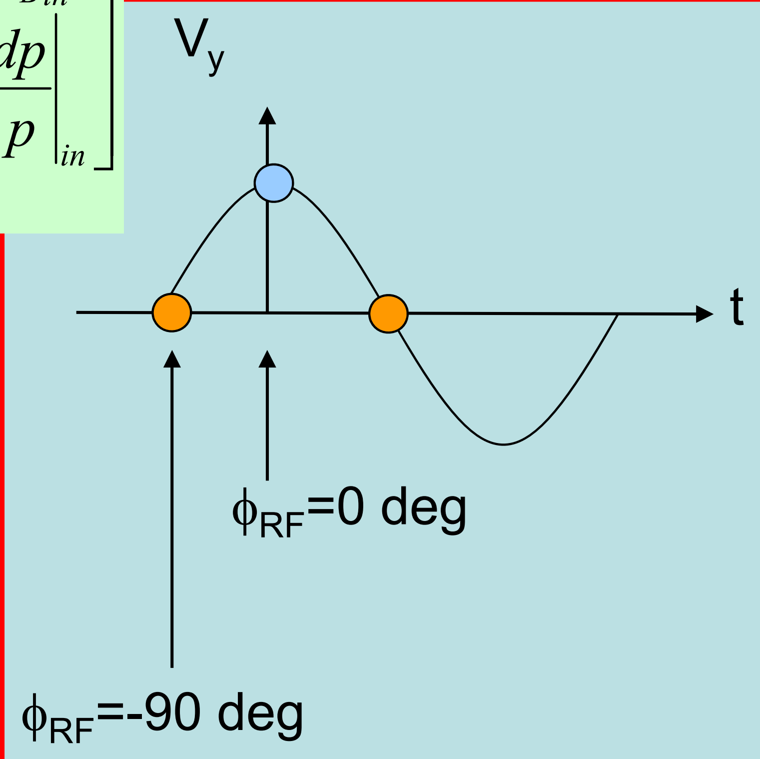
Dispersion terms given by the RFD deflecting voltage if we are on crest (ϕ_{RF}=0deg)

$$C = \frac{E_{defl}}{E_B}\cos(\phi_{RF})$$

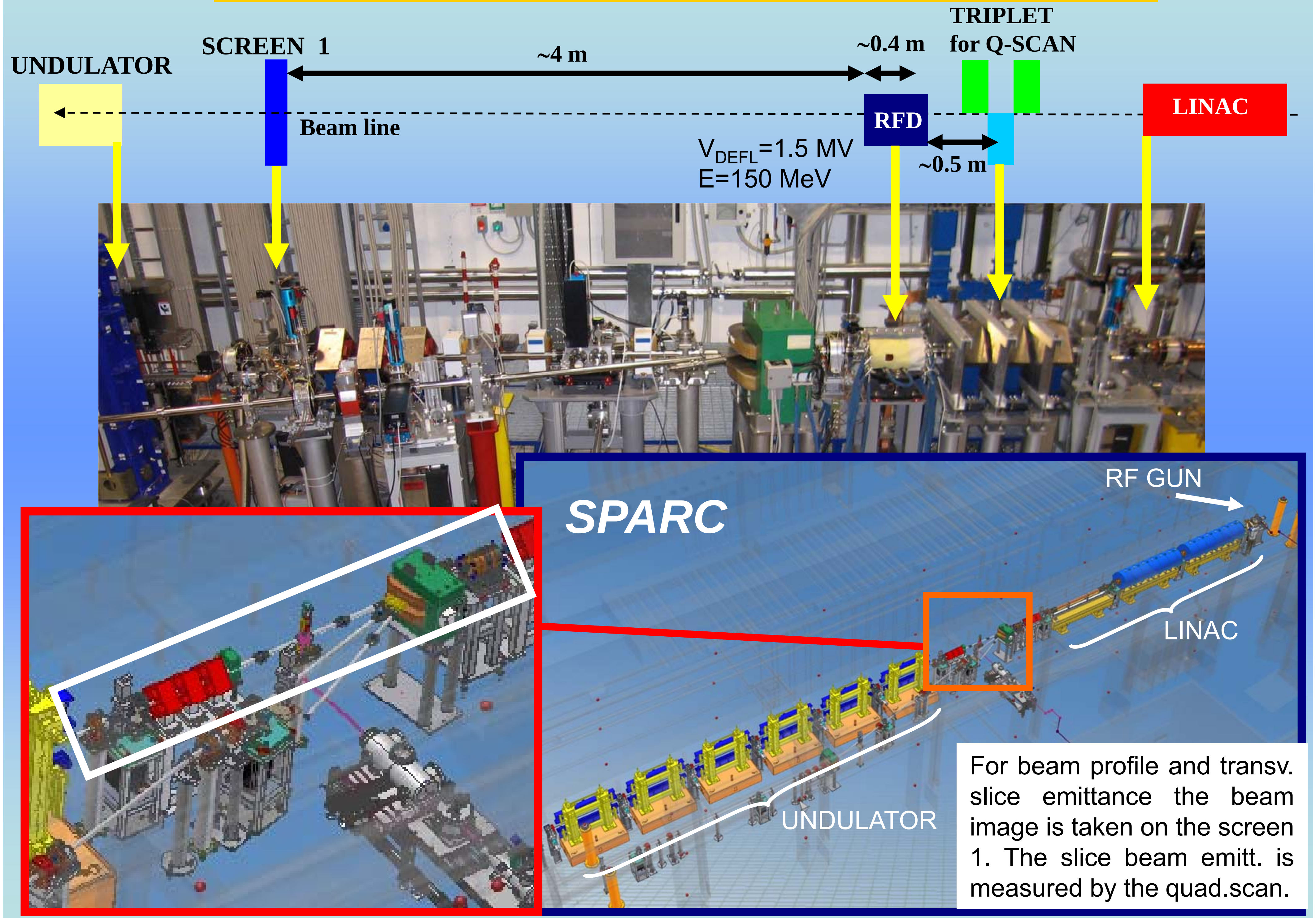
$$\begin{bmatrix} y_{out} \\ y'_{out} \\ t_{B\,out} \\ \left.\frac{dp}{p}\right|_{out} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & L_{RFD} & 1/2\,BL_{RFD}^2 & 1/2\,CL_{RFD}^2 \\ 0 & 1 & BL_{RFD} & CL_{RFD} \\ 0 & 0 & 1 & 0 \\ DL_{RFD} & 1/2\,DL_{RFD}^2 & 0 & 1 \end{bmatrix}}_{M_{\mathrm{RFD}}} \begin{bmatrix} y_{in} \\ y'_{in} \\ t_{B\,in} \\ \left.\frac{dp}{p}\right|_{in} \end{bmatrix}$$

$$D = -\frac{E_{defl}\omega_{RF}}{cE_B}\sin(\phi_{RF})$$

Energy variation due to the longitudinal e-field off axis

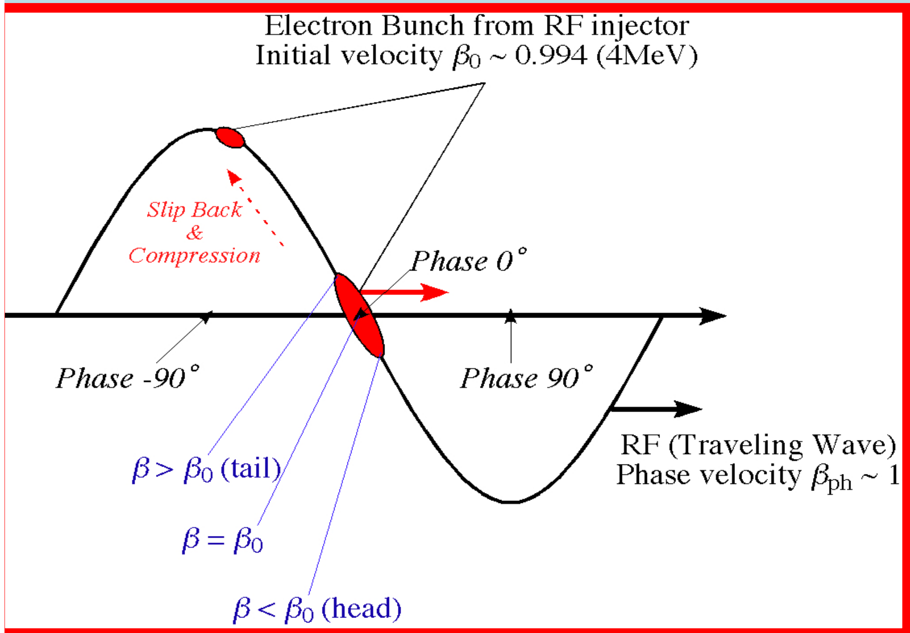


General meas. setup: beam profile measurements



For beam profile and transv. slice emittance the beam image is taken on the screen 1. The slice beam emitt. is measured by the quad.scan.

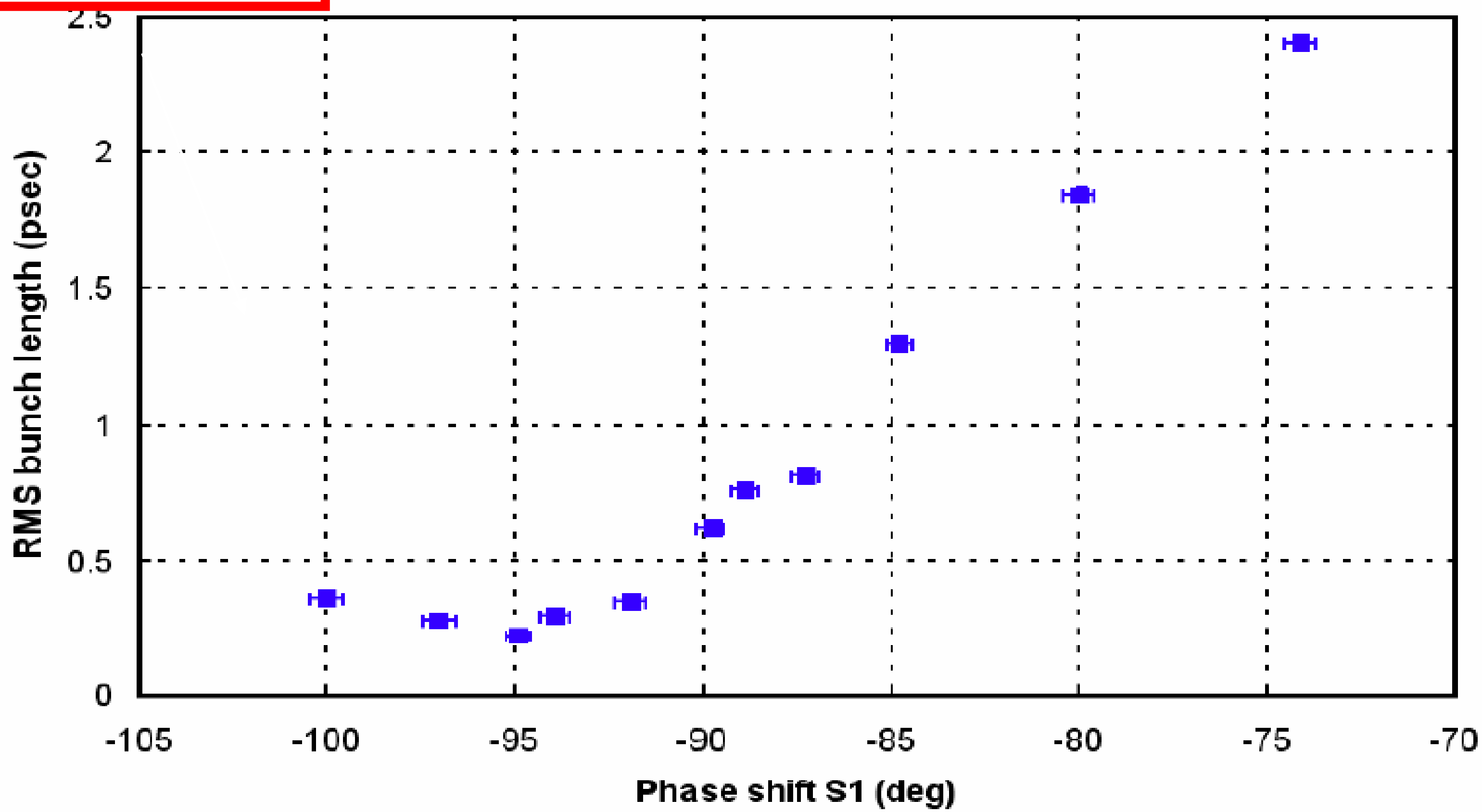
Beam profile measurements: measurement@SPARC (1/2)



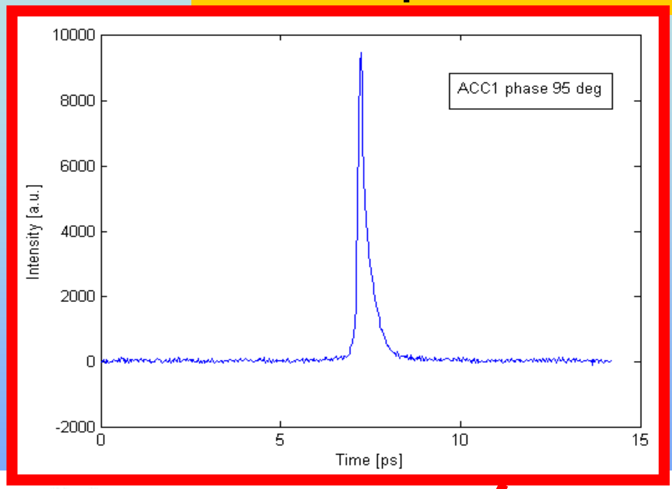
VELOCITY BUNCHING MEASUREMENTS

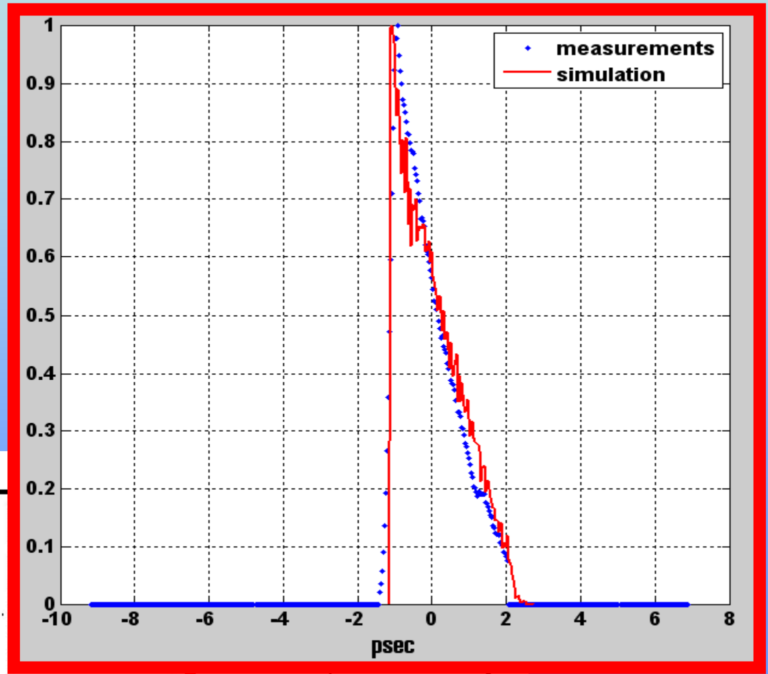
If the beam injected in a long accelerating structure at the crossing field phase and it is slightly slower than the phase velocity of the RF wave, **it will slip back to phases where the field is accelerating, but at the same time it will be chirped and compressed**.

We operated with a **quasi-Gaussian long. laser profile** ~7.5 ps FWHM long with 300 mm transverse spot size and 300 pC. The beam acceleration on crest corresponds to the phases around -75 deg. In this condition bunch length is length measured at the linac exit was 2.5 ps with an energy of 150 MeV.

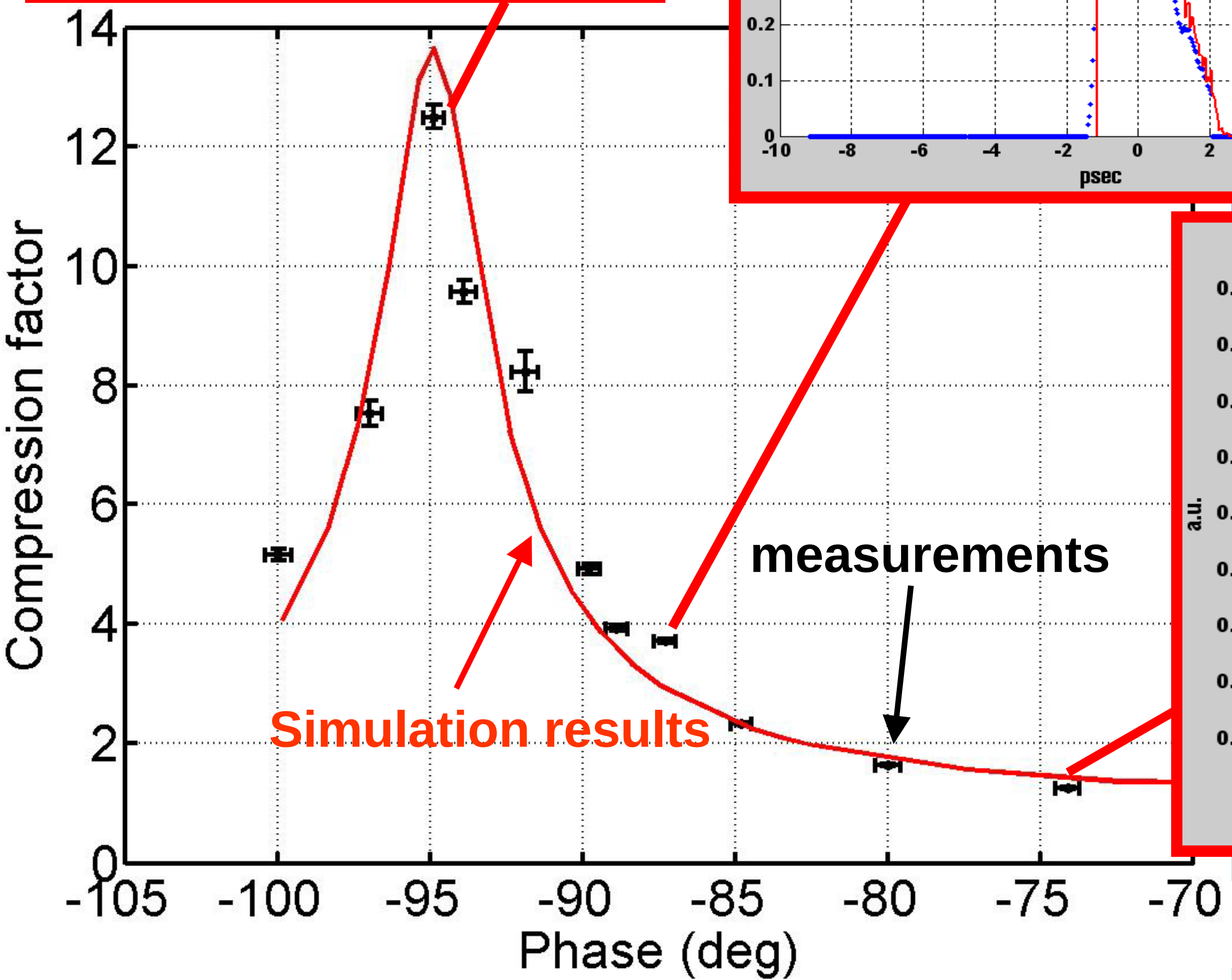


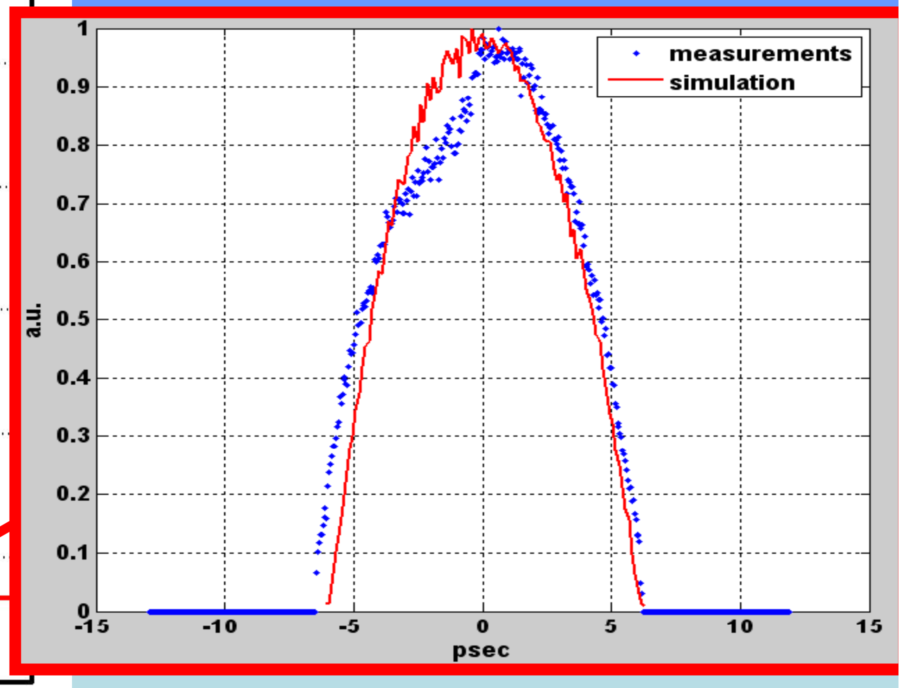
Beam profile measurements: measurement@SPARC (2/2)





The longitudinal beam profile measurements are crucial for this experiment because, **while the bunch is compressed, it also change its longitudinal distribution.**



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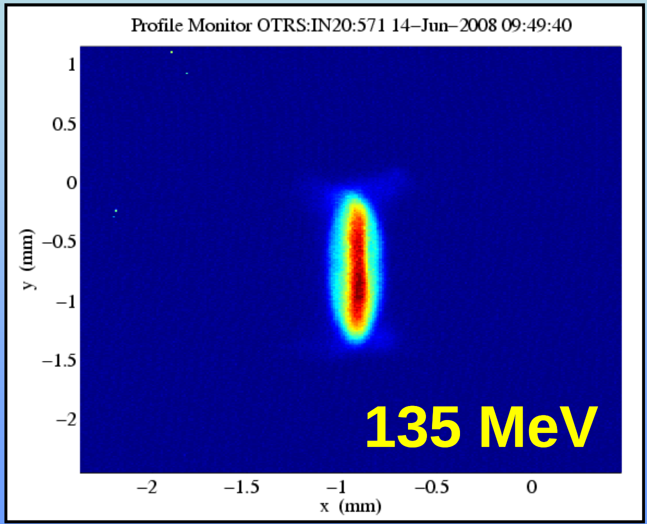
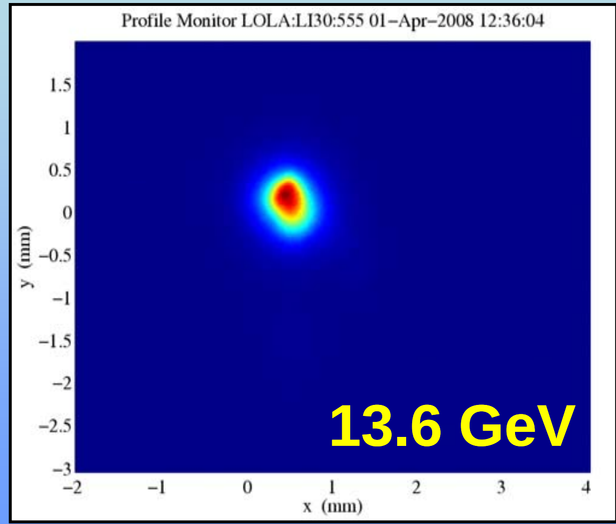
Experimental Demonstration of Emittance Compensation with Velocity Bunching

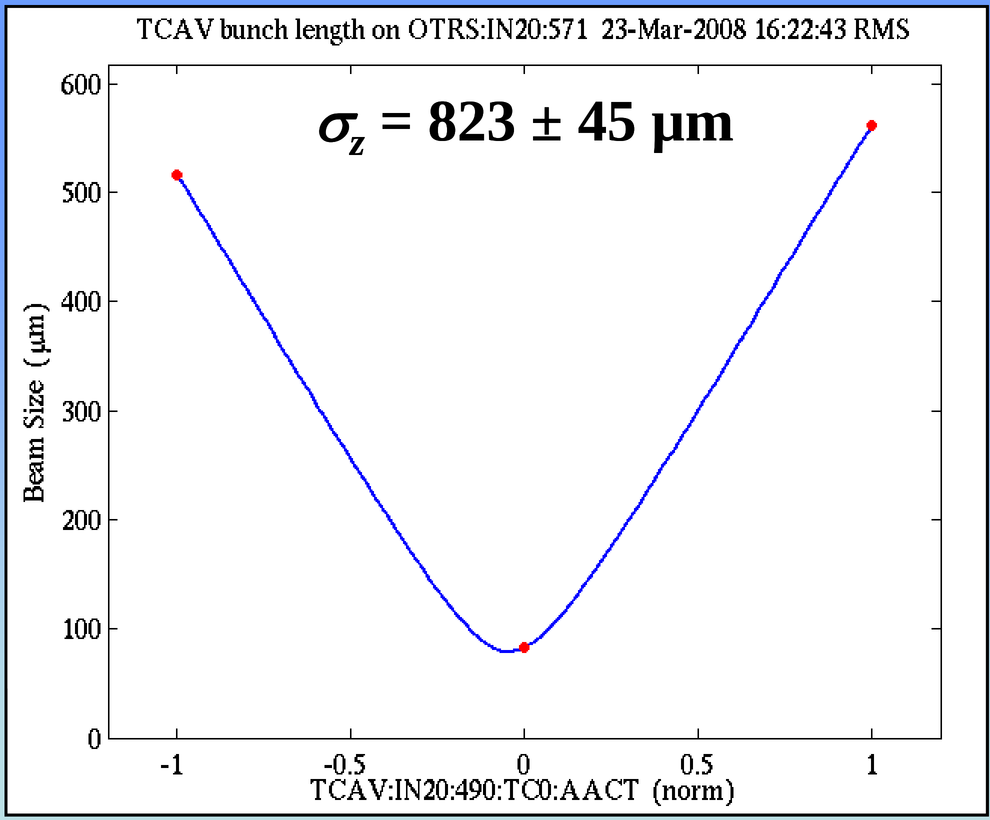
Beam profile: measurement@ LCLS (courtesy P. Emma)

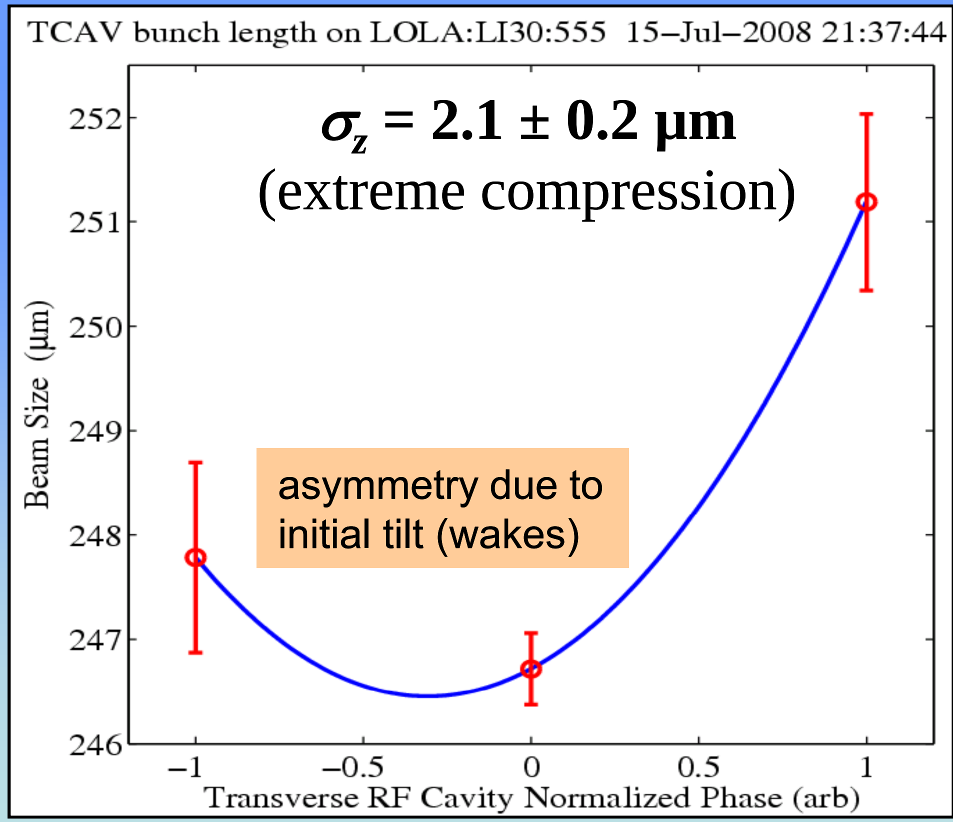


Use **Two Different Transverse RF Deflectors** to Measure Bunch Length at **135 MeV** and also at **13.6 GeV**

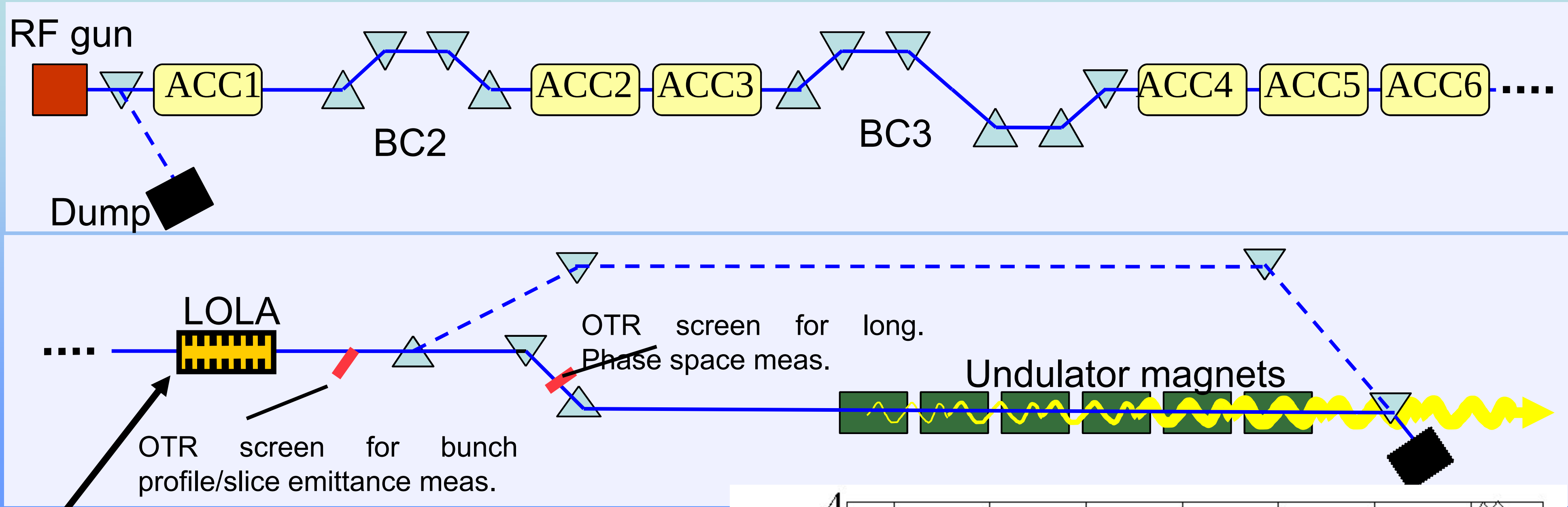
TW Structure
(LOLA CAVITY)
$V_{RFD} \geq$ **15 MV**
f_{RF}**=2.856 GHz**



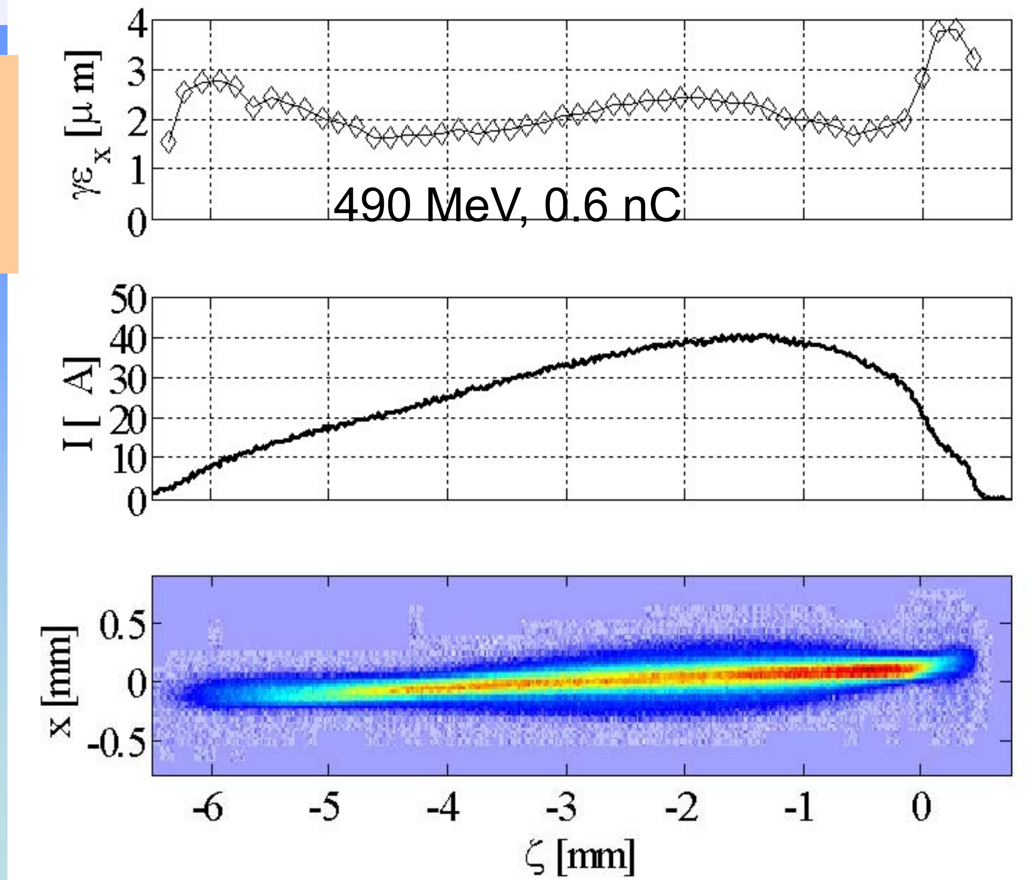




Beam profile: measurement@FLASH (courtesy C. Gerth)

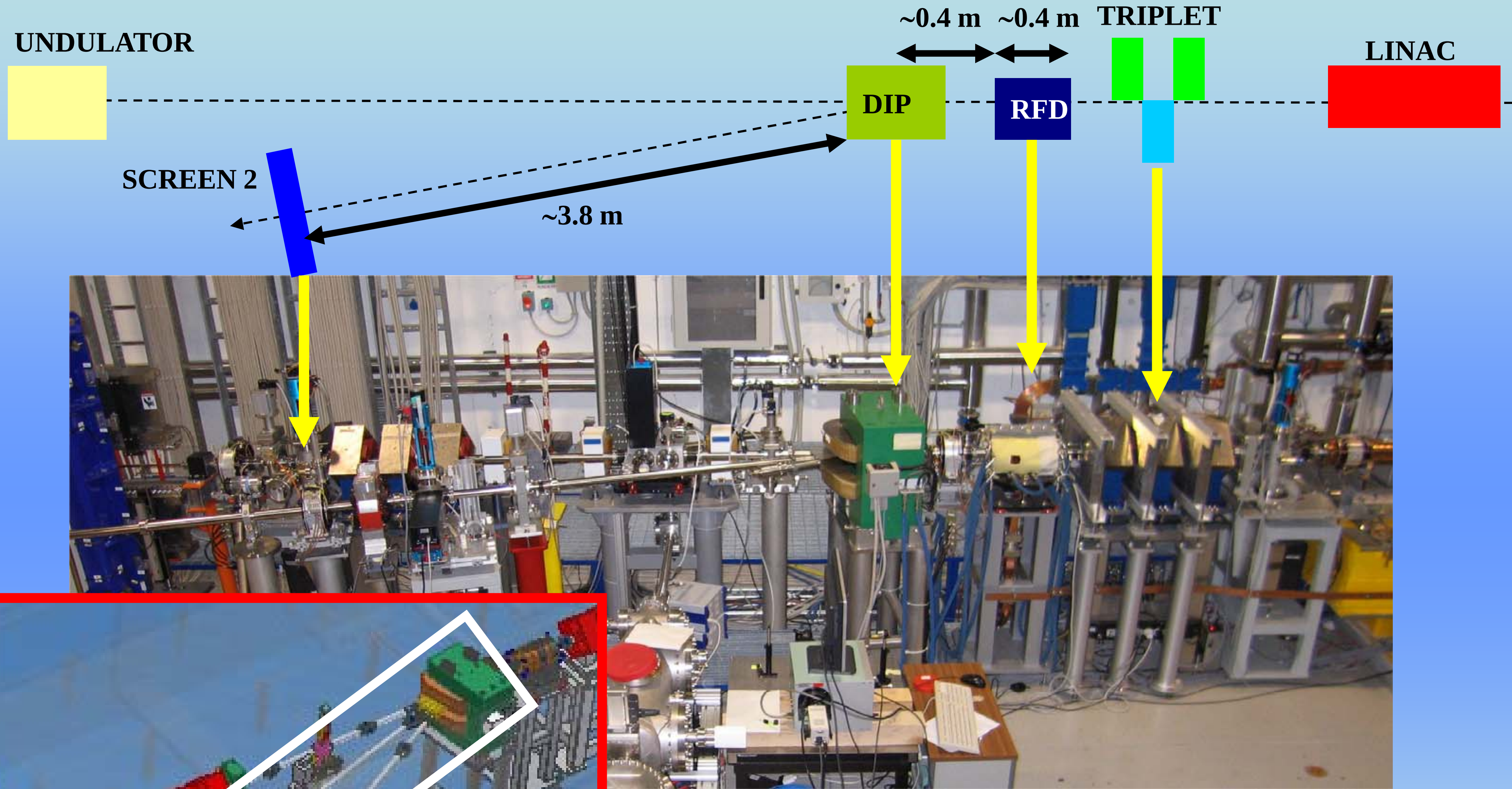


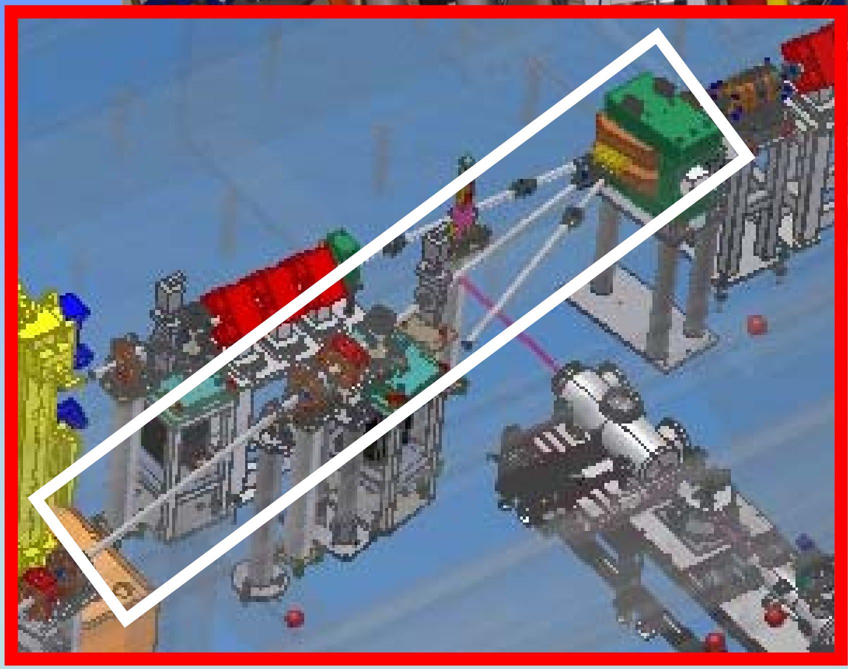
Frequency: 2.856 GHz
Length: 3.6 m
VRFD~25 MV@20 MW P_{IN}
σ_{tB_RES}=20fs



On-crest operation

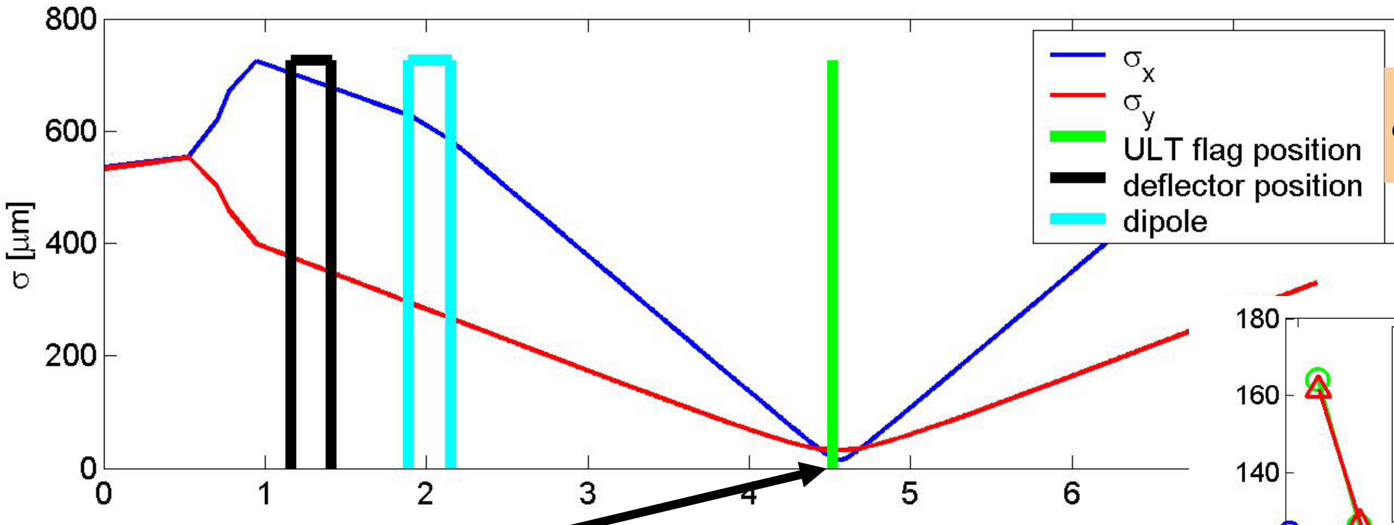
General measurement setup: longitudinal phase space



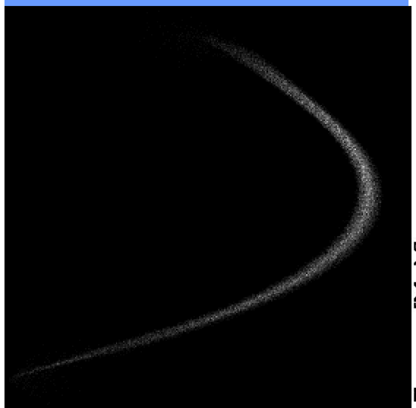


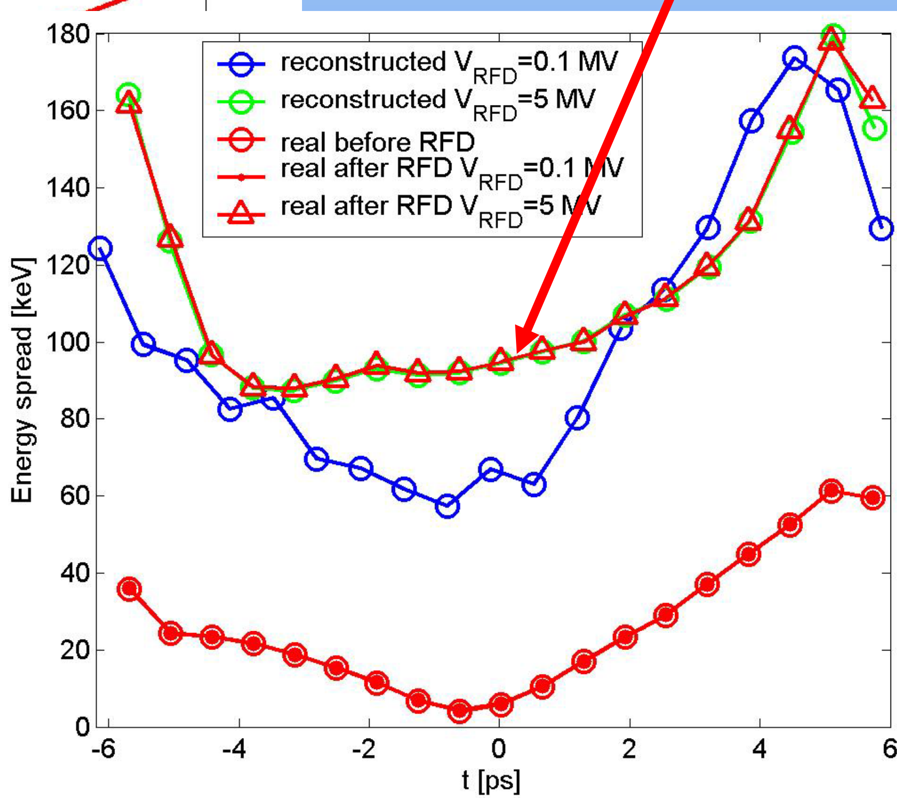
The longitudinal phase space can be characterized using the combination of RFD and dipole. In this case the beam is projected into the screen 2. In order to have enough longitudinal resolution the **vertical dimension at the screen position has to be taken under control**. From the phase space picture the slice energy spread can be extrapolated by slicing the beam vertically and measuring the beam thickness in energy as function of time.

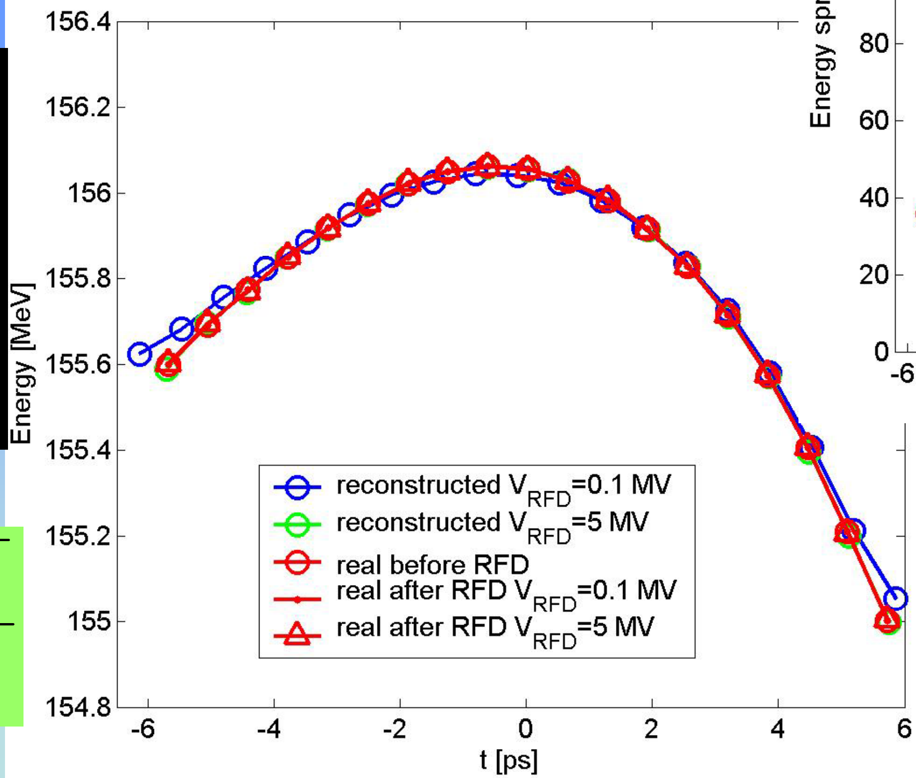
Long phase space: virtual measurement



$$\sigma_{E\_RFD} \cong \frac{\omega_{RF}}{c}\hat{V}_{y\_RFD}\sigma_{y\_RFD} = 107\,[keV]$$







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

Also the horizontal β-function at the screen has to be reduced as much as possible in order to reduce the emittance contribution to the energy spread measurement. **In any case the dominant systematic error is the energy spread induced by the RFD**

Long phase space: subtraction of the RFD contribution to σ_E

For each slice

$$\sigma_E^2 + \sigma_{E\_RFD}^2 = \sigma_{E\_MIS}^2 \Rightarrow \begin{cases} \sigma_E^2 + \sigma_{E\_RFD\_1}^2 = \sigma_{E\_MIS\_1}^2 \\ \sigma_E^2 + \sigma_{E\_RFD\_2}^2 = \sigma_{E\_MIS\_2}^2 \end{cases}$$

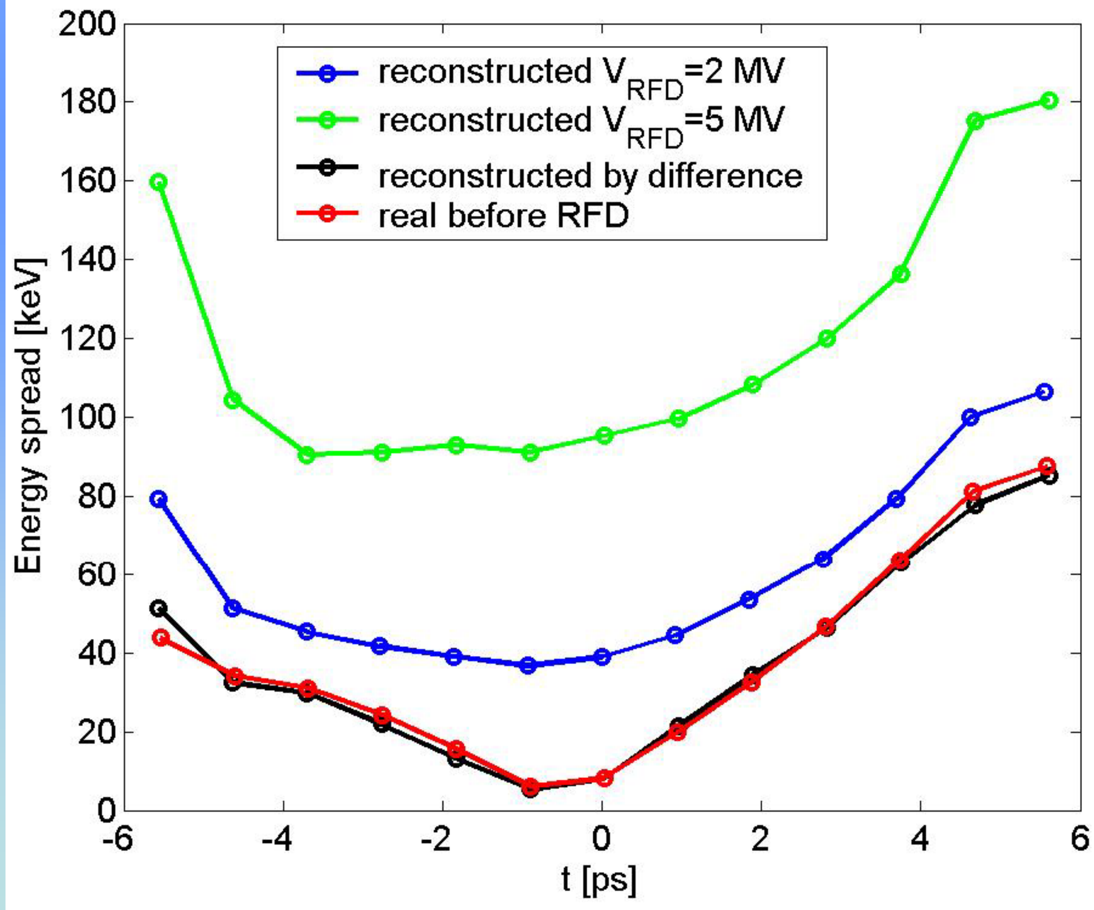
$$\left(\frac{\omega_{RF}}{c}\hat{V}_{DEFL\_1}\right)^2 \sigma_{y\_RFD}^2 - \left(\frac{\omega_{RF}}{c}\hat{V}_{DEFL\_2}\right)^2 \sigma_{y\_RFD}^2 = \sigma_{E\_MIS\_1}^2 - \sigma_{E\_MIS\_2}^2$$

$$\sigma_{y\_RFD}^2 = \left(\frac{c}{\omega_{RF}}\right)^2 \frac{\sigma_{E\_MIS\_1}^2 - \sigma_{E\_MIS\_2}^2}{\hat{V}_{DEFL\_1}^2 - \hat{V}_{DEFL\_2}^2}$$

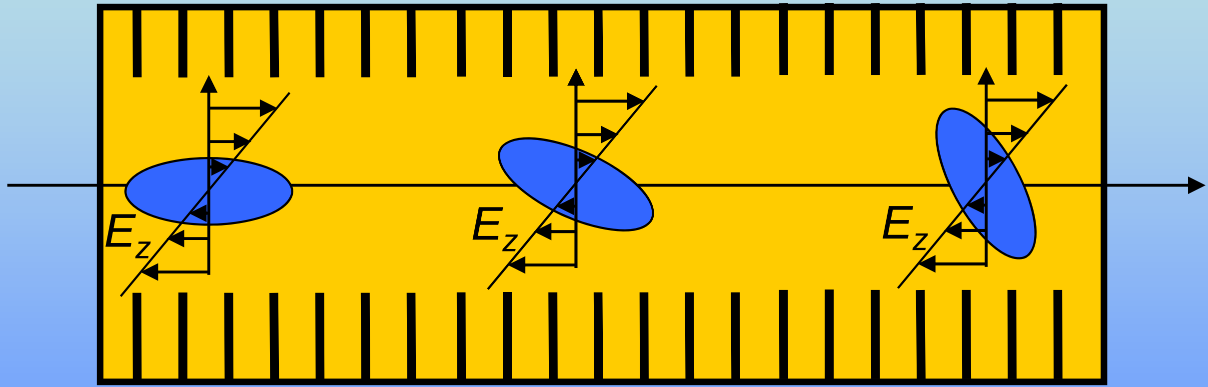
$$\sigma_{E\_RFD} \cong \frac{\omega_{RF}}{c}\hat{V}_{DEFL}\sigma_{y\_RFD} \qquad [eV]$$

$$\sigma_E^2 = \sigma_{E\_MIS}^2 - \sigma_{E\_RFD}^2$$

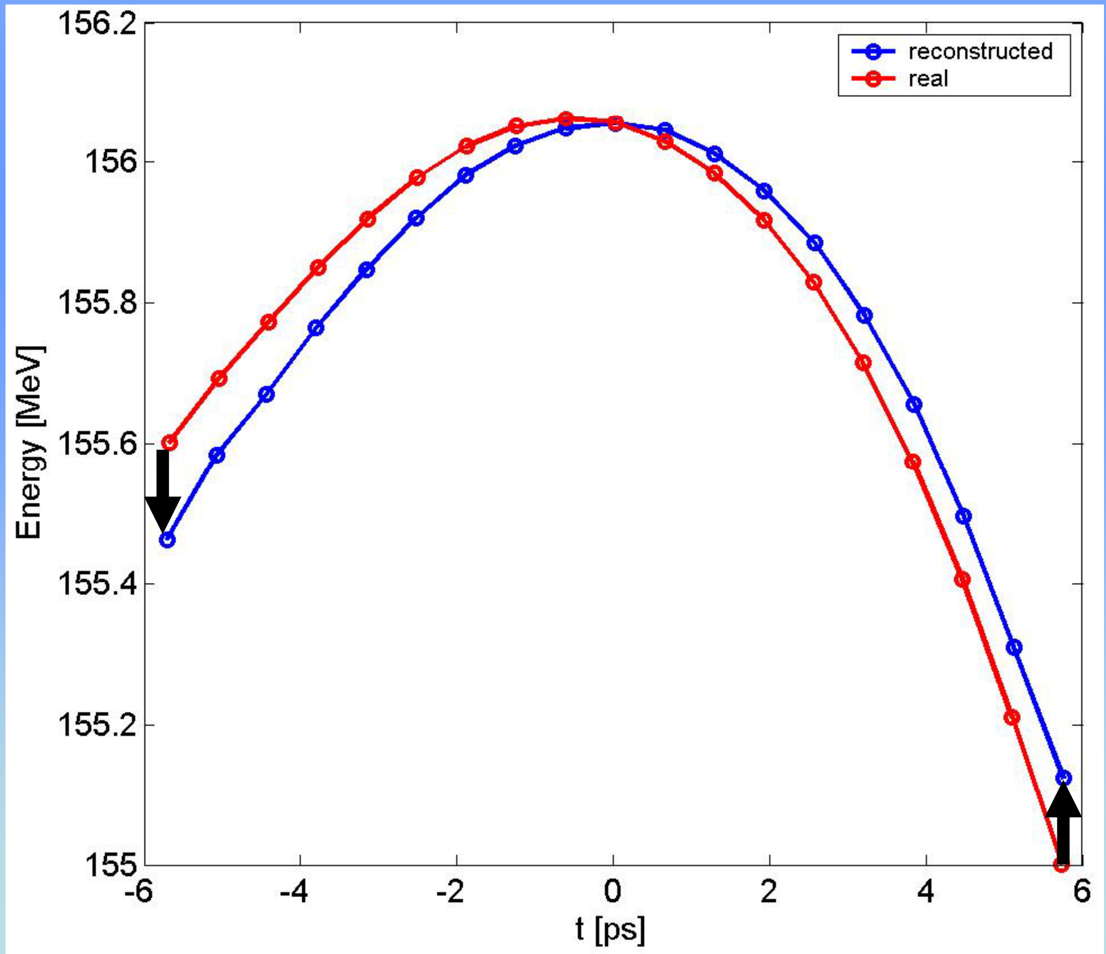
The contribution of the deflector to the slice energy spread can be taken into account performing two measurements at two different deflecting voltages and using the following formulae to evaluate the sigma σ_{yB_RFD} of each slice.



Long phase space: effect of long RFD structures

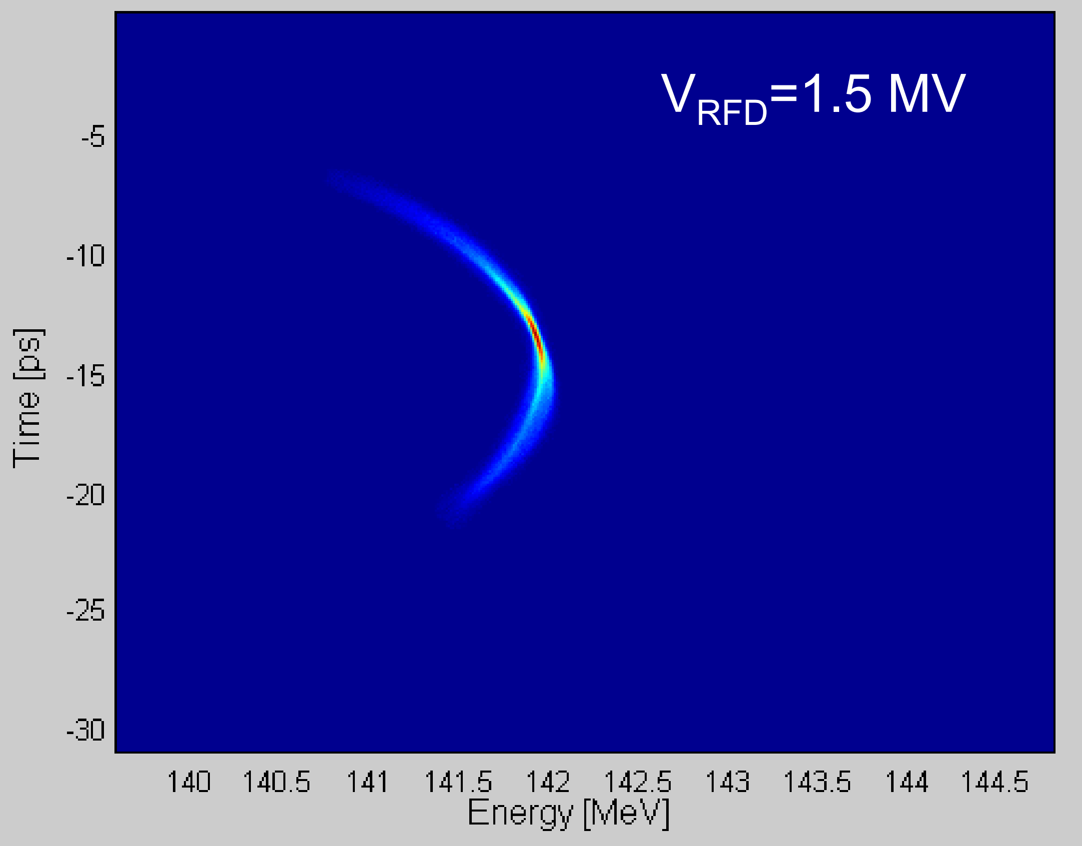


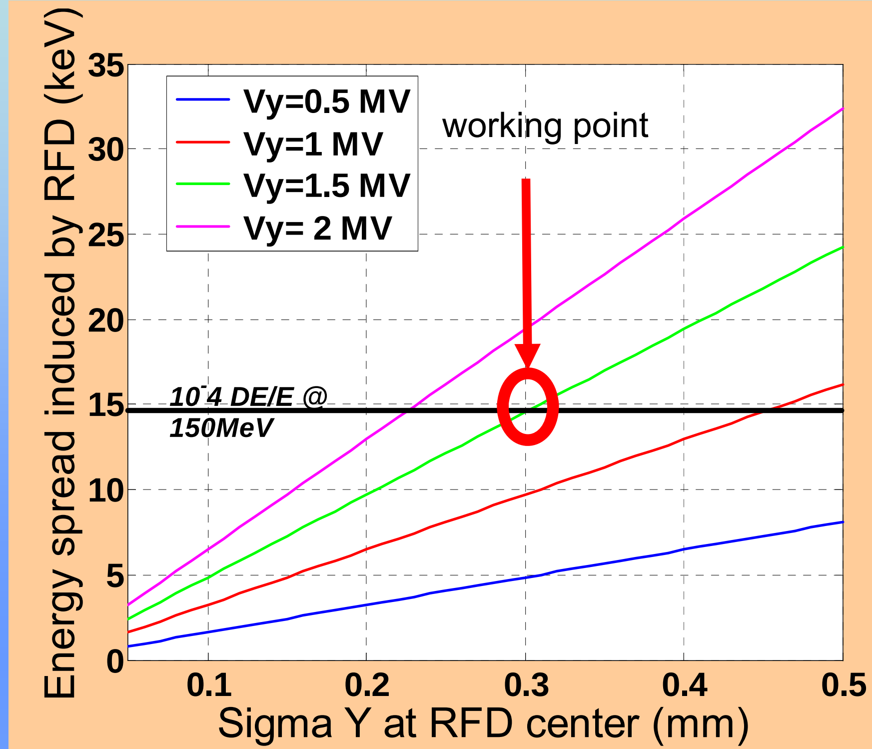
If we consider a long RFD, we can have effects also on the measured average energy of each slice because the bunch head-tail rotate along the deflector and experience a non-zero average electric field



Example:
Assuming a L_{RFD}=0.8 m @ SPARC

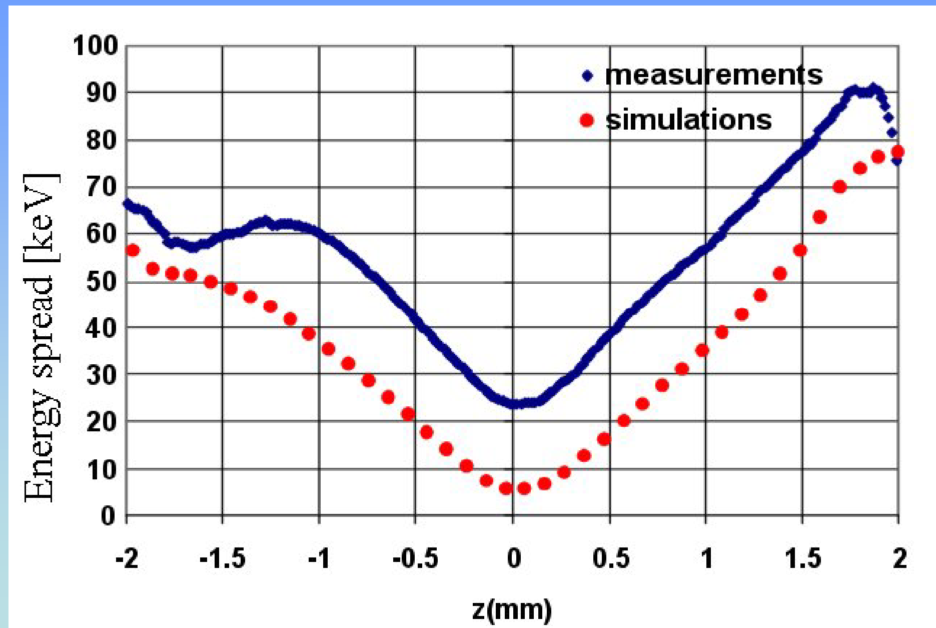
Long phase space: measurement @ SPARC



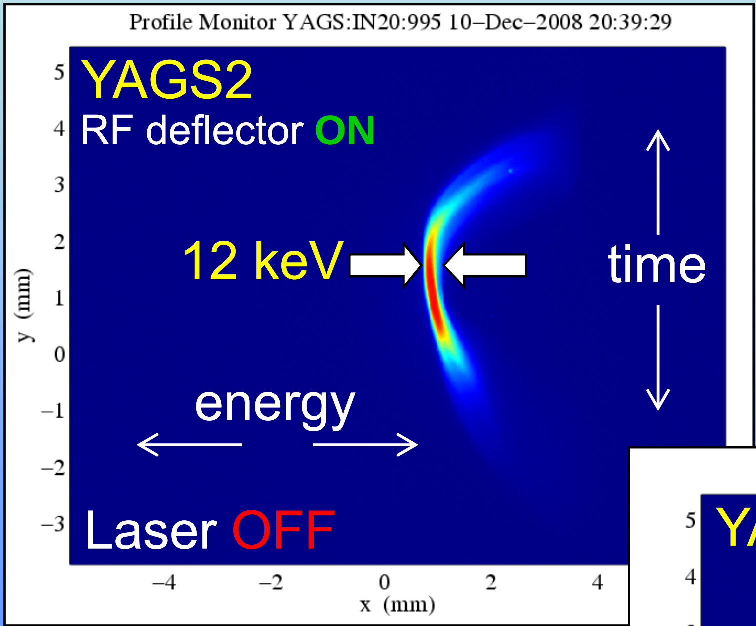


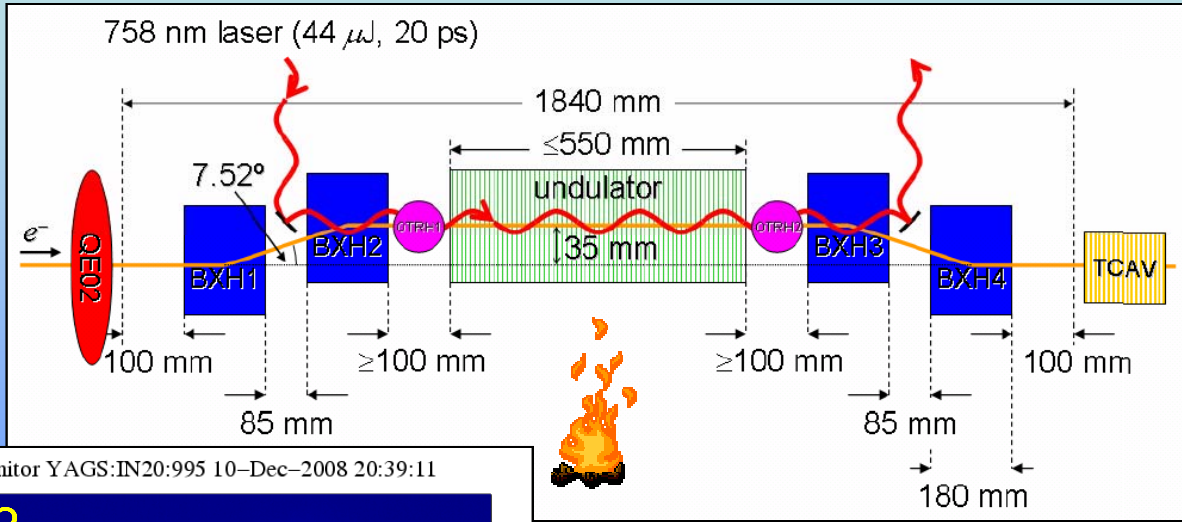
From the plot the slice energy spread can be extrapolated and compared with simulations. The main discrepancy between the simulations and the experimental data is given by the **RFD contribution** that has been estimated to be ~15 keV.

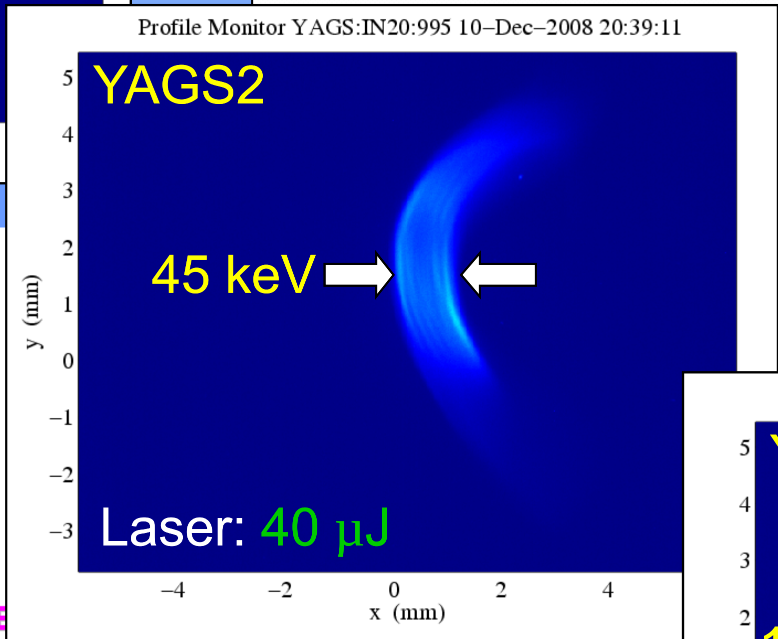
The **emittance contribution** has not been subtracted from the measurements, but it has been estimated to be less than 10%.



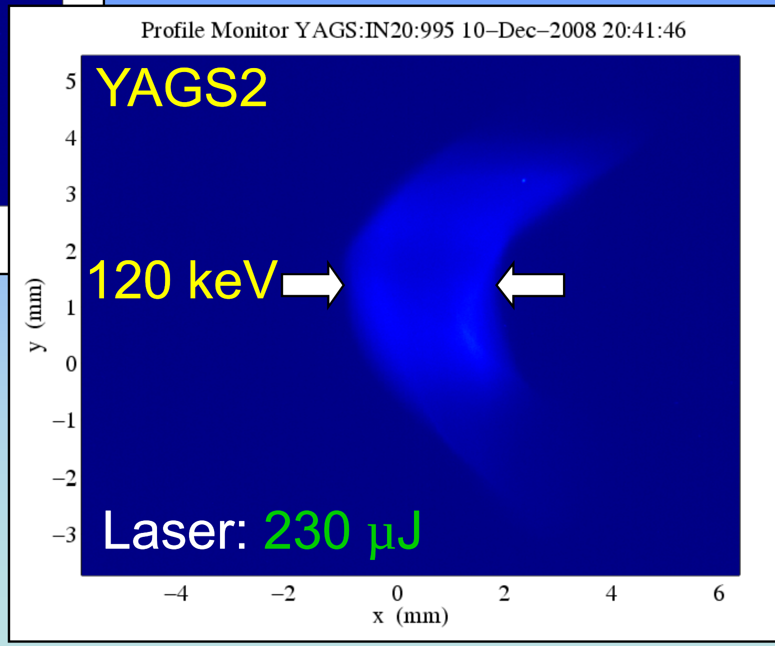
Long phase space: measurement @ LCLS (courtesy P. Emma)

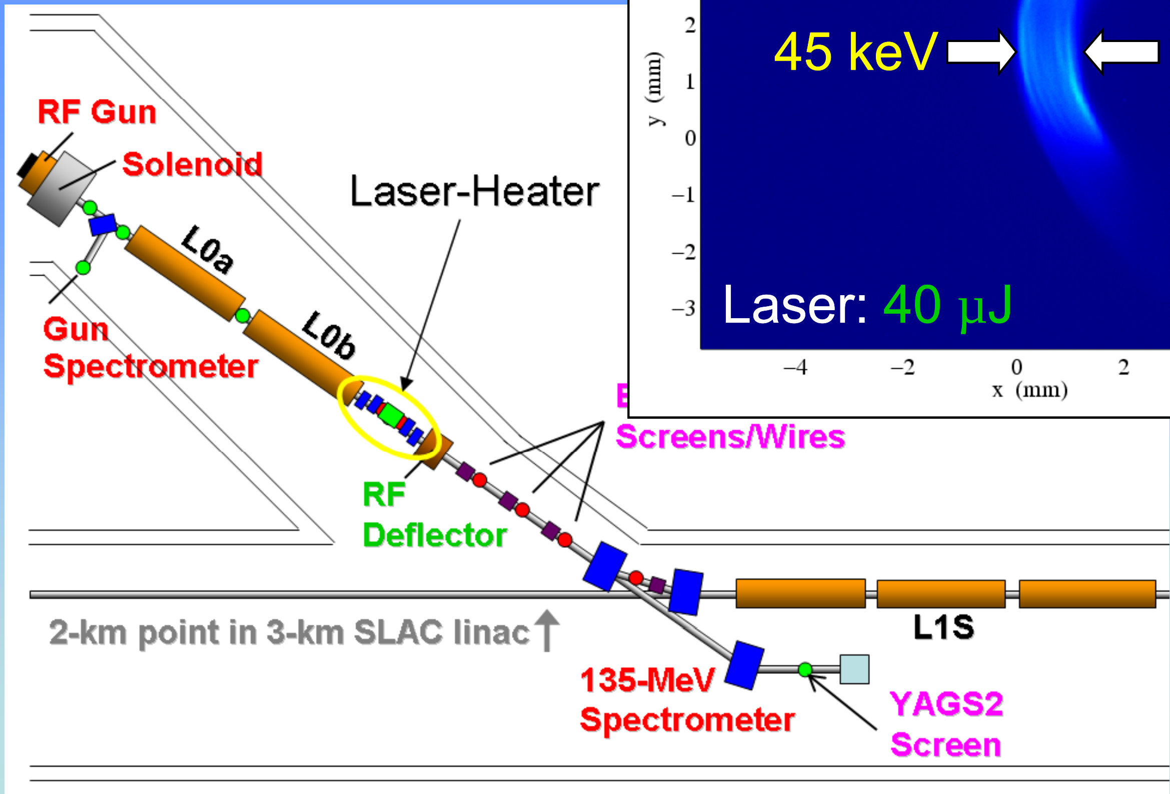






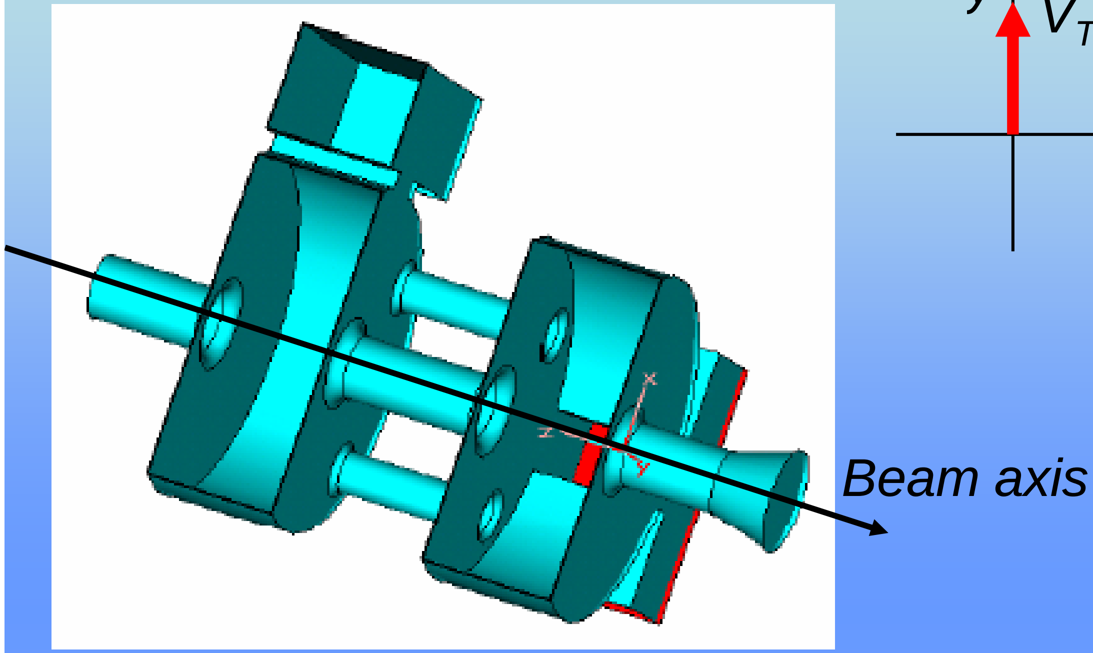
Use Transverse RF to measure sliced *E*-spread of “Laser-Heater”

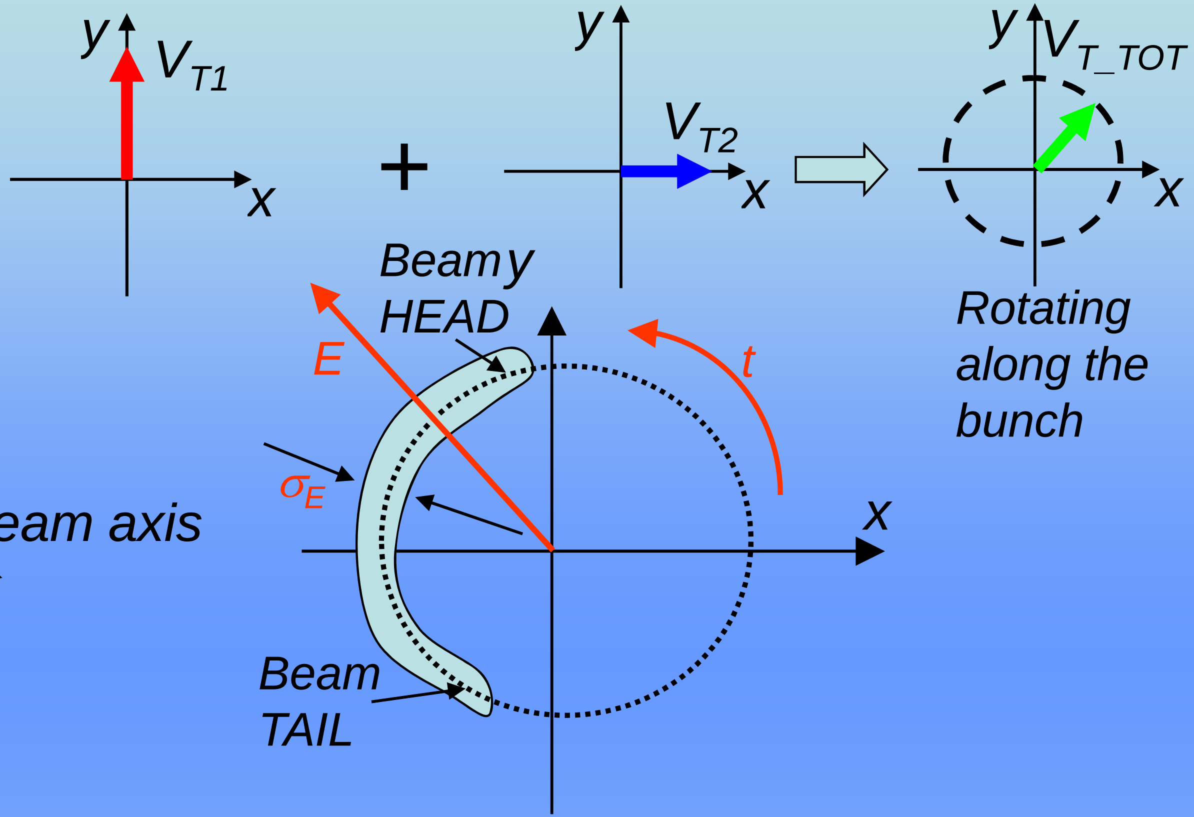




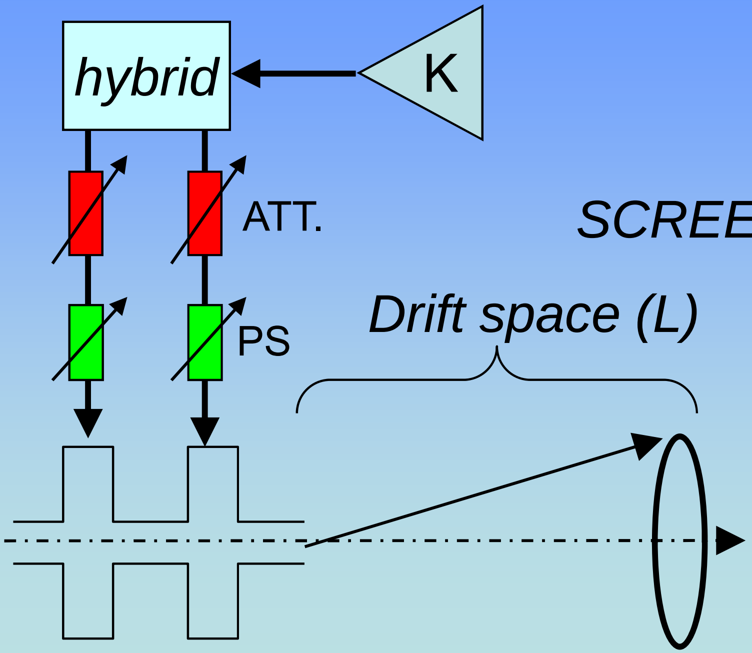
Advanced RFD structures: circular polarized RF deflector

[Haimson et al, AIP, 647, 2002]





POWER SCHEMES



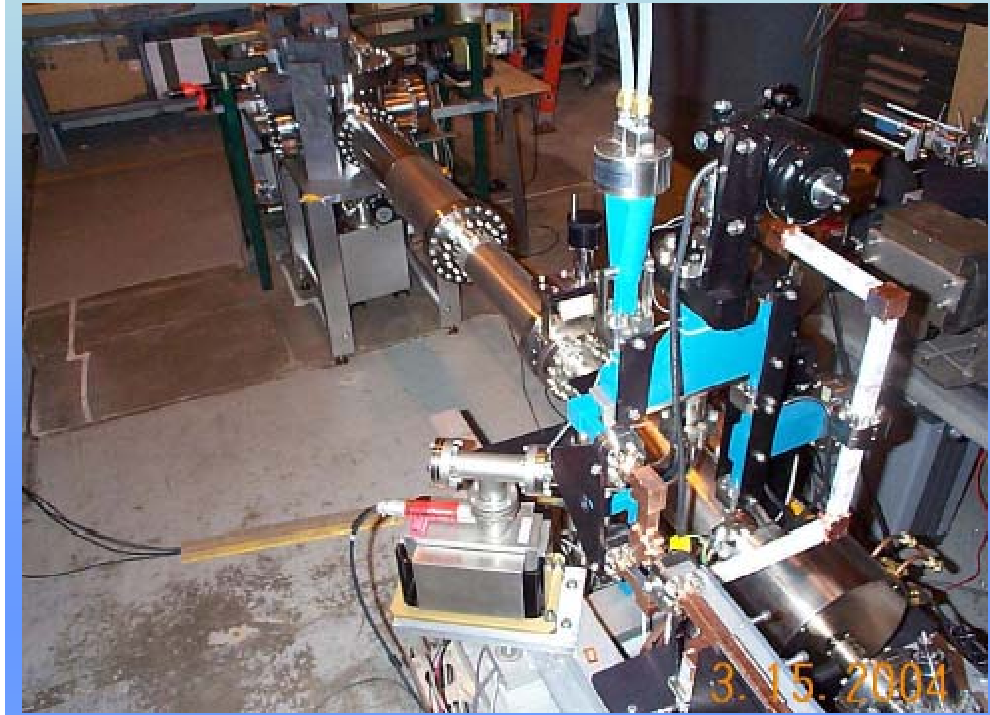
$$\sigma_{t_B\_RES} = \frac{\sigma_B}{\frac{V_T}{E/e}\omega_{RF}L}$$

$$\left.\frac{\Delta E}{E}\right|_{RES} = \frac{(E/e)\sigma_B}{V_T L}$$

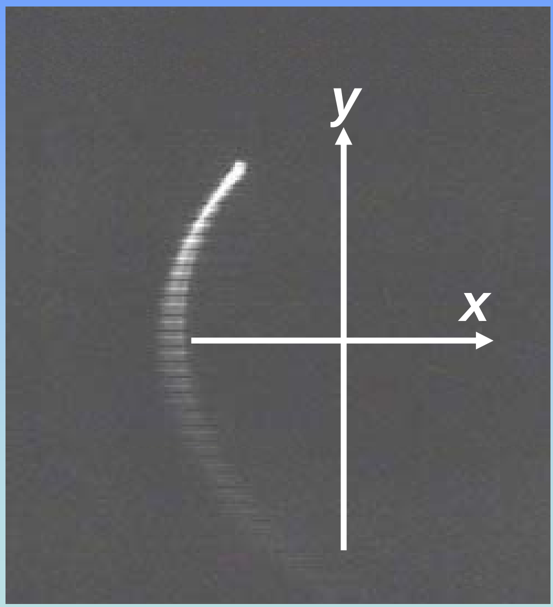
There is still an induced energy spread!

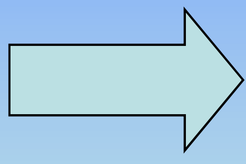
Circular polarized RF deflectors: measurements

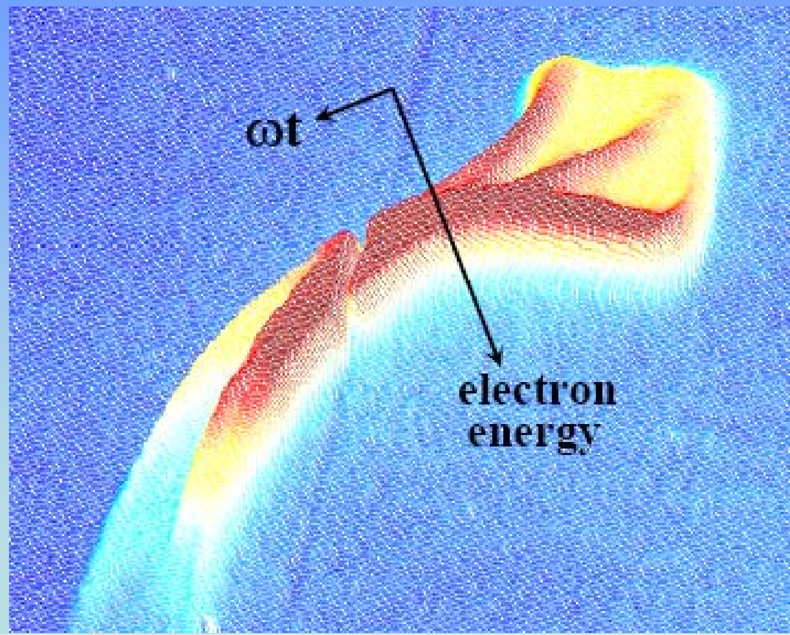
[J. Haimson et al, AIP, 737, 2004]



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

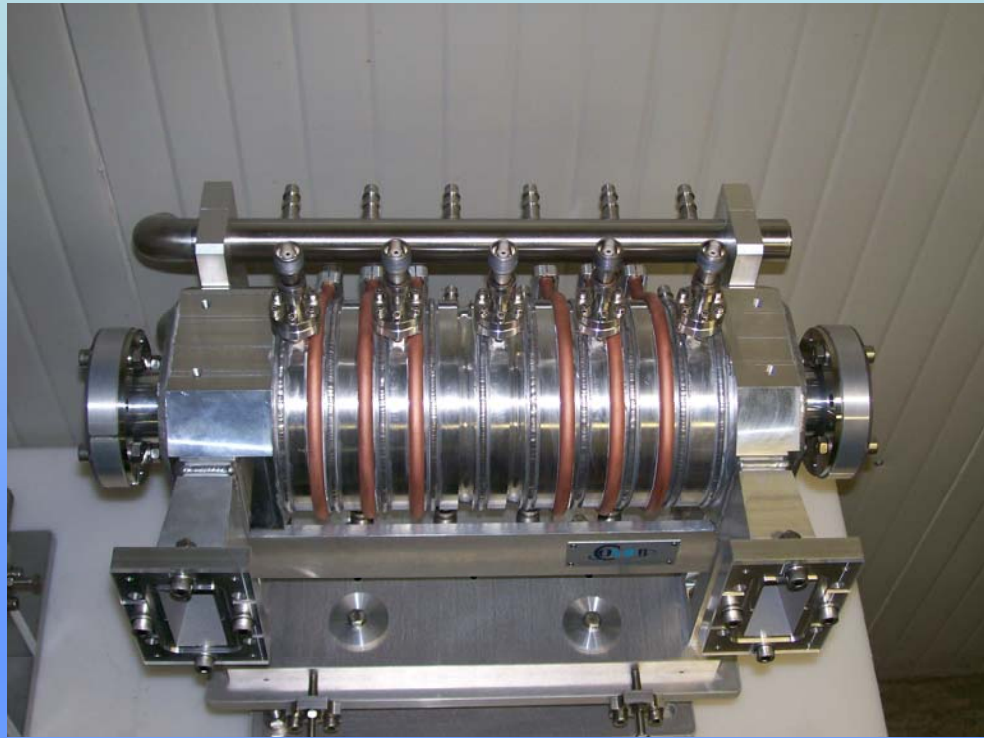


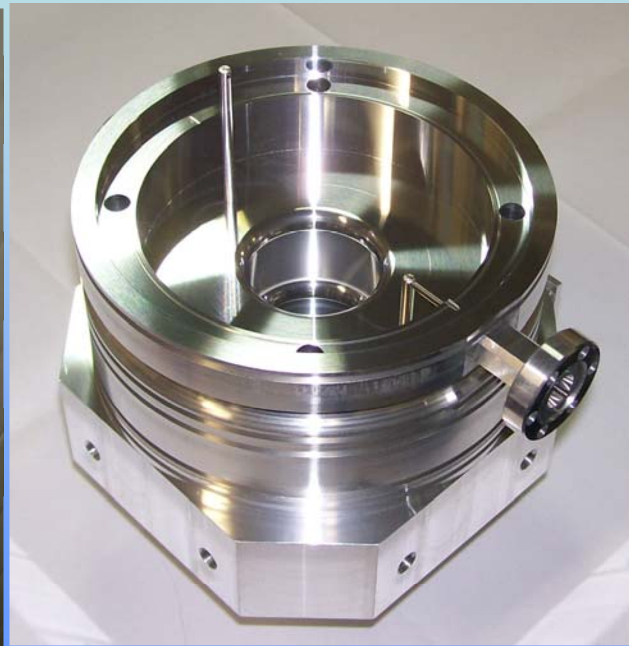


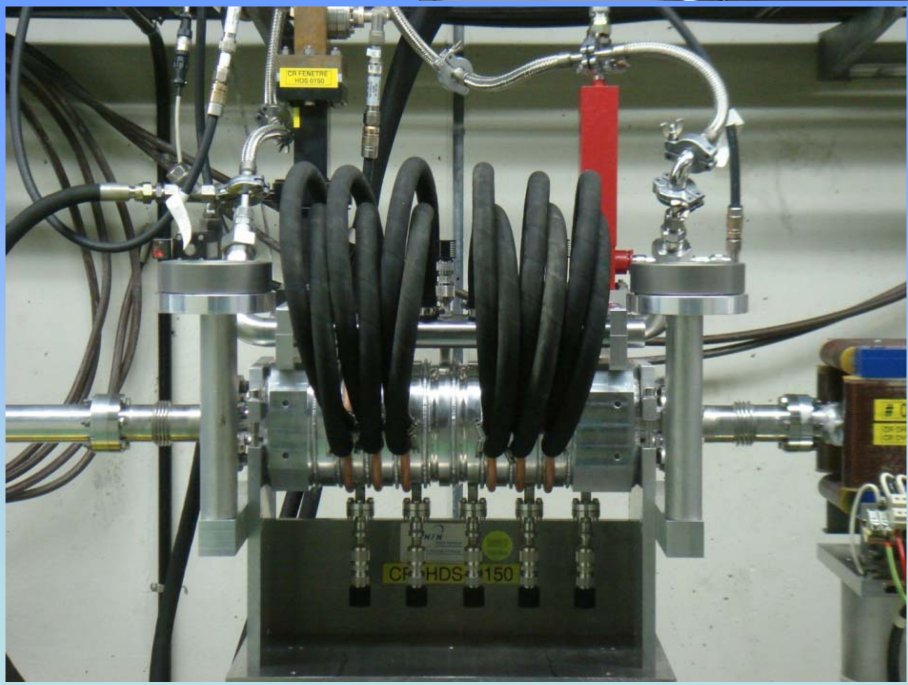


Advanced RFD structures: Aluminum RF deflectors

The new RFD of the **CTF3 Combiner Ring** have been built in ***aluminium*** to reduce the cost and the delivery.







The cells have been machined, clamped together with tie rod to guarantee the RF contacts and welded.

The structure has been installed with success without observing MP phenomena.

D. Alesini et al.,, PAC 09.

CONCLUSIONS

RFDs are fundamental devices for both longitudinal phase space characterization allowing reaching ***resolution below 10 fs***.

SW or TW structures can be used depending on the particular application.

The measurement setups and the experimental results, in the ***SPARC case***, have been shown and discussed (the RFD technique has been fundamental in the ***velocity bunching*** experiment at SPARC).

A possible solution to ***take into account the contribution of the RFD in the energy spread slice*** has been also illustrated.

Important new results have been also reached in other accelerator facilities like ***LCLS or FLASH.***

Circular polarized RFD deflectors allow the measurement of the long. Phase space without dipoles.

New important results have been recently obtained ***in RFD fabrication with alluminum***

THANK YOU