RF beam diagnostics
2nd part

A. Mostacci

With the help of

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Luca Ficcadenti - INFN

OUTLINE

RF beam diagnostics – 2nd lecture

Longitudinal diagnostics

Bunch arrival monitor (passive cavity)

Bunch length diagnostics

RF deflector for bunch length measurement

Design of the structure and realisation issue

Beam measurement and calibration

Novel ideas

Only 1 example from the design, the realisation to the beam measurement

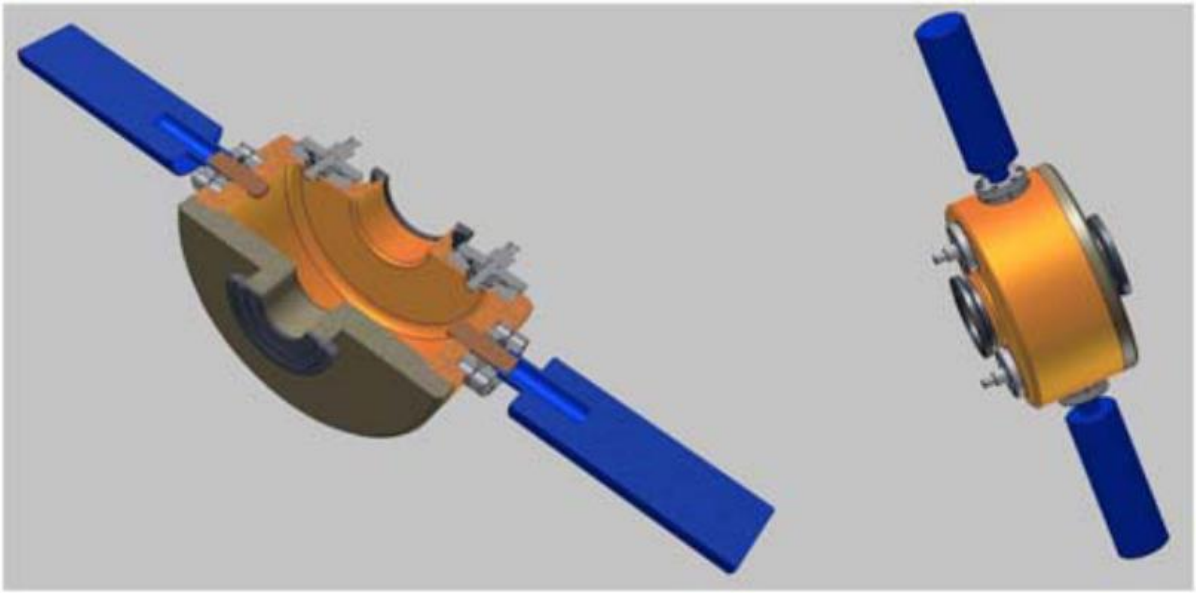
General techniques

Higher frequencies

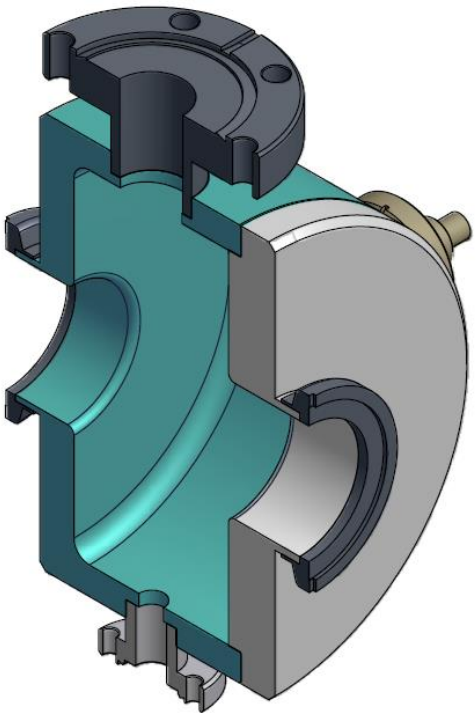
BUNCH ARRIVAL MONITORS

A resonant idle cavity can be placed directly along the LINAC beam trajectory, and a decaying voltage oscillation synchronous with the bunch passage can be coupled out of the cavity and demodulated, with no need of photodiodes and RF amplifications.

The bunch arrival monitor cavity is equipped with two tuning plungers. A manual tuner will be used for coarse frequency regulation, while a motorized fine tuner will be remotely controlled to maintain the coherency between the cavity free oscillations and the reference frequency.



BUNCH ARRIVAL MONITOR PARAMETERS



TM010 – 2142 MHz

$R/Q \approx 65\ \Omega$

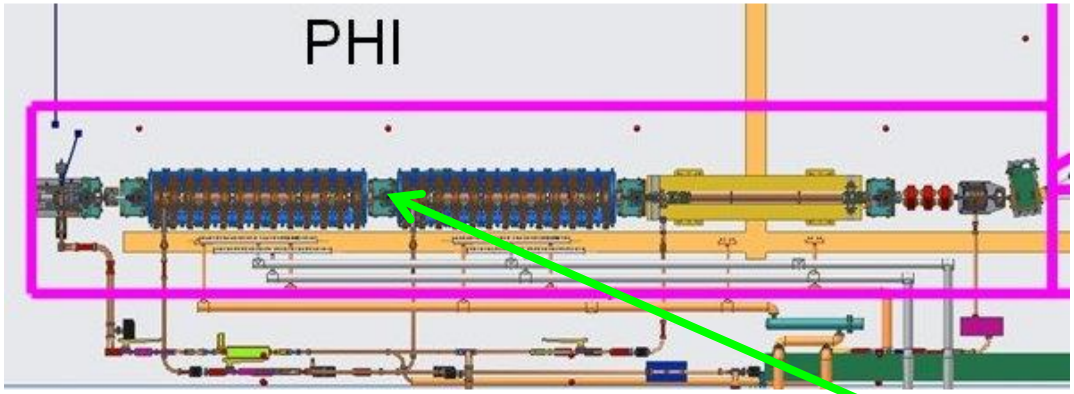
$Q_0 \approx 18000$

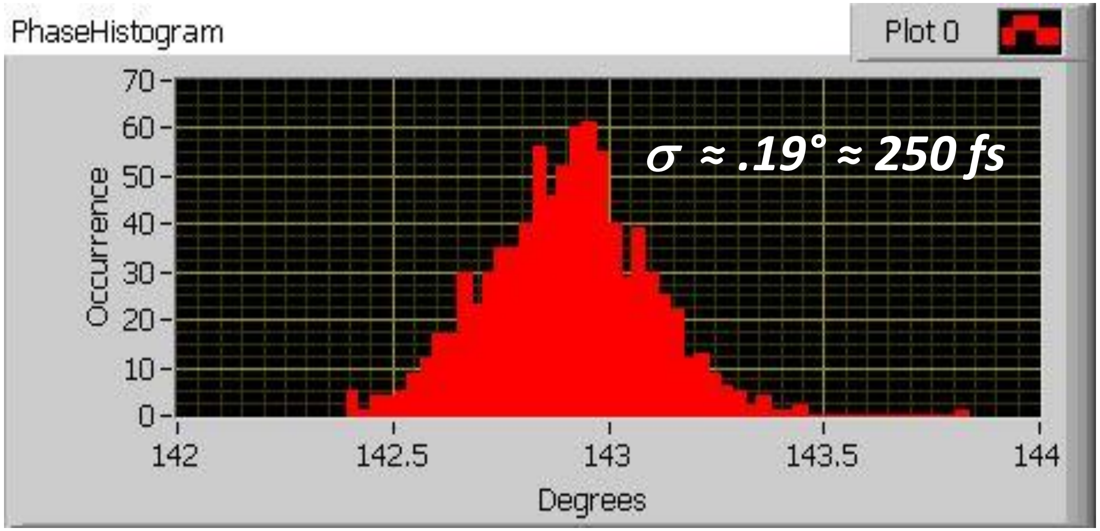
$Q_{ext} = 36000$

V_p (@ 1 nC) = 3.5 V

$\Delta f_{tun} \leq 10$ kHz

BUNCH ARRIVAL MONITOR INSTALLATION





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LONGITUDINAL DIAGNOSTICS IN LINAC

Depending on the characteristic scale length, several techniques can be used to measure electron beam longitudinal parameters in a LINAC

Time domain

Streak camera: ~ ps down to sub-ps

RF deflecting cavity: ~ ps down to fs scale

Frequency domain

Autocorrelation of coherent radiation emitted by a relativistic bunch: ~ ps down to fs scale

Spectrometers acting on Transition or Diffraction radiation: ~ ps down to sub-ps

Optical methods

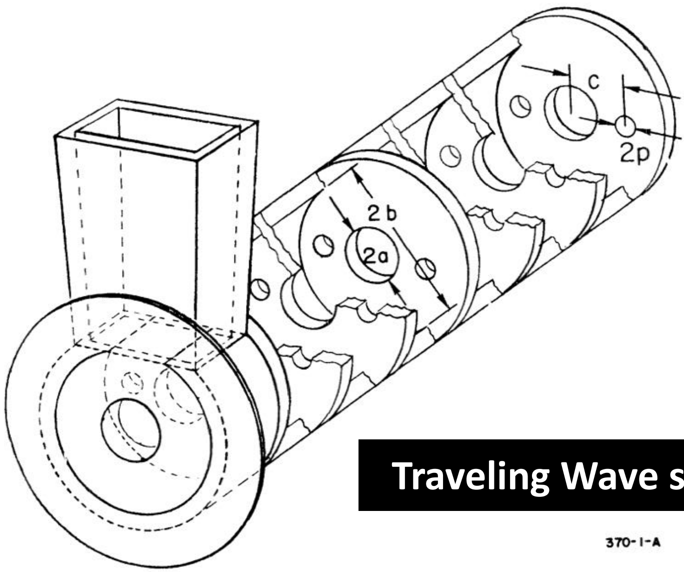
Electro-optic sampling which uses the wakefield induced by the beam in a crystal to modulate the field of a laser: down to few tens of fs

Courtesy of E. Chiadroni

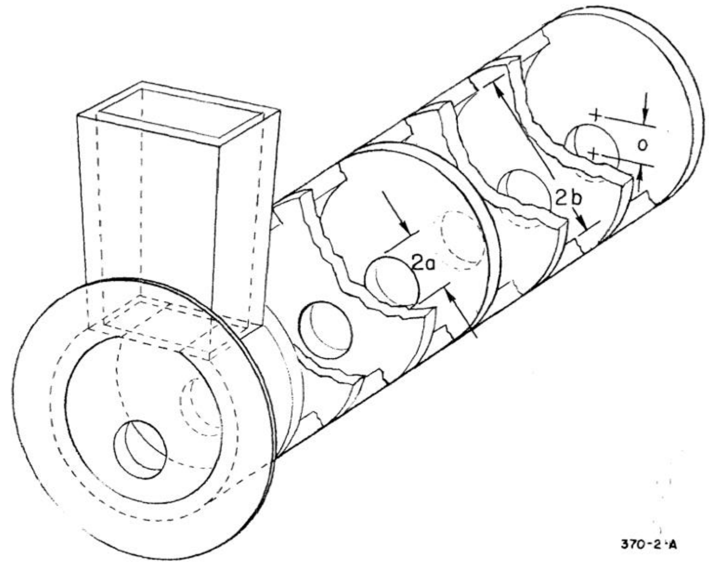
HISTORY

An RF deflecting field can directly streak the electron beam

Deflecting mode cavities were originally invented in the early 1960s as a way to separate different species (masses) of particles in an accelerator
SLAC-PUB-135, Aug. 1965



Traveling Wave structures

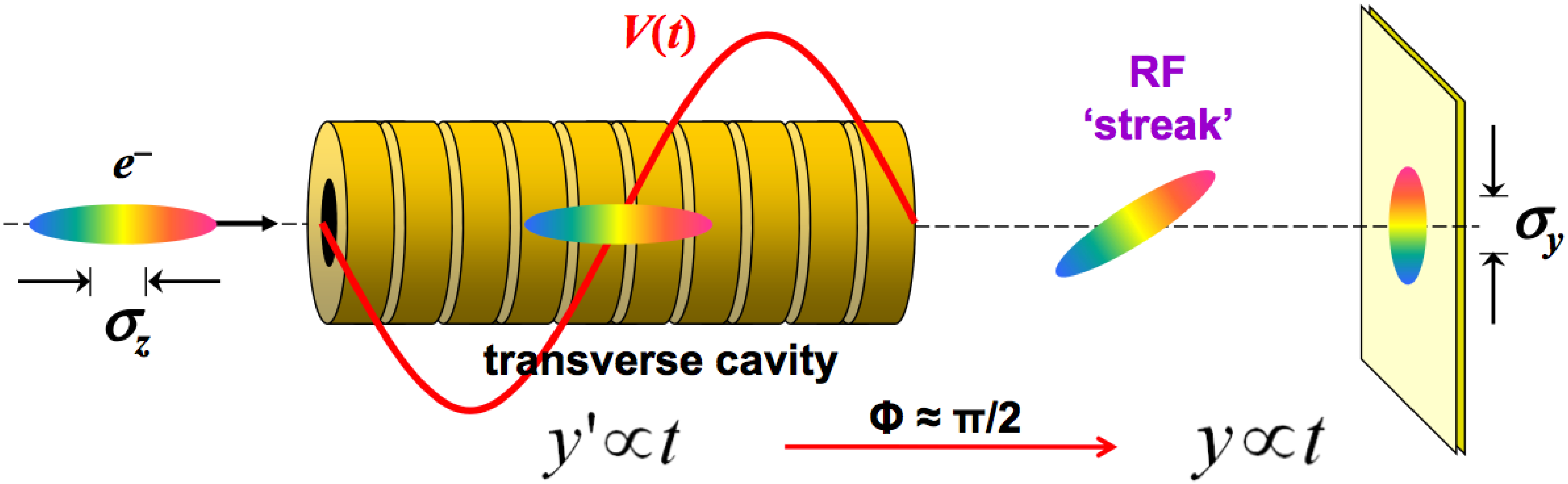


TM11-type to maximize deflecting efficiency. The two small lateral holes in the disks are used to prevent mode rotation.

TM01-type by strongly off-centre iris. It has a non-zero longitudinal accelerating or decelerating field on axis.

Courtesy of E. Chiadroni

THE IDEA

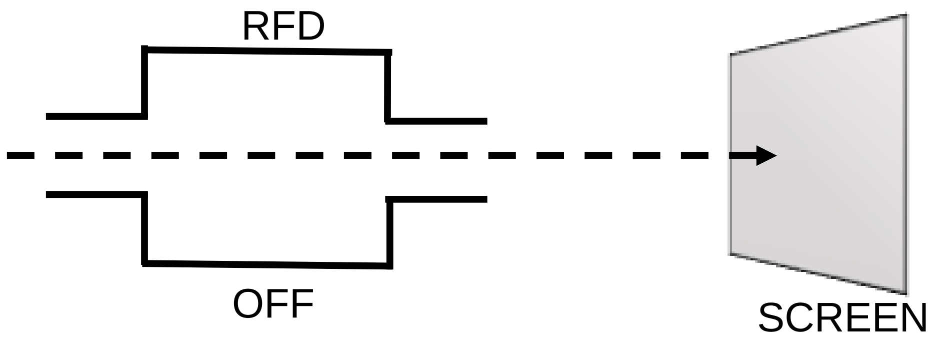


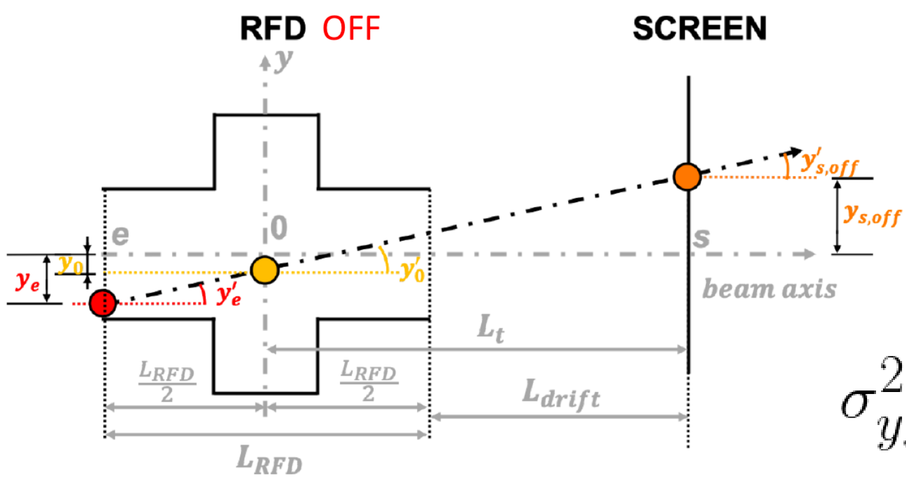
When a beam passes through a transverse cavity at the zero-crossing phase, the transverse cavity imprints on the beam a transverse angular kick (e.g. in vertical direction) that varies linearly with the longitudinal position. After 90 degrees phase advance, the angular distribution is converted to spatial distribution, and the vertical axis on some screen downstream of the transverse cavity becomes the time axis.

V(t) is the integrated transverse Lorentz force per unit charge.

Courtesy of E. Chiadroni

PREMISE: RF DEFLECTOR OFF





Correlations between spot size and divergence at the RFD center

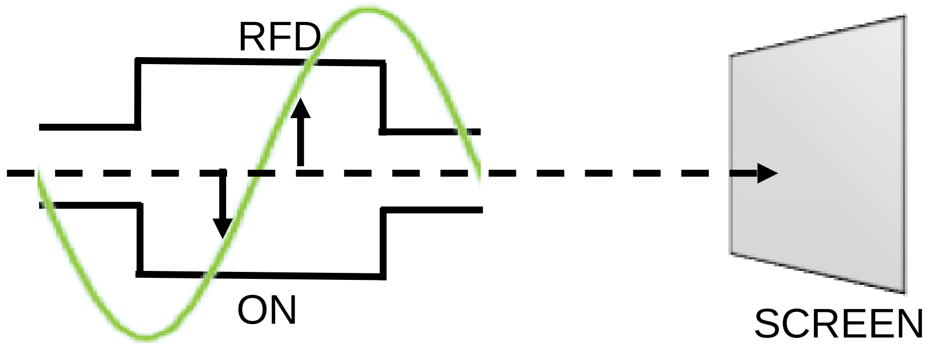
Divergence at the RFD center

$$\sigma^2_{y_{s,off}} = \sigma^2_{y_0} + 2L_t\sigma_{y_0 y'_0} + L_t^2\sigma^2_{y'_0}$$

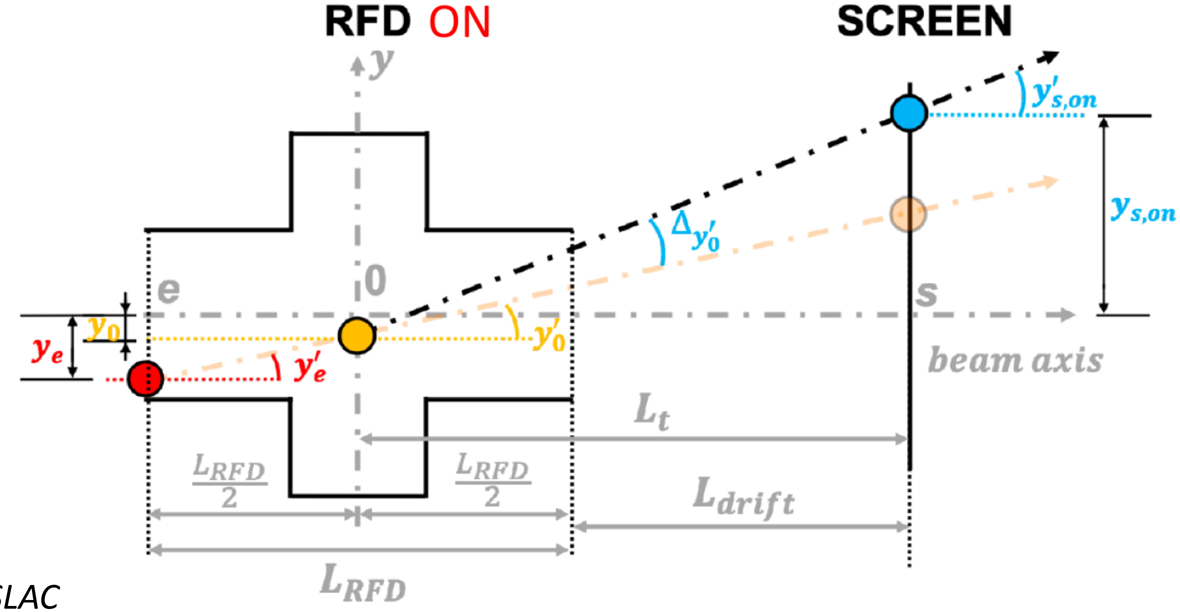
Spot size at the RFD center

Courtesy of A. Gilardi - SLAC

BEAM DEFLECTION



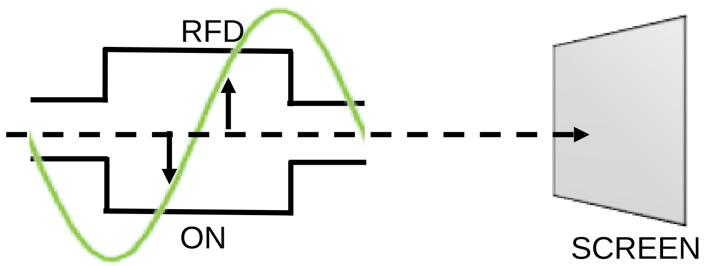
Neglecting the energy spread and energy chirp (correlations between energy and time) contributions.

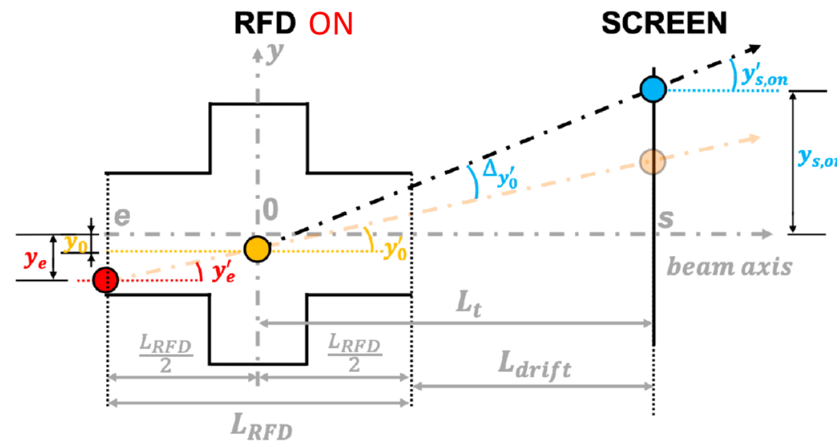


Courtesy of A. Gilardi - SLAC

BEAM SIZE AFTER DEFLECTION

Courtesy of A. Gilardi - SLAC





Bunch length

Correlation between longitudinal position and transverse position at the RFD center

$$\sigma^2_{y_{s,on}}(\varphi) = \sigma^2_{y_{s,off}} + K^2_{cal}(\varphi)\sigma^2_{t_0} + 2K_{cal}(\varphi)\sigma_{y_0 t_0} + 2K_{cal}(\varphi) L_t \sigma_{y'_0 t_0}$$

Spot size with RFD off

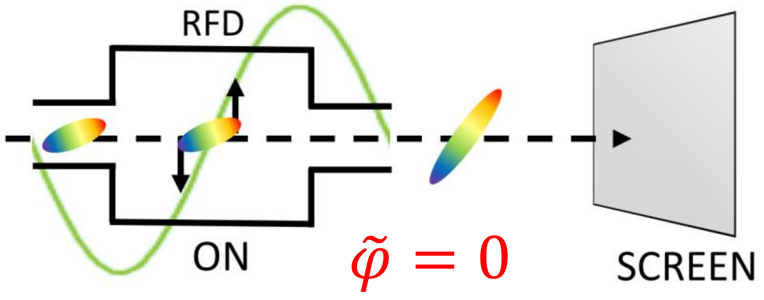
Calibration factors related with RFD characteristics

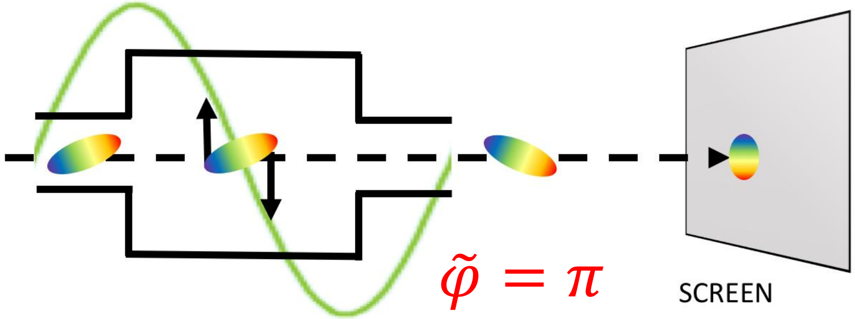
Correlation between longitudinal position and transverse divergence at the RFD center

BUNCH LENGTH MEASUREMENT

Cancel correlations between longitudinal position and transverse position/divergence

$$\sigma^2_{y_{s,on}}(\varphi) = \sigma^2_{y_{s,off}} + K^2_{cal}(\varphi)\sigma^2_{t_0} + 2K_{cal}(\varphi)\sigma_{y_0 t_0} + 2K_{cal}(\varphi)L_t\sigma_{y'_0 t_0}$$





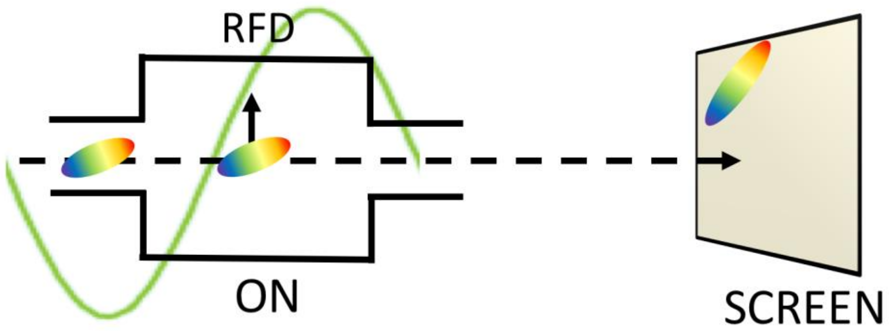
$$\overline{\sigma_{y_{s,on}}}^2(\varphi) = \frac{\sigma^2_{y_{s,on}}(\varphi) + \sigma^2_{y_{s,on}}(\varphi + \pi)}{2} = \sigma^2_{y_{s,off}} + K^2_{cal}(\varphi)\sigma^2_{t_0}$$

$$\sigma_{t_0} = \frac{\sqrt{\overline{\sigma^2_{y_{s,on}}} - \sigma^2_{y_{s,off}}}}{|K_{cal}(\varphi)|}$$

$$K_{cal}(\varphi) = 2\pi f_{RF} \frac{eV_{defl}}{E_{beam}} L_t \cos\varphi$$

Courtesy of A. Gilardi - SLAC

SELF-CALIBRATION



$$\sigma_{t_0} = \frac{\sqrt{\sigma^2_{y_{s,on}} - \sigma^2_{y_{s,off}}}}{|K_{cal}(\varphi)|}$$

$$K_{cal}(\varphi) = 2\pi f_{RF} \frac{eV_{defl}}{E_{beam}} L_t \cos\varphi$$

At phases different from 0, the centroid is deflected. By measuring the deflection of the centroids one can derive the calibration constant.

The measurement is self-calibrated, meaning that the constant can be measured independently by the measurement of the beam energy or the deflecting voltage.

RESOLUTION LIMIT

The resolution limit is typically assumed when the deflected spot size equals the un-deflected beam size.

$$\sigma_t^{res} = \frac{E_{beam}}{eV_0}\frac{1}{L_t}\frac{1}{2\pi f_{RF}}\sigma_{y,off}$$

Maximum deflecting voltage available

Focusing system is set to have the minimum spot size of the undeflected beam (it results in the best phase advance between the deflector and the screen).

Andrea Mostacci
(Sapienza University, INFN-Roma)

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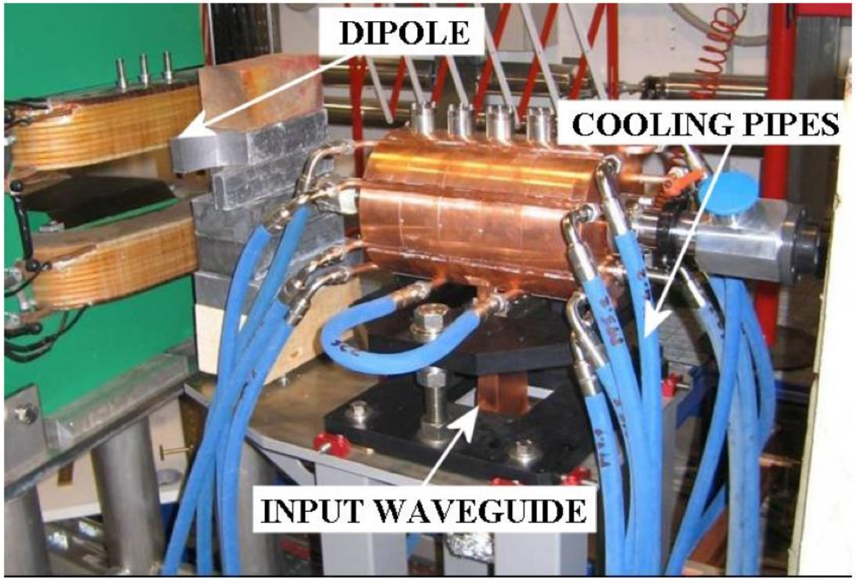
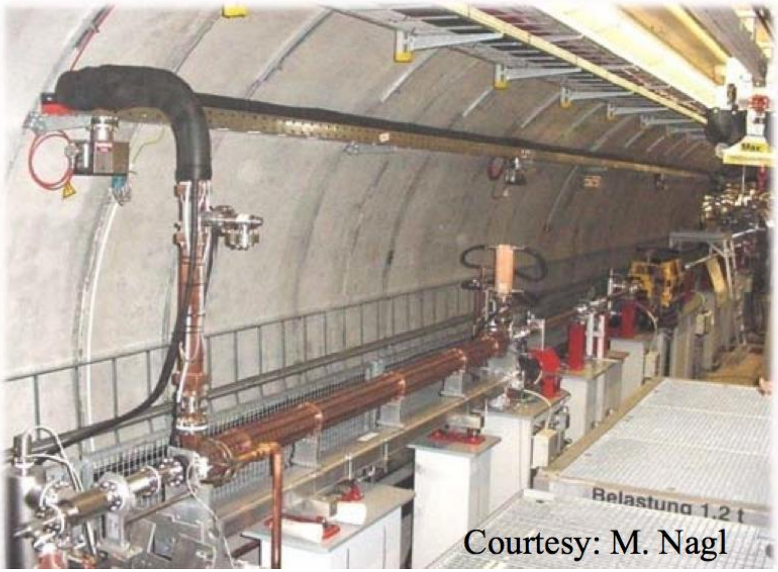
EXAMPLES OF RF DEFLECTORS

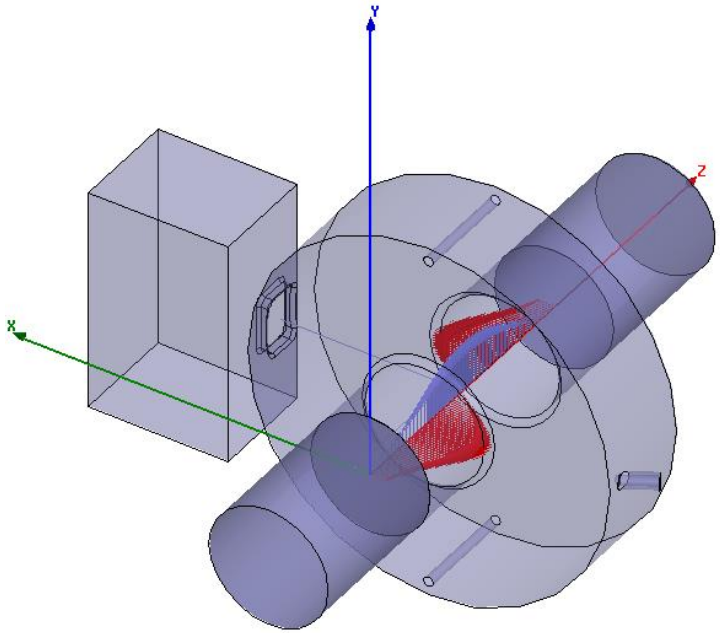
SPARC@LNF-INF
5-cell Standing Wave
operating on the π mode at 2.856 GHz



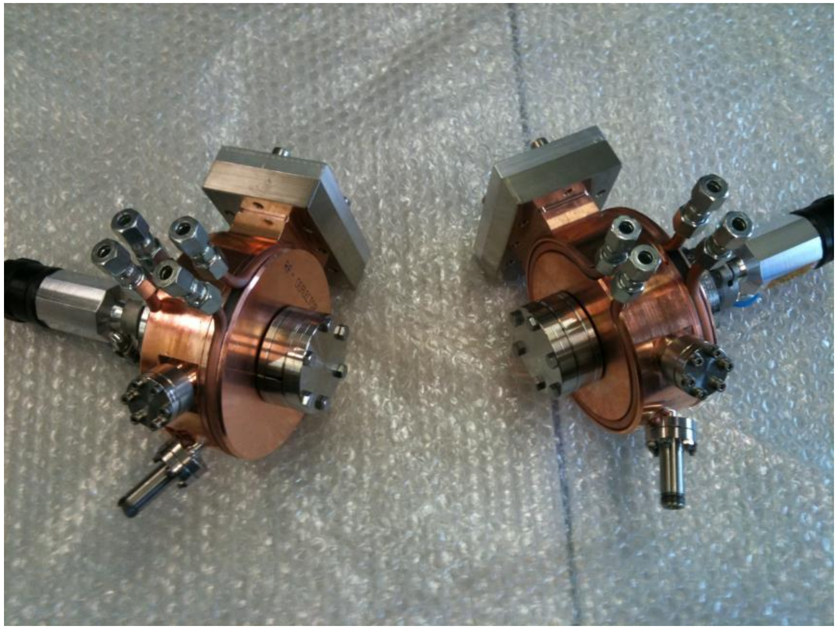
LOLA@FLASH
Traveling Wave
operating at 2π/3 at 2.856 GHz



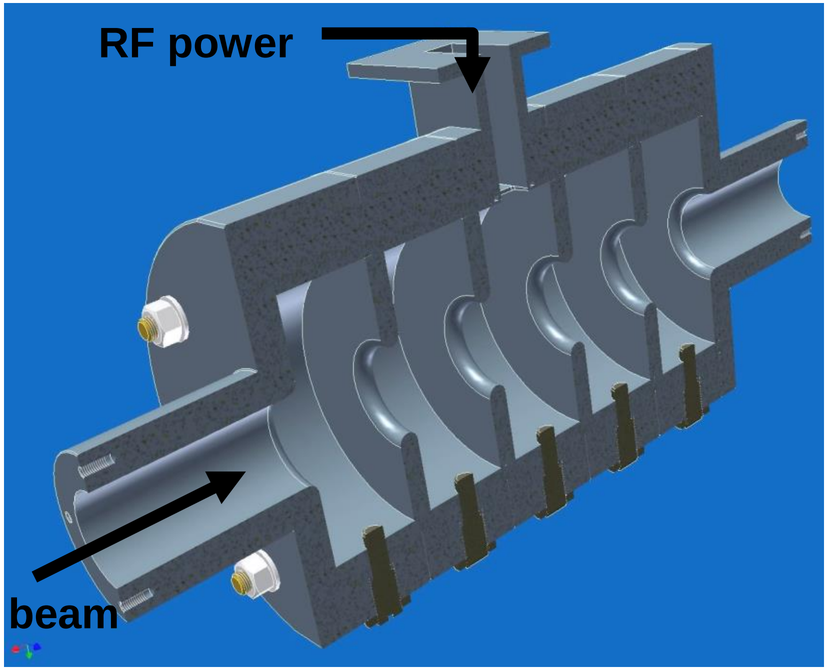
EXAMPLES OF RF DEFLECTORS - 2



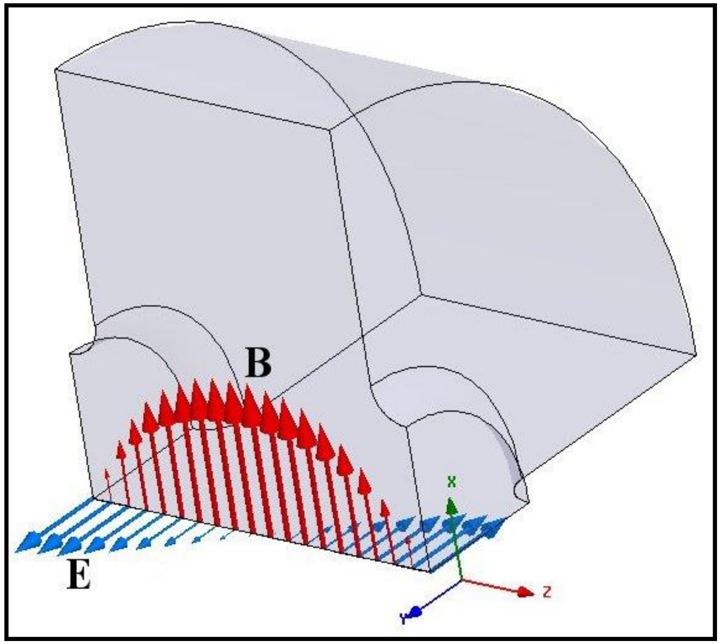
TM110-like mode



SPARC STANDING WAVE RF DEFLECTOR

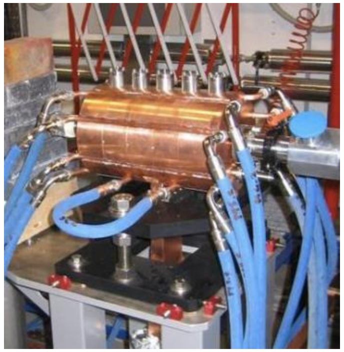


TM110-like mode

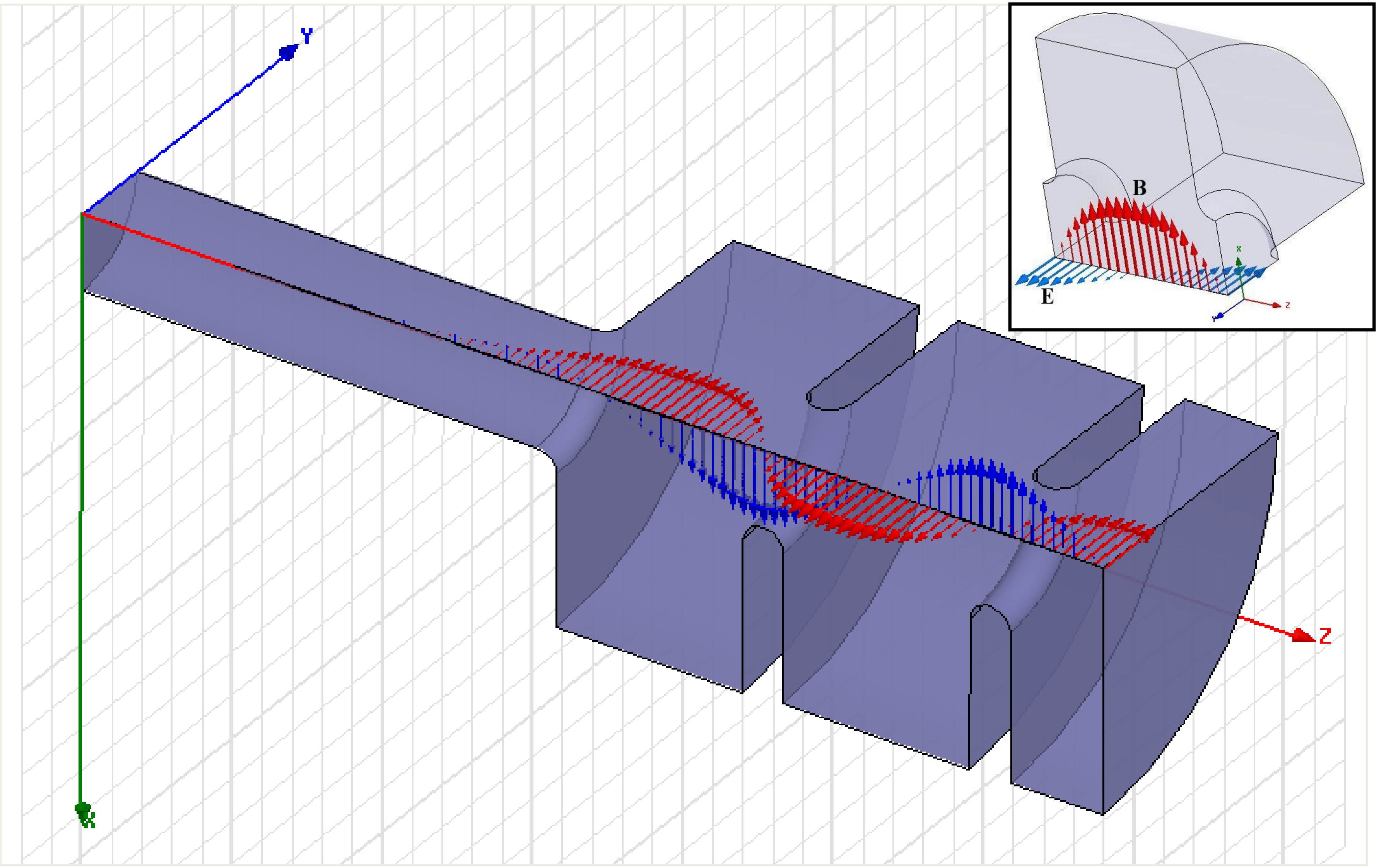


Res. freq.: 2.856 GHz

Q_{ext} = 14000 **Q_0 = 14000**

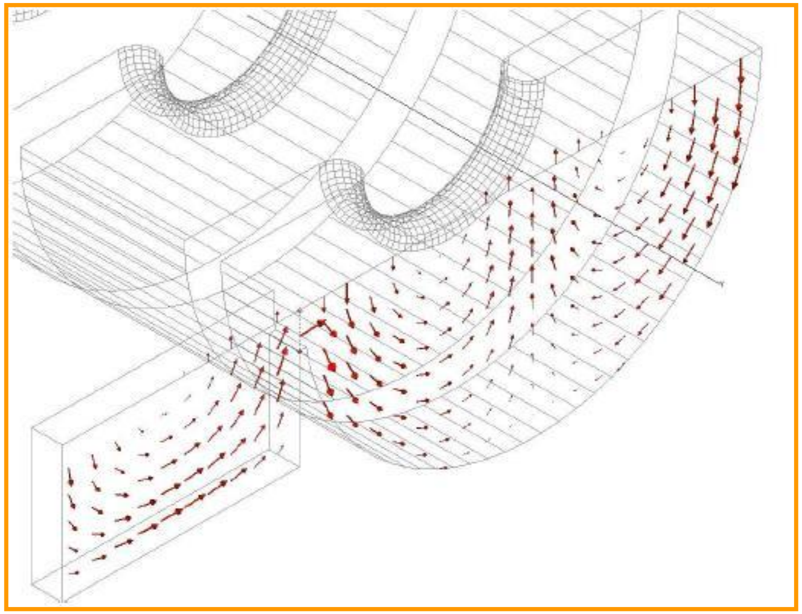


TM110-LIKE MODE FIELD PATTERN

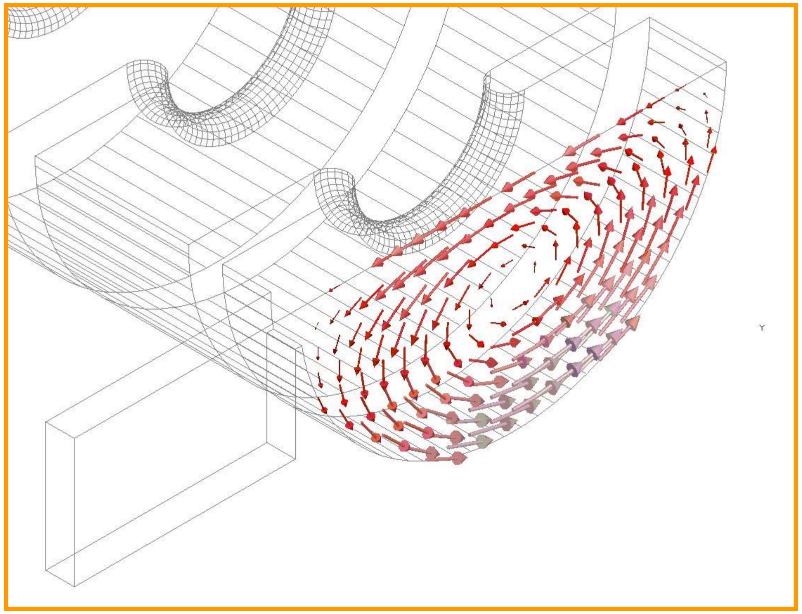


CILINDRICAL SYMMETRY

Cylindrical symmetry is a problem for deflecting structures



Working polarisation



Orthogonal polarisation

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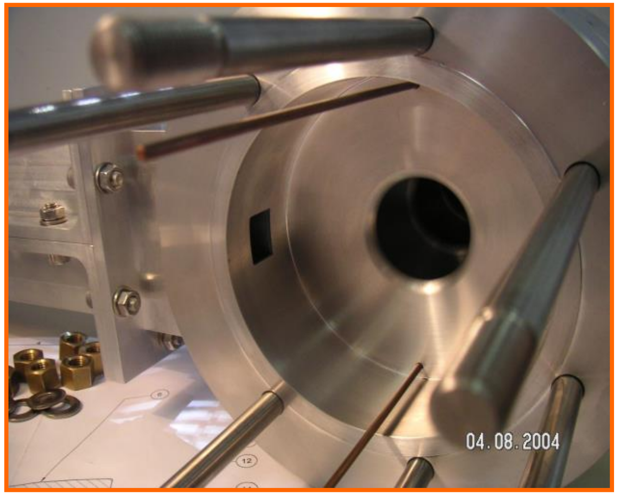
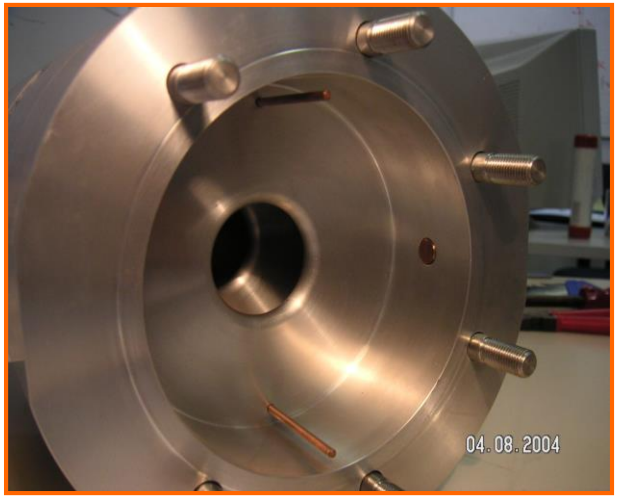
TUNING RODS

Cylindrical symmetry is a problem for deflecting structures

Detune one of the polarisations.

Slater theorem can be used.





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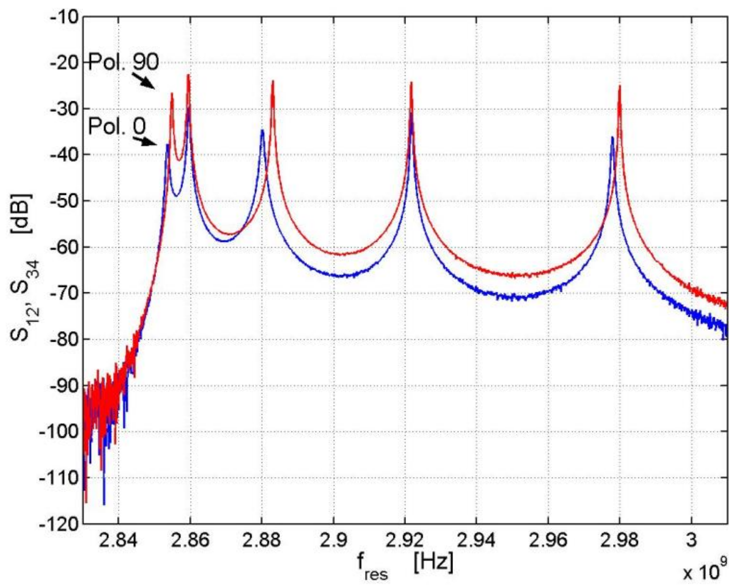

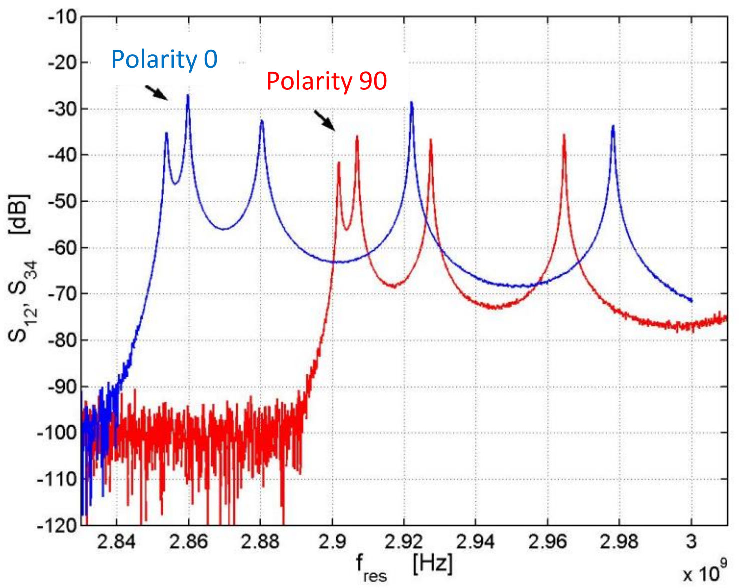

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BEAD PULL MEASUREMENT

Field measurement inside the cavity: bead-pull technique.

The perturbation Δf of the resonant frequency f_0 depends on the field in the position of the small (dielectric or metallic) perturbing object (W being the energy stored in the cavity).

Slater theorem

Dielectric beads

$$\left(\frac{\Delta f}{f_0}\right)_{diel} \simeq k_{Ed}\varepsilon_0 \frac{\left|\vec{E}\right|^2}{W}$$

Metallic beads

$$\left(\frac{\Delta f}{f_0}\right)_{met} \simeq k_{Em}\varepsilon_0 \frac{\left|\vec{E}\right|^2}{W} - k_{Bm}\mu_0 \frac{\left|\vec{B}\right|^2}{W}$$

$$\frac{\left|\vec{B}\right|^2}{W} \simeq \frac{1}{k_{Bm}\mu_0}\left[\left(\frac{\Delta f}{f_0}\right)_{met} + \frac{k_{Em}}{k_{Ed}}\left(\frac{\Delta f}{f_0}\right)_{diel}\right]$$

Measurement

Calibration

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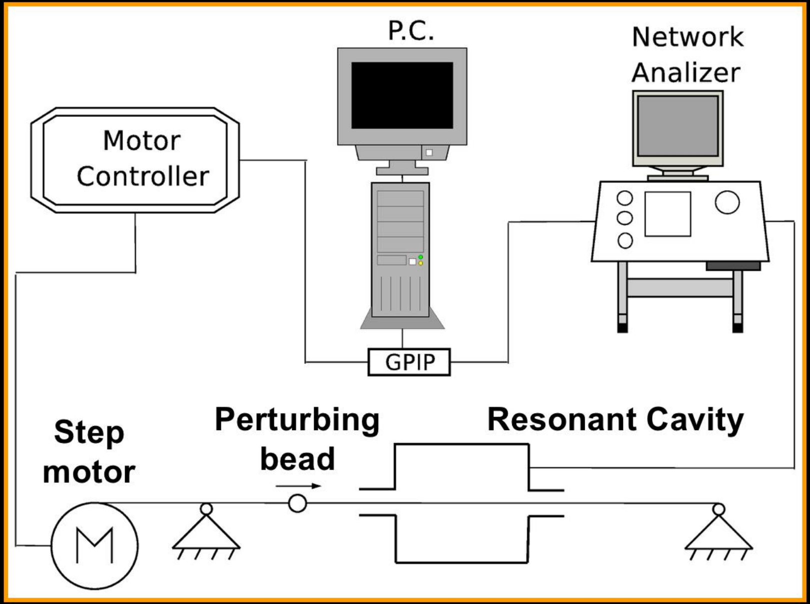
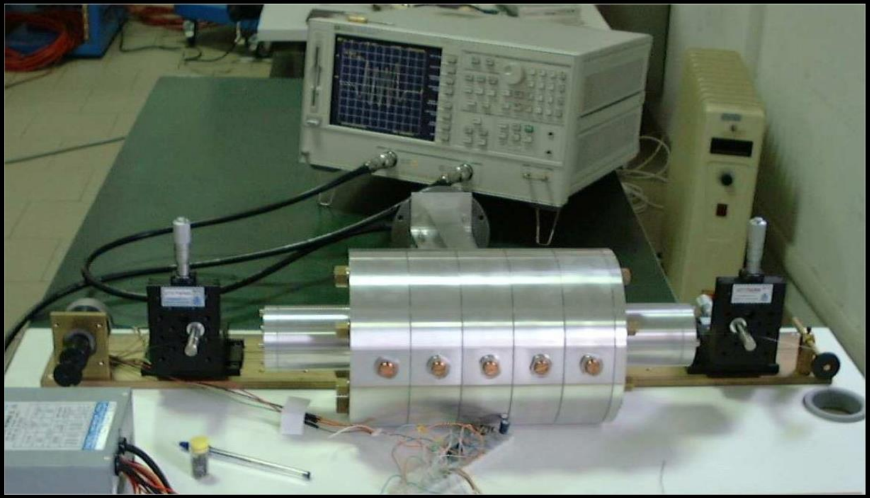
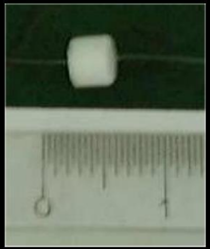
MEASUREMENT SET-UP

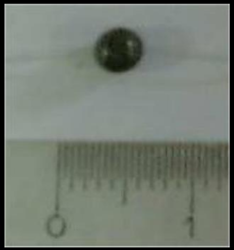


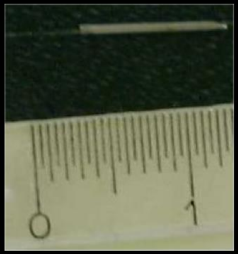


$$\frac{\Delta f(z)}{f_0} \simeq \frac{1}{2Q_L} \tan\left(\angle S_{12}(z)\right)$$

Perturbing beads







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BEAD CALIBRATION

Copper brazed pill-box cavity

$$\left(\frac{\Delta f}{f_0}\right)_{met} \simeq k_{Em}\varepsilon_0 \frac{\left|\vec{E}\right|^2}{W} - k_{Bm}\mu_0 \frac{\left|\vec{B}\right|^2}{W}$$

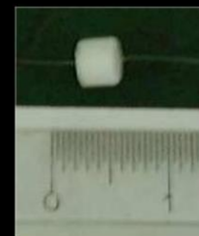
$$\left(\frac{\Delta f}{f_0}\right)_{diel} \simeq k_{Ed}\varepsilon_0 \frac{\left|\vec{E}\right|^2}{W}$$

Measurement **Simulation/Theory**

TM_{010} Only E_z field on axis

TM_{110} Only $B_\perp$ field on axis

TE_{111} Only $E_\perp$ field at the center



Dielectric cylinder

$TE_{111} \longrightarrow k_{Ed}$

Metallic sphere

$TM_{110} \longrightarrow k_{Bm}$

$TE_{111} \longrightarrow k_{Em}$

Metallic needle

$TM_{010} \longrightarrow k_{Em}$

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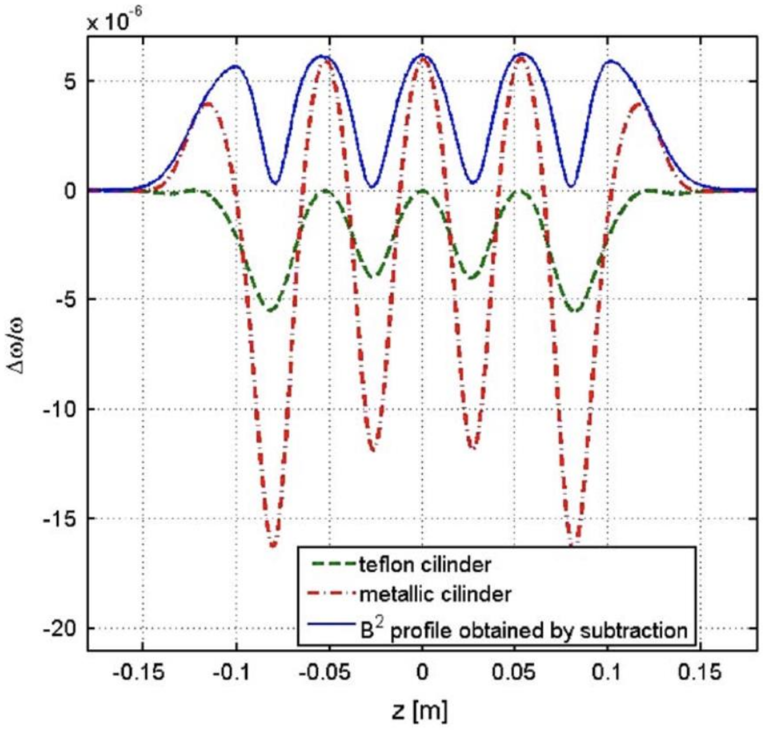
COMBINING MEASUREMENTS

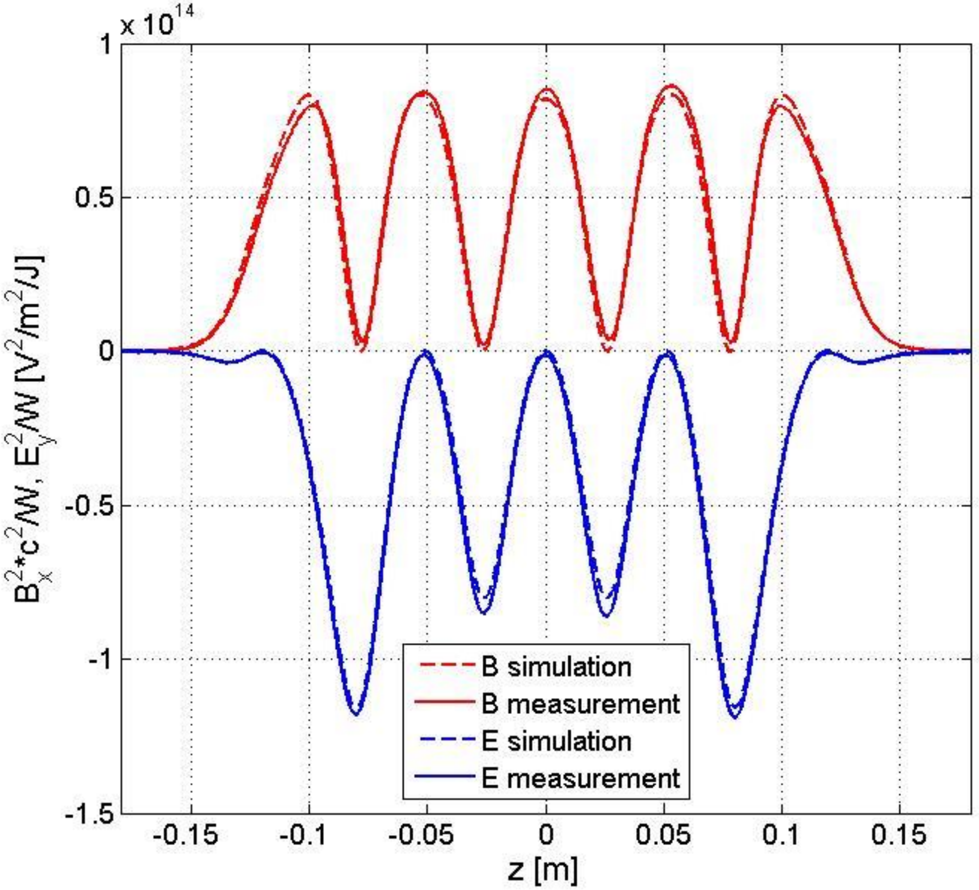
$$\frac{\left|\vec{B}\right|^2}{W} \simeq \frac{1}{k_{Bm}\mu_0}\left[\left(\frac{\Delta f}{f_0}\right)_{met} + \frac{k_{Em}}{k_{Ed}}\left(\frac{\Delta f}{f_0}\right)_{diel}\right]$$

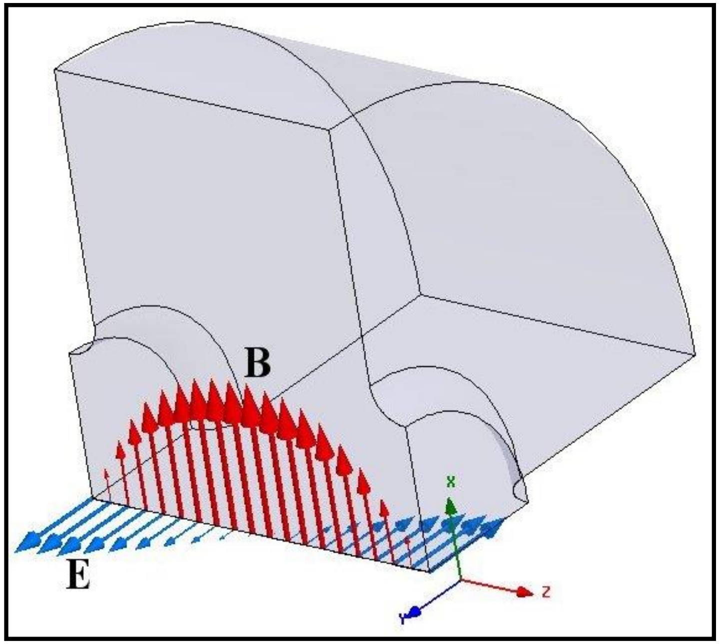
Measurement: $\left(\frac{\Delta f}{f_0}\right)_{met}$, $\left(\frac{\Delta f}{f_0}\right)_{diel}$

Calibration: $k_{Bm}\mu_0$, $\frac{k_{Em}}{k_{Ed}}$



FIELD MEASUREMENT





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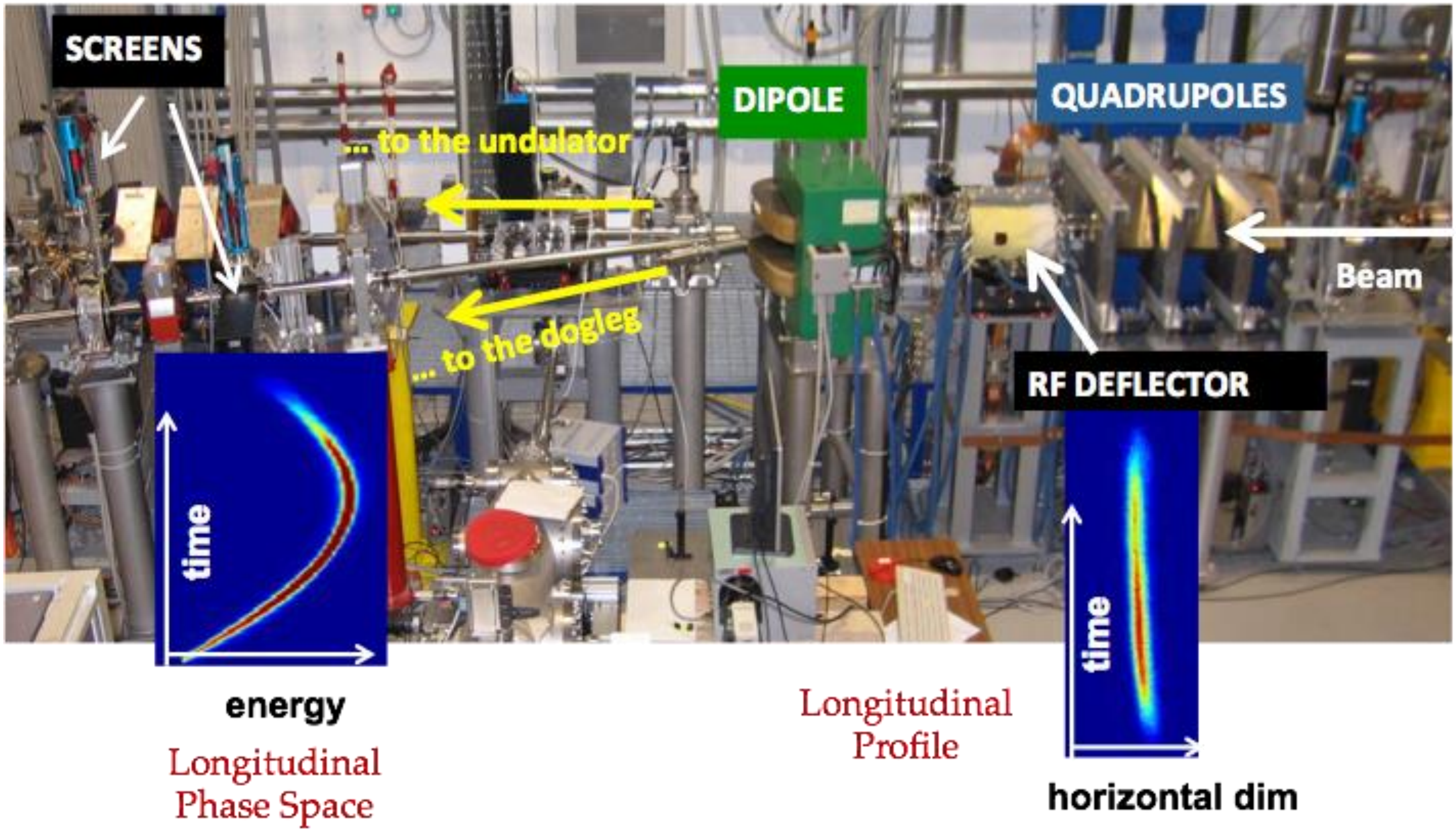
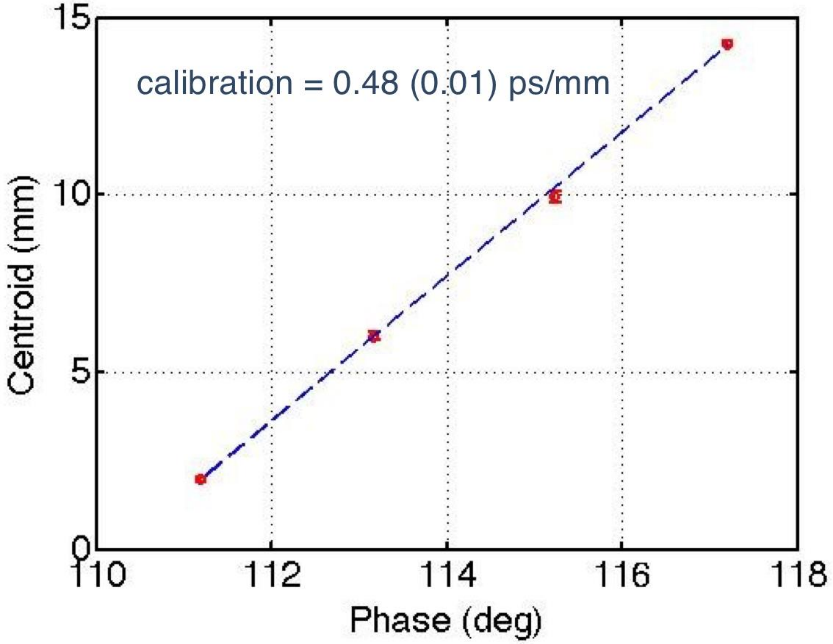
LONGITUDINAL PHASE SPACE MEASUREMENT

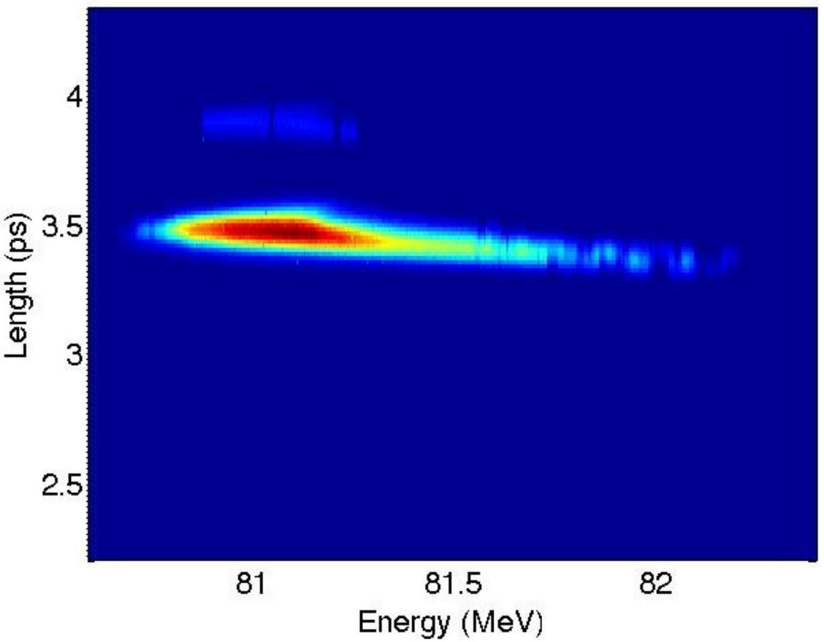


Courtesy of E. Chiadroni

CALIBRATION AND LENGTH MEASUREMENT

SPARC@LNF-INFN





$$\sigma_{ys} = 70\ fs$$
$$\sigma_{yB} \cdot \text{calibration} = 45\ fs$$

⇒

$$\sigma_t = 50\ fs$$

Courtesy of E. Chiadroni

BUNCH TRAIN - LONGITUDINAL PHASE SPACE

SPARC@LNF-INFN

Measurements with 200pC

Gun energy 5.7MeV

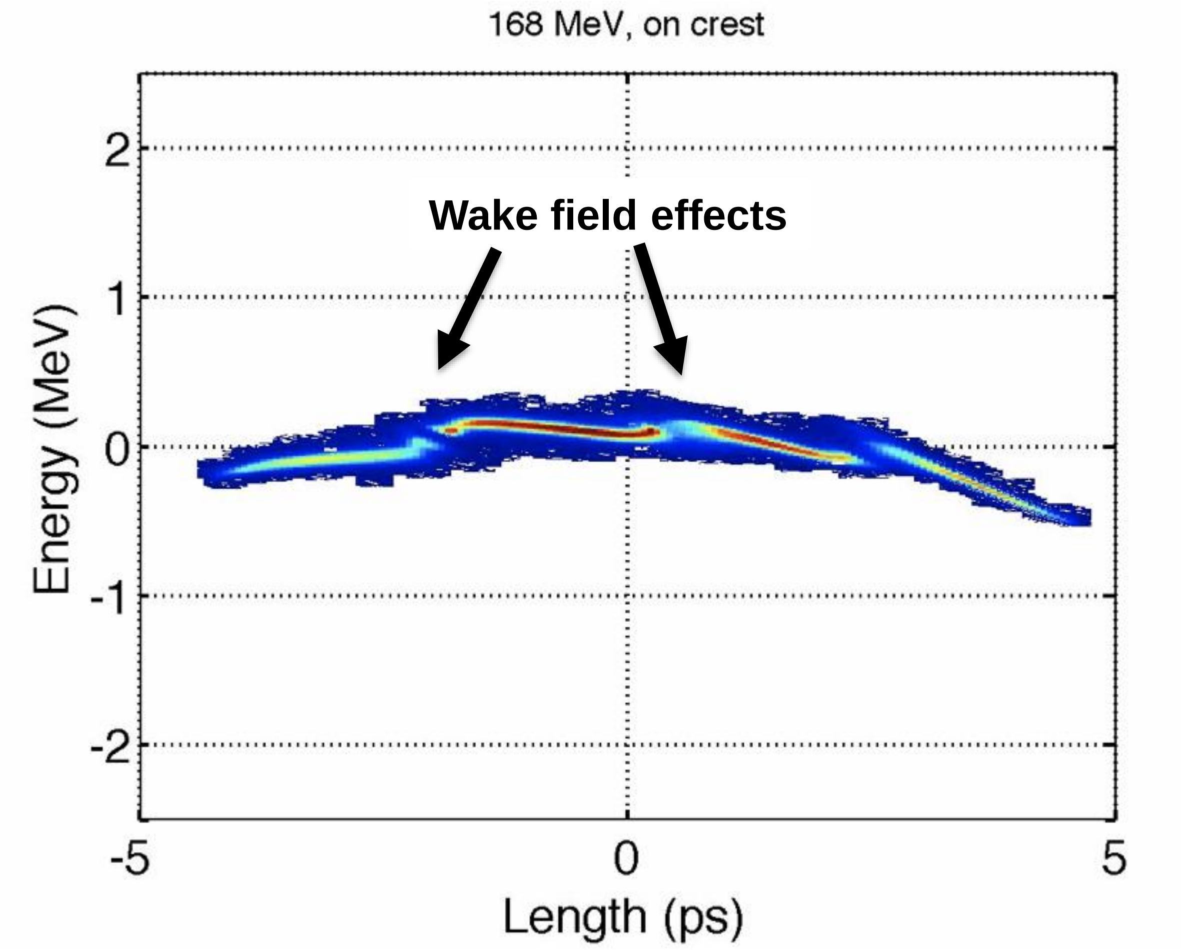
Charge
40pC/80pC/50pC/30pC

Energy 168 MeV

Energy Spread <0.8%

Bunch length on crest
2.1263 (0.0087) ps

Gun ext. phase
35 deg



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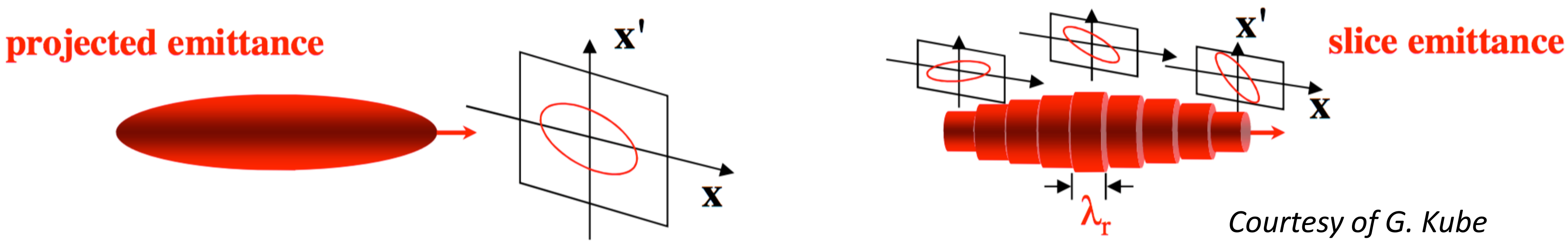
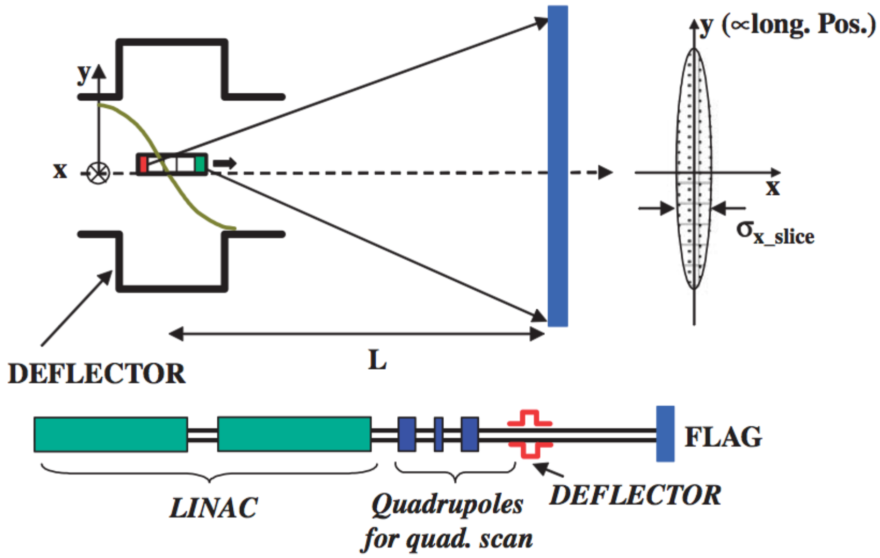
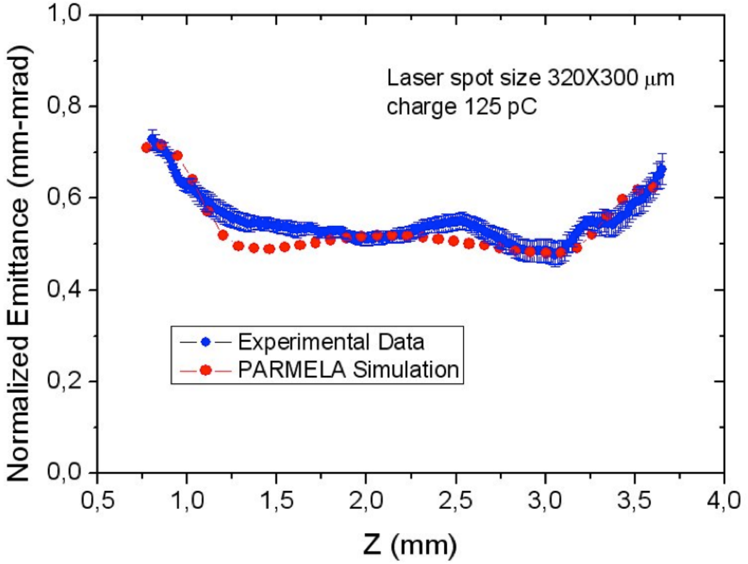
TIME RESOLVED MEASUREMENT

Combined with a quadrupole scan technique, RFD allows for the measurement of the slice emittance on the plane orthogonal to the streaking direction

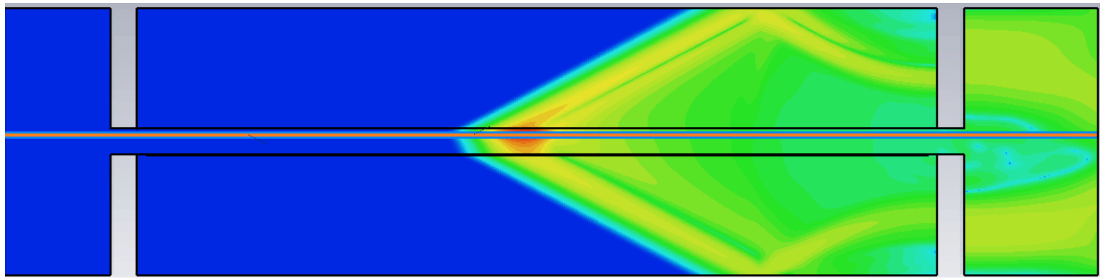


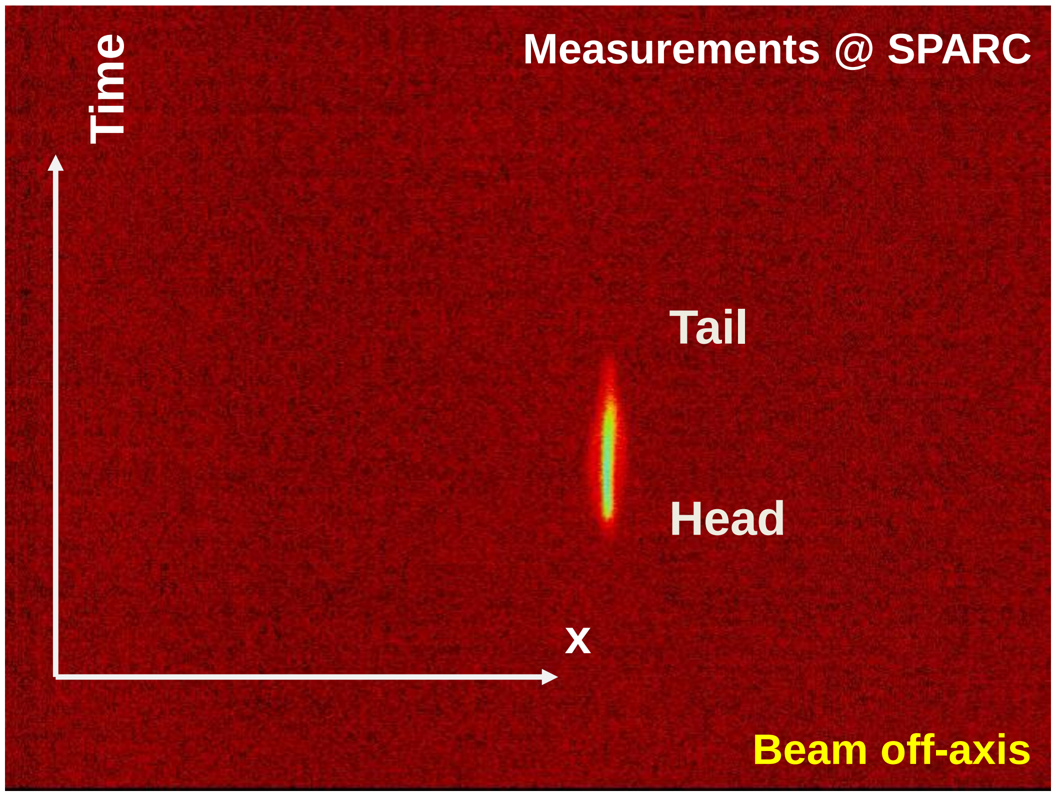




ELECTRON BEAM IN DIELECTRIC CAPILLARY

Wakefield simulations





OUTLINE

Longitudinal diagnostics

Bunch arrival monitor (passive cavity)

Bunch length diagnostics

RF deflector for bunch length measurement

Design of the structure and realisation issue

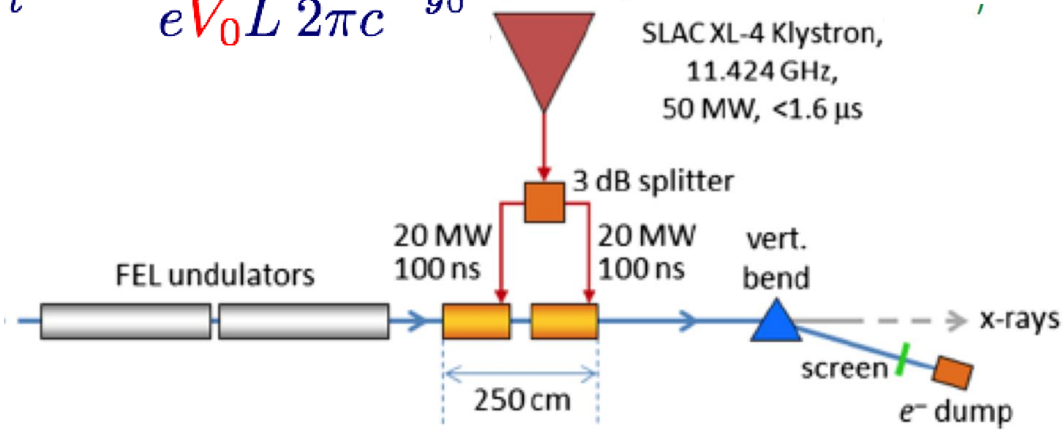
Beam measurement and calibration

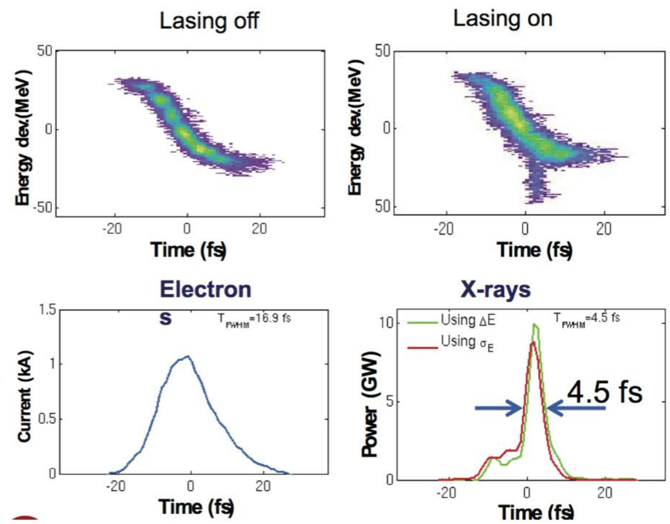
Novel ideas

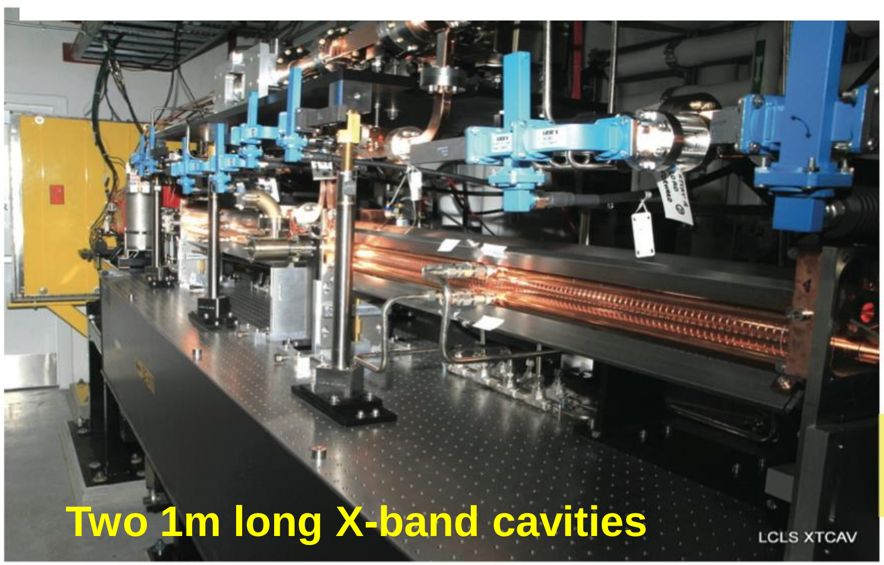
Andrea Mostacci
(Sapienza University, INFN-Roma)

RFD CAVITY FOR FS-SCALE BEAM (1)

$$\sigma_t^{res} = \frac{E}{eV_0 L}\frac{\lambda}{2\pi c}\sigma_{y_0}$$







X-band TCAV	
Frequency	11.424 GHz
Max kick	48 MV @ 40 MW

	14 GeV	4.3 GeV
Temporal resolution	3 fs	1 fs

RFD CAVITY FOR FS-SCALE BEAM (2)

- X-band TDS enabled ~sub-fs temporal resolution
- TDS after undulator section at LCLS:
  - daily tuning of FEL operation
  - online single-shot FEL pulse characterization

Direct Measurement of Sub-10 fs Relativistic Electron Beams with Ultralow Emittance

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(Received 5 November 2016; published 12 April 2017)

Proceedings of IPAC2017, Copenhagen, Denmark THPIK0

HIGH POWER TEST OF SINAP X-BAND DEFLECTOR AT KEK

Jianhao Tan, Dechun Tong, Qiang Gu, Wencheng Fang, Xiaoxia Huang, Zongbin Li, Toshiyasu Higo, Zhentang Zhao*

RF design of X-band RF deflector for femtosecond diagnostics of LCLS electron beam

Cite as: AIP Conference Proceedings **1507**, 682 (2012); https://doi.org/10.1063/1.4773780
Published Online: 21 December 2012

Valery A. Dolgashev, and Juwen Wang

MOPE094 Proceedings of IPAC'10, Kyoto, Japan

X-BAND TRAVELLING WAVE DEFLECTOR FOR ULTRA-FAST BEAM DIAGNOSTICS*

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ARTICLE

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Few-femtosecond time-resolved measurements of X-ray free-electron lasers

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PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17**, 102801 (2014)

Design and application of multimegawatt *X*-band deflectors for femtosecond electron beam diagnostics

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(Received 3 December 2013; revised manuscript received 12 August 2014; published 2 October 2014)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 120701 (2011)

Femtosecond x-ray pulse temporal characterization in free-electron lasers using a transverse deflector

Y. Ding,[1,*] C. Behrens,[2] P. Emma,[1] J. Frisch,[1] Z. Huang,[1] H. Loos,[1] P. Krejcik,[1] and M-H. Wang[1]
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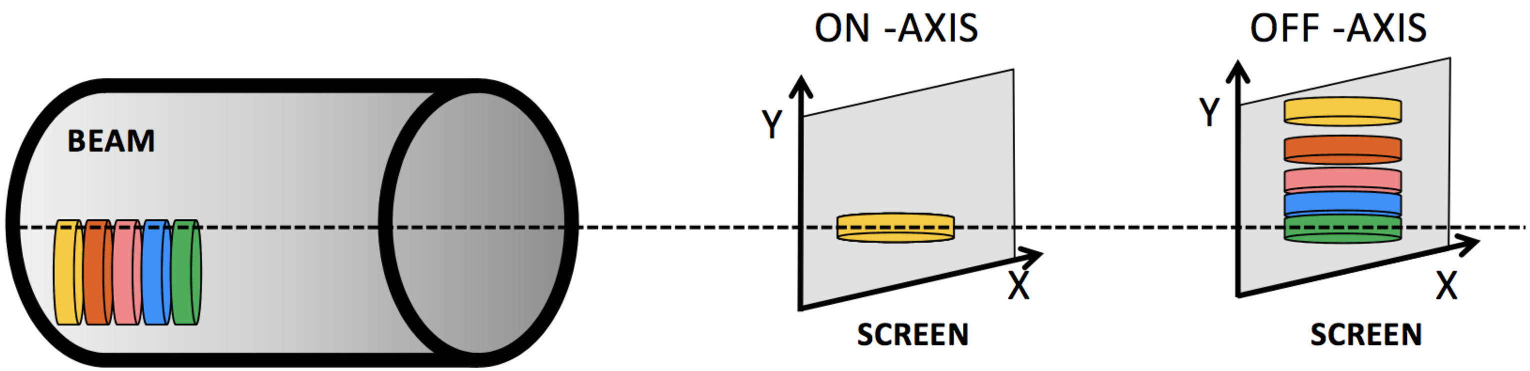
(Received 18 August 2011; published 7 December 2011)

Courtesy of P. Craievich - PSI

PASSIVE STREAKER WORKING PRICIPLE

Courtesy of S. Bettoni- PSI



- The method to time-resolve the longitudinal profile is based on the self-transverse-wakefield generation
- A correlation between temporal position of the particle along the bunch and transverse position at a downstream screen is introduced
- The beam passes off-axis through a structure capable of generating a strong <u>monotonic</u> transverse wakefield along the full bunch length
- Cylindrical or planar, corrugated or dielectric-lined geometries may be used without altering the principle
- Potentially sub-fs resolutions achievable

S. Bettoni et al., **Passive Streaking Using Transverse Wakefield for Ultrashort Bunch Diagnostics** , IPAC 2017

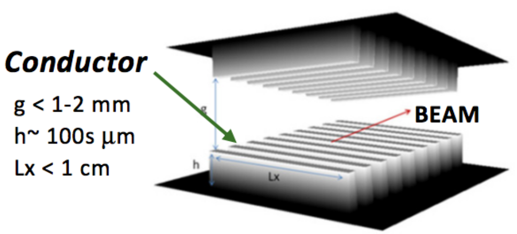
PASSIVE STREAKER WORKING PRICIPLE

Courtesy of S. Bettoni- PSI

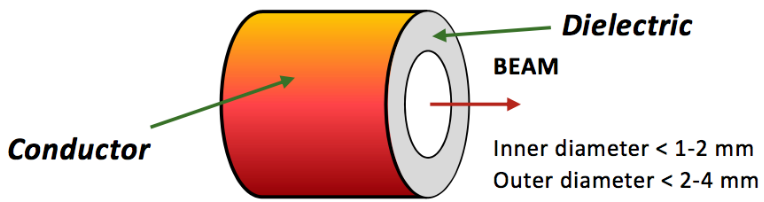
Several sources can be used to do such a measurements.
The requirements are:

- ❑ Function monotone along the full bunch length
- ❑ Amplitude of the wakefield enough to limit the length of the device to a reasonable value (~few meters)

CORRUGATED



DIELECTRIC LINED-WAVEGUIDE



More typically corrugated ⇨

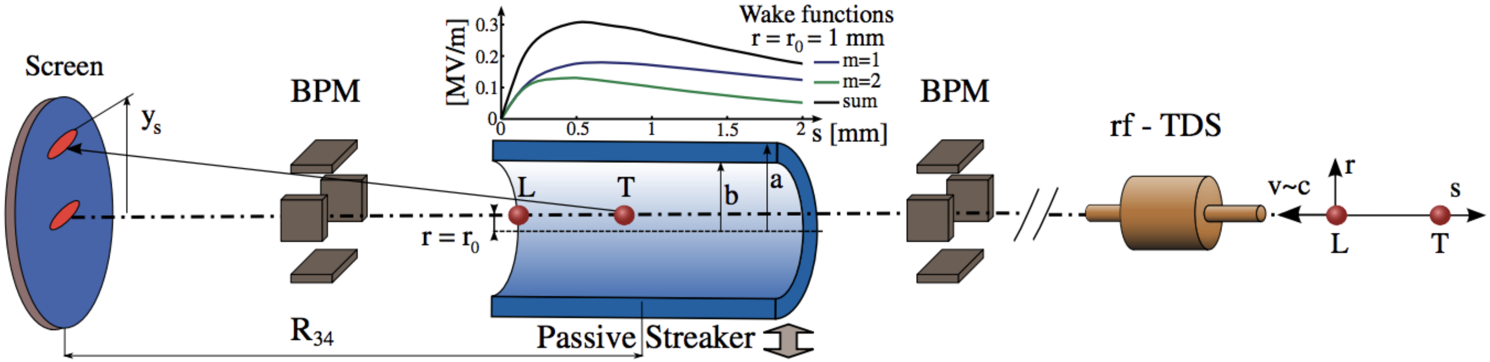
Flat	Round
Easily tunable	More difficult to tune
Reduced amplitude (by $\pi^2/16$)	Maximum amplitude

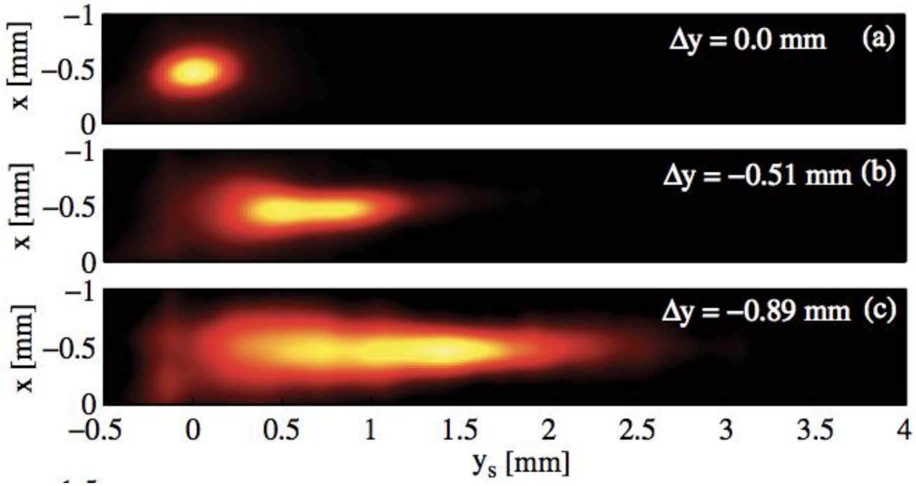
⇦ More typically dielectric lined

S. Bettoni et al., **Passive Streaking Using Transverse Wakefield for Ultrashort Bunch Diagnostics** , IPAC 2017

PASSIVE STREAKER EXPERIMENT@PSI

Courtesy of S. Bettoni- PSI





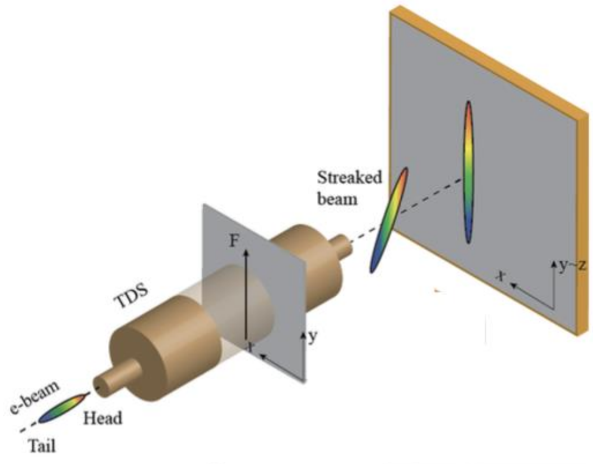
S. Bettoni et al., **Temporal profile measurements of relativistic electron bunch based on wakefield generation**, PRAB 19, 021304 (2016)

THE POLARIX

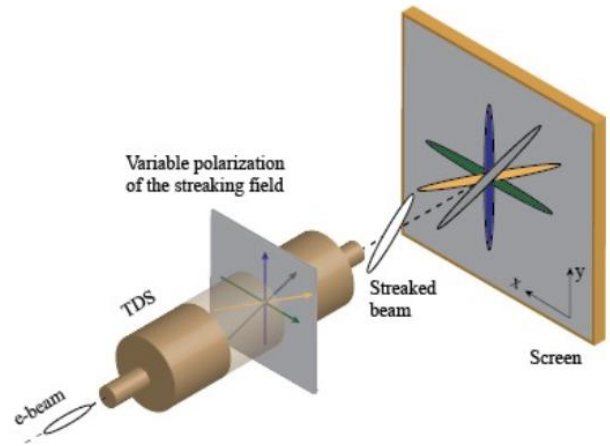
Courtesy of P. Craievich - PSI

TDS are RF-based devices used for the manipulation and/or the diagnostics of charged particle beams to retrieve longitudinal/temporal proprieties

Conventional TDS: streaking in a fixed polarization (i. e. vertical or horizontal)



POLARIzable X-band Transverse Deflection Structure – POLARIX TDS



The longitudinal distribution of the e-bunch is mapped into the transverse one thanks to the time dependent transversely deflecting field

$$\sigma_{t,R} \geq \frac{\sigma_{y0}}{S} = \sqrt{\frac{\varepsilon_{N,y}}{\gamma\beta_d}}\,\frac{pc}{eV_\perp}\,\frac{1}{ck_{rf}\sin(\Delta\psi_{ds})}$$

P. Craievich et al., **Post-undulator beam measurements with PolariX TDS in SwissFEL**, SPIE Optics + Opticselectronics – 26 April 2023, Prague, Czech Republic

THE POLARIX DIAGNOSTIC CAPABILITIES

Courtesy of P. Craievich - PSI

- Bunch length measurement (Method capable of fs and sub-fs longitudinal resolution)
- Longitudinal charge profile measurement (1D)
- Combined with dipole → longitudinal phase space measurement
- Combined with quadrupole scan or multi-screen lattice → slice emittance measurement on the plane perpendicular to the streaking direction, slice transverse phase space reconstruction - slice emittance on different transverse planes
- Measure of the FEL-induced lasing effects imprinted on the electron beam longitudinal phase space: first reference C. Behrens et al., Nat. Comm. 5, 3762 (2014)
- 5D/6D phase-space characterization becomes possible by different streaking planes and using tomographic methods
- Reconstruction of the 3D charge density

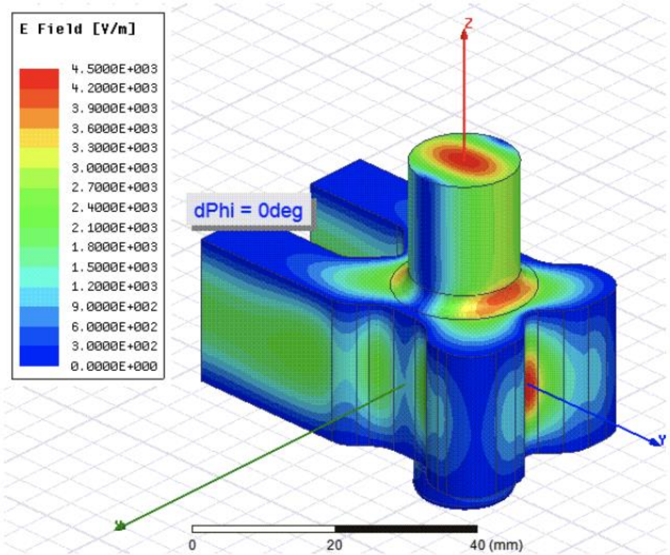
PAUL SCHERRER INSTITUT PSI   CERN   DESY.

P. Craievich et al., **Post-undulator beam measurements with PolariX TDS in SwissFEL**, SPIE Optics + Opticselectronics – 26 April 2023, Prague, Czech Republic

VARIABLE POLARIZATION – X BAND

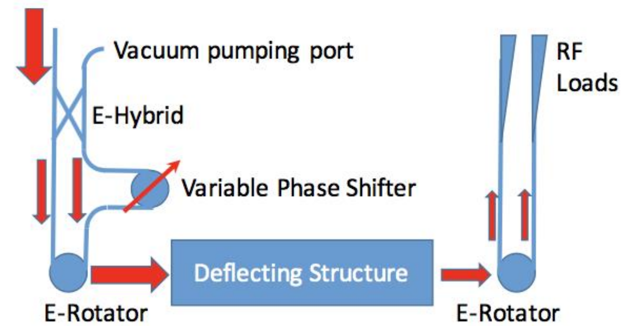
Courtesy of P. Craievich - PSI

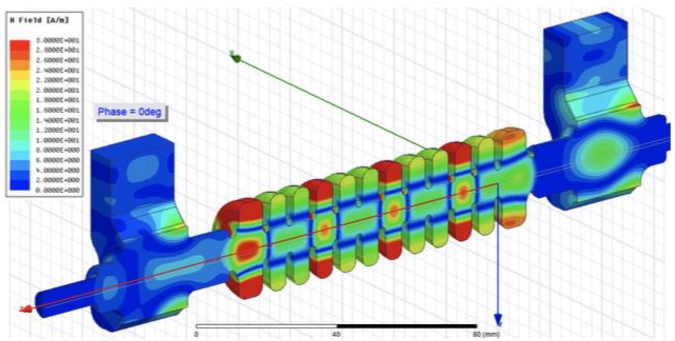
Variable polarization circular TE11 mode launcher: E-rotator



Phase difference between port 1 and port 2:

- 0 degree -> vertical polarization
- 180 degree -> horizontal polarization





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P. Craievich et al., Phys. Rev. Accel. Beams, 2020
B. Marchetti et al., Sci. Rep., 2021

P. Craievich et al., **Post-undulator beam measurements with PolariX TDS in SwissFEL**, SPIE Optics + Opticselectronics – 26 April 2023, Prague, Czech Republic

CONCLUSION

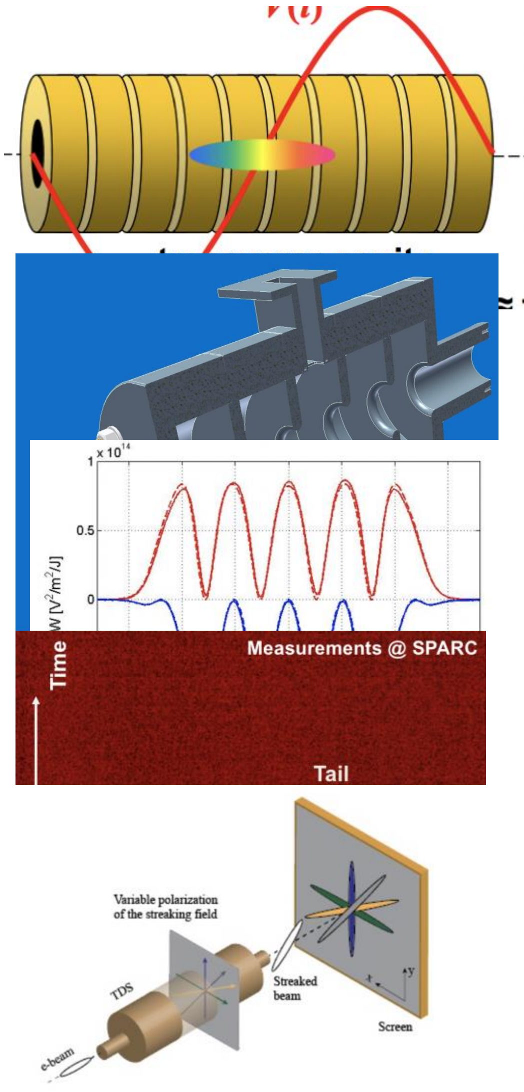
RF deflector for bunch length measurement

Various issues of **design and operating** a RF diagnostic device

Bead pull measurement of magnetic fields

Wakefields measurements

Novel ideas



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