

# Crab cavities for light sources and particle colliders

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Rama Calaga, CERN  
IPAC26, 20 May 2026



# Outline

An overview with select examples on the usage of crab & deflecting cavities in particle accelerators.

It is not comprehensive\*, but meant to emphasize the diversity of applications with some focus on technological challenges

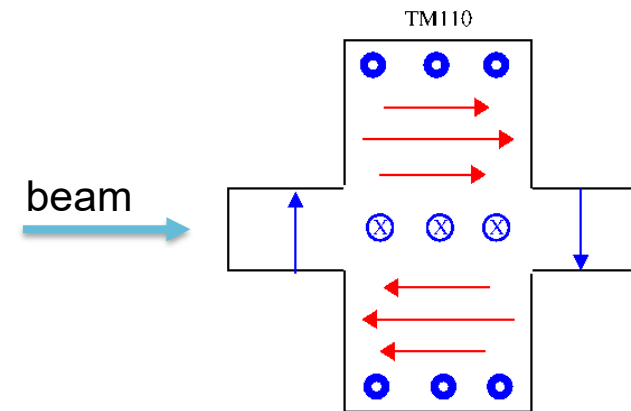
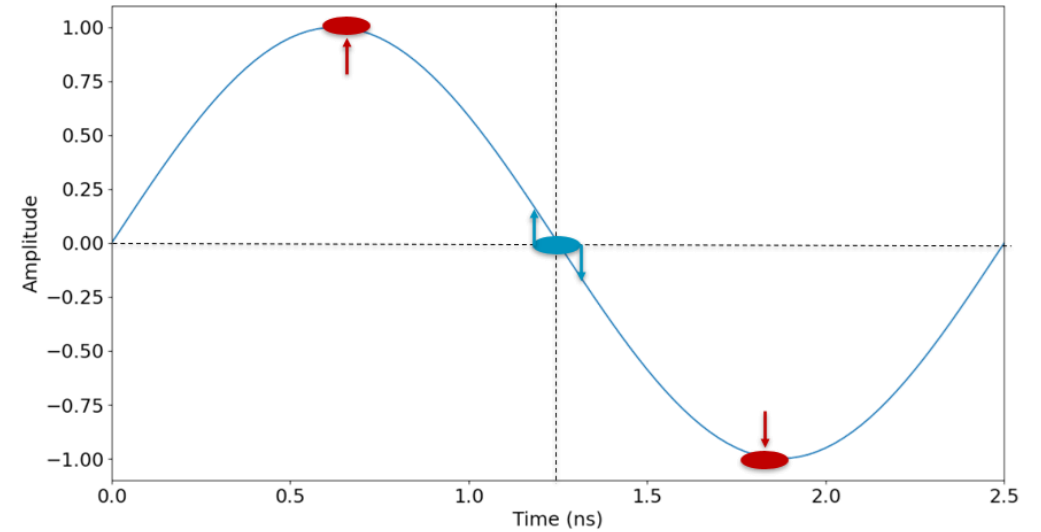
- References that have treated similar topic in the past:
  - ICFA Workshop on Deflecting Cavities, [I](#) & [II](#)
  - Deflecting Cavities - [CAS 2010](#), [JAS 2017](#)
  - SRF2019 – [SRF crabbing and deflecting cavities](#)
  - LINAC22 – [Crab & deflecting cavities for Linear Accelerator](#)



\* Not all projects & ideas could be covered here

# Transverse (Dipole) RF Cavities

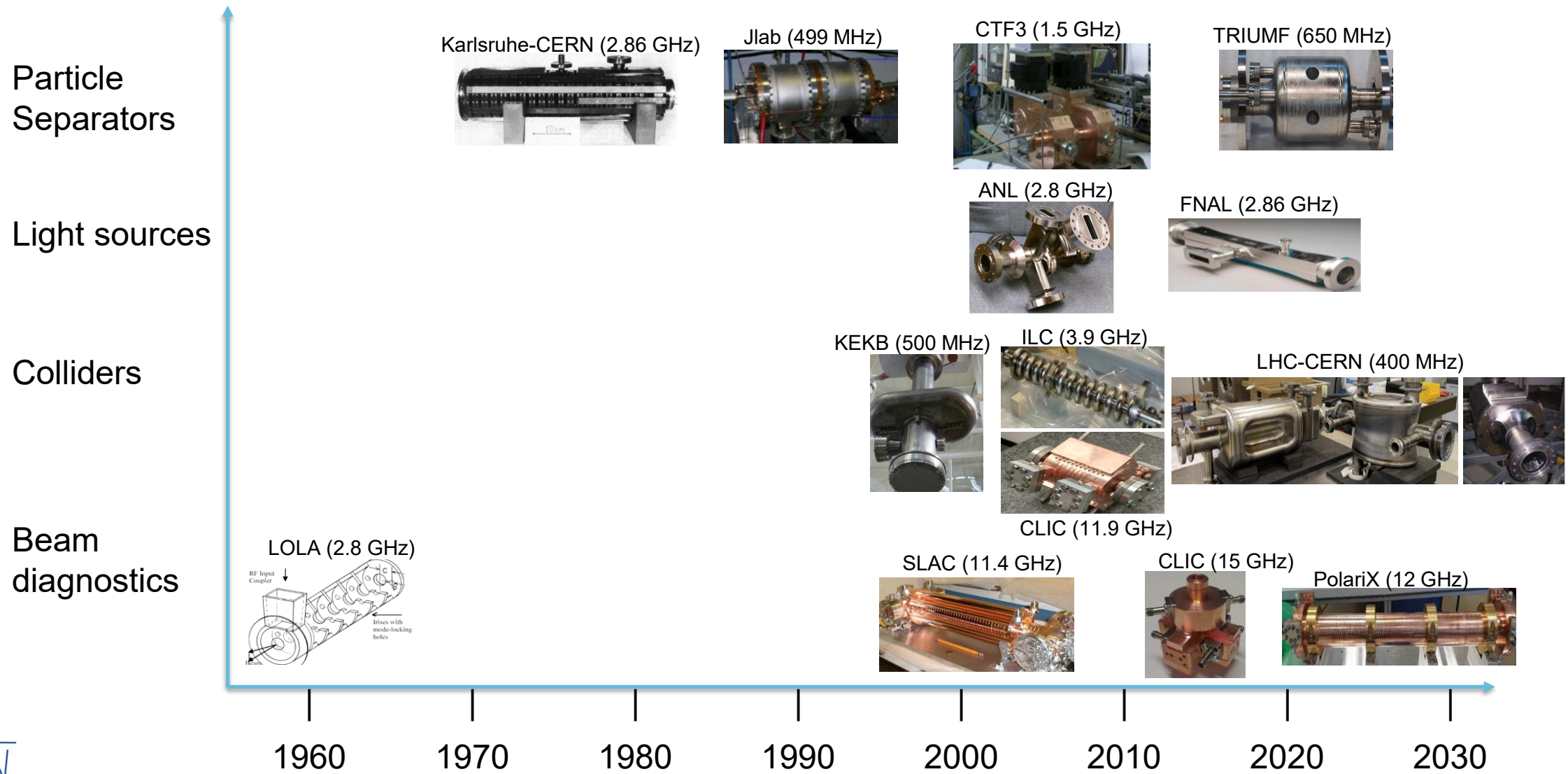
- A time varying transverse kick imparted to the particle bunch with transverse mode in a RF cavity
- Depending the RF phase w.r.t the bunch center, the particle bunch can either receive a net transverse kick or head-tail rotation
- Such a RF cavity (principally dipole-mode) has been proposed and used for a several applications in particle accelerators since 60's



$$\Delta p_y = -\frac{i \cdot e}{\omega} \cdot \frac{dV_z}{dy}$$

(PW theorem)

# Landscape, 50+ years

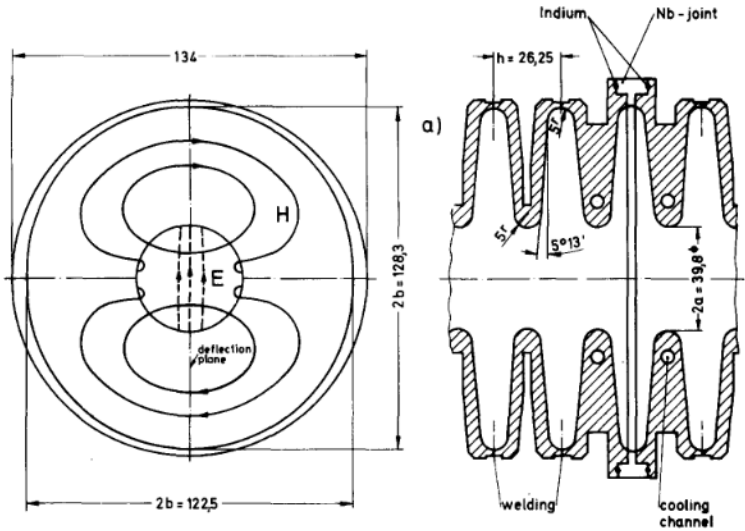


\* Not comprehensive

# Particle Separators & Combiners



# Particle Separators



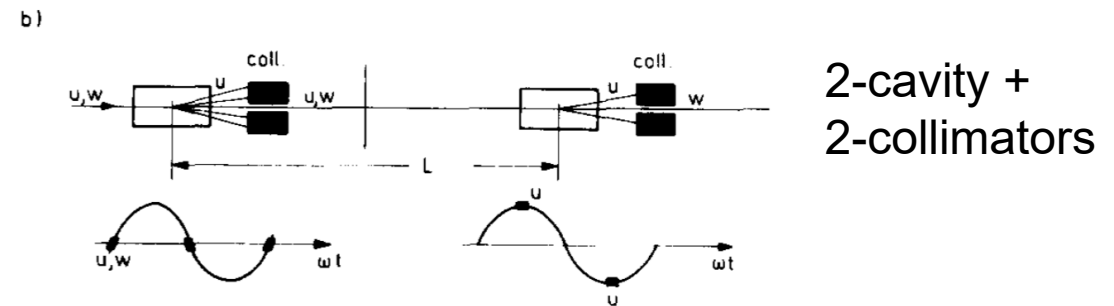
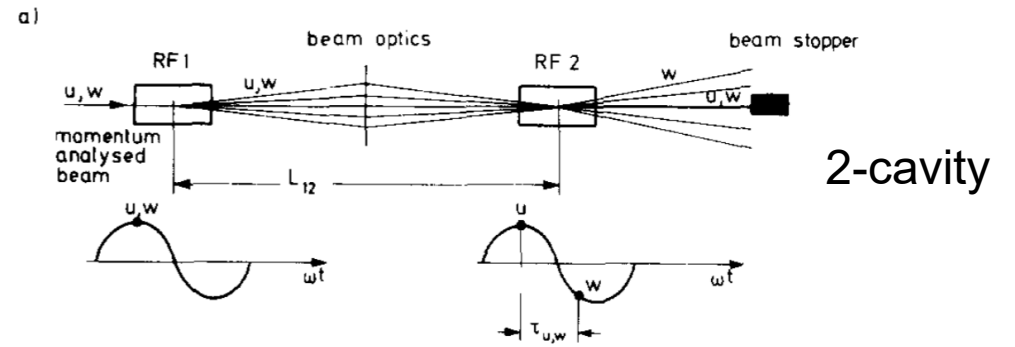
RF separator for 3-36 GeV/c from the SPS, early superconducting RF deflector

Study unknown heavy particles, baryonic states/exchange,  $K^\pm$  & p-bar

Velocity separation of different species

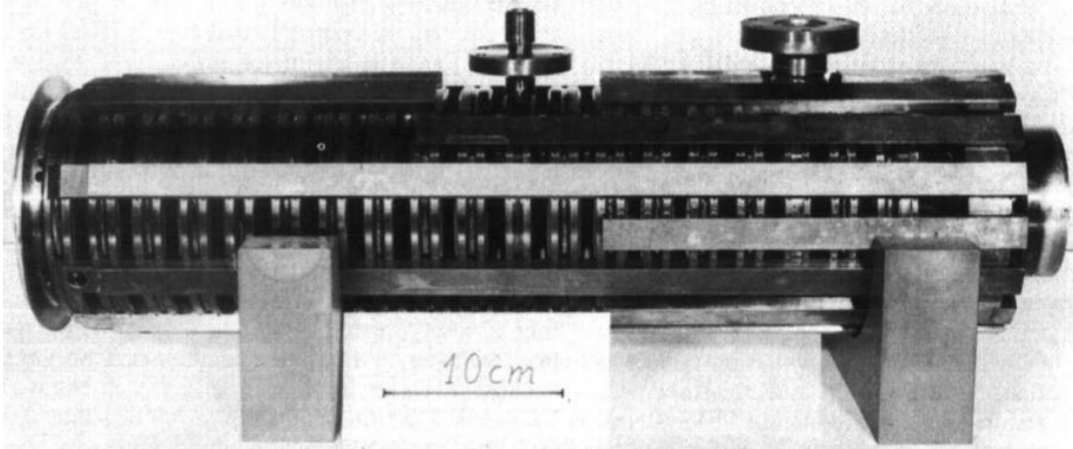
$$\Delta\phi = \frac{\omega L}{c} \left( \frac{1}{\beta_1} - \frac{1}{\beta_2} \right)$$

Separation of different bunches using RF phase



# Particle Separators

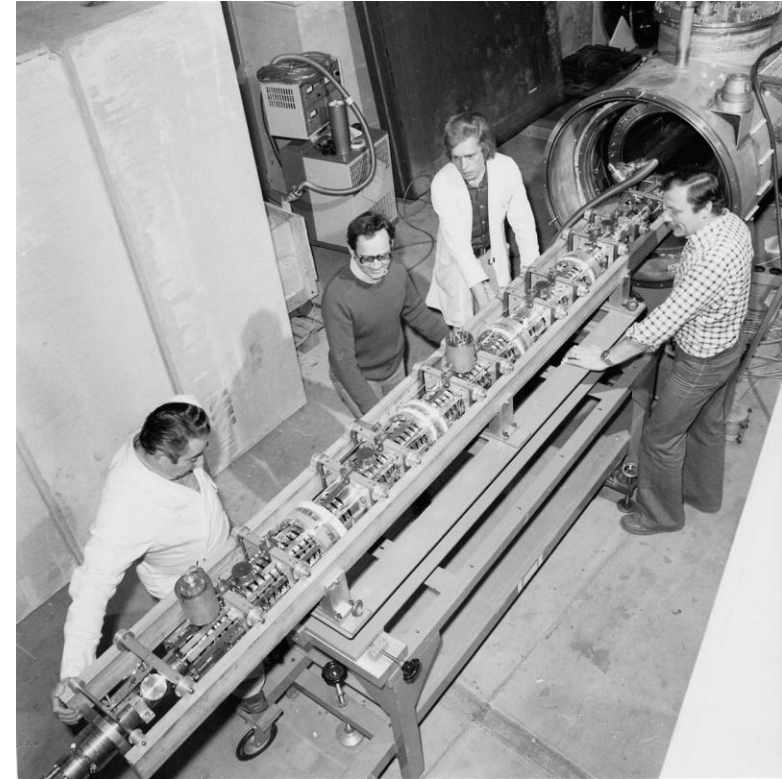
Early superconducting RF separator



Frequency = 2.865 GHz,  $V_T = 1.5 - 2.0$  MV  
Length = 3.0m, 104 cells  
Machined from bulk Niobium

Used later at the U-70 experimental setup at IHEP

Karlsruhe-CERN RF Separator



Citron, Lengler et al., NIM 164 (1979)

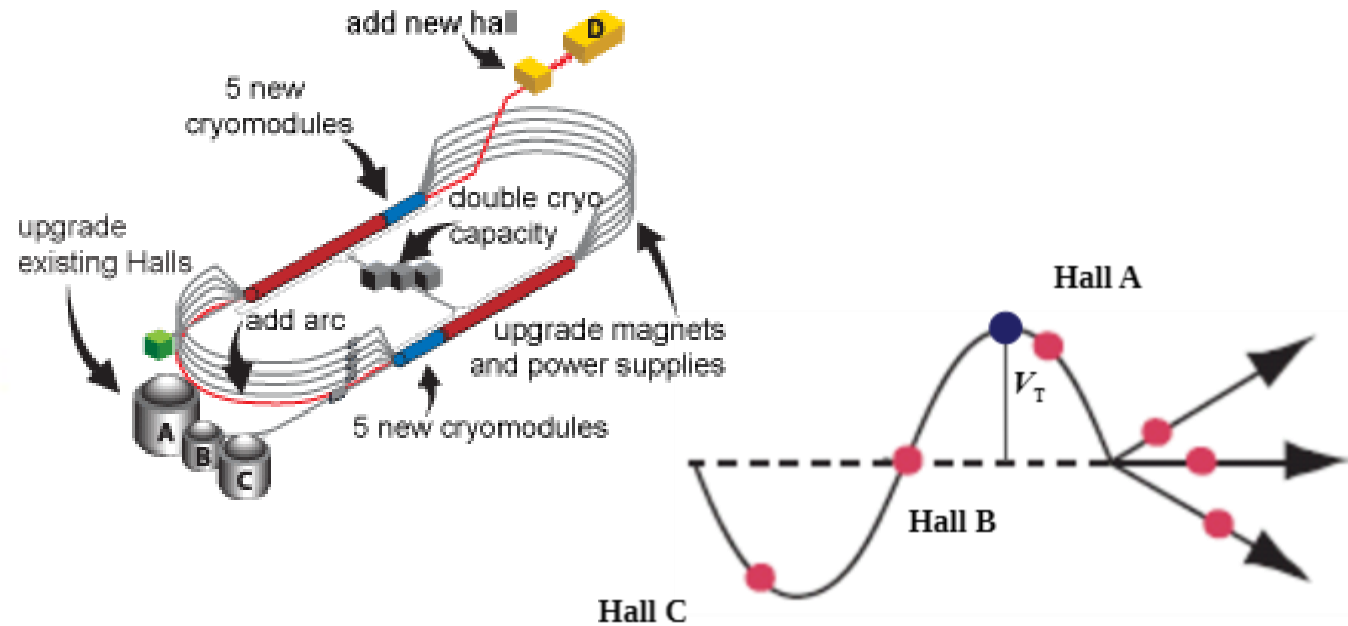
# Particle Separators

- Late 90's at CEBAF accelerator, the use of RF deflector in the recirculating multi-pass CW linac
- The transverse kick to the electron bunches using a 499 MHz cavity in a 2-cell configuration. The design is almost 4 times more compact and high shunt impedance

Normal conducting 4-rod deflector

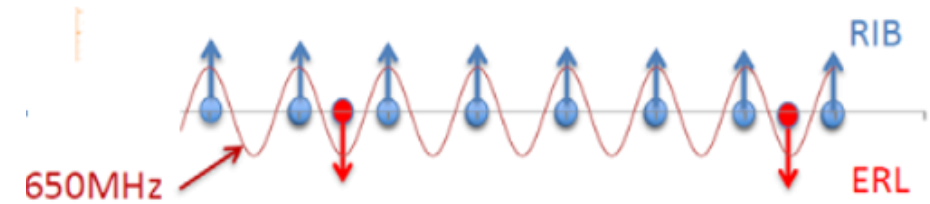


Hovater et al., CERN-1996-007

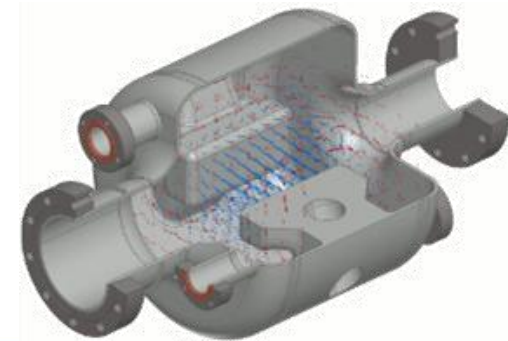


# TRIUMF Deflector

- More recently, a 650 MHz SCRF deflector to separate the beam from the ARIEL electron linac
- Beam deflected to the ERL (intense THz source) or the RIB facility (single pass) with interleaved bunch trains into 1.3 GHz buckets
- A compact RF dipole like topology machined in reactor grade Niobium for a cost-effective manufacturing process



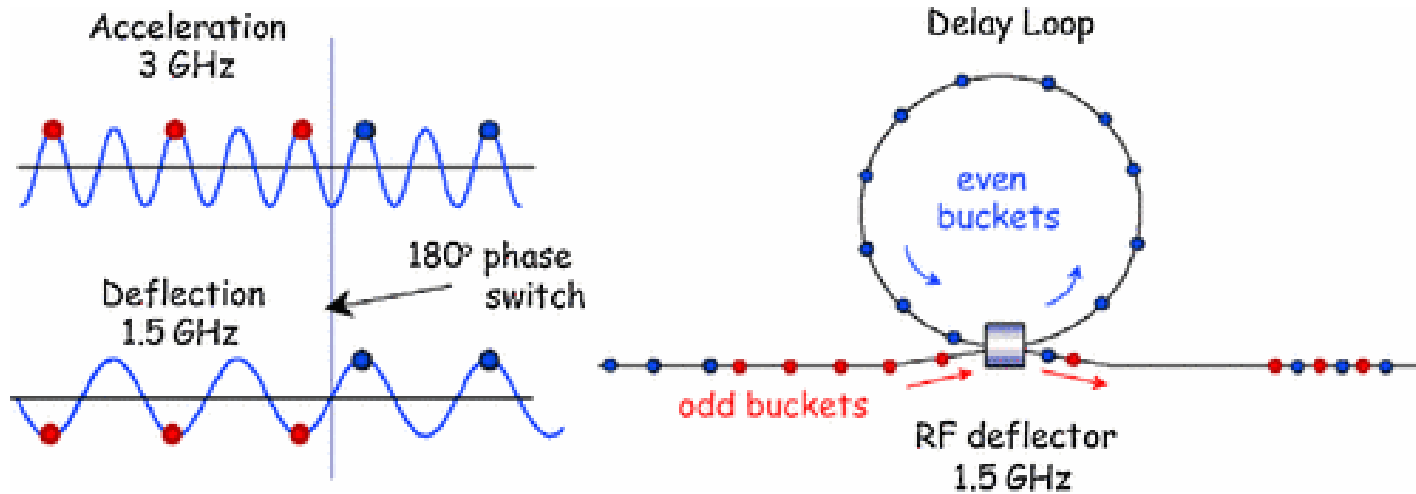
Freq = 650 MHz  
Voltage = 0.3 MV  
RF power: 50 W



D. Storey, Ph.D. project

# Particle Combiner

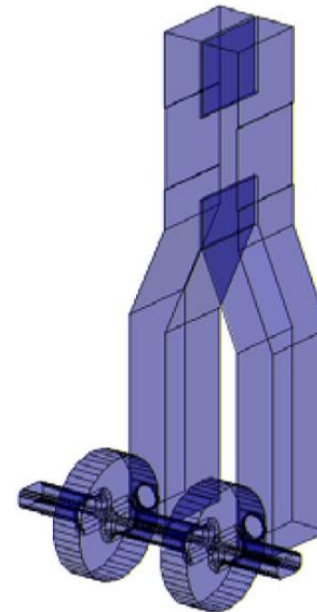
Recombination of the injected/extracted bunches at the CLIC CTF3 delay loop



Frequency = 1.5 GHz  
Voltage = 4.5 MV  
RF power: 50 MW - pulsed

D. Alessini et al., PRST-AB 12, 031301

Transverse deflector at to reduce the bunch spacing by factor 2 and at a 2<sup>nd</sup> stage by factor 5

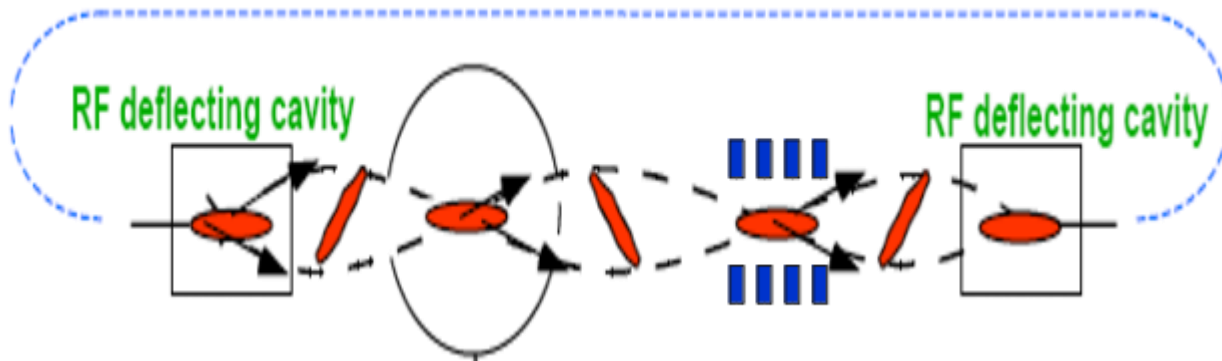


# Light Sources & FELs

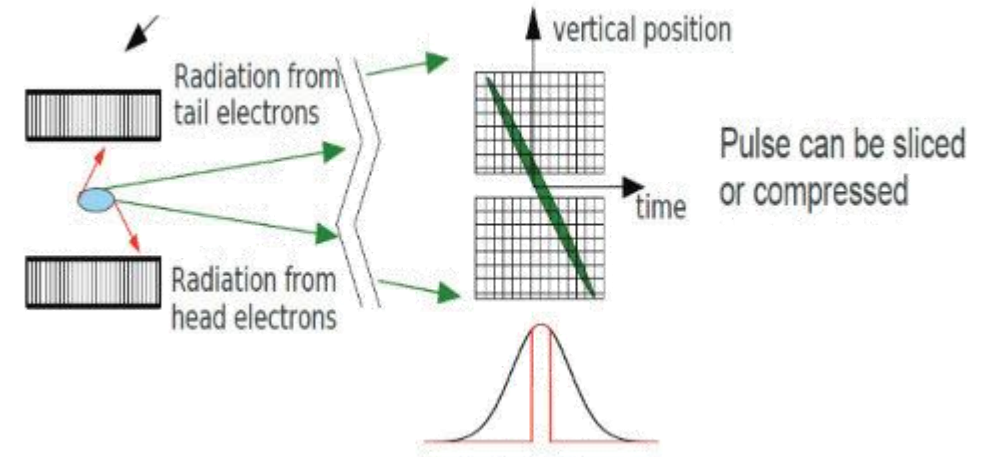


# X-ray Pulse Compression, I

- Induce a x-z correlation using RF deflector ( $\phi = \text{crabbing phase}$ ). Bunch passing through an undulator has an angle dependent divergence for the emitted x-rays
- Passing it through a collimation slit or crystal for x-ray pulse slicing or compression to achieve picosecond x-ray pulses



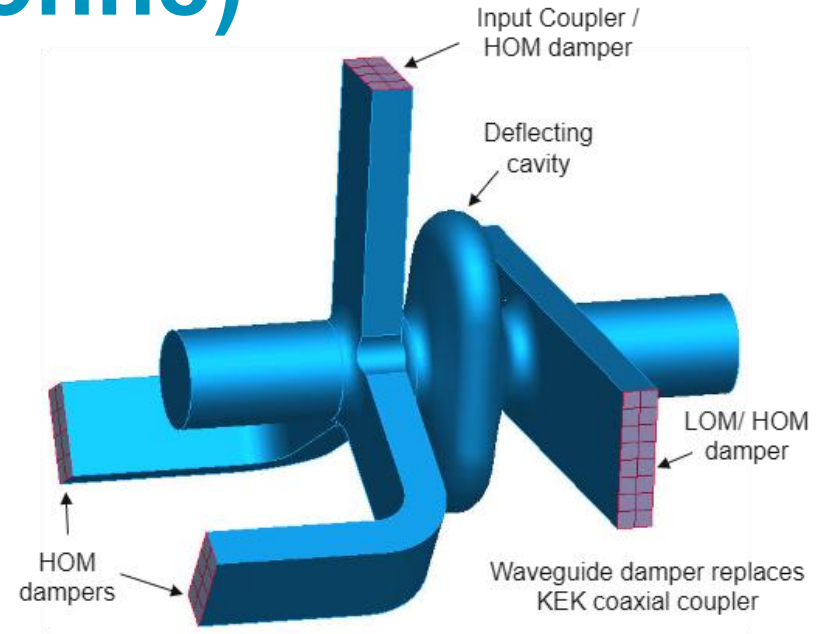
A. Zholents et al., NIMA 425, 385 (1999)



# APS upgrade (Argonne)

- Short pulse X-ray (SPX) generation at light sources, for example the Argonne light source upgrade to achieve  $\sim 2$  ps pulses
- Four heavily damped TM110-type SRF cavity (LOM, SOMs, HOMs) to produce the voltage of 2 MV

Frequency = 2.815 GHz  
 $V_T = 2$  MV (4-cavities)  
RF power: 20 kW



Compact single-cell cavity / damper assembly

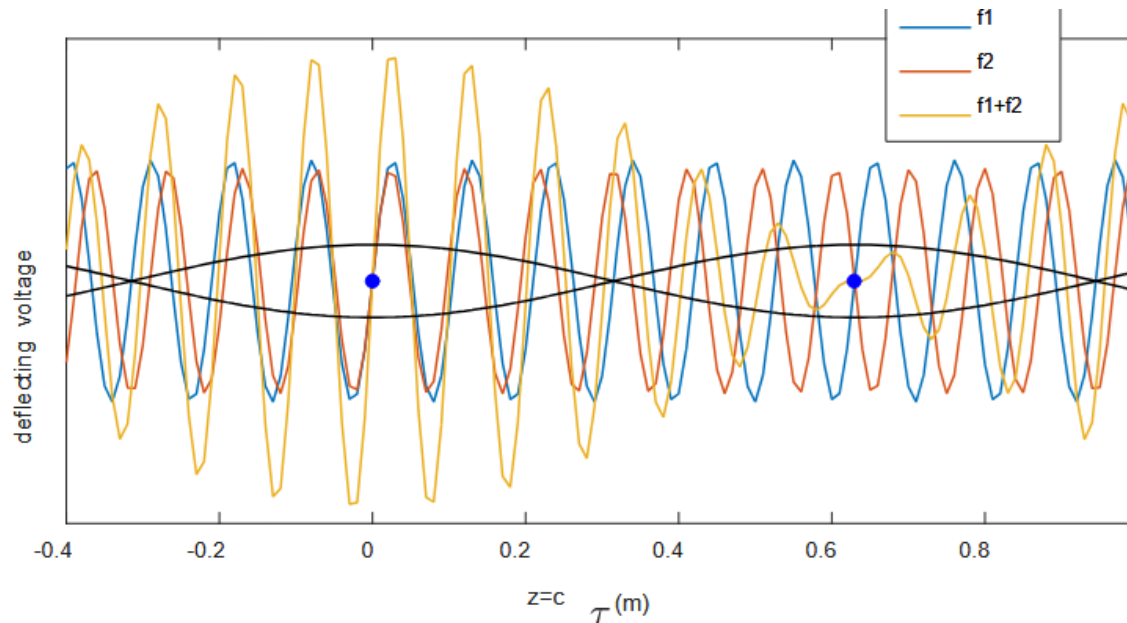
J. Mammosser, A. Nassiri et al., SRF 2013

# X-ray Pulse Compression, II

- Induce a x-z correlation using two crab cavities at the same location but with two frequencies

$$f_1 = n f_0; \quad f_2 = (n + 1/2) f_0$$

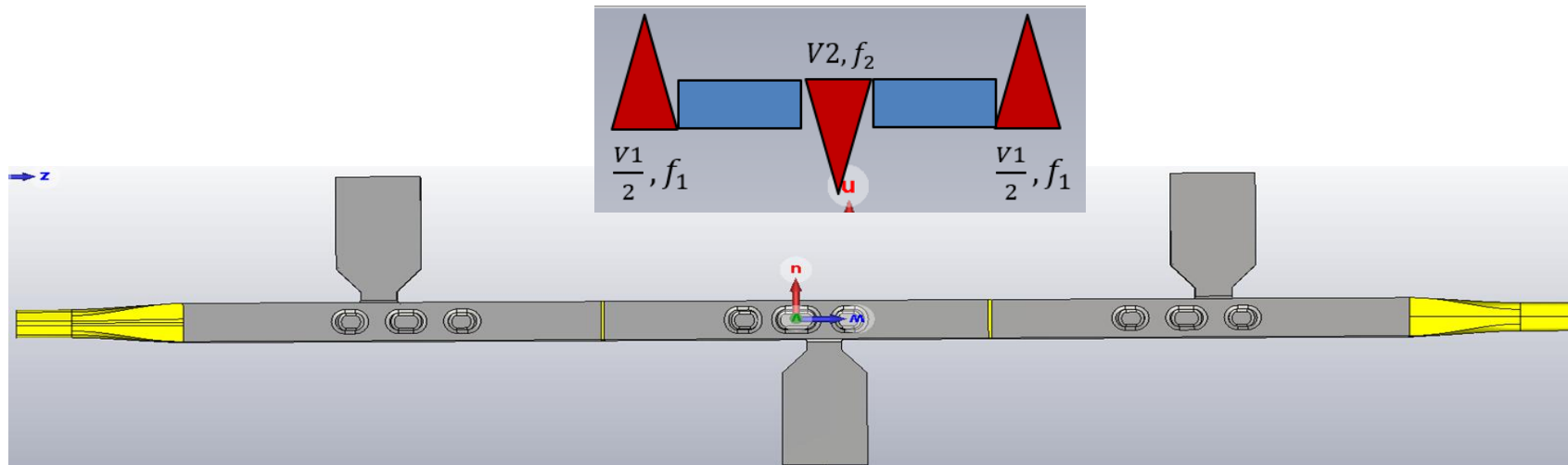
- The combined RF kick has the feature that half of the buckets have a crabbing kick while the other half are “not affected”



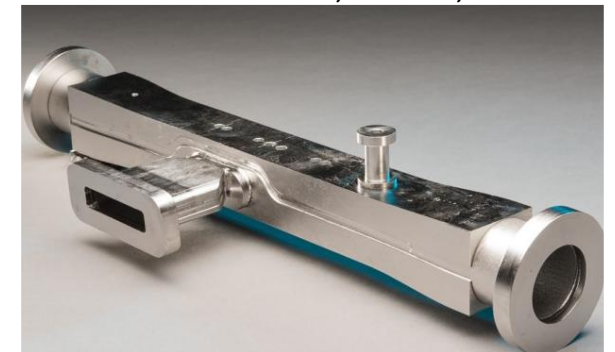
A. Zholents, NIMA 798, 111 (2015)  
X. Huang, Zholents et al. PRAB 2016

# Elettra 2.0, Trieste

- This scheme was adopted at Elettra 2.0 upgrade as a possible option
- The two frequencies 3 GHz and 3.25 GHz are the 6<sup>th</sup> and 6.5<sup>th</sup> harmonic of the main RF
- A QMiR type topology is chosen for the deflecting structure with a three-cavity setup to provide the kick to the relevant bunches



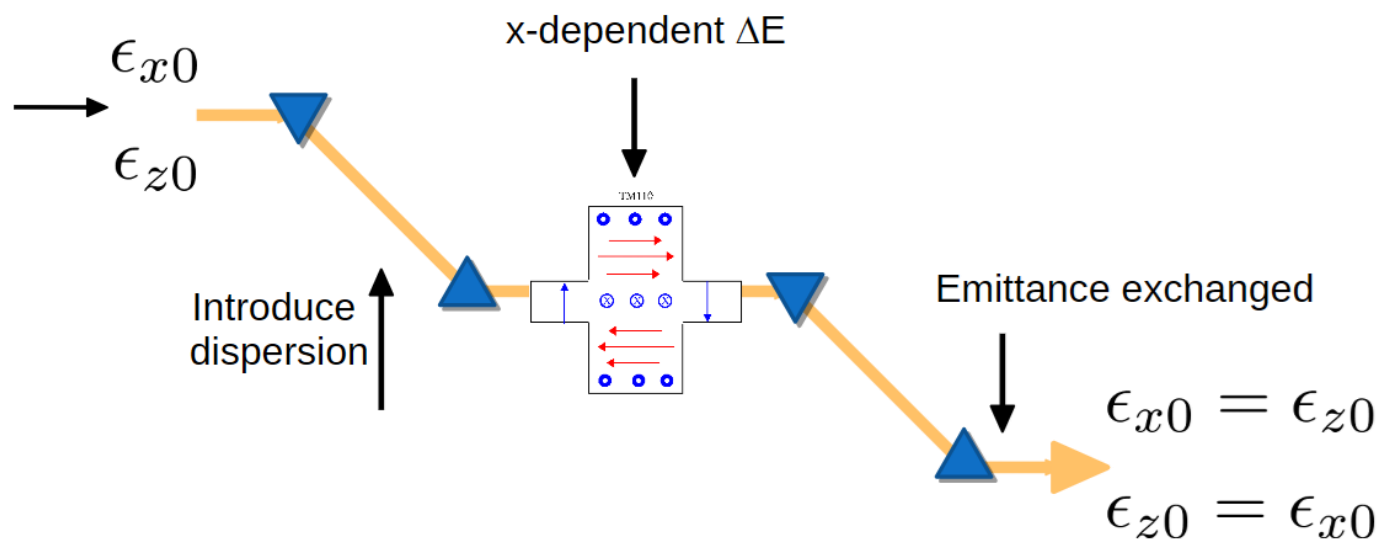
QMiR, A. Lunin, et. al., Physics  
Procedia Vol. 79, 54 –62, 2015



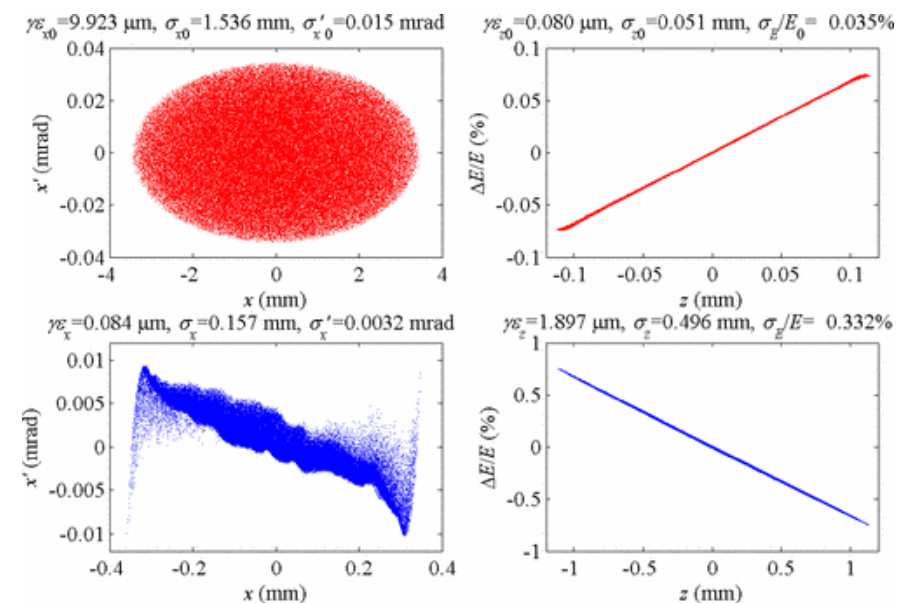
S. Di Mitri et al., CDR of Crab cavities for  
picosecond x-ray pulses at ELETTRA 2.0, 2025

# Emittance Exchanger

- Emittance exchange between transverse and longitudinal planes
  - Use RF deflector to give x-dependent energy kick ( $\delta p/p \sim \delta x$ )
  - Particles with  $\delta p/p$  getting position change ( $\delta x \sim \eta \delta$ )
  - Emittance exchange for the right choice of kick =  $-1/\eta$

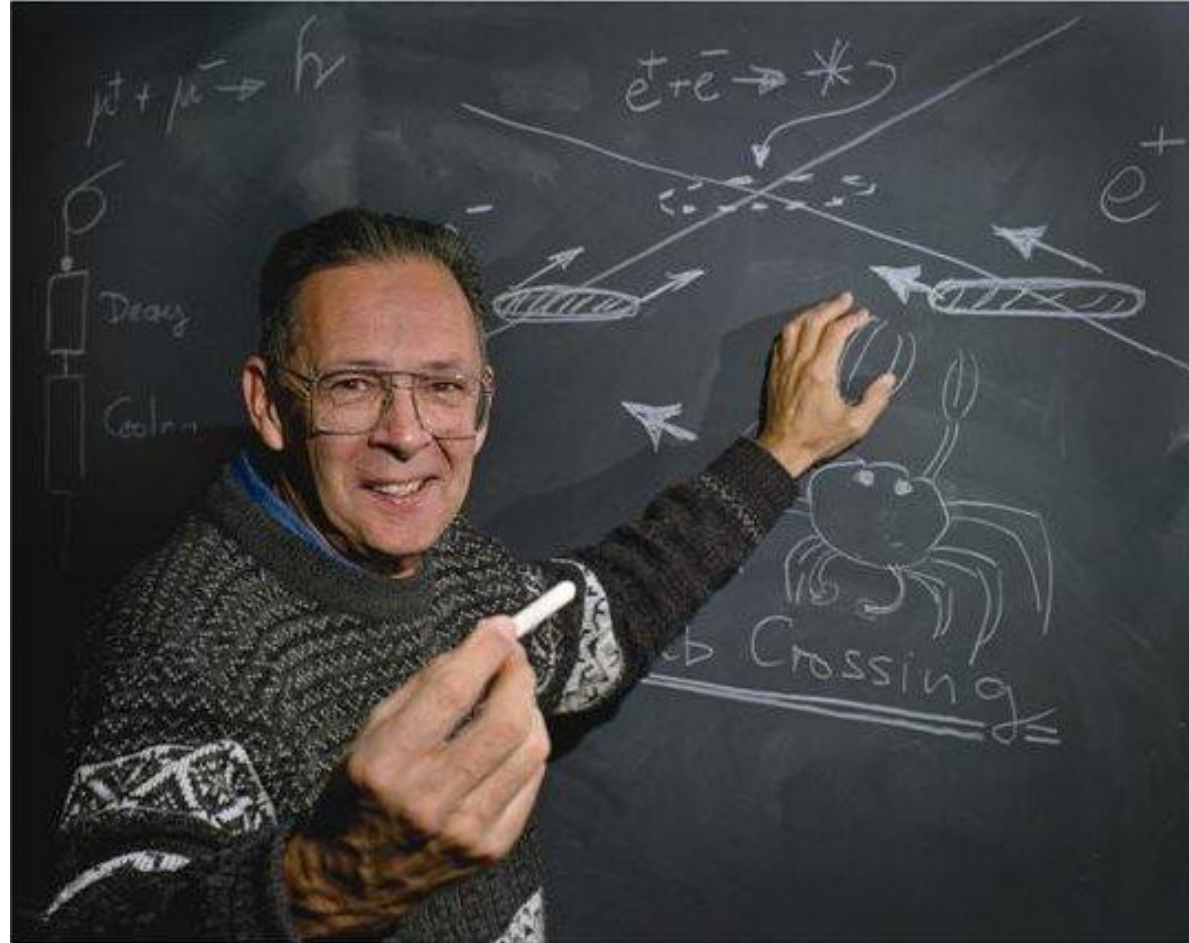


Cornacchia, Emma, PRST AB **5**, 084001 (2002), PRST AB **9**, 100702 (2006).



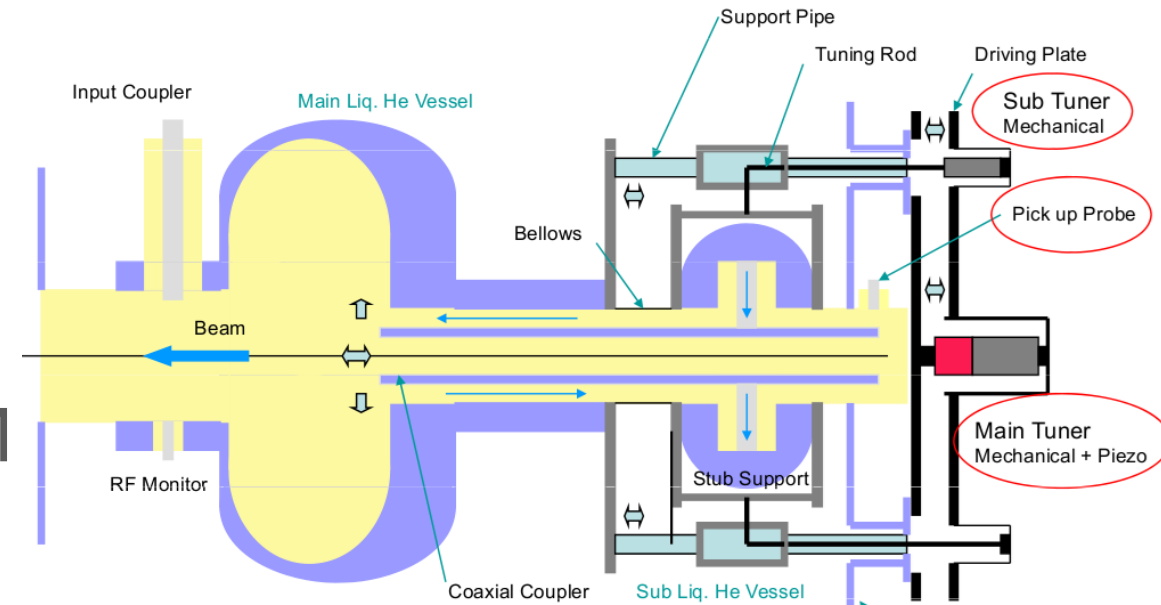
# Crab Crossing for Luminosity

R. Palmer, 1988, Linear Collider

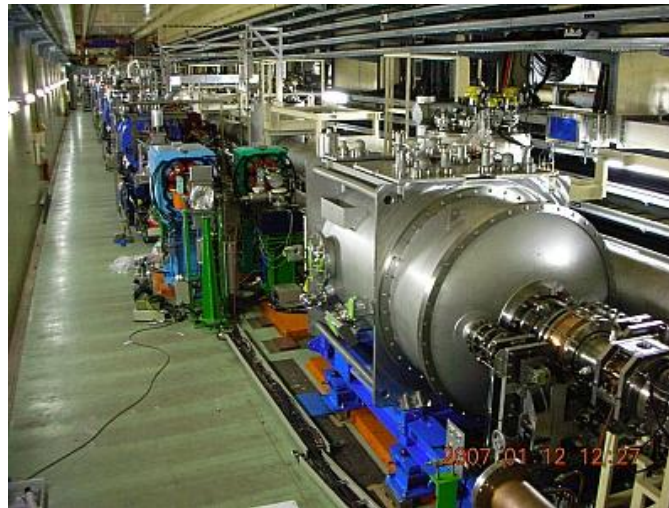


# KEKB B-Factor

- First implementation in the  $e^+e^-$  machine at KEKB ( $TM_{110}$  mode)
- Squashed elliptical cell to separate the opposite polarization
- Beam-pipe coaxial coupler for HOM damping + tuning



Hosoyama et al., SRF 1996

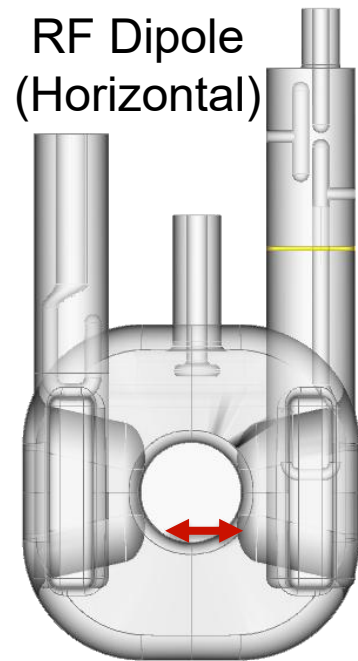


Funakoshi et al., CERN-2014-004.27, 2014

Frequency: 508.9 MHz  
RF power: 50-120 kW

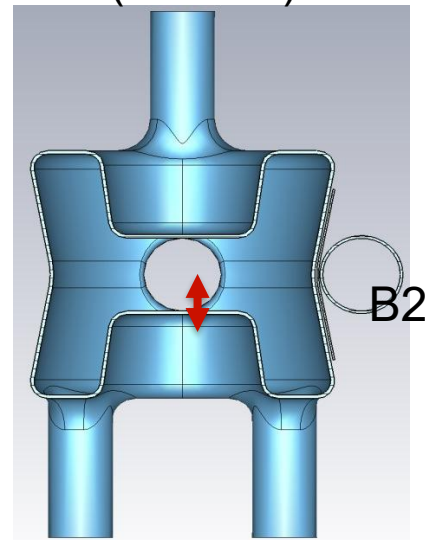
# HL-LHC Crab Cavities

- HL-LHC will be the first proton collider to implement crab crossing
- Two compact crab cavities with very strong HOM damping & several novel technologies to realize the implementation for HL-LHC



PRAB 16, 002001

Double Quarter Wave  
(Vertical)



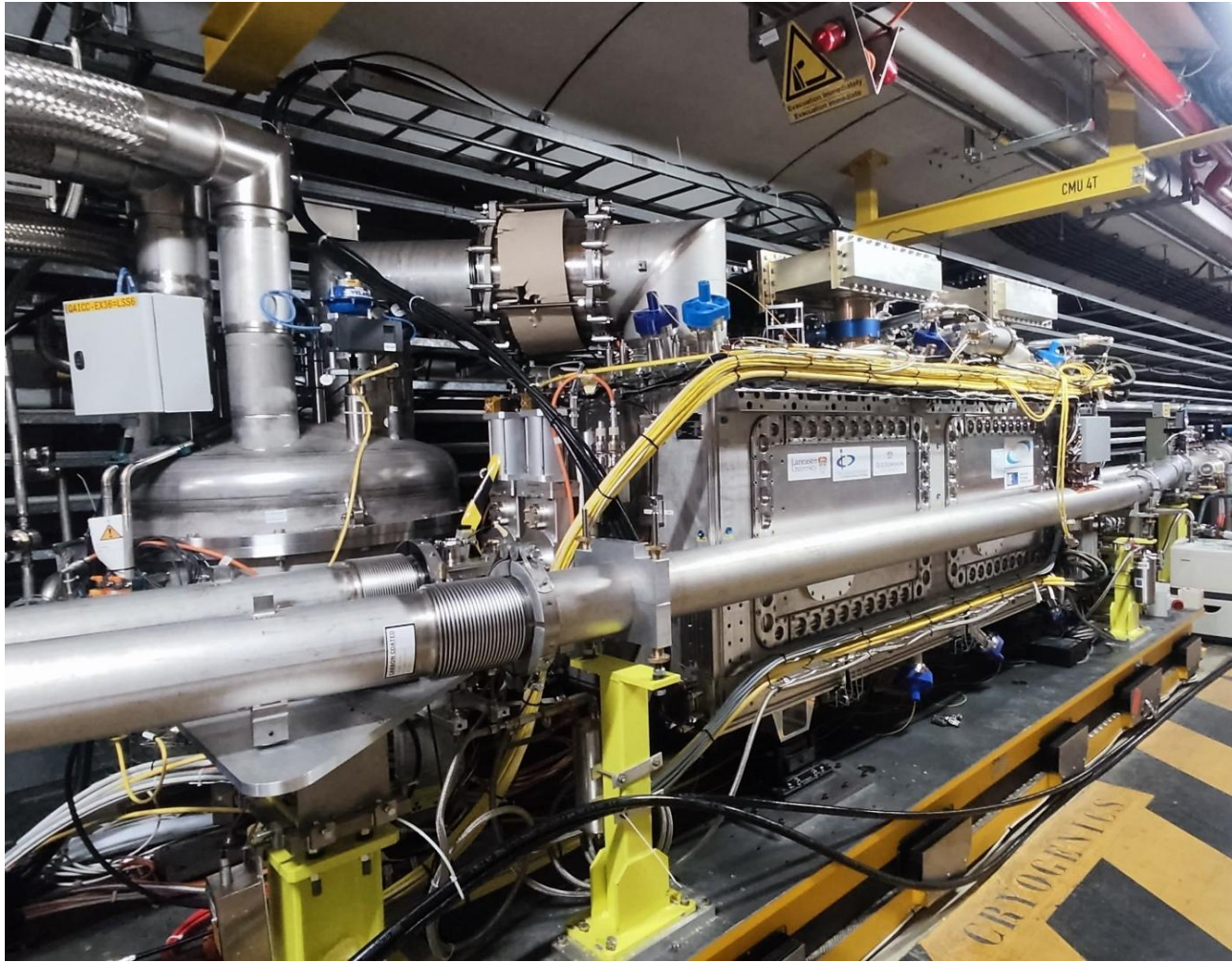
PRAB 21, 082002



Frequency: 401.8 MHz

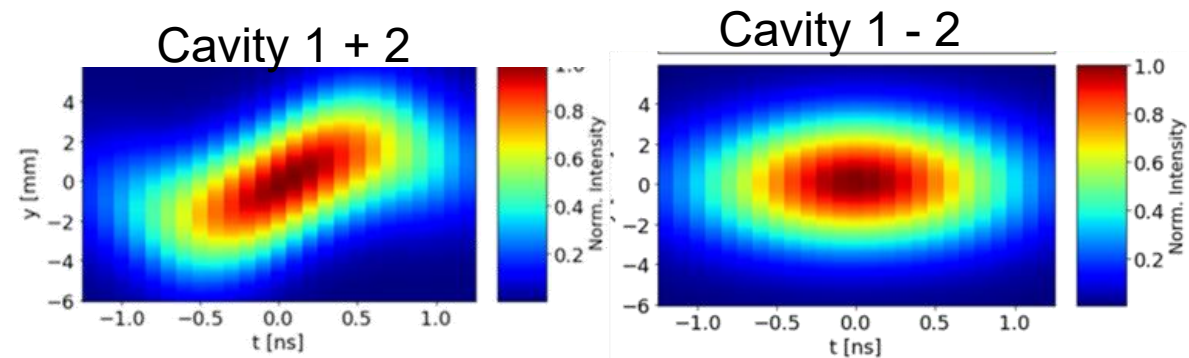
RF power: 15-40 kW

# HL-LHC Crab Cavities



DQW & RFD prototype cryomodules tested with proton beam in the SPS (2018-26)

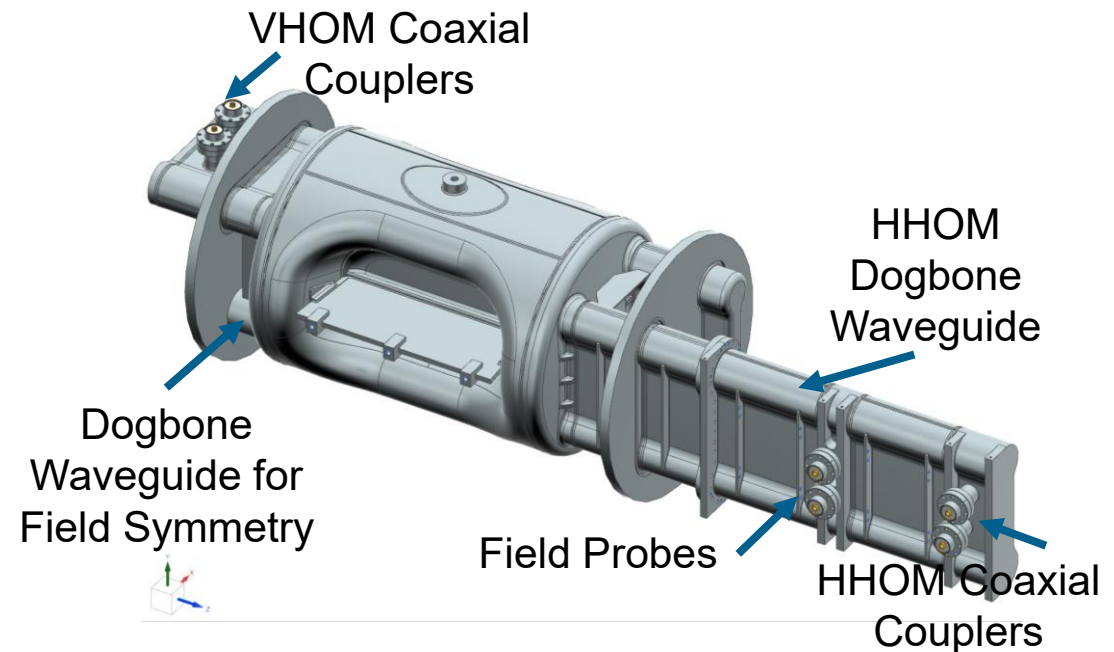
Many beam experiments to study aspects related to RF noise, impedance and other operational aspects



# Electron-Ion Collider

- EIC Hadron beam will require a two-frequencies for a linearized transverse kick. The electron beam will use a single frequency crab cavity
- The RF dipole topology at 197 MHz as the driving cavity with a 2<sup>nd</sup> harmonic at 394 MHz
- The low frequency required for EIC poses particular challenge in terms of physical size
- Symmetric waveguide stubs with coaxial couplers used for RF couplers both input and HOM

Frequency	Cavities		$V_t$ [MV]	
	HSR	ESR	HSR	ESR
197 MHz	8/4	-	33.8	-
394 MHz	4/4	2/2	4.75	2.9



EIC conceptual design report;  
S. de Silva, B. Xiao, private communication

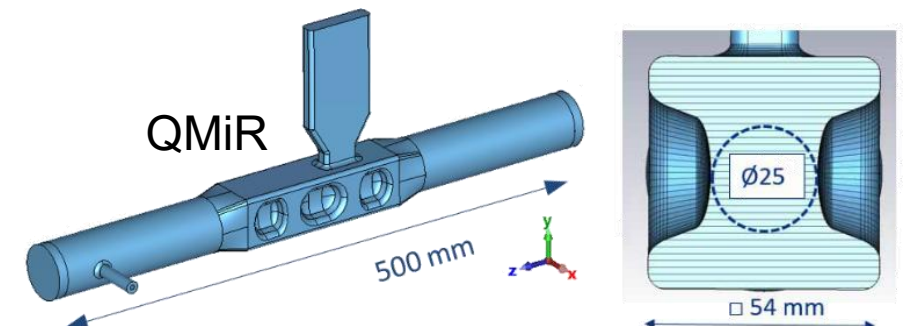
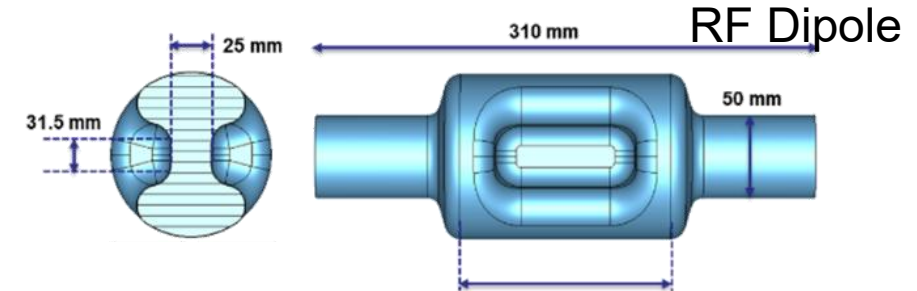
# ILC Crab Cavities

- ILC\* will require crab cavities to efficiently collide the beams (80 % or more luminosity) at different center-of-mass energies
- The first proposal was a multi-cell  $TM_{110}$  elliptical cavity at 3.9 GHz. This concept was later superseded by two new designs (RF dipole & QMiR type) under new collaborations
- Vertical offsets at the nano-meter level due to wakefields, alignment & RF noise will be a critical challenge

3.9 GHz, 13-cell  $TM_{110}$  Cavity



C. Adolphsen et al., ILC-CC TDR



P. McIntosh et al., SRF 2023

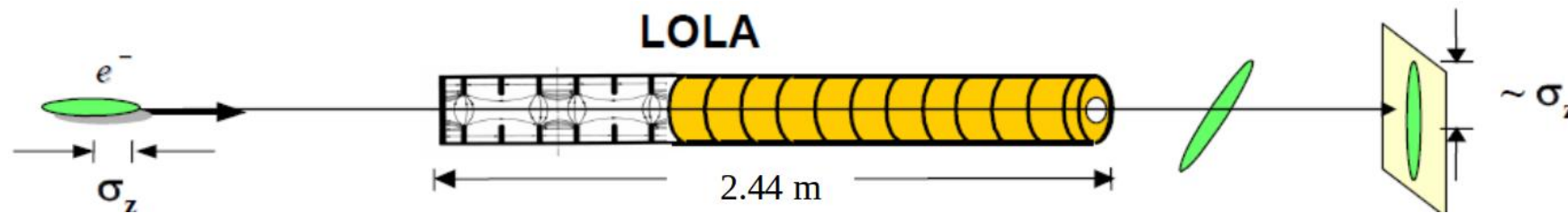
\* CLIC to use X-band technology

# Beam Diagnostics



# Beam Diagnostics

- Early bunch length diagnostics for very short bunches (10's fs) were made possible with transverse deflecting structures to map the longitudinal to the transverse and screen downstream
- S-band deflecting structures at 2.85 GHz, also known as the LOLA deflectors with disc loaded waveguides with precise holes to fix the polarization of  $TM_{110}$
- Used in FLASH-DESY, ECHO-7 at SLAC, LCLS



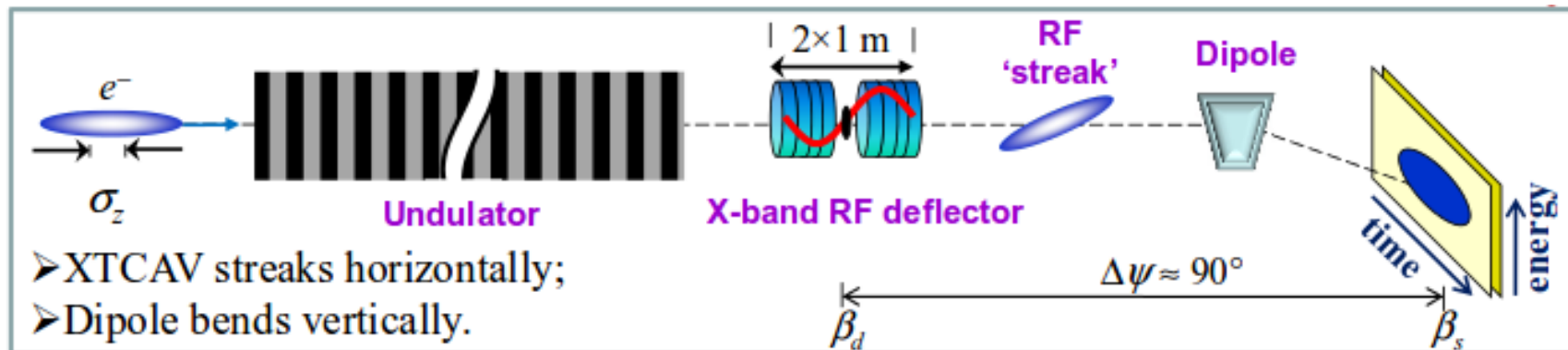
$$\sigma_z \approx \frac{\sigma_x E_0}{kV_{\perp} R_{12}}$$

P. Emma et al., LCLS-TN-00-12

# Beam Diagnostics

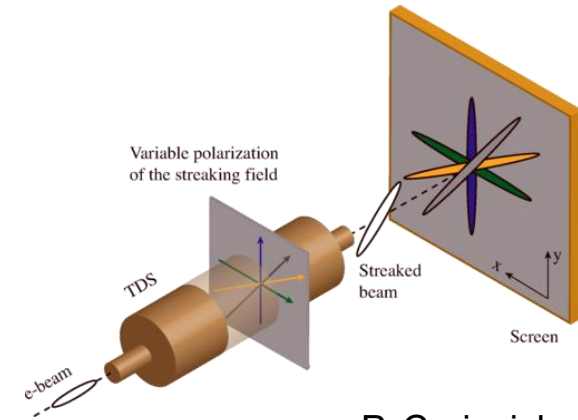
- Femto second longitudinal diagnostics for FELs required to go to X-band frequencies (11.45 GHz)
- Energy loss scan for measuring x-ray pulse as a function of time. A dipole “spectrometer” translates energy into a transverse coordinate
- Time jitter & temporal diagnostics for ultra-short bunches

P. Krejcik et al., IBIC2013

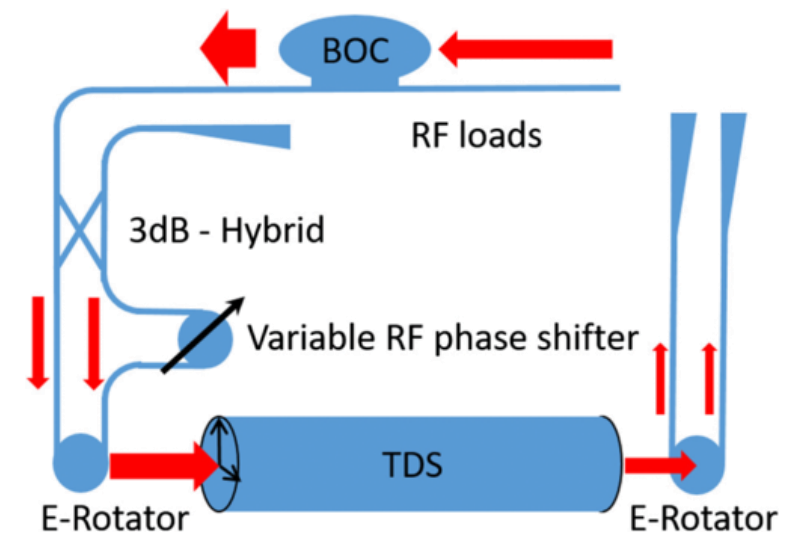


# Beam Diagnostics

- X-band transverse deflecting structures with an azimuthally variable kick and projected to a screen downstream – PolariX for a 6D phase space characterization
- A novel RF transmission line with a proper phase shift is implemented to drive the two degenerate modes  $TM_{110}$  modes
- Such a system was successfully implemented at DESY and PSI

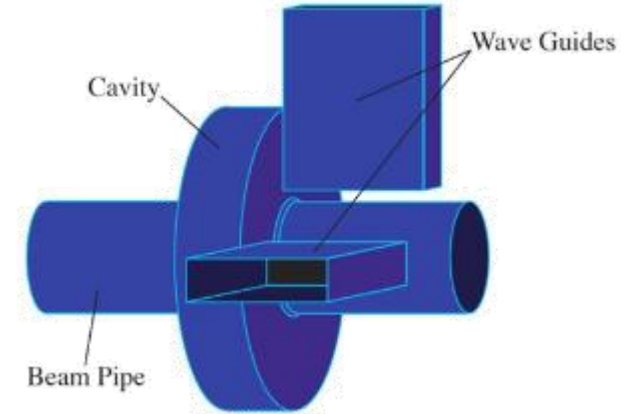


P. Craievich et al., Phys. Rev. Accel. Beams **23**, 112001

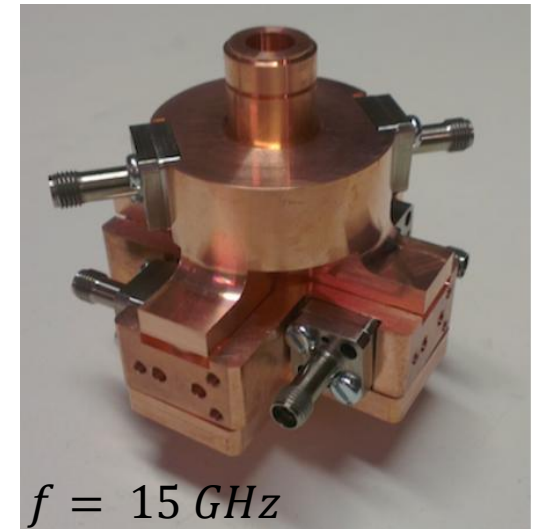


# Beam Diagnostics

- Deflecting cavities offer a unique possibility to directly measure the the transverse offset of the beam from the induced voltage
- Waveguides with chosen polarizations are used to couple mainly to the  $TM_{110}$  dipole mode to measure the induced voltage
- Such systems were proposed (ex: CLIC, ILC) and implemented to reach resolutions of  $10's\ nm$  in single shot



J. Towler, IBIC2015



# Final Comments

- Deflecting and crab cavities have come a long way over the many any decades
- In the recent past, significant advancements towards high field dipole cavities has opened a new dimension to extend the discovery potential of particle accelerators

# Questions ?

