Transverse Deflecting Cavities - to Crab or not to Crab

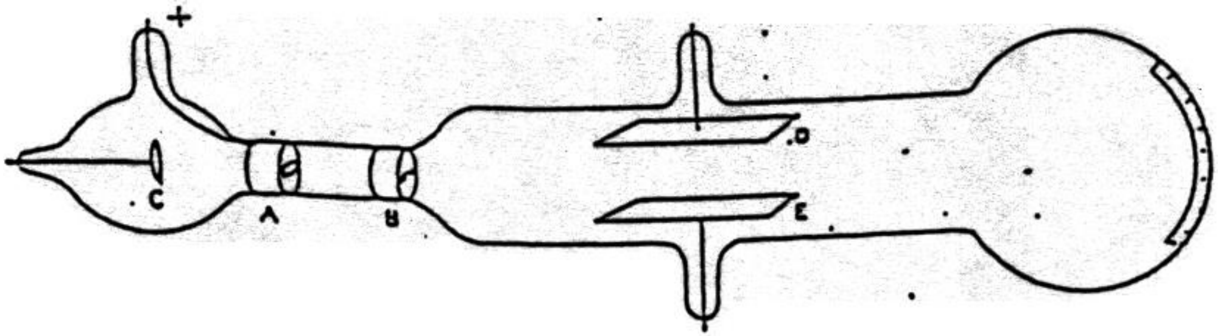
Andrew Hutton

Jefferson Lab

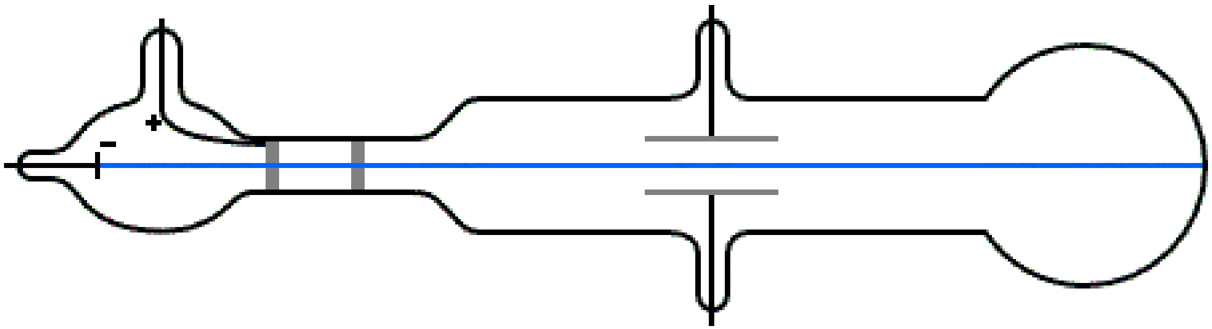
Outline

- RF Separators
  - Early work at SLAC, CERN
  - CEBAF room temperature separators
  - CEBAF SRF dipole separator prototype (ODU)
- Crab cavities
  - Crab Crossing
  - KEK implementation
  - LHC – Cockcroft, BNL, ODU
- What’s next for transverse deflecting cavities?
  - Crab Cavities
  - Short Pulse Cavities for APS
  - Diagnostics
  - Harmonic kicker
  - ERL Merger

J. J. Thomson 1897



Thomson's illustration of the Crookes tube by which he observed the deflection of cathode rays by an electric field (and later measured their mass-to-charge ratio). Cathode rays were emitted from the cathode C, passed through slits A (the anode) and B (grounded), then through the electric field generated between plates D and E, finally impacting the surface at the far end.



First RF Separator Idea 1956

- Pief Panosky proposed using a cylindrical cavity for velocity separation of particles:

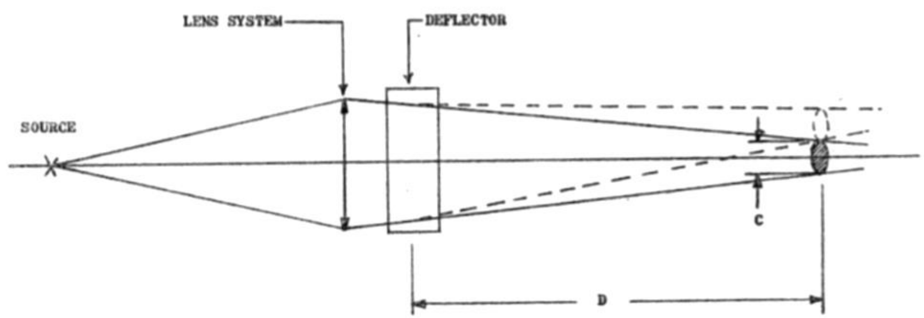


FIG. 4.— Geometrical disposition of mass-sensitive deflector for continuous source.

- There is an interesting comment at the end of the paper
  - "The devices discussed here were originally proposed to use cavities operated in a TE mode. When it was realized that the deflection in a TE mode would vanish identically, W. A. Wenzel proposed the use of the TM modes discussed here"
- All transverse deflecting cavities use either TM modes or, more recently, TEM modes

NOT

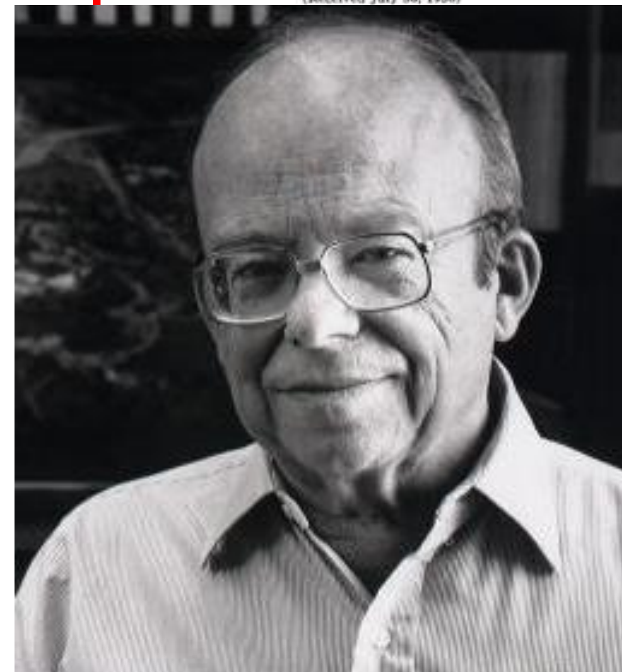
Some Considerations Concerning the Transverse Deflection of Charged Particles in Radio-Frequency Fields

W. K. H. Panofsky,* High-Energy Physics Laboratory and Department of Physics, Stanford University, Stanford, California

AND

W. A. Wenzel,† Radiation Laboratory, University of California, Berkeley, California

(Received July 30, 1956)



where n is an integer. These quantities are related by the usual equation

$$k_c^2 = k_0^2 - k_g^2. \quad (5)$$

We thus have:

for all TE modes,

$$p_\perp = 0; \quad (6)$$

for TM modes,

$$p_\perp = \frac{e}{c}\frac{k_c^2}{k_0 k_g}\int_0^d E_\perp\left(z, t_0+\frac{z}{v}\right)dz = \left(\frac{k_0}{k_g}-\frac{k_g}{k_0}\right)\frac{e}{c}\int_0^d E_\perp\left(z, t_0+\frac{z}{v}\right)dz, \quad (7)$$

where t_0 is the starting time and $E_\perp(z,t)$ gives the dependence of the transverse electric field on axial distance and time.

Hence we find very generally that in a TE mode the deflecting impulse of the magnetic field always cancels the impulse of the electric field, while in a TM mode it multiplies the electric impulse by a factor independent of the velocity.

* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
† Supported by the U. S. Atomic Energy Commission.

RF Separator Development at CERN 1963

- This idea was developed at CERN by M. Bell, P. Bramham, R. D. Fortune, E. Keil and B. W. Montague (1963) and was operational in 1965

THE CERN RADIO FREQUENCY PARTICLE SEPARATOR - FIRST OPERATION

P. BRAMHAM, R. D. FORTUNE, E. KEIL, H. LENGELER, B. W. MONTAGUE
CERN, Geneva

and

W. W. NEALE
Imperial College, London

Received 3 March 1965

This gives me the opportunity to acknowledge Bryan Montague, my teacher, mentor and friend when I came to CERN

- An excellent scientist
- A wonderful person
- A whimsical sense of humor

First RF Separator Installation CERN 1965

- RF Particle Separator used transverse deflecting fields for velocity selection
  - In this case, kaons were separated from pions for bubble chamber studies

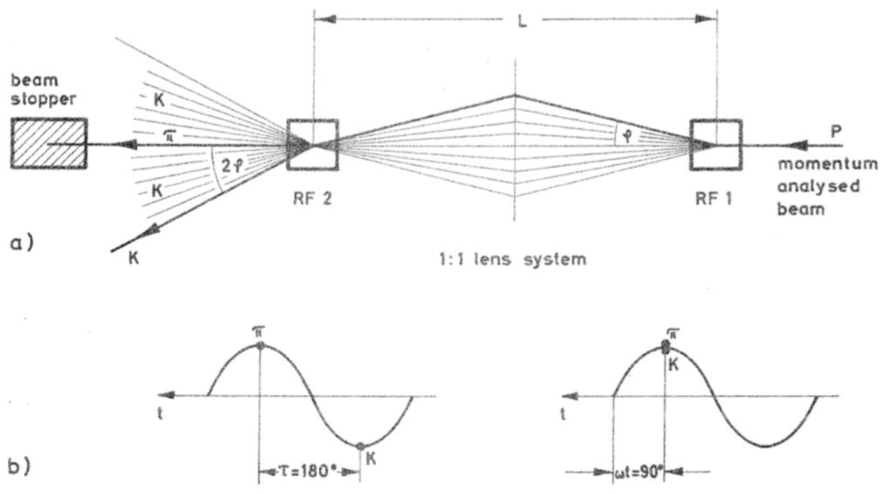
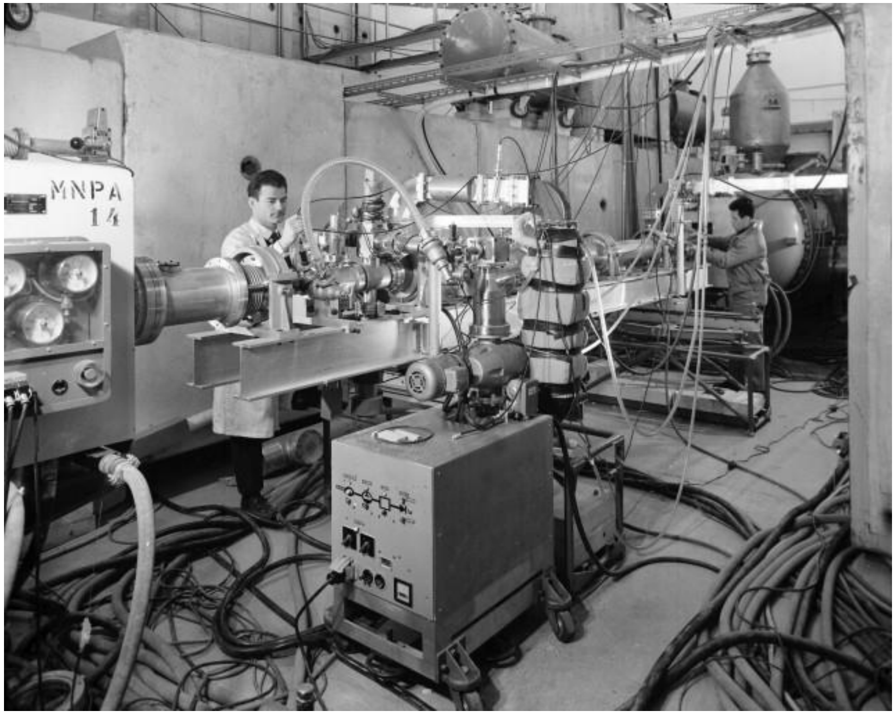


Fig. 1a: Principles of operation of RF-Separator
1b: Phase relations of two particles of different rest-mass with respect to travelling wave



RF Beam Separation

- CEBAF needed separation of beams
  - Christoph Leeman invented the concept of 4-rod RF separators in 1990
  - Used successfully in CEBAF for over 25 years

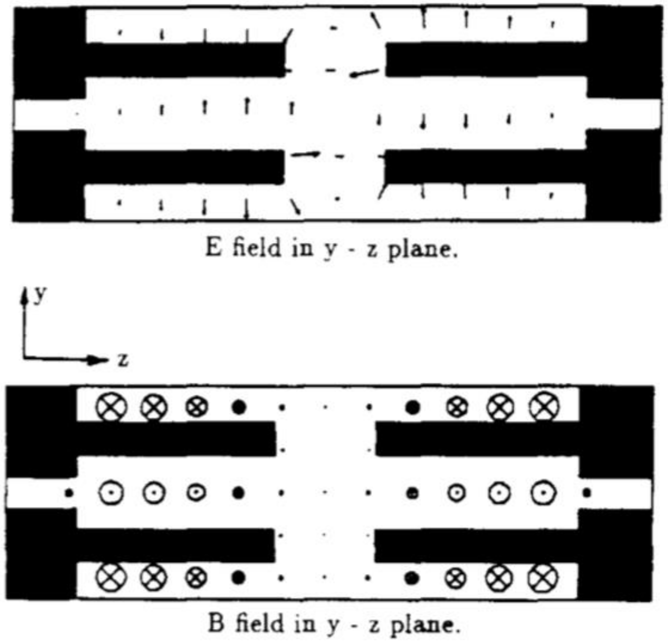
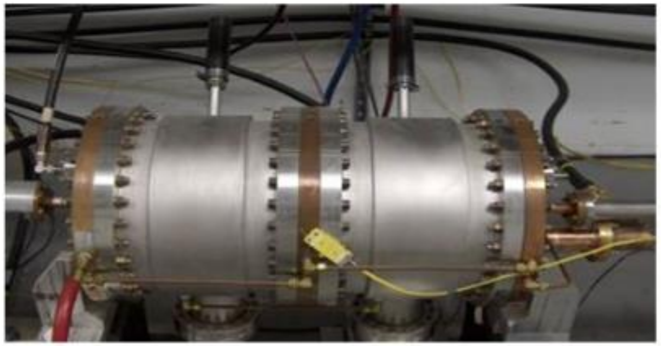


Figure 6. Field patterns in a half-wavelength cavity.

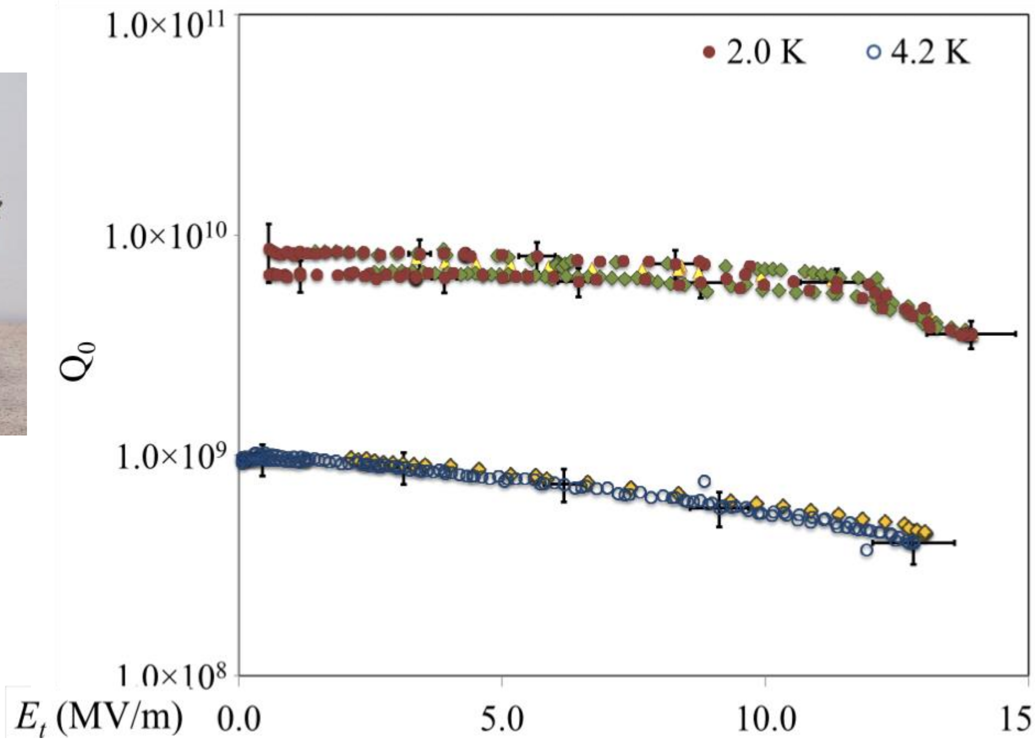


CEBAF separator cavity

CEBAF SRF Dipole Separator Prototype

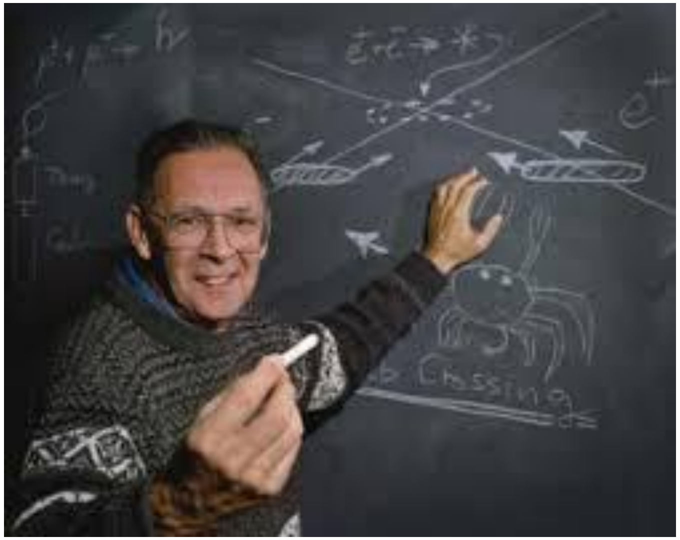
- In 2013, Jean Delayen developed a superconducting RF separator for CEBAF 12 GeV Upgrade
  - Prototype was developed successfully
  - Not installed (delivering liquid Helium to the area was judged too expensive)
  - An RF version of J.J. Thomson's dipole

J. Delayen, S. de Silva, HK Park, ODU



Crab Cavities

- Idea first proposed by Bob Palmer in 1988
- Used in almost every collider design study since then



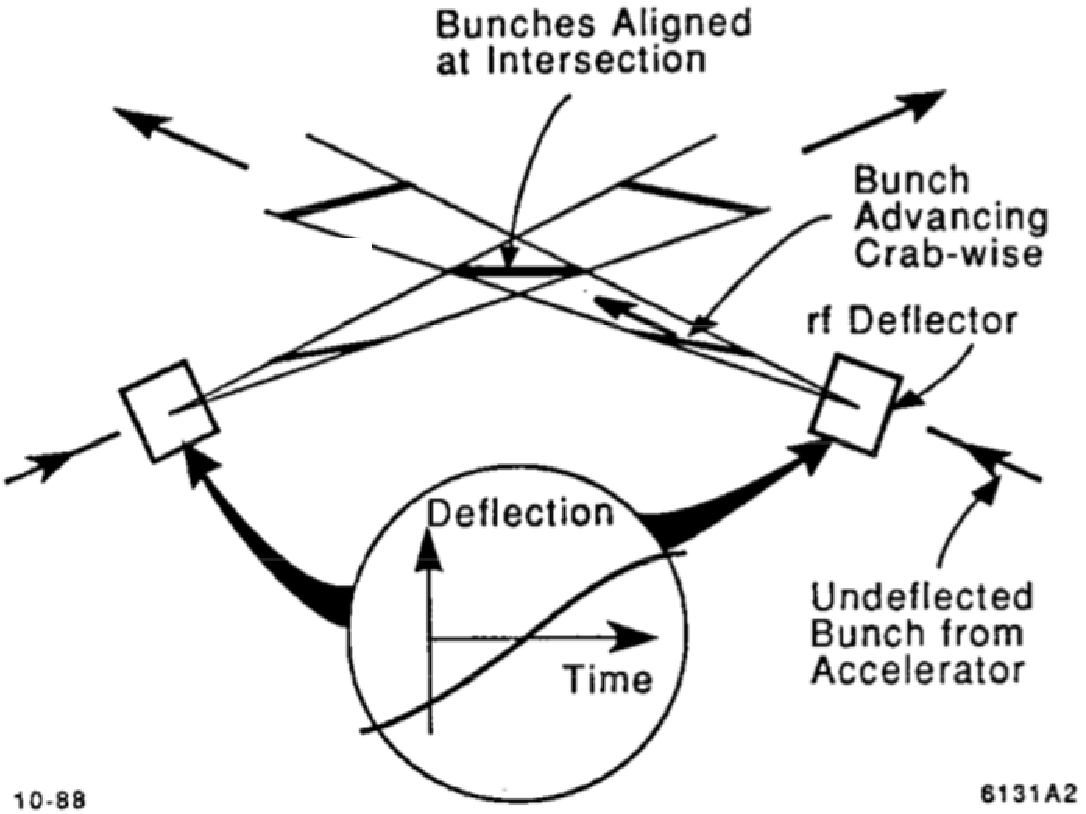


Fig. 2. Crab-wise crossing.

SLAC-PUB-4707
December 1988

Crab cavity operation in KEKB

- First crab cavity operation was conducted in KEKB in 2007. Since then KEKB was operated for physics run with crab crossing until shutdown in June 2010.
- Two heavily-damped superconducting crab cavities were operated stably with high current beams up to 1.7 A in the electron ring (LER) and 1.35 A in the positron ring (HER).
- The specific luminosity per bunch with the crab on was about 20% higher than that with the crab off.
- This gain in luminosity is higher than that obtained from recovery of geometrical loss, although lower than that predicted by beam-beam simulation.

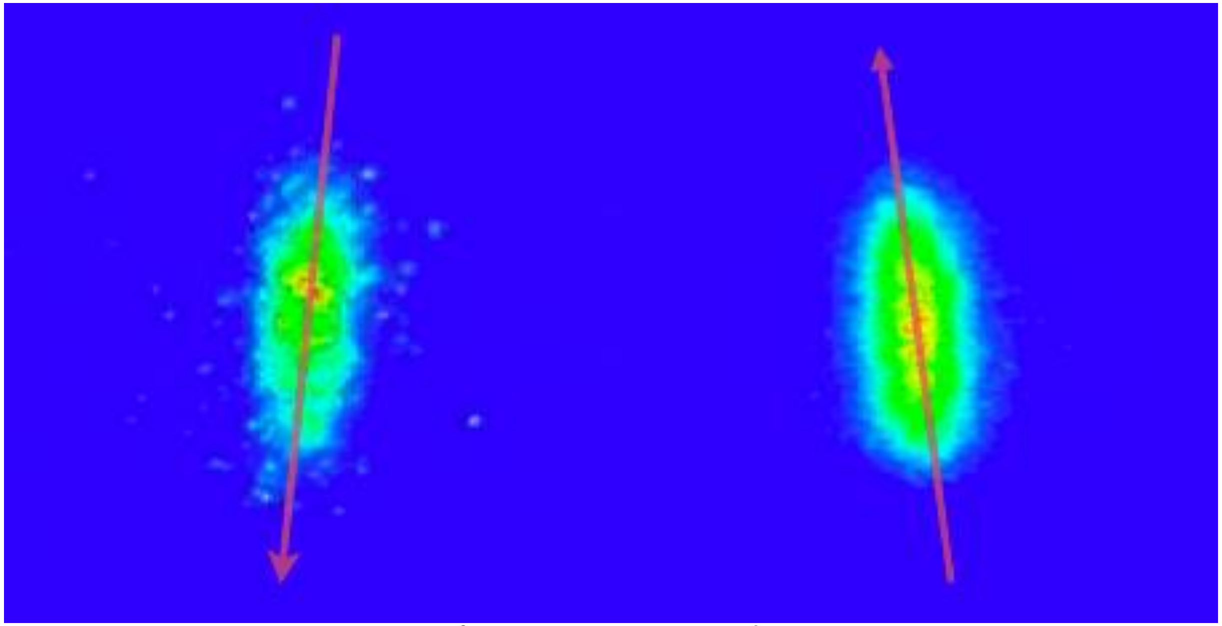
Beam was indeed tilted!

Observation with Streak Cameras (H. Ikeda et al)

inside of the rings

outside of the rings

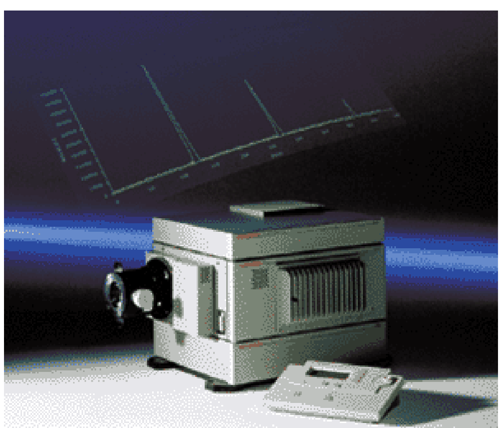
longitudinal



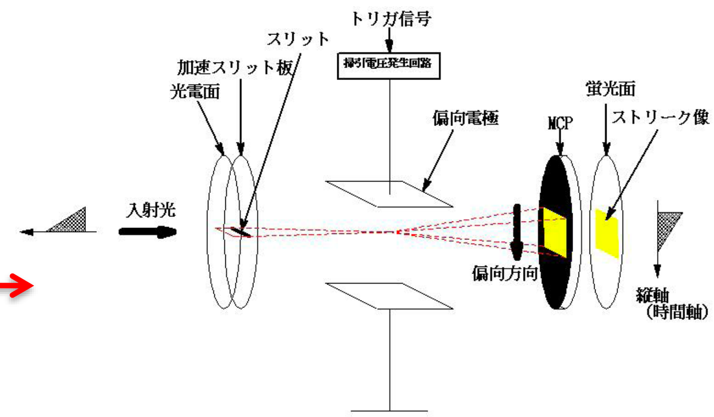
LER

horizontal

HER



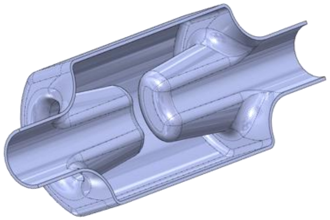
The streak camera

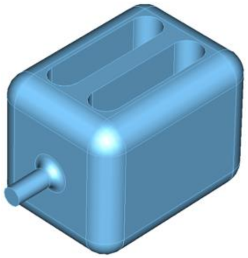


Kazunori Akai, KEK

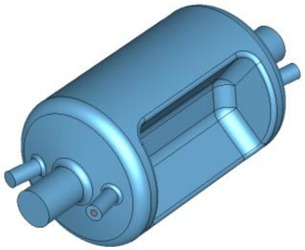
Geometries and Concepts for HL-LHC

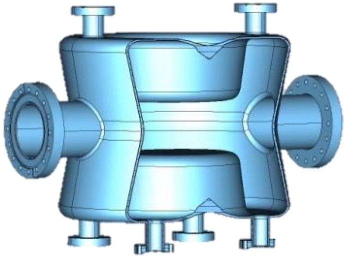
- Cavities operating in "TEM-like" modes
  - 4-rod cavity
    - 4 quarter-wave resonators (deflection from both E and H)
  - Parallel-bar
    - 2 half-wave resonators (deflection from E)
    - Evolved into RF-dipole

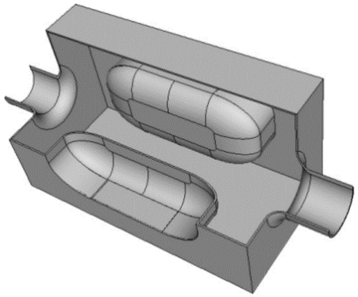




- Cavities operating in "TE-like" mode (cannot be pure TE)
  - RF-dipole
  - Double quarter-wave
  - Ridged waveguide







Jean Delayen, ODU and JLab

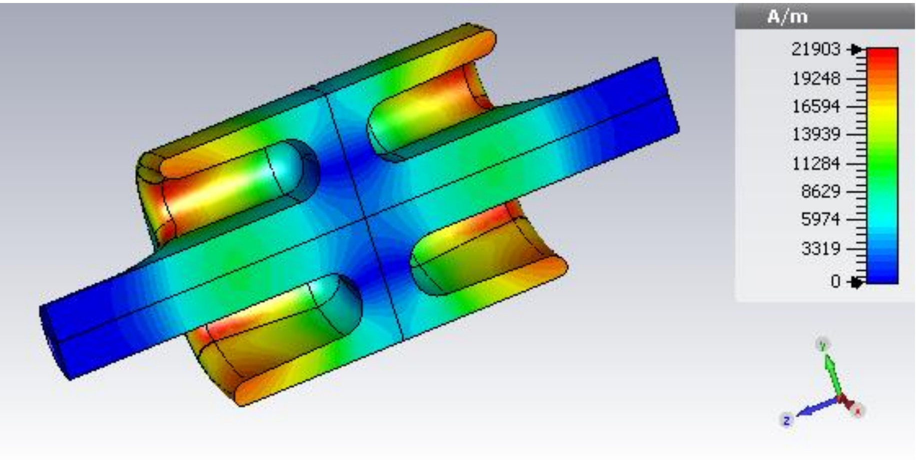
4R crab cavity – Cockcroft - JLab

We increased the separation between the rods and made the rods wider

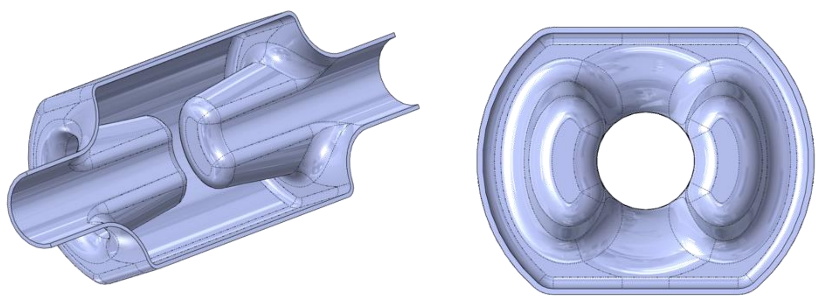
This allowed lower peak fields, made the rods stiffer to microphonics, and allowed better cooling of the tips

An added benefit was that the multipole components (sextupole) became close to zero

This meant they were close to the outer can which brought the monopole mode closer in frequency

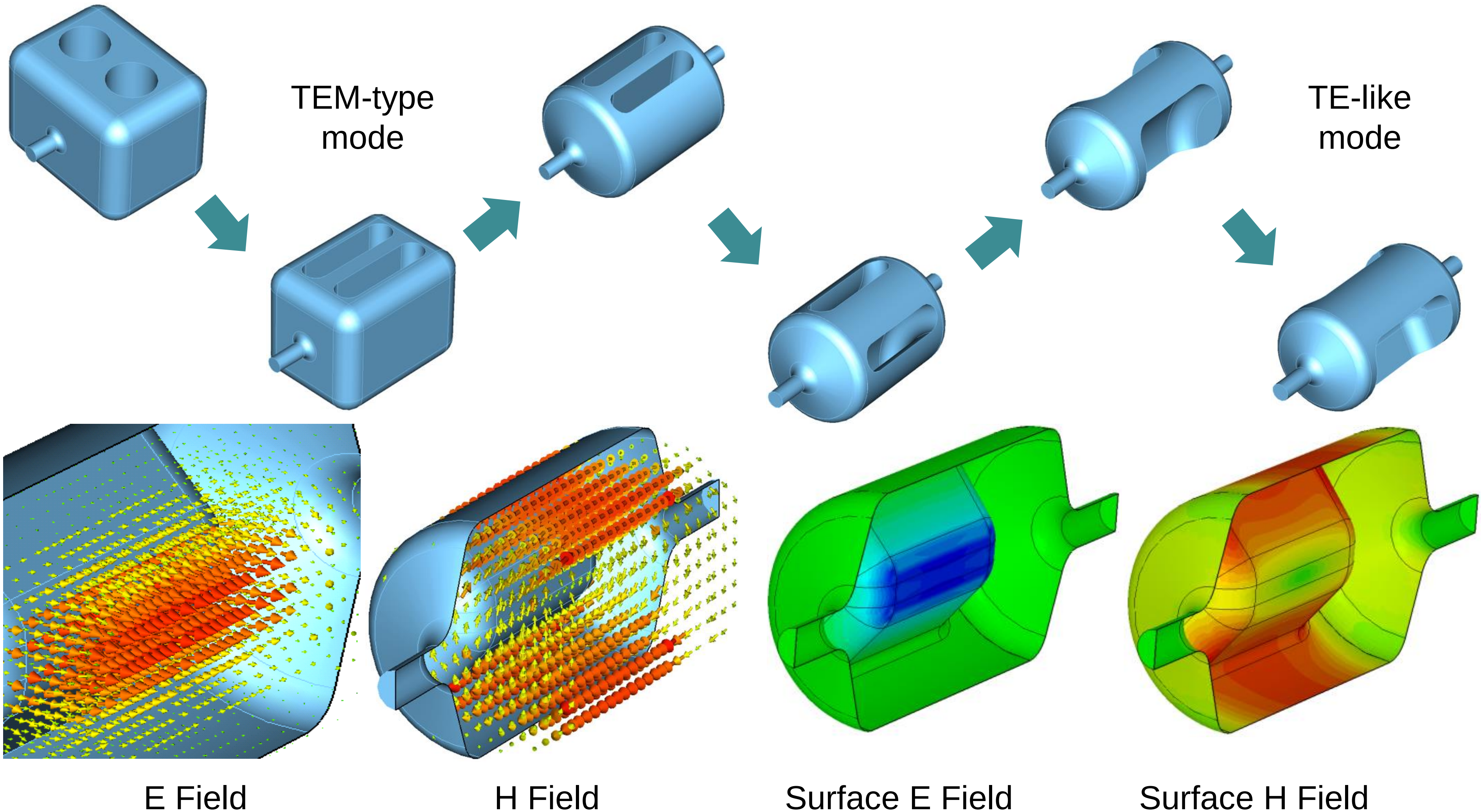


B field



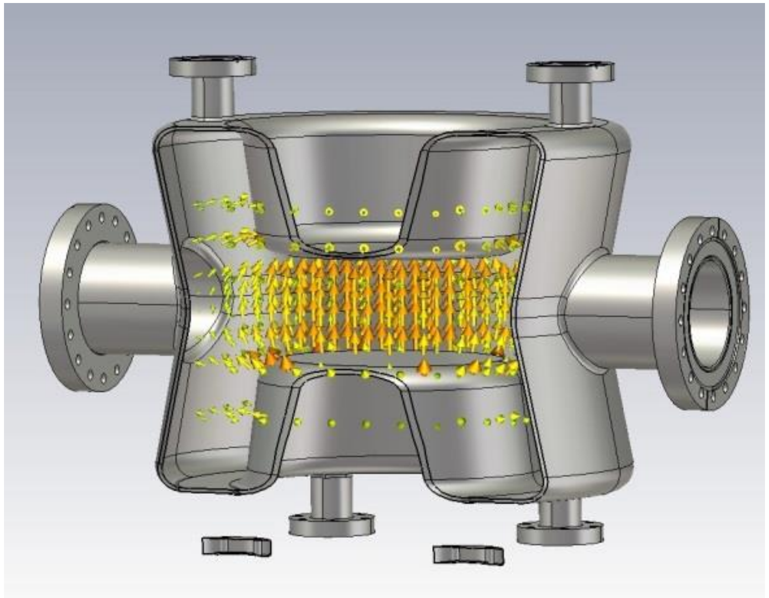
Emax @3.4MV	32.7 MV/m
Bmax @3.4MV	77.5 mT
Transverse R/Q	580 Ohms

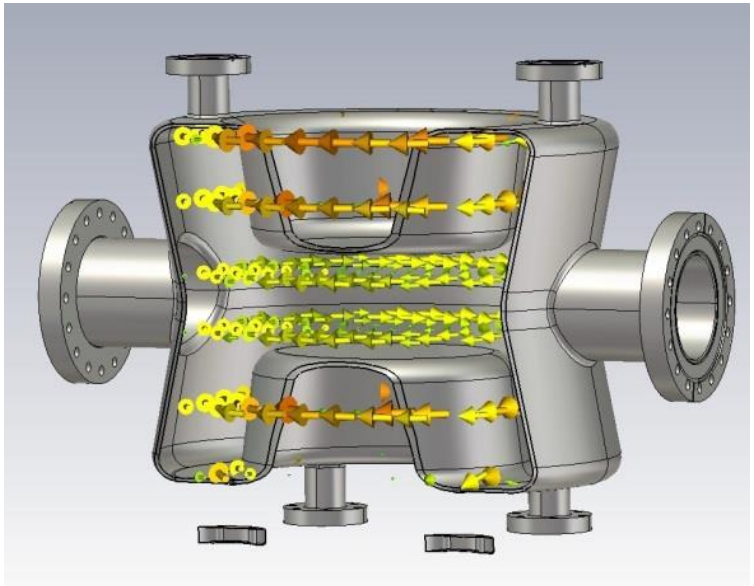
Parallel-Bar Cavity to RF-Dipole Cavity (ODU)



S. U De Silva and J. R. Delayen, "Design evolution and properties of superconducting parallel-bar rf-dipole deflecting and crabbing cavities, PRSTAB 16, 012004 (2013)
S. U. De Silva, PhD thesis, ODU 2014

The Double Quarter Wave Cavity





Electric field (left) and magnetic field (right) of the fundamental mode

B. Xiao et al, PRSTAB 18, 041004 (2015)

BROOKHAVEN NATIONAL LABORATORY

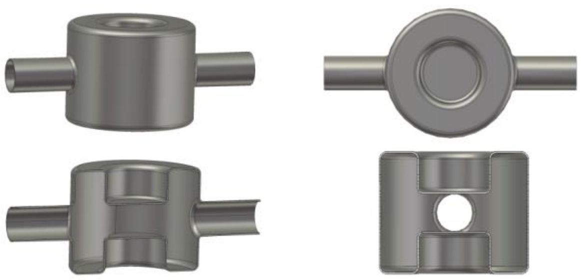
High Luminosity LHC

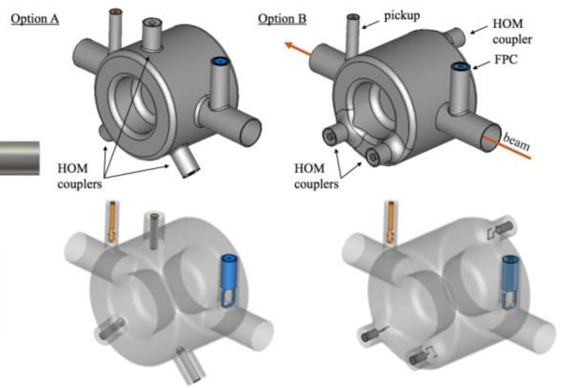
What's next for Deflecting Cavities?

- Crab Cavities
- Short Pulse Cavities for APS
- Diagnostics
- Harmonic kicker
- ERL Merger

Double Quarter Wave Crab Cavity for eRHIC

	LHC - HL	Ring - Ring eRHIC (with cooling)	
	p-p	proton	electron
Full Crossing Angle (mrad)	0.59	22	22
Energy (GeV)	7000	275	18
rms Bunch length (cm)	7	7	1.7
Ave. Current (A)	1.09	0.81	0.26
Frequency (MHz)	400	338	338
Scheme	Vertical/Local	Horizontal/Local	
beta function @ IP (m)	0.15	0.90	0.51
beta function @ crab cavity (m)	2616	1200	150
Horizontal beam size (um)	7	106	106
Piwinski angle (rad)	2.95	5.19	1.76
Voltage(MV)	12.4	13.0	3.2
Number of cavities per side per IP	4	4	2
Voltage per cavity (MV)	3.1	3.25	1.6
R/Q (Ohm)	426	373	373
Power (kW)	50	40	5
Cavity horizontal full length (m)	0.33	0.16	0.16
Cavity vertical full length (m)	0.29	0.20	0.20
Cavity longitudinal full length (m)	0.35	0.20	0.20





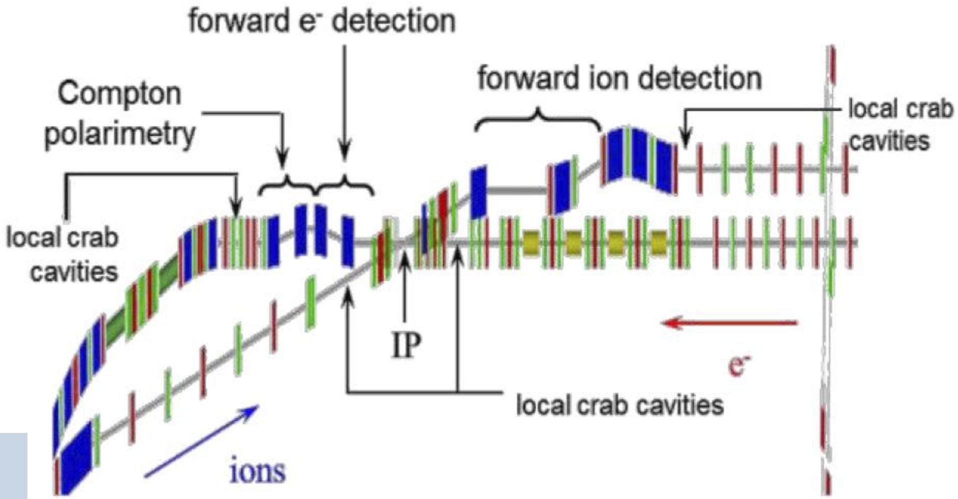
- Simple symmetric design for easy fabrication, effective cleaning and minimum dimensions.
- Power required for cavity is less than HiLumi LHC.
- Tuner, helium vessel, cryomodule can all be adopted from CERN experience.
- With DOE NP R&D funding for the next two years, we are supported for following the entire SPS crab cavity experiments and further analysis with RHIC.

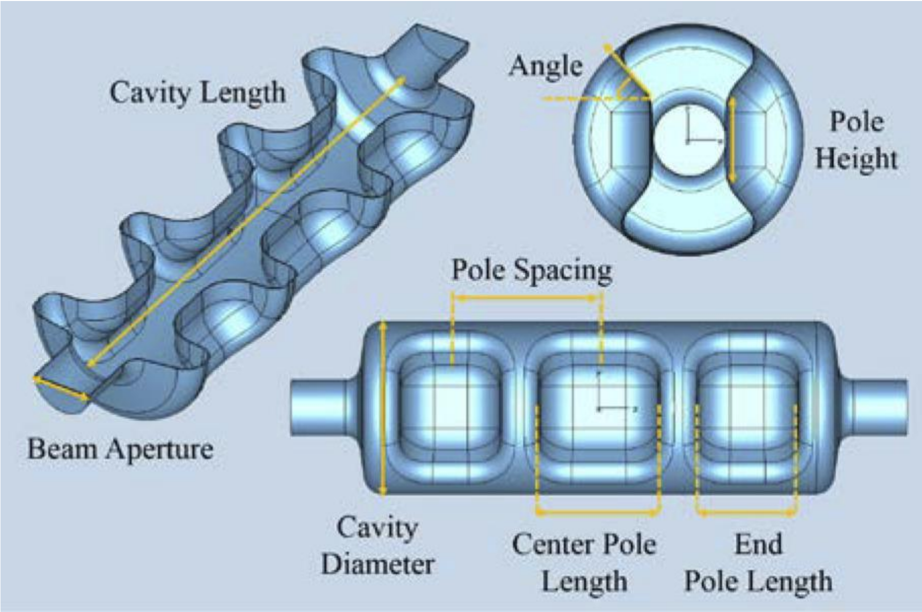
- The higher order mode damping for crab cavity has two options under investigation: electric (option A) and magnetic (option B) coupling.
- The high pass filter will adopt similar concept for HiLumi LHC crab cavity.

Qiong Wu, BNL

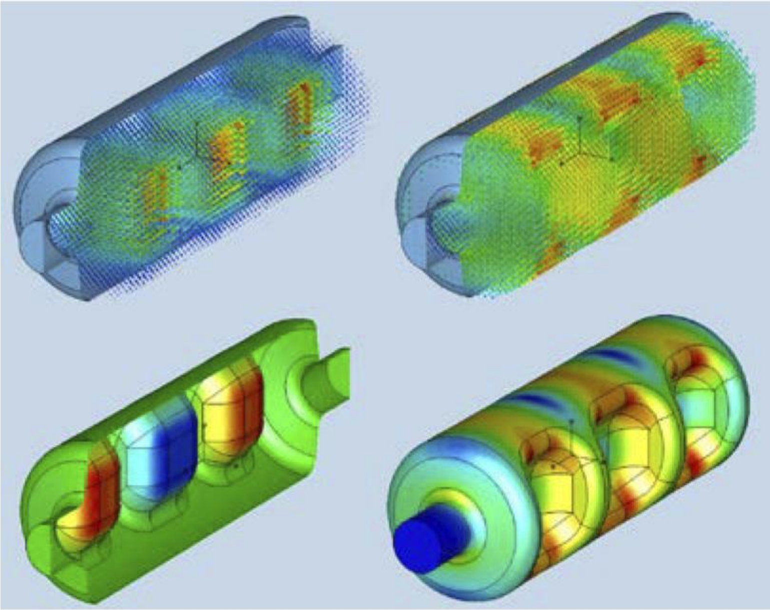
JLEIC Crab Cavity System

- Crab systems are being optimized by ODU and JLab
- Multi-cell cavities are required because of the large crossing angle ±25 mrad
- Frequency is 952 MHz

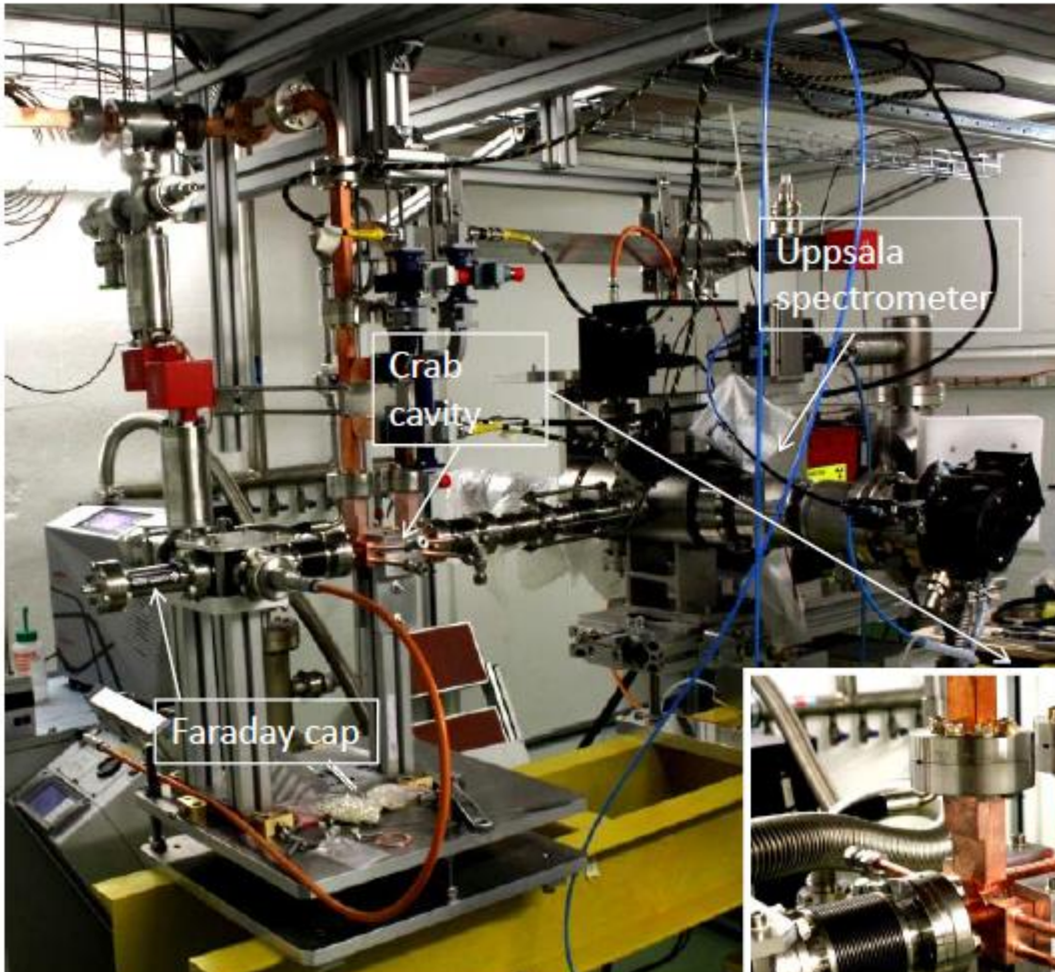




J. Delayen, S. de Silva, HK Park, ODU



CLIC Crab Cavity



- TDC resolution is proportional to frequency x Voltage
- X-band TDC lead to better resolution
- Lancaster's X-band "crab" cavity currently running on XBOX2 to measure the maximum possible transverse gradient

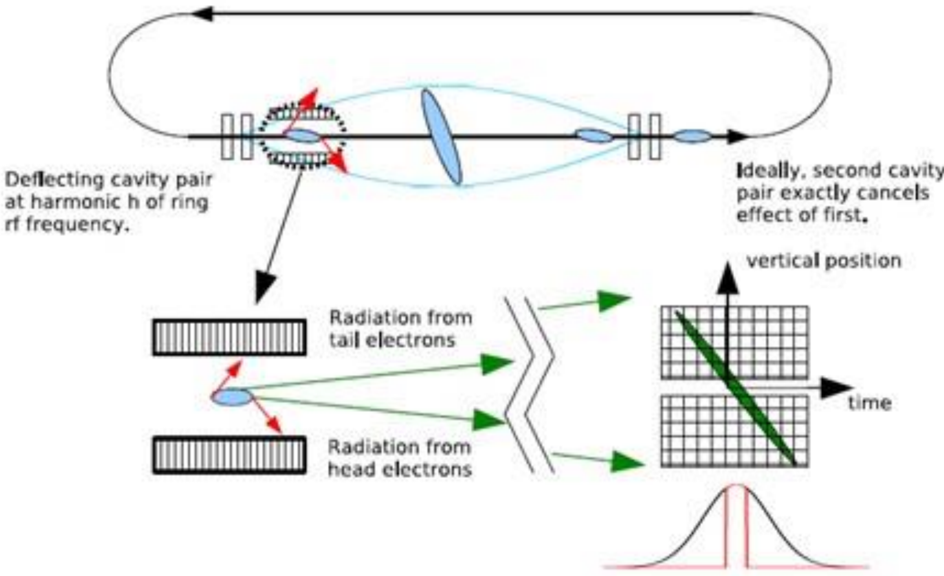
STFC ASTeC

CERN

Graeme Burt, Lancaster University

APS Short Pulse Upgrade

- Bunches are rotated so that the synchrotron radiation pulses are shortened



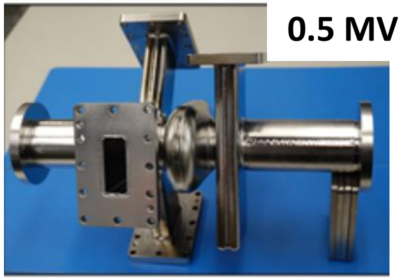
- Requires high frequency (2.815 GHz) crab cavities
- Cavity is small compared to damping for Higher Order Modes (HOM) and Lower Order Modes (LOM)

Fabrication and Testing of Deflecting Cavities for APS
J. Mammosser et al, Proc. SRF2013, Paris, France

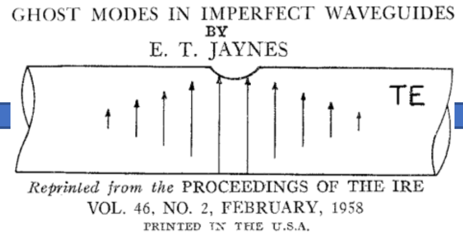
Superconducting Quasi-Waveguide Multicell Resonator (QMiR) for the Advanced Photon Source SPX Project

Original ANL deflecting cavity

0.5 MV kick

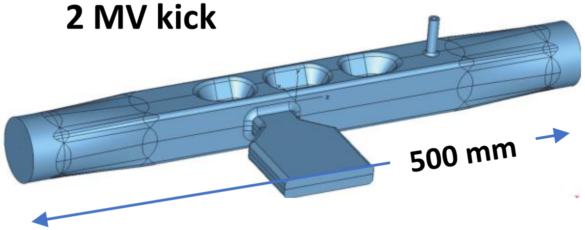


The idea



QMiR deflecting cavity[1,2]

2 MV kick

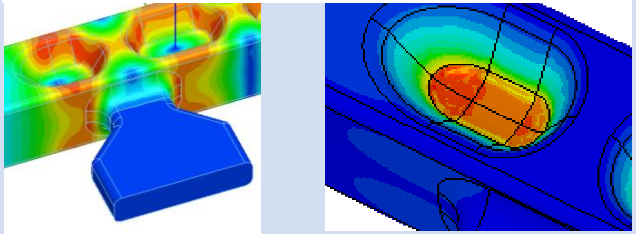


Sparse HOMs spectrum

Freq., [GHz]	R/Q, [Ω]	Q_{ext}
4.304	1.3	55
4.409	39	530
4.471	37	400
4.530	0.35	5900
5.080	132	390
5.114	39	108

Freq	2815 MHz
V_{kick}	2 MV
E_{max}	55 MV/m
B_{max}	76 mT
$(R/Q)_Y$	520 Ω
G	130

Highly optimized surface EM-fields

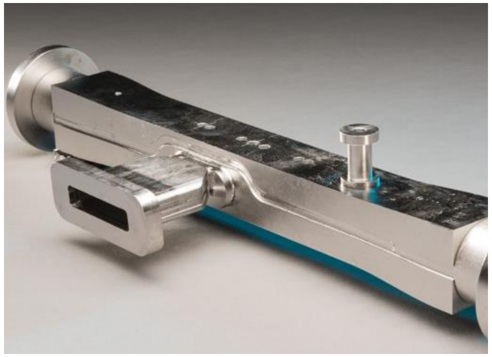


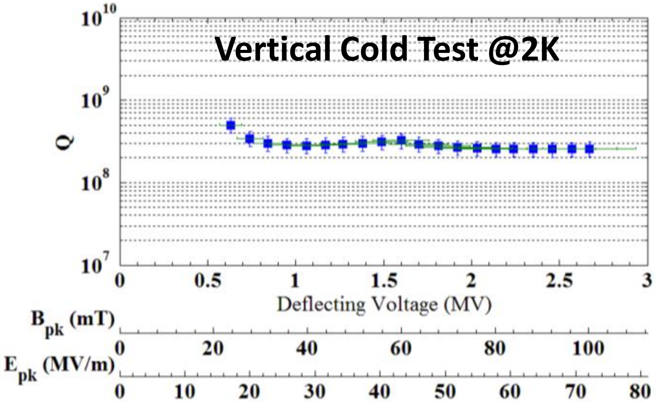
Key Features:

- High efficiency operation
- Compactness
- No need for HOM-couplers!
- Sparse HOM spectrum
- **World record in VTS test:**

2.7 MV kick, no quench, no MP

QMiR Cavity Prototype



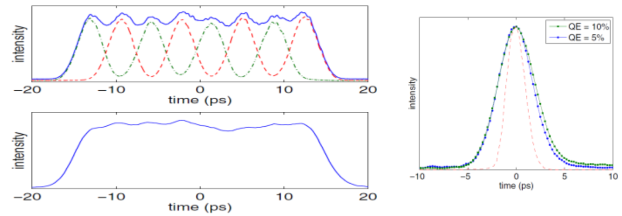


[1] A. Lunin, et. al., Physics Procedia Vol. 79, 54 –62, 2015

[2] Z. Conway, et. al., WEPR050, IPAC14, Dresden, Germany, 2014

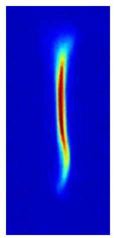
Measure beam temporal profile with TDC

- **L-band**

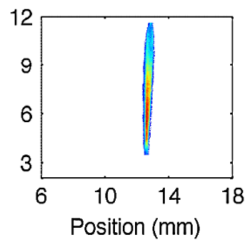


Cornell University

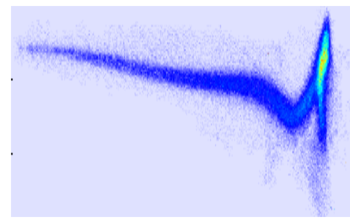
- **S-band**



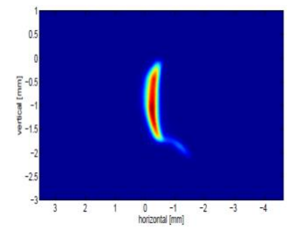
LCLS



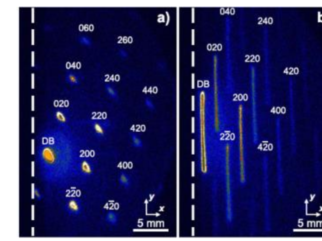
SPARC



FLASH

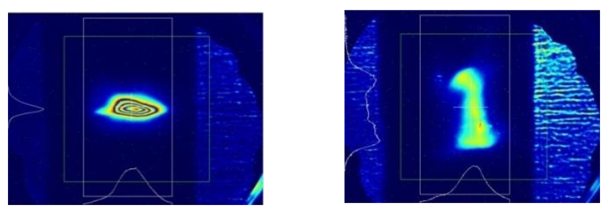


PSI



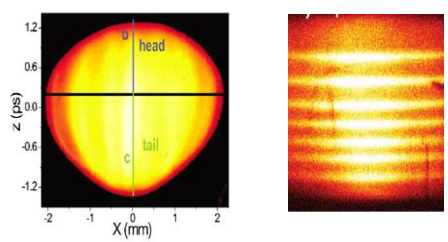
Tsinghua University

- **C-band**

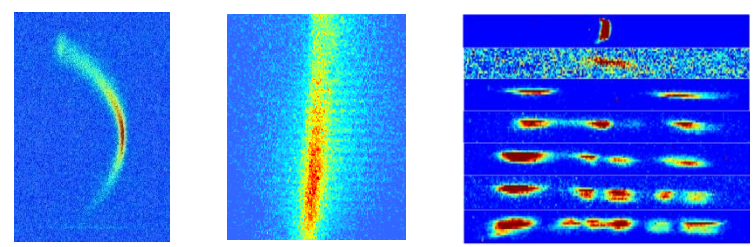


SACLA

- **X-band**



UCLA

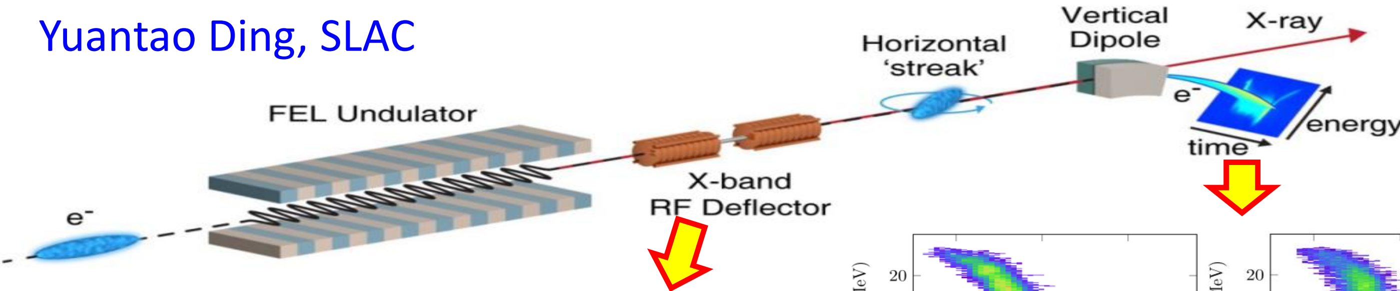


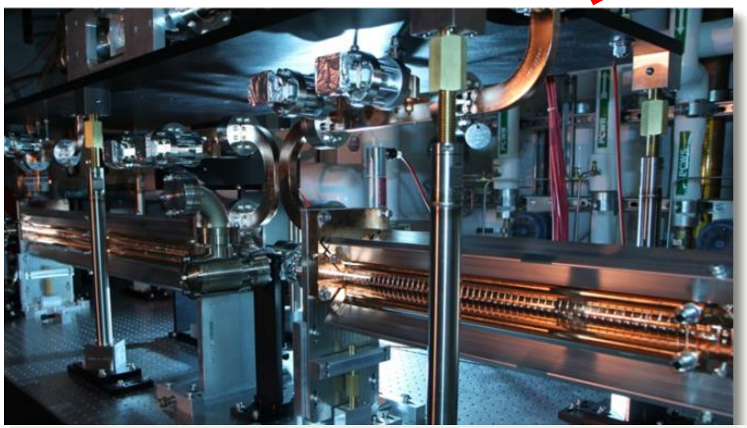
NLCTA, SLAC

Dao Xiang, IPAC12

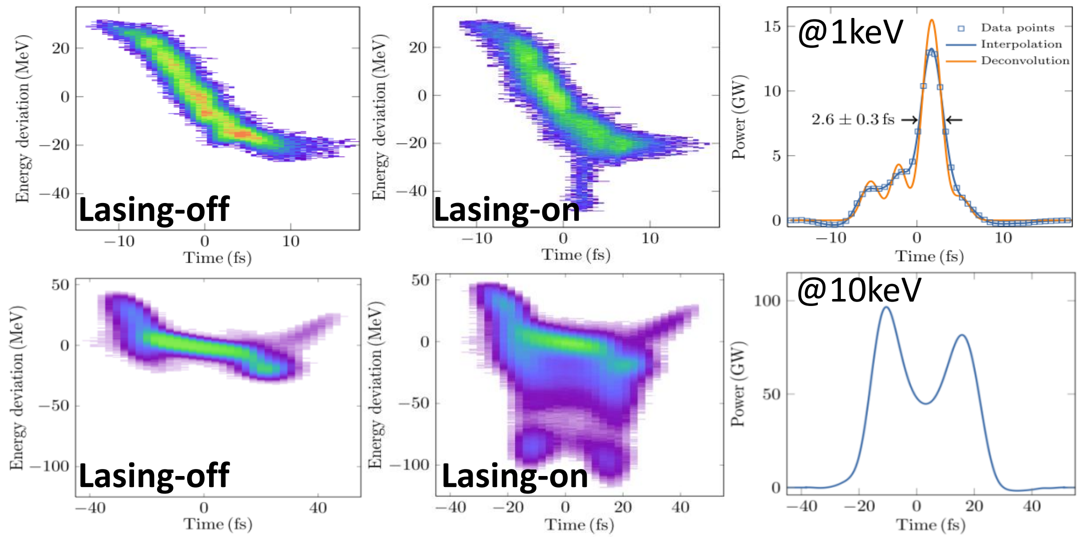
Femtosecond X-ray diagnostics with an X-band radio-frequency transverse deflector at the Linac Coherent Light Source

Yuantao Ding, SLAC





Reconstructed
X-ray profile



Scientific Achievement

X-Band RF accelerator technology developed at SLAC allows us to 'streak' the electron beam and make noninvasive, single-shot time-resolved measurements of lasing footprint with previously unattained **single-femtosecond resolution**.

Significance and Impact

For the first time we can directly measure the x-ray power profile for users, and gain new insight in lasing dynamics.

Research Details

- Electron beam is streaked horizontally and viewed on a screen in a vertically resolved energy spectrometer, revealing time-energy phase space after the undulator.
- The upper plots show an example of an ultra-short soft x-ray pulse with a measured **2.6-fs pulse duration**.
- The lower plots are for hard x-rays revealing a significant double-horned temporal profile with **peak power ~100 GW**.

U.S. DEPARTMENT OF ENERGY | Office of Science

Work was performed at the Linac Coherent Light Source, SLAC.
Published in ***Nature Communications 5, 3762 (2014)***.

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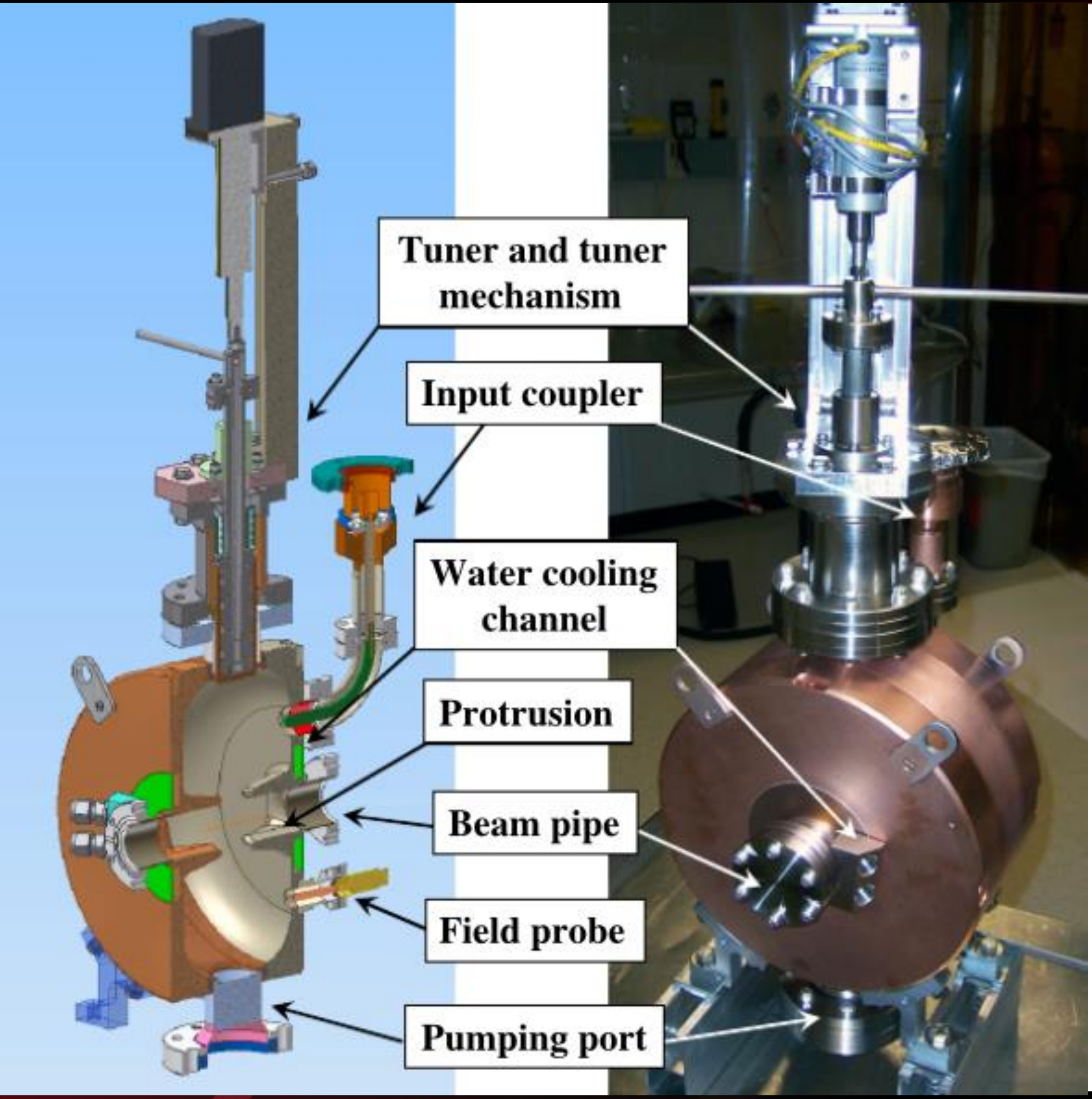
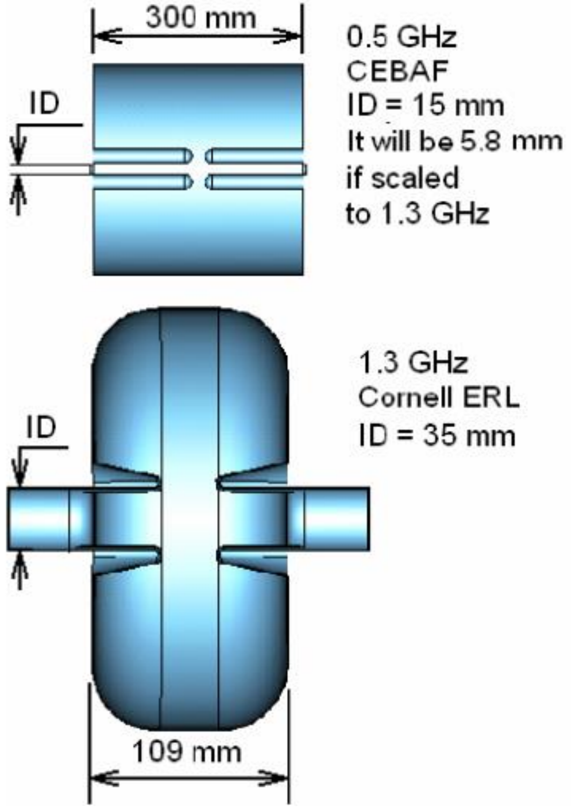
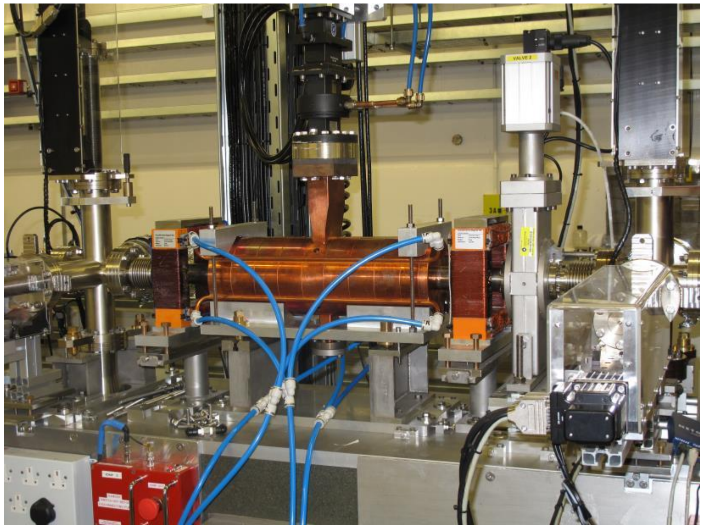
Cornell RF Separator Cavity



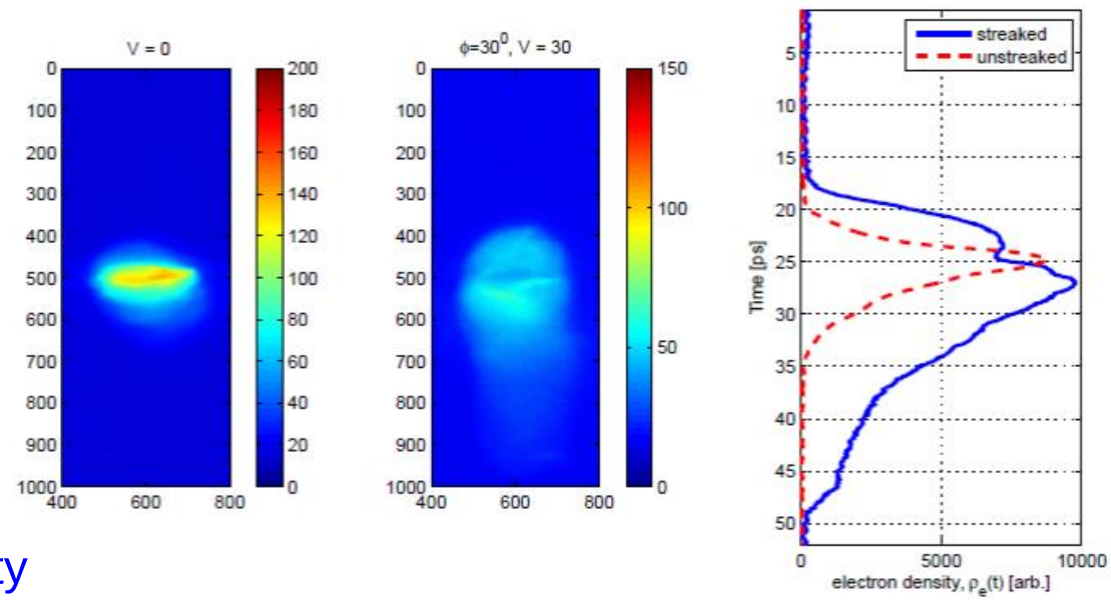


https://www.classe.cornell.edu/rsrc/Home/Research/SRF/2010/Deflecting_cavity.pdf

TDC @ VELA

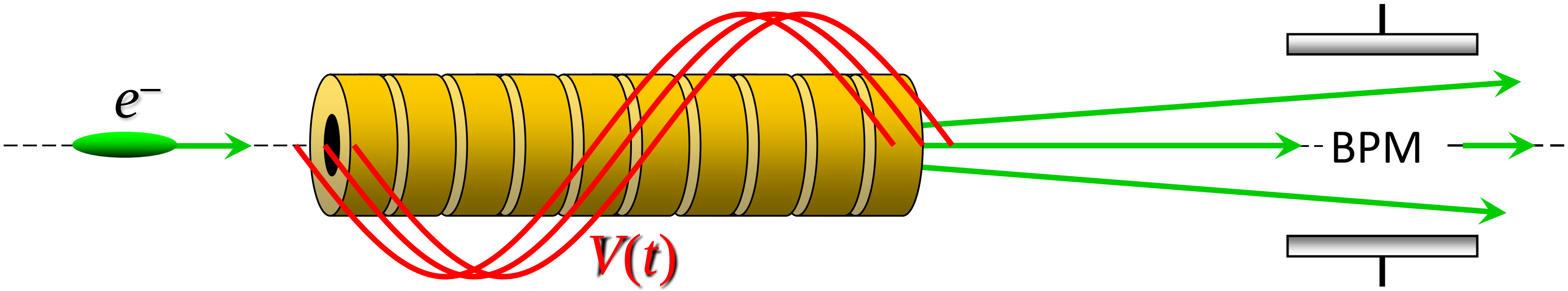


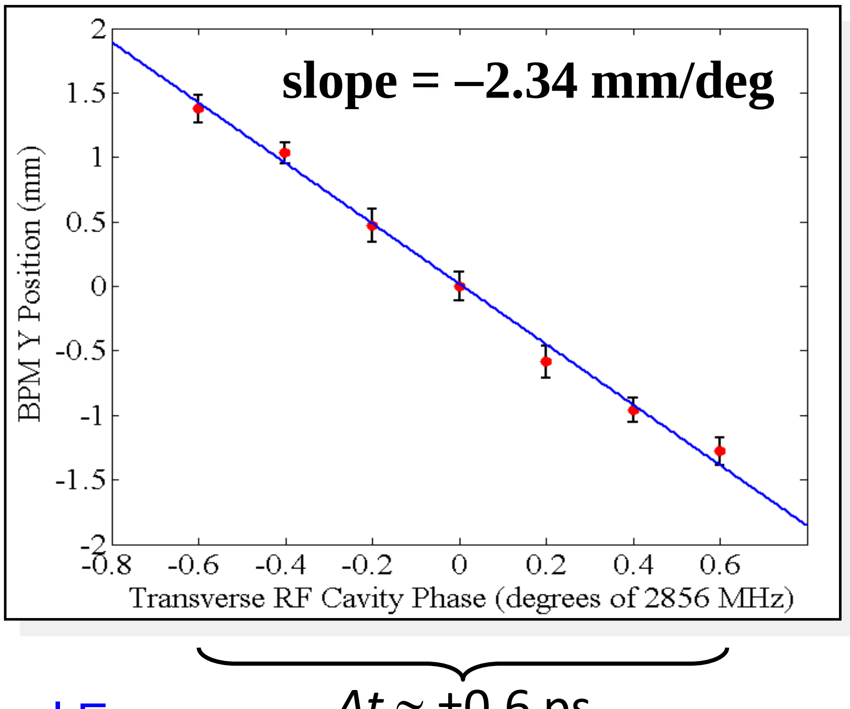
- S-band Transverse Deflecting Cavity designed by Lancaster University and ASTeC installed at VELA
- Will allow much more detailed diagnosis of bunches (slice properties, bunch length with femtosecond resolution)



Graeme Burt, Lancaster University

Measuring Bunch Arrival Time Jitter (LCLS)





- We can also use two cavities to measure phase synchronisation between two RF sources
- If we have two cavities in anti-phase the transverse kick's will cancel out
- Any phase error between the two cavities will result in a transverse momentum
- This can be used to accurately measure synchronisation systems required for FELs

Paul Emma

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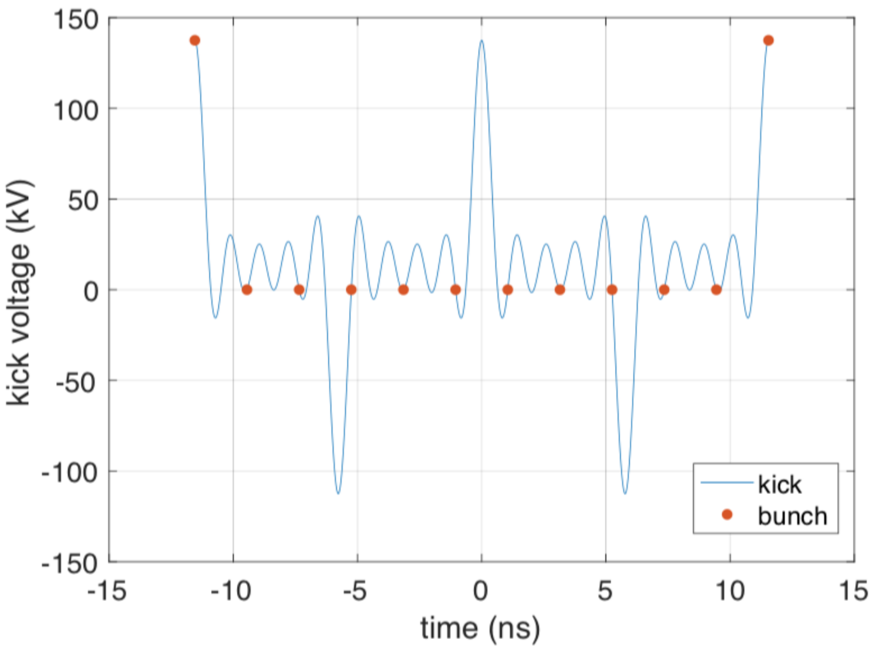
Note similarity with RF particle separator

Electron Cooling for JLEIC

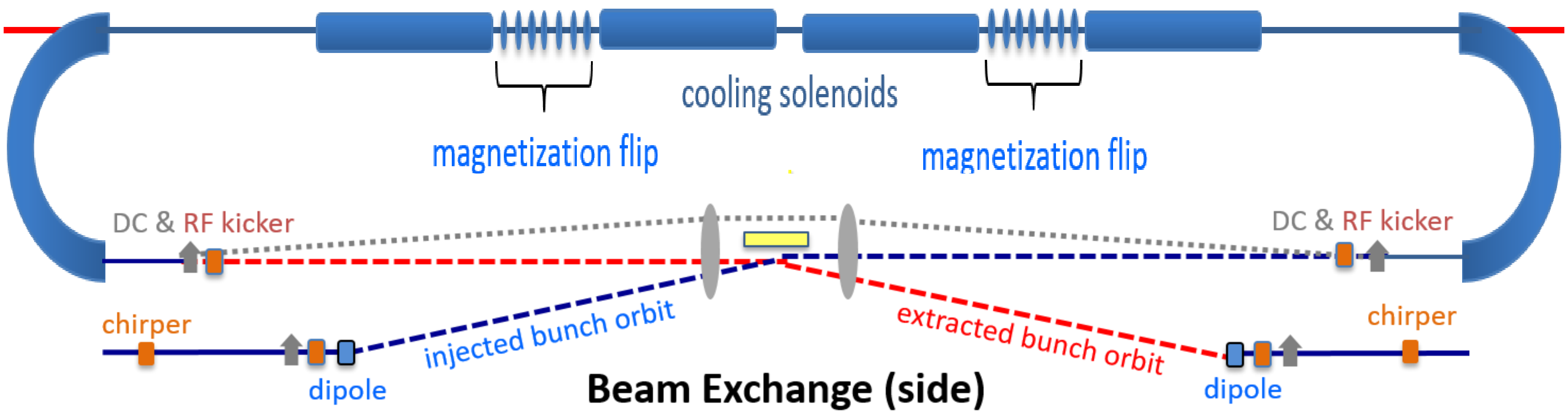
- Electron cooling of the high-energy ion beams in JLEIC is required to maintain small emittance
  - Energy too high for DC cooling – means an Energy Recovery Linac
  - Current is too high for an electron gun ~1 Amp
  - Use a Cooler Circulator ring to re-use electrons 11 times
  - Use kicker to exchange every 11th bunch

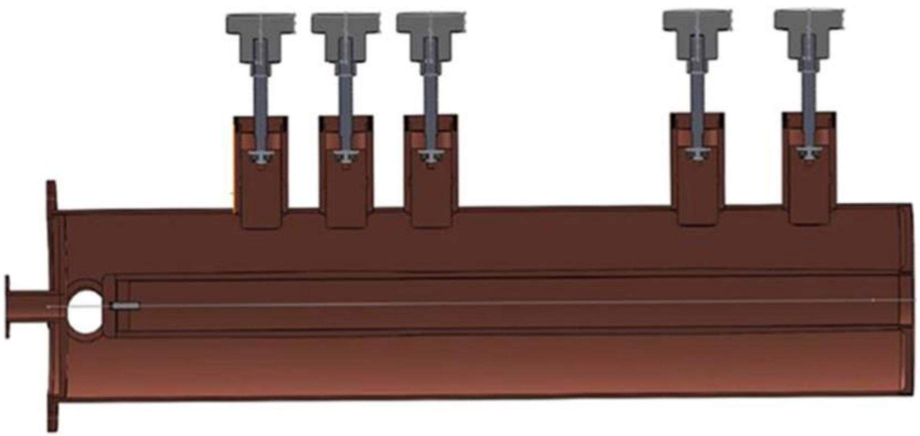
- Use harmonic RF cavities to produce the Fourier components of a periodic narrow pulse pulse
- These cavities simultaneously resonate at five harmonics of the bunch frequency
- This produces a train of narrow pulses using CW RF waves for stability and reproducibility



Yu. Huang et al. Phys. Rev. Accel. Beams 19, 084201 (2016)

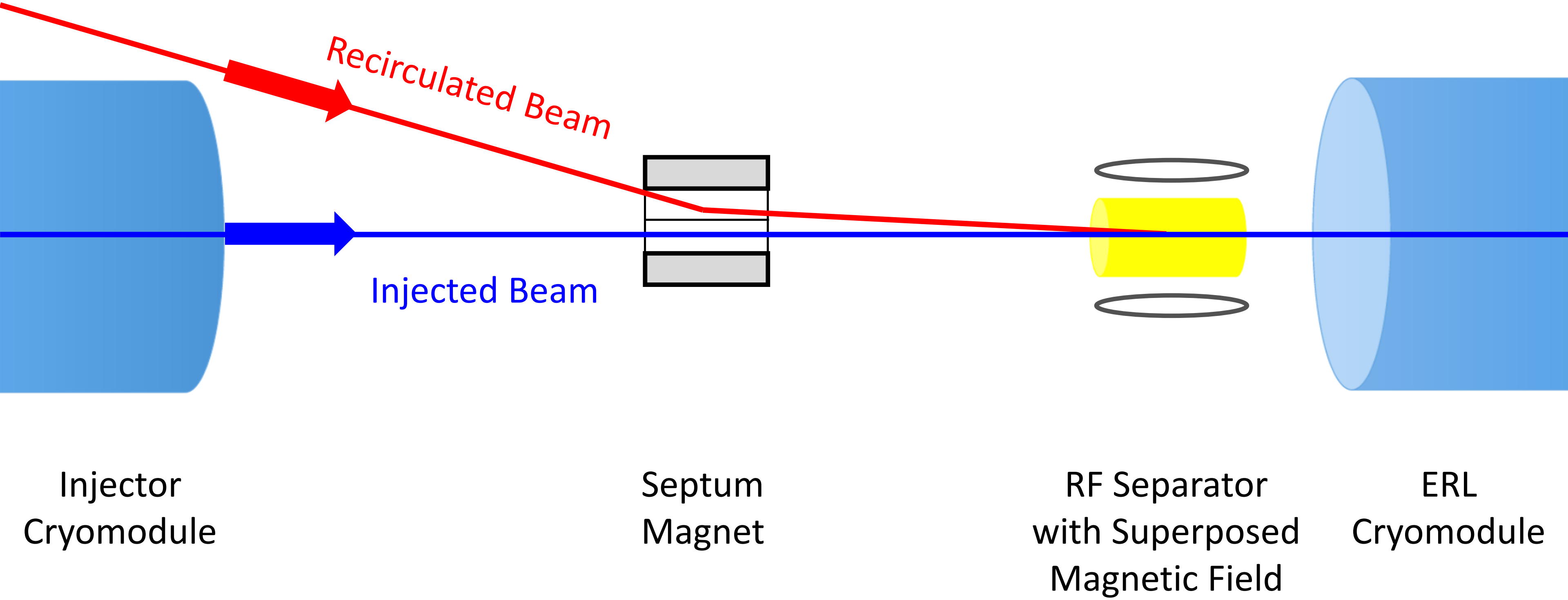
Harmonic Kicker Cavity





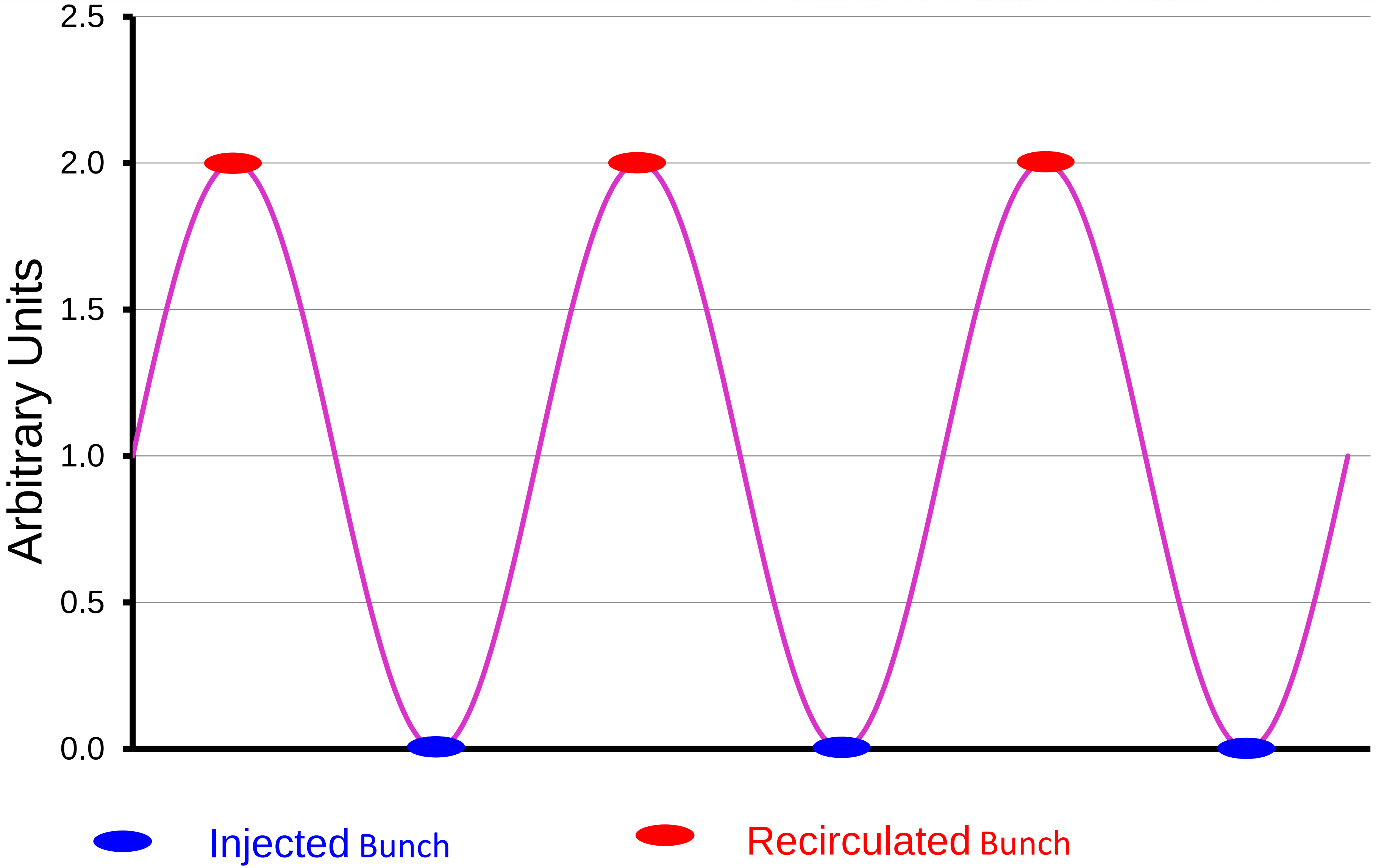
Yu. Huang et al. Phys. Rev. Accel. Beams 19, 122001 (2016)

Straight Merger with No Bending of Low Energy Beam



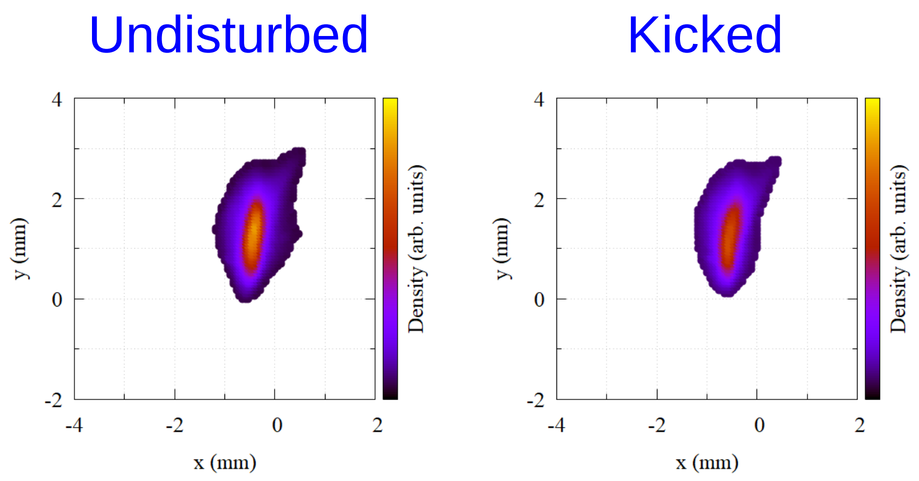
A. Hutton, JLab-TN-18-024

Waveforms


2.5
2.0
1.5
1.0
0.5
0.0
Arbitrary Units
Injected Bunch
Recirculated Bunch

First Experimental Test

- Had an opportunity to test the concept at Cornell
  - Used the RF Separator on the CBETA diagnostic line
  - Had 5 days to mount the experiment and take data



- Successfully showed that the concept worked
  - Now need to design the optimum RF Separator for the job

K. E. Deitrick, A. Hutton, S. Overstreet, A. C. Bartnik, and C. M. Gulliford,
Proc. 29th Linear Accelerator Conference (LINAC'18), Beijing, China, paper THPO010

Acknowledgement

- Thanks to everyone who helped by sending their slides and correcting mine
  - Kazunori Akai – KEK
  - Karen Burkey – HEPL, Stanford
  - Graeme Burt – Cockcroft Institute
  - Jean Delayen – ODU and JLab
  - Yuantao Ding – SLAC
  - Paul Emma – SLAC
  - Georg Hoffstaetter – Cornell
  - Andrei Lunin - Fermilab
  - Bob Rimmer – Jefferson Lab
  - Qiong Wu – BNL
  - Dao Xiang – SLAC

  - And of course – Google!

Conclusion

- Transverse RF Separators have a solid future
- Investment in crab cavities for LHC will pay off in other fields

Thanks