Integration of Crab Crossing to IR

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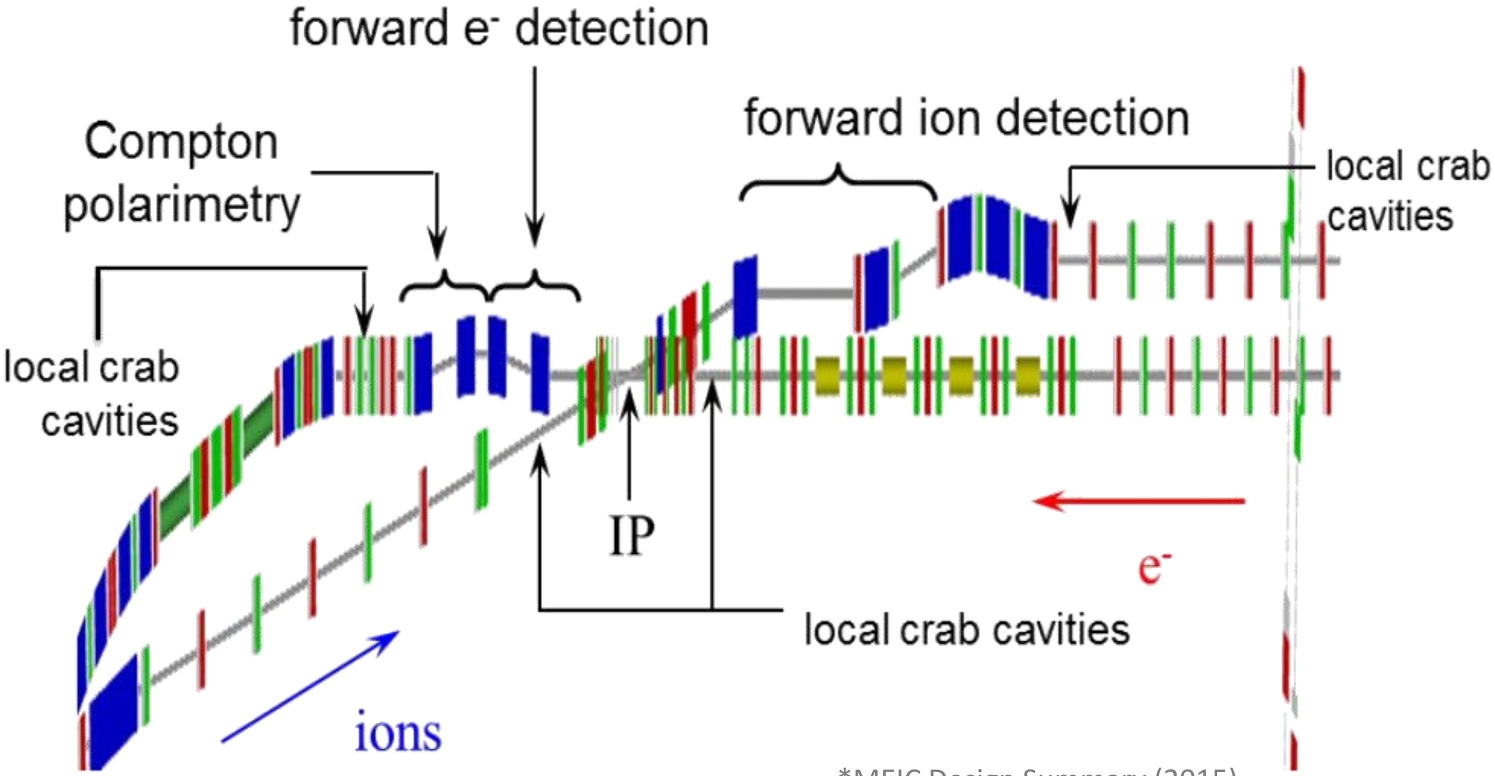
Outline

- Approach & requirements.
- A word on hardware.
- Simplifications on the Interaction Region.
- FFB and phase advance (1st Order).
- Synchro-Betatron coupling.
- Transverse coupling.
- Particle tracking methods.

The MEIC Luminosity Approach

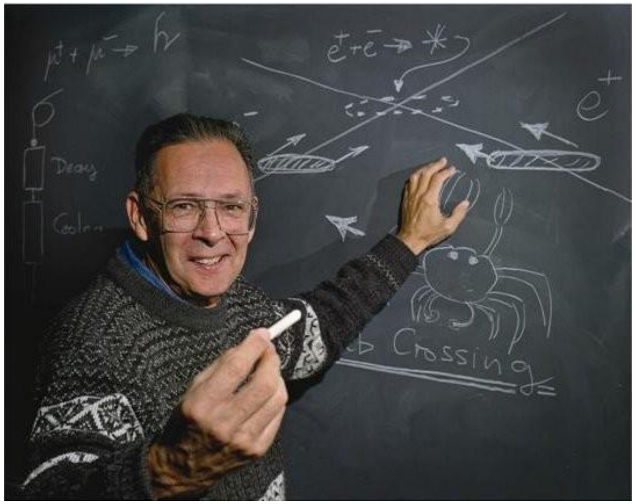
- **Short bunches for both species.**
- **Small transverse emittance.**
- **Ultrahigh collision frequency CW beams.**
- **Staged electron cooling.**
- **Small final focusing β^*.**
- **Large beam-beam tune shift.**
- **Crab crossing.**

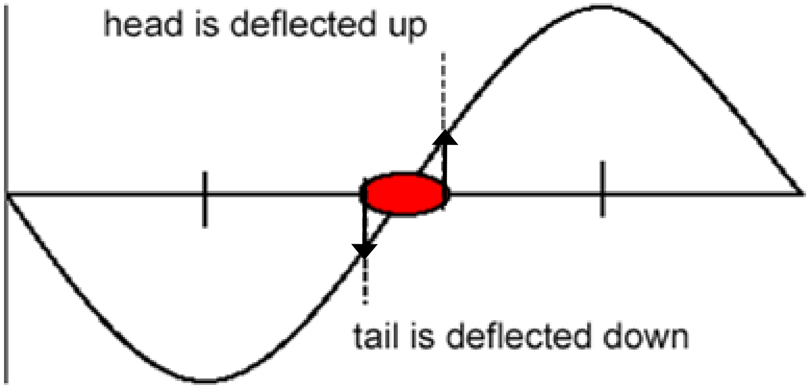
The Interaction Region

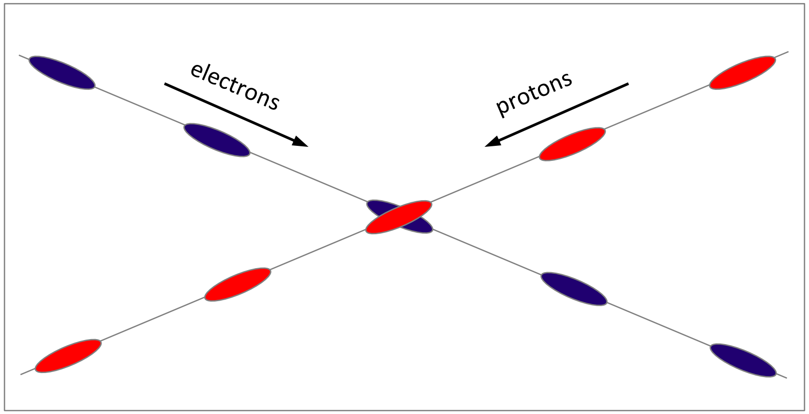


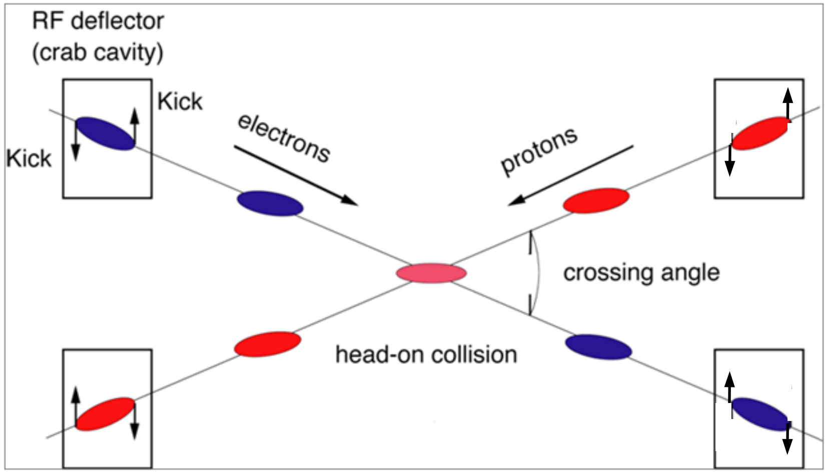
*MEIC Design Summary (2015).

The Crabbing Concept







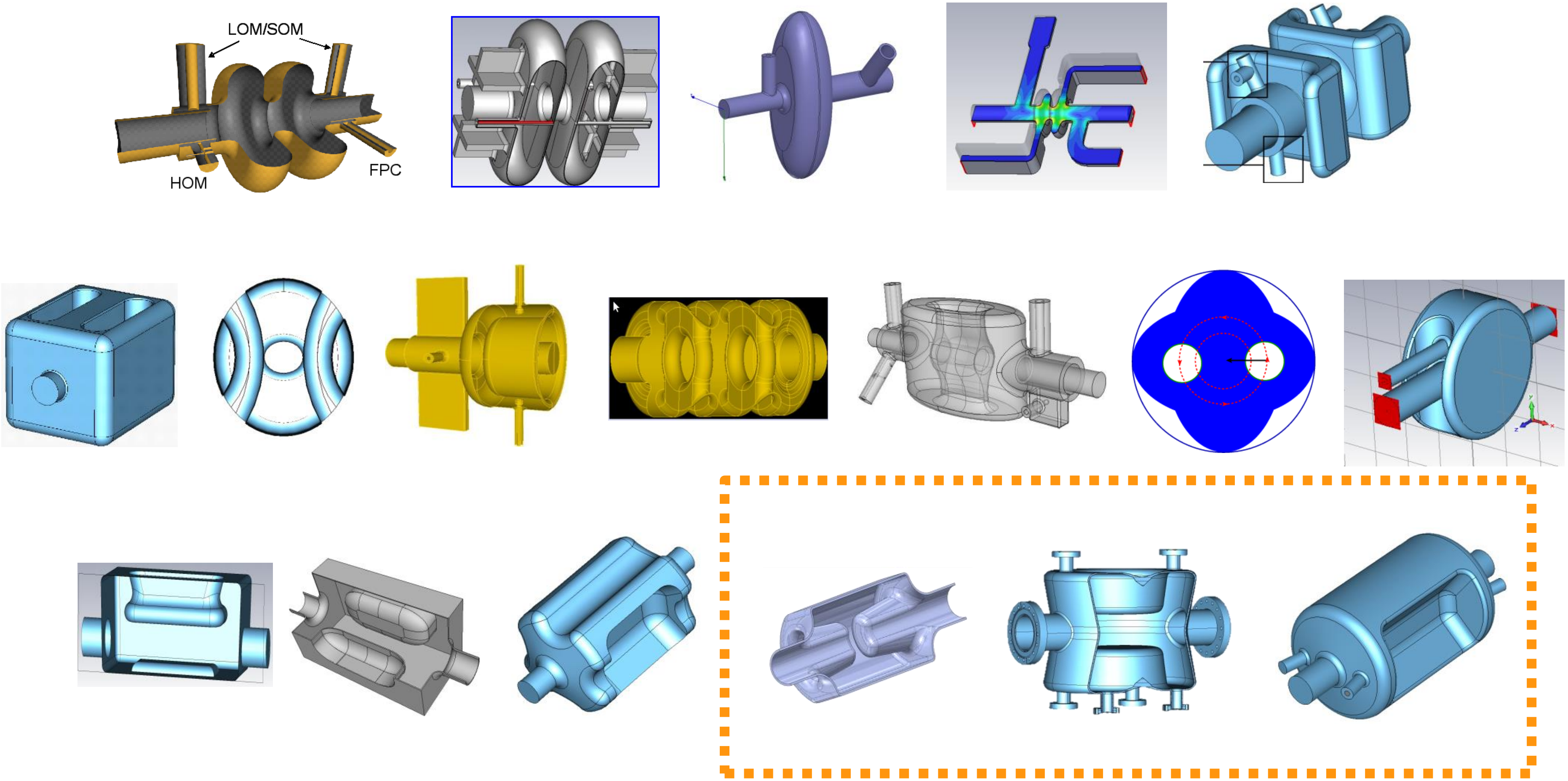


*R. Palmer, SLAC-PUB-4707 (1988).

Meet the candidates

*Slide taken from Q. Wu from BNL at IPAC2015

R. Calaga, Chamonix '12

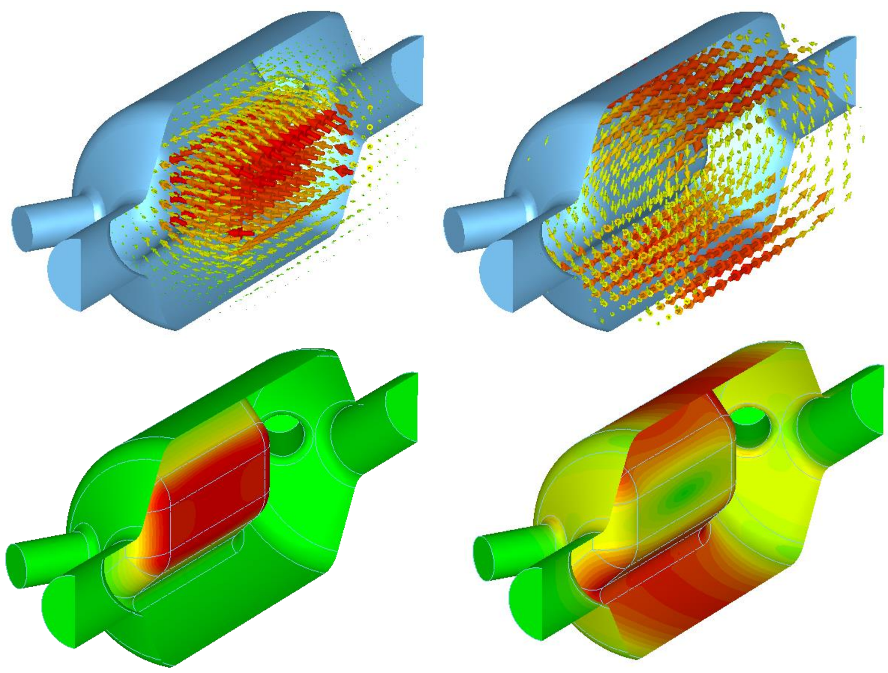


Exotic zoo of crab cavities developed in about 4 years (BNL, CERN, CI-JLAB, FNAL, KEK, ODU/JLAB, SLAC)
Three cavities remaining after down-selection.

Transverse Kick
(e.g. 750 MHz SRFD)

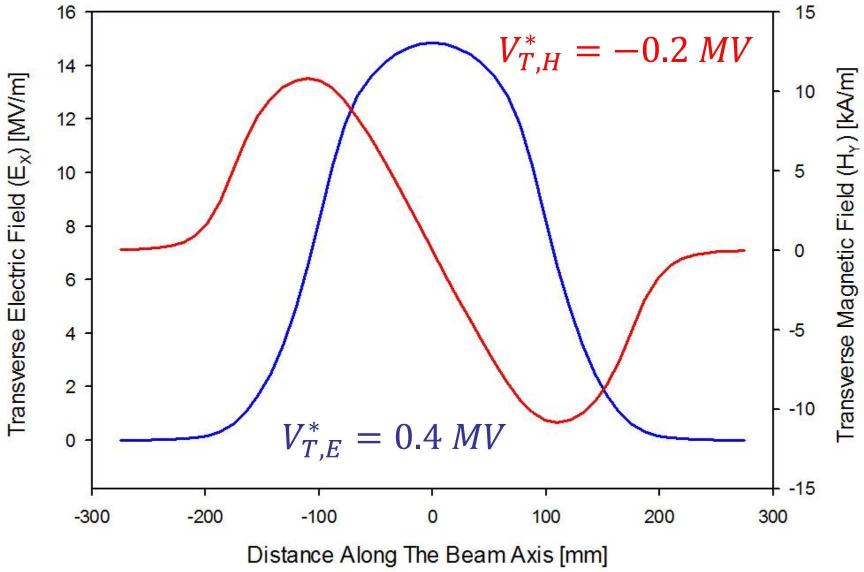
$$V_T = \int_{-\infty}^{\infty} \left[E_x(z) \cos\frac{\omega z}{c} + cB_y(z) \sin\frac{\omega z}{c} \right] dz$$

Electric Field **Magnetic Field**



$$E_T = \frac{V_T}{\lambda/2} \Rightarrow V_T^* = 0.2\ MV$$

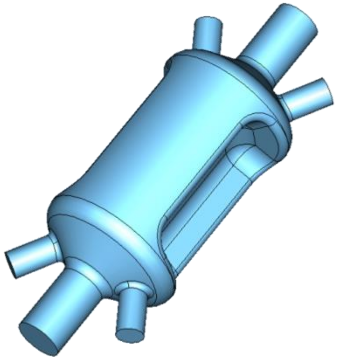
$$E_T^* = 1\ {}^{MV}/_{m}$$

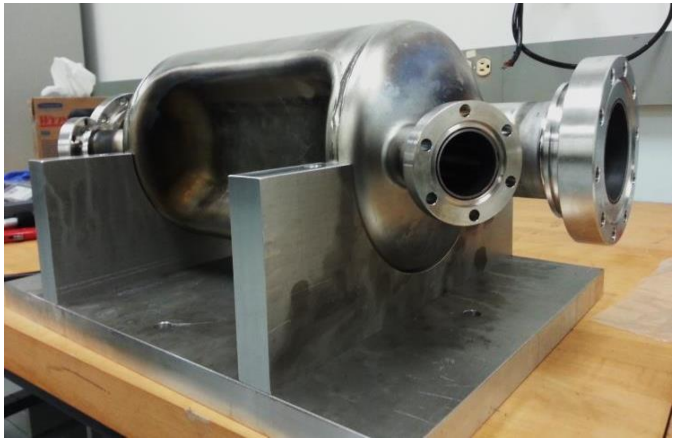


750 MHz Crabbing Cavity

- **Crabbing cavity for proposed Medium-Energy Electron-Ion Collider (MEIC)**
- **Desired net deflection**
  - **e^- beam: 1.35 MV**
  - **p beam: 8 MV**

Parameter	750 MHz	Unit
Nearest mode to π mode	1062.5	MHz
Deflecting voltage (V_T^*)	0.2	MV
Peak electric field (E_P^*)	4.29	MV/m
Peak magnetic field (B_P^*)	9.3	mT
Geometrical factor ($G = QR_S$)	136.0	Ω
$[R/Q]_T$	125.0	Ω
At $E_T^* = 1$ MV/m		

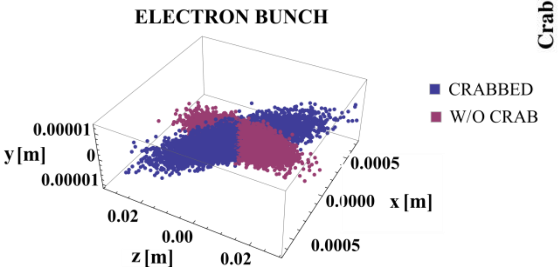


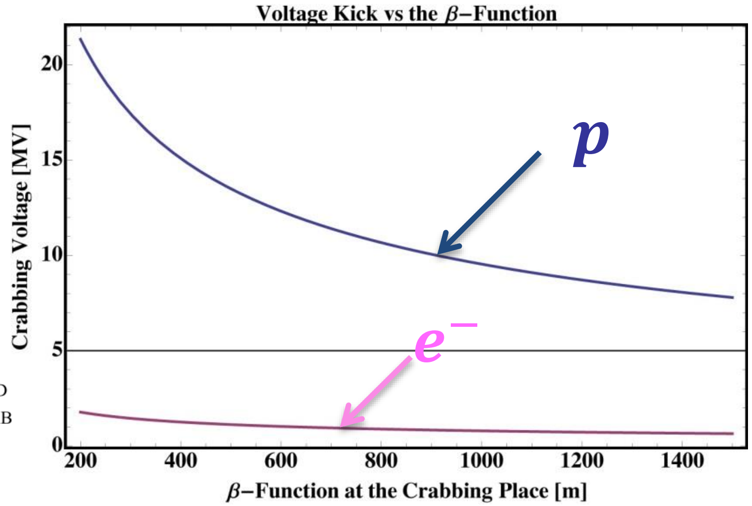


MEIC Crabbing Requirements

- **High repetition.**
- **Big crossing angle.**

$$V_T = \frac{cE_b \tan\frac{\boldsymbol{\theta_c}}{2}}{\omega_{rf}\sqrt{\beta_x^* \beta_x^c}}$$





Parameter	Units	Electron	Proton
Beam energy E_b	GeV	5	60
Bunch frequency n_b	MHz	750.0	
Crossing angle φ_c	mrad	**50**	
Betatron function at the IP β_x^*	cm	10	
Betatron fn. at the crab cavity β_x^c	m	300	1400
Integrated kicking voltage V_T	**MV**	**1.35**	**8**

“*New*” Crab Cavities for MEIC

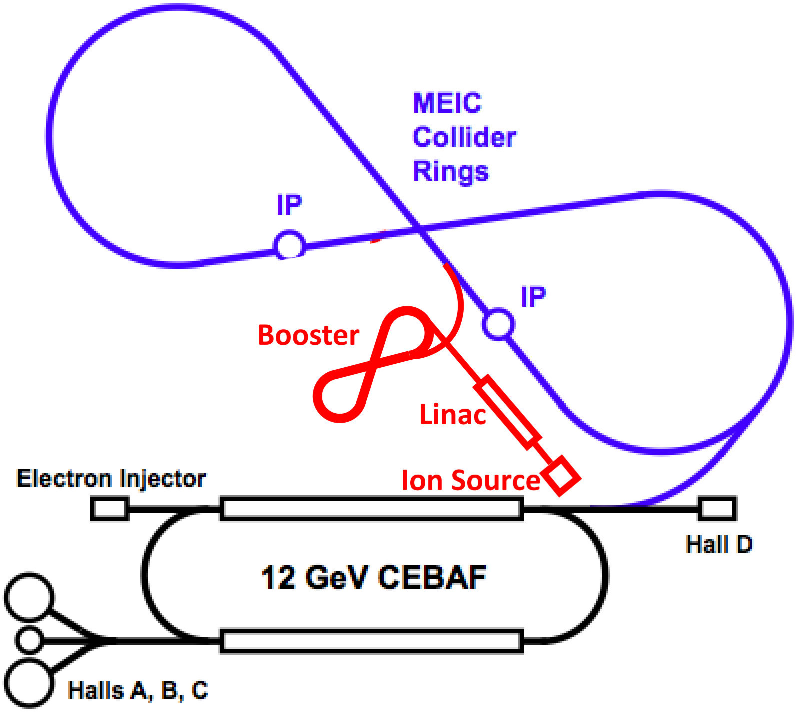
- Up to 100 GeV polarized protons and 10 GeV polarized electrons
- $\mathcal{L} \sim 7.5 \times 10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

Based on RFD design *(SRF technology)*:

Crab cavities	100 GeV proton	10 GeV e-
freq [MHz]	952	952
$N_{cavities}$	6	2
V_{defl} [MV]	14.48	1.76

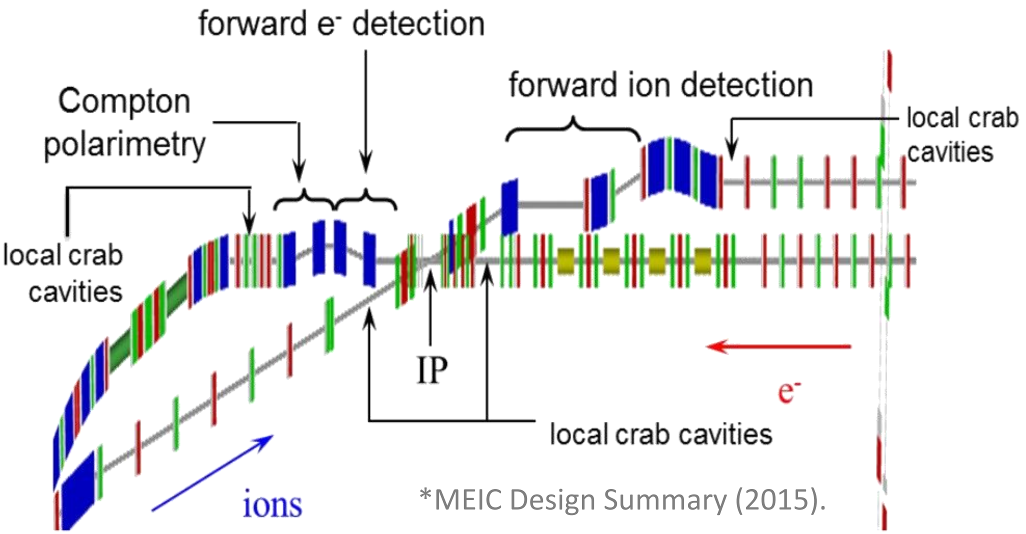
Full crossing angle θ_C= 50 mrad

- *Horizontal local crabbing scheme*

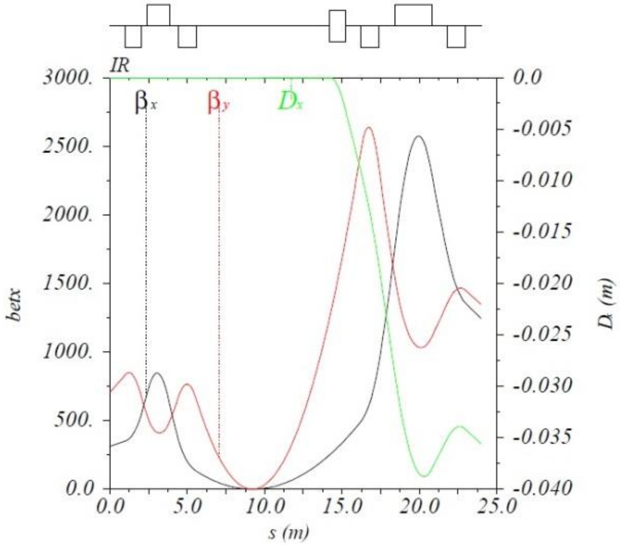


Simplified IR Layout

- Simplifying for both electrons and protons a symmetric IR with respect to the IP



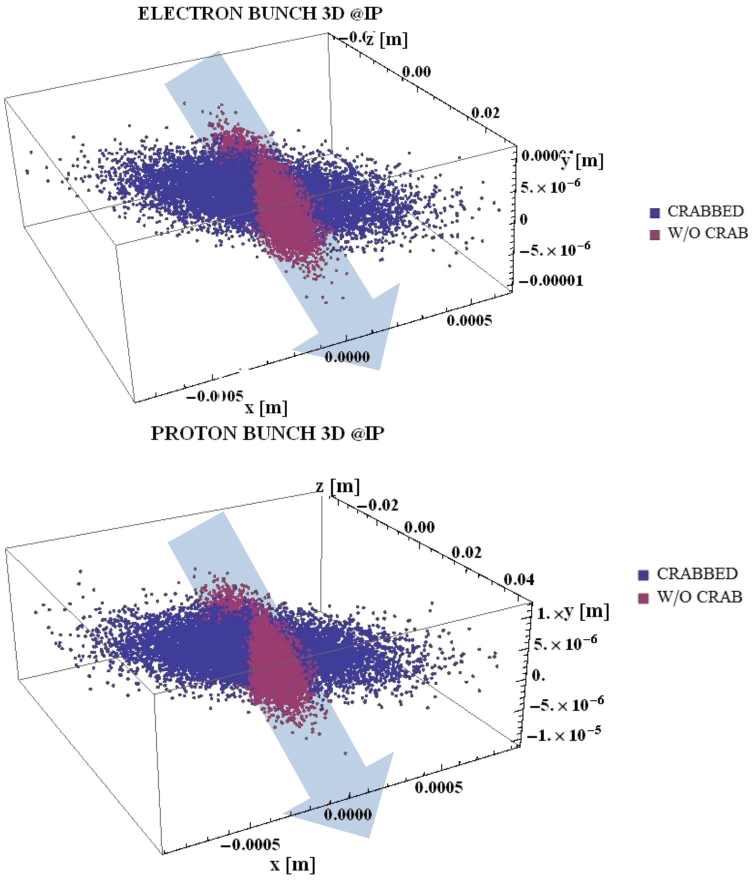
*MEIC Design Summary (2015).



Linear Crabbing Matrix

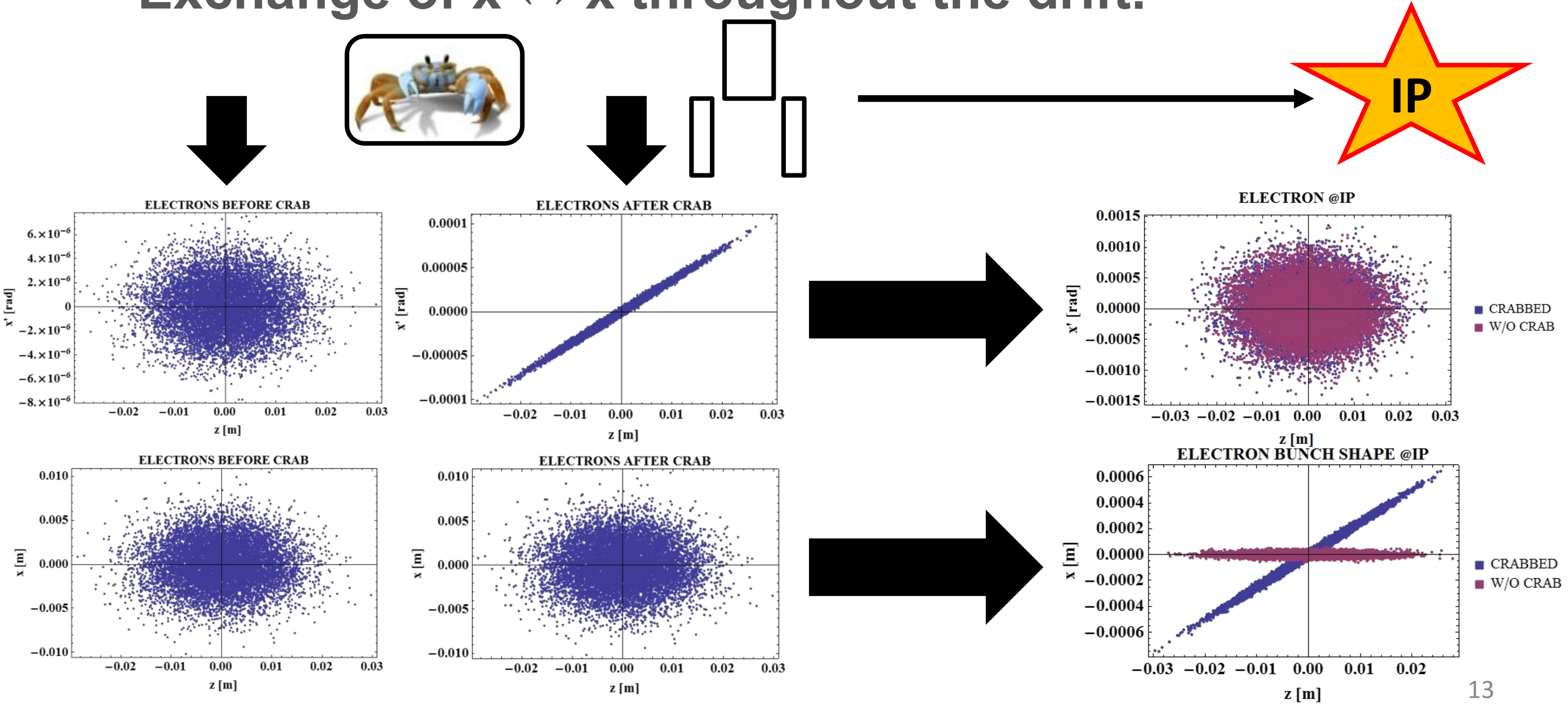
- **Mixing of x' with z and z' with x.**
- **F = 7 m, $\theta_C = 50\,mrad$.**

$$M_{Crab} \cong \begin{pmatrix} \begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix} & \begin{matrix} 0 & 0 & 0 \\ 0 & \dfrac{\tan\left({}^{\theta_C}/_2\right)}{F} & 0 \\ 0 & 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \dfrac{\tan\left({}^{\theta_C}/_2\right)}{F} & 0 & 0 \end{matrix} & \begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix} \end{pmatrix}$$

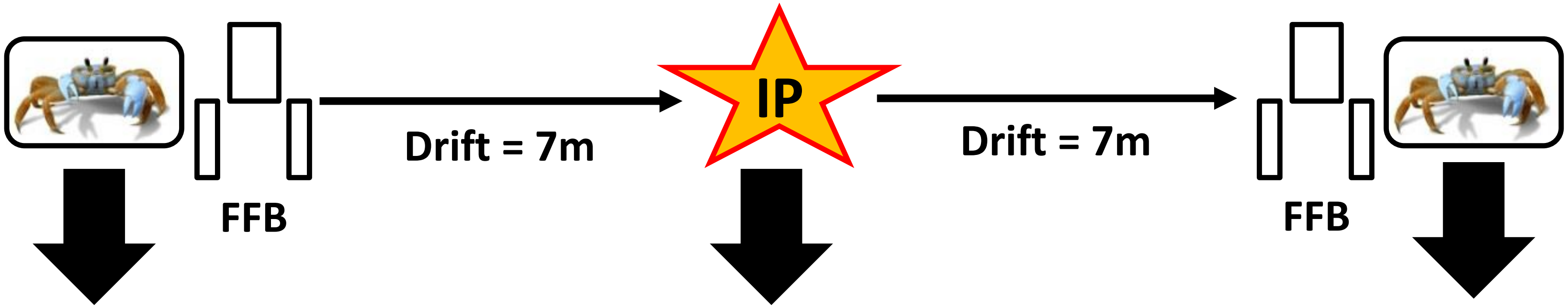


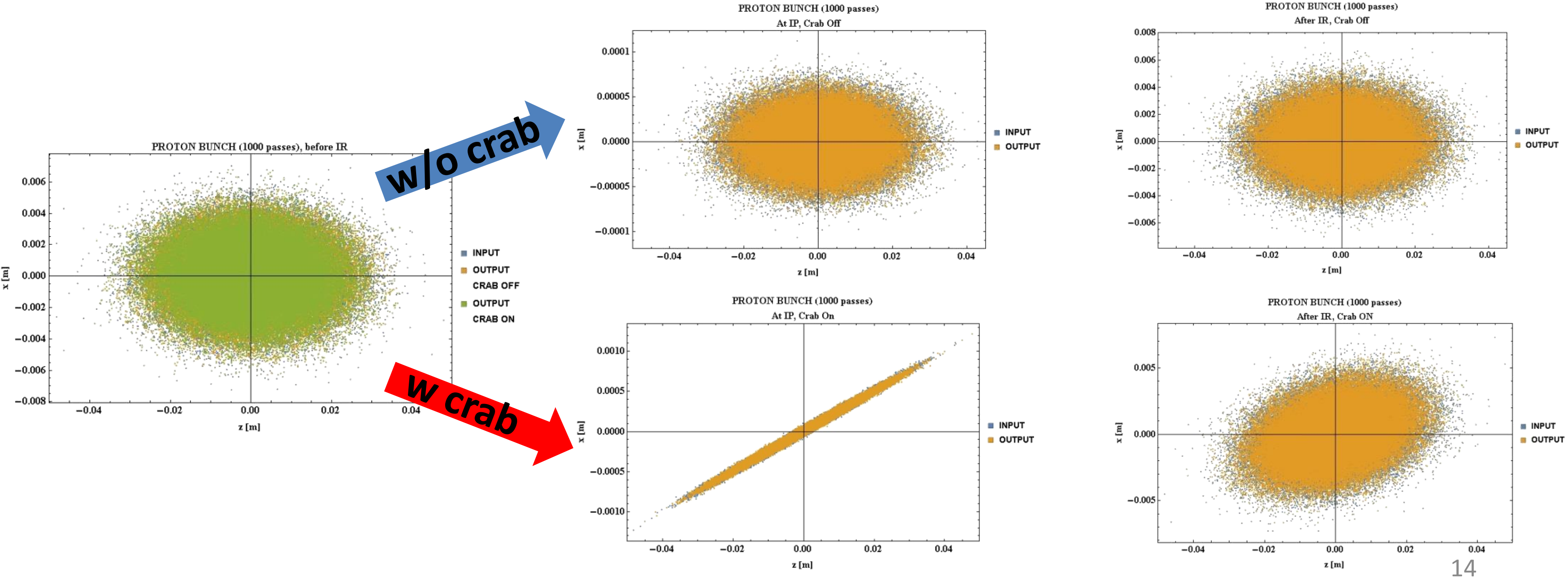
Linear Crabbing Matrix (2)

- **Instantaneous change on x’ not x at the crab.**
- **Exchange of x’↔ x throughout the drift.**



1000 Passes (protons)





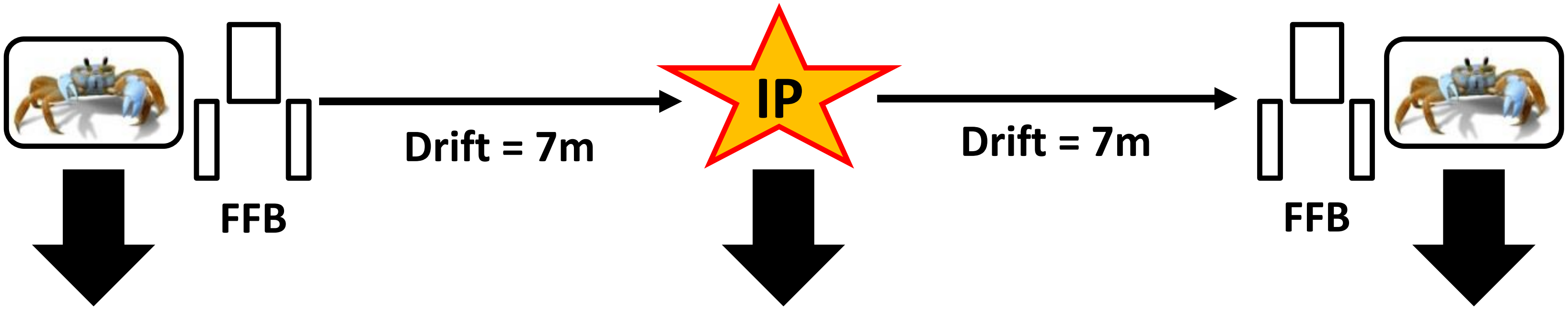
FFB and Phase Advance

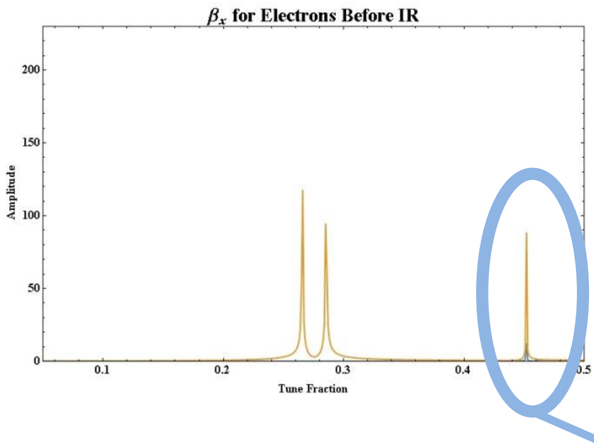
- **All cases in the literature assume $\Delta\psi_{x1,2} = \pi$, then in the transfer matrix from the 1st to 2nd crab $m_{12} = 0$.**
- **But, comparing the transfer matrices:**
  - ➢ One obtained from direct matrix multiplication (RHS)..
  - ➢ Other using the Courant Snyder parameterization (LHS).

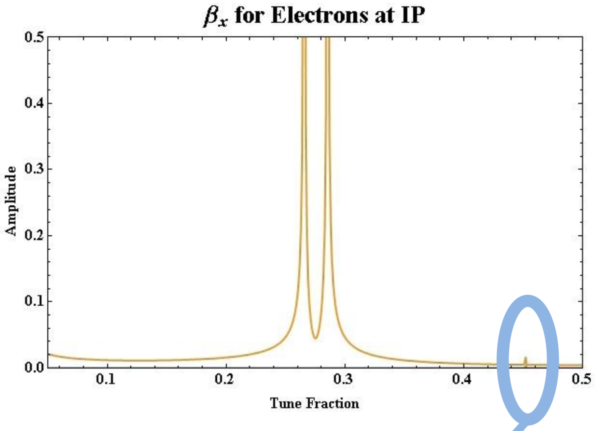
$$m_{12} = \sqrt{\beta_{C1}\beta_{C2}}\sin\left(\Delta\psi_{x1,2}\right) = 2D$$

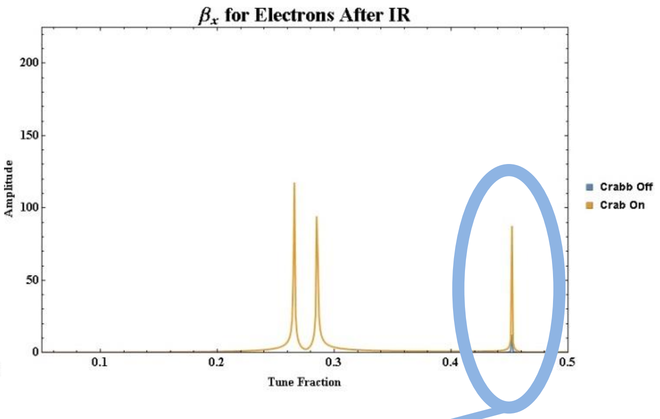
- **So $\sin\left(\Delta\psi_{x1,2}\right) = 0$, implies $\sqrt{\beta_{C1}\beta_{C2}} \to \infty$, where 2*D* denotes the distance from one crab to the other.**

Synchro-Betatron Coupling



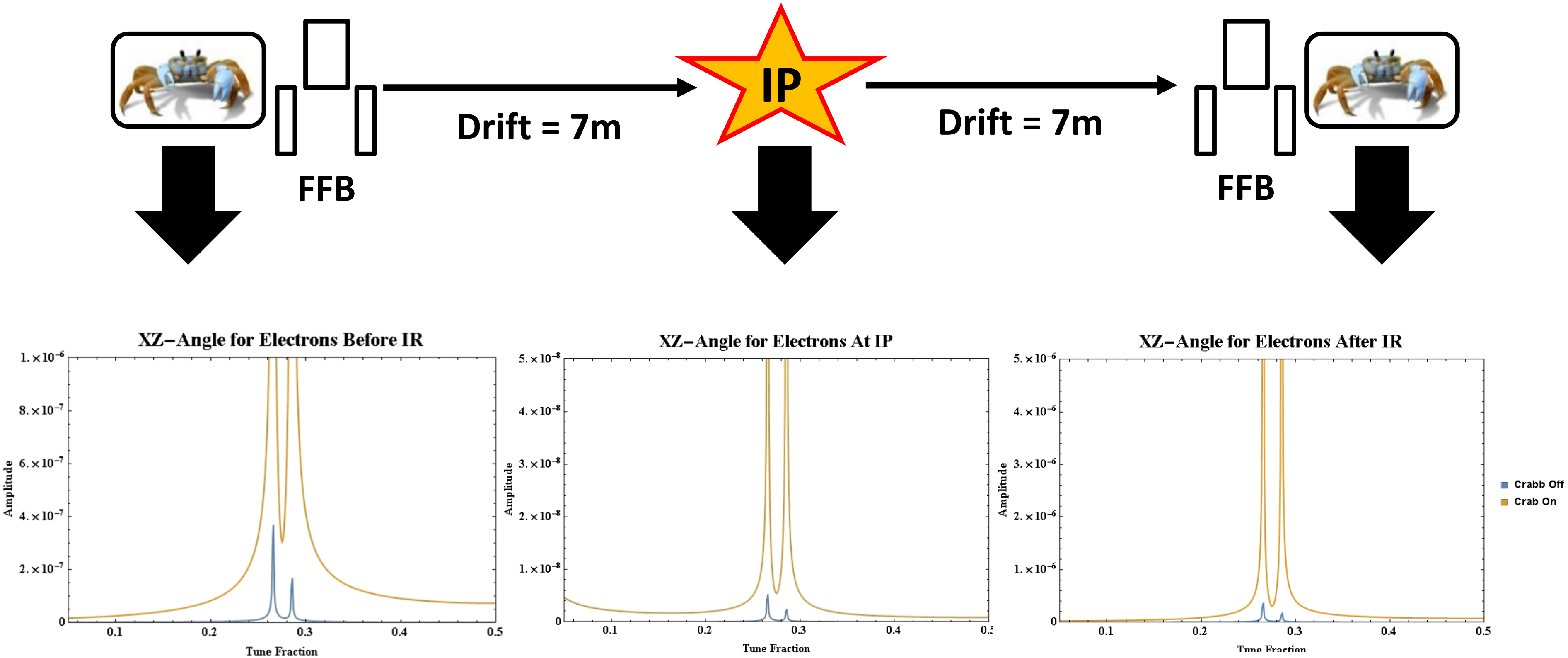






2*Betatron Fractional Tune

Synchro-Betatron Coupling (2)



- Synchrotron fractional tune present in the xz-correlation due to crabbing.

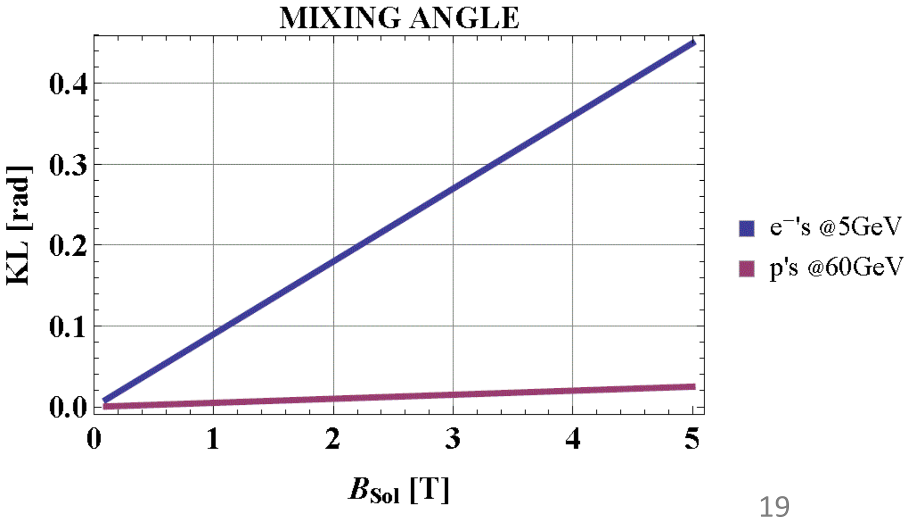
Transverse Coupling

- Solenoids between the crabs and the IP will cause vertical and horizontal coupling, this will have a repercussion on the crabbing angle.

Transverse Coupling (2)

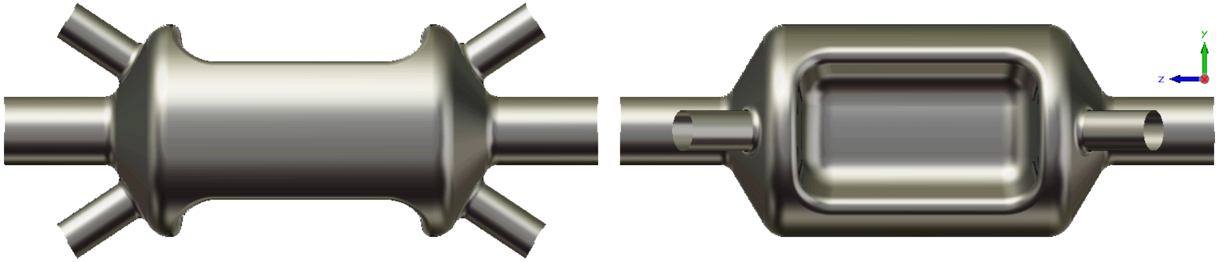
- **The solenoid strength $B_{Sol} = KL$, where *L* is the solenoid length, $K \equiv \frac{qB_{Sol}}{2P}$, with *q* the particle charge, and *P* its momentum.**

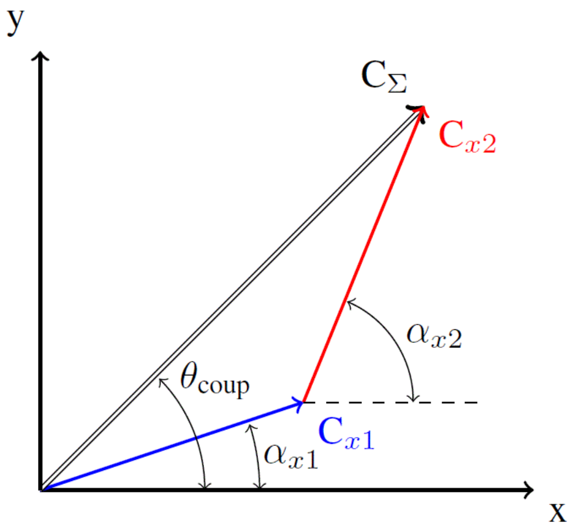
Transverse coupling at the IP



Twin Crabs

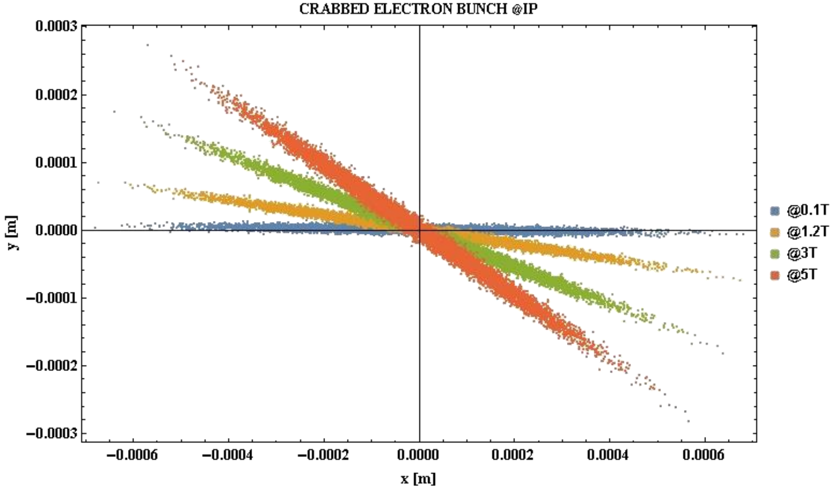
- The simplest solution is to rotate the crab by the proper KL angle, for a fixed value of B_{Sol}.
- If the solenoid strength needs to be cover a range, a solution is a superposition of kicks: “twin crabs”.



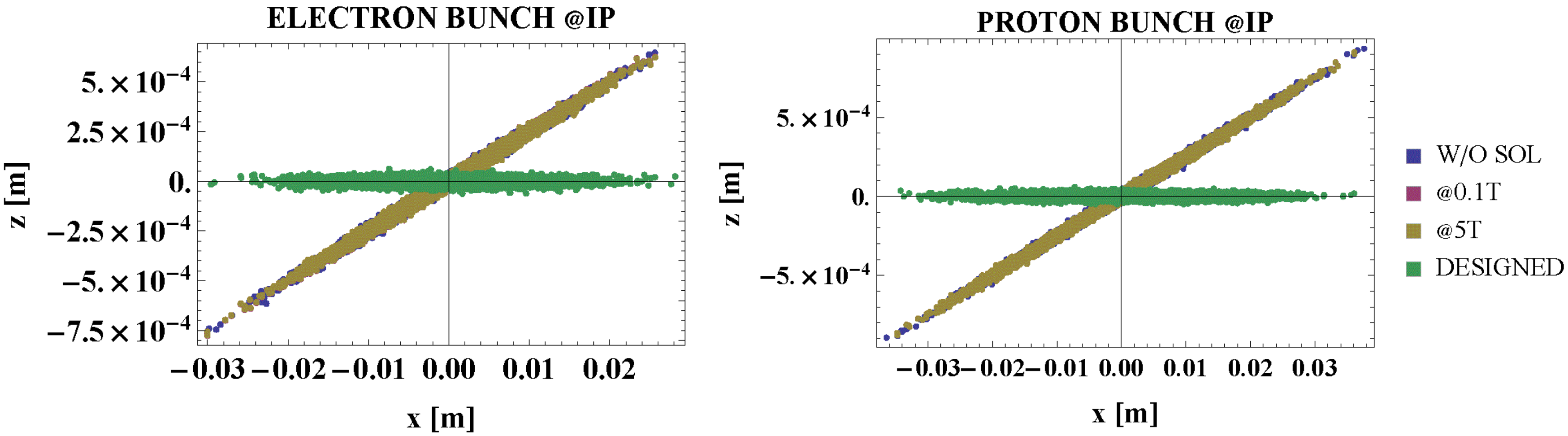


Twin Crabs (2)

- If not compensated, the crabbing correction “leaks” to the transverse plane.

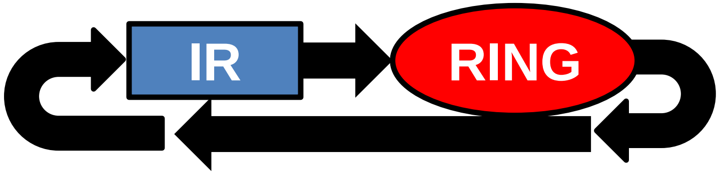


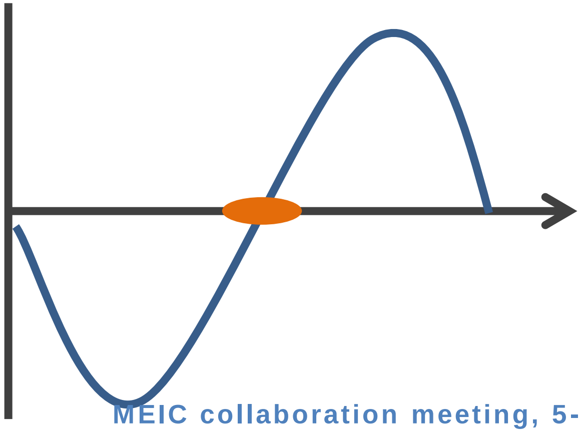
- Using the twin crabs:



Particle Tracking

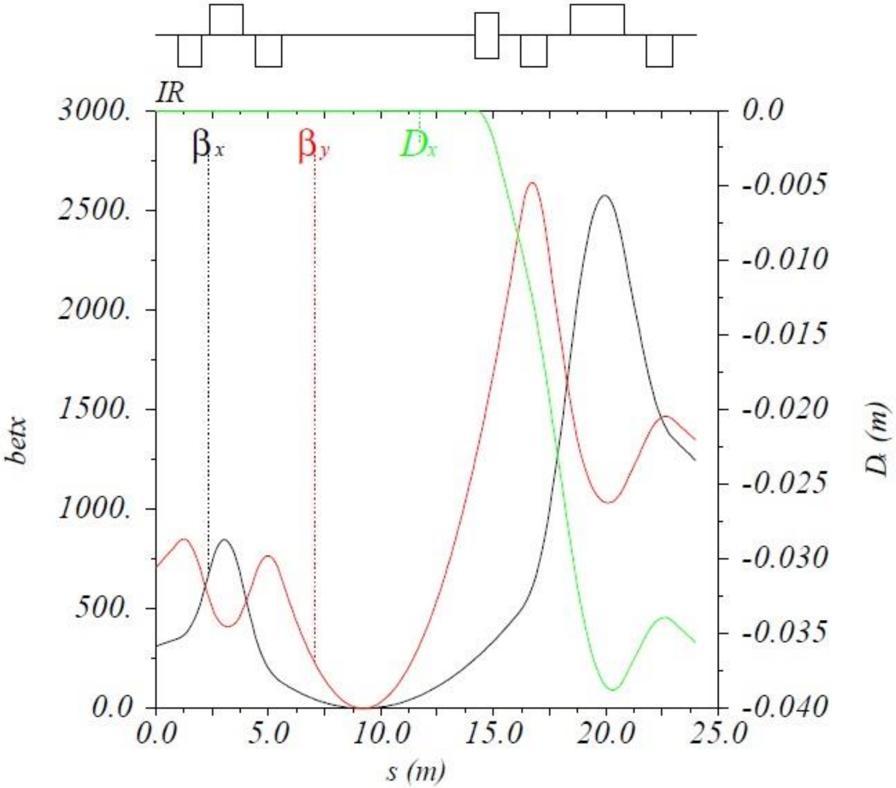
- We find the ring (no IR) linear transfer matrix with MADX.
- Describing the IR with standard linear elements in ELEGANT and the ring as the zero-length transfer matrix.
- The crabs as RF multipole at zero-crossing, (i.e. MRFDF with $\varphi = 270°$).





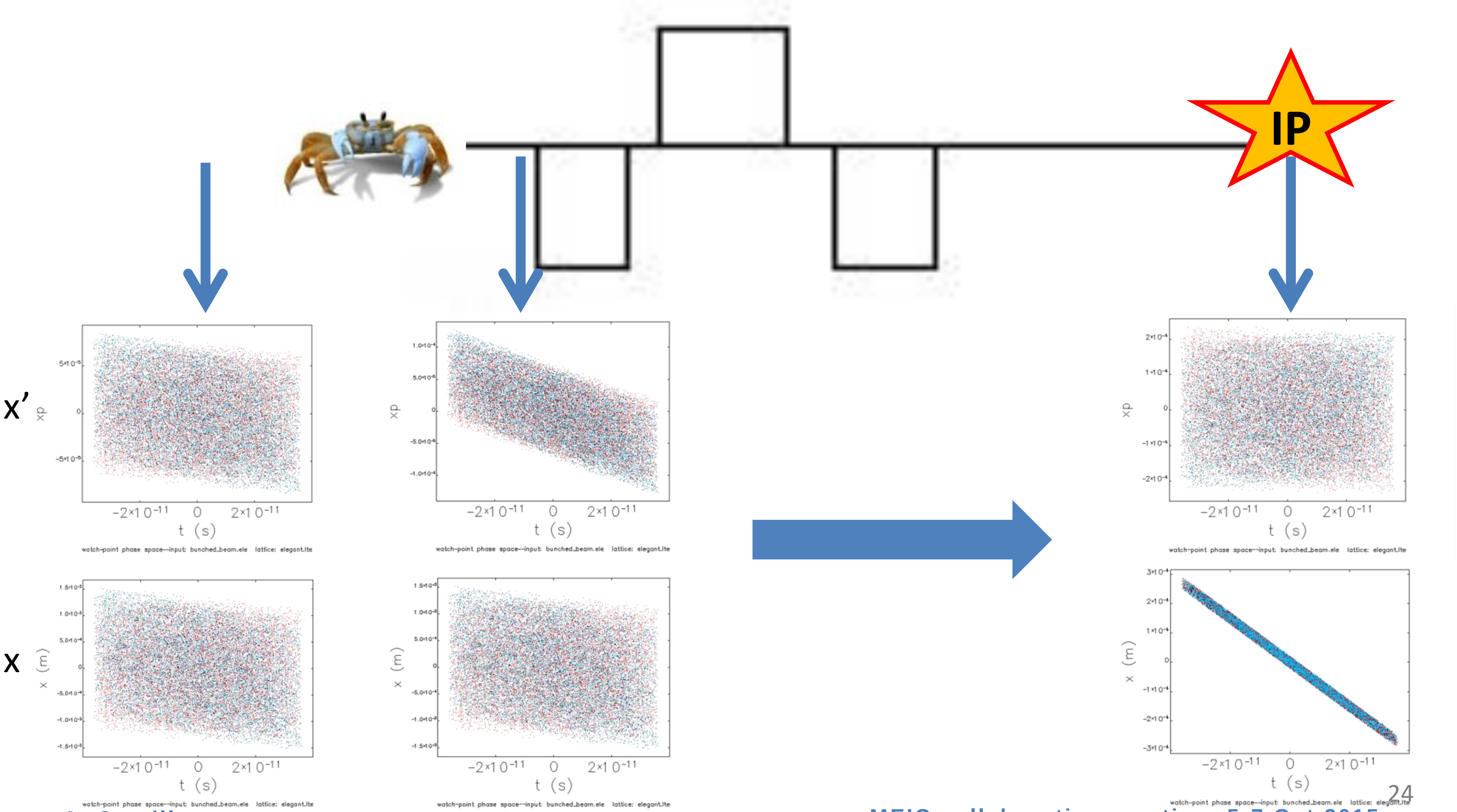
IR Layout (protons)

- **The crabs are the only non-linear elements in this model.**



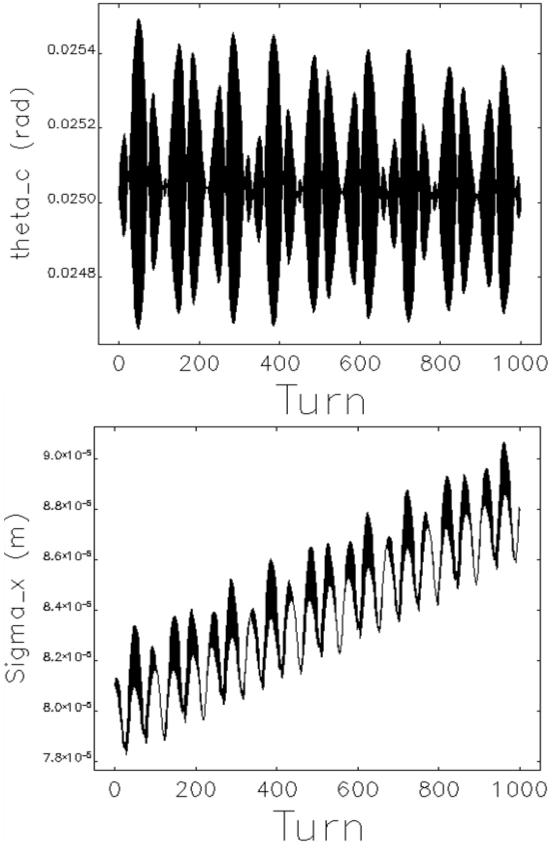
Tracking w Crabbing (2)

- 1st half of the IR, crabbing.

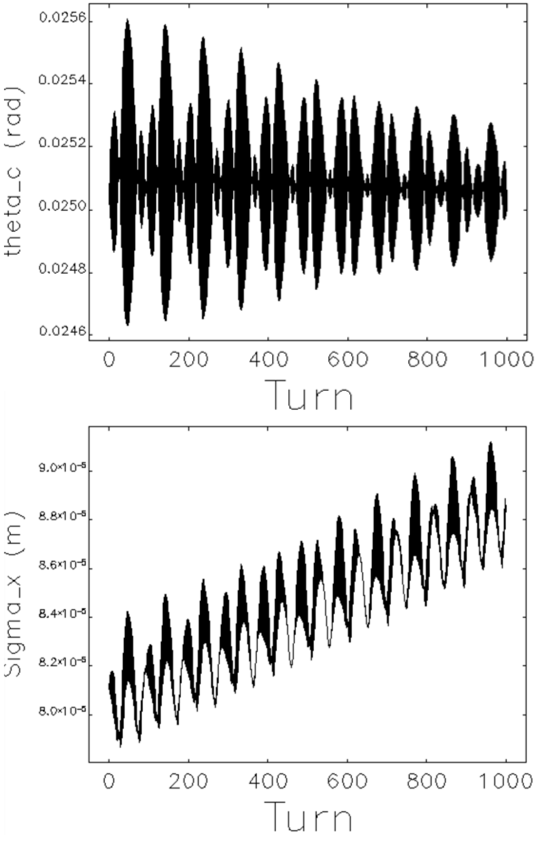


Tracking w Crabbing (3)

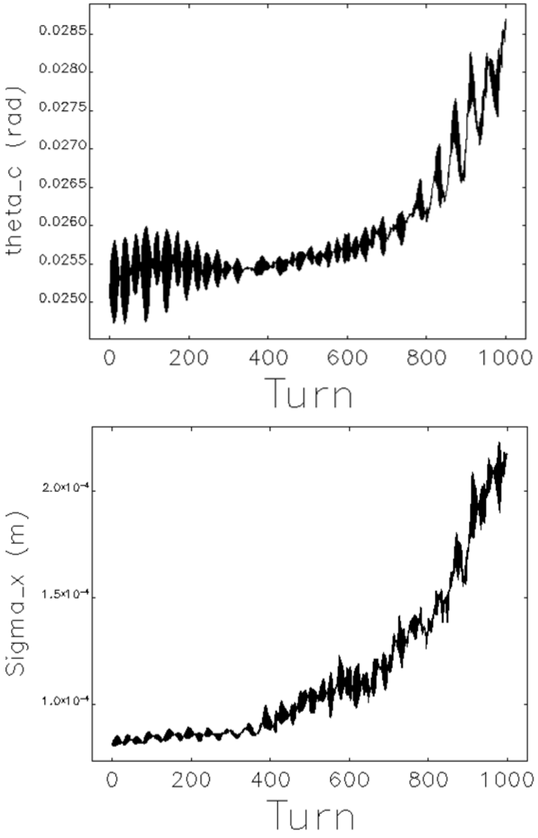
Pure Dipole



Small Sextupole

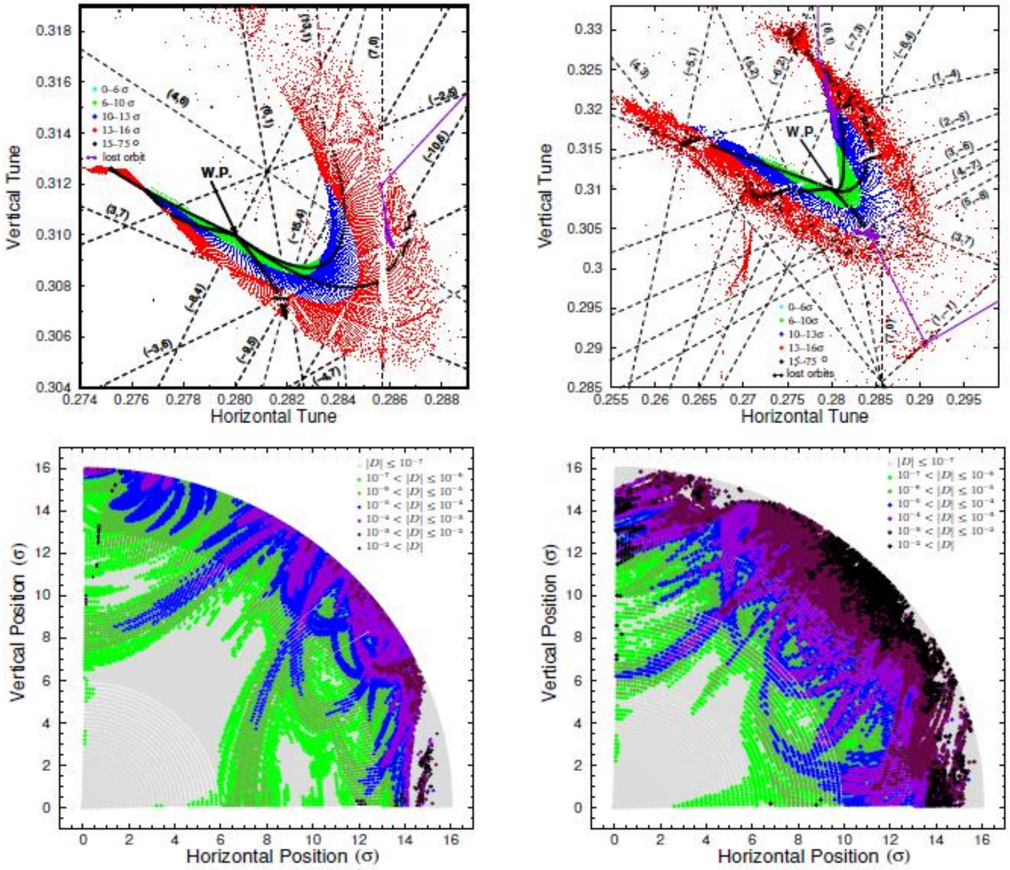


Large Sextupole



Non Linear Analysis

Target Errors for the LHC



- **Next steps with Sextupoles + crab cavities:**
  - **Frequency Map Analysis.**
  - **Diffusion Map Analysis.**

Y. Papaphilipou, Target errors in the LHC.
http://arxiv.org/pdf/1406.1545.pdf

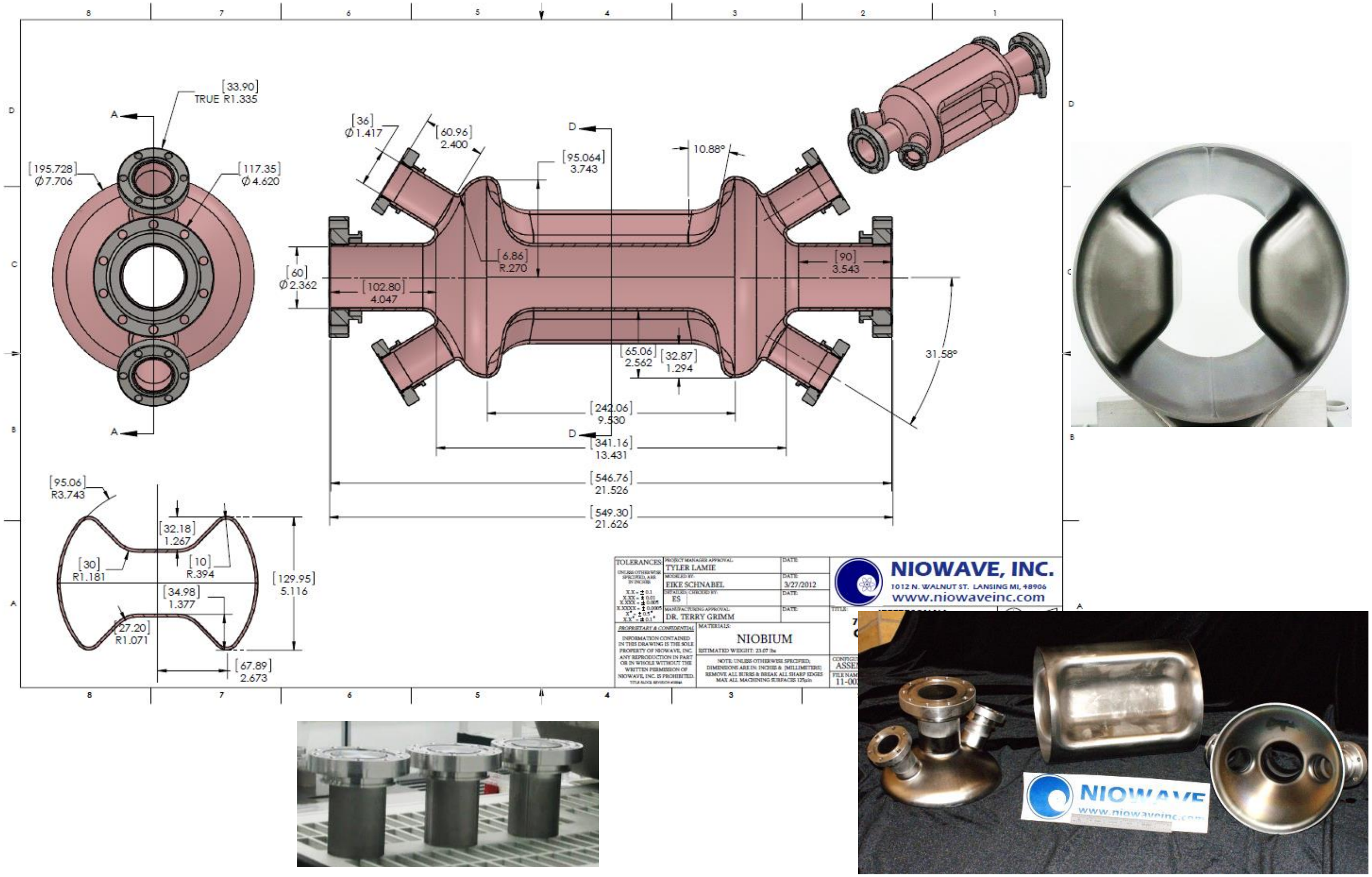
Thanks

Center for **A**ccelerator **S**cience-**ODU**

References

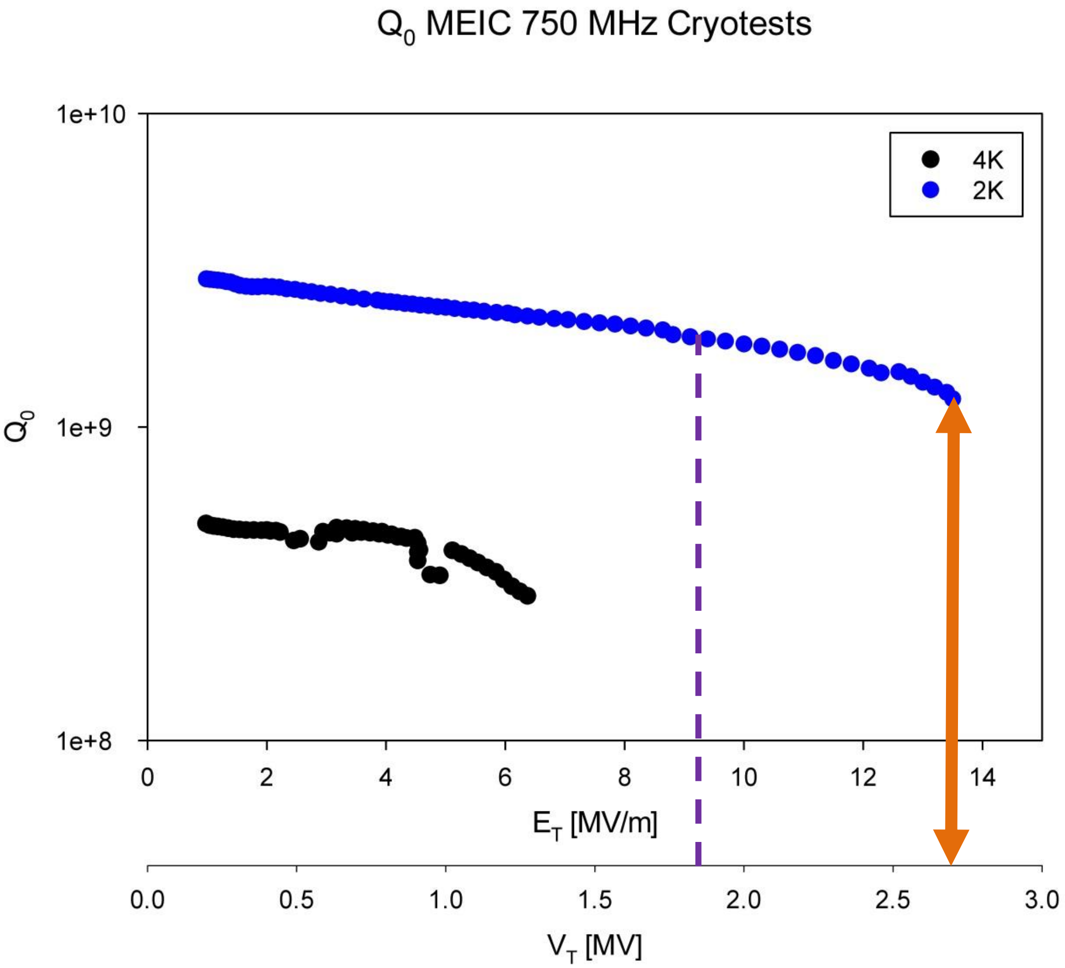
- A. Castilla, et al, Modeling Crabbing Dynamics in an Electron-Ion Collider, presented in IPAC2015.
- A. Castilla, et al, Multipole Budget of Crab Cavities for an Electron-Ion Collider, presented in IPAC2015.
- A. Castilla, et al, Employing Twin Crabbing Cavities to Address Variable Transverse Coupling of Beams in the MEIC, in Proceedings for IPAC2014.
- A. Castilla and J. Delayen, Multipole and Field Uniformity Tailoring of a 750 MHz RF Dipole, in Proc. for LINAC2014.
- M. Borland, ANL-ELEGANT Users Manual.
- Y. Papaphilippou, Detecting chaos in particle accelerators through the frequency map analysis method, arXiv:1406.1545v1, 2014.
- Q. Wu, Crab Cavities: Past, Present, and Future of a Challenging Device, IPAC2015.

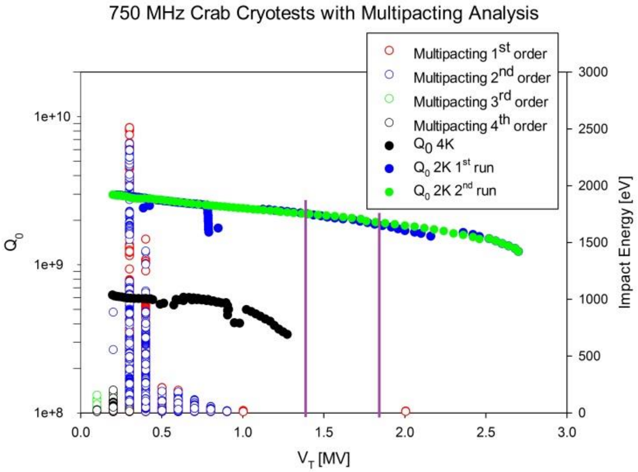
How Does It Looks Like?



Images courtesy of Niowave, Inc.

750 MHz Crabbing Cavity



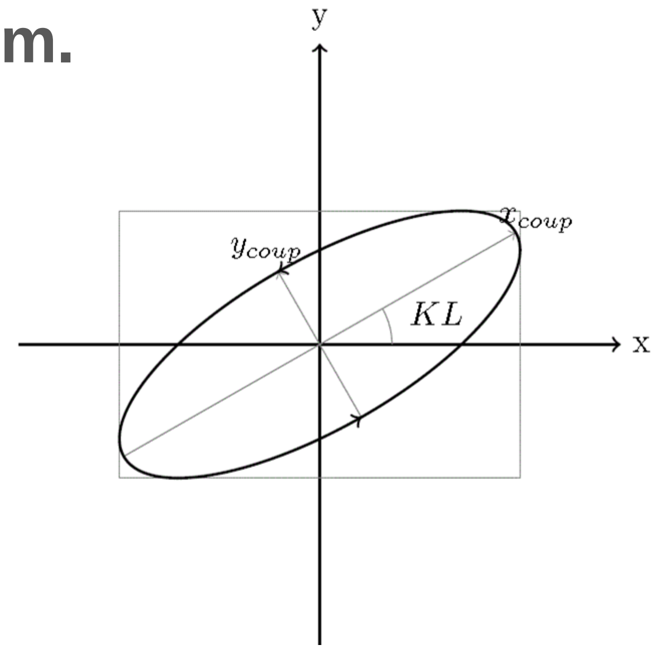


- **Multipacting levels were easily processed at 2 K.**
- **Design requirement of <2 MV can be achieved with 1 cavities**
- **Achieved fields at 2.0 K**
  - **E_T = 13.5 MV/m**
  - **V_T = 2.7 MV**
  - **E_P = 60.08 MV/m**
  - **B_P = 125.69 mT**

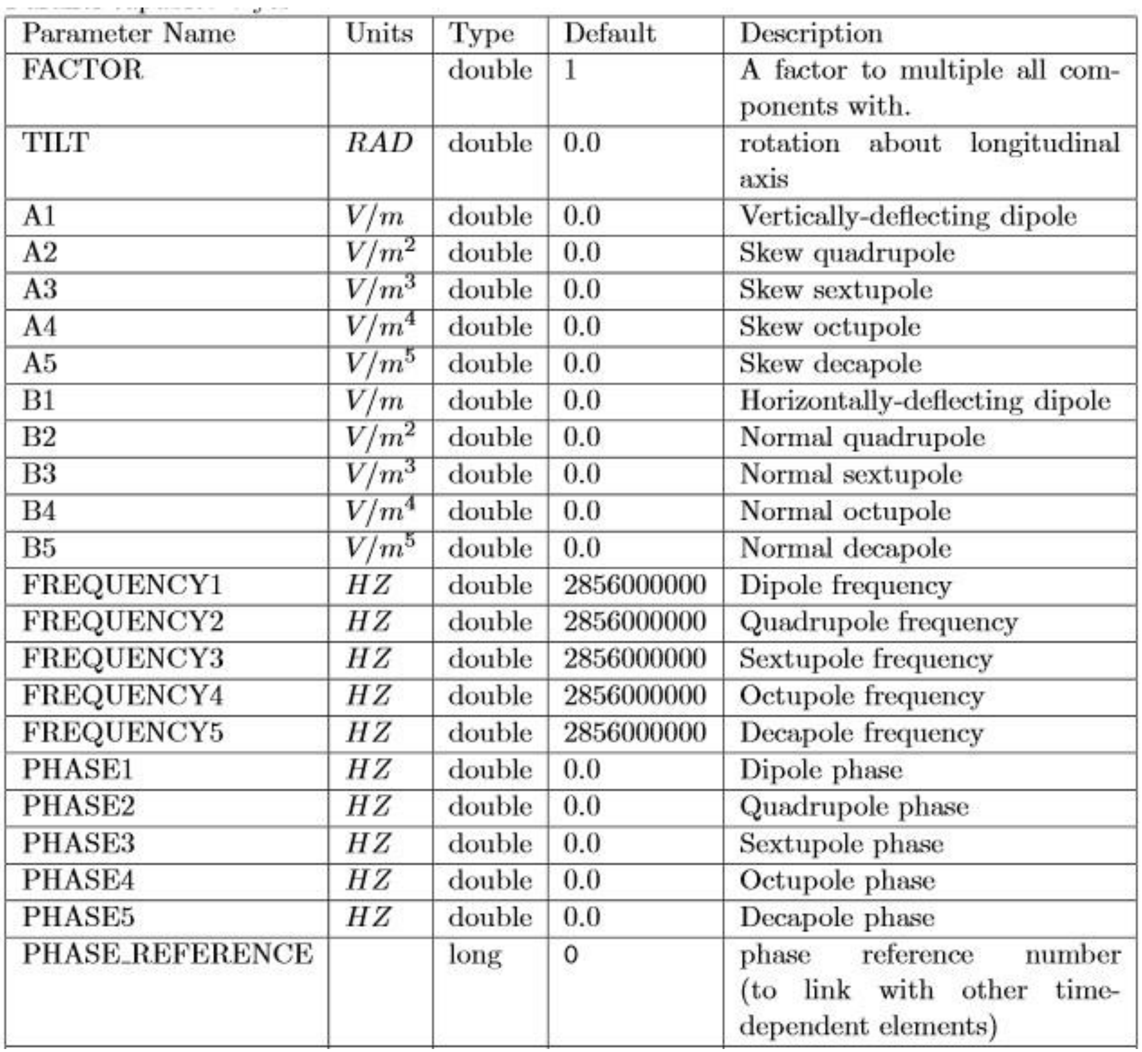
Transverse Coupling (…)

- The solenoid strength $B_{Sol} = KL$, where *L* is the solenoid length, $K \equiv \frac{qB_{Sol}}{2P}$, with *q* the particle charge, and *P* its momentum.

Transverse coupling at the IP



ELEGANT MRFDF



Parameter Name	Units	Type	Default	Description
FACTOR		double	1	A factor to multiple all components with.
TILT	RAD	double	0.0	rotation about longitudinal axis
A1	V/m	double	0.0	Vertically-deflecting dipole
A2	V/m^2	double	0.0	Skew quadrupole
A3	V/m^3	double	0.0	Skew sextupole
A4	V/m^4	double	0.0	Skew octupole
A5	V/m^5	double	0.0	Skew decapole
B1	V/m	double	0.0	Horizontally-deflecting dipole
B2	V/m^2	double	0.0	Normal quadrupole
B3	V/m^3	double	0.0	Normal sextupole
B4	V/m^4	double	0.0	Normal octupole
B5	V/m^5	double	0.0	Normal decapole
FREQUENCY1	HZ	double	2856000000	Dipole frequency
FREQUENCY2	HZ	double	2856000000	Quadrupole frequency
FREQUENCY3	HZ	double	2856000000	Sextupole frequency
FREQUENCY4	HZ	double	2856000000	Octupole frequency
FREQUENCY5	HZ	double	2856000000	Decapole frequency
PHASE1	HZ	double	0.0	Dipole phase
PHASE2	HZ	double	0.0	Quadrupole phase
PHASE3	HZ	double	0.0	Sextupole phase
PHASE4	HZ	double	0.0	Octupole phase
PHASE5	HZ	double	0.0	Decapole phase
PHASE_REFERENCE		long	0	phase reference number (to link with other time-dependent elements)

*ANL-ELEGANT USER MANUAL

ELEGANT MRFDF (2)

- The (2*i)th-pole component b_i is defined as:

$$\Delta p_x = \frac{e}{mc^2} \sum_{i=1}^{5} \frac{b_i}{k_i} x^{i-1} \cos(\varphi_i)$$

where

$$\Delta x' = \frac{\Delta p_x}{p_z} \;, \quad p_{x/z} = \beta_{x/z}\gamma \;,$$

and

$$k_i = \frac{\omega_i}{\beta c}$$