XAL Status at TRIUMF

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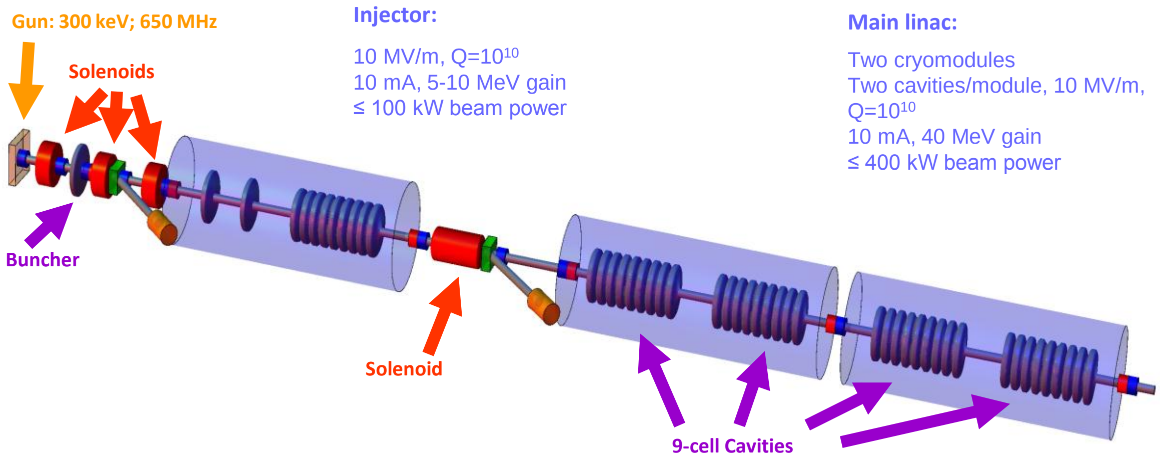
XAL Status at TRIUMF

- XAL identified as the framework for high level applications at TRIUMF
- Initial introduction & exploration – 2009
  - Talk by John Galambos
  - Tutorial by Paul Chu during PAC
  - Evaluation of infrastructure (Database, PV with physical units, modeling, ...)
- XAL infrastructure on test systems – 2010 (Thanks to help from Paul Chu)
  - Connected to EPICS control of ion source line
  - XML description of ion source line
  - Integration with virtual accelerator
  - Some example applications (automated data acquisition, ...)
- Low-β model development with intended application on Electron Linac – 2011
  - Deferring database decision (Use XML as test bed to gain experience and define database content needed)
  - Integrated into XAL framework
- Testing and application of low-β model on VECC test facility (not integrated with XAL yet) – 2011-2012
- Model based machine control included as one of Accelerator Division commitments for next 5-Year Plan

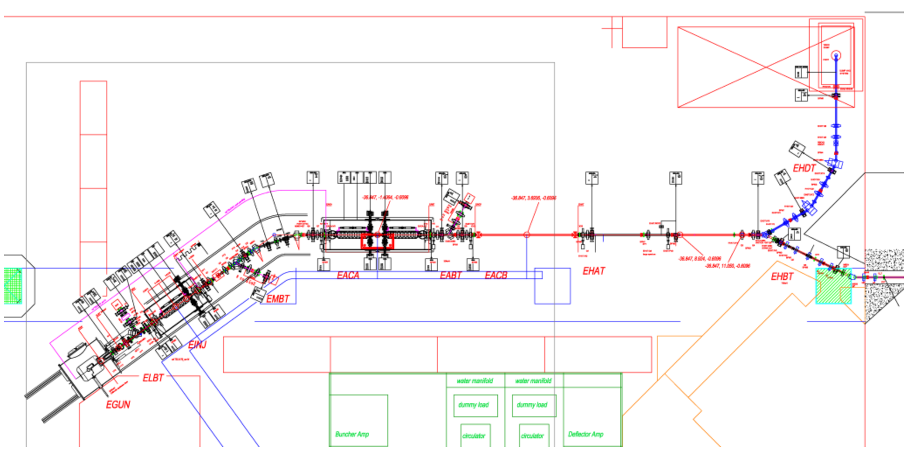
TRIUMF Electron Linac

- 45-75 MeV, 10 mA electron driven photo fission RIB facility
- Injector consists of 300 keV source and SRF acceleration to 10-15 MeV
- Linac accelerates to 45 MeV single pass or 75 MeV after recirculation
- Potential extension to energy recovered FEL at 47 MeV.

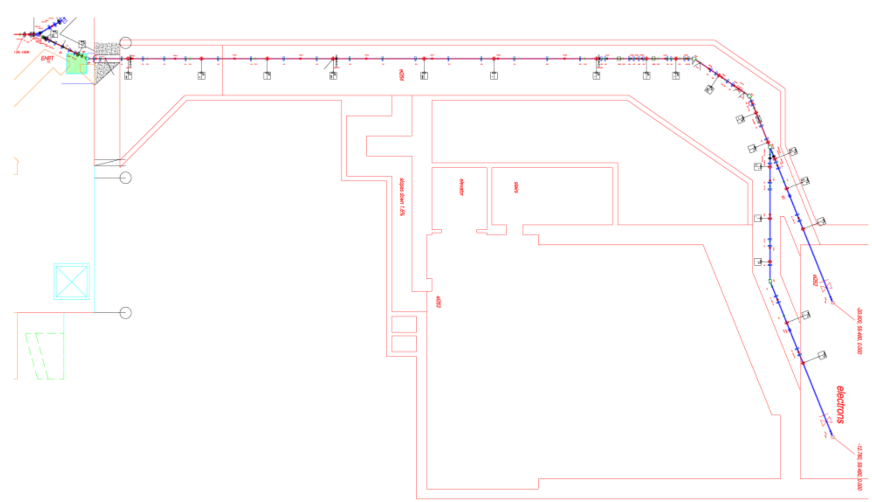
Injector and Linac Concept



Layout of Injector and Linac



Layout of 50 MeV Transport to Target



This will be the destination for XAL based control

Low-β Transport Model – to be Integrated with XAL

Motivated by the need to efficiently and correctly model E Linac at front end (300 keV – few MeV)

Time varying fields and Time coordinate are the main focus of this formulation

⇒ Analytical models have not been very successful in modeling RF effects on electrons below a few MeV; Off-design situation is even less tested.

Difficulties In Low-β Modeling by Analytical Model

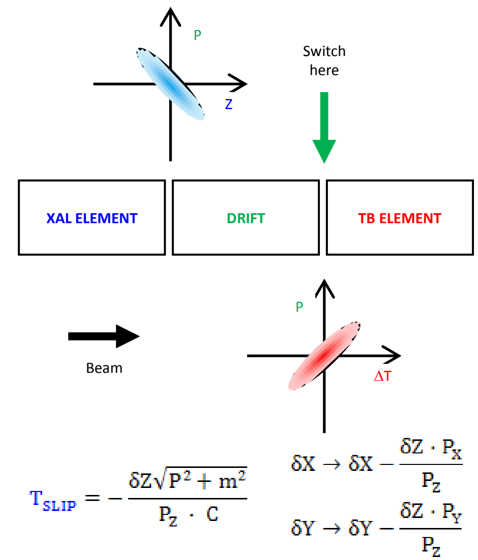
- Velocity changes within cavities
- Non-relativistic dynamics and arrival-time dependence
- Significant momentum transfer between longitudinal and transverse dimensions
- Higher order aberrations in solenoids and in cavities
- Strong chromaticity due to large momentum spread
- Elements inside fringe field of each other due to tight spacing and compact structure
- Non-trivial space charge requiring finer subdivision of elements
- Inadequate mechanism for time-varying elements off design phase
- Over-complex model when all 6 coordinates are needed to describe an element
- Effects on temporal distribution described by transfer matrices based on S-coordinates

A tracking program suffers from none of these difficulties, but it would be too slow to use online.

⇒ Single particle tracking results can be captured in interpolatable and polynomial-expandable data, to be used as an efficient online model with correct physics.

Empirical Model

- Time based formalism
  - Time slip accumulated w.r.t. reference at any S-coordinate
  - Arrival phase at time dependent components
- Compatibility/Interchangeability with XAL modeling scheme
  - Conversion between coordinates
  - Space charge modeling



Index	1	2	3	4	5	6
Coord.	δX (m)	δP_X (MeV/C)	δY (m)	δP_Y (MeV/C)	T_{SLIP} (ns)	P_Z (MeV/C)

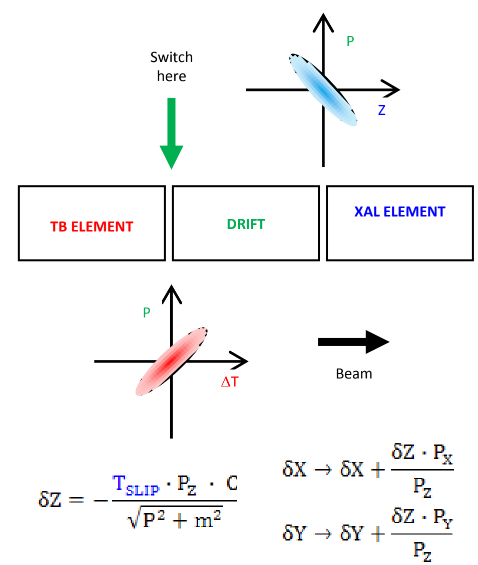
5th coordinate: Cumulative time elapsed relative to design at any given point.

$$T_{SLIP}^{N} = T_{SLIP}^{N-1} + \left(\Delta T^{N} - \Delta T_{DESIGN}^{N}\right)$$

At each such element this is translated into relevant unit, such as phase lag relative to design.

$$\Phi^{N} = \Phi_{DESIGN}^{N} + \Omega \times T_{SLIP}^{N-1}$$

Design phase Φ_{DES} as well as the interpolation table for cavities are <u>locally</u> referred to the cavity entrance and do <u>not</u> have to be redefined each time they are relocated.



Empirical Model

- Assigning building blocks of this model to XAL infrastructure

Properties of:	Element transport	Design machine state	Actual machine state	Specific input beam
Data	Empirical interpolation table	• Hardware (B_{DES}, Φ_{DES}) • Beam (ΔT_{DES}, P_{DES} …)	Hardware setting (amplitude, phase….)	• Instantaneous (α, β, P) • Cumulative (T_{SLIP})
Implementation	Element attribute	Element attribute	PV	Probe

- Deterministic vs Dynamic propagation & optimization
  - Deterministic propagation/optimization
    - Single-particle transport
    - On-design transport
    - Analytical optimization techniques
  - Dynamic propagation/optimization
    - Beam distribution needed
    - Off-design transport
    - Empirical, heuristic optimization techniques

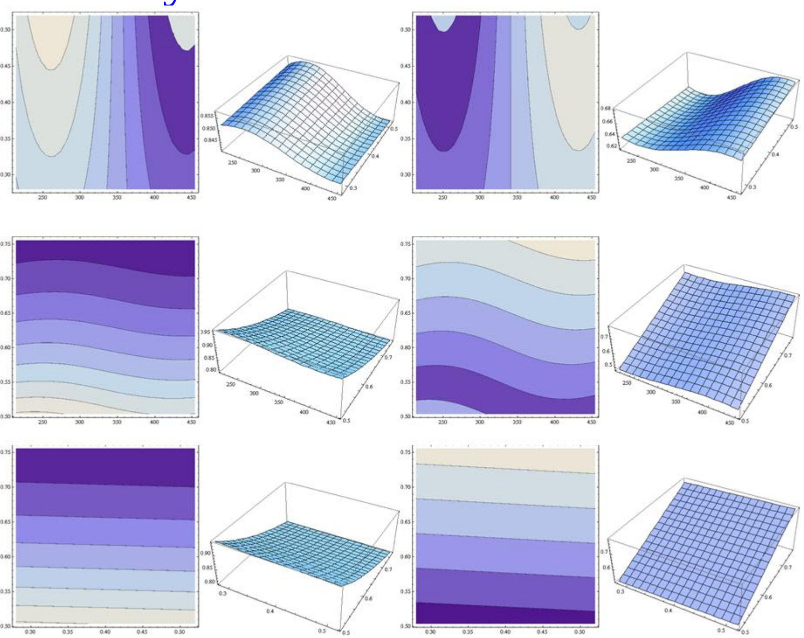
	Single Particle Diag./Control	Phase Space Diag./Control	Beam Propagation – No Space Charge	Beam Propagation – Space Charge
Needed/ Affected Elements	• Optical elements • Steering elements • BPM	• Optical elements • Phase space monitors	• Optical elements • Phase space monitors • Steering elements • BPM	• Optical elements • Phase space monitors
Object Method Used	• Transfer matrix concatenation • Extract higher order transport coefficients	• Transfer matrix concatenation • Extract higher order transport coefficients	• Propagate beam distribution without space charge	• Propagate beam distribution with space charge
Design Particle as Reference	• Mostly (transfer matrices extracted from design trajectory)	• Mostly (transfer matrices extracted from design trajectory)	• No (Each particle executes own transport)	• No (Each particle executes own transport)
Segmented Optical Elements	• Needed for elements inside fringe fields • Effect handled by matrix inversion	• No perceivable needs • Matrix inversion is sufficient	• Needed for elements inside fringe fields • Needed for inspection inside optical elements	• Needed for compounding space charge effects in subdivided steps
Dimensions	• Transverse planes only • Longitudinal plane only	• Transverse planes only • Longitudinal plane only	• Full 6D or subspace	• Full 6D or subspace
Optimization Methods	• Linear methods • Other analytic methods • Empirical methods	• Linear methods • Other analytic methods • Empirical methods	• Linear methods • Other analytic methods • Empirical methods	• Empirical methods
Examples	• Misalignment analysis • Orbit correction • Energy offset diagnosis/correction	• Phase space measurement (e.g., linear tomography) • Betatron matching	• General simulation of beam propagation and experimental procedures	• Tomography based on empirical optimization • Empirical matching • General simulation of experimental procedures

Empirical Model

- Interpolation table and expansion coefficients

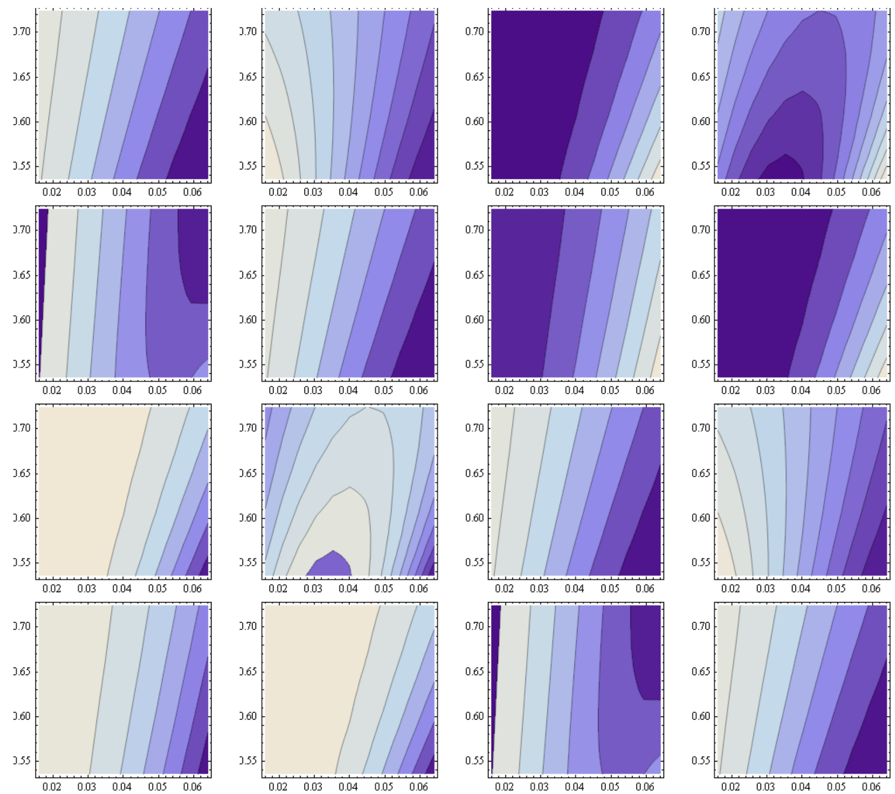
Extract transport properties calculated by tracking program in the form of

- Transit time ΔT, Exit momentum P, and Exit transverse coord. (δX, δP_X, δY, δP_Y)
- Expanded in powers of Entry transverse coord. (δX, δP_X, δY, δP_Y)
- Interpolated as functions of
  - Phase Φ (e.g., RF)
  - Tuning parameters (B, ΔE....)
  - Entry momentum P.



Contour and 3D plots showing dependence of ΔT (left) & P_{TOTAL} (right) at exit of buncher cavity. Top to bottom:

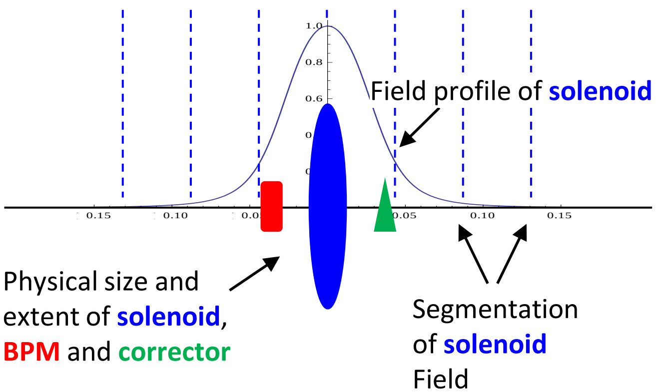
- P=0.65 MeV; Scan over amplitude (MV/m) and phase (°)
- Amplitude=0.4 MV/m; Scan over P_{IN} (MeV) and phase (°)
- Phase=440°; Scan over P_{IN} (MeV) and amplitude (MV/m)

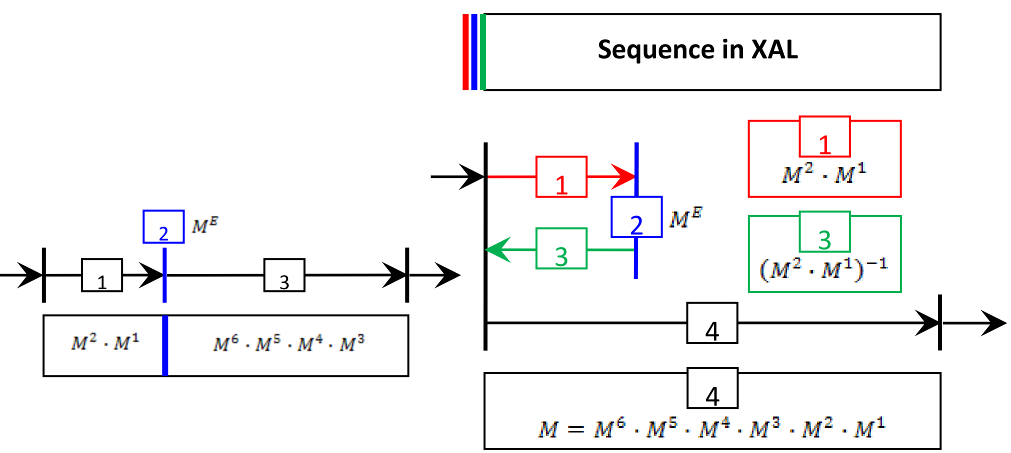


4×4 Contour plots showing dependence of 4×4 transverse transfer matrix coefficients on P_{IN} (MeV) and B field (T).

Empirical Model

- Segmentation of Elements
  - Elements in each other's fringe field – Interpolation table constructed for slices
  - Space charge modeling using XAL SC algorithm converted to time based





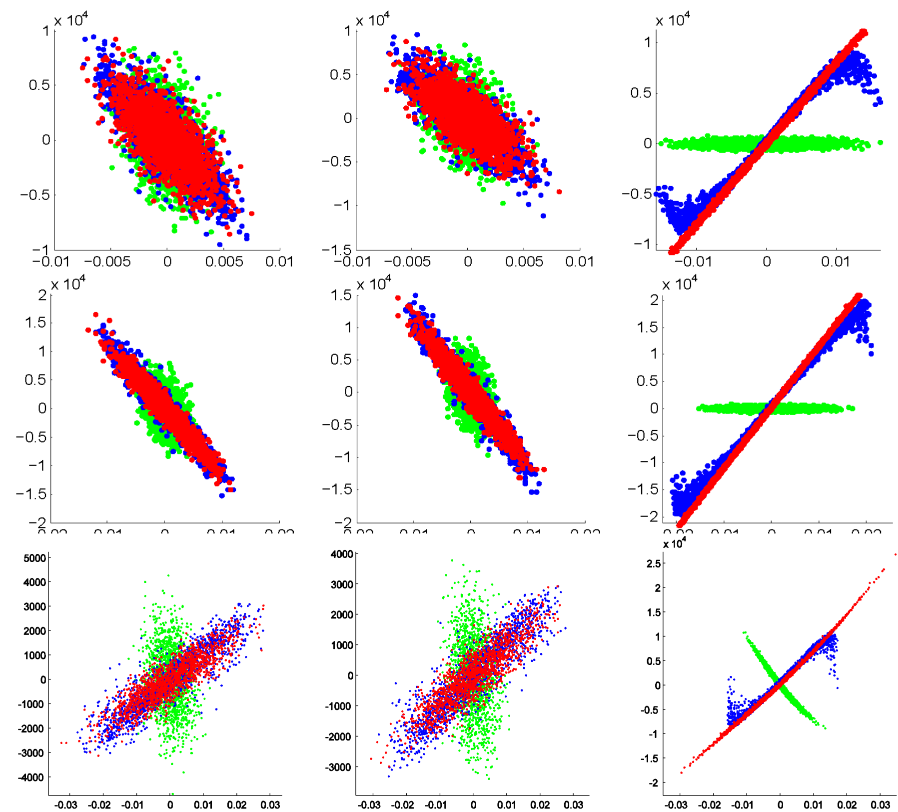
Space charge propagation by time-based empirical model through subdivided segments using equivalent ellipsoidal beam ansatz (red) vs Astra (blue). Green is propagation w/o space charge.

Left to right: P_X (eV)-X(m), P_Y (eV)-Y(m), P_Z (eV)-Z(m)

Top: 100 pC through solenoid.

Middle: 300 pC through solenoid.

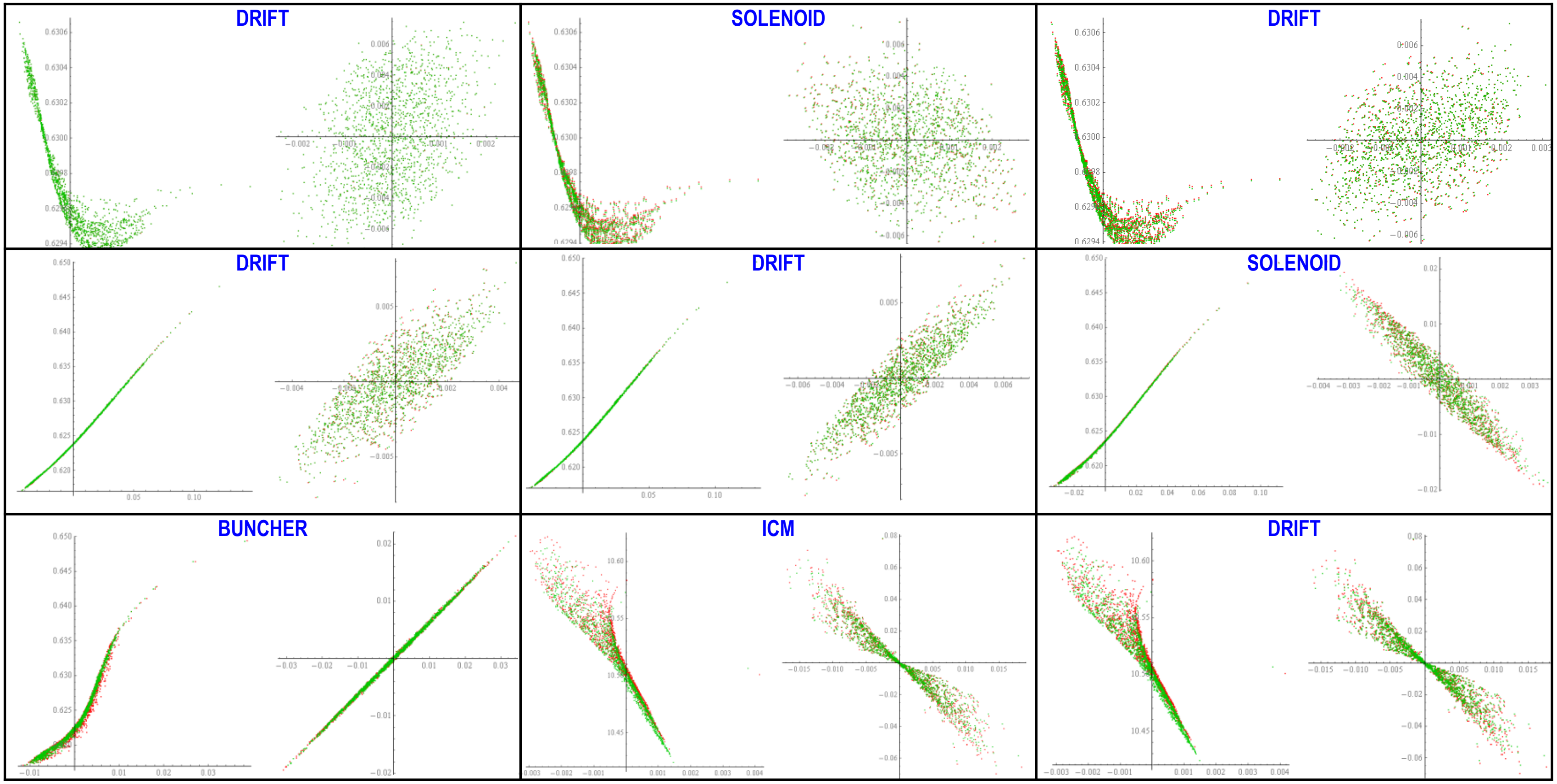
Bottom: 300 pC through solenoid + cavity + solenoid.



Propagation of Realistic Ensemble Using Empirical Model

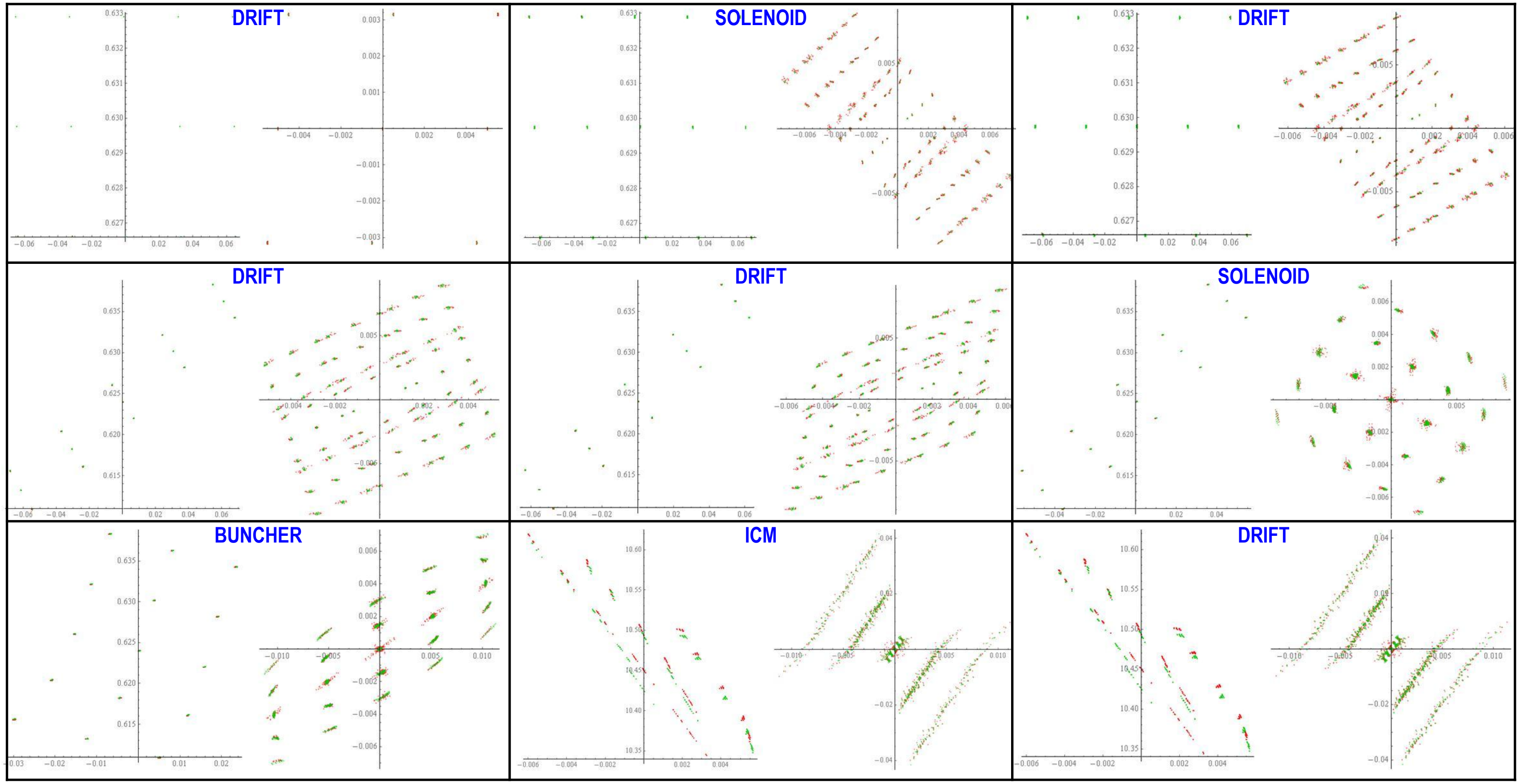
- Test ability to capture complex time dependent low energy dynamics
- Up to 4^{th} order expansion is needed

Beam propagation by Empirical Model (green) & Astra (red) **from 300 keV to 10 MeV through two solenoids, one buncher and one ICM cavity.** All plots: Left: P_Z (MeV/C) vs ΔT (ns); Right: $\delta P_{X/Y}$ (MeV/C) vs $\delta X/Y$ (m). Thermionic gun output is used for initial distribution.

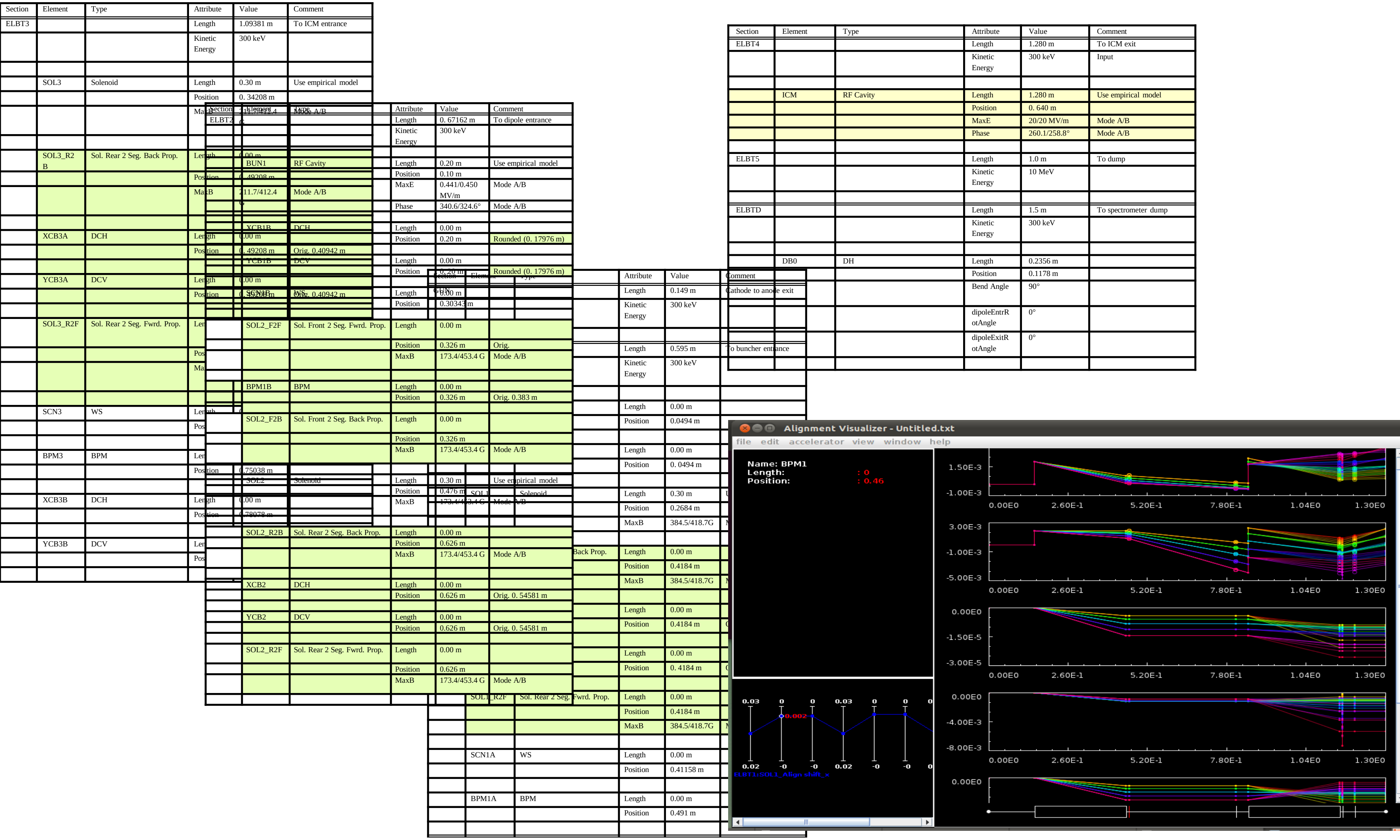


Propagation of 6D Grid Using Empirical Model

Same comparison between Empirical Model (green) & Astra (red) Large amplitude 6 D grid is used for initial distribution.



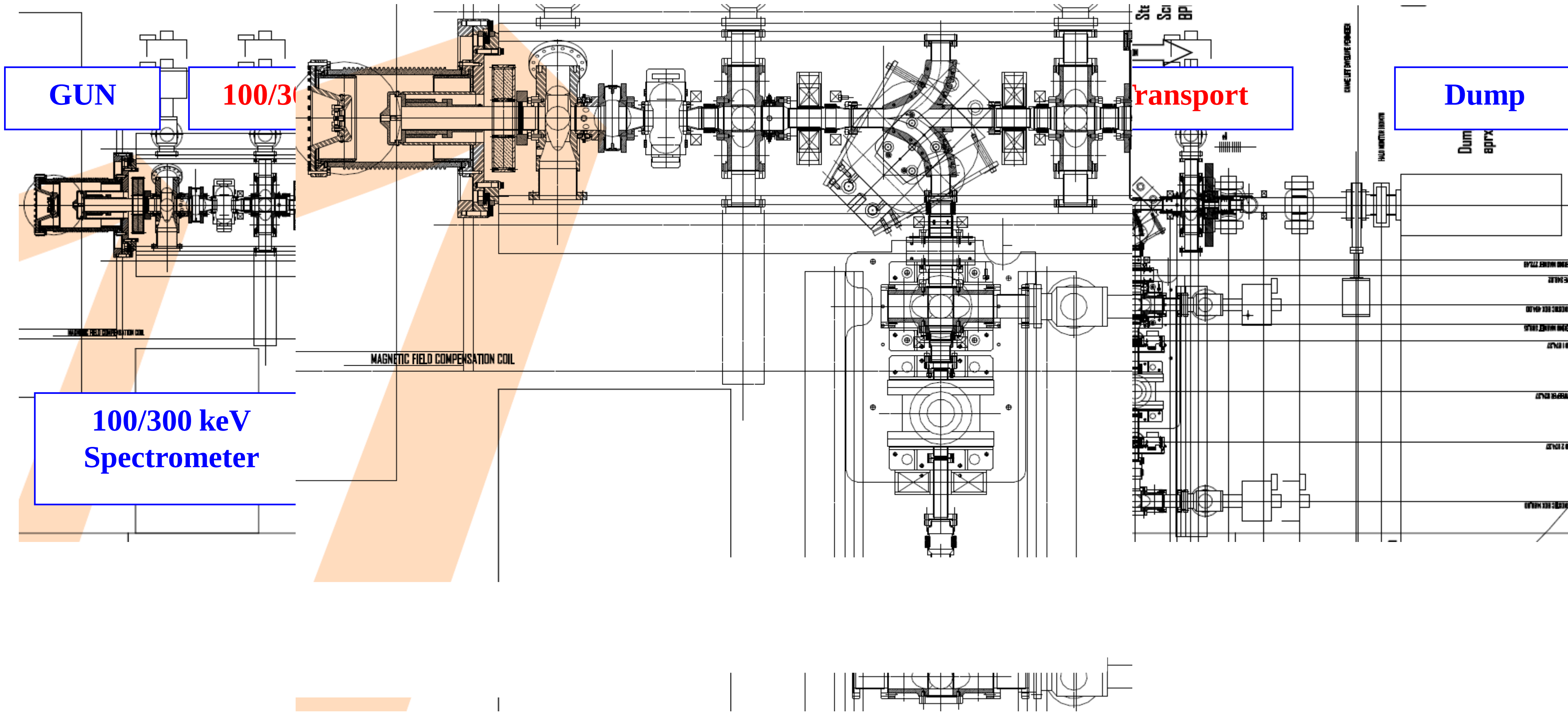
Some Applications Were Developed on Virtual Accelerator



A demo high level application program built on XAL framework using low energy empirical model to perform solenoid misalignment analysis

VECC Test Facility – Prototype of E Linac Front End

Full Complement



Beam Based Characterization of VECC

Purpose

- Understand & Debug VECC longitudinal & transverse transport – Resolve discrepancy / Update model
- Enable translation of beam phase space between any two points
- Provide basis for model based high level diagnostic & control algorithms

6D Transport

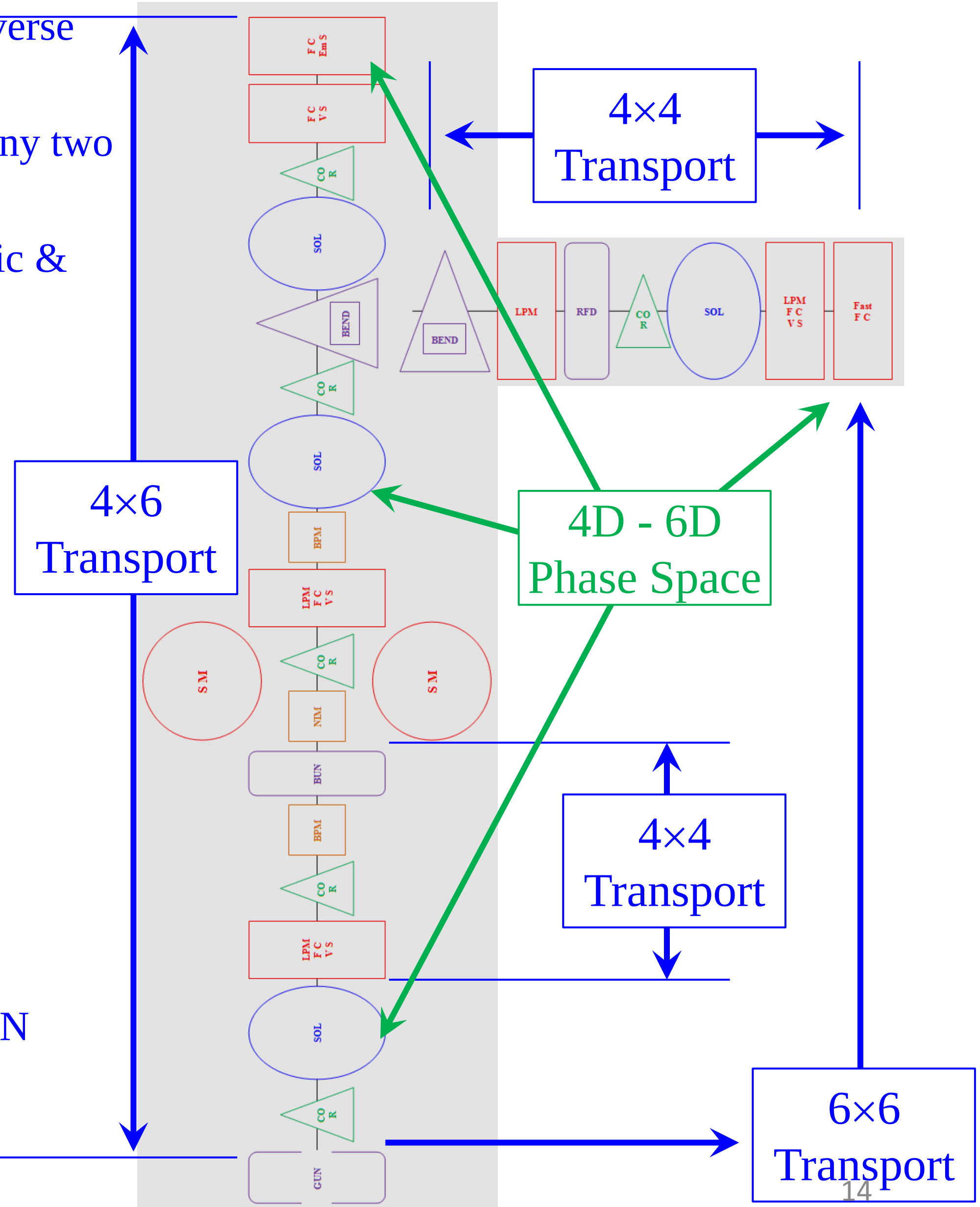
- Between key locations
- Across key components
- Amplitude dependence
- Critical to phase space determination

6D Beam Phase Space

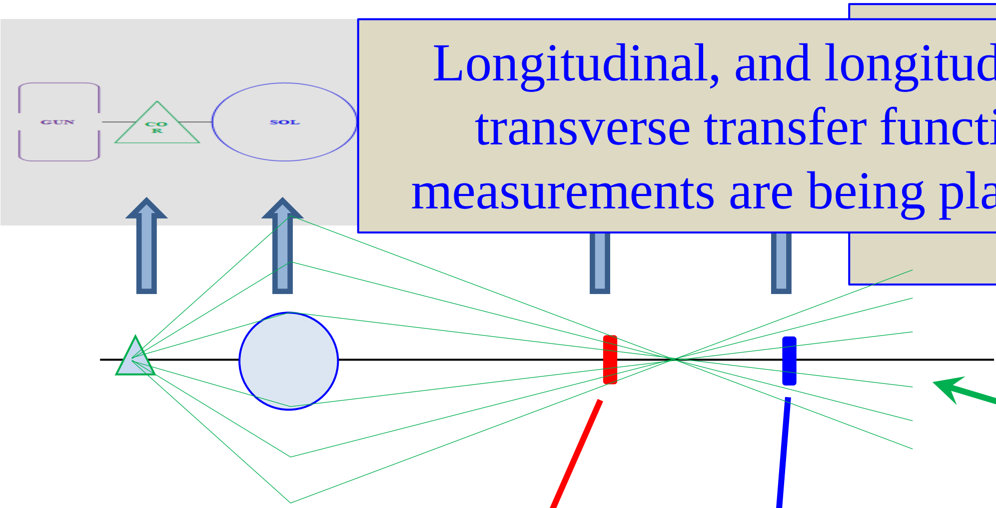
- At key locations
- Consistency with 6D transport
- Consistency among different methods
- Dependence on space charge

Offline Feasibility Studies

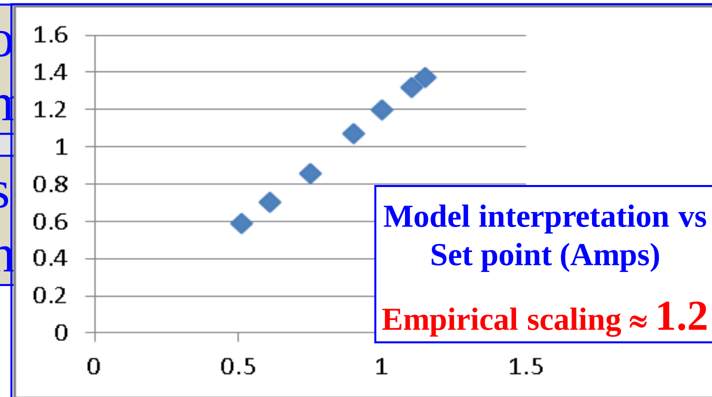
- GPT simulation - Configuration robustness and S/N
- Empirical transport model – Fast exp. simulation
- Special machine tune for measurements



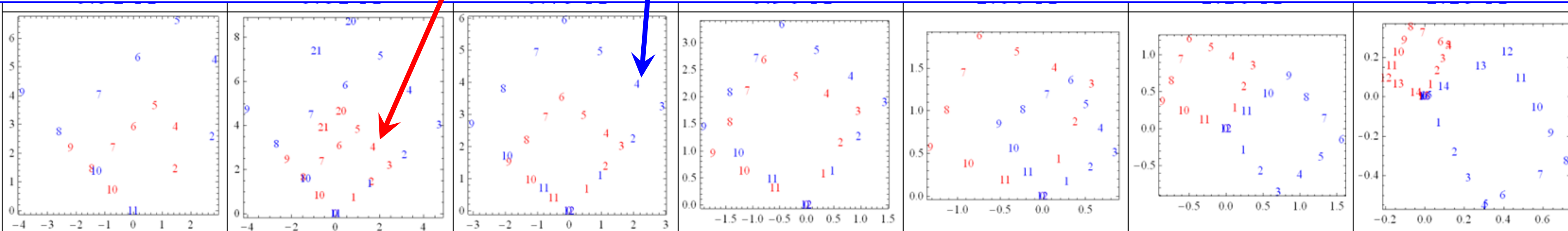
Transport Model Measurement & Calibration



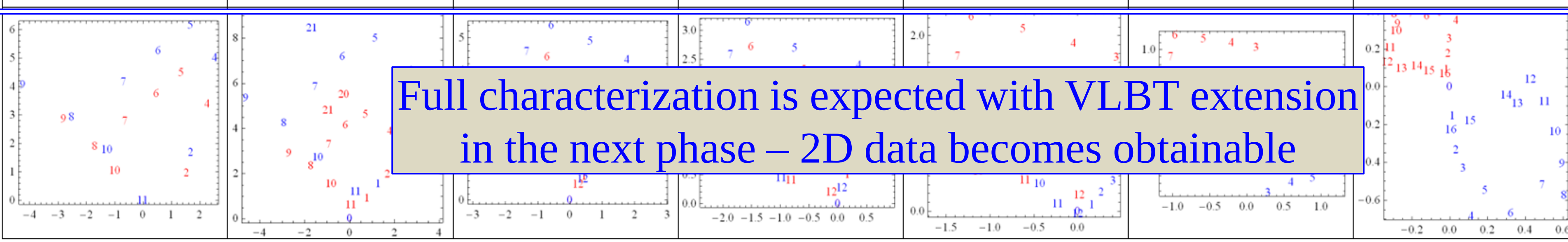
Longitudinal, and longitudinal-transverse transfer function measurements are being planned.



Orbit scan patterns launched across Solenoid & recorded at BPM1A and BPM1B at various solenoid strengths



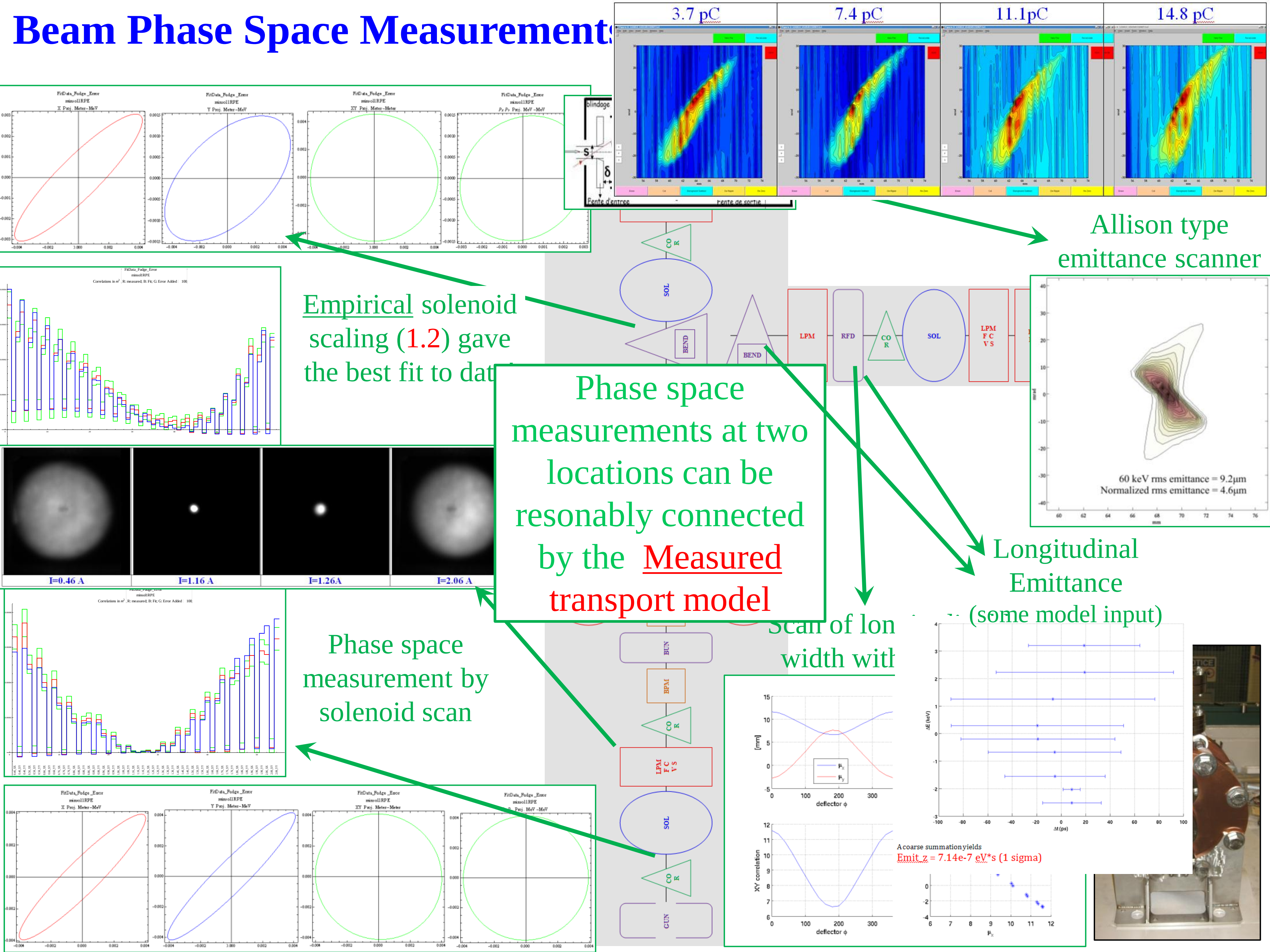
0.51 A	0.61 A	0.75 A	0.90 A	1.00 A	1.10 A	1.15 A



Full characterization is expected with VLBT extension in the next phase – 2D data becomes obtainable

Top: Model interpretation of data; Bottom: Data

Beam Phase Space Measurement



Allison type emittance scanner

Empirical solenoid scaling (1.2) gave the best fit to dat

Phase space measurements at two locations can be resonably connected by the Measured transport model

Phase space measurement by solenoid scan

Scan of lon

width wit

Longitudinal Emittance

(some model input)

Summary

• XAL identified as the framework for TRIUMF E Linac

• Commitment from Accelerator Division for model based control

• Complementary low-β model developed and being beam tested

• Major infrastructure work awaits (Database, PV with physical units….)

• Ambitious plan for comprehensive high level model based diagnostic and control – However resource needs be identified.

• Help/collaboration from community would be key.