# DYNAC Simulation code for linacs: An introduction

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# Outline

- Origins of the DYNAC beam dynamics simulation code
- Main characteristics and features
- Example input and output files & graphics
- Bench marking
- GUI development

# Forerunner of DYNAC was developed in the 1980s by P.Lapostolle and S.Valero

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- Simulation and commissioning of heavy ion booster at SACLAY
  - Booster consisting of long complex super-conducting helical shaped accelerating elements

- Based on a Liouvillian set of equations of motion in a thin lens approximation (as in PARMILA), but modified to be able to simulate multi-gap asymmetric fields

# At CERN, further development of what became DYNAC started in the late 1980s

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- Goal was to be able to simulate both CERN heavy ion linac (Linac 3) design contenders:
    - IH linac design developed at GSI (reference particle and center of gravity of beam do not coincide!)
    - Quasi-Alvarez design developed at CERN
- In the 1990s, introduction of a new Liouvillian set of equations in a thick lens approximation and 3D space charge (routines SCHERM and HERSC)
- DYNAC used on different machines:
    - Simulation and commissioning of CERN heavy ion linac (Linac 3)
    - Simulation of CERN 180 mA proton MEBT-DTL (Linac 2)
    - Simulation of low energy electrons in multi-gap super conducting cavities at SACLAY

# DYNAC characteristics driven by developments in and requirements from accelerator design (slide 1 of 4)

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- In the 1960s a theory was derived (P. Lapostolle, A.Carne, M. Promé), giving a general definition of TTF and justifying the use of a 'thin lens' method for the treatment of the gaP

- These equations, respecting Liouville's theorem, refer to a trajectory which crosses the mid gap plane of single symmetric short accelerating gaps

- For the development of heavy ion multi-gap super conducting helical cavities at SACLAY which present no exact symmetry, a new formalism was needed

# DYNAC characteristics driven by developments in and requirements from accelerator design (slide 2 of 4)

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- A new formalism was derived in 1980 (P. Lapostolle, S. Valero):
    - Asymmetric and multi-gap cavities are treated as the second half of a double length one (sum of symmetrical and anti-symmetrical fields), using the mid cavity calculation formalism with the input values
    - The phase evolution is considered linear and includes a phase jump
- But for particles accelerated through long accelerating elements with complex electromagnetic fields (transit time is ≅ 10 pi , velocities vary by ≥ 10%) another set of equations is required

# DYNAC characteristics driven by developments in and requirements from accelerator design (slide 3 of 4)

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- In 1994 a full set of quasi-Liouvillian equations, accurate beyond the second order, was introduced in DYNAC [1]
  - Due to the fact that *r* and *r´* are not canonically conjugate variables, developing second order corrections to improve the transverse motion computation is hardly possible. This difficulty has been resolved with the ***Picht transformation***: $R = r\sqrt{\beta\gamma}$
  - The ***equivalent accelerating field*** replaces the complex real field distribution acting on the particle by one giving equivalent dynamics but simpler in form. The phase evolution is now represented by a polynomial of the fifth order.
  - With the equivalent field, the TTFs and their derivatives can be defined for the synchronous particle, which then allows to calculate the particle dynamics directly from Taylor series.

[1] P.Lapostolle, E.Tanke, S.Valero, ”A New Method In Beam Dynamics Computations For Electrons And Ions In Complex Accelerating Elements”, Particle Accelerators, 1994,Vol.44, pp. 215-255.

# DYNAC characteristics driven by developments in and requirements from accelerator design (slide 4 of 4)

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- Today (like 30+ years ago!) it is desirable to have a fast beam dynamics code
  - The analytical formalism (previous slide) is by far faster than a numerical method, but cannot handle multi-charge state beams
  - In using Bode's rule applied to the 'reduced coordinates' resulting from a Picht transformation, the numerical method in DYNAC is faster than other step by step methods. This method supports multi-charge state beams.
  - DYNAC uses an analytical approach in its 3-D space charge routine HERSC [1], which is faster than P2P routines and avoids certain issues with 3D-PIC

[1] P. Lapostolle et al, "HERSC: A New 3 Dimensional Space Charge Routine For High Intensity Bunched Beams", presented at the LINAC2002 conference

# DYNAC has a wide spread of features (slide 1 of 2)

- Can handle single and multi-charge state beams
  - Input distributions can be read or generated
- Contains 3 methods for standard accelerating elements
  - Thin lense (e.g. for DTL cells)
  - Thick lense (analytical method); single charge state beams
  - Fast numerical method; single and multi-charge state beams
- Also contains models for RFQ, electron gun and electrostatic lenses
  - For the RFQ, the beam dynamics in the RMS and in the Fringe Field can be calculated either by using the potential function or the profile of the electrodes

# DYNAC has a wide spread of features (slide 2 of 2)

- Contains 3 space charge routines:
  - ➢ SCHEFF based on 2D PIC method in PARMILA, but modified to
    - ◆ be relativistic
    - ◆ avoid as much as possible empty cells in the 2D mesh
    - ◆ treat space charge of multi-charge beams for disconnected bunches (e.g. in a bending magnet)
  - ➢ SCHERM 3D method, based on multi-ellipsoid representation (in transverse planes only)
  - ➢ HERSC 3D analytical method, without any basic assumptions on the bunch distribution. Space charge fields are directly calculated from Poisson's equation
- SCHERM & HERSC cannot be used for multi-charge state beams

# DYNAC is freeware

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- Code package based on freeware
  - Compiler is gfortran
  - Graphics post-processor based on GNUplot
  - Same program and interface under LINUX, MAC and WINDOWS
- Code package contains
  - Source code
  - User guide
  - Graphics post processor
  - Example input files
- Code package is freeware and is available from:

  http://dynac.web.cern.ch/dynac/dynac.html

# Input file based on sequential set of keywords with concomitant data

```
RDBEAM
ESS_MEBT_in_63mA.dst
0
352.21 0.
938.2796 1.
3.6223537 1.
EMITGR
PROTON BEAM AT ESS MEBT INPUT (62.5 mA)
0 5
.5 80. .5 80. .5 .5 50. 1.0
SCDYNAC
1
62.5  3.
0
;---- lat.mebt_2014.v1_nom.dat 8-Jun-2014
DRIFT
  15.00
;MATCH_FAM_GRAD 66 8
QUADRUPO
  4.00     -1.48652     0.920
```

*Define input beam*

*Request emittance plots*

*Select space charge routine*

*First beam line element*

*Second beam line element*

***Currently there are 61 keywords available***

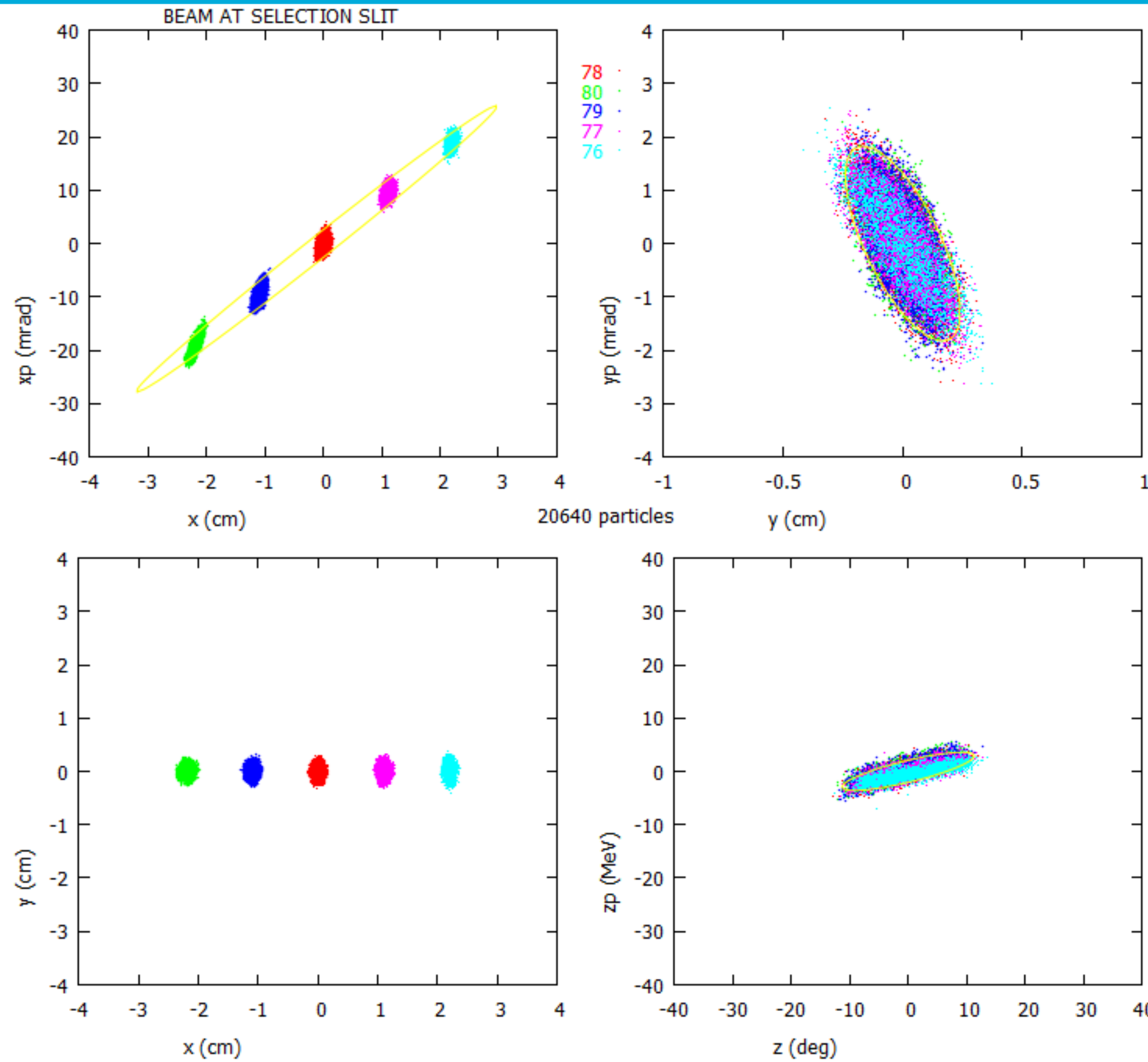
# Selection of output data files available

- dynac.dmp
  - Element by element data such as emittances, energy, TOF
  - Useful for plotting emittance, energy evolution etc
- dynac.short
  - Comprehensive list of more detailed element by element beam data
- dynac.long
  - Very detailed output file, can be of use for debugging
- Other files are available, such as the one used by the graphics post processor or particle distribution files where ever requested with the WRBEAM card

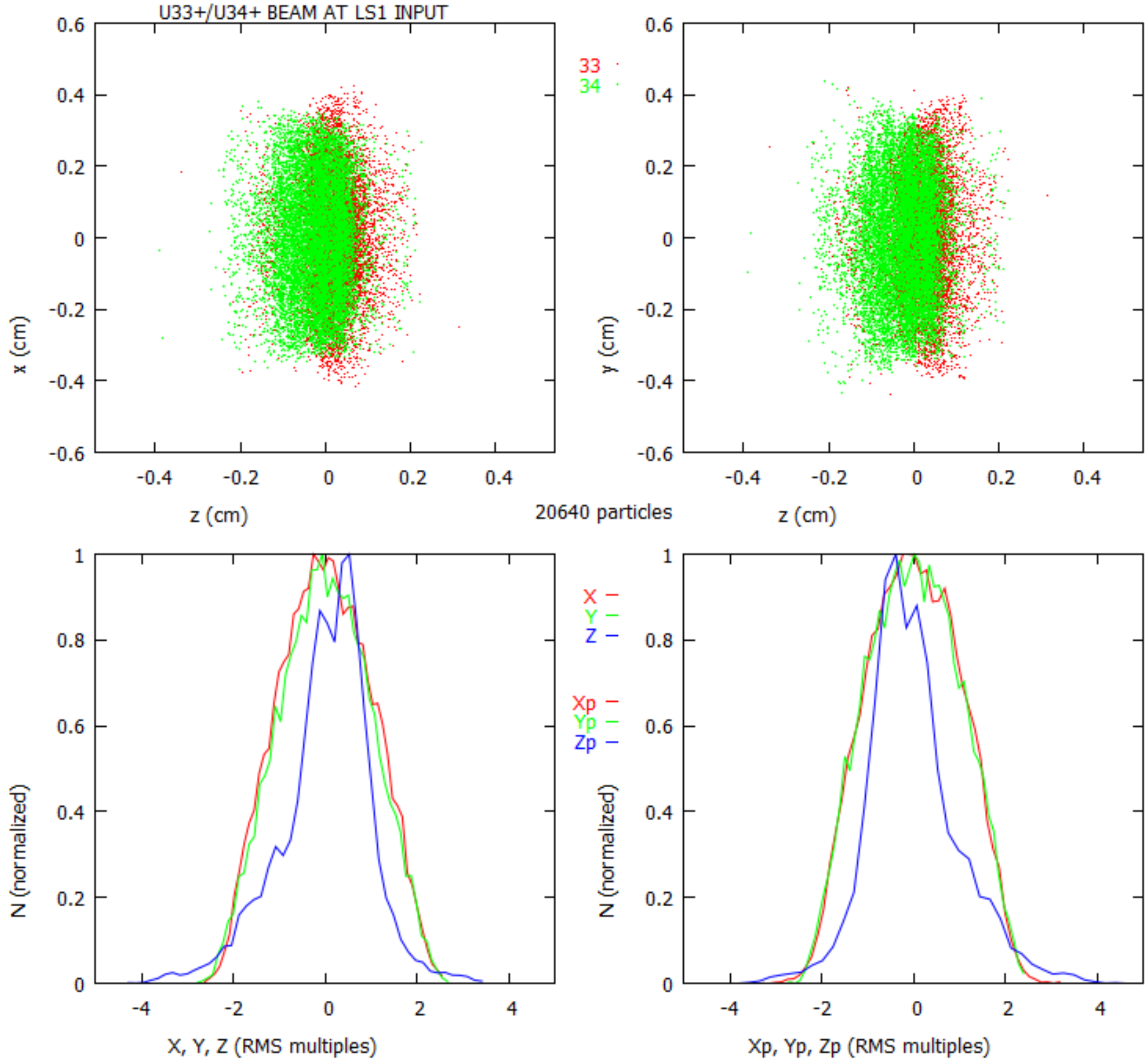
# Example of dynac.short output data file

```
******** DYNAC V6.0R10 (Beta), 8-Aug-2014 *********
 Input file: dynac_rb_sp_scherm.in
 Started on Sat Aug 09 2014 at 19:29:49
 ESS DTL 62.5 mA benchmark
****************************************************
  Energies are in [MeV], phases in [deg] lengths in [mm] ,tof in [deg]
  ** For lenses followed by : Cummulative length, element type, length
  ** For emit followed by
  * Line 1: Particle reference:  beta, energy, tof   COG: energy, tof, energy offset, tof offset
  * Line 2: COG coordinates for x  xp  y  yp (mm and mrad)
  * Line 3: alpha-x beta-x(mm/mrad) alpha-y beta-y(mm/mrad) alpha-z beta-z(ns/keV)
  * Line 4: alpha-z beta-z(deg/keV) emit-z(non norm.,keV.deg) f(MHz)
  * Line 5: dPHI(deg)  dW(keV)   r12   long. emittance  (keV.ns) particles left
  * Line 6:   x(mm)    xp(mrad)  r12   hor.  emittance  (norm & non norm, mm.mrad)
  * Line 7:   y(mm)    yp(mrad)  r12   vert. emittance  (norm & non norm, mm.mrad)
****************************************************
          Simulation with       49058  particles
          First order transport matrix
          Beam intensity    62.50      mA
          Space charge calculations with SCHERM
 Space charge calculated for accelerating elements only
****************************************************
**********         beam (emit card)        **********
  0.08759  0.3620000E+01  0.0000000E+00  0.3621451E+01  0.2380946E+00   0.14514E-02   0.23809E+00 MeV-deg
   0.001    0.002    0.000    0.003 mm and mrad
  0.13327E+01   0.21507E+00  -0.41424E+01   0.76190E+00  -0.12273E+00   0.21953E-02
  -0.1227   0.278351E+00   0.583986E+03 keV.deg   352.210 MHz
  0.12750E+02    46.15    0.1218    4.606 ns.keV    49058. particles left
   1.665     12.899   -0.7999   0.11335E+01 mm.mrad (norm)   12.889 (non norm)
   3.177     17.768    0.9721   0.11649E+01 mm.mrad (norm)   13.246 (non norm)

   25.00 mm  Quadrupole:  length =  0.25000E+02 mm  aperture radius =  0.50000E+01 mm
  field = -0.29972E+01 kG  K2 = -0.21779E-01 cm-2 gradient = -0.59944E+01 kG/cm
  momentum =  0.27524E+03 kG.cm  particles left   49058.
   50.00 mm  Quadrupole:  length =  0.25000E+02 mm  aperture radius =  0.50000E+01 mm
  field = -0.29972E+01 kG  K2 = -0.21779E-01 cm-2 gradient = -0.59944E+01 kG/cm
  momentum =  0.27524E+03 kG.cm  particles left   49058.

  100.24 mm Ac. gap   1 length   75.24 mm field  0.30000E+01 kV/mm  phase of RF (middle): -0.36300E+02 deg
```

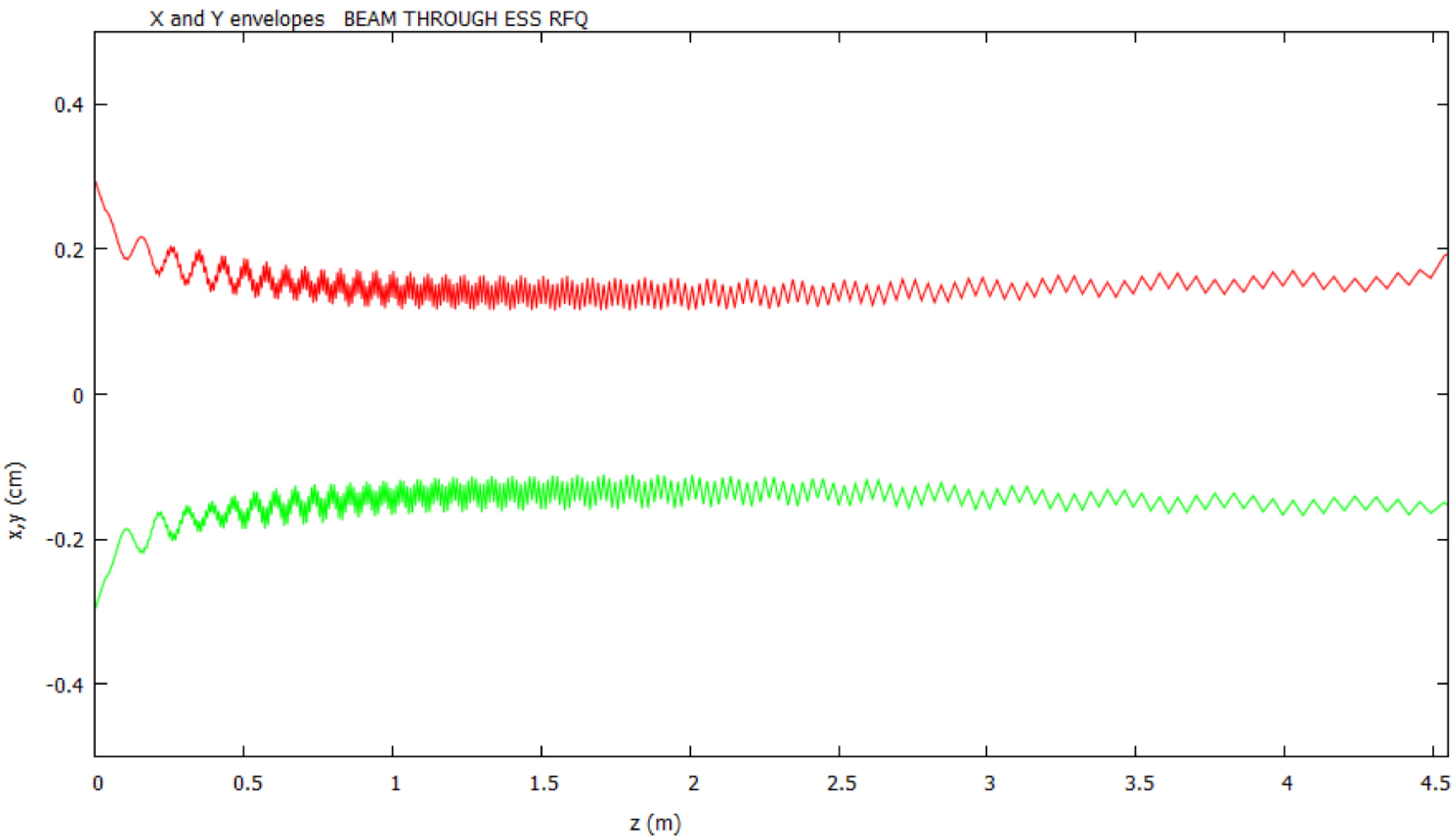
# Out of the box graphics based on GNU Plot: *Emittances for multi-charge state beam*



# Out of the box graphics based on GNU Plot: *Profiles for multi-charge state beam*



# Out of the box graphics based on GNU Plot: *Beam envelopes*



# Benchmarking with measurement: MEBT behind CERN LIS RFQ

- Longitudinal phase plane measurements behind a 4 gap buncher

Measurement vs. simulation

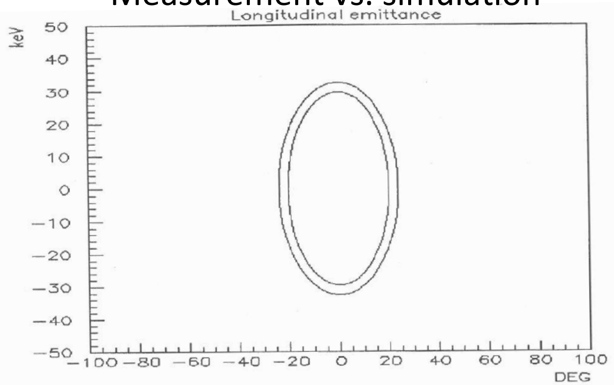
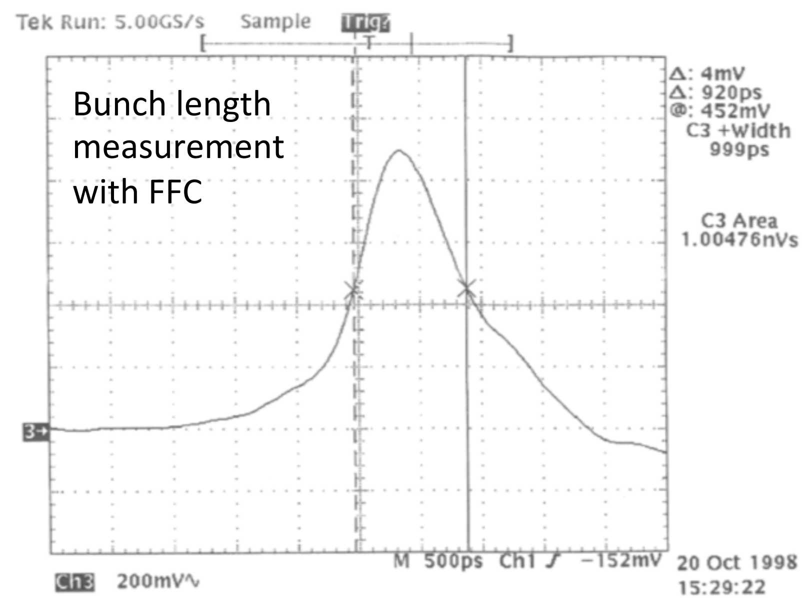
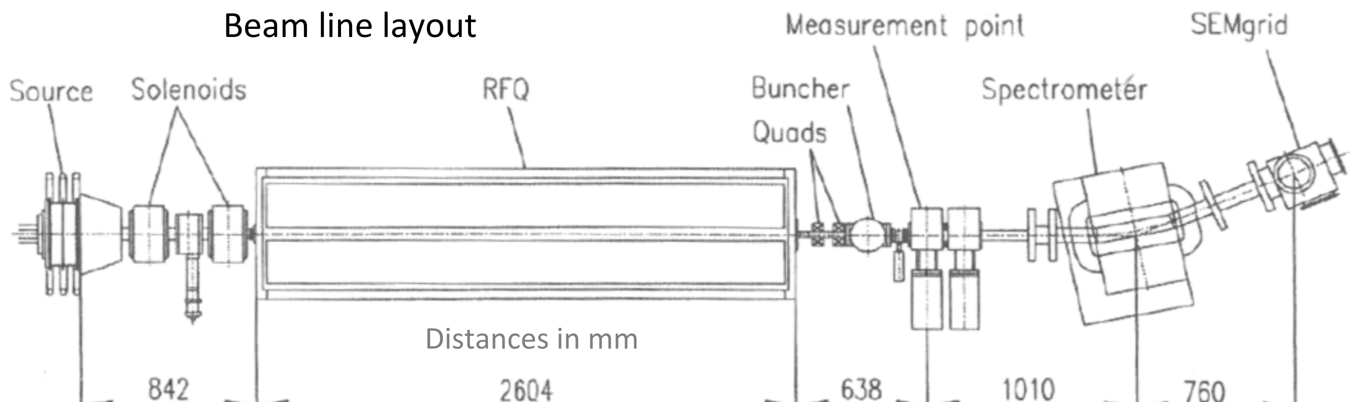



Fig 7 The (total) longitudinal emittance at the measurement point as measured using the BLVD (bigger ellipse) and calculated by DYNAC (smaller ellipse) for the same buncher setting.




Beam line layout



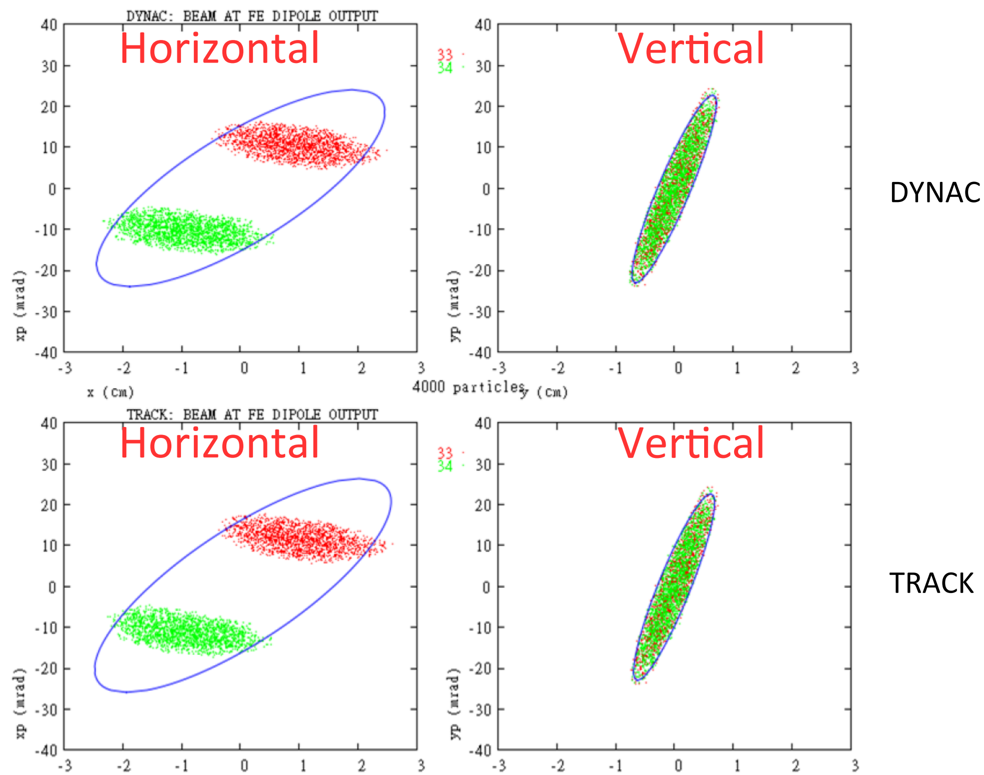
# Benchmarking with TRACK: FRIB electrostatic dipole

- The DYNAC hardedge model for this dipole, which has an effective field length of 1 m, has been benchmarked against TRACK, which used a 3-D representation of the 1.7 m long field. This dipole has a field gradient of about 0.93.

Table 1: DYNAC and TRACK horizontal emittance data for a multi-charge state beam tracked through a FE dipole

| Parameter | $U^{33+}$ | $U^{34+}$ |
|---|---|---|
| $\alpha_x$,DYNAC | 0.431 | 0.360 |
| $\alpha_x$,TRACK | 0.465 | 0.440 |
| $\beta_x$,DYNAC | 2.586 | 2.695 |
| $\beta_x$,TRACK | 2.605 | 2.551 |
| $\varepsilon_x$,DYNAC | 54.03 | 53.72 |
| $\varepsilon_x$,TRACK | 54.28 | 53.94 |

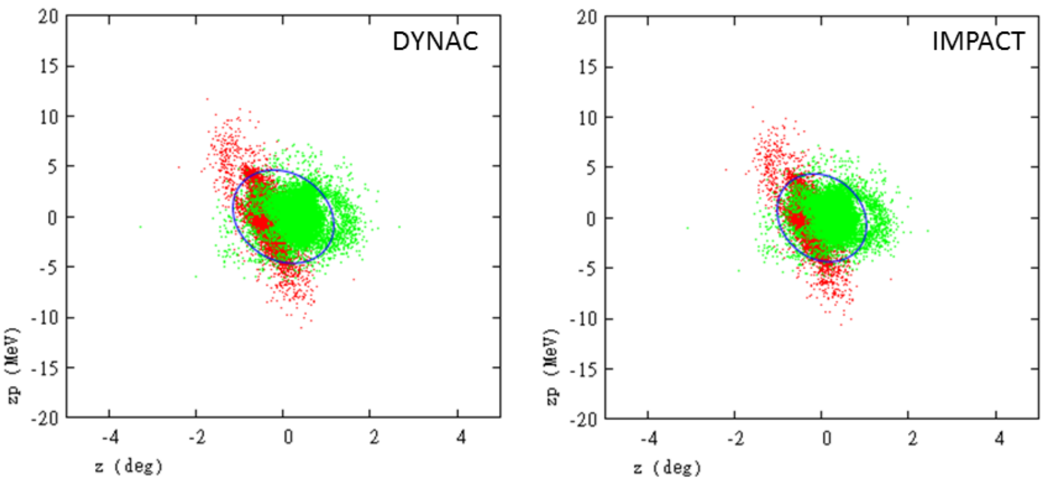
- The differences in the vertical phase plane are smaller than in the horizontal one.



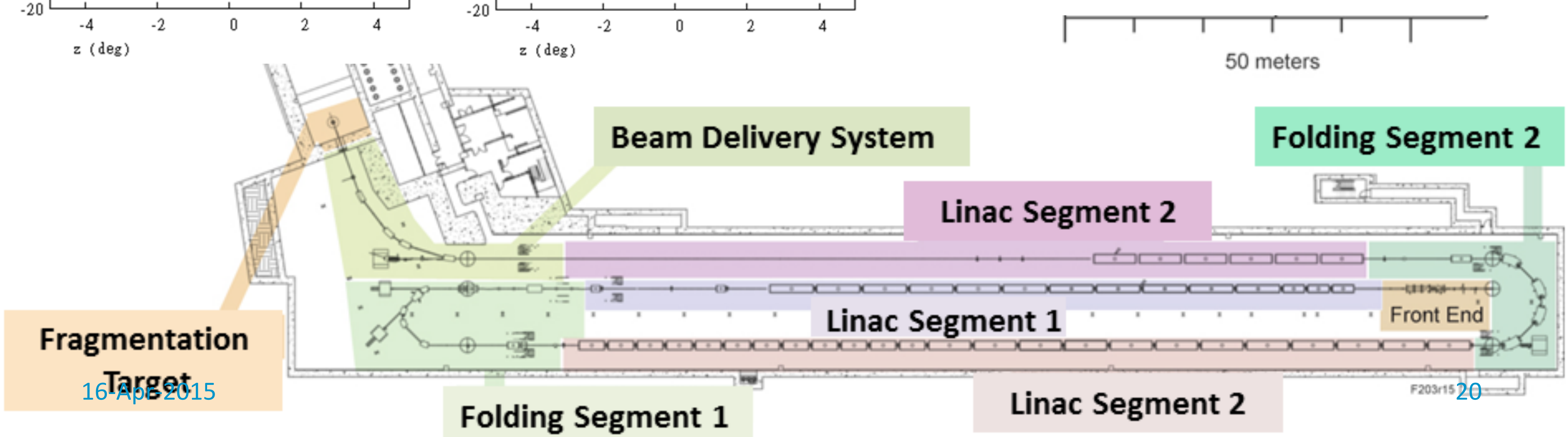

The output distributions are shown for a 12 keV/u uranium beam with charge states 33+and 34+.

# Benchmarking with IMPACT: FRIB Linac Segment 1

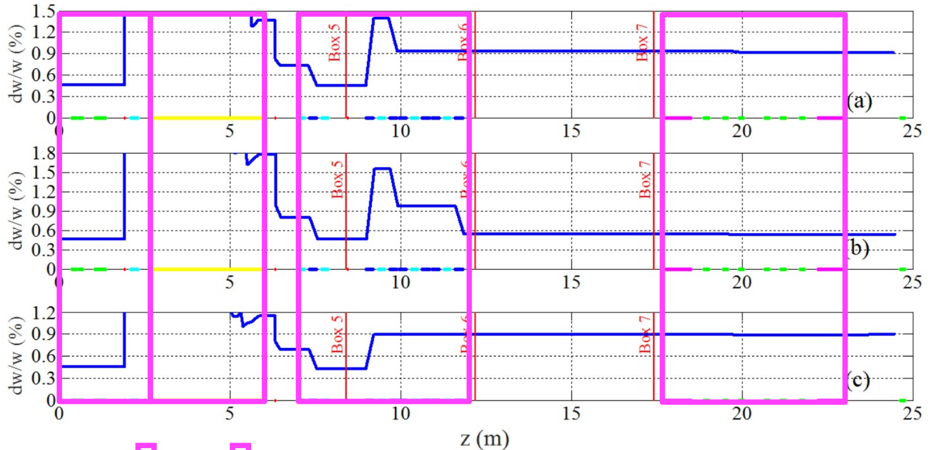
- U33+, U34+ beam, passing through the 100 accelerating cavities of FRIB Linac Segment 1




| | $U^{33+}$ | | | $U^{34+}$ | | |
|---|---|---|---|---|---|---|
| | H | V | L | H | V | L |
| $\alpha_{DYNAC}$ | 0.016 | -0.029 | 0.844 | -0.379 | -0.095 | 0.056 |
| $\alpha_{IMPACT}$ | -0.008 | 0.051 | 0.813 | -0.277 | 0.012 | 0.082 |
| $\beta_{DYNAC}$ | 0.396 | 0.378 | 1.6E-4 | 0.248 | 0.243 | 2.5E-4 |
| $\beta_{IMPACT}$ | 0.429 | 0.422 | 1.6E-4 | 0.261 | 0.279 | 2.6E-4 |
| $\varepsilon_{DYNAC}$ | 2.284 | 2.279 | 2181.1 | 2.333 | 2.360 | 2944.7 |
| $\varepsilon_{IMPACT}$ | 2.287 | 2.283 | 1965.8 | 2.316 | 2.348 | 2580.1 |



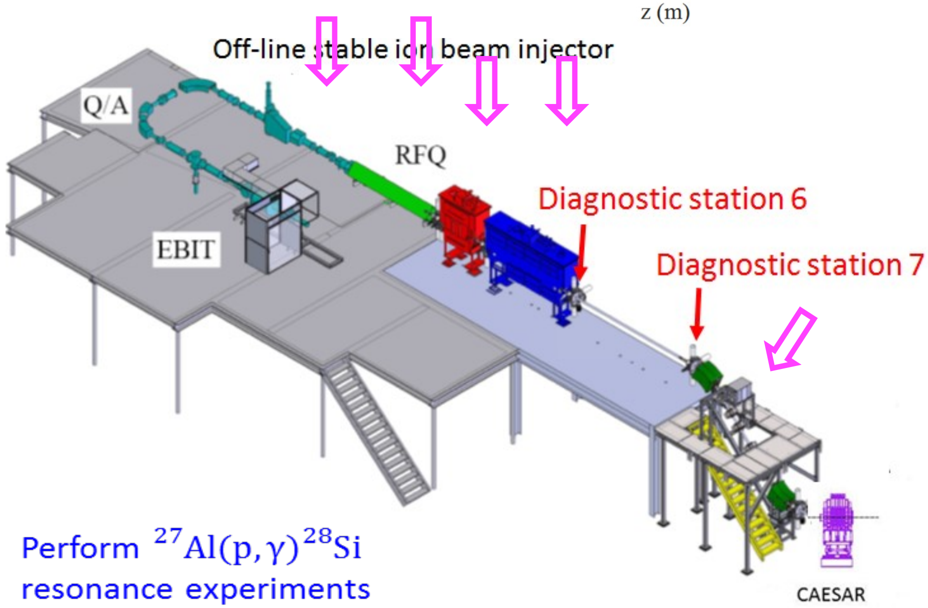
# Benchmarking with measurement: ReA Linac at MSU/NSCL




Beam energy:
992 keV/u
(No L091 rebuncher)

992 keV/u
(use L091 rebuncher)

632 keV/u




Perform $^{27}Al(p,\gamma)^{28}Si$ resonance experiments

*Courtesy Ling-Ying Lingy/MSU*

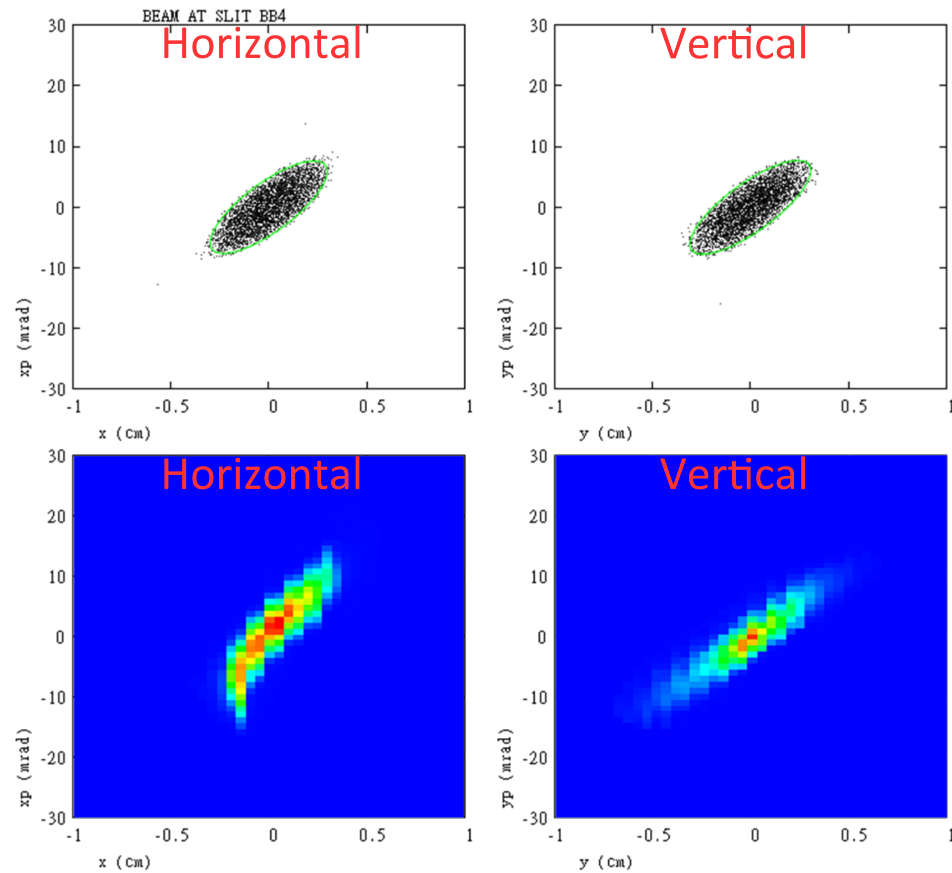
| | $^{27}Al(p,\gamma)^{28}Si$ 992 keV resonance without the L091 rebuncher | $^{27}Al(p,\gamma)^{28}Si$ 992 keV resonance with the L091 rebuncher |
|---|---|---|
| Measurement | **0.922** + 0.123/-0.105 | **0.627** + 0.244/-0.145 |
| Simulation | **0.909** | **0.531** |

| | $^{27}Al(p,\gamma)^{28}Si$ 632 keV resonance |
|---|---|
| Measurement | **0.803** + 0.138/-0.142 |
| Simulation | **0.892** |

Comparison of the measurement and DYNAC simulation for beam energy spread (in %) with 95% of the beam particles enclosed

# Benchmarking with measurement: NSCL/ReA RFQ

- 600 keV/u RFQ output beam following acceleration from 12 keV/u through an RFQ
- Simulation (top) vs. measurement (bottom)
- Differences in part explained by:
  - insufficiently known input beam parameters
  - ~10% emittance fluctuation observed in measurement results



# Benchmarking with TraceWin: ESS Linac

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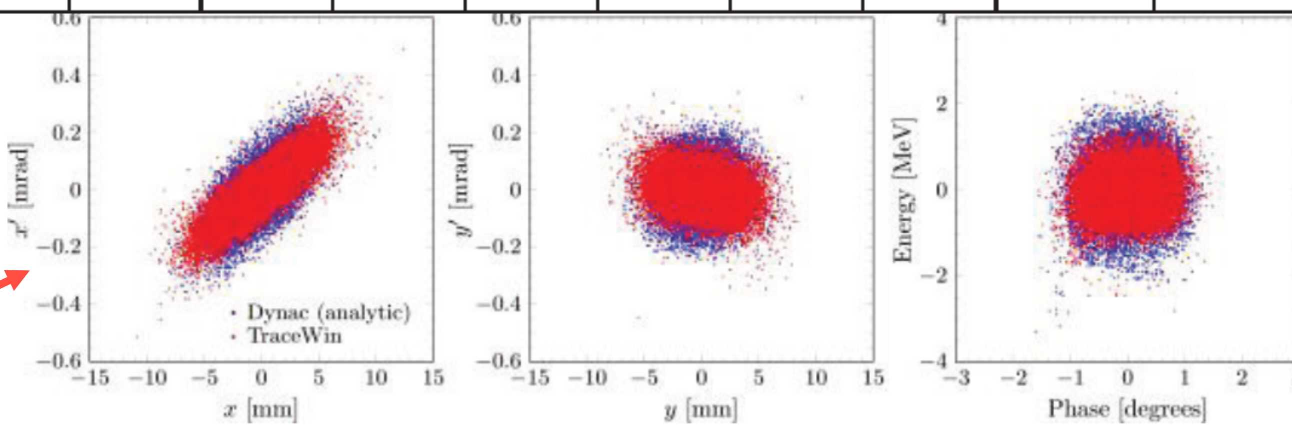
- CPU times for the End-to-End simulations with DYNAC was
  - ~350 s for the numerical method (> 2x faster than TraceWin)
  - ~54 s for the analytical method
- Reducing the number of particles to 1000, 2.5 s was achieved with DYNAC

| | DYNAC (numerical method) | | | DYNAC (analytical method) | | | DYNAC (analytical method, 1k part.) | | | TraceWin (25 steps per $\beta\lambda$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | xx' | yy' | w-$\phi$ | xx' | yy' | w-$\phi$ | xx' | yy' | w-$\phi$ | xx' | yy' | w-$\phi$ |
| $\alpha$ | -1.03 | 0.12 | -0.12 | -1.09 | 0.11 | -0.10 | -1.05 | 0.22 | -0.24 | -1.81 | 0.32 | -0.15 |
| $\beta$ | 35.29 | 26.54 | 0.0014 | 36.55 | 27.19 | 0.0016 | 37.68 | 25.80 | 0.0015 | 60.8 | 44.22 | 0.0022 |
| $\varepsilon_{rms}$ | 1.36 | 1.33 | 1345 | 1.26 | 1.27 | 1358 | 1.15 | 1.26 | 1323 | 1.27 | 1.28 | 1270 |

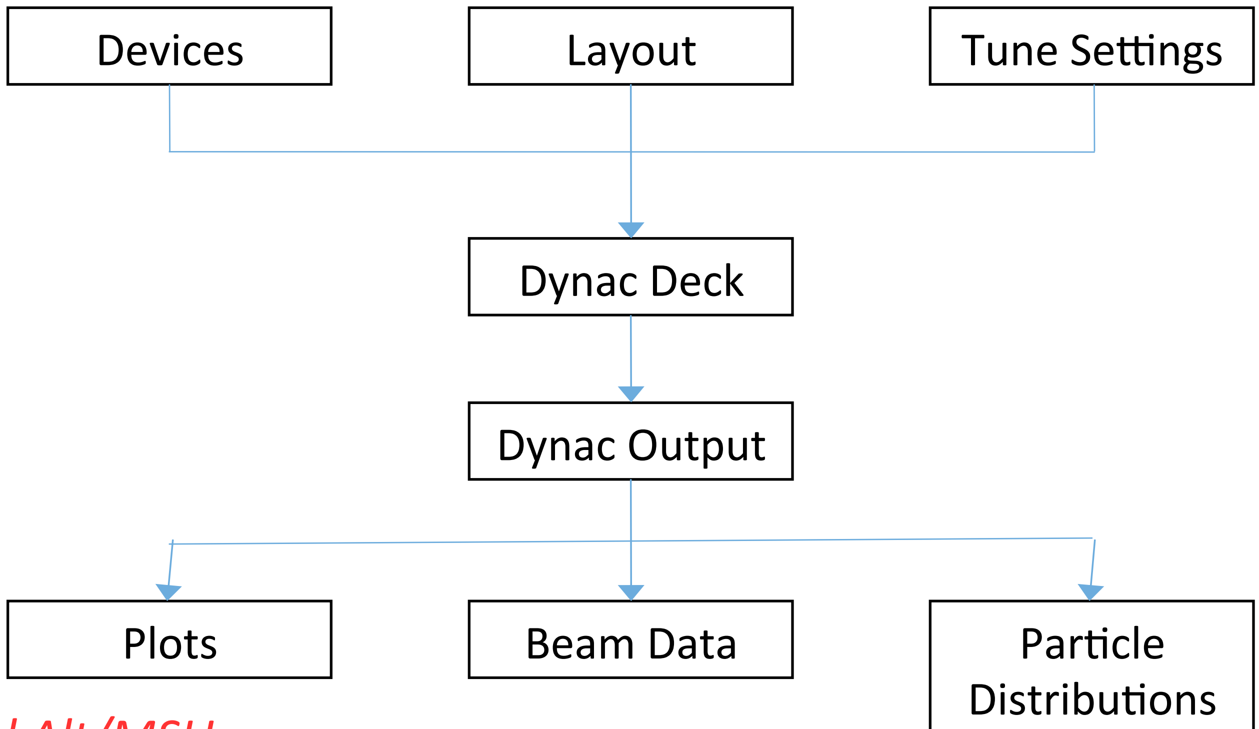
ESS linac output data

ESS linac output distributions



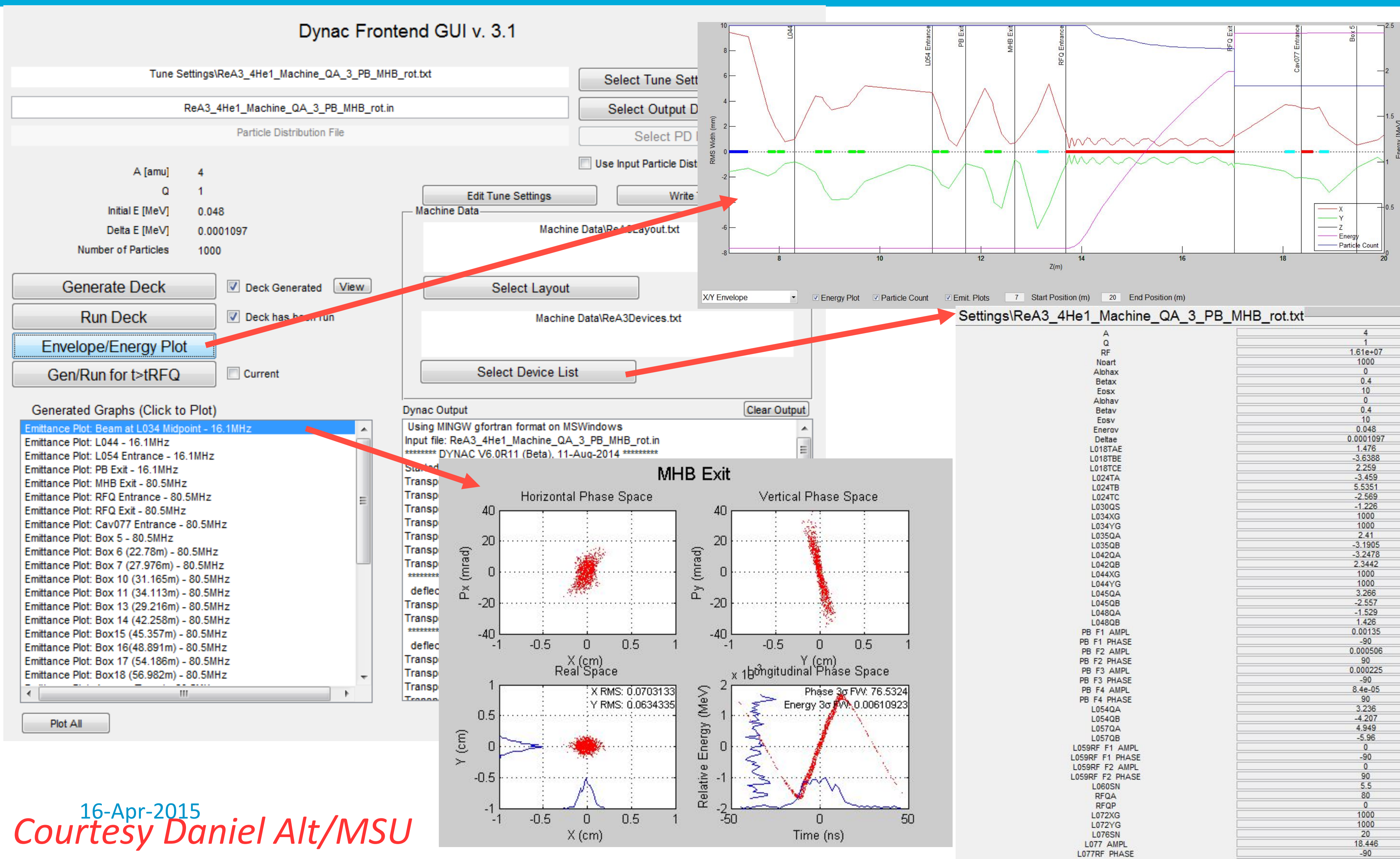
# MATLAB based GUI being developed at NSCL/ReA

- Graphical front end for Dynac at https://github.com/NSCLAlt/DynacGUI
- Designed to streamline editing and plotting
- Separate input files by function




*Courtesy Daniel Alt/MSU*

# MATLAB based GUI Development Example




16-Apr-2015

*Courtesy Daniel Alt/MSU*

Thank you for your attention!

# Back up slides....

# Back up slides 1 of 2

- In the 1960s a theory was derived (P. Lapostolle, A.Carne, M. Promé), giving a general definition of TTF and justifying the use of a 'thin lens' method for the treatment of the gap, yielding the following longitudinal equations:

$$\Delta W = qVT(\bar{k})I_0(\bar{k}\bar{r})\cos\bar{\varphi} + qV\frac{\partial}{\partial k}\left\{T(\bar{k})\bar{k}I_1(\bar{k}\bar{r})\right\}\bar{r}'\sin\bar{\varphi}$$

$$\Delta\varphi = \frac{qV}{W}\bar{k}\frac{\partial}{\partial k}\left\{T(\bar{k})I_0(\bar{k}\bar{r})\right\}\sin\bar{\varphi} - \frac{qV}{W}\bar{k}\frac{\partial^2}{\partial k^2}\left\{T(\bar{k})kI_1(\bar{k}\bar{r})\right\}\bar{r}'\cos\bar{\varphi}$$

# Back up slides 2 of 2

- DYNAC contains a set of very accurate quasi-Liouvillian beam dynamics equations, introduced in 1994.

$$\Delta W = q \int_0^L E_z(z,0,t) \left[1 + \frac{\omega^2 (R^2 + 2RR'z)}{4c^2\beta^3\gamma^3}\right] dz$$

$$\Delta\varphi = \frac{q}{m_0c^2}\frac{\omega}{c}\int_0^L \frac{1}{\beta^3\gamma^3} E_z(z,0,t) \left[1 + \frac{\omega^2 (R^2 + 2RR'z)}{4c^2\beta^3\gamma^3}\right] zdz$$

$$\frac{d^2R}{dz^2} - R\frac{q}{2m_0c^3}\frac{1}{\beta^3\gamma^3}\frac{\partial E_z}{\partial t} + R\left(\frac{q}{2m_0c^2}\right)^2 \frac{\gamma^2+2}{\beta^4\gamma^4}E_z^2 = 0.$$

$$\Delta R = \frac{q}{2m_0c^3}\int_0^L \frac{1}{\beta^3\gamma^3}\frac{\partial E_z(z,0,t)}{\partial t}(R + R'z)zdz - \frac{q^2}{(2m_0c^2)^2}\int_0^L \frac{\gamma^2+2}{\beta^4\gamma^4}E_z^2(z,0,t)(R+R'z)zdz$$

$$\Delta R' = \frac{q}{2m_0c^3}\int_0^L \frac{1}{\beta^3\gamma^3}\frac{\partial E_z(z,0,t)}{\partial t}(R + R'z)dz - \frac{q^2}{(2m_0c^2)^2}\int_0^L \frac{\gamma^2+2}{\beta^4\gamma^4}E_z^2(z,0,t)(R+R'z)dz$$