Upgrade of MAD-X for HL-LHC project and FCC studies

ICAP'18

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Overview

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- MAD-X = Methodical Accelerator Design 10
  - ➡ delivered on Linux, MacOSX and Windows (32 & 64 bits).
  - ➡ standalone all-in-one application (no dependency), open source, CERN copyright.
  - ➡ 3-4 releases / year, built and tested every night (~ 500 test suites).
  - ➡ support, website, e-groups, git repository, issue tracker (~600 tickets).
  - ➡ directly available from AFS (worldwide) shared file system for Linux.

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- Single particle beam code.
  - ➡ motion of particles in 5D-6D phase space under external fields.
  - ➡ design, optics, tracking, matching, slicing, orbit steering, orbit correction, orbit measures, fields and alignment errors, aperture offsets, aperture margins, emittance equilibrium, frozen space charge, radiation, survey, plots, etc…

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- Scripting language.
  - ➡ sequences, commands, variables, macros, tables, files, and more…
  - ➡ special constructs: `if-else`, `while`, `macro`, `line`, `table`.
  - ➡ deferred expressions (`bx := sqrt(betx);`).
  - ➡ global workspace.

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  - ➡ validation, tolerances, margins, studies.
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  - ➡ legacy physics for large machines (e.g. LHC).
  - ➡ PTC for smaller machines, 6D (also 4D, 5D, 56D), complex topology, high orders.
  - ➡ front-end to Sixtrack (long term tracking, DA studies).
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  - ➡ +95% are clones or generated (history, variants, layout dump).

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- CERN has ~8 millions lines of MAD-X scripts.
  - ➡ +95% are clones or generated (history, variants, layout dump).
- Used world wide.
  - ➡ community is about 500 users.
  - ➡ used in many projects (often ignored by team).
  - ➡ colliders, boosters, storage rings, linacs, gantries, transfer lines, FFAG, racetracks, …

Scripting language

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- Weak string “parsing”, still good enough for complex macros (=input generator).

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```
sorttable(tblname, colname, coldir) : macro = { ! optimized shellsort
  sorttable.__g = 1 ; sorttable.count = 0 ;
  sorttable.__n = table(tblname, tablelength)+1 ;
  while (sorttable.__g <= sorttable.__n+1) {
    sorttable.__g = sorttable.__g * 3 + 1 ;
  }
  sorttable.__g = floor(sorttable.__g / 3) ;
  while ( sorttable.__g > 0 ) {
    sorttable.__i = sorttable.__g ;
    while (sorttable.__i < sorttable.__n) {
      setvars table = tblname, row = sorttable.__i ; sorttable.__t = colname*coldir ;
      fill    table = tblname, row = sorttable.__n ;
      sorttable.__j = sorttable.__i - sorttable.__g ; sorttable.__f = 1 ;
      while (sorttable.__j > 0 && sorttable.__f > 0) {
        setvars table = tblname, row = sorttable.__j ; sorttable.__v = colname*coldir ;
        if (sorttable.__v < sorttable.__t) {
          sorttable.count = sorttable.count + 1 ;
          fill table = tblname, row = sorttable.__j + sorttable.__g ;
          sorttable.__j = sorttable.__j - sorttable.__g ;
        } else { sorttable.__f = 0 ; }
      }
      sorttable.count = sorttable.count + 1 ;
      setvars table = tblname, row = sorttable.__n ;
      fill    table = tblname, row = sorttable.__j + sorttable.__g ;
      sorttable.__i = sorttable.__i + 1 ;
    }
    sorttable.__g = floor(sorttable.__g / 3) ;
  }
  shrink table = tblname ;
}
```

Functions (op), commands, factories (elem)

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Functions (op), commands, factories (elem)

- Functions (and unary/binary operators) return a number
  - unary operator: $(-x)$
  - binary operators: x+y, x−y, x*y, x/y, x^y (power)
  - relational operators: x==y, x<=y, x>=y, x<y, x>y, x<>y
  - logical operators: *lexpr* && *lexpr* (and), *lexpr* || *lexpr* (or)
  - **abs**(x), **sqrt**(x), **exp**(x), **log**(x), **log10**(x)
  - **sin**(x), **cos**(x), **tan**(x), **asin**(x), **acos**(x), **atan**(x),
  - **sinh**(x), **cosh**(x), **tanh**(x)
  - **erf**(x), **erfc**(x) (error functions)
  - **round**(x), **floor** (x), **ceil** (x), **frac**(x) (integral and fractional parts)
  - **ranf**(), **gauss**(), **tgauss**(x) (random number generators)

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- **abs**(x), **sq**
- **sin**(x), **co**
- **sinh**(x), **c**
- **erf**(x), **er**
- **round**(x),
- **ranf**(), **ga**

- **exit**, **quit**, **stop** stop execution
- **call** runs (load) scripts, **return** returns from current script
- **exec** expands macros in current script (defined with **macro**)
- **system** runs shell commands (platform & shell specific)
- **value**, **show**, **help** query global environment
- **option**, **title**, **set** setup global environment
- **beam** setups physics environment
- **use**, **select** setup specific environment (commands, modules)
- **assign** sets output file for echoing
- **print**, **printf** print raw text and formated text
- **copyfile**, **renamefile**, **removefile** portable files manipulation
- **plot**, **setplot**, **resplot** plotting facilities

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- **beam** se
- **use**, **sel**
- **assign** s
- **print**, **p**
- **copyfile**
- **plot**, **se**

- **sequence** : sequence
- **marker**: marker
- **drift** : drift
- **sbend**, **rbend**, **quadrupole**, **sextupole**, **octupole**, **multipole**, **solenoid**, **dipedge**, **rfmultipole**: magnets
- **rfcavity** , **twcavity**, **crabcavity**, **rfmultipole**: cavities
- **kicker**, **hkicker**, **vkicker**, **tkicker**: correctors
- **ecollimator**, **rcollimator**: collimators*
- **monitor**, **hmonitor**, **vmonitor**, **blmonitor**: monitors
- **instrument**, **placeholder**: placeholders
- **srotation**, **yrotation**: rotations
- **elseparator**, **beambeam**, **matrix**: others

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Callouts:
- angle (k0l), k1, [k2]
- sbend with e1=e2=theta/2
- k1
- k2
- knl[], ksl[], lrad
- orbit correction
- X,R,T

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- SURVEY: 3D geometrical tracking (global frame, design orbit)

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Survey, Track, Twiss, Match

- SURVEY: 3D geometrical tracking (global frame, design orbit)
- TRACK: 6D particles tracking (symplectic)
  - ➡ thin lens tracking (D-K-D), 6D closed orbit.
  - ➡ can track thick elements: ***dipole, quadrupole and solenoid.*** ***NEW***
  - ➡ can track thousand particles (no hard limits, ***OMP parallelization***). ***NEW***
  - ➡ synchrotron radiation (***distribution and quantum***). ***NEW***
  - ➡ can (re-)evaluates time dependent expressions every turn (freq=F0/N).

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- TWISS: 5D optical tracking (almost symplectic) up to 2nd order (i.e. X,R,T)
  - ➡ thick lens tracking, optical functions (Courant-Snyder), 4D-5D closed orbit, beta blocks.
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- MATCH: global non-linear optimiser
  - ➡ handle multiple sequences and beta blocks.
  - ➡ local/global constraints, ranges, equality or inequality.
  - ➡ direct (run `TWISS`) or indirect (run macro, `PTC_TWISS`).
  - ➡ can match at any positions inside elements. ***NEW***

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```
match use_macro, ... ;
... vary statements ...
macro1: macro = { ... madx statements ... }
constraint expr= "lhs1 < | = | > rhs1" ;
constraint expr= "lhs2 < | = | > rhs2" ;
... constraint statements ...
macro2: macro = { ... madx statements ... }
... constraint statements ...
macro3: macro = { ... madx statements ... }
... constraint statements ...
... methods statements ...
endmatch ;
```

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Makethin improvement

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Makethin improvement

- Convert thick sequence into thin sequence (in place).
  - ➡ new module (2015-) in C++ by H. Burkhardt.
  - ➡ generalise TEAPOT symplectic integration scheme for n>4 slices to minimise beta beating using better interpolation (i.e. than `SIMPLE`) of thick quadrupole.
  - ➡ can keep dipole, quadrupole and solenoid thick.

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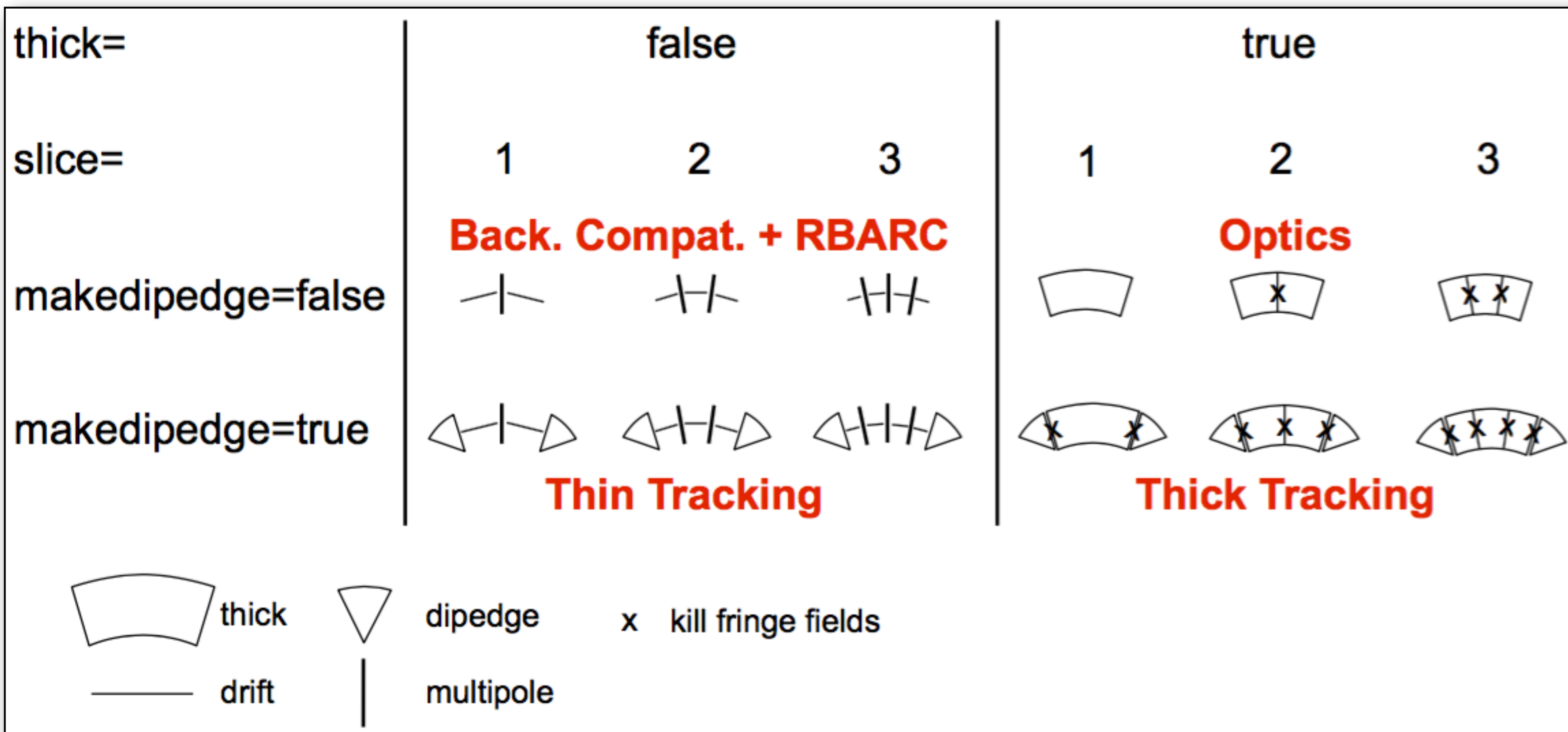

Synchrotron radiation effects

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Synchrotron radiation effects

- Fixed and improved in Twiss, Track and Emit modules.
  - ➡ originally implemented in MAD8 for high-energy e+e− collider (LEP) at CERN.

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  - ➡ originally implemented in MAD8 for high-energy e+e− collider (LEP) at CERN.
- 4 levels of activation
  - ➡ *no radiation*, corresponding to the usual Hamiltonian dynamics.
  - ➡ *deterministic radiation*, all particles radiate as a single particle on the closed-orbit.
  - ➡ *deterministic radiation*, with full dependence on canonical coordinates to generate natural radiation damping (Track and Emit only).
    Preferred method for dynamic aperture calculations in high-energy lepton rings.
  - ➡ *Individual quantum excitation* with stochastic photon emissions, provides particle distributions and equilibrium emittances (Track only).

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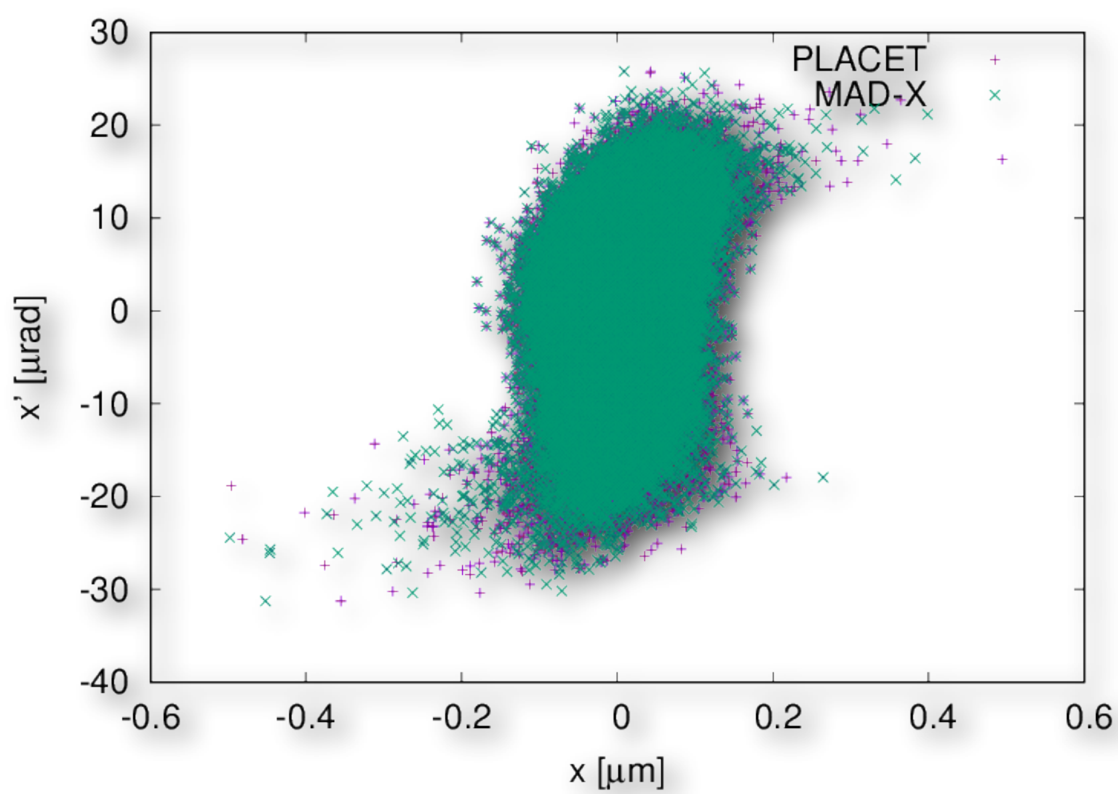

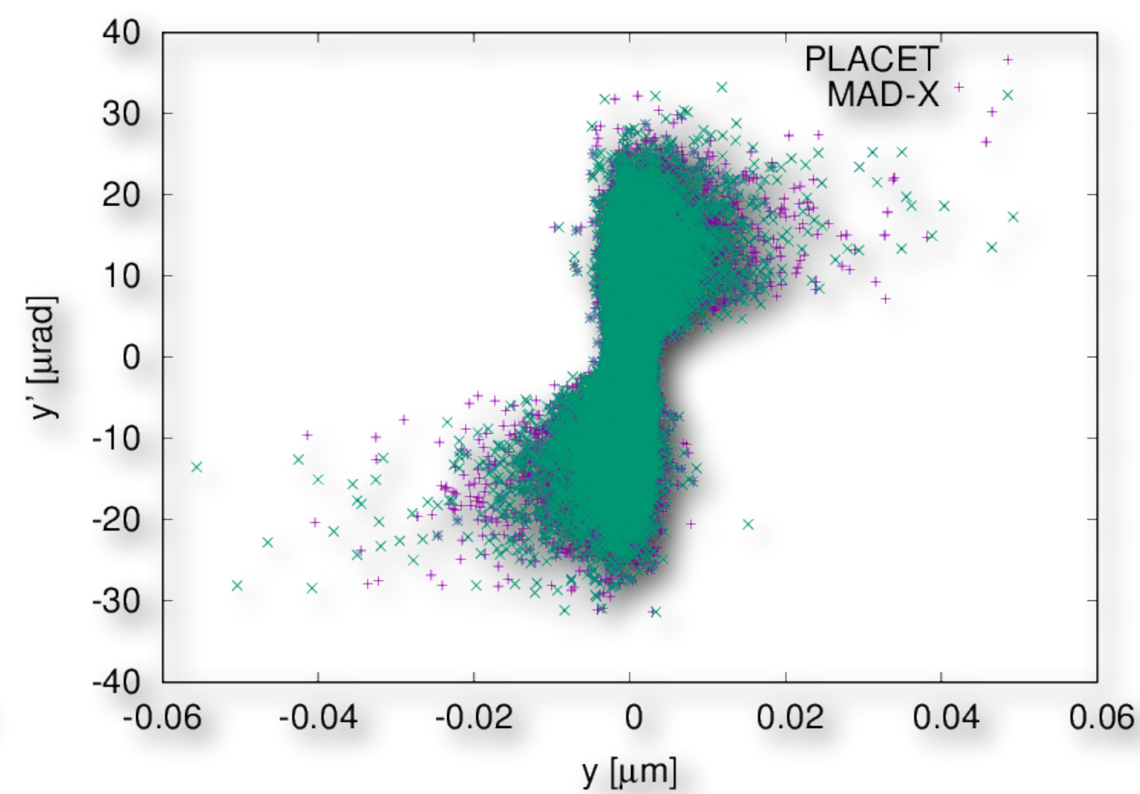

Frozen space charge

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Frozen space charge

- The code has undergo a complete refactoring
  - ➡ new separate Fortran module.
  - ➡ simplify support and extension without changing the model.
  - ➡ could become a new separate MAD-X command in the future.

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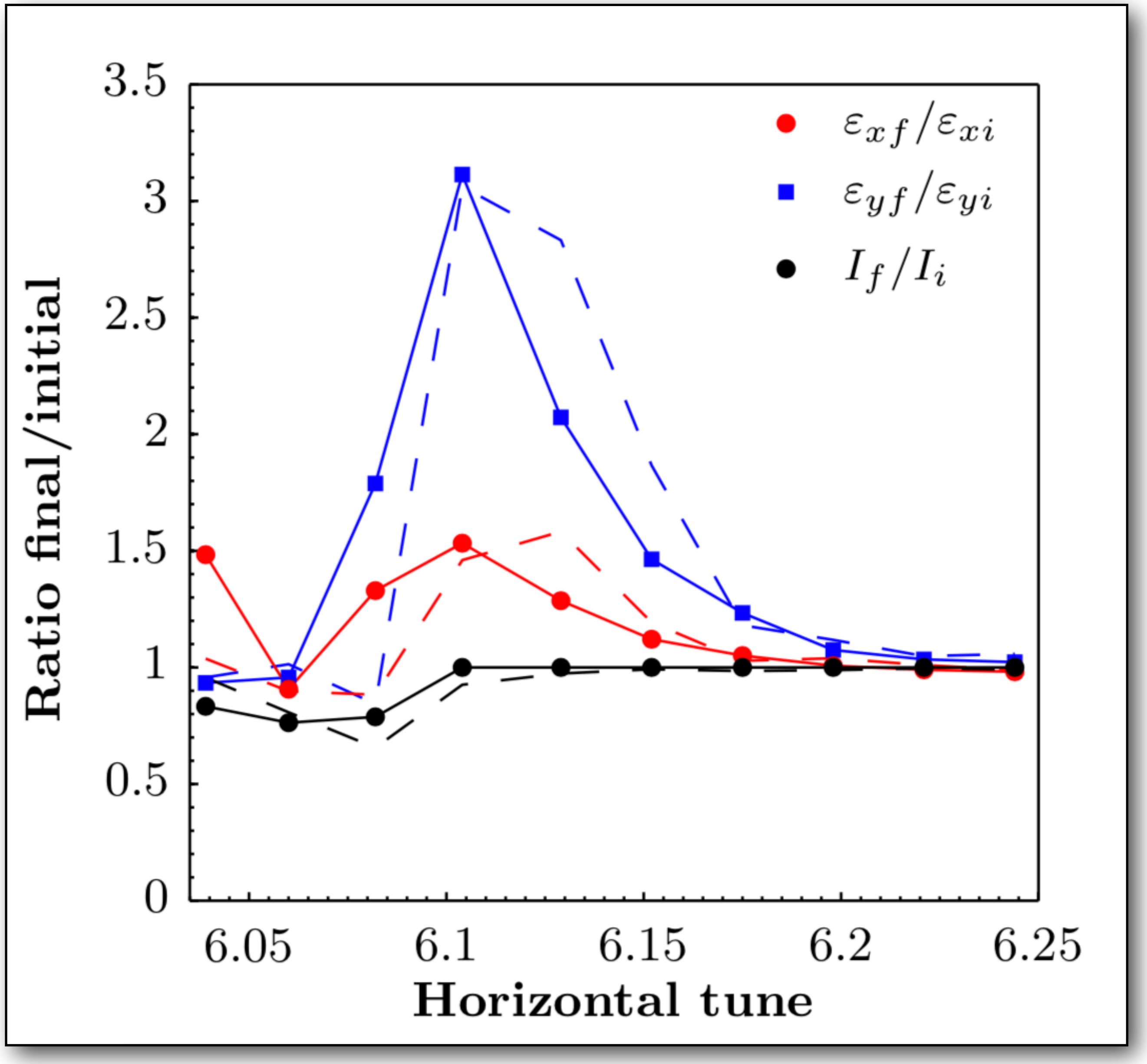

Emittance growth and beam intensity as computed with MAD-X (adaptive mode). Experimental data are shown with dashed lines.

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Linear coupling review

- Review triggered by negative beta functions in the presence of strong coupling
  - ➡ occurred for a single seed leading to strong misalignment in HL-LHC studies.
  - ➡ tried two alternate implementations without success (Sagan & Rubin, Talman).
  - ➡ added the flip mode to the implementation (fixed the problem).
  - ➡ added a couple missing checks to validate assumptions.
  - ➡ review the theory and the implementation from scratch (lost knowledge).
  - ➡ review fixed typos in the manual and restored the understanding of the method.

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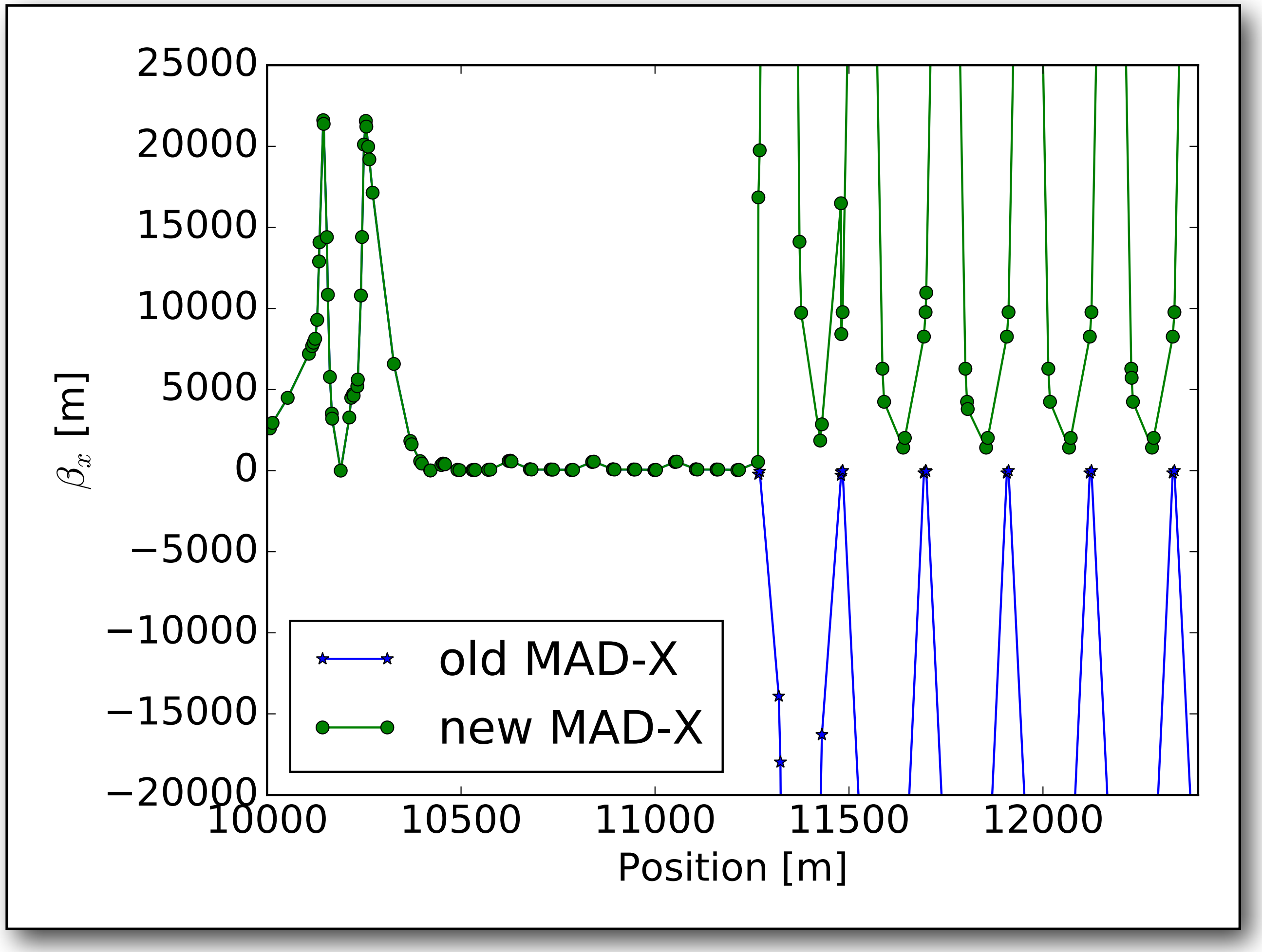
Negative (blue) beta functions in HL-LHC studies, right after the skew quadrupole starting from IP (left). Coupling is so strong that optics is not stable.
Fixed in recent released (green).



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Linear coupling review (initialisation)

- Restore the derivation of the equations, provide intermediate validity checks and more stable formula (see the links in refs for details).

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$$\vec{X}(s_2) = M\vec{X}(s_1),$$

$$M = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = R_M \begin{pmatrix} E & 0 \\ 0 & F \end{pmatrix} R_M^{-1} = R_M M_\perp R_M^{-1}.$$

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$$M =$$

$$\begin{aligned} \mathrm{eig}(M) = \mathrm{eig}(M^{-1}) &= \{(\lambda_i, \lambda_i^{-1}),\ i = 1..2\}, \\ \mathrm{eig}(M + \bar{M}) &= \{\Lambda_i = \lambda_i + \lambda_i^{-1},\ i = 1..2\}, \\ \det(M + \bar{M} - \Lambda I) &= (\mathrm{tr}\, A - \Lambda)(\mathrm{tr}\, D - \Lambda) - |C + \bar{B}| = 0, \\ \Lambda_{A,D} = \frac{1}{2}(\mathrm{tr}\, A + \mathrm{tr}\, D) &\pm \frac{1}{2}\,\mathrm{sign}(\mathrm{tr}\, A - \mathrm{tr}\, D)\sqrt{\Delta}. \end{aligned}$$

Eigenmodes

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$$\text{eig}(M) = \text{eig}(M^{-1}) = \{(\lambda_i, \lambda_i^{-1}),\ i = 1..2\},$$

$$\text{eig}(M + \bar{M}) = \{\Lambda_i = \lambda_i + \lambda_i^{-1},\ i = 1..2\},$$

det

Eigenmodes

$$\begin{pmatrix} (\text{tr}\, A - \Lambda_A)I & B + \bar{C} \\ C + \bar{B} & (\text{tr}\, D - \Lambda_A)I \end{pmatrix} \begin{pmatrix} X \\ R_A X \end{pmatrix} = 0,$$

$$\begin{pmatrix} (\text{tr}\, A - \Lambda_D)I & B + \bar{C} \\ C + \bar{B} & (\text{tr}\, D - \Lambda_D)I \end{pmatrix} \begin{pmatrix} R_D Y \\ Y \end{pmatrix} = 0,$$

$$R = -\left(\frac{1}{2}(\text{tr}\, A - \text{tr}\, D) + \frac{1}{2}\,\text{sign}(\text{tr}\, A - \text{tr}\, D)\sqrt{\Delta}\right)^{-1}(C + \bar{B}),$$

$$\text{with } R_A = -\bar{R}_D = R.$$

Eigenvectors

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Linear coupling review (initialisation)

Beams Department

- Restore the derivation of the equations, provide intermediate validity checks and more stable formula (see the links in refs for details).

$$\vec{X}(s_2) = M\vec{X}(s_1),$$

$$M =$$

$$\mathrm{eig}(M) = \mathrm{eig}(M^{-1}) = \{(\lambda_i, \lambda_i^{-1}),\ i = 1..2\},$$

$$\mathrm{eig}(M+\bar{M}) = \{\Lambda_i = \lambda_i + \lambda_i^{-1},\ i = 1..2\},$$

det

Eigenmodes

$$\begin{pmatrix} (\mathrm{tr}\,A - \Lambda_A)I & B+\bar{C} \\ C+\bar{B} & (\mathrm{tr}\,D - \Lambda_A)I \end{pmatrix} \begin{pmatrix} X \\ R_A X \end{pmatrix} = 0,$$

$$\begin{pmatrix} (\mathrm{tr}\,A - \Lambda_D)I & B+\bar{C} \\ C+\bar{B} & (\mathrm{tr}\,D - \Lambda_D)I \end{pmatrix} \begin{pmatrix} R_D Y \\ Y \end{pmatrix} = 0,$$

$$R = -$$

Eigenvectors

$$M_\perp = R_M^{-1} M R_M = g^2 \bar{R}_M M R_M$$

$$= g^2 \begin{pmatrix} I & -\bar{R} \\ R & I \end{pmatrix} \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} I & \bar{R} \\ -R & I \end{pmatrix} = \begin{pmatrix} E & 0 \\ 0 & F \end{pmatrix},$$

$$E = g^2(A - \bar{R}C - (BR - \bar{R}DR)) = A - \bar{R}C = A - BR,$$

$$F = g^2(D + RB + (C\bar{R} + RA\bar{R})) = D + RB = D + C\bar{R}.$$

Normal form

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Eigenmodes

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$$E =$$

$$F =$$

Normal form

$$E = \begin{pmatrix} E_{1,1} & E_{1,2} \\ E_{2,1} & E_{2,2} \end{pmatrix} = \begin{pmatrix} \cos\mu_A + \alpha_A \sin\mu_A & \beta_A \sin\mu_A \\ -\gamma_A \sin\mu_A & \cos\mu_A - \alpha_A \sin\mu_A \end{pmatrix},$$

$$\cos\mu_A = \frac{1}{2}\operatorname{tr} E,\ \ \sin\mu_A = \operatorname{sign}(E_{1,2})\sqrt{-E_{1,2}E_{2,1} - \left(\frac{E_{1,1} - E_{2,2}}{2}\right)^2}$$

$$\beta_A = \frac{E_{1,2}}{\sin\mu_A},\ \ \gamma_A = -\frac{E_{2,1}}{\sin\mu_A},\ \ \alpha_A = \frac{E_{1,1} - E_{2,2}}{2\sin\mu_A},$$

Optical parameters

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Linear coupling review (propagation)

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$$\begin{aligned} M_2 &= M_{12} M_1 M_{12}^{-1} = M_{12}\left(R_{M_1} M_{1\perp} R_{M_1}^{-1}\right) M_{12}^{-1}, \\ M_{2\perp} &= R_{M_2}^{-1} M_2 R_{M_2} = \left(R_{M_2}^{-1} M_{12} R_{M_1}\right) M_{1\perp} \left(R_{M_1}^{-1} M_{12}^{-1} R_{M_2}\right) \\ &= W_{12} M_{1\perp} W_{12}^{-1}\,. \end{aligned}$$

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Linear coupling review (propagation)

Beams Department

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$$R_{M_2} W_{12} = M_{12} R_{M_1},$$

$$g_2 \begin{pmatrix} I & \bar{R}_2 \\ -R_2 & I \end{pmatrix} \begin{pmatrix} E_{12} & 0 \\ 0 & F_{12} \end{pmatrix} = g_1 \begin{pmatrix} A_{12} & B_{12} \\ C_{12} & D_{12} \end{pmatrix} \begin{pmatrix} I & \bar{R}_1 \\ -R_1 & I \end{pmatrix},$$

$$g_2 \begin{pmatrix} I & \bar{R}_2 \\ -R_2 & I \end{pmatrix} \begin{pmatrix} 0 & E_{12} \\ F_{12} & 0 \end{pmatrix} = g_1 \begin{pmatrix} A_{12} & B_{12} \\ C_{12} & D_{12} \end{pmatrix} \begin{pmatrix} I & \bar{R}_1 \\ -R_1 & I \end{pmatrix}.$$

Normal form

Linear coupling review (propagation)

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Normal form

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g_2

Flip mode

$$\begin{aligned} E_{12} &= g_{12}(A_{12} - B_{12} R_1) \\ F_{12} &= g_{12}(D_{12} + C_{12} \bar{R}_1) \\ R_2 &= -g_{12}(C_{12} - D_{12} R_1) E_{12}^{-1} \end{aligned} \qquad \begin{aligned} E_{12} &= g_{12}(B_{12} + A_{12} \bar{R}_1) \\ F_{12} &= g_{12}(C_{12} - D_{12} R_1) \\ R_2 &= -g_{12}(D_{12} + C_{12} \bar{R}_1) E_{12}^{-1} \end{aligned}$$

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$$M_{2\perp} = R_{M_2}^{-1} M_2 R_{M_2} = \left(R_{M_2}^{-1} M_{12} R_{M_1}\right) M_{1\perp} \left(R_{M_1}^{-1} M_{12}^{-1} R_{M_2}\right)$$

Normal form

$$R_{M_2} W_{12} = M_{12} R_{M_1},$$

$$g_2 \begin{pmatrix} I & \bar{R}_2 \\ -R_2 & I \end{pmatrix} \begin{pmatrix} E_{12} & 0 \\ 0 & F_{12} \end{pmatrix} = g_1 \begin{pmatrix} A_{12} & B_{12} \\ C_{12} & D_{12} \end{pmatrix} \begin{pmatrix} I & \bar{R}_1 \\ -R_1 & I \end{pmatrix},$$

$$g_2 \quad \begin{aligned} E_{12} &= g_{12}(A_{12} - B_{12} R_1) \\ F_{12} &= g_{12}(D_{12} + C_{12} \bar{R}_1) \end{aligned} \qquad \begin{aligned} E_{12} &= g_{12}(B_{12} + A_{12} \bar{R}_1) \\ F_{12} &= g_{12}(C_{12} - D_{12} R_1) \end{aligned}$$

Flip mode

$$R_2 \quad \begin{aligned} E_2 &= E_{12} E_1 \bar{E}_{12} / |E_{12}| \\ F_2 &= F_{12} F_1 \bar{F}_{12} / |F_{12}| \\ R_2 &= -(C_{12} - D_{12} R_1) \frac{\bar{E}_{12}}{|E_{12}|} \end{aligned} \qquad \begin{aligned} E_2 &= E_{12} F_1 \bar{E}_{12} / |E_{12}| \\ F_2 &= F_{12} E_1 \bar{F}_{12} / |F_{12}| \\ R_2 &= -(D_{12} + C_{12} \bar{R}_1) \frac{\bar{E}_{12}}{|E_{12}|} \end{aligned}$$

Solution

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$$M_2 = M_{12} M_1 M_{12}^{-1} = M_{12} \left(R_{M_1} M_{1\perp} R_{M_1}^{-1} \right) M_{12}^{-1},$$

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Normal form

$$R_{M_2} W_{12} = M_{12} R_{M_1},$$

$$g_2 \begin{pmatrix} I & \bar{R}_2 \\ -R_2 & I \end{pmatrix} \begin{pmatrix} E_{12} & 0 \\ 0 & F_{12} \end{pmatrix} = g_1 \begin{pmatrix} A_{12} & B_{12} \\ C_{12} & D_{12} \end{pmatrix} \begin{pmatrix} I & \bar{R}_1 \\ -R_1 & I \end{pmatrix},$$

g_2

Flip mode

$E_{12} = g_{12}(A_{12} - B_{12} R_1)$	$E_{12} = g_{12}(B_{12} + A_{12} \bar{R}_1)$
$F_{12} = g_{12}(D_{12} + C_{12} \bar{R}_1)$	$F_{12} = g_{12}(C_{12} - D_{12} R_1)$

R_2

Solution

$E_2 = E_{12} E_1 \bar{E}_{12} / \lvert E_{12} \rvert$	$E_2 = E_{12} F_1 \bar{E}_{12} / \lvert E_{12} \rvert$

F_2

R_2

Optical parameters

$$T_2 = W_{12} T_1 W_{12}^{-1}, \qquad T^{(E,F)} = \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix},$$

$$\alpha_2 = -((E_{2,1}\beta_1 - E_{2,2}\alpha_1)(E_{1,1}\beta_1 - E_{1,2}\alpha_1) + E_{1,2}E_{2,2})/(|E_{12}|\beta_1),$$

$$\beta_2 = ((E_{1,1}\beta_1 - E_{1,2}\alpha_1)^2 + E_{1,2}^2)/(|E_{12}|\beta_1),$$

$$\mu_2 = \mu_1 + \tan^{-1}(E_{1,2}, (E_{1,1}\beta_1 - E_{1,2}\alpha_1)),$$

$$\gamma_2 = (1 + \alpha_2^2)/\beta_2 .$$

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Element specific extensions

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Element specific extensions

- Patches added to `SURVEY`, `TWISS` and `TRACK`
  - ➡ s-rotation, x-rotation, y-rotation and translation elements.
  - ➡ used to change the reference frame.
  - ➡ used to misalign magnets in HL-LHC studies.
  - ➡ used to keep “flat” non-flat beam lines (gantry).

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x-rotation tracking map

$$x^f = x^i + \frac{y p_x^i \tan\theta}{p_z^i - p_y^i \tan\theta}$$

$$p_x^f = p_x^i$$

$$y^f = \frac{y^i}{\cos\theta - p_y^i \tan\theta / p_z^i}$$

$$p_y^f = p_y^i \cos\theta + p_z^i \sin\theta$$

$$t^f = t_i - \frac{y^i (1/\beta_0 + p_t) \tan\theta}{p_z^i - p_y^i \tan\theta}$$

$$p_z = \sqrt{1 + 2p_t/\beta_0 + p_t^2 - p_x^2 - p_y^2}$$

$$p_t = (E - E_0)/P_0 c$$

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- `SBEND` updated in `SURVEY`, `TWISS` and `TRACK`
  - ➡ angle can be different from $k_0 l$ integrated strength.
  - ➡ change horizontal field curvature.
  - ➡ treated as an extra field error not removed by `USE`.

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Beams Department

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- `SELECT` updated and used by `TWISS` and `MATCH`
  - ➡ extended with `INTERPOLATE` to specify points of interpolation (output) within elements.
  - ➡ matching constraints can refer to arbitrary positions.
  - ➡ still under testing (will be in end-of-the-year release)

x-rotation tracking map

$$x^f = x^i + \frac{y p_x^i \tan\theta}{p_z^i - p_y^i \tan\theta}$$

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```
SELECT, FLAG=INTERPOLATE, RANGE=mq1, AT={0.5, 1};
MATCH, SEQUENCE=seq;
VARY, NAME=k1; # vary strength of quadrupole mq1
CONSTRAINT, RANGE=mq1, IINDEX=0, BETX=5;
LMDIF;  # match betx at centre of mq1 varying k1
ENDMATCH;
```

MAD-X PTC extensions

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MAD-X PTC extensions

BE Beams Department

- Interface between MAD-X and PTC/FPP embedded library is constantly improved.
  - ➡ follow-up of new releases of PTC/FPP from E. Forest for update in MAD-X.
  - ➡ synchrotron radiation effects connected to MAD-X, `PTC_TWISS` outputs damping times and equilibrium emittances now.
  - ➡ optimise the sector-bend maps with the exact Hamiltonian by automatic detection of maximum multipole order required, speed-up `PTC_TWISS` on LHC by factor x3.
  - ➡ added `RECLOSS` to record lost particles in table by `PTC_TRACK`.
  - ➡ added 6D closed orbit search with `TOTALPATH`, and correctly calculates the dependence of the beam momentum on RF frequency.
  - ➡ added `NORMAL` and `TRACKRDTS` options to `PTC_TWISS` to output the three tunes, dispersions, eigenvectors, RDTs (generating functions), Hamiltonian, and one-turn map to the new tables `NONLIN` and `TWISSRDT` and hence become available for `MATCH`ing.

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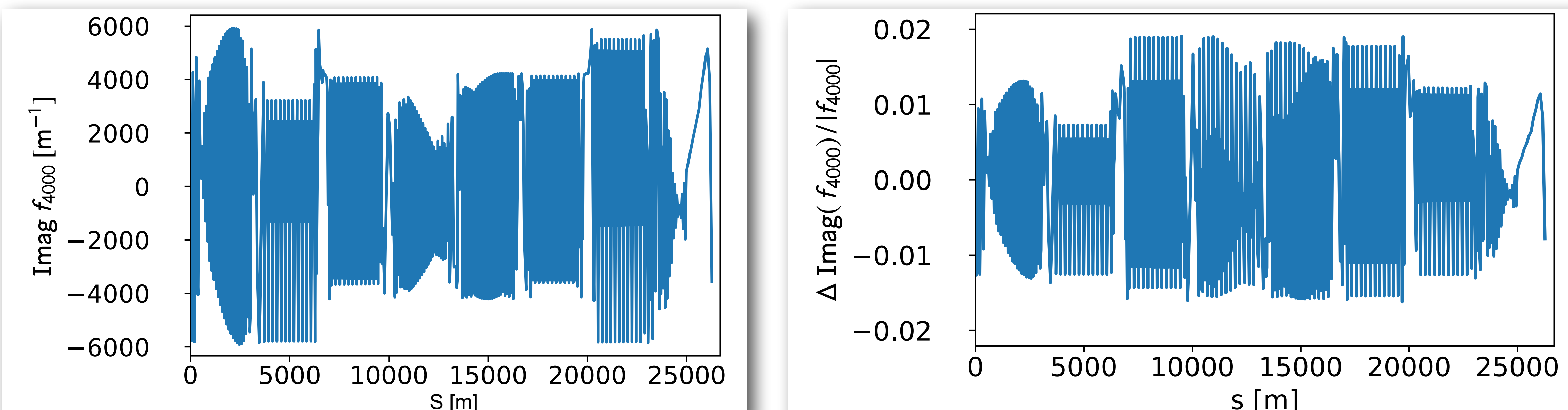

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MAD-X contributors: H. Burkhardt, R. De Maria, F. Schmidt, T. Gläßle, and many others…

PTC/FPP author: E. Forest.

CERN BE/ABP: M. Giovannozzi, G. Arduini, P. Collier.

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MAD season 4 (advertisement)

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MAD season 4 (advertisement)

And the story continue,

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MAD season 4 (advertisement)

And the story continue,

MAD8, MAD9, MAD-X, … MAD-NG

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MAD season 4 (advertisement)

And the story continue,

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alpha release foreseen by end of 2018 for internal use at CERN
beta releases will follow during the long shutdown 2 (2019-20)

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MAD season 4 (advertisement)

BE Beams Department

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MAD *Next Generation* is coming soon!

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Extra slides

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Polymorphic Tracking Code (in MAD-X)

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Polymorphic Tracking Code (in MAD-X)

- Developed by E. Forest (KEK) since the 90’s (+2 books)
  - ➡ continuously updated in MAD-X since 2015 (following Etienne’s releases), new connection from P. Skowronsky.
  - ➡ advanced Fortran 90 Library for beam dynamics, require to develop a Fortran program for your studies.

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  - ➡ advanced Fortran 90 Library for beam dynamics, require to develop a Fortran program for your studies.
- Principle: track high order maps using TPSA from Berz
  TPSA = Truncated Power Series Algebra.
  - ➡ provide true 3D geometry for lattice design (i.e. patches).
  - ➡ provide true 6D physics for beam dynamics (small machines),
    `icase` = 4, 5, 56, 6 (resp. 4D, 5D dp, 6D wo-cav, 6D w-cav),
    `model` = 1, 2, 3 (resp. D-K-D, M-K-M, D-M-K-M),
    `method` = 2, 4, 6 (integrator order, Forest & Ruth, Yoshida scheme).
  - ➡ provide **high order normal forms** analysis (`ptc_normal`, `ptc_twiss`).
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Polymorphic Tracking Code (in MAD-X)

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  - ➡ continuously updated in MAD-X since 2015 (following Etienne's releases), new connection from P. Skowronsky.
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- Principle: track high order maps using TPSA from Berz
  TPSA = Truncated Power Series Algebra.
  - ➡ provide true 3D geometry for lattice design (i.e. patches).
  - ➡ provide true 6D physics for beam dynamics (small machines),
    `icase` = 4, 5, 56, 6 (resp. 4D, 5D dp, 6D wo-cav, 6D w-cav),
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- Give access to the full theory of the perturbation

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- Integrated into MAD-X by F. Schmidt, E. Forest et al. in 2002
  Directly available from MAD-X scripting language.
  Weak connection with only a subset of PTC...

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