AP group meeting, 7-Nov-2002

DYNAC

A multiparticle linac simulation code and tool for linac commissioning

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DYNAC IN A NUTSHELL

- **Multiparticle Fortran code for linac simulation**
  - Same program and interface under LINUX and WINDOWS
  - Graphics postprocessor based on GNUplot
    (both for LINUX and WINDOWS)
  - Code package is freeware; available from :
    http://dynac.web.cern.ch/dynac/dynac.html

- **Contains 3 space charge routines:**
  - ***SCHEFF*** modified, based on 2D PIC method in PARMILA
  - ***SCHERM*** 3D method, based on multi-ellipsoid representation
  - ***HERSC*** 3D analytical method, without any basic assumptions
    on the bunch distribution

HISTORY OF DYNAC (1)

- **First version developed in the 1980s by P.Lapostolle and S.Valero**

- 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

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

HISTORY OF DYNAC (2)

- **Further developed at CERN in the 1990s by P.Lapostolle, E.Tanke and S.Valero**

  - Introduction of a new Liouvillian set of equations in a thick lens approximation and 3D space charge (routines SCHERM and HERSC)

  - Simulation and commissioning of CERN heavy ion linac

  - Simulation of CERN high intensity proton MEBT-DTL (180 mA)

  - Simulation of low energy electrons in multi-gap super conducting cavities at SACLAY

DYNAC FOR USE AT SNS ? (1)

- **Simulation:**

  - DYNAC input file for MEBT-DTL-CCL-SCL has been created:
    * Based on PARMILA type TTFs for DTL and SUPERFISH fields for CCL and SCL
    * Data file is sequential

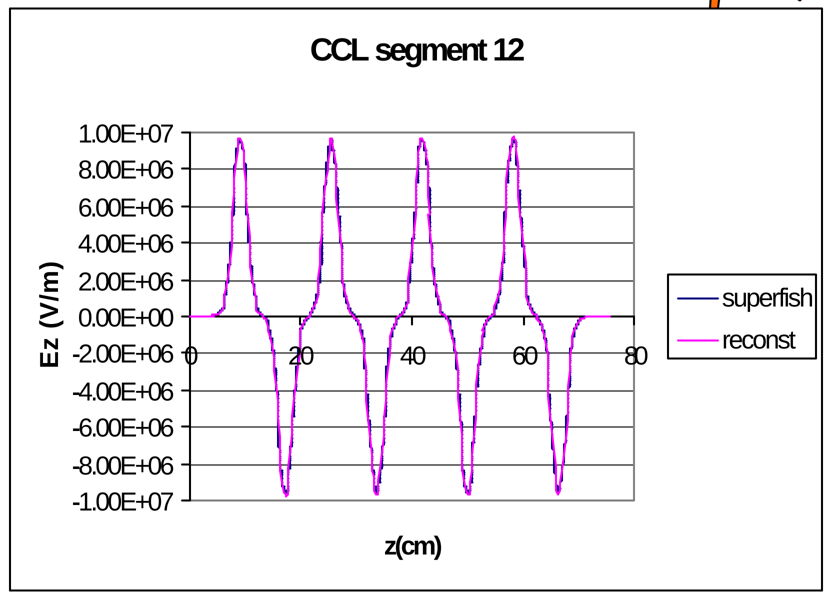
  - Input beam can be read from file (PARMILA standard) or generated by the code

  - 3D space charge simulation with HERSC routine, based on the analytical set of beam self-field equations. This set is the solution of the electrostatic Dirichlet-Neumann problem within the bunch. Excellent tool for investigating halo !

SEQUENTIAL INPUT FILE

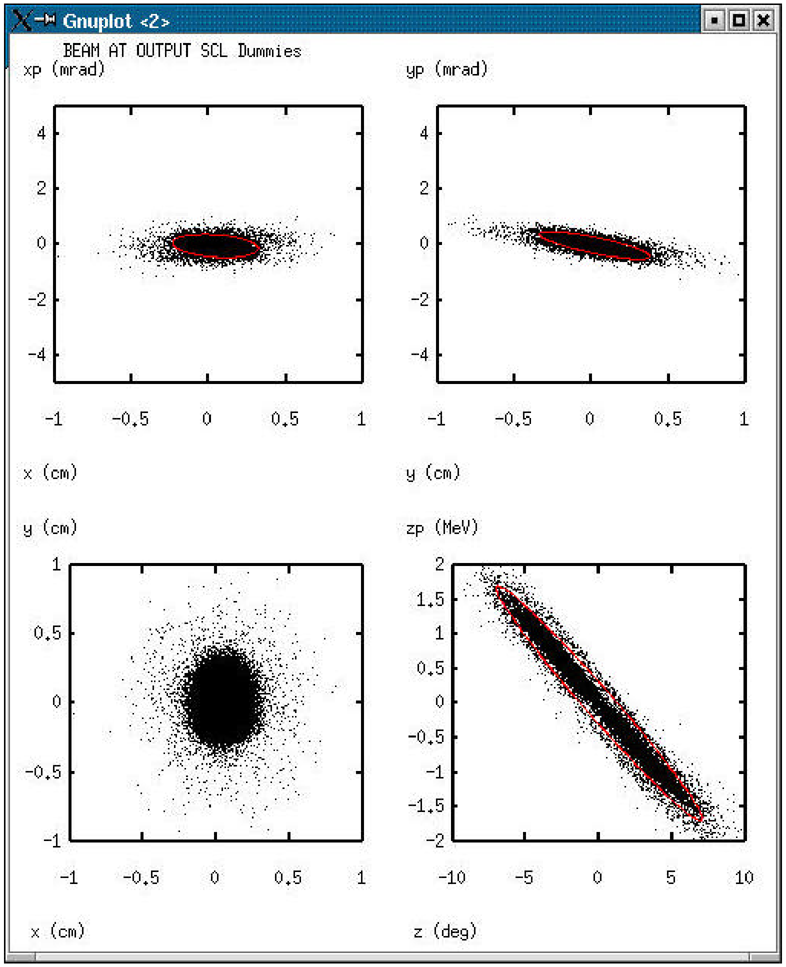
SNS MEBT-DTL TANK1 110601
RDBEAM
111111
1
402.5 0.
939.301404 1. -1.
2.50   0.
SCDYNAC
3
38.   3.
0
DRIFT
9.75
QUADRUPO
6.1 -5.1954957 1.5
CAVSC
1 2.5253 0.07318 5.4326 0.5835
0.0961 0.5652 0.0259 3.5 0. 1.13
-45. 26.63257 0.0021465 402.5 1.

FIELD
2.
CAVMC
1
0. 0.
-154.17115 0
DRIFT
11.67024
CAVMC
2
0. 0.
119.506726 0

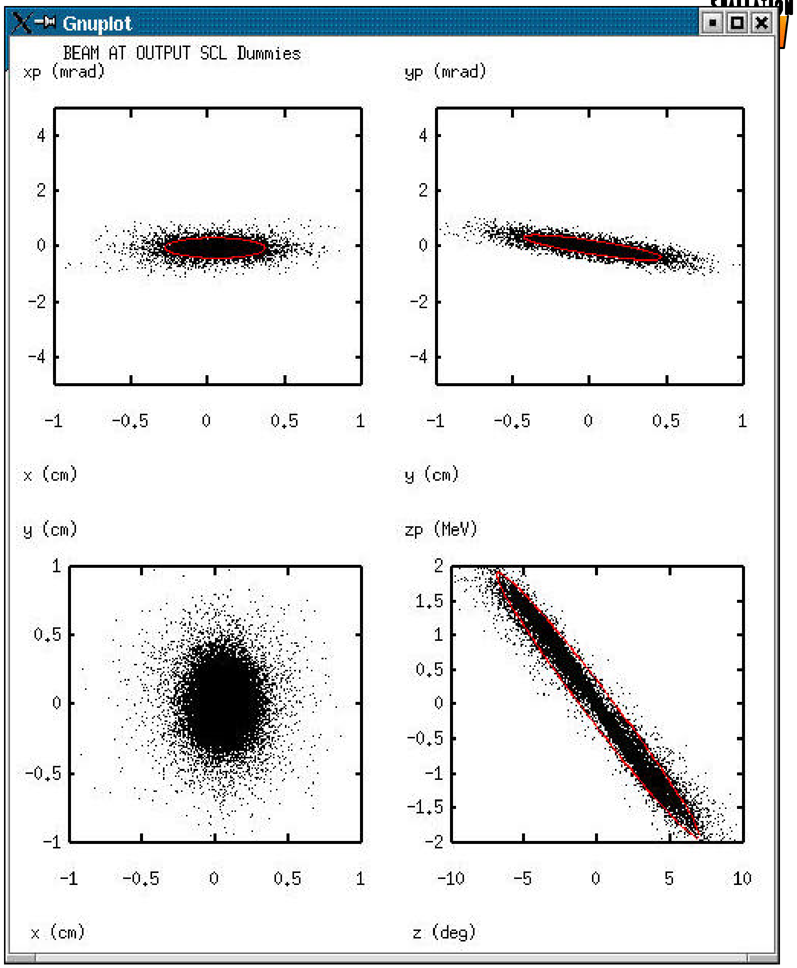


HARM
126.600006   .805E09 1.272727E-08 6
36
0.22145E+06 -0.54067E+07 -0.12518E+06 ……………
CAVMC
……….

INVESTIGATION OF HALO AT SCL OUTPUT



SCHEFF (modified)



HERSC

Brief history of beam dynamics in linear accelerators (1)

Due to the non-linearity, it is necessary to use approximated methods to solve the equations of motion of a particle moving in an accelerating E.M. field. It is firstly assumed that the axial field can be expressed in the form of modes with circular symmetry:

$$E_z(r,z) = \frac{1}{2p}\int_{-\infty}^{\infty}\left(T(k_z)\cos k_z z + S(k_z)\sin k_z z\right)I_0(k_r r)\,dk_z \qquad (1)$$

with the transit time factors $T(k_z) = \int_0^L E_z(0,z)\cos k_z z\,dz$, $S(k_z) = \int_0^L E_z(0,z)\sin k_z z\,dz$

The early linacs made use of the so called Panofsky equation (1950):

$$\Delta W = qV_0 T\cos j \qquad (2)$$

with the transit time factor $T = \sin(kg/2)/(kg/2)$ (3)

where $k = w/v$ and g is the gap length.

Brief history of beam dynamics in linear accelerators (2)

- **The equation (1), not being accompanied by an equation of the evolution of the phase, cannot respect Liouville's theorem.**
- Then in the early 1960's a more elaborate theory (P. Lapostolle, A. Carne, M. Promé) was derived, 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 :

$$\Delta W = qVT(\bar{k})I_0(\bar{k}\bar{r})\cos\bar{\varphi} + qV\frac{\partial}{\partial k}\left\{T(\bar{k})\bar{k}I_1(\bar{k}\bar{r})\right\}\bar{r}'\sin\bar{\varphi} \qquad (4)$$

$$\Delta\varphi = \frac{qV}{W}\bar{k}\frac{\partial}{\partial k}\left\{T(\bar{k})I_0(\bar{k}\bar{r})\right\}\sin\bar{\varphi} - \frac{qV}{W}\bar{k}\frac{\partial^2}{\partial k^2}\left\{T(\bar{k})kI_1(\bar{k}\bar{r})\right\}\bar{r}'\cos\bar{\varphi} \qquad (5)$$

  and similar equations for transverse movement.
- **These equations, respecting Liouville's theorem, refer to** a trajectory which crosses the MID GAP PLANE of **single symmetric <u>short</u> accelerating gaps.**

Brief history of beam dynamics in linear accelerators (3)

- **Mid gap values are needed and may be obtained from an other set of intrinsic equations, making use of the *S* coefficients, as is done in PARMILA.**
- **Initiated by the development of heavy ion multi-gap super conducting helical cavities at SACLAY, which present no exact symmetry, <u>a new formalism was derived</u> from this last approach in 1980 (P. Lapostolle, S. Valero) :**
  - **The field is expressed in the form of a Fourier series expansion, this permitting to compute second order effects**
  - **Asymmetric and multi-gap cavities are treated as the second half of a double length ones (sum of symmetrical and anti-symmetrical fields), using the mid cavity calculation formalism with the input values.**
- **Note that in the 1990's another approach, also derived from this formalism, has been introduced at LANL (H.Takeda, J.Stovall). This approach treats the multi-cell cavity as a succession of symmetrical thins gaps.**

BEAM DYNAMICS IN DYNAC (1)

- **Particles may be accelerated through long accelerating elements with complex electromagnetic fields where their transit time is of the order of 10 pi , their velocities vary by 10% or more. Such problems cannot be satisfactory solved by the previous sets of equations as these are only valid up to the second order (e.g. the phase evolution is considered linear and includes a phase jump).**
- **In 1994 a full set of quasi-Liouvillian equations, accurate beyond the second order, has been introduced in DYNAC (P.Lapostolle, E.Tanke, S.Valero) [1]. It includes new concepts such as the *equivalent accelerating field and the application of the Picht transformation.***
- **These equations, available for all kinds of particles, result in a convenient matrix formalism, allowing checking of the Liouvillian character of longitudinal and transverse motion.**

[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.

BEAM DYNAMICS IN DYNAC (2)

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: $$R = r\sqrt{bg} \qquad (6)$$

With this transformation, the transverse motion can be rewritten:

$$\frac{d^2R}{dz^2} - R\frac{q}{2m_0c^3b^3g^3}\frac{\partial E_z}{\partial t} + R\left(\frac{q}{2m_0c^2}\right)^2\frac{g^2+2}{b^4g^4}E_z^2 = 0 \qquad (7)$$

The dynamics through an accelerating element are obtained from the following integrals:

$$\Delta W = q\int_0^L E_z(z,0,t)[1+F]dz \quad , \quad \Delta j = \frac{q}{m_0c^2}\frac{w}{c}\int_0^L \frac{1}{b^3g^3}E_z(z,0,t)[1+F]zdz \qquad (8)$$

with : $F = \frac{w^2\left(R^2 + 2RR'z\right)}{4c^2b^3g^3}$ **Analogous relations exist for transverse motion.**

BEAM DYNAMICS IN DYNAC (3)

The principle of the *equivalent accelerating field* is to replace the complex real field distribution acting on the particle by one giving equivalent dynamics but simpler in form, permitting an easier computation of the integrals above. Elements having the same *T, S* and derivatives with respect to the *k* of the particle yield identical results. The *'equivalent element'* is chosen in such a way that its accelerating field has a constant amplitude over a cavity of '*equivalent length'* . Contrary to the previous approach, where the phase evolution is considered linear with a correction in the form of a phase jump, this evolution is now represented by a polynomial of the fifth order.

The motion of the particle can be obtained from an expansion around a central particle, and each of the 6D coordinates of the particles are known in any position in the element, permitting multi-step space charge computations.

HIGHLY ASYMMETRIC FIELDS SIMULATED WITH DYNAC

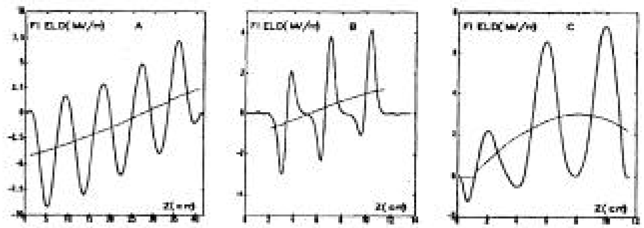


FIGURE 10: In (A) the real field (solid curve) and equivalent field (dots) acting on a 500 keV electron entering a fifth-cell cavity as given by Fig. 6A. (B) as (A) but for a 0.22 MeV/nucleon Pb^{+25} ion entering a quasi-Alvarez cell at $-90°$ from the crest as given by Fig. 6B. (C) as (A) but for a 0.24 MeV/nucleon Pb^{+25} ion into the first three gaps of an interdigital H structure at 101 MHz (peak energy gain of 6 MeV). The asymmetry in the axial field is shown in Fig. 18.

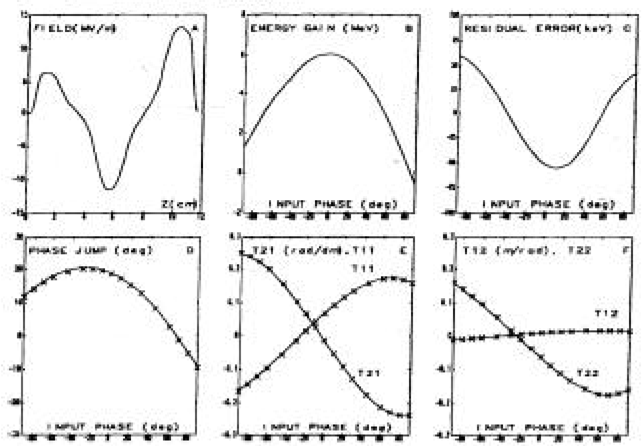


FIGURE 18: Comparison between the numerical computations (solid line) and the new method (crosses) for three gaps of an interdigital H structure at 101 MHz; acceleration of a 0.25MeV/nucleon Pb^{+25} ion with a phase varying from $-90°$ to $90°$ relative to the phase giving a peak energy gain (of 6 MeV). The axial electric field is shown in (A). One notices the asymmetry of the field. (B), (C) and (D) represent the energy gain, the residual error in energy gain and the phase jump. (E) and (F) represent the matrix coefficients in a thin-lense formalism with reduced variables.

SPACE CHARGE IN DYNAC (HERSC) (1)

In the HERSC routine the electrostatic Dirichlet-Neumann problem is transposed from some point to point correspondence onto a functional space spanned by a finite sequence of 3D Hermite functions: $d_{lmn}(x,y,z) = \hbar_l(x)\hbar_m(y)\hbar_n(z)$
These functions requiring no strict limit provided that they are properly scaled.
They are appropriate to represent the bounded continuous and positive distributions of bunches.

$r(x,y,z)$ being the distribution of the bunch, one considers the following limited Hermite series expansion:

$$S(r) = \sum_{l=0}^{l'} \sum_{m=0}^{m'} \sum_{n=0}^{n'} A_{lmn} d_{lmn} \quad \text{with:} \quad A_{lmn} = \frac{1}{\|d_{lmn}\|} \sum_{i=1}^{N} H_l(x_i) H_m(y_i) H_n(z_i)$$

Where (x_i, y_i, z_i) are the coordinates of the particles

and $H_l(x_i)$ is the Hermite polynomial.

SPACE CHARGE IN DYNAC (HERSC) (2)

One proves that $S(r)$ oscillates regularly around r in each Cartesian direction such that two successive oscillations are identical but with alternate sign (‘*Mini-Max’* theorem of Chebitcheff). The beam self-fields being computed from the integration of $S(r)$ instead of the one of r, the compensation between two successive identical oscillations of opposite sign minimizes the difference between these two integrations.

The distributions of clouds of particles having identical analytical characteristics, it can be proven that the lower upper limits l', m' and n', which provide regular oscillations, are always similar and can be predicted at once. Among all the terms in the Hermite series expansions just a few tens of the most significant terms are sufficient.

SPACE CHARGE IN DYNAC (HERSC) (3)

Through the substitution of r by the series expansion $S(r)$ in the potential equation, one can write:

$$\nabla U^* = -q/e_0 \sum_{l=0}^{l^*} \sum_{m=0}^{m^*} \sum_{n=0}^{n^*} A_{lmn} \hbar_l(x) \hbar_m(y) \hbar_n(z)$$

One considers separately each term:

$$\nabla U_{lmn} = -A_{lmn} \hbar_l(x) \hbar_m(y) \hbar_n(z)$$

from which one obtains in the x-direction:

$$E_{lmn} = (-i)^{l+m+n+1} \frac{q}{e_0} A_{lmn} (2p)^{-3/2} \times \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\hat{x}^{l+1} \hat{y}^m \hat{z}^n}{\hat{x}^2 + \hat{y}^2 + \hat{z}^2} e^{-(\hat{x}^2+\hat{y}^2+\hat{z}^2)/2} e^{i(\hat{x}x+\hat{y}y+\hat{z}z)} d\hat{x} d\hat{y} d\hat{z}$$

The integral, computed analytically, yields the set of beam self-field equations of the Dirichlet-Neumann problem within an arbitrary bunch.

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

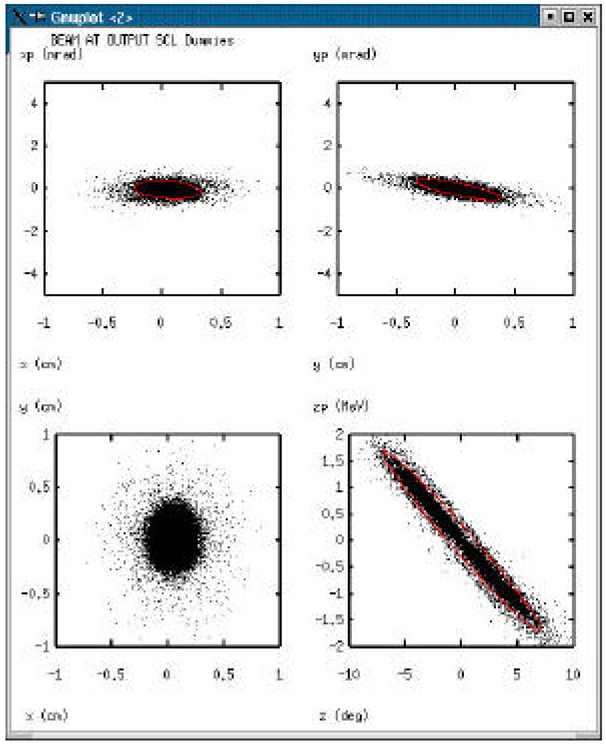
DYNAC FOR USE AT SNS ? (2)

For commissioning purposes 1k particles suffice.

On the AP cluster, the simulation of 1k particles through the MEBT-DTL-CCL-SCL takes 30 seconds.

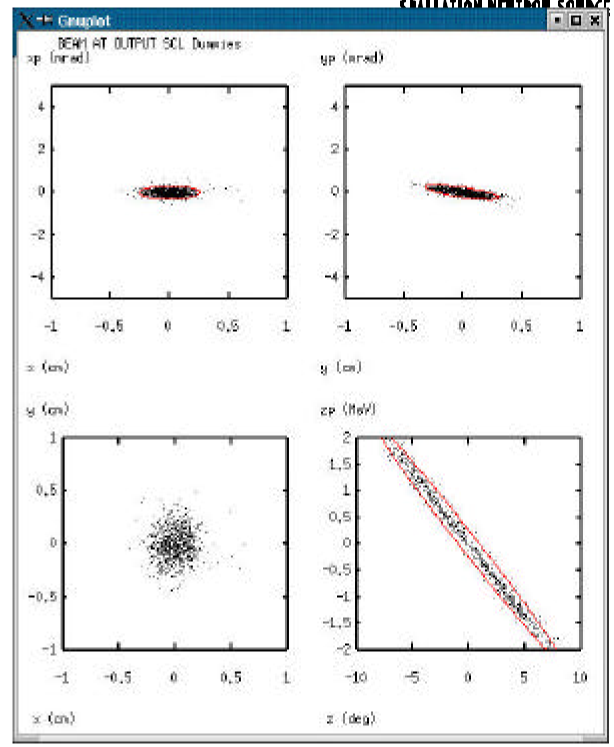
Error studies possible (align, freq,amp,phase).

Procedures (e.g. for phase scan and delta T) are being developed.



10 k particles

7.745	2053.33	-0.9942	5.924 ns.keV
2.169	0.288	0.0416	1.135 mm.mrad
2.820	0.295	-0.7083	1.068 mm.mrad



1k particles

7.652	2066.83	-0.9938	6.063 ns.keV
2.286	0.276	0.0266	1.148 mm.mrad
2.827	0.315	-0.7415	1.088 mm.mrad

SUMMARY / CONCLUSION

For commissioning:

- **DYNAC is an easy to use program**
- **Source code and in-house expertise on its contents are available**
- **The input file for the SNS linac exists**
- **The code is fast enough**
- **Algorithms for commissioning are underway**

For simulation:

- **DYNAC contains a set of Liouvillian beam dynamics equations, not only valid for DTL, but particularly suited for CCL and SCL**
- **DYNAC contains 3 space charge methods. The HERSC method, a 3D analytical method without any restrictions on the bunch shape, will be an excellent tool for investigation of halo**

The same input file and the same code are used both for simulation and commissioning