Linac Beam Dynamics Codes: State of the Art and Perspectives

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Lawrence Berkeley National Laboratory

HB 2008

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  - Office of Advanced Scientific Computing Research
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SciDAC Scientific Discovery through Advanced Computing

Office of Science U.S. DEPARTMENT OF ENERGY

OUTLINE

- **Part 1: Past**
  - —Partial history of beam dynamics codes
- **Part 2: Present**
  - —Current capabilities
- **Part 3: Future**
  - —Hardware
  - —Accelerator code development

Part 1

Partial History of Beam Dynamics Codes

CODES, CAPABILITIES & METHODOLOGIES FOR BEAM DYNAMICS SIMULATION IN ACCELERATORS

PARMELA
PARMTEQ
PARMILA
2D space charge
rms eqns

WARP
SIMPSONS
IMPACT
3D space charge
GCPIC
DA
Symp Integ
Normal Forms
Integrated Maps
COSY-INF
MXYZPTLK

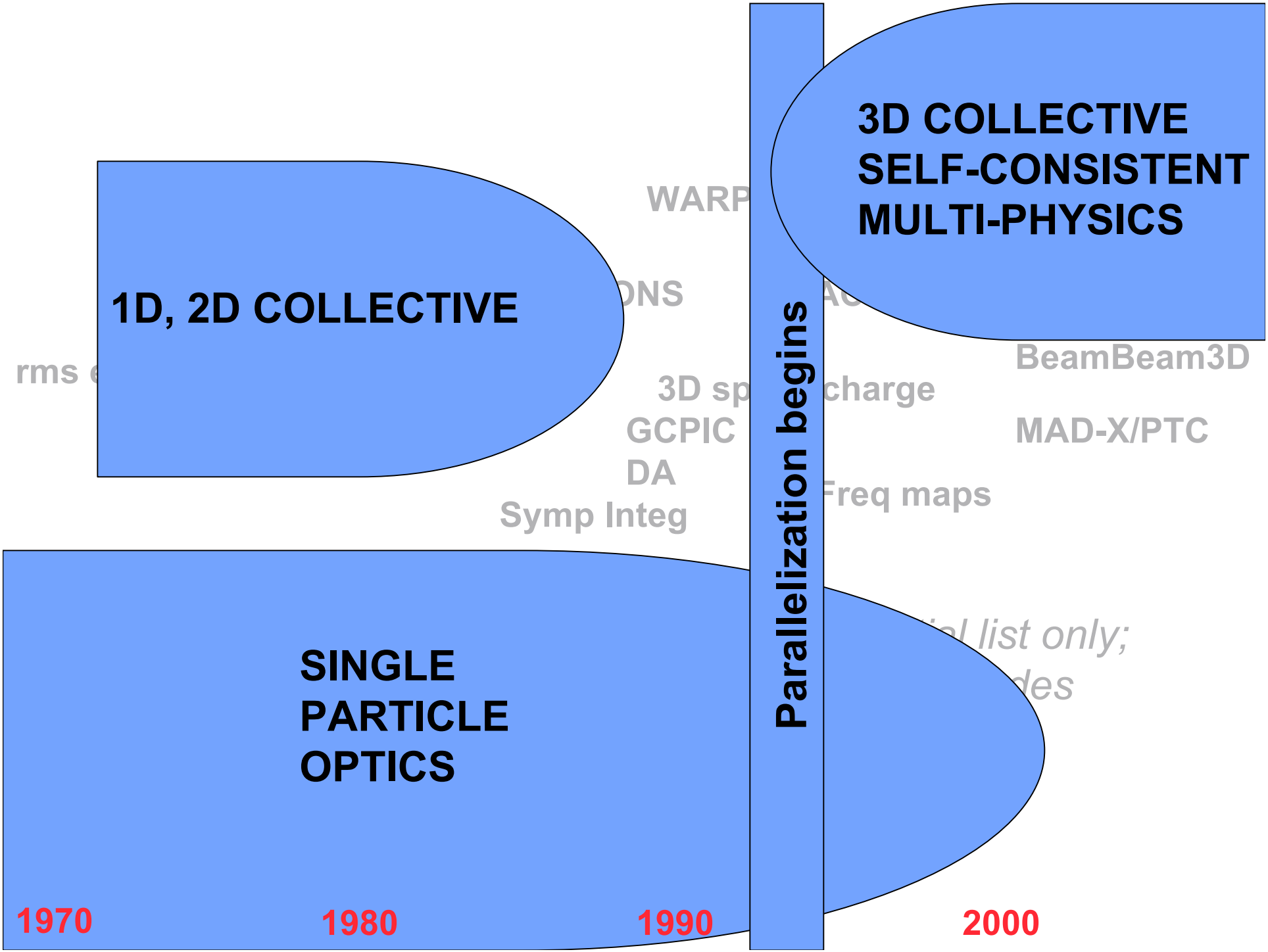
Freq maps

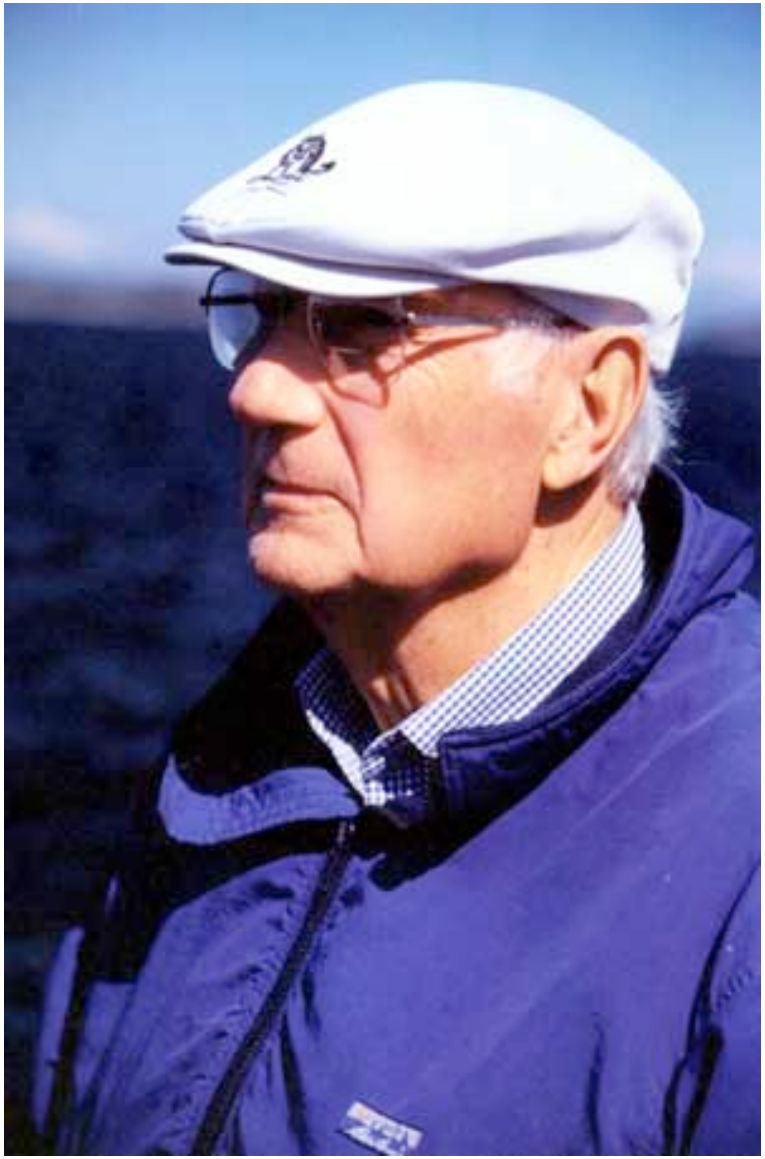
IMPACT-Z
IMPACT-T
ML/I
Synergia
OPAL
ORBIT
TRACK
Dynamion
DESRFQ
BeamPath
BeamBeam3D
MAD-X/PTC
…

MaryLie
Dragt-Finn
MAD
Transport

Partial list only;
Many codes
not shown

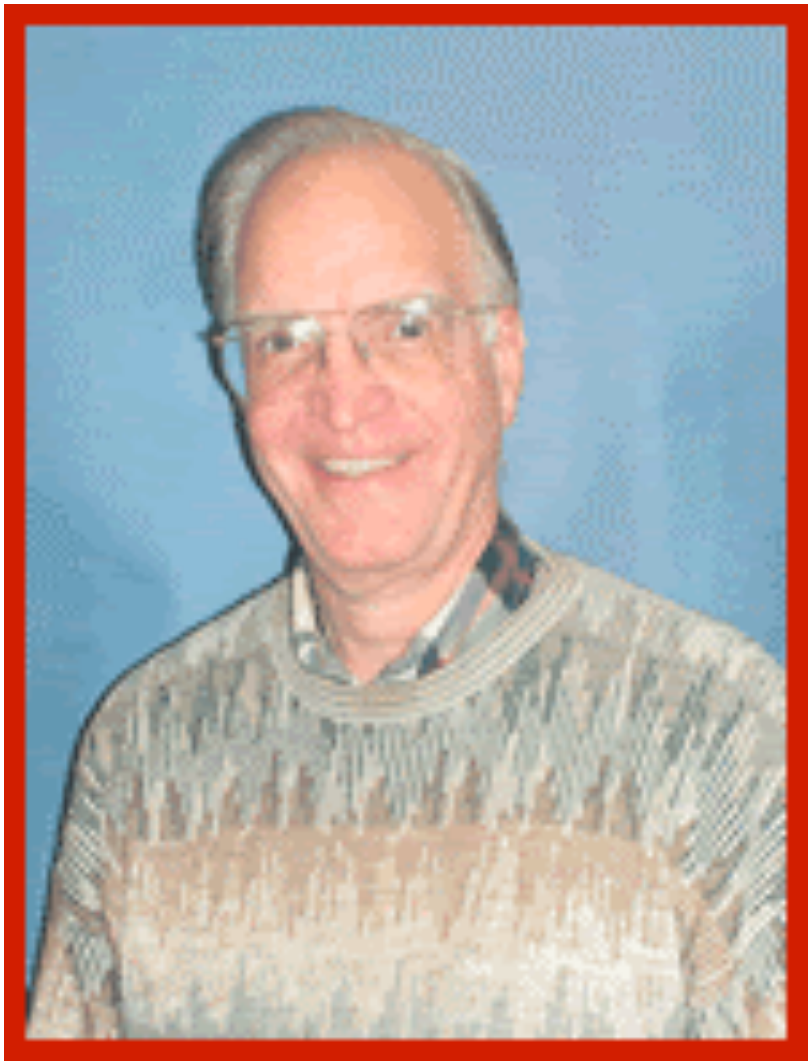
1970 1980 1990 2000


3D COLLECTIVE
SELF-CONSISTENT
MULTI-PHYSICS
1D, 2D COLLECTIVE
SINGLE
PARTICLE
OPTICS
Parallelization begins
WARP
ONS
rms
3D sp
charge
GCPIC
DA
Symp Integ
BeamBeam3D
MAD-X/PTC
Freq maps
1970
1980
1990
2000



$$\zeta^{f} = \sum M\zeta^{i} + \sum\sum T\zeta^{i}\zeta^{i} + \sum\sum\sum U\zeta^{i}\zeta^{i}\zeta^{i} + \ldots$$

$$\zeta^{fin} = \mathcal{M}\zeta^{in}$$



$$\mathcal{M} = e^{:f_2:} e^{:f_3:} e^{:f_4:} \ldots$$

$$\zeta^f = \mathcal{M}\zeta^i = e^{:f_2:}(1 + :f_3: + \frac{1}{2} :f_3:^2 \ldots)(1 + :f_4: + \ldots)\zeta^i$$

$$\zeta^f = \sum M\zeta^i + \sum\sum T\zeta^i\zeta^i + \sum\sum\sum U\zeta^i\zeta^i\zeta^i + \ldots$$

$$\mathcal{M} = e^{:f_2:} e^{:f_3:} e^{:f_4:} \ldots$$

$$\zeta^f = \mathcal{M}\zeta^i = e^{:f_2:}(1 + :f_3: + \frac{1}{2}:f_3:^2 \ldots)(1 + :f_4: + \ldots)\zeta^i$$

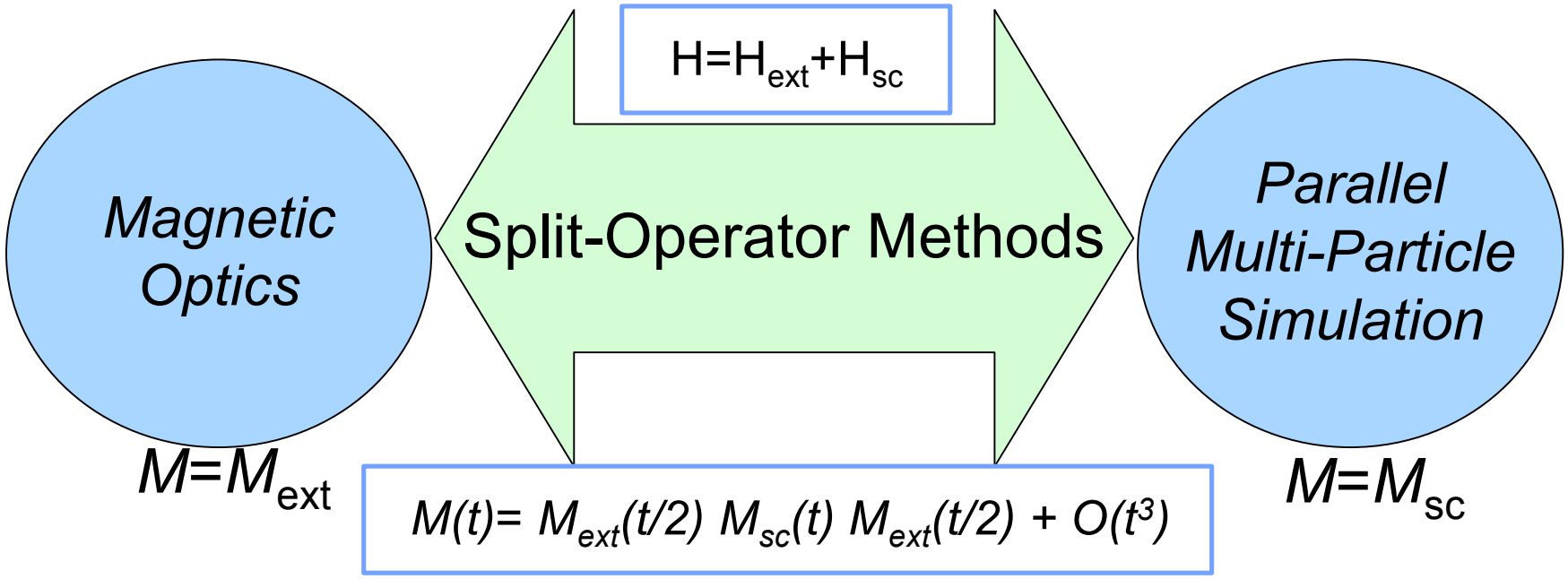
$$\frac{d}{dt} M = JSM$$

$$\frac{d}{dt} f_3 = -H_3^{\text{int}}$$

$$\frac{d}{dt} f_4 = -H_4^{\text{int}} - \frac{1}{2}[f_3, H_3^{\text{int}}]$$

$$\ldots$$

mid-1990's: IMPACT (Integrated Map and Particle Accelerator Tracking code) used Split-operator approach to combining high-order optics with parallel PIC



- **Note that the rapidly varying s-dependence of external fields is decoupled from slowly varying space charge fields**
- **Leads to extremely efficient particle advance:**
  - **— Do not take tiny steps to push ~100M particles**
  - **— Do take tiny steps to compute maps; then push particles w/ maps**

R. Ryne, LBNL

Part 2

Linac Codes: Current Capabilities

Acknowledgements

- Andreas Adelmann (PSI)
- Christopher Allen (ORNL)
- David Bruhwiler, Peter Messmer (Tech-X Corp)
- Yuri Batygin (MSU)
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- George Gillespie (AccelSoft Inc)
- Valentin Ivanov (Muons Inc)
- Robert Jameson (RIKEN)
- Alessandra Lombardi (CERN)
- Ji Qiang (LBNL)
- Frank Krawczyk (LANL)
- A. Kolomiets (ITEP)
- Rudolf Tiede (Goethe-Univ. Frankfurt)
- Leonid Vorobiev (FNAL)
- Stepan Yaramisheve (GSI)

How information was gathered for this portion of the talk

- Sent email asking for input on
  - Specialized codes for portions of hadron linacs (ion sources, RFQs,...)
  - Codes that are strictly used for hadron linac simulations
  - Codes that can be applied to both linacs and rings, and for which there are notable applications involving hadron linacs
- Received ~20 responses

RFQ Matching Code

Leonid Vorobiev (Fermilab)

HB2008: RFQ – Matching Code

L.G.Vorobiev, APC/FNAL, Batavia. Email: lgv@fnal.gov

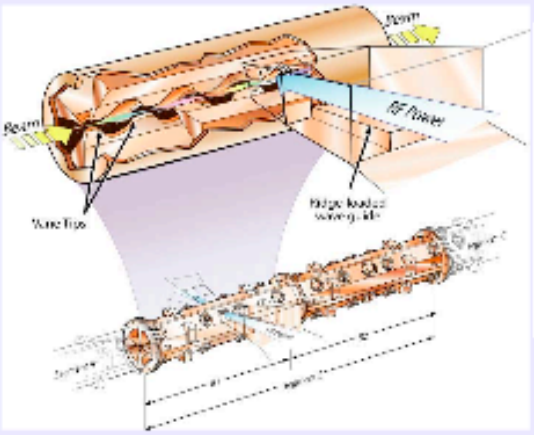
RFQ linac *(Invented by Kapchinsky, Teplyakov)* **are the most adequate for low-β, high-current beams, bridging ion source, DTLs and other RFQs.**

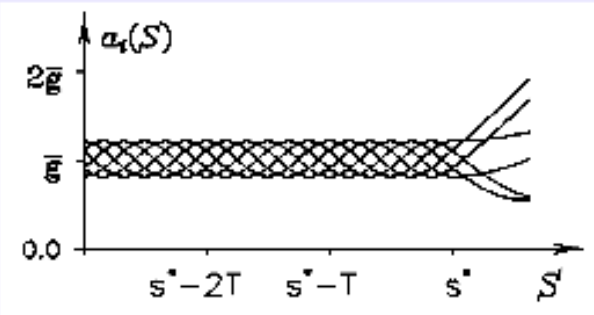
Motivation: RFQ Dynamic matching (Input/Output RFQ optimization)

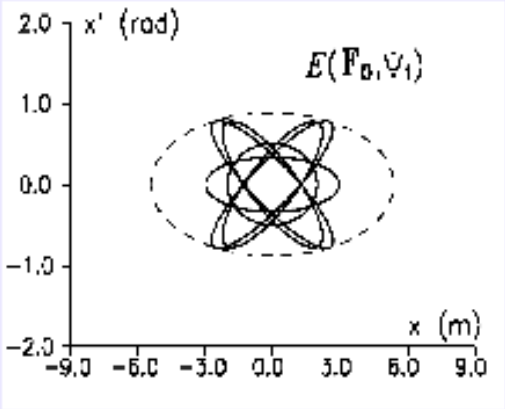
RFQ Idea:
Focusing & Acceleration combined

Horizontal beam envelopes & phase ellipses at $s=s^*$ for (y,y') - similar

Layout







Plot by L.M. Young, et al. LANL

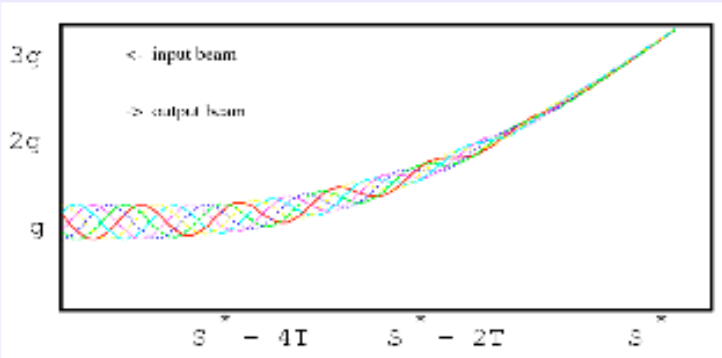
HB2008: RFQ Matching

L.G.Vorobiev (FNAL)

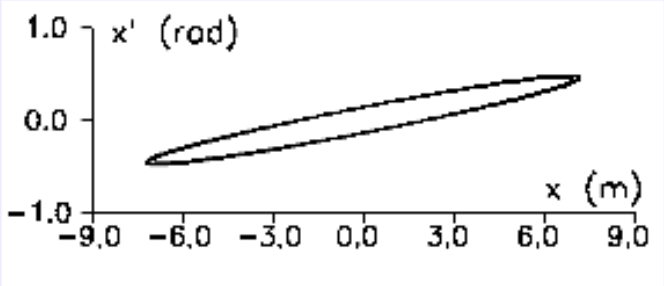
Conventional RFQ matching:

Long adiabatic sections for transverse & longitudinal matching.

Envelopes



Phase ellipses at $s=s^*$



Matching Goal: High current, narrow aperture, short length (=higher acceleration rate).
Optimization: Non-adiabatic matching sections to be found: ***F(s)*.**

"Shape function" F(s) is implanted into $K_{x,y}(s)$ in Beam Equations (KV model):

$$\begin{cases} a_i''(s) + K_x(s)a_i(s) - \dfrac{Q}{a_i(s)+b_i(s)} - \dfrac{\varepsilon_x^2}{a_i(s)} = 0 \\ b_i''(s) + K_y(s)a_i(s) - \dfrac{Q}{a_i(s)+b_i(s)} - \dfrac{\varepsilon_y^2}{b_i(s)} = 0 \end{cases}$$

$$K_x(s) = \alpha F(s)\cos(2\pi s/T + \theta_i), \quad K_y(s) = -K_x(s)$$

$$i = 1,\ldots N; \quad Q = 4qI / AI_p(\beta\gamma)^3, \; I_p = 3.13\times10^7 \text{ A}$$

HB2008: RFQ, Non-adiabatic matching sections

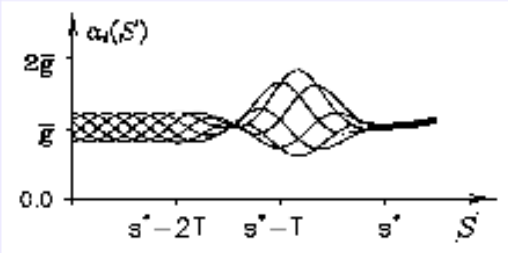
L.G.Vorobiev (FNAL)

Goal function: $\Phi(F(s)) \rightarrow \min$

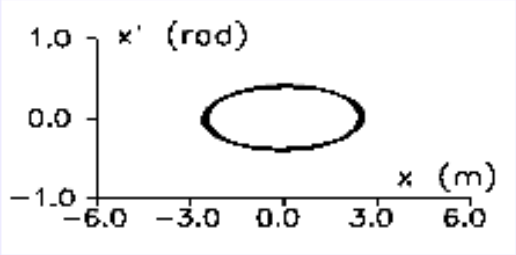
"Φ" estimates quantitatively the matching quality (E.G.: stationary beam waist, the fixed length of matching section, current insensitivity, etc.)

Method: Gradient projection upon the constraint tangent hyperplane (see Refs.)

Envelopes

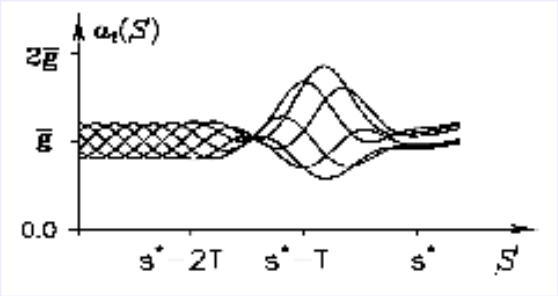


Phase ellipses at $s=s^*$

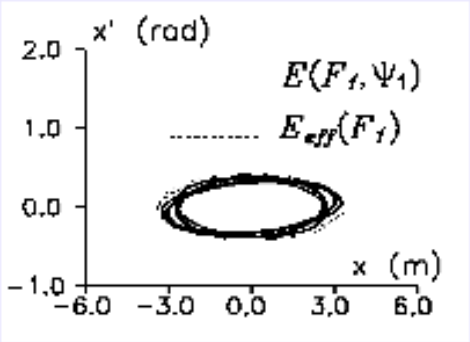


OPTIMIZATION #1: Stationary, Short, but Sensitive to current variations:

Envelopes



Phase ellipses at $s=s^*$

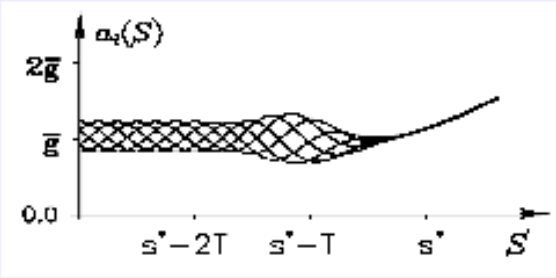


HB2008: RFQ, Optimal non-adiabatic sections

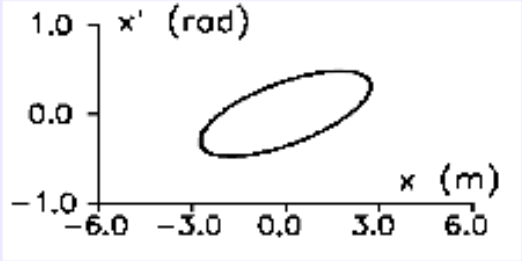
L.G.Vorobiev (FNAL)

Optimal solution #2: Insensitive to current variations

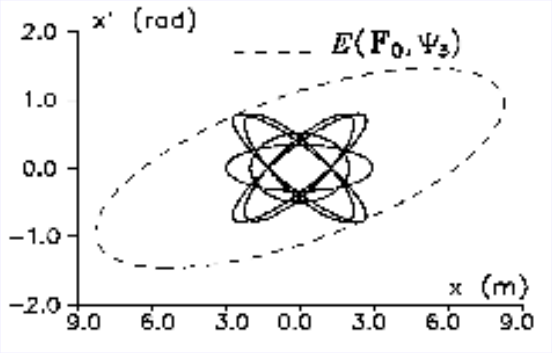
Optimal Envelopes



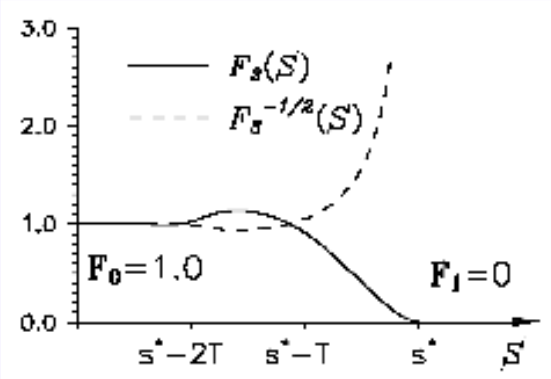
Optimal Phase ellipses at $s=s^*$



Phase ellipses at $s=s^*$ before optimization



Solid line – focusing strength
Dashed line – RFQ vanes profile



HB2008: Applications, RFQ Linac tree

L.G.Vorobiev (FNAL)

Heavy Ion Driven Inertial Fusion

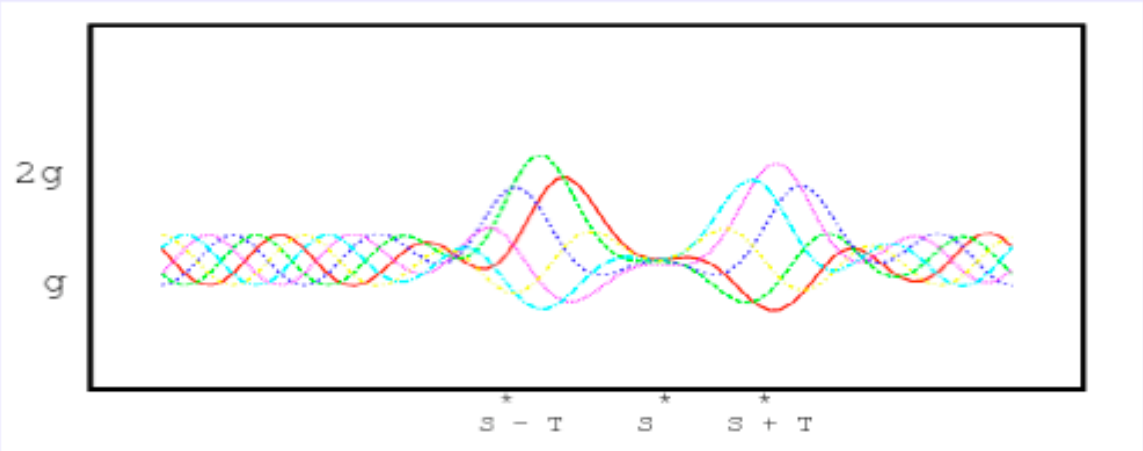
Accelerator Driver = RFQ linac-tree + Resonant Linacs
+ Long Transport (Compression) + FFS (as in HIBALL)

Matching of RFQ with the ion source, DTLs, etc.

RFQ funneling tree in HIDIF driver:

Matching of 2 or several RFQs

RFQ1 with lower frequency **RFQ2 with higher frequency**



Envelopes with different phases are plotted with different linestyles

HB2008: RFQ Summary/References

L.G.Vorobiev (FNAL)

RFQ matching code generates vane profiles, providing:

- Stationary waist / diverging / converging beam
- Low sensitivity to current variations
- High acceleration rate due to short length

Works both for RFQ input & output; for continuous and bunched beam.

References

- **Optimizer (theory and algorithm):**
  L.G. Vorobiev, D.G. Koshkarev: Preprint ITEP-4, ITEP, Moscow, Russia (1992).
- **RFQ matching sections:**
  D.G. Koshkarev, L.G. Vorobiev: NIM, Section A, vol. 336, p. 291-300, (1993).
- **Optimal shaping for optics and other beam applications:**
  L.G. Vorobiev, R.W. Müller: GSI-96-06 Report , GSI-98-02 Report, GSI-98-03 Report; GSI, Darmstadt, Germany.

DESRFQ

Andrei Kolomiets (ITEP)

DESRFQ – a Code for Design of Radio Frequency Quadrupole

A.A. Kolomiets * , T.E. Tretjakova, S.G. Yaramyshev

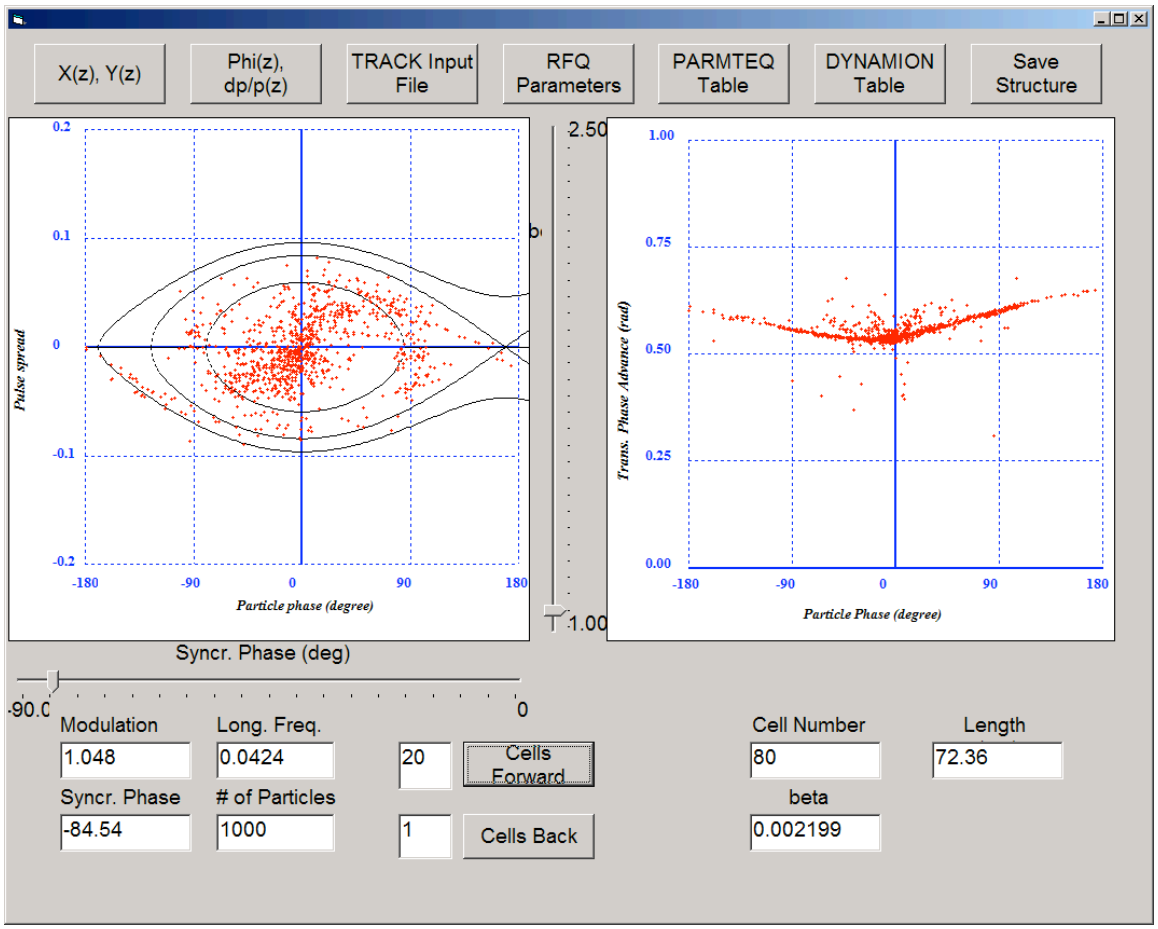
Institute for Theoretical and Experimental Physics (ITEP)
Moscow, Russia

* e-mail: kolomiets@itep.ru

Main Code Features

- The easy input of the initial RFQ parameters.
- Visual representation of the numerous calculated parameters (transverse and longitudinal phase advances, acceptance, current limit, maximum field strength at the electrode surface, Coulomb parameter, etc). The code shows the distributions of these values along axis and allows the easy study how they depend on the input.
- The possibility to use a number of predefined tables ($\varphi s(\beta)$ and $m(\beta)$) earlier created by user for calculation of electrode profile.
- The code allows the study of the influence of these functions on the main RFQ parameters using direct changing of their graphical representations.
- The calculation of the RFQ structure is carried out cell by cell interactively. User can correct values of synchronous phase and modulation at any cell at any moment. User can return to the previous cells to correct design more and more to reach desired result.
- The beam dynamics is calculated in parallel with structure design – the particle distribution in phase space in the given cell is presented immediately after its determination.
- The code uses an improved representation of the field in an RFQ working aperture solving Laplace equation taking into account real geometry of the electrodes. Size of the grid, where Laplace equation for electric potential is solved, depends of the main parameters of the cell.
- The beam dynamics is calculated taking into account space charge forces. It allows to reach precise RFQ design for accelerating beam of high intensity.

DESRFQ Window for Interactive Work



After definition of the main RFQ parameters, mathcing section and preliminary laws of modulation and synchronous phase, the main window is opened. It contains two diagrams. One of them presents particle distribution in ψ - $\Delta p/p$ phase space and set of phase trajectories corresponding to the different values of Hamiltonian potential function.

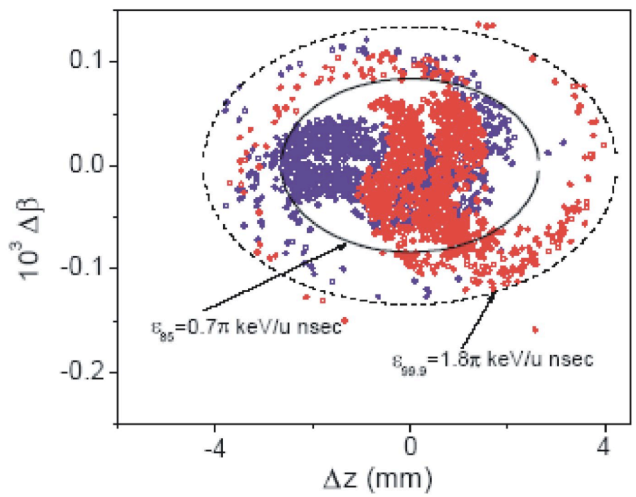
Three phase trajectories shown in diagram correspond to almost linear oscillation, to border of stability region (separatrix) and unstable longitudinal motion.

Stability of transverse particles motion is illustrated in diagram "μ - φ_s ", where μ - phase advance. Value of phase advance for each particle for current focusing period is calculated from beam dynamics simulations taking into account realistic field distribution and space charge forces.

In this window designer can interactively introduce modulation and synchronous phase for each cell and generate output files for different simulation codes.

Implementation to the RFQ design

27 MHz Heavy Ion RFQ (ITEP, Moscow)	in operation since 1999
TWAC project (ITEP, Moscow)	under construction
Heavy Ion High Current GSI-RFQ (GSI, Darmstadt)	upgrade planned in 2009
Heavy Ion RFQ for RIA (ANL, Argonne)	project
Proton RFQ for FAIR (GSI, Darmstadt)	project



RIA RFQ: U^{28+} and U^{29+} ions are accellerated simultaneously . (Long. distribution at RFQ output)

27 MHz Heavy Ion High Current RFQ (ITEP)

LIDOS RFQ desiger

Alexandr Durkin

LIDOS RFQ DESIGNER

- Contains ADVISER part which is based on simple models of physical process and is intended for fast calculations of many version; using visual results of this part user can go from current version to better one and to find optimal version.
- Gives possibility to simulate beam dynamic of several type of ions simultaneously, ions are differ by charge number (including sign) and mass number.
- Calculates a real field grid for total channel (from rms-section to Crandall cell)
- Takes into account coupling gaps.
- Calculates statistic taking into account tolerances on machining, tuning, adjustment and so on.

LINACSrfq, pteqHI

R. A. Jameson (Inst. Angewandte Physik,
Goethe Univ. Frankfurt)

LINACSrfq + pteqHI

(A general linac design code; rfq design module)

(RFQ simulation code, with PARMTEQ roots, extensively modified and extended)

R.A. Jameson
Inst. Angewandte Physik, Goethe Uni. Frankfurt
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Tel: +49-69-798-47403,Fax: -47407, E-mail jameson@riken.jp

LINACS Design Code – based on rms envelope equations. For any type of hadron linac; presented here specifically for RFQs.

Unique Features:

- Literally every linac parameter is available to the designer, affording unparalleled design flexibility and opportunities.
- Includes control of the space-charge physics of the linac – phase advances, tune shift, tune ratios, synchronous phase rules, precise application of beam equilibrium (equipartitioning), avoidance of resonances, a priori control of emittance and beam equilibrium behavior along the linac - affords unique ability to design from desired beam physics performance to the external fields required to achieve this performance (beam-driven, from-inside-out design approach). Goal to have design requirements reproduced by simulation is largely achieved.
- Also includes complete control of external fields, including multipole components, for standard "outside-in" design approach, where only external fields are specified and beam performance is then observed in a simulation program.

pteqHI RFQ Simulation Code - roots from original Los Alamos time-domain PARMTEQ version, originally written by B. Chidley with multipole and other expansions by K.R. Crandall.

Unique Features:

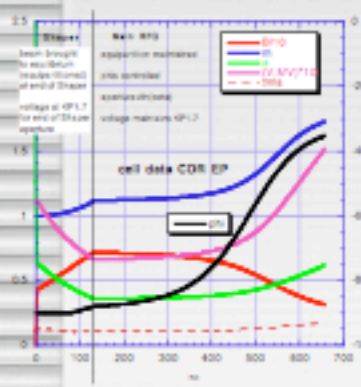
- Extensively modified to remove approximations (e.g., no paraxial approximation), upgrade dynamics, provide error checking.
- Expanded for use with heavy ions (simultaneous handling of multiple masses, charge states).
- Close coupling to LINACS design code.
- Analysis methods for beam behavior inside the RFQ.
- Versatile test-bed for comprehensive code comparisons from working designer's point of view, e.g., rz-mesh and 3-D space charge subroutines, beam-loss criteria, dynamics and space-charge meshing options, handling of off-optimum conditions, accuracy testing.

Presently in extensive upgrade to include Poisson solver capability.

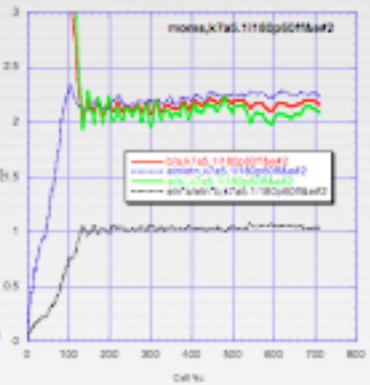
IFMIF Conceptual-Design-Reference (CDR) Equipartitioned RFQ

"RFQ Designs and Beam-Loss Distributions for IFMIF", R.A. Jameson, Oak Ridge National Laboratory Report ORNL/TM-2007/001, January 2007

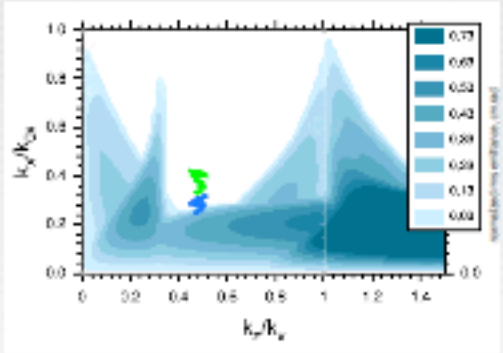
***Objective** - Keep the 130 mA D+ beam in equilibrium (equipartitioned) from the shaper end to 5 MeV; achieved using equipartitioned design strategy, with adjustment for emittance growths and actual space-charge form factor.*



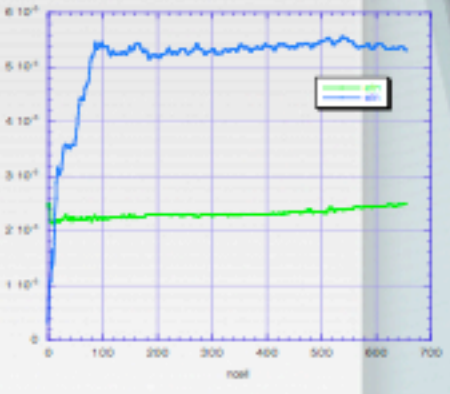
Vane parameters for the 140 mA CDR, 5 MeV, D+ equipartitioned RFQ. Aperture (a) and trms = transverse rms beam radius are in cm. (m) is the vane modulation, V is the vane voltage, B is the transverse focusing strength. Phi is the synchronous phase (phis). Rho/r0 = 0.75. Input current = 140 mA, input energy = 0.100 MeV, input transverse normalized rms emittance = 0.20 mm.mrad. Length ~12.3 m.



Equipartitioning ratio, and corresponding beam size, emittance and tune ratios for the IFMIF CDR RFQ using the 2-term potential.



Hofmann Chart for eln/etn=2.0, showing the trajectory for the IFMIF CDR RFQ from the shaper end to the output, using the 2-term potential.

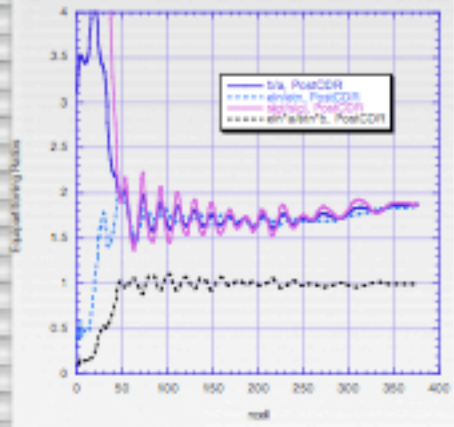


Longitudinal and transverse normalized rms emittances through the IFMIF CDR RFQ.

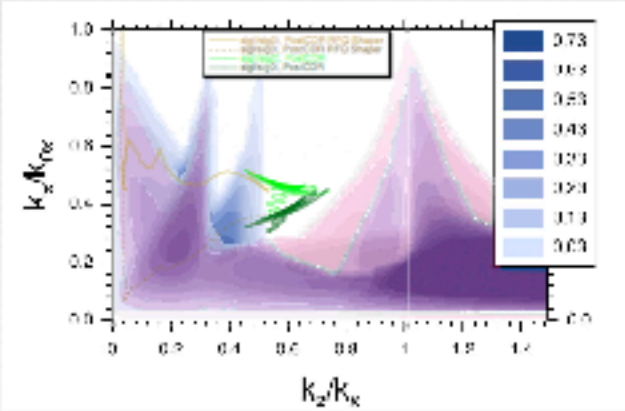
IFMIF Post-CDR Equipartitioned RFQ

"RFQ Designs and Beam-Loss Distributions for IFMIF", R.A. Jameson, Oak Ridge National Laboratory Report ORNL/TM-2007/001, January 2007

***Objective** - Aggressive optimization to minimize length, while maintaining beam equilibrium; achieved by varying the equipartitioning ratios from 1.6 at end-of-shaper, to 2.0 at end-of-RFQ, and using a particular synchronous-phase strategy. Length is reduced from ~12.3 m to ~8 m.*

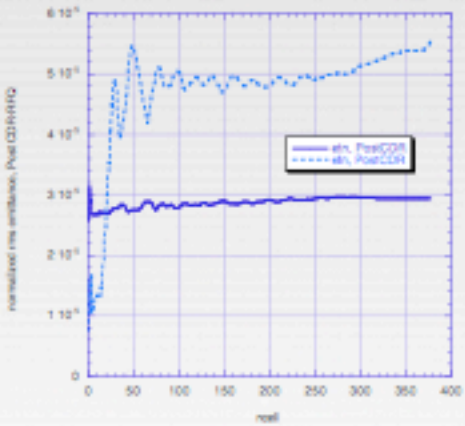


Equipartitioning ratio, and corresponding beam size, emittance and tune ratios, for the Post-CDR equipartitioned RFQ. Simulated with pteqHI including multipole and image-charge effects.



Composite Hofmann Chart for eln/etn=1.4 (underlying blue-toned shadows) and eln/etn = 2 (overlying magenta toned shadows), to convey the required change in the EP ratios from 1.6 at EOS to 2 at the end of the RFQ.

The Post-CDR equipartitioned RFQ trajectories for the shaper and from the EOS to the output are shown. There is no resonance growth.



Transverse and longitudinal rms normalized emittances for the Post-CDR equipartitioned RFQ. The longitudinal emittance growth is planned, using the synchronous-phase rule; there is no resonance growth.

Laser Ion Source (LIS) Direct Plasma Injection Scheme (DPIS) into ≥ 100 mA C4+ RFQ

"Design of ≥ 100 mA C4+ RFQ for Laser Ion Source", R. A. Jameson, M. Okamura, T. Katayama, The Institute of Physical and Chemical Research (RIKEN), Hirosawa 2-1, Wako-shi, Saitama, 351-0198, Japan, RIKEN-AF-AC-43, December 2003, ISSN 1346-2431

"Direct plasma injection scheme in accelerators", M. Okamura, T. Takeuchi, R. A. Jameson, S. Kondrashev, et.al., Invited paper, published as part of the Proceedings of the 12th International Conference on Ion Sources, Jeju, Korea, August 2007. RSI 79, 02B314 (2008)

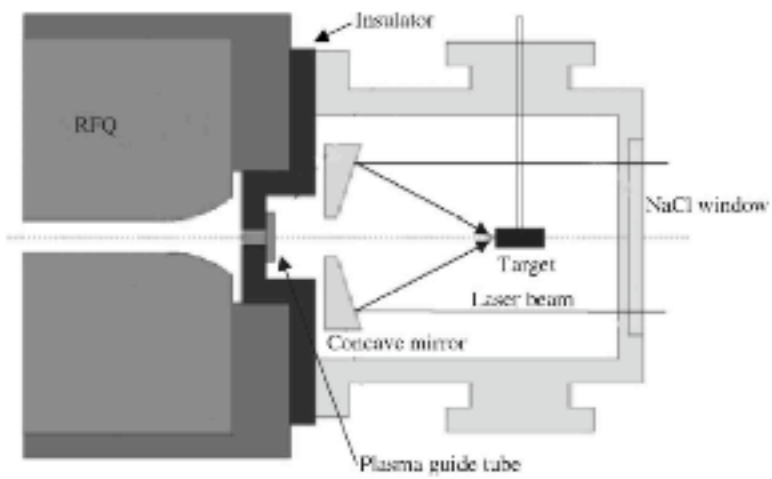


FIG. 1. Schematic view of DPIS. High voltage is applied to the mirror, target, plasma guide tube, and the chamber.

A 1.2 MeV 100 mA C4+ design current RFQ was designed for maximum acceptance, and built to test direct injection from a laser ion source. A unique feature is a strong DC field at the beginning of the RFQ. A mixture of C4+, C5+ and C6+ ions are injected. Extensive analysis of the experimental results confirms the design expectations and verifies the pteqHI simulation code multiple heavy-ion features.

DYNAMION

Stepan Yaramyshev (GSI)

Versatile multiparticle code DYNAMION

A. Kolomiets, T. Tretyakova (ITEP, Moscow)

W. Barth, S. Yaramyshev (GSI, Darmstadt)

DYNAMION code

- has been written in ITEP for the simulations of the beam dynamics in high current linacs;

- development was strongly supported by GSI and recent improvement is going on in collaboration GSI-ITEP

High level of DYNAMION reliability was demonstrated by numerous comparisons of measured data and simulated results for the operating linacs in ITEP, INR, GSI, CERN and ANL

S. Yaramyshev et al, "Development of the versatile multi-particle code DYNAMION", Nuclear Inst. and Methods in Physics Research A, Vol 558/1 pp 90-94, (2005)

E-mail: S.Yaramyshev@gsi.de

DYNAMION code

Main features:

- time integration of **3-D equation of particle motion** in the most common form;

- **end-to-end** simulations of beam dynamics in a linac, consisting of the arbitrary sequence of the RFQs, DTLs and transport lines can be done **in one run;**

- **external** electrical field in an RFQ and DTL is calculated inside the code solving the Laplace equation **for the real topology** of the elements;

- **transport lines** may include magnetic and electrical lenses (quadrupole, octupole, etc.), bending magnets, solenoids, slits, steerers, apertures, stripper sections, etc ...

Can be used in the code:

- **external** electromagnetic fields, **measured** or **simulated** by special codes;

- **multi-charged** beam (particles with different mass to charge ratio);

- input particle distribution from **measured emittance** or other calculations;

- **misalignments** of the elements.

DYNAMION: Space charge solvers

3-D space charge treatment:

- Particle-particle interaction with a special routine to avoid artificial collisions;
- PIC solver (*T. Tretyakova, ITEP, Moscow);*
- Semi-analytical solver (*A. Orzhekhovskaya, GSI, Darmstadt).*

* Special treatment of continuous beams and of the bunching process.

Analysis of the results:

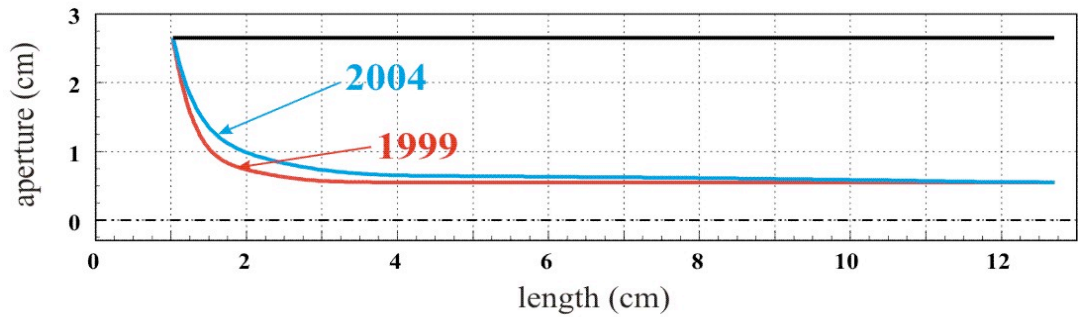
- each particle has an **unique ID-number**, i.e. a detailed analysis of its trajectory is available;

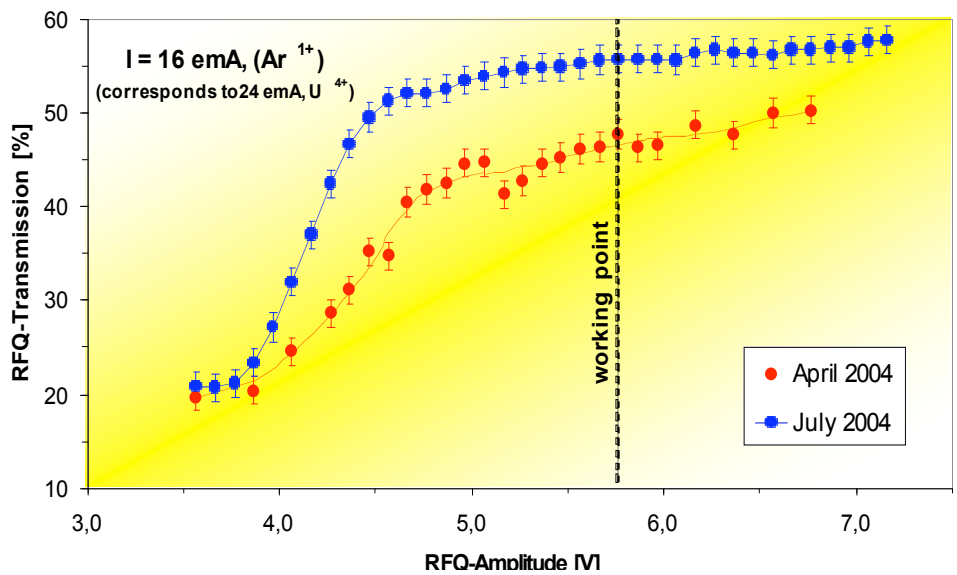
- local **phase advance** for each particle can be calculated in parallel with the beam dynamics simulations.

GSI-HSI-RFQ Upgrade 2004

- Heavy Ion High Current GSI-RFQ beam dynamics designed were performed by Prof. A. Schempp (IAP, Frankfurt), 1999
- New Input Radial Matcher was designed by S. Yaramyshev (GSI, Darmstadt), 2004

Only change: IRM with length of about 10 cm; HSI-RFQ length is more than 9 meter.





Heavy Ion High Current RFQ: Measured transmission before (red) and after (blue) the upgrade.

Simulated results (DYNAMION) and measurements before and after the upgrade are in a good coincidence.

A complete upgrade of the HSI-RFQ electrodes is planned for 2009.
(new design from A. Kolomiets and S. Minaev, ITEP, Moscow)

DYNAMION implementation

Proton High Current (200 mA) Linac (ITEP, Moscow)	**commissioned in 1993**
Booster section for proton linac (Moscow Meson Factory, Troitzk)	**in operation since 2000**
Heavy Ion High Current 27 MHz-RFQ (ITEP, Moscow)	**in operation since 2002**
GSI-UNILAC: LEBT, RFQ, MEBT, IH-DTL, stripper section, Alvarez-DTL, transport channel to the synchrotron (GSI, Darmstadt)	**since 1991**
Upgrade of the High Current Heavy Ion RFQ (GSI, Darmstadt)	**upgraded in 2004**
Superconducting RFQ (LNL, Legnaro)	**in operation since 2004**
High Current RFQ for the TWAC project (ITEP, Moscow)	**under construction**
Therapy linac (HIT, Heidelberg)	**recently under upgrade**
Heavy Ion Front-End of the Linac3 (CERN, Geneva)	**1999**
12 MHz Split coaxial RFQ (ANL, Argon)	**2000**
High Power Linac for transmutation (ITEP, Moscow)	**2000 (project)**
Study of the beam halo formation and small particle losses	**1992 - 2000**
Proton High Current RFQ for FAIR (GSI, Darmstadt)	**2004 (project)**
DTL section of the Linac4 (CERN, Geneva)	**2005 (project)**

BeamPath

Yuri Batygin (NSCL/MSU)

Particle-in-cell- code BEAMPATH for beam dynamics simulation with space charge in linear accelerators and beamlines (NIM-A, Vol. 539 (2005), p.p. 445 – 489)

Yuri Batygin, NSCL, Michigan State University

Multi-particle tracking with space charge in accelerating and focusing elements:

- arbitrary order multipole lenses
- axial-symmetric magnetic lenses (solenoids, permanent magnets)
- RF gaps and cavities
- radio frequency quadrupoles (RFQ)
- waveguides
- bending magnets
- user defined element

Types of beam symmetry for space charge calculation:

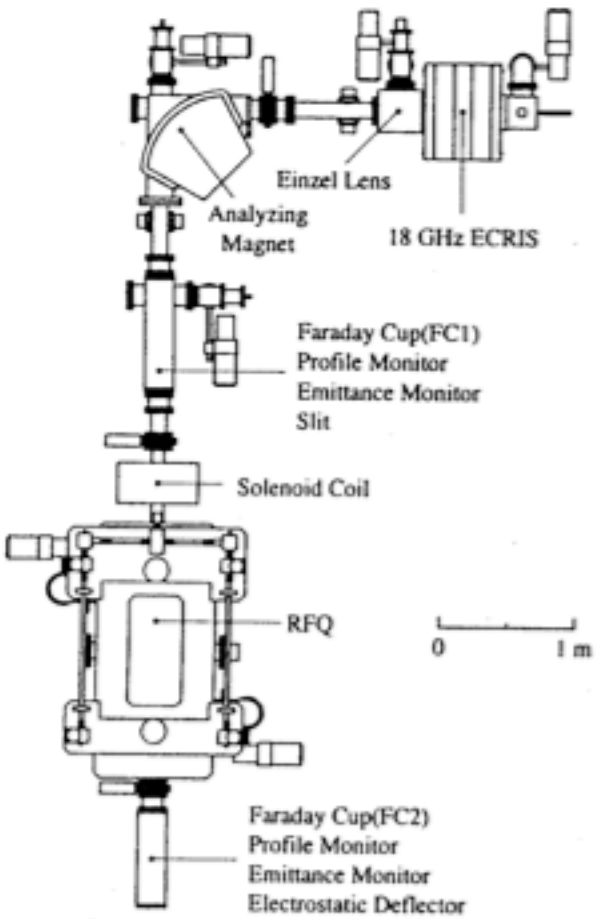
- z – uniform beam (XY mesh)
- axial symmetric beam (RZ mesh)
- quadrupole symmetric beam (XYZ mesh)

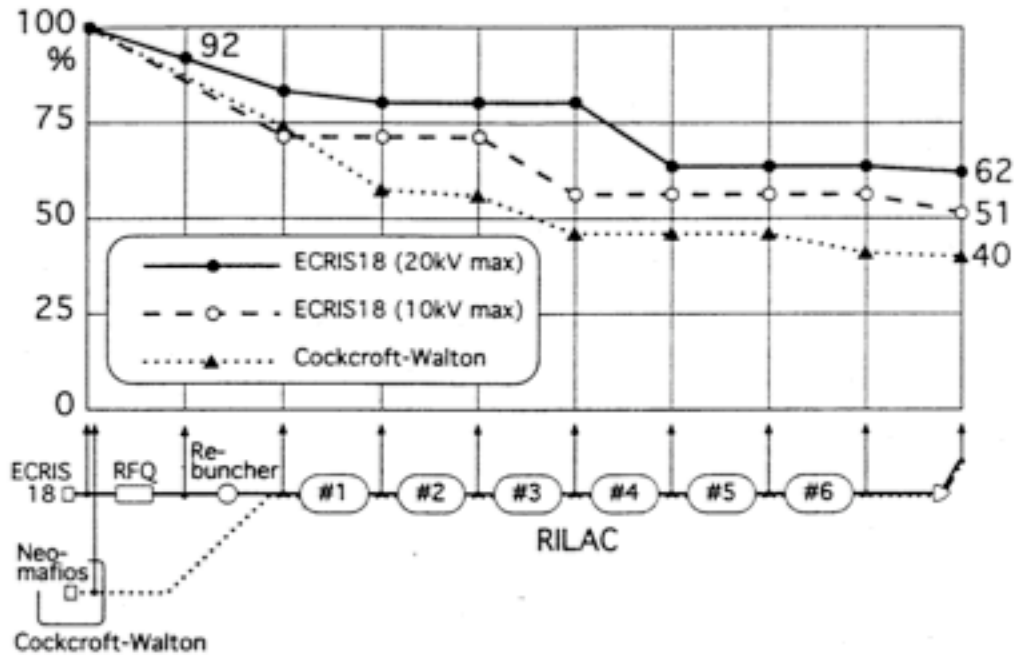
Initial beam distributions: KV, Gaussian, Water Bag, Parabolic, user-defined

Additional feature: integration of Bargmann-Michel-Telegdi (BMT) equation for spin precession in electromagnetic field together with particle tracking (study of polarized beams):

$$\frac{d\vec{S}}{dt} = \frac{q}{m\gamma}\vec{S} \times \left[(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} + \left(G\gamma + \frac{\gamma}{1+\gamma}\right)\frac{\vec{E} \times \vec{\beta}}{c}\right]$$

Improvement of performance of RIKEN injector of heavy-ion



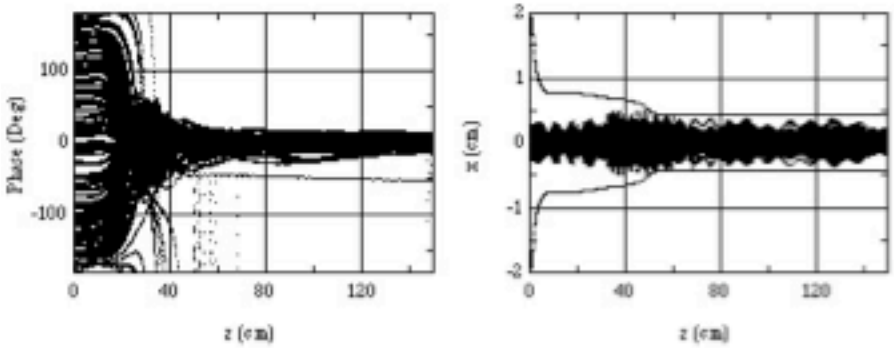


Improvement of beam transmission through RIKEN low-energy beam transport line:

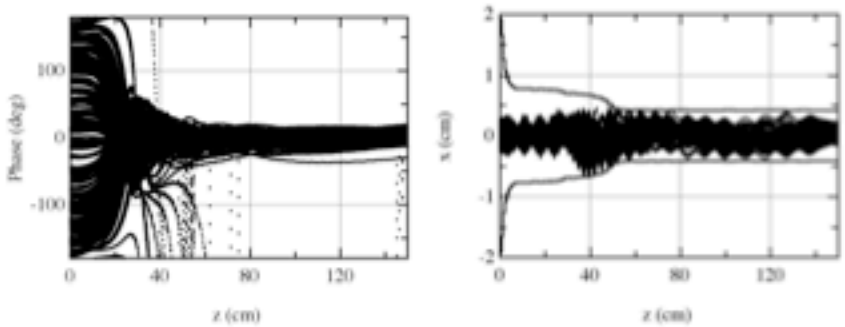
- increase of extraction voltage from ECR source from 10 kV to 20 kV
- increase of voltage in Einzel lenz from 10 kV to 20 kV
- change of polarity of voltage in Einzel lens
- change of electrodes design in RFQ linac

Study of beam dynamics in RIKEN RFQ

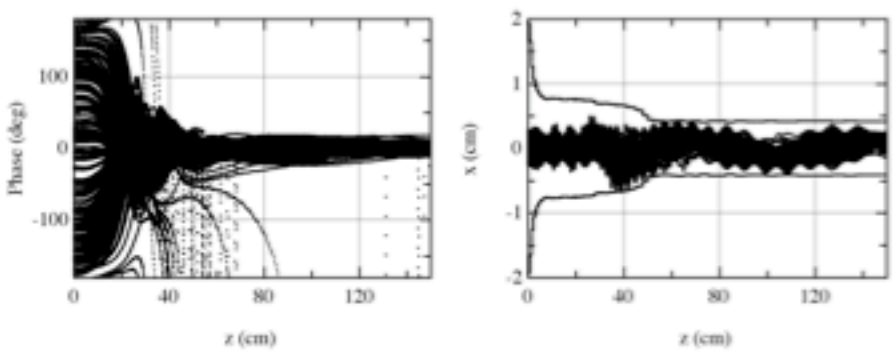
0 μm



± 50 μm



± 100 μm



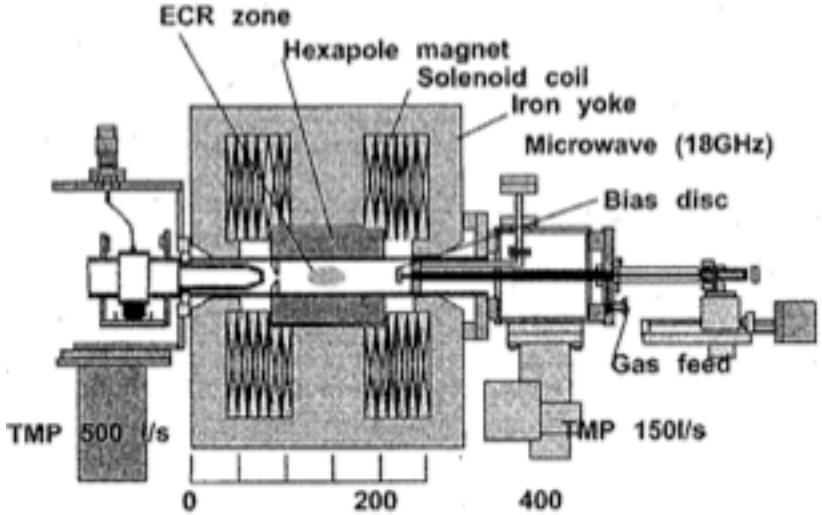
Effect of vane tips fabrication error on beam dynamics

Beam transmission efficiency and reduction of phase space density in RFQ due to errors in vane fabrication.

	δ , microns	I = 0		I = 1 mA	
		$\frac{N_f}{N_o}$	$\frac{j_f}{j_o}$	$\frac{N_f}{N_o}$	$\frac{j_f}{j_o}$
1.	0	0.94	0.75	0.87	0.58
2.	50	0.92	0.73	0.85	0.56
3.	100	0.80	0.57	0.70	0.46

First experimental value of maximum heavy ion beam transmission efficiency was 88 %
(O. Kamigaito, et al, Proc. EPAC 1996, p. 786)

Simulation of one-component plasma in RIKEN 18 GHz ECR ion source
(J. Appl. Physics, 83, (2), 1998, p.684)

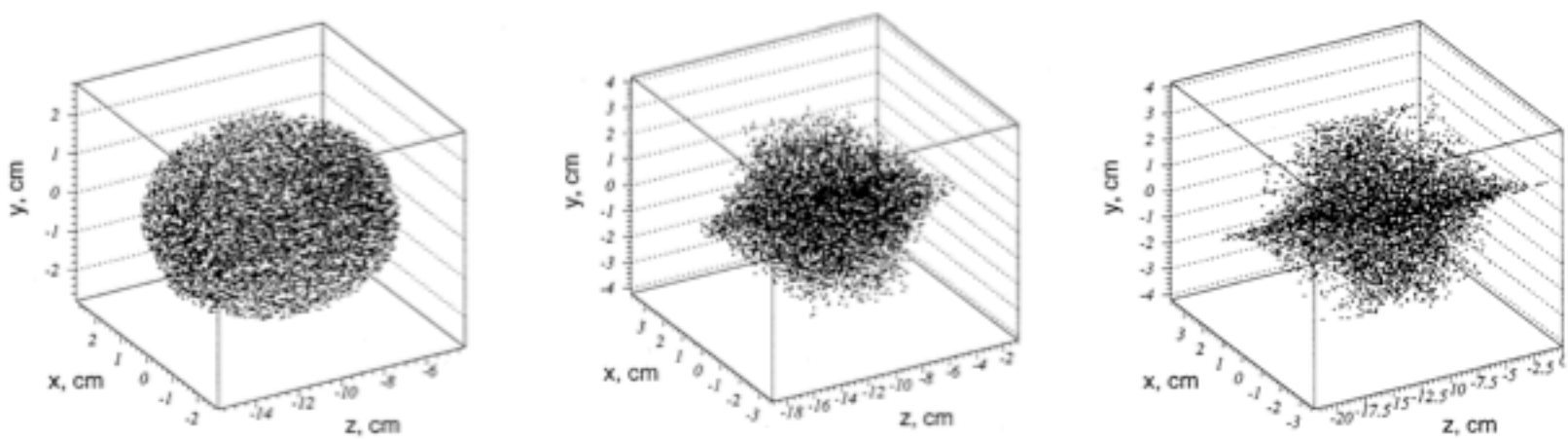


RIKEN 18 GHz ion source.

Numerical parameters

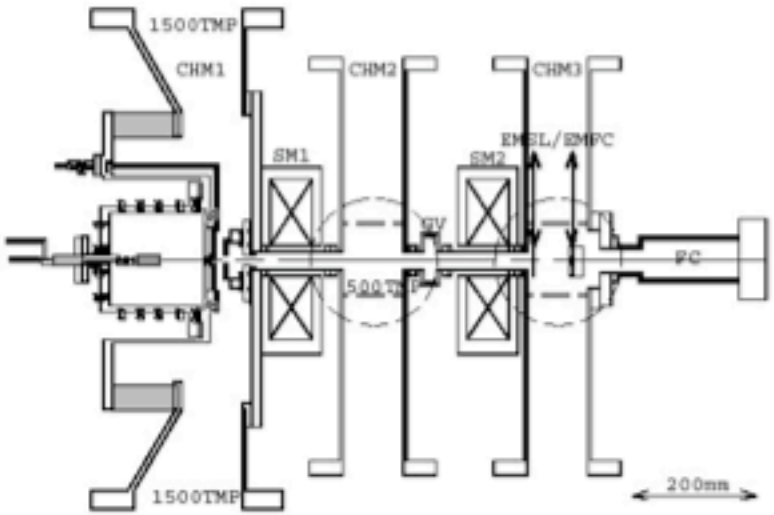
Solenoid Field	0.4….1.3 Tesla
Sextuple Field B_oR^4	0.08 T/cm^2
Ion	Ar^{+5}
Average Ion Energy	1 eV
Number of Particles	10^5
Integration Step	2.24×10^{-2}
Time of Simulation $w_L t$	200
CPU Time (for VAX Alpha)	37 Hours

$\omega_L t = 0$ $\omega_L t = 22.4$ $\omega_L t = 67.2$



Ion confinement in the ECR zone.

Study of KEK low-energy beamline using BEAMPATH (S.Fujimura, A.Ueno, Proc. LINAC 1996, p. 334)



CHM:vacuum chamber, SM:solenoid electromagnet
EMSL:movable slit for emittance measurement
EMPC:movable Faraday-cup with slit for emittance measurement
GV:gate valve, FC:Faraday-cup
TMP:1500or5001/s turbo molecular pump

Fig. 1 A schematic drawing of the experimental setup viewing from the upper position.

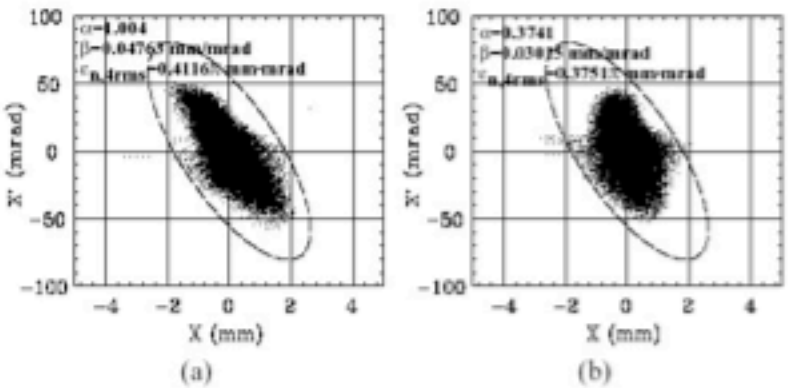


Fig. 2 Particle distributions in the horizontal emittance phase space measured at the entrance of the RFQ; (a) when the vacuum pressure in CHM2 was 3.7×10^{-6} Torr in the typical operation and (b) when it was 3.7×10^{-5} Torr.

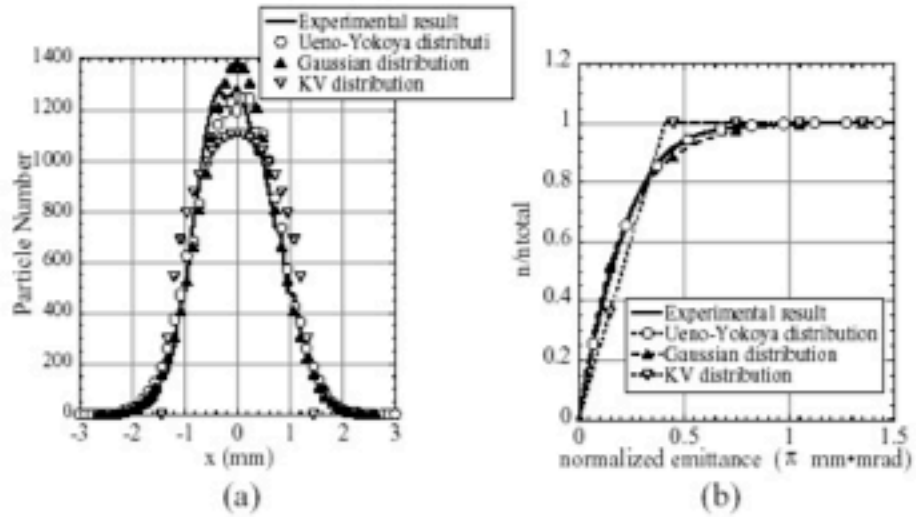


Fig. 3 Comparison of the experimental results with the simulated results; (a) the beam profiles and (b) the relationships between the normarized emittance and the beam fraction in the emittance.

Parameters of the LEBT

	(Typical)	(500TMP-GV close)
Beam energy (keV)	50	50
Vacuum pressure in CHM1 (Torr)	1.6×10^{-5}	1.6×10^{-5}
Vacuum pressure in CHM2 (Torr)	3.7×10^{-6}	3.7×10^{-5}
Beam Intensity at FC (mA)	16	14
Coil current of SM1 (A)	335	←
Coil current of SM2 (A)	360	←
4 times normalized rms emittance (π mm·mrad)	0.4116	0.3751

Beam emittance growth and hollow beam formation in Einzel lens

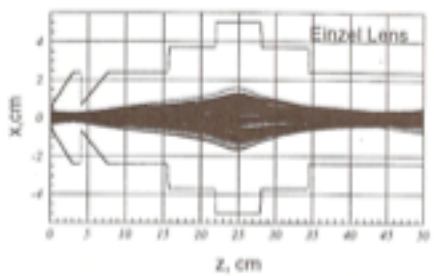


Fig. 1 Particle trajectories in the extraction region of the ECR ion source: extraction gap 4cm, lens voltage 14 kV, position of lens center 25 cm, coefficient $C_Q R^2$ = 0.15.

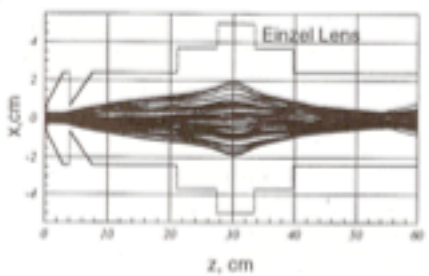


Fig. 2. Particle trajectories in the extraction region of the ECR ion source: extraction gap 4cm, lens voltage 12.5 kV, position of lens center 30.4 cm, coefficient $C_Q R^2$ = 0.3.

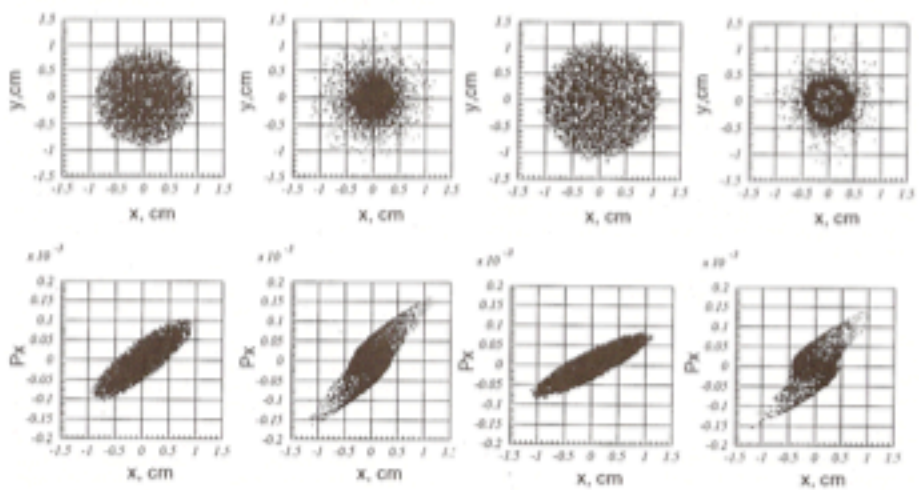
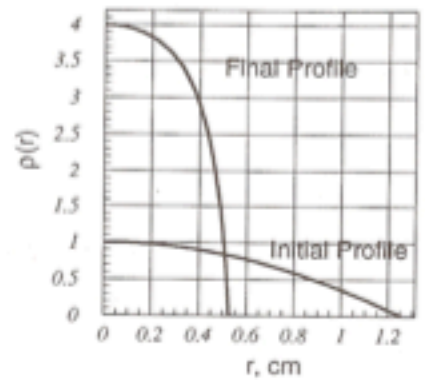
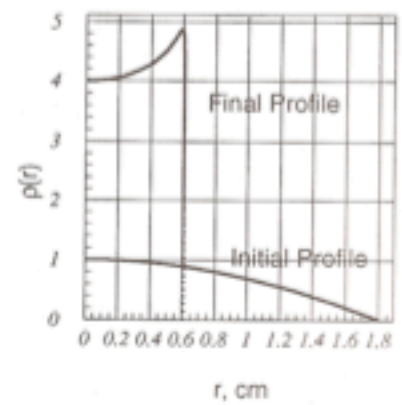


Fig. 3. Cross sections of the beam (top) and phase space projections of particles (bottom) at z= 14 cm (left column) and at z=51 cm (right column) for the extraction system presented in Fig. 1. RMS emittance growth is $\varepsilon_f/\varepsilon_0$ =1.15.

Fig. 4. Cross sections of the beam (top) and phase space projections of particles (bottom) at z=16 cm (left column) and at z = 60 cm (right column) for the extraction system presented in Fig. 2. RMS emittance growth is $\varepsilon_f/\varepsilon_0$ = 1.3.

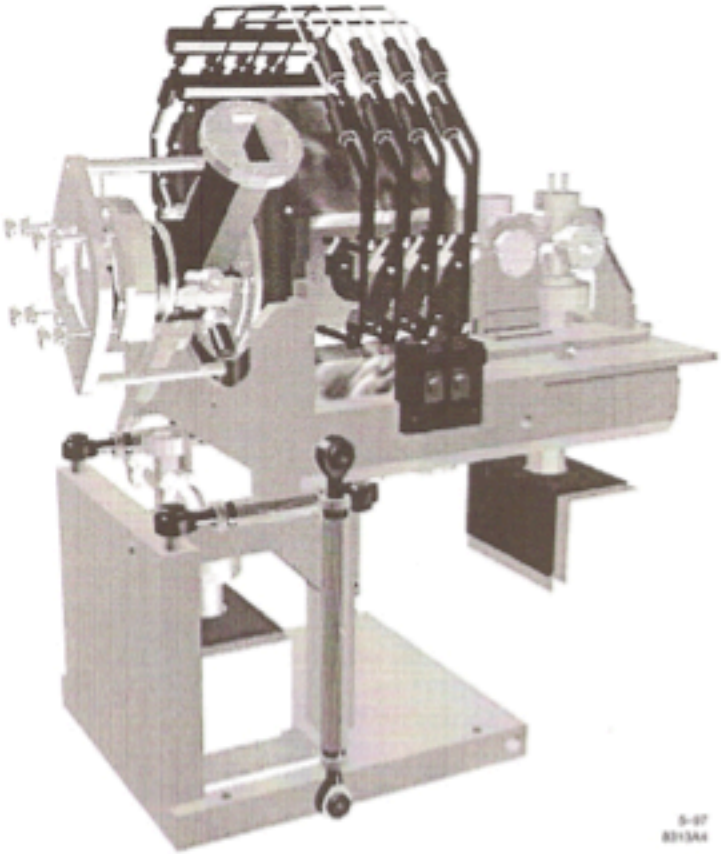




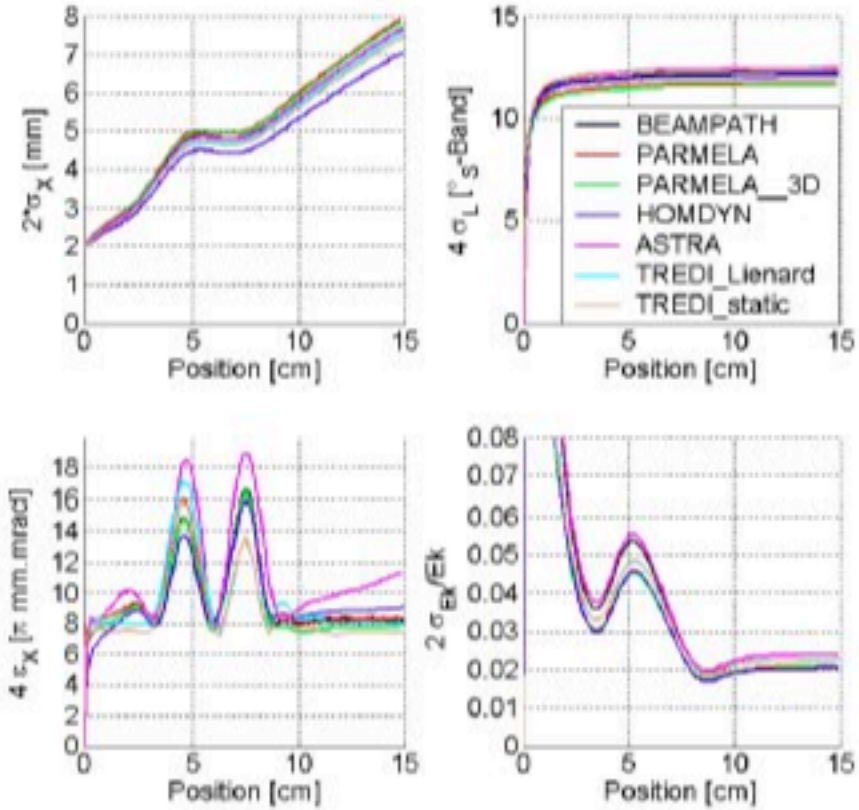
Beam density redistribution after lens with focal length f and spherical aberration coefficient C_s as a function of position $\tau = \frac{z}{f}$ for weak nonlinear field $C_s R^2$=0.15 (left) and strong nonlinear field $C_s R$ =0.3 (right):

$$\rho(r) = \frac{\rho(r_o)}{[1-\tau\,(1+\frac{C_s}{f}\frac{r_o^2}{f^2})]^2 - 2\,\tau\,\frac{r_o^2}{f^2}\frac{C_s}{f}\,[1-\tau(1+\frac{C_s}{f}\frac{r_o^2}{f^2})]}$$

Code comparison for simulation of SLAC photo-injector (Proc. PAC 2003, p.3548)



Perspective of gun assembly.



Comparison of evolution of beam size, bunch length, emittance and energy spread.

Code	Platform	CPU	Num. particles	Mesh points $N_r \times N_z$	Mesh size $h_r \times h_z$	Integration step	CPU time (s)
HOMDYN	PC Win		75 slices			0.13°	45
BEAMPATH	PC Win	1 GHz	10^4	256 x 2048	50x50μm^2	0.1°, 1°	8000
PARMELA	"	1 GHz	$2.5\ 10^4$	25 x 75	"	"	9846
" spch3d	"	1 GHz	10.10^4	32 x 32 x 1024	Automatic	"	$1.4.10^4$
ASTRA	"	1.8 Ghz	$1.5\ 10^4$	20 x 60	Automatic	Adaptative	420
Tredi Stat.	16 nodes	1.8 GHz	$5.0\ 10^4$	20 x 30	Automatic	Adaptative	$7.5\ 10^3$
Tredi Lien.	PC Win	1.8 GHz	$5.0\ 10^4$	20 x 30	Automatic	Adaptative	$7.4\ 10^4$

LORASR

Rudolf Tiede, Ulrich Ratzinger (Goethe-Univ. Frankfurt)

See talk by R. Tiede Thursday at this meeting on KONUS Beam Dynamics using H-Mode Cavities

LORASR Code Features - Overview

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Longitudinale und **ra**diale **S**trahldynamikrechnungen mit **R**aumladung

- General :
  - Single particle tracking along drift tube sections, quadrupole lenses, short RFQ sections including fringe fields and dipole magnets.
  - Running on PC-Windows platforms (Lahey-Fujitsu Fortran 95).
- Available Elements :

Element	Description
Magnetic quadrupole lens	Hard edge approximation, no fringe fields !
Dipole bending magnet	Motion across a constant dipole field described by the Lorentz law, second order Taylor´s multipole expansion, fringe fields included !
Accelerating gap	$\beta\lambda/2$-type structure, "slim" *) drift tubes without focusing elements, parametric input of the gap fields, valid for a fixed r_a/r_i ratio (=1.4).
RFQ section	Standard RFQ 2-term-potential, fringe fields included !
Space chage routine	Particle in cell 3D FFT algorithm.

*) New: Solenoid lens

*) "thick" Alv. DTL – type as well

LORASR: Recent Code Development

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

- **Implementation of a new space charge routine based on a PIC 3D FFT algorithm.**
  - **Benchmarking with other codes within the framework of the 'High Intensity Pulsed Proton Injector' (HIPPI) European Network Activity** (CARE-Note-2006-011-HIPPI, **see also talk by L. Groening**).

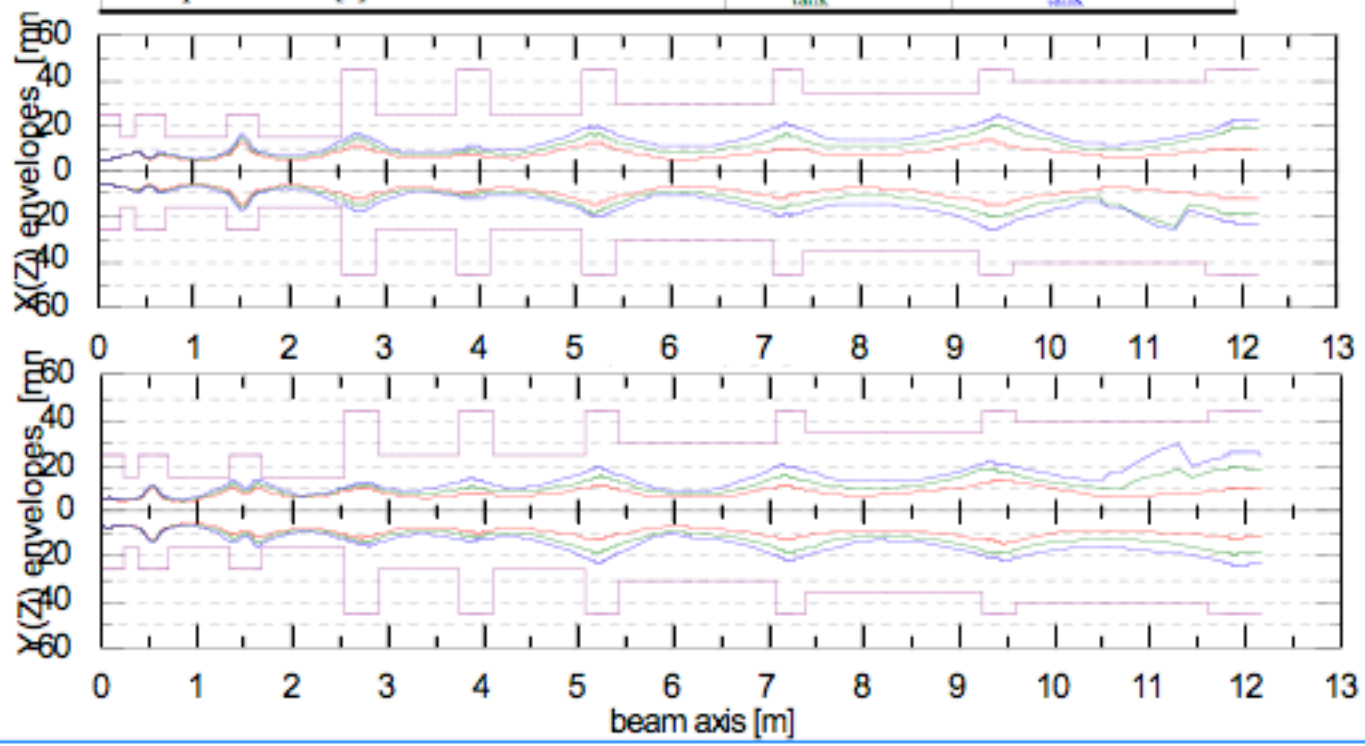
- **Implementation of machine error setting and analysis routines.**
  - **Error study on the FAIR Proton injector (talk by G. Clemente).**
  - **Error study on the initial IAP IFMIF design** (TW5-TTMI-001).
  - **Error study on the new IAP designs for IFMIF and EUROTRANS based on solenoidal focusing (C. Zhang**, EPAC08 , THPC112).

- **Implementation of a solenoidal lens routine.**
  - **New IAP designs for IFMIF and EUROTRANS (C. Zhang**, EPAC08 , THPC112).

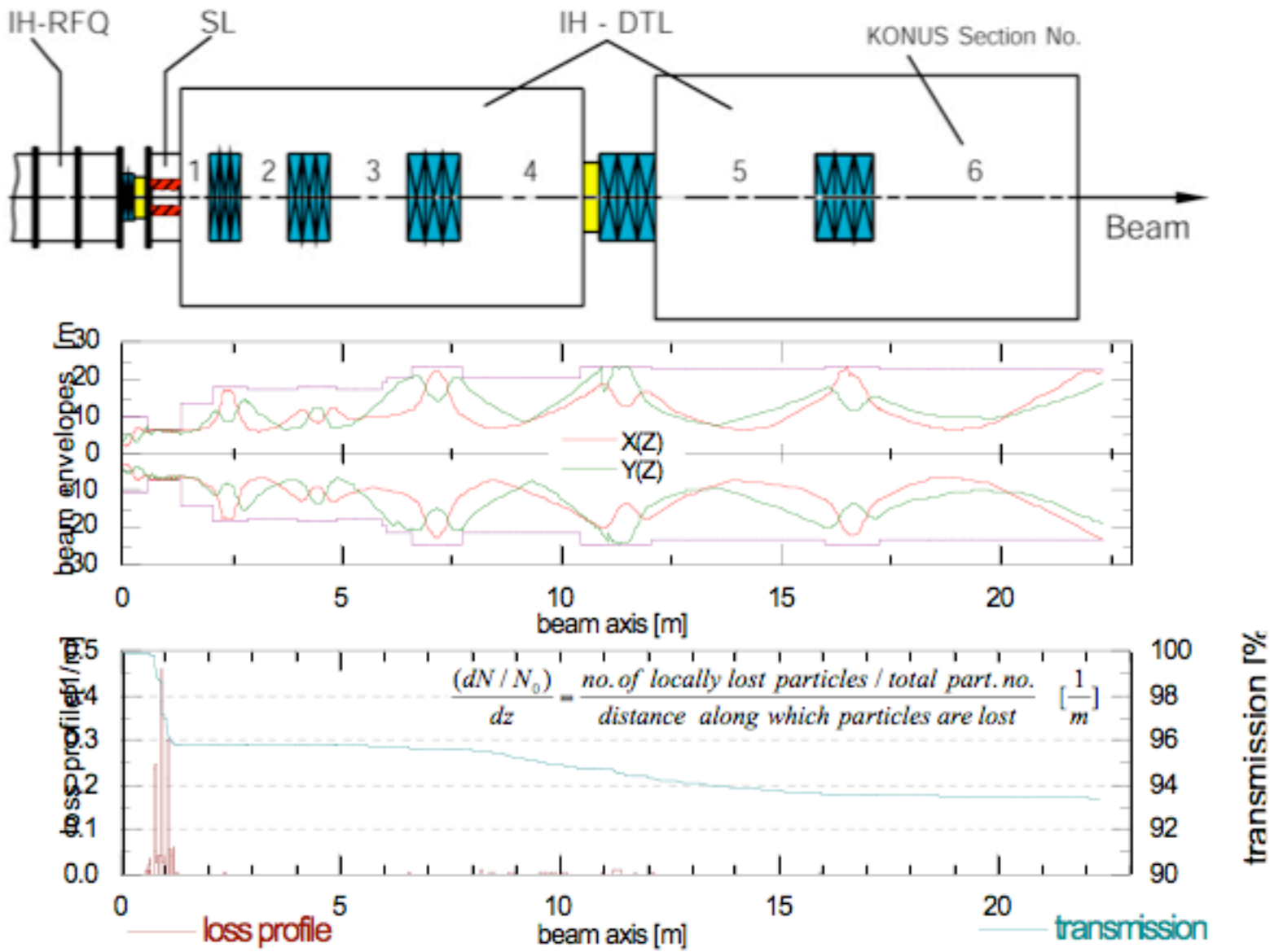
LORASR: Error Study Example (IAP IFMIF-Design)

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Type	Setting1	Setting2
transverse translations of focusing elements [mm]	$\Delta X_{lens} = \pm 0.1$ $\Delta Y_{lens} = \pm 0.1$	$\Delta X_{lens} = \pm 0.2$ $\Delta Y_{lens} = \pm 0.2$
rotations of focusing elements [mrad]	$\Delta\varphi_x = \pm 1.5$ $\Delta\varphi_y = \pm 1.5$ $\Delta\varphi_z = \pm 2.5$	$\Delta\varphi_x = \pm 3.0$ $\Delta\varphi_y = \pm 3.0$ $\Delta\varphi_z = \pm 5.0$
gap and tank voltage amplitude errors [%]	$\Delta U_{gap} = \pm 5.0$ $\Delta U_{tank} = \pm 1.0$	$\Delta U_{gap} = \pm 5.0$ $\Delta U_{tank} = \pm 1.0$
tank phase error [°]	$\Delta\Phi_{tank} = \pm 1.0$	$\Delta\Phi_{tank} = \pm 1.0$



LORASR: Loss Profile Calculation Example (GSI HSI, Beam Current Upgrade Program)



TRACK

Peter Ostroumov (ANL)

TRACK and PTRACK codes (Falls into category II)
© COPYRIGHT 2007 UChicago Argonne, LLC

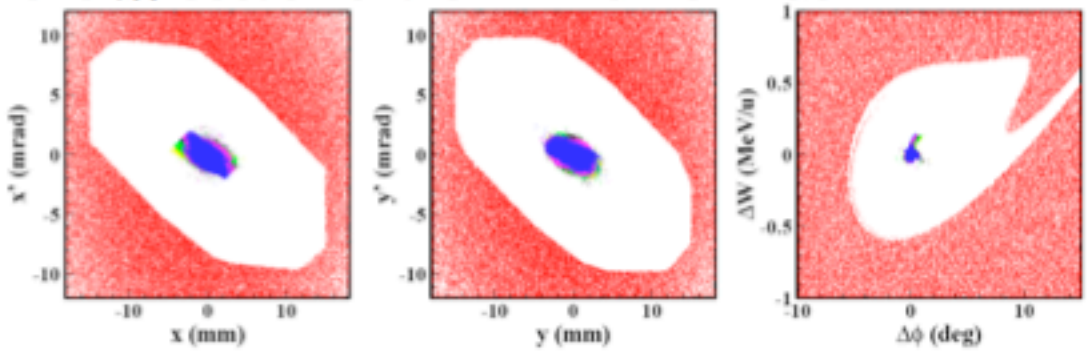
- Developed for design, simulation and commissioning of hadron linear accelerators and related beam transport systems
- Tracks multi-component ion beams
- End-to-end simulation from ion source to target
- Wide range of electromagnetic elements with 3D fields (pre-calculated RF and static electric and magnetic fields)
- Treats interaction of ion beams with matter
- Error simulation for all elements
- Beam loss analysis with exact location of particle loss
- Automatic transverse and longitudinal beam tuning procedures. Realistic transverse correction procedure.
- 3D space charge in Cartesian and Cylindrical coordinates (PIC or CIC method), 2D space charge fro DC beams.
- Optimization of beam parameters in realistic 3D fields (including space charge) based on tracking of probe particles
- Linear and higher order matrices

Unique features and applications of TRACK

- Windows version includes on-line graphics on a PC screen
- Simulates H-minus stripping due to various mechanisms (passage through the stripper, static and RF magnetic field, residual gas, black-body radiation,..)
- Serial version (Windows and Linux) are available at the web-site http://www.phy.anl.gov/atlas/TRACK/
- Parallel P-TRACK can simulate 10^9 particles on 32000 processors. Available at ANL BG/L. Does not have yet Manual.
- Contact persons: P.N. Ostroumov (ostroumov@anl.gov) and B. Mustapha (brahim@anl.gov)
- Applications:
  - Driver and post accelerators for the future Radioactive Beam Facility in the USA
  - 8-GeV Proton Driver for High Intensity Neutrino Source (HINS) and Project X
  - SARAF, CW deuteron linac, Israel
  - RIKEN, high-intensity heavy-ion linac, Japan
  - Several Universities in the USA, BNL, SNS, GANIL, TRIUMF, …

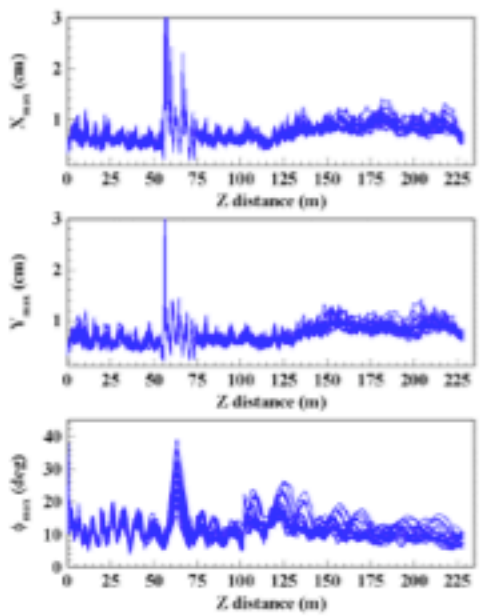
Heavy-ion linac for the Facility for Rare Isotope Beams (FRIB)

- Acceptance and 5-charge state uranium beam image at the entrance to the high-energy section of the FRIB driver linac

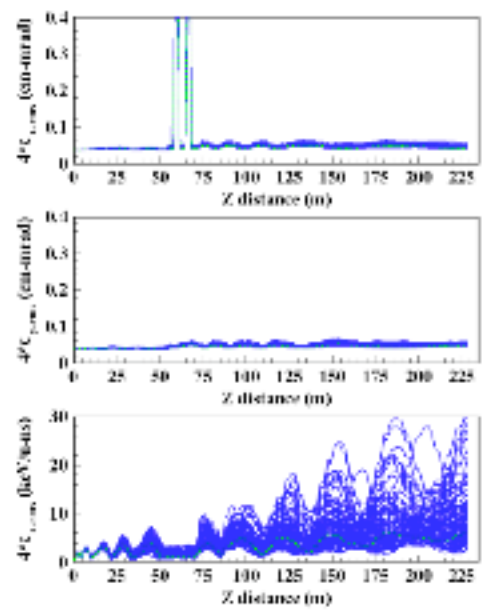


- Beam envelopes and emittances along the linac for multiple seeds

Envelopes

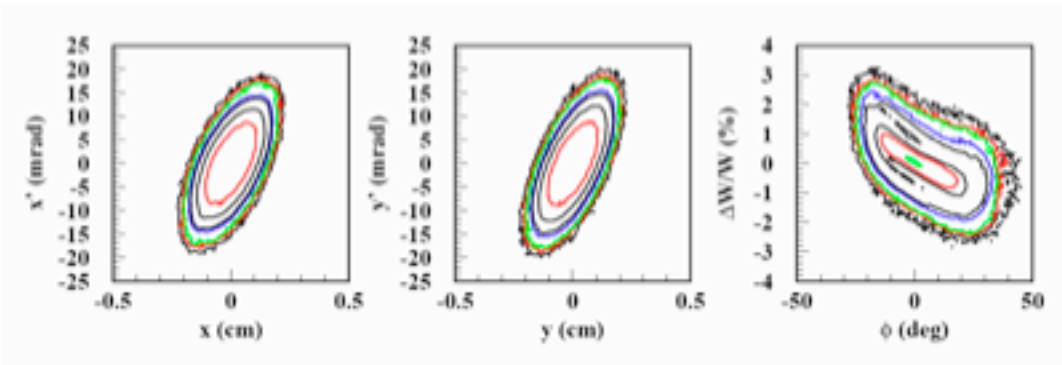


Emittances

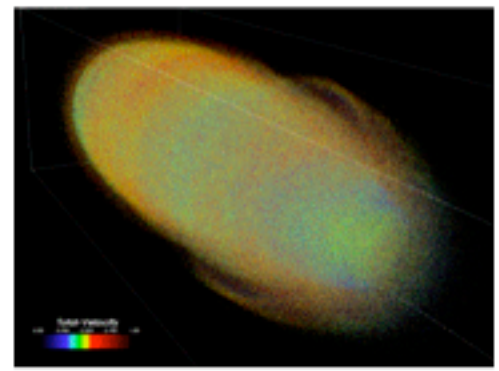


Beam dynamics of normal and superconducting ion linacs:
Large-scale computing for detailed beam dynamics

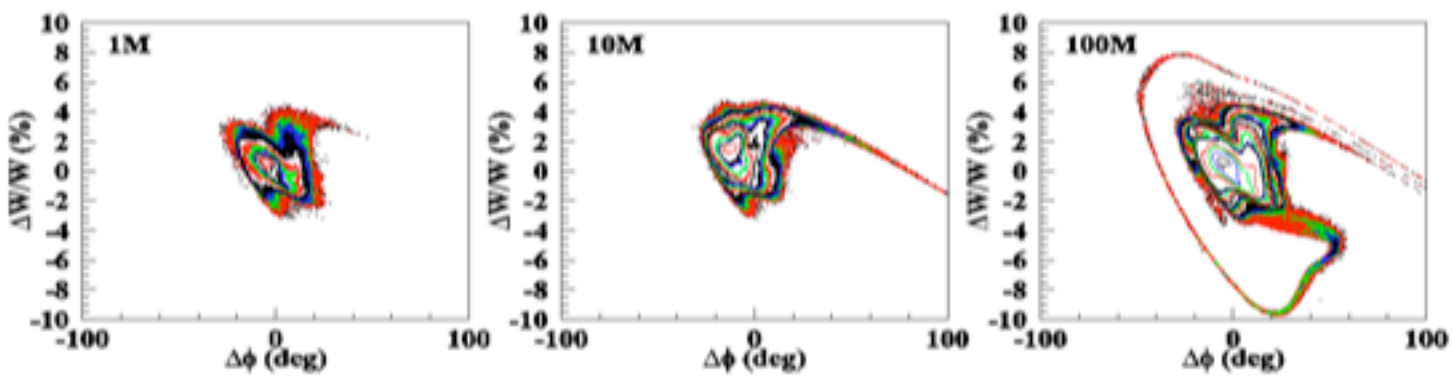
Phase space plots at the exit of HINS (FNAL) RFQ 45 mA H-minus beam
100 million particles



Visualization of 100M particles accelerated in the RFQ



Longitudinal phase space plots in the form of density contours. 1M particles (left), 10M particles (middle) and 100M particles (right). HINS (FNAL), 10 MeV section.

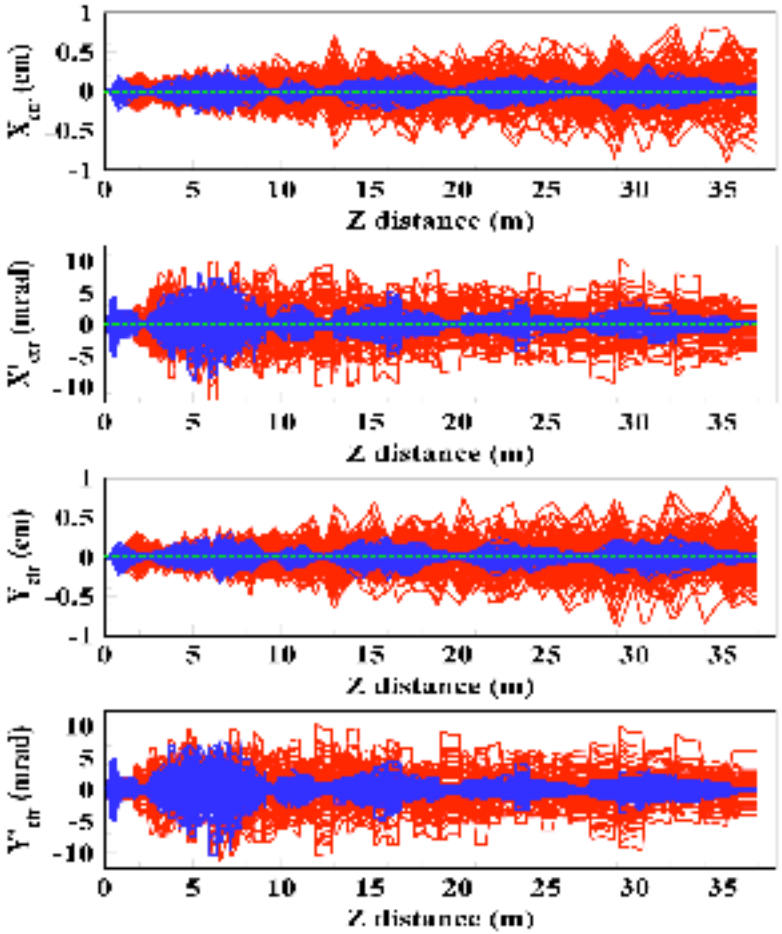


Beam center correction: 100 random set of errors (seeds), HINS Front-end simulations (FNAL)

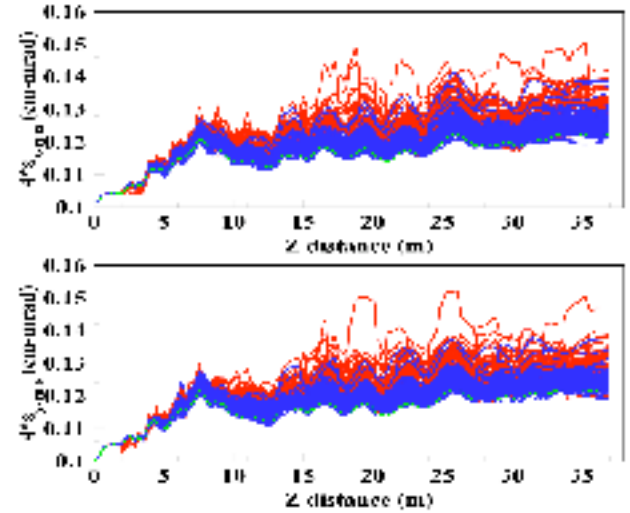
Beam Centers: Position & Angle

Red: before the correction

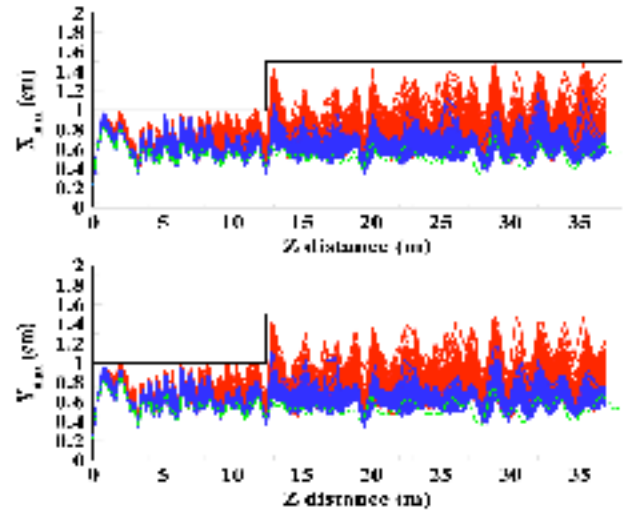
Blue: after the correction



Beam RMS emittances



Beam envelopes

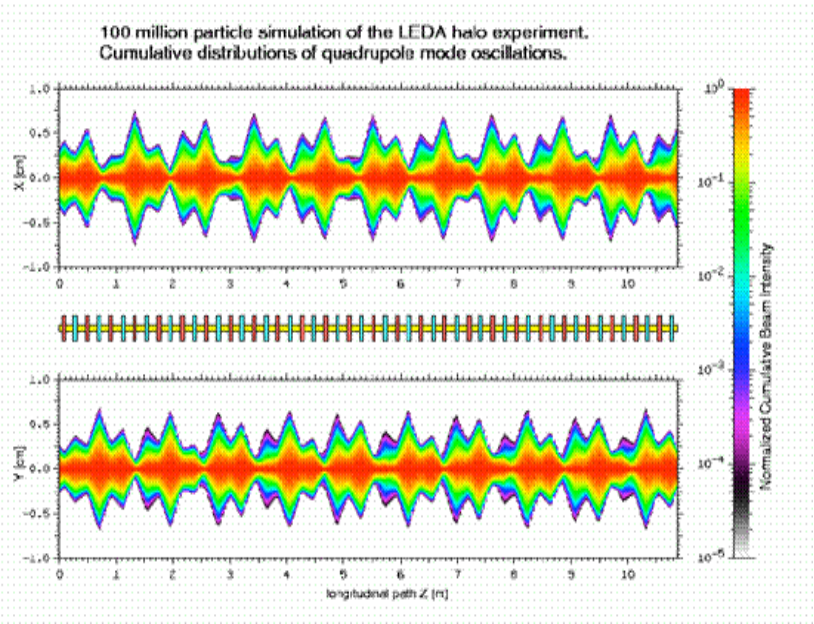


IMPACT

Ji Qiang, Robert Ryne (LBNL)

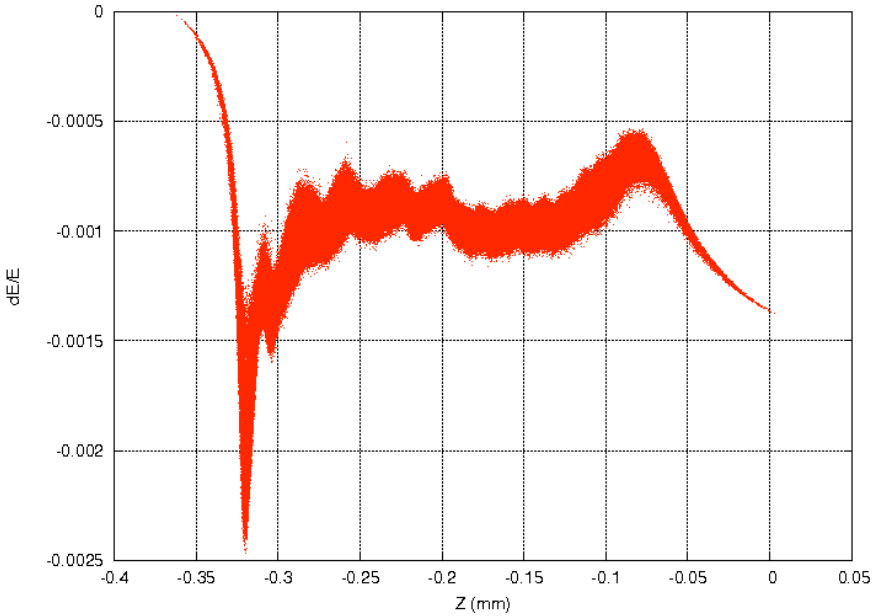
IMPACT-Z

- Parallel PIC simulation using coord “z” as the independent variable
- Key Features
  - Multiple Poisson solvers
    - Variety of boundary conditions
    - 3D Integrated Green Function
    - point-to-point
  - Multi-charge state
  - Machine error studies and steering
  - Wakes
  - CSR (1D)



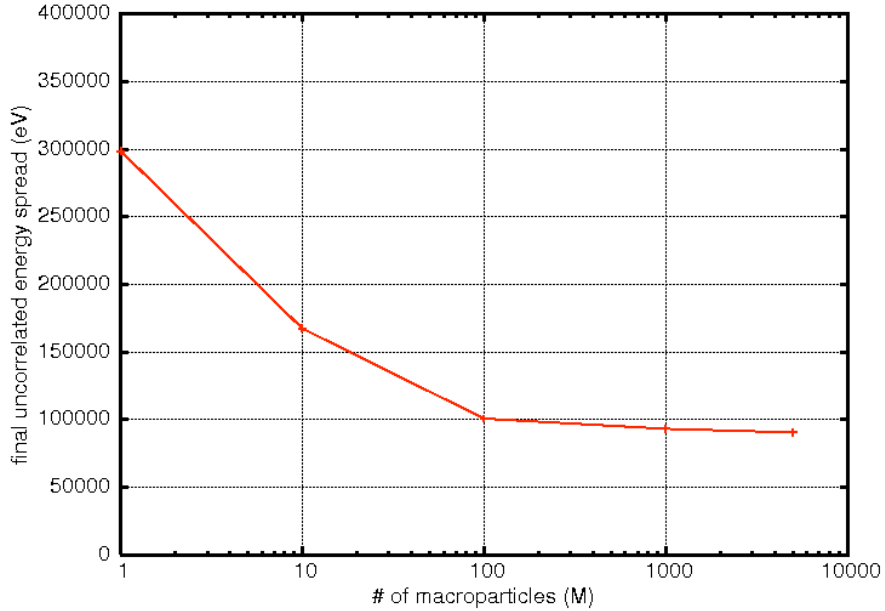
- In use at SNS for linac commissioning
- Also applicable to Project-X design

IMPACT-Z Simulation of FEL Linac



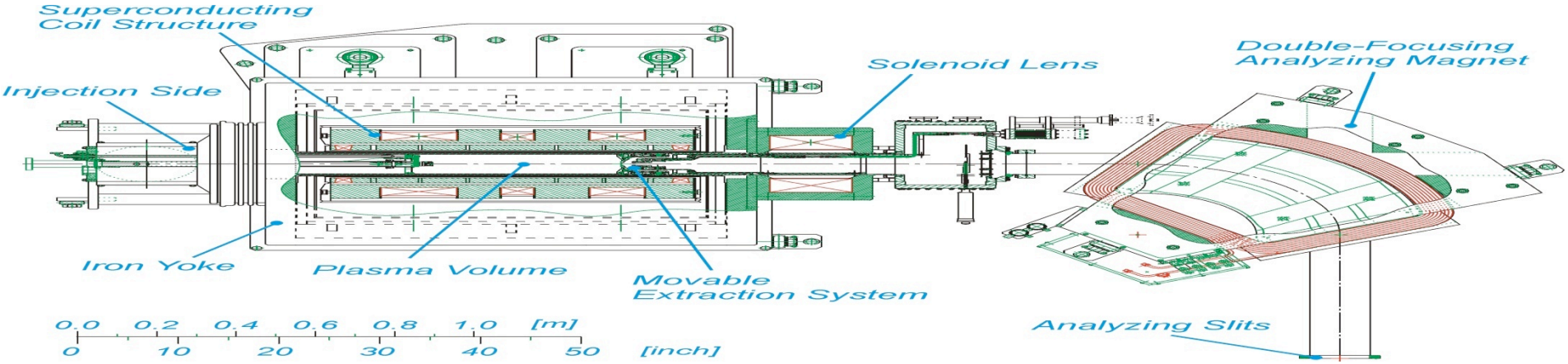
Final longitudinal phase space from **5 billion** particle simulation

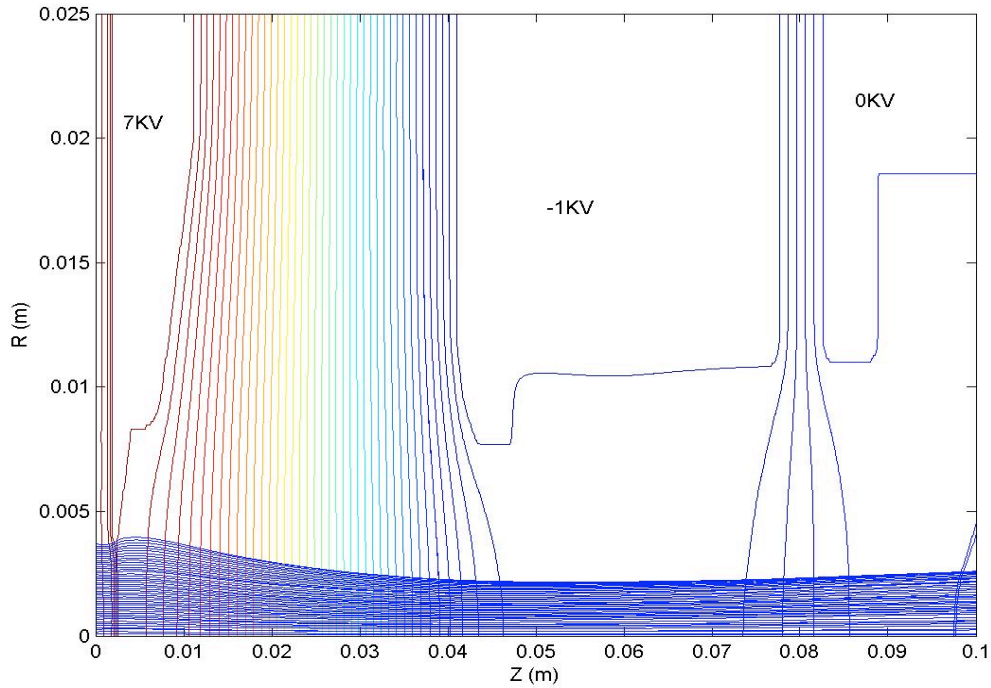
Final uncorrelated energy spread vs. Number of macroparticles



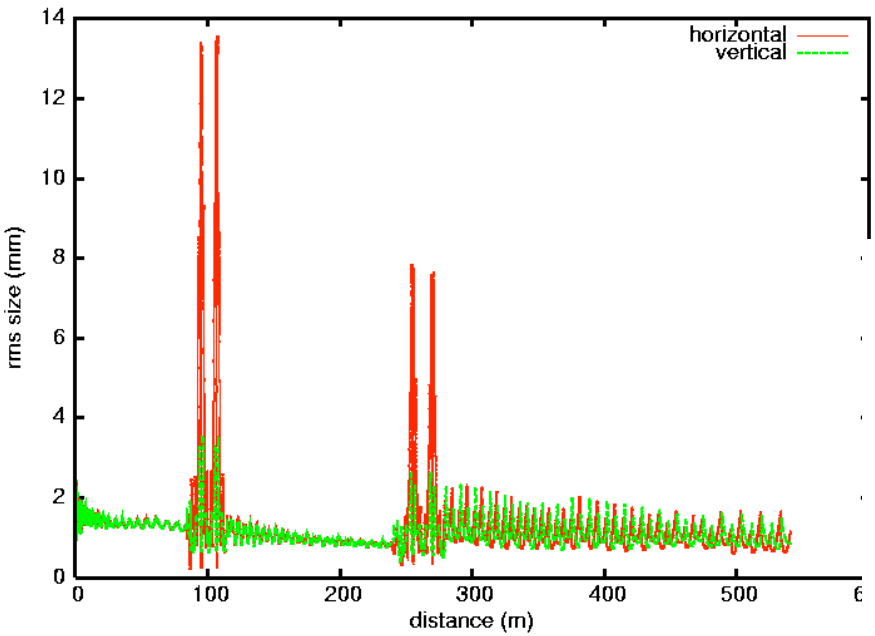
J. Qiang, LBNL

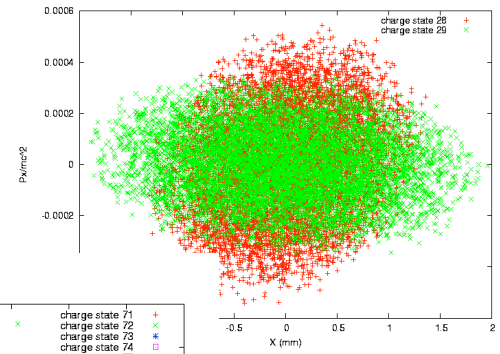
IMPACT Self-Consistent Modeling of H+ Extraction from an ECR Ion Source

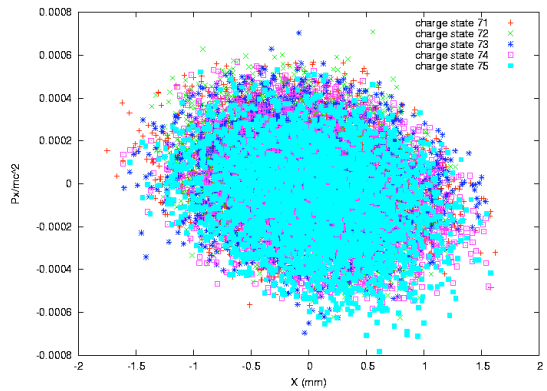


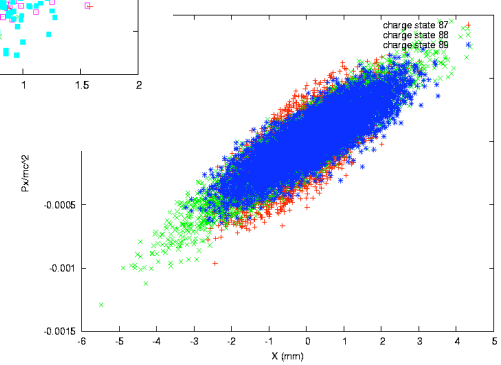


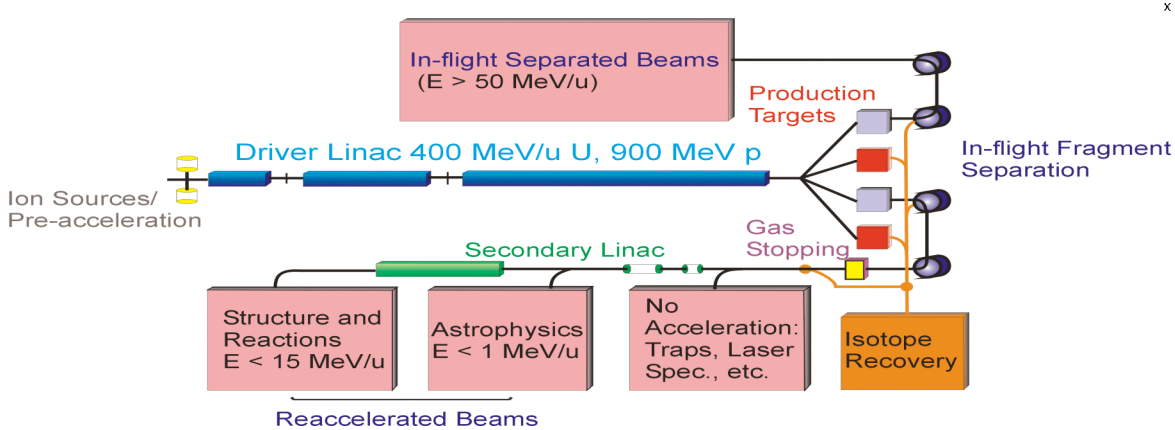
IMPACT-Z multi-charge-state simulation of beam dynamics in proposed MSU RIA linac







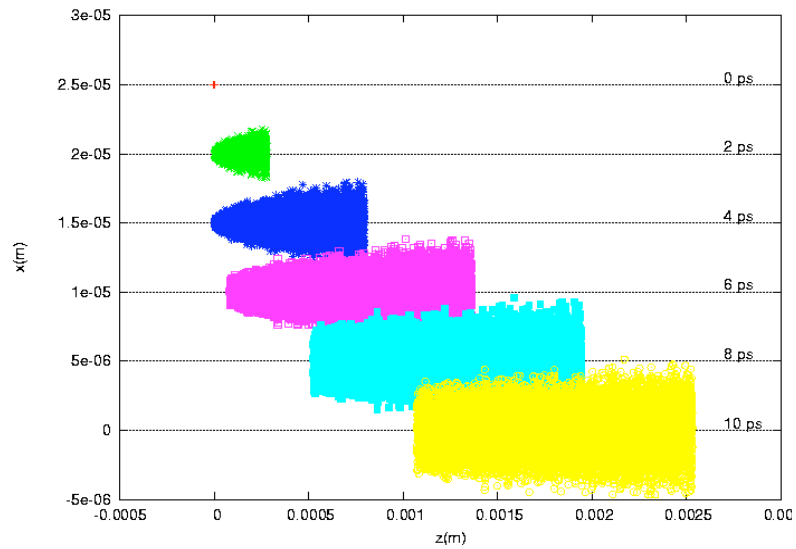




J. Qiang, LBNL

IMPACT-T

- **Parallel PIC simulation using time as the independent variable**
- **Key Features**
  - **Multiple Poisson solvers**
    - **3D Integrated Green Function**
    - **point-to-point**
  - **Energy Binning**
  - **Cathode image effects**
  - **Wakes**
  - **CSR (1D)**



Emission from nano-needle tip including Borsch effect

- **Has been used to study photoinjectors for BNL e-cooling project, Cornell ERL, FNAL/A0, LBNL/APEX, ANL, JLAB, SLAC/LCLS**

PATH

Alessandra Lombardi (CERN)

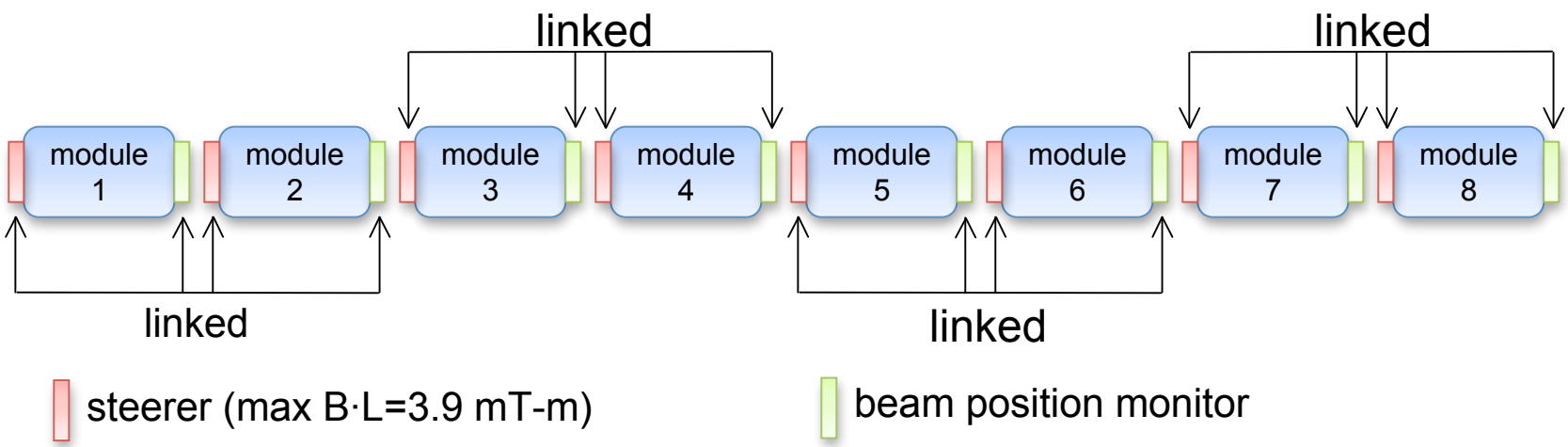
Code PATH-Travel

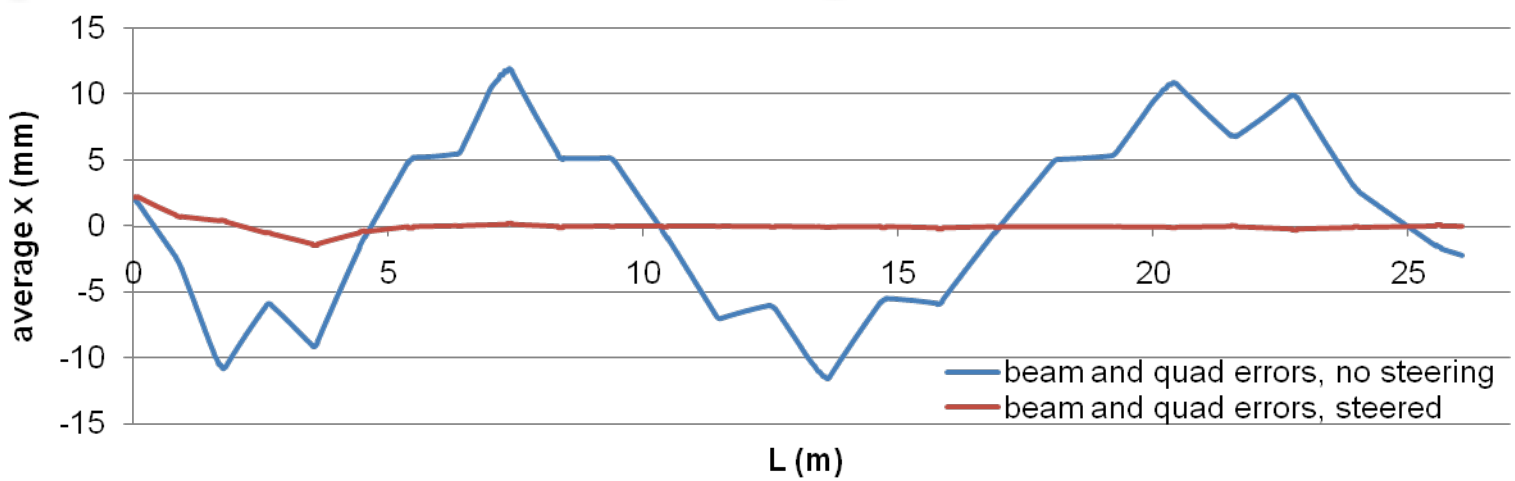
- Originally from J. Farrell, A. Aldridge and D. Rusthoi (LANL) heavily modified at CERN, under the responsibility of A. Lombardi
- Can simulate linear accelerators and transfer lines
- Important features :
  - —2D and 3D space charge (SCHEFF+ point-to-point)
  - —Integration in 2d and 3d field maps (static and RF)
  - —Simulation of up to 10 different ions
  - —Possibility of statistical error studies (machine and beam errors)
  - —Steering modules

Code PATH-Travel

- **Input-output compatible with PARMILA, PARMTEQM, TRACE3d and TRACEWIN**
- **Can run up to 1M particles**
- **Cross-checked with TRACEWIN on LINAC4 and SPL simulations**
- **Included in the GSI code comparison started at HB2004**

Example : Steering in LINAC4 CCDTL





Steerers correct the beam center displacement due to initial beam errors and quad errors to zero at each beam position monitor

Explanation of the example

On the nominal layout of the LINAC4 CCDTL (50-100 MeV) we have run 2000 cases with beam and quadrupoles alignment errors .

We have selected the worst case (=the one with the highest losses) and we have steered the beam back on the nominal orbit with the help of steerers and beam position monitors as shown in the diagram.

The effect on the beam centre trajectory can be seen on the graph at the bottom of the page

You can also refer to the paper on the CERN LINAC simulation to be presented in the “Beam Dynamics in High Intensity Linacs working group”. The simulations presented in that paper are done with PATH.

POISSON-3D

Valentin Ivanov (Muons Inc)

HIGH-ORDER APPROXIMATIONS FOR SPACE CHARGE & THE GREEN'S FUNCTION TECHNIQUE IN FORMING & PROPAGATION OF INTENSIVE BEAMS

Valentin Ivanov

(Muons, Inc., Batavia, Illinois, USA 60510)

•The analytical model to take into account the space charge of the beam on 3D rectangular mesh is implemented;

•The efficiency of the analytical model was studied by comparing the numerical integration, the piecewise-constant & tri-linear analytical models with the exact solution for simple test problems;

• The singularity problems have been studies for different integration schemes;

• The adaptive integration scheme is suggested to increase the efficiency of calculations;

•The algorithms of analytical integration have been implemented in the POISSON-3D code devoted to simulation of a high-current relativistic beam optics in 3D;

• Green's function technique was demonstrated its efficiency in the design of sheet-beam gun for SLAC X-band klystron.

•The field gradients have as an artificial singularities in the inner cells as real singularities on the beam boundary. Those singularities can generate a numerical noise, which lower the accuracy of computations in using of piecewise-constant approximation for space charge density. Linear approximation for space charge density can eliminate all those singularities.

References

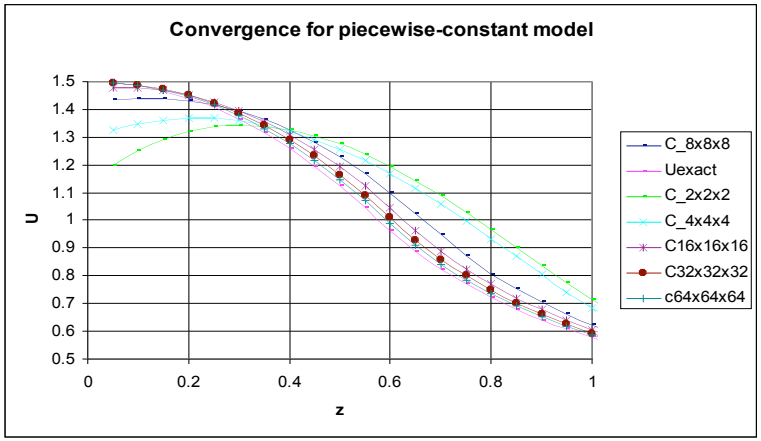
1. V.Ivanov. Numerical methods for analysis of 3D non stationary flows of charged particles, **15**. Trudy Instituta Matematiki, Izd-vo "Nauka", Sibirskoe Otdelenie, 1989.-p.172-187.

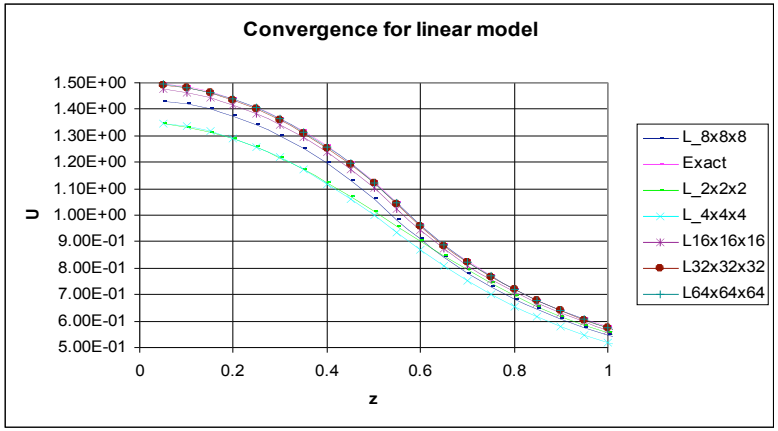
2. V.Ivanov. Green's Function Technique in Forming of Intensive Beams, XV Int. Workshop "Beam Dynamics & Optimization", 10-13 July, 2008, St.. Petersburg, Florida, USA.

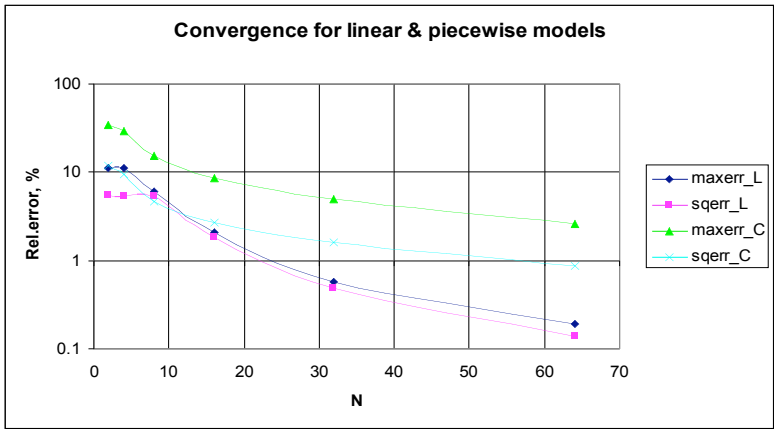
Simple benchmarks

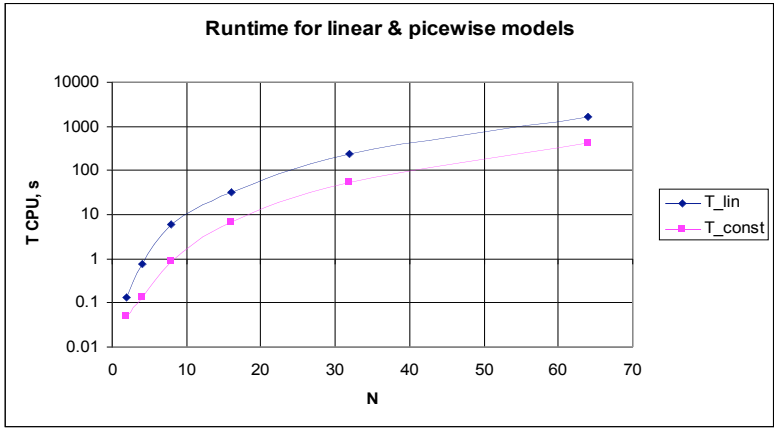
Potential of a sphere with charge density is

$$\varphi(r) = \begin{cases} (R^2 - r^2)/2 + 1/R, & r < R, \\ 1/R, & r > R. \end{cases}$$









PARMILA, PARMELA Trace, PARMTEQ

Frank Krawczyk (LANL)

Parmila

Parmila-Version 2 is an ion linac particle dynamics code. The name comes from the phrase, "Phase and Radial Motion in Ion Linear Accelerators." It is a versatile multi-particle code that generates the linac and transforms the beam, represented by a collection of particles, through a user-specified linac and/or transport system.

Contact:
Frank Krawczyk, Los Alamos National Laboratory, Email: laacg@lanl.gov, Web: http://laacg.lanl.gov

Features:
- Lattice Design
- Tracking (drift-kick method)
- Space-Charge (2D and 3D)
- DTL, CCDTL and CCL cells (represented by Superfish fields)
- Windows only
- Free distribution of executable

Parmela - 1

Parmela - is a multi-particle beam dynamics code used primarily for electron-linac beam simulations. The name comes from the phrase, "Phase and Radial Motion in Electron Linear Accelerators."

It is a versatile code that transforms the beam, represented by a collection of particles, through a user-specified linac and/or transport system. It includes several space-charge calculation methods. Particle trajectories are determined by numerical integration through the fields. This approach is particularly important for electrons where some of the approximations used by other codes (e.g. the "drift-kick" method commonly used for low-energy protons) would not hold. Parmela works equally well for either electrons or ions although is computationally slower due to the numerical integrations. Parmela can read field distributions generated by the Poisson/Superfish group of codes. Members of the code group won a LANL 2000 Distinguished Copyright Award for this code.

Parmela - 2

Contact:
Frank Krawczyk, Los Alamos National Laboratory, Email: laacg@lanl.gov, Web: http://laacg.lanl.gov

Features:

- Tracking (numerical integration, “T-code”)
- Space-Charge (2D and 3D)
- Field import (2D and 3D) from Superfish, Poisson, MAFIA, ...
- Import of arbitrary particle distributions
- Windows or WINE “emulator” under Linux or Mac OS
- Limited distribution (might incur licensing fees)

Trace

Trace - is an interactive beam-dynamics program that calculates the envelopes of a bunched beam, including linear space-charge forces, through a user-defined transport system. Trace 3-D provides an immediate graphics display of the envelopes and the phase-space ellipses and allows nine types of beam-matching options. The transport system may contain drifts, thin lenses, quadrupole lenses, solenoids, double or triplet lenses, bending magnets, rf gaps or cavities, radio-frequency-quadrupole cells, coupled-cavity linac sections, and user-defined elements.

Contact:
Frank Krawczyk, Los Alamos National Laboratory, Email: laacg@lanl.gov, Web: http://laacg.lanl.gov

Features:
- Lattice Design
- Space-Charge (Lapostolle model)
- Windows or WINE “emulator” under Linux or Mac OS
- Free distribution of executable

Parmteq

Parmteq - and several other RFQ design codes comprise this group of codes and are used to design high-performance radio-frequency quadrupole (RFQ) linacs. PARMTEQ is an acronym for "Phase and Radial Motion in a Transverse Electric Quadrupole".

The codes have been experimentally verified in some detail by working hardware at Los Alamos and at other laboratories around the world. As we learn more about linac performance, both experimentally and theoretically, we continue to update these codes. Partial and complete RFQ design-code distributions are available. A partial distribution contains the codes necessary to design the RFQ vane profile and analyze the beam performance including the effects of higher order multipole field components and image charges. A complete distribution also includes the code VANES and several related programs, which generate and analyze machine instructions for numerically controlled machining of the vanes. Multi-particle simulations of the RFQ design are also possible with these codes.

Parmteq

Contact:
Frank Krawczyk, Los Alamos National Laboratory, Email: laacg@lanl.gov, Web: http://laacg.lanl.gov

Features:

- RFQ Design
- RFQ Manufacturing
- Space Charge (2D)
- Calculation of current limits
- Windows or WINE “emulator” under Linux or Mac OS
- Limited distribution (might incur licensing fees)

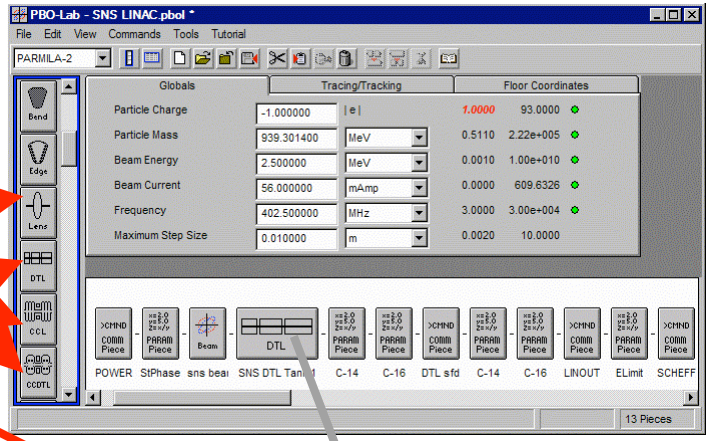
Running Parmila2 via PBO Lab

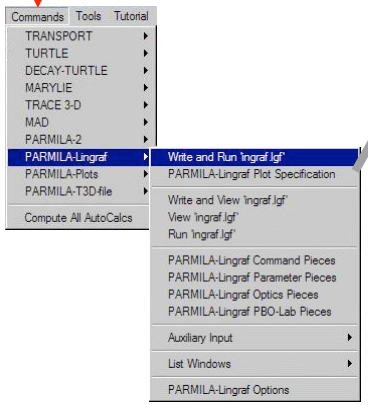
George Gillespie (Gillespie Associates)

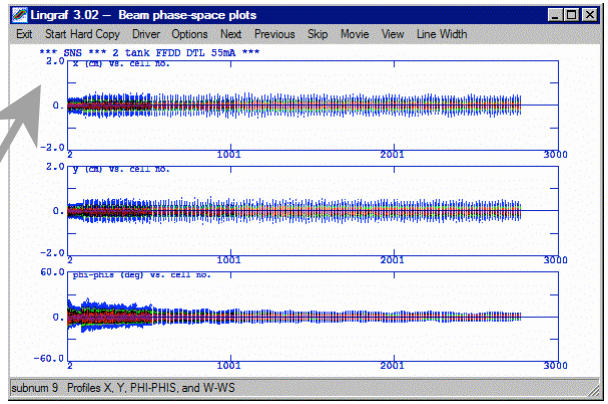
Making PARMILA 2 Easy to Use

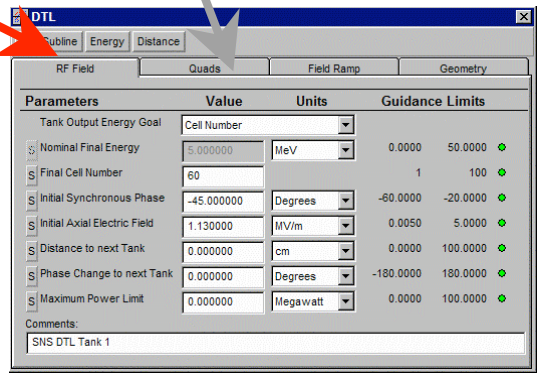
New Module for the Particle Beam Optics Lab (PBO Lab)

- "Drag & drop" beamline setup
- Complex structures (DTL, CCL, …)
- Logical grouping of parameters
- Menus run all parts of PARMILA 2 including PARMILA, Lingraf, …









Advanced Tools Allow PARMILA 2 Design to then be Run with any Other PBO Lab Module: TRACE 3-D, TRANSPORT, TURTLE, MARYLIE, … !

Reference: G. H. Gillespie and B. W. Hill, "An Innovative Graphic User Interface for PARMILA 2," to be presented at the 2008 International Linac Conference, Vancouver, BC, 29 Sep – 3 Oct 2008.

General Particle Tracer (GPT)

Bas van der Geer, Marieke de Loos
(Pulsar Physics)

General Particle Tracer (GPT) code

www.pulsar.nl

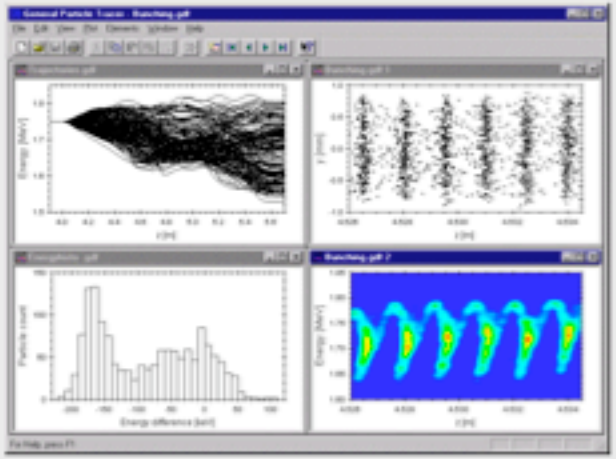
GPT is a well-established (~50 users) commercial code
to study the phase-space evolution of charge particle beams.

The GPT package:

- Tracks ~10^6 sample particles
- with relativistic equations of motion
- on a MS-Windows / Linux machine
- in arbitrary time-dependent external fields
- in full 3D, including space-charge forces.

Applications:

- Charged particle accelerators and beamlines.
- Sources (Photo-cathodes, Field-emitters, …)
- Electrons, protons, muons, …



Contact: Pulsar Physics, info@pulsar.nl

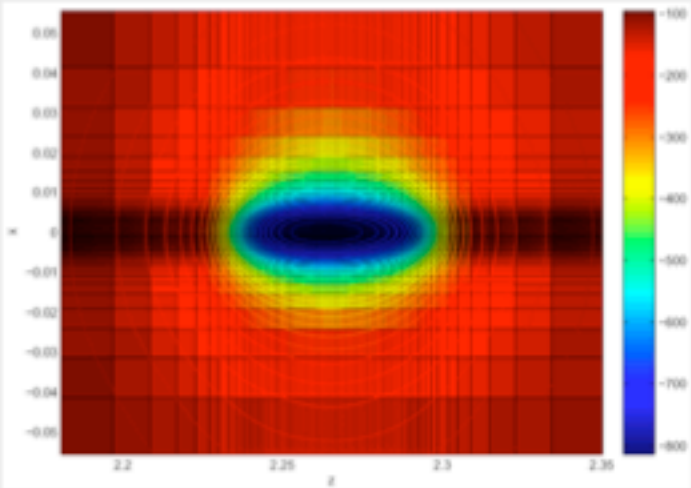
General Particle Tracer (GPT) code

Special feature: 3D space-charge model*

- Anisotropic multigrid PIC solver.
- Scales O(N^1) in terms of CPU time.

Other features:

- GPT can track different species.
- Import externally calculated 2D/3D fields.



DESY TTF gun at z=0.25 m, 200k particles.

- GPT supports *Custom Elements*
  New analytic beamline components can be added without affecting the overall integrity of the code. This offers a safe platform for users to make changes without having to be professional software engineers.

- Field-equations can be parameterized: Post-processing tools make plots of any beam quantity as function of any varying parameter(s).

* G. Pöplau, U. van Rienen, S.B. van der Geer, and M.J. de Loos, *Multigrid algorithms for the fast calculation of space-charge effects in accelerator design*, IEEE Transactions on magnetics, Vol 40, No. 2, (2004), p. 714.

Sample GPT applications #1

BEAM DYNAMICS SIMULATIONS OF SARAF ACCELERATOR INCLUDING ERROR PROPAGATION AND IMPLICATIONS FOR THE EURISOL DRIVER, J. Rodnizki, et. al., Linac 2006 p. 426

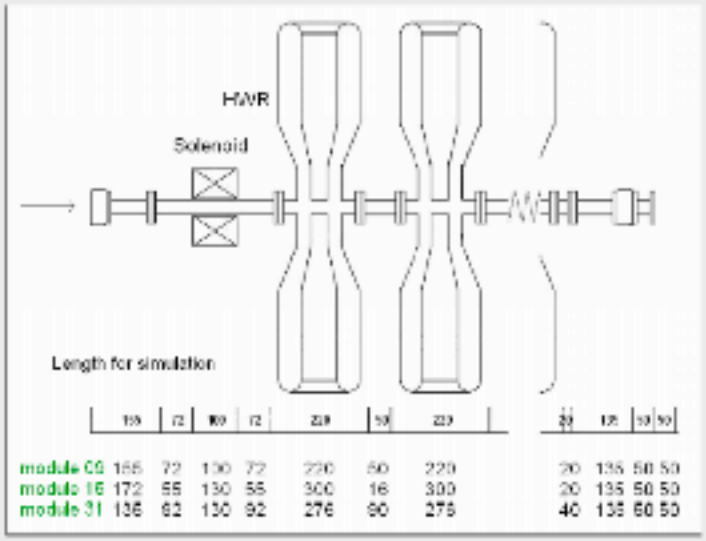
Simulations include:

- Import of 3D fields
- Simulation of alignment errors
- 3D space-charge model

Conclusion (from paper):

(…) The normalized rms transversal emittance growth is 22% in TRACK and 23% in GPT. There are minor differences between GPT and TRACK. The beam bunch energy deviation between the codes along the linac up to 52 MeV at 25 m from the RFQ exit is lower than 0.2%.

(…) The simulation in this work for a proton or a deuteron beam starts downstream a 4 m long, 1.5 MeV/u 176 MHz RFQ. The SARAF lattice consists of three quadrupoles at the 0.65 m MEBT, two low energy cryostats, each containing six HWRs of β0=0.09 and four medium energy cryostats with eight HWRs of β0=0.15 at 176 MHz.



Sample GPT applications #2

STATUS OF THE RAL FRONT END TEST STAND

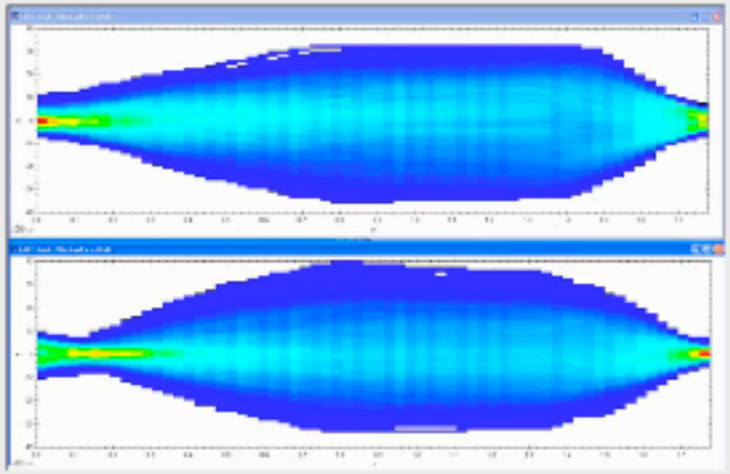
A.P. Letchford, et. al., EPAC 2008 p. 3437.

Excerpts from the paper:

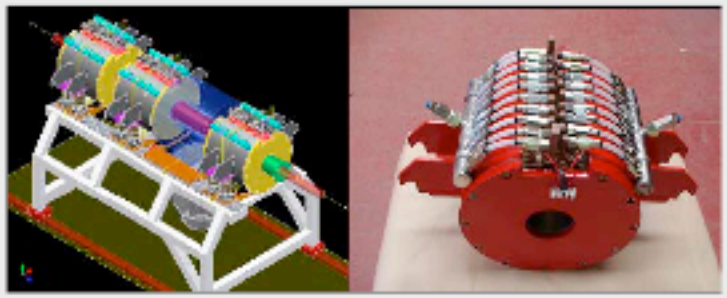
The RAL Front End Test Stand (FETS) project aims to (…) demonstrate a high quality, high current, chopped H^- beam.

The front end test stand consists of an H– ion source, magnetic low energy beam transport (LEBT), 324 MHz RFQ, medium energy beam transport (MEBT) chopper line and comprehensive diagnostics.

Considerable experimental and computational effort, using CST EM & Particle Studio plus General Particle Tracer (GPT), is leading to a much better understanding of the beam behaviour.



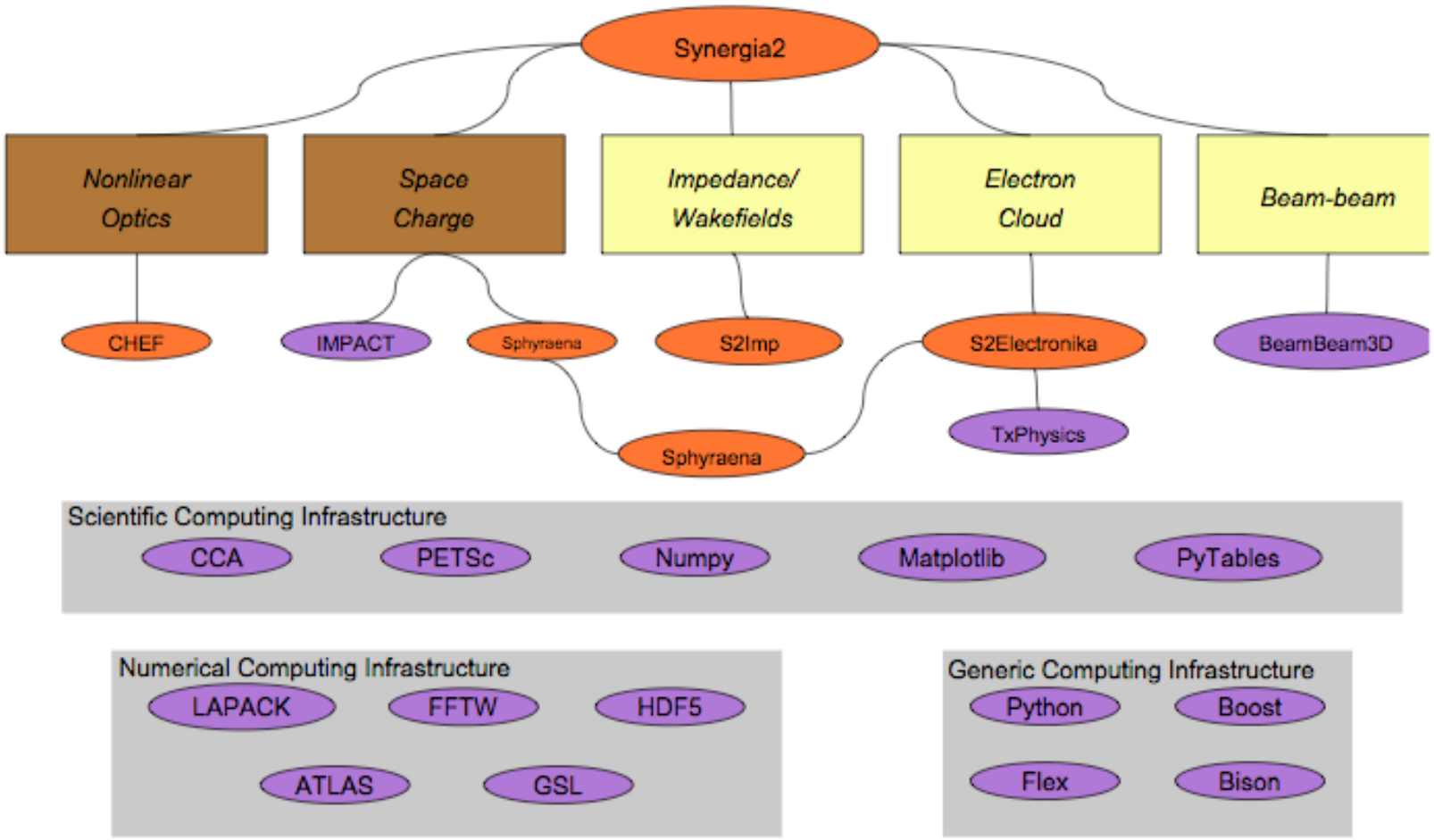
Beam envelopes calculated by GPT



Synergia

P. Spentzouris, J. Amundson
et al. (FNAL)

The Synergia2 Framework



Synergia2 framework development includes multiple advanced accelerator physics topics. Developm is aided by relying on both internally- (orange) and externally- (magenta) developed state-of-the-art packages. New physics modules (yellow) are currently under development.

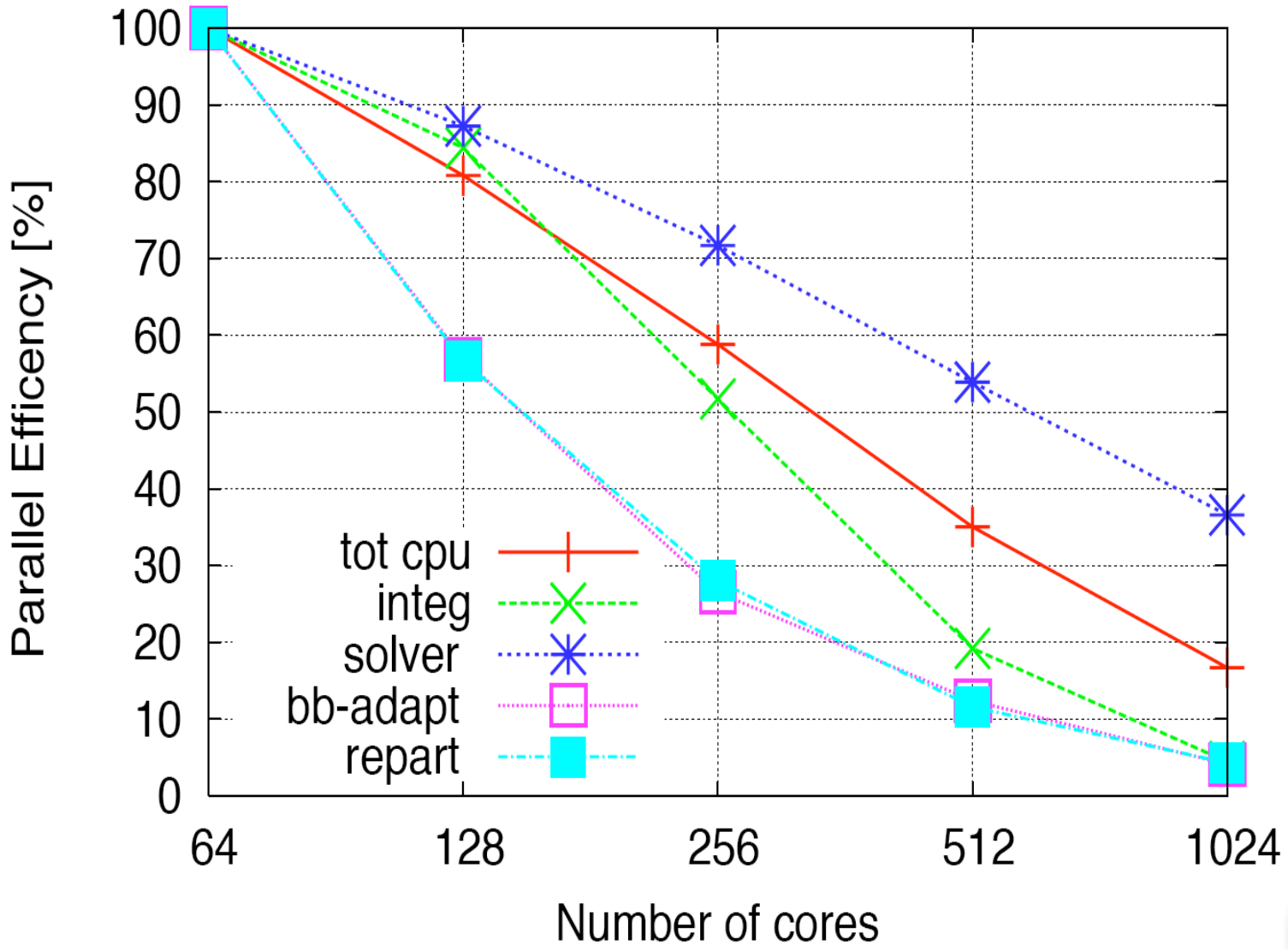
OPAL

Andreas Adelman (PSI)

OPAL (Object Oriented Parallel Accelerator Library)

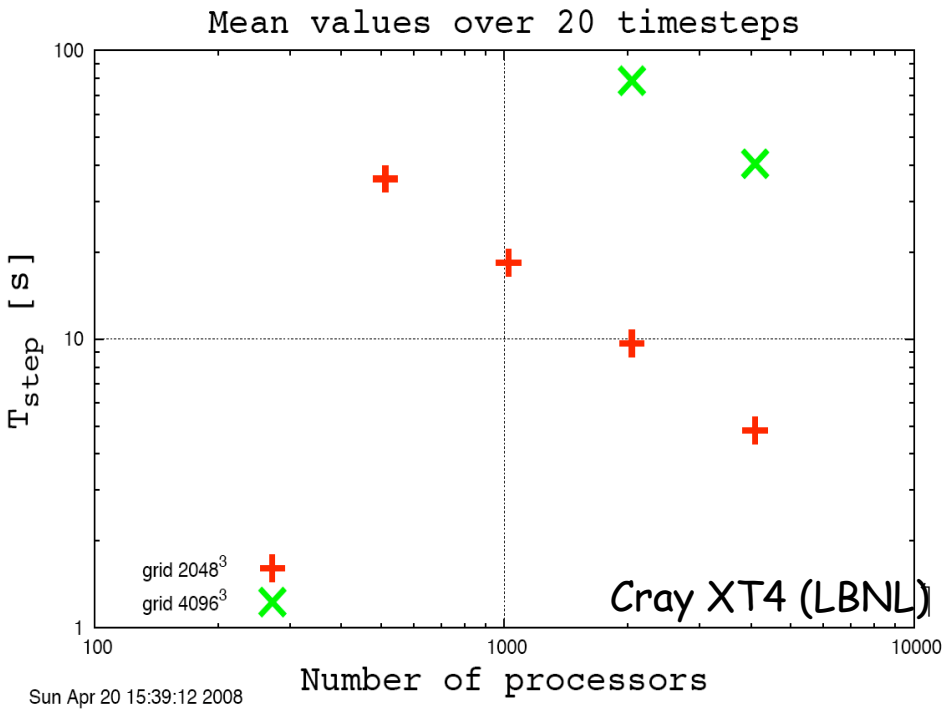
- OPAL is a general tool for charged-particle optics in large accelerator structures and beam lines including 3D space charge
- OPAL flavours: OPAL-t, OPAL-cycl and OPAL-Map
- MAD input language
- OPAL is built from the ground up as a parallel application exemplifying the fact that HPC (High Performance Computing) is the third leg of science, complementing theory and the experiment
- OPAL runs on your laptop as well as on the largest HPC clusters
- OPAL is written in C++ using OO-techniques and MPI
- HDF5 parallel I/O
- Documentation is taken very seriously at both levels: source code and user manual (http://amas.web.psi.ch/docs/index.html)

OPAL Scaling Production Run – I/O small



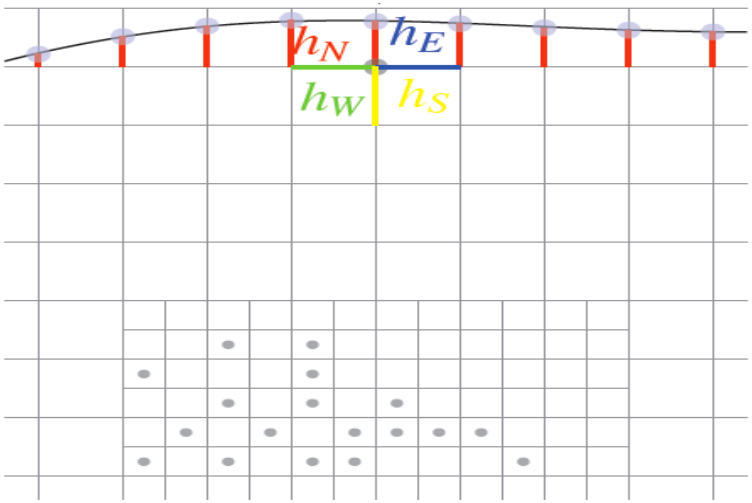
Unique features of the 3D OPAL code

OPAL FFT kernel scaling



- OPAL kernel scaling up 8k cores
- similar scaling obtained on IBM BG/P

Parallel MG ES solver in OPAL



- space charge calculation with exact boundary conditions
- parallel iterative solver reuses previous solution -> speed-up

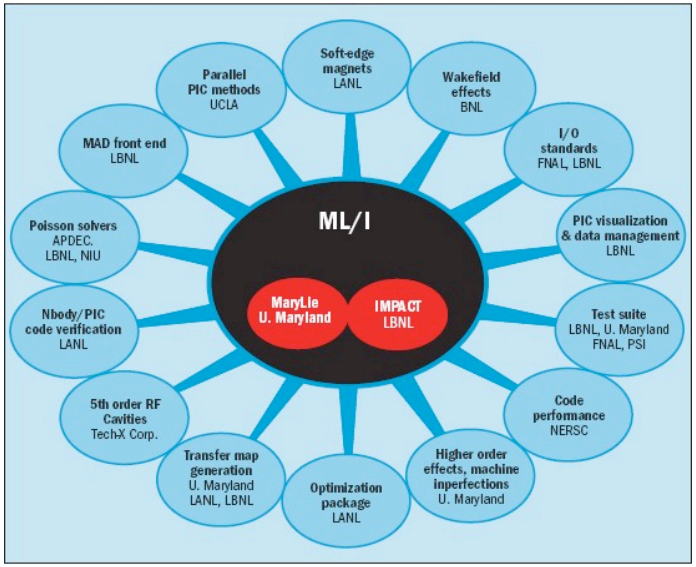
OPAL is used for precise 3D XFEL high brightness beam dynamic calculations as well as for high power Hadron machines.

MaryLie/IMPACT

Robert Ryne (LBNL), Alex Dragt (U Md), Dan Abell, Vahid Ranjbar (Tech-X), et al.

MaryLie/IMPACT (ML/I)

- Combines capabilities of MaryLie code (from U. Md.) with IMPACT code (from LBNL) + new features
- Multiple capabilities in a single unified environment:
  - Map generation
  - Map analysis
  - Particle tracking w/ 3D space charge
  - Envelope tracking
  - Fitting and optimization
- Applied to RHIC, ILC

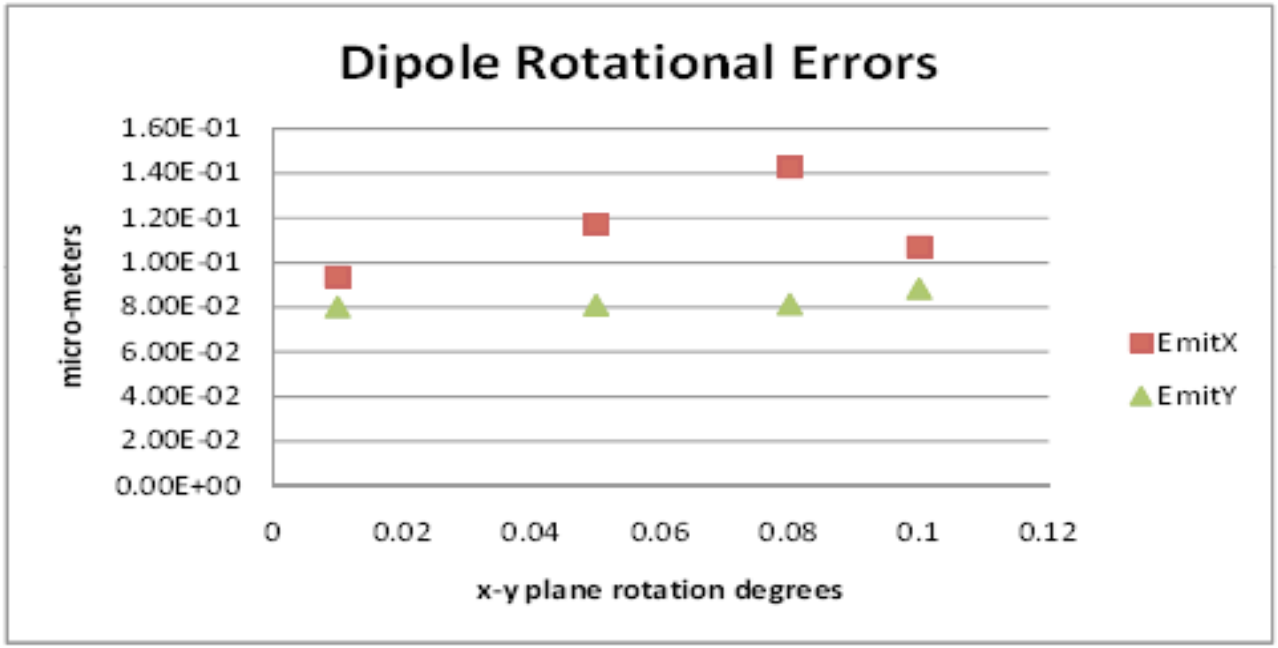


- Parallel
- 5th order optics
- 3D space charge
- Fitting/Optimization
- 5th order rf cavity model (Tech-X)
- Crab cavity model (Tech-X)
- Multiple ref traj for rf cavities
- 3D integrated Green function
- Envelope tracking
- Soft-edged magnets (LANL)
- Coil stacks (LANL)
- MAD-style input compatibility
- Test suite, regression tests
- “Automatic” commands

ML/I application to RHIC e-cooling

- **ML/I has been used to study beam transport through the e-cooling linac including the impact of misalignments on emittance.**

- **Results indicate sensitivity primarily to bend magnet misalignments. In all these cases emittance growth was kept well within tolerances at the level of 0.6 mm displacements or 0.1 degree planar rotations.**



Emittance response to x-y plane rotational misalignments of dipole magnets
(D. Abell,V. Ranjbar, Tech-X; J. Jensen, BNL)

PTC
(Polymorphic Tracking Code)

Etienne Forest (KEK)

See the talk by Dan Abell at this meeting on PTC with space charge

VORPAL

John Cary et al. (Tech-X)

Applied to ECRIS simulations

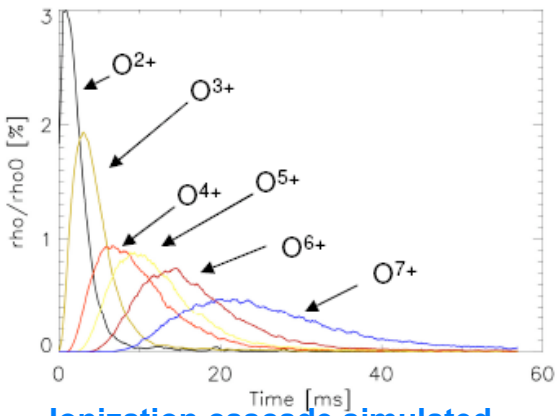
Peter Messmer (Tech-X)

Applied to electron-cooling

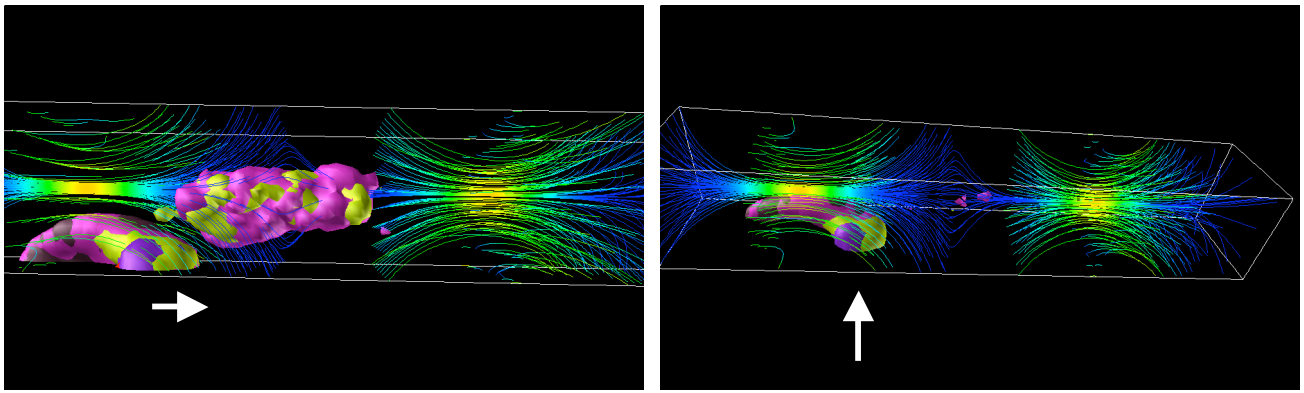
David Bruhwiler (Tech-X)

VORPAL enables detailed investigations of ionization physics and RF power absorption in ECRIS

- VORPAL's collision model enables simulation of ionization cascade
- Spatial distribution of different charge states in 3D magnetic field topology

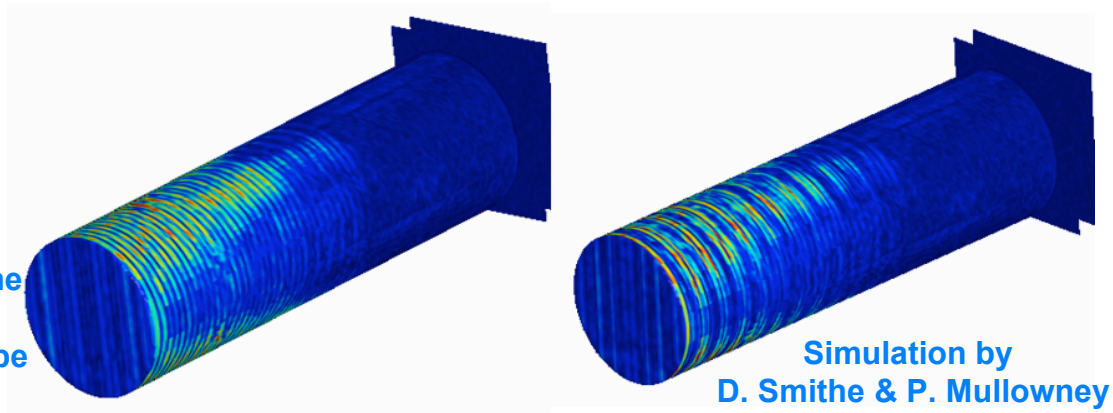


Ionization cascade simulated with VORPAL's kinetic ionization model.



Effect of loading geometry on ion charge-state distribution can be investigated with VORPAL simulations. Axial (left) and radial (right) loading of neutral Oxygen. Isosurfaces for charge states, O^{3+} (yellow) and O^{4+} (purple). Radial loading results in more wall losses -> less efficient

- Resonant power absorption and electron heating



ECR electron heating using single frequency (left) and double frequency (right), showing the beating pattern in the cavity. Effects onto the heating rate and the particle distribution can be investigated.

Simulation by D. Smithe & P. Mullowney

Research supported by DOE SBIR Grant #DE-FG02-05ER84173 (PI: Peter Messmer)

Parallel VORPAL simulations accurately calculate friction force on relativistic Au^{+79} ions in support of electron cooling designs

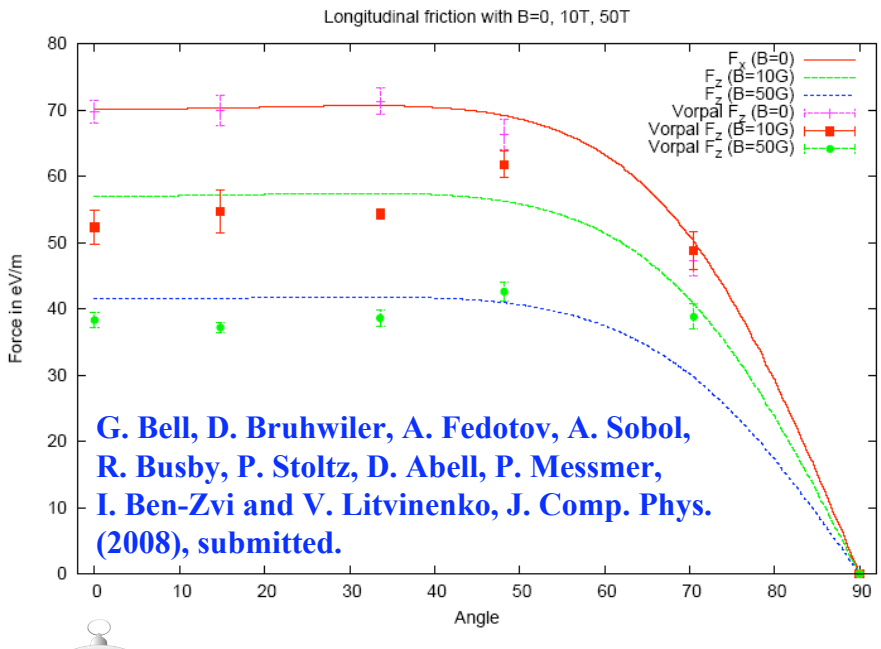
- **Electron cooling of relativistic ion beams is required for high luminosities of electron-ion collider (EIC) concepts**
  - **in the mid-term, RHIC luminosity could be increased ~10x**

I. Ben-Zvi *et al.*, "Status of the R&D towards electron cooling of RHIC," Part. Accel. Conf. (2007).

  - **conventional wiggler could replace expensive solenoid**
    - **e- "wiggle" motion suppresses recombination with ~10 Gauss**
    - **provides focusing; reduces risk**
    - **friction force should be reduced only by $\rho_{min} \rightarrow \rho_w$ in Coulomb log**

$$\rho_w = \frac{\Omega_{gyro}}{k_w^2 v_{beam}} \sim 1.4x10^{-3} \lambda_w^2[m] B_w[G]/\gamma$$

      - suggested independently by V. Litvinenko and Ya. Derbenev
      - confirmed via VORPAL simulations



G. Bell, D. Bruhwiler, A. Fedotov, A. Sobol, R. Busby, P. Stoltz, D. Abell, P. Messmer, I. Ben-Zvi and V. Litvinenko, J. Comp. Phys. (2008), submitted.

Parallel VORPAL simulations are being used to study the modulator of a coherent electron cooling (CEC) system

- **Coherent Electron Cooling concept**
  - **uses FEL to combine electron & stochastic cooling concepts**

    Litvinenko & Derbenev, "Free Electron Lasers and High-Energy Electron Cooling," FEL'07 Proc.
  - **a CEC system has three major subsystems**
    - modulator: **the ions imprint a "density bump" on e- distribution**
    - amplifier: **FEL interaction amplifes density bump by orders of magnitude**
    - kicker: **the amplified & phase-shifted e- charge distribution is used to correct the velocity offset of the ions**
  - **standard electron cooling could work well for RHIC II…**
  - **but CEC could be orders of magnitude better:**
    - **stronger interaction implies shorter cooling times**
    - **effectiveness does not scale strongly with ion beam energy**
      - Could even be relevant to the LHC
  - **modulator is being simulated with VORPAL**

    Bell *et al.*, "VORPAL simulations relevant to Coherent Electron Cooling," EPAC Proc. (2008).

XAL Framework

Christopher Allen (ORNL)

On-line modeling in SNS control room

- **High-level control applications at SNS are built overthe XAL framework**
  - https://wiki.ornl.gov/sites/xaldocs/default.aspx
  - https://wiki.ornl.gov/sites/xaldocs/XAL%20Documentation/Papers/WE116-CKAllen.pdf
- **On-line model is currently capable of:**
  - **Single particle simulation**
  - **Transfer matrices**
  - **RMS envelope simulation**
  - **Machine beta functions**
- **Architecture is the novel aspect of the on-line model**
  - **Relatively easy to add new capabilities**

SELECTED ALGORITHMS & METHODS

Space Charge Templates

Leonid Vorobiev (Fermilab)

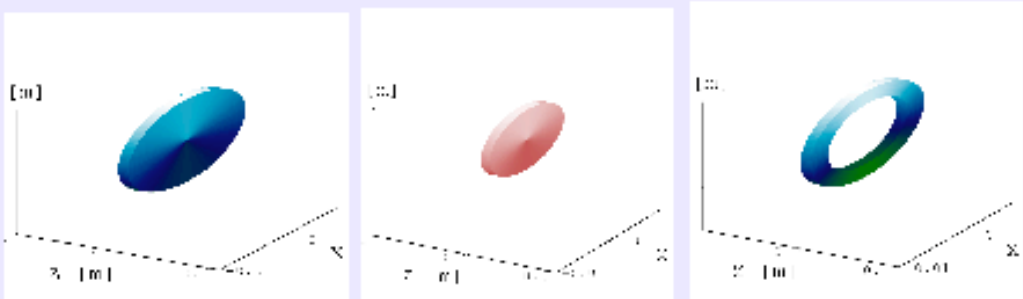
Space Charge Templates for 3D beam simulation

L.G.Vorobiev* APC/FNAL, R.C.York NSCL/MSU
* Corresponding author; lgv@fnal.gov

Motivation:

- **Fast: orders of magnitude faster, compared to PICs**
- **Accurate: exact for a large family of 3D distributions**
- **Modest Memory Demands**
- **Increased the accelerator/beam design space**

3D Templates = Elliptic Discs or Rings:

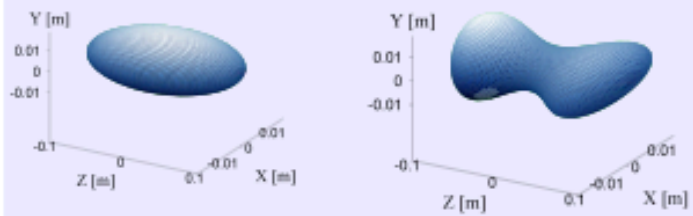


Disk-Template (Basis/Library)
Ring-Template=Superposition of positive (BLUE) & negative (RED) derived from Disc-Templates

Templates: Concept

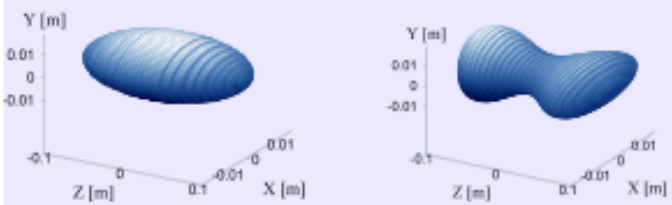
Template code deals with macro-particles, as standard 3D PICs
Template substitute Grid (density & Poisson) Solvers in particle tracking codes:

$$\{\text{Particles}\}_{old} \rightarrow \begin{bmatrix}\text{Template}\\ \text{Method}\end{bmatrix} \rightarrow \begin{Bmatrix}\text{Trajectories}\\ \text{Integrator}\end{Bmatrix} \rightarrow \{\text{Particles}\}_{new}$$



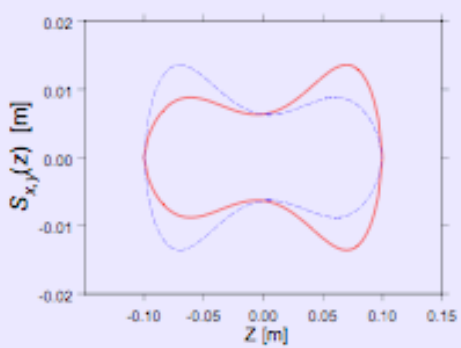
3D beam (non-elliptical!)
Within conducting
Boundary (not shown)

$$\begin{cases} \Delta u_{beam}(\mathbf{x}) = -4\pi\rho_{beam}(\mathbf{x}), & \mathbf{x}\in\Re \\ u_{beam}(\mathbf{x})\big|_{\partial\Re} = \overline{U}_{beam}(\mathbf{x}) \end{cases}$$



3D Templates within
the same boundary

$$\begin{cases} \Delta u_{tmp}(\mathbf{x}) = -4\pi\sigma_{tmp}(\mathbf{x}), & \mathbf{x}\in\Re \\ u_{tmp}(\mathbf{x})\big|_{\partial\Re} = \overline{U}_{tmp}(\mathbf{x}) \end{cases}$$



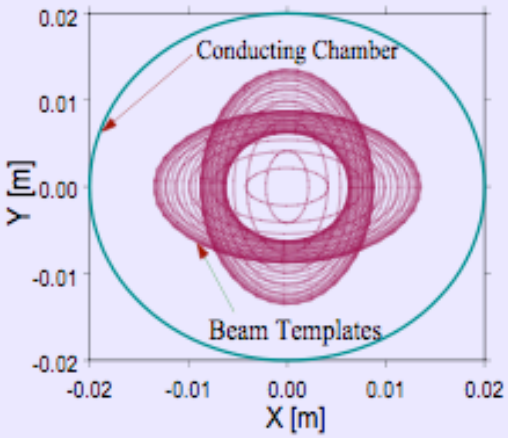
Instead of 3D Poisson Equation for Beam, Convolve Template Potentials

$$u_{beam}(x,y,z) = \int u_{tmp}(x,y,z-\tilde{z}, S_{x,y}(\tilde{z}), \Lambda(\tilde{z}))d\tilde{z}$$

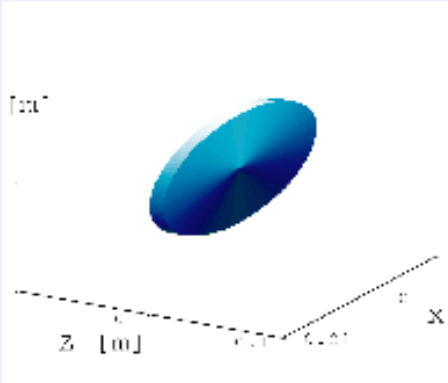
$$S_{x,y}(z) - \text{ Shape Function (3D Shell)}$$

Templates: Disc/Ring 2D Densities

Library of Templates

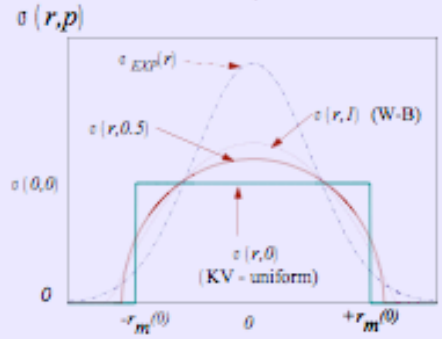


Disc Template

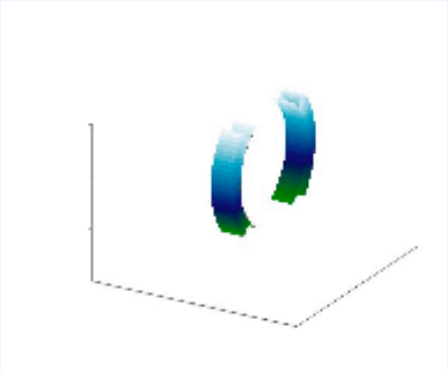


Assigned densities

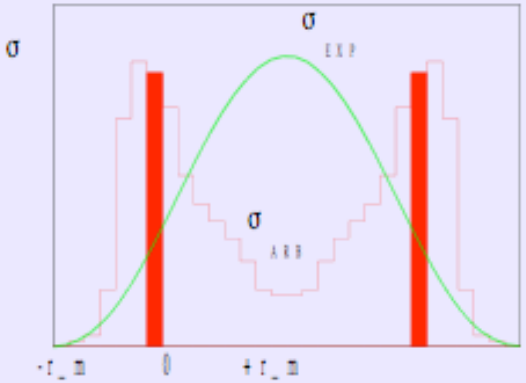
$$\sigma(x,y,p) = \sigma_m(p)\left(1 - \frac{x^2}{x_m^2(p)} - \frac{y^2}{y_m^2(p)}\right)^p$$



Ring template



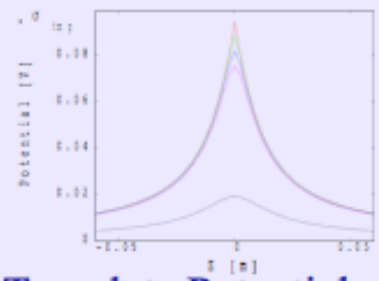
More General densities



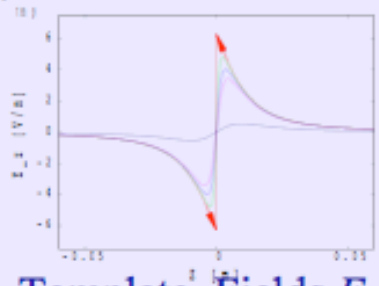
Template potentials/fileds are scaled proportionally to the number of comprised particles

Templates: Library, Reproduction of total SC

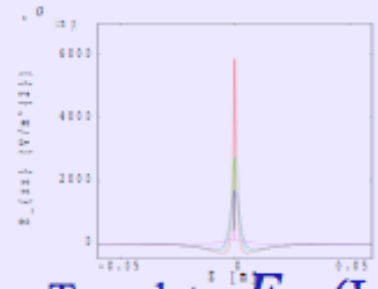
- Free Space & R-Z symmetry: **Analytics**
- Boundaries & Arbitrary Geometries: Pre-calculation **+ Parameterization**



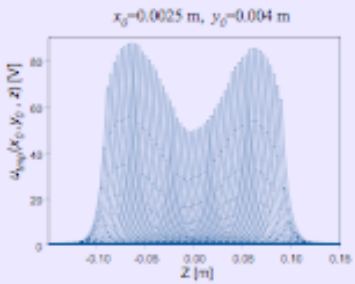
Template Potentials (Library)



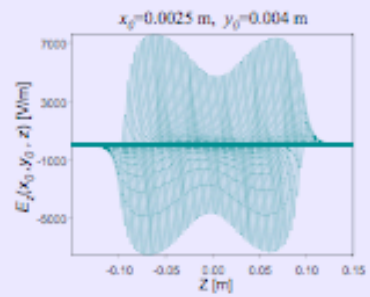
Template Fields E_z (Library)



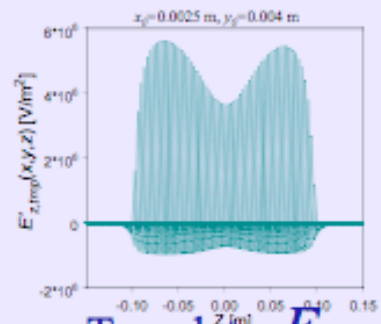
Template E_{zz} (Library)



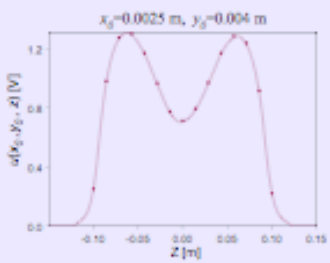
Template Potentials



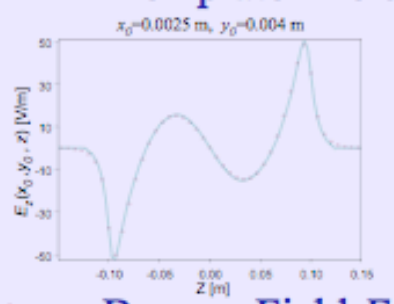
Template Fields E_z



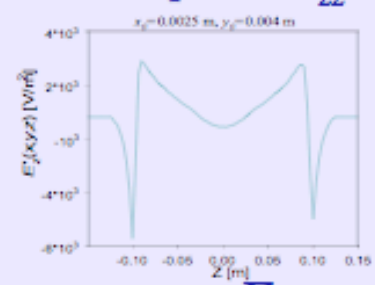
Template E_{zz}



Beam Potential

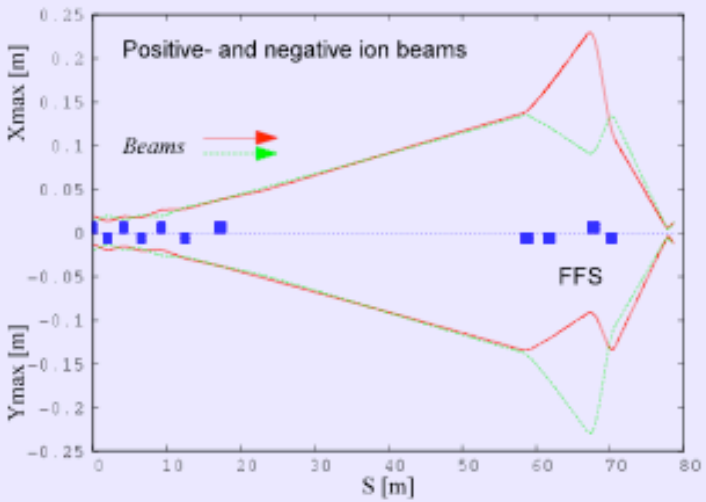


Beam Field E_z



Beam E_{zz}

Templates: Example Application



Example: FFS for Heavy Ion Fusion

Mission critical: Losses→ min

Templates increase performances by 2-3 orders of magnitude in comparison with standard PICs: 30 min vs 2 days

→ Optimization in automatic mode

Templates: Heirarchy/Bibliography

- Template foundations: MSUCL-1117 (1998); PAC'99 p.2781
- 2D envelopes within boundaries PAC'01, p.3075
- Sub 3D (one or more thick slices) PRST-AB, 114201
- 3D fully parametrized PAC'03, p.3533
- 3D axially-symmetric in free space + Ring-Templates FERMILAB-PUB-08-236-APC

Templates: Summary

Template's Foundation:	Principle of Superposition in Electrodynamics
Templates - Special functions	Pre-calculated Macro Green's functions
Range	from 2D to 3D beams including boundaries
Scalable & Exact	for a large family of distributions
Modest Memory Demands	due to parameterization
Performance	10^2-10^3 times faster than conventional PICs
Optional SC Solvers in existing PICs	
Limitations	Clusters, filaments, complex boundaries

⇓

Design & Optimization in Automatic Mode
Increased design space for one-passage structures & Rings

Lorentz transform algorithm

Jean-Luc Vay (LBNL)

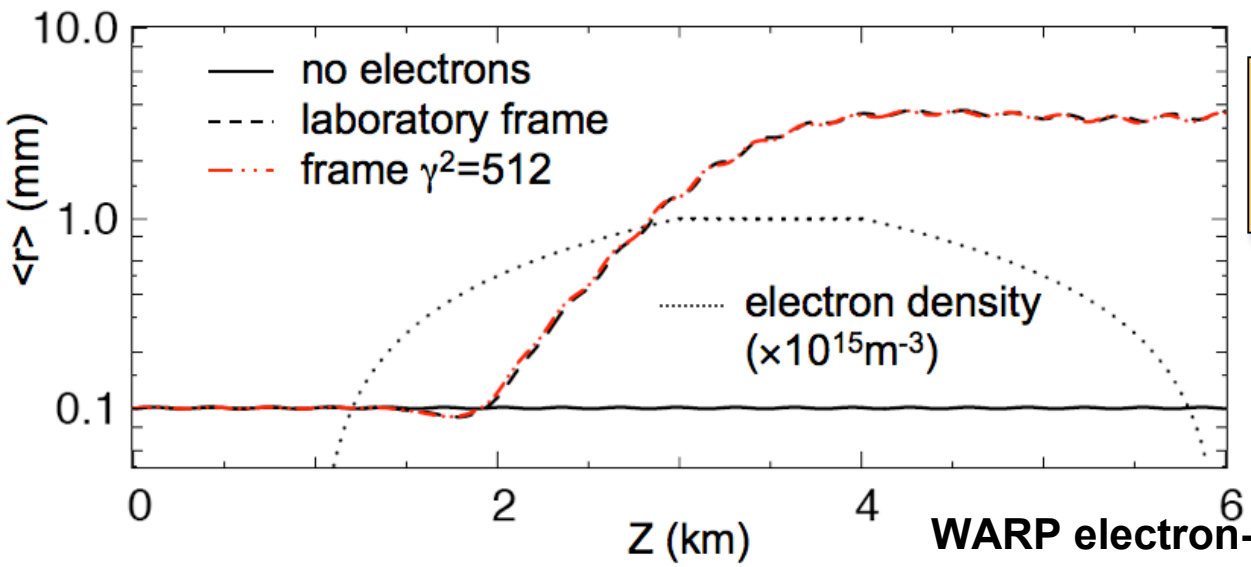
Noninvariance of space- and time-scale ranges under a Lorentz transformation (J.-L. Vay)

Key observation: ***range*** of space and time scales is ***not*** a Lorentz invariant; the ***optimum*** frame to minimize the range is ***not necessarily*** the lab frame

Choosing optimum frame of reference to minimize range can lead to dramatic speed-up for relativistic matter-matter or light-matter interactions.

speedup (PIC in boosted frame vs PIC in lab frame) reported so far:

x1000 3-D e-cloud driven beam instability (LBNL),
x45,000 2-D free electron laser toy problem (LBNL),
x1,500 1-D laser-plasma acceleration (Tech-X),
x150 2-D, x75 3-D laser-plasma acceleration (IST, Portugal).



CPU time (8 procs):
- lab frame: >2 weeks
- frame γ^2=512: <30 min

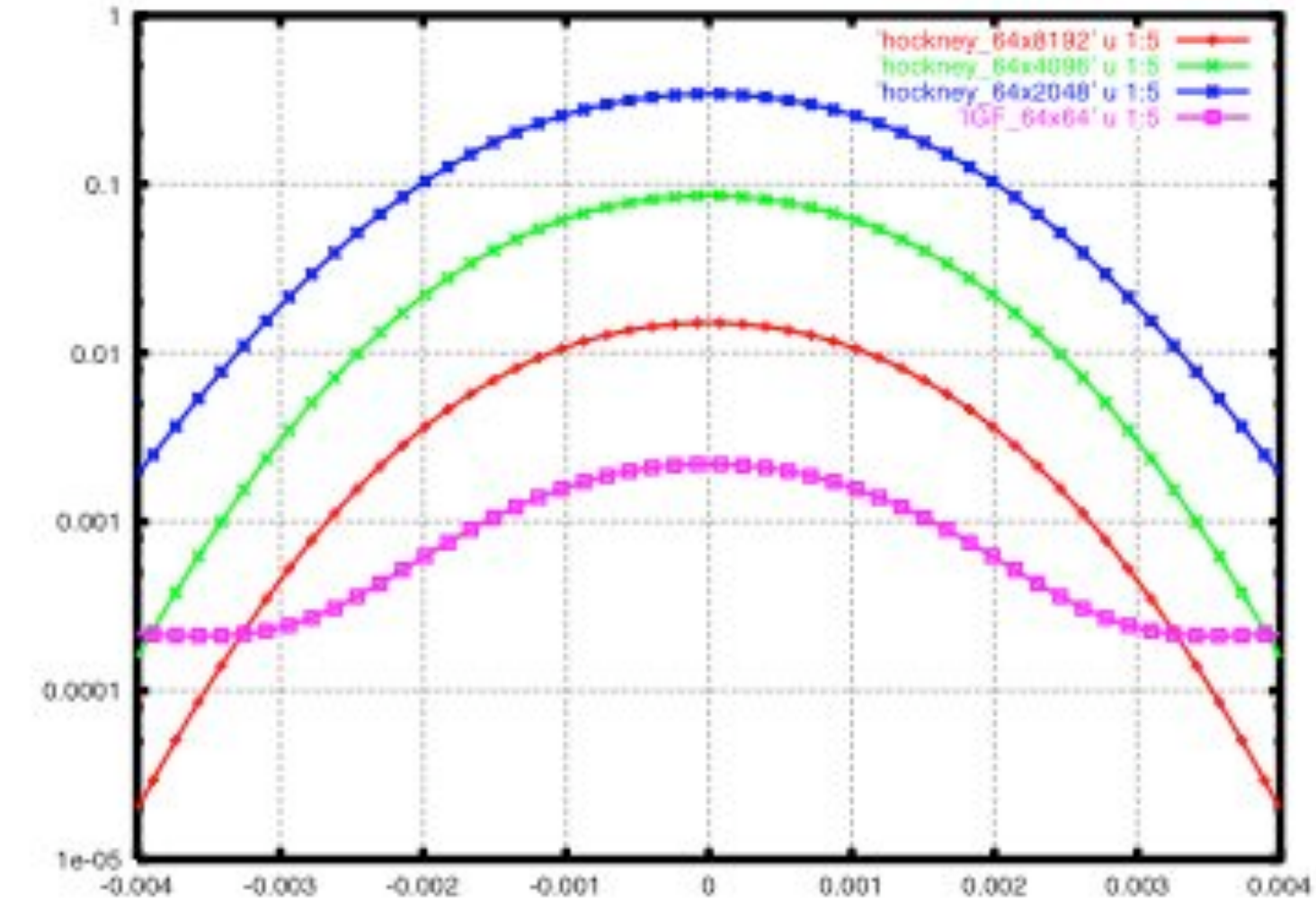
Speedup x1000

WARP electron-cloud instability simulation

Integrated Green Function (IGF)

D. Abell (Tech-X), V. Ivanov (Muons Inc.),
K. Ohmi (KEK), J. Qiang, R. Ryne (LBNL)

Integrated Green Function: Efficient Poisson solver for problems with high aspect ratio



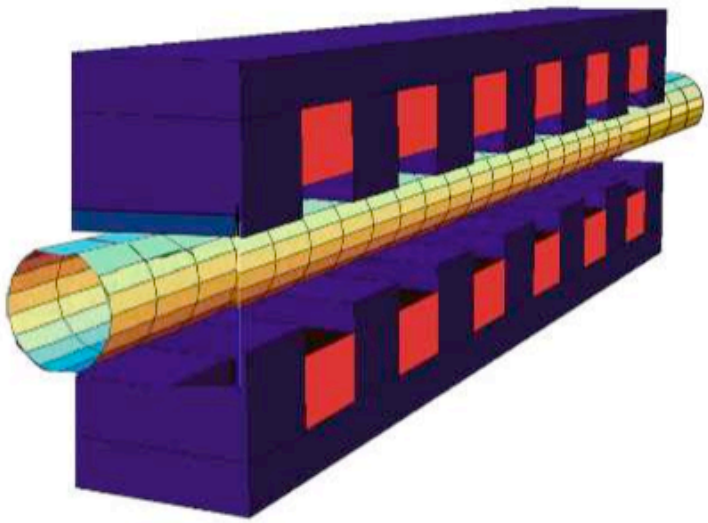
R. Ryne, LBNL

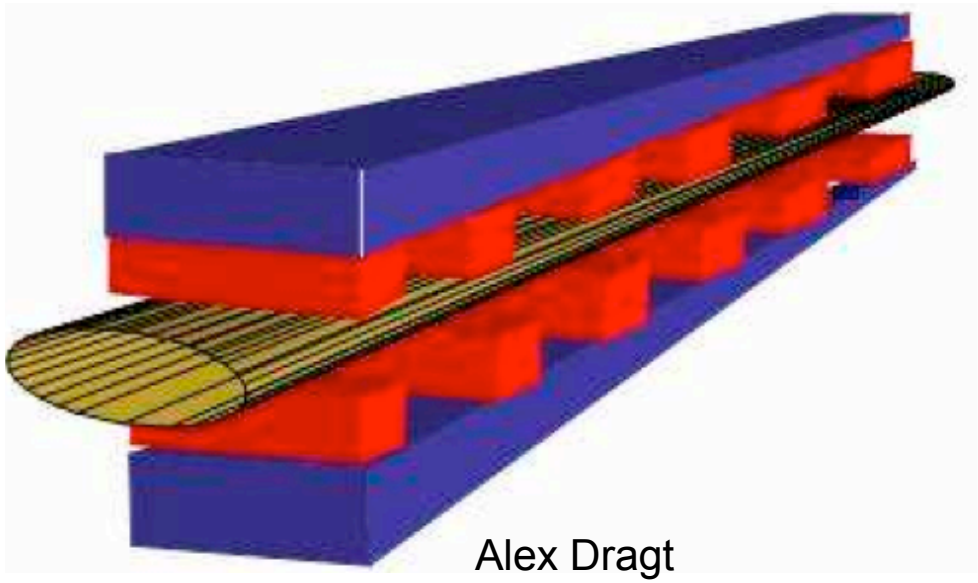
Old: 64x2048, 64x4096, 64x8192

New: 64x64

Map Production from Surface Data

A. Dragt (U. Md.), D. Abell (Tech-X), M. Venturini (LBNL), P. Walstrom (LANL),…





CODES, CAPABILITIES & METHODOLOGIES FOR BEAM DYNAMICS SIMULATION IN ACCELERATORS

PARMELA
PARMTEQ
PARMILA
2D space charge
rms eqns

WARP
SIMPSONS
IMPACT
3D space charge
GCPIC
DA
Symp Integ
Normal Forms
Integrated Maps
COSY-INF
MXYZPTLK

Freq maps

IMPACT-Z
IMPACT-T
ML/I
Synergia
OPAL
ORBIT
TRACK
Dynamion
DESRFQ
BeamPath
BeamBeam3D
MAD-X/PTC
…

MaryLie
Dragt-Finn
MAD
Transport

Partial list only;
Many codes
not shown

1970 1980 1990 2000

Observations on codes

- **There is an increasingly large overlap in capabilities of "linac codes" and "ring codes"**
  - **Accelerating cavities, beam optics, space charge, wakes, steering…**
- **Codes for modeling intense beams in rings contain much of what is needed for linac modeling, except for:**
  - **specialized systems such as ion sources, RFQs,…**
- **Ring codes of course have their own unique capabilities**
  - **1-turn map analysis, injection painting,…**

Part 3

The Future

Trends in supercomputer performances

- Fastest computers (from TOP500 list, www.top500.org)
  - —1998: Intel ASCI Red, 1.3 Tflops
  - —2000: IBM ASCI White, 5 Tflops
  - —2002: Earth Simulator, 35 Tflops
  - —2004: IBM BlueGene/L, 70 Tflops
    - June 2005: 137 Tflops
    - Nov 2005: 280 Tflops (131K cores)
    - 2007: 478 Tflops (213K cores)
  - —2008: see next slide

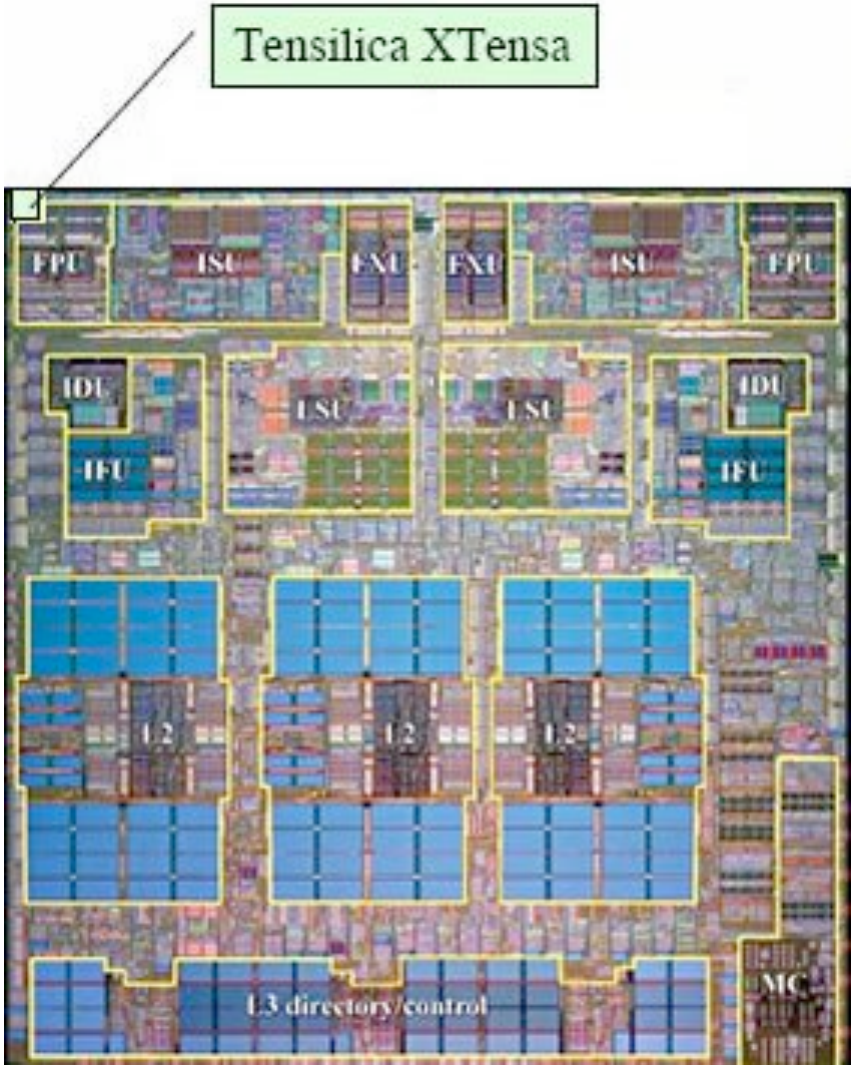
June 2008: "Roadrunner," developed by IBM in collab. with DOE and LANL, achieves 1 petaflop sustained performance

prefix	symbol	multiplier
tera	T	10^12
peta	P	10^15
exa	E	10^18
zetta	Z	10^21
yotta	Y	10^24

prefix	symbol	multiplier	Year
tera	T	10^12	1998
peta	P	10^15	2008
exa	E	10^18	2018 ?
zetta	Z	10^21	
yotta	Y	10^24	

LBNL and CSU scientists working with Tensilica propose "climate computer" with 20M cores

- **Small size**
- **Low power**
- **4 MW, 200 petaflops**



GPU's gaining popularity

- **1 teraflop**
- **4 GB**
- **1.4 billion transistors**
- **240 cores**
- **$1700**

For comparison:
Photo shown at PAC 2001
3.4 Tflops!

Future Directions (speculation)

- Increased emphasis on parameter scans & optimization on massive (>100K proc) computers
  - —Multi-level parallelism
- Growth of "small scale" parallel codes
  - —to take advantage of multi-core & GPUs
- Increased emphasis on multi-physics and multiple capabilities in a single package
- New modeling approaches will become tractable
  - —New CSR models
  - —6D Direct Vlasov
    - $128^6 = 4.4 \times 10^{12}$
- New opportunities for modeling in control rooms

It won't be easy

- **"I know how to get 4 horses to pull a cart, but I don't know how to make 1024 chickens do it."**

  Enrico Clementi

- **Looking at a machine like Roadrunner:**
  - **—12,240 horses (PowerXCell 8i processors)**
  - **—6,120 chickens (dual-core opterons)**

Announcement

2009 International Computational Accelerator Physics Conference (ICAP09)

Aug 30 - Sept 4, 2009

Mark Hopkins Intercontinental Hotel in the heart of San Francisco

Organized by LBNL and SLAC

We hope to see you there!