Simulations of Transmission Efficiency for RFQ Injection Line: Status

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21-Feb-2018

PIP General Meeting

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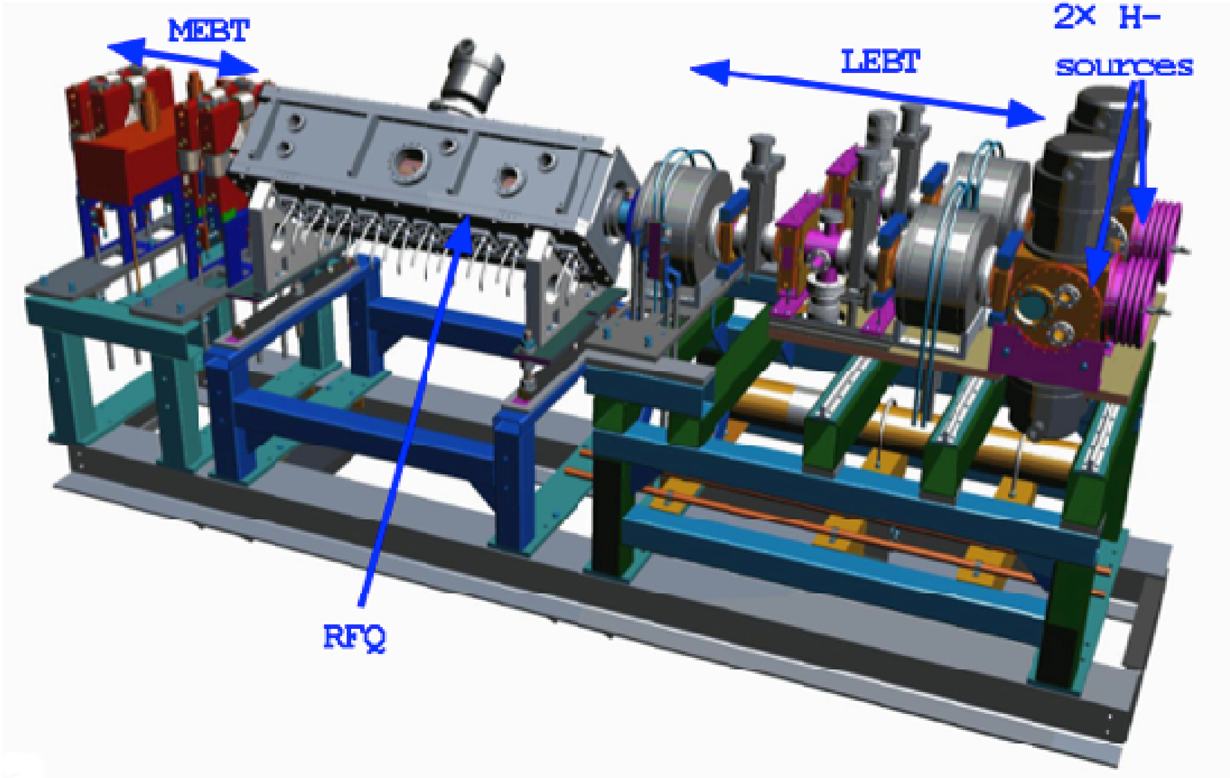
The RFQ Injection Line Configuration & References



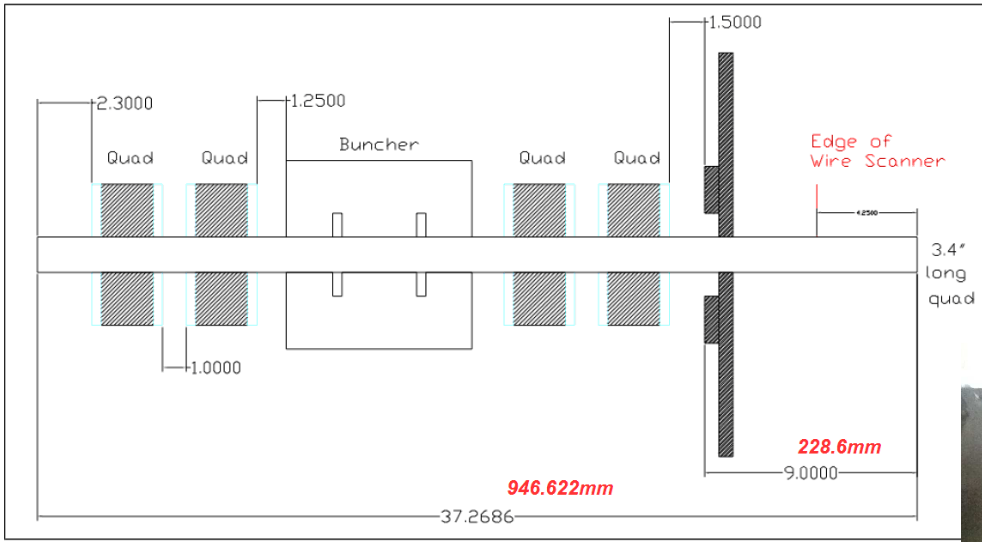
Parameter	Value	Units
Input energy	35	keV
Output energy	750	keV
Frequency	201.25	MHz
Number of cells	102	
Length	120	cm
Minimum radial aperture	0.3	cm
Maximum peak surface field	25.18	MV/m
Peak cavity power+beam power	~140	kW
Duty factor (80 μs, 15 Hz)	0.12	%
Design current	60	mA
Modulation m	$1 \leq m \leq 1.95$	
Intervane voltage	72	kV
Transmission efficiency	98	%

[1] C.Y. Tan et al, "The 750 keV RFQ Injector Upgrade", (final writeup) 11/Dec/2013 BeamDoc#3646-v16 (154p.)

[2] C.Y. Tan et al, "PIP I: RFQ Injector", talk, Acc seminar, BeamDoc 4563-v2 (48pp)

[3] C.Y. Tan, "Pre-Injector Upgrade Updates", **(>75)** talks on the current status (BeamDocs 8/Dec/2008÷10/Sep/2014)

The RFQ Injection Line - MEBT

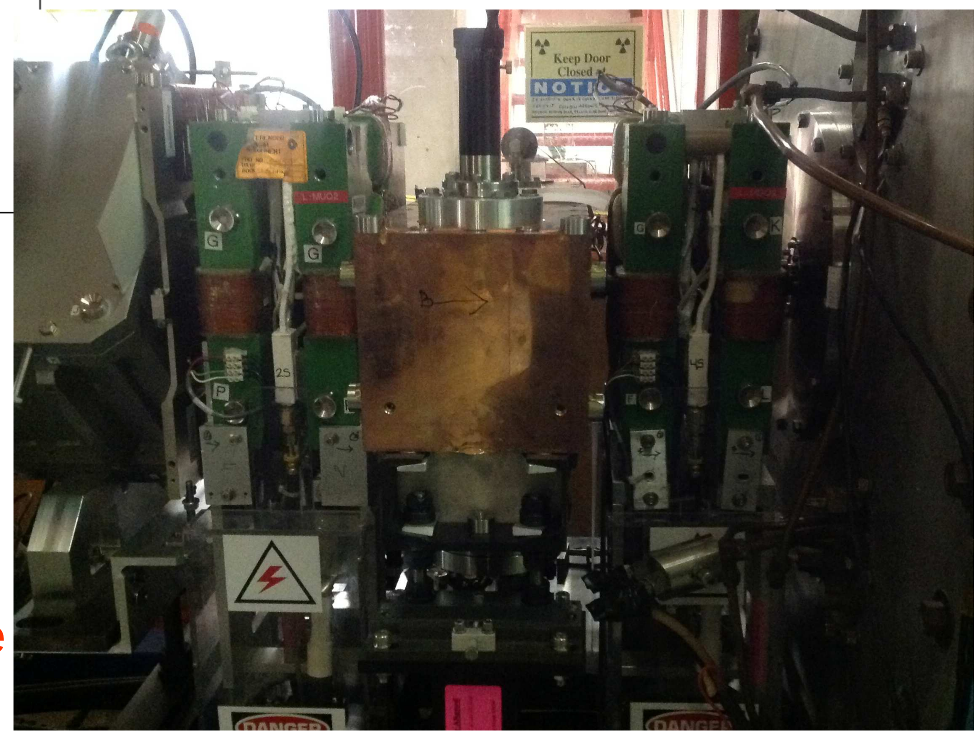


MEBT consists of:

1 buncher (2-gap with grid-foc);

2 sets of q-doublets (for matching)

4 sets of steerers in both planes



No any beam diagnostics in RIL (?):

a) Between ion source & LEBT;

b) Between LEBT & RFQ

c) Between RFQ & MEBT;

Front of DTL: Toroid; BLM; Emittance probe

Problem description by C.Y.Tan (20/Jun/2017)

- The **present transmission** (2017) from the H- source to the beginning of Tank 1 is <u>rather poor</u> during normal ops.
- Although the best efficiency that was seen just after installation (Jun/2013) was 65 mA at L:ATOR and 36 mA at L:T01IN, these numbers were not routinely seen during operations since then

T1=13-JUN-2013 12:35:19

at the LEBT (L:ATOR), entrance of Tank 1 (L:T01IN) and Tank 3 (T03IN)

L:ATOR mA	L:T01IN mA	L:T03IN mA
Mean 64.871	Mean 35.726	Mean 30.888

- The goal is to improve the transmission efficiency from the source to Tank 3 with **the base line of 28 mA at L:T01IN** that is seen during normal operations.

Possible ways for problem resolving by C.Y.Tan

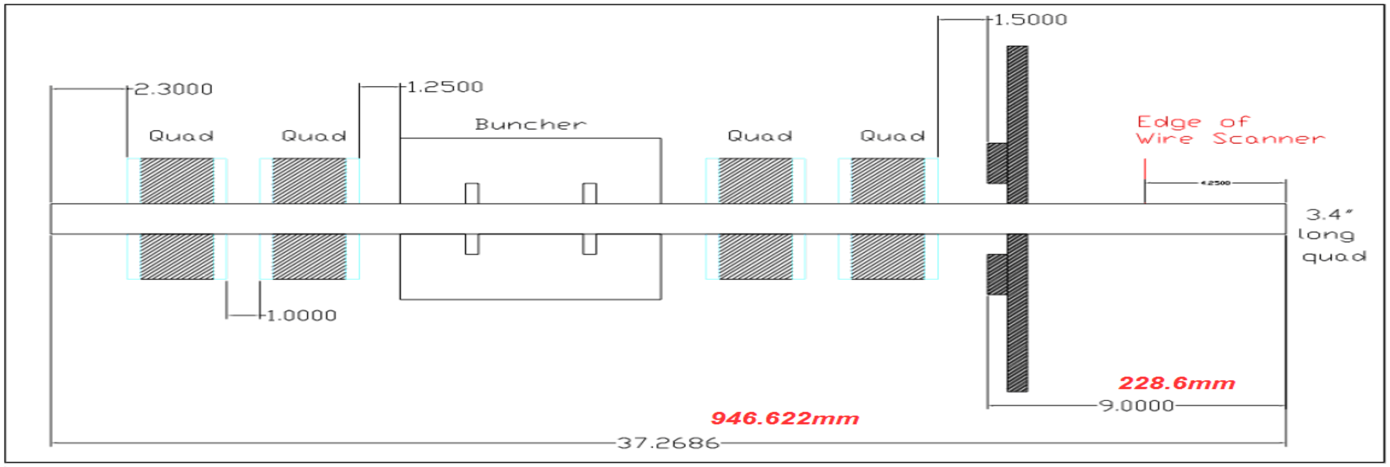
The parameter search for improving the efficiency must always include the laser notcher.

Possible configurations to be considered:

1) Checking the present MEBT design and if element locations are optim.
    1a) need for reinstallation of dipole correctors at RFQ exit

2) "RFQ+Tank1" (completely removing the MEBT)
    2a) it was considered in [1], but was tech. risky w/o knowing details

3) "RFQ+DS-doublet+Tank1" (removing UpS Doublet & Buncher)
    3a) DnS Doublet gives some focusing before Tank1 quads



Possible ways for problem resolving (continued)

4) Completely replacing the FNAL RFQ with the LANL RFQ

MWS file for LANL 4-rod RFQ is available from S.Kurennoy

4a) LANL has a similar 4-rod RFQ that has the same Win/out=35/750keV.

Diffrerences between FNAL & LANL 4-rod RFQ:

4a1) LANL RFQ is ~30cm longer &improves upon the FNAL design, i.e. LANL RFQ removed the dipole kick of the beam at exit (? x'=y'=0)
4a2) In principle, the LANL RFQ should not have an energy error, but it has not been tested with beam yet.

4b) Redo items 1 to 3 above to see if it is worth replacing the FNAL RFQ with the LANL RFQ.

VK's add-ons: a) just borrow whole LANL tank; b) borrow LANL electrodes & build own clone using LANL drawings; c) RF design & mech. build for a new "symmetrical" 4-rod RFQ borrowing either LANL or FNAL **thick** electrodes.

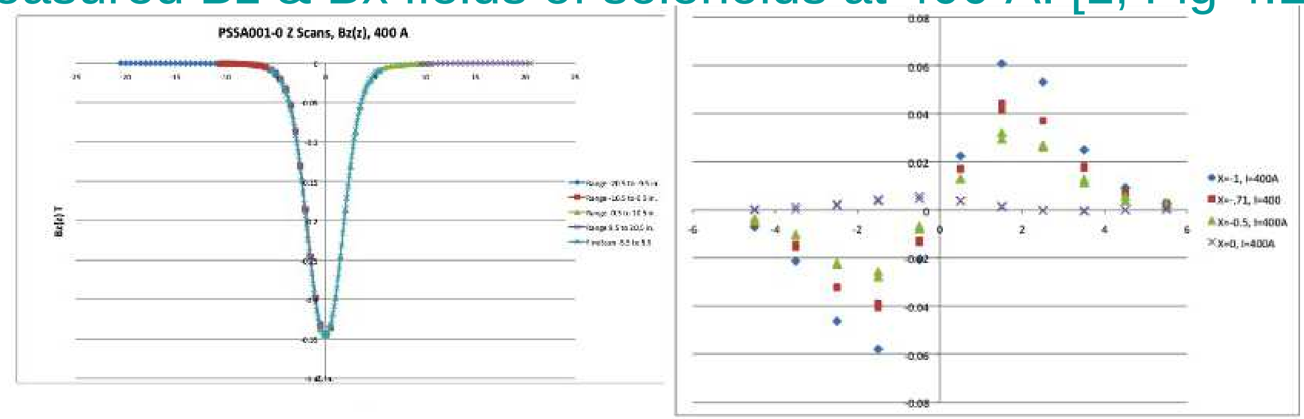
Simulations & meas done during design of Inj-Line

- LEBT: simuls with TRACE-2D (linear beam envelopes); w/o tracking in real fields (bell-shape & non-linearities; gas-focusing)
- Beam emittance was measured only once (before assembling whole Inj-Line) & traced to RFQ entry. (VK: beam ε, β, α for diff. params?)
- RFQ: simuls with PARMTEQM (ideal two-term potential function assuming sin-modulated hyperbolic electrodes fed with ideal time-varying quadrupolar RF potentials: +V;-V;+V;-V)
- Real simuls done at LANL by Kurennoy helped to resolve 4-rod RFQ problems [1-3]; only for operating point at 60mA
- MEBT: simuls with TRACE-3D (lin. beam envel.) & with PARMILA2 (exe only, ideal Qs and RF-fields w/o real field with expanded fringe fields and non-linearities)
- Routine emittance meas at entry Tank1 are possible, if needed (?)
- Tanks1-3: simuls with historical PARMILA lattice (out of reality [1]) used as a criterion for matching MEBT beam

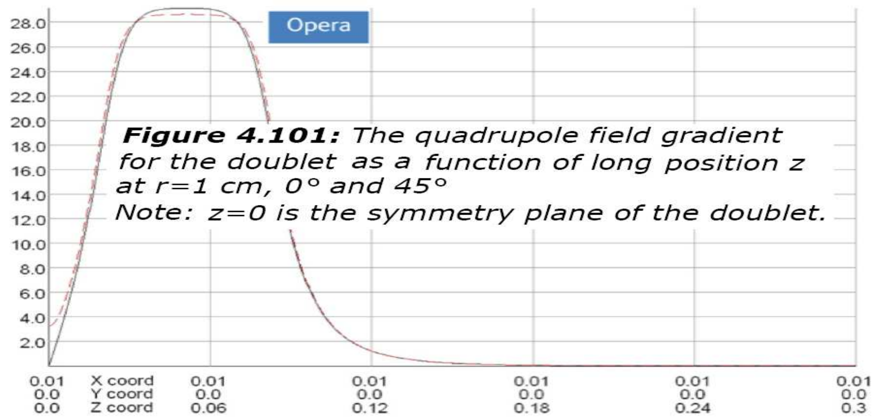
VK: the above items are a standard for 4-vane RFQ with a good beam quality, but for 4-rod RFQ (???)

Illustration of non-ideal fields in LEBT & MEBT

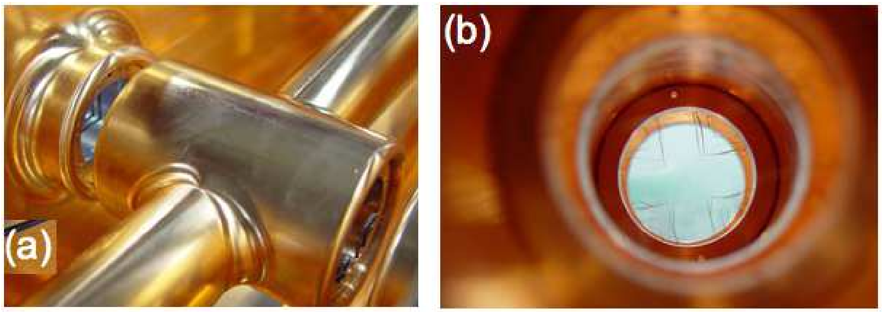
Measured Bz & Bx fields of solenoids at 400 A. [1, Fig 4.18]



Q-field gradient at r=1cm vs z [1, Fig 4.101]
z=0 is simmetry plane of doublet



Buncher DT with grids. [1, Fig 4.92]



Overview of peculiarities of Schempp's 4-rod RFQ

Peculiarities cover the following:

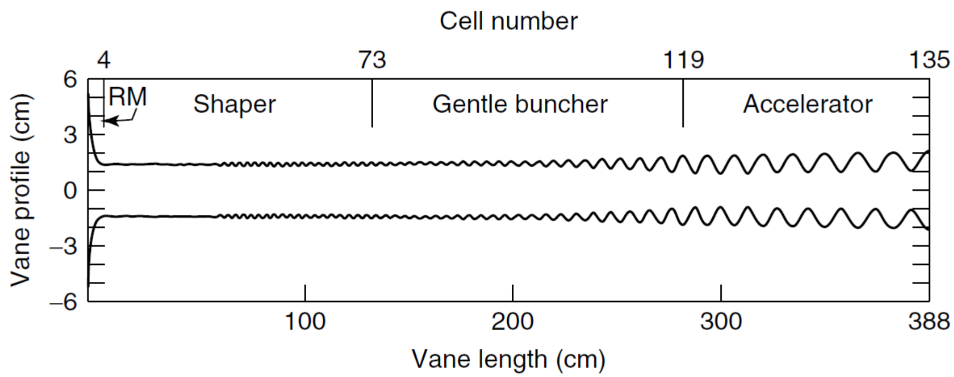
- RFQ design (cell parameters)
- Transfer from ideal-to-real electrodes
- Electrode excitation in 4-rod RFQ:
  dipole field & distortions in radial matcher

Comments:

- "Dipole" problems were recognized from late 1980s
- Dipole: resolving is continuing since 1995- up to 2010s
- R-Matcher: copy of 4-vane RM electrode geometry
- Possible alternatives (symmetrical 4-rod structures)

RFQ designs: classical vs Schempp's

Classical Design for High-Current RFQ: LANL Four-Section Procedure



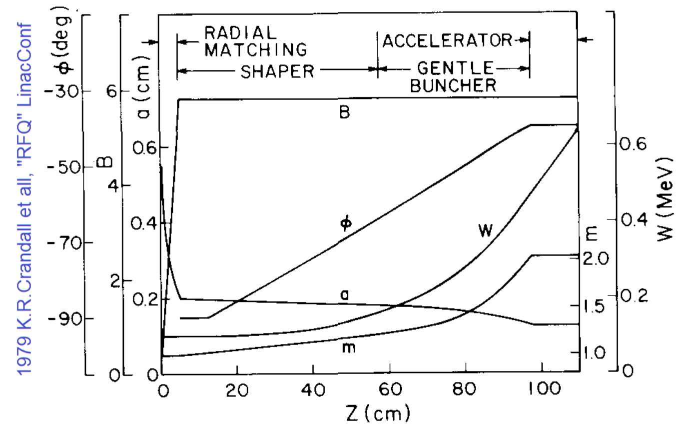
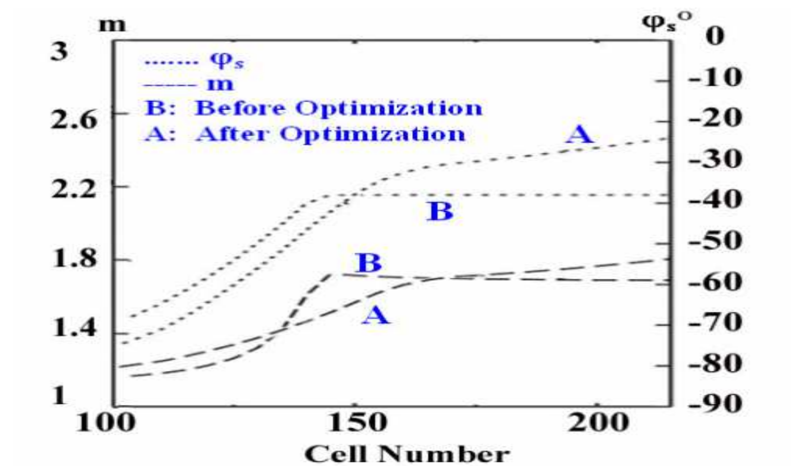


Fig. 6. Parameters for the 425-MHz test design.

New design approach by A, Schempp et al. optimized for compact RFQs

started from 1988 & developed in 2000s:
A.Schempp, Design of Compact RFQs, EPAC-88;
C.Zhang,…,A.Schempp, Linac 2004;



Check FNAL design vs I inj

Input beam parameter by manufacturer [1,fig.4.45]

Well matched beam !!!

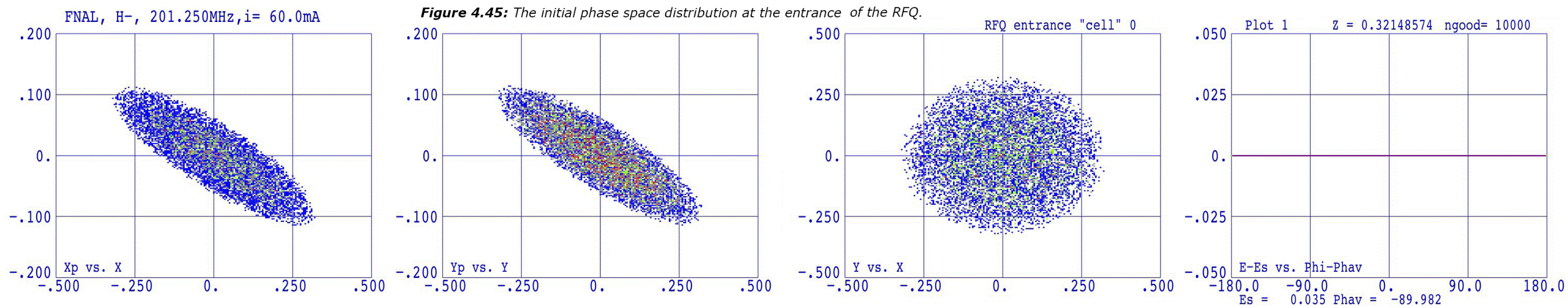
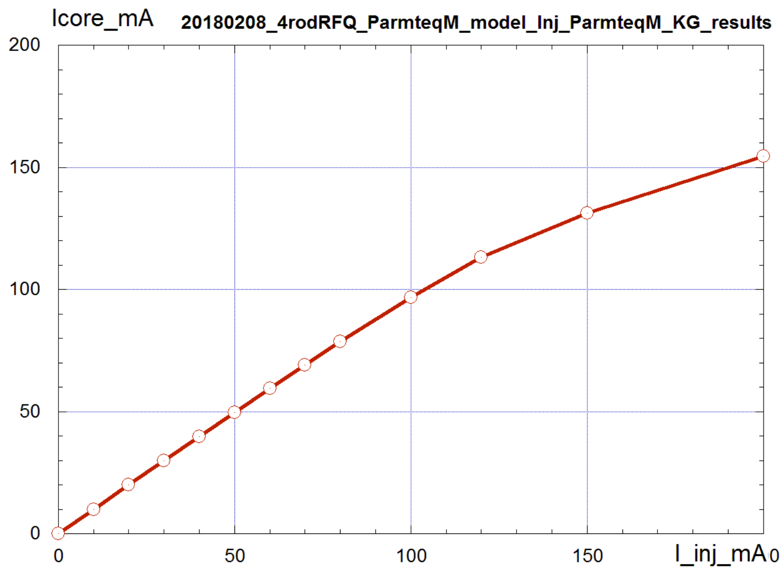
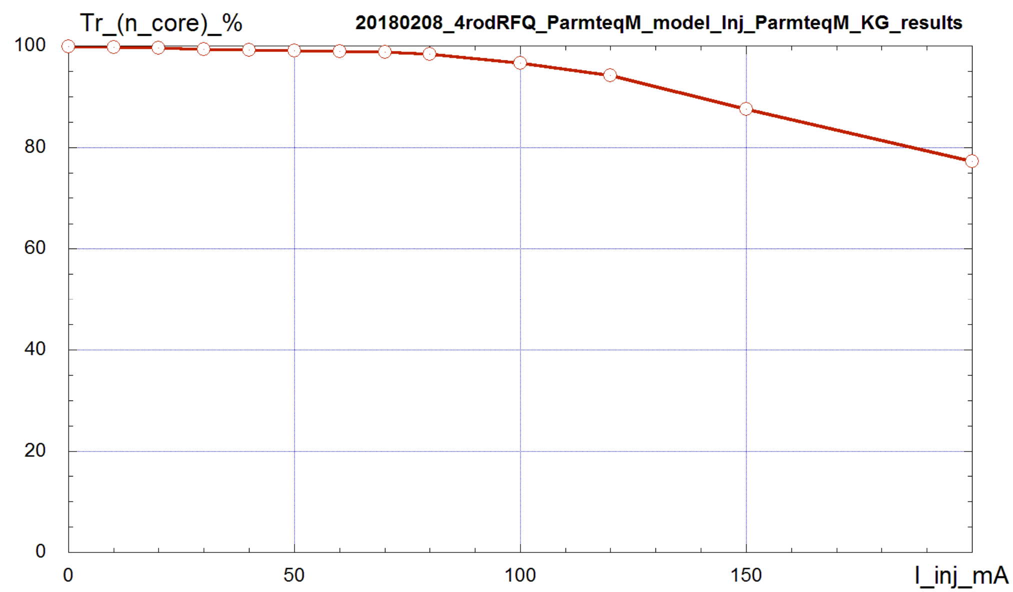


Figure 4.45: *The initial phase space distribution at the entrance of the RFQ.*

Excellent beam transmission up to 120mA; twice higher of nominal 60mA !!!

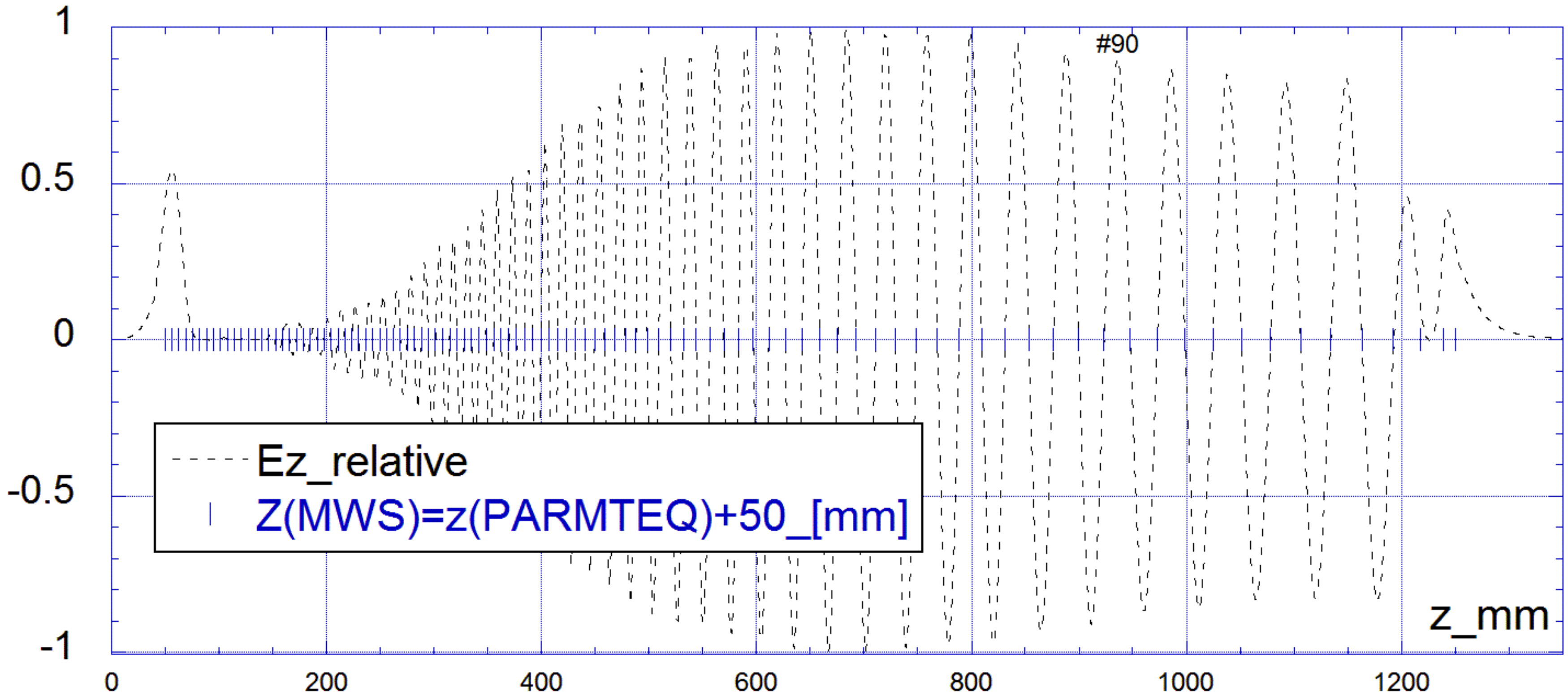




Transfer from ideal-to-real electrodes

Real electrodes always differ from ideal (sin-modulated hyperbolic) electrodes

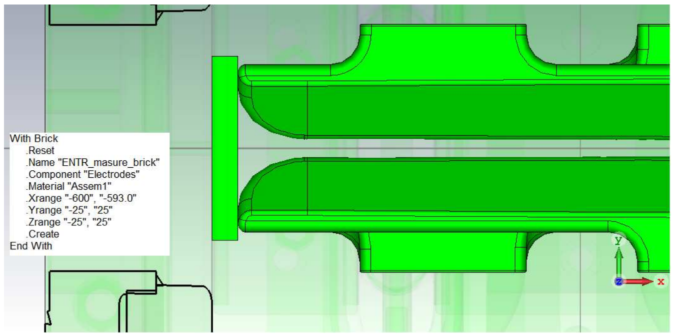
Inspect PARMTEQM long. cell-end coordinates vs CST model Ez field



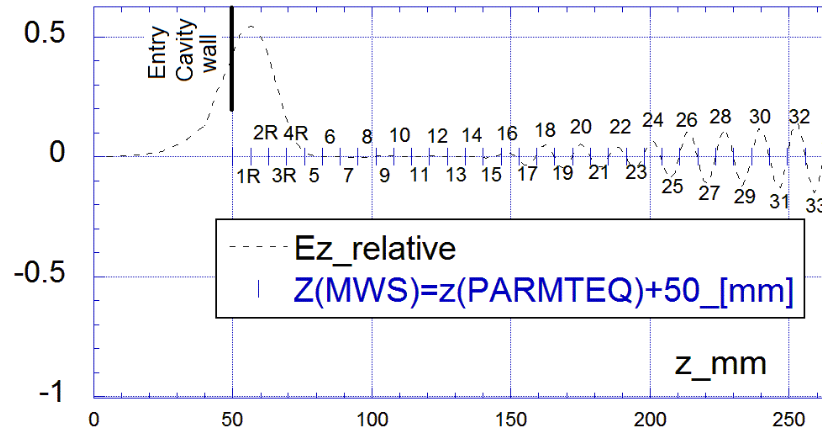
Quite excellent coincidence between real electrode long modulation & design data provided by PARMTEQM (for inside cells)

Transfer from ideal-to-real electrodes

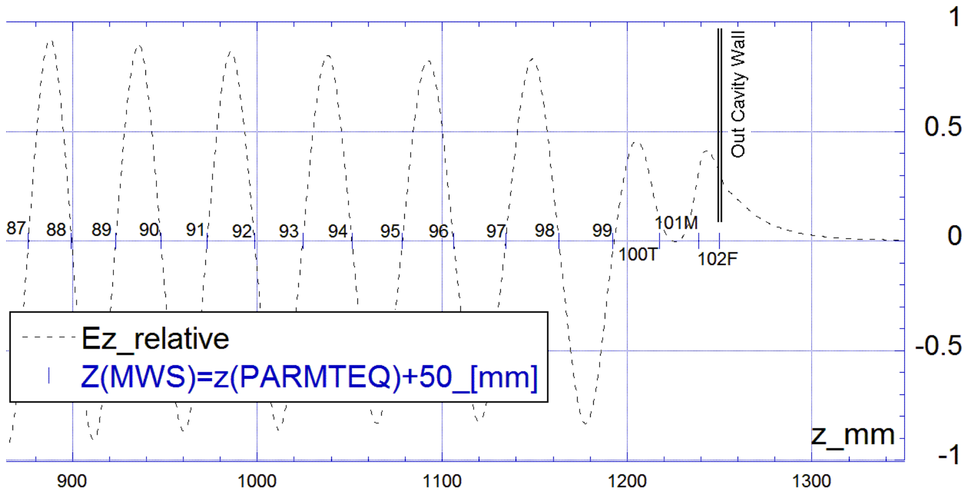
Electrode cut **at entry** – measured gap ~7mm, while simple surface rounding within cells "2R"÷"4R" (RM)

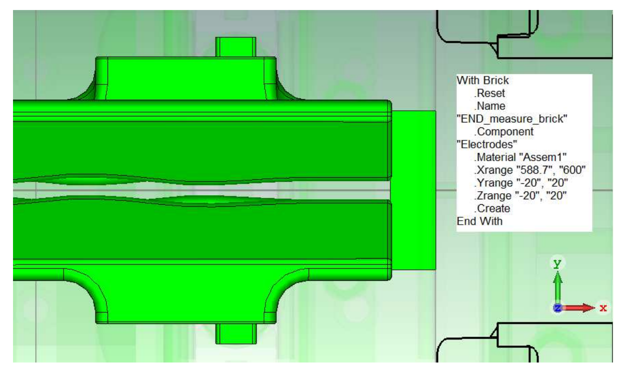


(ejected "1R")



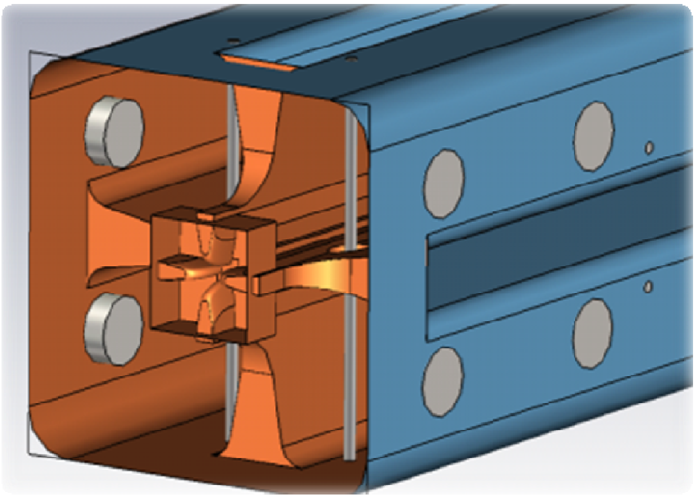
Electrode abrupt cut at exit – measured exit gap ~11.3mm corresponds to cell "102F"



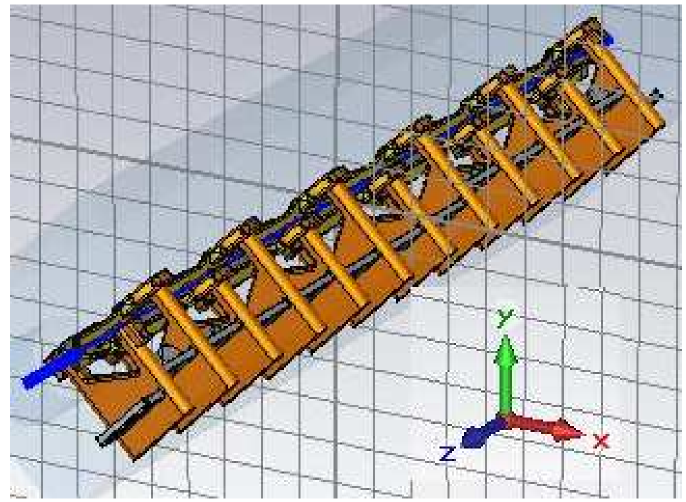


Electrode excitation in RFQ resonators

Symmetric “ideal” quadrupolar electrode feeding in 4-vane RFQ



“Specific” electrode feeding in Schempp’s 4-rod RFQ led to dipole field in regular part field distortions in radial matcher (e.g. Ez)



Since real electrodes differ from ideal it may be interesting to study performances of FNAL RFQ electrodes in an ideally excited structure like 4-vane RFQ (time-varying quadrupolar RF potentials: +V;-V;+V;-V)

Such simulation could be performed as CST PS for RF fields calculated in CST EM Studio project allowing to assign time-varying potentials to electrodes (Electro-quasi-static simulator)

“Dipole-field” & Radial matcher problems

Detailed overview and discussion in APC seminar:
V.Kapin, “Overview of 4-rod RFQs peculiarities”, 4-Apr-2013
https://indico.fnal.gov/event/6375/

“Dipole” problems were recognized from late 1980s:
V.Kapin, in Proc. EPAC, 1994; J.Klabunde et al., in Proc. Linac 1994

Curved Ref. Orbit – sum of const. “beam offset” & “coherent osc.”:
V. Kapin, "A New Analysis of 4-rod RFQ Linac with Intrinsic Field Distortions", Jpn. J. Appl. Phys. Vol.36 pp.2415-2427 (1997).

RM electrode shape suggested for split-coaxial RFQ suits to 4-rod RFQ:
S.Arai, Split Coaxial RFQ, GSI-81-11, 1983
Alternative RM as quarter-wave resonator built in 4-rod RFQ:
V.Kapin, in Proc Linac-1994.

Obvious problem elimination – usage symmetrical structures (e.g. like Split-Coaxial RFQ and other examples presented in my APC-seminar)

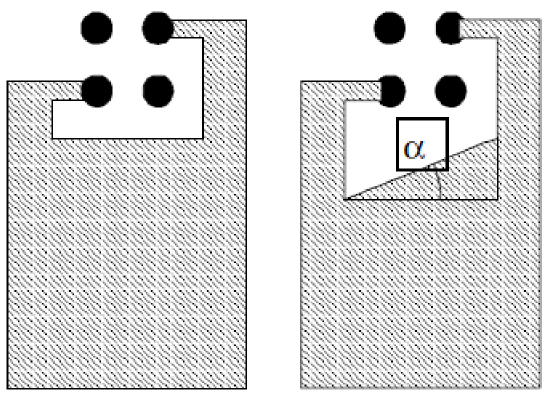
Problem treatments by Schempp's group

Up to now Schempp's 4-rod RFQ:

- Minimization of "dipole field" (since 1995- up to 2010s)
- R-Matcher: a copy of RM electrode geometry used in 4-vane RFQ (ignoring a difference in vane excitation: "0,V" instead of "+V,-V"})

PAC-1995

PAC-1995: Dipole-components of the electrode-voltage can be reduced by shaping the stems with an angle α as shown in fig. 1



PAC-2011

U. Bartz#, A. Schempp, PAC-2011

To reduce the dipole ratio, the stems have a diagonal cut out with a defined angle (Figure 7). This modification becomes more effective for RFQ structures with a higher resonator frequency.

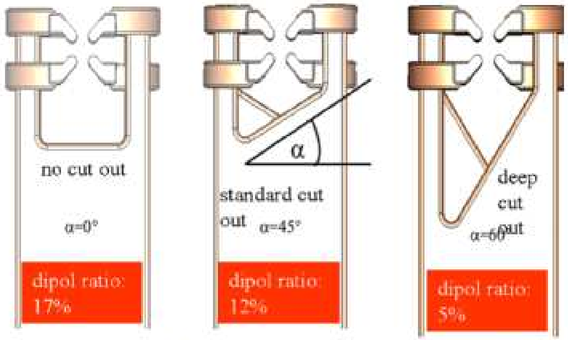


Figure 7: Optimization of the dipole ratio.

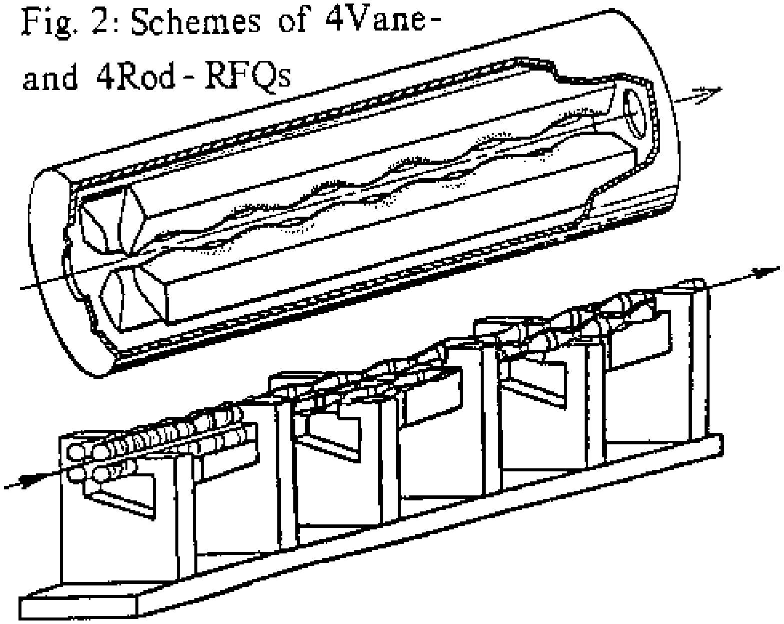
As result by 2012: 4-rod RFQ for FNAL has voltage amplitude between neighboring electrodes in 4 quadrants: 1.26; 1.54; 1.27; 0.97 => considerable dipole fields!!!

4-rod vs 4-vane: Schempp's tests in 1988

PERFORMANCE OF THE DESY RFQs **EPAC-88** 587

A. Schempp, M. Ferch,* P. Schastok,** H. Klein,
Institut für Angewandte Physik, J.W.Goethe Universität, 6000 Frankfurt/M11, FRG

Fig. 2: Schemes of 4Vane- and 4Rod-RFQs



4Rod RFQ, the maximum H^-current 36 mA
4Vane RFQ maximum current 43 mA

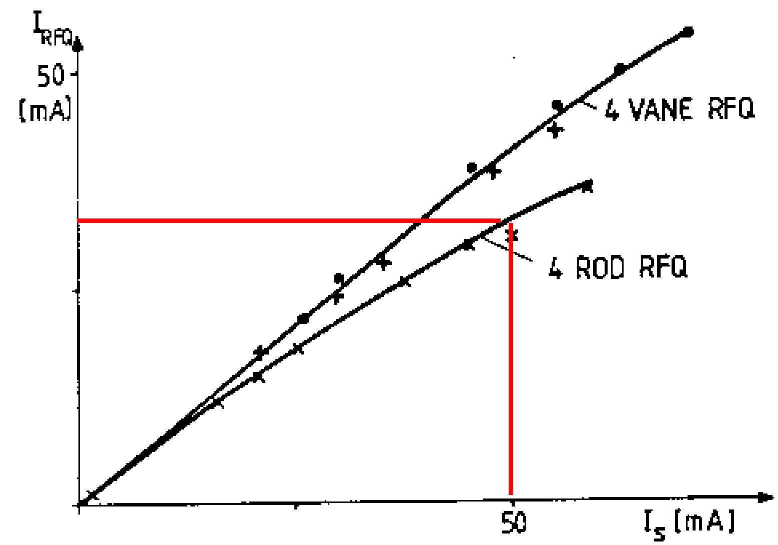


Fig. 7: RFQ output current I_{RFQ} as function of Ion source current

Two RFQs have been built as injectors for the 50 MeV H^--Linac for the HERA project at DESY. A 4-Vane RFQ as well as a 4 Rod RFQ deliver 750 keV H^- The RFQ design is summarized by: input energy 18keV, output energy 750keV, total length 118 cm, frequency 202.56 MHz, inter vane voltage 70.5 kV, beam current 20 mA ,

Approaches for Transmission Improvement in FNAL RFQ Injection Line (see Tan's formulations)

Possible sources of transmission degradation:
either *physical degradation* of components or wrong *tuning-matching* procedures could not reach original parameters

- Physical degradation (test either visually or measure parameters on bench): spare quads, solenoids, buncher, and RFQ (!)
- Wrong tuning-matching procedures due to changed conditions (some of parameters are out of original range, e.g. LEBT beam depends on parameters including ion source regimes, vacuum conditions etc.)

In the latter case there is need to understand details of beam losses and consider a possibility to re-utilize lost beam improving/optimizing operating conditions in MEBT (& LEBT)
=>Realistic simulations in real fields for all components (RFQ, quadrupoles, buncher)

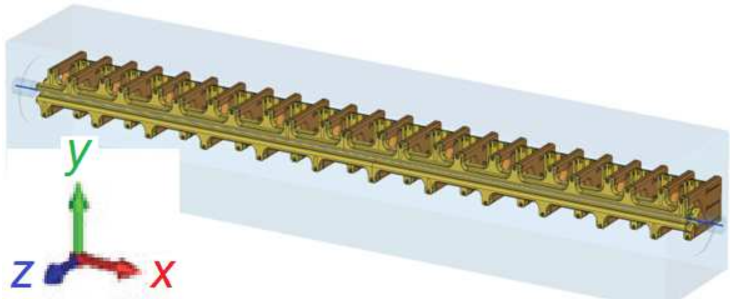
Choice of simulation tools for problem resolving

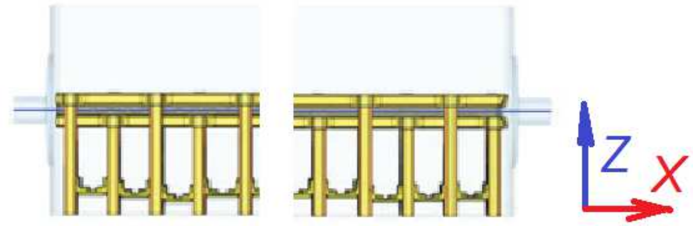
- Trace-2D/3D for linear matching in LEBT/MEBT
- PARMILA (old) – multi-particle tracking in MEBT/DTL and calculate accepances of DTL (a “target”-value for linear matching with Trace)
- Due to an increase beam size after RFQ & bell-shape fields in magnets => need for tracking in real fields =>
  ready for usage code is the Particle Studio (PIC-solver) of CST

- Details for CST simulation for FNAL 4-rod RFQ in LANL:
  [4] S.Kurennoy, “MWS E/M fields”report LA-UR-12-26388(2012);
- [5] S.Kurennoy, “Beam Dynamics” report LA-UR-13-21653(2013);
- E/M fileds by MWS -> import to Particle Studio;
- Initial particle distribution by PARMILA2 converted to *.pit of PS
- Since PS – is not specialized beam dynamics code, it no built-in diagnostics; then convert *.pit at RFQ exit to PARMILA format
- Time consuming (order ~24hrs for one RFQ pass at TD-server), license for PIC is busy frequently; => very restricted simul. conditions

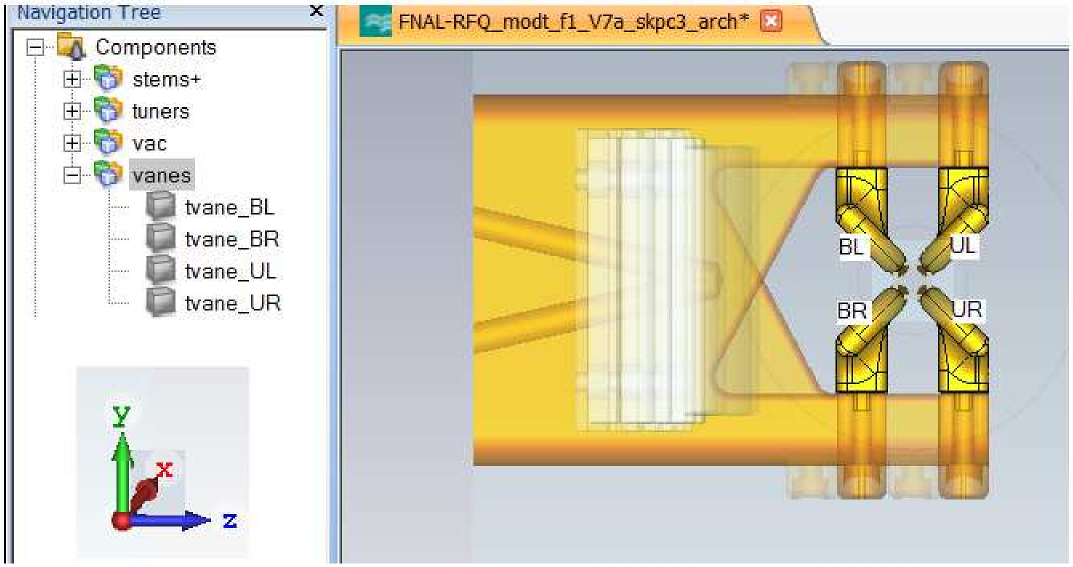
Kurennoy's CST model for FNAL 4-rod RFQ

Manufacturer (Kress GmbH) CAD models of FNAL 4-rod RFQs was imported in CST.



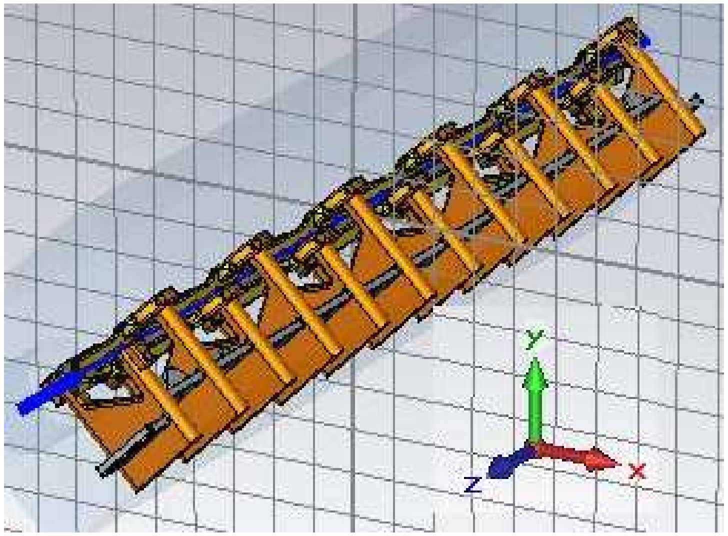


model C (configuration with new thin vanes) - with different beam pipes UpS= {∅31.75; L=50}mm and DnS= {∅100; L=100}mm attached to the RFQ cavity;
L"C"model=50+1200+100=1350mm



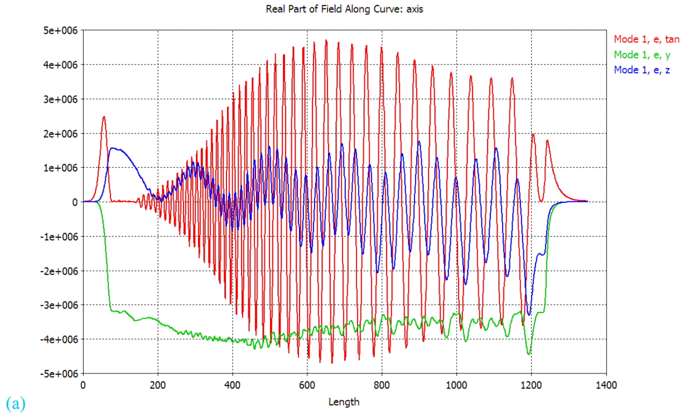
Preparation of 4-rod RFQ model

Model has been **rotated** to adjust to FNAL Linac Coordinates to exclude a need for coordinate Rotations in Injection Line simulations

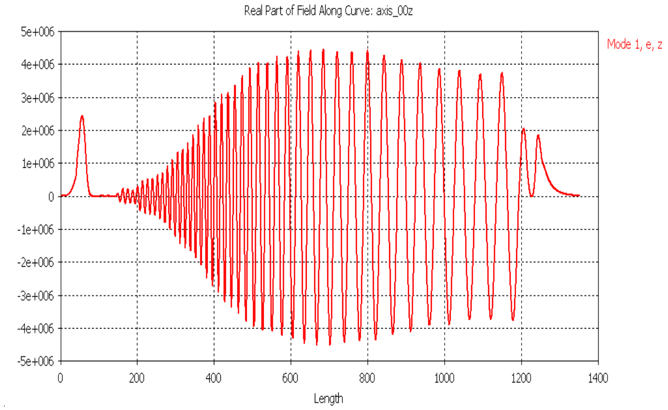


Field amplitude for CST model has been Adjusted to nominal electrode voltage U=72kV

Fields in Kurennoy report [4]

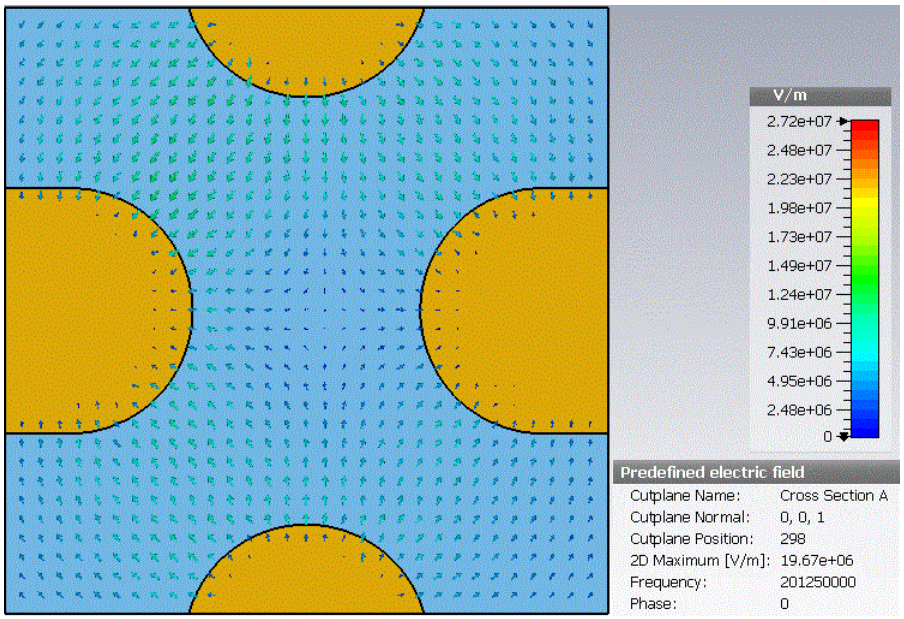


Ez in rotated model

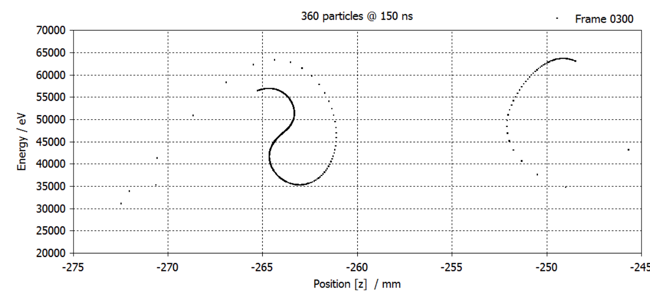


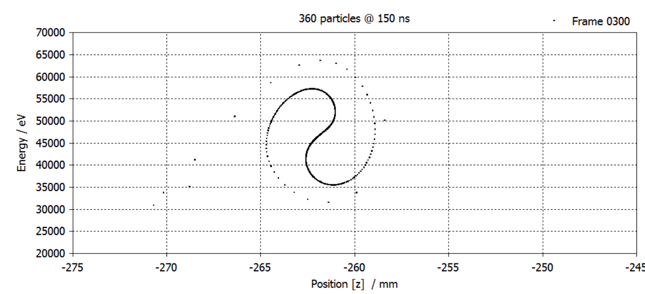
Preparation of 4-rod RFQ model (continued)

Fields has been exported to PS.
Example for z=297mm (end cel90);



RF phase for imported fields has been Adjusted with injected beam having 360deg. Extend: before/after



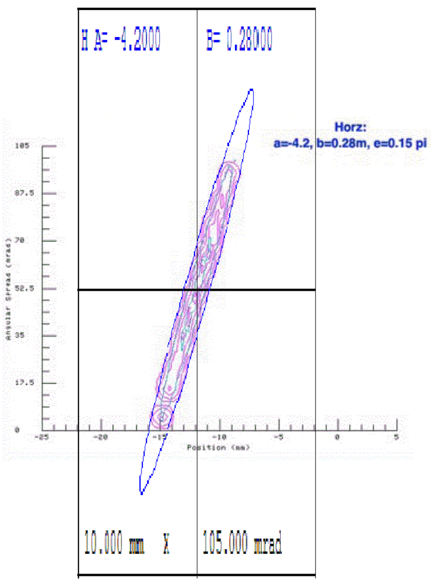


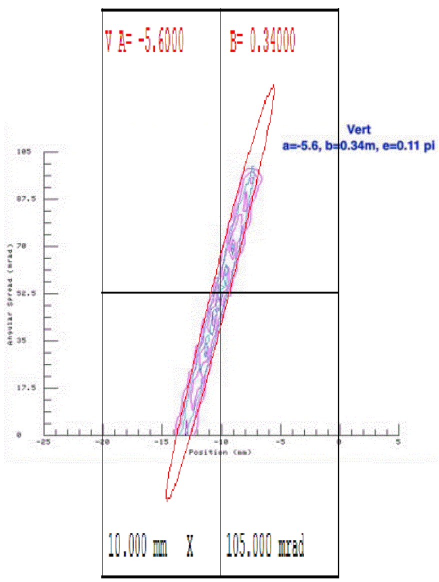
CST allows extended aperture in comparison with PARMTEQM (not as circle/rectangular inscribed within pole tips)

Input beams: Measured traced to CST model entry

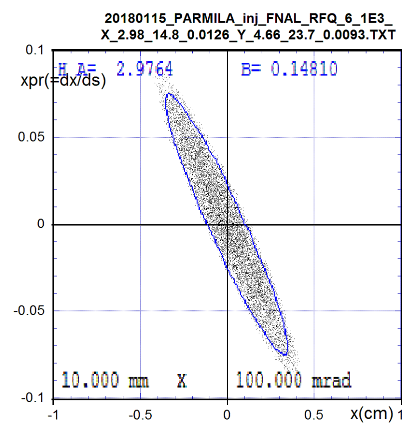
Measured emittances has been traced to RFQ model entrance with TRACE-3D. Then, for the obtained TWISS parameters PARMILA generated distribution

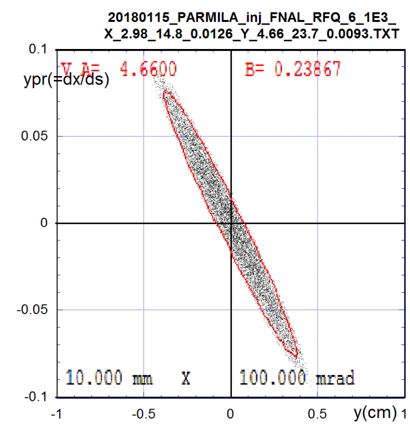
Original measured emittances overlapped with TRACE-2D ellipces at emitt. probe





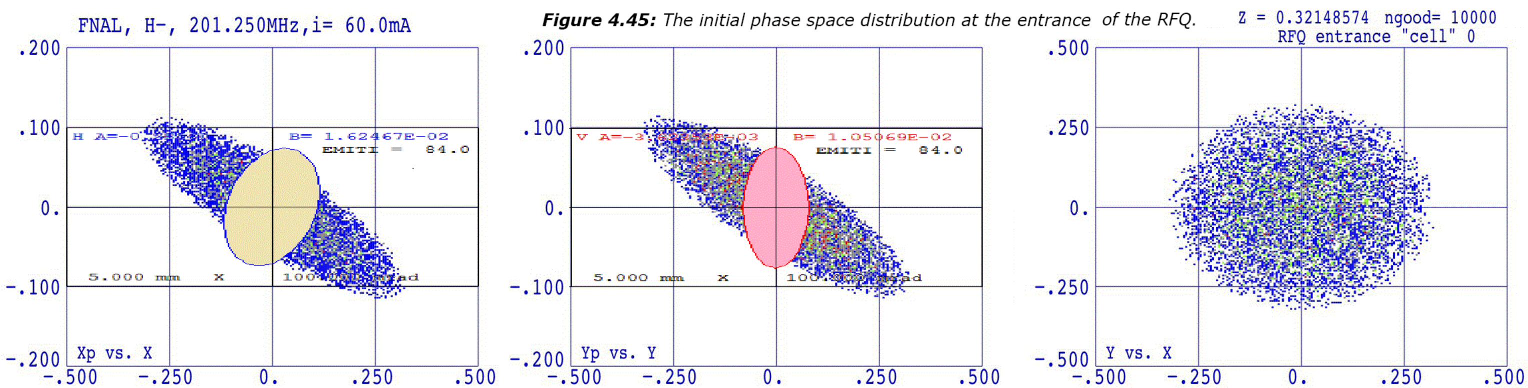
PARMILA distribution overlapped with Trace 2D emittances of measured emittances at entry MWS model



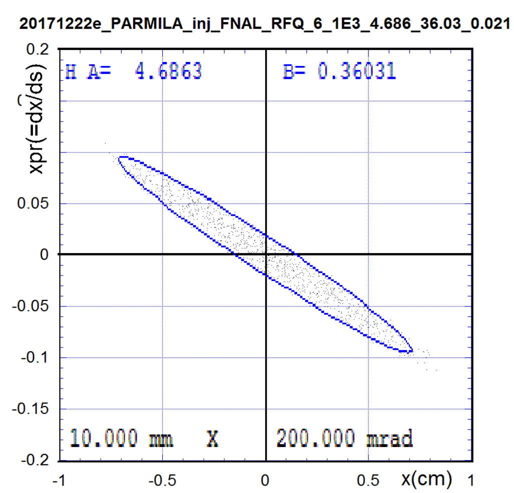


Input beams: ParmteqM (manufacturer) to CST entry

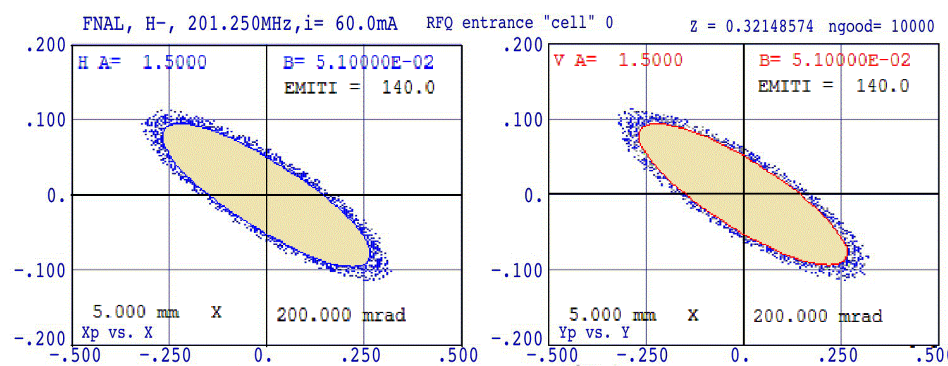
Comparison of Trace-2D ellipses for measured emittances with manufacturer distribution used for PARMTEQM simulations



PARMILA generated distribution overlapped with Trace 2D emittances for of "ParmteqM" (manufact) distribution

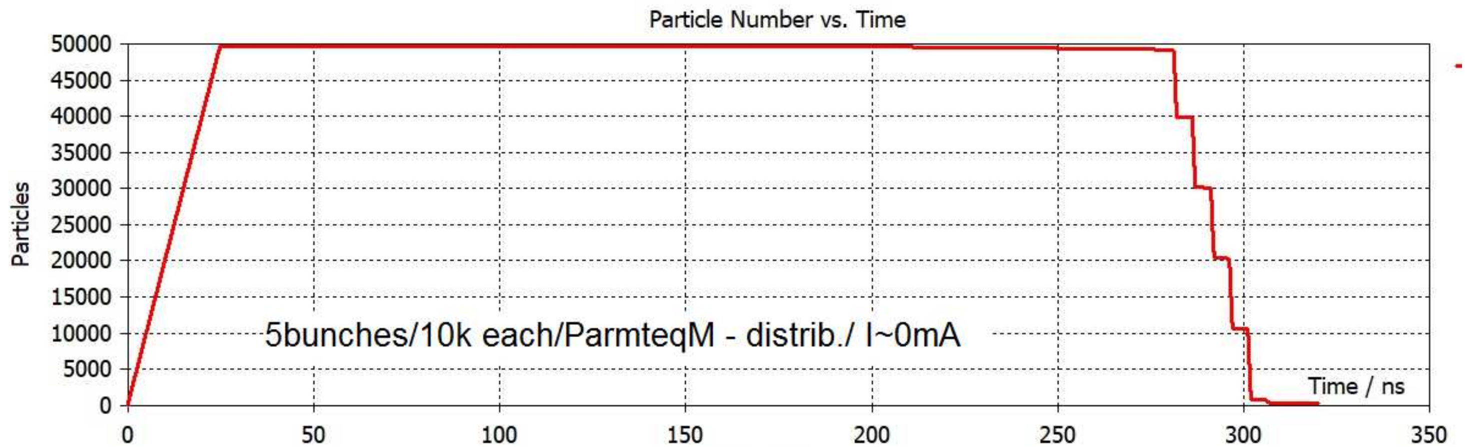


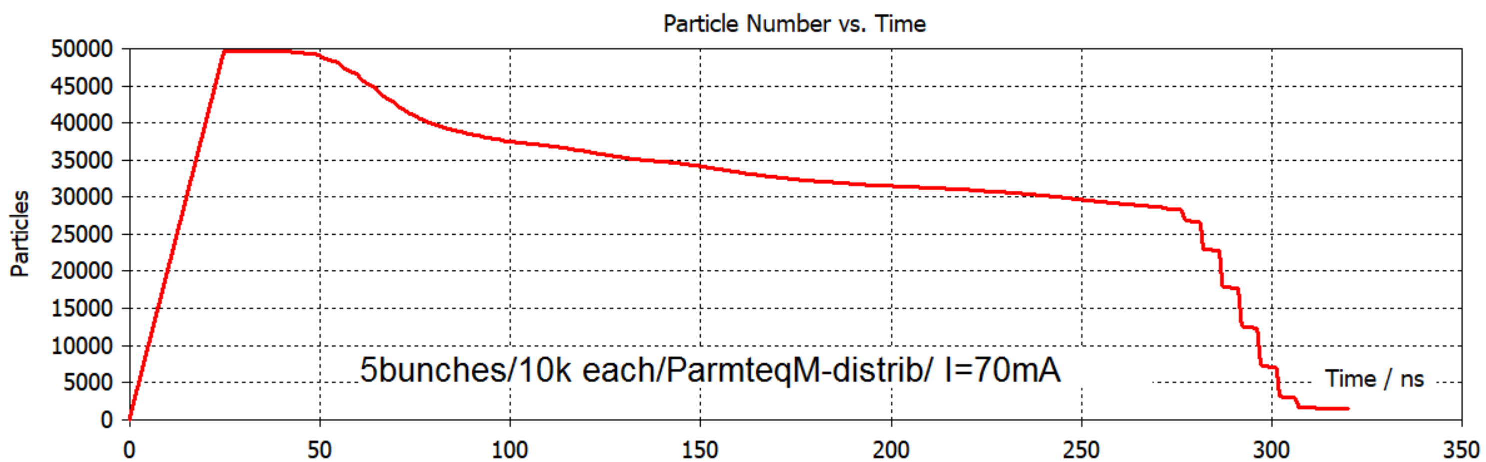
Original ParmteqM distribution overlaped with Trace2D ellipces



5-bunch trains are used for non-zero beam currents

Total number of particles in structure for ParmteqM (manufacturer) distribution during simulations for I=0 (upper plot) & 70mA (bottom plot)

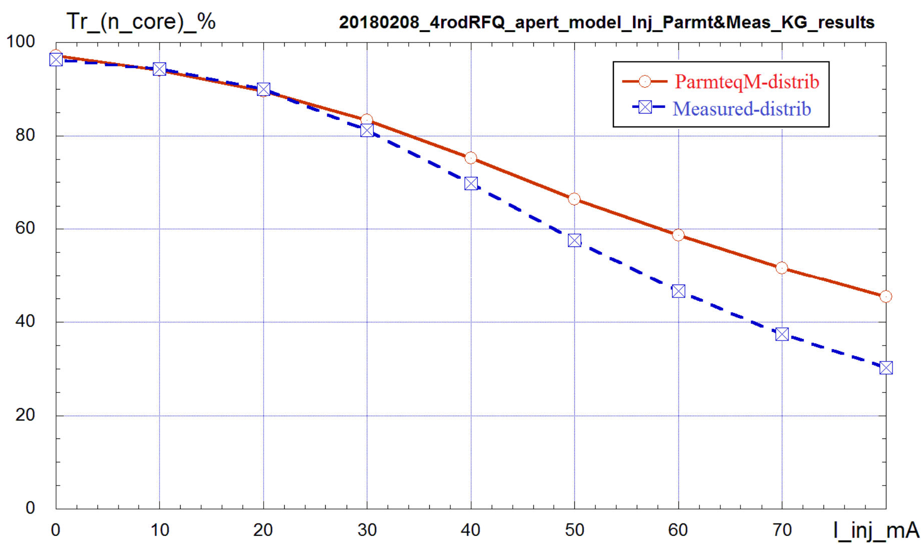




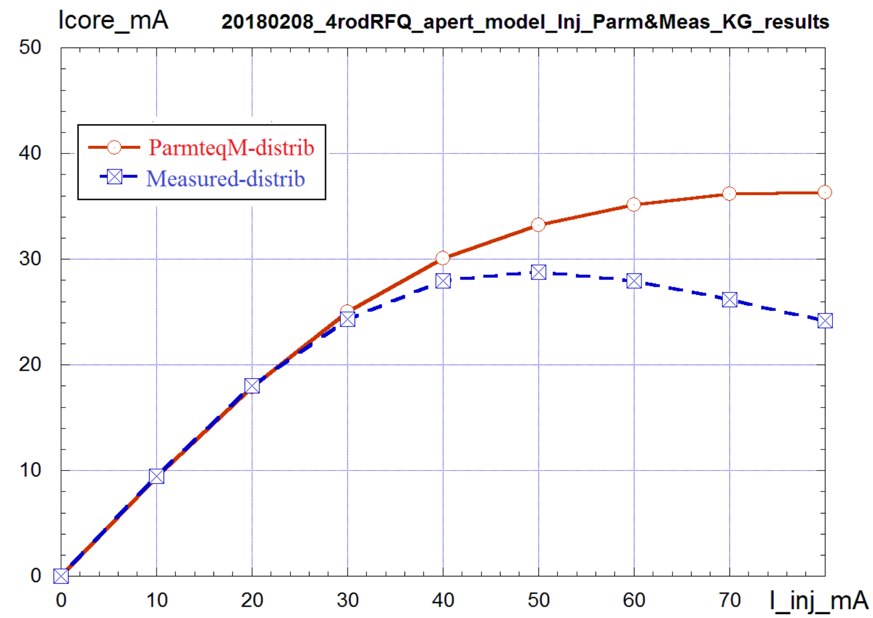
We use the 3-rd bunch for export to next external code (e.g. PARMILA)

Simulation of RFQ parameters vs I injected beam

Use 2 distributions: ParmteqM (manufacturer) as a matched large emittance; Measured emittance as a mismatched small emittance beam



Results obtained after post-processing CST *.pit files at RFQ exit to PARMILA format



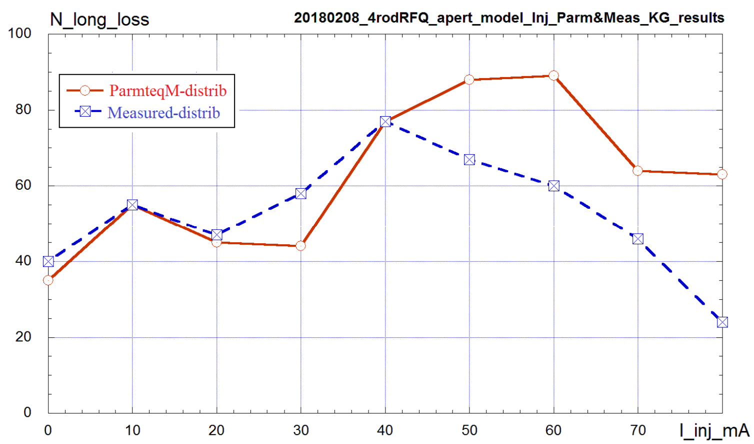
For nominal beam current inj=60mA:
a) ParmteqM (manufacturer) distribution – 35mA at RFQ exit (60%);
b) Measured distribution – 28mA (45%)

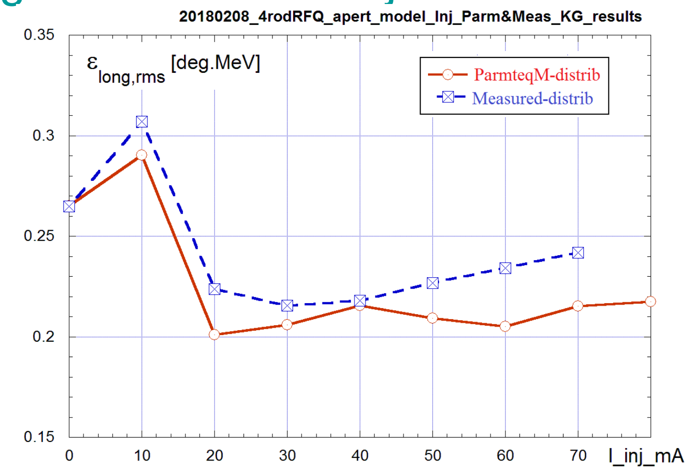
Most parameters are worse in comparison to the ideal ParmteqM simulation

One point of plots ~24hrs !!!

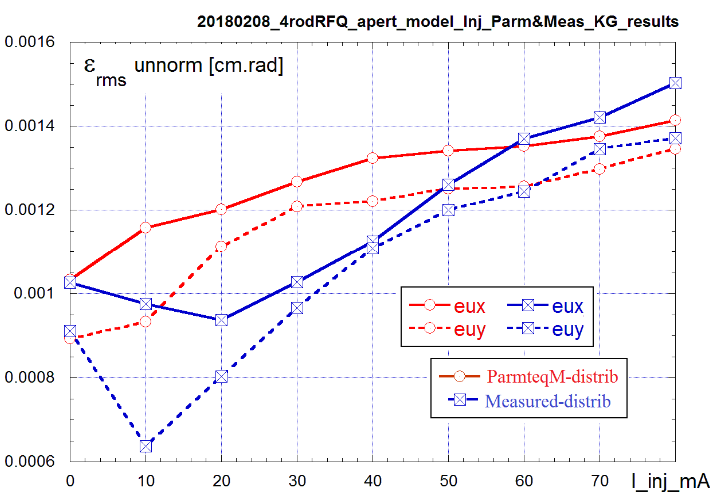
Another parameters vs I injected beam

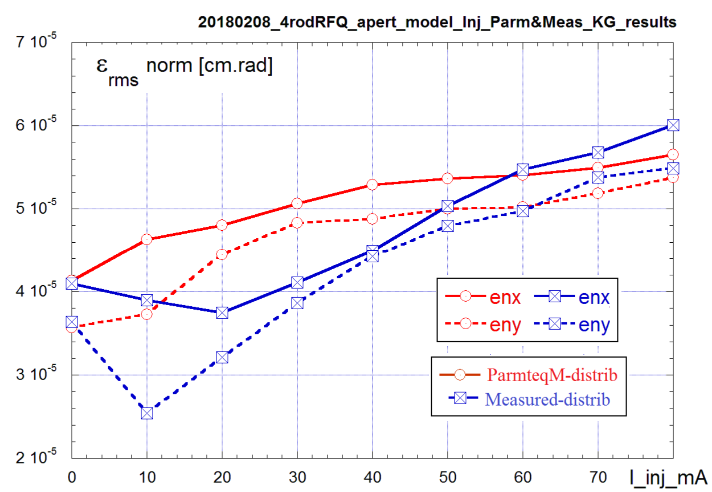
“Longitudinal” Losses (energy < 700keV) & long emittance vs I inj





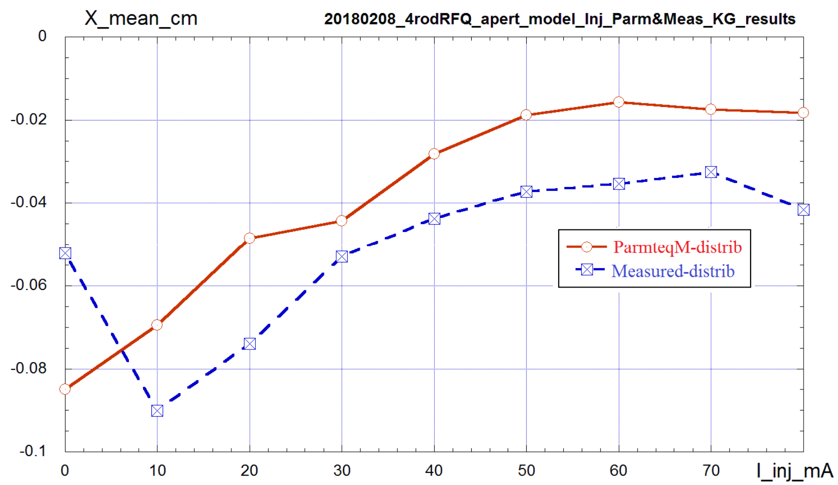
Transverse unnormalized and normalized emittances

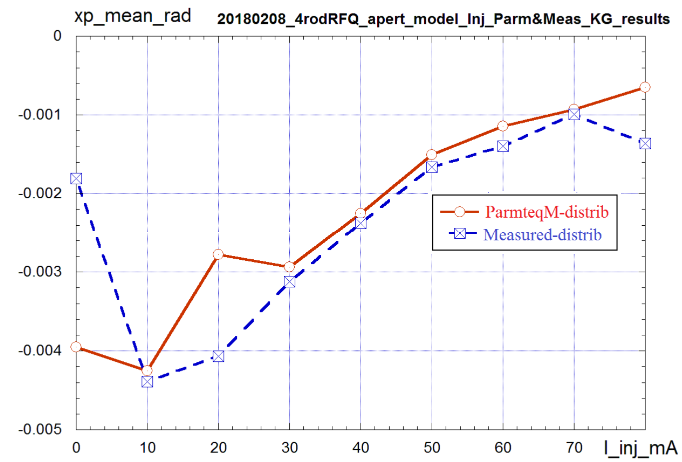




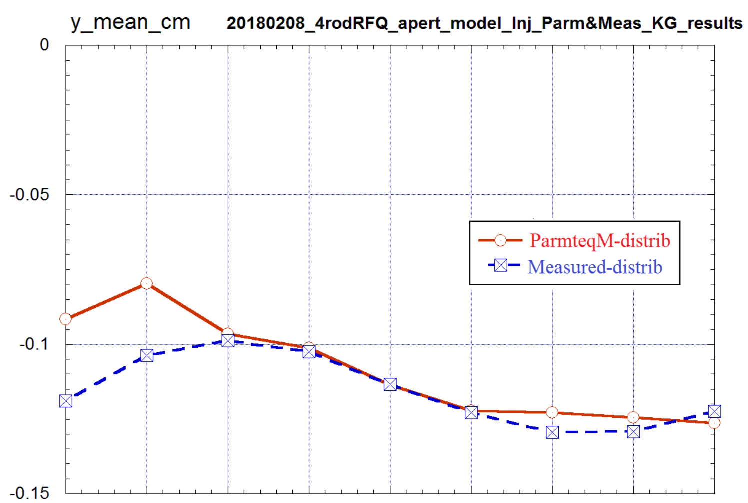
Another parameters vs I injected beam

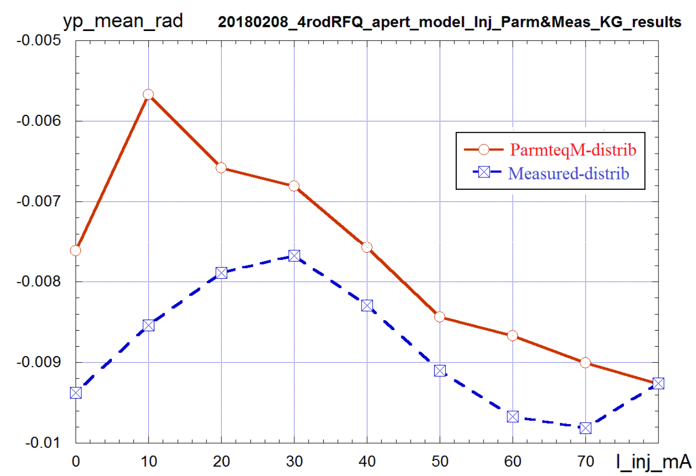
Beam average position and angle in X-plane vs I inj





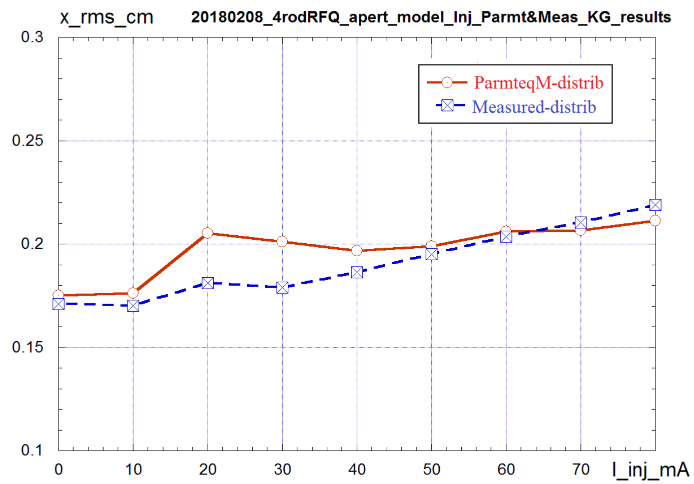
Beam average position and angle in Y-plane vs I inj

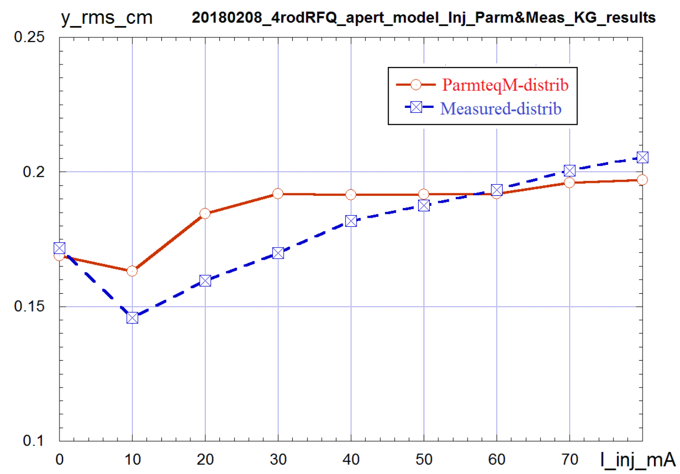




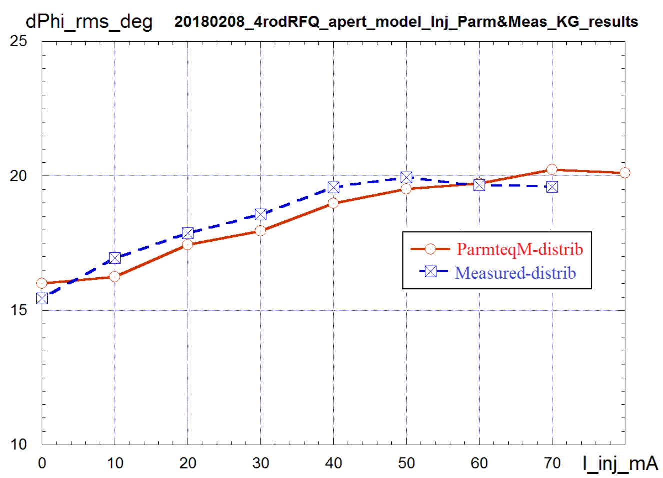
Another parameters vs I injected beam

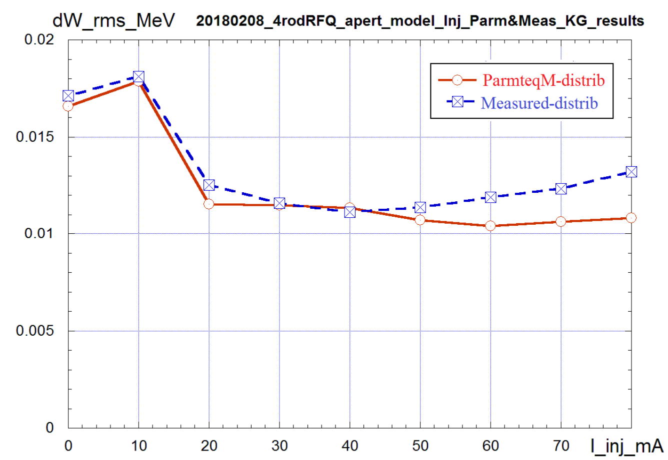
Beam RMS sizes vs I inj for X and Y planes





Beam RMS sizes vs I inj for Phi and W coordinates



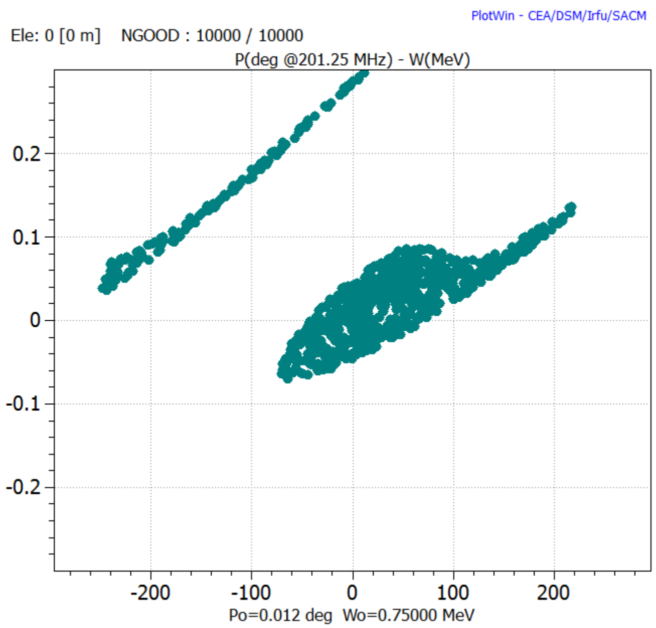


On-going simulations and tasks

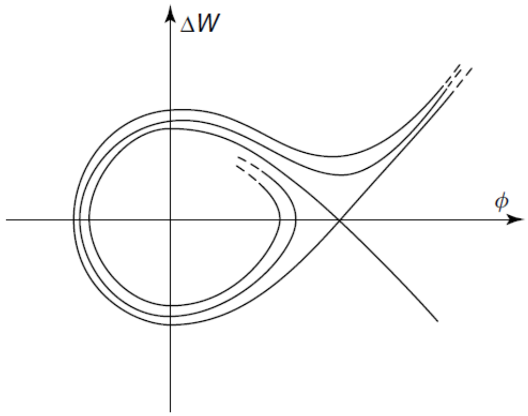
- MEBT simulations Trace-3D for ideal fields
- DTL acceptance from old PARMILA model (parts IDs !)
- Multi-particle simulations in MEBT with old PARMILA with parameters derived by TRACE-3D
- CST model for real fields in MEBT and tracking
- ideal excitation of existing thick electrodes to complete plots vs Iinj for both matched & mismatched beams:
  a) ideal electrodes & ideal RF voltages (ParmteqM)
  b) real electrodes & ideal RF voltages (CST EM/PS)
  c) real electrodes & real RF voltages (CST MWS/PS)
- implement a new notch aperture (rerun some results)

On-going: previous FNAL DTL studies by VK

- V. Kapin, " Status of Low-Energy Linac Lattice Update" /Talk given on 13 Feb. 2013 PIP general meeting/, Beams-doc-4293-v1 (works with old PARMILA)
- V. Kapin, "TraceWin Lattice for FNAL Drift-Tube Linac: Status", talk on 30-Jul-2014 at PIP General Meeting, 2014, Beams-doc-4646-v1



2014 - TraceWin

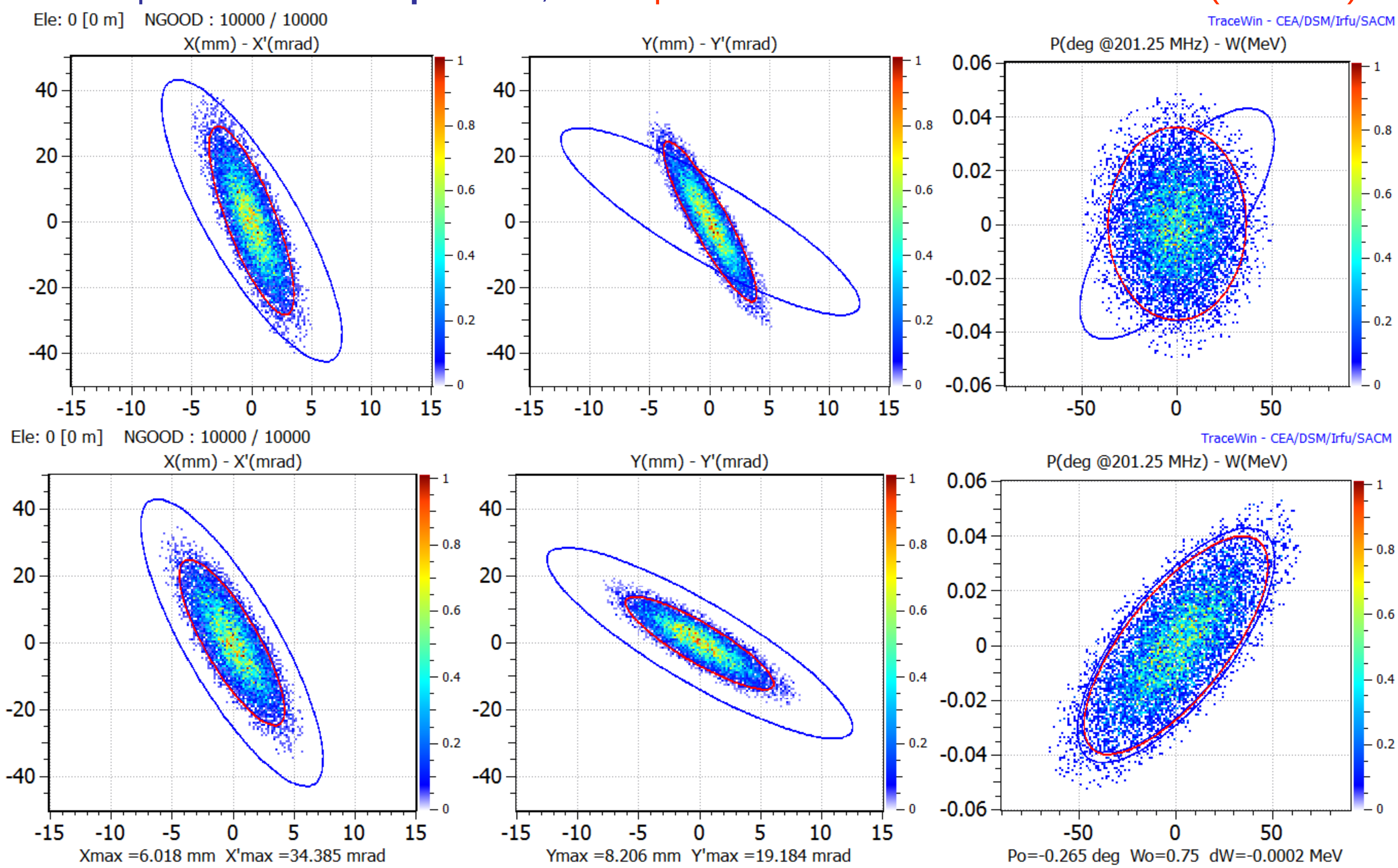


Wangler-2008, p.183

Figure 6.5 Longitudinal phase-space trajectories when acceleration is taken into account. The separatrix shape is called the *golf club*.

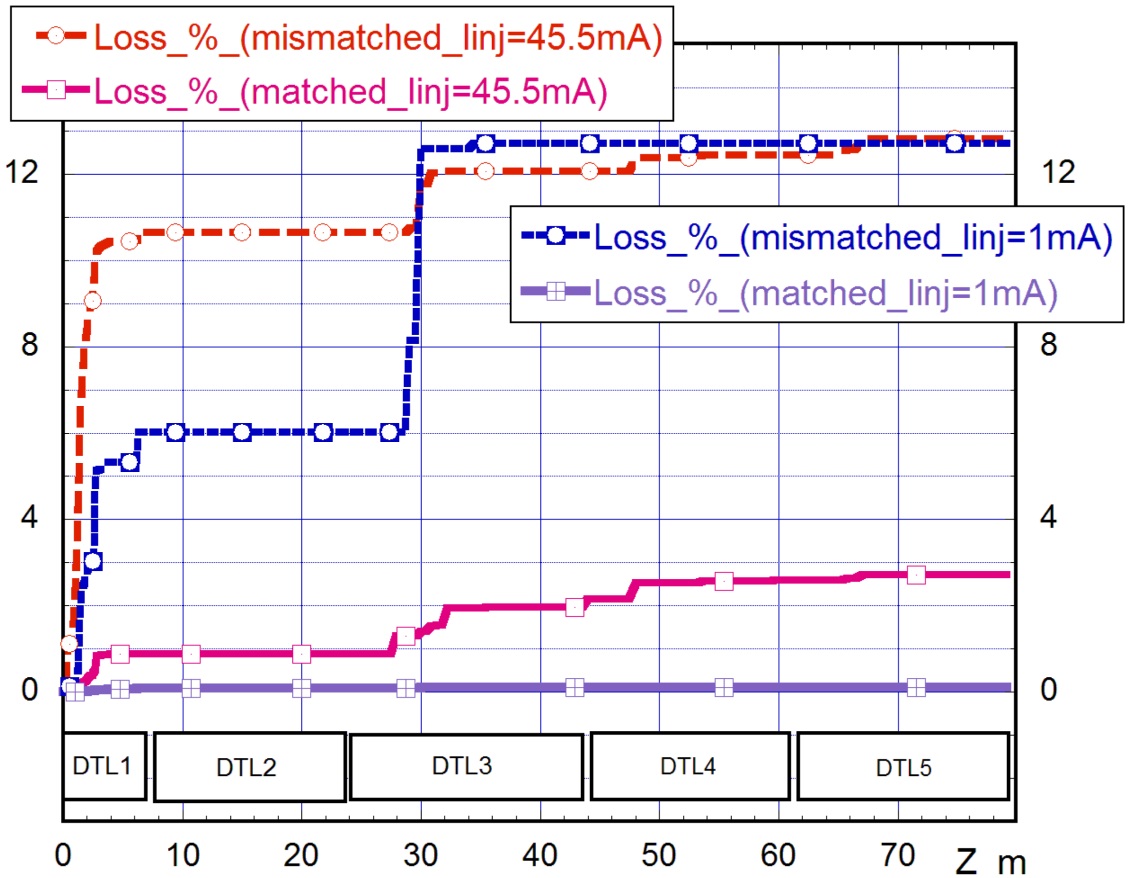
On-going: mismatched vs matched beam to DTL

Blue ellipses - DTLs **acceptances**; red elipses: Total 5-rms beam Emittances (unnorm.)



2014 - TraceWin

Losses %: matched vs mismatched (I_{inj}=1mA& 45mA)

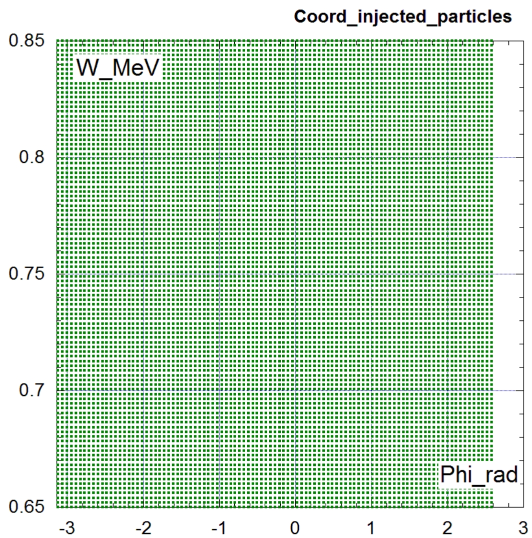


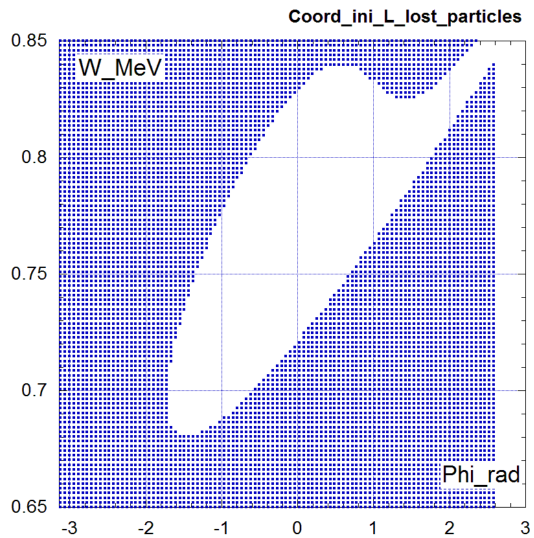
2014 - TraceWin

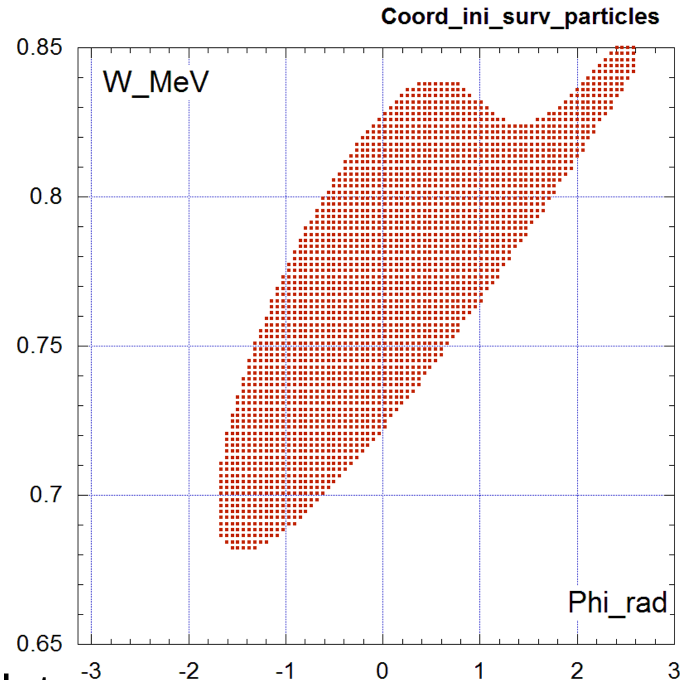
Also slides for an increased **acceptances** for smoothed quadrupole strength along DTL *G*(*n*q)

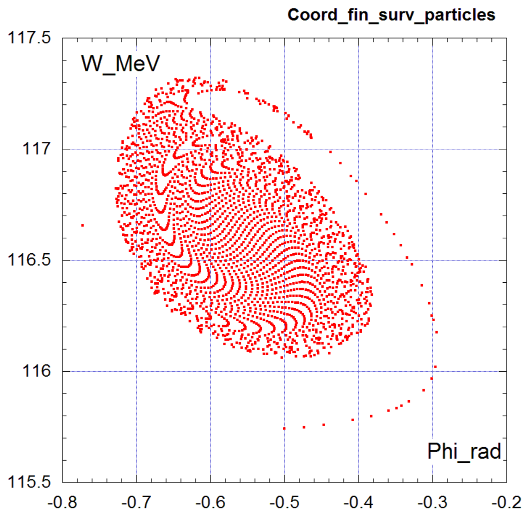
On-going: DTL L-acceptance from old PARMILA

I beam=0, x=y=0, xp=yp=0





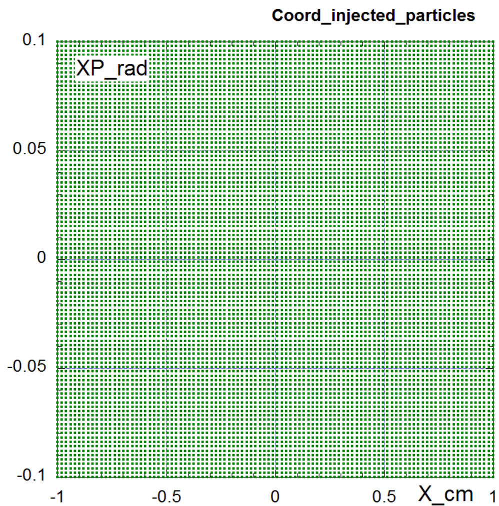


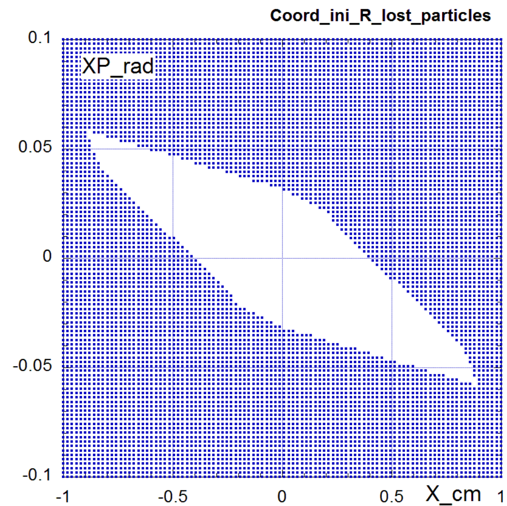


Adapt Parmila to calculate
L-acceptance parameters at injection (survived):

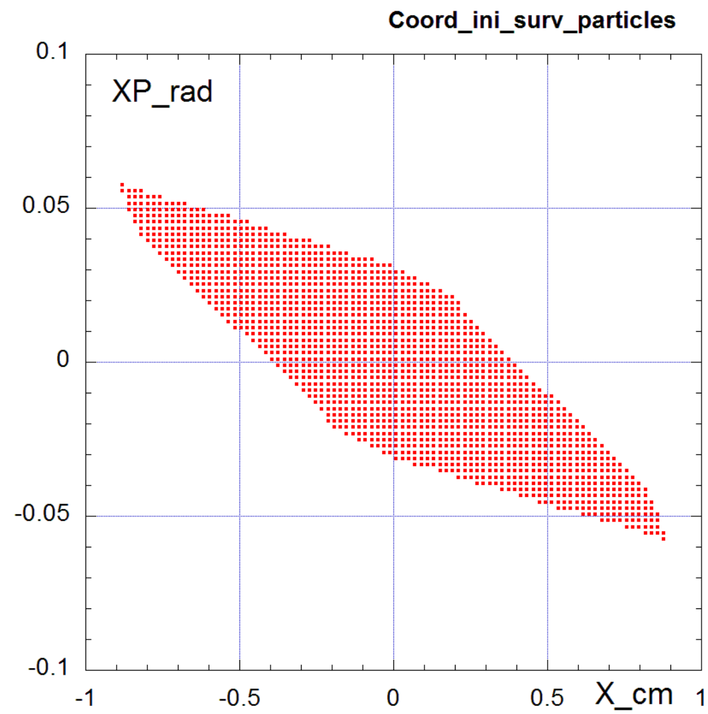
Phi_mean_deg = 4.168 [deg]
W_mean_MeV = 0. 770[MeV]
sigma_dPhi_deg = 55.8 [deg]
sigma_dW_MeV = 0.041 [MeV]

On-going: DTL X-acceptance from old PARMILA





I=0, y=0, yp=0, PhiS, W=0.75MeV



X-acceptance parameters at injection:

Phi_mean_deg = - 32 [deg];

W_mean_MeV = 0. 750[MeV];

sigma_x_cm = 0.406 [cm];

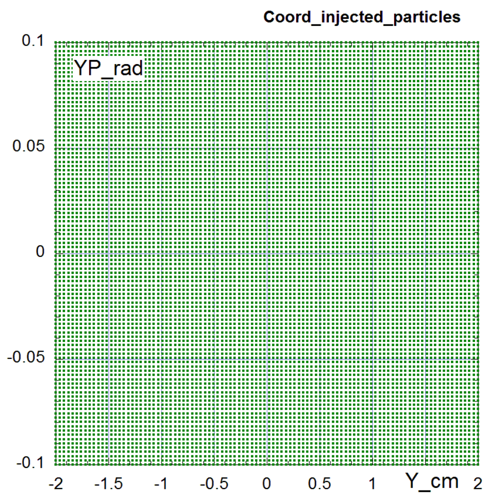
sigma_xp_rad = 0.027 [rad]

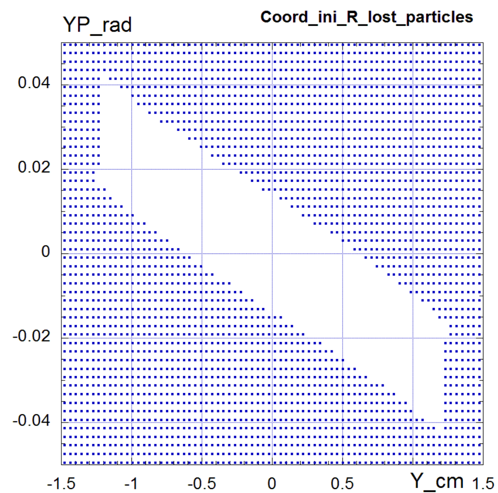
ex_rms_un_cm_rad = 5.758E-03 [cm.rad];

ex_rms_norm_cm_rad = 230E-06 [cm.rad]

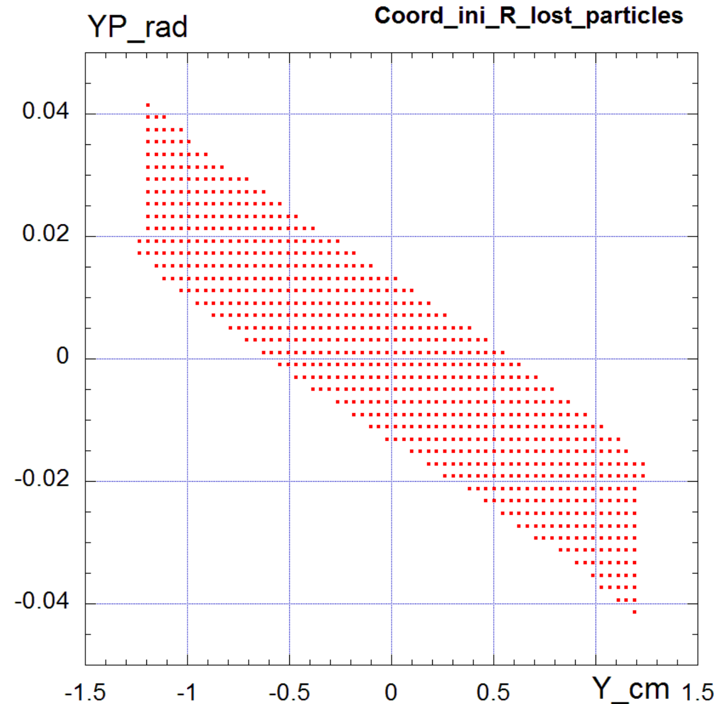
beta_x_cm = 28.732E+00 [cm]; alfa_x = 1.611[-]

On-going: DTL Y-acceptance from old PARMILA





I=0, x=0, xp=0, PhiS, W=0.75MeV

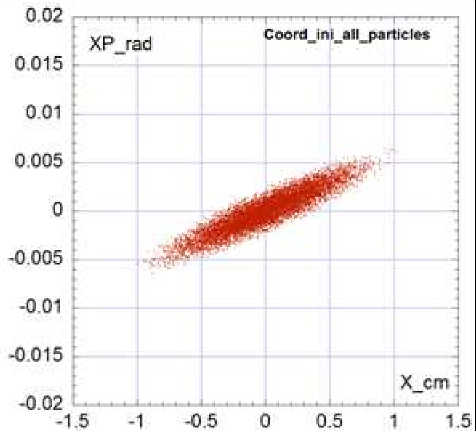
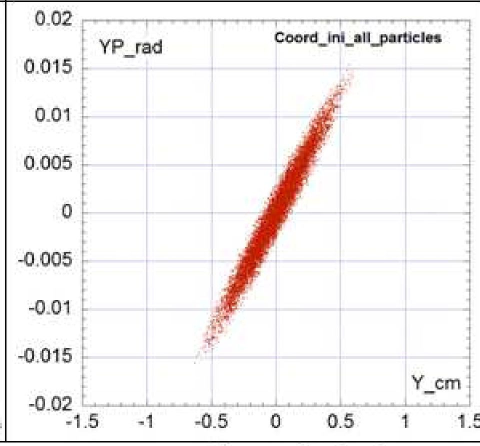
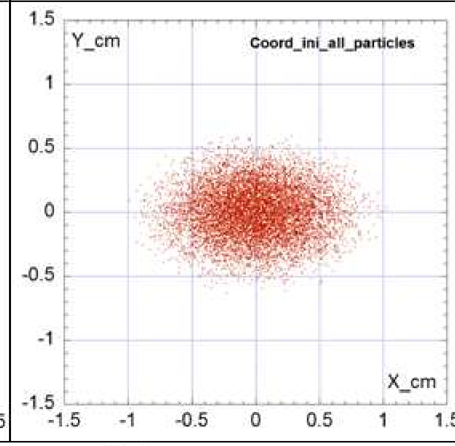
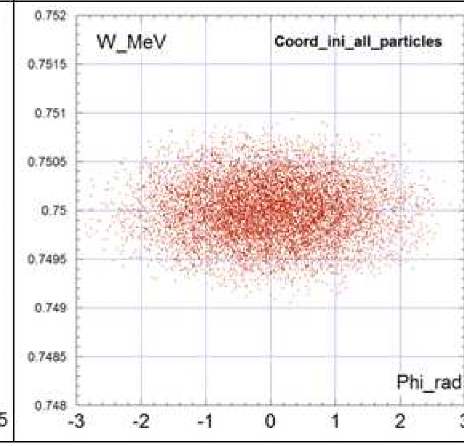
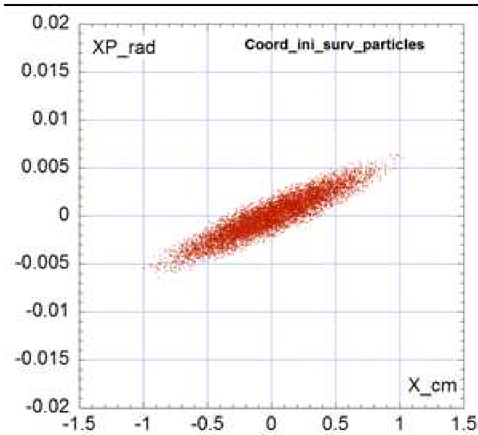
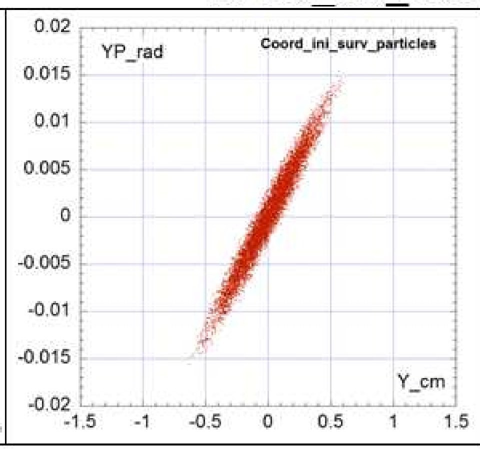
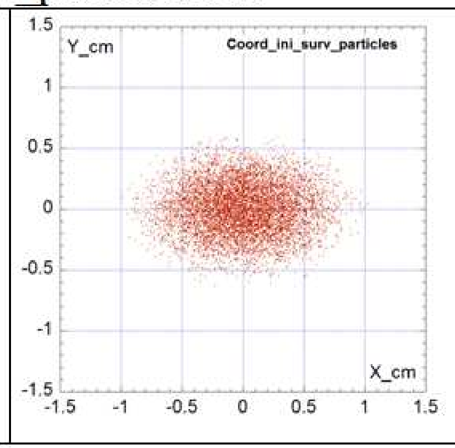
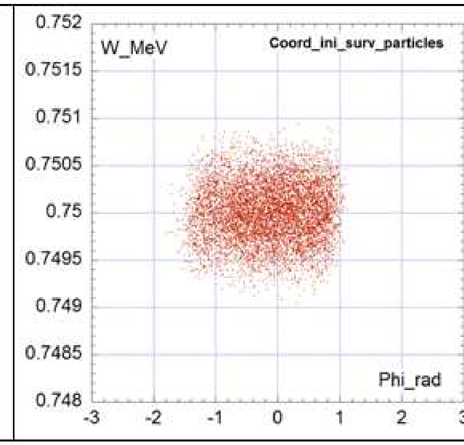


Y-acceptance parameters at injection:

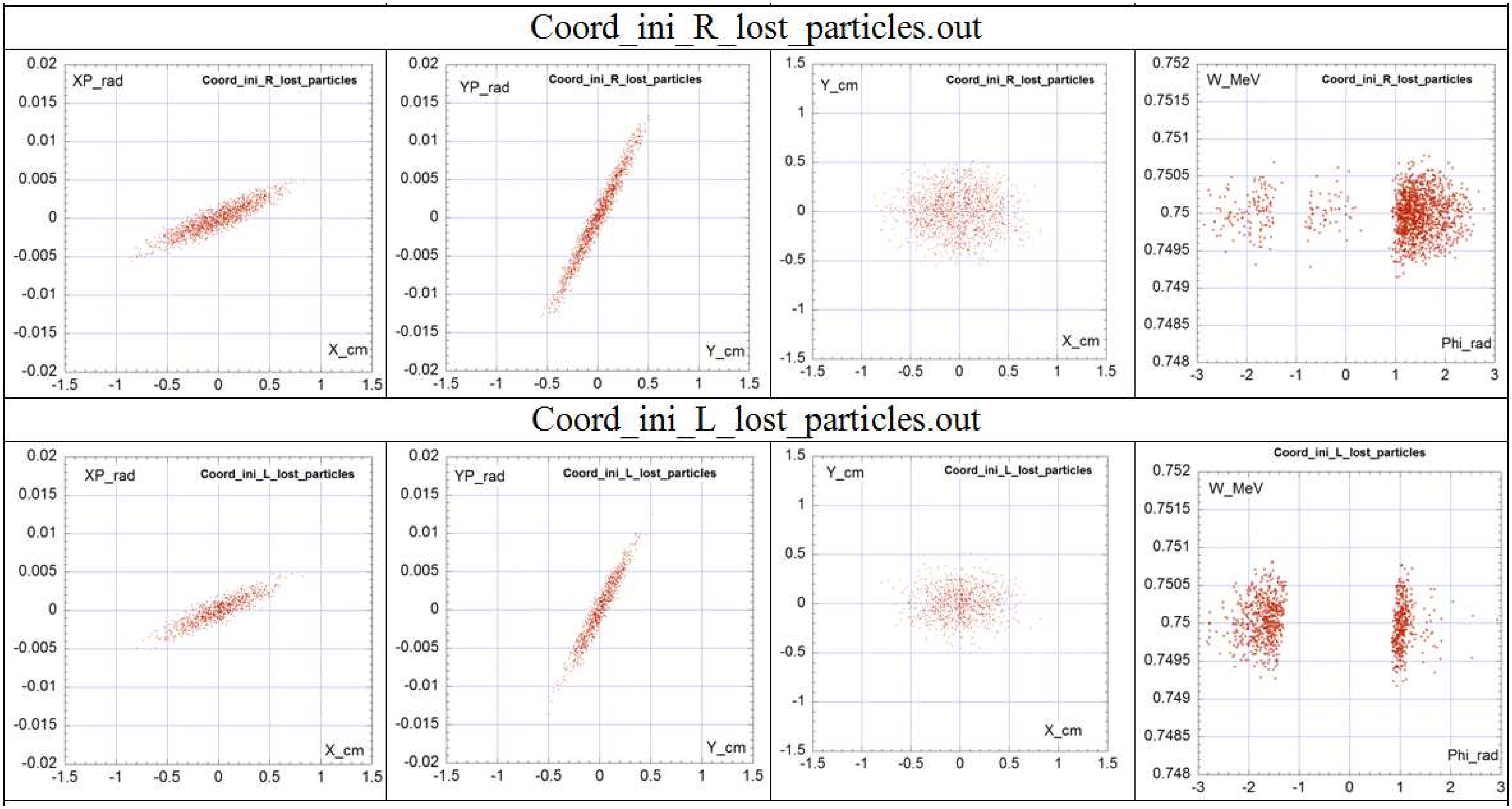
Phi_mean_deg = - 32 [deg];
W_mean_MeV = 0. 750[MeV];
sigma_y_cm = 0.701 [cm];
sigma_xp_rad = 0.018 [rad]
ey_rms_un_cm_rad = 5.484E-03 [cm.rad];
ey_rms_norm_cm_rad = 219E-06 [cm.rad]
beta_y_cm = 89.5 [cm]; alfa_x = 2.059[-]

Beta & alfa => Ellipse
=> Reduce Emitance till
Minimal losses =>
Ellipse (“target”-function) for
TRACE 3D at MEBT exit

PARMILA feature for losses analysis

Coord_ini_all_particles.out			
X-X'	Y-Y'	X-Y	Phi-W
			
Coord_ini_surv_particles.out			
			

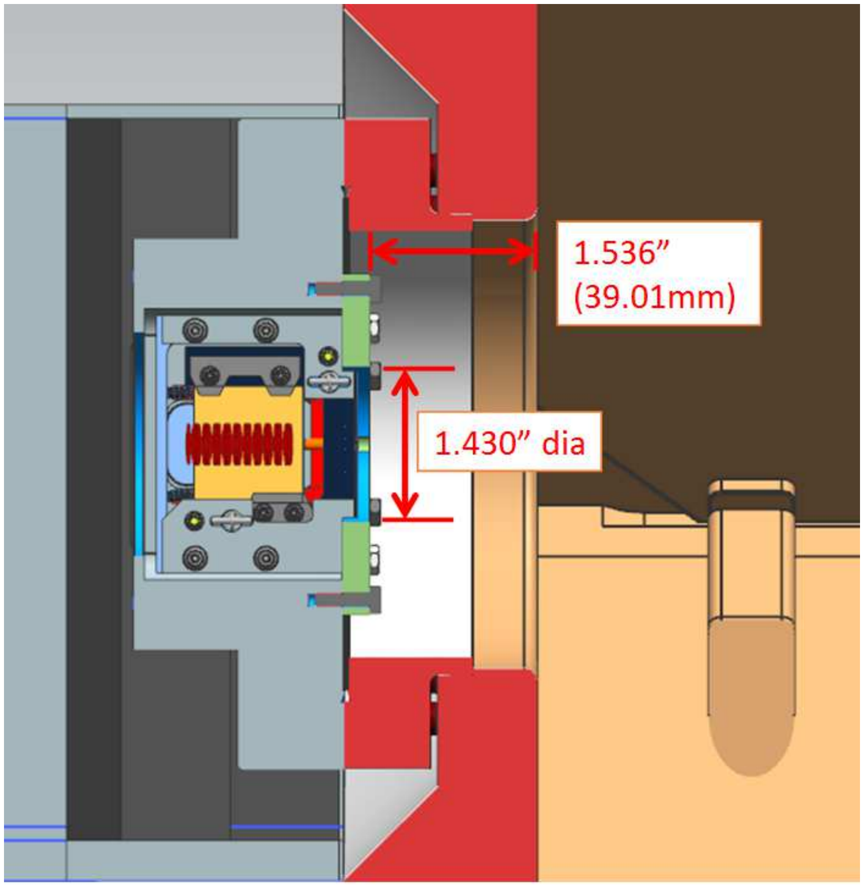
PARMILA feature: R & L losses



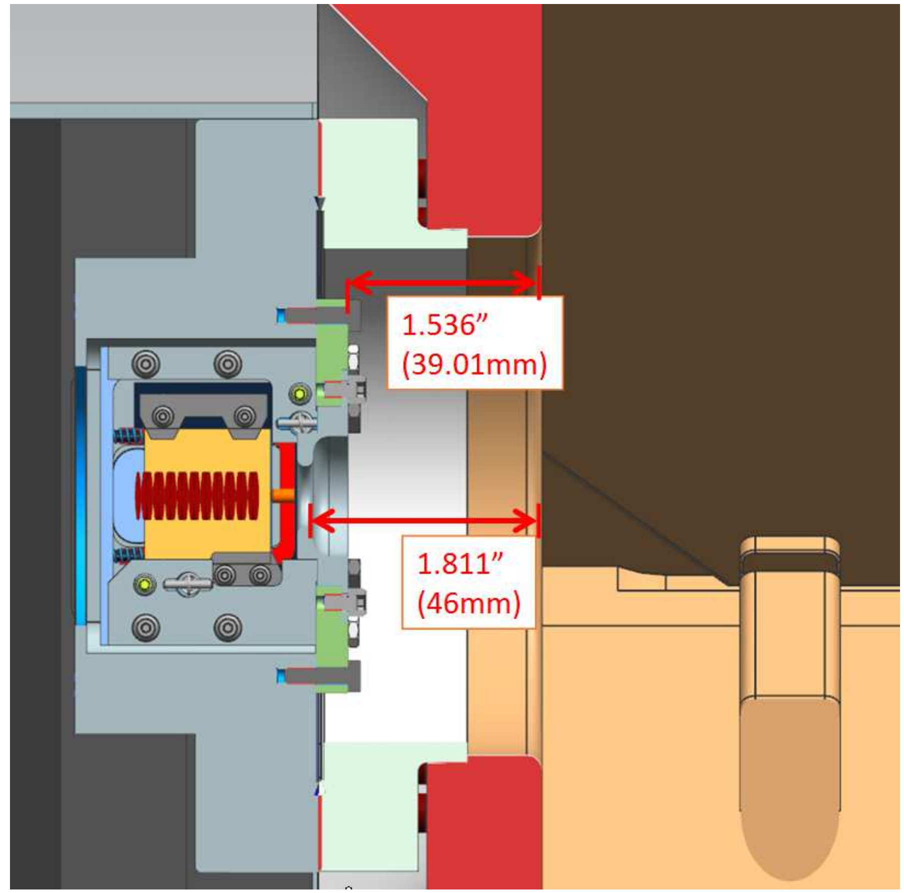
Location of lost particles (for R & L –collimation)

New Laser Notcher Aperture (drawing by Kevin Duel)

Notcher was installed
~ in summer of 2014



New diaphragm with i.d. 12mm has
been installed recently (Feb of 2018)



The notcher is inserted inside of exit pipe with length of 100mm assumed in CST model

Exit field distortion ?

Conclusion

CST model for FNAL RFQ is adapted for beam dynamic analysis and post-processing:

- RF fields by CST coincide well with ParmilaM cell length
- Exported RF fields agrees with results in Kurennoy report
- Amplitude and phase of exported RF fields are tuned and nominal exit beam parameters are obtained
- Beam parameters for manufacturer beam and measured beam vs the current of the injected beam are obtained
- Mismatched beam shows transmission drop to 45% for 60mA
- Matched beam corresponds to best exp. parameters (Tr~60%)
- Further simulation procedure is overviewed and preparation for MEBT optimization are under a way
- Next: Learn controls for RIL and suggest both simulations in LEBT and experimental studies (IS+LEBT calibrations vs many params)