Summary report of the working group B

Beam Dynamics in High Intensity Linacs

by conveners
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Questions to working group

- **1. Summarize the state of the art in linac simulation capabilities. What are the weaknesses? What developments are needed?**
- **2. Summarize recent developments in benchmarking experimental data with simulations. What critical experiments are needed to further refine the theory and simulations?**
- **3. Summarize the present understanding and limitations of linac beam dynamics in operating linacs.**
- **4. Summarize the primary limitations to beam intensity in existing high-intensity linear accelerators.**
- **5. Summarize the key open questions in the beam dynamics of high-intensity linacs and opportunities to advance the field.**

- 9 invited talks
- 4 contributed talks
- 2 posters
- 2 dedicated discussion sessions + 1 joint discussion session

1. Summarize the state of the art in linac simulation capabilities. What are the weaknesses? What developments are needed?

- There has been tremendous progress in computing power of parallel computers
- There is number of linac beam dynamics codes capable of using this power
- The computing power allows using more dense grids for space charge calculations, more advanced algorithms, 3-D e-m fields, and more particles
- Online models synchronized to live machine status (e.g. XAL for single particle and envelope) are available

CODES, CAPABILITIES & METHODOLOGIES FOR BEAM DYNAMICS SIMULATION IN ACCELERATORS

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

PARMELA
WARP
PARMTEQ
PARMILA
SIMPSONS
IMPACT
2D space charge
rms eqns
3D space charge
GCPIC
DA
Freq maps
Symp Integ
Normal Forms
Integrated Maps
COSY-INF
MXYZPTLK
MaryLie
Dragt-Finn
MAD
Transport

Partial list only; Many codes not shown

From R. Ryne talk

1970 1980 1990 2000

Large Scale Beam Dynamics Simulations using PTRACK

- ATLAS
  - ✓ 100 millions particles full simulation
- Radio Frequency Quadrupole (RFQ)
  - ✓ 100 millions particles full simulation
  - ✓ 865 millions particles part simulation
  - ✓ 865 millions particles full simulation
- Fermi Lab. Proton Driver Linac (PD)
  - ✓ 100 millions particles simulation
  - ✓ 100 seeds with 10 millions particles each
  - ✓ 865 millions particles simulation

$$100\times10^7 = 10^9$$

One billion particle statistics!

- ❖ Spallaton Neutron Source (SNS)
- ❖ Facility for Rare Isotopic Beam (FRIB)

☆ 100K particles takes 14 hours with 1 CPU
While with 16 CPU, takes 1 hour;
And with 64 CPU, takes **20 minutes!**

☆ 1,000,000 particles on BG takes 5.5 days!
Now with 64 CPU, takes about 2.2 hours!
And with 256 CPUs, it only takes **38 minutes!**

☆ Now we can simulate **865M** particles through RFQ with 32,768 CPU in 5 hours.

☆ Using BG/P with 65,536 CPU, it is possible to simulate ~ **Billions** of particles.

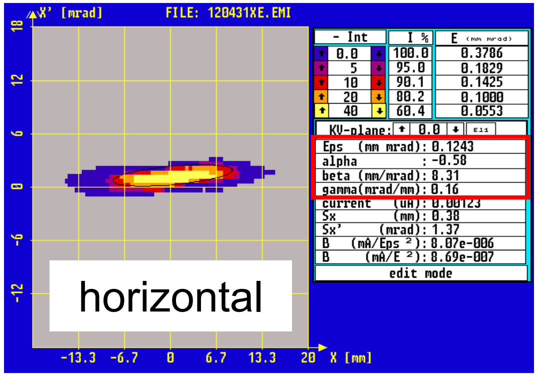
☆ 10^{11} particles still is a challenge

From J. Xu talk

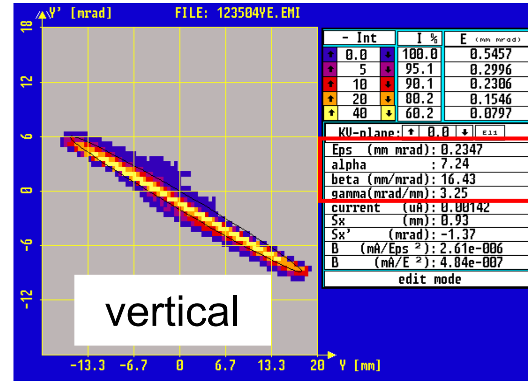
1. Summarize the state of the art in linac simulation capabilities. What are the weaknesses? What developments are needed?

- Still there is no “the one” code, which is totally trustworthy to the community. Developers trust and promote their own codes.
- There are many small but important details in setting up simulations with different codes, which makes direct comparison of the results difficult and increase probability of erroneous results.
- Problem of defining the initial distribution of particles

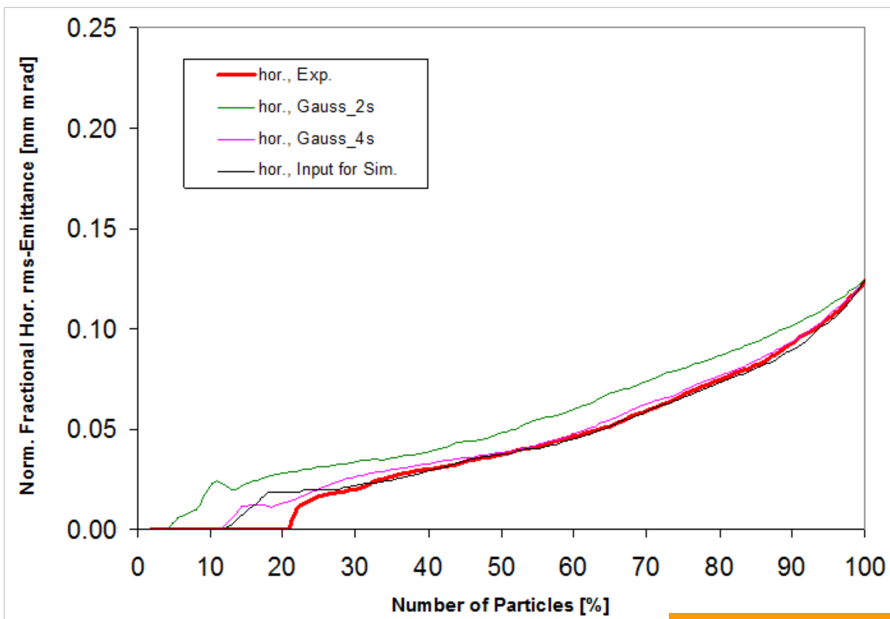
Re-construction of initial type of Distribution

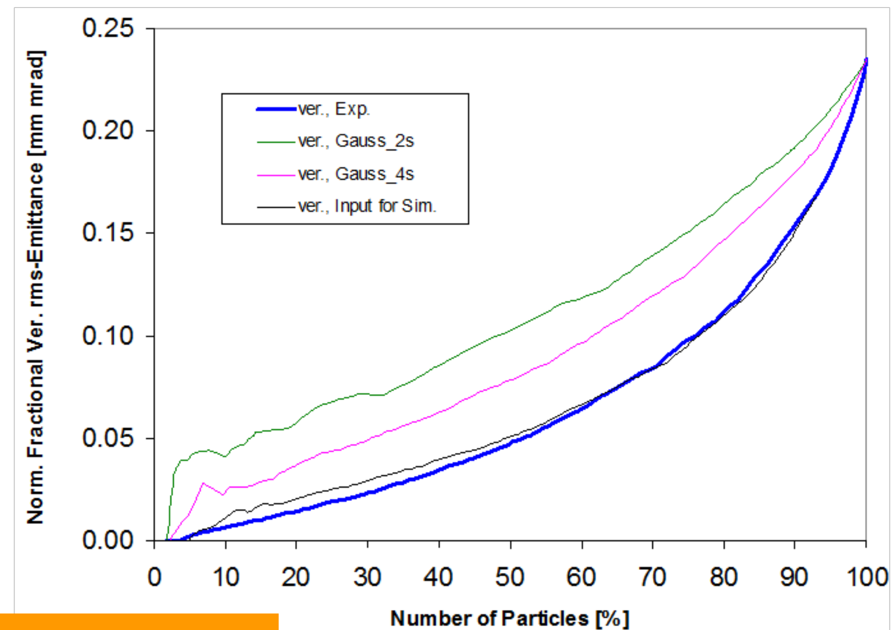


measured in front of DTL



measured initial distribution inhabits different amount of halo horizontally and vertically





From L. Groening talk

Re-construction of initial type of Distribution

- Gauss, Lorentz, Waterbag distributions do not fit the measured amount of halo
- Several functions tried in order to fit halo in both planes
- function found as:

$$\frac{dN}{dV} = f\left(X, X', Y, Y', \Phi, \delta P/P\right)$$

$$\tilde{R}^2 = X^2 + X'^2 + Y^{1.2} + Y'^{1.2} + \Phi^2 + (\delta P/P)^2$$

$$f(\tilde{R}) = \frac{a}{2.5 \cdot 10^{-4} + \tilde{R}^{10}}, \quad \tilde{R} \leq 1$$

$$f(\tilde{R}) = 0, \qquad \tilde{R} > 1,$$

applying different powers for different planes the amount of halo can be reproduced

From L. Groening talk

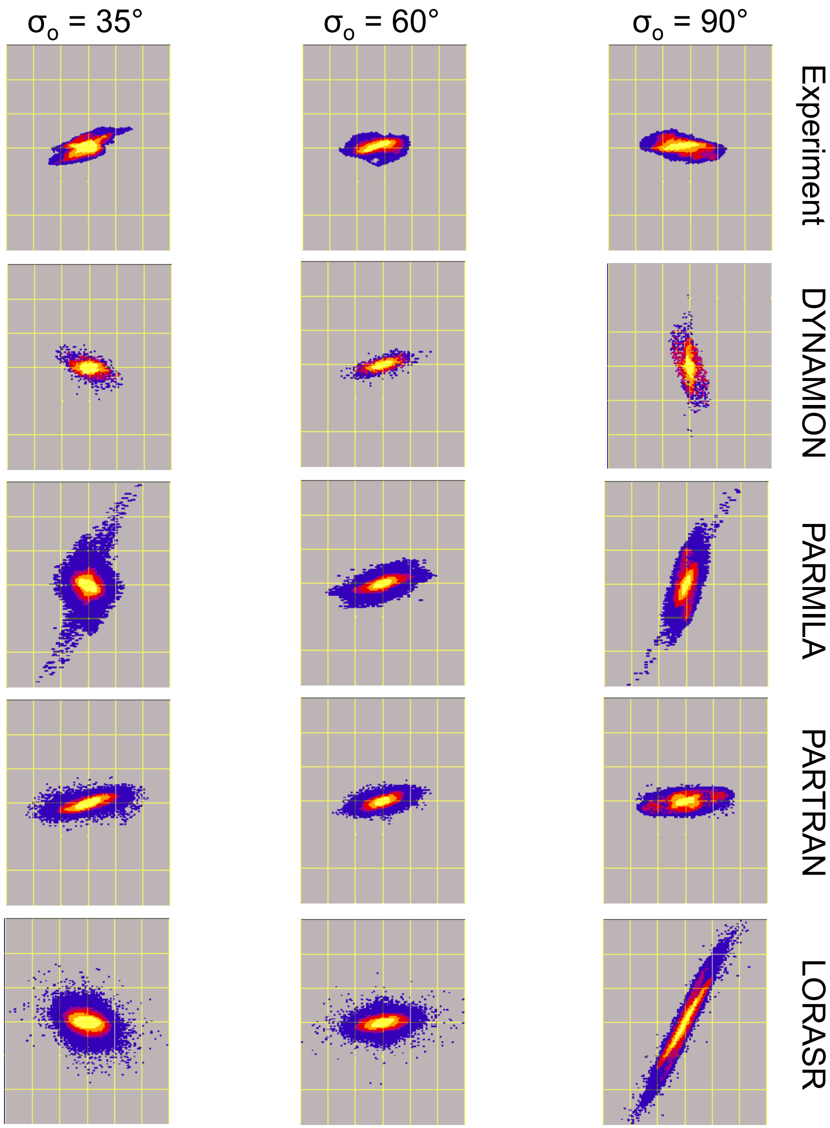
1. Summarize the state of the art in linac simulation capabilities. What are the weaknesses? What developments are needed?

- The achieved number of particles in simulation is sufficient for realistic modeling of a bunch in a linac. Further increase of number of particles can be useful for general study of possible importance of correlations in initial 6-D distribution.
- The problem of initial distribution is of urgent importance:
  - Are correlations between degrees of freedom of the initial distribution important?
  - How to generate 6-D distribution when only 2-D or 1-D projections are known?
  - Is RFQ output distribution more trustworthy than an artificial 6-D distribution generated from the projections?
- More realistic boundary description is desirable, especially for RFQ simulations

2. Summarize recent developments in benchmarking experimental data with simulations. What critical experiments are needed to further refine the theory and simulations?

- Dedicated benchmarking experiments are rare because they are quite time and resource consuming
- Very thorough benchmarking experiment at GSI
  - 4 different codes. Output emittance was measuremed for different phase advances in the linac.
  - Puzzling discrepancy between the codes. Differences in model descriptions is suspected. Should verify accuracy of the models with zero current calculations.
- Or is it true problem with the codes?
  - In many past cross-checks good agreement between various codes was observed. Typically cross checking is done close to the design set points for well matched beam. There are reports of non-discrepancies for non-matched beams but no systematic study has been done.

Shapes of Final Horizontal Distributions



	Int / Int_max [%]
(blue)	0 – 5
(purple)	5 – 10
(red)	10 – 20
(orange)	20 – 40
(yellow)	40 -100

- agreement for intermediate σ_o
- disagreement for low/high σ_o
- high σ_o: attached wings (islands)

From L. Groening talk

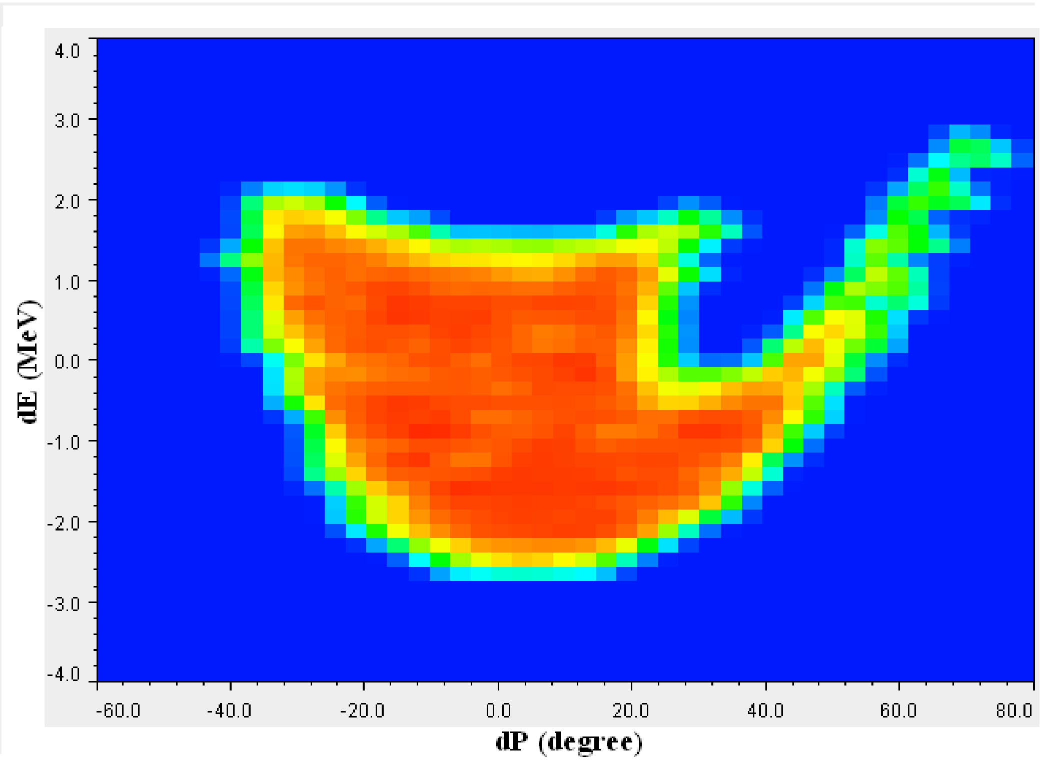
2. Summarize recent developments in benchmarking experimental data with simulations. What critical experiments are needed to further refine the theory and simulations?

- As a first step codes should be cross checked using a simple model but non-matched beam
  - Long FODO structure with bunchers
  - Zero current simulations should agree
  - Compare more than just RMS emittance or RMS beam size. Profiles, phase space footprint, etc.
  - Compare results for different degree of mismatch
- Longitudinal measurements can provide a missing piece of information.
  - Longitudinal diagnostics is scarce

3. Summarize the present understanding and limitations of linac beam dynamics in operating linacs.

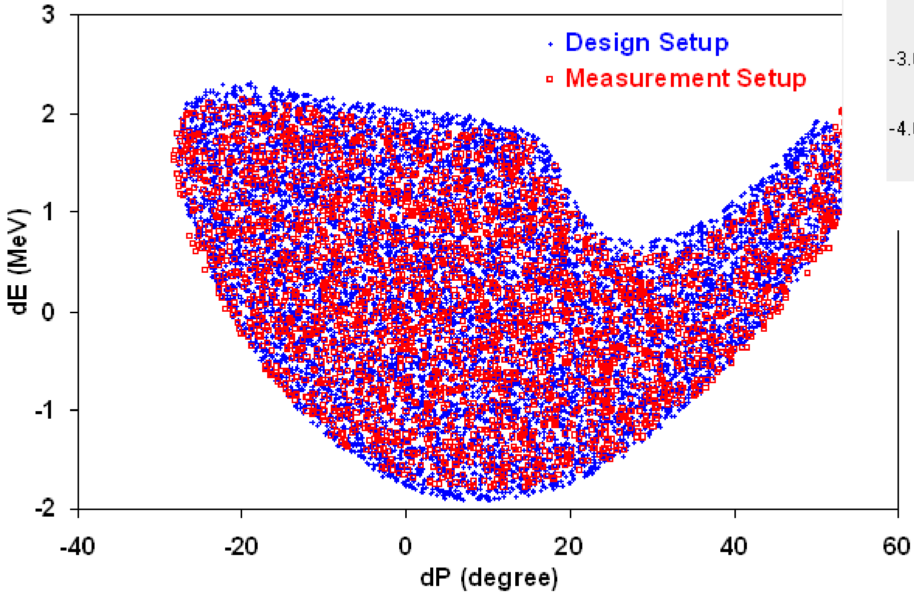
- There is no complete understanding of all beam dynamics details in new linacs
  - Unexpected losses in SNS SCL
  - Transverse tails development in JPARC linac
- But the linacs performance is close to expectation and there is steady progress in refining the models
- New measuring techniques and tuning methods are being developed
- Modeling of single particle motion is close to full success in the SNS linac
  - Some phenomenological factors have to be used

Y. Zhang, et. al., submitted to PRST-AB



BCM measured acceptance

Model predicted the SCL longitudinal acceptance

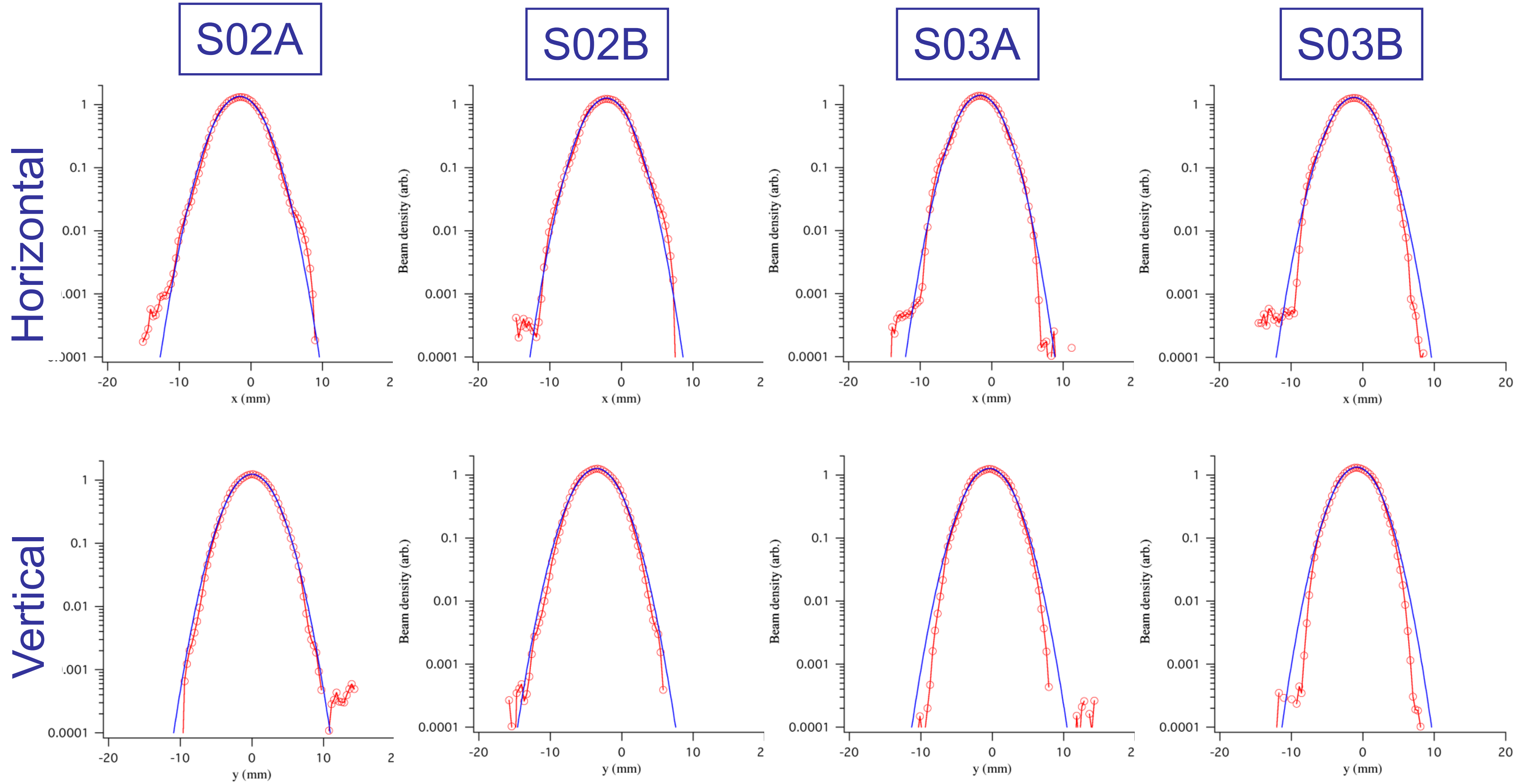


From Y. Zhang talk

SCL longitudinal acceptance measurement with BCM and BLMs

Measured profile at DTL exit

From M. Ikegami talk

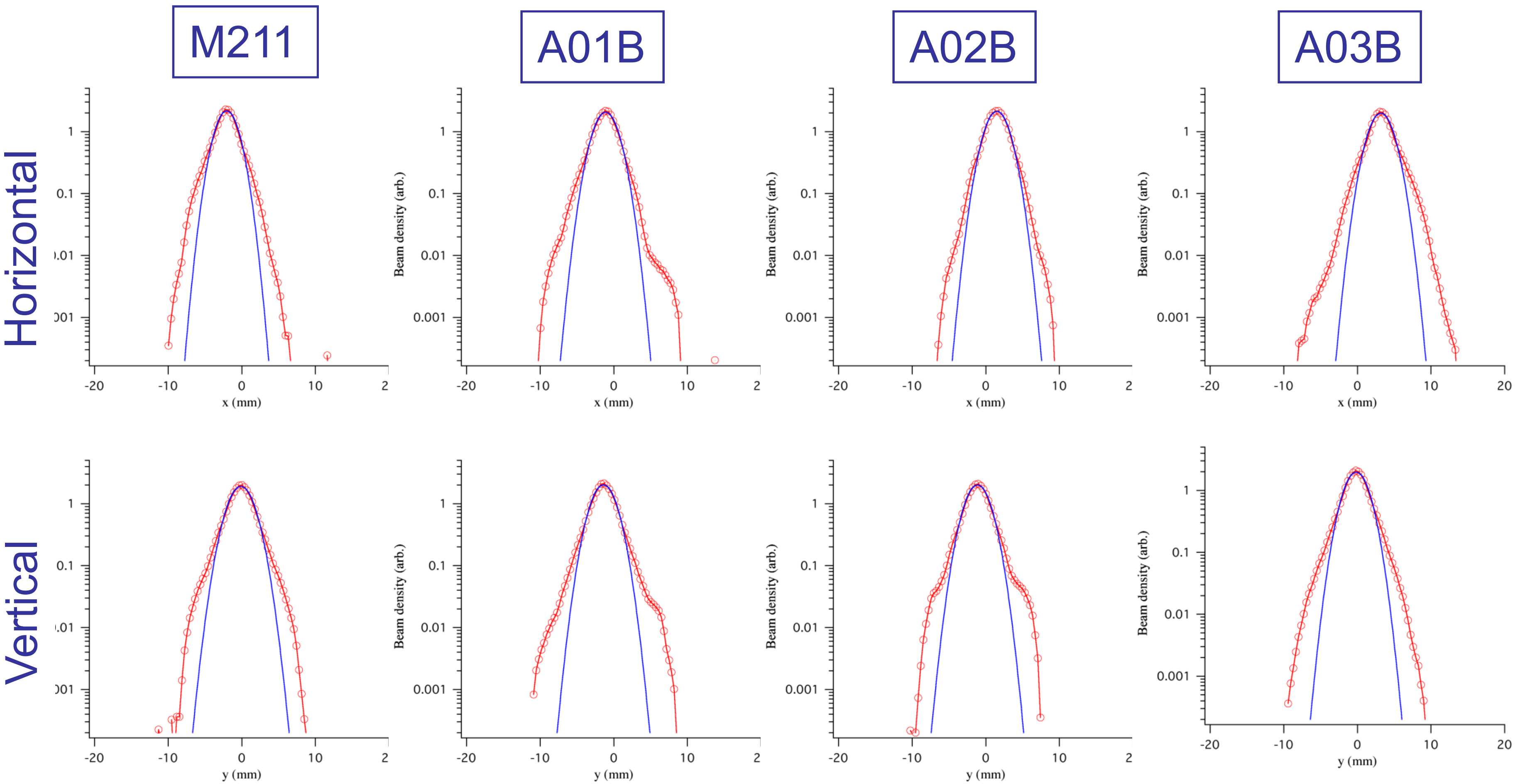


Beam profile is mostly Gaussian at DTL exit.
Red circle: Measurement, Blue line: Gaussian fit

30 mA

From M. Ikegami talk

Measured profile at SDTL exit



Clear halo is developed at SDTL exit while there is no significant emittance growth.

Red circle: Measurement, Blue line: Gaussian fit

30 mA

3. Summarize the primary limitations to beam intensity in existing high-intensity linear accelerators.

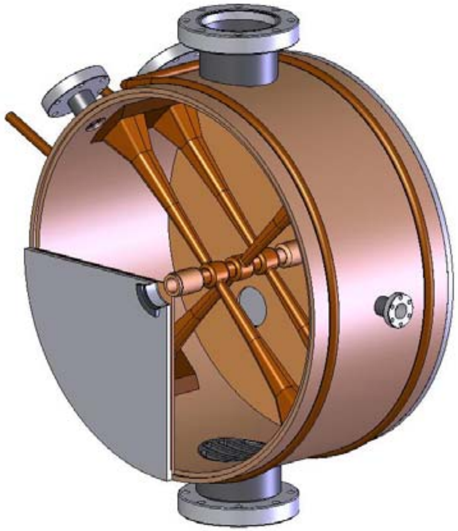
- SNS linac is the most powerful to date. Loss limiting intensity has not been achieved yet. It is possible that design limitations other than beam dynamics will limit the maximum intensity (e.g. available RF power)
- There is general agreement that with increasing beam power in the emerging projects beam loss caused by the intensity effects will ultimately limit the maximum power.
  - Expected fractional losses are extremely small
  - Understanding of halo formation remains the most important problem at the intensity frontier.

5. **Summarize the key open questions in the beam dynamics of high-intensity linacs and opportunities to advance the field.** (1)

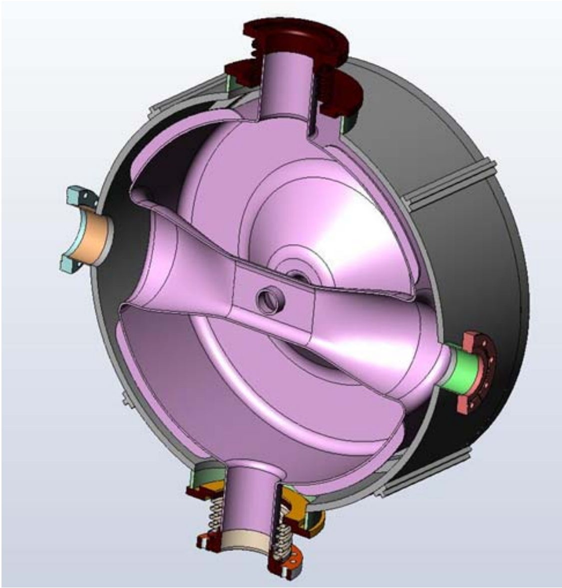
- Extending use of superconducting cavities to lower energies
- Use of solenoids for transverse focusing at low energy
  - allow stronger focusing per unit length, higher accelerating gradients can be used
  - Maintaining round beam cross section at lower energy can reduce halo development

Accelerating cavities (not to scale)

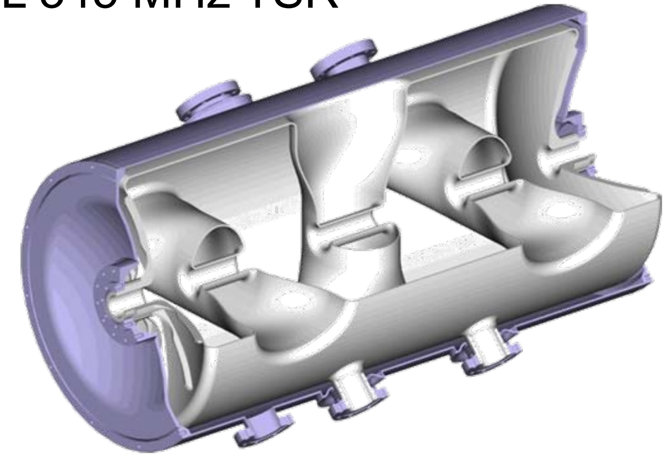
NC spoke



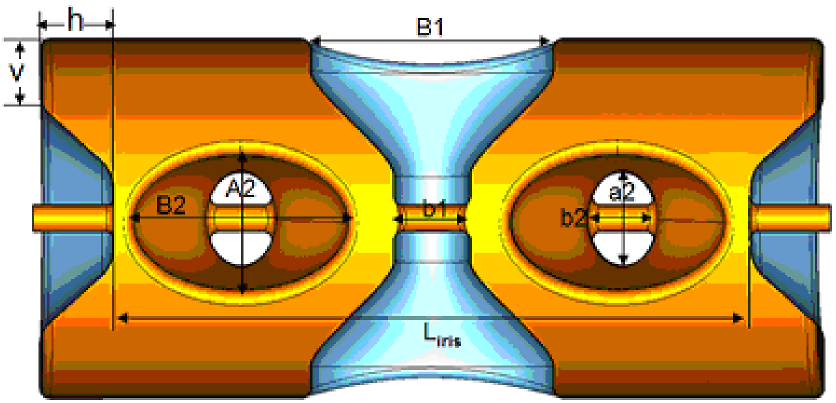
SC single spoke



ANL 345 MHz TSR



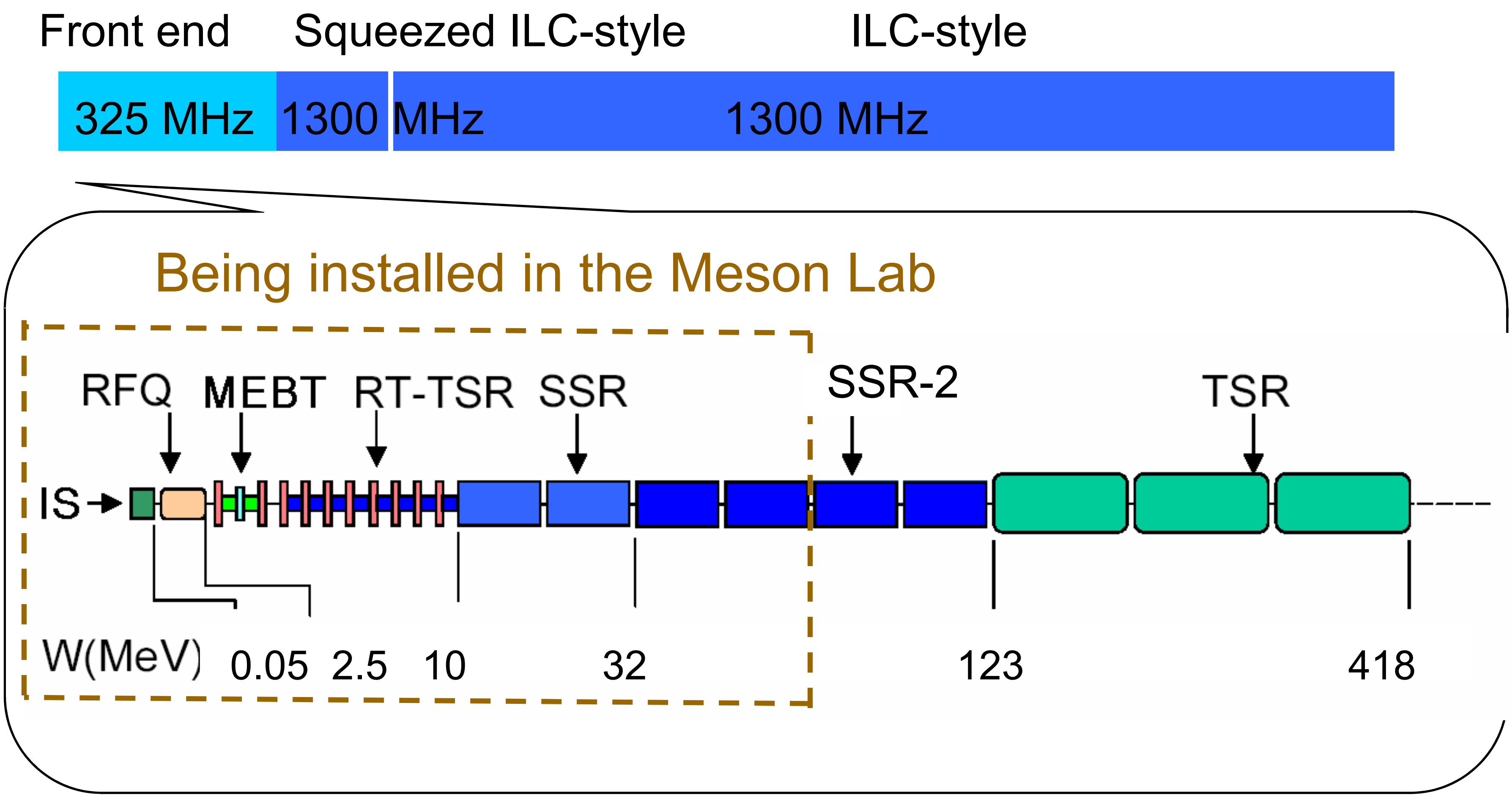
FNAL 325 MHz TSR



From P. Ostroumov talk

Linac Structure

Major Linac Sections



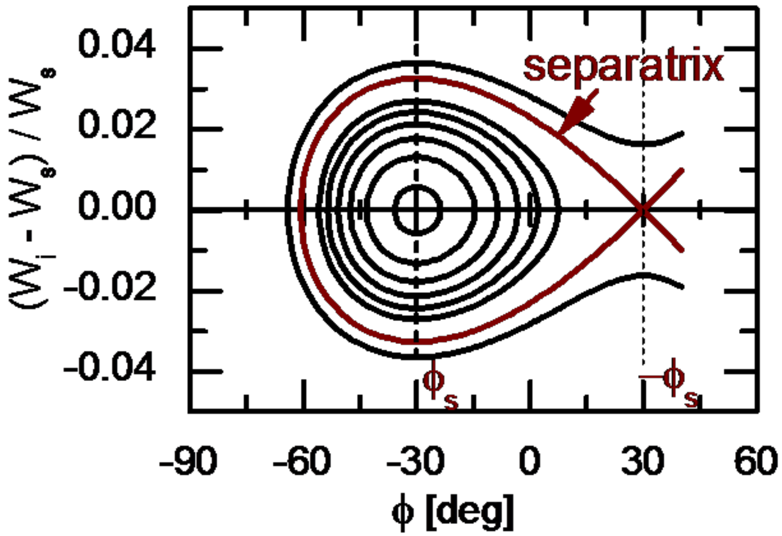
From P. Ostroumov talk

5. **Summarize the key open questions in the beam dynamics of high-intensity linacs and opportunities to advance the field.** (2)

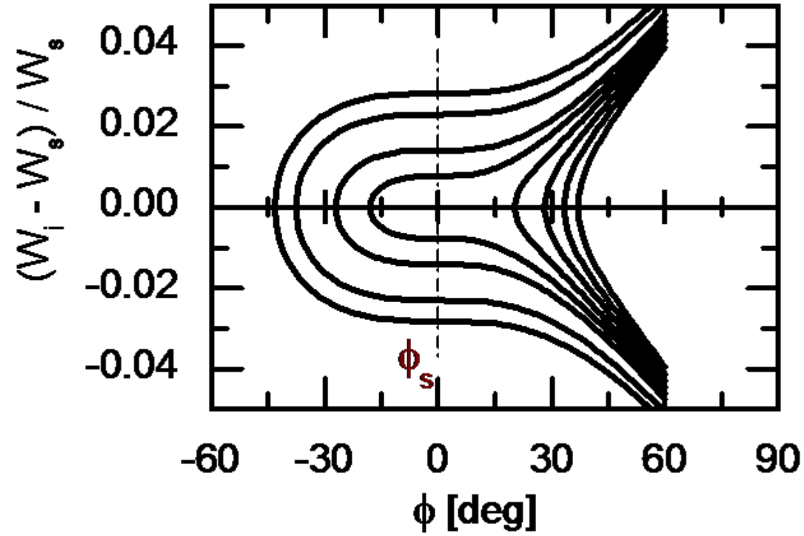
- Use of H-mode cavities with higher shunt impedance
  - KONUS beam dynamics
  - Has being around for many years, now extending to high intencity applications

Particle Trajectories in Longitudinal Phase Space at $\phi_s = 0°$

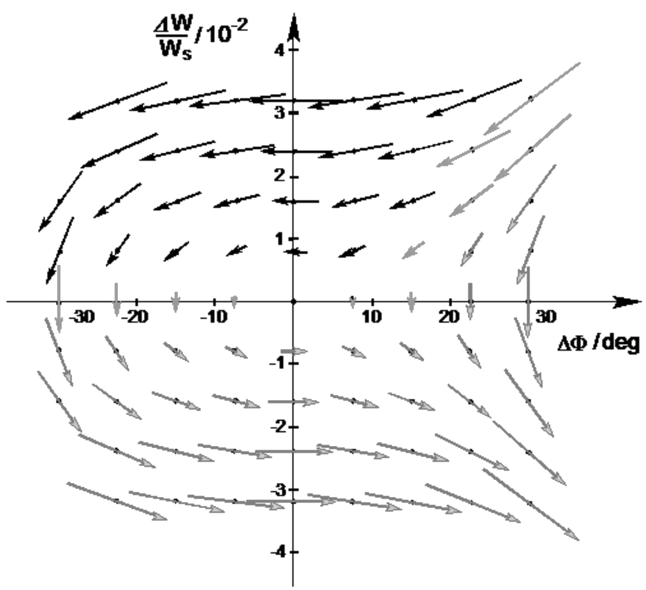
$\phi_s = -30°$



$\phi_s = 0°$

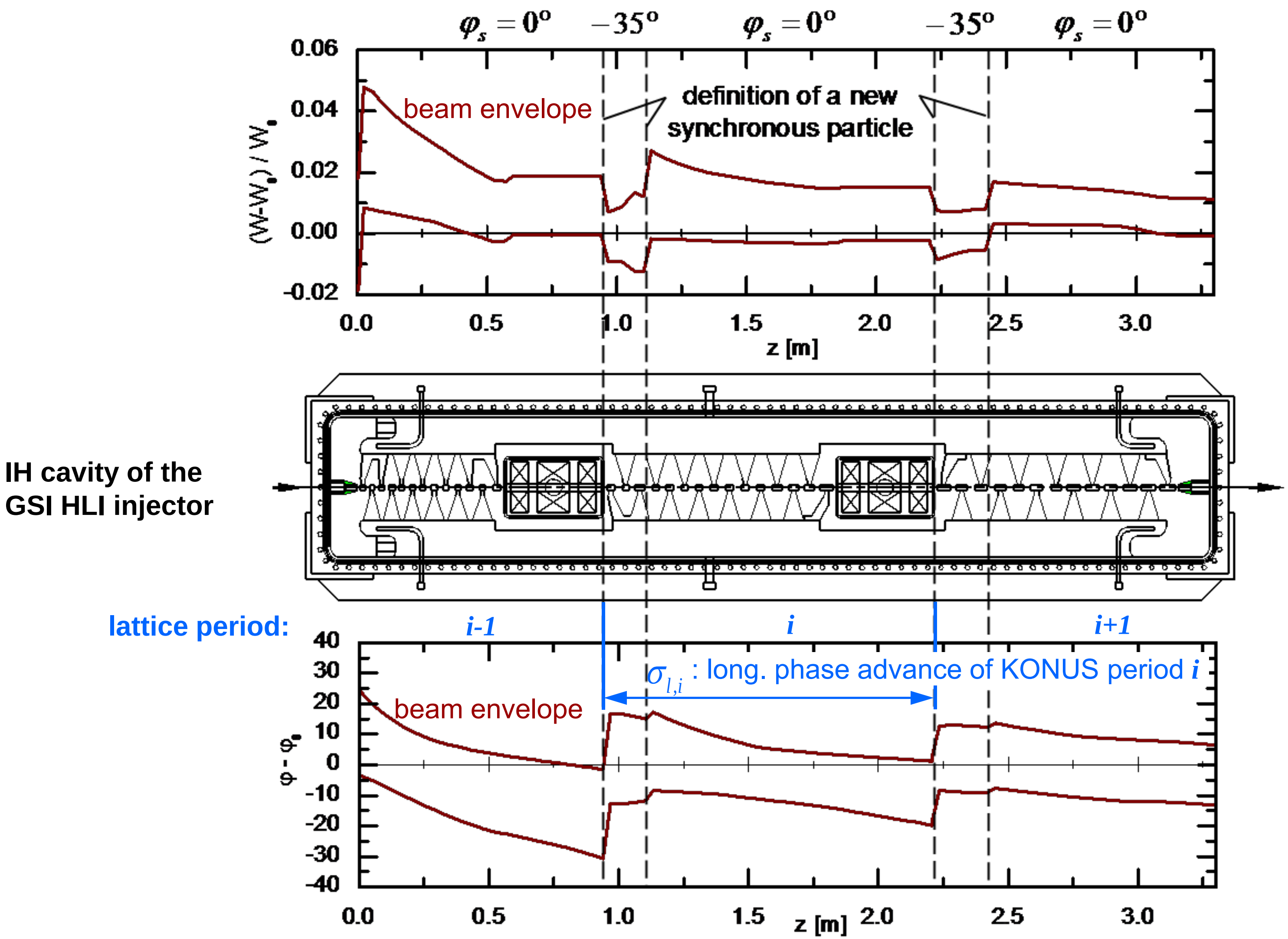


Black arrows:
area used by KONUS



From R. Tiede talk

Combined 0° Structure Overview and Definition of the Longitudinal KONUS Lattice Period

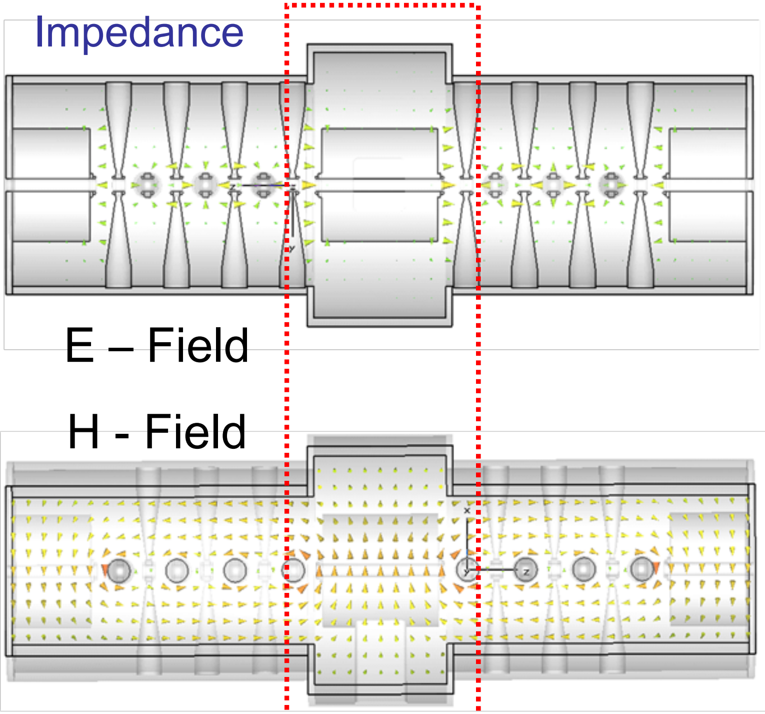


From R. Tiede talk

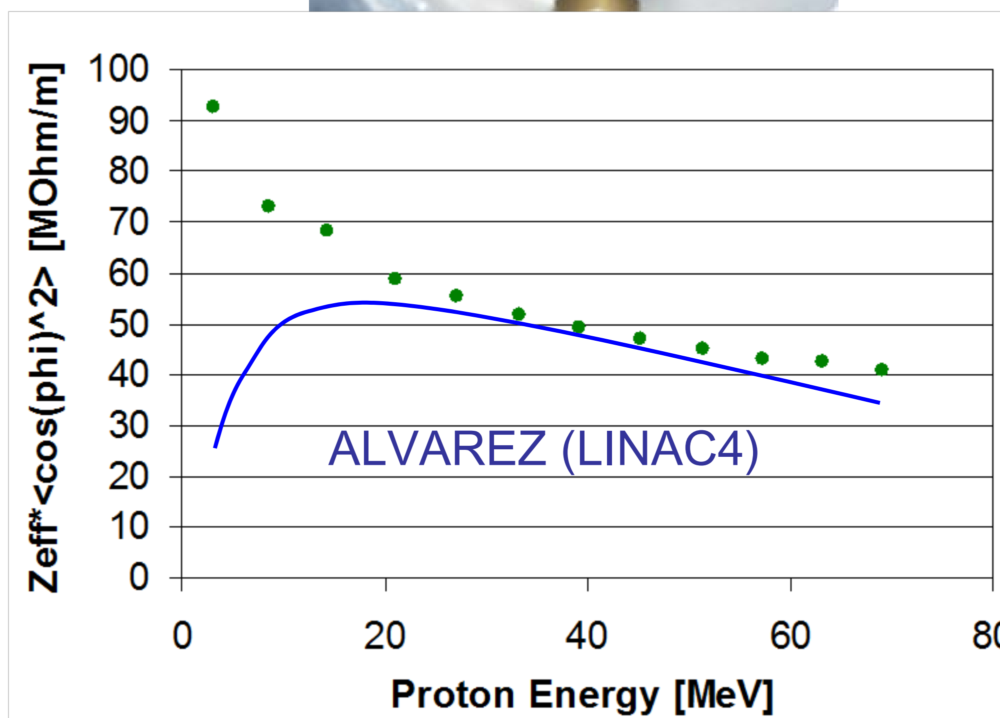
DTL: Rf-coupled Crossed-bar H-Cavities

From G. Clemente talk

H-Mode cavities in combination with the KONUS Beam Dynamics ⇒ Highest Shunt Impedance



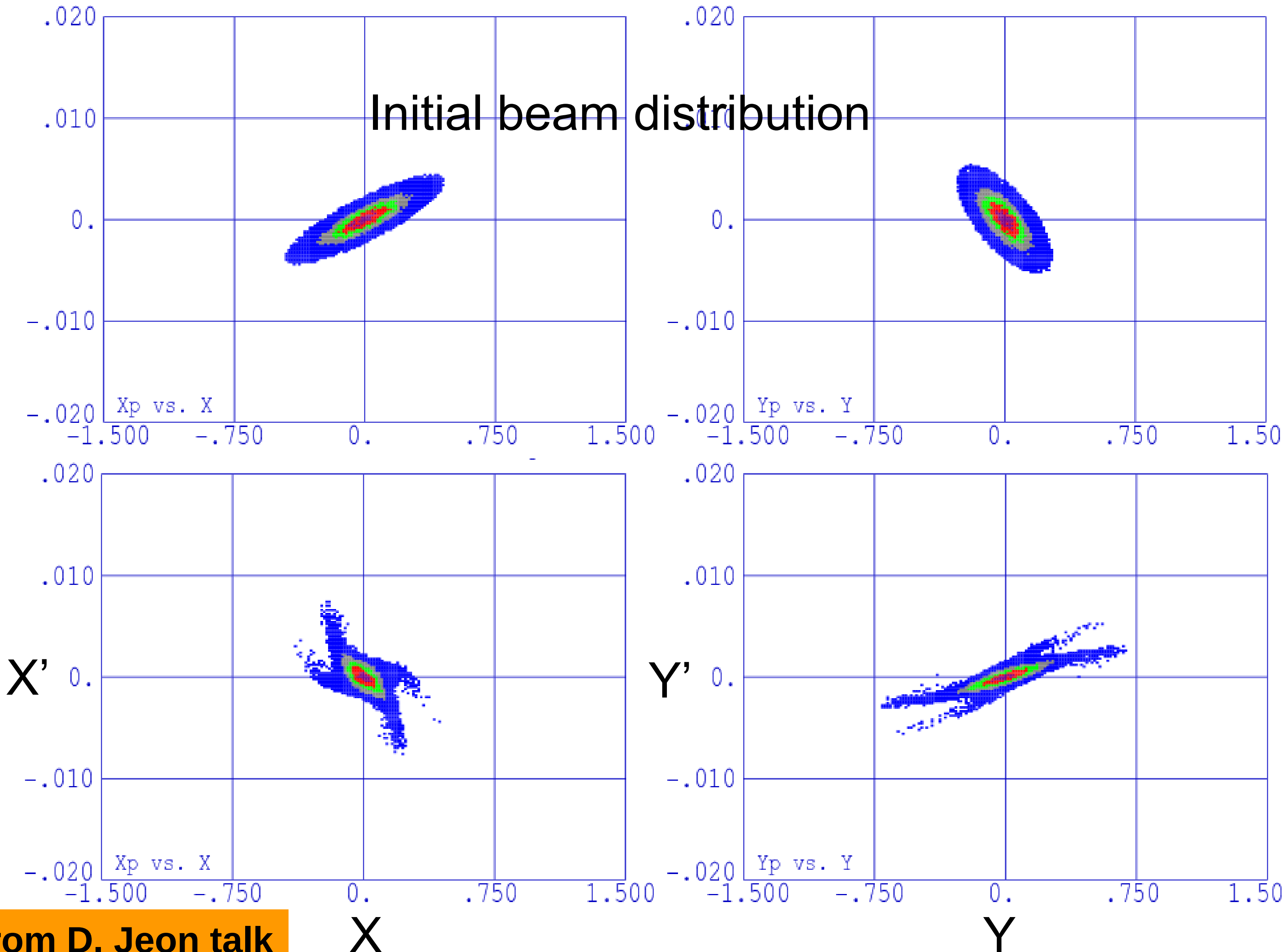
- reduce number of klystrons
- reduce place requirements
- profit from 3 MW klystron development
- avoid use of magic T's
- reduce cost for rf-equipment



5. **Summarize the key open questions in the beam dynamics of high-intensity linacs and opportunities to advance the field.** (3)

- Further advances in understanding of space charge induced halo grow
  - 4:1 resonance observation in simulations

Beam distribution when crossing the 4ν=1 resonance from below

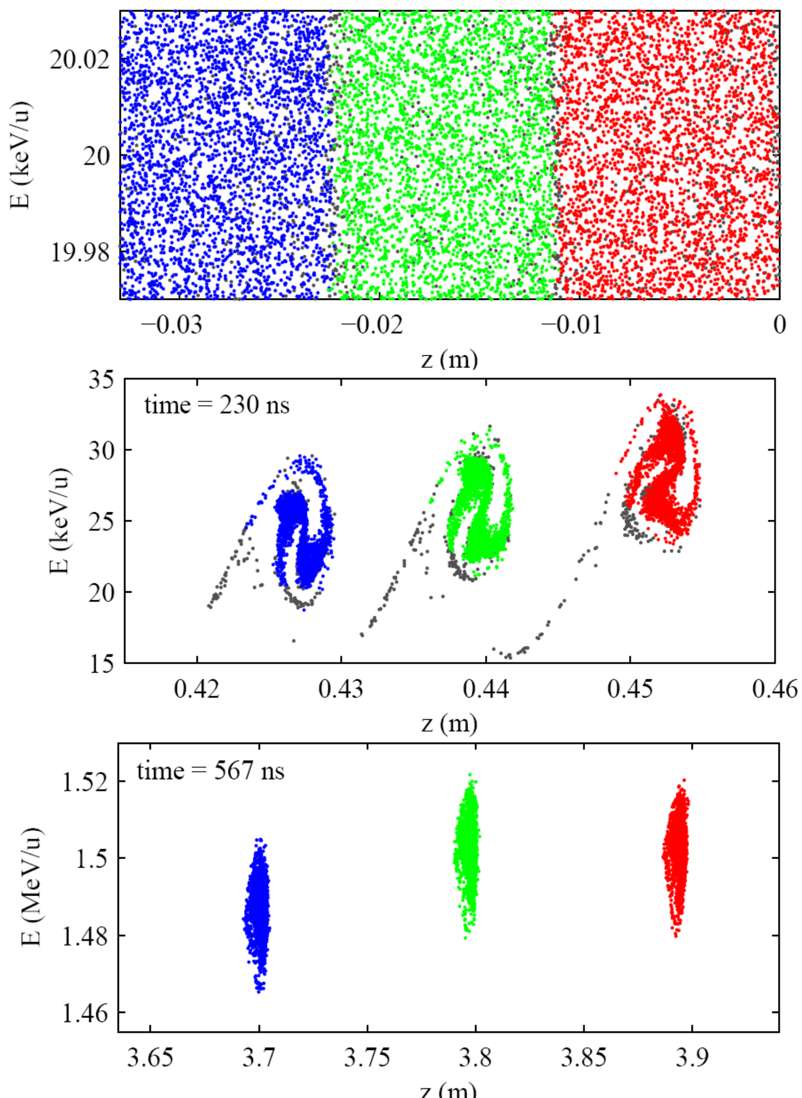


From D. Jeon talk

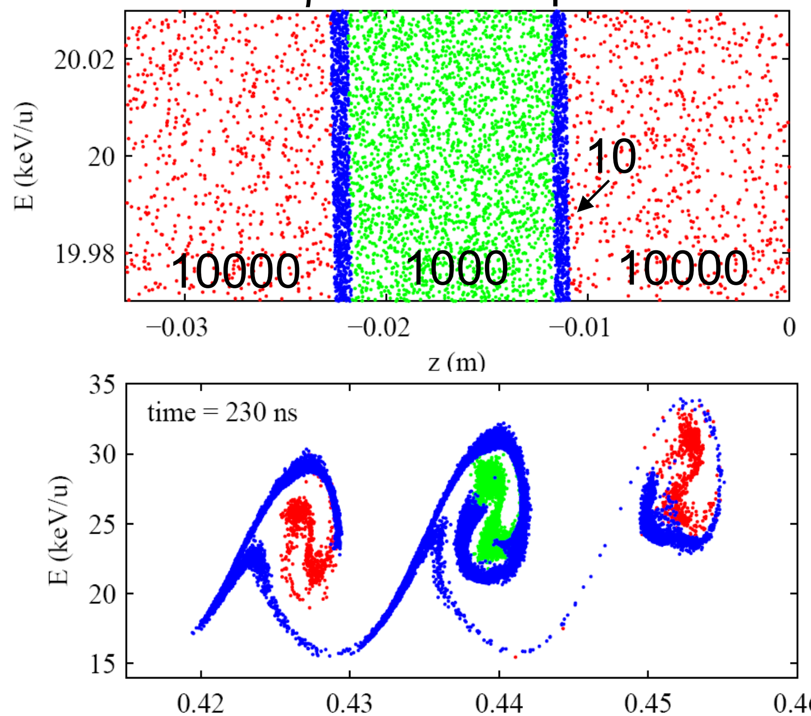
5. Summarize the key open questions in the beam dynamics of high-intensity linacs and opportunities to advance the field. (4)

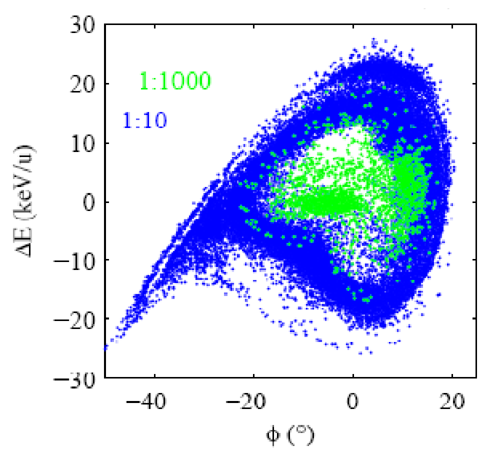
- Large dynamic range calculation of longitudinal tale development in RFQ using tail emphasis method

3βλ - regular



3βλ – tail emphasis





2.1 million (3.4 mA) macro particles at RFQ exit equivalent to simulation of 3 bunches with 42.6 million (1:10) macro-particles (each 0.3 nA) at RFQ entrance for 4mA CW at 176 MHz.

B. Bazak *et al.* submitted 2008

RFQ entrance norm rms $\varepsilon_{x,y}$=0.2 π mm mrad. Emittance growth <10%.

From J. Rodnizki talk

- Good old schemes still are in use

From F. Gerigk talk

Linac4 Layout

45keV → 3MeV → 3MeV → 50MeV → 102MeV → 160MeV

H-	RFQ	CHOPPER	DTL	CCDTL	PIMS
RF volume source (DESY)	Radio Frequency Quadrupole	Chopper	Drift Tube Linac	Cell-Coupled Drift Tube Linac	Pi-Mode Structure
45 kV	352 MHz	352 MHz	352 MHz	352 MHz	352 MHz
1.9m	3 m	3.6 m	18.7 m	25 m	22 m
LEBT	1 Klystron	11 EMquad	3 tanks	21 tanks	12 tanks
	0.6 MW	3 cavities	3 klystrons	7 klystrons	8 klystrons
			4 MW	6.5 MW	~12 MW
			111 PMQuad	21 EMQuads	12 EMQuads

Total Linac4:
80 m,
19 klystrons

Beam Duty cycle:
0.1% phase 1 (Linac4)
3-4% phase 2 (SPL)
(design for losses : 6%)

4 different structures,
(RFQ, DTL, CCDTL, PIMS)

Ion current: 40 mA (avg. in pulse), 65 mA (bunch)

Many thanks to the speakers for interesting presentations and to the working group participants for lively and fruitful discussions.