Space charge studies in the HIPPI project

Ingo Hofmann, GSI Darmstadt
Accelerator Physics Seminar, DESY, April 23, 2007

1. Introduction to Care-HIPPI
2. Code Benchmarking
3. Resonances in Linacs!
4. GSI/FAIR and UNILAC-Experiments
5. Comparison Measurement-Simulation (ongoing work)
6. Outlook

HIPPI Structure

- High Intensity Pulsed Proton Injectors (HIPPI) was set up in 2003 as a Joint Research Activity inside the CARE (Coordinated Accelerator Research in Europe) Integrated Activity partially funded by the EU.

- Main objective: Research and Development of the technology for high intensity pulsed proton linear accelerators up to 200 MeV (and starting from 3 MeV).

- HIPPI time span: 5 years, 1.1.2004 - 31.12.2008

- HIPPI is a (temporary) coordination of the existing high-intensity linac R&D programs of 9 EU laboratories.

- Financial background: about 16 M€ total HIPPI cost (lab manpower included), including 3.6 M€ EU Contribution (22%).

- EU contribution mainly goes to: temporary staff, some hardware (mainly 700 MHz test stand),organization of meetings.

The 3 HIPPI Projects

Integrated Activities must result in upgrading of existing infrastructures:
HIPPI aims at the upgrade of 3 accelerator facilities

	GSI-FAIR	CERN-Linac4		RAL	
		Linac4 mode	SPL mode		
Beam Energy	70	160		180	MeV
Beam Current (pulse)	70	40		40	mA
Repetition Rate	4	2	50	50	Hz
Beam Pulse Length	36	400	720	300	μs
Average Current	10	32	1440	600	μA
RF Frequency	324	352 - 704		324 - ?	MHz
Transv. Emittance (100%)	2.8	2.1			μm, norm.
RFQ Energy	3	3		3	MeV
Overall Linac Length	~ 30	~ 80		~ 80	m
Accelerating Structures(s)	RFQ, CH	RFQ, DTL, CCDTL, SCL		RFQ, DTL	
Average RE Gradient	2.3	2.0 (1.7 to 90 MeV)		~ 2	MeV/m
Installed RF Power (linac)	6 x 2.5 MW	13 x 1 MW + 4 x 4 MW			

HIPPI Technical Goals

In the proposal a set of HIPPI Goals was established.

Normal Conducting Structures: $ZT^2 > 40\ M\Omega/m$, 3 … 100 MeV, low cost

Superconducting Structures: $E_{acc} > 7$ MV/m, $Q > 10^{10}$, 5 … 200 MeV

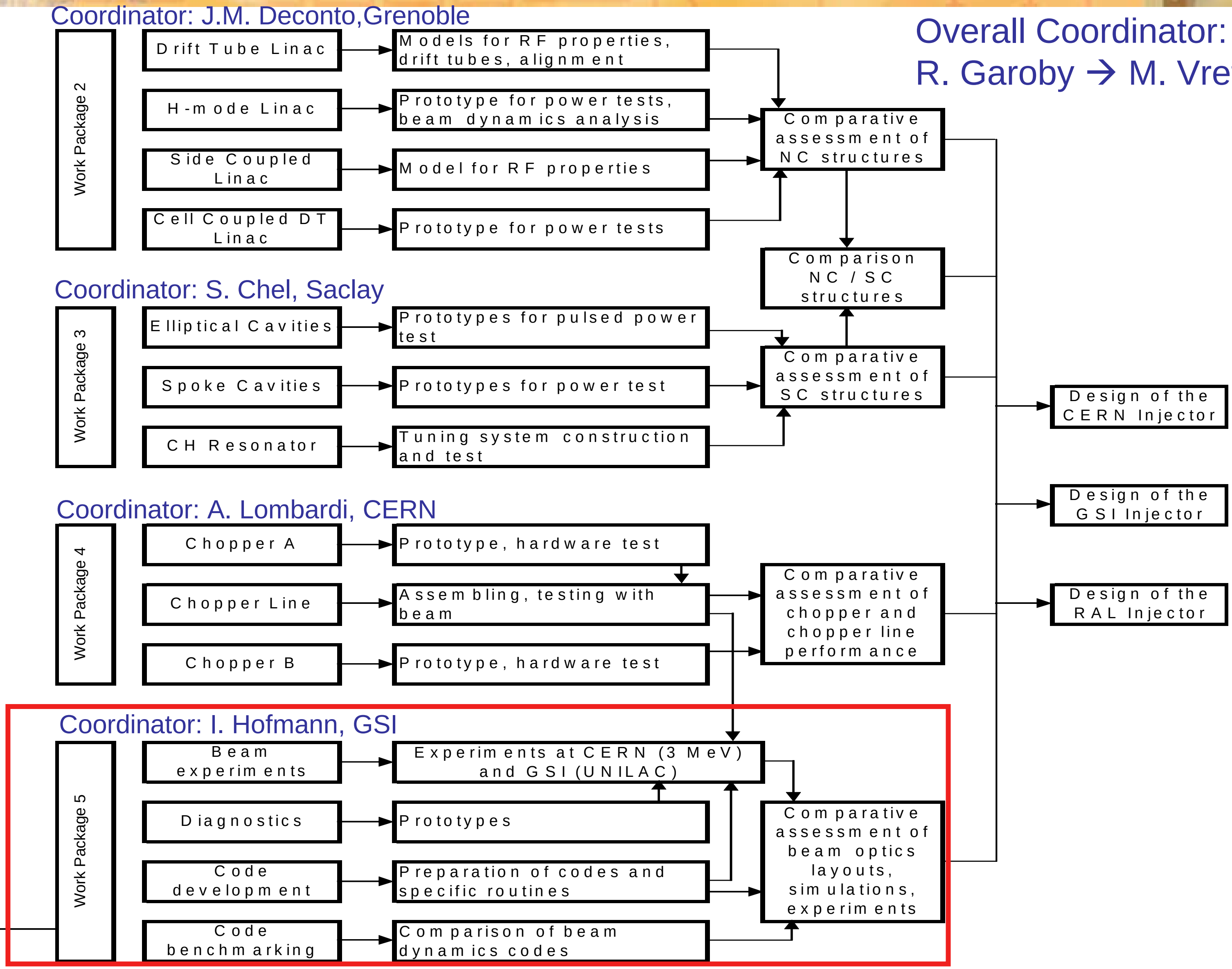
Chopper: $\tau < 2$ ns, minimum emittance growth

Beam Dynamics:

- benchmarking of codes
- design for loss < 1 W/m up to 3.5 GeV
- do we have enough confidence in codes to optimize and verify design before construction?
- do we understand enough about sources of emittance growth, halo formation and beam loss in linacs?

The HIPPI Programme

Overall Coordinator:
R. Garoby → M. Vretenar, CERN



Beam simulation code "Benchmarking" became a high-priority activity

"Nobody believes in simulation besides the simulationists
Everybody believes in experiment besides the experimentalist"

Simulation and experiments are complementary approaches to study the behaviour of beams:

Simulations are

- usually based on imperfect models missing part of the real behaviour
- give high flexibility, where particular interactions (particle-particle, particle-mean field, beam-beam, beam-wall, beam-rest gas, beam-electron clouds etc.) or boundary or initial conditions can be turned on/off and parameters can be varied
- allows identification of phenomena with particular physical effects
- diagnostics is "perfect" in the sense that unconstrained information can be extracted at any time.

Experiments have

- an underlying "perfect" model
- but the complexity of interactions in accelerators makes it often impossible to disentangle the main sources
- parameters can be varied only over a limited range
- diagnostics is usually quite imperfect and limited in resolution.

Participants "HIPPI Code Benchmarking Project"

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Steps in "Benchmarking"

The first "trivial" step is that of "debugging", making sure the code does what it is written for.

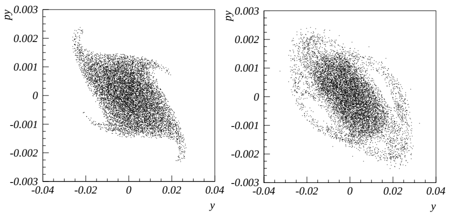
Thereafter:

1. **Verification:** The task is to prove that a computerized model of a beam in a well-defined environment agrees with a theoretical model, for which assured analytical solutions exist. Hence verification is
   - a quite precisely defined task and a test within the framework of the underlying model, and not under most general conditions as would occur in real beams
   - problems here are largely of mathematical or numerical nature due to algorithms, time steps, grids, and convergence problems and similar.
2. **Comparison:** A comparison with other (already tested) codes gives enhanced assurance.
   - often codes are not too rigorously comparable, especially if the underlying concepts differ, and one needs to learn where discrepancies might stem from.
3. **Validation:** Comparing code results with experimental data is crucial, but limited.
   - a realistic goal cannot be to validate a code as such, which is practically impossible
   - validation is always more vague – due to the limited representation of real beams and environments - and limited to a particular problem and its modelling
   - therefore validation is more a (possibly open-ended) process and not a unique task.

GSI Unilac offers unique test-bed herefore:
space charge dominated, diagnostics, need improvement!
requested and obtainedexperimental beam-time herefore!

Resonant process also in linacs
(used to in rings)

- *Here: p or ion linacs with direct space charge force main interaction*
- Ideal linear forces: normalized emittances invariant
- Nonlinear forces due to space charge (also RF)
- 1990's: Halo is parametric resonance of single particles with mismatched beam core
- 1983: Structure resonances due to periodic focusing (I.H., L.J. Laslett, L. Smith, *Particle Accelerators* 13, 1983)

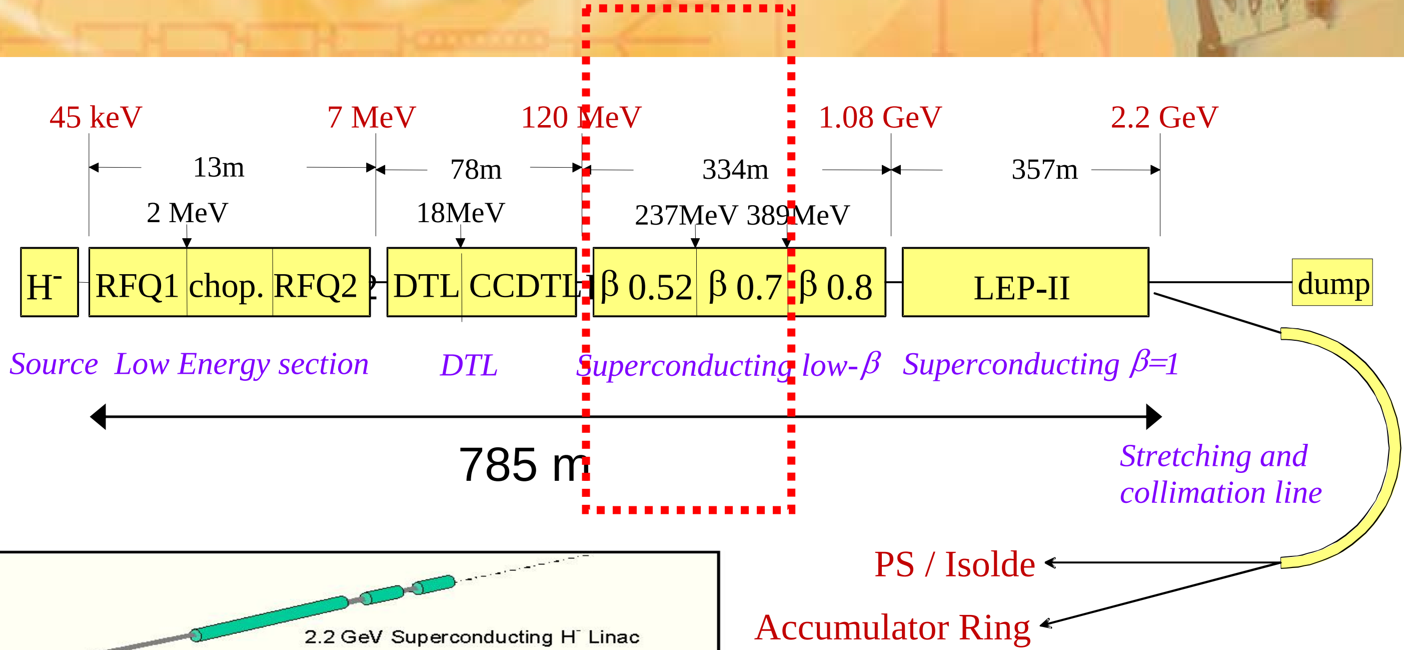


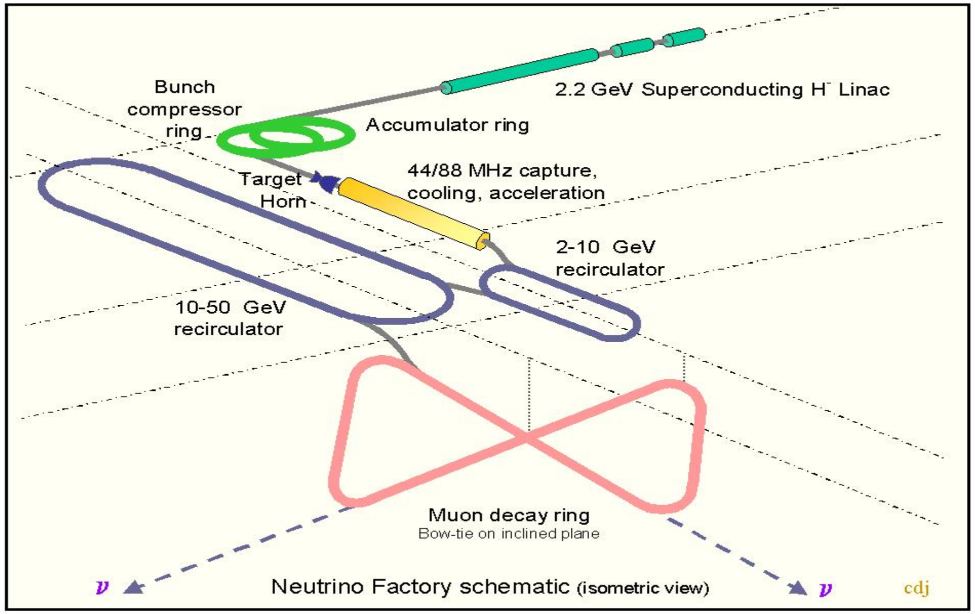
periodic interaction
of this mode with lattice

- 1998 ff: Equipartitioning
- Aim is to demonstrate this on UNILAC – first experimental evidence of theoretical predictions

CERN SPL and the Neutrino Factory

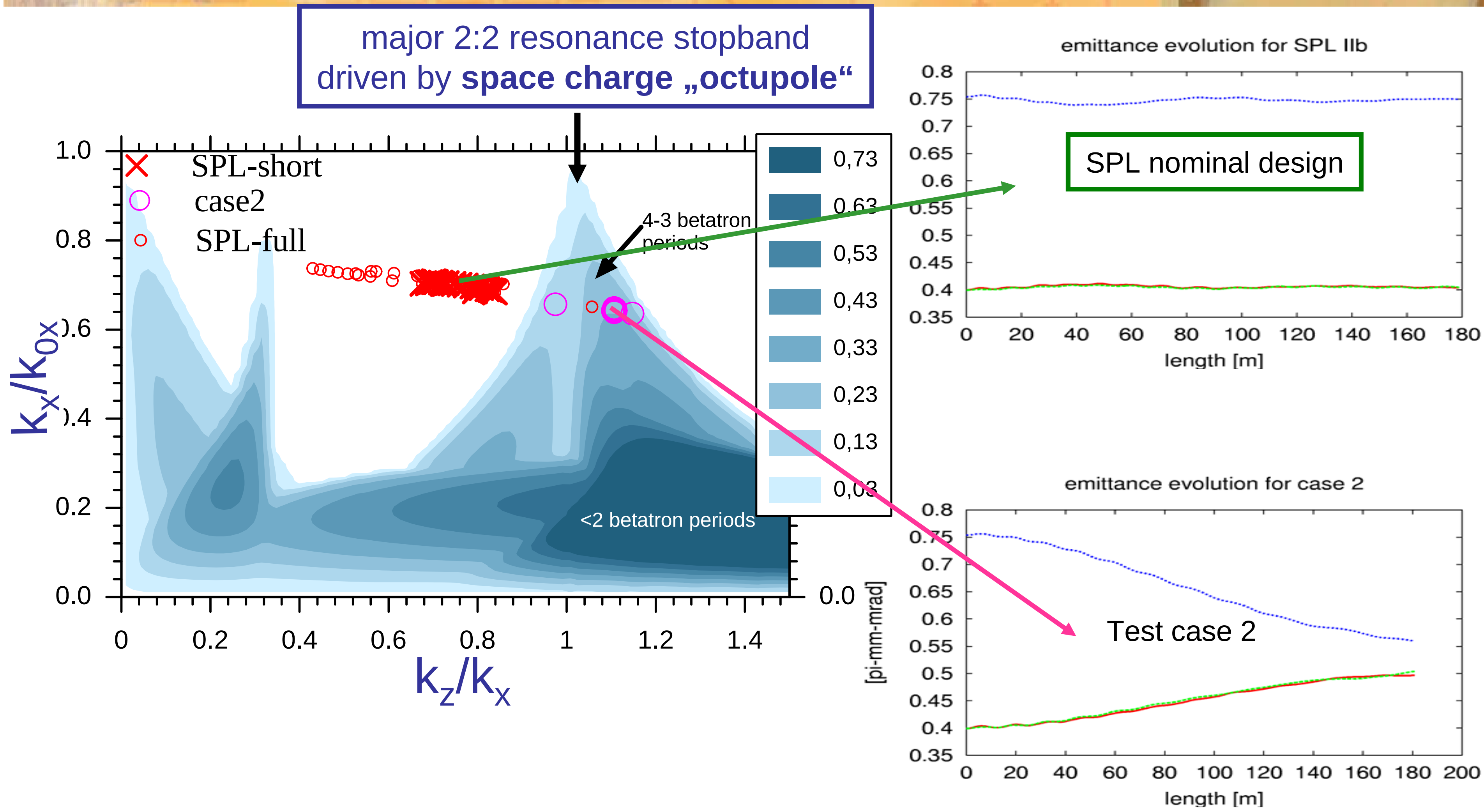
"older Version": F. Gerigk/CERN, 2002



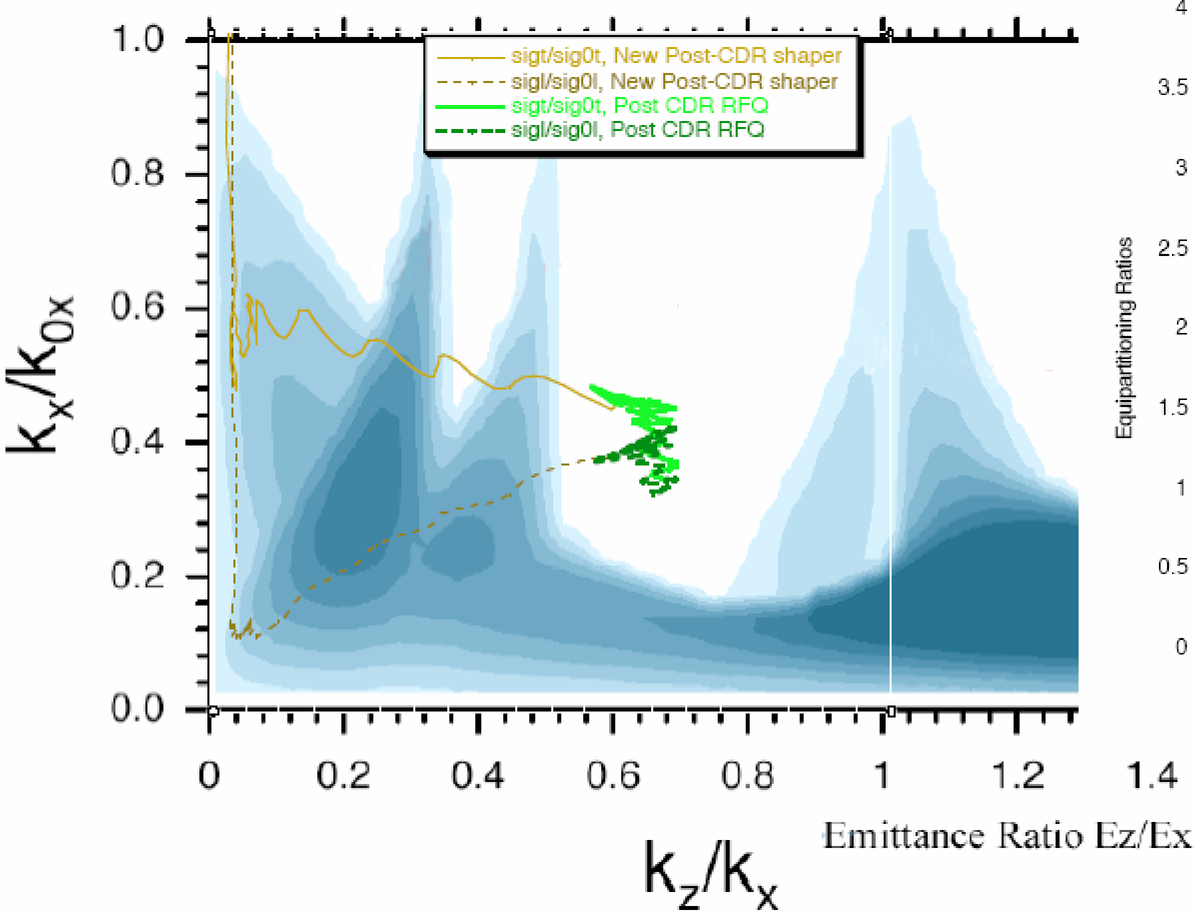


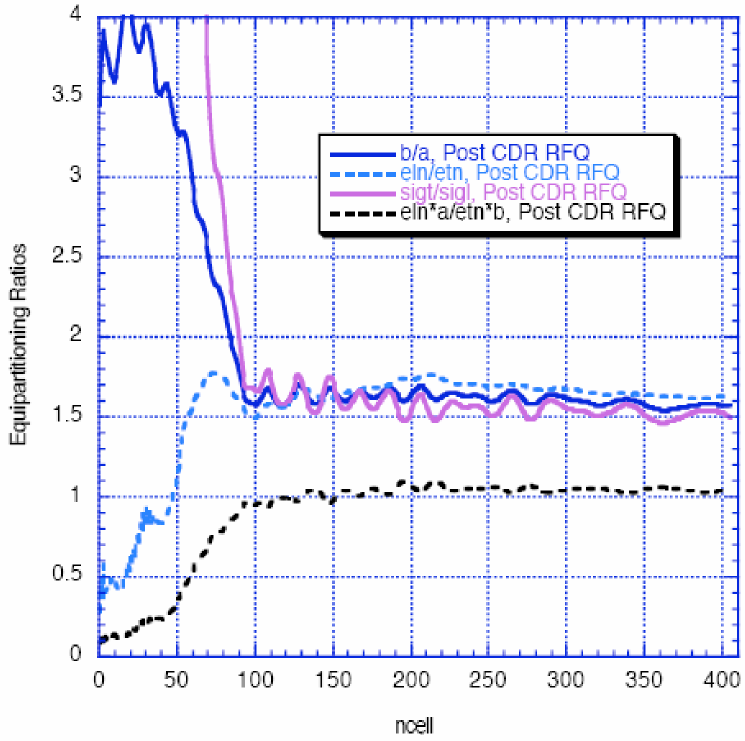
"Stability Charts" for $\varepsilon_z / \varepsilon_{x,y}$=2: CERN SPL study

(F. Gerigk/CERN, 2002)



IFMIF RFQ-design, 2007 (R.A. Jameson)



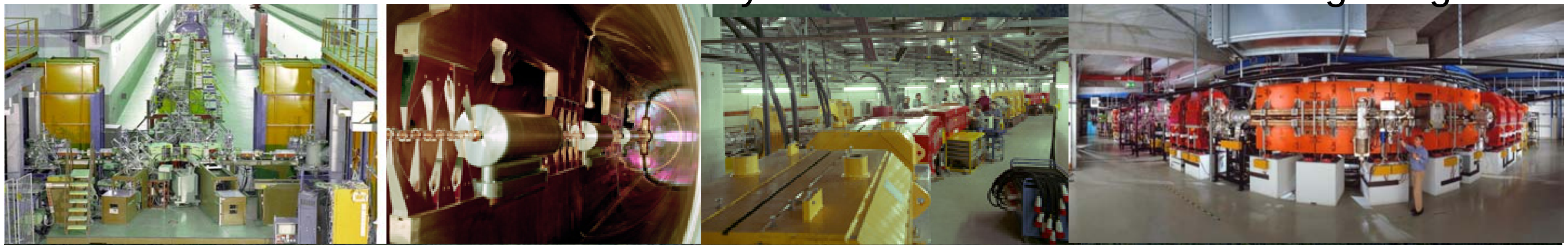


Emittance Ratio Ez/Ex = 1.4

Fig. 6.2-2. Hofmann Chart for eln/etn=1.4, showing the intermediate RFQ trajectory for the shaper and from the EOS to the output, using pteqHI including multipole and image-charge effects.

GSI heavy ion accelerator facility

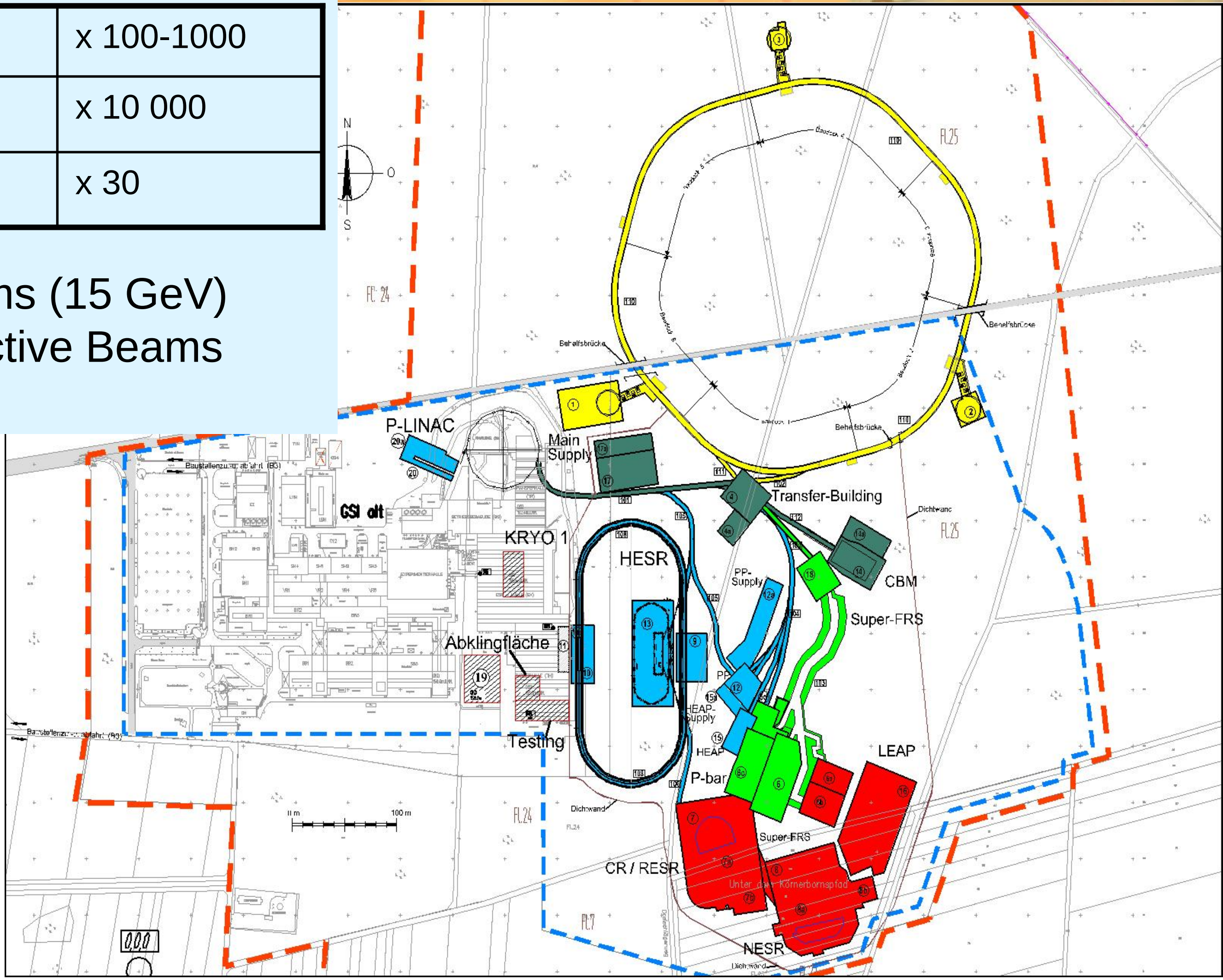
UNILAC Synchrotron SIS18 Cooler storage ring ESR



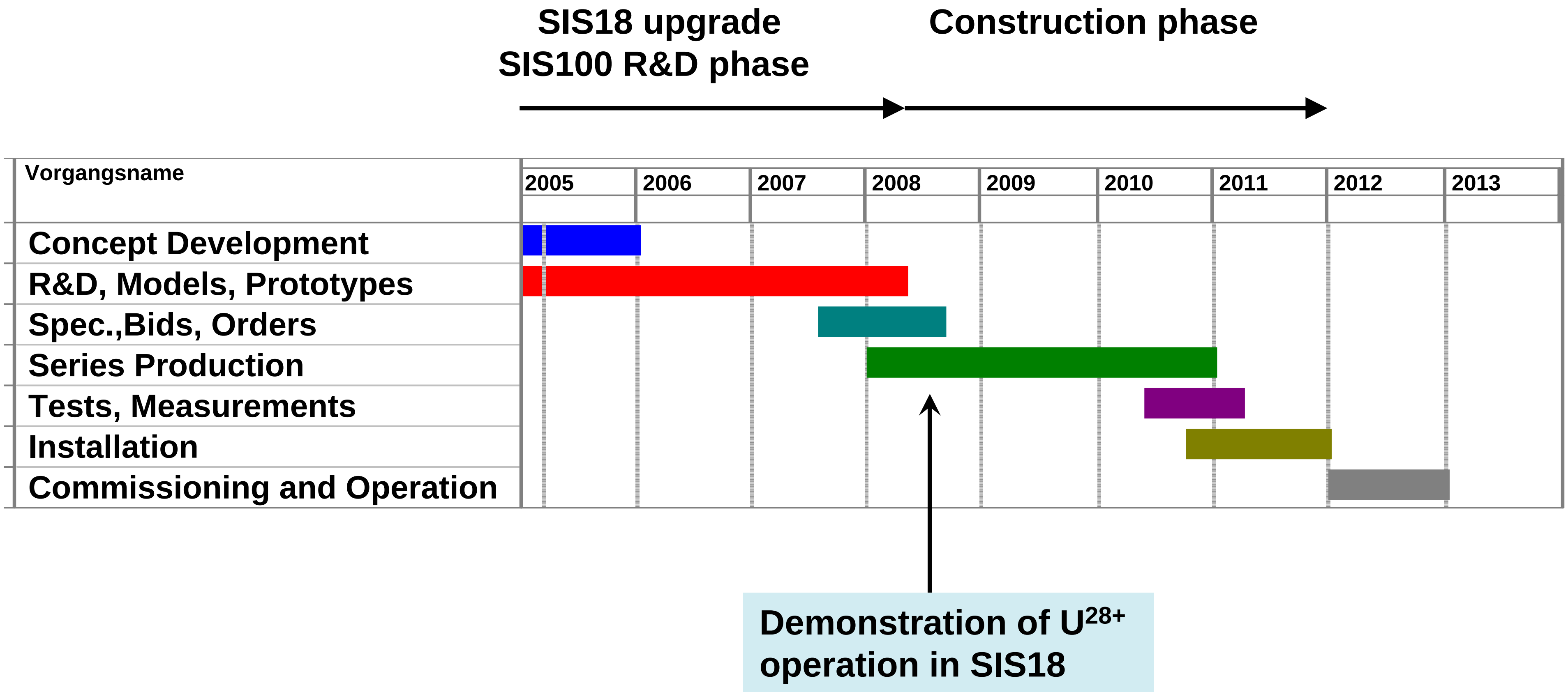
GSI: FAIR Accelerator Facility

Primary Beam Intensity	x 100-1000
Secondary Beam Intensity	x 10 000
Heavy Ion Beam Energy	x 30

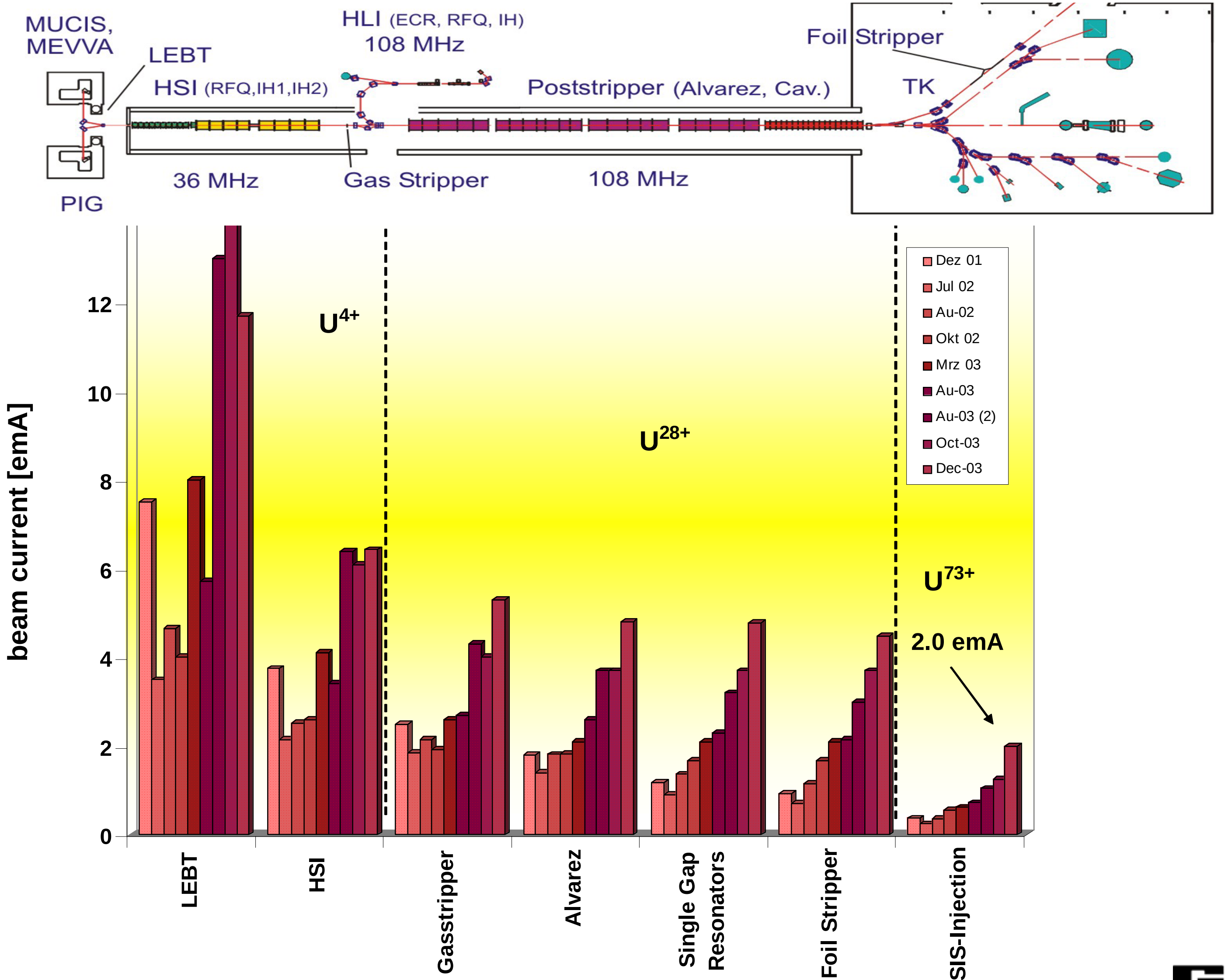
- New: Cooled pbar Beams (15 GeV)
- Intense Cooled Radioactive Beams
- Parallel Operation



SIS100 Project Overview

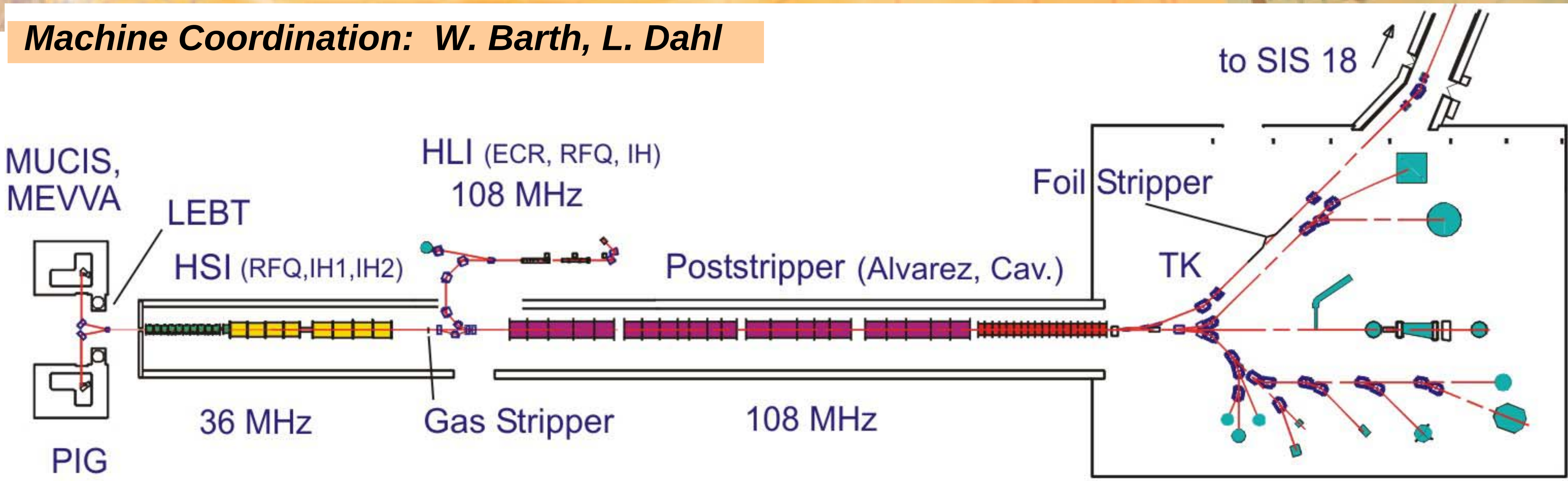


Status – Uranium Beams

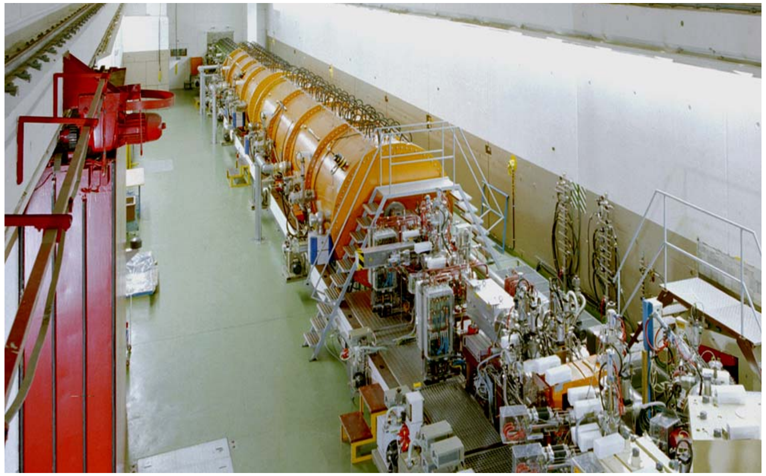


UNIversal Linear ACcelerator

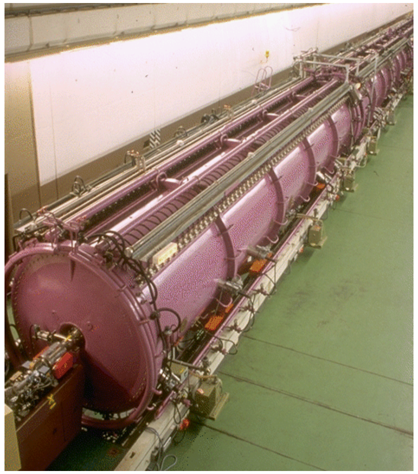
Machine Coordination: W. Barth, L. Dahl



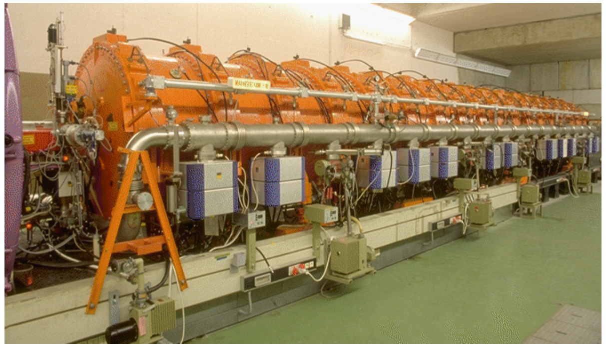
High Current Injector HSI



ALVAREZ



Single Gap Resonators



UNILAC Code Benchmarking for the HIPPI project

A. Franchi, W. Bayer, G. Franchetti, L. Groening, I. Hofmann, A. Orzhekhovskaya, S. Yaramyshev, X. Yin ***GSI Darmstadt***
A. Sauer, R. Tiede, G. Clemente ***IAP, Frankfurt am Main, Germany***
R. Duperrier, D. Uriot ***CEA, Saclay, France***
G. Bellodi, F. Gerigk, A. Lombardi, T. Mütze ***CERN, Geneva, Switzerland***
D. Jeon ***SNS, Oakridge, USA***

- comparison and validation of 3D linac codes in the high current regime using the UNILAC structure
- several codes are available and currently run for such simulations
- static tests of Poisson solvers
- dynamical tests: are tune shifts calculated correctly?
- full tracking with "ideal" input and matching
- full tracking with <u>measured</u> input and matching

Participating linac codes

code (a.o.)	*platform*	*GUI*	*parallel*	*particles*	*s. c. solver*	*boundary conditions*	*CPU time*
DYNAMION	Windows (Li)Unix	no	no	$5x10^3$	3D p-p		1.3 days 2.5 days
HALODYN	(Li)Unix	post	yes	$1x10^6$	3D PIC	closed	1.0 day
IMPACT	(Li)Unix	no	yes	$1x10^6$	3D PIC	open closed	4.0 days 2.5 days
LORASR	Windows	yes	no	$1x10^6$	3D PIC	closed	N.A.
PARMILA	Windows	post	no	$1x10^5$	2D PIC 3D PIC	open	1.5 days 7.0 days
PARTRAN	Windows	post	no	$1x10^5$	3D PIC	open	6.0 days
PATH	Windows	yes	no	$1x10^5$ $2x10^4$	2D PIC 3D p-p	open	1.5 days 1.5 days

Table 1: Summary table with an indication of the requested CPU time for different choice of solvers and boundary conditions. See text for the discussion on the choice of the number of macro-particles, the integration step and grid resolution. All the codes having a post-processor for the graphical analysis are labeled with "post" in the GUI entry.

Static tests of space charge field accuracy

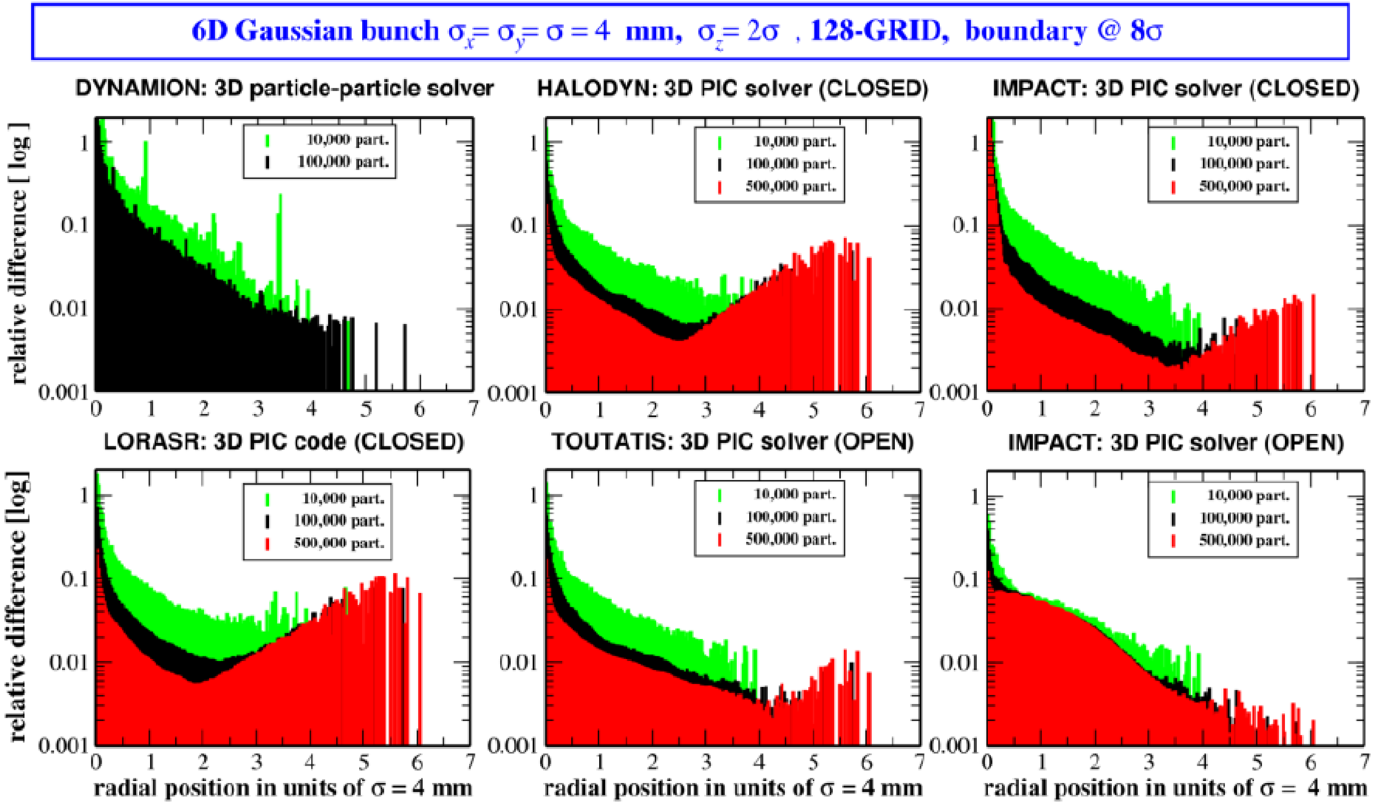


Figure 3 Field error δE/E for DYNAMION and PIC codes with a grid resolution of 128^3 (129^3)

Dynamical tests - ideal input (Gaussian distribution)

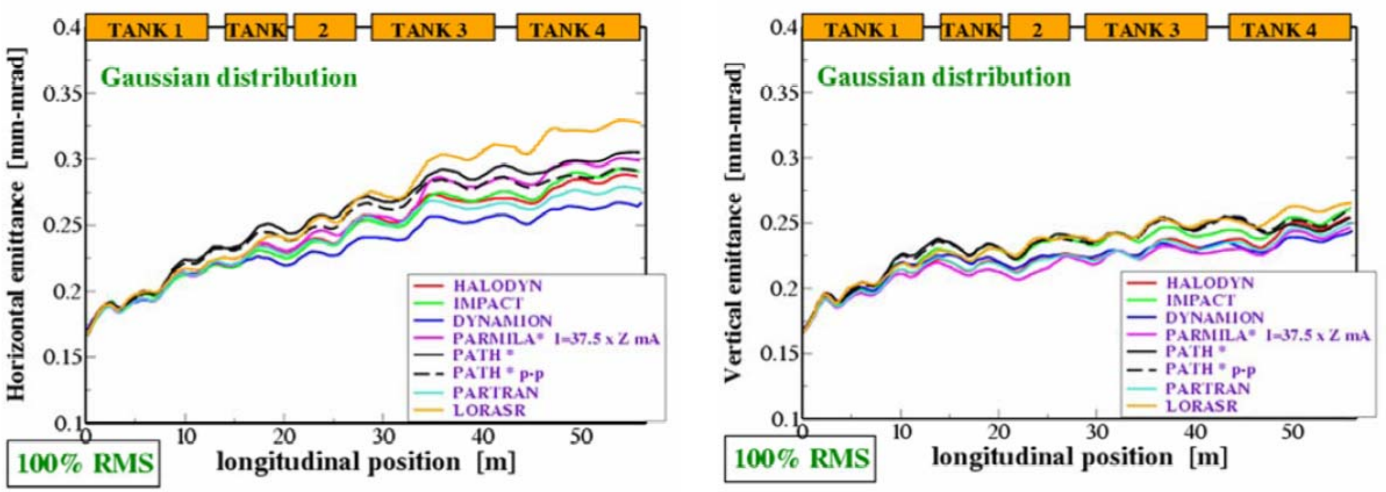


Figure 20 CASE 2: normalized transverse RMS emittance computed by all the codes along the DTL.

for most codes (except LORASR) < +/- 10% deviation in transverse emittance
→ good enough for comparison with experiment

Longitudinal: problem is bucket containment: lost particles treated differently

before after code adjustments

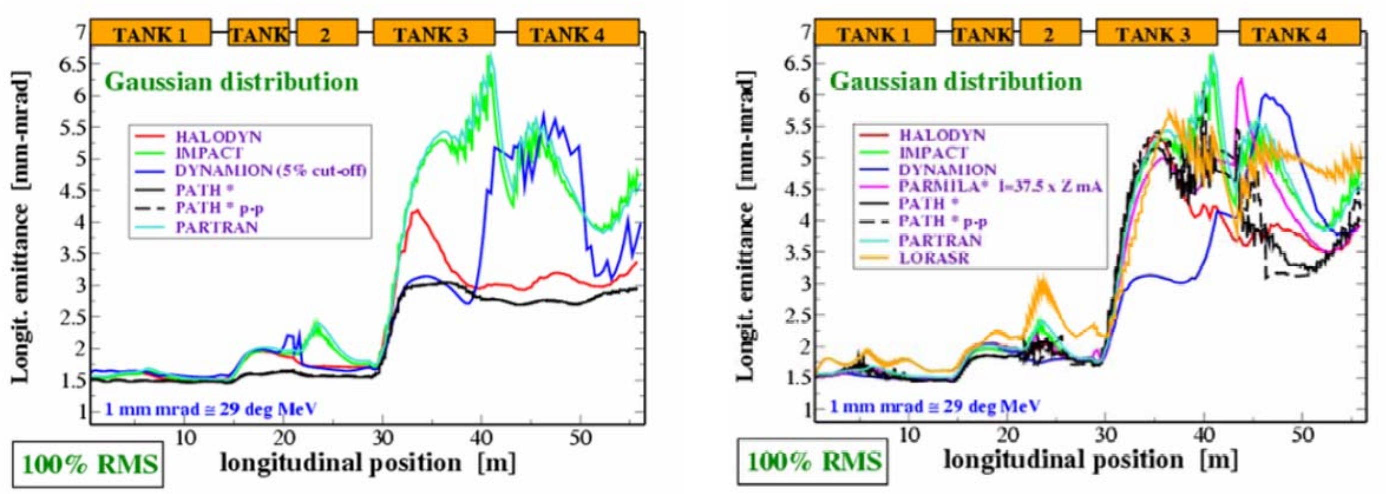


Figure 21 CASE 2: normalized longitudinal RMS emittance computed by all the codes along the DTL, before the code adjustments (left) and after (right).

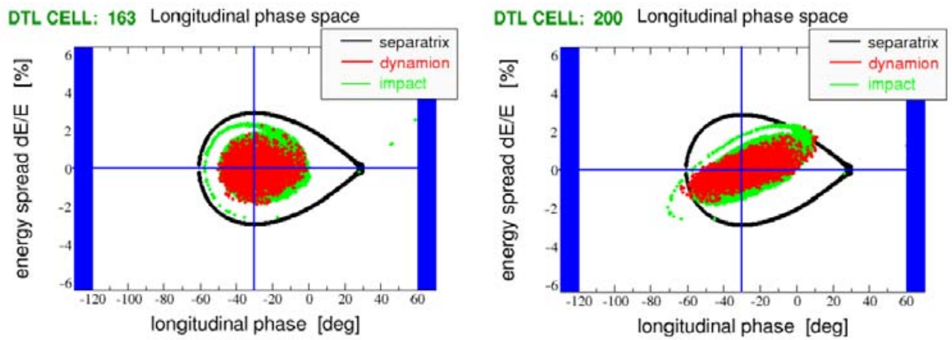
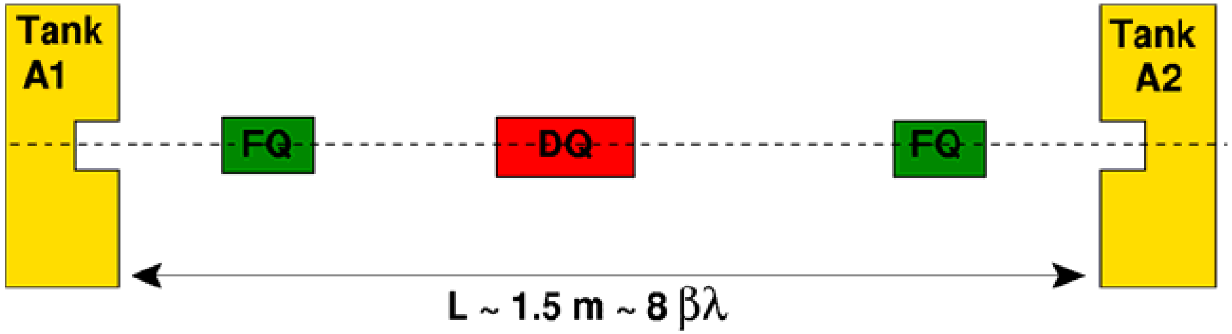
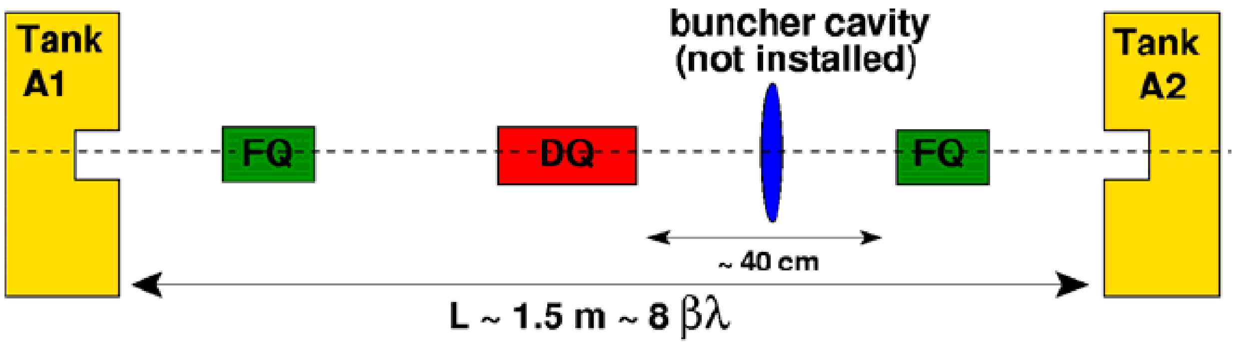


Figure 23 CASE 2: Longitudinal phase space at the exit of tank 1 (left) and at the entrance of tank 2A (right), as simulated by IMPACT (10^6 macro-particles) and DYNAMION ($5x10^3$ particles).

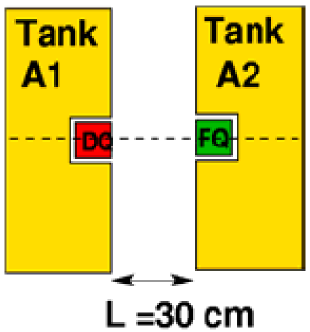
We found that inter-tank 1-2 is too long
and causes lack of longitudinal focusing



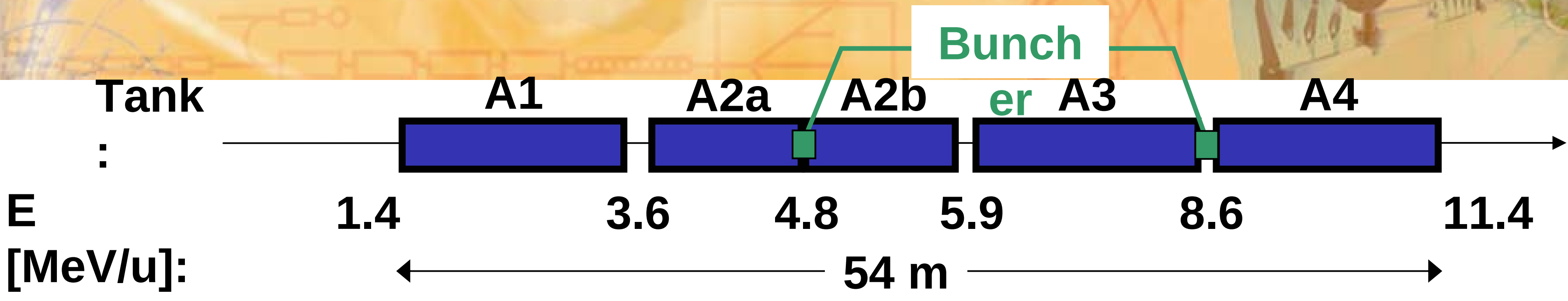
possible cures:



preferrable:



Parameters of UNILAC Alvarez DTL



5 independent rf-tanks + 2 bunchers

108 MHz, 50 Hz, 5 ms

192 rf-cells

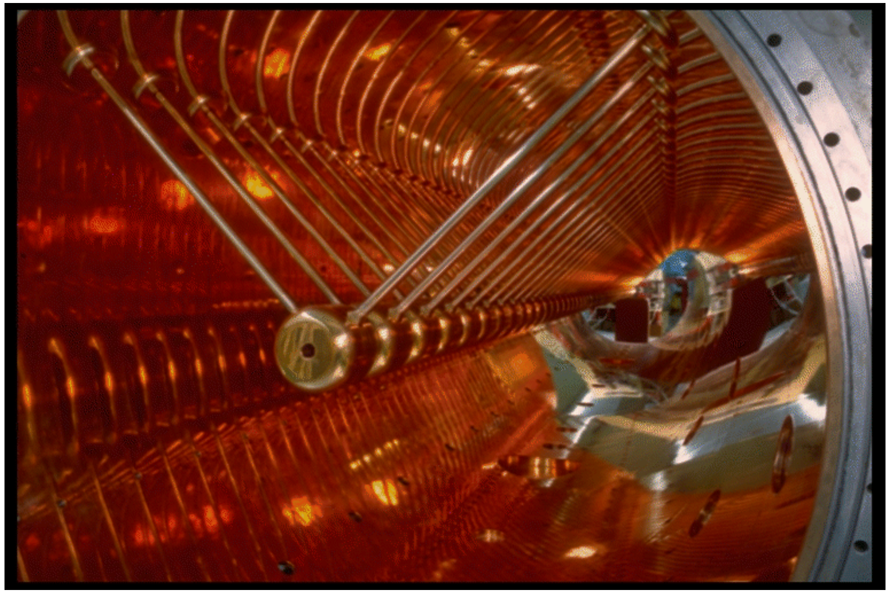
DTL based on F-D-D-F focusing

dc-quads grouped to 13 families

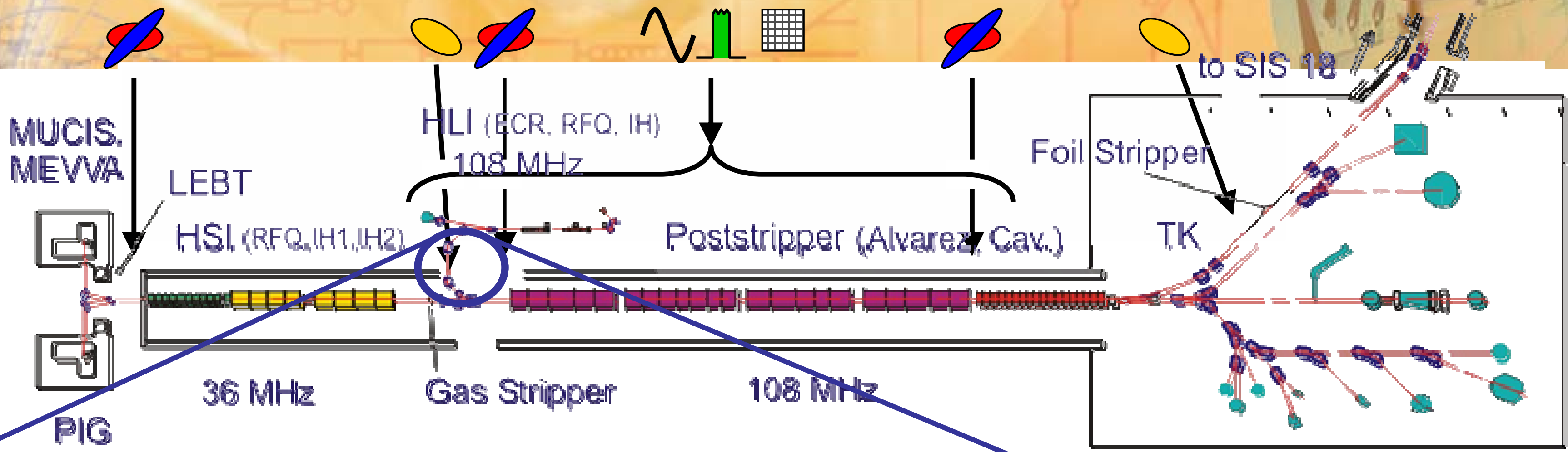
Inter-tank focusing : F-D-F

Transv. acceptance (norm.) = 15 μm

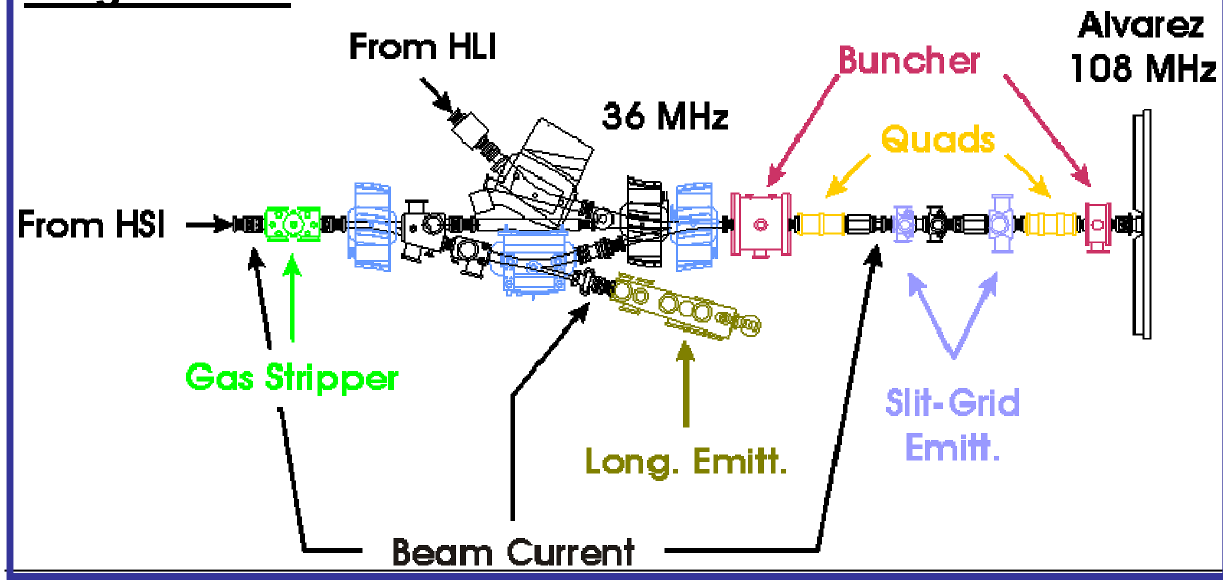
Synchr. rf-phases -(30°,30°,30°,25°,25°)



Overview of Beam Diagnostics Equipments



Stripper & matching section with selected beam diagnostics



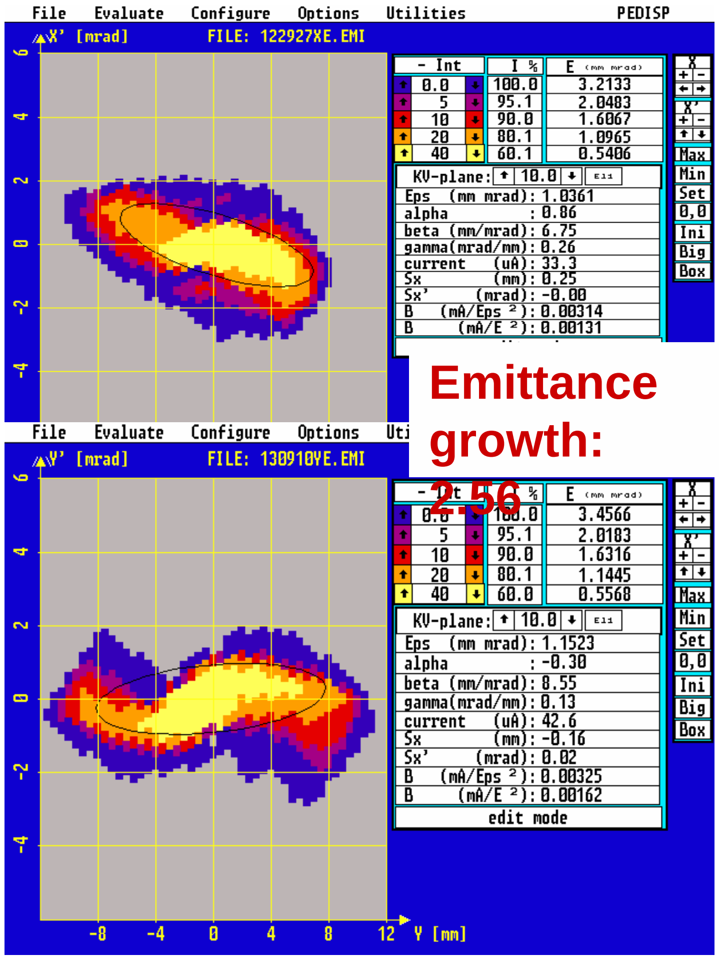
Beam diagnostic devices:

- transverse emittance
- longitudinal emittance
- phase probe
- beam current transform
- beam profile grid

(1 emA $^{40}Ar^{10+}$)

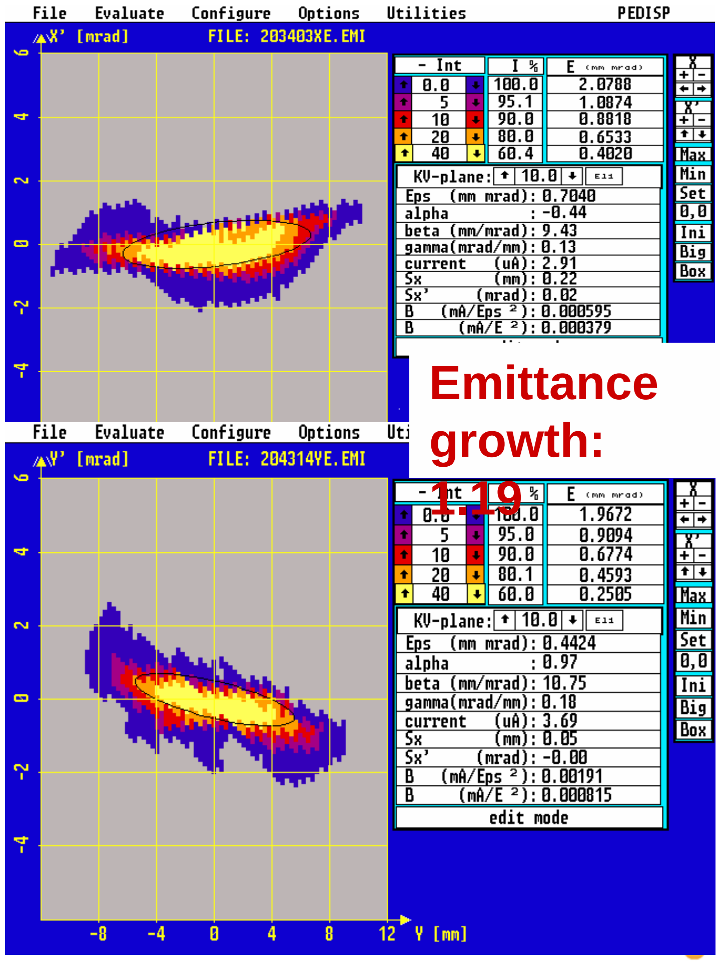
Results of HIPPI I (Sept. 2006): Transv. Emittance *After* DTL

Before optimisation:



Emittance growth: 2.56

After optimisation:

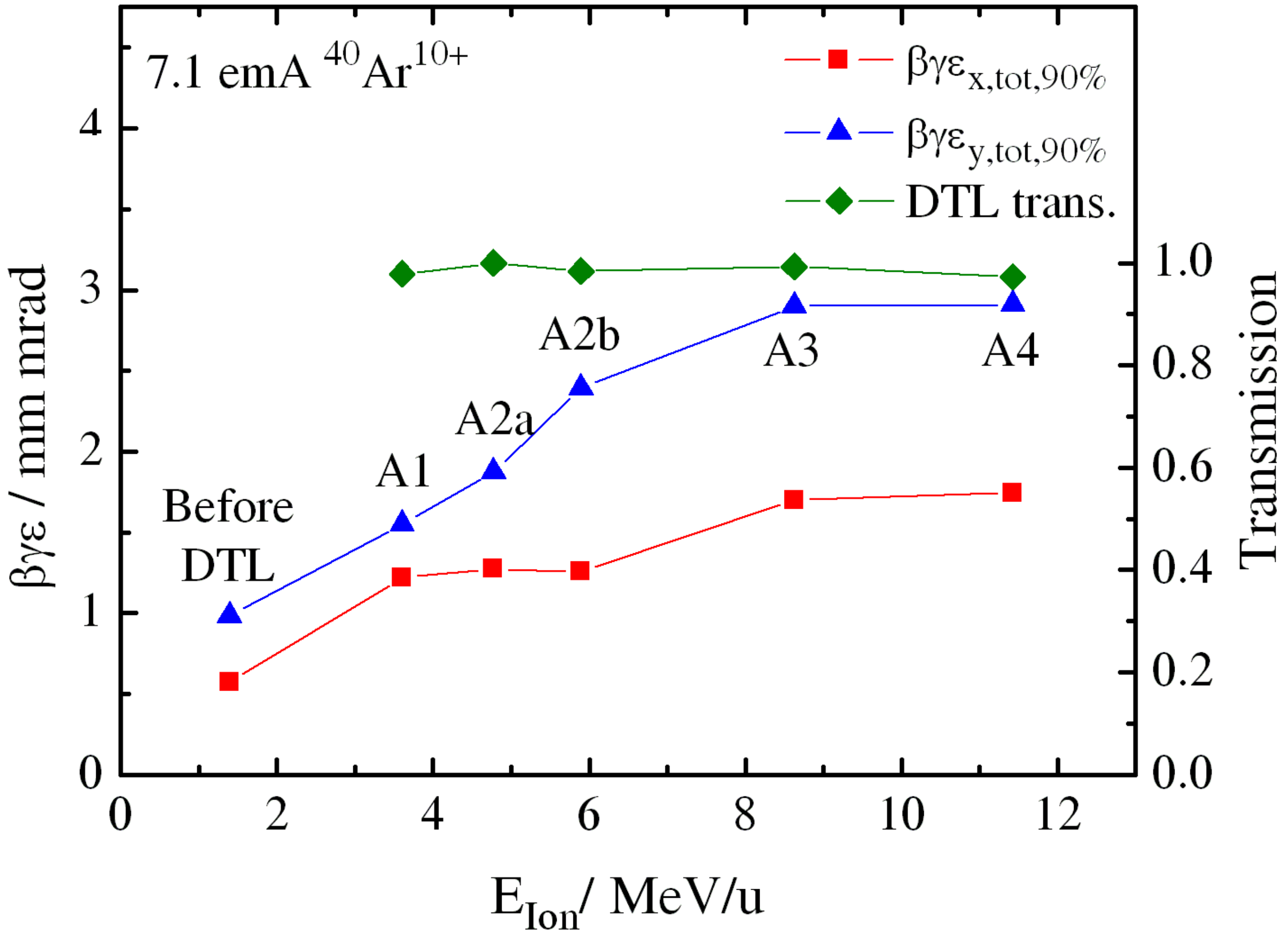


Emittance growth: 1.19

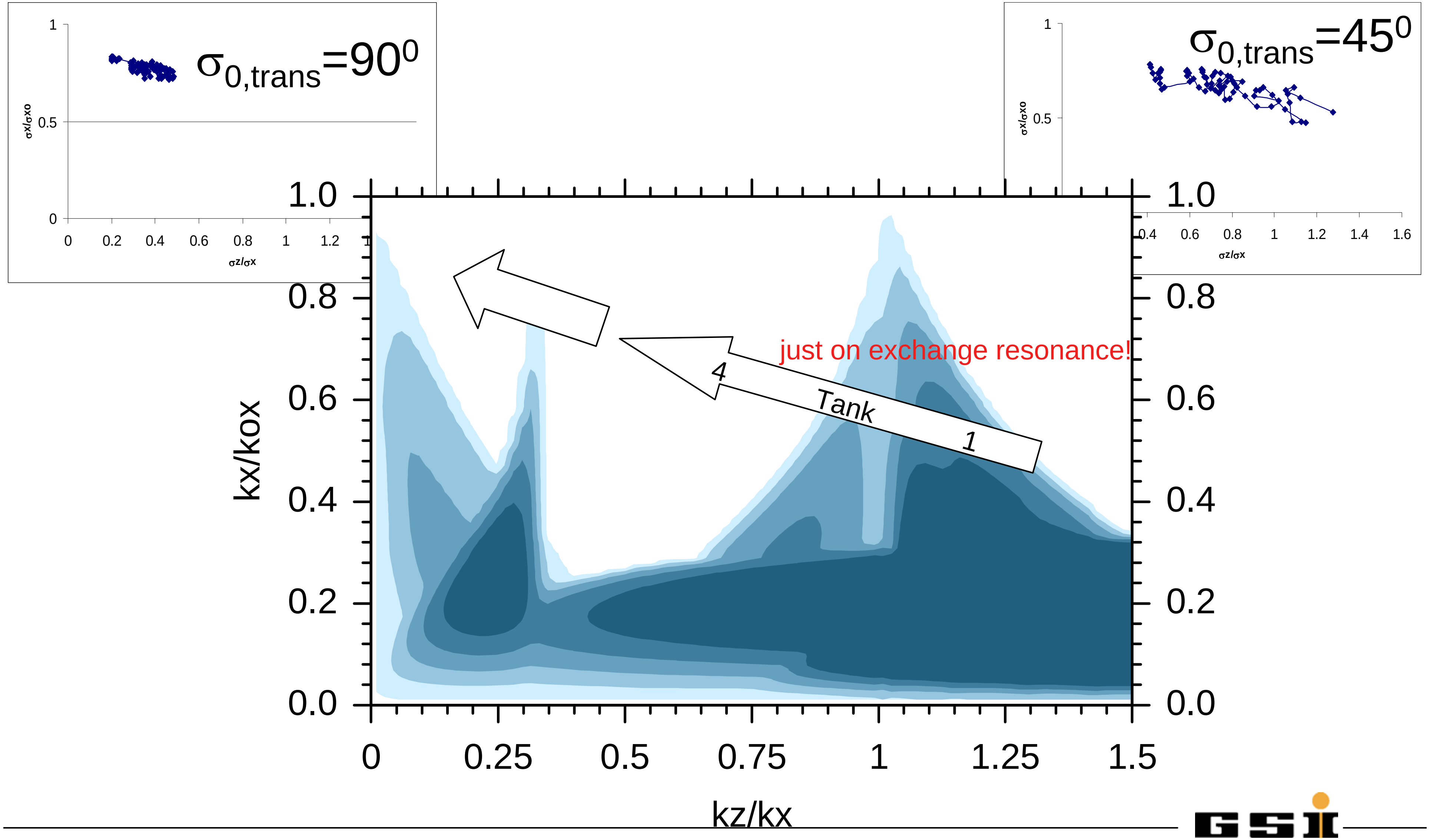
Results of HIPPI II: Beam Energy & Emittance

(7.1 emA $^{40}Ar^{10+}$)

undesirable emittance growth → injection loss into SIS18

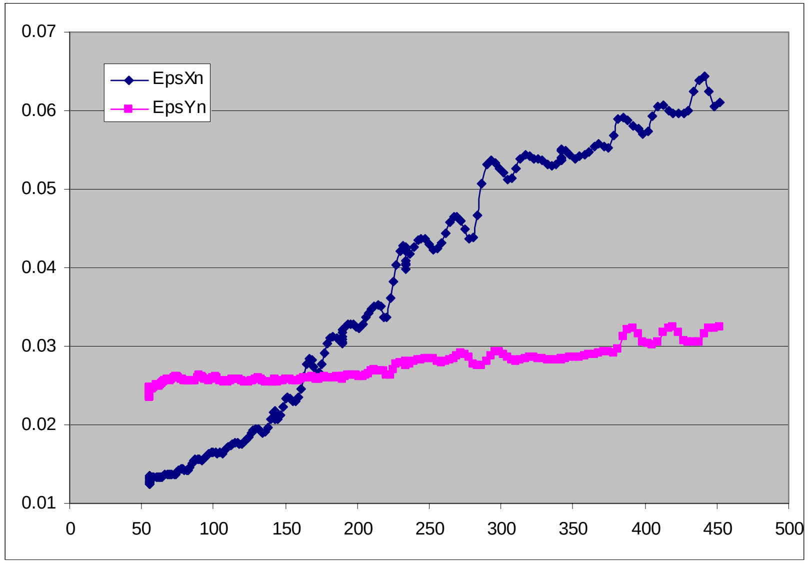


Parmila simulations through UNILAC-Drift tube linac



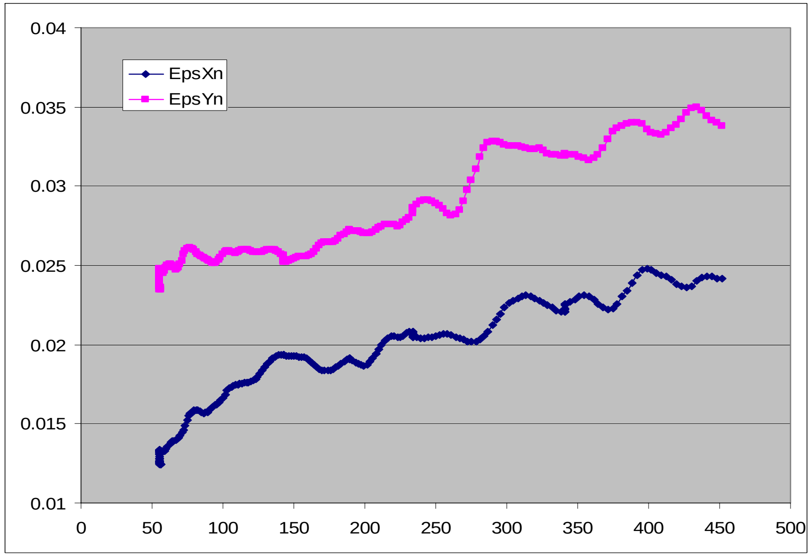
4-th order structure resonance

$\sigma_{0,trans}=90^0$

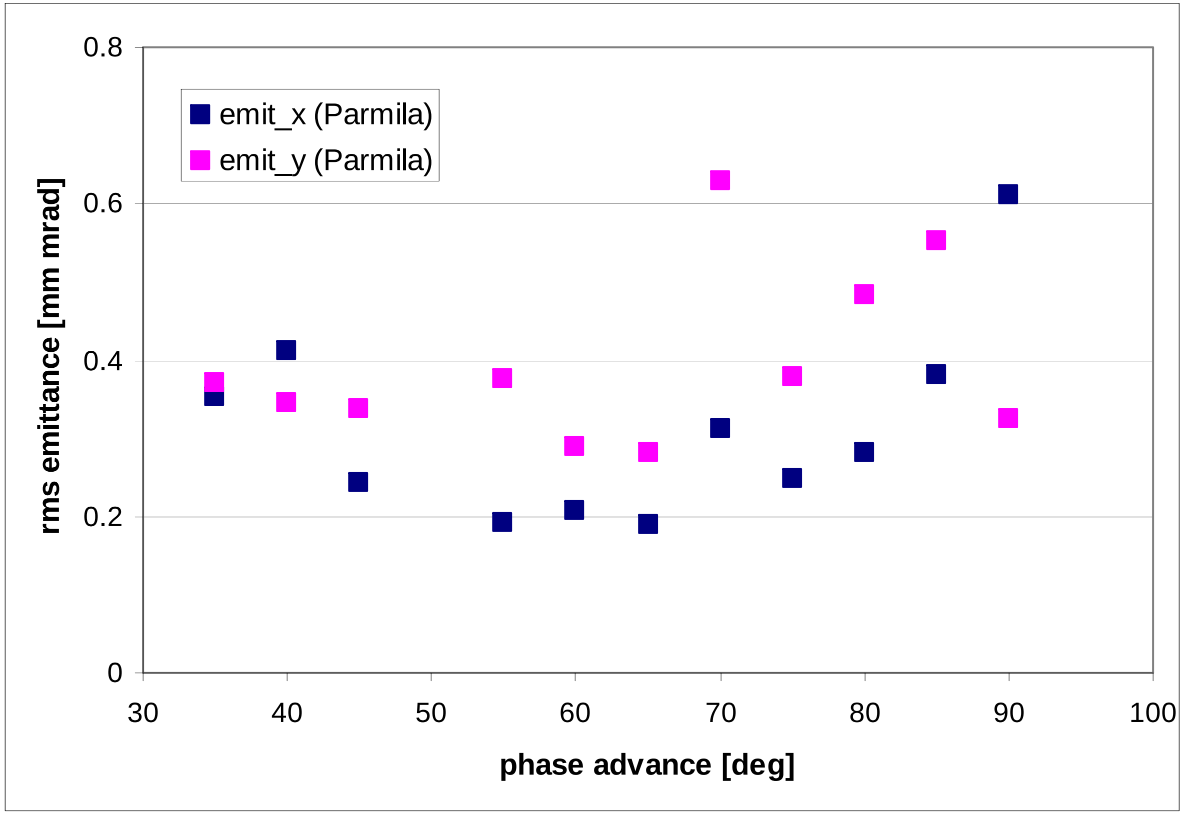


long.-trans. emittance coupling

$\sigma_{0,trans}=45^0$



Predict minimum around $\sigma_{0,trans}=60^0$



preliminary confirmation by experiments – work in progress

Conclusion

- Code benchmarking (space charge effects) with UNILAC of mutual benefit for HIPPI and GSI-FAIR
- in principle "complete" set of diagnostics
- code deviations sufficiently small (<10%) if no loss from bucket
- first experiments done – under evaluation
- evidence for resonant emittance growth phenomena
  - emittance exchange
  - structure resonance
  - mismatch emittance growth
- need another cycle to eliminate uncertainty on longitudinal data