Commissioning and Operation of the 1.5 GeV Harmonic Double-Sided Microtron at Mainz University

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magazzini del cotone
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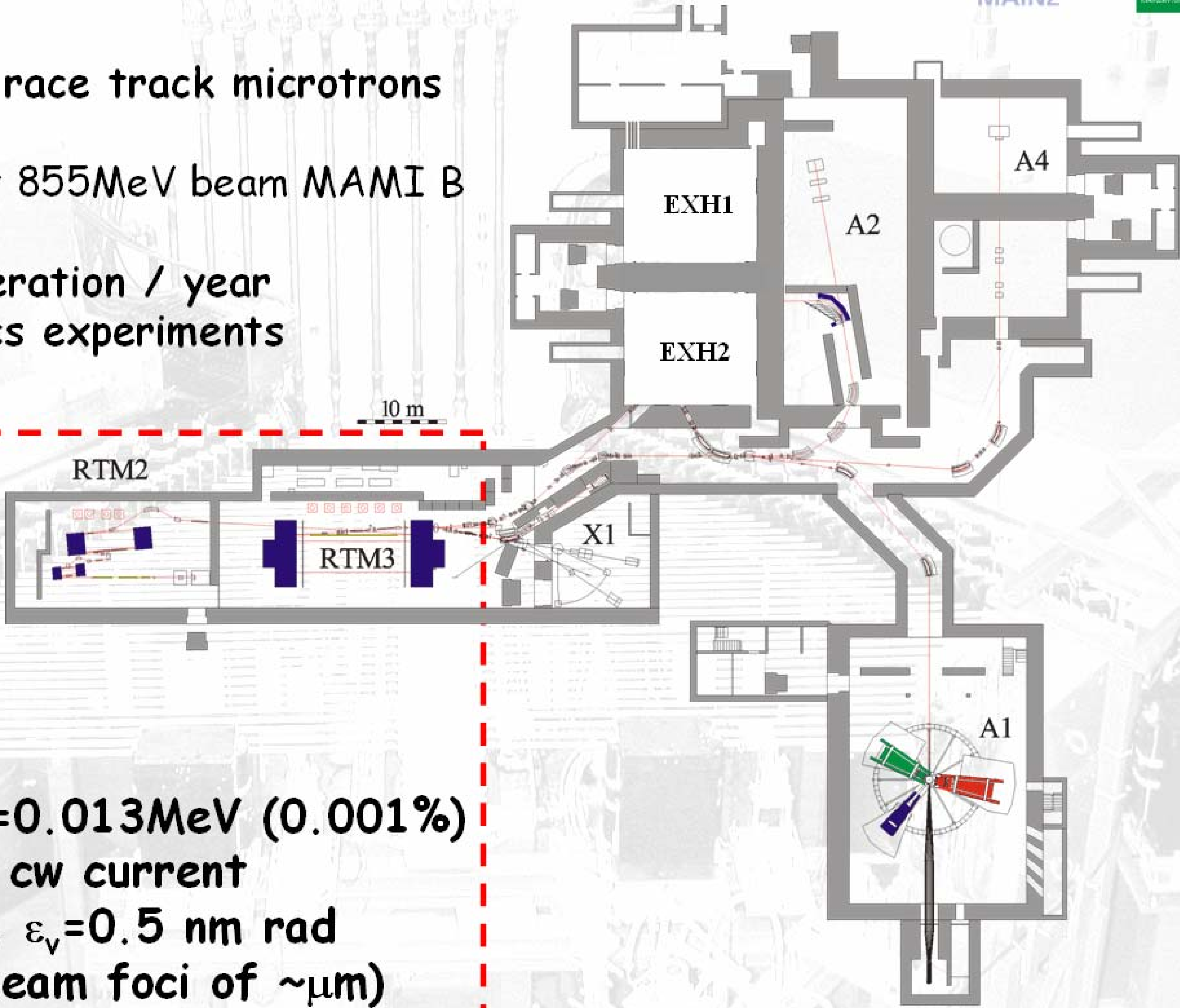
- **Short Introduction: The Mainz Microtron MAMI**
- **Harmonic Double-Sided Microtron (HDSM) Design**
  dipoles with field gradient, harmonic rf-system
- **Construction**
  dipole field correction, 4.90GHz rf-systems
- **Commissioning**
  first beam, first beam measurements, first experiment
- **Operation**
  beam parameters, operation statistic
- **Future Prospects**

The Mainz Microtron MAMI B

cascade of three race track microtrons

10.08.1990: first 855MeV beam MAMI B

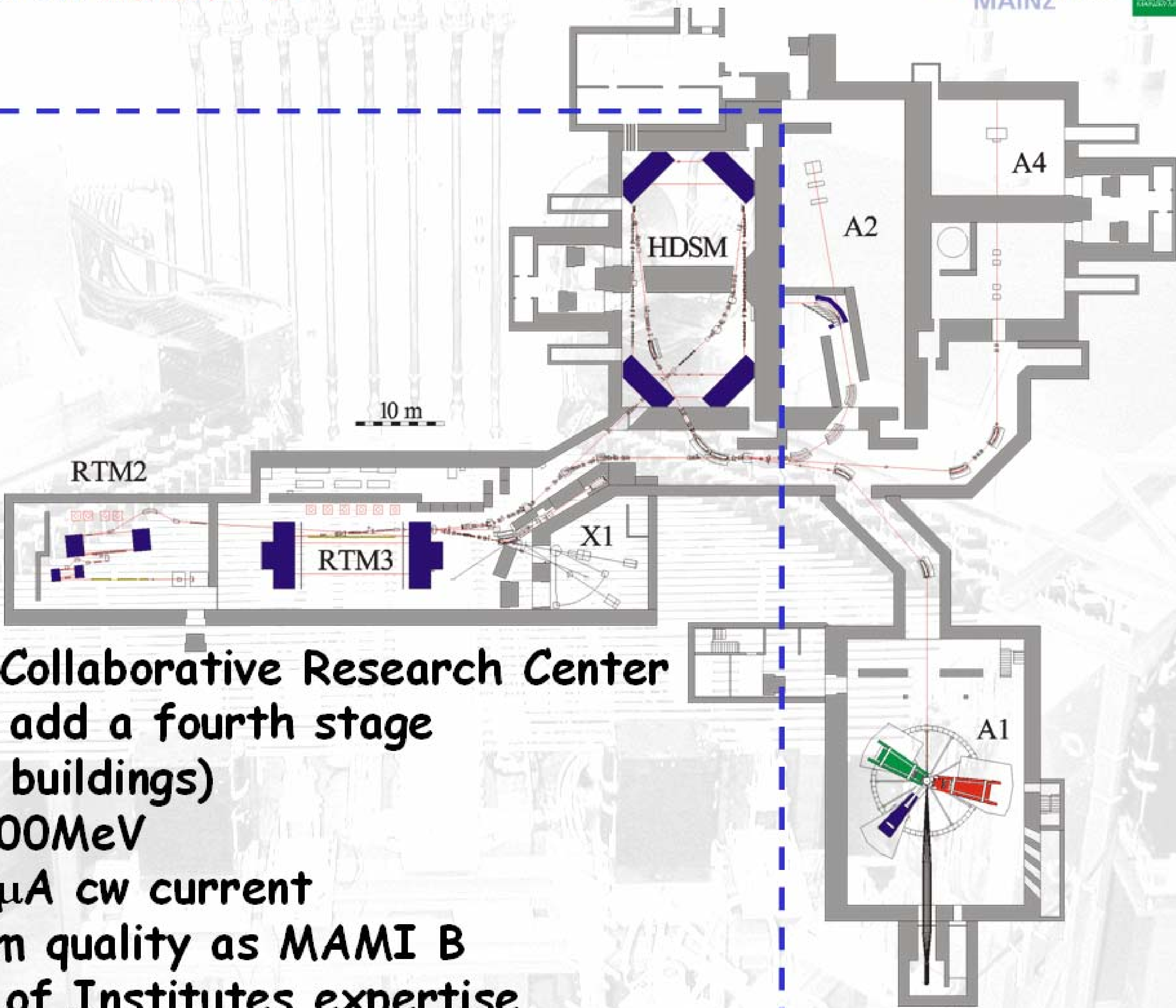
6000 – 7000h operation / year
for nuclear physics experiments



- 883MeV, σ_E=0.013MeV (0.001%)
- max. 103μA cw current
- ε_h=8 nm rad, ε_v=0.5 nm rad
  (allows for beam foci of ~μm)
- Halo: < 10^{-5} at r > $5 \cdot \sigma_r$

The Mainz Microtron MAMI B, RTM3

The Mainz Microtron MAMI C



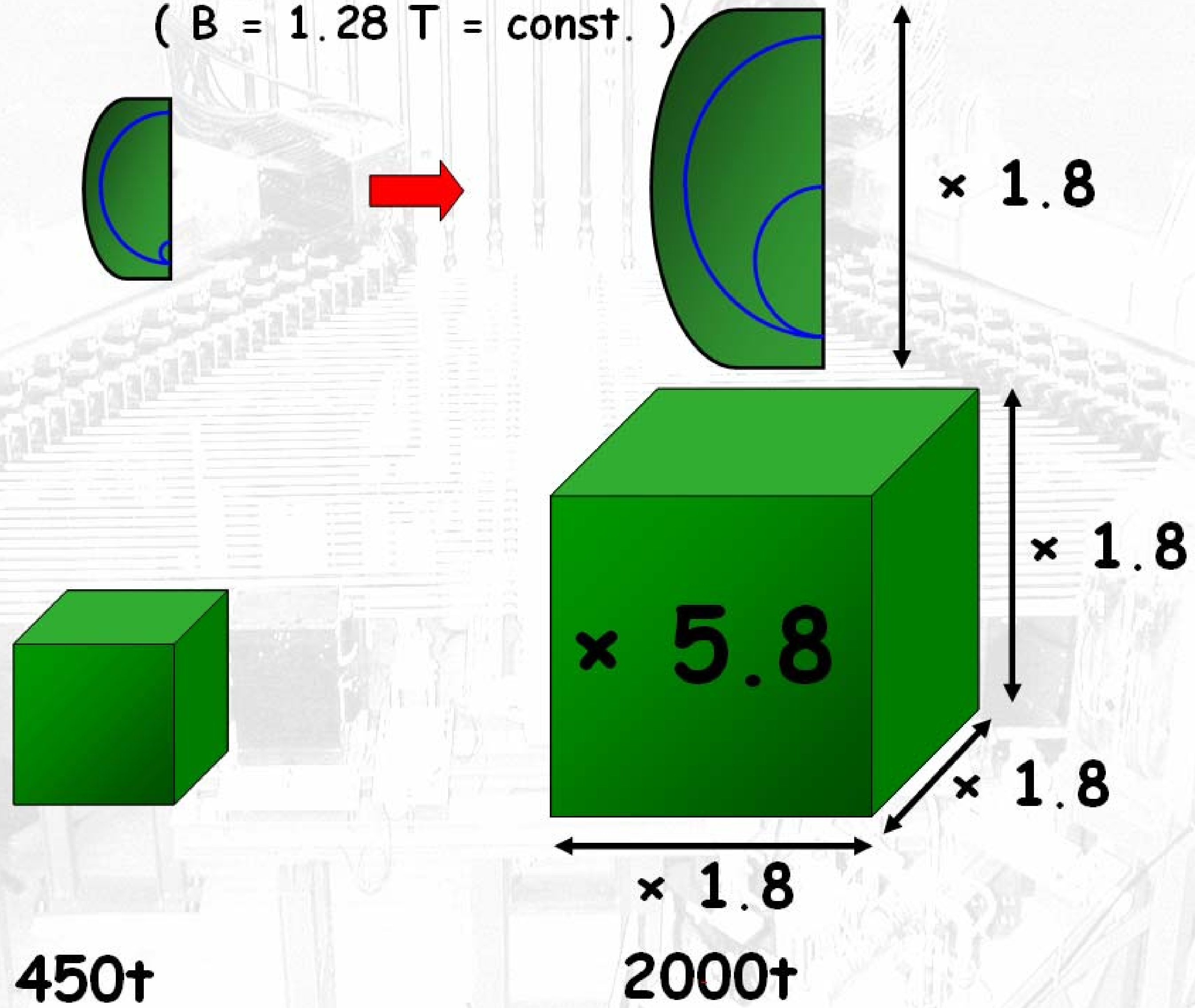
1999: new Collaborative Research Center
Decision to add a fourth stage
(in existing buildings)

- goal: ~1500MeV
- max. 100μA cw current
- same beam quality as MAMI B
- make use of Institutes expertise (nc-cw linac structures, magnet design)

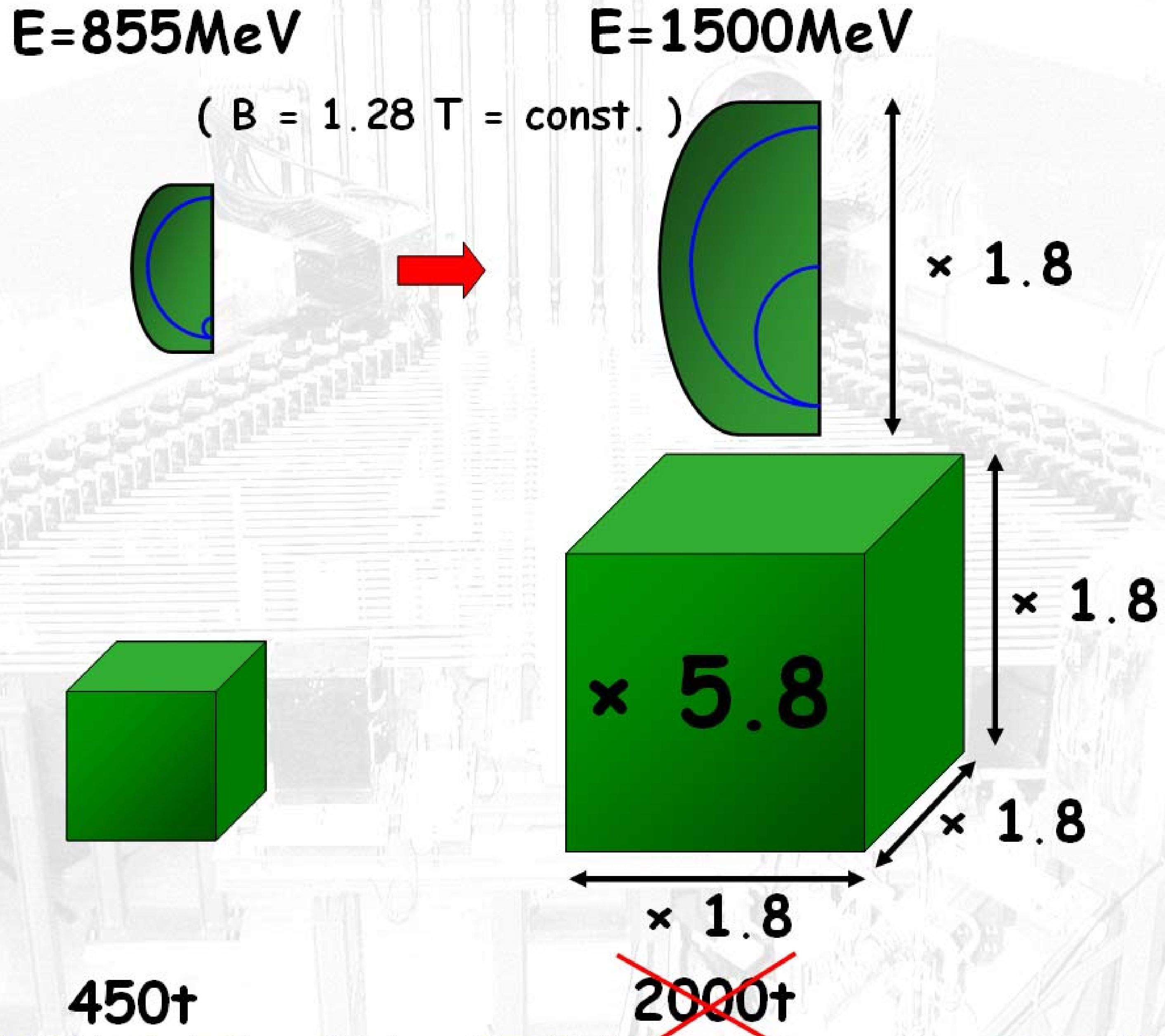
A fourth race track microtron ?

E=855MeV E=1500MeV

(B = 1.28 T = const.)



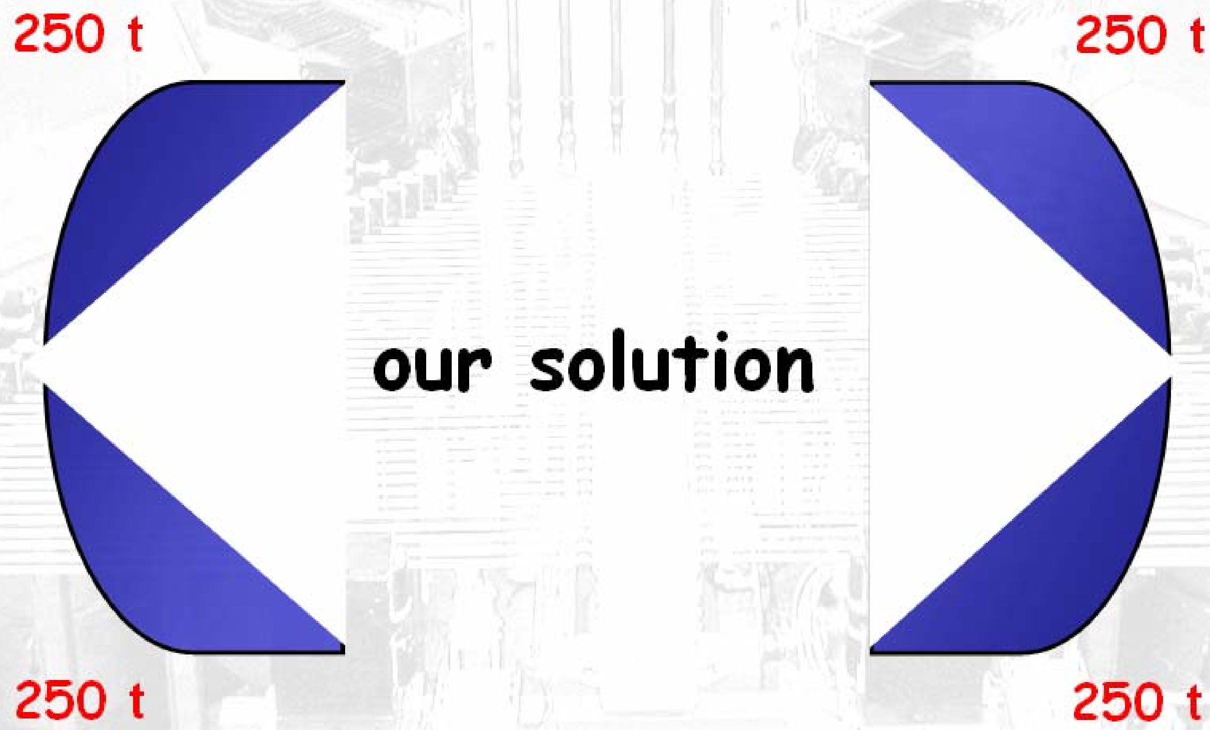
A fourth race track microtron ?



Double Sided Microtron
(K.-H. Kaiser)

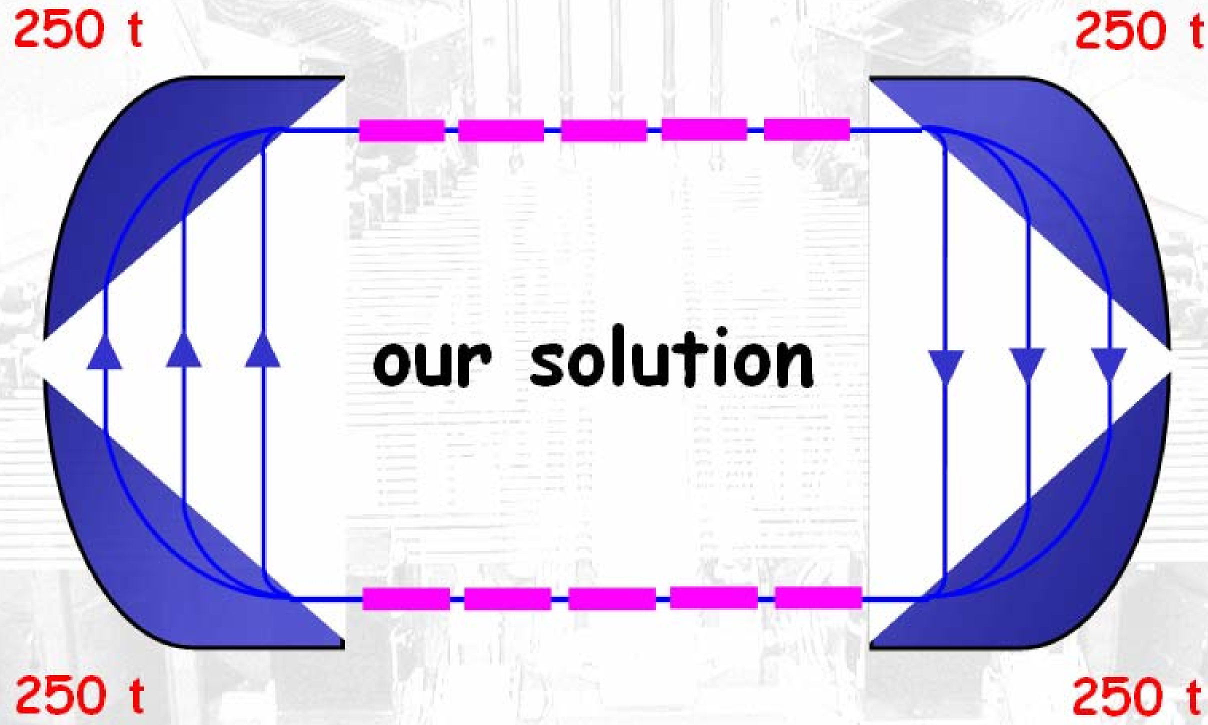
HDSM Design

Double Sided Microtron
(K.-H. Kaiser)



Double Sided Microtron

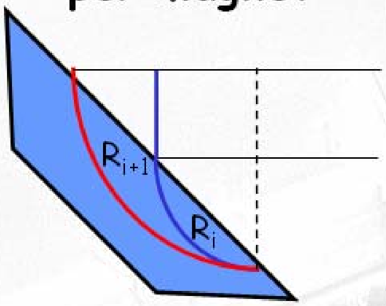
(K.-H. Kaiser)



43 turns, 855MeV → 1500MeV

dynamic coherence condition of a DSM:
path length increase from turn to turn must be equal to 2×λ

per magnet



$$\Delta E = \lambda \cdot \frac{e \cdot c \cdot B}{\pi - 2}$$

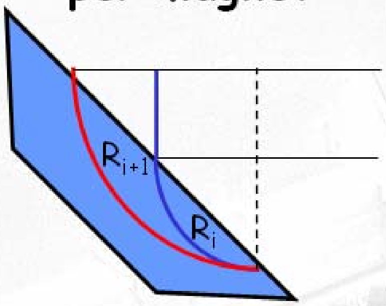
$$\left\{ \frac{2\pi}{4} (R_{i+1} - R_i) - (R_{i+1} - R_i) \right\} \cdot 4 = 2 \cdot (\pi - 2) \cdot \Delta R = 2 \cdot \lambda$$

phase advance / turn must be 2×2π in a DSM !

e.g.: B=1.28T, λ=0.1224m (2.45GHz) ⇒ ΔE=41.1MeV
(with nc cw-sections: linac ~ 45m)

dynamic coherence condition of a DSM:
path length increase from turn to turn must be equal to $2\times\lambda$

per magnet



$$\Delta E = \lambda \cdot \frac{e \cdot c \cdot B}{\pi - 2}$$

$$\left\{ \frac{2\pi}{4} (R_{i+1} - R_i) - (R_{i+1} - R_i) \right\} \cdot 4 = 2 \cdot (\pi - 2) \cdot \Delta R = 2 \cdot \lambda$$

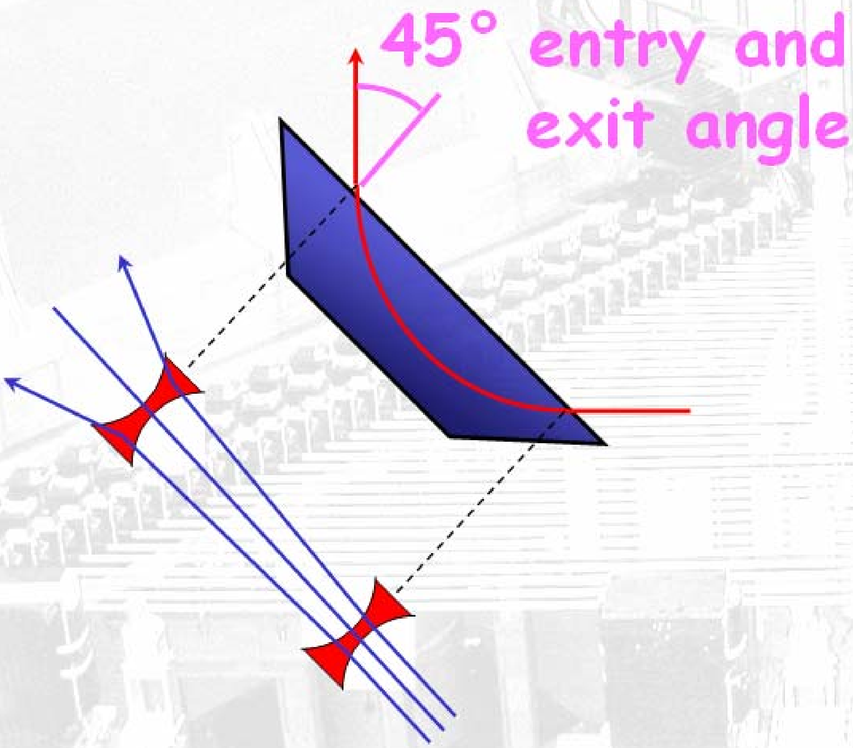
phase advance / turn must be $2\times2\pi$ in a DSM !

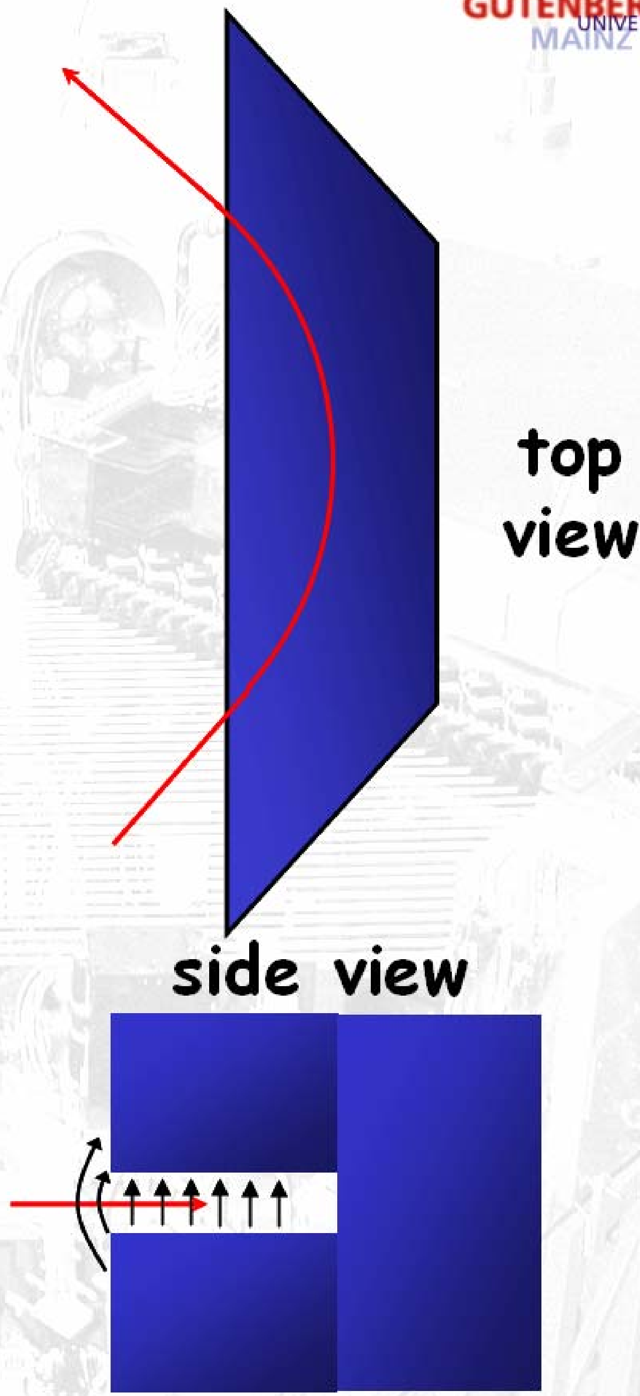
e.g.: $B=1.28T$, $\lambda=0.1224m$ (2.45GHz) $\Rightarrow \Delta E=41.1MeV$
(with nc cw-sections: linac ~ 45m)

Therefore here: $\lambda_{DSM}=0.5 \cdot 0.1224m \Rightarrow \Delta E=20.5MeV$
(linac ~ 20m)

The fundamental frequency of the DSM must be 4.90GHz instead of 2.45GHz !

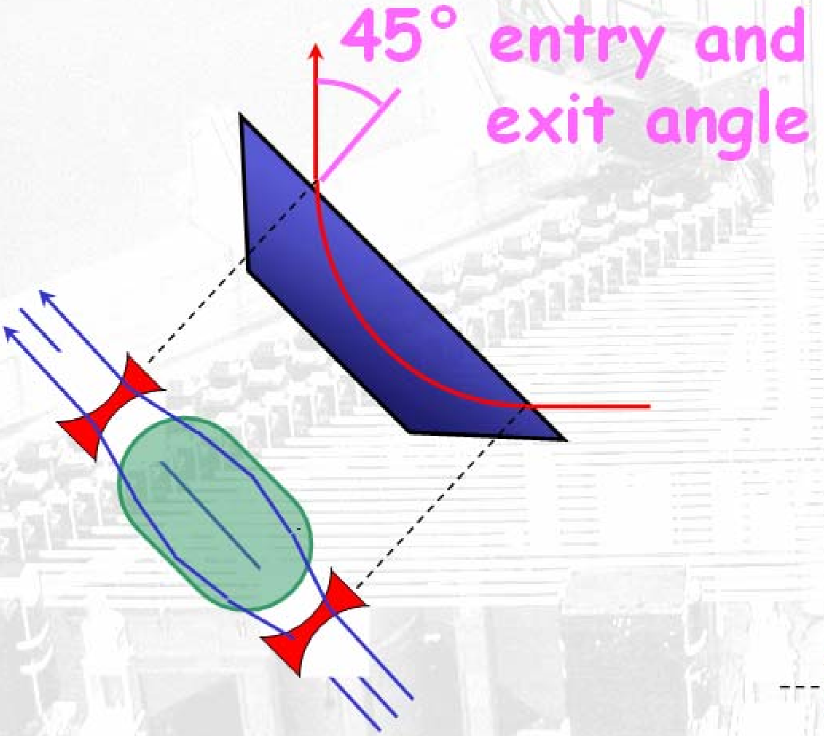
compensation of vertical fringe-field defocusing ?



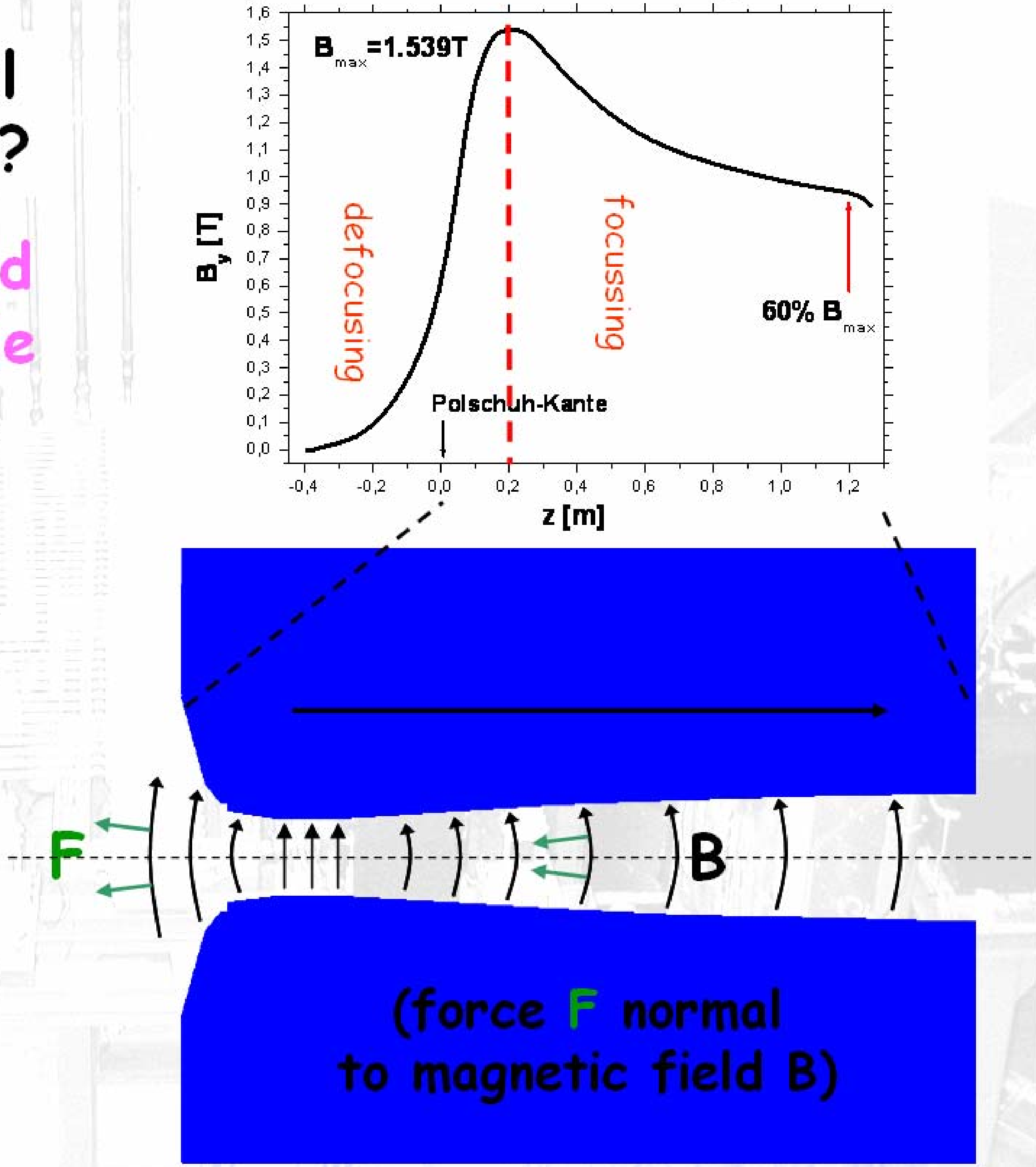


HDSM Design, field gradient

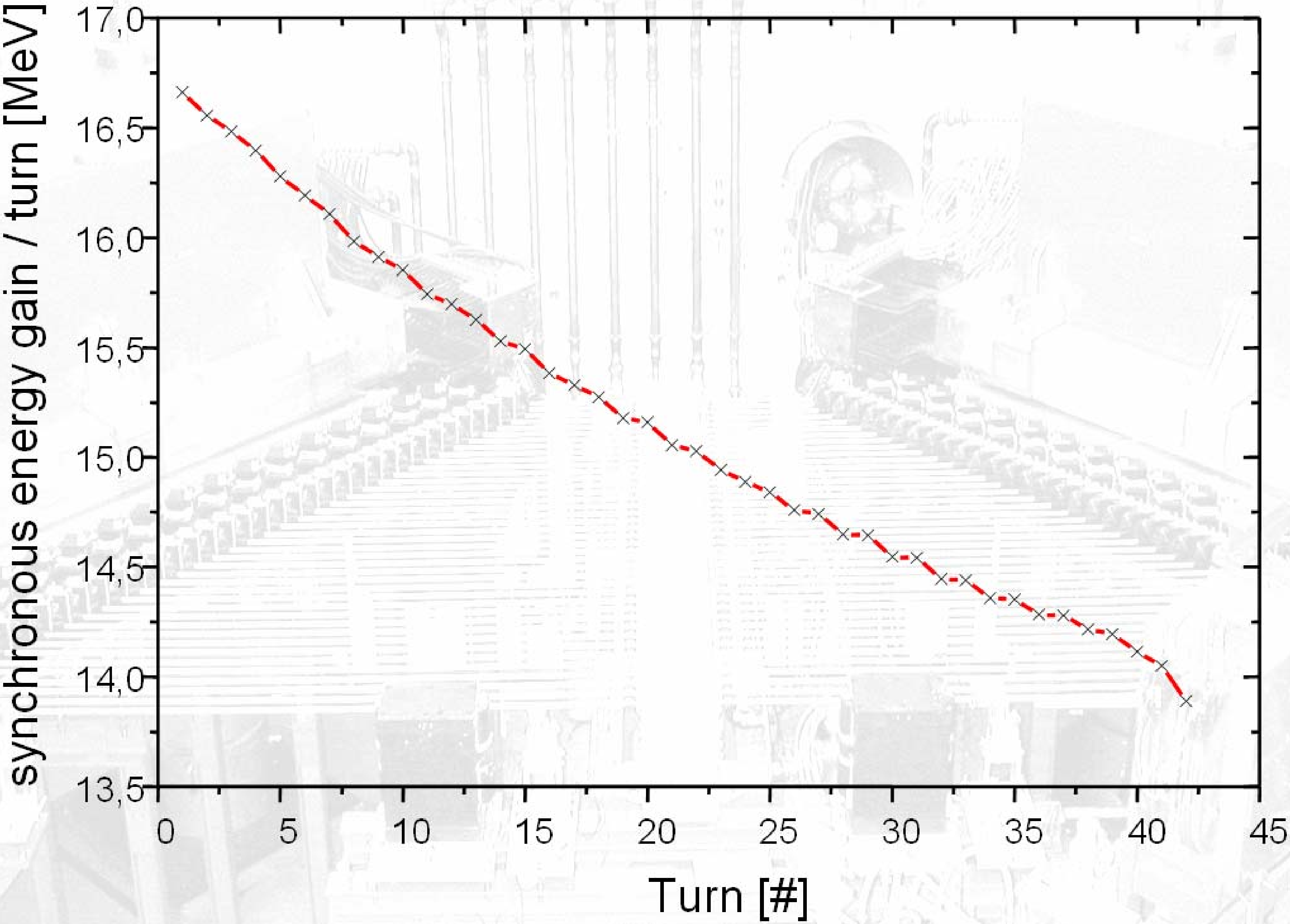
compensation of vertical fringe-field defocusing ?



dipole with field-gradient

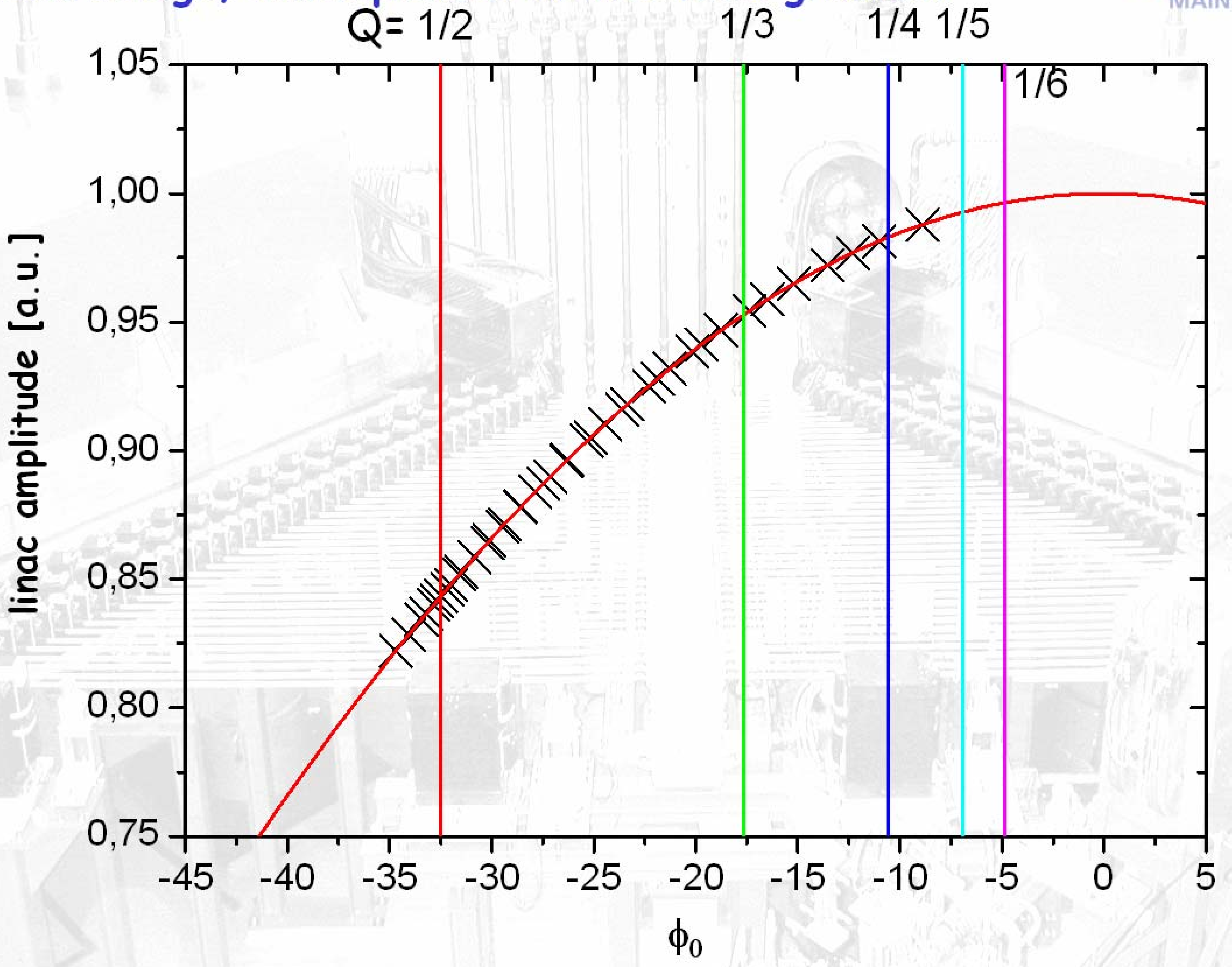


HDSM Design, consequences of the field gradient

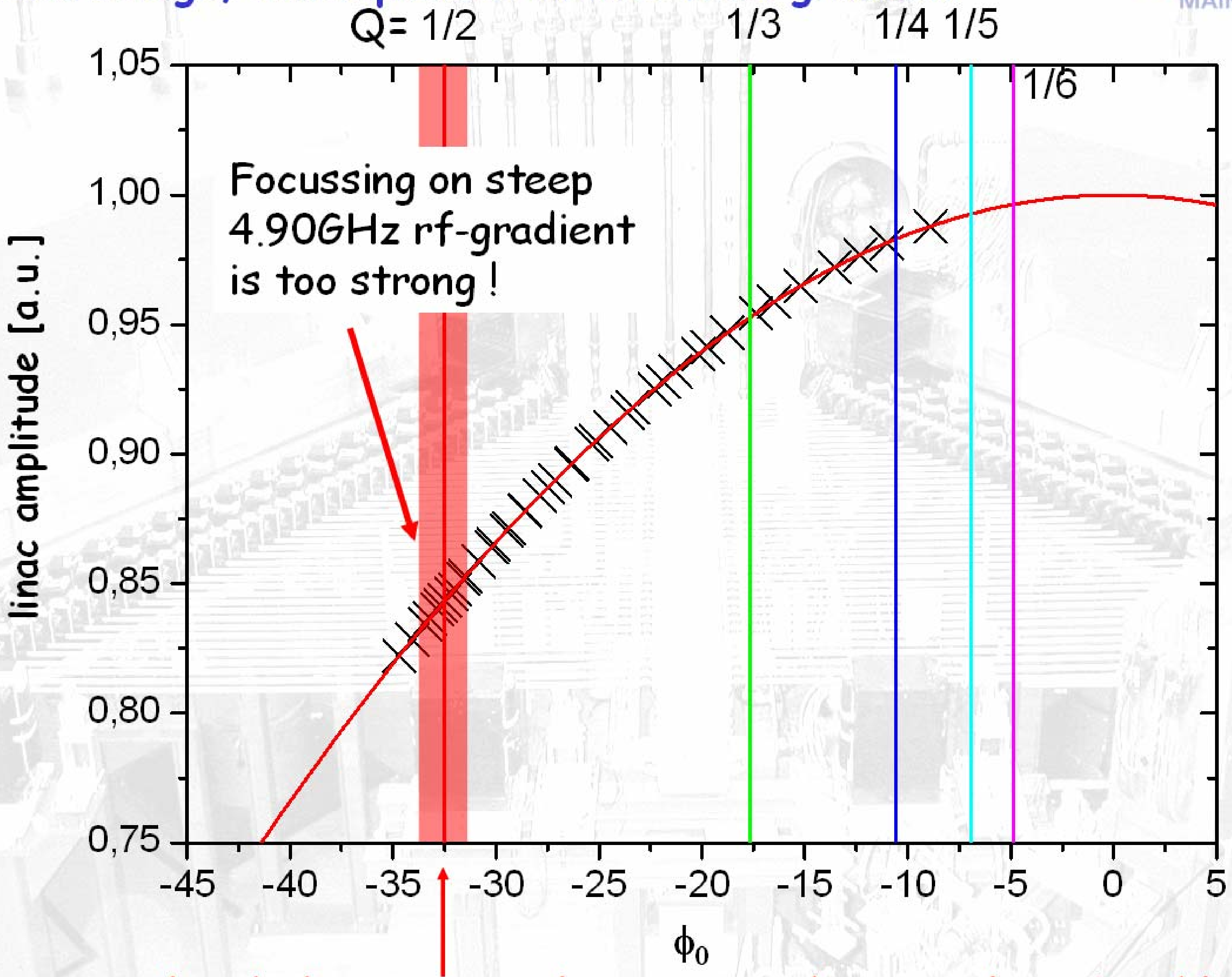


With increasing energy the beam intrudes deeper and deeper into the 90° dipoles and experiences, compared to a homogenous dipole, turn by turn a relatively decreasing field-integral, which requires less energy gain per turn to fulfil the dynamic coherence condition.

HDSM Design, consequences of the field gradient



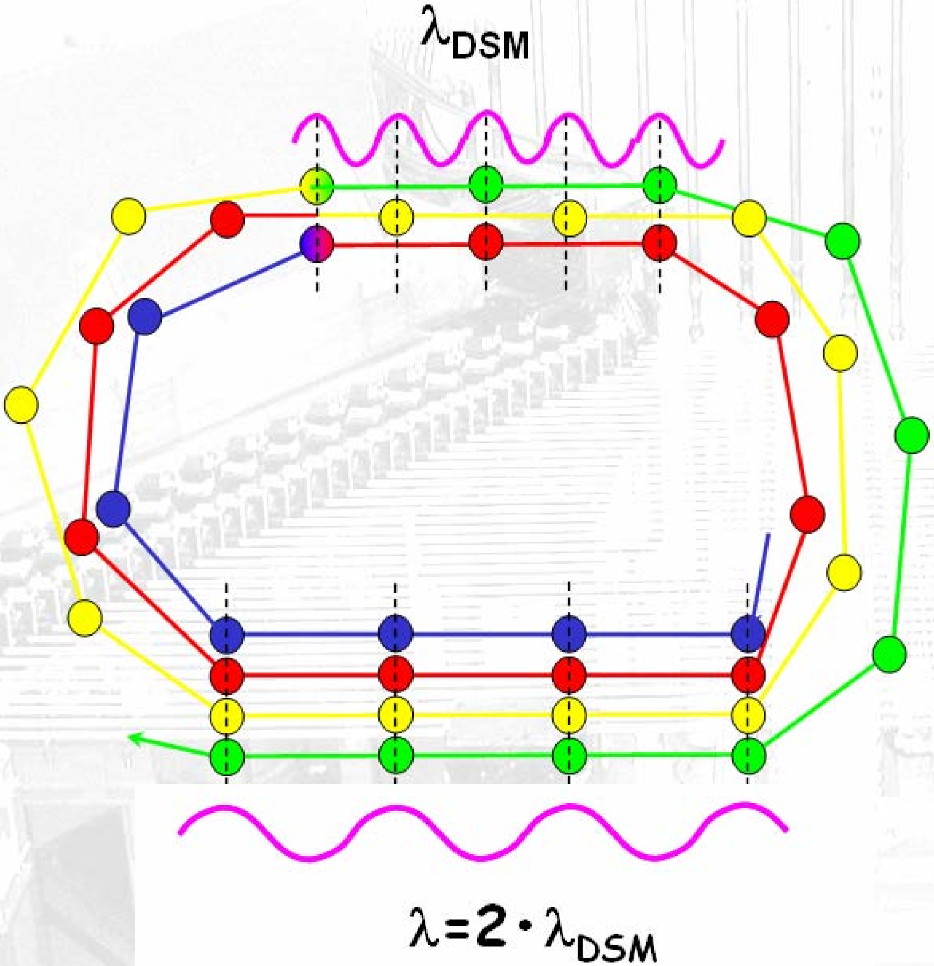
HDSM Design, consequences of the field gradient



stop band when certain phasing error between linac 1 and linac 2

Scheme of longitudinal bunch positions in a DSM

(remember: sub-harmonic injection with 2.45GHz into a 4.90GHz rf-system)



$l_1 = 23$ (2x11.5)

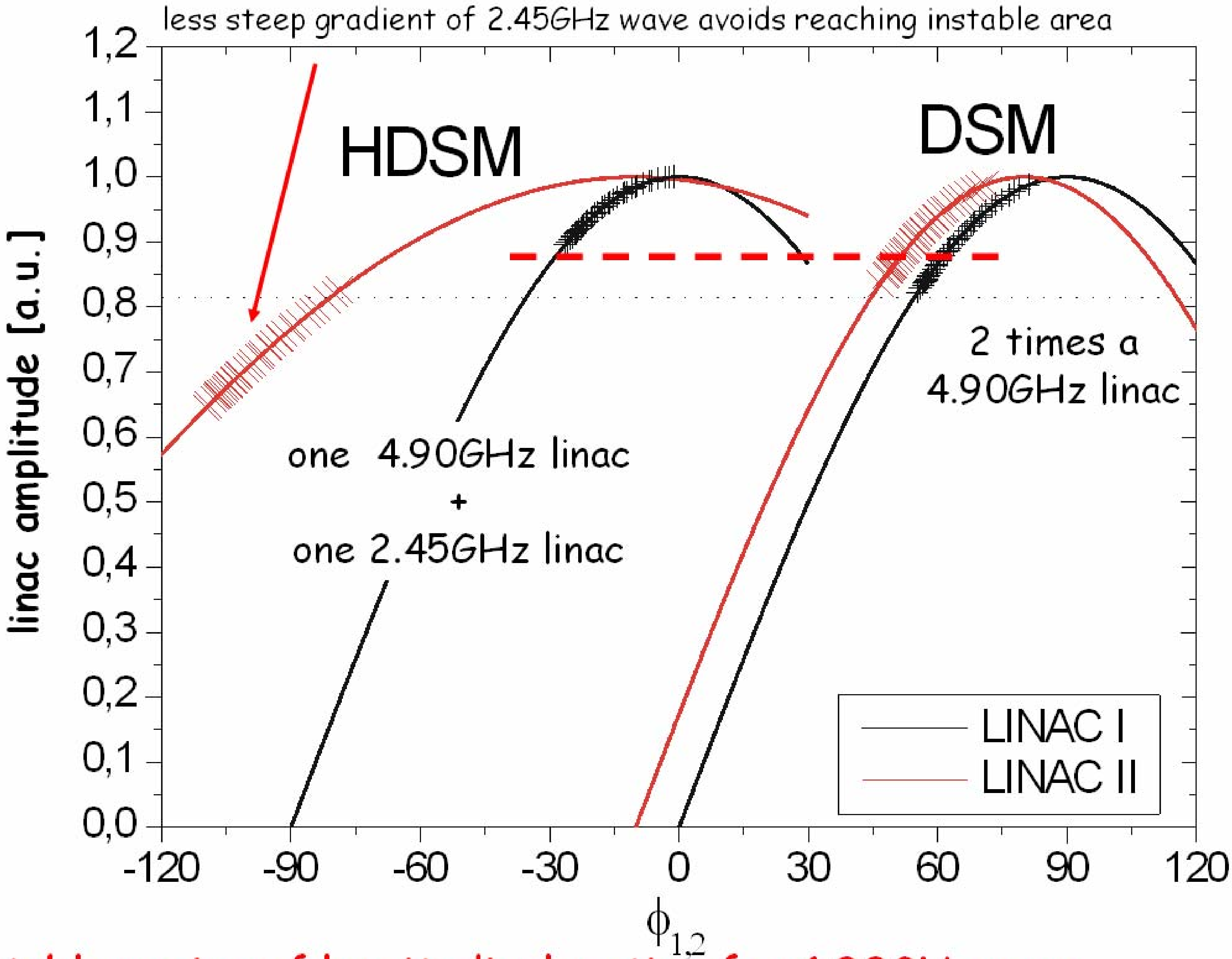
$l_2 = 25$ (2x12.5)

(in units of λ_{DSM})

2 Linacs, operating at ν_1=4.90GHz resp. ν_2=2.45GHz

Harmonic Double Sided Microtron (HDSM)

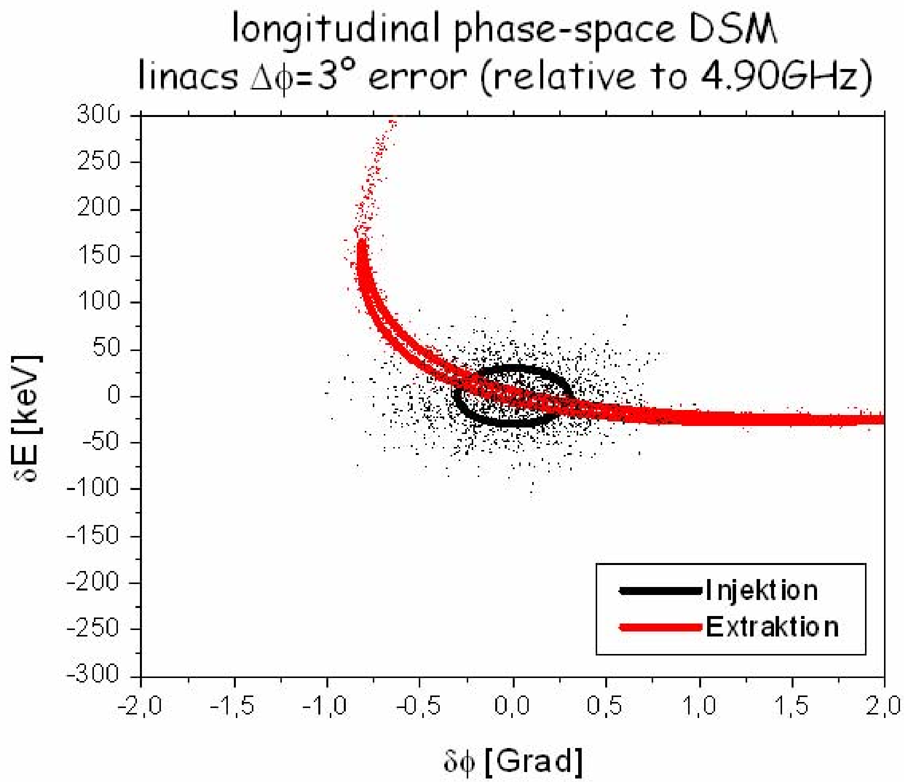
HDSM Design, harmonic operation



- - - instable region of longitudinal motion for 4.90GHz wave

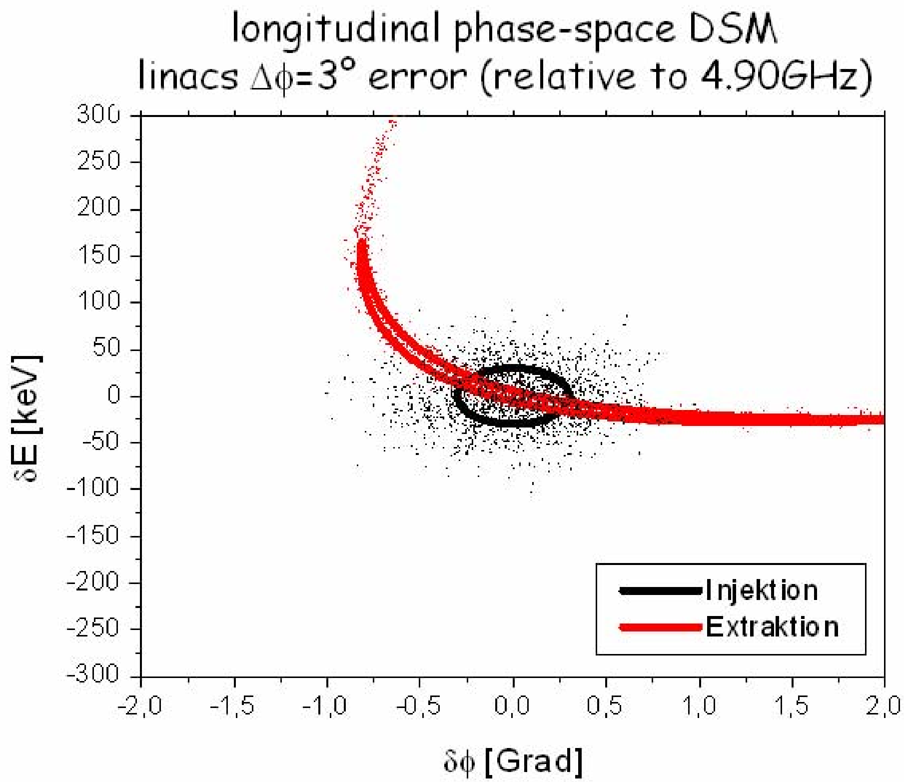
Harmonic-operation
(highest longitudinal beam stability)

DSM, 2 x 4.90GHz linac

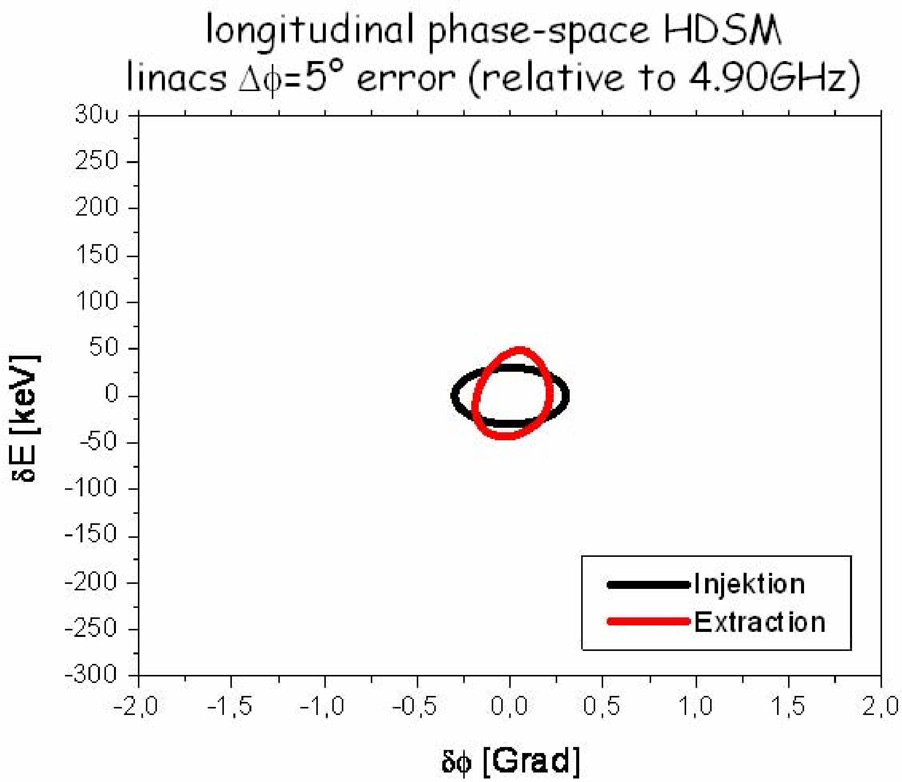


Harmonic-operation
(highest longitudinal beam stability)

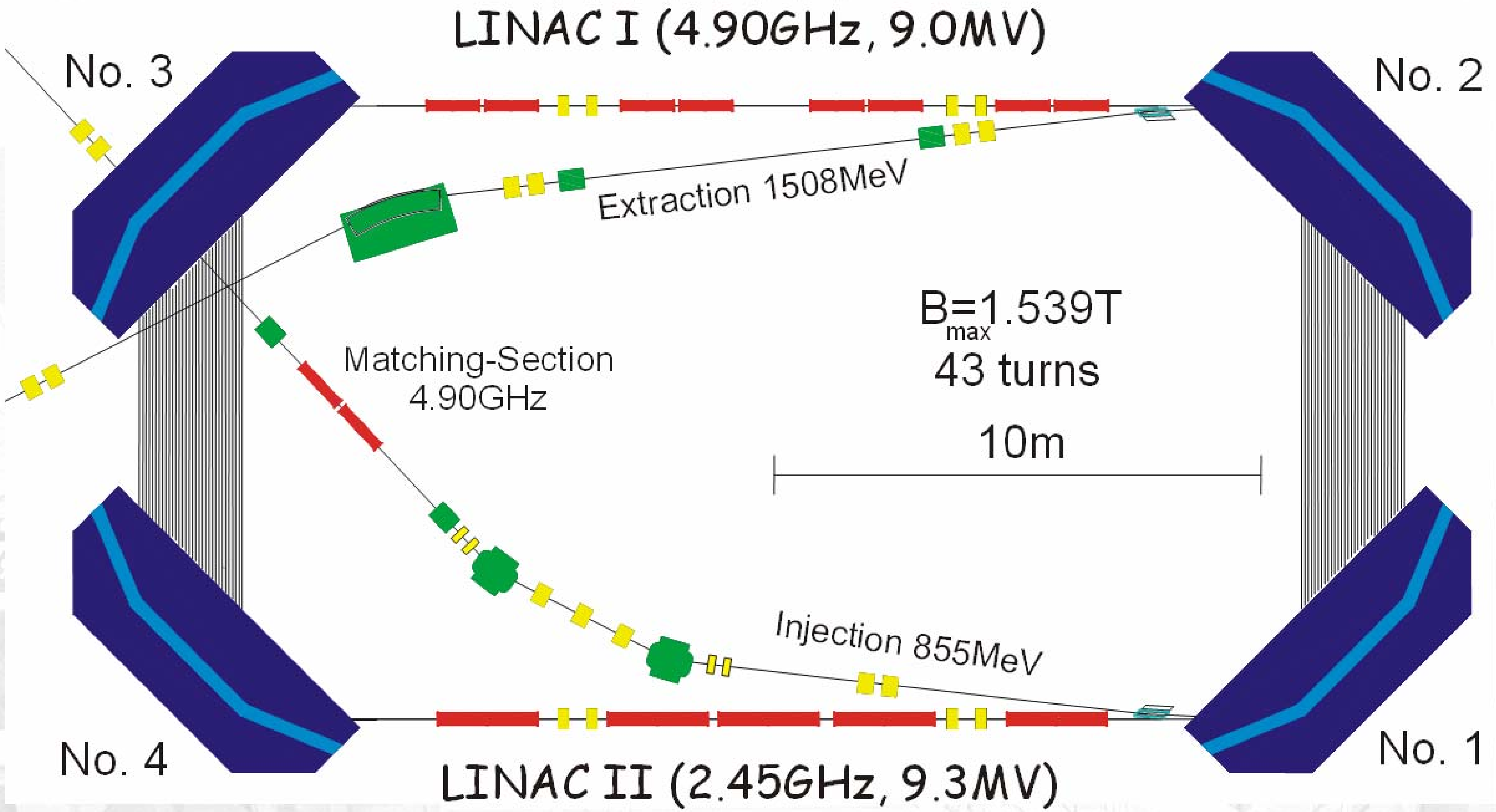
DSM, 2 x 4.90GHz linac



HDSM, 4.90GHz + 2.45GHz Linac

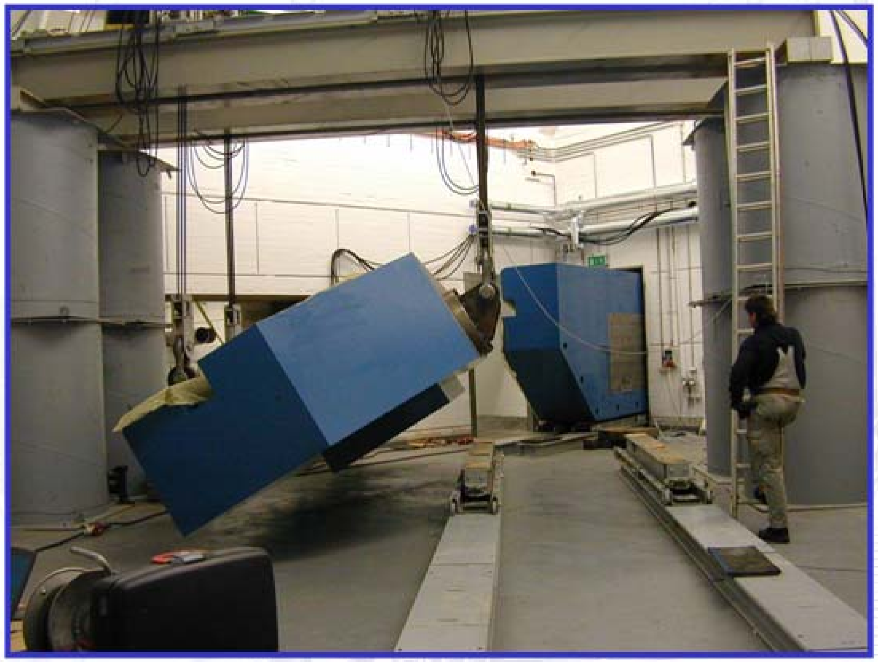


The Harmonic Double Sided Microtron (HDSM)



Best approximation to the inherent stable and reliable RTM principle

Construction: dipoles with field gradient



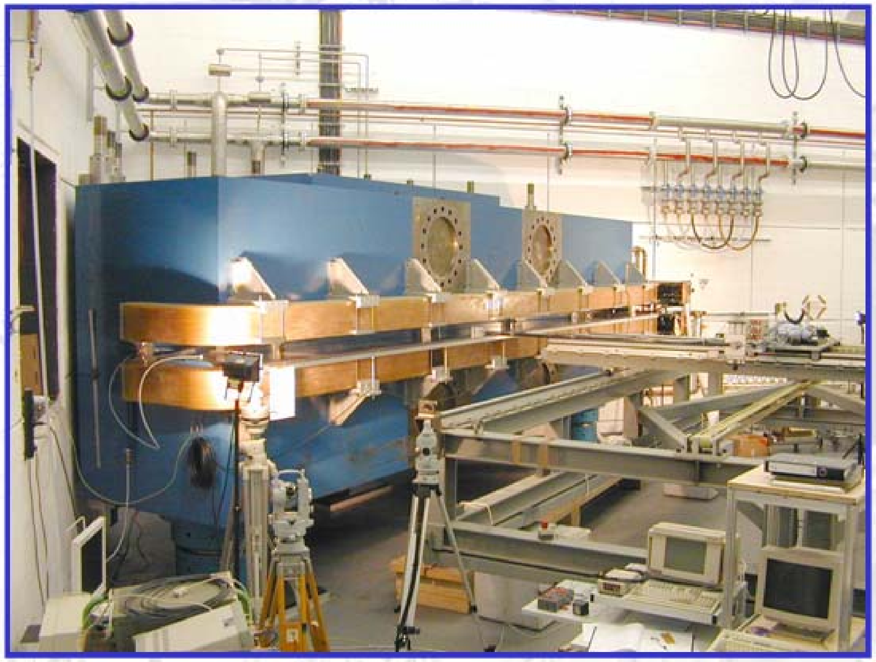
Design and construction drawings by KPH

Transport and installation of all four magnets finished in 2002

measurement of the magnetic field of all 4 magnets to get the data for the construction of surface correction coils

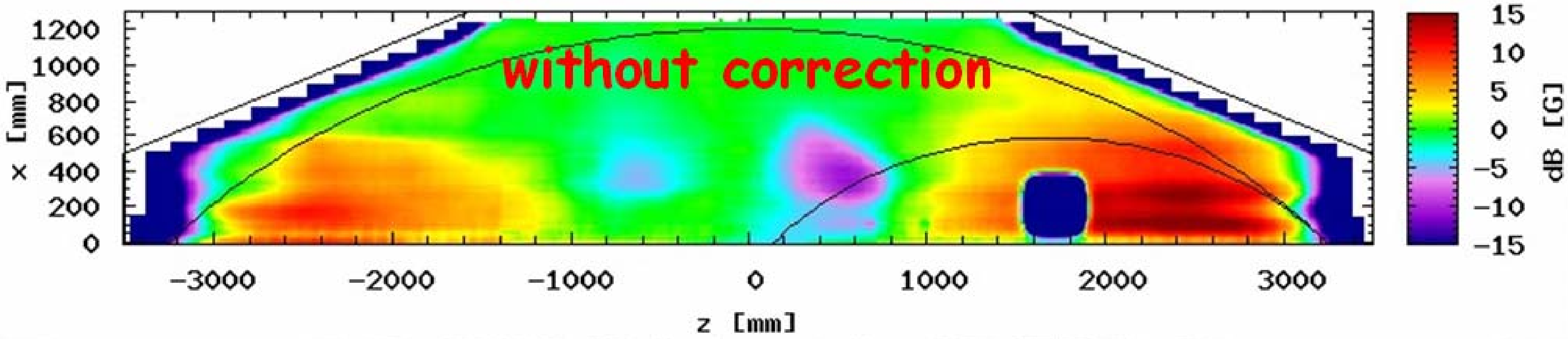
Magnet as it is: $\Delta B/B \sim 10^{-3}$
(in the central area: $\sim 10^{-4}$, excellent manufacturing quality)
required is: $\Delta B/B \sim 10^{-4}$

measurements finished: 09/2003
correction coils ready and checked, magnets finally assembled: 03/2006



Construction: field correction

HDSM dipole 03, field map
(normalized to ideal field gradient, B_{max}=1.539T for 1508MeV)



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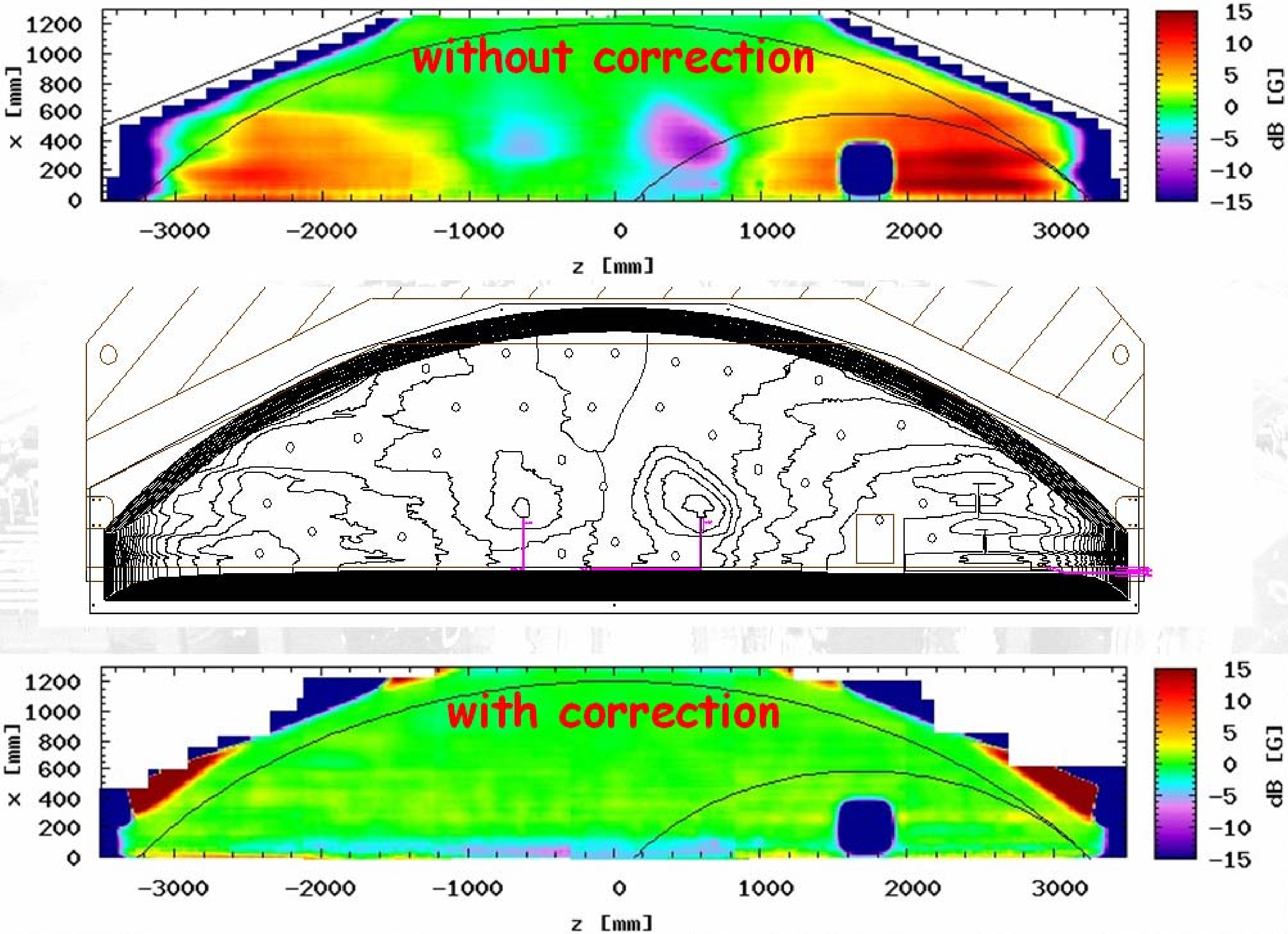
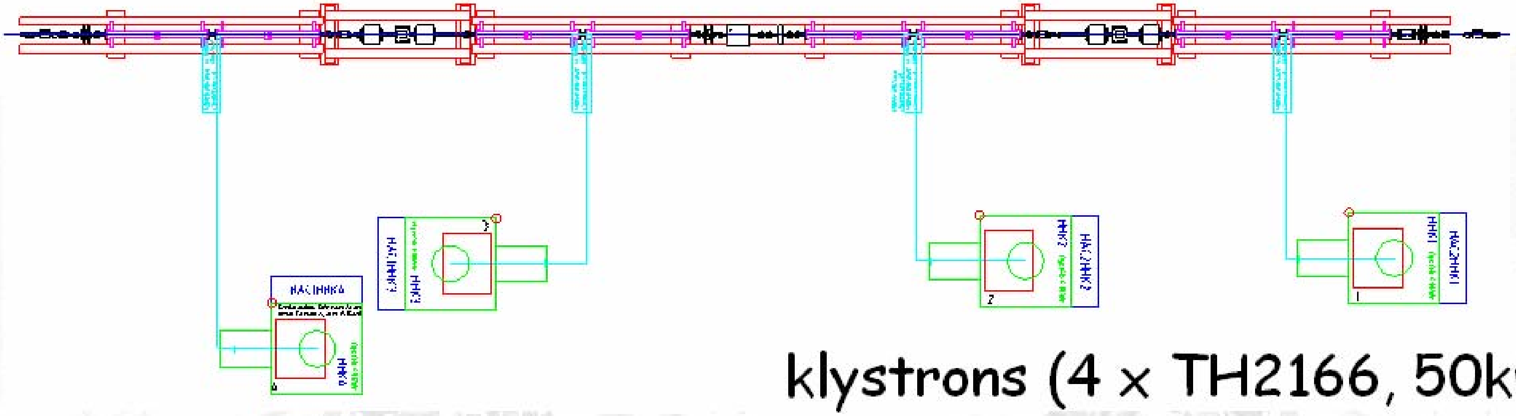


Construction: 4.90GHz linac

8 linac sections ("in house" development, 35ACs, 81MΩ/m)

9.0MV: 117kW rf-power + 38kW beam loading (@100μA)

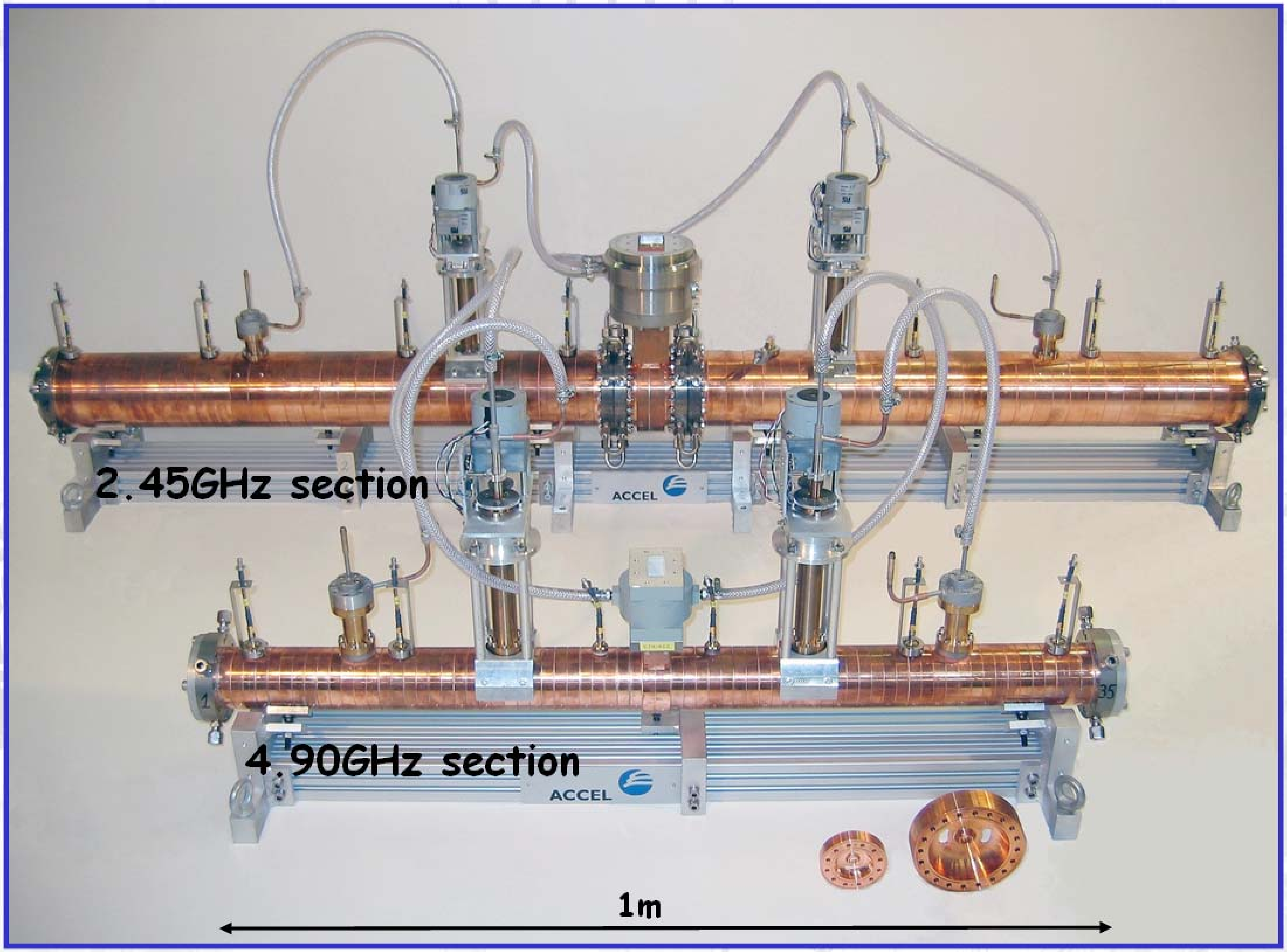


klystrons (4 x TH2166, 50kw cw)

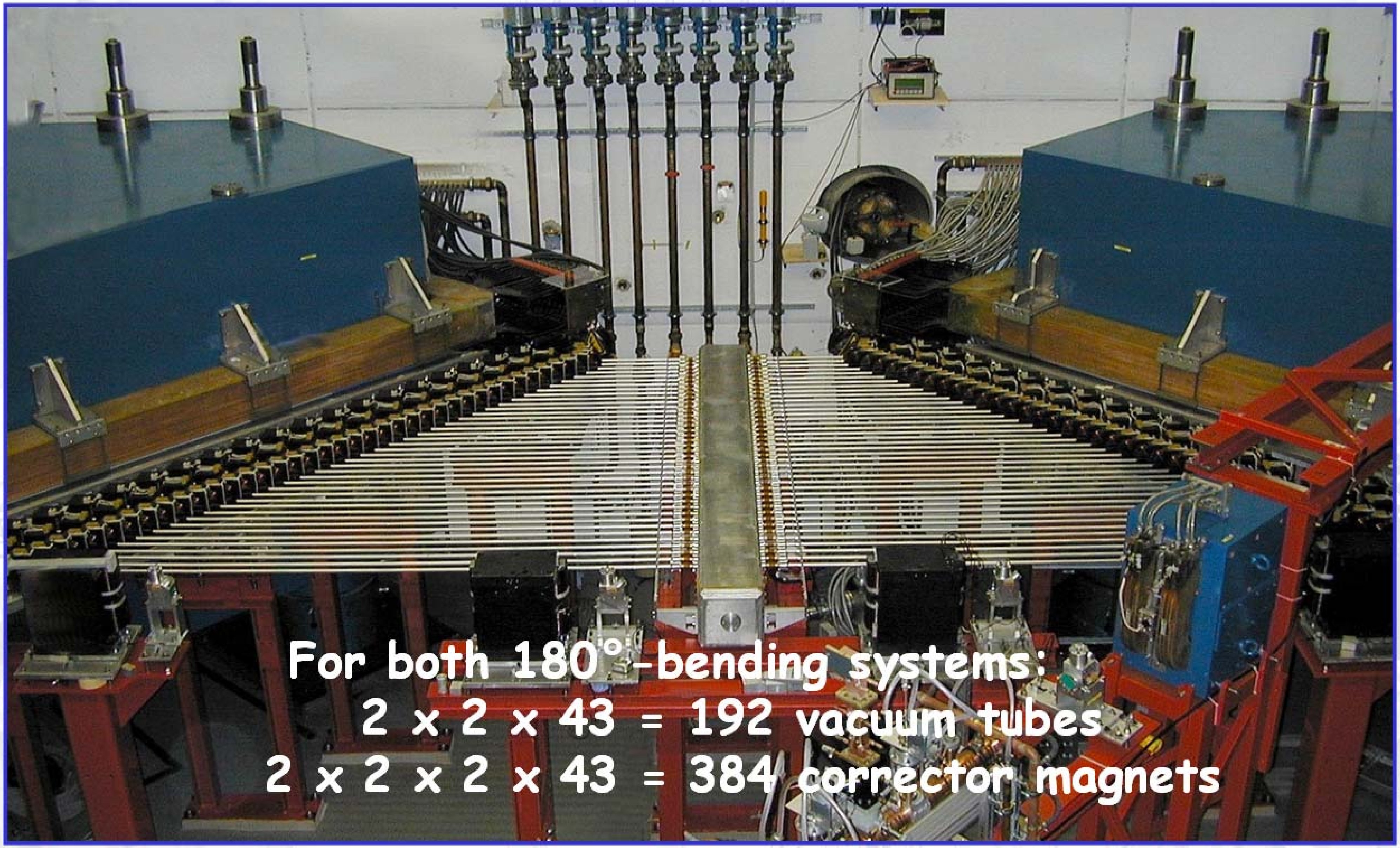
- successful section prototype test: 07/2003
- last section delivered: 02/2006
- first module (No. 3) tested: 08/2006
- ready installed, under vacuum, power tested: 21.11.2006
- final phasing: 06.12.2006

4.90GHz/50kW cw klystron TH2166:

Construction: 4.90GHz linac



Construction: 180°-bending system



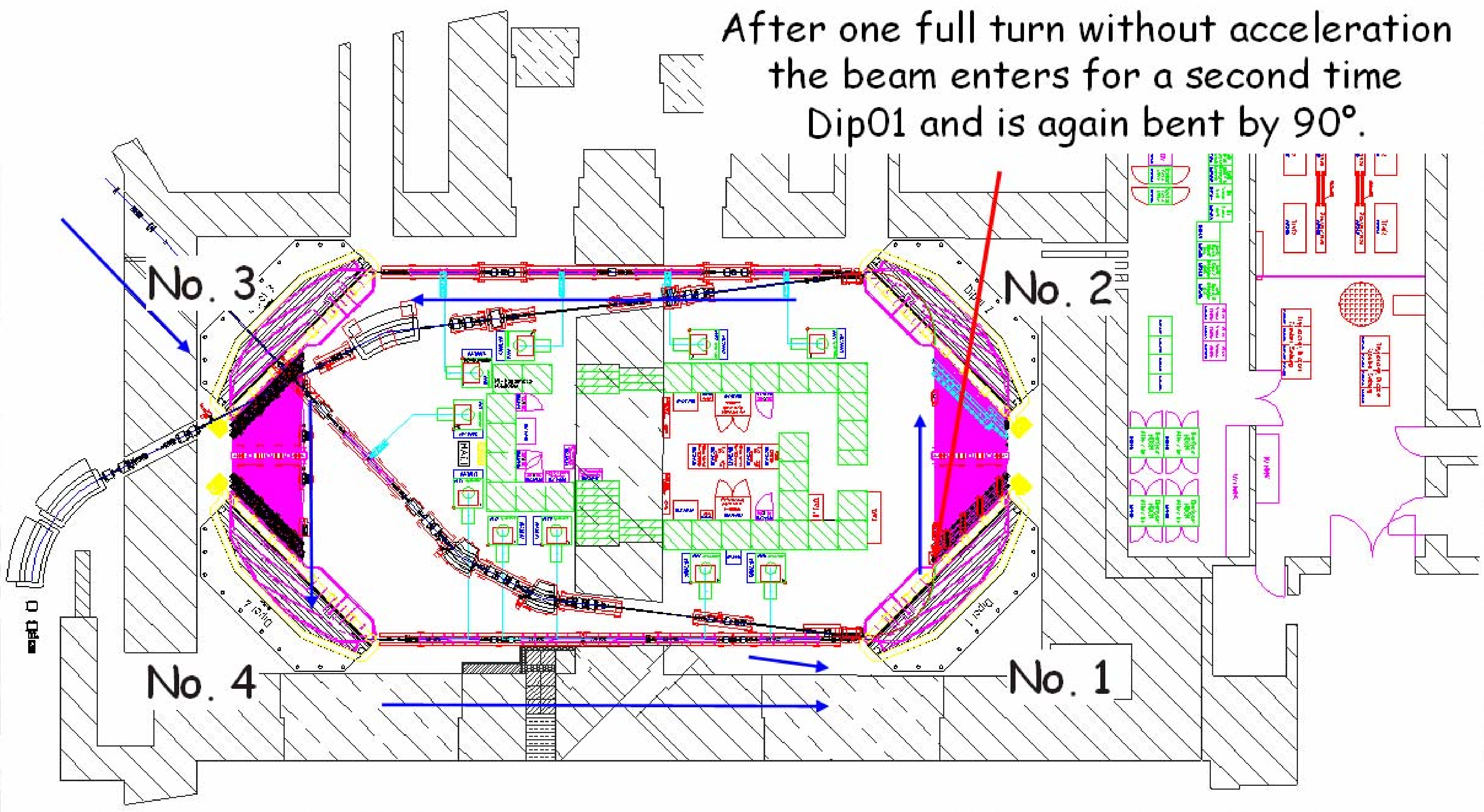
Commissioning: November 2006, first full turn

(4.90GHz linac not ready, no acceleration)

Field in Dip03+04 reduced by ~9MeV/855MeV = 1.05%

Commissioning: November 2006, first full turn

(4.90GHz linac not ready, no acceleration)

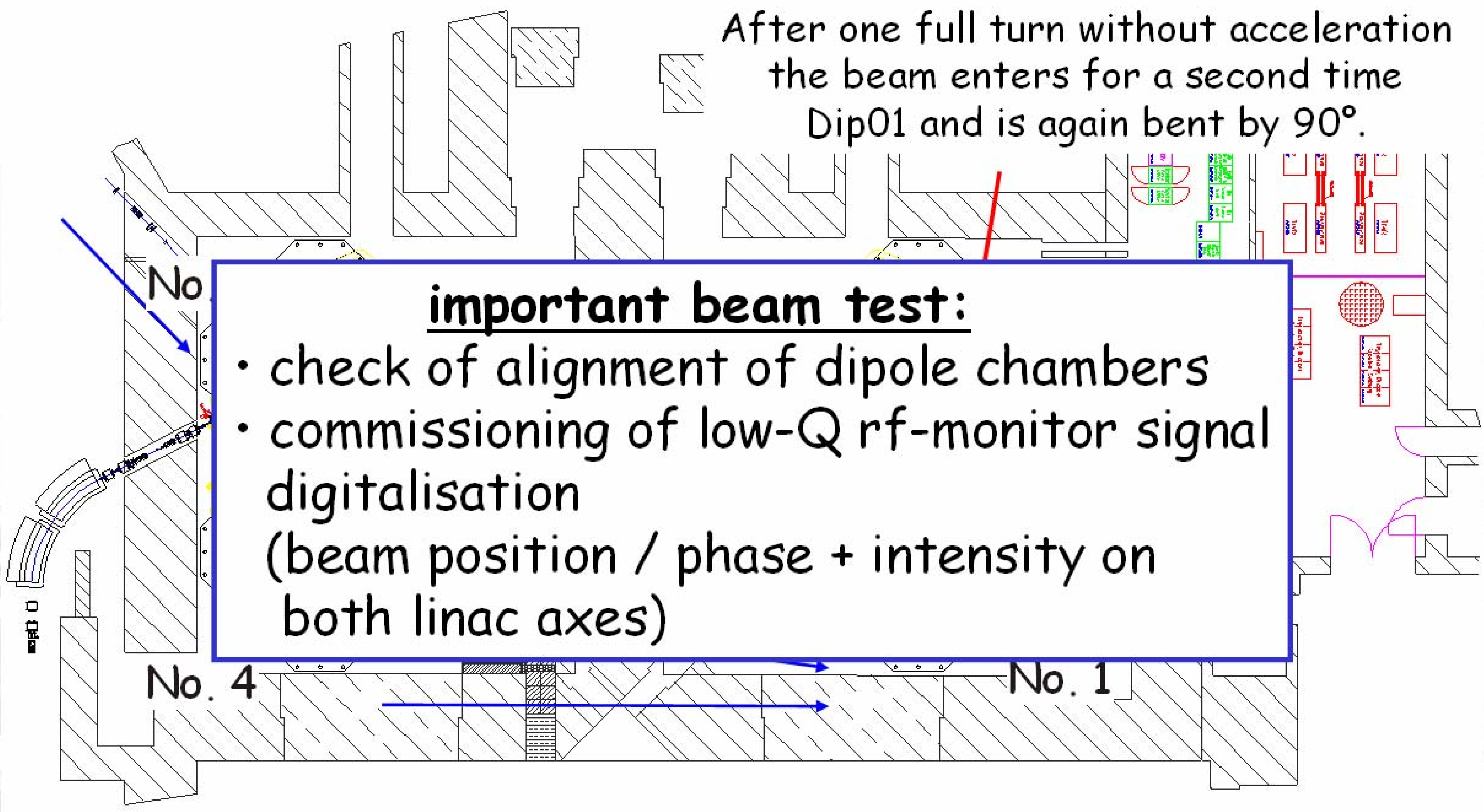


Field in Dip03+04 reduced by ~9MeV/855MeV = 1.05%

Commissioning: November 2006, first full turn

(4.90GHz linac not ready, no acceleration)

After one full turn without acceleration the beam enters for a second time Dip01 and is again bent by 90°.



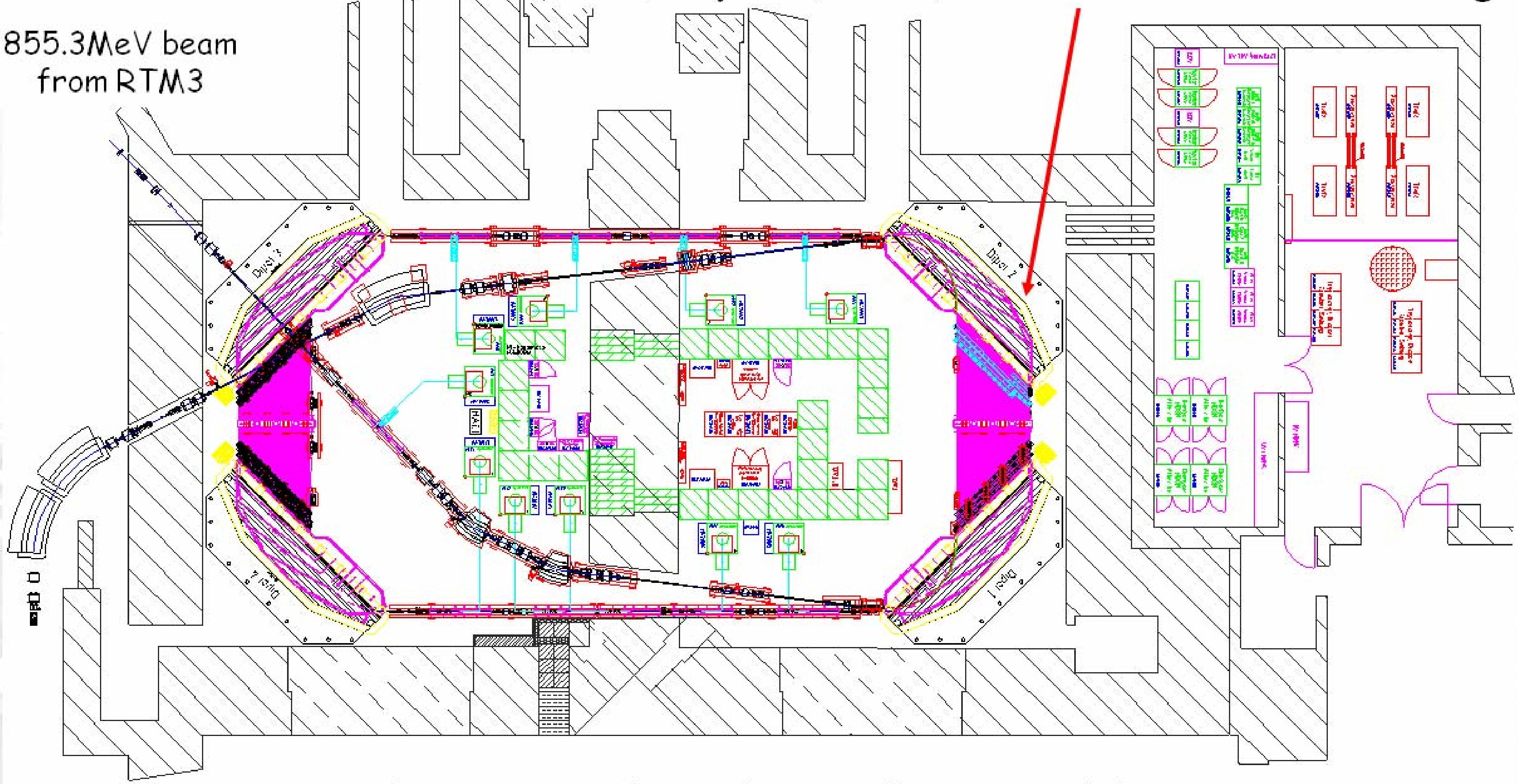
important beam test:

- check of alignment of dipole chambers
- commissioning of low-Q rf-monitor signal digitalisation (beam position / phase + intensity on both linac axes)

Field in Dip03+04 reduced by ~9MeV/855MeV = 1.05%

Commissioning: 19. December 2006, 43 turns

43 turns: 19^{31}h (after ~8h)
diagnostic pulse mode:
100μA peak, 12ns, max. 10kHz = 12nA average



(extraction beamline still not ready)

Commissioning: 19. December 2006, 43 turns

43 turns: 19^{31}h (after ~8h)
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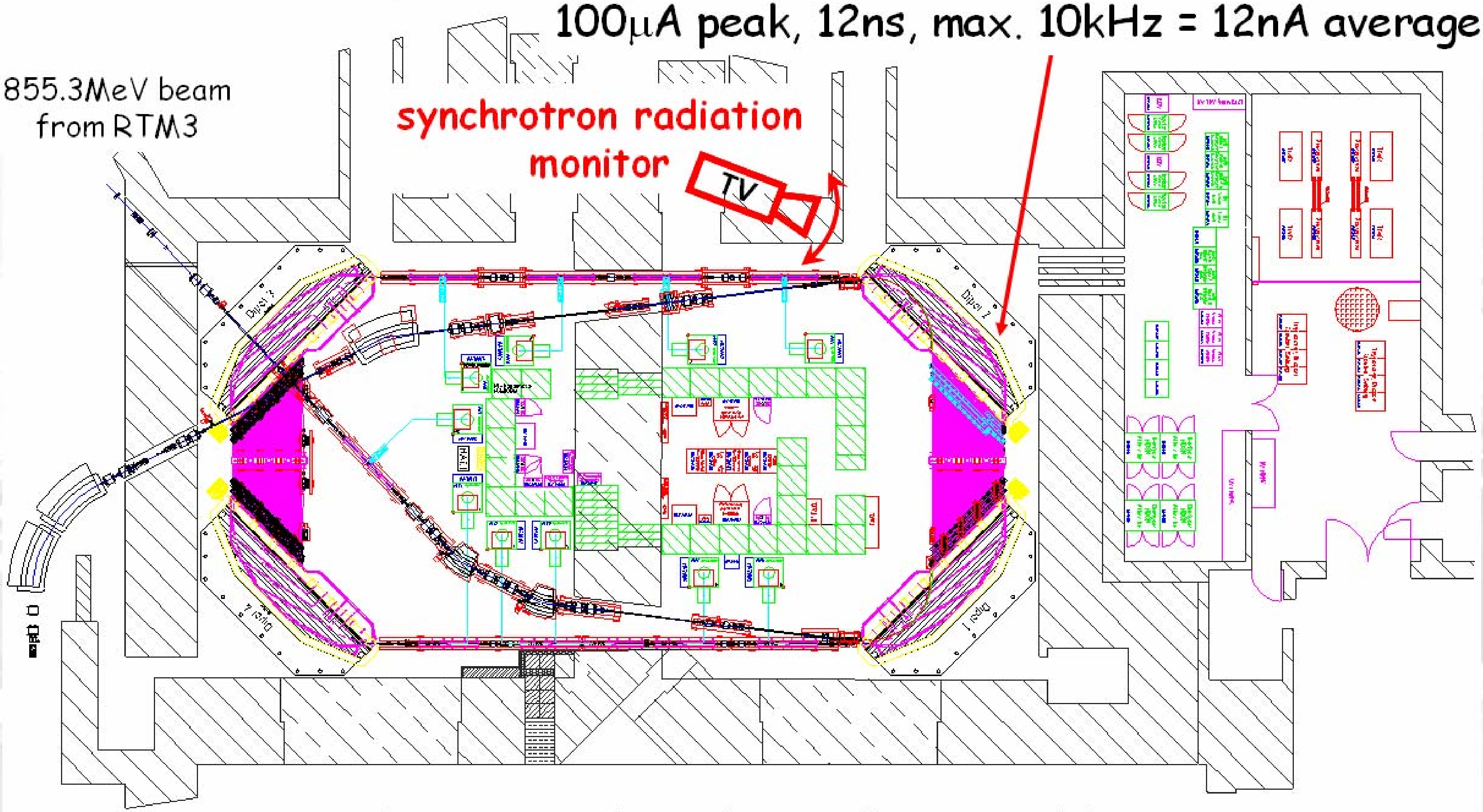
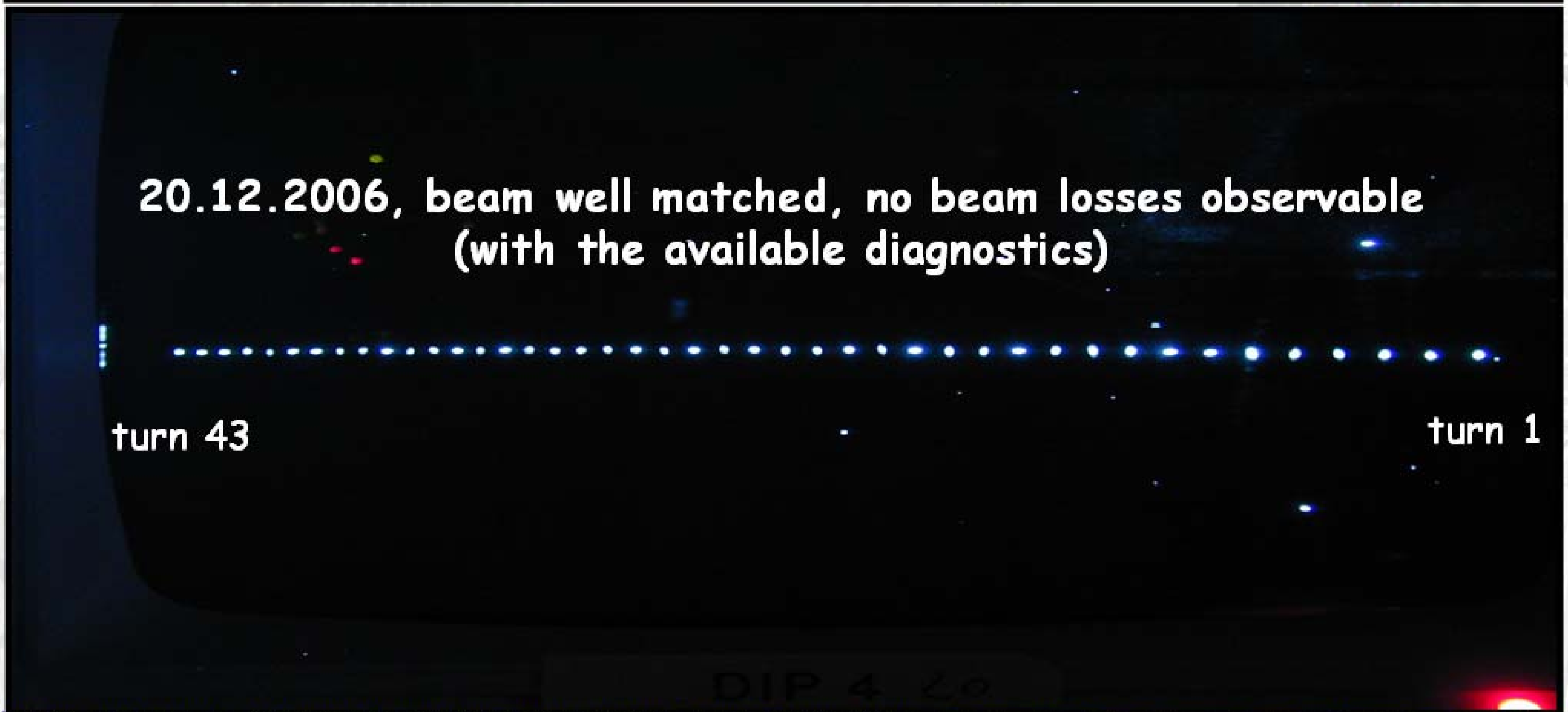
100μA peak, 12ns, max. 10kHz = 12nA average

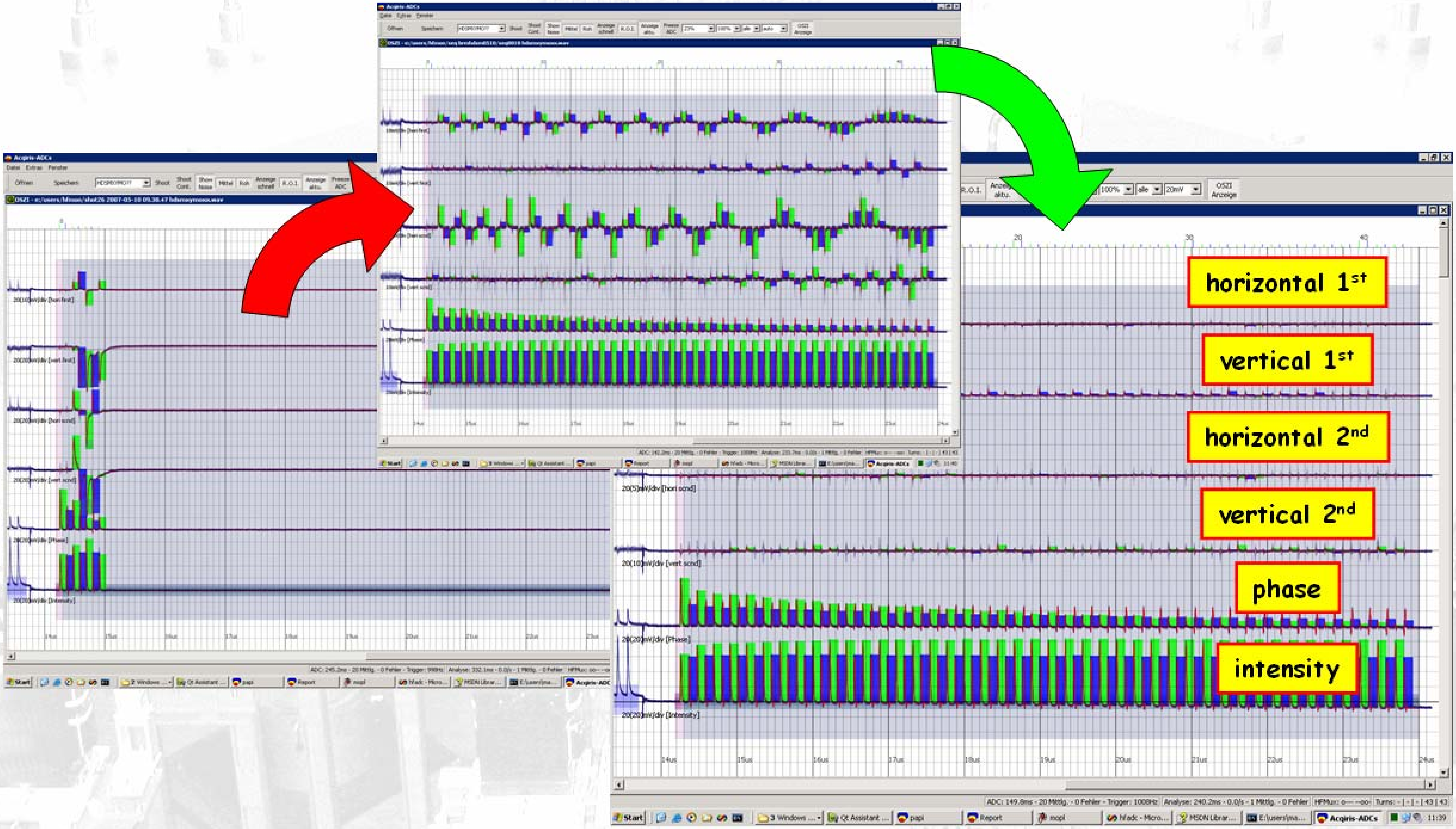


(extraction beamline still not ready)


19.12.2006, beam not well matched, beam losses observed
turn 43
turn 1
DIP 4

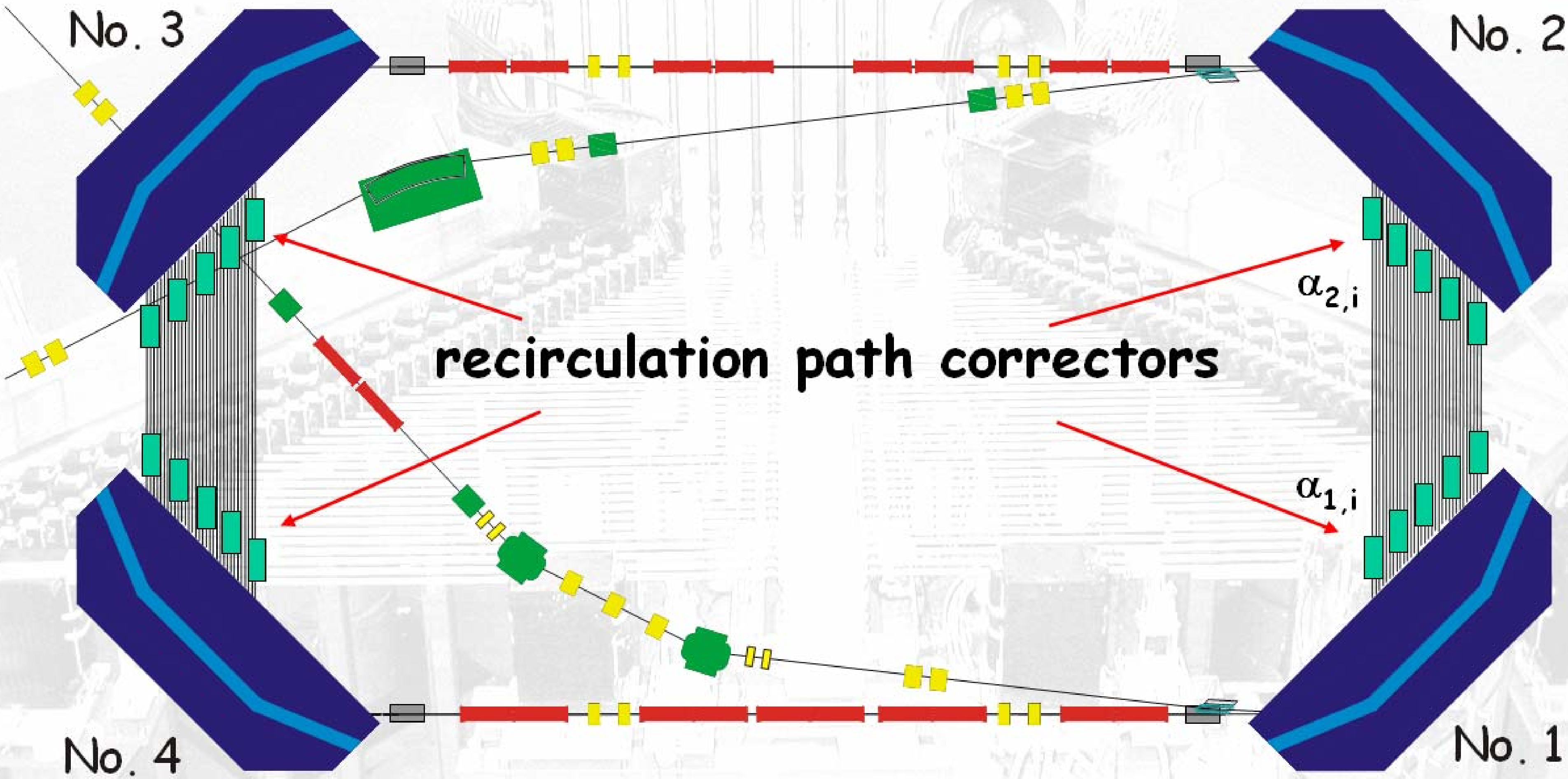

20.12.2006, beam well matched, no beam losses observable
(with the available diagnostics)
turn 43
turn 1

Commissioning: position and phase measurement

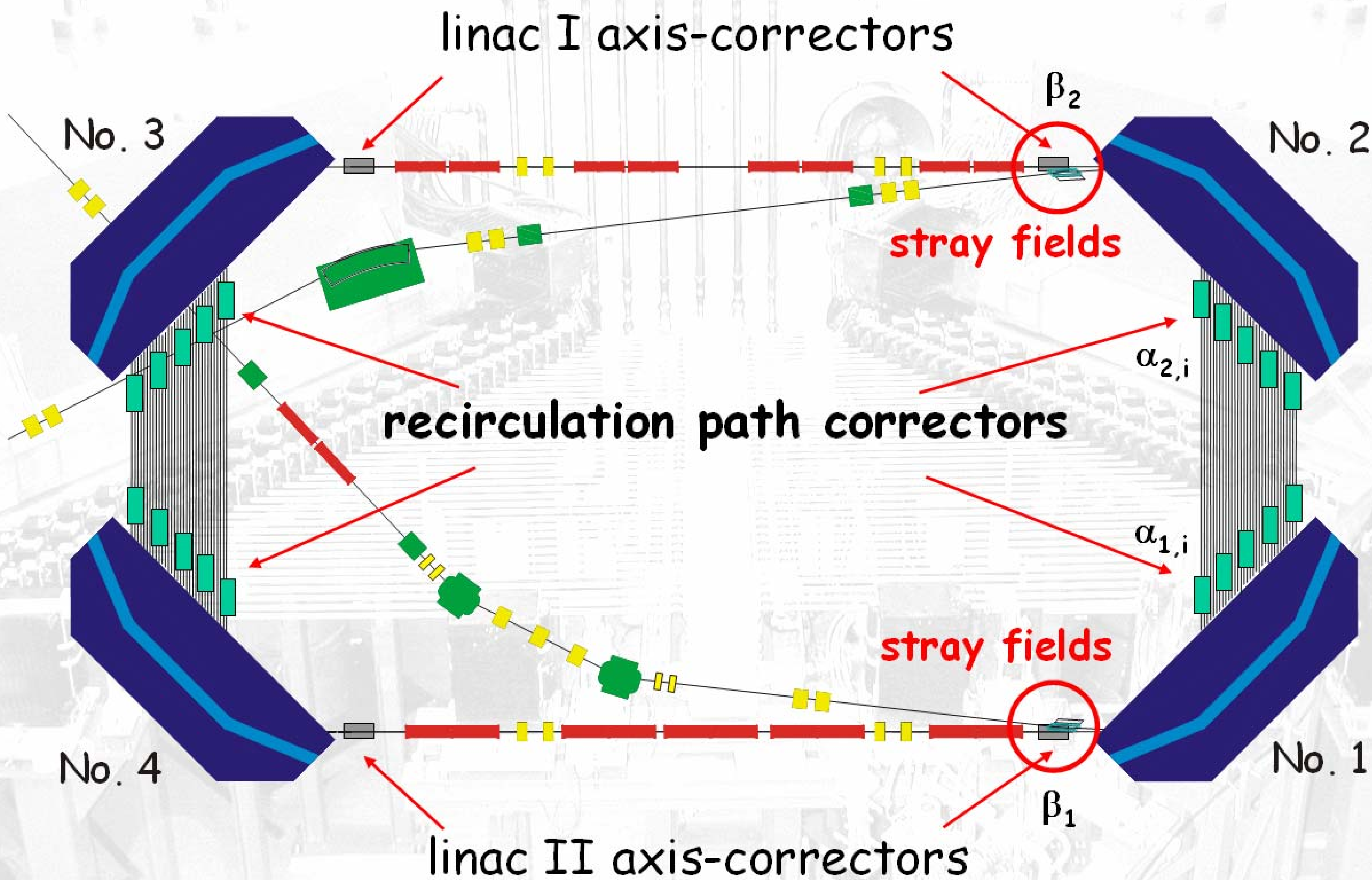


signals of low-Q rf-monitors of both HDSM-linacs
- 4.90GHz-linac
- 2.45GHz-linac

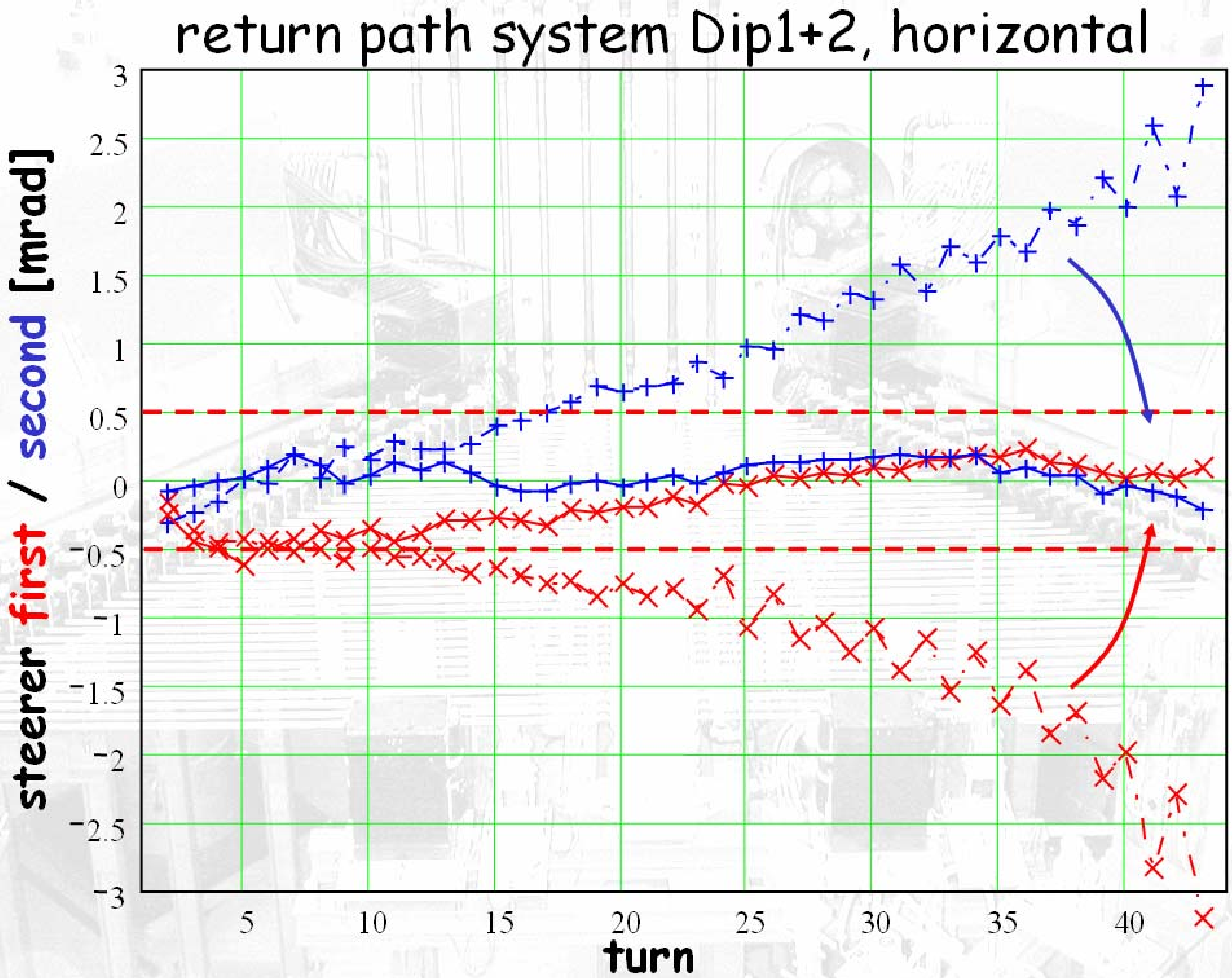
Commissioning, optimisation of corrector magnets



Commissioning, optimisation of corrector magnets

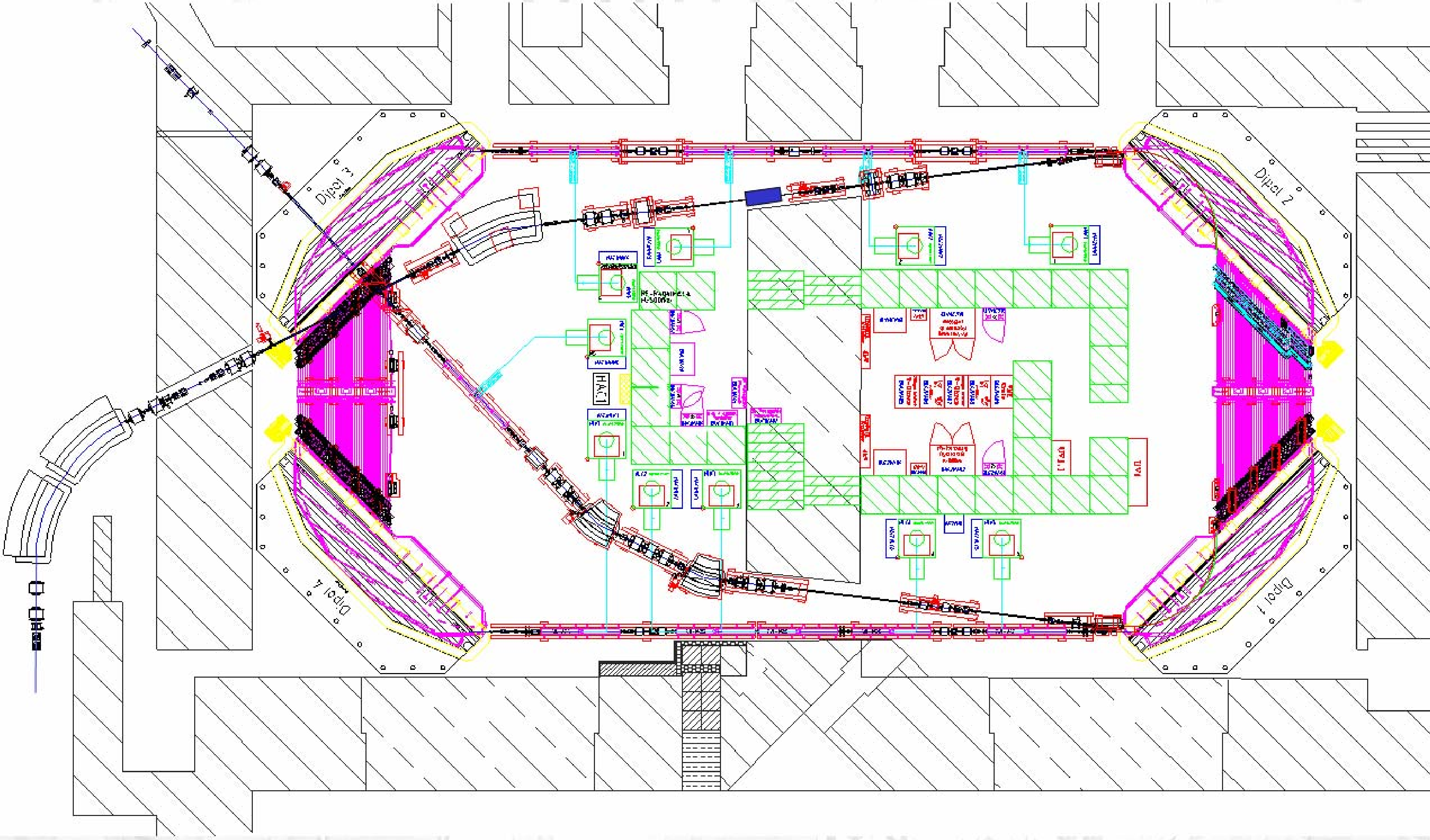


Commissioning: optimisation of corrector magnets

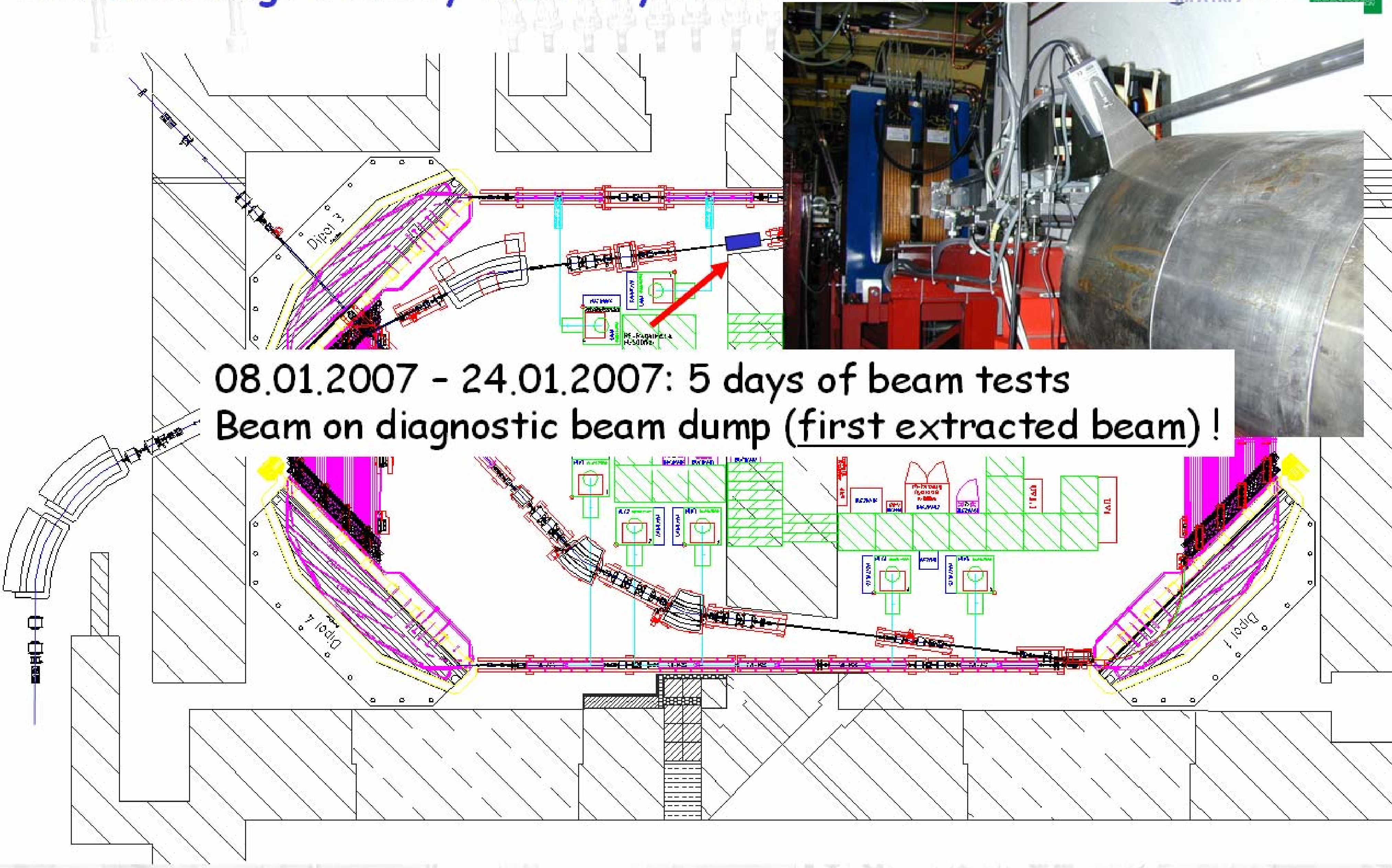


(design max. values: horizontal 3mrad, vertical 2mrad @ 1.5GeV)

Commissioning: January-February 2007

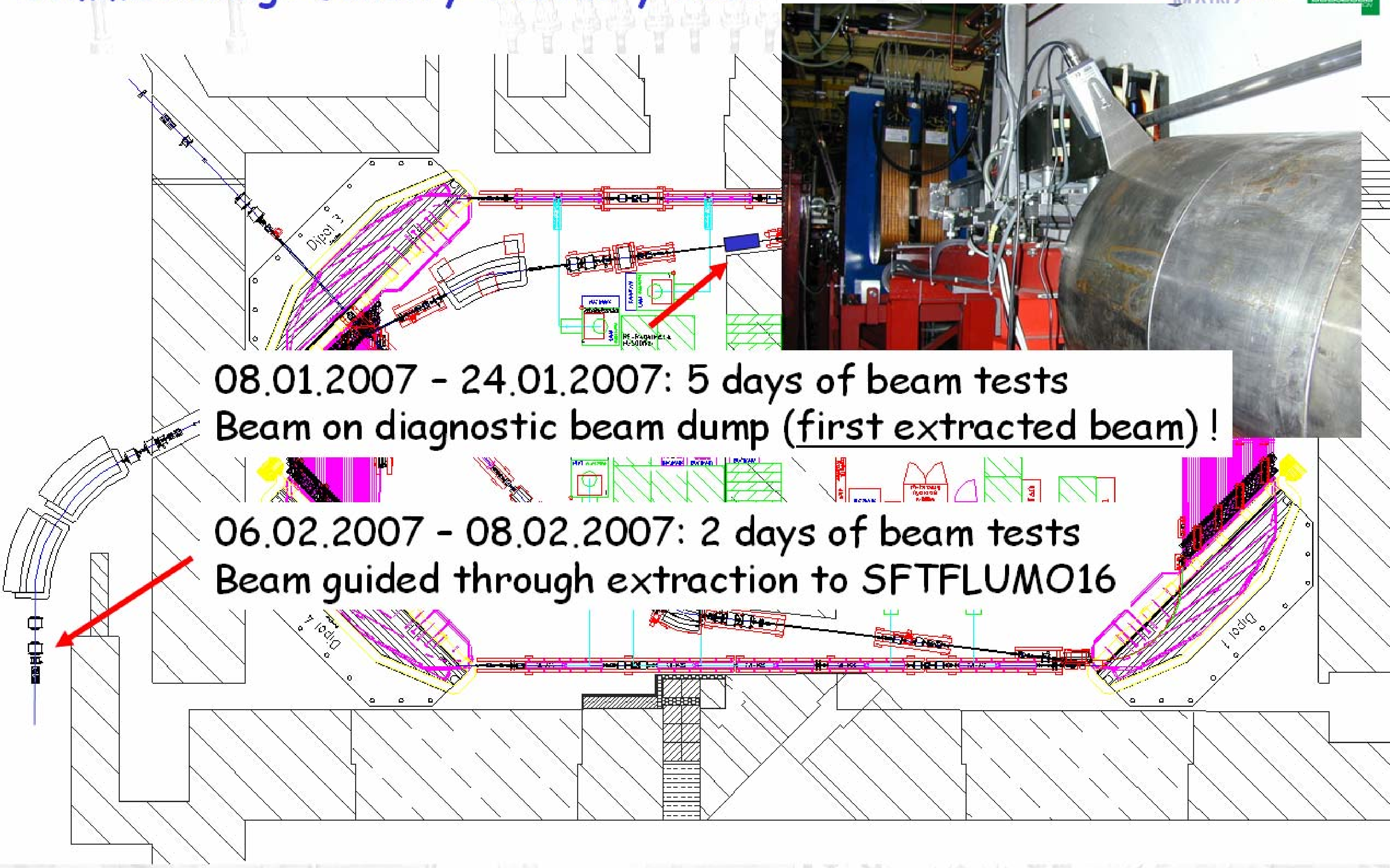


Commissioning: January-February 2007



08.01.2007 - 24.01.2007: 5 days of beam tests
Beam on diagnostic beam dump (<u>first extracted beam</u>) !

Commissioning: January-February 2007



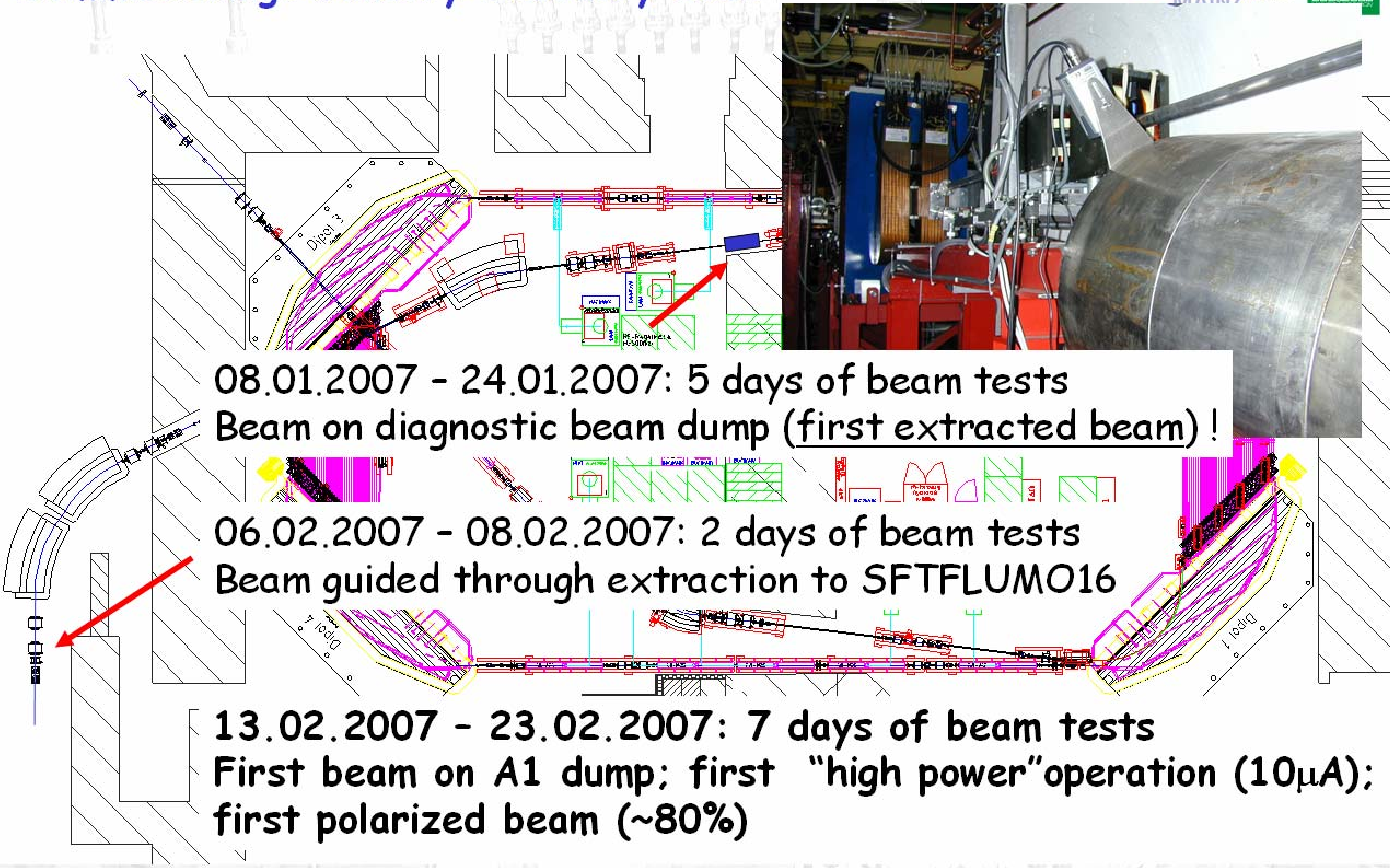
08.01.2007 – 24.01.2007: 5 days of beam tests

Beam on diagnostic beam dump (first extracted beam) !

06.02.2007 – 08.02.2007: 2 days of beam tests

Beam guided through extraction to SFTFLUM016

Commissioning: January-February 2007



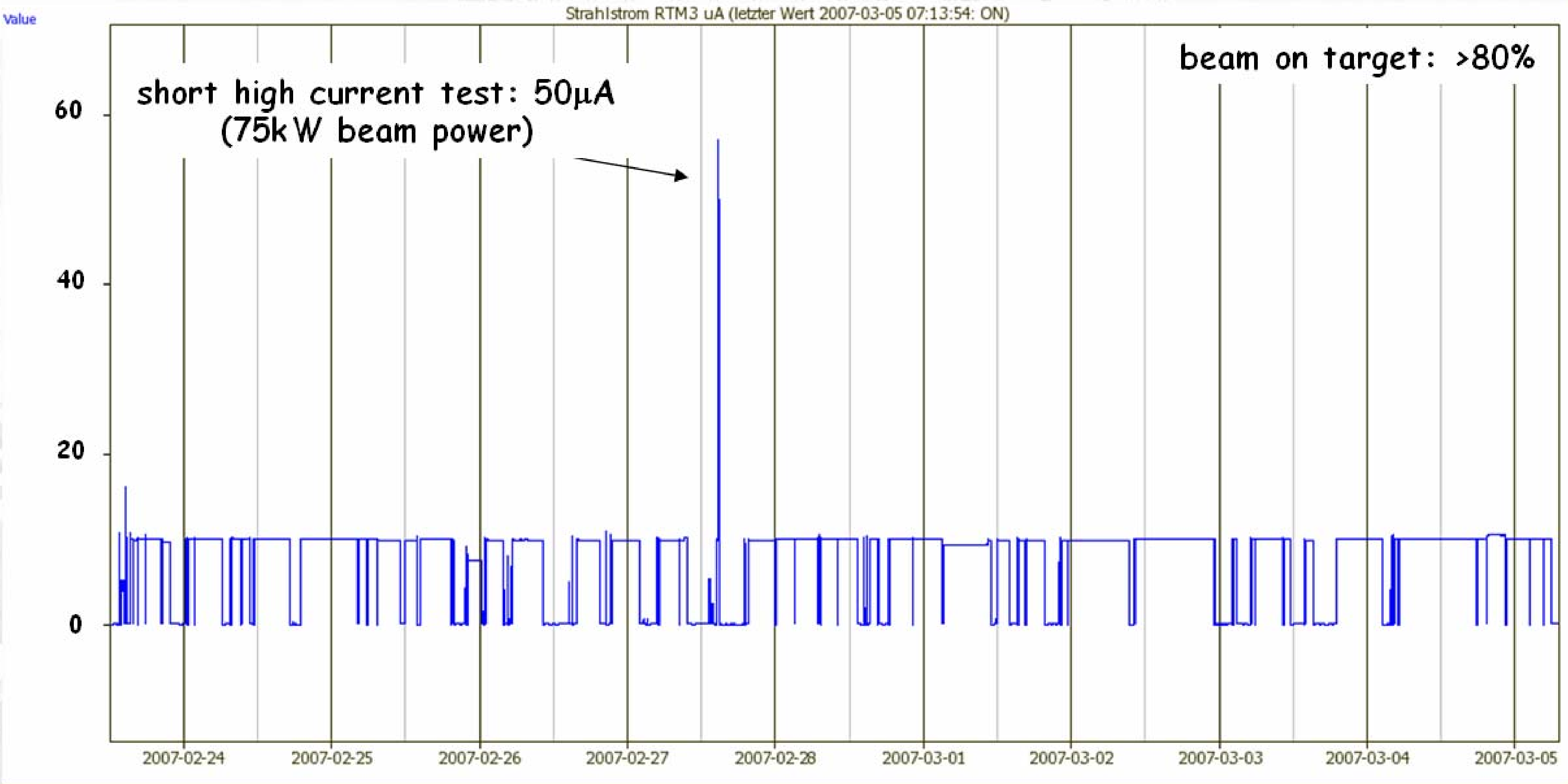
08.01.2007 – 24.01.2007: 5 days of beam tests
Beam on diagnostic beam dump (<u>first extracted beam</u>) !

06.02.2007 – 08.02.2007: 2 days of beam tests
Beam guided through extraction to SFTFLUM016

13.02.2007 – 23.02.2007: 7 days of beam tests
First beam on A1 dump; first "high power" operation (10μA); first polarized beam (~80%)

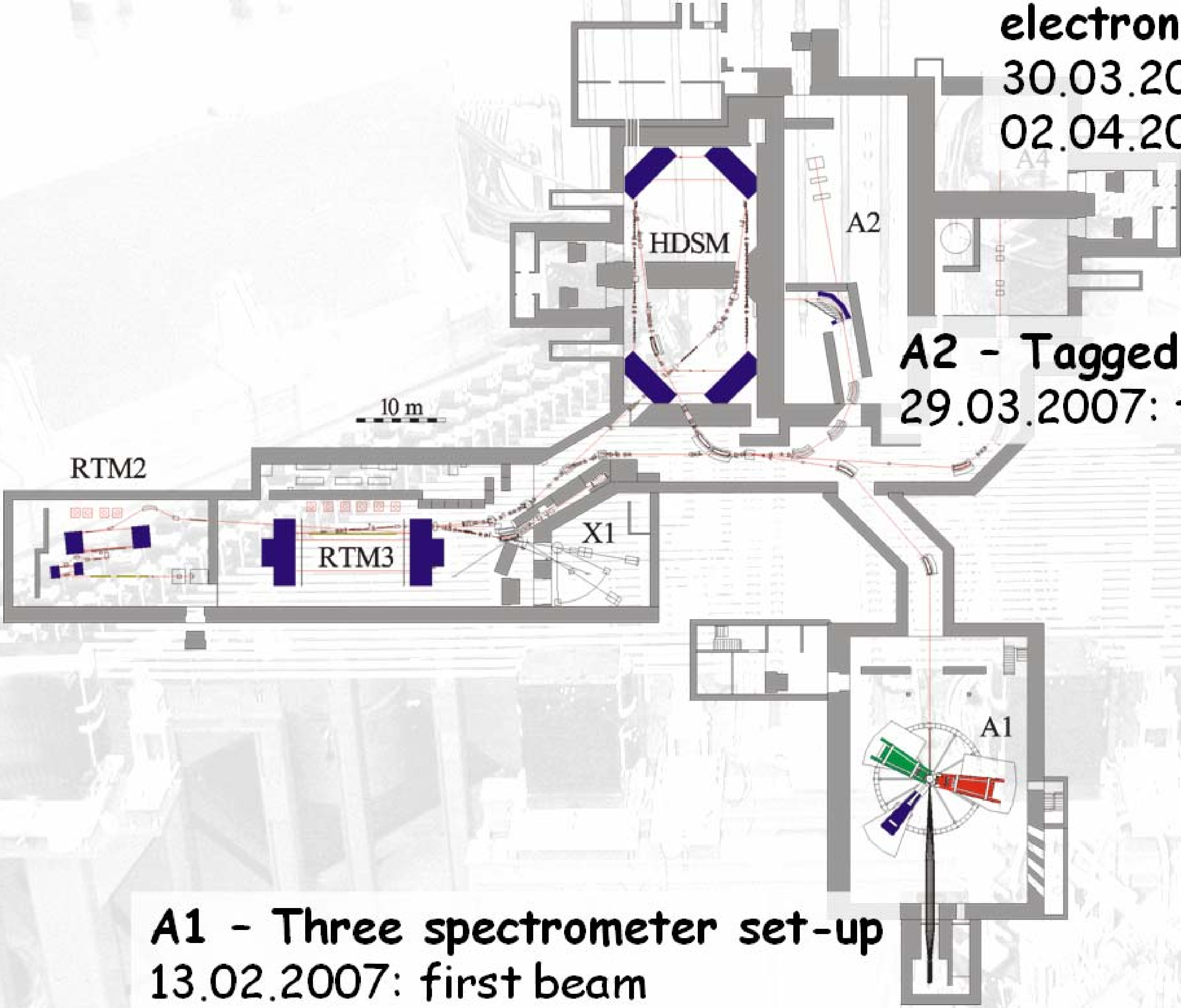
Operation: first user run

23.02.2007 – 05.03.2007 user operation
1.508GeV, 10μA,
polarised beam ~83%



Fr., 23.02.2007, 12.00 till Mo., 05.03.2007, 6.00

Operation: all experimental stations commissioned with beam within only 1½ months

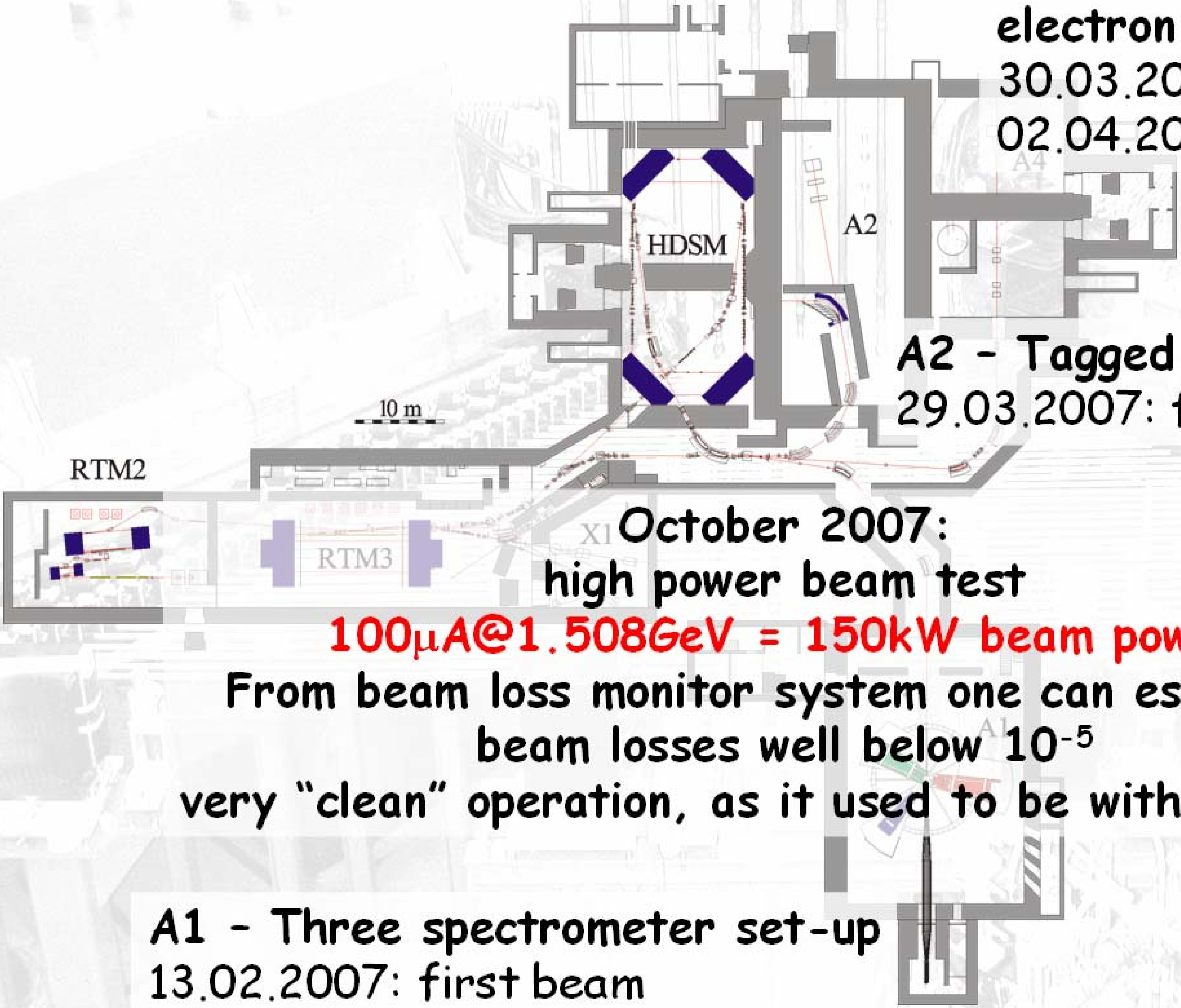


A4 - Parity violating electron scattering
30.03.2007: first beam
02.04.2007: 15μA

A2 – Tagged photon beams
29.03.2007: first beam

A1 – Three spectrometer set-up
13.02.2007: first beam

Operation: all experimental stations commissioned with beam within only 1½ months



A4 - Parity violating electron scattering
30.03.2007: first beam
02.04.2007: 15μA

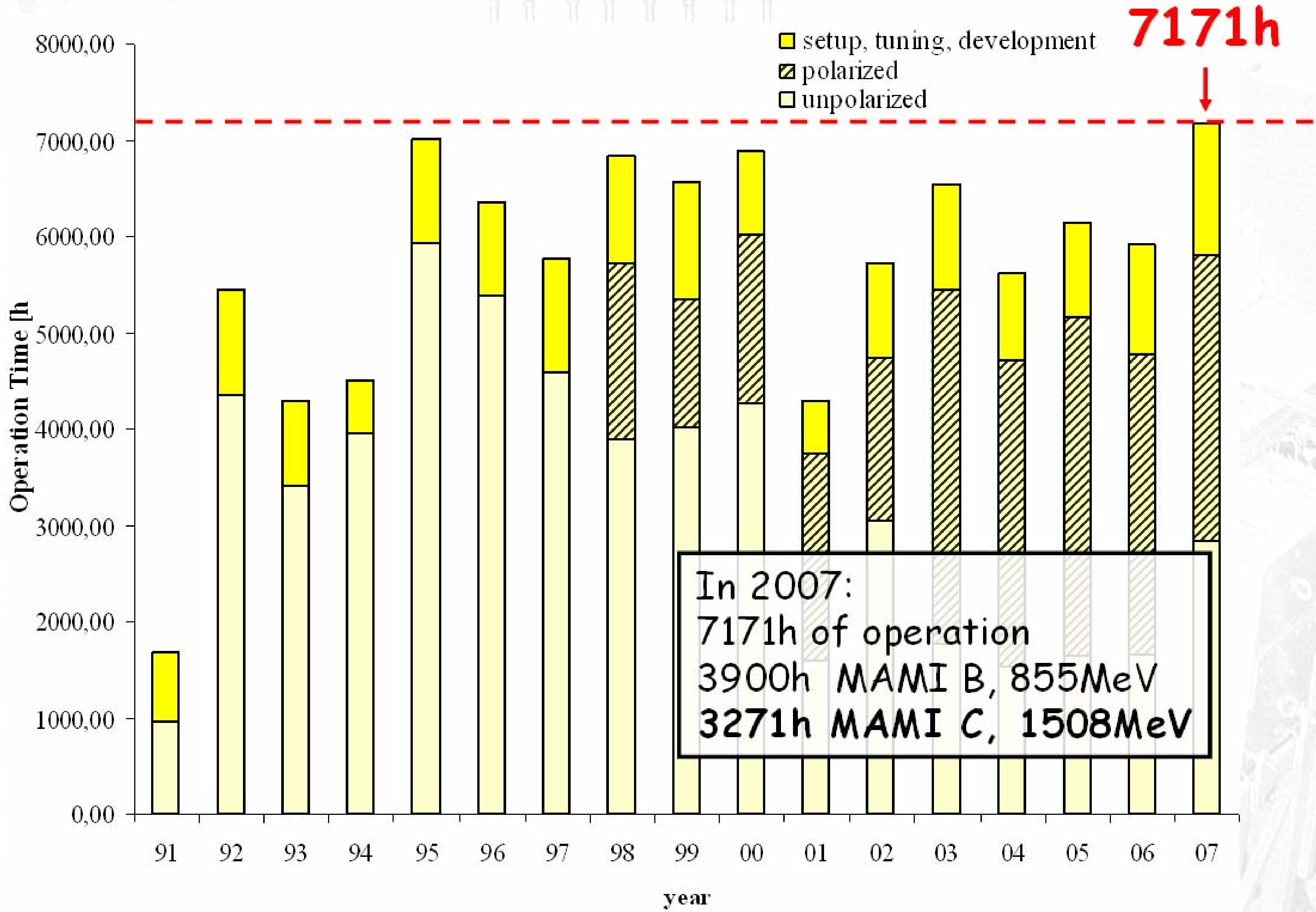
A2 – Tagged photon beams
29.03.2007: first beam

October 2007: high power beam test
100μA@1.508GeV = 150kW beam power
From beam loss monitor system one can estimate: beam losses well below 10^{-5}
very "clean" operation, as it used to be with MAMI B

A1 – Three spectrometer set-up
13.02.2007: first beam

Operation: beam time statistic

10.08.1990 – 02.05.2008: 100.000h of operation with MAMI



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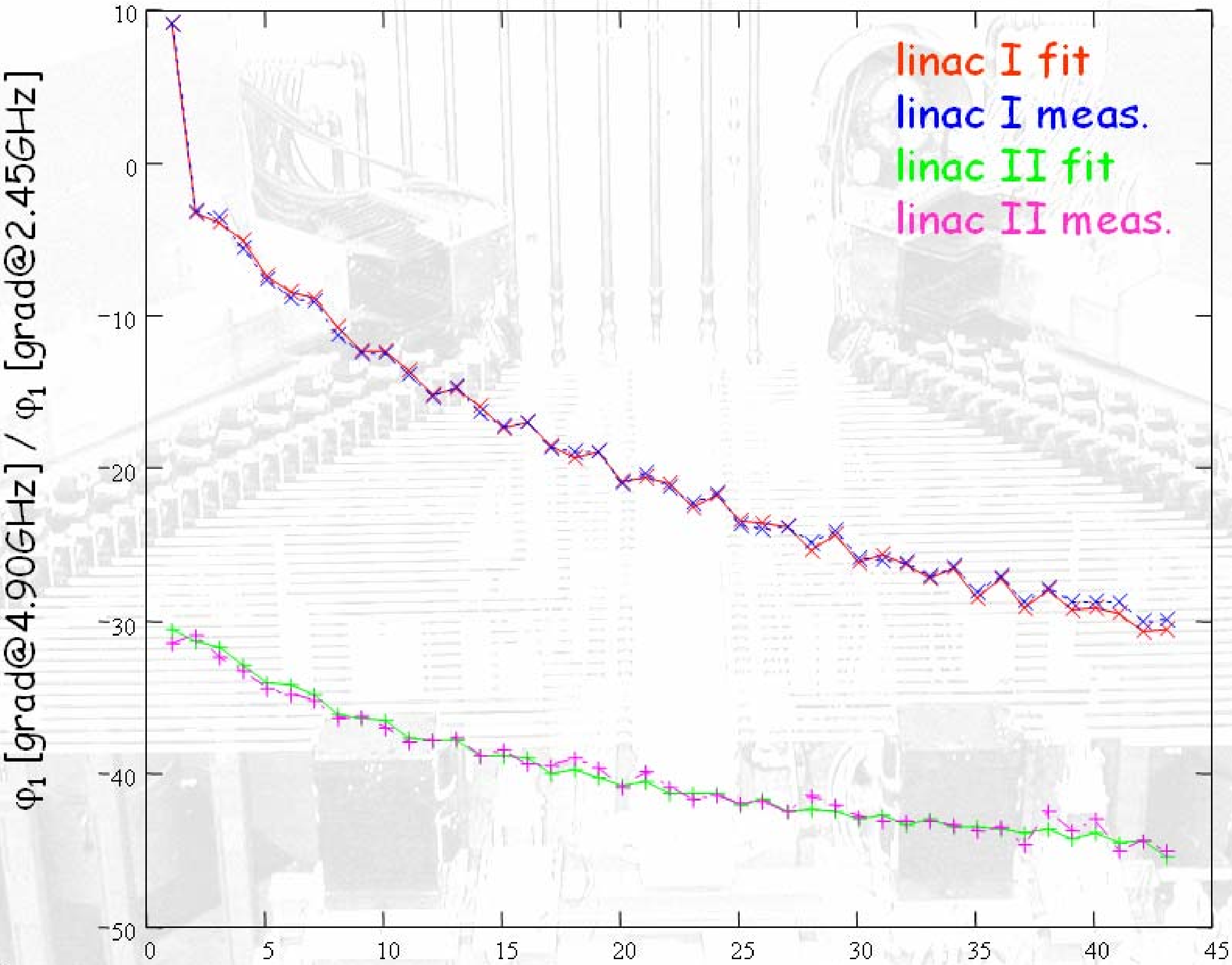
evaluation of measured phases



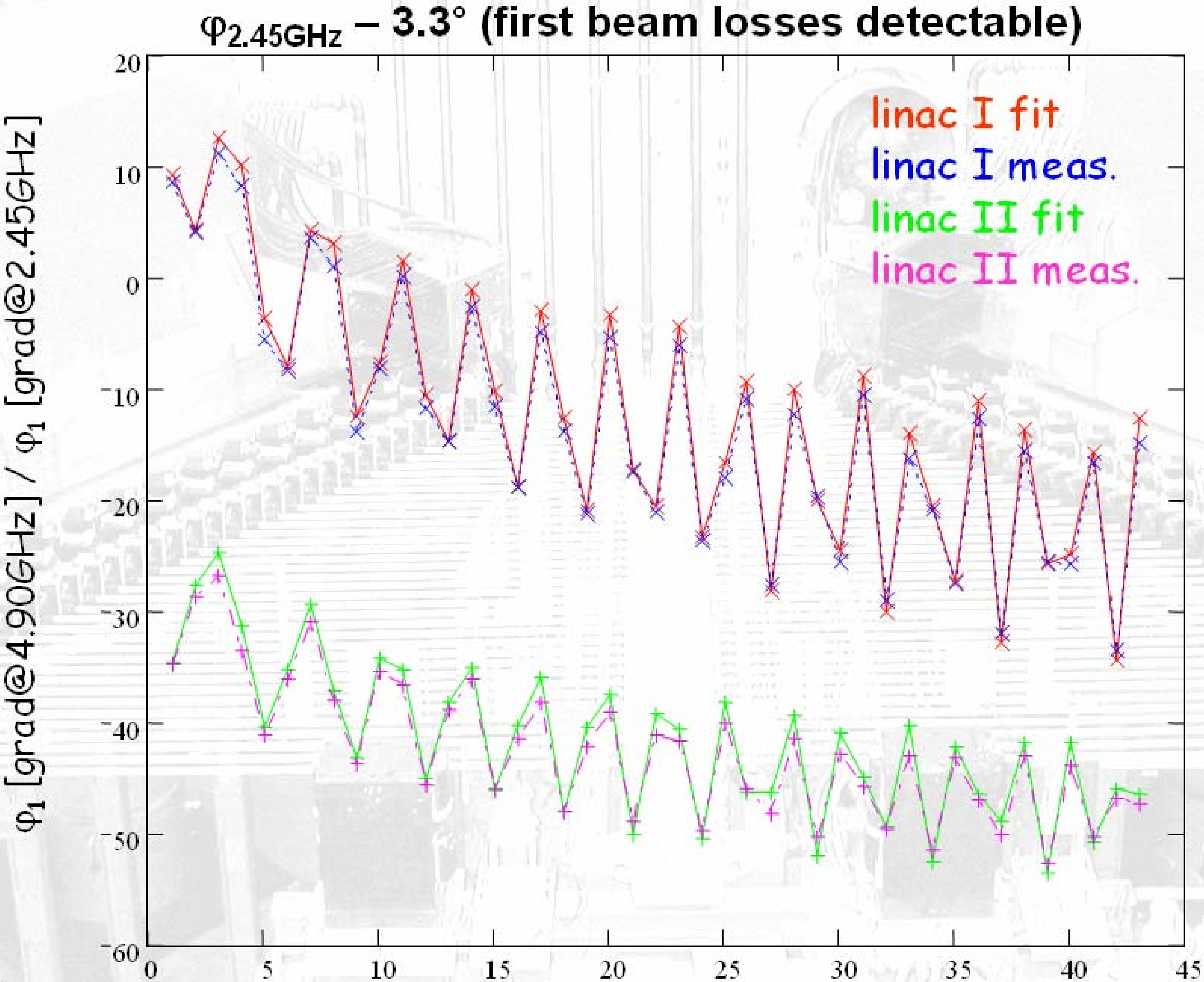
result of fit

4.90GHz-Linac (linac I): +9.2° / 8.60MV (ΔE_{tot}=343MeV) (measured: +9.1°)

2.45GHz-Linac (linac II): -30.6° / 9.46MV (ΔE_{tot}=310MeV) (measured: -31.5°)

E_{INJ}=855.243MeV (ΔE_{inj}=80keV), E_{out}=1508.8MeV

evaluation of measured phases



result of fit

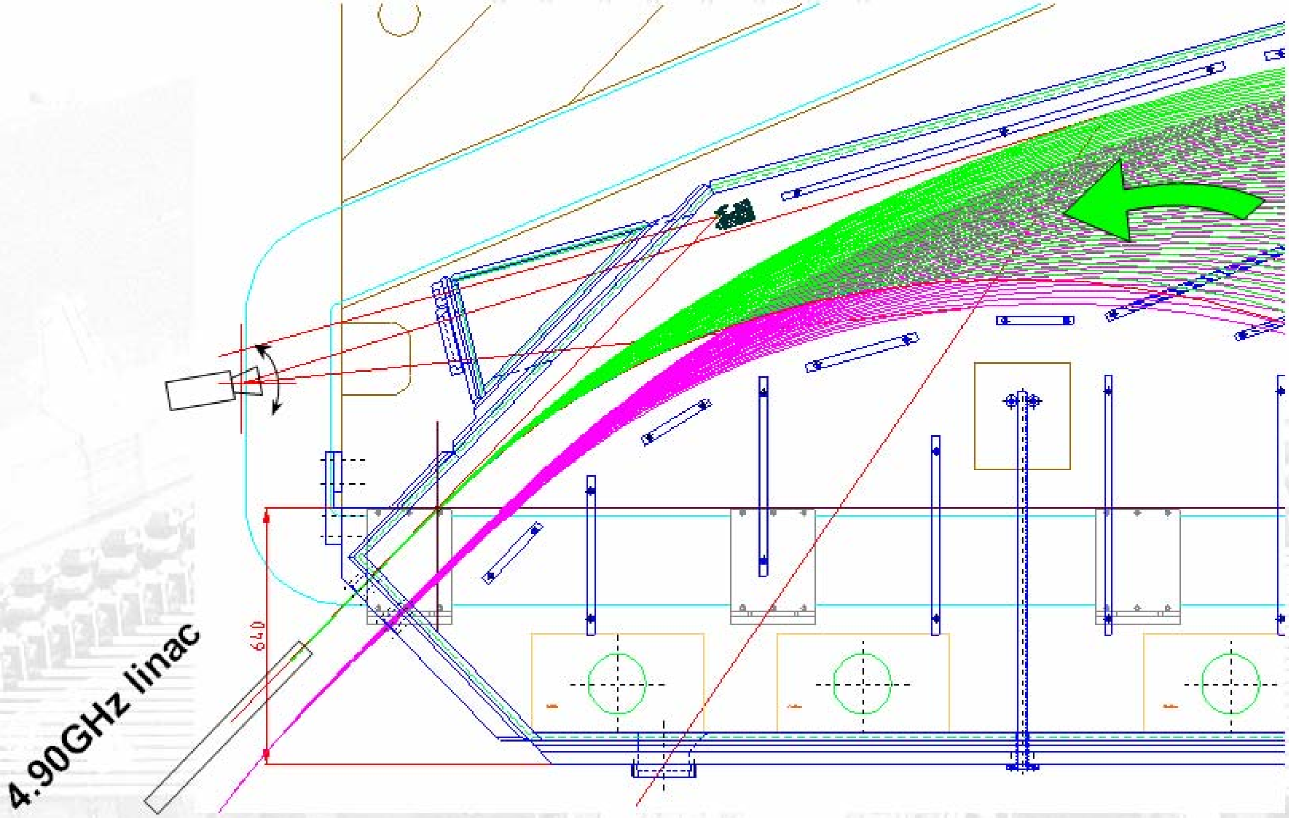
4.90GHz-Linac (linac I): +9.2° / 8.60MV (measured: +9.1°)

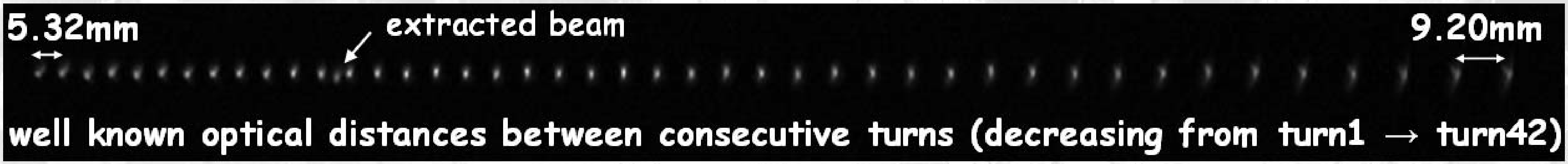
2.45GHz-Linac (linac II): -34.5° / 9.46MV (measured: -34.8°)

E_{INJ}=855.243MeV, E_{out}=1509.2MeV

Operation: emittance measurement

making use of return path synchrotron radiation monitor



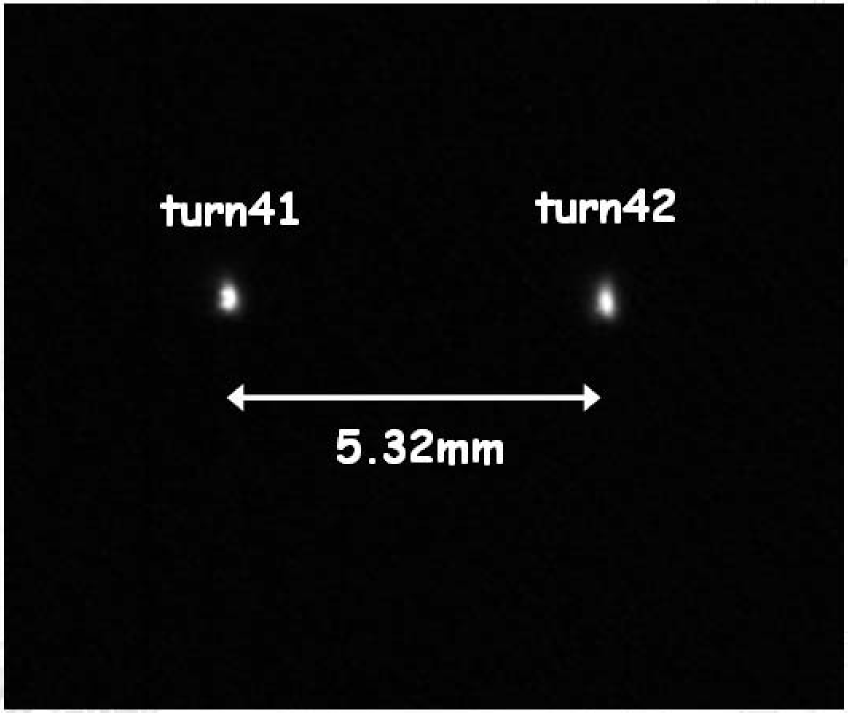


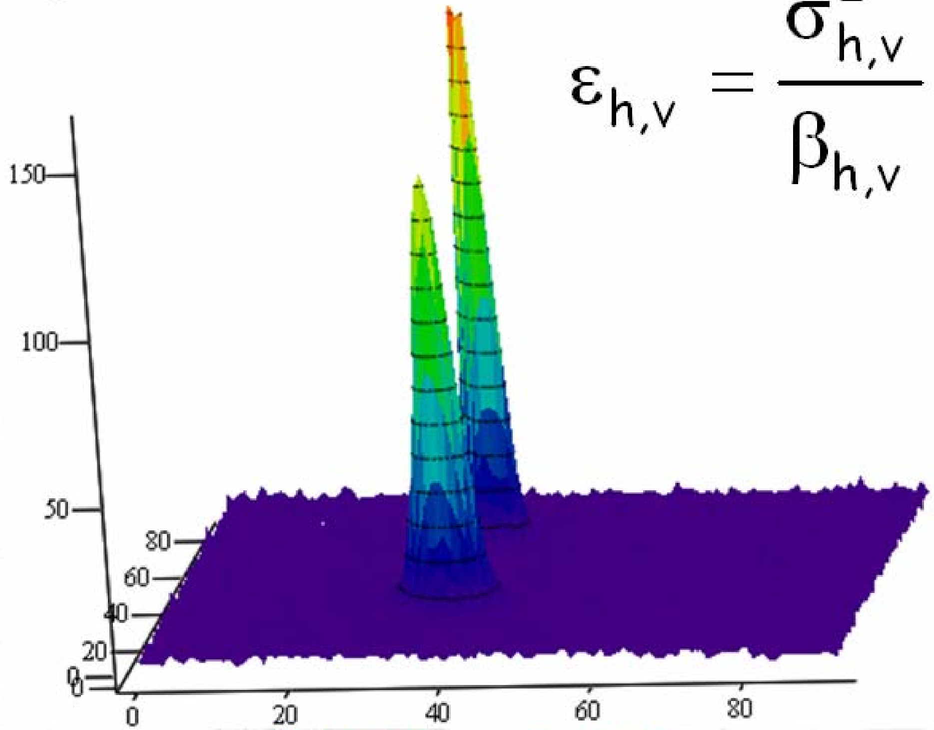
turn42 turn1

CCD camera (640pix × 480pix), min. shutter time 10μs
pixel size: h=8.3μm / v=8.3μm

Operation: emittance measurement

10μA cw, 10μs shutter time (30.05.2007)
(current and shutter adjusted for no saturation)





$$\varepsilon_{h,v} = \frac{\sigma_{h,v}^2}{\beta_{h,v}}$$

σ_h = 2.215pix = 0.301mm,
β_h ~ 7.4m

$\rightarrow \varepsilon_h$ = **12 nmrad**
(influence of finite energy width of only 80keV in dispersive section is negligible)

σ_v = 2.05pix = 0.279mm,
β_v ~ 40.3m

$\rightarrow \varepsilon_v$ = **1.9 nmrad**
(measurement limited due to optical resolution of the system)

Simulations predict:
ε_h=9 nmrad and ε_v=0.4 nmrad

Future prospects:

- making efficient use of return path synchrotron light monitor:
  emittance measurements, automated matching procedures

- phase cavities for relative energy measurements:
  energy stabilisation up to 10^{-6} for parity violating electron scattering at 1.508GeV

- measurements of absolute beam energy (10^{-4}):
  making use of well known dipole fields

- end energy increase:
  first test E_{inj}=883MeV $\rightarrow$ E_{out}=1557.3MeV
  then higher fields, new correction plates, rf-systems
  testing the limits of our design

- We have designed, built and commissioned the first Harmonic Double Sided Microtron
- A HDSM allows for two times higher maximum energy for the same iron weight compared to an RTM
- The HDSM operates very reliable and stable. It delivers a high power (150kW), low emittance beam with very small energy spread and > 80% polarization
$\rightarrow$ best continuation of the outstanding RTM principle