The FAIR p-Linac: Technical Overview and Diagnostic Instruments

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for the GSI Beam Diagnostics Department

- GSI and the FAIR Project
- p-Bar production chain
- p-Linac Technical Layout
- p-Linac Diagnostics
  - Beam Position and Energy using BPMs
  - Beam Induced Fluorescence for Transverse Profiles
- Summary

GSI and the FAIR Project

Existing GSI facility:
UNILAC & **SIS18** as injectors

FAIR: Facility for Antiproton and Ion Research

UNILAC:
Length: 120 m
Energy: 11 MeV/u

p-LINAC: high current 70 mA, 70 MeV

SIS100: superconducting, 100 Tm, 1-29 GeV/u, **high current operation p to U**
p: 2.5×10^{13}, U^{28+}: 5×10^{11} /pulse

SIS300: 300 Tm, acceleration up to 30 GeV/u

HEBT: fast & slow extraction, low & high currents

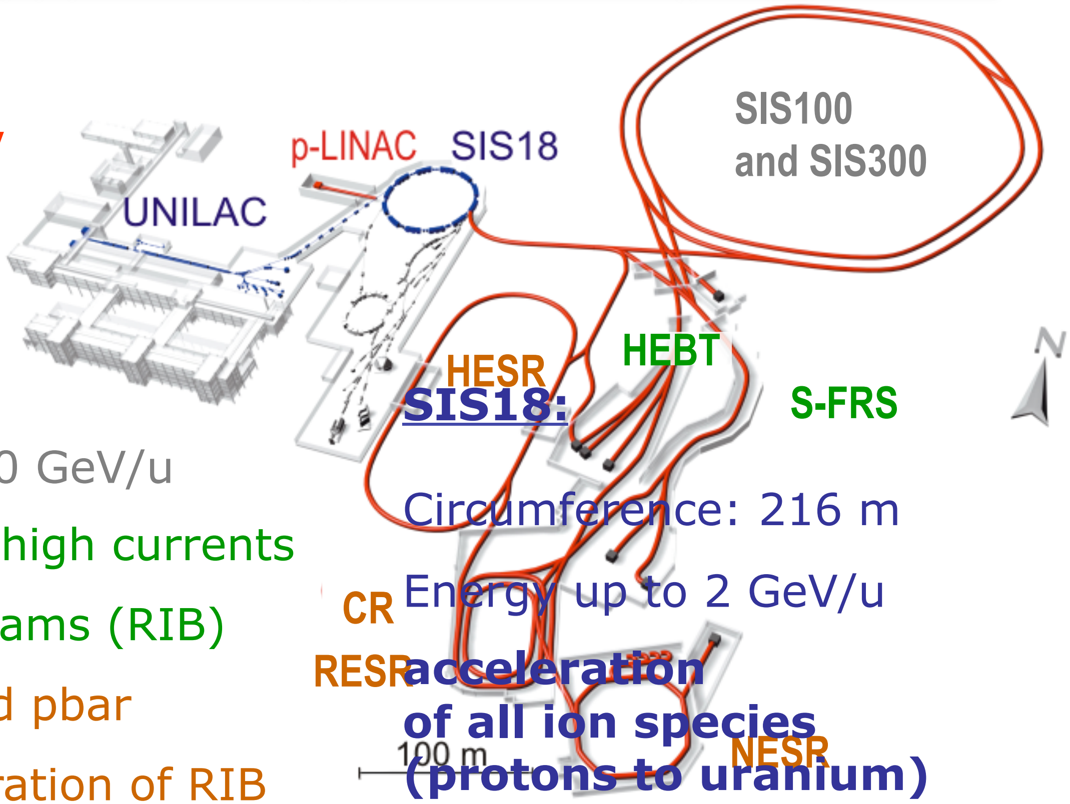
S-FRS: production of rare-isotope beams (RIB)

CR: stochastic **cooling** of RIB and pbar

RESR: accumulation of pbar, deceleration of RIB

NESR: versatile experimental ring for stable ions, RIB, pbar cooling, gas-target, e-A collider

HESR: storage and acceleration of pbar to 15 GeV/u



SIS18:

Circumference: 216 m

Energy up to 2 GeV/u

acceleration of all ion species (protons to uranium)

Modularized FAIR Version

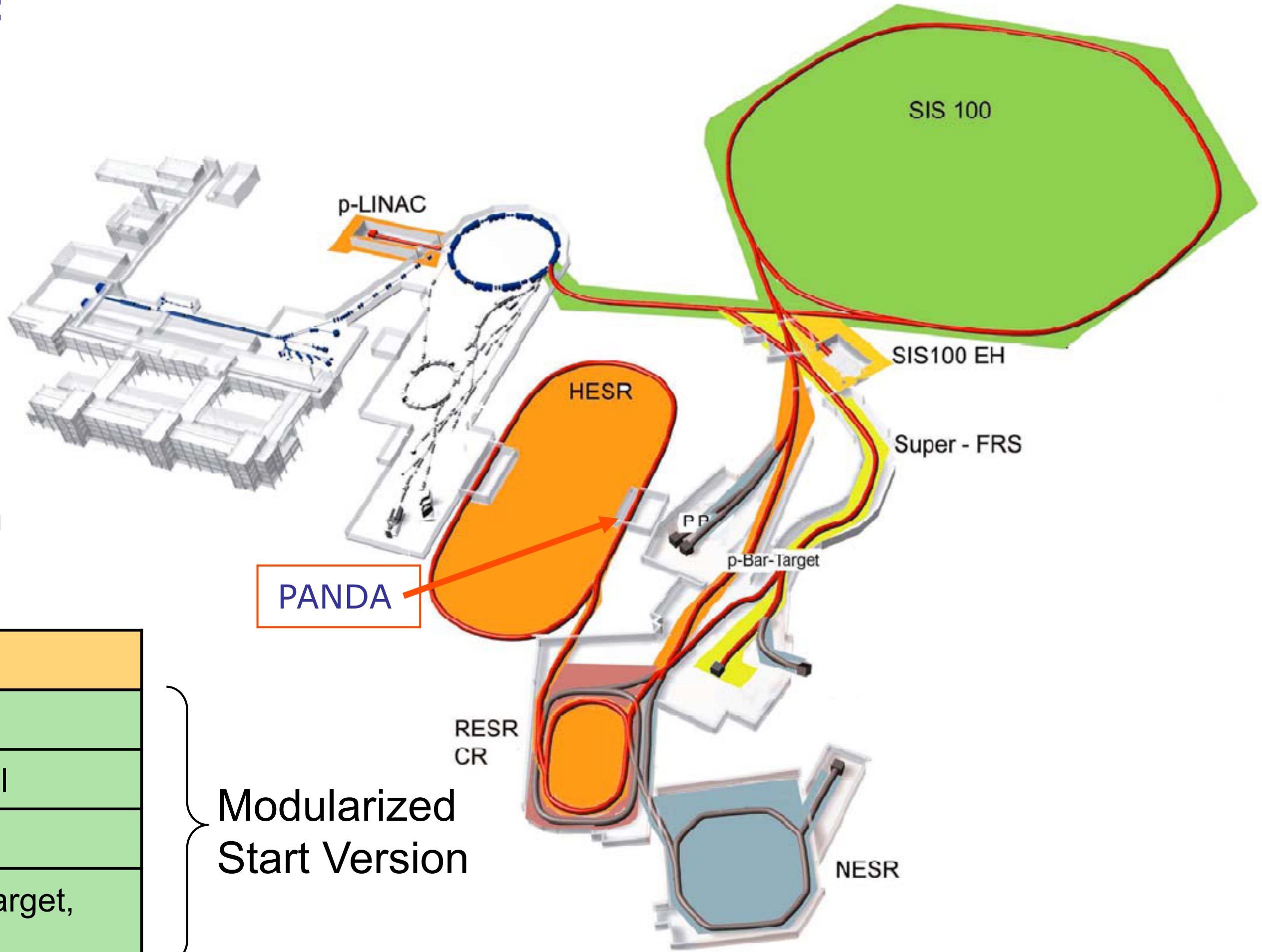
International Steering Committee:

For soon start of the FAIR construction

FAIR Joint Core Team and Scientific and Technical Issues Working Group

were mandated to prepare a proposal for

a start version accounting for recent cost estimates and firm funding commitments



Module	Color	Machine
0	green	SIS100
1	ochre	Experimental hall
2	yellow	Super-FRS
3	orange	p-Linac, p-Bar-Target, CR, HESR
4	blue-gray	NESR, experiment stations
5	red-brown	RESR

Modules 0–3: Modularized Start Version

Modules 4–5: Final Stage

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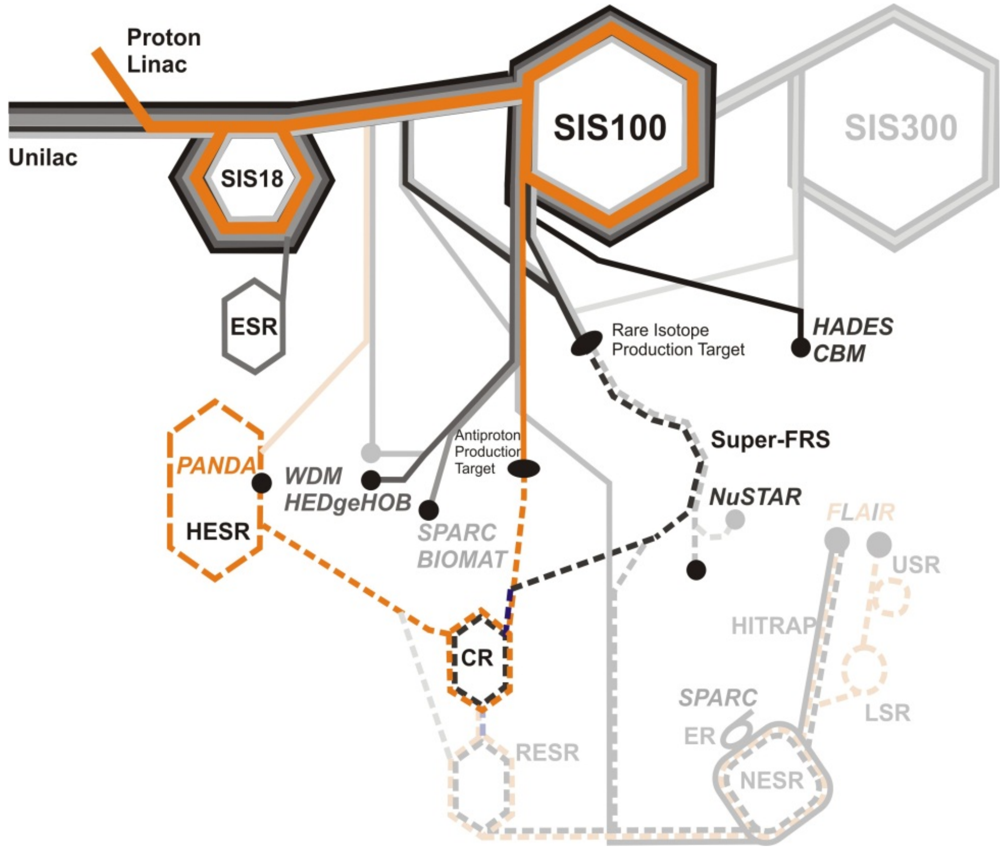
Beam Production for PANDA

p-Linac → SIS18 → SIS100 → pBar-Target → pBar Separator → CR → HESR

PANDA Experiment

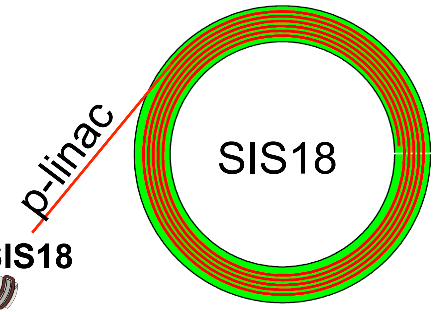


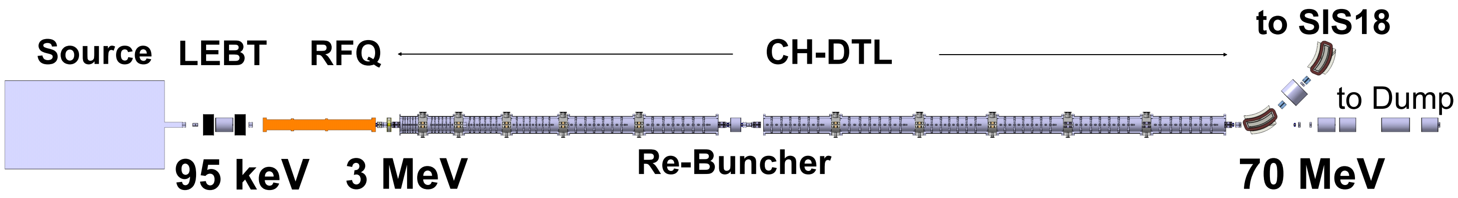
Antiproton production:

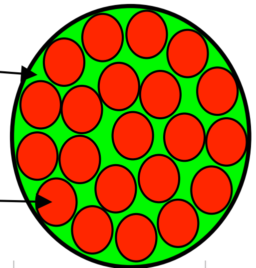
- 4 * (p-Linac, SIS18) → SIS100
- 2 bunches per injection into "barrier bucket"
- compression into 1 bunch
- acceleration in SIS100 to 29 GeV
- antiproton target and separator
- → CR, stochastic cooling
- accumulation in HESR, then acceleration / deceleration to final energy.

Proton Beam: p-Linac to SIS18

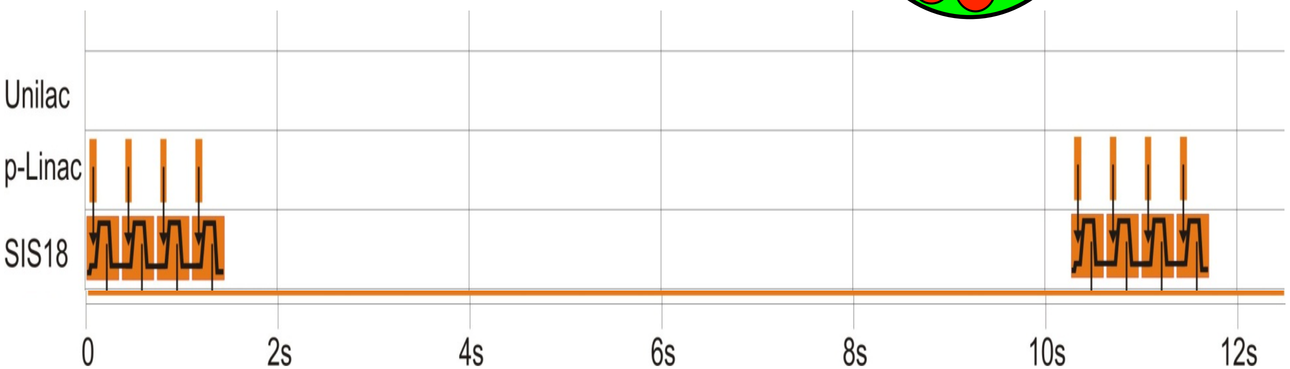
- p-Linac: dedicated **high current injector 70 MeV proton beam** for pBar production
- 35 mA beam current, 36 μs macropulse, 4 Hz repetition rate
- 1 p-Linac macropulse fills SIS18 up to space charge limit (18 turn-MTI)







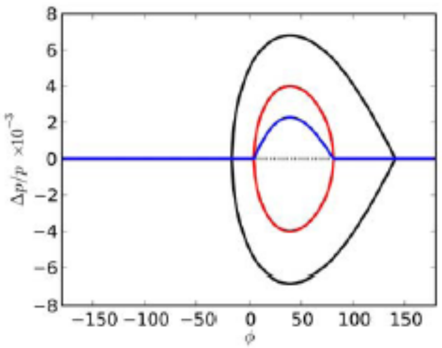
η_{MTI} := red area / green area
= filling factor



pBar Operation of SIS100

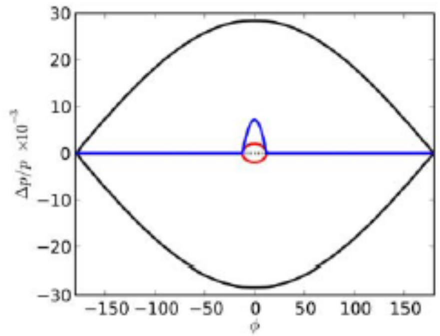
- acceleration of proton beam 4 GeV to 29 GeV
- during subsequent acceleration bunch length shrinks below 50 ns

Start acceleration



'rf gymnastics'

Final Energy
29 GeV, bunch: 50 ns



RF bucket
bunch boundary
bunch form

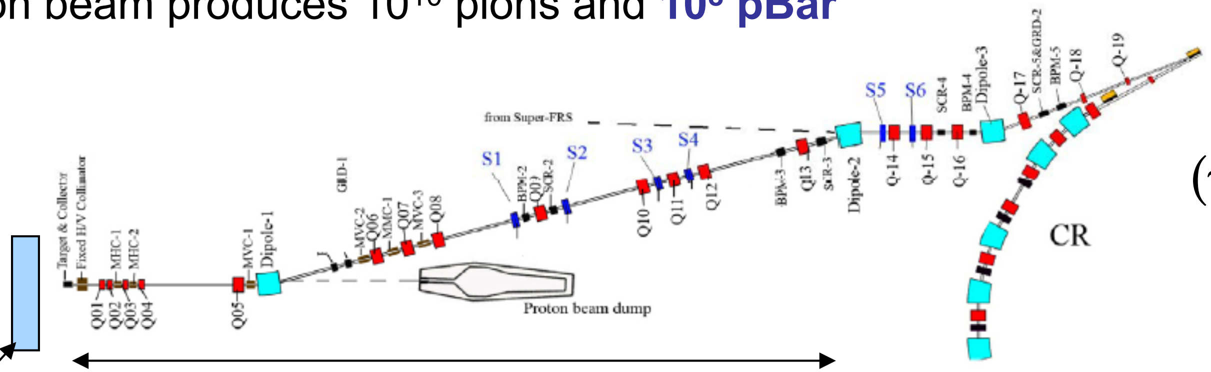
	Bunch pattern	Harmonic numbers	Duration (approx.)
Injection from SIS-18	4 bunches / 6 empty	10	1.1 s
Merging	2 bunches / 3 empty	10→5	0.1 s
Batch compression	2 bunches / 8 empty	5→6→7→8→9→10	0.3 s
Merging	1 bunch / 4 empty	10→5	0.1 s
Acceleration	1 bunch / 4 empty	5	0.4 s

pBar Target and Separator

Primary proton beam produces 10^{10} pions and **10^{8} pBar**

29 GeV protons

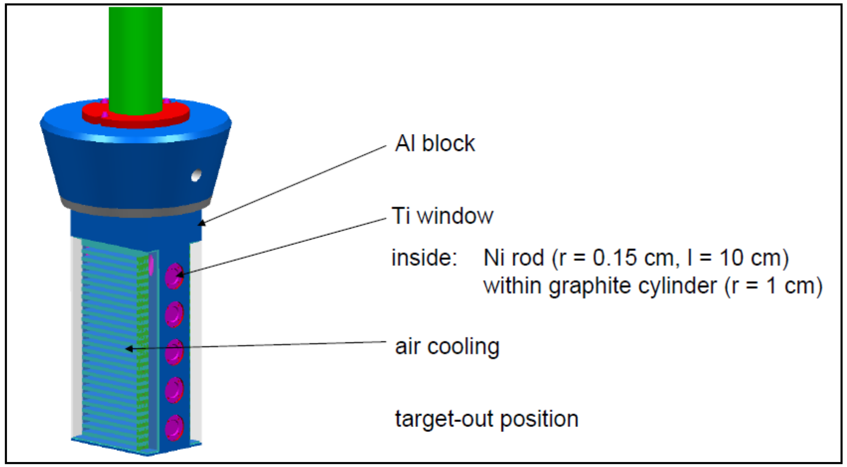
SIS100 →



(τ_{π}= 26 ns)

pBar Separator

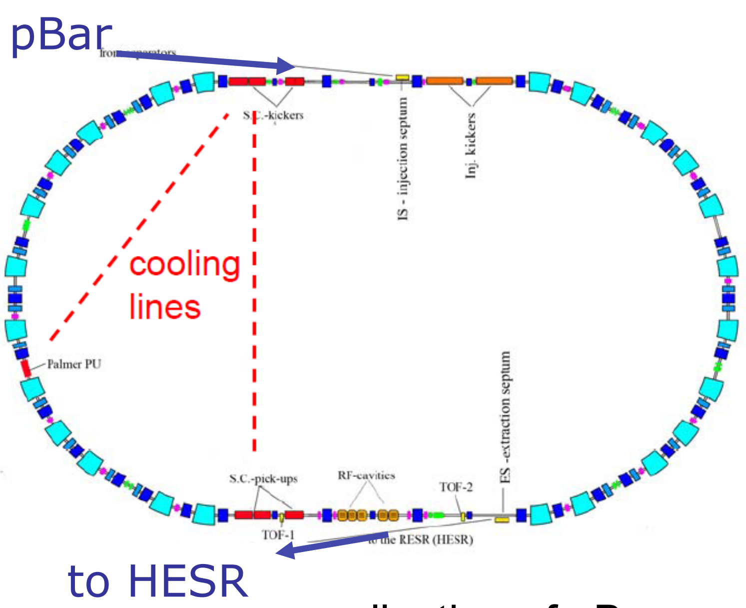
pBar Target



- pBar generated in **inelastic collisions of high-energy protons with target protons**
- p A → $\bar{p}$ X, X represents all particles of shower
- wide angular distribution of pBar
- pBar threshold 5.6 GeV for primary protons
- at 29 GeV maximum production and collection yield is reached for **pBar energy of 3 GeV**
- 3 GeV pBar → max. 13 Tm magnetic rigidity required for HEBT, CR, HESR

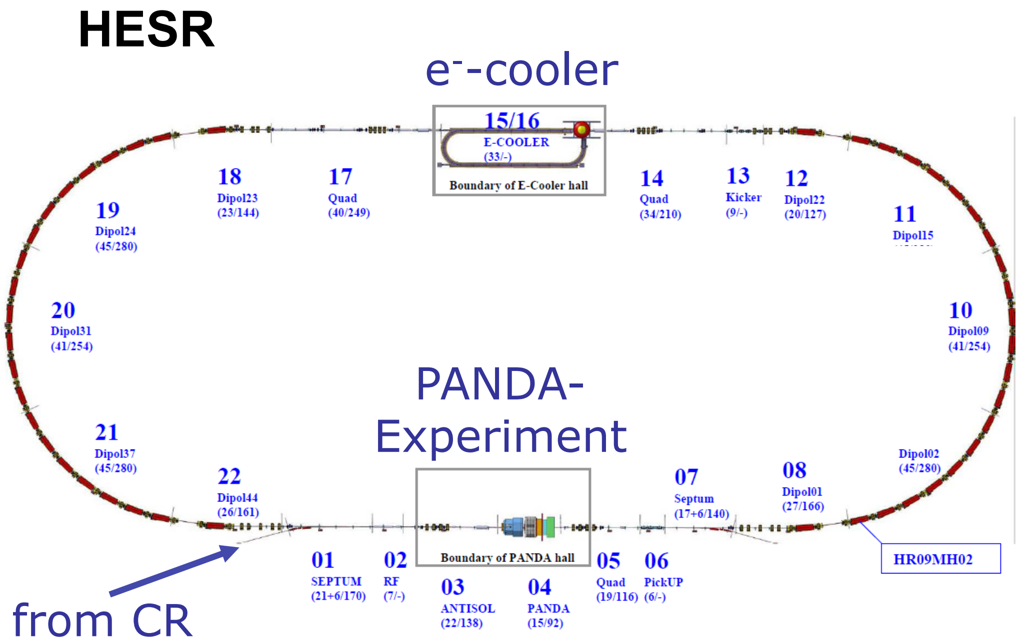
pBar Operation in CR / HESR

Collector Ring

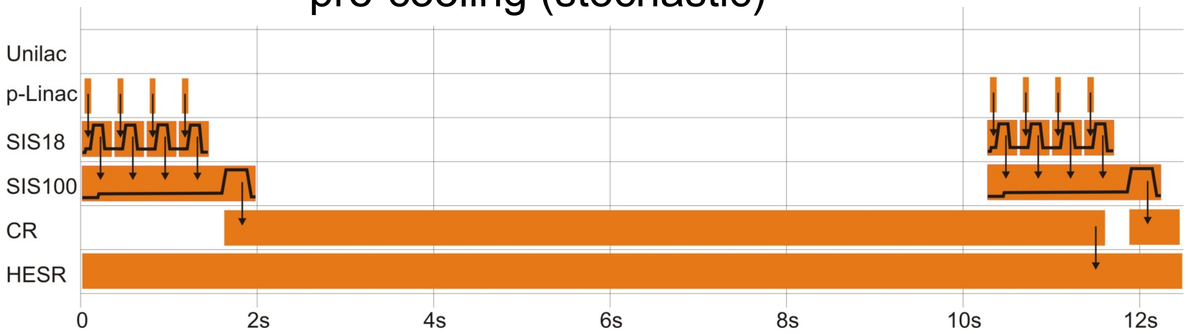


- collection of pBar
- pre-cooling (stochastic)

High Energy Storage Ring



- accumulation of CR beam
- stacking using barrier buckets
- combined (electr.+stoch.) cooling



PANDA – Anti-Proton ANnihilation at DArmstadt

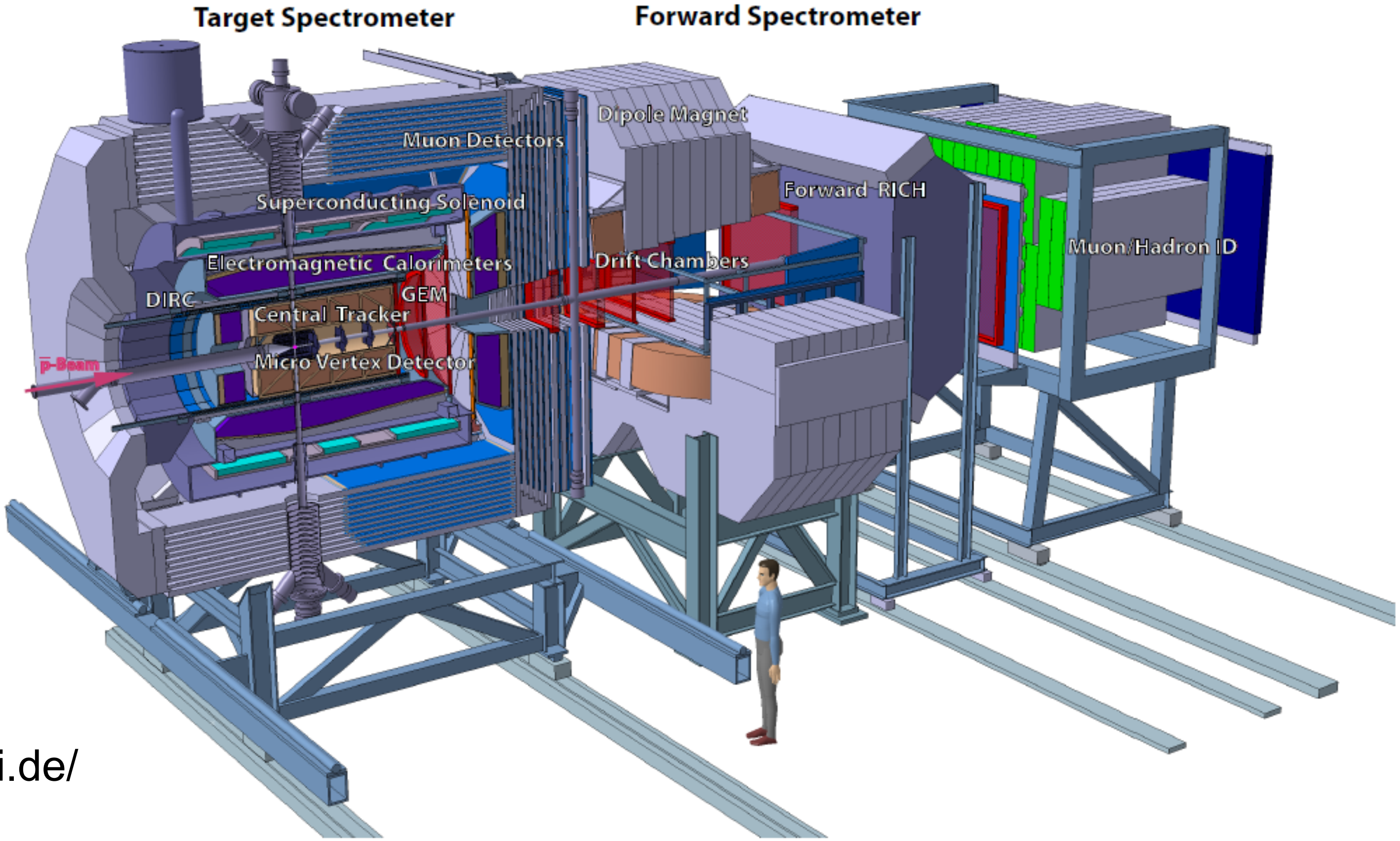
The PANDA Collaboration: 450 scientist from 17 countries

Goal: basic research on various topics covering
weak and strong forces, exotic states of matter
and the structure of hadrons.

PANDA physics cases:

- Hadron Spectroscopy
- Nucleon Structure
- Hadrons in Mater
- Hypernuclei

→ http://www-panda.gsi.de/



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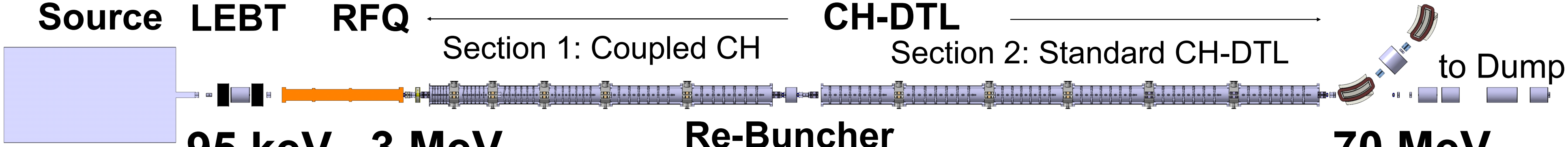
p-Linac: Overview



Beam energy	**70 MeV**
Beam current (op.)	**35 mA**
Beam current (des.)	**70 mA**
Beam pulse length	**36 µs**
Repetition rate	**4 Hz**
Rf-frequency	**325.224 MHz**
Tot. hor. emit. (norm.)	**2.1 / *4.2* µm**
Tot. mom. spread	**≤ ± 10^{-3}**
Linac length	**≈ 35 m**

- first Linac based on room temperature **'crossbar H-type' structure (CH-DTL)** with **KONUS beam dynamics**
- **rf is multiple of UNILAC HSI resonance** frequency (36.136 MHz), fits to 3 MW klystrons of J-PARC (324 MHz)
- intertank-section for diagnostics (beam intensity, position, energy, profile)
- goal: production of **2×10^{16} protons/h**

p-Linac: ECR Ion Source (SILHI) / LEBT

	Required	SILHI
H^+ current	100 mA	105 mA**
Full beam	<115 mA	110 mA**
Energy	95 keV	95 keV
Duty cycle	4 Hz	4 Hz
Pulse length	>36 µs	>300 µs**
Emittance*	0.3 π mm mrad	≤0.5 π mm mrad**
Noise	<±5 %	±7 %**
Life time	months	months
Availability	>90 %	99 %

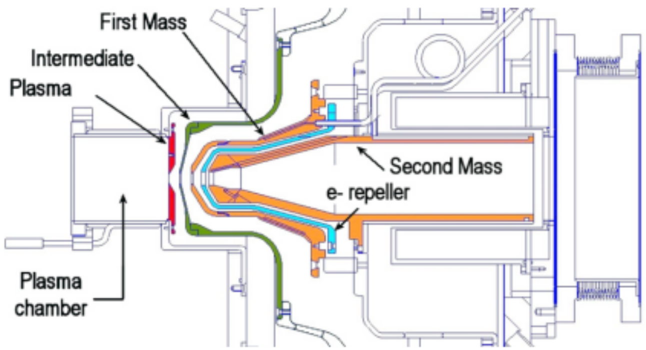
*(norm., rms), **(typical values, not optimized for pulsed operation)

Source d'**i**ons **l**egères d'**h**aute **i**ntensité

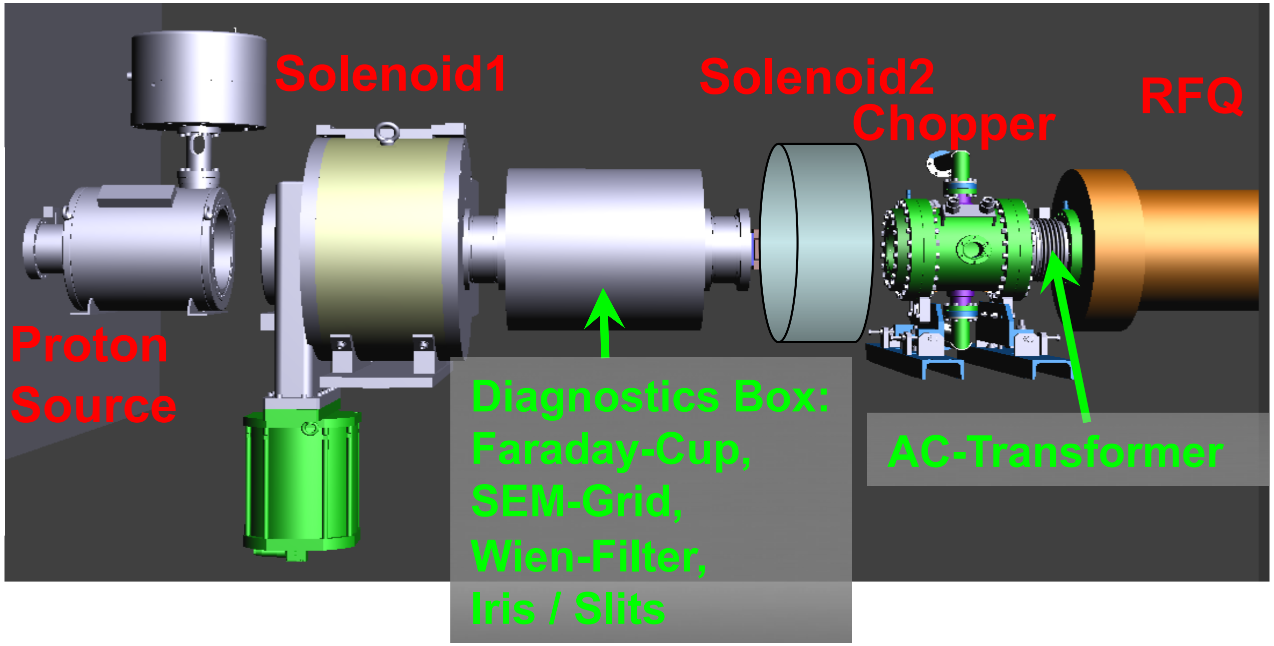
ECR-type proton source: H^+, H_2^+, H_3^+

SILHI source and major part of LEBT delivered as French in-kind contribution (CEA Saclay)

Pentode Extraction System of SILHI Source



Preliminary LEBT Design

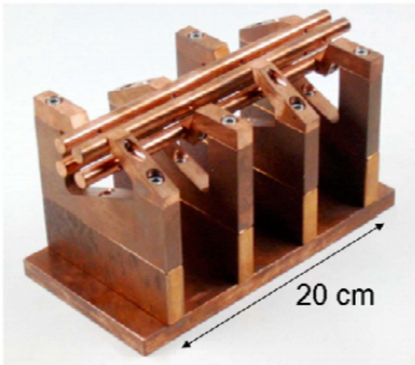


pLinac: RFQ and CH-Structure

Radio-Frequency Quadrupole

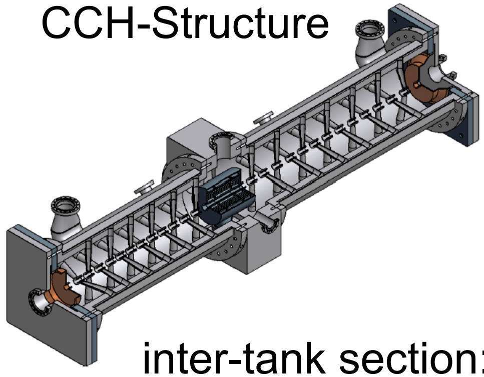
- acceleration: 95 keV to 3 MeV
- current: 90 mA
- ε_{norm}= 2 µm
- 4-rod easier to manufacture than 4-vane

Model of 4-rod RFQ

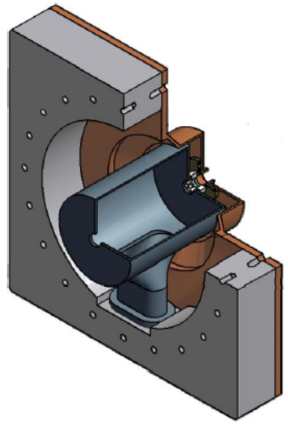


→ *L. Groening et al., LINAC2004, MOP06 ; G. Clemente et al., HB2010, MOPD26*

CCH-Structure



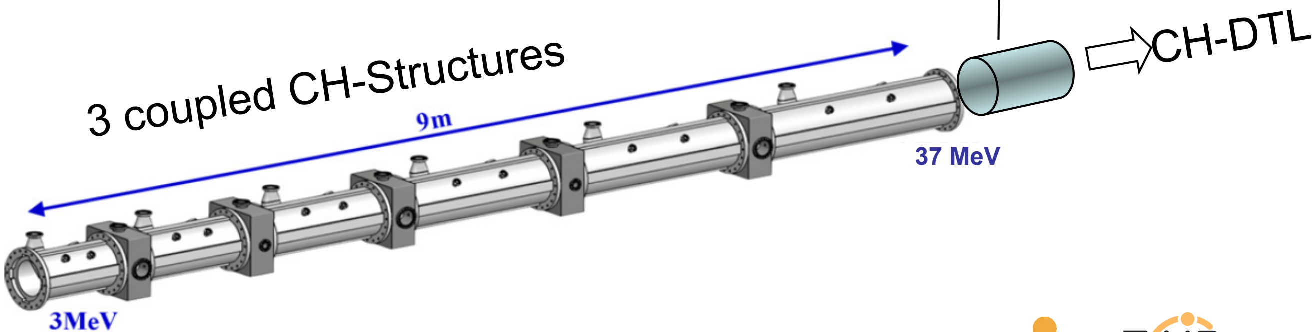
inter-tank section: quadrupole triplet ... and bpm!



CH-DTL	
3 CCH	37 MeV
3 CH-DTL	70 MeV
rf	325.224 MHz
emittance	<2.8 µm
mom. spread	< 0.1%
rf pulse	70 µs
max. beam pulse	36 µs

→ *R. Brodhage et al., IPAC2010, MOPD031*

1.6 m Diagnostic Section:
BPM / Phase probe
BIF, ACT



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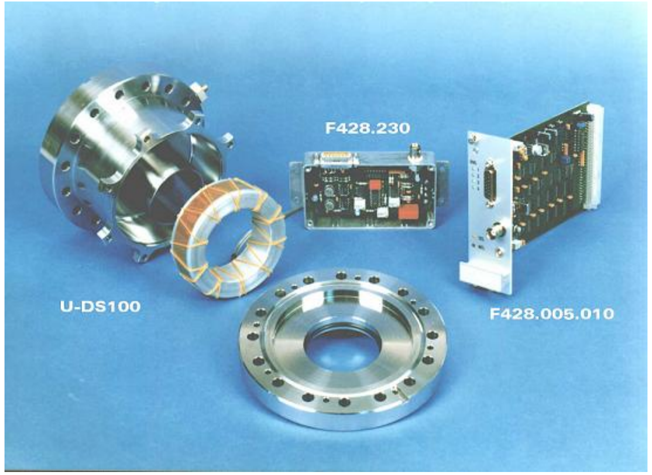
Beam Diagnostics for FAIR p-LINAC

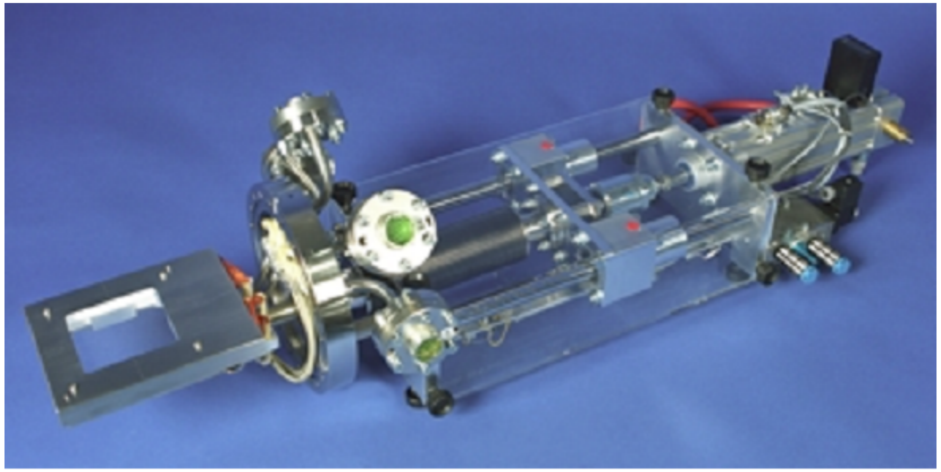
Beam Parameter	Device	#	Non-destructive	Remark
Current	Transformer	**9**	**Yes**	Dynamic transmission interlock
	Faraday Cups	**4**	**No**	Only used as beam dump
Profile	SEM-Grid	**4**	**No**	Standard, requires trans. control
	BIF (fluorescence)	**4**	**Yes**	Under development
Transverse emittance	Slit-Grid	**3**	**No**	Standard
Position	**BPM**	**15**	**Yes**	Online display
Mean energy	**BPM**	**(15)**	**Yes**	Time-of-flight or phase
Bunch shape	Non intersecting BSM		**Yes**	Novel, under development
Charge states	Wien Filter	**1**	**Yes**	From CEA Saclay

'Standard' Diagnostic Equipment

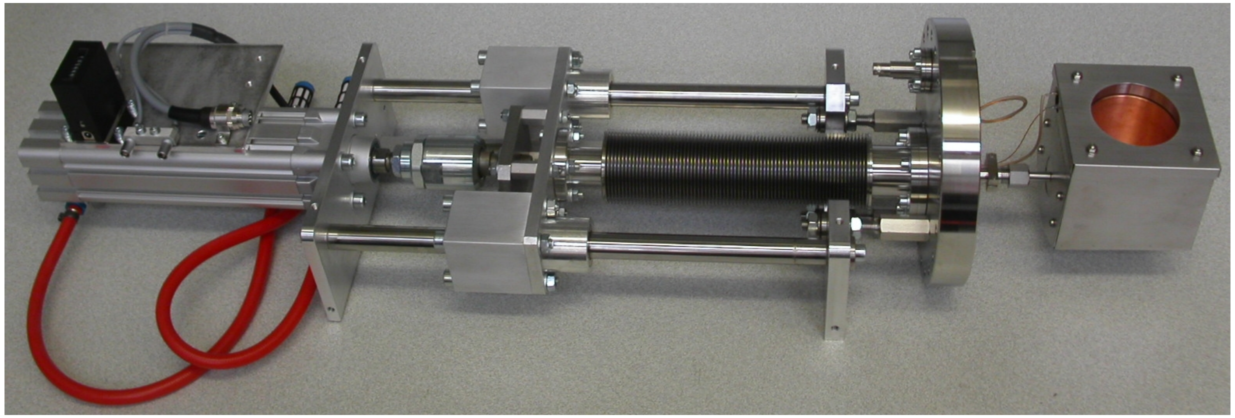
AC-Current Transformer



SEM-Grid



Faraday-Cup

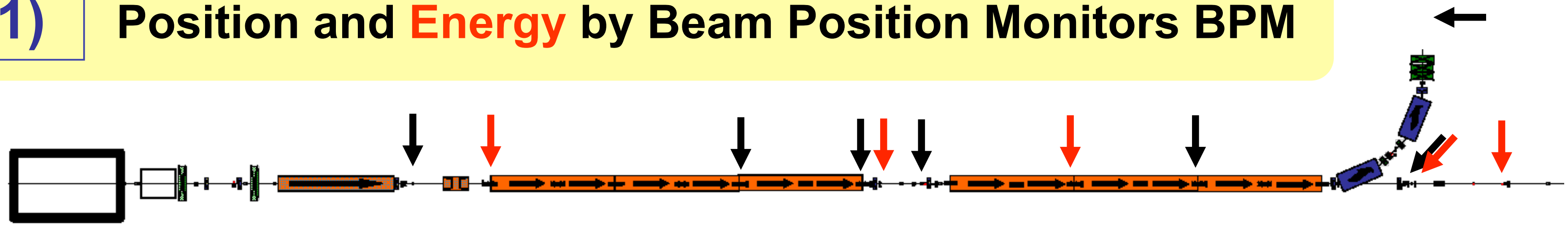


2 Examples: Beam Position/Energy & Profile

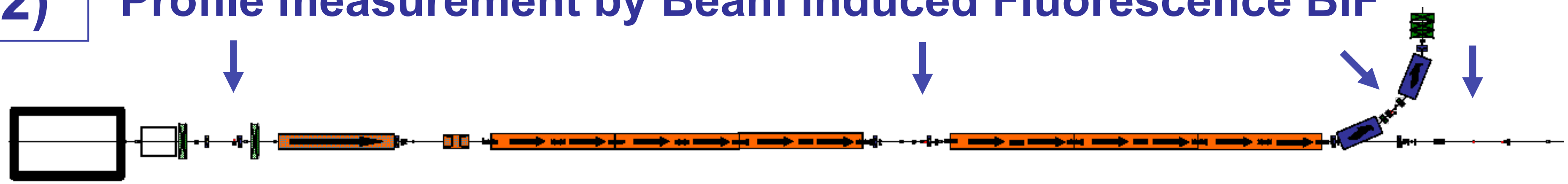
Focus on 2 examples for 'non-standard' diagnostic components

High beam intensity → non-intercepting methods !
→ precise detection of position and profile !

1) Position and Energy by Beam Position Monitors BPM



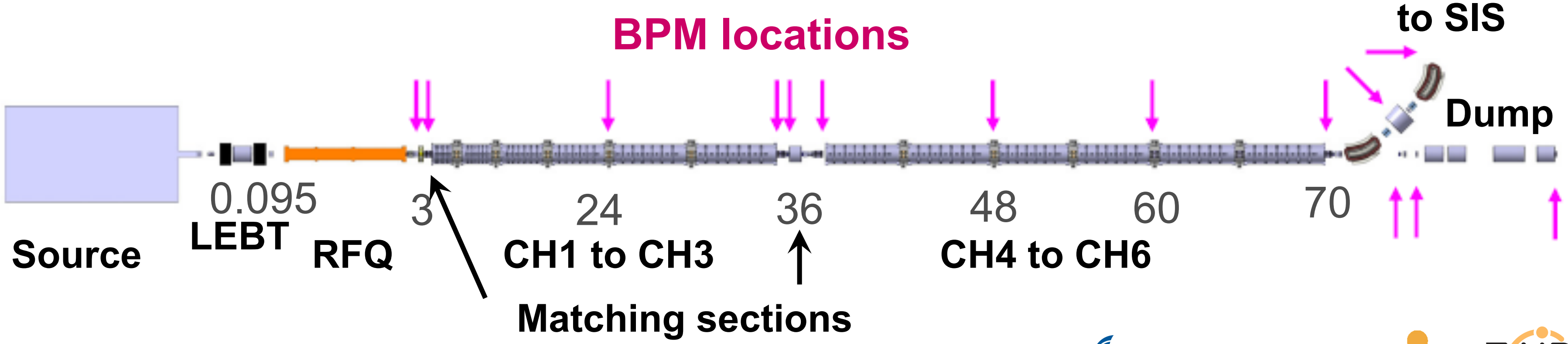
2) Profile measurement by Beam Induced Fluorescence BIF



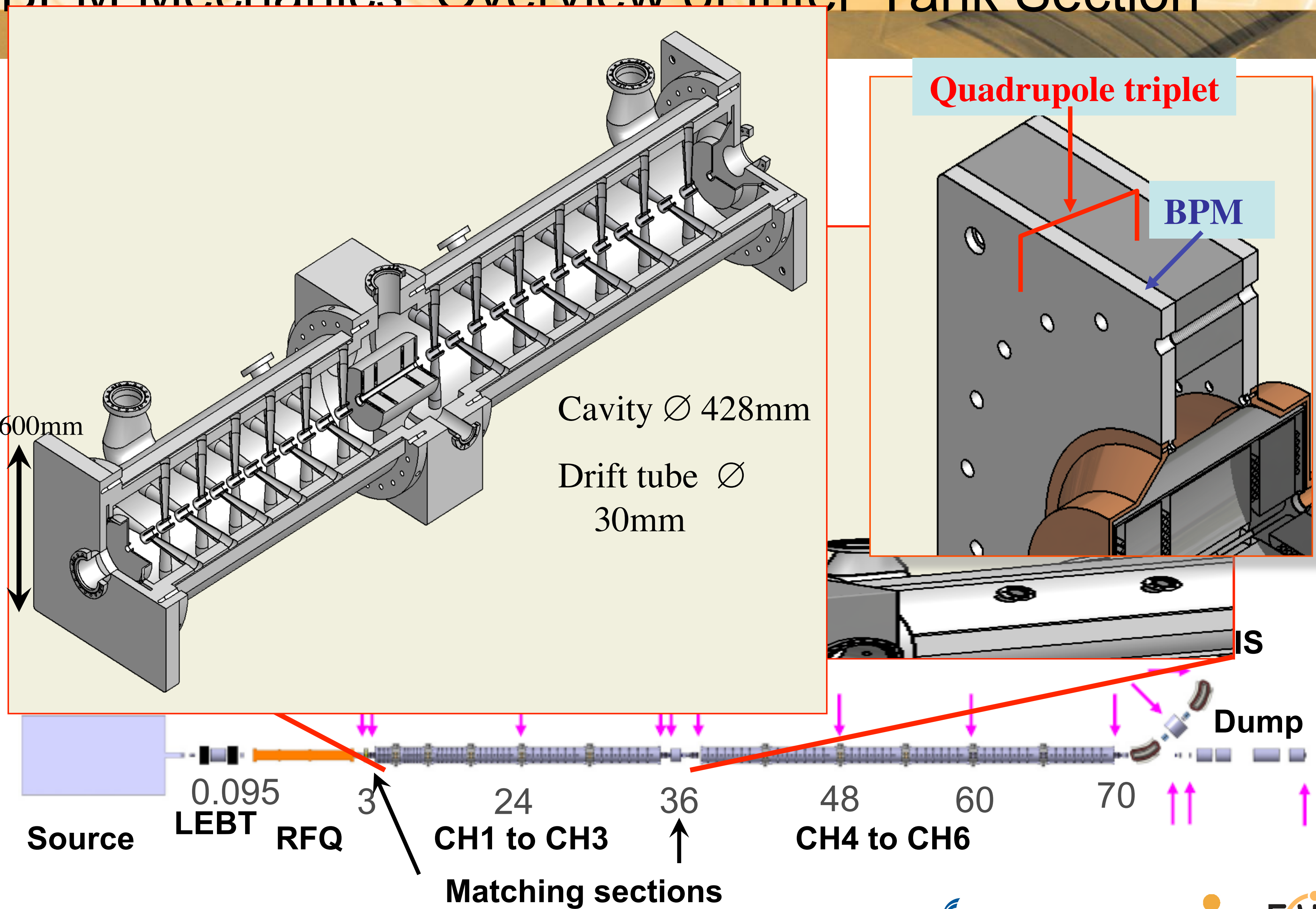
Requirements for p-Linac BPMs

- Dynamic range 60 dB, i.e. 0.3 mA or 1 % I_{nom} measurable (UNILAC >100 dB)
- Relative beam current: by sum signal
- **Position evaluation**: resolution better 0.1 mm within 30 µs (t_{pulse}=36 µs) ➡ Low-β !
- **Phase evaluation** / Energy via TOF: resolution $\Delta\varphi=1^0$ equals Δt=10 ps ➡ KONUS !
- Observation with ≈1µs time steps desirable
- 14 locations, **button-type BPMs** preferred due to compactness
- Only two types (Ø30mm or Ø50mm) to prevent systematic errors for phase measurement
- Some **BPMs must be installed between the rf – cavities**

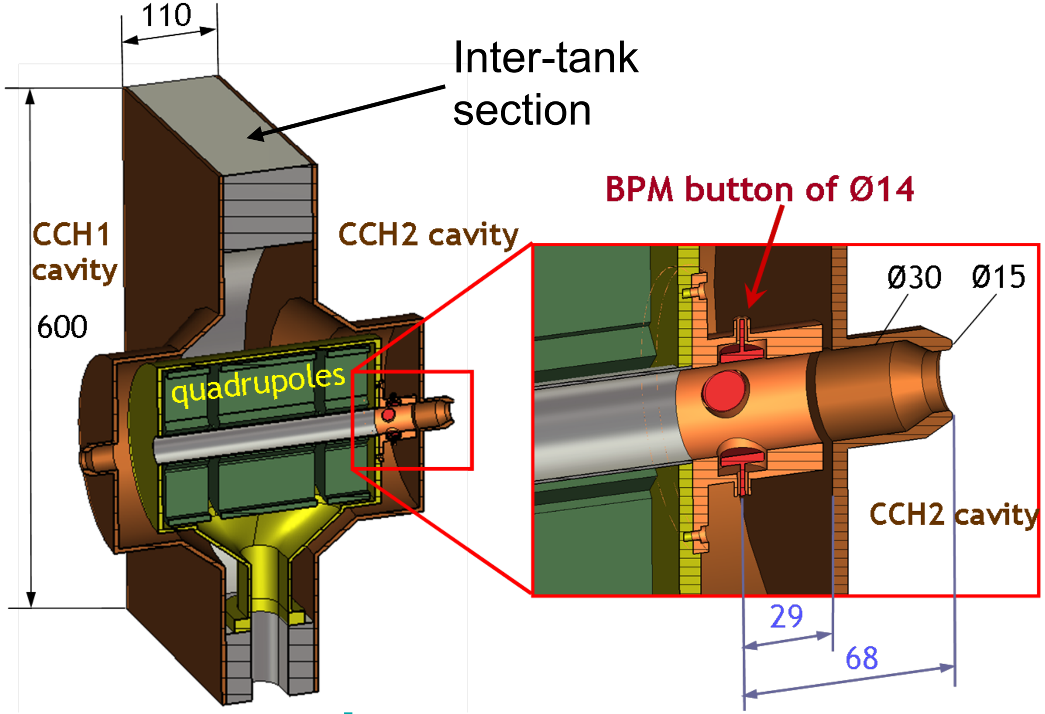
  ⇒ possible rf-leakage ⇒ **position evaluation on 2nd harmonics at 650 MHz**



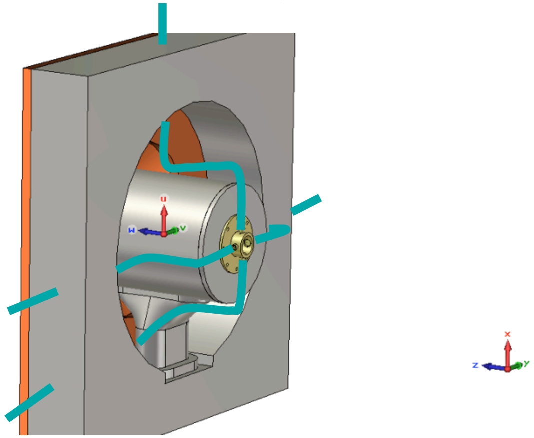
BPM Mechanics: Overview of Inter-Tank Section



BPM Mechanics: 3 BPMs inside Inter-Tank Section



Example: button-type BPM (Company Megitt)



Challenges for mechanical realization:

- Short insertion length ≈ 30 mm
- Almost no accessibility ⇒ difficulty of cable rooting
- Closed box ⇒ Thermal investigations required
- Production process has to be elaborated
- Collaboration with University Frankfurt

FEM Simulations for Button-Type BPMs

Usage of BPMs for position reading

Here: design consideration for FAIR p-LINAC

Using button types (commercially available)

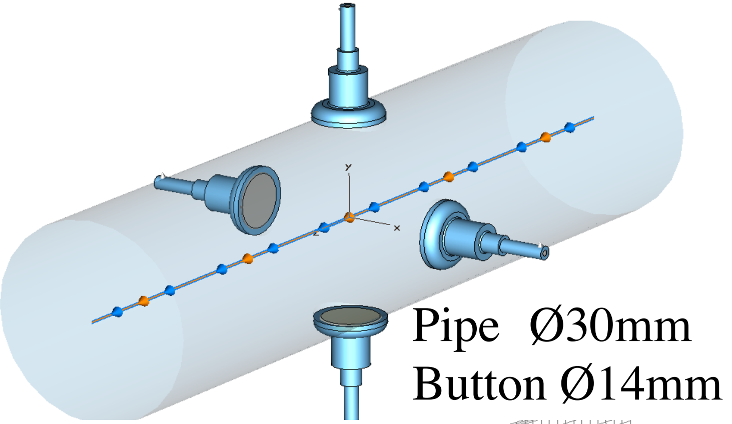
→ Design and test of BPM buttons as part of French in-kind by CEA Saclay

Design using CST calculations

- different β along lattice
- Position for n^{th} rf harmonics

Parameters:

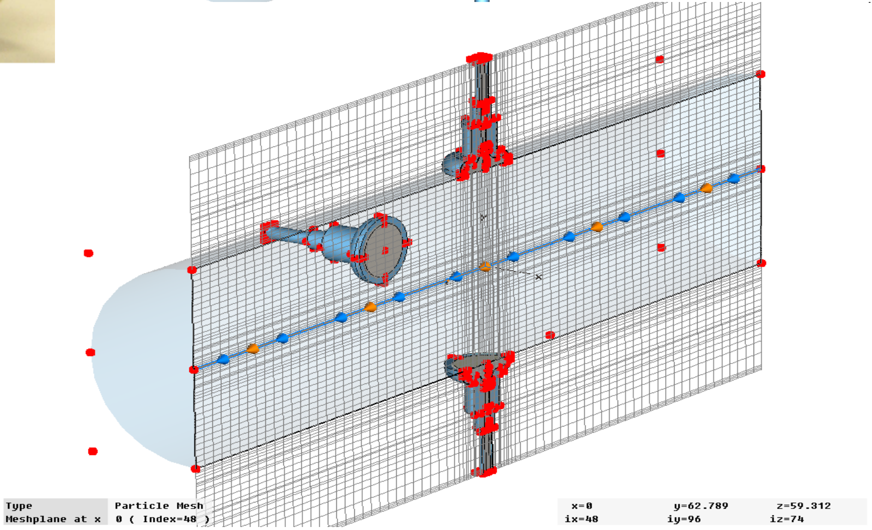
- BPM aperture: Ø 30 mm
- f_{rf} = 325 MHz
- bunch length σ_t = 150 ps



Simulations:

- CST Particle Studio for 0.1< β < 0.3
- Gaussian charge distribution of σ_t = 150 ps
- Wake Field Solver used
- ~1.8×10^6 mesh cells

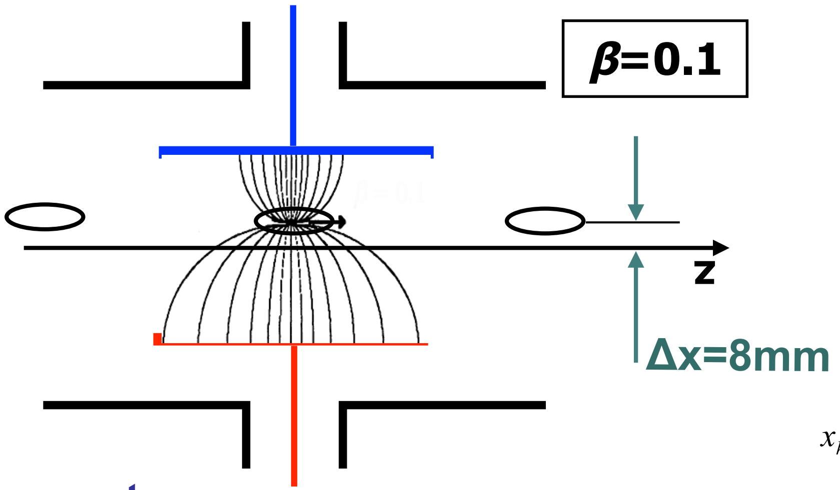
Simulation time ~20 h / task



Collaboration with CEA/Saclay and TU-Darmstadt

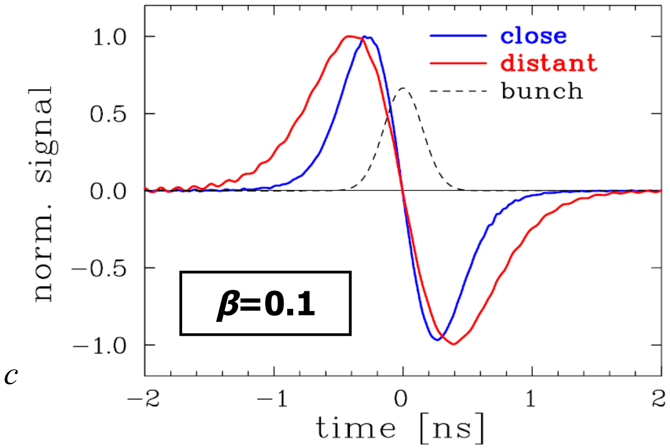
P. Kowina (GSI) et al., DIPAC'09, C. Simon (CEA) et al , DIPAC'11

FEM Simulations for low-β Beam



$$x_{hor} = k \cdot \frac{U_{Left} - U_{Right}}{U_{Left} + U_{Right}} + c$$

Position Dependance of Signal Shape

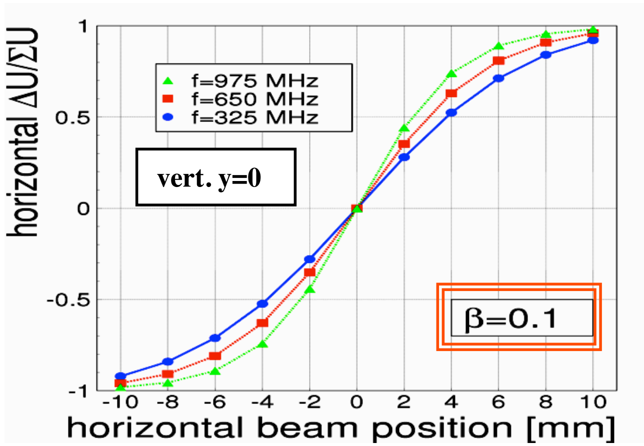


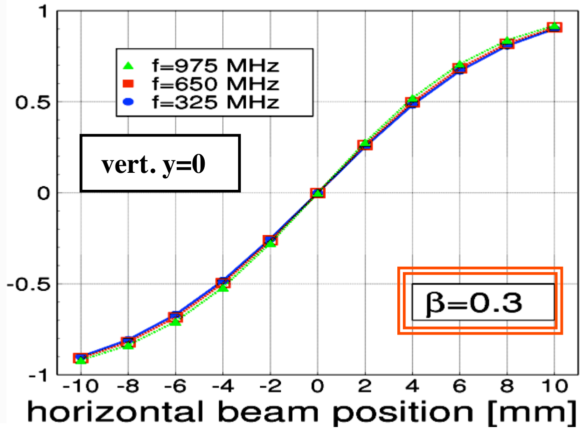
Parameters:

- BPM aperture: Ø 30 mm
- f_{rf} = 325 MHz
- bunch length σ_t = 150 ps

Results:

- signal shape and spectrum position dependent
- position sensitivity depends on frequency (chosen rf harmonics)
- Non-linear reading, but linear for β>30% as expected from simple model





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P. Kowina (GSI) et al., DIPAC'09, C. Simon (CEA) et al , DIPAC'11

Position Maps for low-β Beam: Frequency Dependance

Parameters:

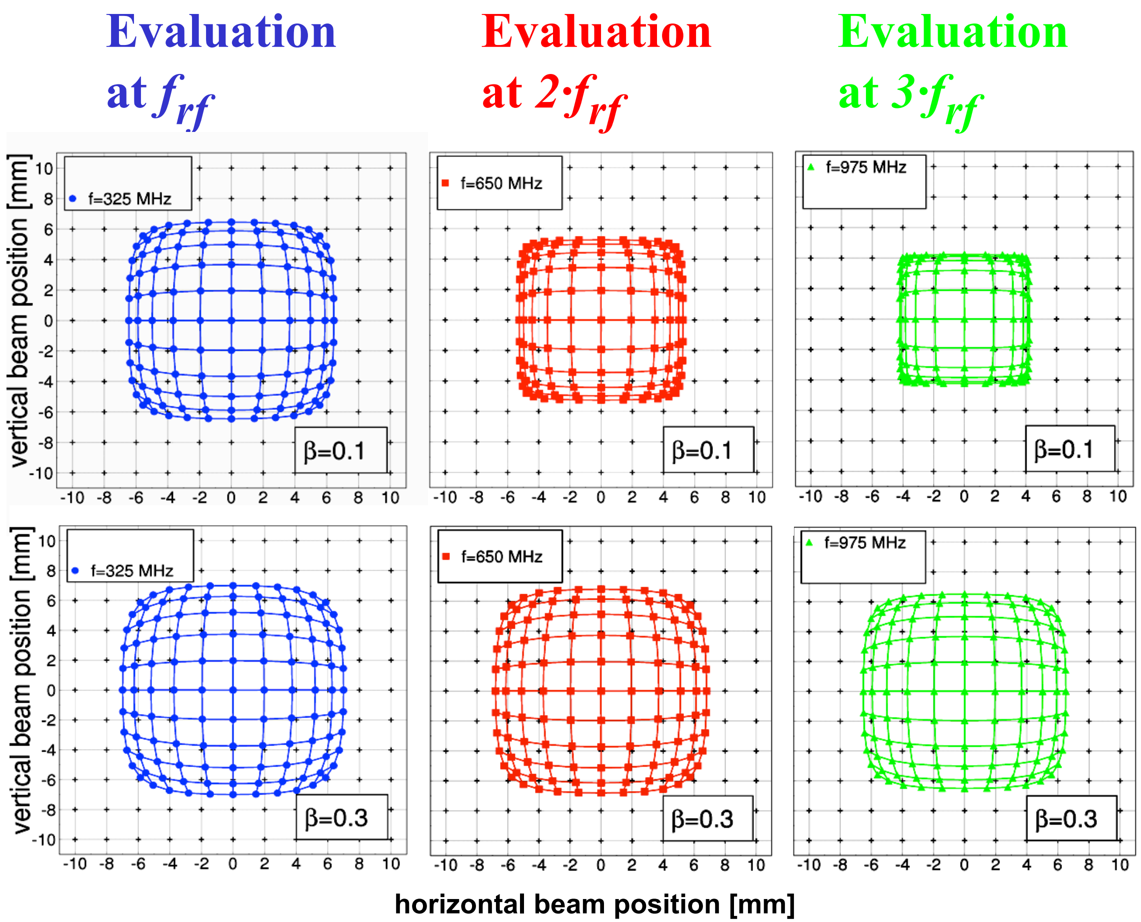
- BPM aperture: Ø 30 mm
- f_{rf} = 325 MHz
- bunch length σ_t = 150 ps

Results:

- Readout is non-linear
- xy-coupling
- sensitivity map depends on β and frequency (chosen rf harmonics)
  - strong dependence for β ≤ 0.1
  - weak dependence for β ≥ 0.3

Consequences:

- sensitivity maps to be prepared for each location (β) and harmonics
- BPMs usable for limited beam displacement:
  e.g. for β = 0.1 and 3 rd rf harmonics ±5 mm only i.e. ~30 % of aperture!



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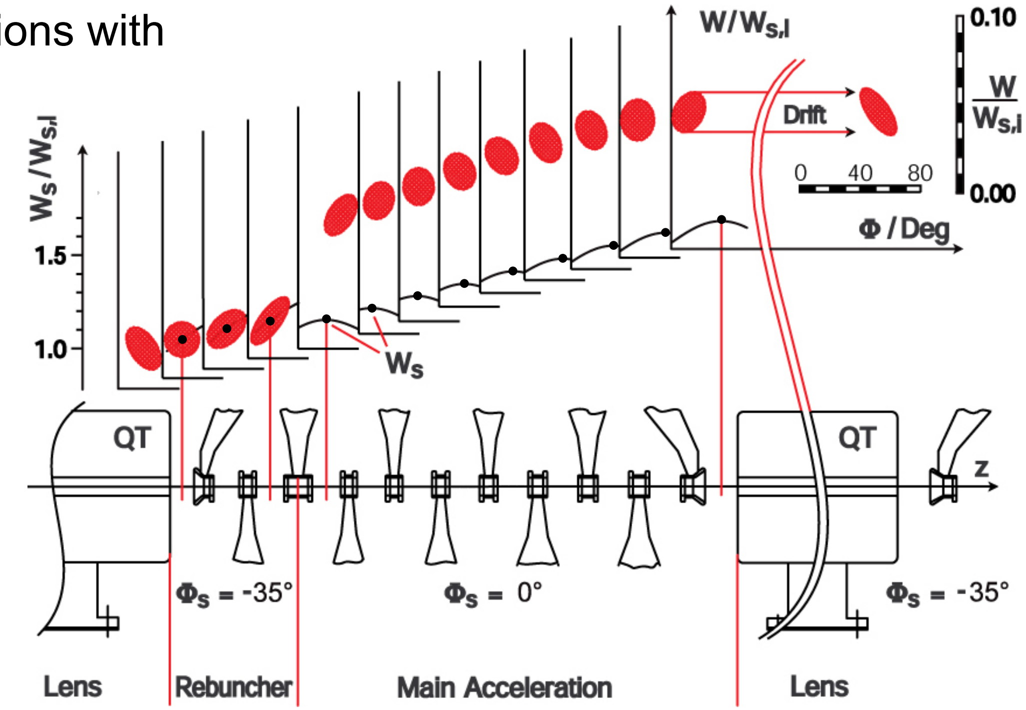
P. Kowina (GSI) et al., DIPAC'09, C. Simon (CEA) et al , DIPAC'11

BPM – Requirements for Energy Measurement

KONUS: Kombinierte Null Grad Struktur

Basic idea: devide each lattice period into regions with separated tasks (in contrast to e.g. Alvarez)



KONUS period consists of:

I) 0° acceleration section

main acceleration along a 0° synchronous particle structure with asynchronous injection and greater bunch energy than sync. particle

II) quadrupole triplet or solenoid lens

transverse focusing

III) rebuncher section

Longitudinal focusing by few bunching gaps operated at ϕ_s= - 35°

Advantages:

- high efficiency (shunt impedance) of H-mode resonators
- low rf wall losses, low capacity load due to slim drift tubes

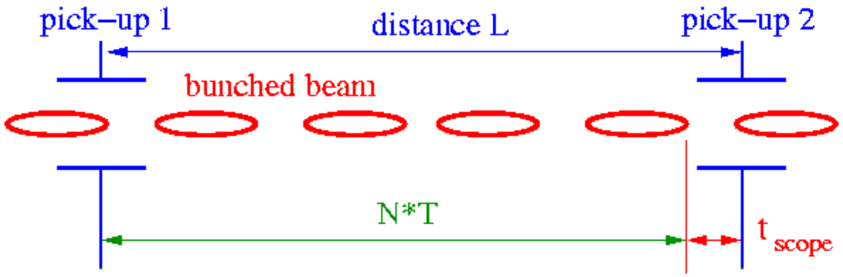
→ higher eff. field gradient (< 7 MV/m) than e.g. Alvarez

Important Requirement:
precise monitoring / control of bunch phase $\Delta\phi$ = 1°(8.5 ps at 325 MHz !!) and energy

Successful KONUS-Linacs: Pb-Injector (CERN), HSI/HLI (GSI), ISAC (TRIUMF)

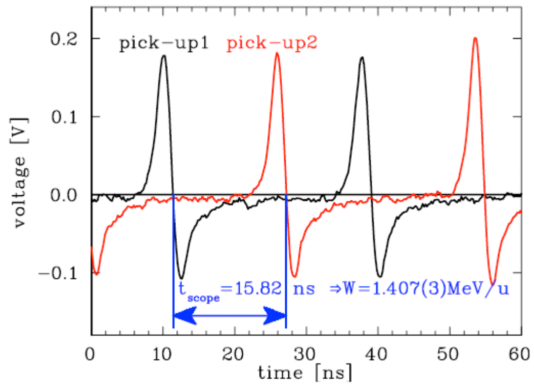
BPM – Techniques for Energy Measurement

Time-of-Flight (TOF)



'classic' formula: $\beta = \frac{1}{c} \cdot \frac{L}{N \cdot T + t_{scope}}$

Time-domain TOF Measurement (scope)

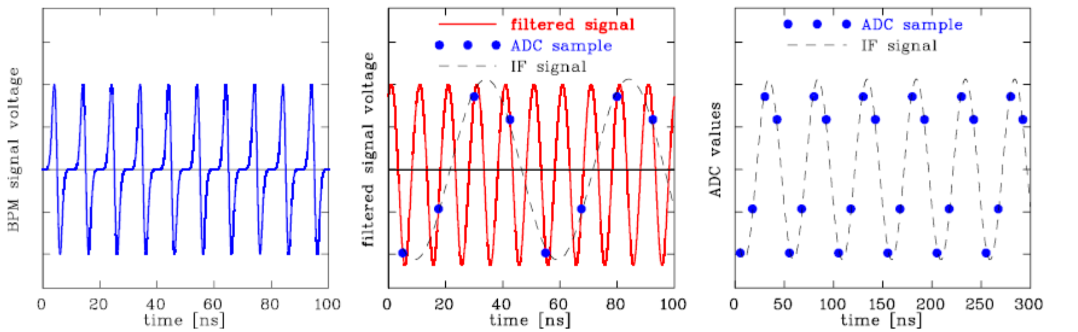


.... digital signal processing...

Under-Sampling

sample a bandpass filtered signal at sample rate below the usual Nyquist rate

$$f_{sample} = \frac{4}{4n+1} \cdot f_{acc}$$

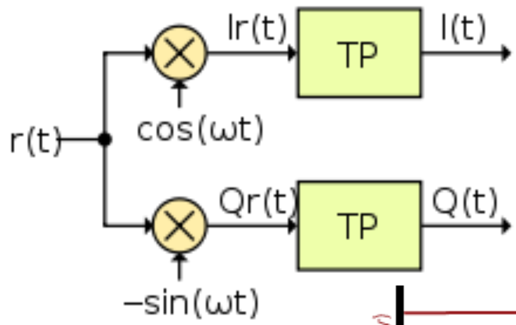


BPM signal, f_{acc} = 100 MHz

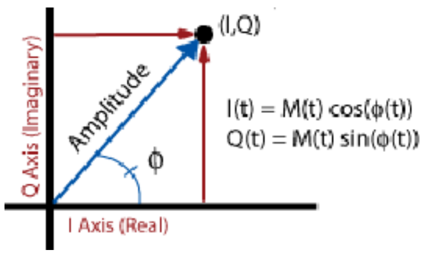
filtered signal

digitized signal $f_{sample} = 4/5 f_{acc}$ = 80 MHz

I-Q-Demodulation



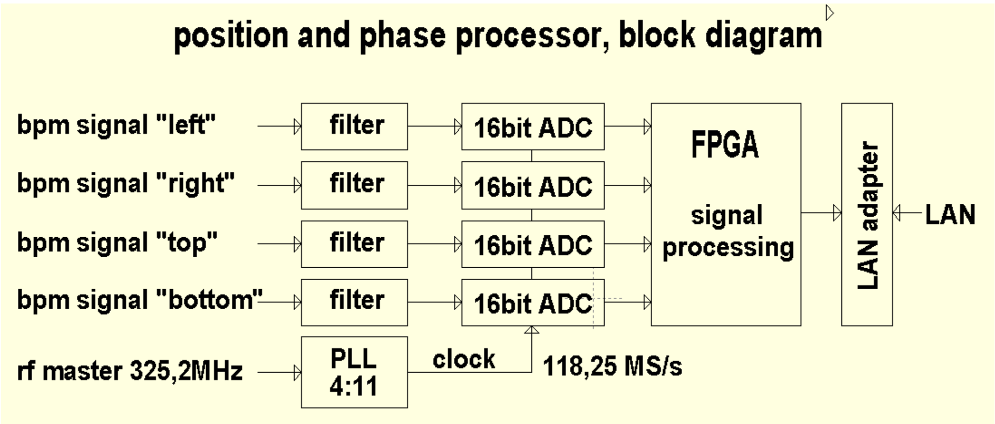
- down-mixing
- low-pass filtering
- decimation



Digital Signal Processing for BPMs

Possible novel 'all in one' readout by Digital Receiver technology:

- Analog filter at $2 \cdot f_{acc}$=650 MHz
- Under-sampling with 16-bit ADC at $4/11 \cdot f_{acc}$=118 MS/s
- Digital processing on FPGA for relative current (sum), position (difference) and ToF (phase)
- Possible production by Company I-Tech within as Slovenian in-kind contribution



Status and concerns:

- Successful test-bench demonstration by I-Tech and CIEMAT
- Expectation: well suited for relative current and position measurements

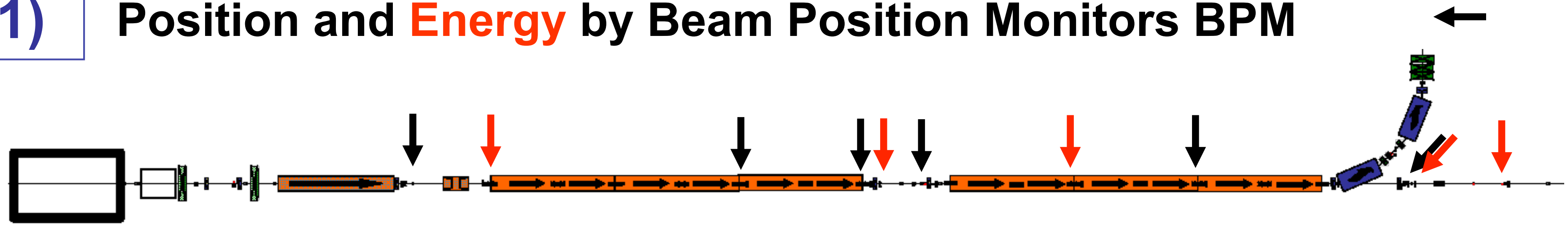
Open issues for TOF-Measurements (phase detection)

- Effects on varying bunch shapes, e.g. deformed bunches?
- Accuracy for measurement with two BPMs?
- Ambiguity for variable number of bunches between BPMs?

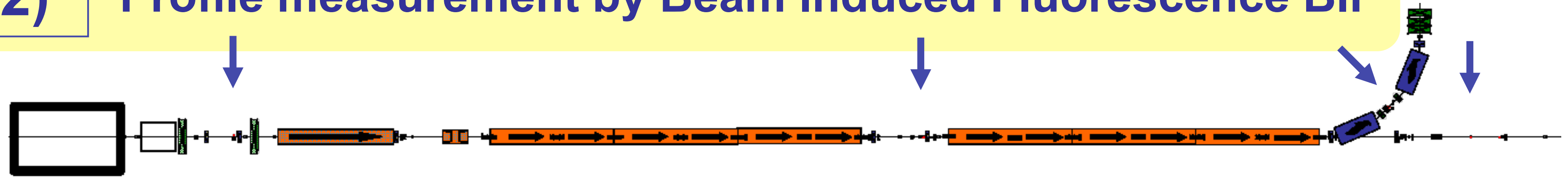
Installation Locations BPM and BIF

➡ Focus on 2 examples for 'non-standard' diagnostic components

1) Position and Energy by Beam Position Monitors BPM



2) Profile measurement by Beam Induced Fluorescence BIF



Beam Induced Fluorescence Monitor

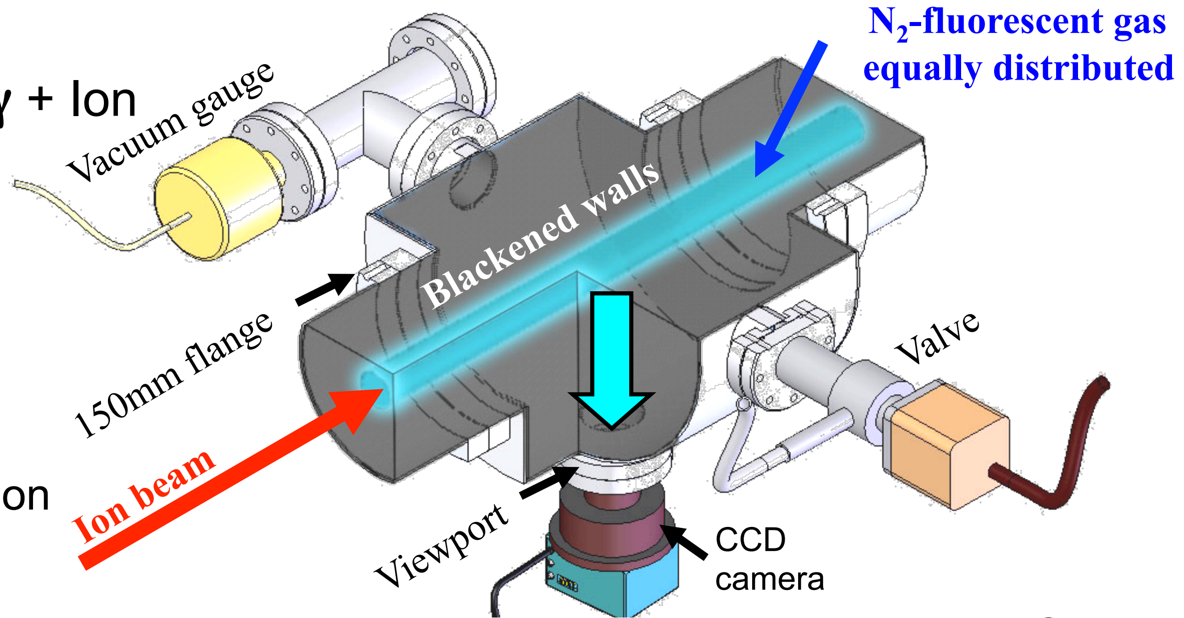
Detecting ***photons*** from working gas molecules, e.g. Nitrogen

$N_2 + Ion \rightarrow (N_2^+)^* + Ion \rightarrow N_2^+ + \gamma + Ion$

390 nm< λ< 470 nm

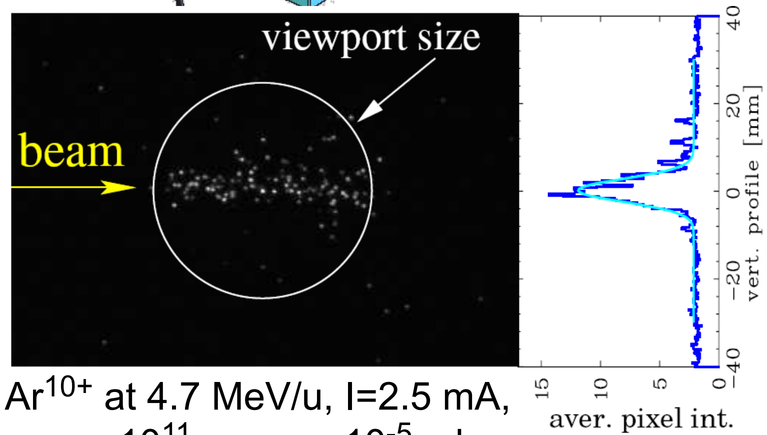
emitted into solid angle Ω to camera

single photon detection scheme



Features:

- Transv. profile: projection in z-direction
- High resolution (here 0.2 mm/pixel) can be matched to application
- Single pulse observation possible down to ≈10 µs time resolution
- Commercial Image Intensifier
- Less installations inside vacuum as for IPM



Beam: Ar^{10+} at 4.7 MeV/u, I=2.5 mA, 10^{11} ppp, p=10^{-5} mbar

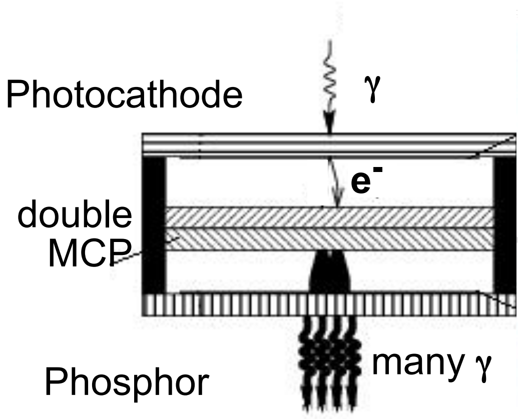
P. Forck, Proc. IPAC'10

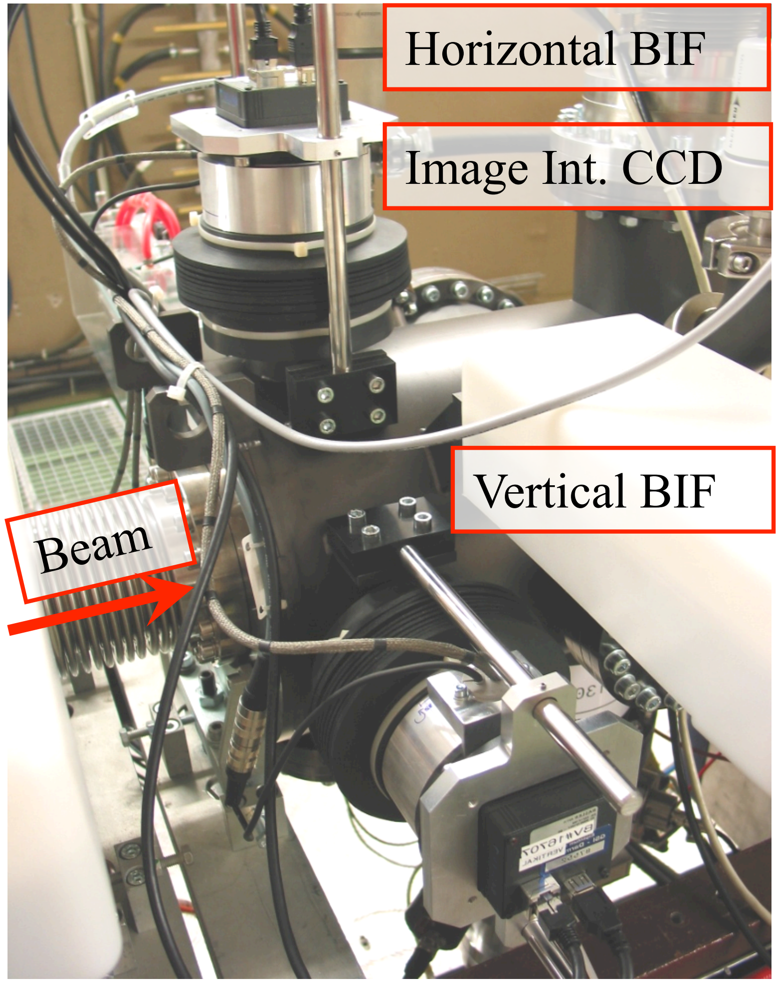
F. Becker et al., Proc. DIPAC'07, DIPAC'11

BIF: Technical Realization at UNILAC

Example: BIF-Station at GSI-UNILAC

- Insertion length: 25 cm
- 2 image intensified CCD cams, single photon counting by V-stack MCP (10^6 amplification)
- Commercial image intensifier, low background
- Reproduction scale 0.2 mm/pixel
- Remote controlled gas inlet + gauge
- Pneumatic feed-through for LED calibration
- In operation at 4 locations at UNILAC





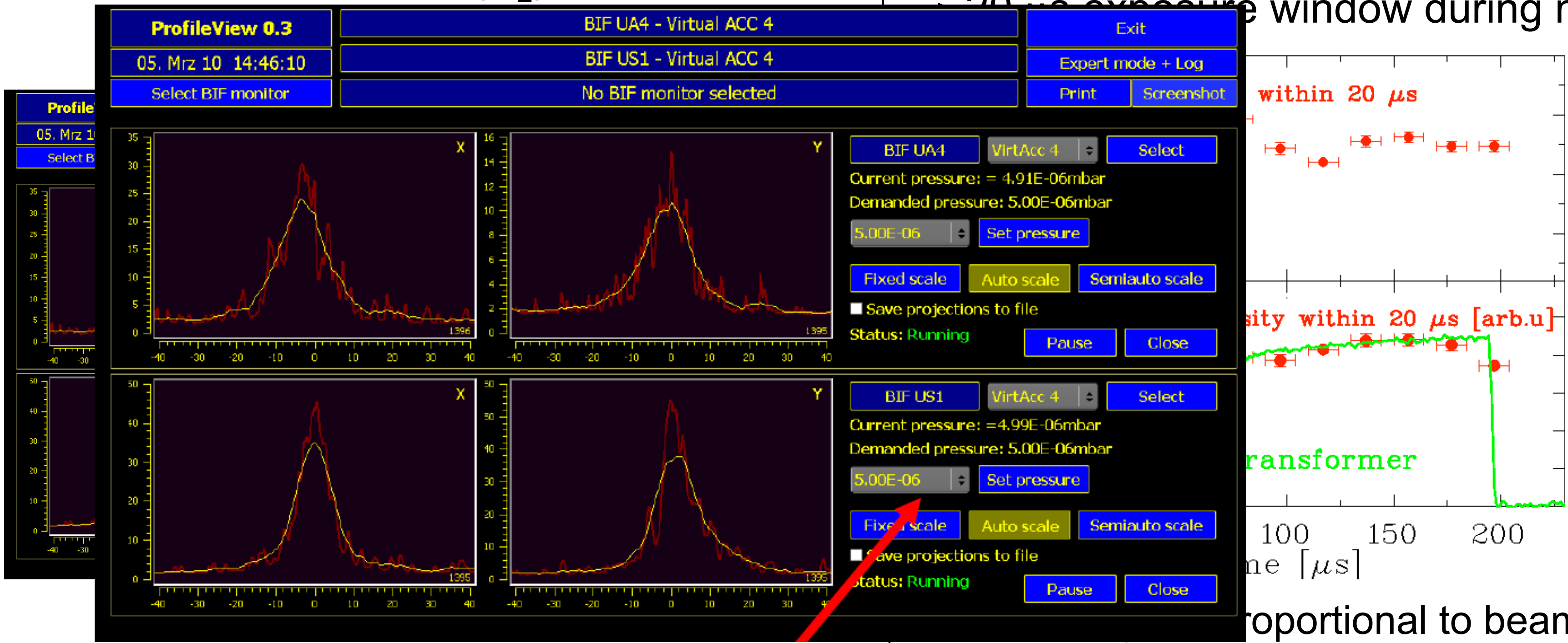
Examples from Ion LINAC at GSI

Single pulse observation

One single macro pulse of 200 μs

Typical vacuum pressure*:*

p=10^{-6} to 10^{-5} mbar (N_2)



System ready for operational usage:

Presently at 4 locations along UNILAC

3 more in preparation.

Time resolved observation

Variation ***during*** the macro pulse detectable:

Switching of image intensifier (within 100 ns)

→ 20 μs exposure window during macro-pulse

8 mA Ar^{10+}

at 11 MeV/u

…roportional to beam current

Further application: Background suppression by matching the exposure to beam delivery

Summary

- FAIR

  multi-national large-scale accelerator project

  p-Bar production chain for PANDA experiment

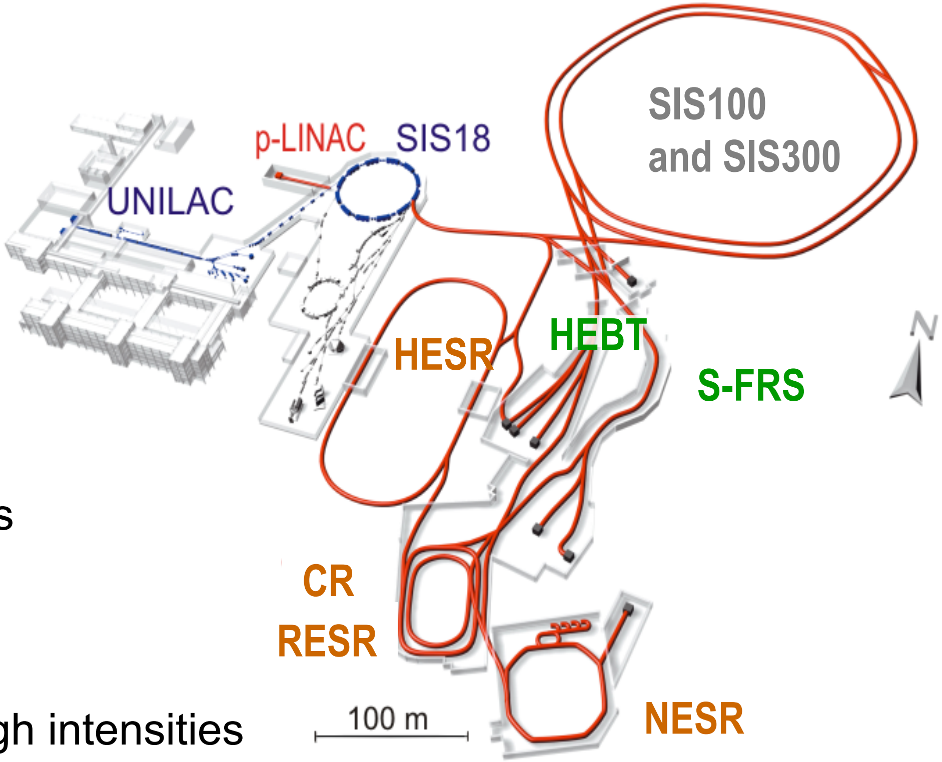
- p-Linac

  SILHI source for high-intensity proton beams

  coupled ch-structures, KONUS beam dynamics

- Beam Diagnostics

  mainly non-intercepting instruments due to high intensities



BPMs: - strong mechanical boundary conditions for in-tank installation
- low-β effects (bunch shape, position sensitivity)
- digital processing for phase/energy detection

BIF: - high spatial resolution of complete macropulse
- no mechanical parts inside vacuum required
- 4 monitors as standard tools for UNILAC operation

Acknowledgements

CEA - Saclay

BPM-team: C. Simon, F. Senée, O. Napoly and colleagues

Ion Source Team: R. Gobin, N. Chauvin and colleagues

IAP University Frankfurt

H. Podlech, R. Brodhage, U. Ratzinger

Thank you for your attention!

GSI/FAIR

p-Linac Team: L. Groening, R. Hollinger, G. Clemente

Beam Diagnostics: P. Forck, P. Kowina, F. Becker

DITANET

4th DITANET Topical Workshop on High Intensity Proton Beam Diagnositics

Spare Transparencies...

BPM Parameters

	Range	Precision	Resolution
Transverse position	0 to 5 mm	0.3 mm	0.1 mm
Longitudinal phase	0-360°	1°	1°

Aperture	30 mm intertank section, 50 mm transfer lines
Length	50 mm (at connector location, shorter at pipe radius)
Vacuum pressure	$5*10^{-8}$ mbar
Beam energy	From 3 MeV to 70 MeV
Bunch frequency	325.225 MHz
Repetition rate	4 Hz
Beam pulse length	36 μs nominal, 100 μs maximum
Bunch length	150 ps average (actual length depends on location)
Linearity	+/- 5 mm
Dynamic range	0.1 mA - 100 mA
Position resolution 1σ	0.1 mm averaged over the full macro pulse of 30 μs duration about 0.5 mm for 3 μs duration
Absolute precision	0.3 mm, requires a concept of beam-based alignment
Phase resolution	1° (8.5 ps) averaged over the full macro pulse of 30 μs duration
Phase accuracy	1° averaged over the full macro pulse of 30 μs duration
Drift over 1 hour	Less than 0.1 mm, less than 1°, long term drifts are compensated by calibrations with test signals

Parameters Faraday-Cup

2.7.6.1.2 Faraday Cups DTL

Number of devices		1
Aperture radius	mm	15
Length w/o chamber	mm	150
Number of pneum. drives		1
Radius of Cup active area	mm	10
High voltage	kV	1
Induction by permanent magnets	mT	10
Number of ranges for electronics		3
Full scale	mA	1, 10, 100
Current resolution	mA	0.01, 0.1, 1 (=1% FS)
Bandwidth of analog output	MHz	10
Output to control system		Integrated current

Parameters AC-Transformer

2.7.6.2.2 ACT Beam Transformers LEBT

Number of devices		1
Aperture radius of chamber	mm	80
Radius of clearance	mm	75
Length w/o chamber	mm	150
Number of ranges for electronics		3
Full scale	mA	1, 10, 100
Current resolution	mA	0.01, 0.1, 1 (=1% FS)
Droop	% for 100 µs	< 1
Analog bandwidth (achieved)	MHz	0.5
Analog bandwidth (projected)	MHz	1
Acquisition bandwidth	MHz	2
Interlock generation source		yes
Reaction time interlock generation	µs	2

Parameters SEM-Grid

2.7.6.3.2 Profile Wire Grids DTL

Number of devices		1
Aperture radius	mm	17.5
Length w/o chamber	mm	150
Number of stepping motor devices		2
Detection area	mm^2	32 x 32
Wires per plane		32
Wire spacing	mm	1
Wire thickness	mm	0.1
Number of ranges for electronics		5
I/U conversion	µA/V	0.01 … 100

Parameters BPM / Phase Probe MEBT

2.7.6.5.1 Combined BPM-Phase Probe MEBT, DTL

Number of devices		9
Aperture radius	mm	17.5
Radius of clearance	mm	30
Length w/o chamber	mm	40
Pre-amplifier type		broadband
Number of ranges for pre-amplifier		3
Dynamic range	dB	80
Analog bandwidth	GHz	3
Acquisition bandwidth for position	MHz	1
Position resolution @ 1 MHz	mm	1
Position resolution for one macro-pulse	mm	0.3
Accuracy	mm	1
Phase resolution	deg	1

Parameters BPM / Phase Probe Inflection

2.7.6.5.2 Combined BPM Phase Probe Inflection, DUMP

Number of devices		4
Aperture radius (inflection)	mm	20
Aperture radius (dump)	mm	50
Radius of clearance	mm	25
Length w/o chamber	mm	40
Pre-amplifier type		broadband
Number of ranges for pre-amplifier		3
Dynamic range	dB	80
Analog bandwidth	GHz	2
Acquisition bandwidth for position	MHz	1
Position resolution @ 1 MHz	mm	1
Position resolution for one macro-pulse	mm	0.3
Accuracy	mm	1.5
Phase resolution	deg	1

Parameters Bunch Structure Monitor

2.7.6.6 Bunch Structure Monitor

Number of devices		1
Aperture radius	mm	50
Clearance	mm^2	75 x 75
Length w/o chamber	mm	400
High over all	m	2
Voltage for electric field box	kV	30
Voltage of energy analyzer	kV	±5
Diameter MCP	mm	70
Voltage MCP	kV	2
Voltage phosphor	kV	5
CCD camera resolution		SVGA
Refresh rate	fps	> 4
Resolution	deg	1