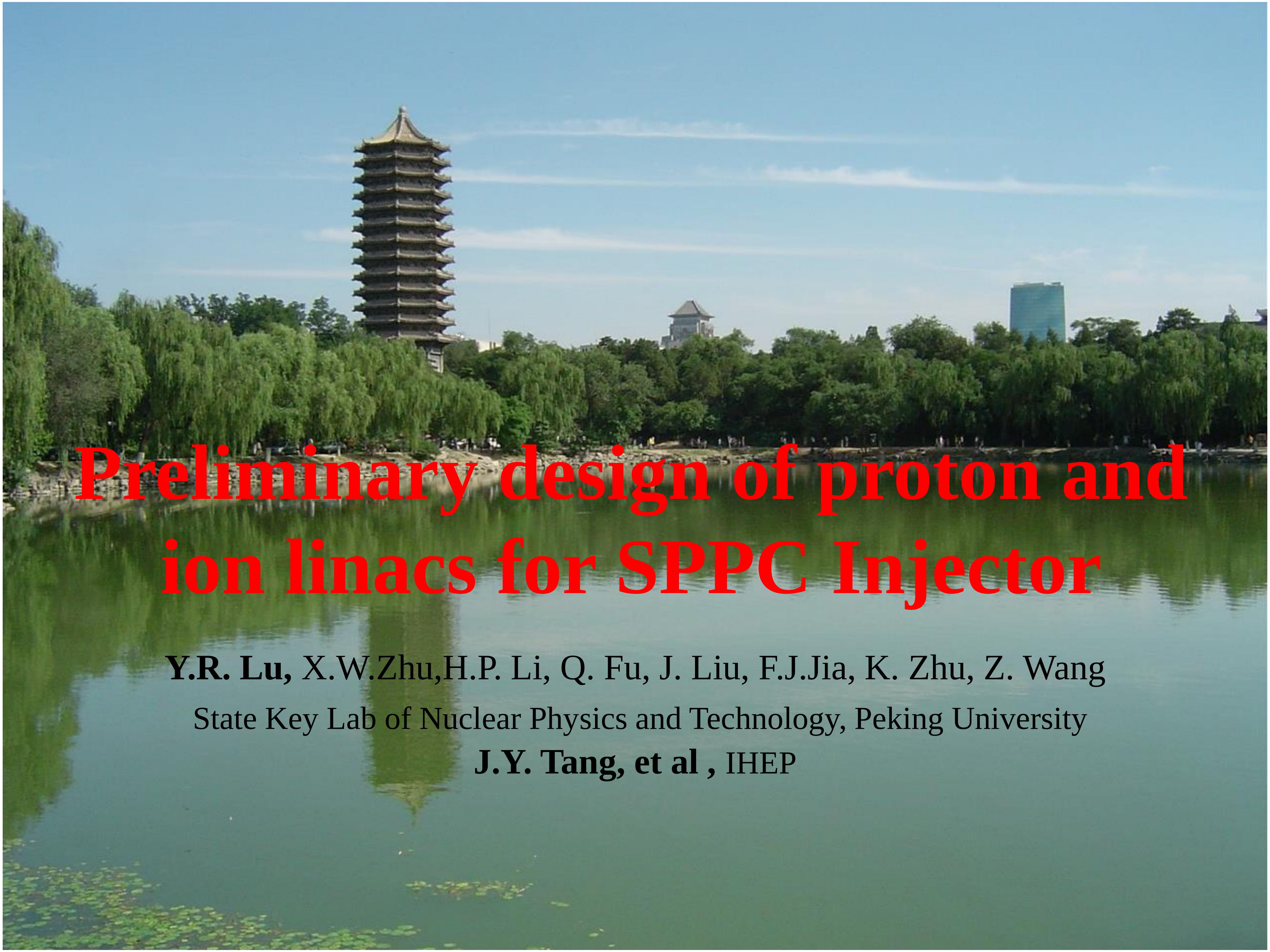


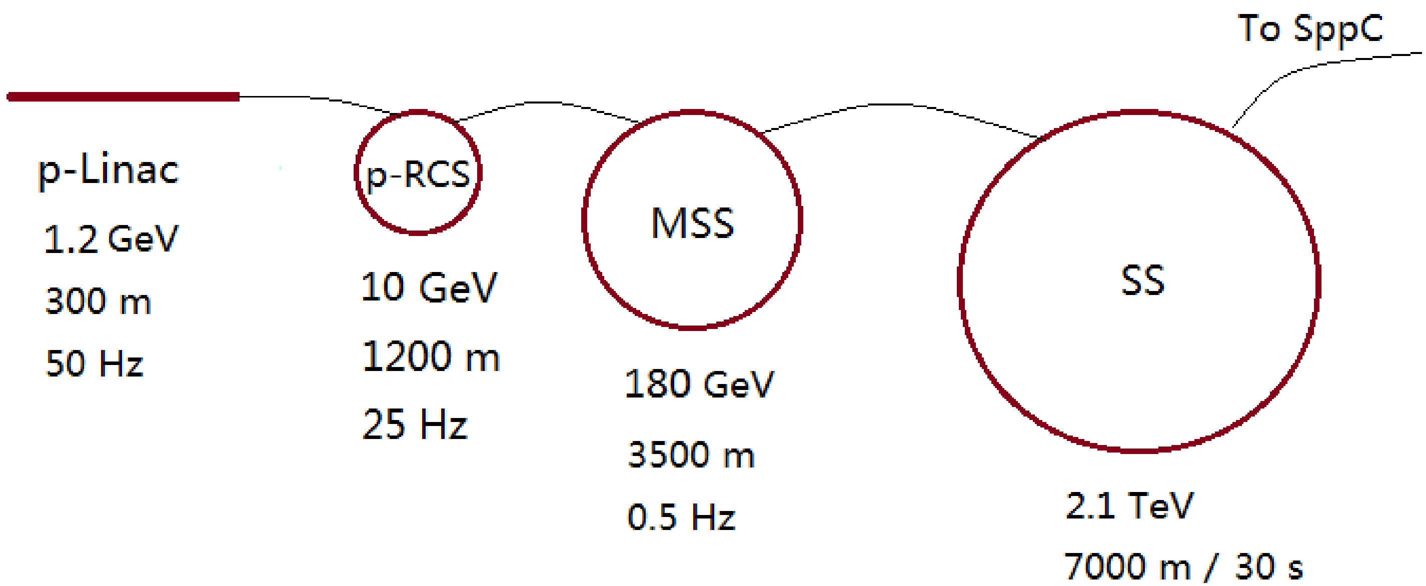
Preliminary design of proton and ion linacs for SPPC Injector

Y.R. Lu, X.W.Zhu,H.P. Li, Q. Fu, J. Liu, F.J.Jia, K. Zhu, Z. Wang
State Key Lab of Nuclear Physics and Technology, Peking University
J.Y. Tang, et al , IHEP

Contents

A. General requirements
B. Brief introductions of injector systems for proton and ion accelerators
C. Preliminary design of proton and ion linacs.
D. Conclusions

Injector chain (J.Y.Tang 1/3)
(for proton beam)



p-Linac: proton superconducting linac

p-RCS: proton rapid cycling synchrotron

MSS: Medium-Stage Synchrotron

SS: Super Synchrotron

Ion beams have dedicated linac (i-Linac) and RCS (i-RCS)

Some key features(J.Y.Tang 2/3)

- p-linac:
  - Superconducting linac, H- beam, pulsed mode, similar to the SNS linac,
  - Almost mature technology
  - Beam energy may be increased from 1.2 GeV to 1.5-2.0 GeV (ref. SPL, ESS)
- p-RCS
  - Rapid cycling synchrotron, high power (1.7 MW), first in this energy range
  - Painting injection by stripping, fast extraction
  - Technically challenging, beam loss control,
  - Reference: a scheme for the proton driver for Neutron Factory; J-PARC/RCS
- MSS
  - Bunch structure formation by longitudinal splitting (RF barrier for gap?)
  - Reference: CERN/SPS, FNAL/MI (but higher beam power, 1.2 MW)
- SS
  - TeV with high repetition, high energy in beam, SC magnets (ref: LHC, Tevatron) [B: 8 T; RF: 200 MHz]
  - Slow extraction may be needed (test beam and other physics programs)
- There are different schemes in RF acceleration and bunch formation along with the injector complex.

Major parameters for the injector chain(J.Y.Tang 3/3)

	Value	Unit		Value	Unit
p-Linac			MSS		
Energy	1.2	GeV	Energy	180	GeV
Average current	0.7	mA	Average current	21	uA
Length	~300	m	Circumference	3600	m
RF frequency	325/650	MHz	RF frequency	40	MHz
Repetition rate	50	Hz	Repetition rate	0.5	Hz
Beam power	0.82	MW	Beam power	1.2	MW
p-RCS			SS		
Energy	10	GeV	Energy	2.1	TeV
Average current	0.19	mA	Accum. protons	5.3E14	
Circumference	900	m	Circumference	7200	m
RF frequency	36-40	MHz	RF frequency	200	MHz
Repetition rate	25	Hz	Repetition period	30	s
Beam power	1.7	MW	Protons per bunch	2.0E11	
			Dipole field	8	T

Contents

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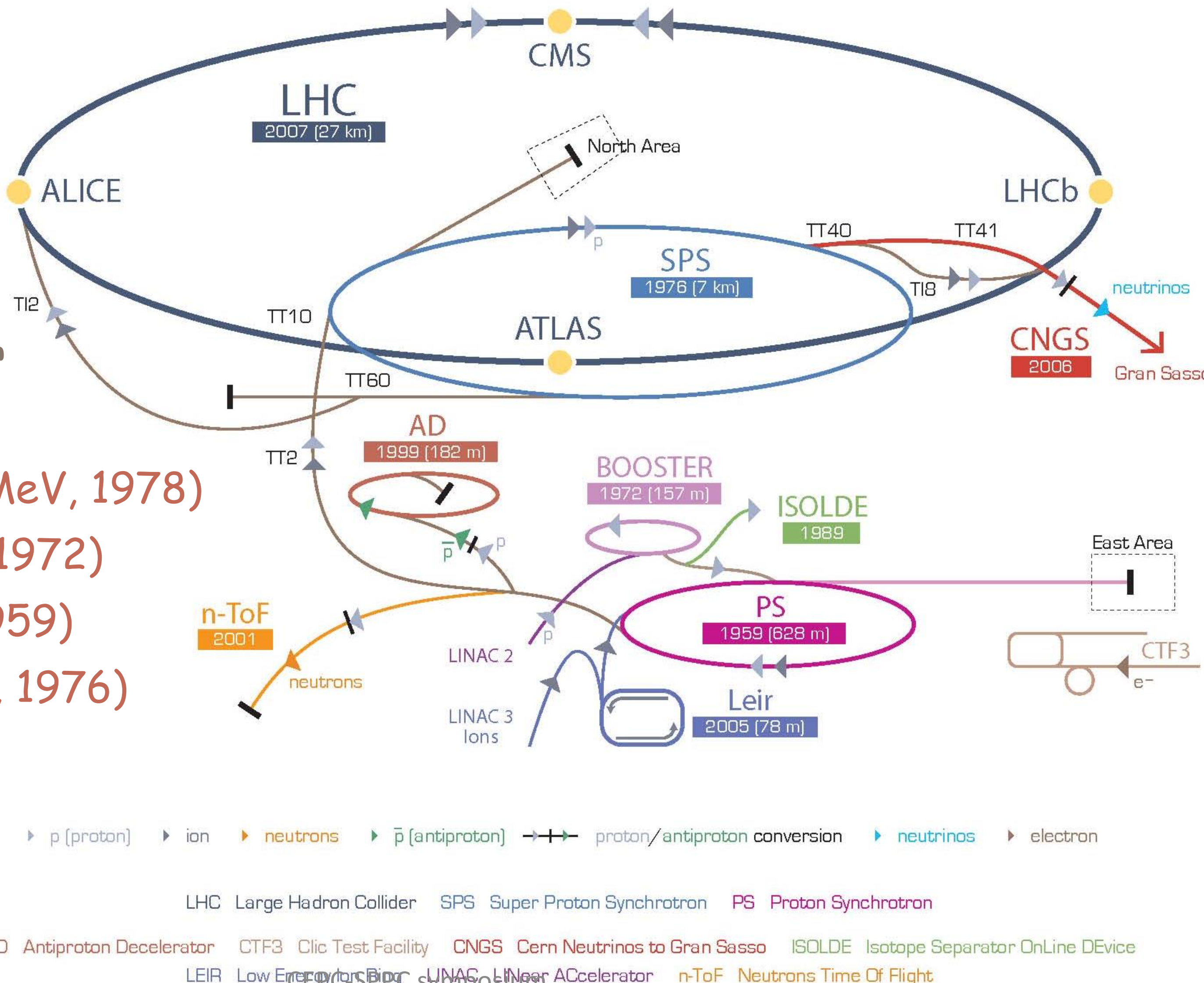
CERN Accelerator Complex



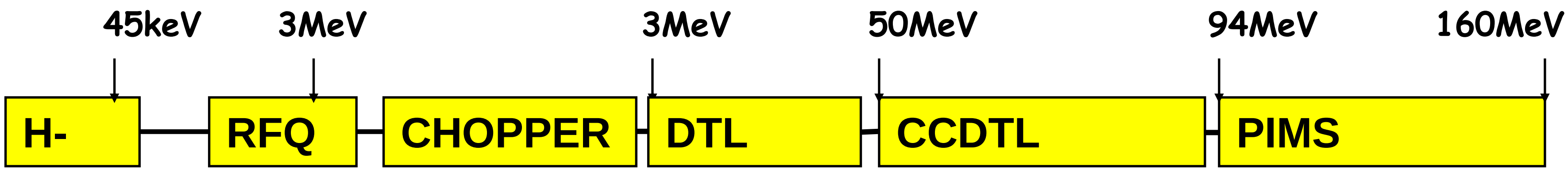
LHC Injector

- Lianc2 (p, 50 MeV, 1978)
- PSB (1.4 GeV, 1972)
- PS (28 GeV, 1959)
- SPS (450 GeV, 1976)

Implementation of The New Injectors: Stage 1 – Linac4 (2/2)

- Block Diagram

Linac4: 80 m, 18 klystrons



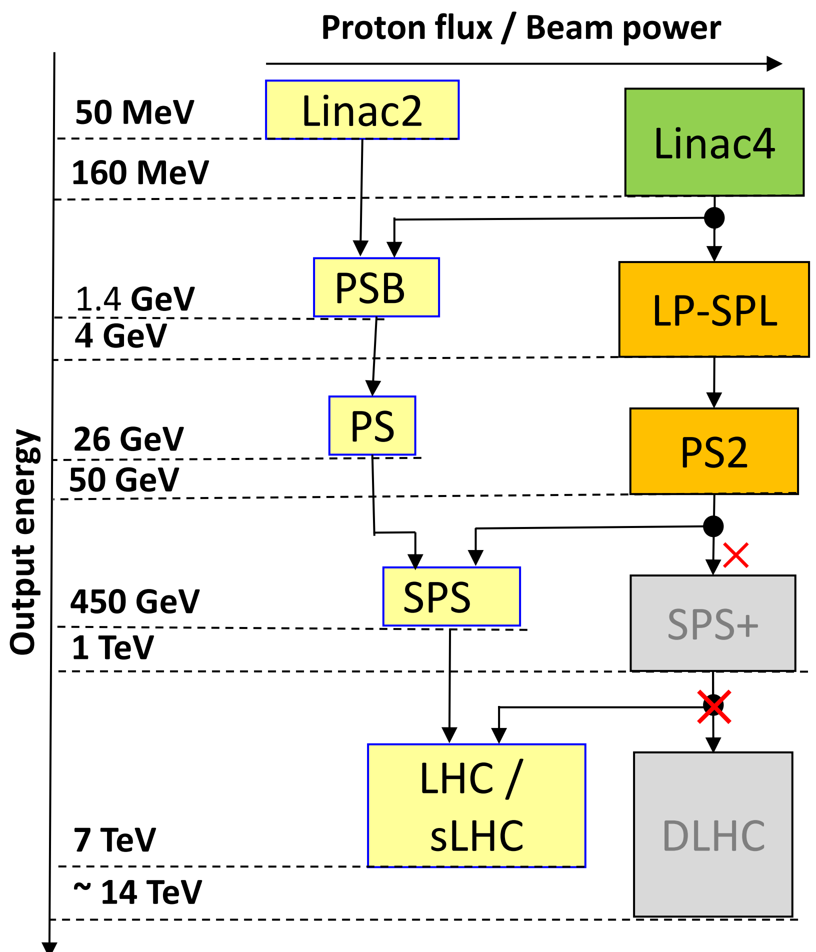
Linac4

RF volume source (DESY) 45 kV Extrac.	Radio Frequency Quadrupole 3 m 1 Klystron 550 kW	Chopper & Bunchers 3.6 m 11 EMquad 3 cavities	Drift Tube Linac 18.7 m 3 tanks 3 klystrons 4.7 MW 111 PMQs	Cell-Coupled Drift Tube Linac 25 m 21 tanks 7 klystrons 7 MW 21 EMQuads	Pi-Mode Structure 22 m 12 tanks 8 klystrons ~12 MW 12 EMQuads

Ion current: 40 mA (avg.), 65 mA (peak)

RF accelerating structures: 4 types (RFQ, DTL, CCDTL, PIMS)
Frequency: 352.2 MHz
Duty cycle: 0.1% phase 1 (Linac4), 3-4% phase 2 (SPL), (design: 10%)

Injector Complex Upgrade – Proton Operation



Linac4: H- Linac (160 MeV)
LP-SPL: Low Power- Superconducting Proton Linac (4 GeV)
PS2: High Energy **PS** (4 to 50 GeV – 0.3 Hz)
SPS+: Superconducting **SPS** (50 to1000 GeV)
sLHC: 'Superluminosity' **LHC** or High Luminosity **LHC** (up to 10^{35} $cm^{-2}s^{-1}$peak)
DLHC: 'Double energy'` **LHC** (1 to ~14 TeV)

Stage 1: Linac4
- **construction 2008 – 2014**

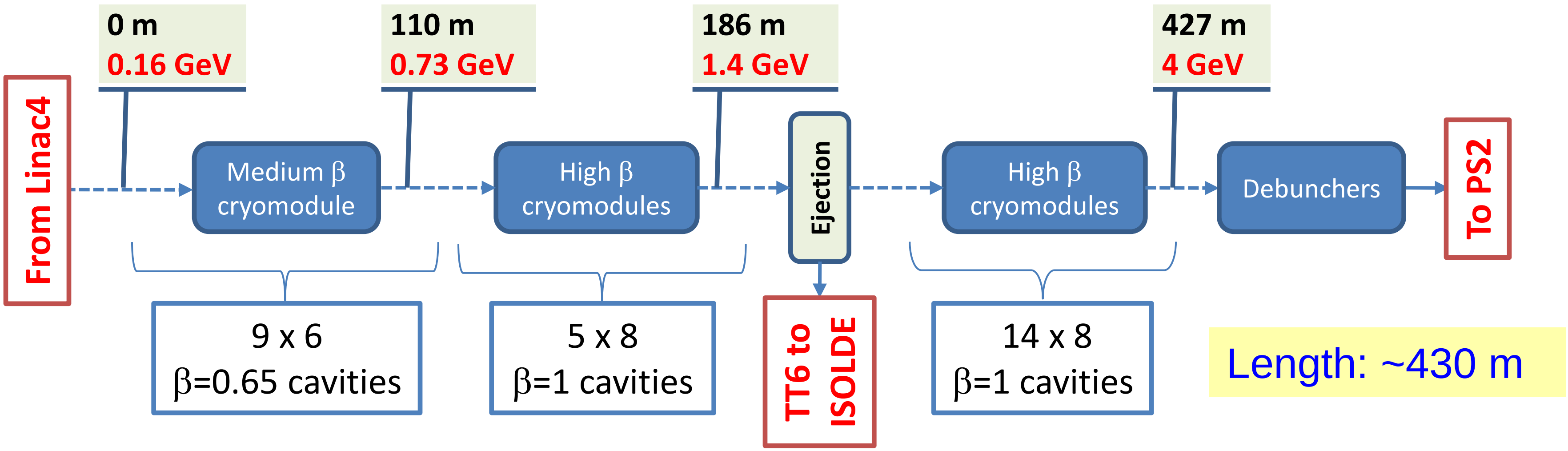
Stage 2: PS2 and **LP-SPL**: preparation of Conceptual Design Reports for
- **project approval mid 2012**
- **start of construction begin 2013**

*× denotes SPS+ & DLHC are not included in the CDR-2014.

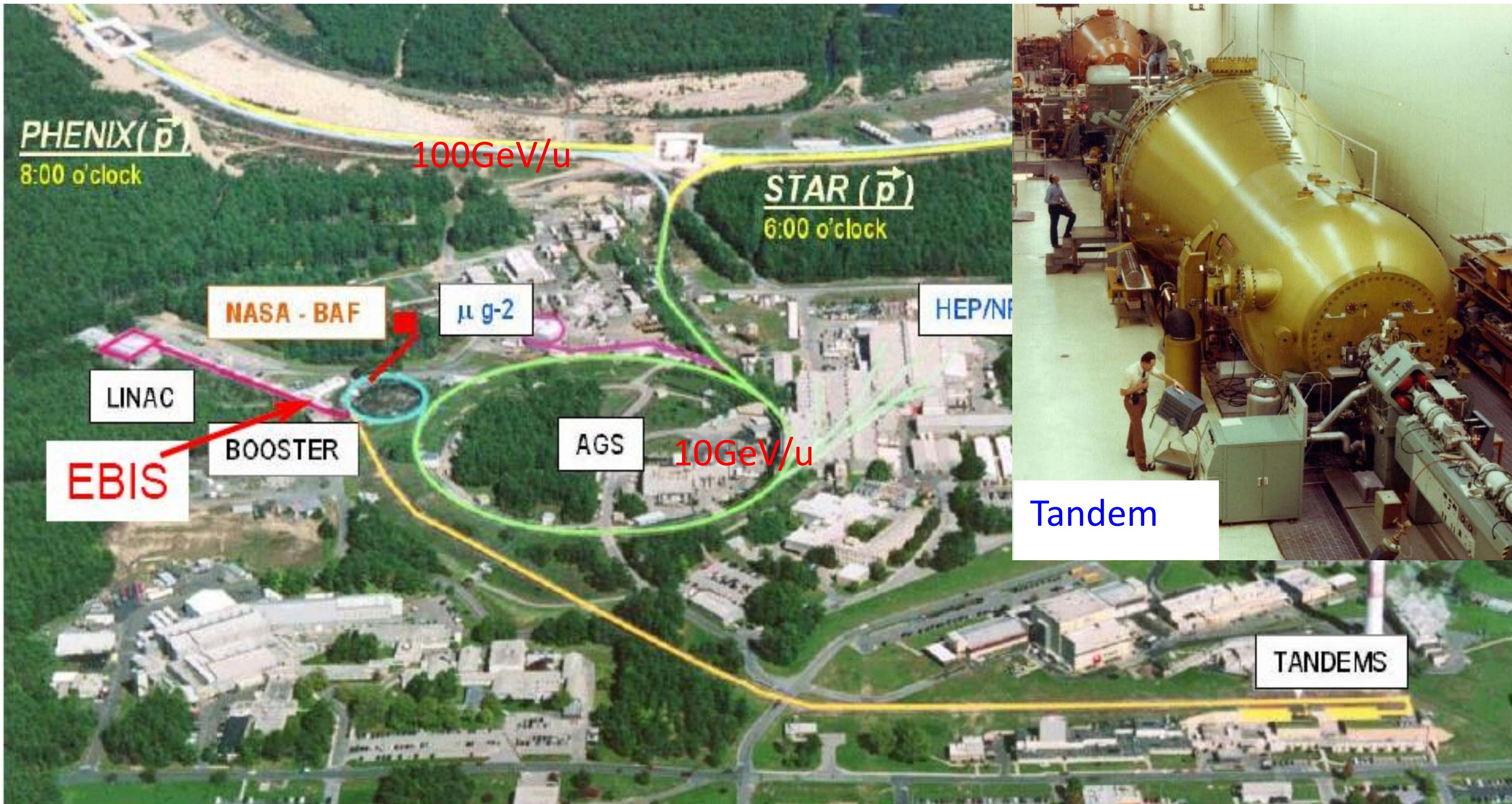
Implementation of The New Injectors: Stage 2 – LP-SPL to PS2

- Block Diagram

SC-linac (160 MeV 4 GeV) with ejection at intermediate energy



Previous RHIC Accelerator Complex & Its Heavy Ion Injector



Major parameters for RHIC

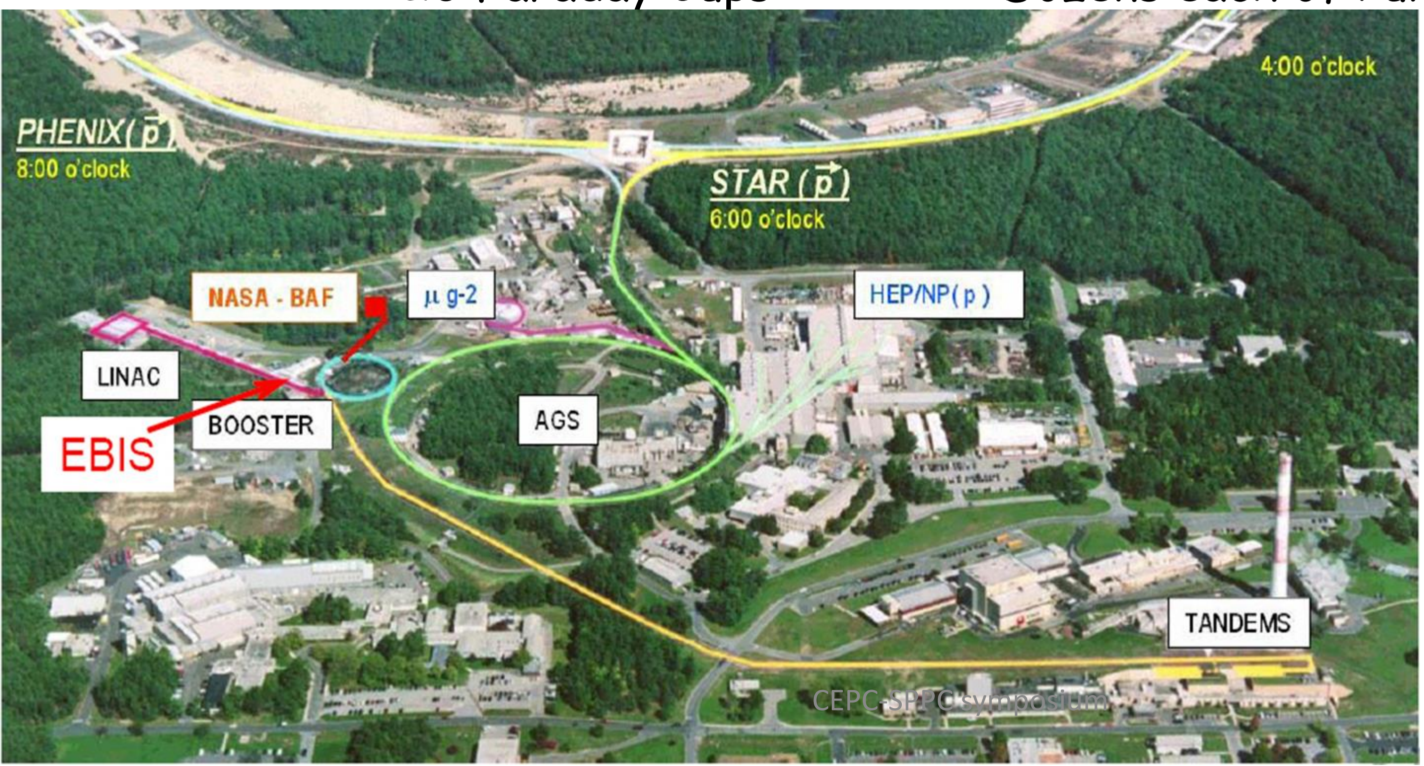
Parameter	Value	Units
Kinetic energy, inj.-top, Au	10.8–100	GeV/u
(each beam), protons	28.3–250	GeV
No. of bunches/ring	60 (120)	
Circumference	3833.845	m
Number of crossing points	6	
β^*, injection, H/V	10	m
β^*, low-beta insertion, H/V	1	m
Betatron tunes, H/V	28.19/29.18	
Magnetic rigidity, injection	79.0	Tm
top energy	839.5	Tm
Number of dipoles (192/ring + 12 common)	396	
Number of quadrupoles (276 arc + 216 insertion)	492	
Dipole field at 100 GeV/u, Au	3.45	T
Arc dipole effective length	9.45	m
Arc quadrupole gradient	71.2	Tm

*Definitions: β^*, interaction point beta; H/V, horizontal/vertical.

Upgrade Scenario for RHIC Heavy Ion Pre-Injector

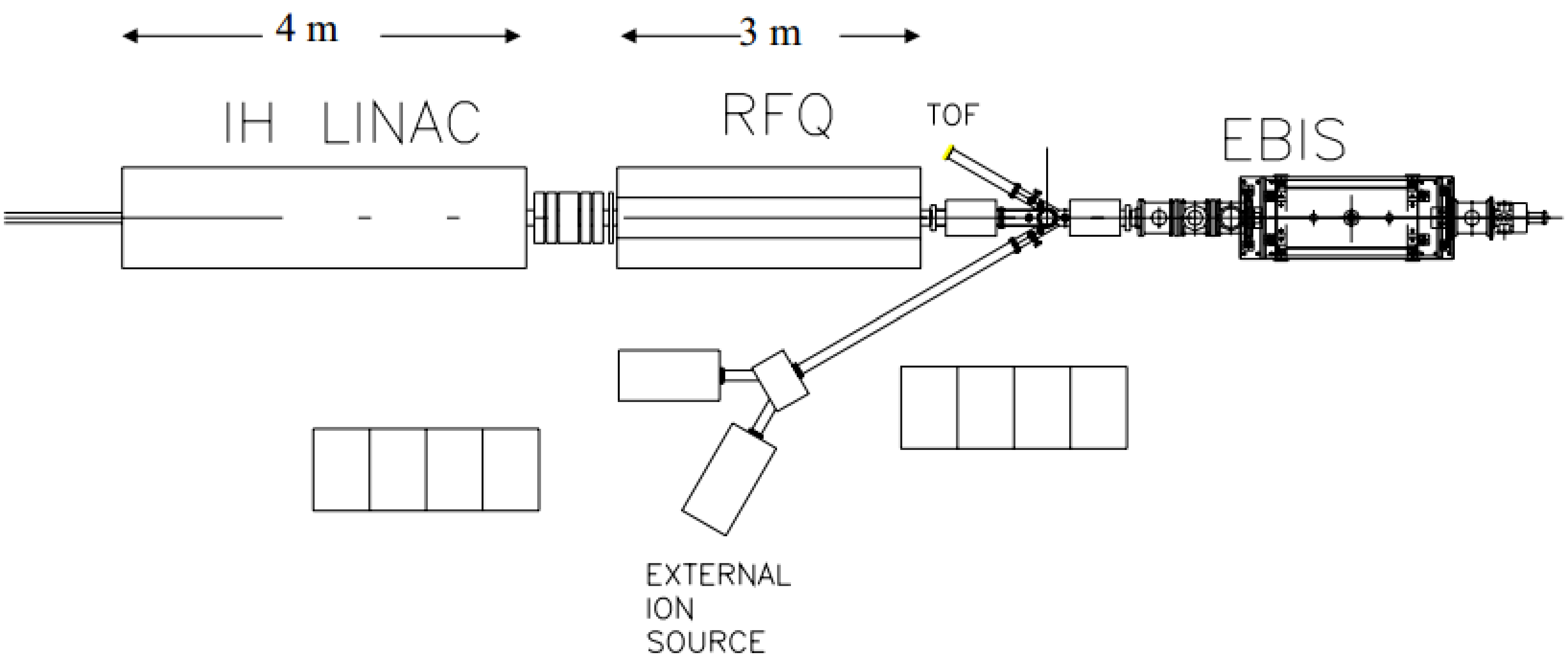
- The Tandem:
  - Tandem to Booster transport line is 860m long.

    44 Quadrupoles
    6 Large Dipoles
    20 Faraday Cups
    71 Steering Dipoles
    25 Multiwires
    Dozens each of Pumps...



✓ After upgrade, transport from the EBIS to the Booster will be only 30 m long.

The Proposed Linac-Based RHIC Pre-Injector



- RFQ: 17 – 300 KeV/u; 100 MHz
- Linac: 0.3 – 2.0 MeV/u; 100MHz

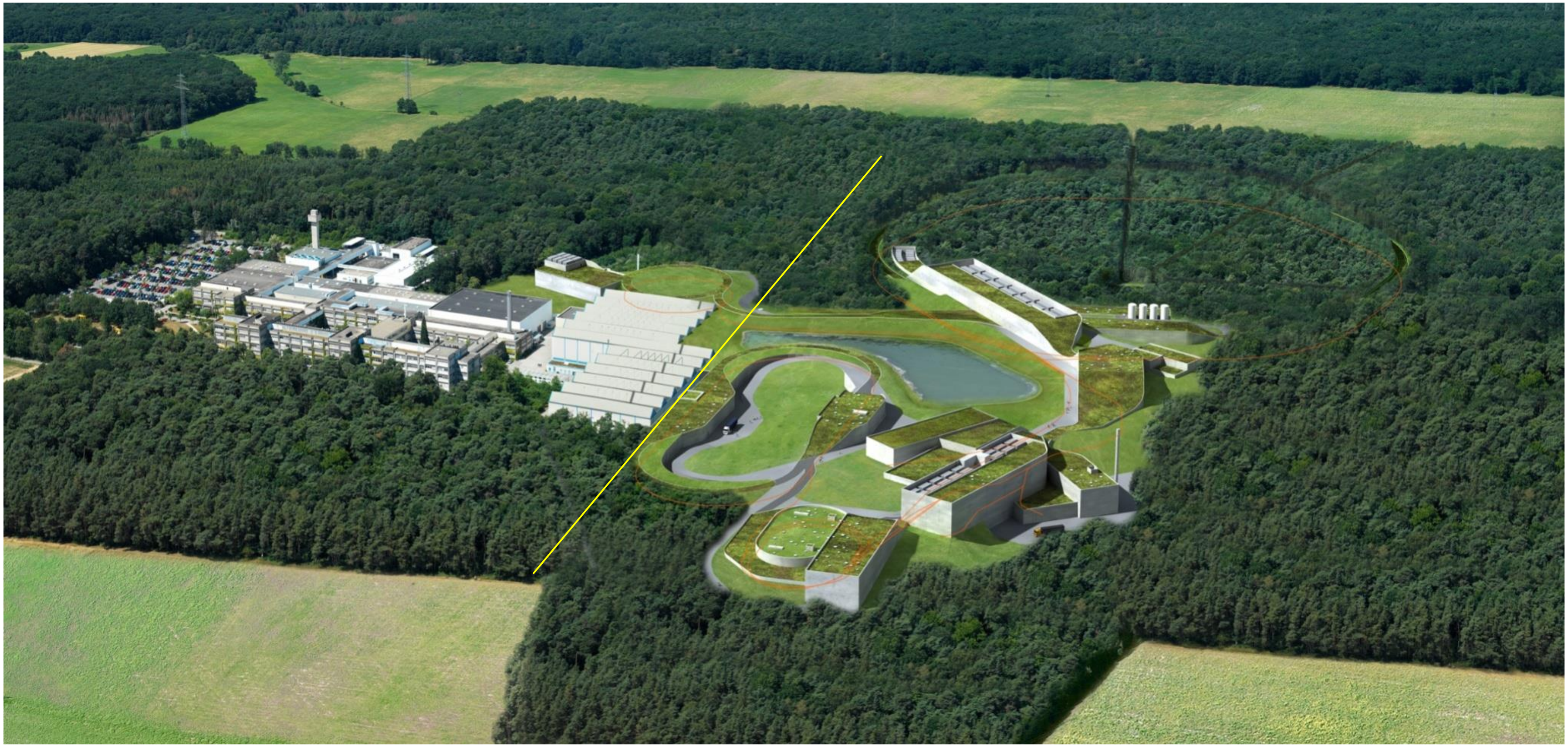
RFQ Beam Dynamics Design Parameters

Frequency	100.625 MHz
Input energy	17 keV/u
Output energy	0.3 MeV/u
Mass to charge ratio	6.25
Beam current	10 mA
Outp trans. emitt rms norm. 90%	< 0.38 π mm mrad
Output long. emittance 90%	< 220 deg keV/u
Transmission	98%
Electrode voltage	70 kV
RFQ length	3.1 m
Cell number	191
Aperture min - max	2.96-5.25 mm

Main Parameters of IH-DTL Required for RHIC Injection

Charge-to-mass ratio	Q/A	0.16–1.0
Operating frequency	MHz	100.625
Input energy	MeV/u	0.3
Output energy	MeV/u	2.0
Beam current	mA	0 - 10
Cavity length	m	> 2.5
Transverse output emittance (norm, 90% effective)	mm*mrad	0.6 π
Output energy spread (90%)	keV/u	± 1.7
Transmission	%	100
Maximum repetition rate	Hz	5
Eff. shunt impedance	MΩ/m	253

FAIR



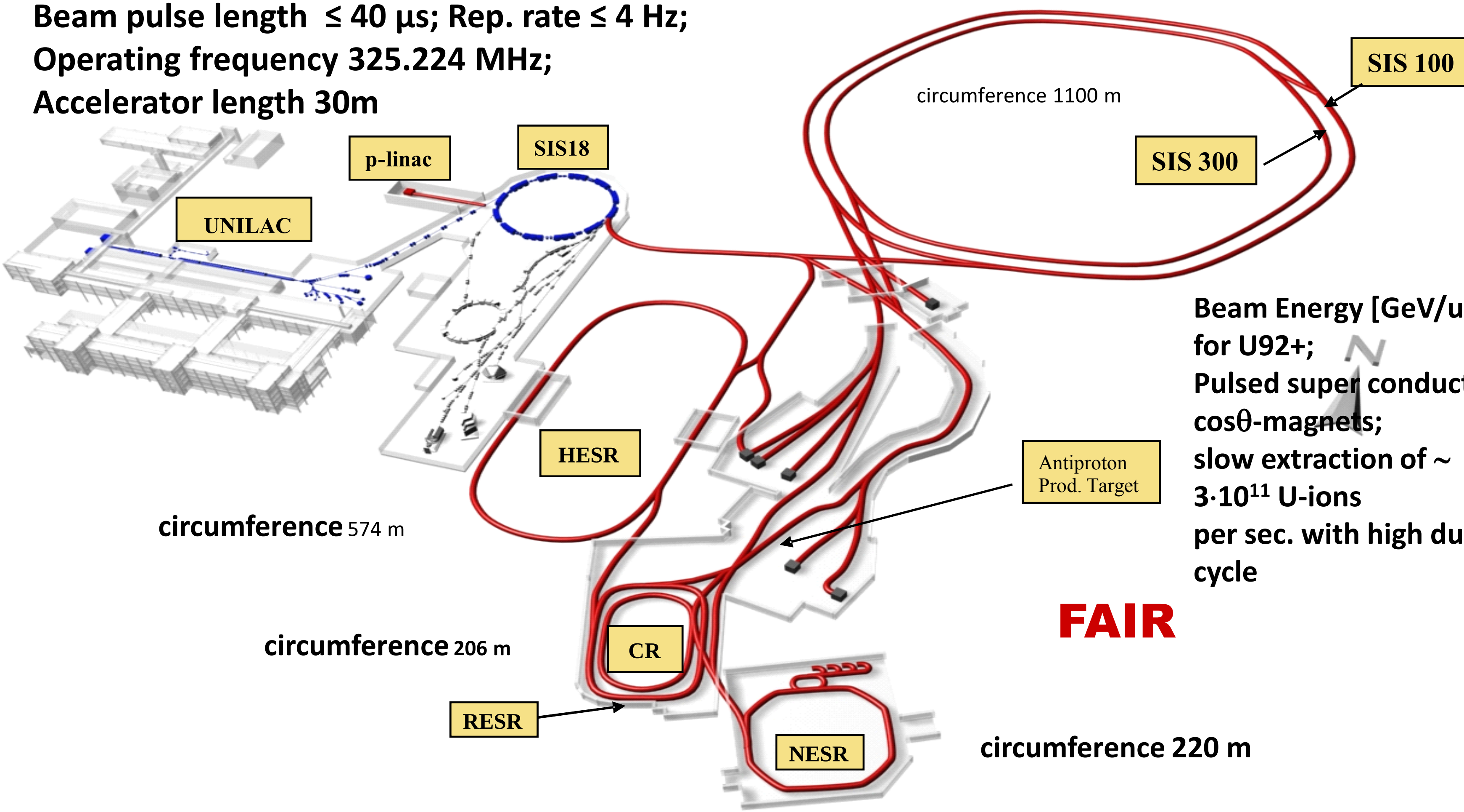
China, Finland, France, Greece, Great Britain, India, Italy, Austria, Poland, Romania, Russia, Sweden, Slovakia, Slovenia and Spain.

FAIR

GSI

Beam Energy 70 MeV; max. Current 70 mA;
$7\cdot10^{12}$ Protons per pulse;
Beam pulse length ≤ 40 µs; Rep. rate ≤ 4 Hz;
Operating frequency 325.224 MHz;
Accelerator length 30m

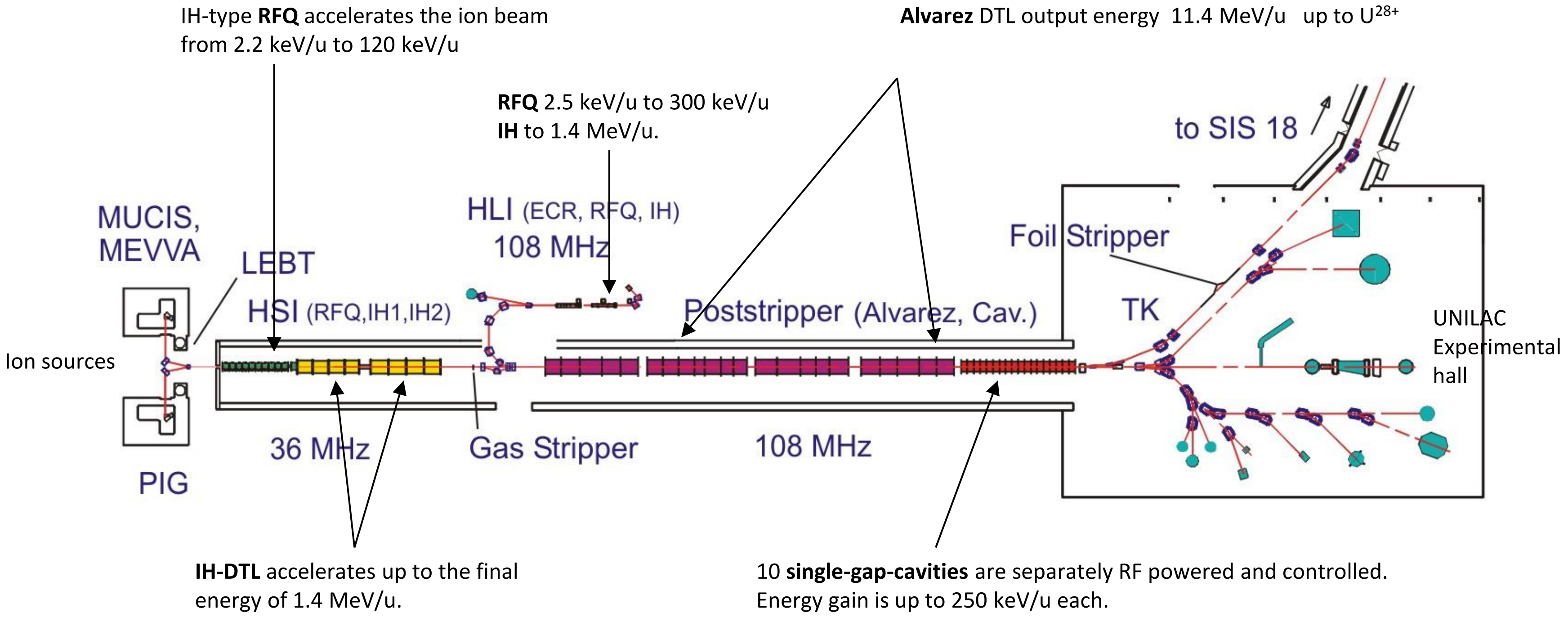
Beam Energy [GeV/u] 2.7 for U28+ to 29 for protons;
Bunch compression to ~60 ns of $5\cdot10^{11}$ U ions,
fast and slow extraction; $5\cdot10^{-12}$ mbar operating vacuum



Beam Energy [GeV/u] 34 for U92+;
Pulsed super conducting cosθ-magnets;
slow extraction of ~ $3\cdot10^{11}$ U-ions per sec. with high duty cycle

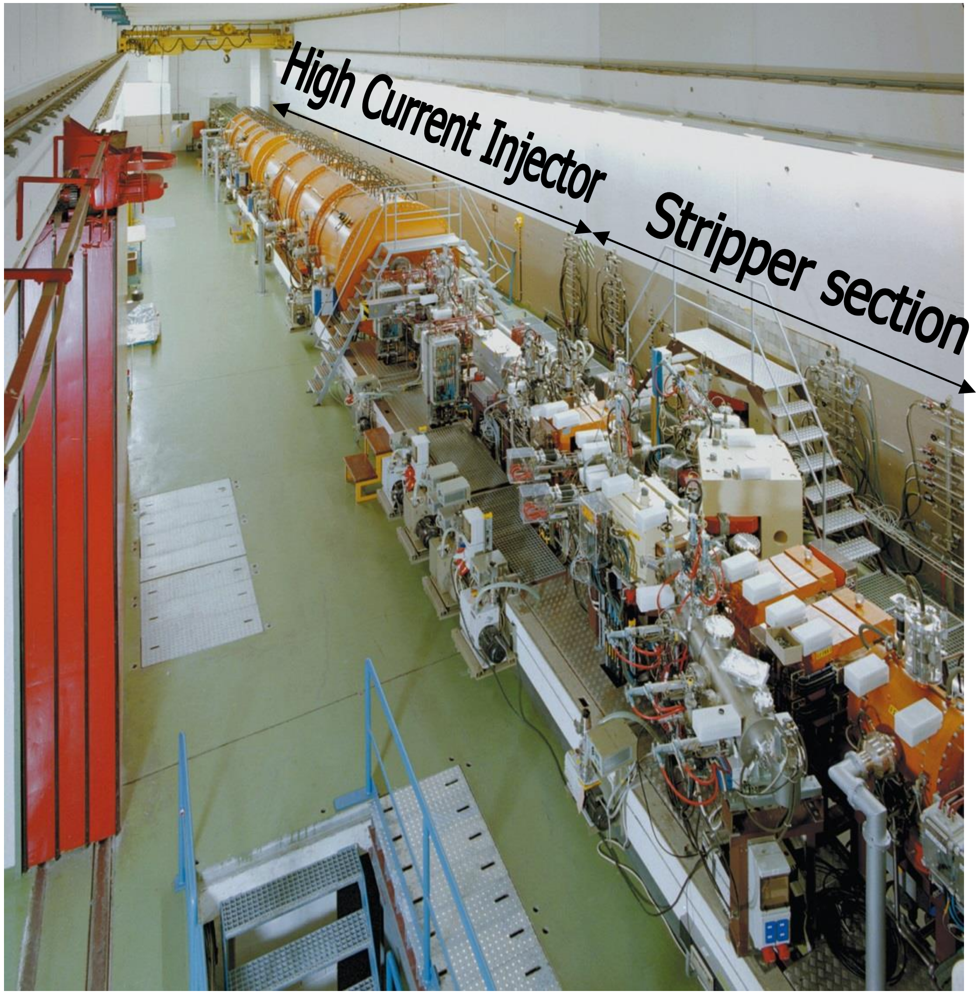
GSI Accelerators

The Linear Accelerator UNILAC (UNIversal Linear ACcelerator),
Length 120 meter, Ions up to 20 % of velocity of light (60.000 km/s)



UNILAC layout

GSI Accelerators



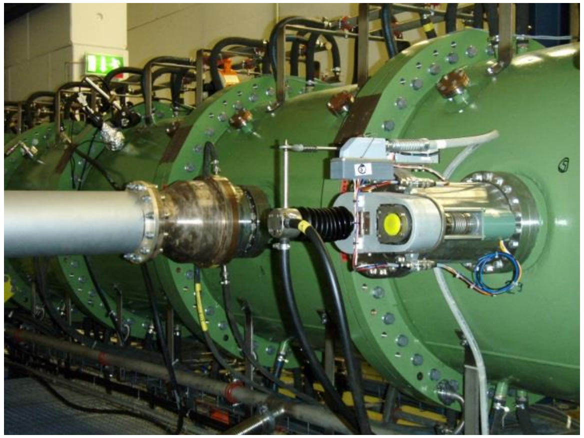
Excellent performance for more than 30 Years, meanwhile problems with cavity cooling and vacuum

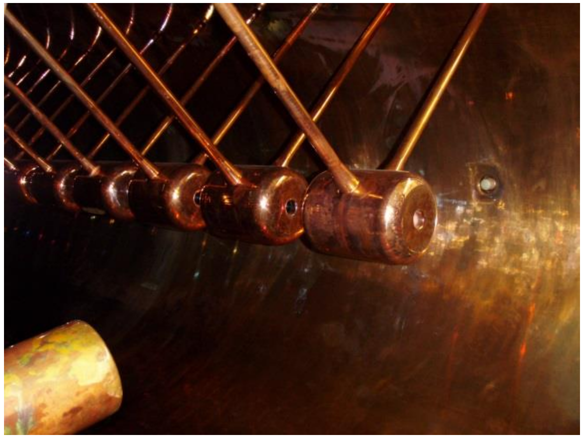
High current injector [HSI]:
RFQ and IH structures by Ulrich Ratzinger
RFQ renewed by Stepan Yaramyshev

GSI Accelerators

UNILAC RF performance

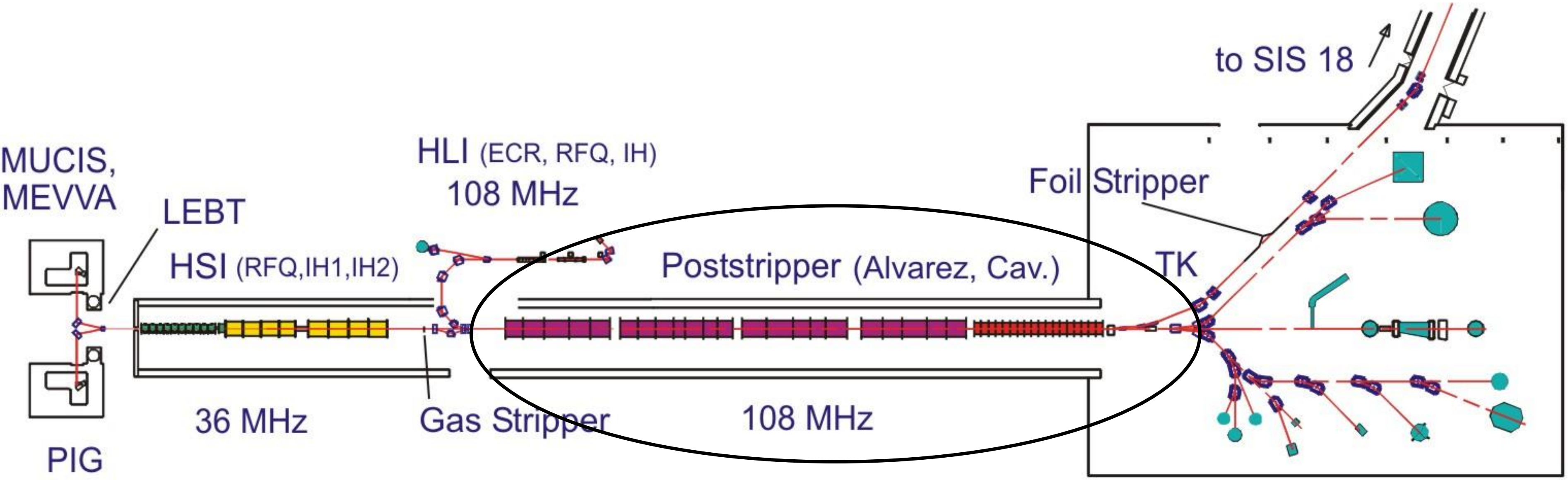
Operating Frequencies	36, 108, 216 MHz
RF Power	up to 2 MW (1,6 MW) pulsed (5ms @ 50 Hz)
Accelerator Cavities	RFQ, IH-Structures, Alvarez-Type-Structures, Single-Gap-Structures as well as Quarter wave and Spiral-Resonators
Tube types	RS 2024, RS 1084 and RS 2074 all Siemens types by Thales
Number of sockets	24 x RS 2024 29 x RS 1084 8 x RS 2074
Solid State Amps	various types used as drivers and RF supply for Bunchers from 2 to 8 kW





GSI Accelerators

UNILAC future



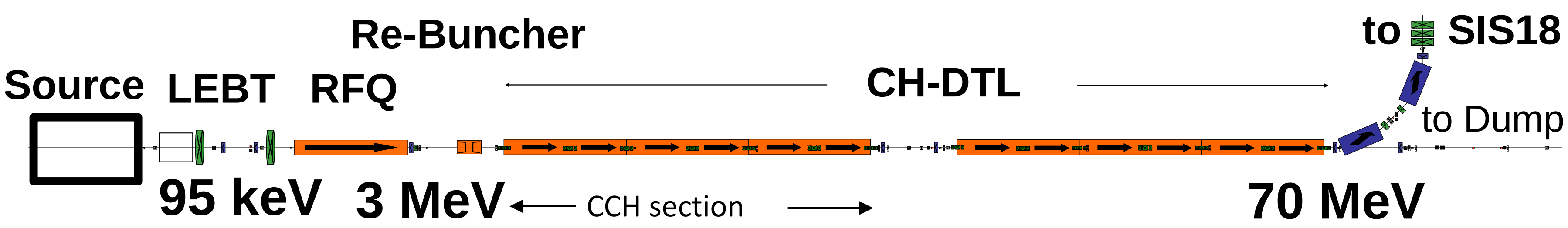
FAIR Injector HE LINAC
short pulse machine

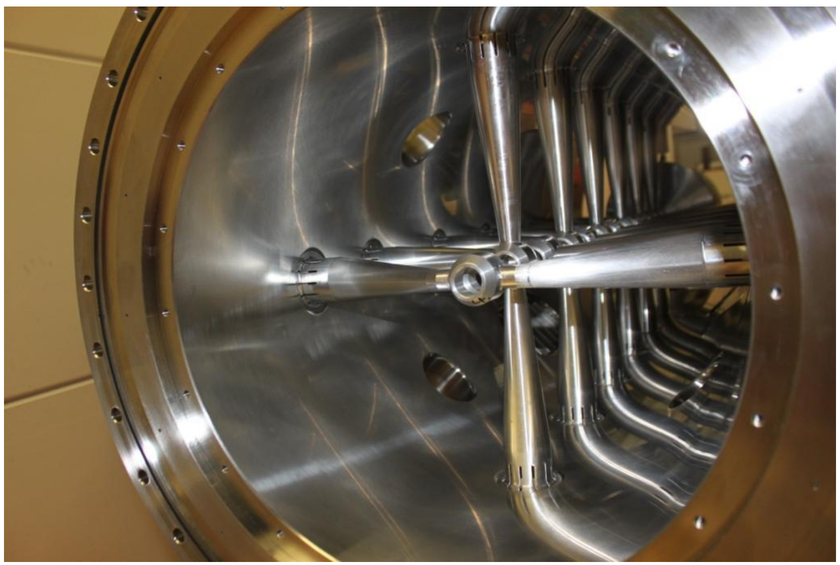
15 mA U28+
11,4 MeV/u
100 µs beam pulse
~1% duty factor

replacement of the Alvarez structures by IH
renewing of RF amplifiers 2 MW
power tube not obsolete for the next 20 years
solid state drivers
digital LLRF

FAIR Accelerators

Proton Linac



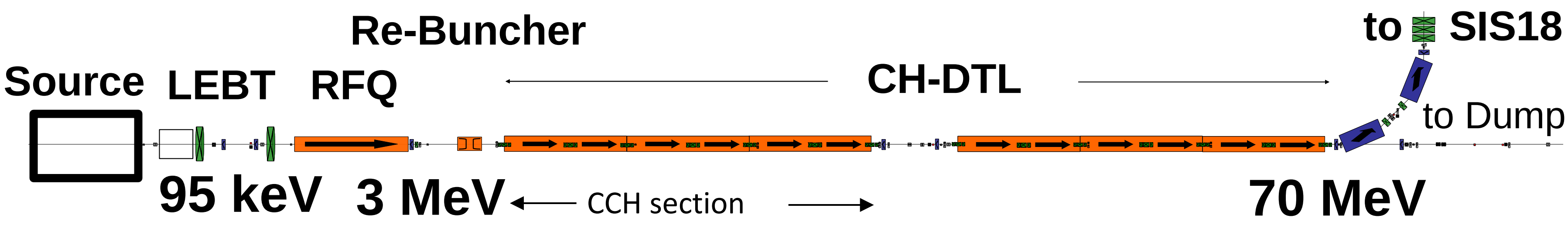


picture taken on 30th of March 2012

Source	H+, ECR, 95 keV, 110 mA
LEBT (2-solenoid foc.)	95 keV, 100 mA, 0.3 µm*
RFQ (4-rod / 4-windows)	3 MeV, 90 mA, 0.4 µm* *(norm., rms)
DTL (352 MHz, rt) current emittance rel. momentum spread rf pulse max. beam pulse max. repetition rate	11 CH-structures, 70 MeV 90 mA (design) 70 mA (operation) 2.8 µm** $\pm 5 \cdot 10^{-4}$ 250 µs 25 - 100 µs 5 Hz **(norm., tot)
Overall linac length	≈ 30 m

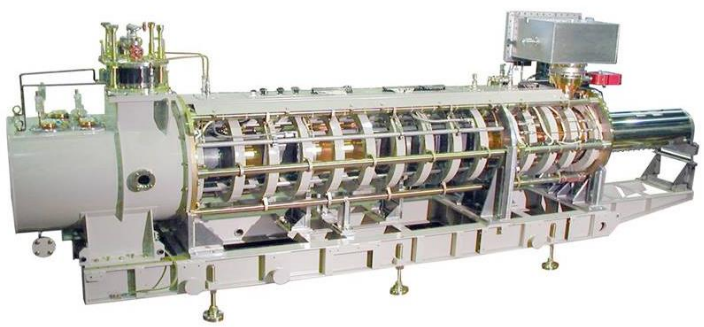
FAIR Accelerators

Proton Linac



- **ECR proton source & LEBT**
- **RFQ**
  - **1 Klystron (~1.5 MW)**
- **3 re-bunchers**
  - **3 Solid State Amplifier (~45 kW)**
- **6 * 2 accelerating cavities (CCH-DTL)**
  - **6 Klystrons (2.5 MW)**
- **2 dipoles, 45 quadrupoles, 7 steerers**
- **10 turbo pumps, 34 ion pumps, 9 sector valves**
- **41 beam diagnostic devices**

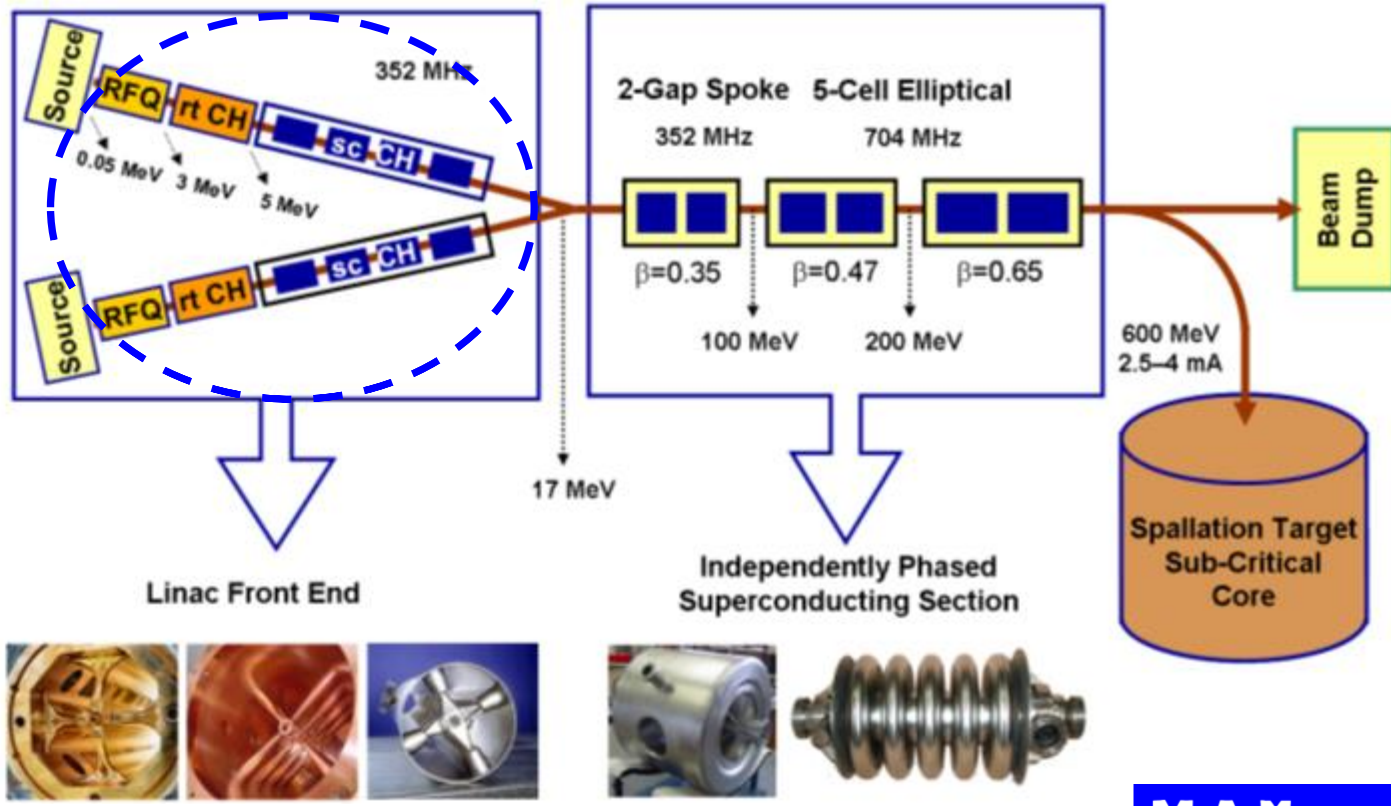
= 10 RF systems in total



Klystron
325.224 MHz
2.8 MW @ 1‰ duty factor

Accelerator Driven Systems ADS

The European MYRRHA Project



MAX MYRRHA Accelerator eXperiment, research & development programme

SEVENTH FRAMEWORK PROGRAMME

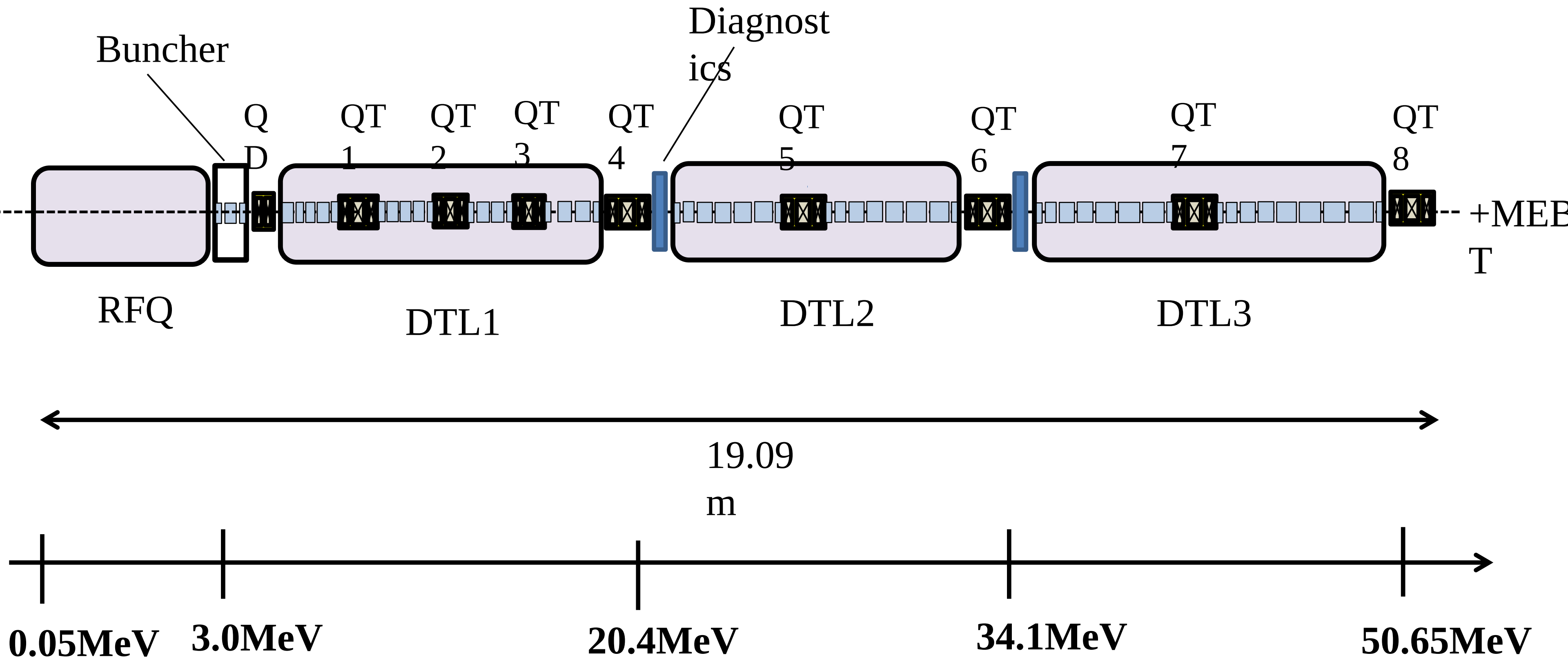
IAP Team for the MAX Project:

<u>Horst Klein</u>, Dominik Mäder, Holger Podlech, Ulrich Ratzinger,

Alwin Schempp, Rudolf Tiede, Markus Vossberg, Chuan Zhang

Preliminary Design of Proton Linac (50MeV ,40mA）

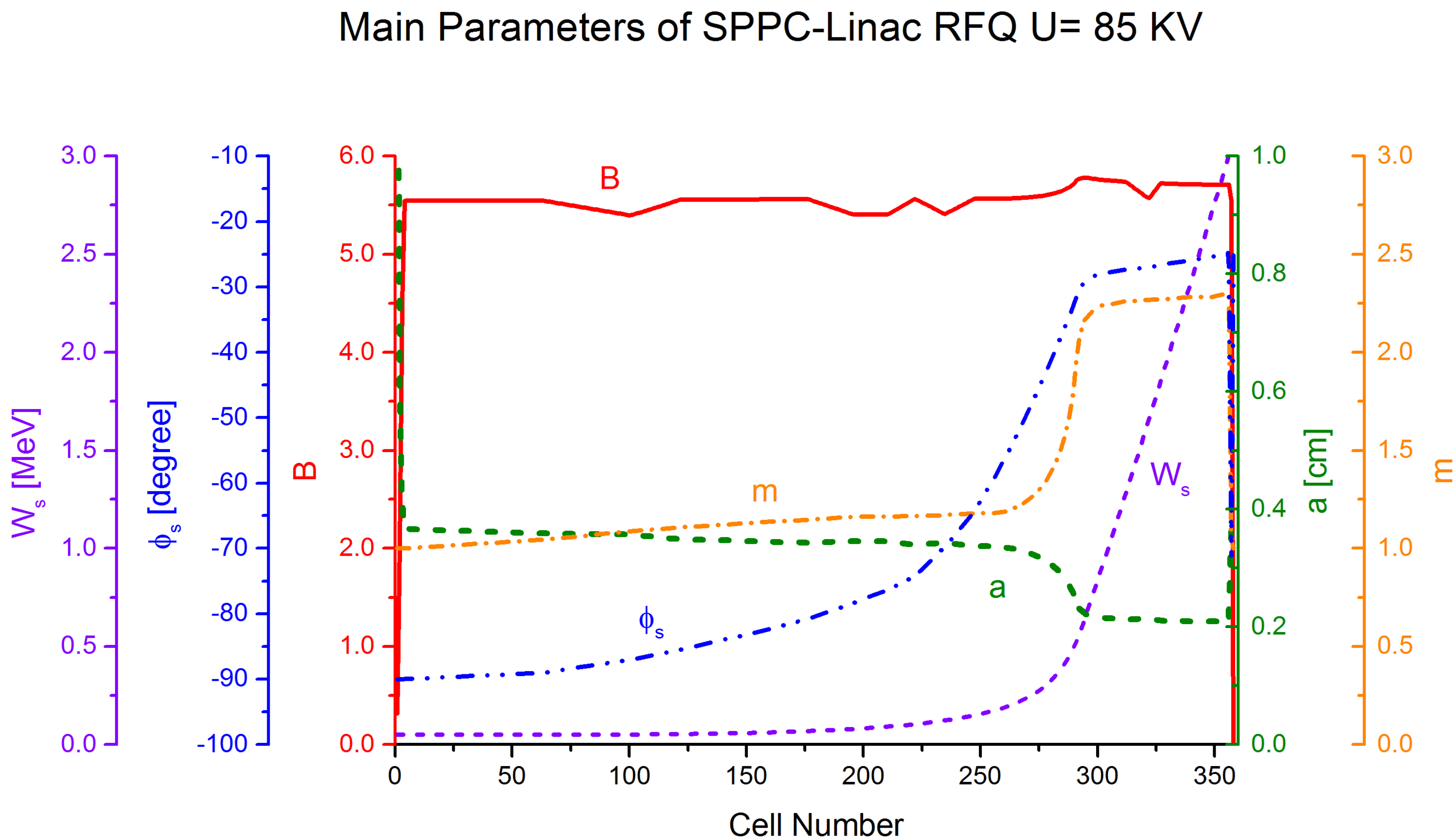
Schematic layout

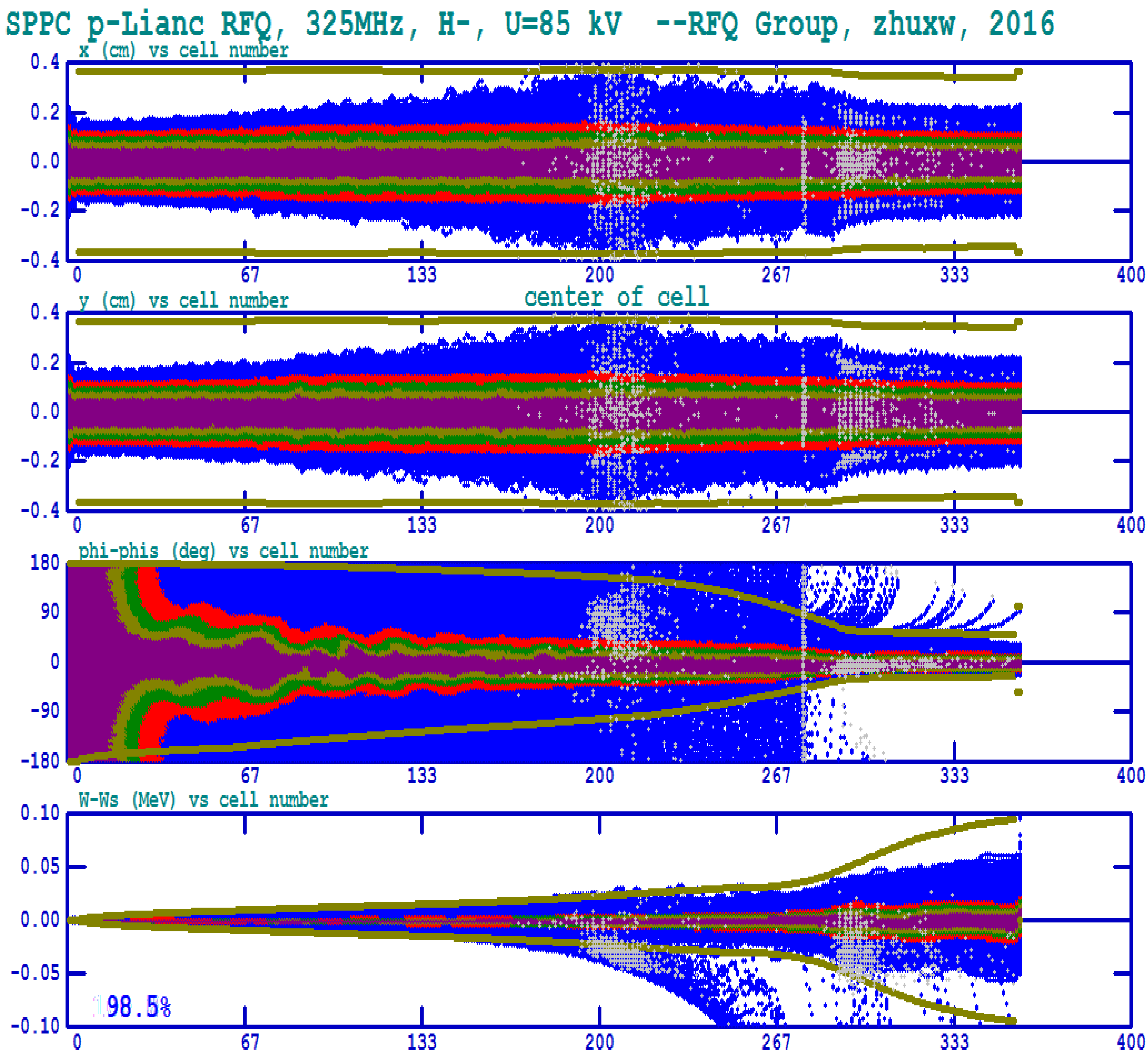


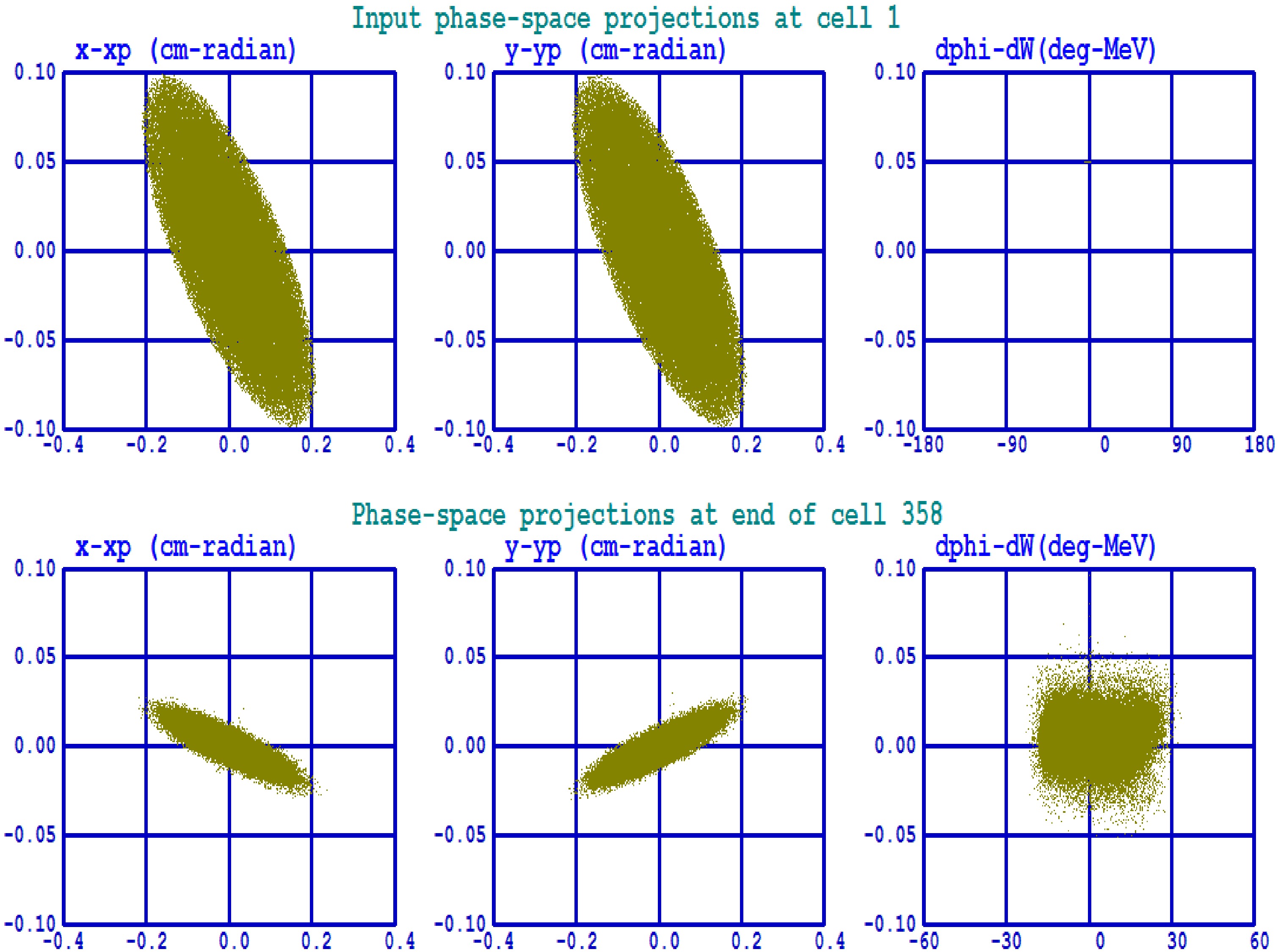
- SPPC p-Linac RFQ Beam Dynamics Parameters

Parameters	SPPC
Particle	H-
Frequency	325 [MHz]
Injection Energy	50 [KeV]
Output Energy	3.0 [MeV]
Beam Current	40 [mA]
Duty Factor	1.7%
Vane Length	3.619 [m]
Norm. RMS Input Emittance	0.25 [mm.mrad]
Norm. RMS output Emittance	0.23 [mm.mrad]
Vane Voltage	85 [KV]
Peak Surface Field	32.03 [MV/m] (1.79 Ek)
Mean Aperture	3.673 [mm]
Transmission Efficiency	98.5% [91.3%, 80 mA]
Energy Spread	1.11%

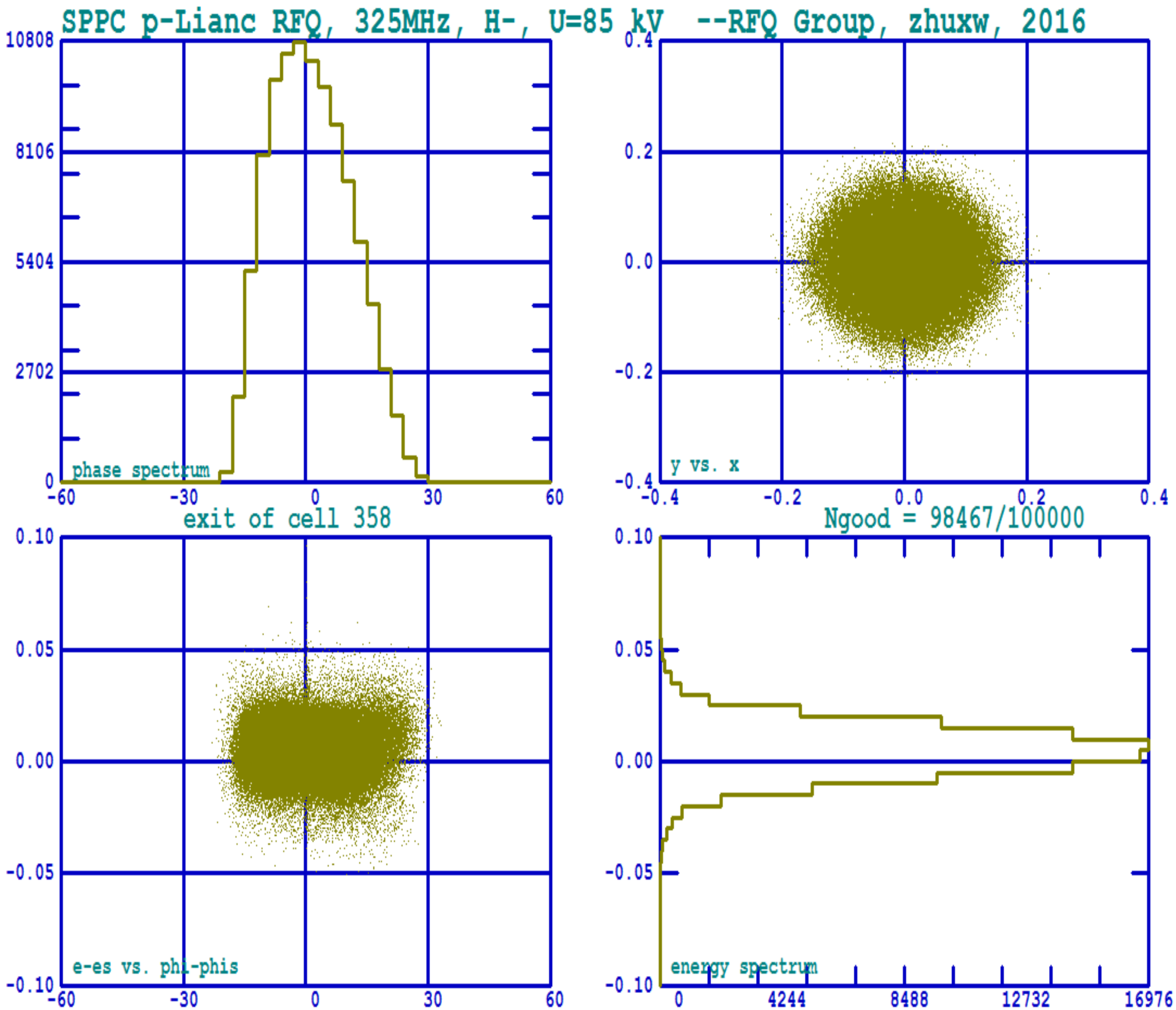
- SPPC p-Linac RFQ Main Parameters Versus Cell Number



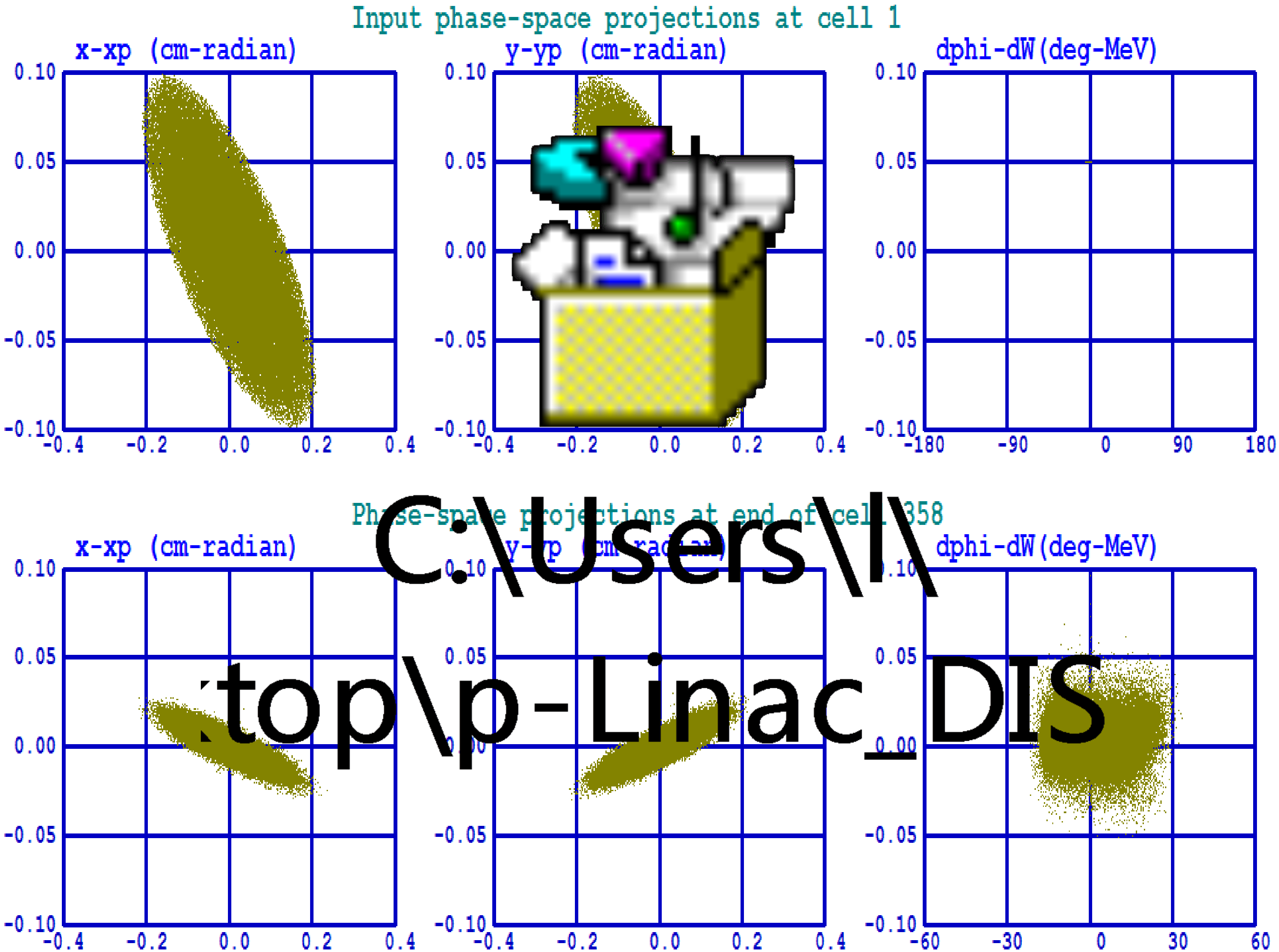

SPPC p-Lianc RFQ, 325MHz, H-, U=85 kV --RFQ Group, zhuxw, 2016
x (cm) vs cell number
0.4
0.2
0.0
-0.2
-0.4
0
67
133
200
267
333
400
y (cm) vs cell number
center of cell
phi-phis (deg) vs cell number
180
90
0
-90
-180
W-Ws (MeV) vs cell number
0.10
0.05
0.00
-0.05
-0.10
98.5%



Input phase-space projections at cell 1
x-xp (cm-radian)
y-yp (cm-radian)
dphi-dW(deg-MeV)
0.10
0.05
0.00
-0.05
-0.10
-0.4
-0.2
0.0
0.2
0.4
-180
-90
0
90
180
Phase-space projections at end of cell 358
x-xp (cm-radian)
y-yp (cm-radian)
dphi-dW(deg-MeV)
-60
-30
0
30
60



SPPC p-Lianc RFQ, 325MHz, H-, U=85 kV --RFQ Group, zhuxw, 2016
10808
8106
5404
2702
0
phase spectrum
-60 -30 0 30 60
0.4
0.2
0.0
-0.2
-0.4
y vs. x
-0.4 -0.2 0.0 0.2 0.4
exit of cell 358
0.10
0.05
0.00
-0.05
-0.10
e-es vs. phi-phis
-60 -30 0 30 60
Ngood = 98467/100000
0.10
0.05
0.00
-0.05
-0.10
energy spectrum
0 4244 8488 12732 16976



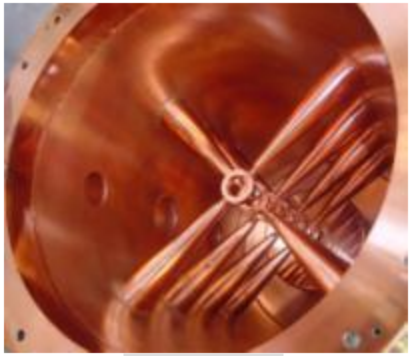
Input phase-space projections at cell 1
x-xp (cm-radian)
y-yp (cm-radian)
dphi-dW(deg-MeV)
Phase-space projections at end of cell 358
x-xp (cm-radian)
y-yp (cm-radian)
dphi-dW(deg-MeV)
C:\Users\l\
top\p-Linac_DIS

DTL parameters:

Parameters	DTL1	DTL2	DTL3
Frequency(MHz)	325	325	325
Input/output energy(MeV)	3.02/20.44	20.44/34.10	34.10/50.65
Length(cm)	~435	~403	~495
Gap number	58	35	36
Transmission(%)	99.98	99.99	99.99
Acceleration gradient(MV/m)	4.00	3.39	3.34
Max field(MV/m)	13.09	17.78	17.20
Kilpatric Factor (17.86MV/m)	0.73	0.996	0.963

Room Temperature Low and Medium Energy Cavities

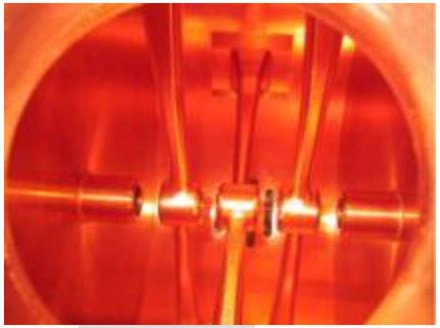
IAP Frankfurt



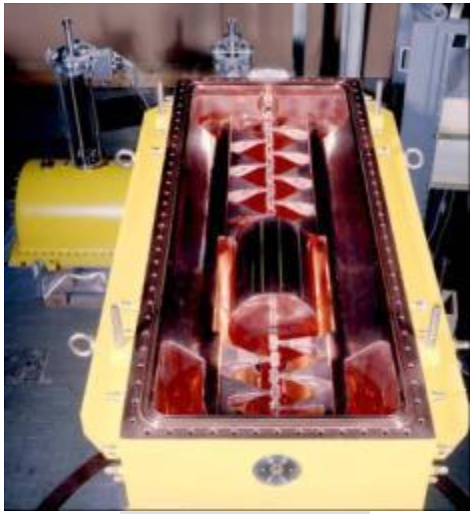
IAP

GSI

CERN



FNAL

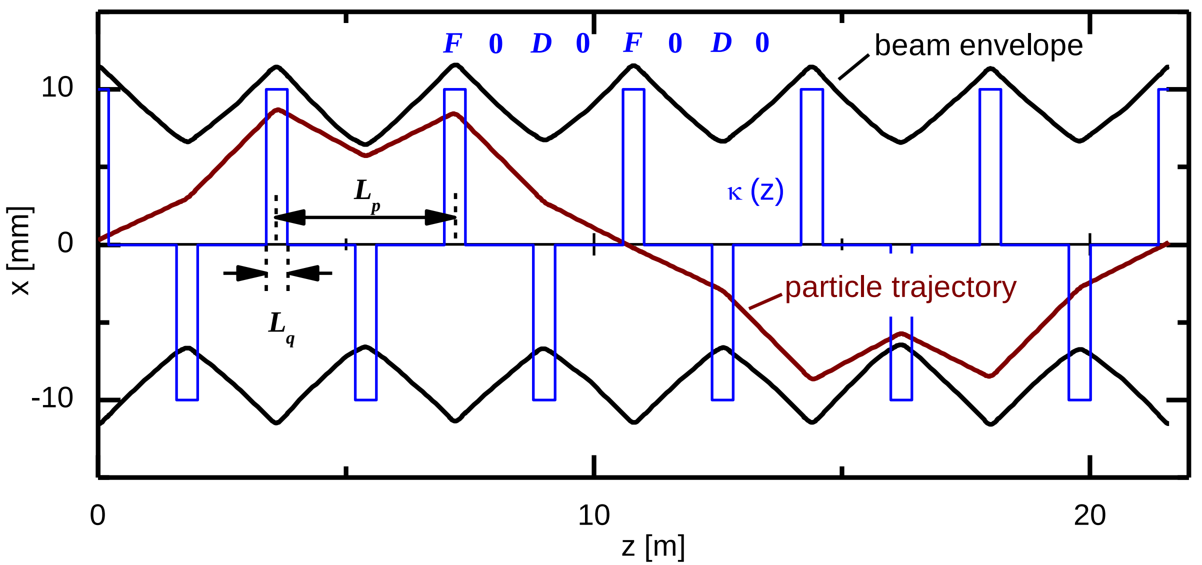


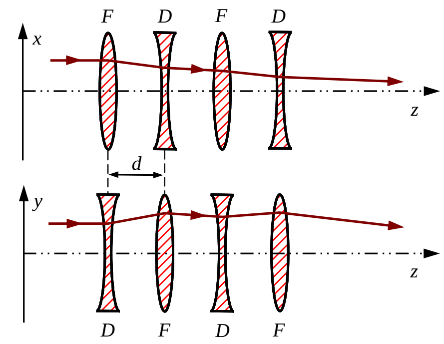
REX-ISOLDE

Linac beam dynamics

Standard concept: negative synchronous particle

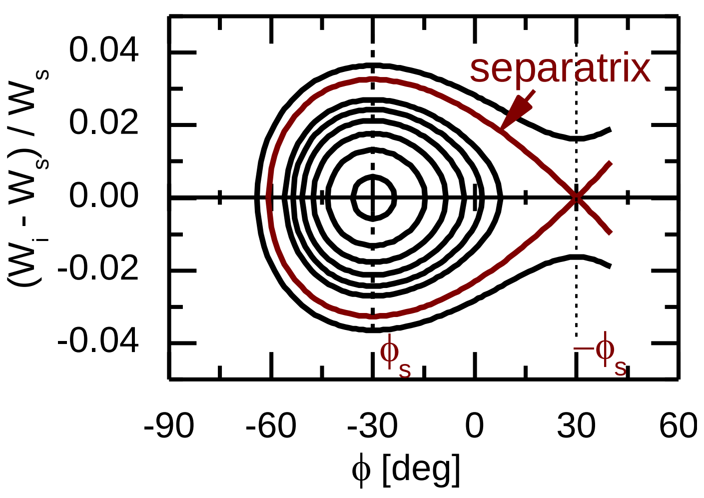
$\sigma_t < 90°$





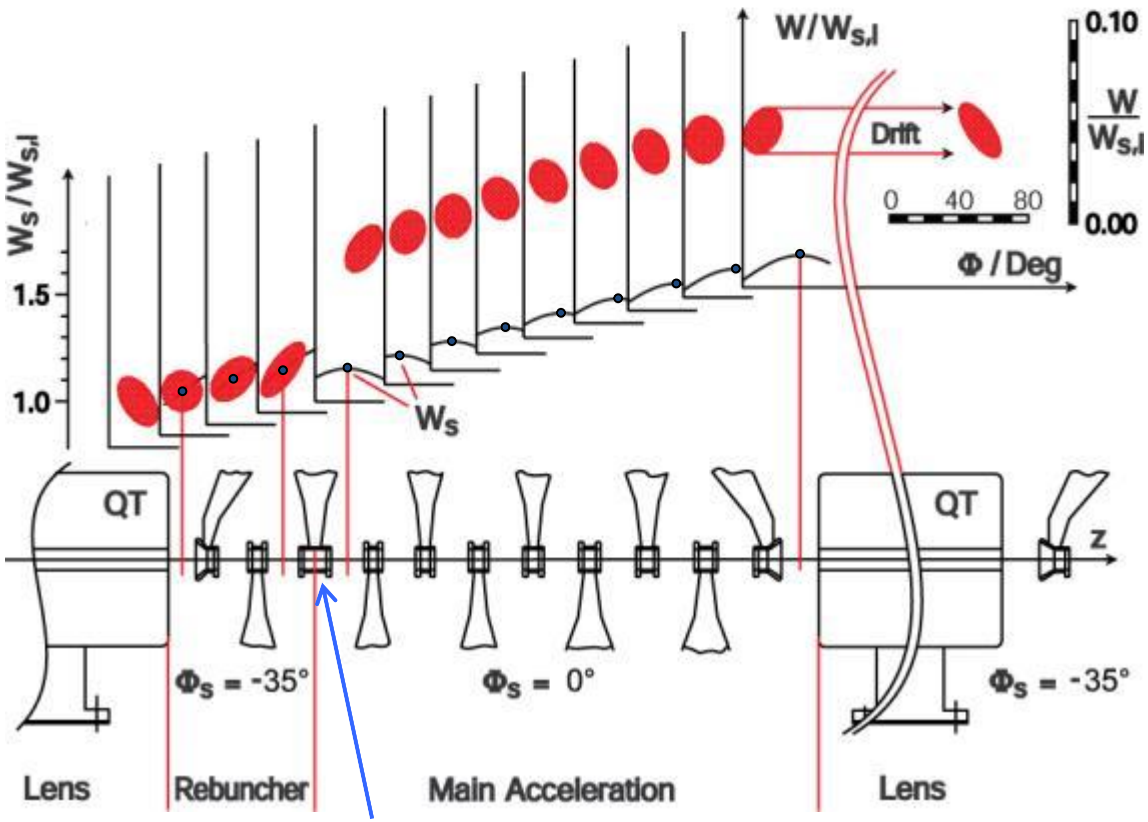
Strong focusing concept in periodic lattice

$\phi_s = -30°$



$$W_i - W_s = \pm\sqrt{\frac{1}{\pi} A \cdot m_0 \cdot c^2 \cdot \gamma_s^3 \cdot \beta_s^3 \cdot \lambda \cdot qE_0T \cdot (\varphi_i \cdot \cos(\varphi_s) - \sin(\varphi_i) - C)}$$

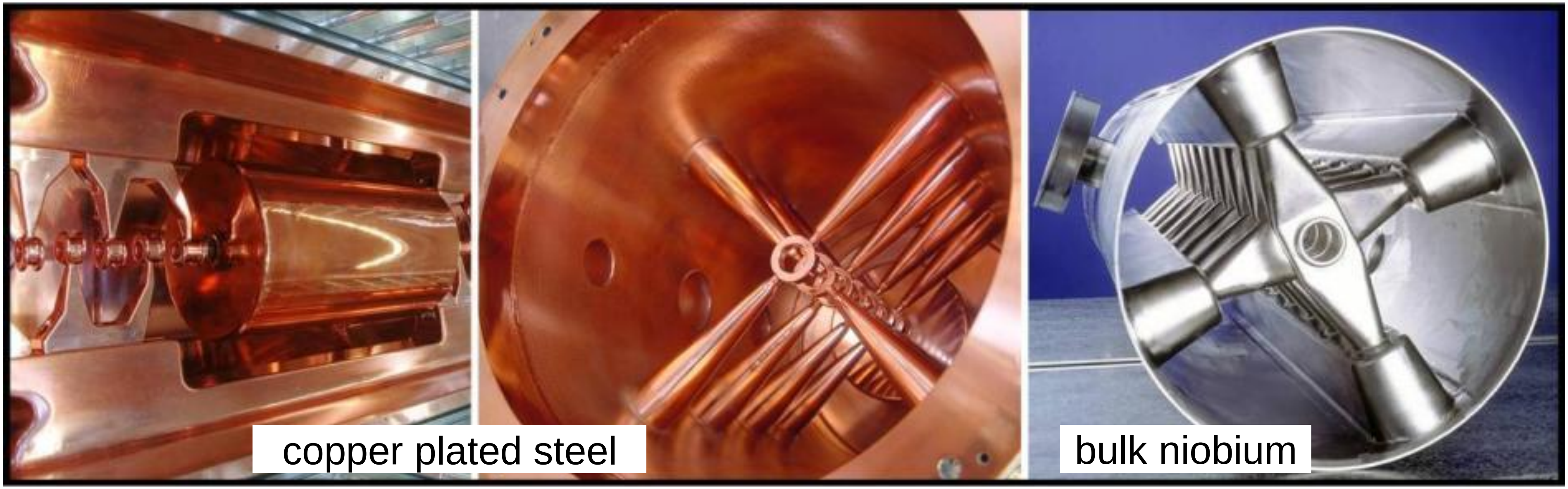
Alternative concept for efficient βλ/2 H-type structures: Combined 0 deg Structure KONUS （LORASR）



Phase shift at transition: rebunching → 0° section

One structure period consists of a quadrupole triplet, a rebunching section and a main acceleration section.

Room temperature cavity development

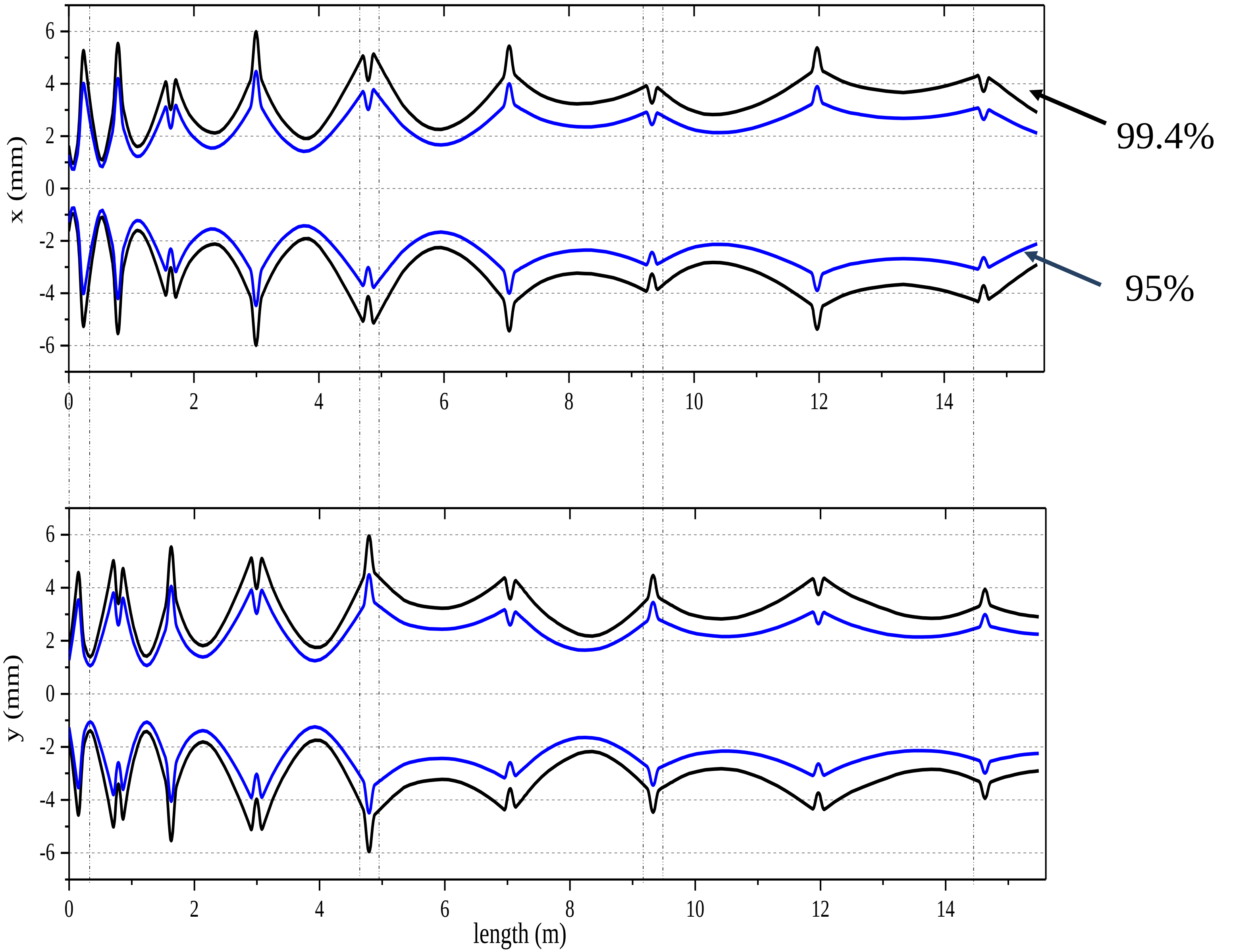


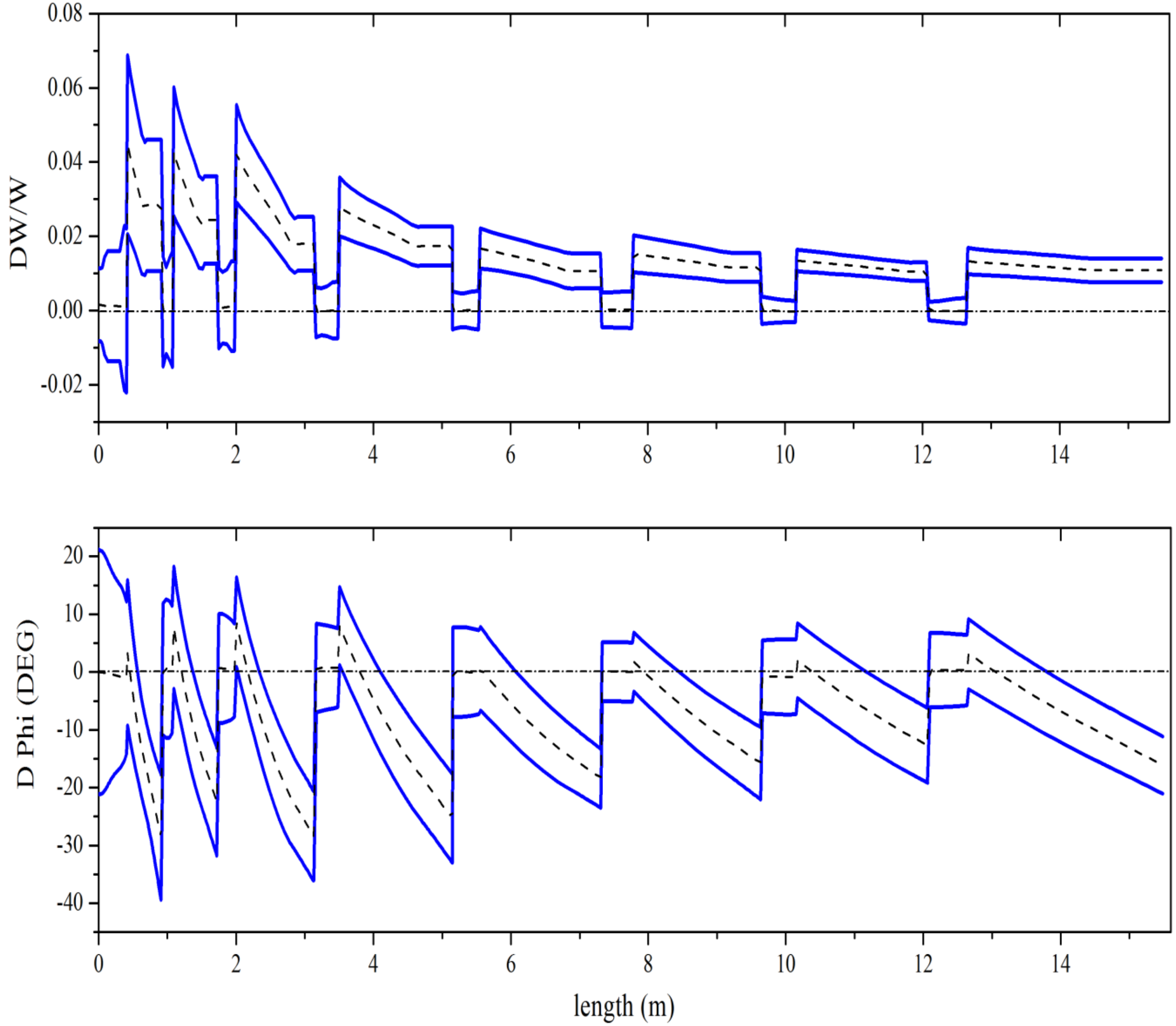
r.t. IH-DTL
W < 30 MeV
30-250 MHz

r.t. CH-DTL
W < 150 MeV
150-700 MHz

s.c. CH-DTL
W < 150 MeV
150-700 MHz

Beam envelope





DW/W
0.08
0.06
0.04
0.02
0.00
-0.02
0
2
4
6
8
10
12
14
D Phi (DEG)
20
10
0
-10
-20
-30
-40
length (m)

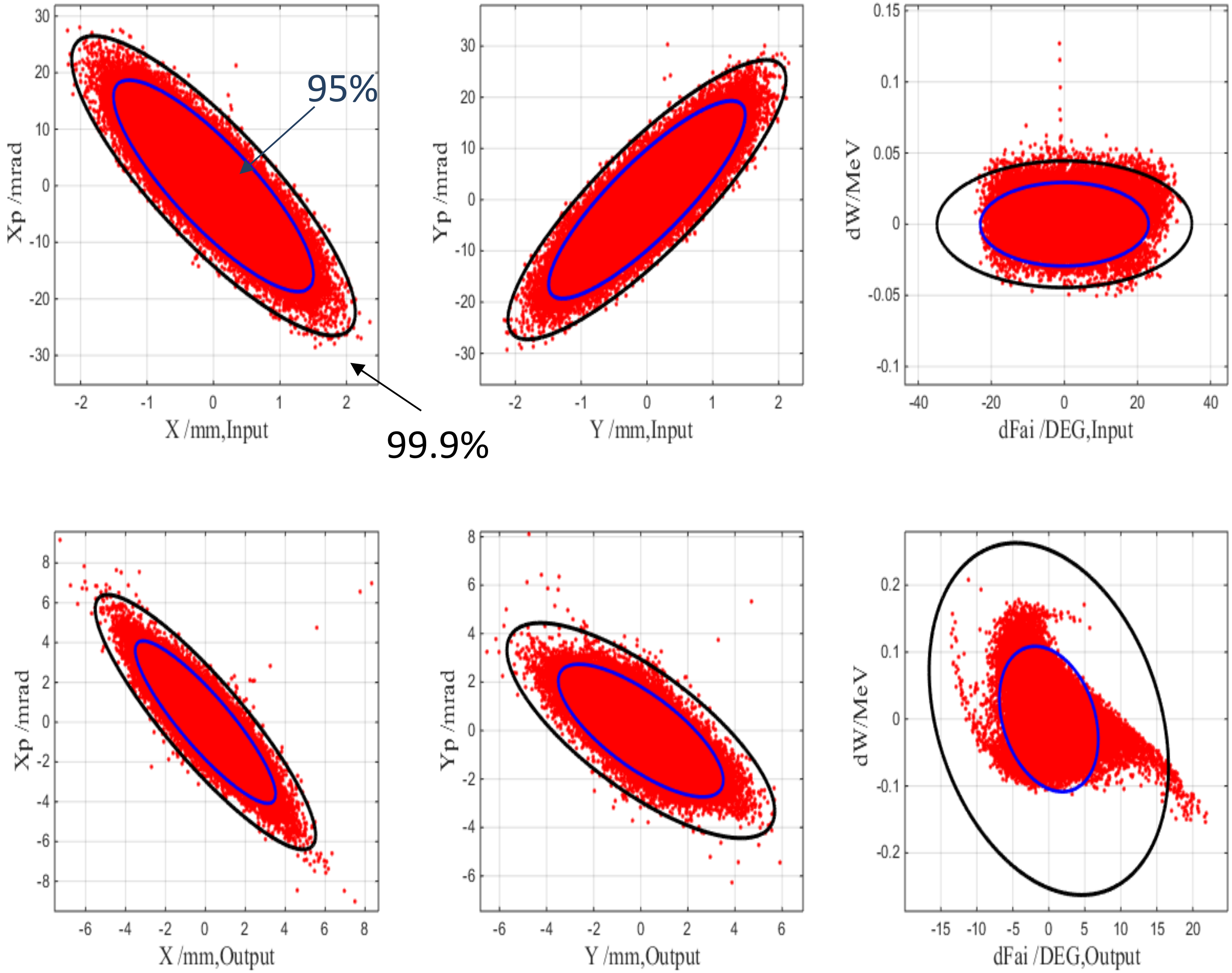
Quadrupole lens parameters:

Diameter=20mm

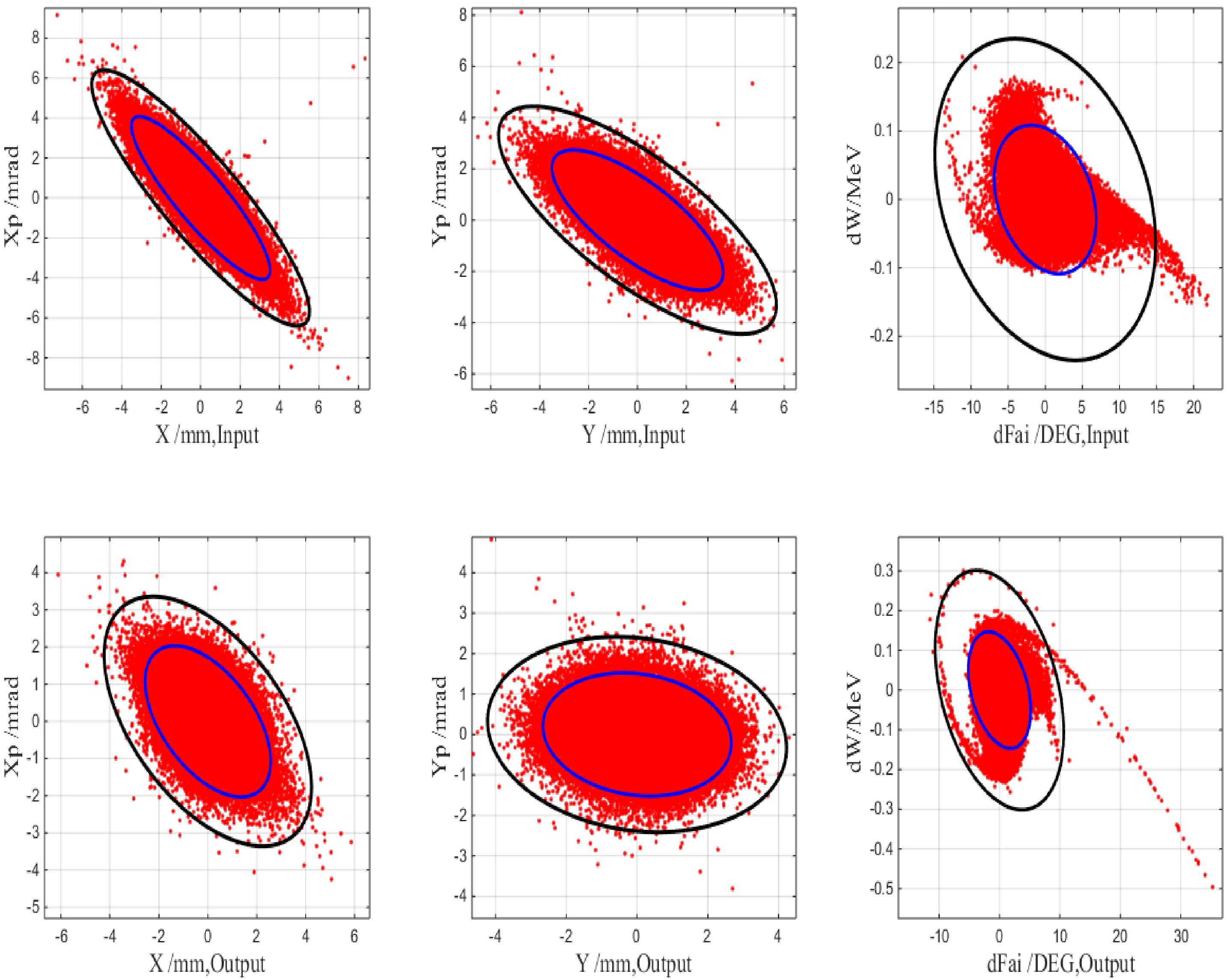
Quadrupole	QD	QT1	QT2	QT3	QT4
Eff.Space (mm)	20	20/20	20/20	20/20	20/20
Eff.Pole length (mm)	48/48	36/66/36	37/68/37	39/70/39	38/71/38
Field gradient (T/m)	79/77	82/79.5/82	82/81.5/82	80/83/80	80/81/80

Quadrupole	QT5	QT6	QT7	QT8
Eff.Space (mm)	20/20	20/20	20/20	20/20
Eff.Pole length (mm)	39/75/39	39/75/39	39/75/39	39/75/39
Field gradient (T/m)	73.5/74/73.5	73/75/73	73.5/74/73.5	73/74/73

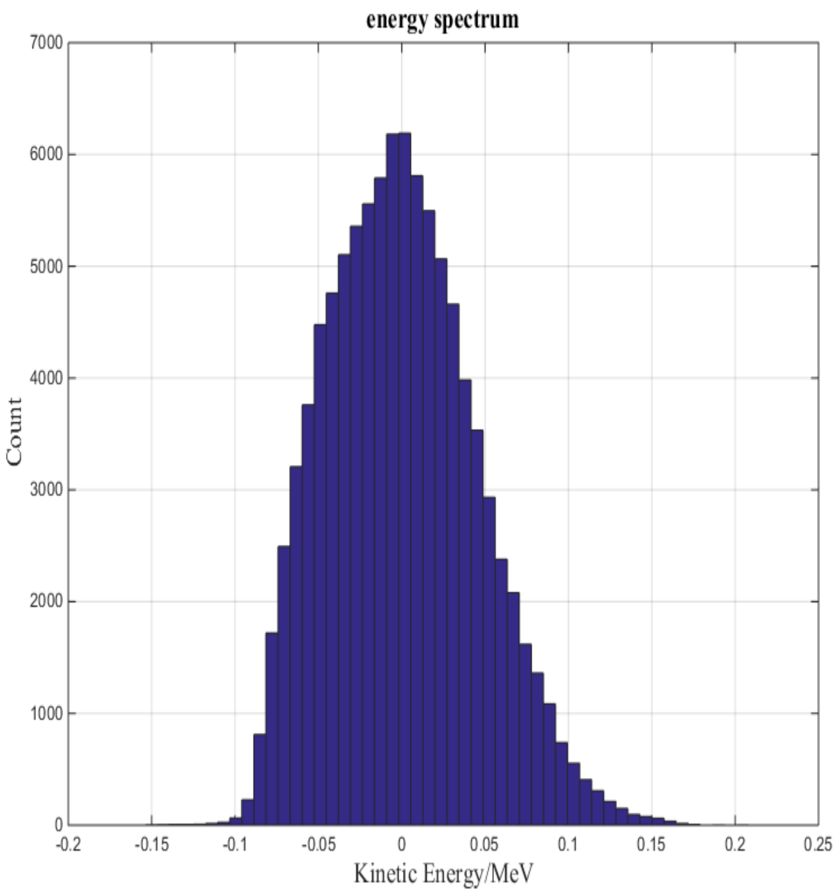
Particle No. 98449



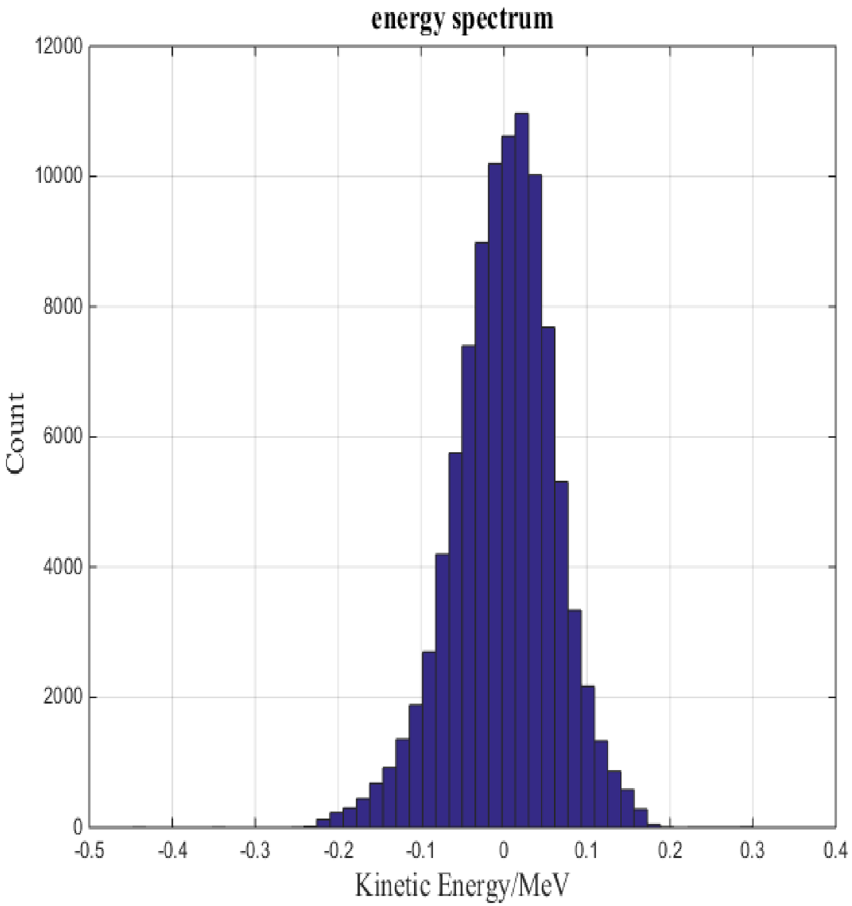
Particle No. 98433



Energy spectrum

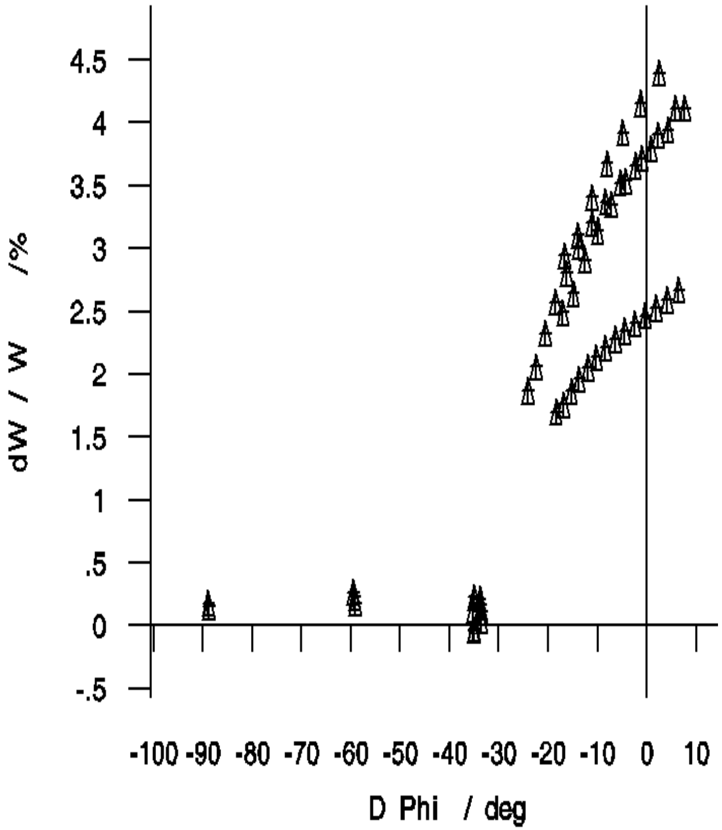


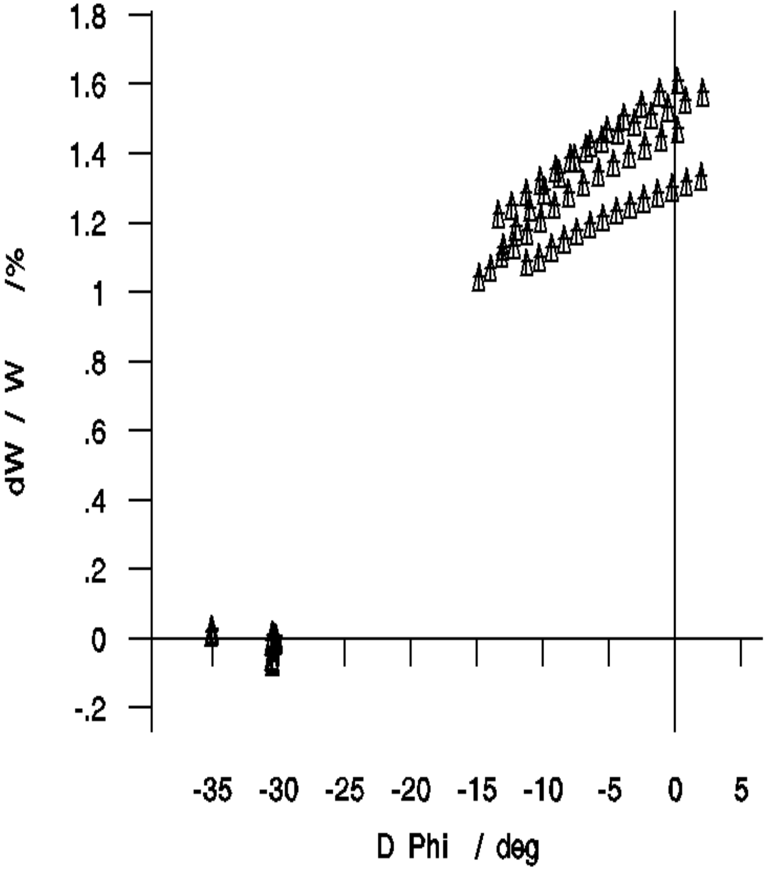
能散：$\frac{0.05\text{MeV}}{20.438\text{MeV}} = 0.245\%$



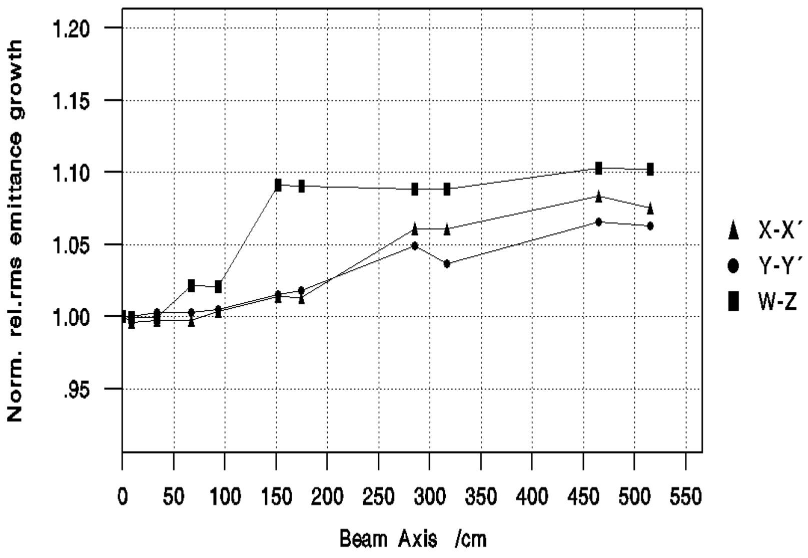
能散：$\frac{0.08\text{MeV}}{50.65\text{MeV}} = 0.158\%$

Bunch Center

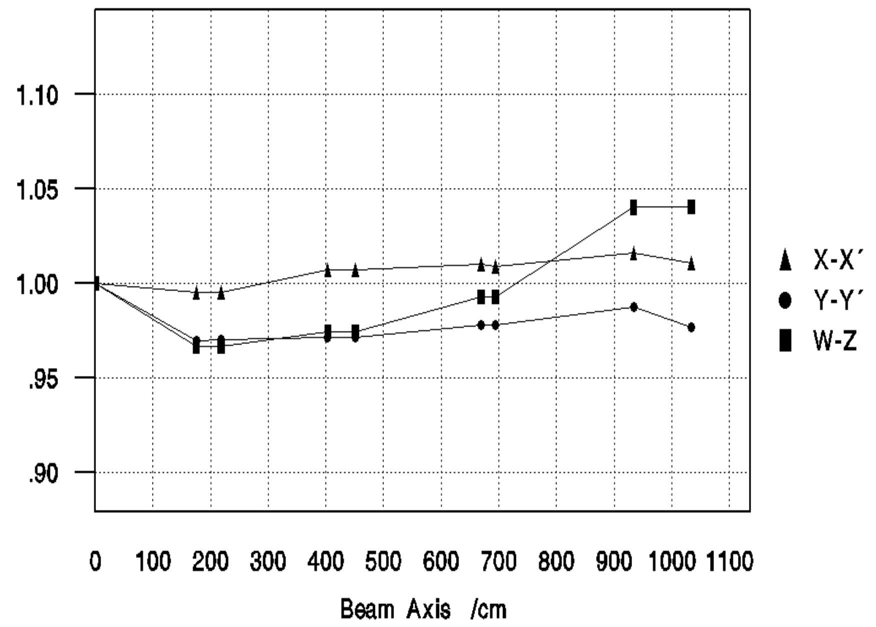




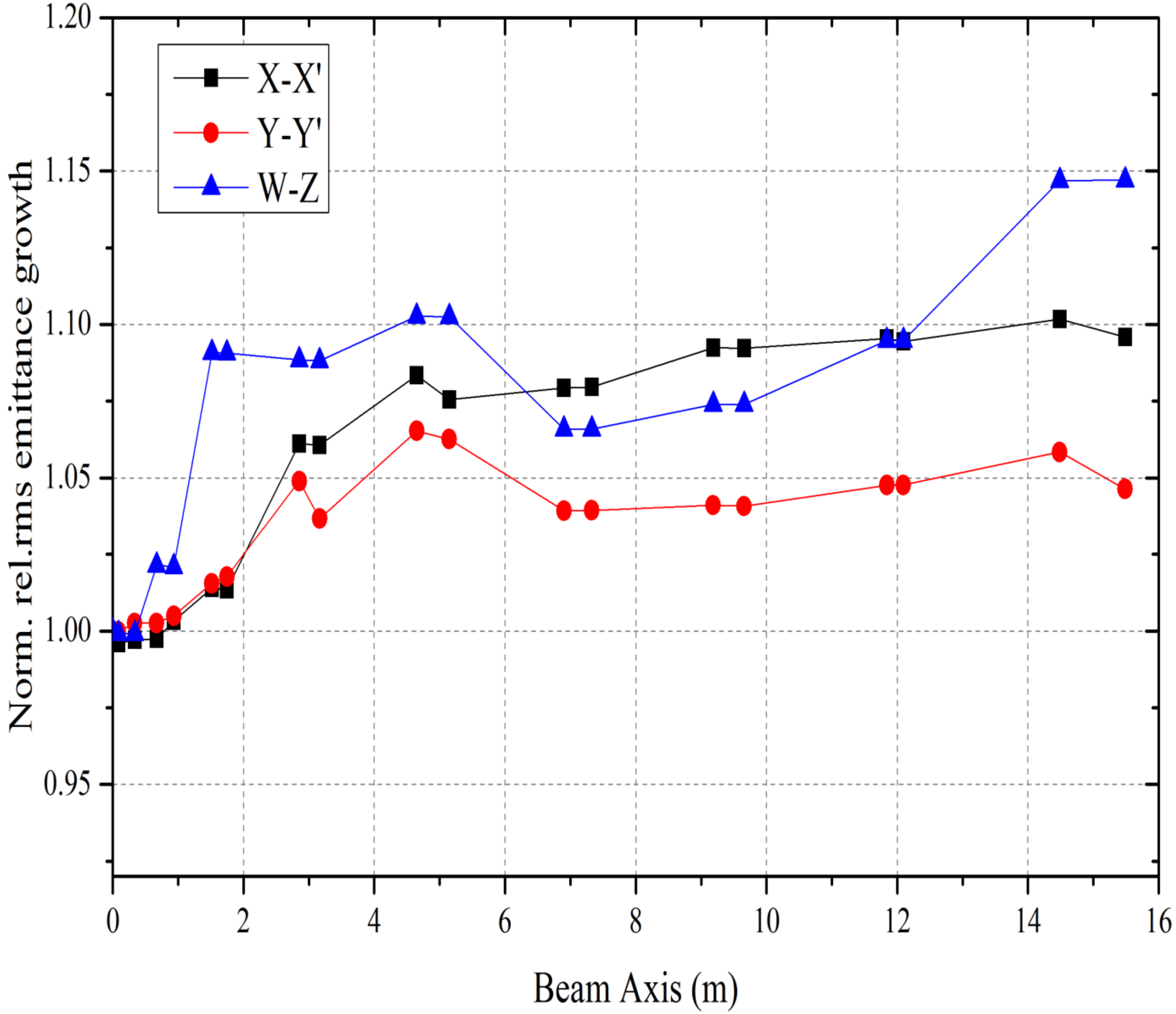
Emittance



Norm. rel.rms emittance growth
1.20
1.15
1.10
1.05
1.00
.95
0
50
100
150
200
250
300
350
400
450
500
550
Beam Axis /cm
X-X′
Y-Y′
W-Z

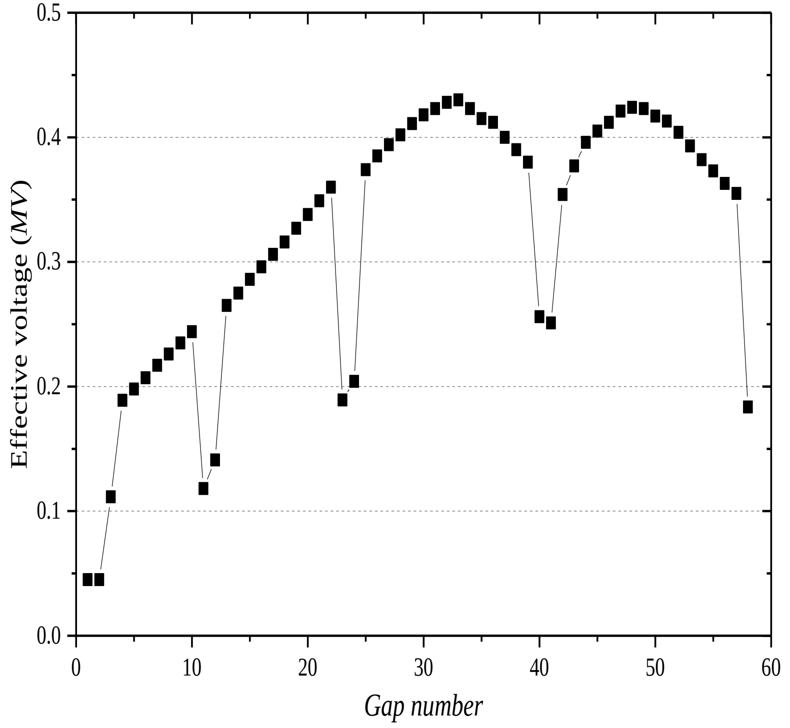


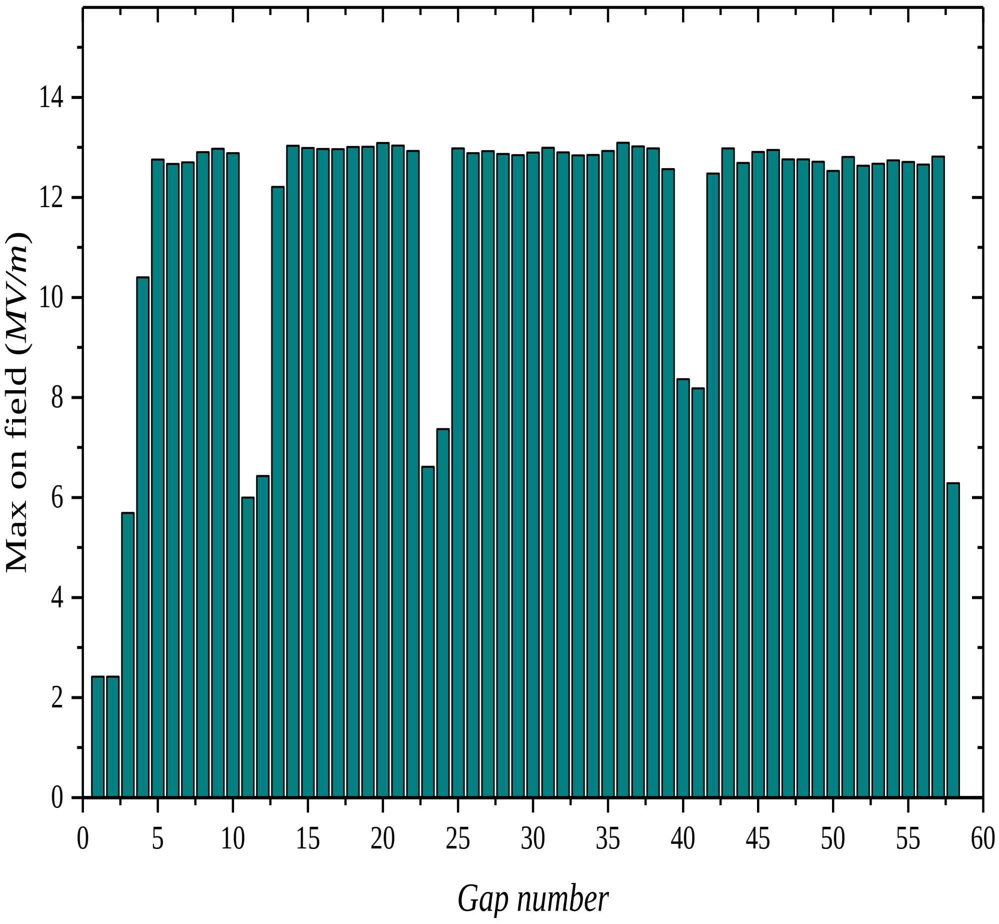
1.10
1.05
1.00
.95
.90
0
100
200
300
400
500
600
700
800
900
1000
1100
Beam Axis /cm
X-X′
Y-Y′
W-Z

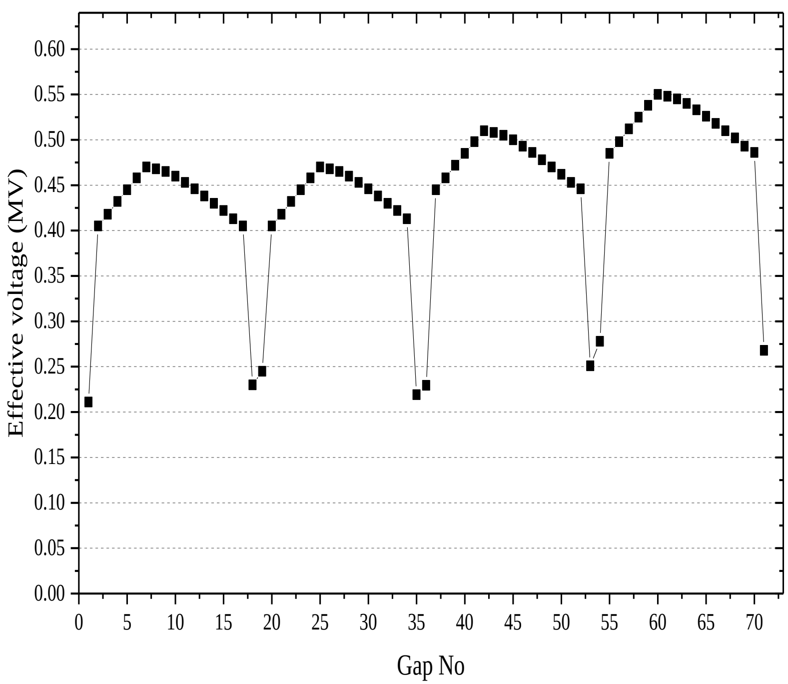


X-X'
Y-Y'
W-Z
Norm. rel.rms emittance growth
Beam Axis (m)
1.20
1.15
1.10
1.05
1.00
0.95
0
2
4
6
8
10
12
14
16

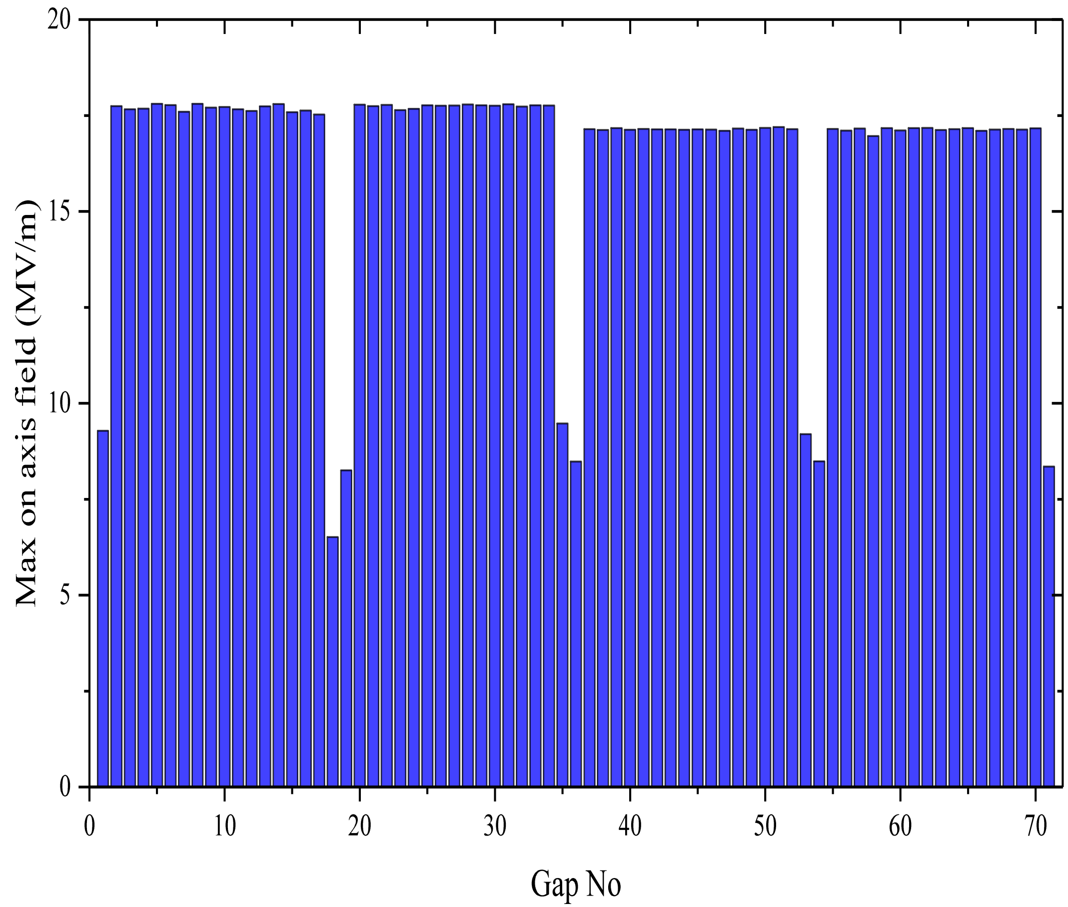
Voltage & Field





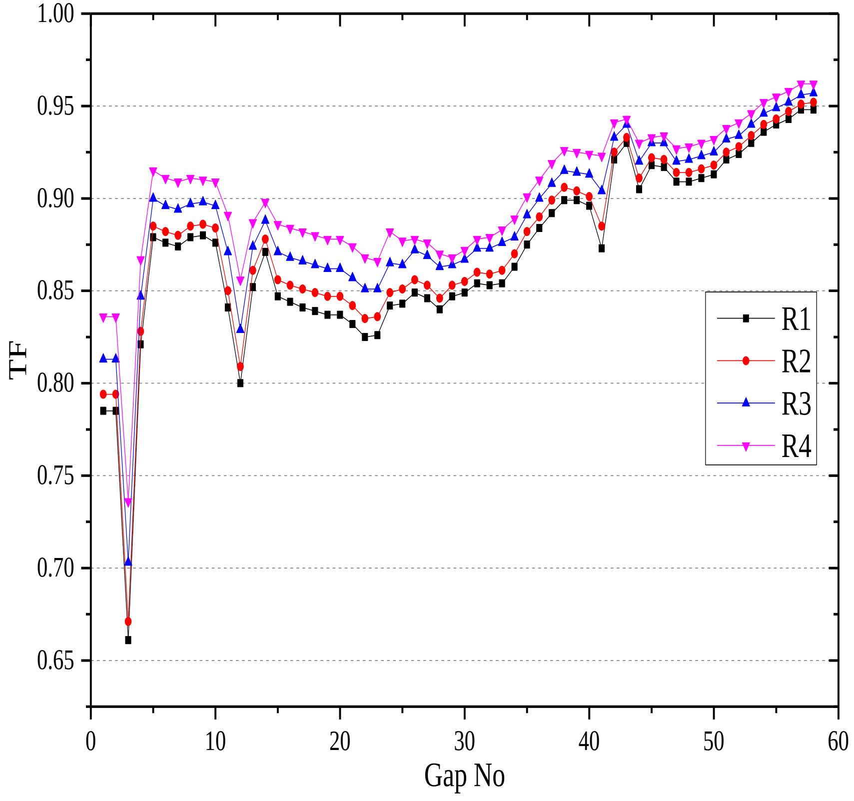


Effective voltage (MV)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Gap No



Max on axis field (MV/m)
0
5
10
15
20
0
10
20
30
40
50
60
70
Gap No

Transit Time Factor (TTF)



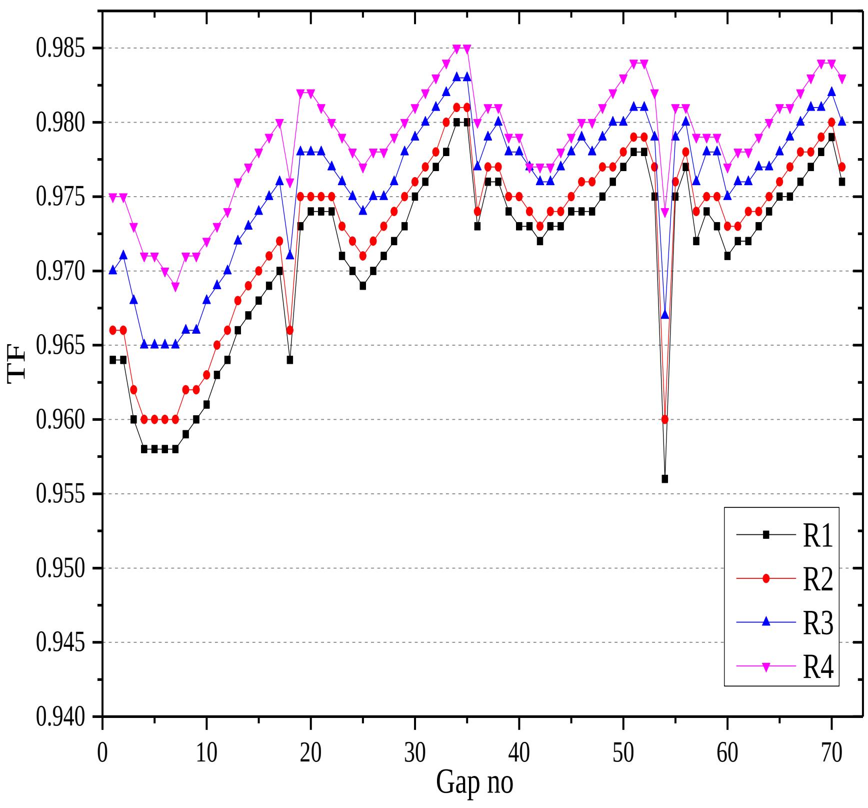
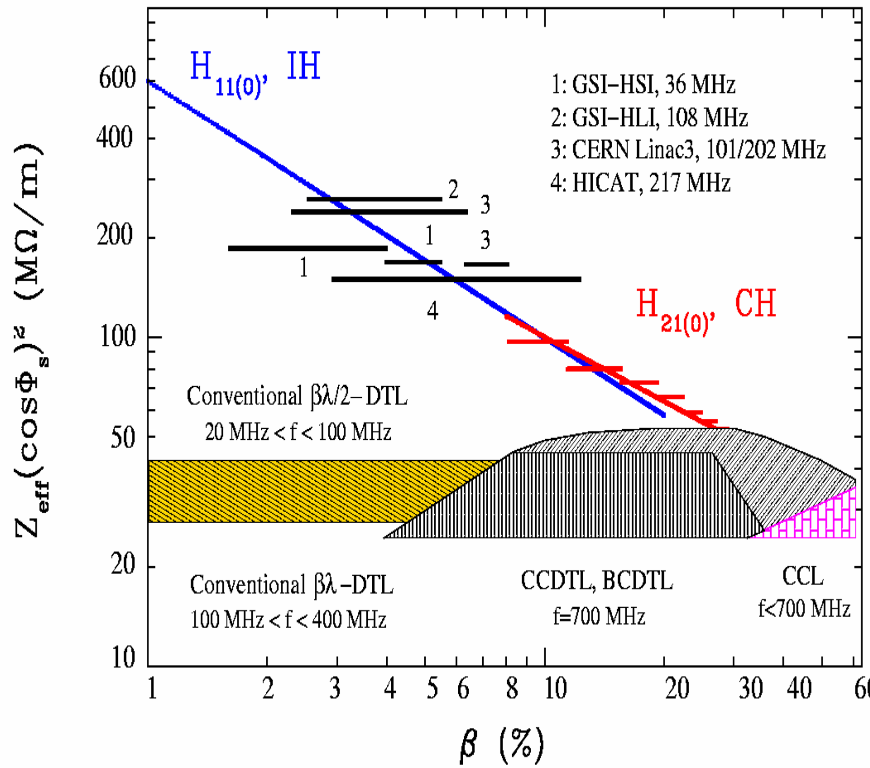


Table 1: Parameters of low-energy accelerating structures

Struct.	"Best" β	f, MHz	$Z_{sh}T^2$, MΩ/m
RFQ	$0.005 \leq \beta \leq 0.03$	4-rod: $10 \leq f \leq 200$ 4-vn: $100 \leq f \leq 425$	$\approx 1-3; \sim \beta^{-2}$
IH	$0.01 \leq \beta \leq 0.1$	$30 \leq f \leq 250$	$300 \rightarrow 150$
CH	$0.1 \leq \beta \leq 0.4$	$150 \leq f \leq 800$	$150 \rightarrow 80$
DTL	$0.1 \leq \beta \leq 0.4$	$\beta\lambda$: $100 \leq f \leq 500$	$25-50$

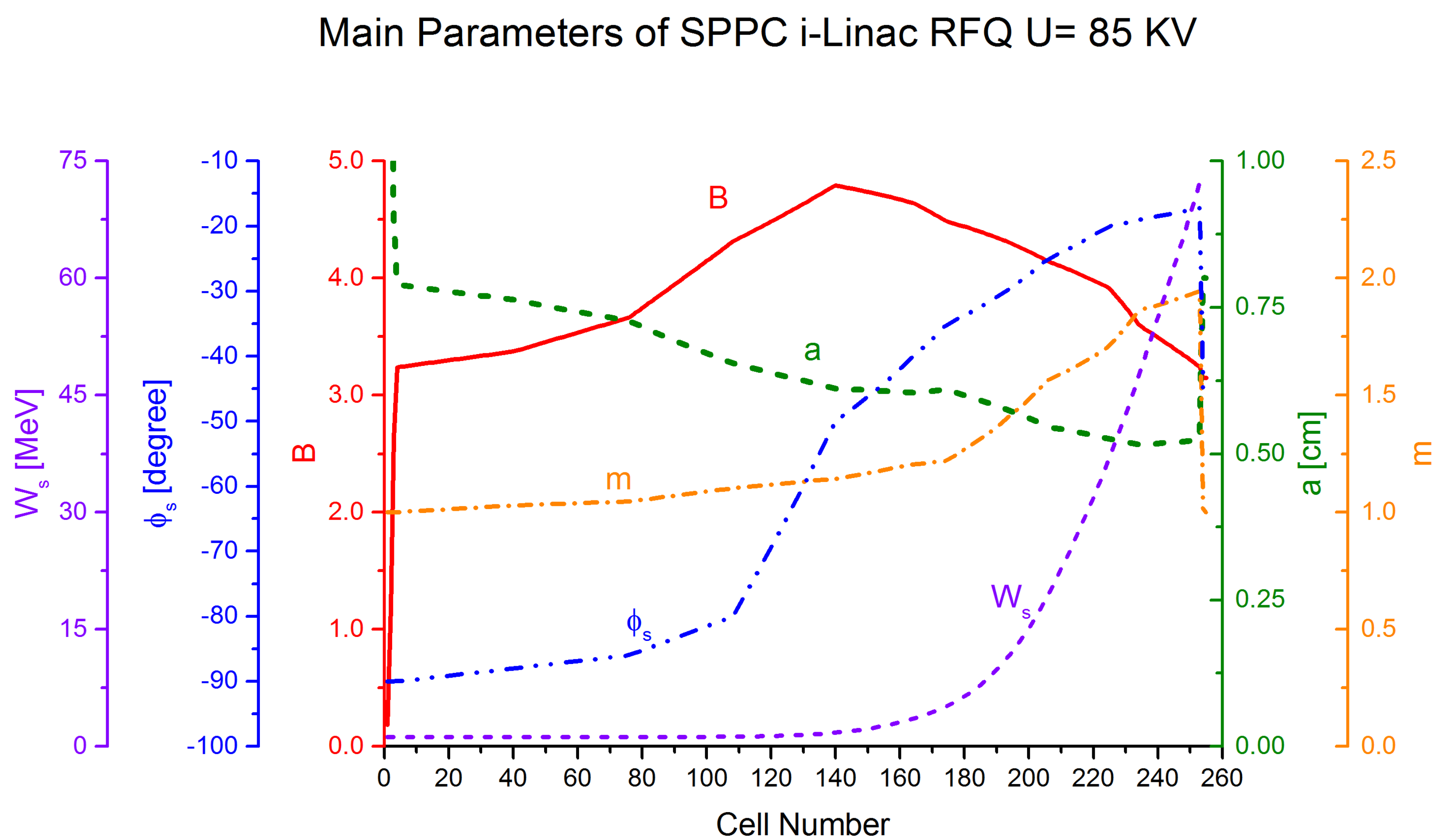


DTL1: CH , Z_{eff} =100MΩ/m, P=696KW

DTL2: CH, Z_{eff} = 60MΩ/m, P=771KW

DTL3: CH, Z_{eff} =52MΩ/m, P=1.06MW

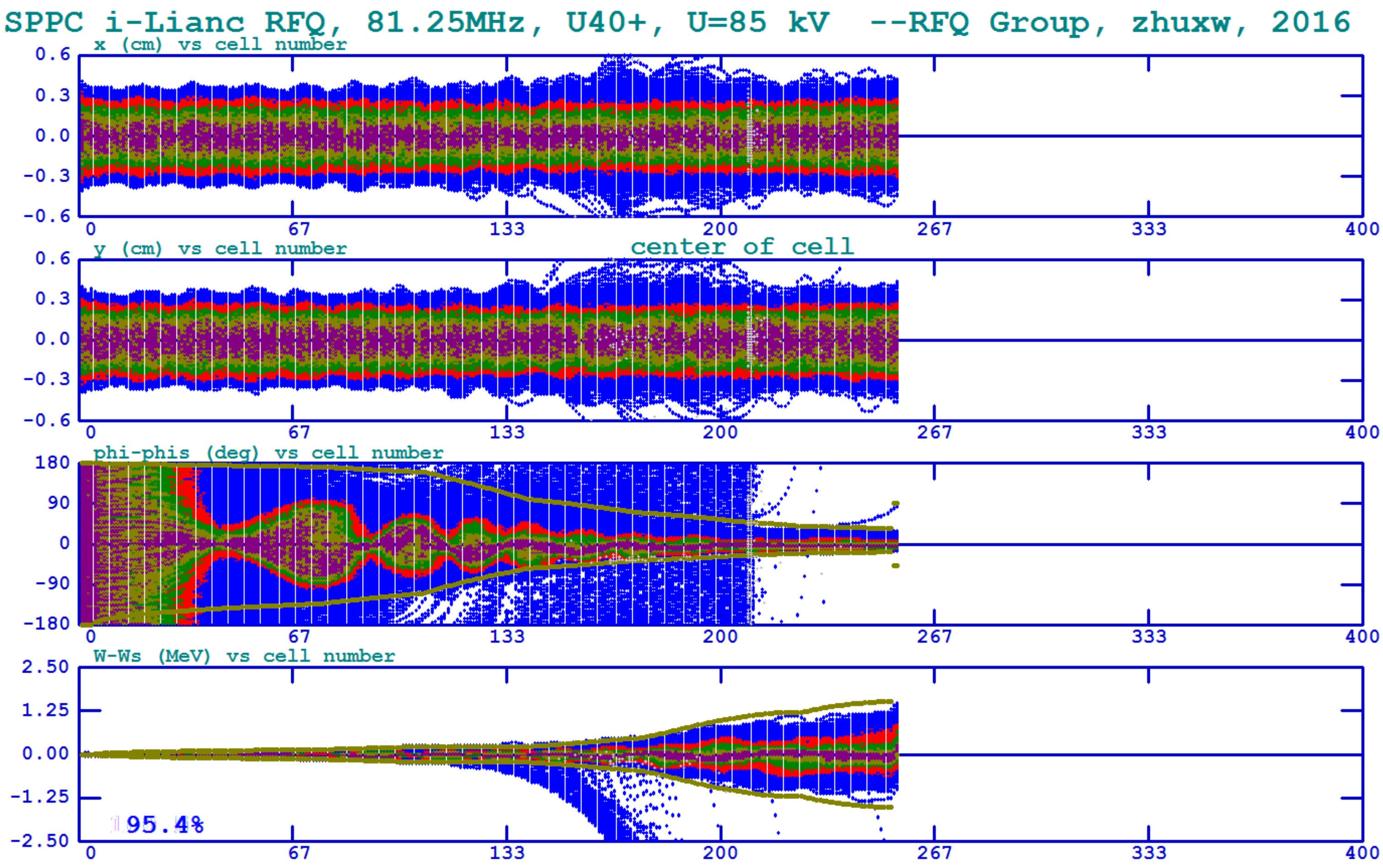
• SPPC i-Linac RFQ Main Parameters Versus Cell Number



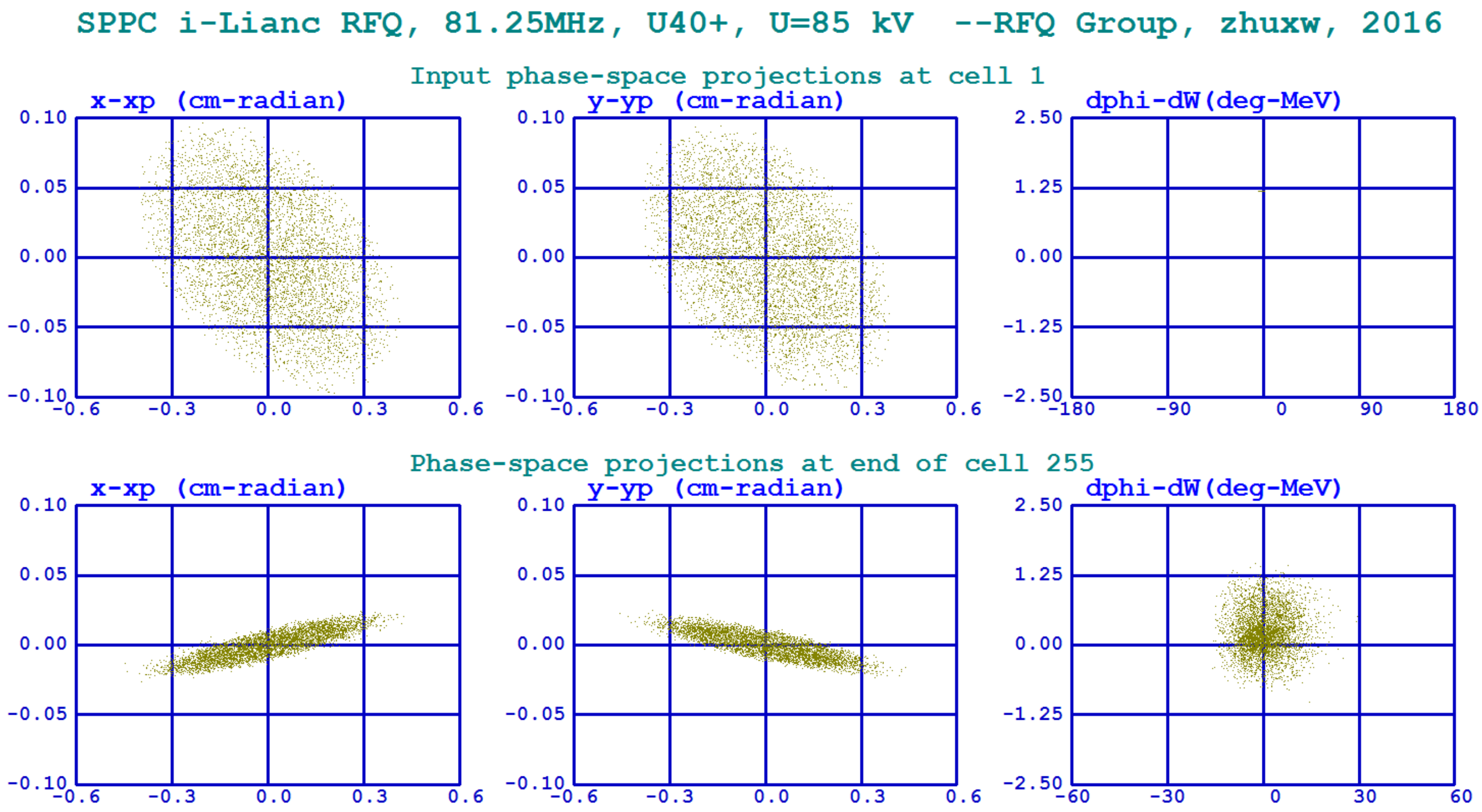
- SPPC i-Linac RFQ Beam Dynamics Parameters

Parameters	SPPC i-Linac RFQ
Particle	U40+
Frequency	81.25 [MHz]
Injection Energy	5 [AKeV]
Output Energy	300 [AKeV]
Beam Current	3 [emA]
Vane Length	3.487 [m]
Norm. RMS Input Emittance	0.2 [mm.mrad]
Vane Voltage	85 [KV]
Peak Surface Field	17.83 [MV/m] (1.69 Ek)
Aver. / Min. Aperture	5.871 / 5.161 [mm]
Transmission Efficiency	95.4% [88.8%, 6 emA]
Energy Spread	0.4%

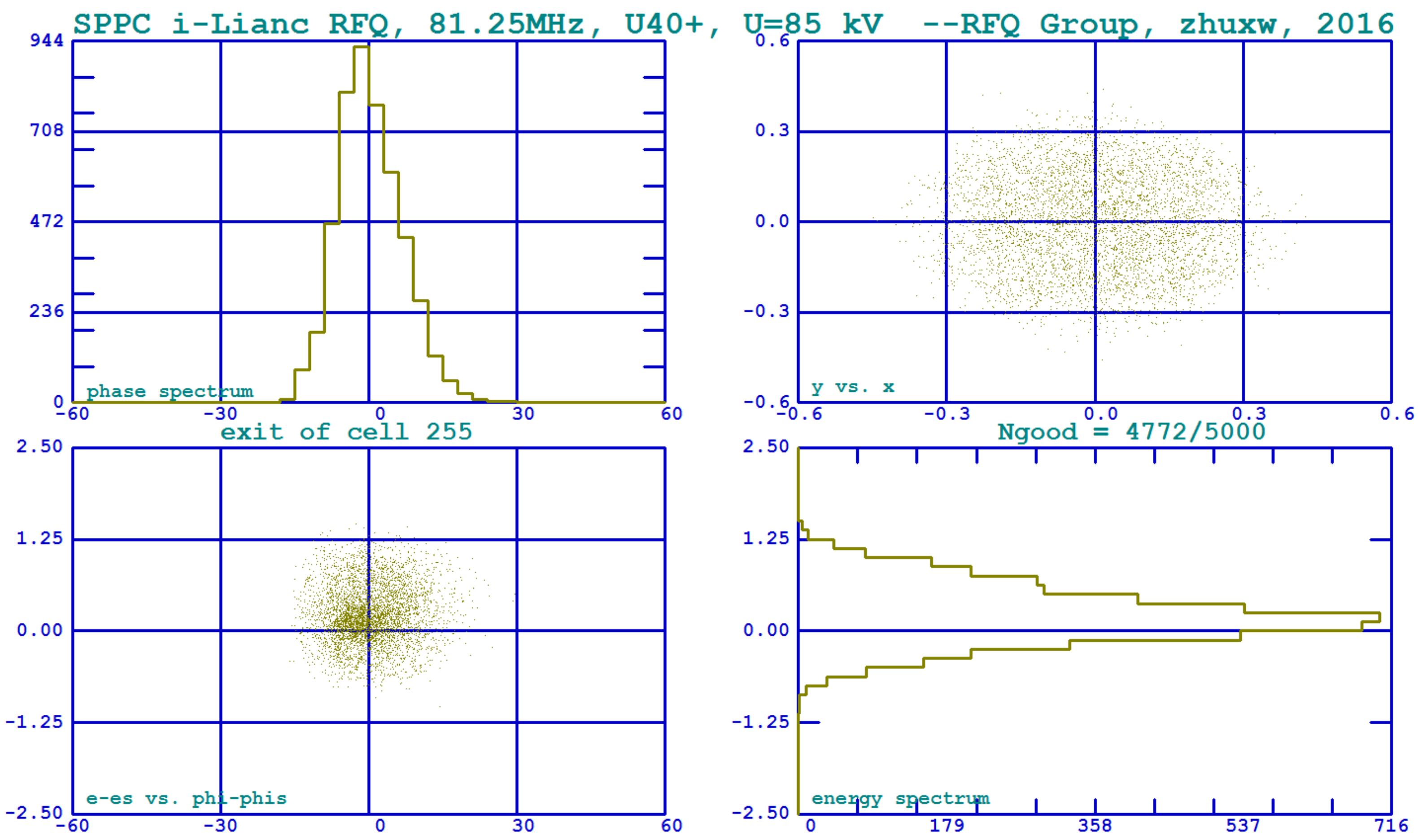
- SPPC i-Linac RFQ Beam Transport Simulation (1/3)



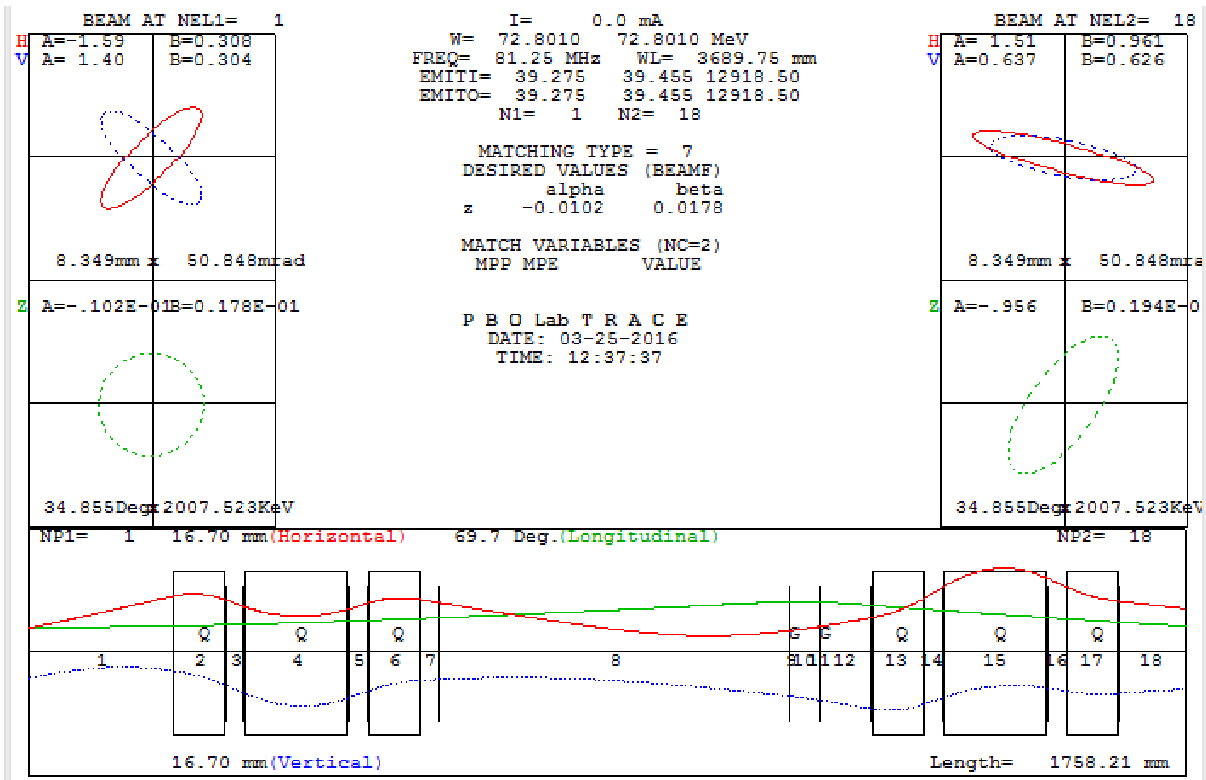
- # SPPC i-Linac RFQ Beam Transport Simulation (2/3)



- SPPC i-Linac RFQ Beam Transport Simulation (3/3)



• The MEBT Design between RFQ Exit and IH-DTL

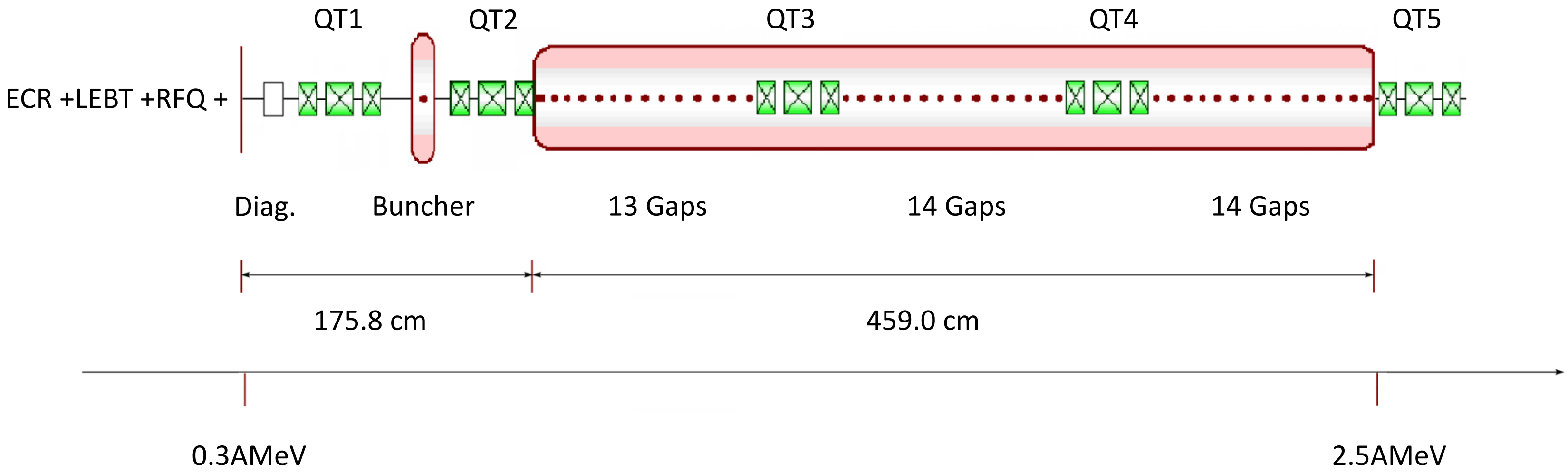


Diagnostics | QT1 | Drift | Buncher | QT2 | Drift

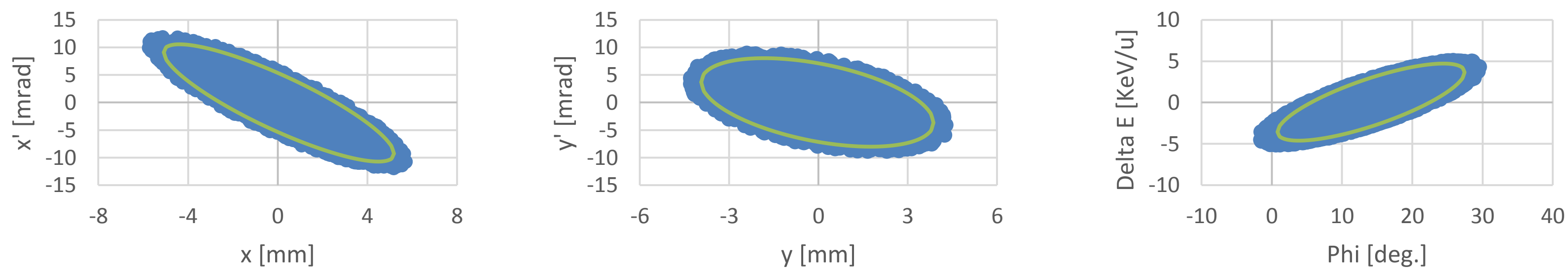
RFQ Exit — DTL Entrance

	QT1		Buncher		QT2
DIA.	20 mm	EFF. GAP Volt.	0.043 MV	DIA.	20 mm
EFF. LGTH.	80, 160, 80 mm	PHASE of RF	-90 Deg.	EFF. LGTH.	80, 160, 80 mm
FIELD GRAD.	3950, -3100, 3405 G/cm			FIELD GRAD.	-3594, 2534, 2215 G/cm

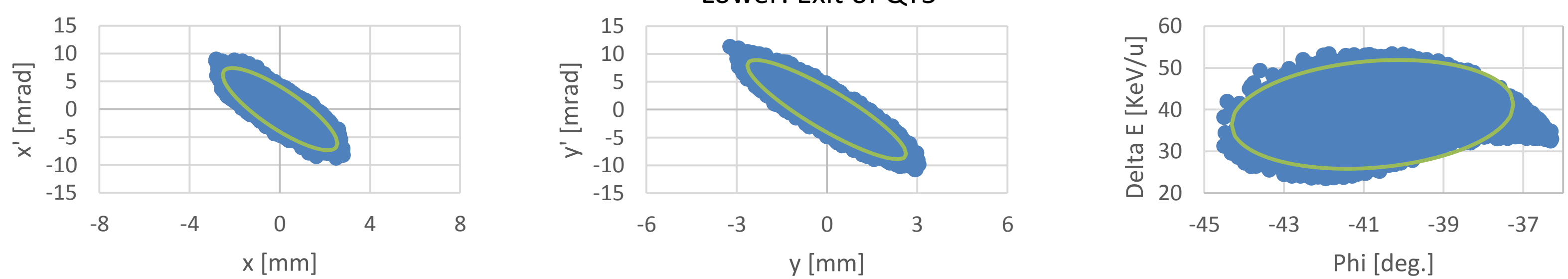
• Schematic Layout of IH-DTL for SPPC i-Linac



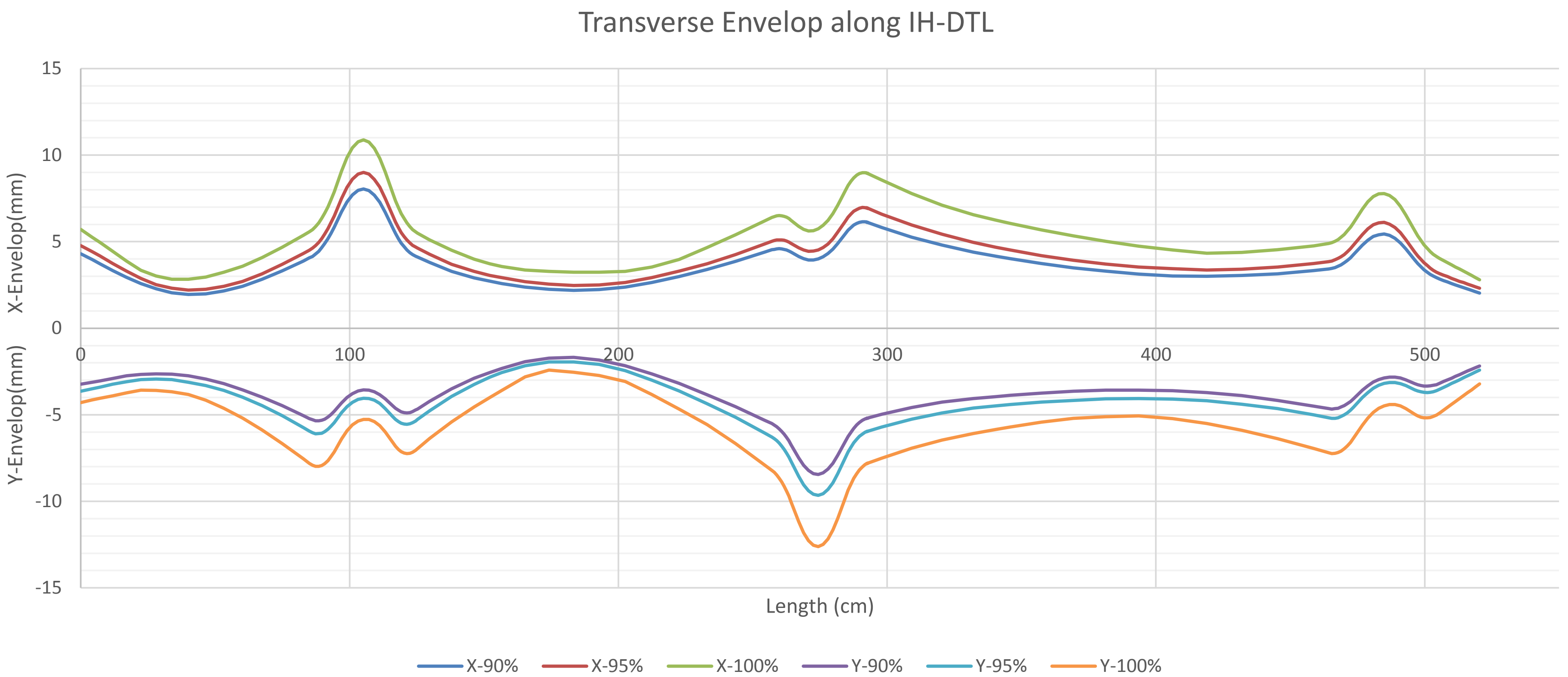
Upper: Exit of QT2



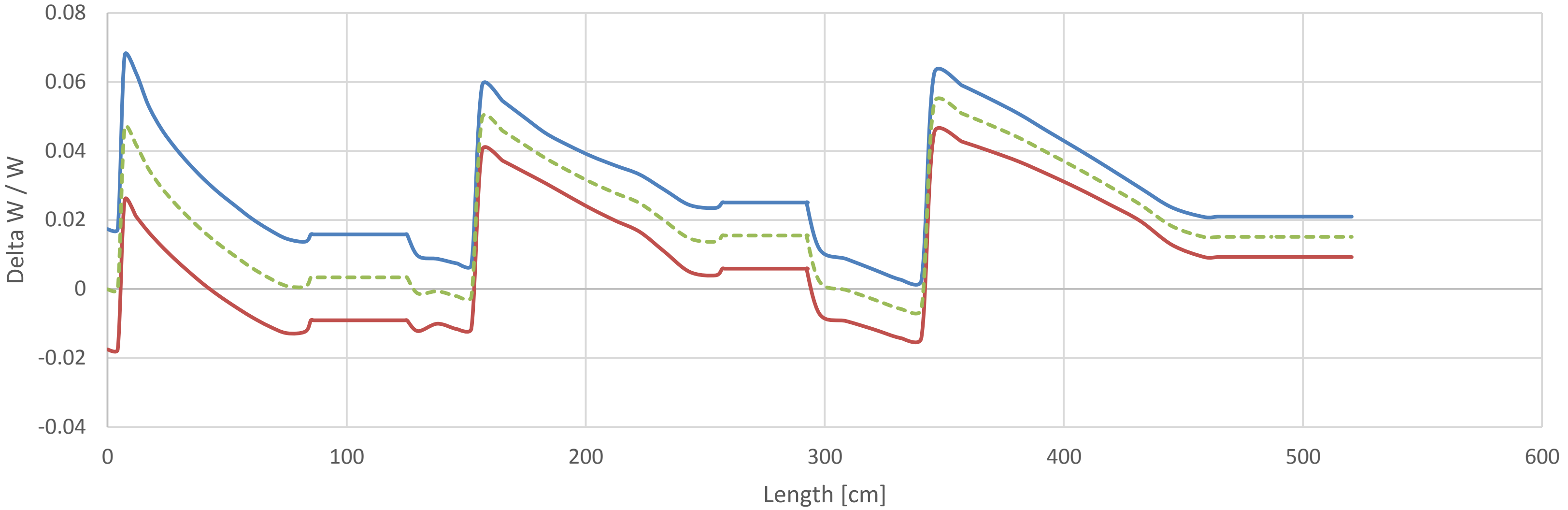
Lower: Exit of QT5

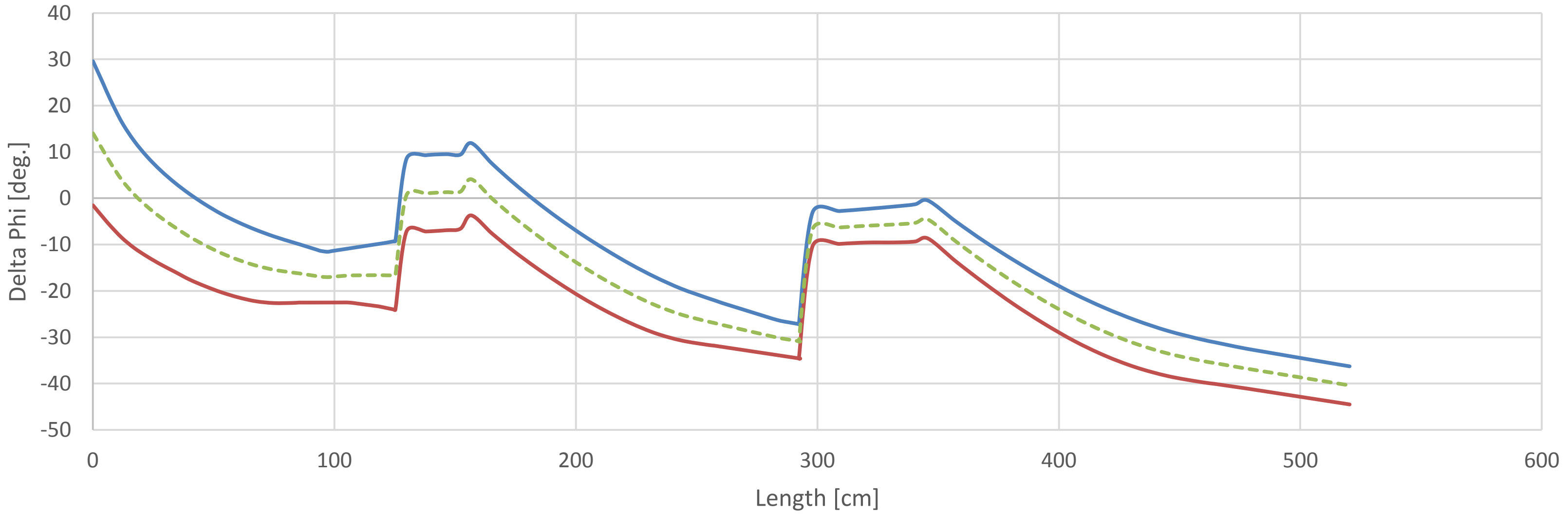


- The Transverse 90%, 95%, 100% Envelops along IH-DTL

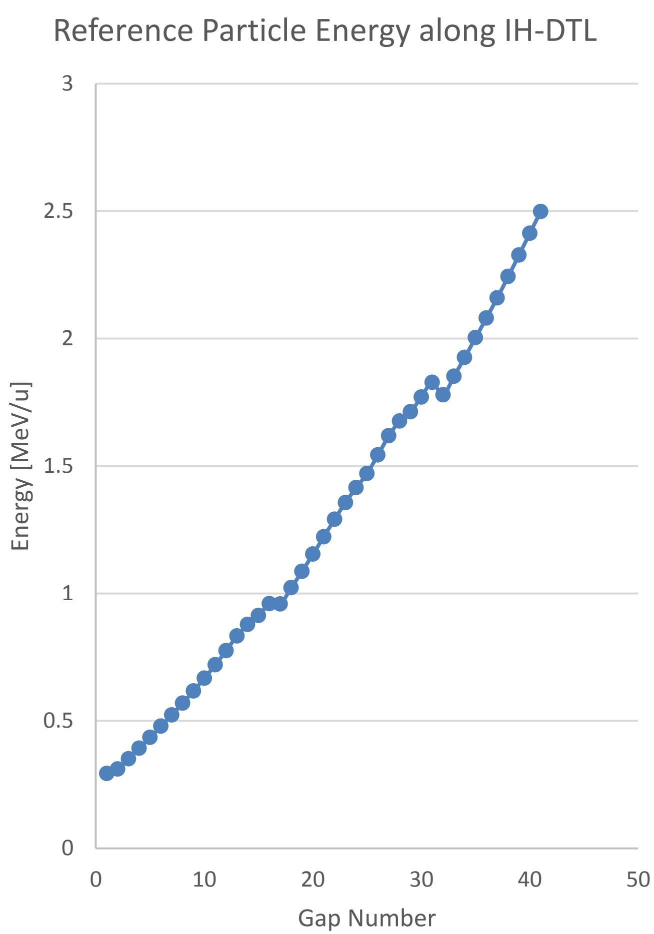


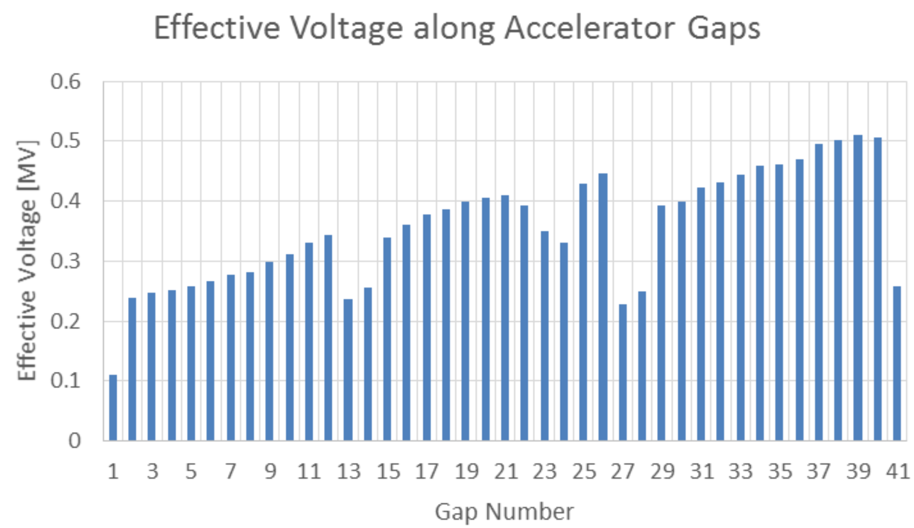
- The Longitudinal Envelops along IH-DTL

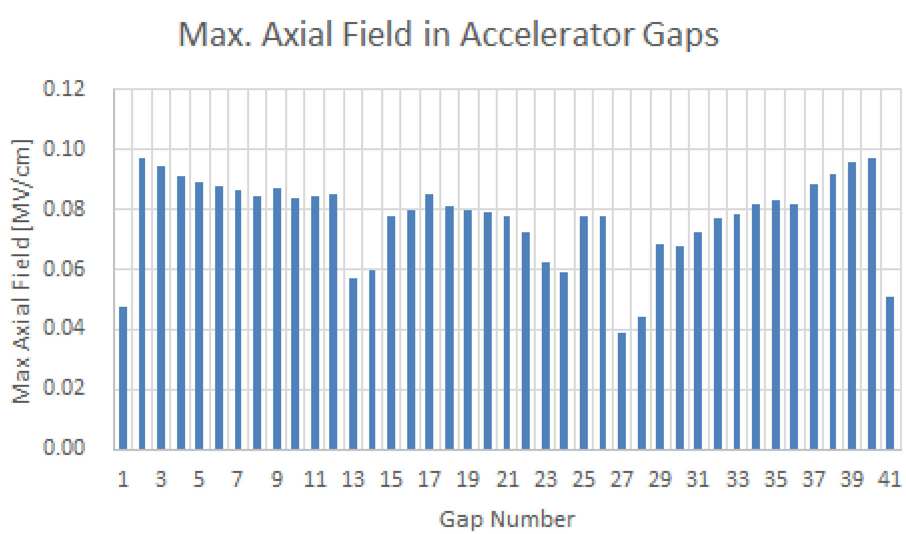




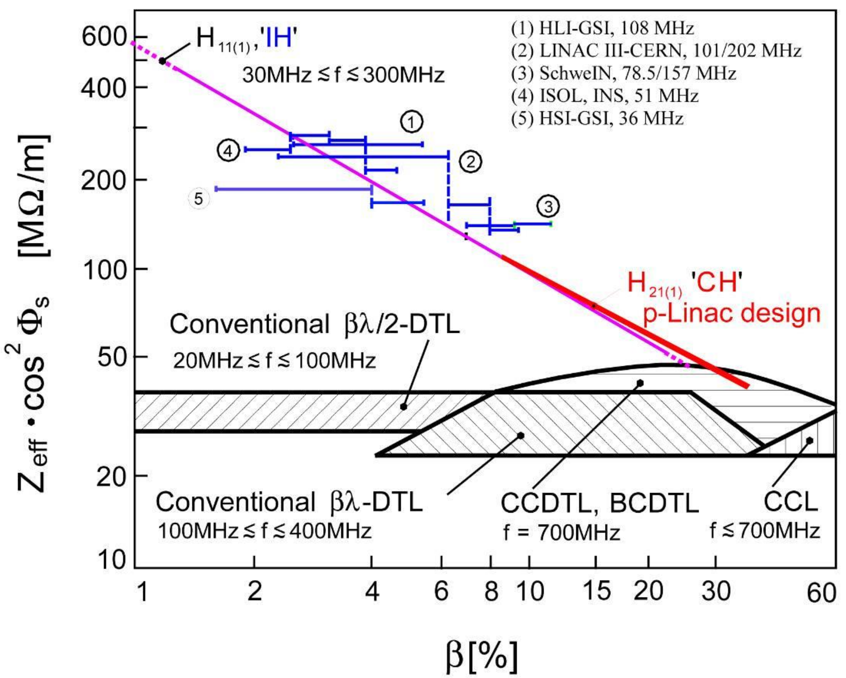
- The Synchronous Particle Energy, Effective Voltage & Max. Axial Field along IH-DTL

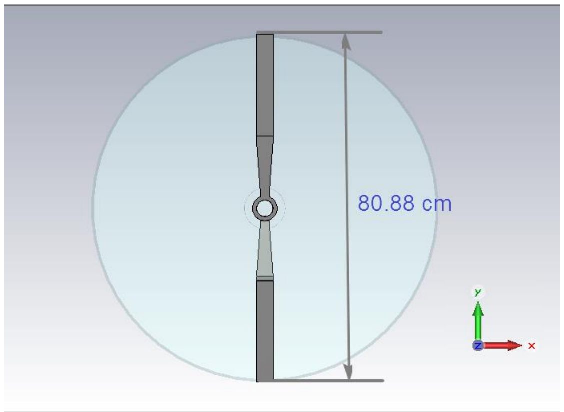






- # Cavity Loss Estimation of The IH-DTL & Cavity Dimension



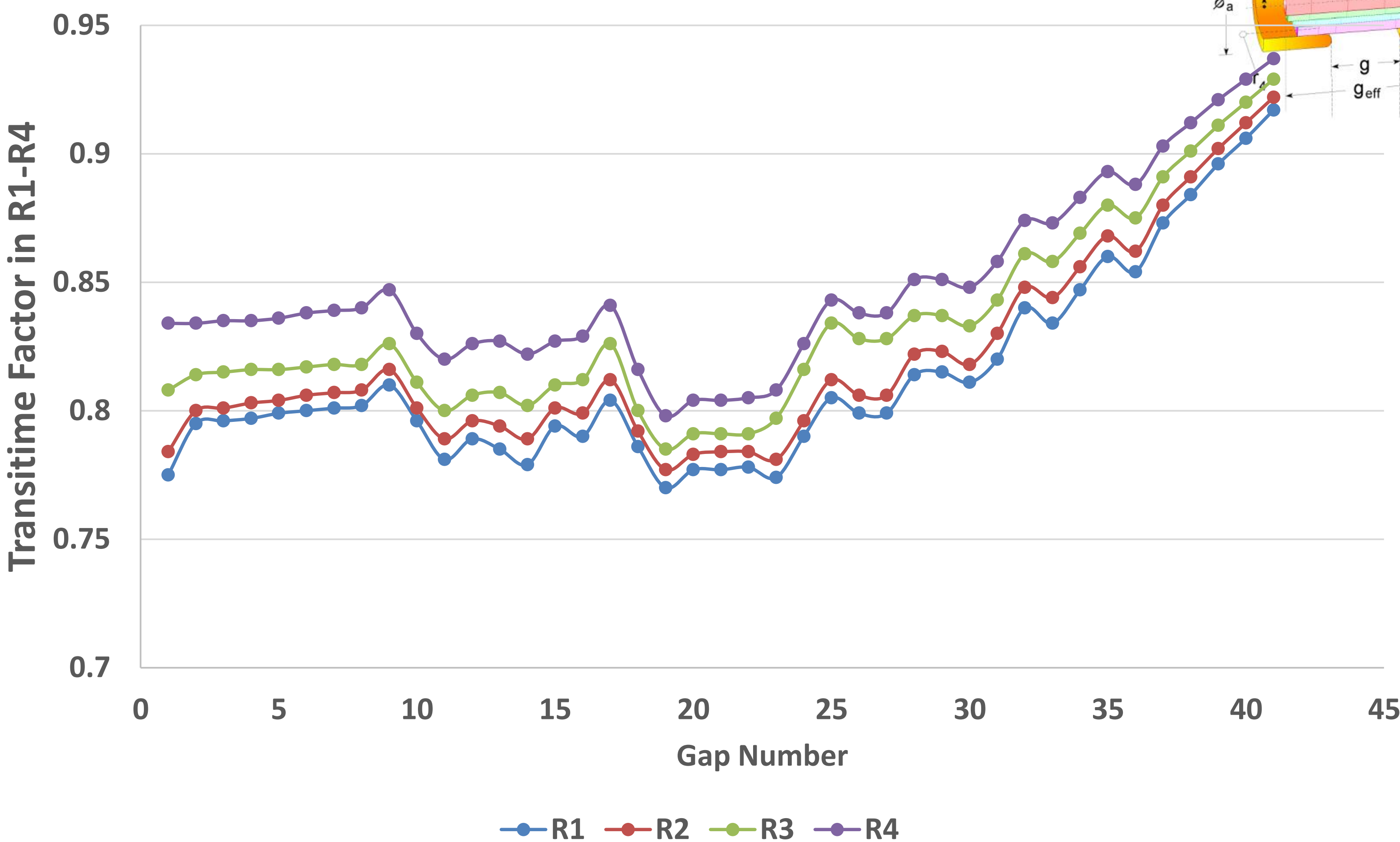


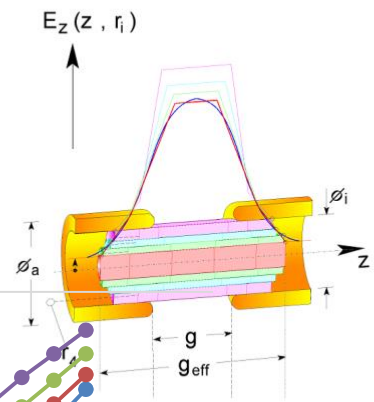
- By interpolation, the product $Z_{eff} \cdot Cos^2\varphi_s$ could be calculated for each gap;
- The total cavity power consumption is about 340 KW;
- With intrinsic Q value of 29000 and L/D ~ 6 (4.58 m / 0.88 m), from CST MWS Simulation, which benefit from less power consumption & easier tuning;

- Where

$$Z_{eff} \cdot Cos^2\varphi_s = \frac{V_{gain}^2}{P_{loss} \cdot L_{tank}}$$

- Transit Time Factor in R1-R4





Conclusions

- Proton RFQ , 325MHz, 40mA, 0.05MeV/3.02MeV, 85kV, 3.61m, 98.5%
- Proton DTL linac, 3 cavities, Length 19m, 50MeV, RF Power about 2.5MW (peak),100% Transmission
- Heavy Ion RFQ , U40+, 81.25MHz, 5-300AkeV, 3.5m. Heavy Ion DTL , 0.3AMeV~2.5AMeV , Total length is about 10.0m. Less emmittance growth, good transmission, less power consumption.


谢谢大家！