# Re-Design of the Ultra-low Energy Storage Ring USR

**Dr. Alexander I. PAPASH**

QUASAR Group (www.quasar-group.org)

E-mail: Alexander.Papash@quasar-group.org

# ABSTRACT

- In the future Facility for Low-energy Antiproton and Ion Research (FLAIR) at GSI, the Ultra-low energy electrostatic Storage Ring (USR) will provide cooled beams of antiprotons and possibly also highly charged ions down to energies of 20 keV/q

- Possible opertion at lower energies is being investigated

- A large variety of the envisaged experiments demands a very flexible ring lattice to provide a beam with variable cross section, shape and time structure, ranging from ultra-short pulses to coasting beams

- The preliminary design of the USR worked out in 2005 was not optimized in this respect and had to be reconsidered

- The final layout of the USR with a focus on its “split-achromat” geometry, and the combined fast/slow extraction is presented here

## Part 1

# USR Lattice and Ring Parameters

# INTRODUCTION

- In the future Facility for Low-energy Antiproton and Ion Research (FLAIR) at GSI, the Ultra-low energy electrostatic Storage Ring (USR) will provide cooled beams of antiprotons in the energy range from 300 to 20 keV and probably (under discussion) down to 1 keV (e-cool not available at lowest energies)
- highly charged ions down to E=20*Q/A keV/A and even lower energies might be possible (optional if vacuum is better than P~$10^{-13}$ Tor and decision will be made to build cryogenic version of USR like CSR at MPI)
- light ions could be available in the room temperature ring (P~$10^{-11}$ Tor) (depends on decision of scientific community)
- Different modes of USR operation -- e-cool, bunch-debunch with longitudinal Phase Space "gymnastics", deceleration, in-ring experiments, fast/slow extraction are foreseen
- A large variety of the envisaged experiments demands a very flexible ring lattice to provide a beam with variable cross section, shape and time structure, ranging from ultra-short pulses to coasting beams
- The preliminary design of the USR worked out in 2005 was not optimized in this respect and had to be reconsidered
- Modified layout of the USR Lattice is based on "split-achromat" geometry which allows maximum flexibility to satisfy different operation options

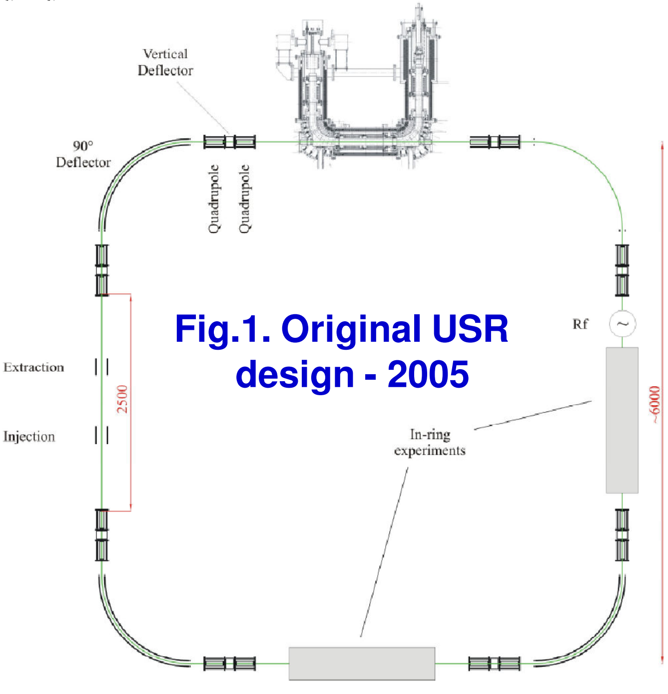


Fig.1. Original USR design - 2005

Fig. 4: Overview of the USR

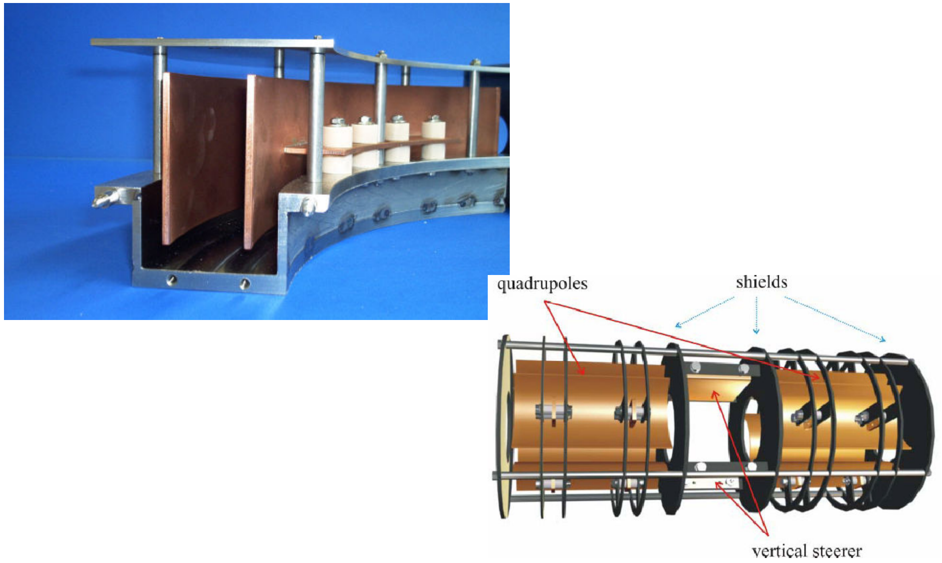


Fig.2 Original version of ESD and ESQ doublet

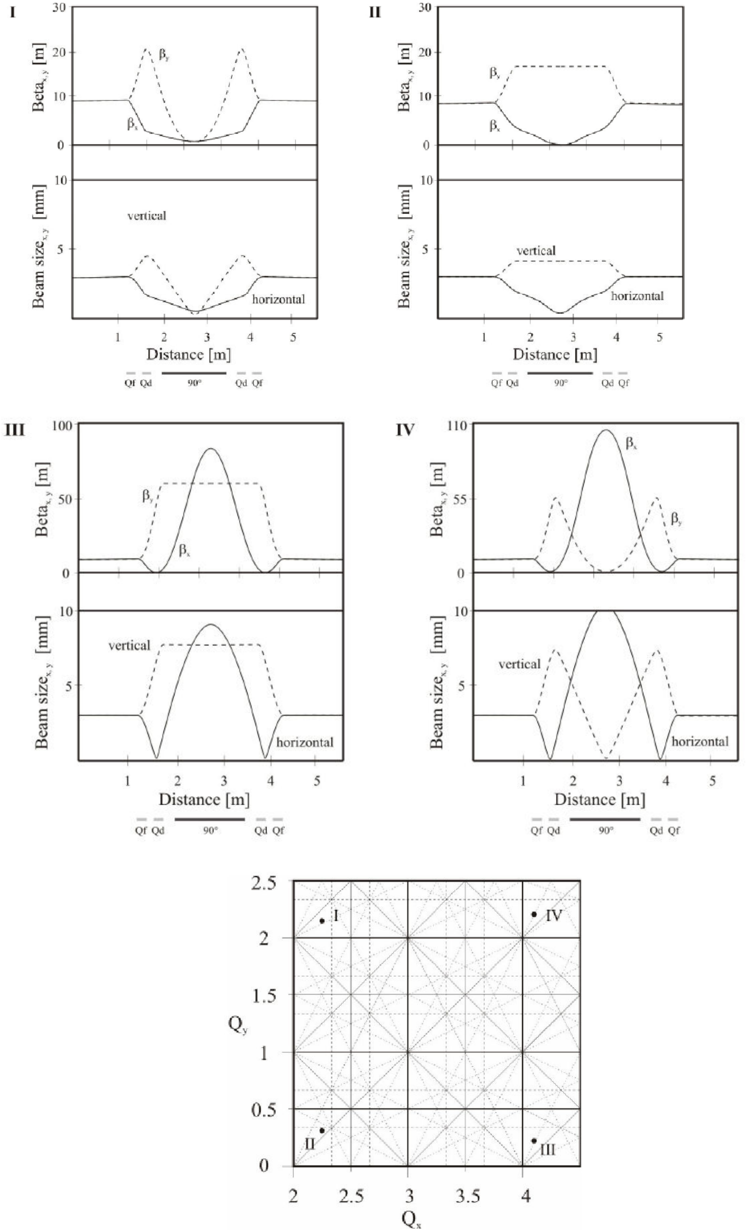
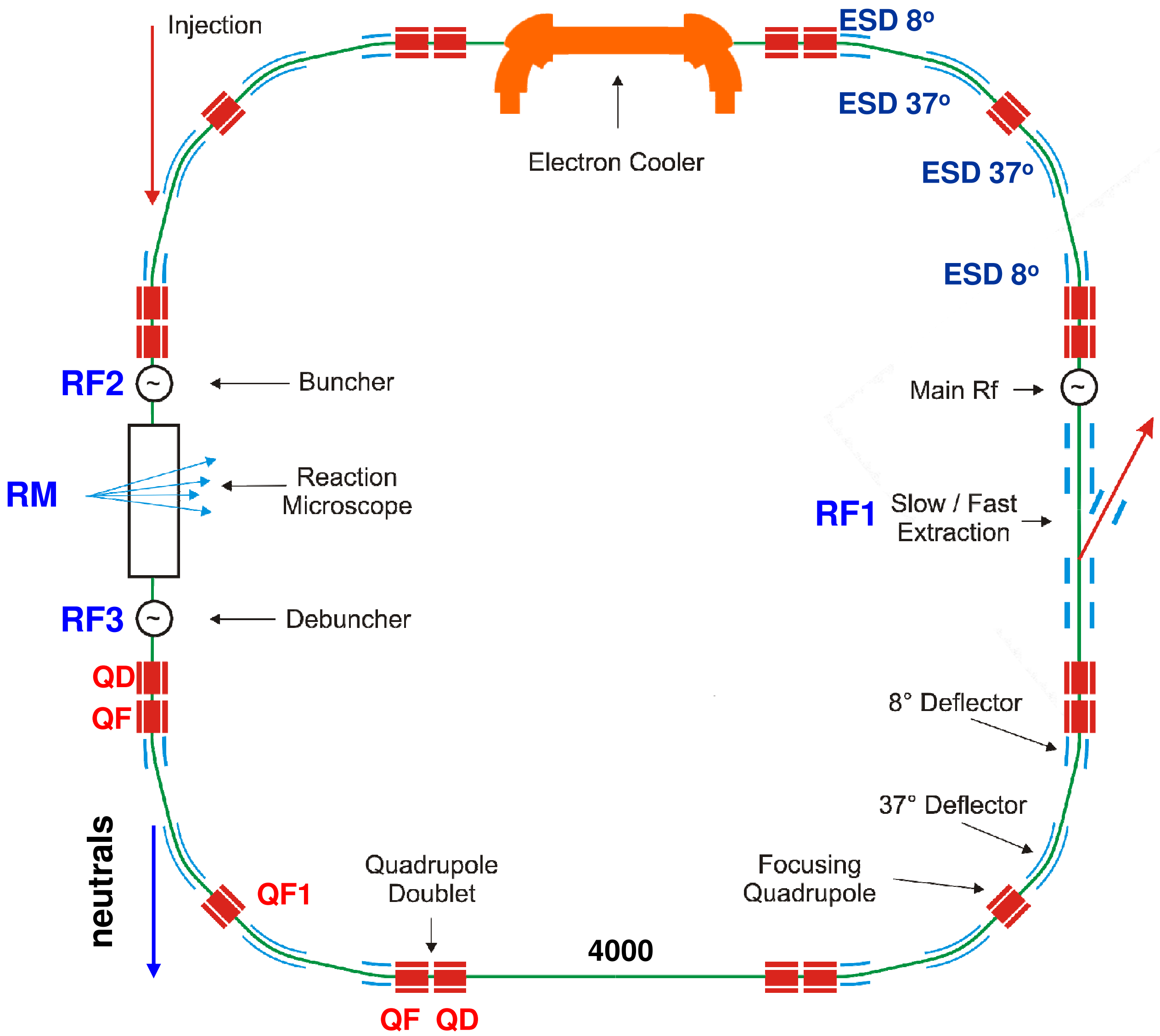


Fig.3. Betatron tunes and beta-functions of original version of the USR Lattice -2005 (90-degree ESD bend)



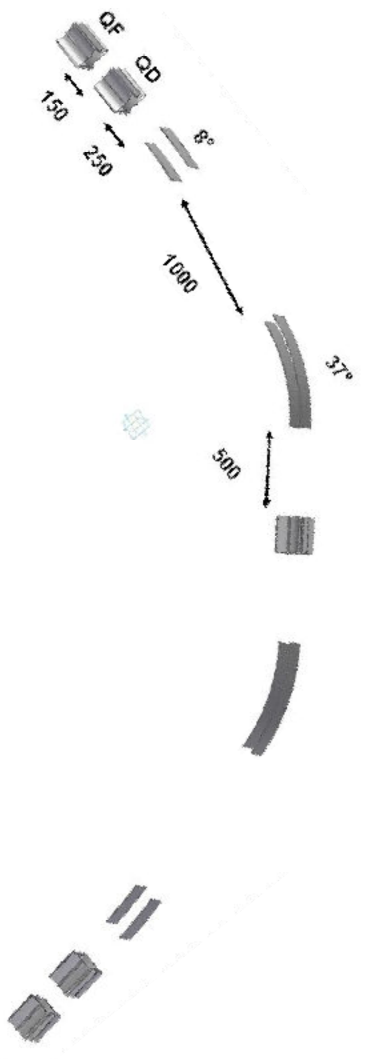
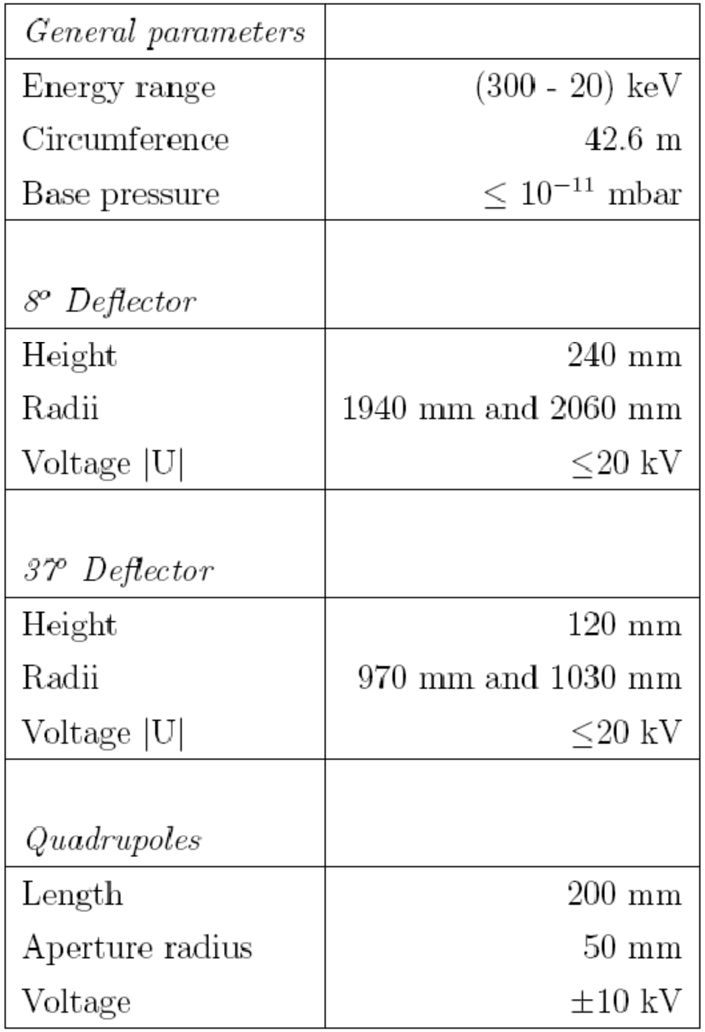


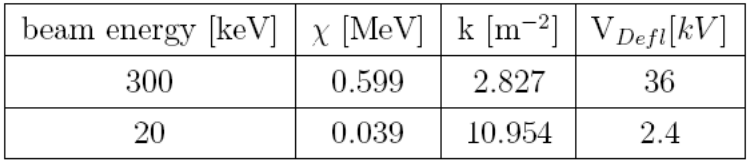
**Fig.4. Layout of USR Ring. Modified design 2008-2009. Location of RF cavities for short pulse operation mode is shown as was used in MAD-X input for simulations of ultra-short bunch operation mode**

**Fig.5. USR corner Section. Split Achromat Cell. Measurements of neutrals is avaiable with open angle ±0.7°**

# Table 2. The USR ES Deflectors and ES Quads paraemters



| *General parameters* | |
|---|---|
| Energy range | (300 - 20) keV |
| Circumference | 42.6 m |
| Base pressure | $\leq 10^{-11}$ mbar |
| *8° Deflector* | |
| Height | 240 mm |
| Radii | 1940 mm and 2060 mm |
| Voltage \|U\| | ≤20 kV |
| *37° Deflector* | |
| Height | 120 mm |
| Radii | 970 mm and 1030 mm |
| Voltage \|U\| | ≤20 kV |
| *Quadrupoles* | |
| Length | 200 mm |
| Aperture radius | 50 mm |
| Voltage | ±10 kV |



| beam energy [keV] | $\chi$ [MeV] | k [$m^{-2}$] | $V_{Defl}[kV]$ |
|---|---|---|---|
| 300 | 0.599 | 2.827 | 36 |
| 20 | 0.039 | 10.954 | 2.4 |

## The USR ring consists of two sets of ESD

- 8 ° cylinder deflectors
- central bending radius of *R=2 m*,
- plate distance of *d=120 mm*,
- *U=±18 kV voltage applied to plates*.

- The main 37 ° deflection is realized by deflector with
- *R=1 m*,
- d*=60mm*,
- and same voltage U=±18 kV

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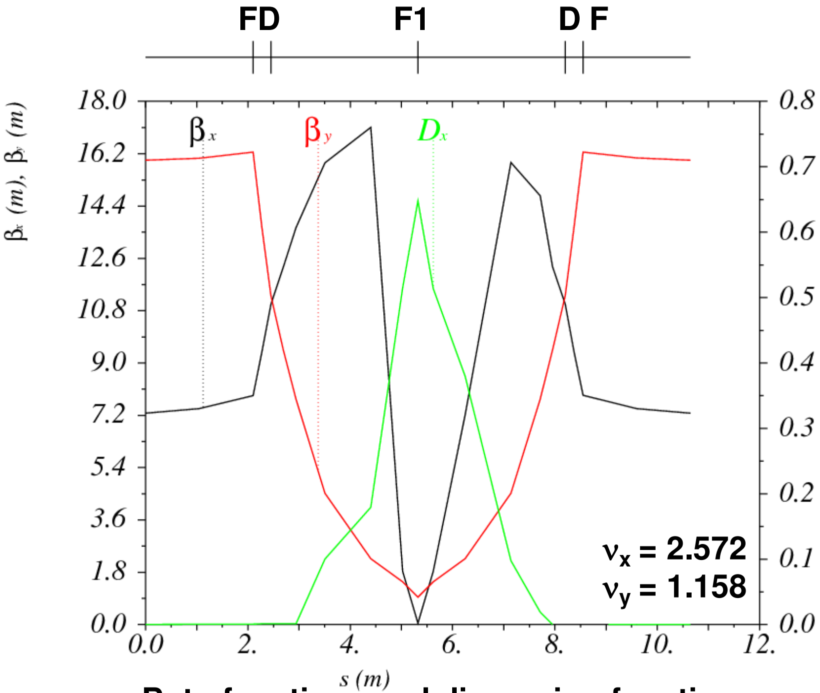
Transverse beam modulation is done with electrostatic quadrupoles with

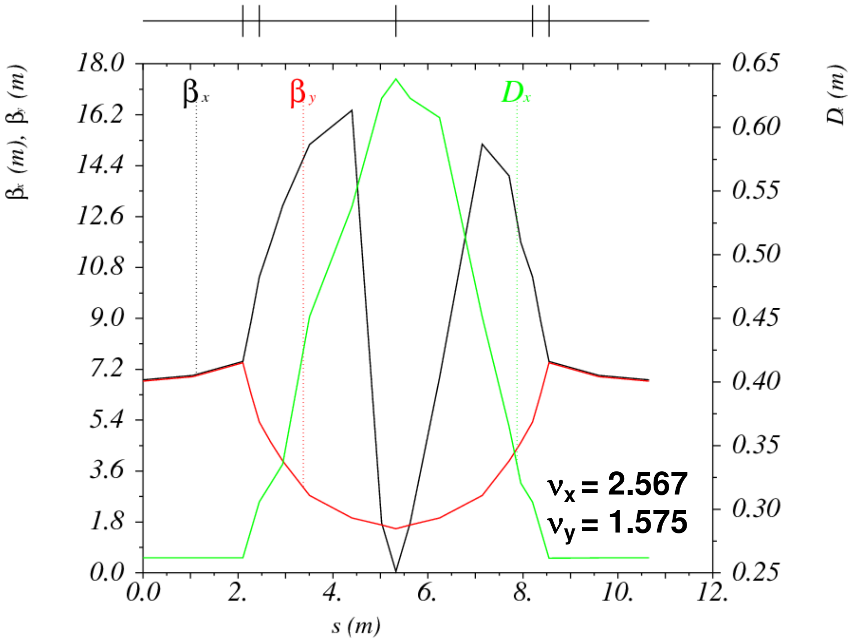
- $R_{ap}$*=100 mm*
- an effective length $L_{eff}$*=200 mm*.
- The voltages that are required
- to focus 300 keV pbars are
- *U1=-6.1 kV*,
- *U2=+4.4 kV*,
- and *U3=+6.35 kV*.

**Fig.6a. USR cell. MAD-X**
**Achromat Mode. D=D'=0**



**Beta-functions and dispersion function in one ring quarter. This achromatic mode is used during short bunch operation.**

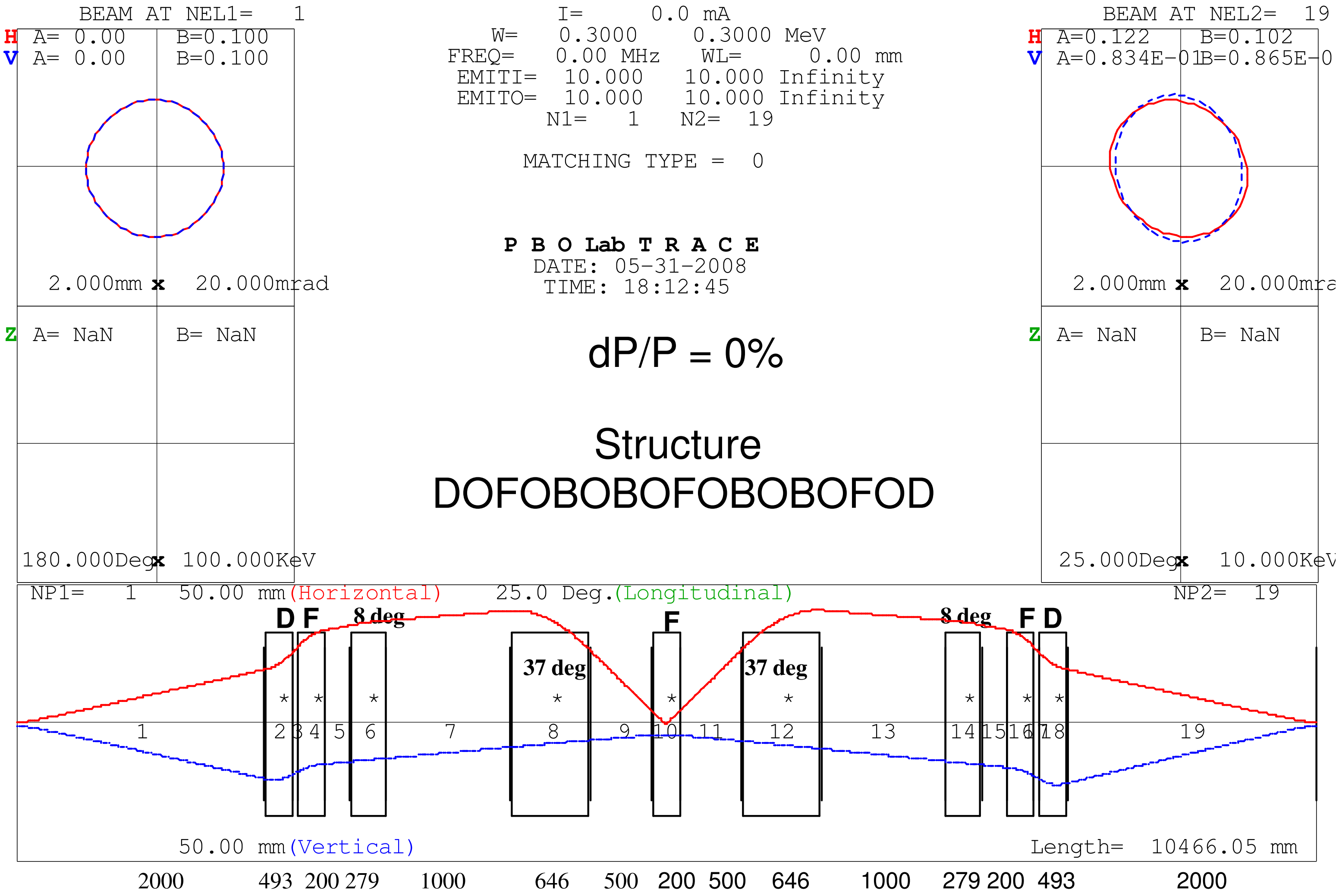
**Fig.6b. USR cell. MAD-X**
**„Round Beam“ Mode $\beta_X = \beta_Y$**



**Beta-functions and dispersion function in one ring quarter. This "round beam" mode is used during injection, fast extraction, cooling and deceleration.**

- **Dispesrion might be adjusted from +1m to -0.5 m by variation of QF1 strength**
- **D=D'=0 (achromat) mode availabe in all 4 m long straight sections**
- **Axial betatron tune increased from 1,158 to 1,67 if QF1 voltage is reduced to ZERO**
- **DOUBLET Mode is available (QF1=0)**
- **Split bending sections allows operation with neutrals (open angle ±0.7$^{O}$)**
- **Split achtromat Lattice support short bunch operation mode**
- **Split short ESD sections minimize non-linear coupling effects between transverse and longitudinal motion**

# USR Lattice - One cell. QQ+8+37+Q+37+8+QQ (incl. Fringe Field) TRACE3D



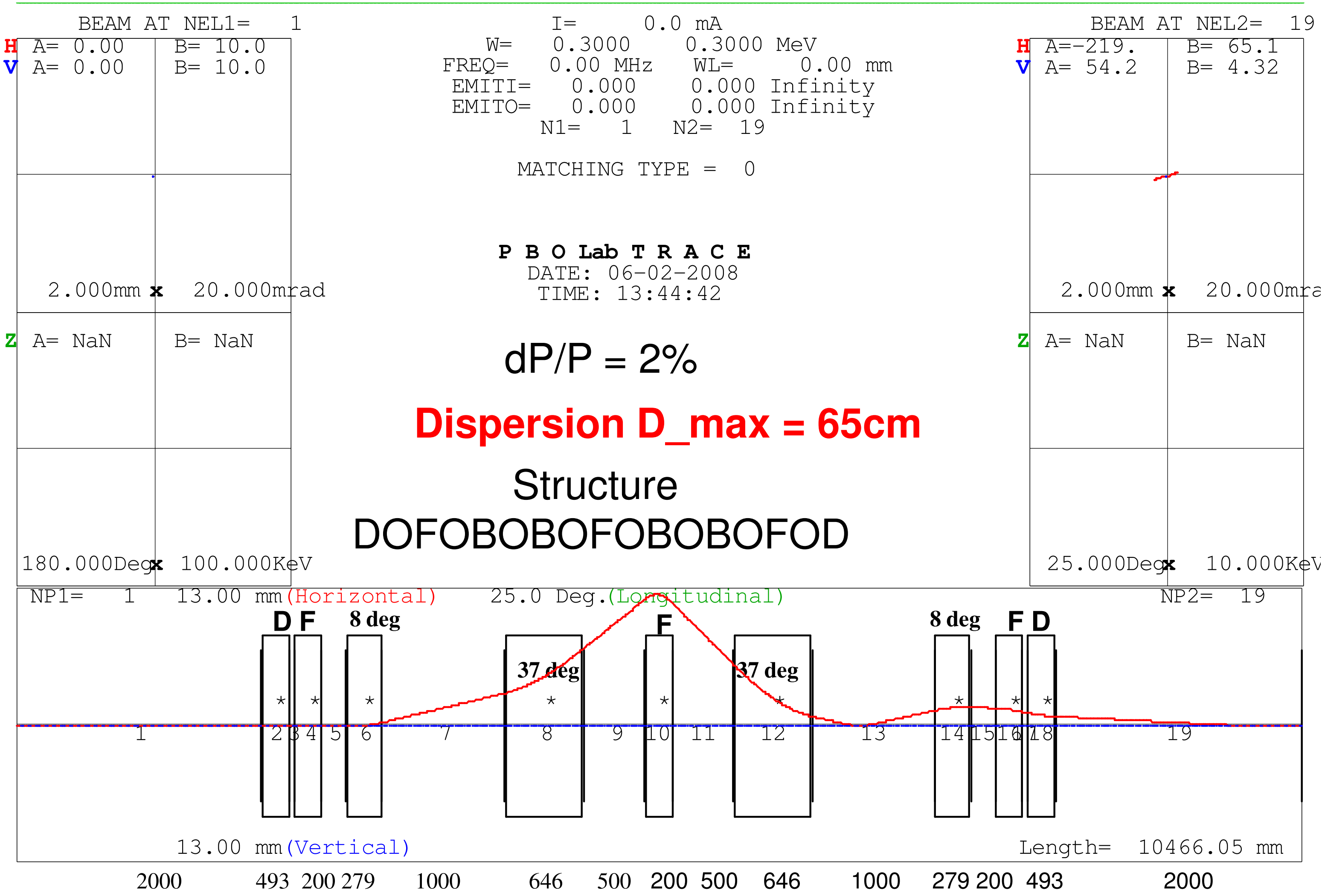
dP/P = 0%

Structure
DOFOBOBOFOBOBOFOD

**Fig.7a.** E = 300 keV. A = 1. Momentum Spread **dP/P= 0.00%.** Start Beam size : X = 1 mm, X‘ = 10 mrad.
**ESD 8 deg :** R=2000 mm, aperture = 12cm. **ESD 37deg**: R=1000 mm, apert = 60 mm, **(incl.fringe field)**
**ES_Quads**: L= 200 mm, 2R(aperture)=100 mm **(incl. fringe field)**
U1 = – 6.1 kV U2 = + 4.399 kV U3 = + 6.35 kV

TRACE3D simulations

# USR Lattice. QQ+8+37+Q+37+8+QQ (incl. Fringe Field) „TRACE3D“



```
      BEAM AT NEL1=    1                    I=      0.0 mA                          BEAM AT NEL2=   19
H  A= 0.00    B= 10.0              W=    0.3000     0.3000 MeV               H  A=-219.    B= 65.1
V  A= 0.00    B= 10.0           FREQ=    0.00 MHz    WL=      0.00 mm        V  A= 54.2    B= 4.32
                                 EMITI=    0.000     0.000 Infinity
                                 EMITO=    0.000     0.000 Infinity
                                      N1=   1    N2=  19

                                    MATCHING TYPE =   0

                                    P B O Lab T R A C E
                                     DATE: 06-02-2008
                                      TIME: 13:44:42
   2.000mm x   20.000mrad                                                   2.000mm x   20.000mra
Z  A= NaN     B= NaN                                                     Z  A= NaN     B= NaN

180.000Deg x  100.000KeV                                                 25.000Deg x  10.000KeV
 NP1=    1     13.00  mm(Horizontal)      25.0  Deg.(Longitudinal)                    NP2=   19

               13.00  mm(Vertical)                                      Length=   10466.05 mm
```

dP/P = 2%

**Dispersion D_max = 65cm**

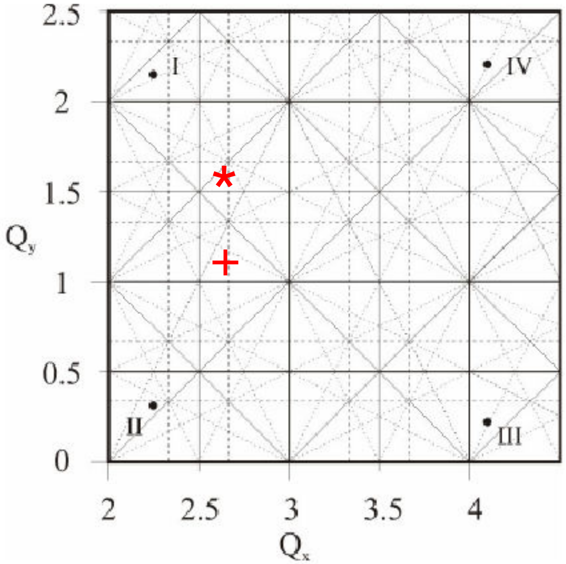
Structure

DOFOBOBOFOBOBOFOD

**Fig.7b**. E = 300 keV. A = 1. Momentum Spread **dP/P= 2%.** Beam size : X =0.0001 mm, X‘ = 0.0001 mrad. **ESD 8 deg :** R=2000 mm, aperture = 12cm. **ESD 37deg**: R=1000 mm, apert = 60 mm, **(incl.fringe field)** **ES_Quads**: L= 200 mm, 2R(aperture)=100 mm **(incl. fringe field)**
U1 = – 6.1 kV U2 = + 4.399 kV U3 = + 6.35 kV

TRACE 3D Simulations

**Fig.8. Betatron tune shifts of new USR Lattice**



**Shown above is part of the USR tune diagram where the**

**+ Achromatic (D = 0 )**

*** round beam**

**operation modes are depicted**

**Table 1. USR Lattice parameters Beam energy $E_P$= 20 keV. Different Modes of operation**

| Parameter | Achromatic | Round beam | Doublet |
|---|---|---|---|
| $\gamma_{tr}$ / $\alpha$ | 2.87 / 0.12 | 2.87 / 0.12 | 2.87 / 0.12 |
| $\nu_x$ | 2.572 | 2.567 | 2.552 |
| $\nu_y$ | 1.158 | 1.575 | 1.67 |
| $\xi_y$ / $\xi_x$ | -8.6 / -3.0 | -8.3 / -1.5 | -8.4 / -1.3 |
| $D_{max}$ / $D_{min}$ (m) | 0.65 / 0 | 0.64 / 0.26 | 0.64 / 0.3 |
| $\beta_x^{\max}$ / $\beta_y^{max}$ (m) | 17.2 / 16.3 | 16.3 / 7.4 | 16.7 / 6.2 |
| $K_{QD}$ (m$^{-2}$) | -2.415 | -2.4 | -2.415 |
| $k_{QF}$ (m$^{-2}$) | +1.065 | +1.065 | +1.065 |
| $k_{QF1}$ (m$^{-2}$) | +6.87 | +0.85 | 0 |

# Extraction Set-Up

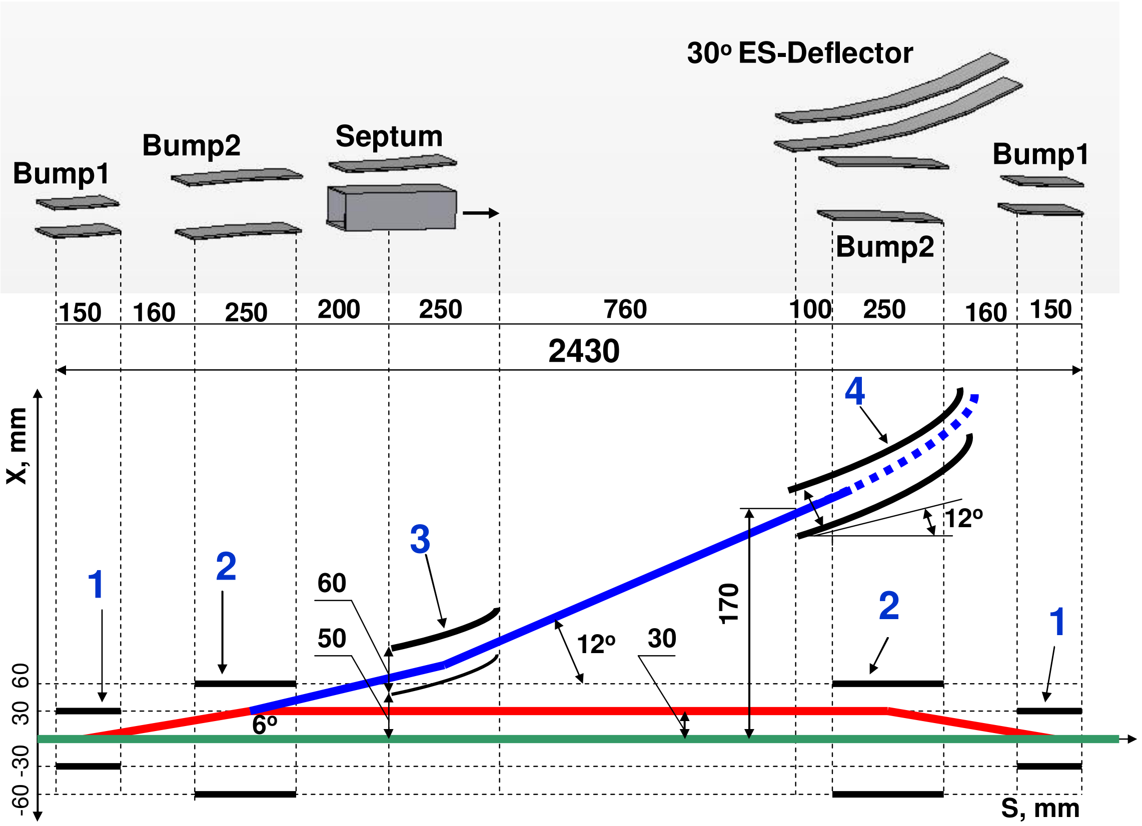


Fig.9. Position of the USR beam extraction elements

**Extraction system located in one of the USR straight sections and consists of the following elements:**
**2 parallel plate deflectors (*$d_{gap}$=60mm, U=±2 kV*),**
**2 large parallel plate deflectors (*$d_{gap}$=120mm, U=± 3 kV*),**
**1 extraction septum,**
**1 cylinder deflector shifted from the beam axis by 50mm.**

**The septum entrance is tilted with respect to the axis by 6° (*$d_{gap}$ 60mm, U=+3 kV, r=2.5 m*).**
**A final 30° deflector guides the extracted ions to the external experiments.**

**Computer simulations of the extracted orbit were done using the codes OPERA3D and SIMION. Preliminary specifications were reported at EPAC08 and slightly modified during the optimization process.**

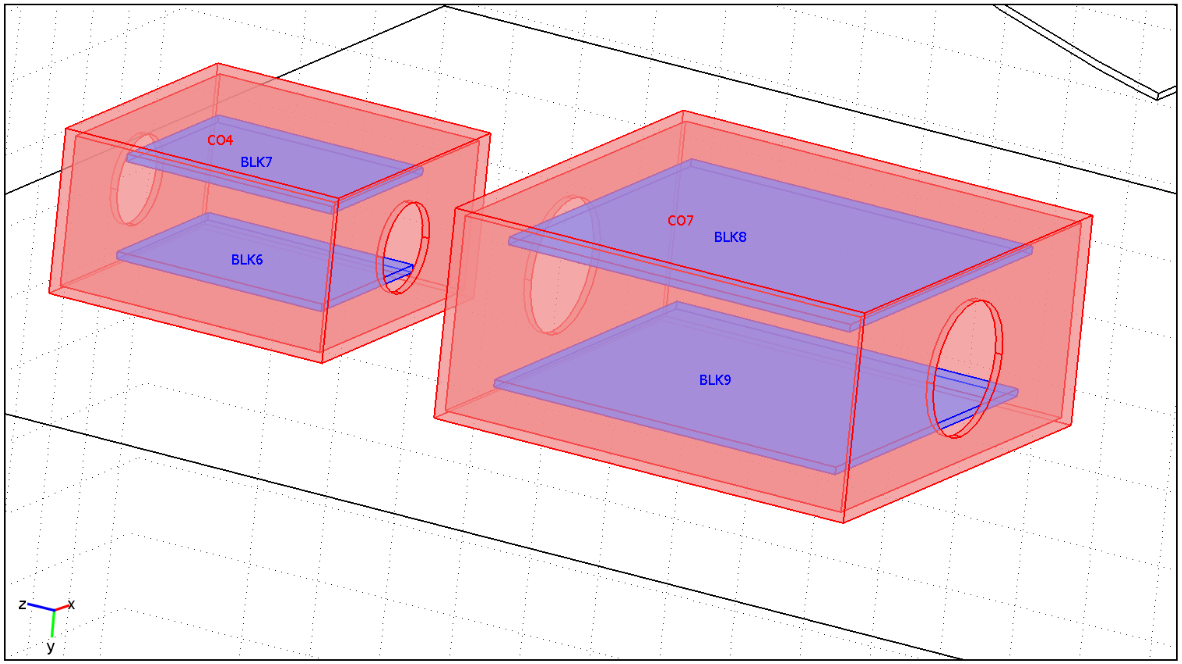
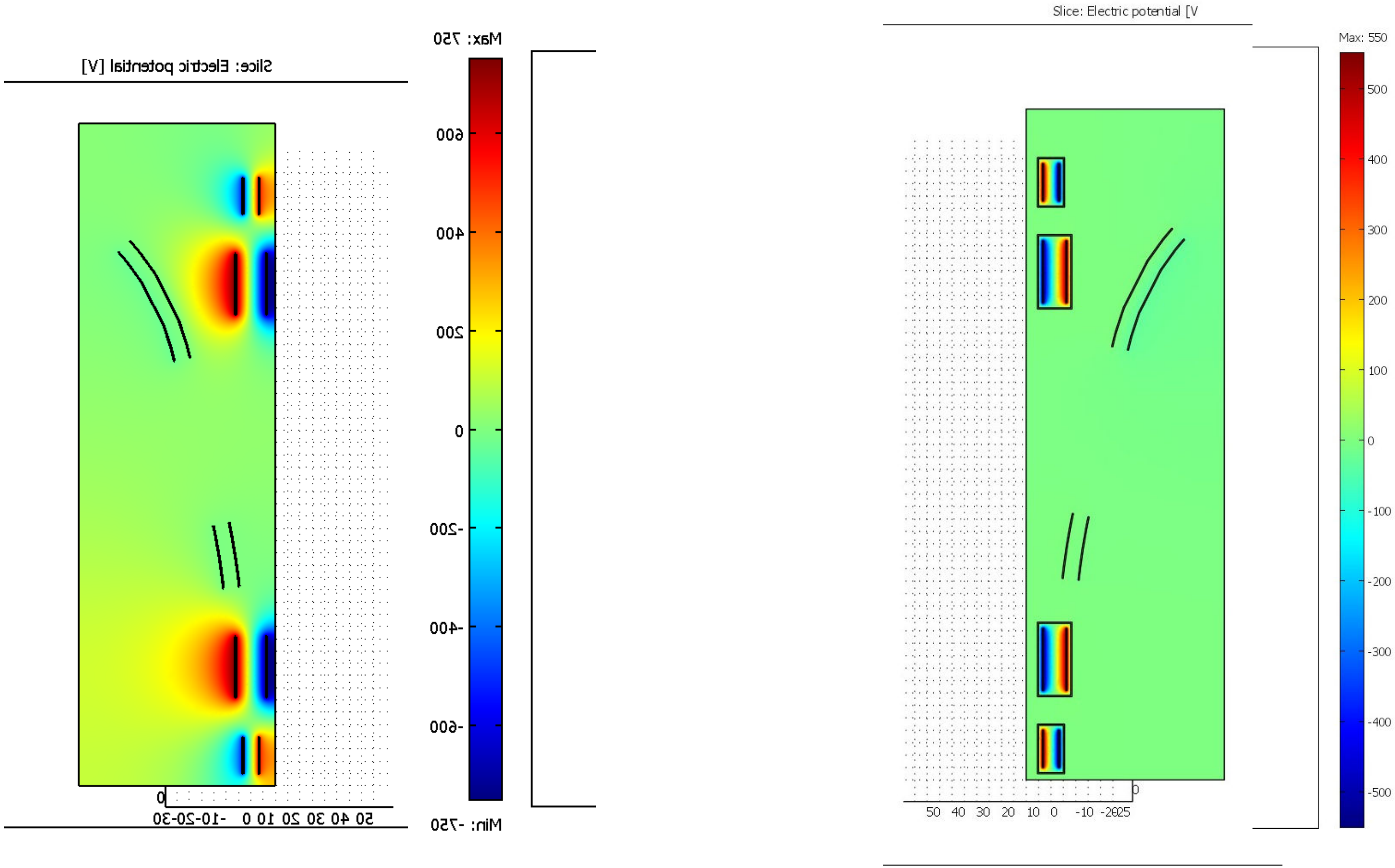


Fig. 10. View of the grounded housings in the extraction electrodes.



(a)

(b)

**Fig.11. Electric field distribution in the Model**
**(a) – without edge shielding**
**(b) with shields**

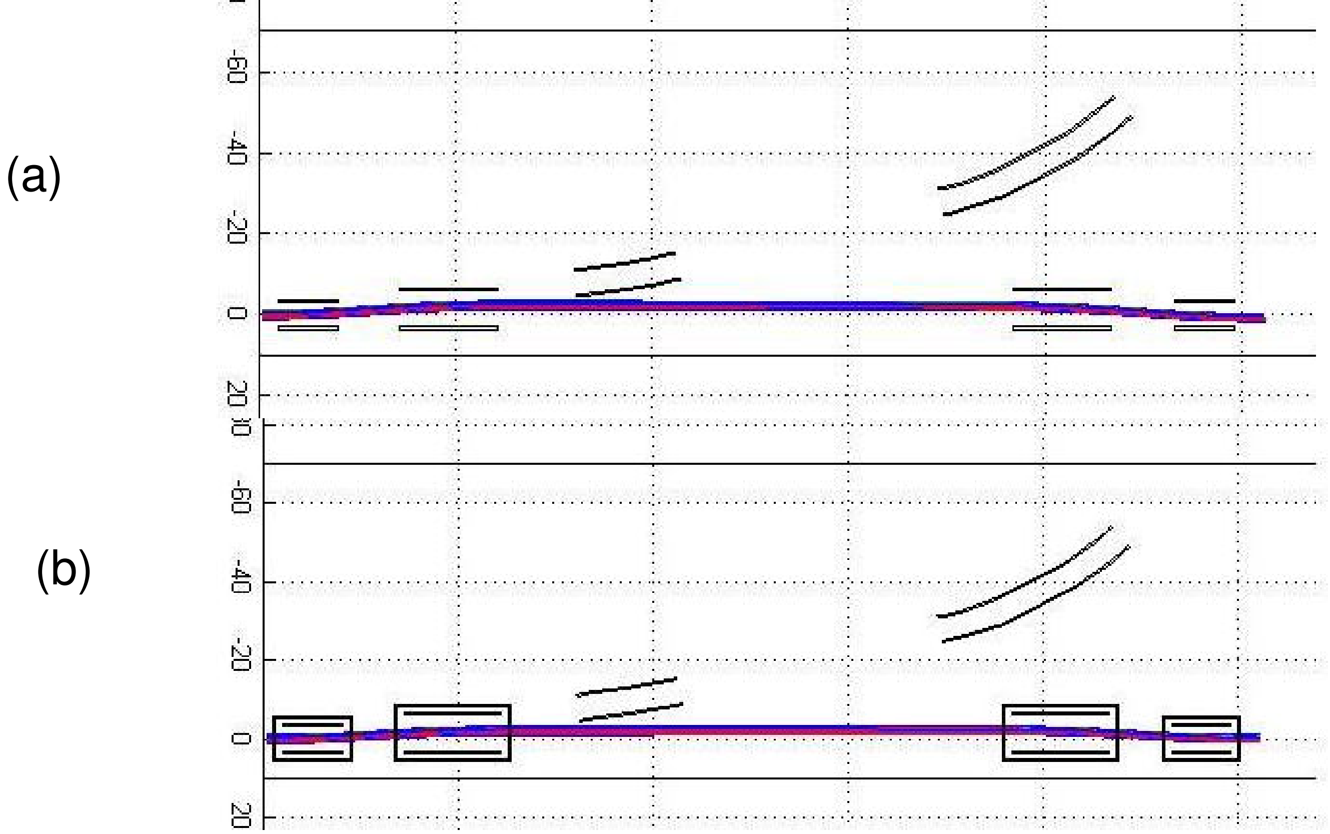


Fig.12. USR beam trajectory in the bump – (a) without and (b) with grounded housings

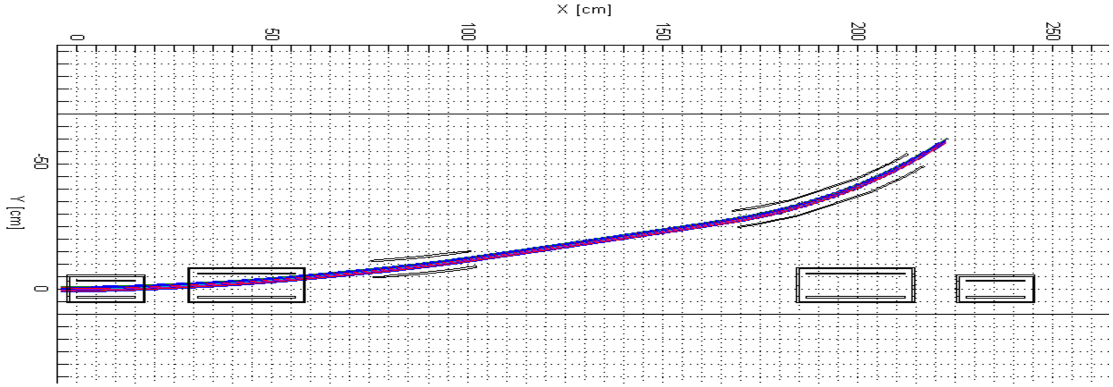


Fig. 13.  Trajectory of the extracted beam

Part 2

# Short Bunch Operation Mode

Part 2

## Abstract

- **One of the central goals of the Ultra-Low energy Storage Ring (USR) project within the future Facility for Low-energy Antiproton and Ion Research (FLAIR) is to provide very short bunches in the 1-2 nanoseconds regime to pave the way for kinematically complete measurements of the collision dynamics of fundamental few-body quantum systems**

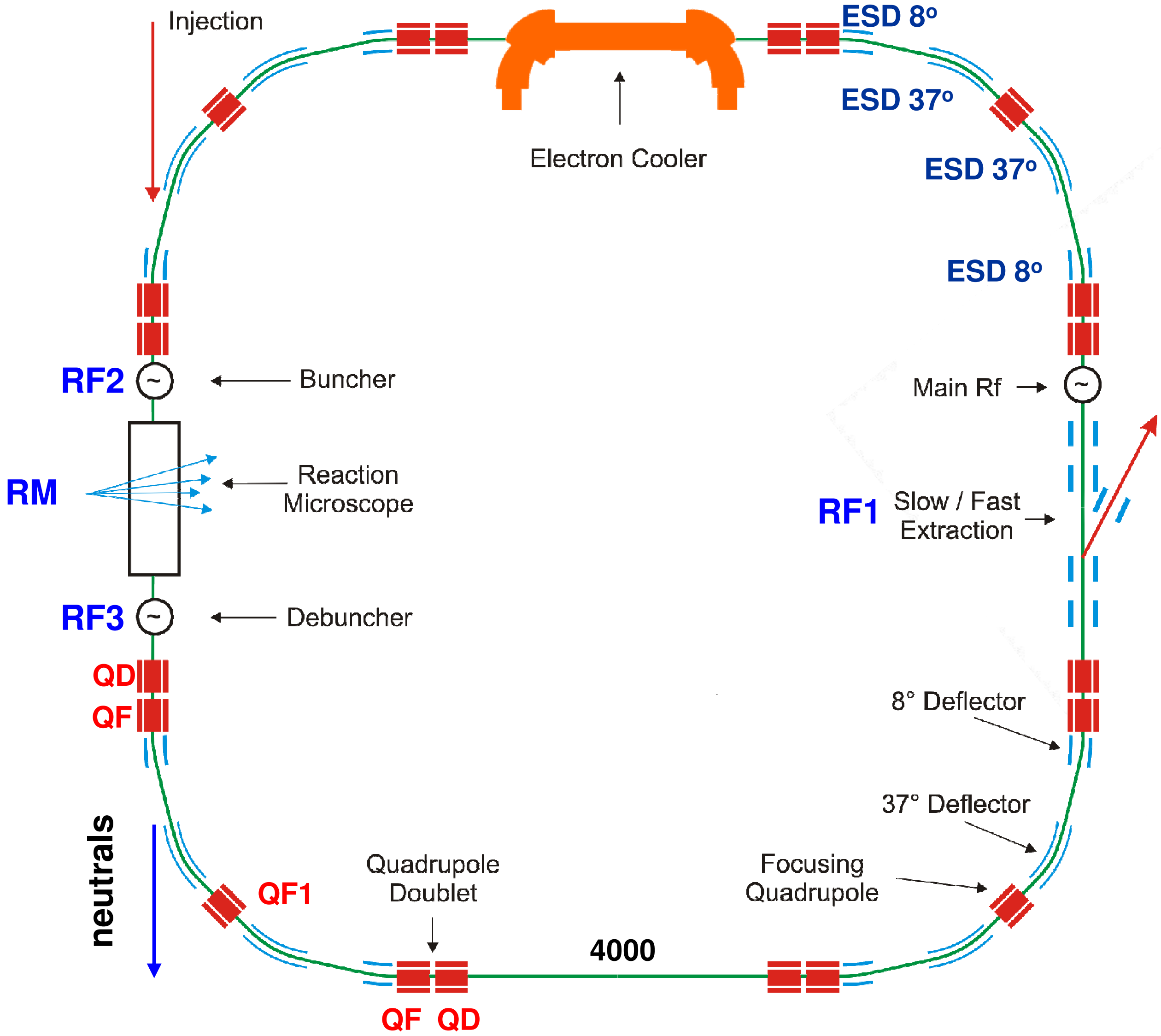
- **These bunches could then be used for collision studies with atomic or molecular gas jet targets where the time structure of the bunches would be used as a trigger for the experiments in the Reaction Microscope**

- **A possible approaches to realize shortest bunches in an electrostatic storage ring are studied:**
  - **Mupltiple Isoadiabtic split of RF frequency**
  - **Bunch compression - decompression**

- **Results of ESME as well as MAD-X simulations are discussed**

# Iso-adiatic Split of RF frequency

## (results of ESME simulations)



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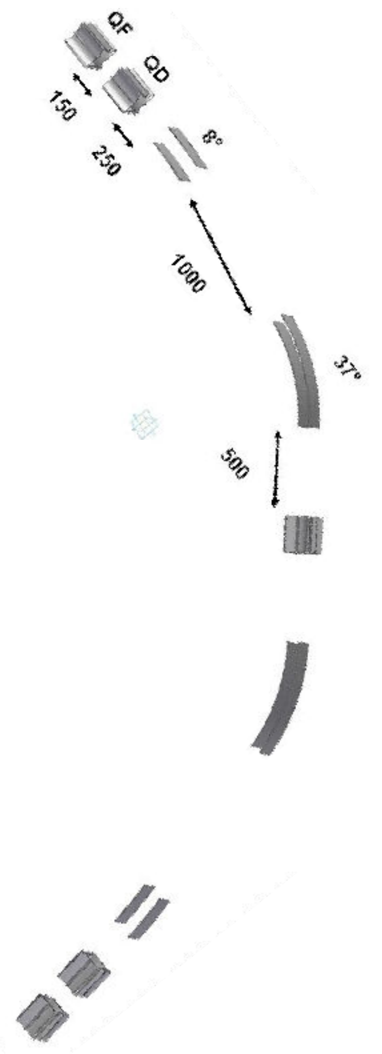


**Fig.5. USR corner Section. Split Achromat Cell. Measurements of neutrals is avaiable with open angle ±0.7°**

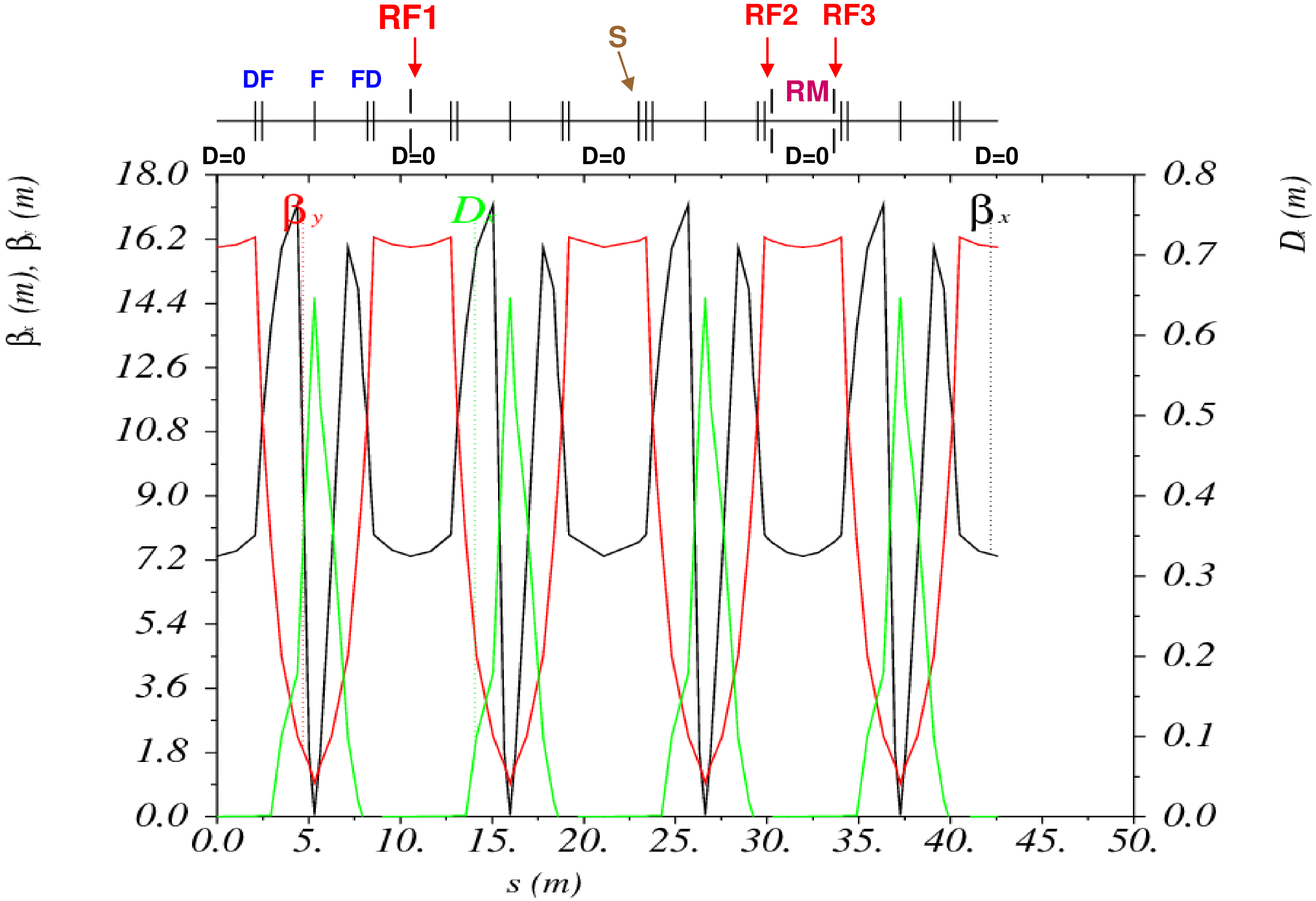
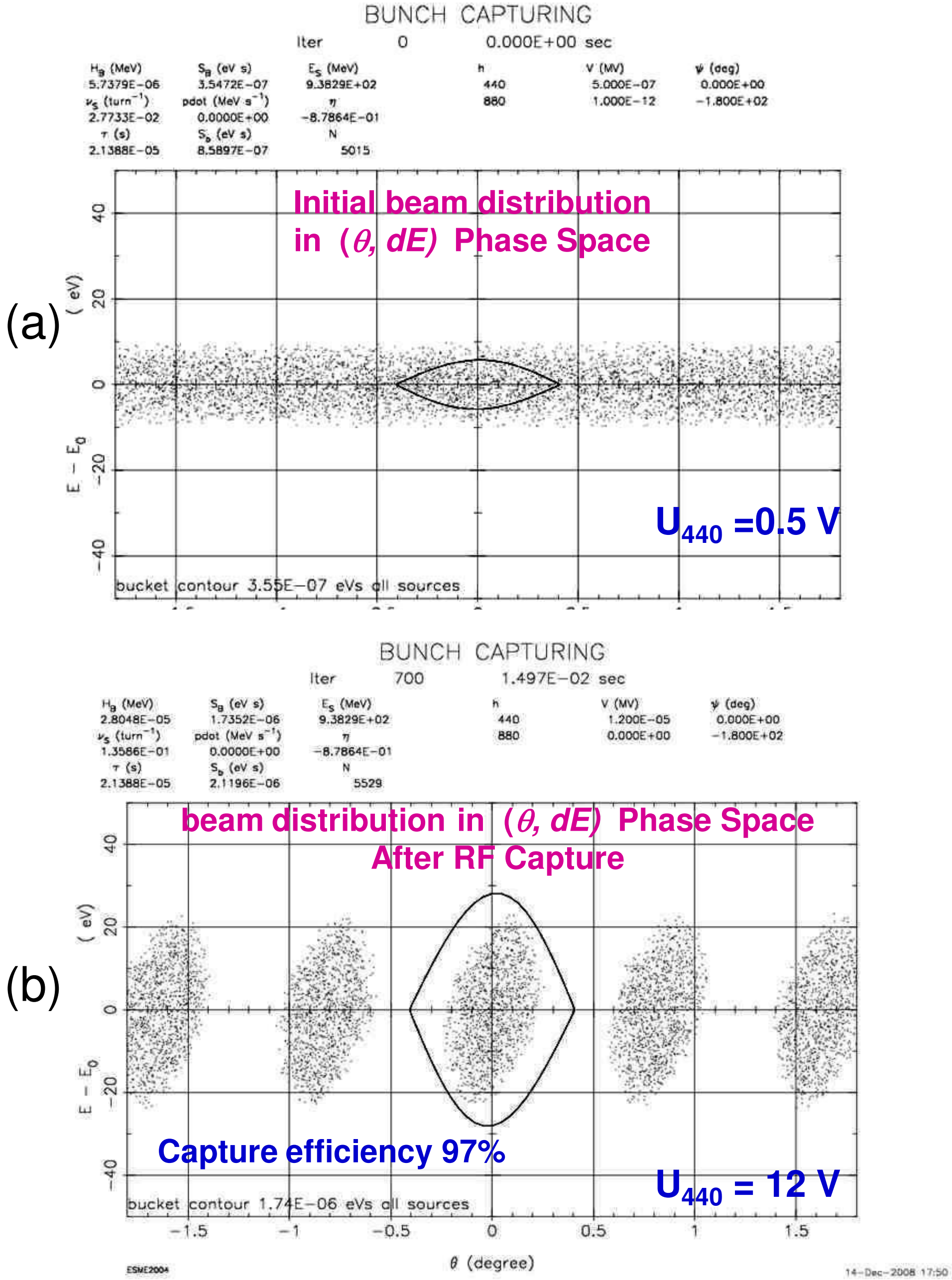


Fig.14. USR Ring Lattice. Beta-functions and Dispersion during Short Pulse operation mode (D = D' = 0 in straight sections) is shown

# Table 2. USR High Harmonic (short bunches) Mode of Operation

| **Parameter** | | **8° + 37° + 37° + 8° deflectors** | |
|---|---|---|---|
| | | Injection | Extraction |
| Energy, | keV | 300 | 20 |
| Circumference $L$, | m | 42.984 | 42.984 |
| $\beta = v/c$ | | $2.53 \cdot 10^{-2}$ | $6.53 \cdot 10^{-3}$ |
| Rotation period $T = L/\beta c$, μs | | 5.667 | 21.957 |
| Rotation frequenc, $F_{rot}$ | kHz | 176.46 | 45.5436 |
| RF frequency $F_{RF}$, | MHz | 20.1164 | 20.0392 |
| RF harmonic number $h_{RF}$ | | 114 | 440 |
| Bucket RF width, | ns | 49.71 | 49.9 |
| Buncher drift space, | cm | 200 | 200 |
| Buncher voltage, | kV | 21.5 | 0.37 |
| Expected Pulse width, | ns | 2 | 2 |
| Momentum spread (before / after e-cooling) | | $5 \cdot 10^{-3}$<br>$5 \cdot 10^{-4}$ | <br>$5 \cdot 10^{-4}$ |
| Achromat Mode Dispersion | | 0.7 | 0.7 |
| $D_{max} / D_{min}$, | m | 0 | 0 |
| $dP/P$, % | | 0.5 % | ≤ 2% |
| Transition Factor, | $\gamma_{tr}$ | | 2.2 |
| Momentum compaction, | $\alpha$ | | 0.207 |
| Frequency slip factor, | $\eta$ | | -0.8 |
| Synchr. freq. $\Omega_S$, | kHz | | $1.7 \times V_{RF}^{1/2}$ |
| Range of RF voltage change | | | 10…2000 |
| Momentum $pc$, | MeV | 23.72 | 6.12 |
| Magnetic rigidity $BR$,, T·m | | 0.07908 | 0.0204 |
| Time-of-flight $\tau_{ef}$ in the buncher gap 20mm, ns | | 2.6 (19°) | 10 (70°) |
| $\beta$ - (at buncher location), m | | | 5 |

# Fig.15. Isoadiabatic capture by 20 MHz RF Cavity. ESME SIMULATIONS
## a) coasting beam b) after bunching



Beam energy
**E = 20 keV**

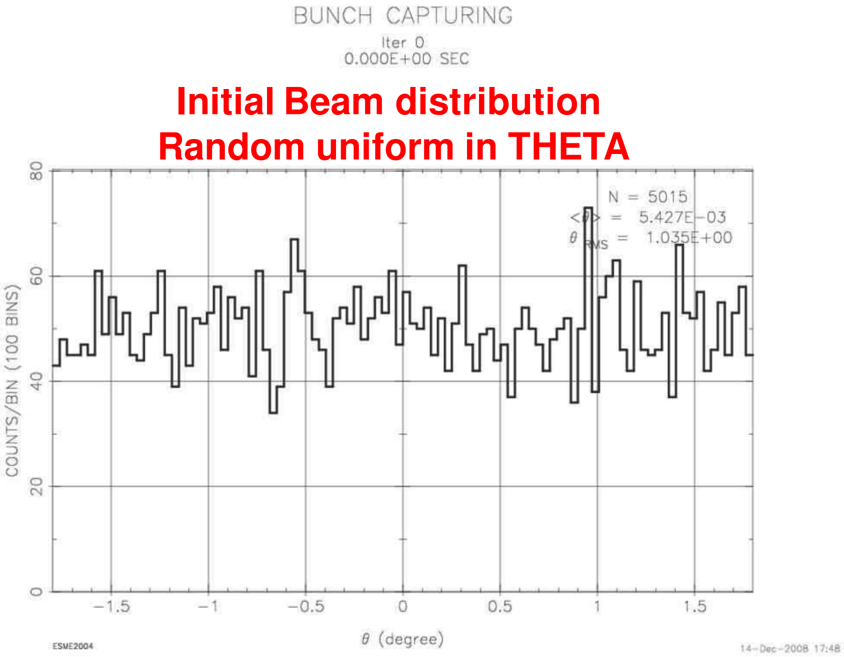
Coasting beam distribution in Energy –
**Parabolic**
$\delta E / E = \pm 5 \cdot 10^{-4} = \pm 10$ eV
(after e-cooling)

Initial distribution in THETA –
**Random uniform**

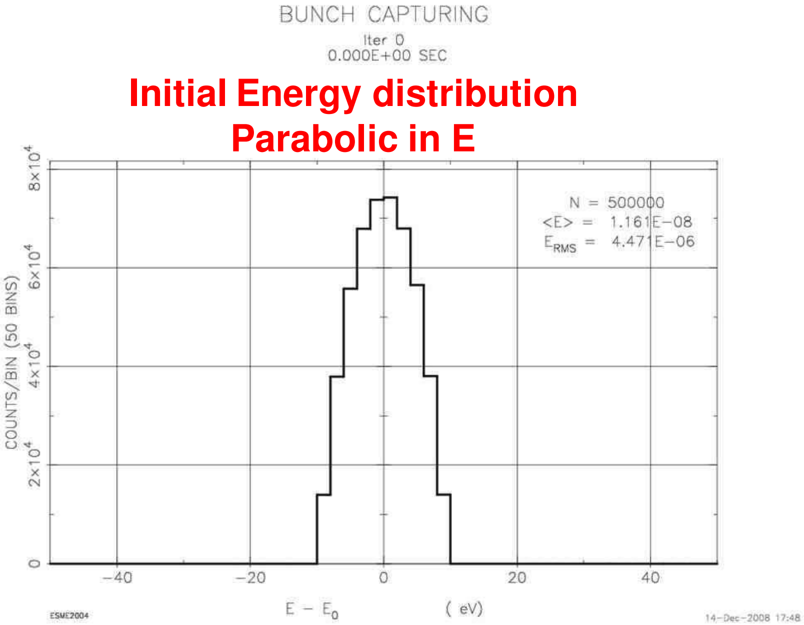
Isoadiabatic increasing of RF Voltage
**from 0.5 to 12 V**
**final amplitude might be varied from 8 to 20 V**

Voltage Rump time
**$T_{Rump}$ = 10 ms**
**might be varied from 2 to 50 ms**

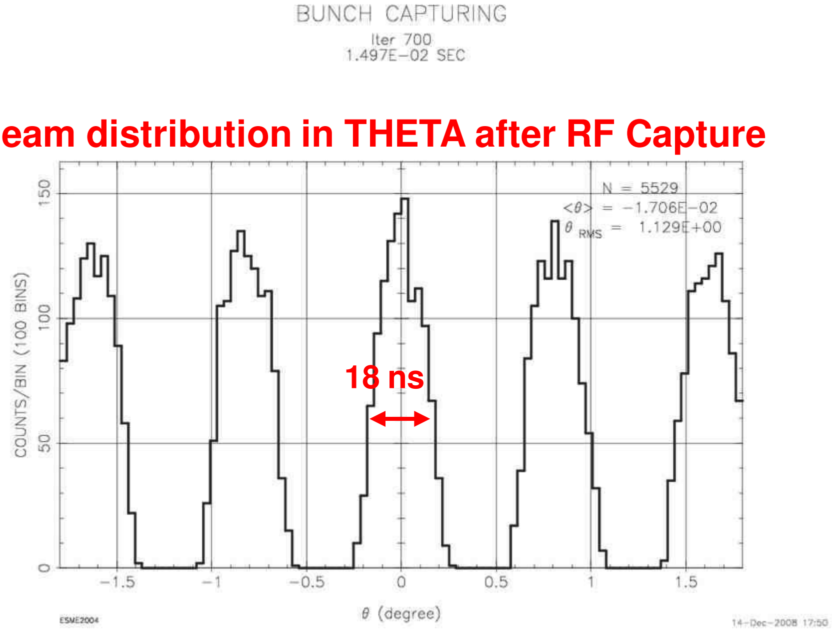
# Fig.16. Isoadiabatic capture (20 MHz RF Cavity). Peak structure. ESME SIMULATIONS



Initial Beam distribution
Random uniform in THETA

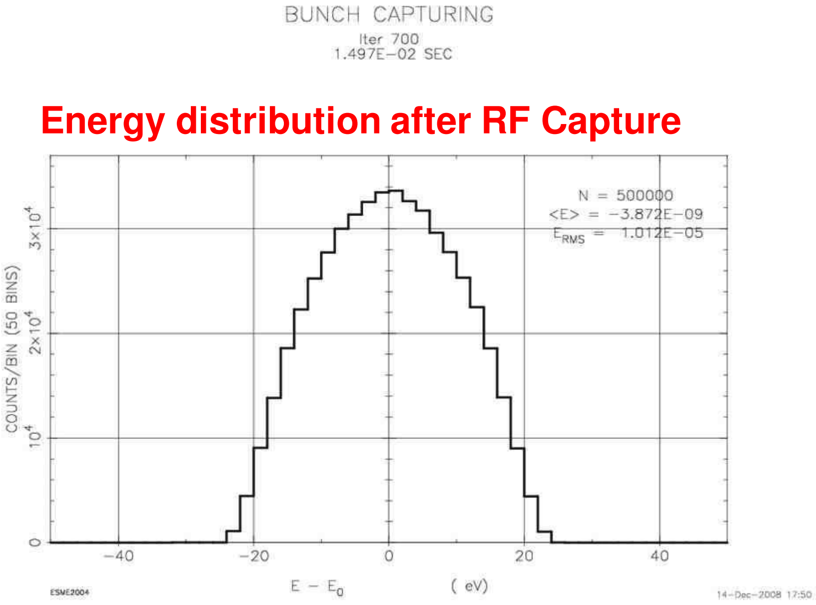


Initial Energy distribution
Parabolic in E



Beam distribution in THETA after RF Capture

18 ns

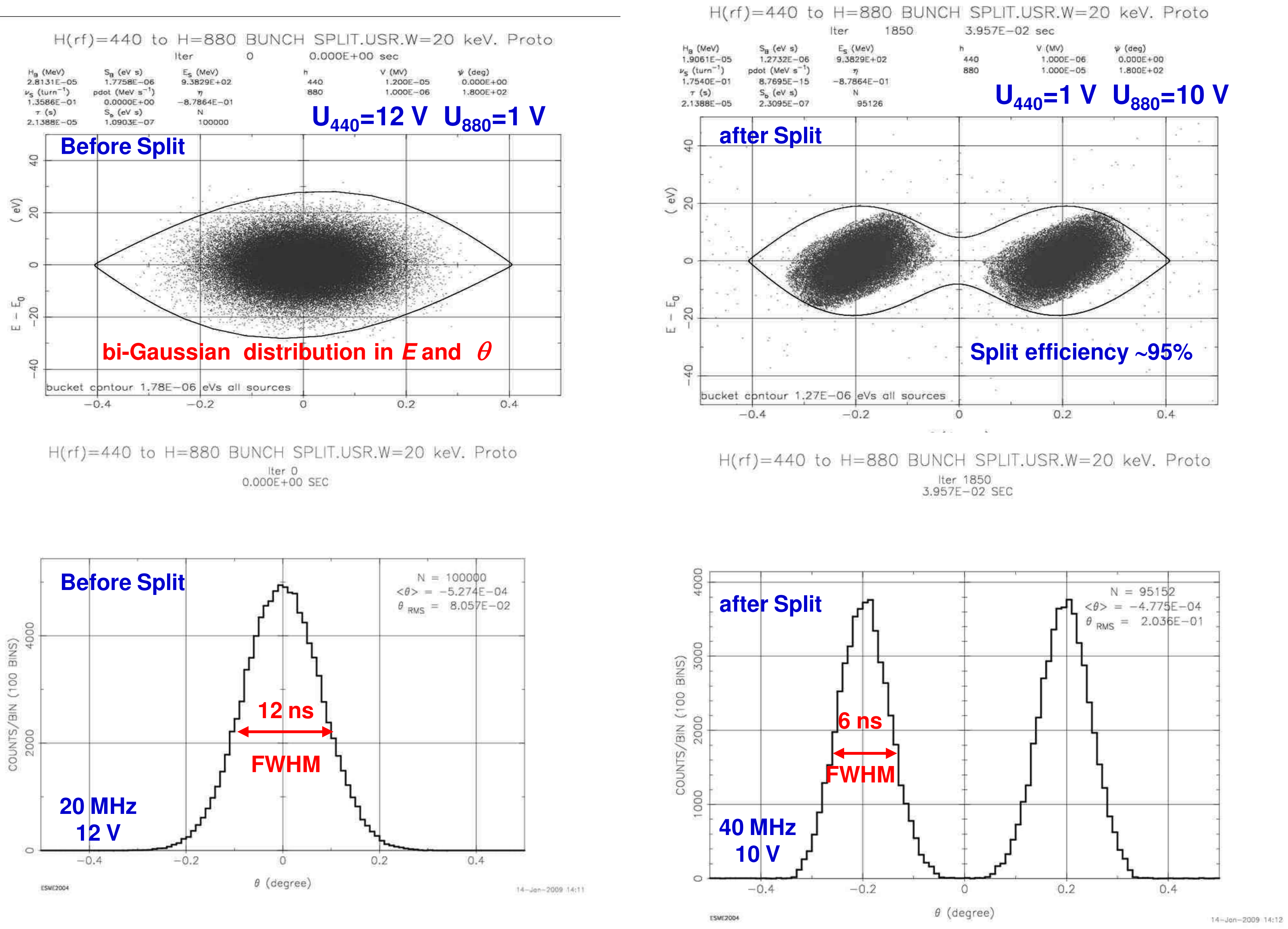


Energy distribution after RF Capture

- **No stable solution was found in ESME simulations for direct RF capture of coasting beam into 2 ns bunches by applying of 160 MHz RF voltage**

- **Multiple iso-adiabatic split might be considered as an option to create ultra-short pulses of 20 keV pbars**

# Fig.17. Isoadiabatic SPLIT of RF frequency 20 to 40 MHz (h$_{RF}$ = 440 to h$_{RF}$ = 880)



**Before Split**

$U_{440}$=12 V $U_{880}$=1 V

bi-Gaussian distribution in *E* and $\theta$

**after Split**

$U_{440}$=1 V $U_{880}$=10 V

Split efficiency ~95%

**Before Split**

12 ns

FWHM

20 MHz
12 V

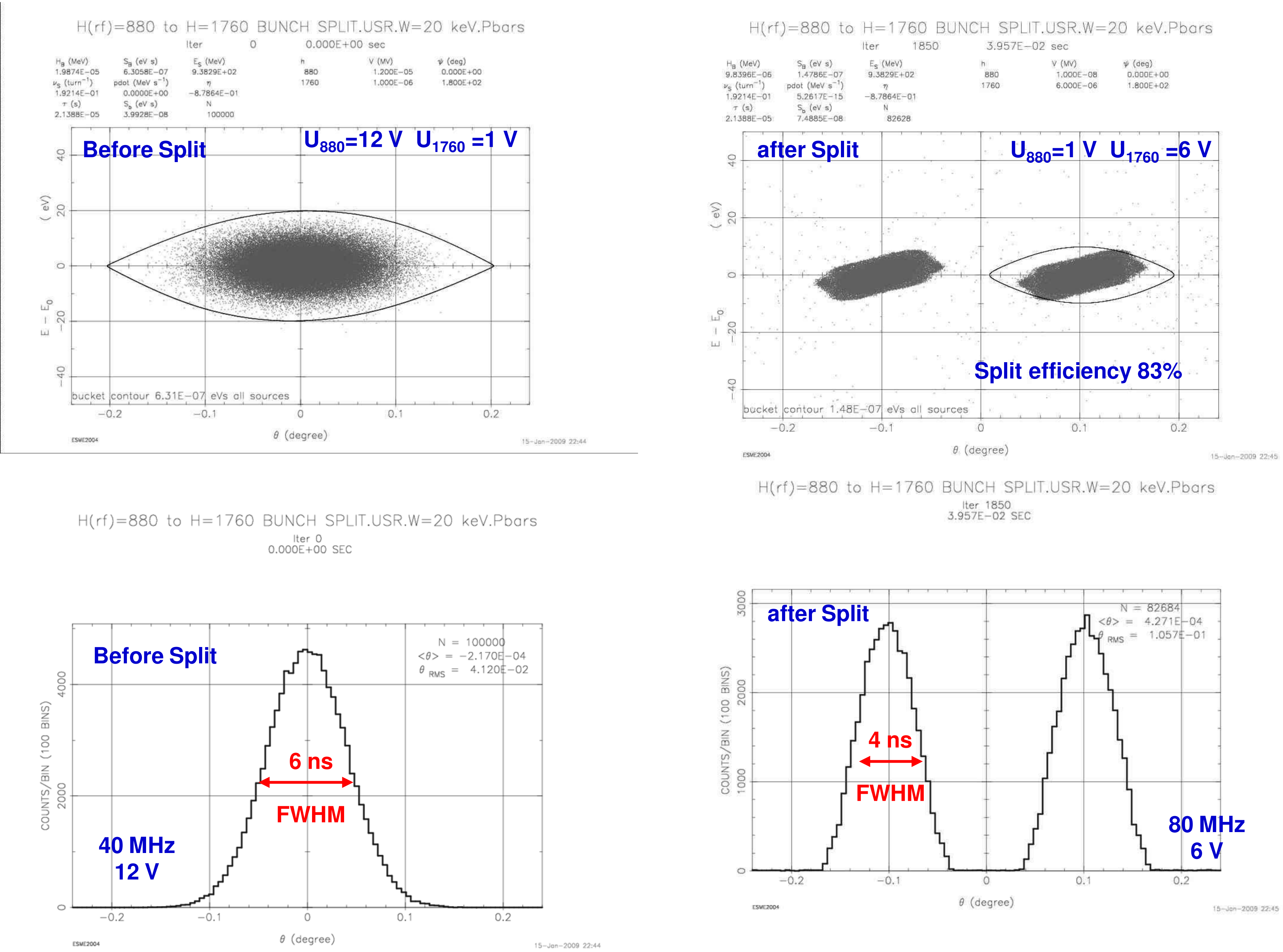
**after Split**

6 ns

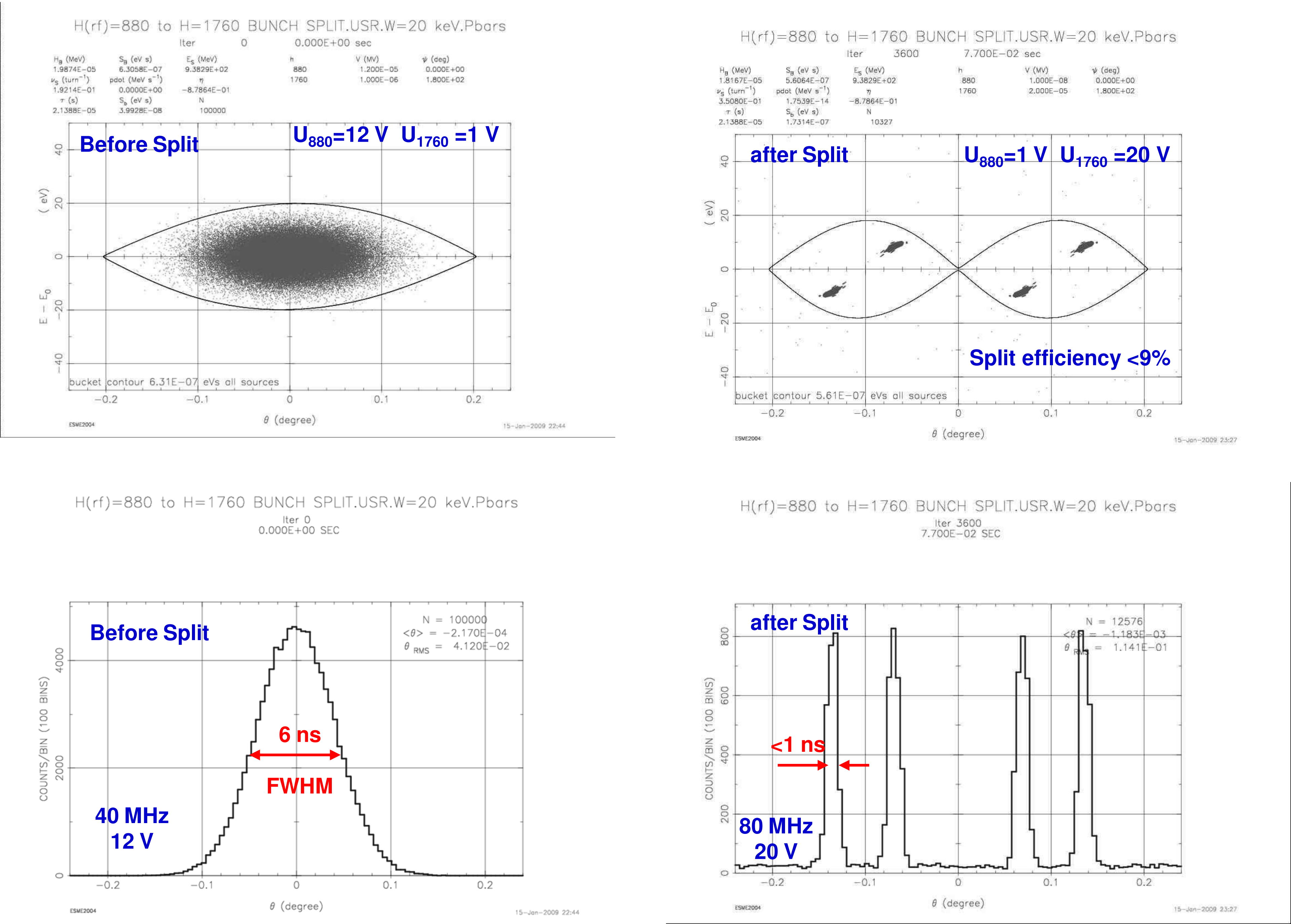
FWHM

40 MHz
10 V

# Fig.18. Isoadiabatic SPLIT RF frequency 40 to 80 MHz ($h_{RF}$ = 880 to $h_{RF}$ = 1760)



# Fig.19. SPLIT RF 40 to 80 MHz Two quasi-stable peaks ($U_{880}$= 12 V to $U_{1760}$ = 20 V ).



**Before Split**

$U_{880}$=12 V $U_{1760}$ =1 V

**after Split**

$U_{880}$=1 V $U_{1760}$ =20 V

**Split efficiency <9%**

**Before Split**

6 ns

FWHM

40 MHz
12 V

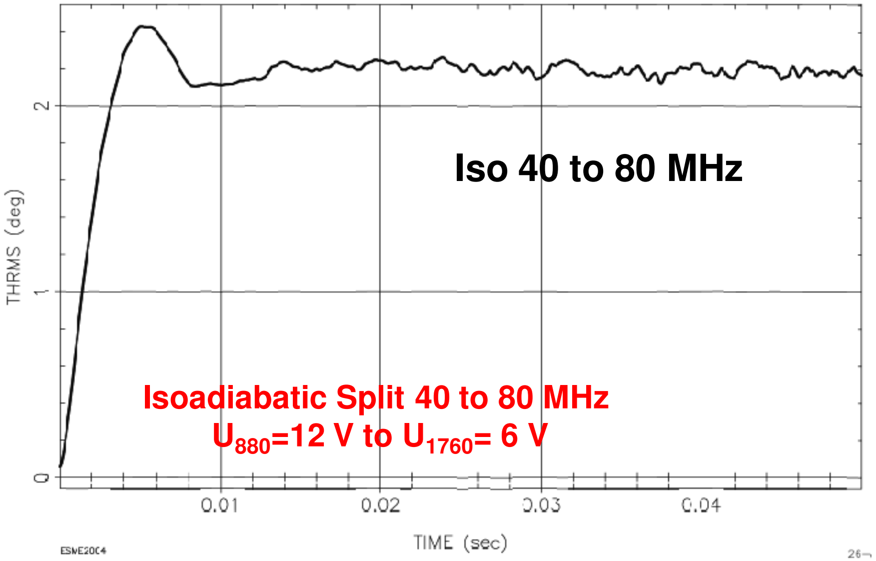
**after Split**

<1 ns

80 MHz
20 V

# Fig.20. Pulse stability in Time. Comparison of Isoadiabatic and quasi-stable Split.

## $\theta_{RMS}$ as function of time

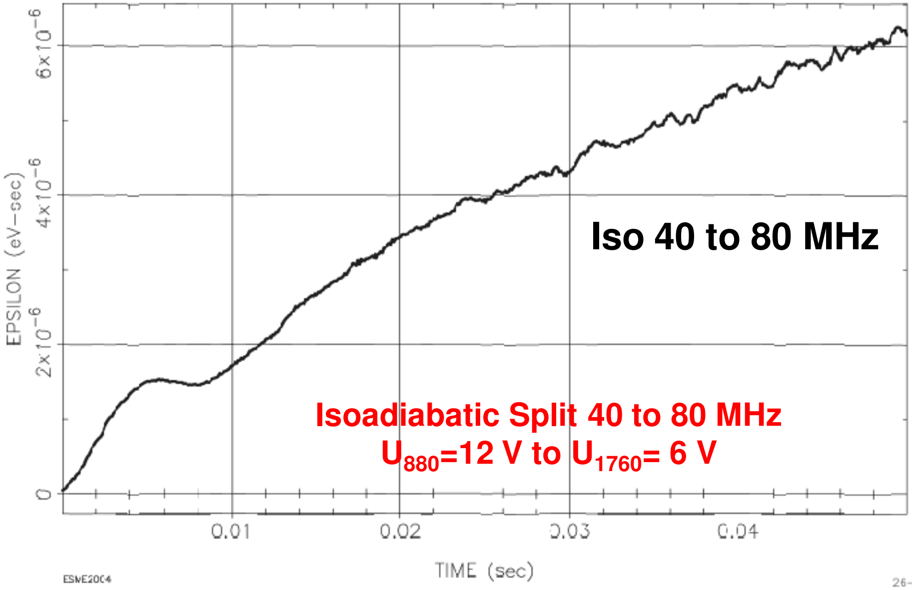


**Iso 40 to 80 MHz**

**Isoadiabatic Split 40 to 80 MHz**

**$U_{880}$=12 V to $U_{1760}$= 6 V**

## $\varepsilon_{RMS}$ as function of time

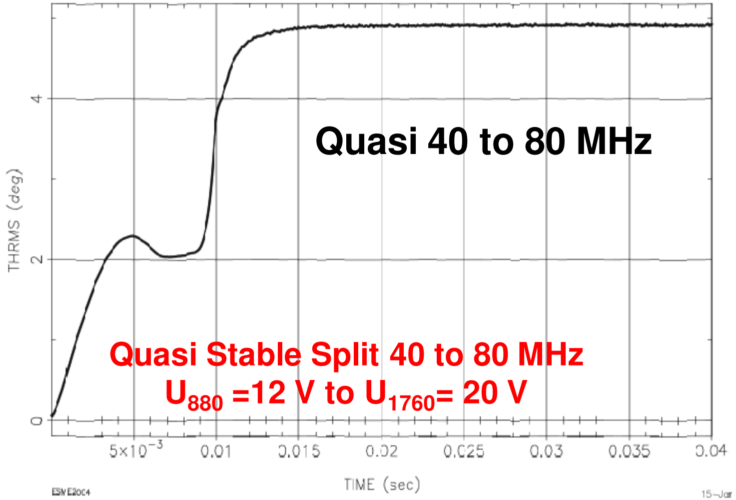


**Iso 40 to 80 MHz**

**Isoadiabatic Split 40 to 80 MHz**

**$U_{880}$=12 V to $U_{1760}$= 6 V**

## $\theta_{RMS}$ as function of time

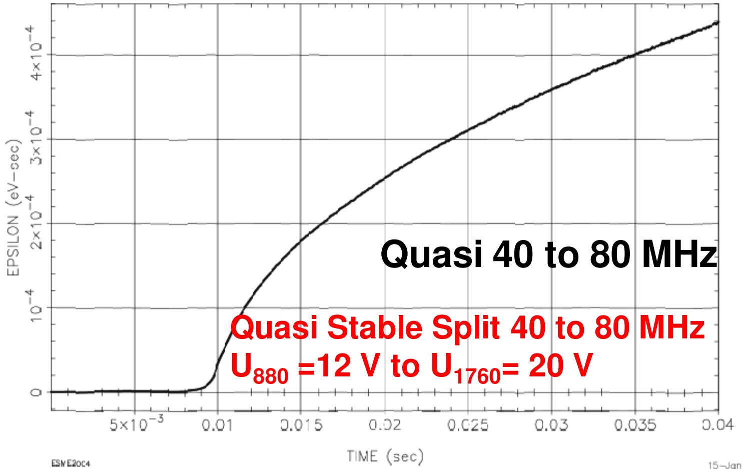


**Quasi 40 to 80 MHz**

**Quasi Stable Split 40 to 80 MHz**

**$U_{880}$ =12 V to $U_{1760}$= 20 V**

## $\varepsilon_{RMS}$ as function of time

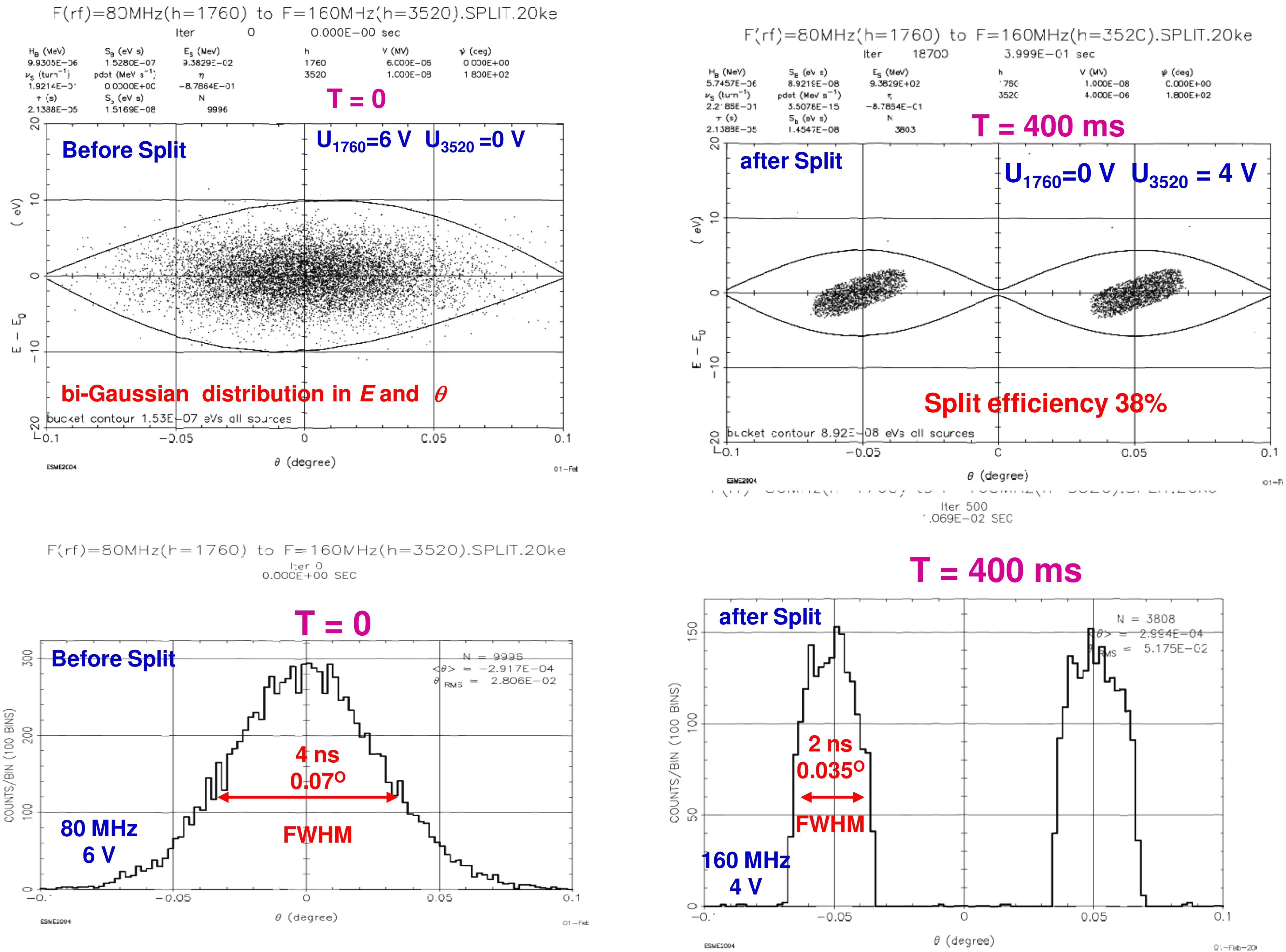


**Quasi 40 to 80 MHz**

**Quasi Stable Split 40 to 80 MHz**

**$U_{880}$ =12 V to $U_{1760}$= 20 V**

# Fig.21. Isoadiabatic SPLIT RF frequency 80 to 160 MHz ($h_{RF}$ = 1760 to $h_{RF}$ = 3520)



# Table 3. The USR Short Pulse Operation Mode. Multiple split of RF frequencies

| **Transition Mode** | **RF Capture iso-adiabatic** | | **Bunch Split iso-adiabatic** | | | **Split in two quasi stable peaks** | |
|---|---|---|---|---|---|---|---|
| $F_{RF}$, **MHz** | DC to 20 MHz | DC to 40 | 20 to 40 | 40 to 80 | 80 to 160 | 20 → 40 | 40 → 80 |
| $h_{RF}$ | 440 | 880 | 440 to 880 | 880→ 1760 | 1760 to 3520 | 440→880 | 880→1760 |
| Pulse Width FWHM , **ns** | DC→ 18 | DC→ 12 | 12→ 6 | 6 → **4** | **4 to 2** | 12→ **1** | 6 → **<1** |
| Transition efficiency | 97% | 97.7% | 95% | **83**% | **38** % | 11% | 9% |
| Initial Beam Distribution | θ - Rand<br>E- Parab | θ - Rand<br>E- Parab | BiGauss (95%) | Bi-Gauss 95% | Bi-Gauss (95%) | Bi-Gauss (95%) | Bi-Gauss (95%) |
| Number of particles | 500000 Coast | 500000 coast | 100000 one bunch | 100000 One bunch | 100000 one bunch | 100000 one bunch | 100000 one bunch |
| Total Efficiency Capture+ Split | DC beam to **4 ns** pulses **75%** | | | | DC beam to **2 ns** pulses **30%** | DC beam to **1 ns** (quasi stable split) **8 – 10%** | |
| V1(in–fin), **V** | 0.5–12 | 1–8 | 12–1 | 12–0.01 | 6 - 0 | 12–1 | 12–0.01 |
| V2(in–fin), **V** | 0 | 0 | 1–10 | 1–6 | 0 - 4 | 1–40 | 1–20 |
| Transition time, ms | 10 | 5 | 10 | 10 | 10 | 10 | 10 |
| Total observation time, **ms** | stable 150 | stable 220 | stable 40 | Stable 200 | Stable 400 | stable 400 | Pulse stable 80 |
| INITIAL Energy Spread ΔE (95%) eV | ±10 | ±10 | ±20 | ±16 | ±8 | ±20 | ±14 |
| FINAL Energy Spread ΔE (95%) eV | ±20 | ±14 | ±16 | ±8 | ±4 | ±4 | ±2.5 |
| $F_{rot}$ **(kHz)** $T_{rot}$ **(μs)** | 46.755 kHz<br>21.388 μs | | | | | | |
| $\nu_S = F_S / Frot$ | 0.136 | 0.157 | 0.175 | 0.192 | 0.22 | 0.35 | 0.35 |
| $F_S$ , **kHz** | 6.08 | 7.3 | 8.2 | 9 | 10.3 | 16.3 | 16.3 |

# Bunch Compression-decompression (RF „gymnastics“)

## (MAD-X simulations)

- The “short pulse” operation mode split up in two steps:

- First, the cooled coasting beam of low energy ions is adiabatically captured by a high harmonic RF cavity (20 or 40 MHz)
- into ~12-18 ns pulses

- Second, the beam is compressed to short pulses with a desired width of ~2 ns by an RF buncher located in front of the reaction microscope

- Drift for timing focus is limited to 2 m (straight section is 4 m)

- To limit the beam energy spread, RF decompression is then done at after the experiment

- Results of MAD-X simulations are presented

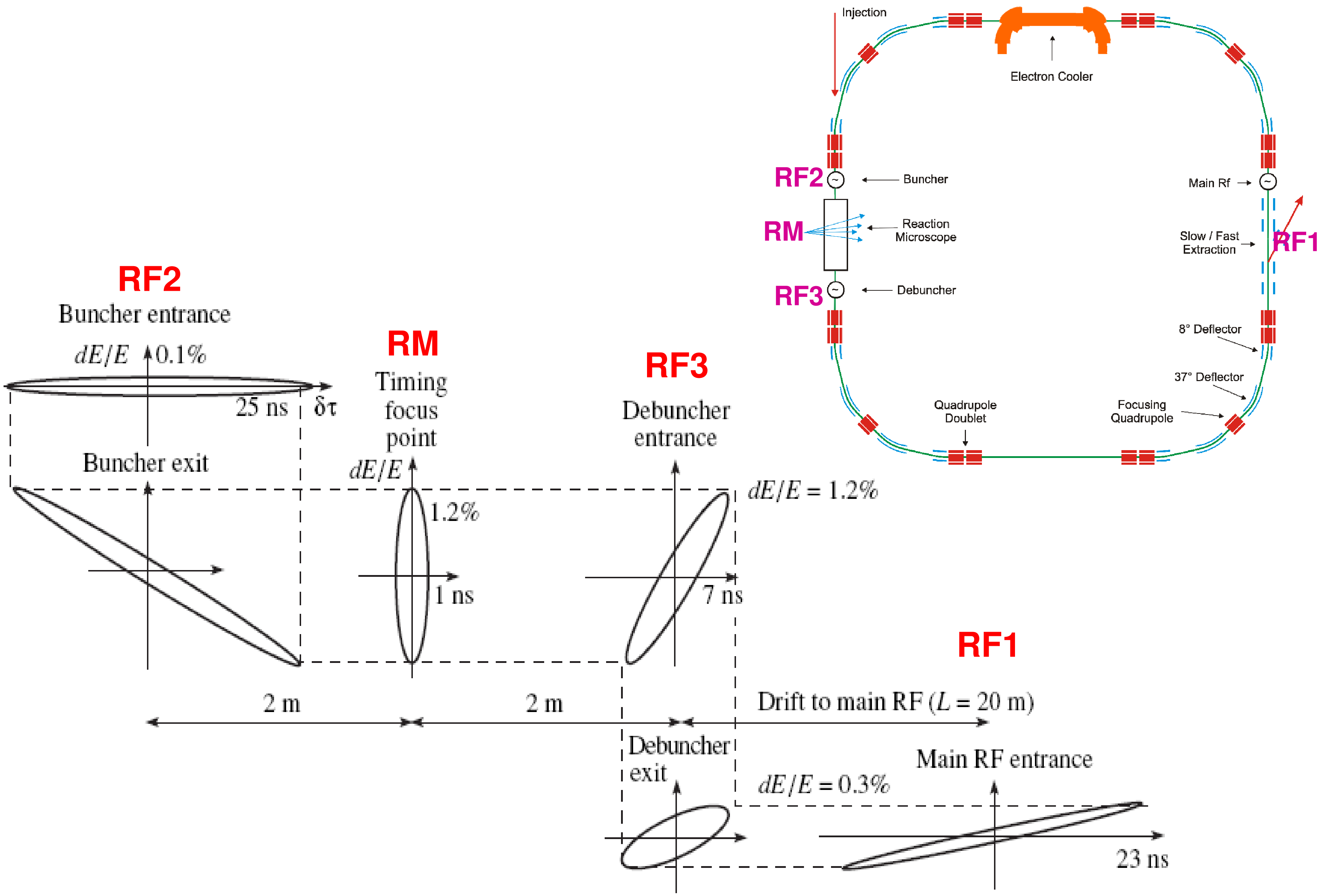


Fig 22. Evolution of the longitudinal phase space during phase „gymnastics“ in the USR. The locations of the RF systems and the Reaction Microscope are indicated

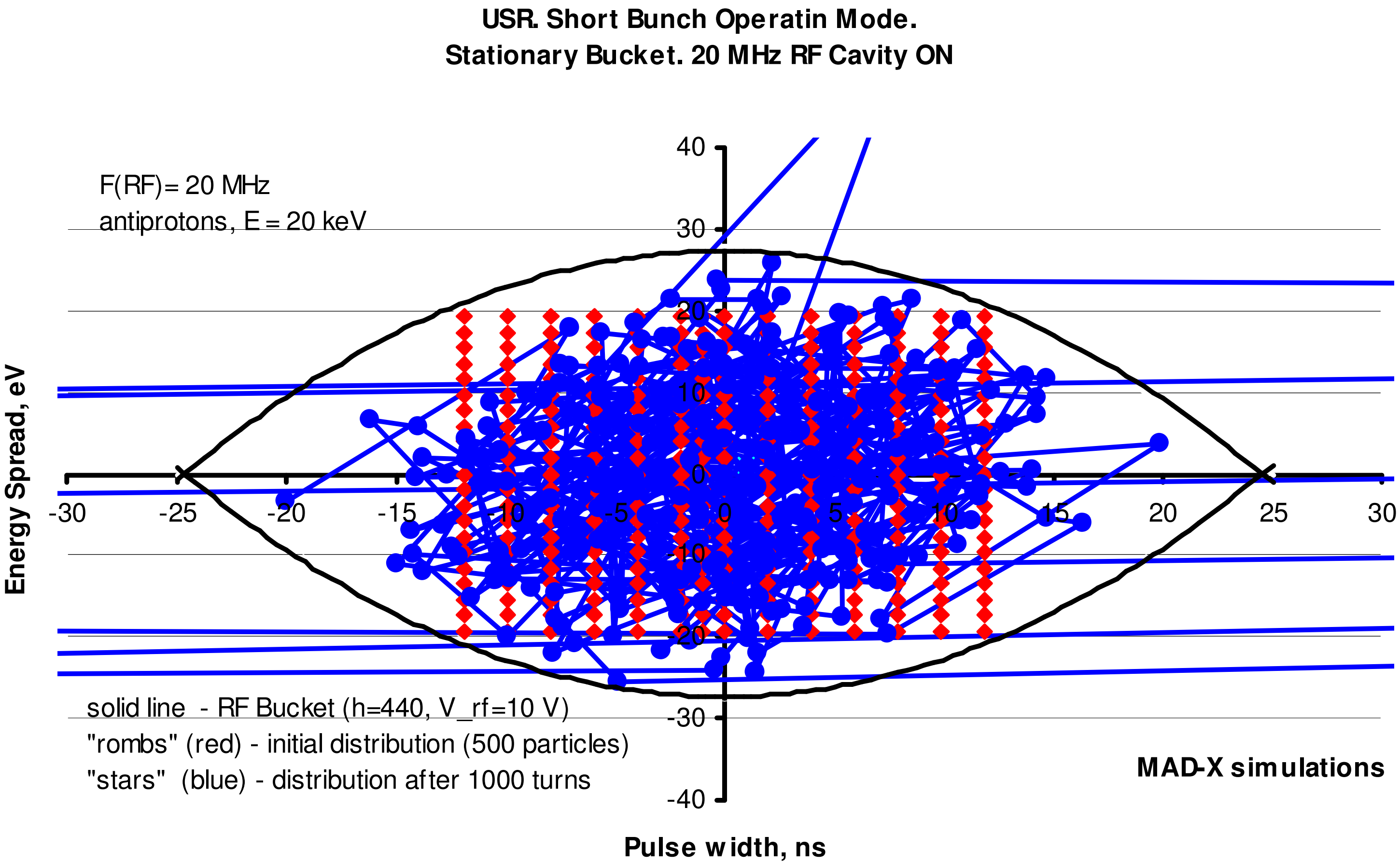
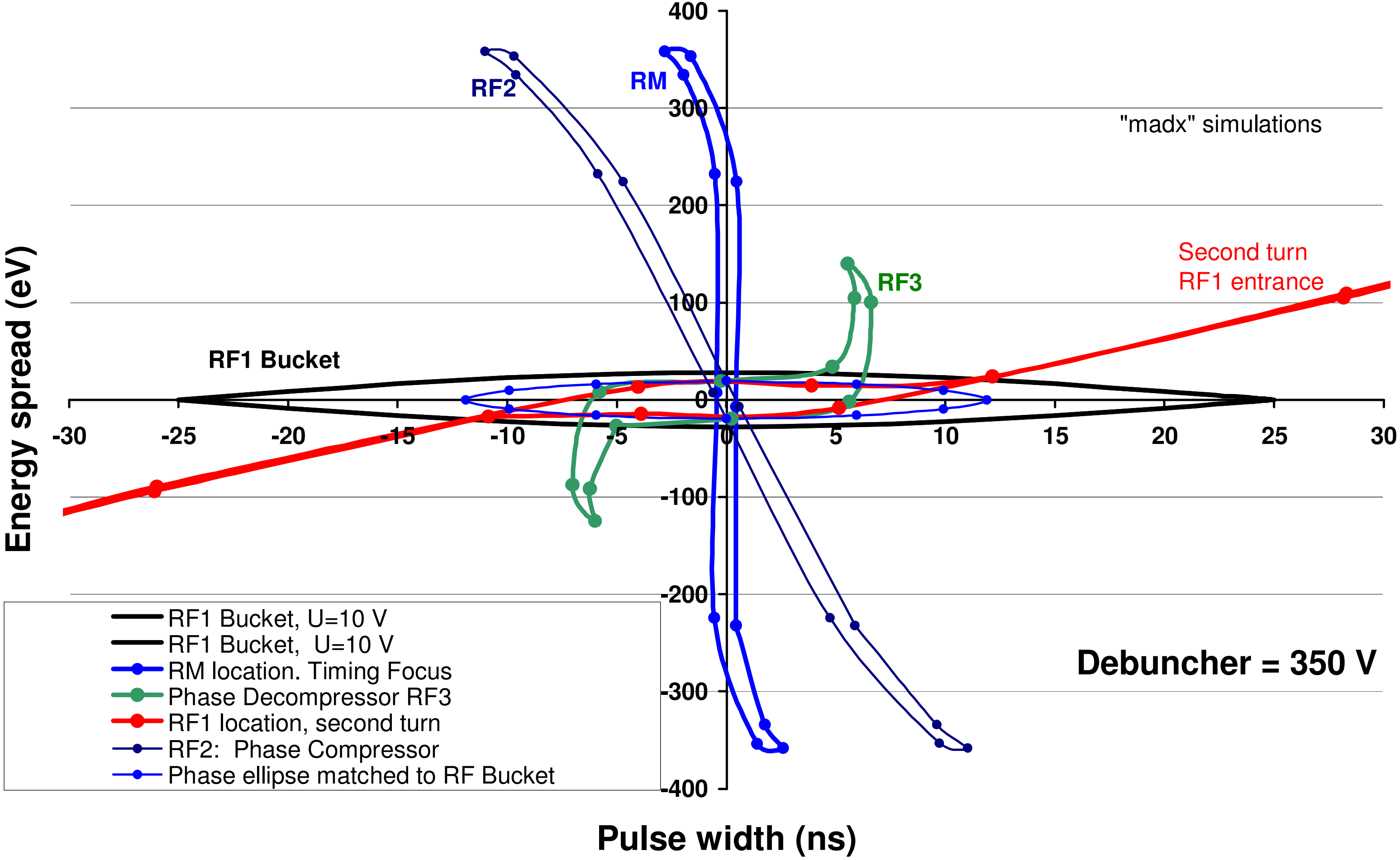


**Fig. 23. Stationary Bucket and beam distribution in Longitudinal Phase Space (MAD-X). U(RF1) = 10 V, F = 20 MHz (h = 440) RF2=RF3=0**
**Red points – initial distribution (500 particles random population),**
**δφ = ± 12 ns, δE = ±20 eV**
**Blue „stars“ – distribution after 1000 turns (20 ms)**

**Results of MAD-X simulations are consistent with ESME RF capture results**

# Fig.24. **Longitudinal Phase Space. USR Short Pulse Operation Mode.**

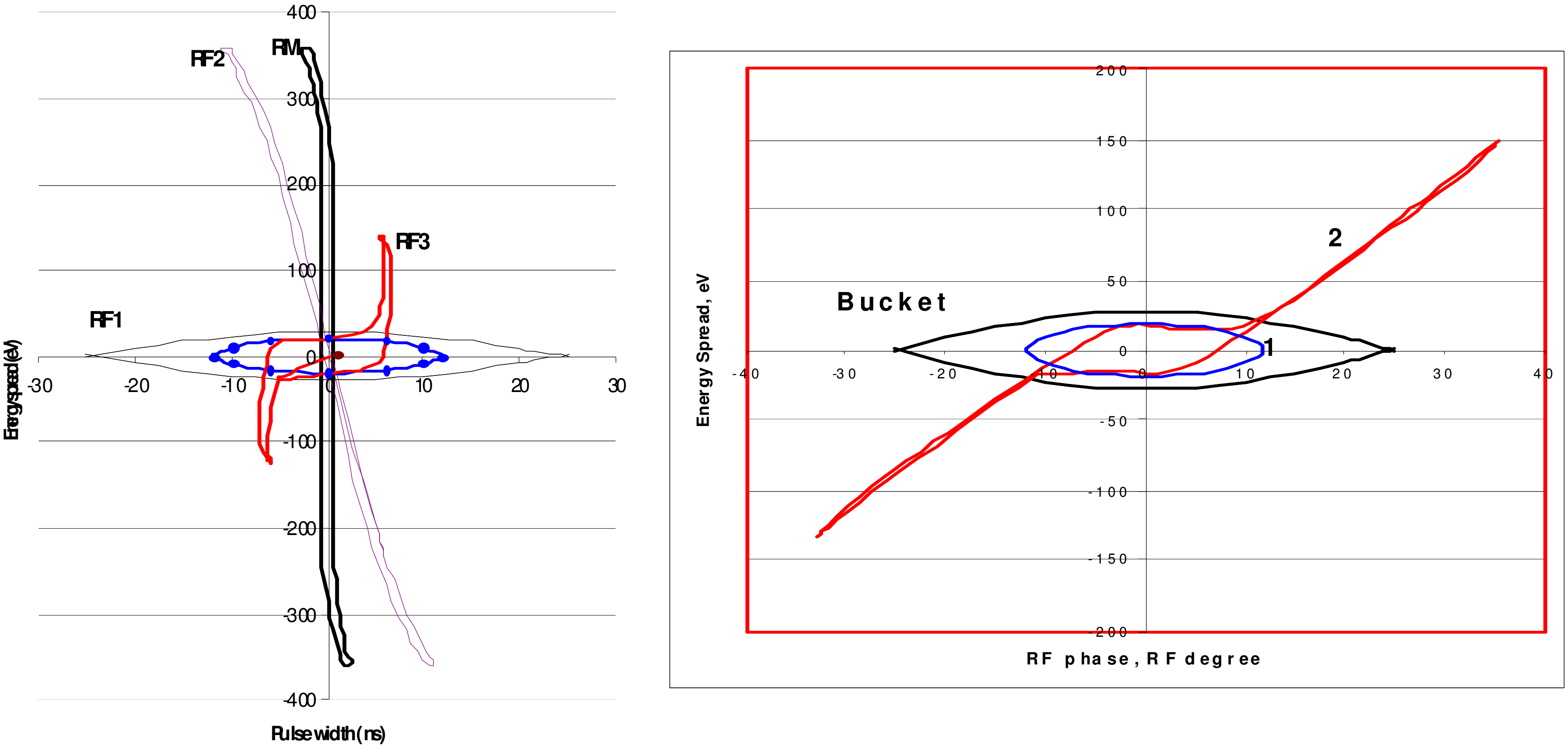


RF1 - High Harmonic RF Cavity: h(RF) = 440 F(RF) = 20 MHz V (RF1) = 10 V (Bucket)

RF2 - Phase compressor: U(RF2)=370 V is optimized to reduce pulse width to 1 ns at Reaction Micriscope location

RF3 - Energy Compressor: U(RF3) = - 350 V

**To minimize non-linear effects caused by RF one could apply Saw shape RF voltage**



a )

b )

**Fig.25. Non-adiabatic behavior of the phase space ellipse during bunch rotation in the USR.**

**a) A voltage of 370 V in the buncher is sufficient to generate pulses of 1 ns duration,**

**b) Decompression should be done by applying of 350 V to de-buncher**

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