Detector Recovery/Improvement Via Elevated-temperature-annealing (DRIVE) - a new approach for Si detector applications in high radiation environment in SLHC

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6 RD50 Collaboration Workshop
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Outline

1. Goal
2. Experimental
3. Recovery of detector reverse current
4. Changes of TCT signal under ETA
5. Results on N_{eff} recovery
6. Microscopic defects after ETA
7. Summary

Goal of the study

Goal of the study:

recovery of detector parameters by manipulation of the effective space charge concentration N_{eff} in irradiated Si detectors using elevated temperature annealing (medium T)

We will show that thermal treatments initially lead to the enhanced reverse annealing, **after which the recovery of**

detector reverse current
and SCSI (from negative to positive)

occur

Earlier results

Earlier results:

- The manipulation of the space charge sign using elevated temperature annealing (ETA) was demonstrated recently for non-irradiated detectors processed from p-type CZ Si in which introduction of thermal donors resulted in SCSI from negative to positive:

  - M. Bruzzi, et al., "N_{eff} tuning in MCz-Si detectors by isothermal annealing", pres. 5th CERN RD50 Workshop, Florence, Oct 14-16, 2004,
  - Z. Li and J. Härkönen, pres. 5th CERN RD50 Workshop, Florence, Italy, October 14-16, 2004

- Annealing of radiation defects induced by electrons

Experimental

- Detectors: p^+-n-n^+ pad structures with multiple GRs processed at HIP from n-type MCZ Si with a resistivity of 1 kOhm·cm

- Irradiation (at HIP):

protons 24 GeV/c		protons 20 MeV	
P352-18	9.00E+13	**C1-3**	5.90E+13
P352-59	3.60E+14	**D2-3**	1.20E+14
P352-48	5.00E+14		

Annealings

- multistep process with a variable time
- T: 150-450°C
- t_{ann}: variable, 10 min up to 120 min
- nitrogen flow
- fast cooling (~10 min)

E_p	**protons 24 GeV/c**			**protons 20 MeV**	
#	P352-18	P352-59	P352-48	C1-3	D2-3
F_p (cm^{-2})	$9 \cdot 10^{13}$	$3.6 \cdot 10^{14}$	$5 \cdot 10^{14}$	$5.9 \cdot 10^{13}$	$1.2 \cdot 10^{14}$
annealing steps	8	12	13	8	10
T (°C)	150-450	300-450	450	430-450	430-450

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Experimental techniques

Measurements:

After each annealing step (at BNL):

- I-V and C-V dependences
- current pulse response using TCT with a laser pulse generation of non-equilibrium carriers

After final detector annealing (at Ioffe Institute):

Spectra of deep levels (C-DLTS)

Experimental results

Three stages of the changes of detector characteristics irrespective to E_p and F_p:

1. **Reverse annealing**:
   I_{rev} ⇑, V_{fd} ⇑, negative N_{eff} ⇑, W ⇓
   TCT signal from the detector p^+ side disappears

2. **Recovery** of reverse current and the signal from p^+ side

3. **SCSI** from negative to positive

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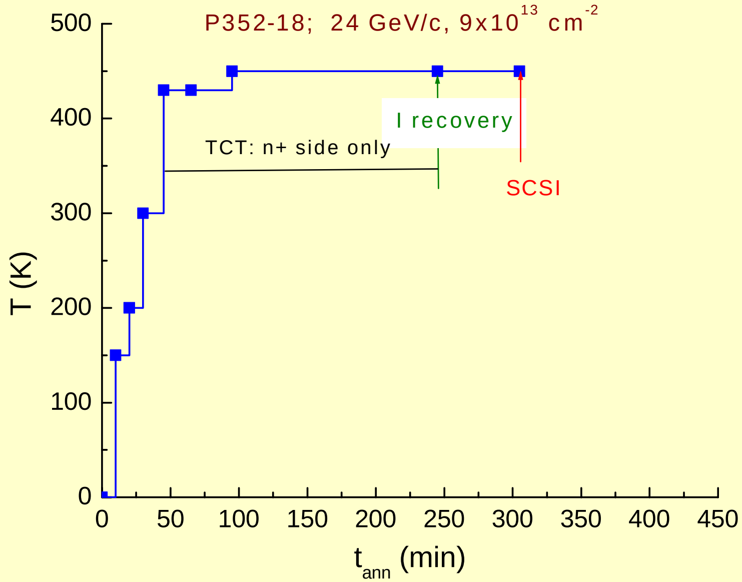
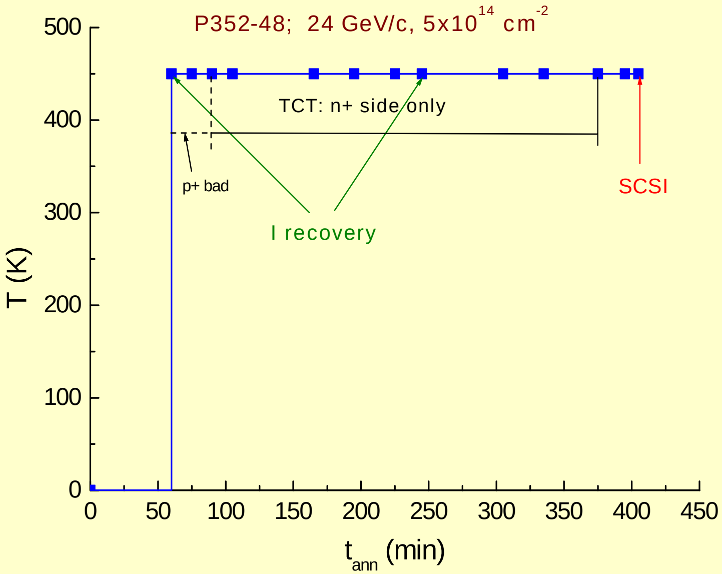
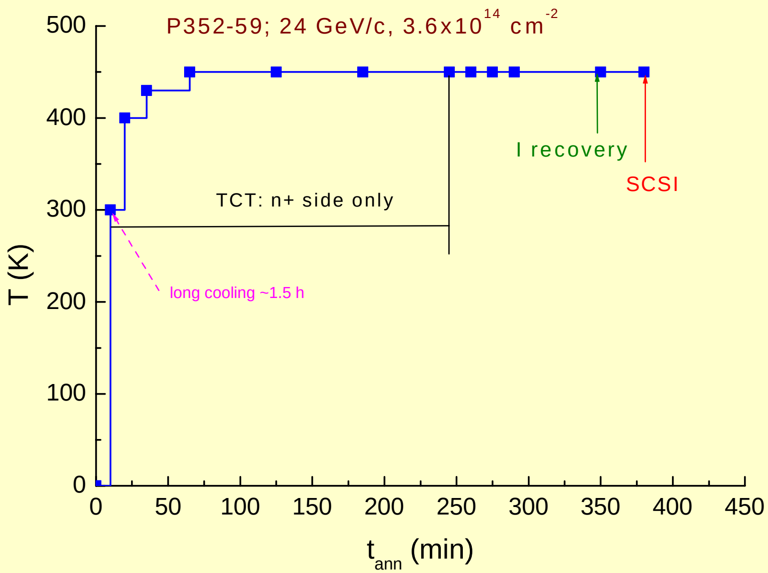
Annealing of detectors irradiated by 24 GeV/c protons







Compensation of acceptor-type radiation induced defects: Thermal Donors are introduced at 430-450°C

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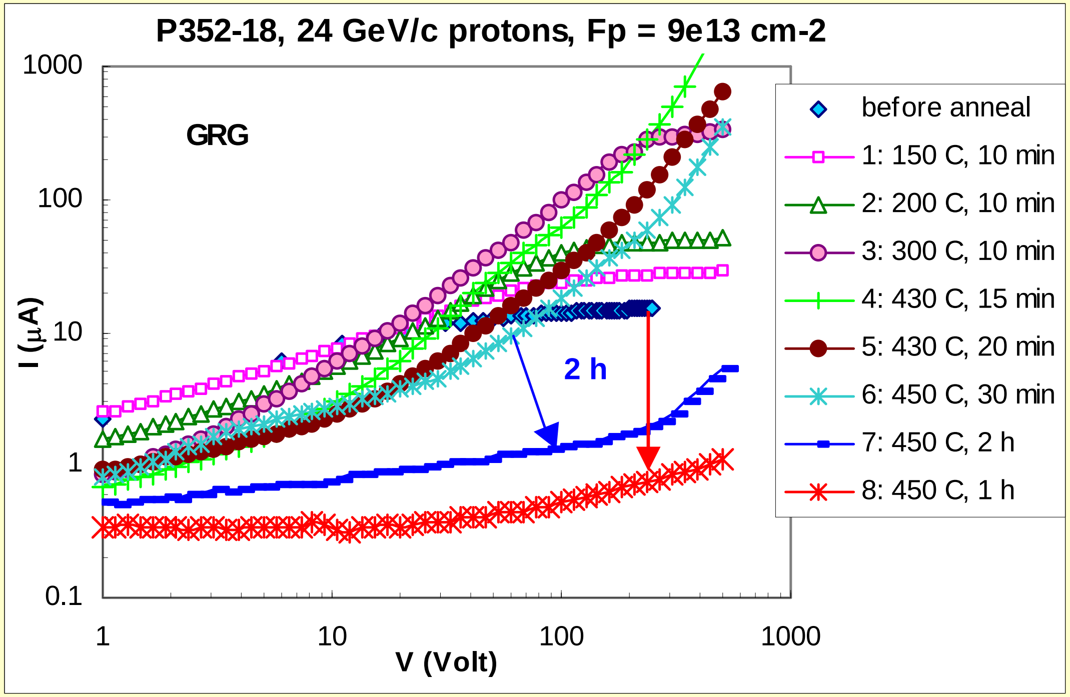
Recovery of reverse current

24 GeV protons, P352-18, $F_p = 9 \cdot 10^{13}$ cm^{-2}



150-300°C –
I_{rev} is still saturated

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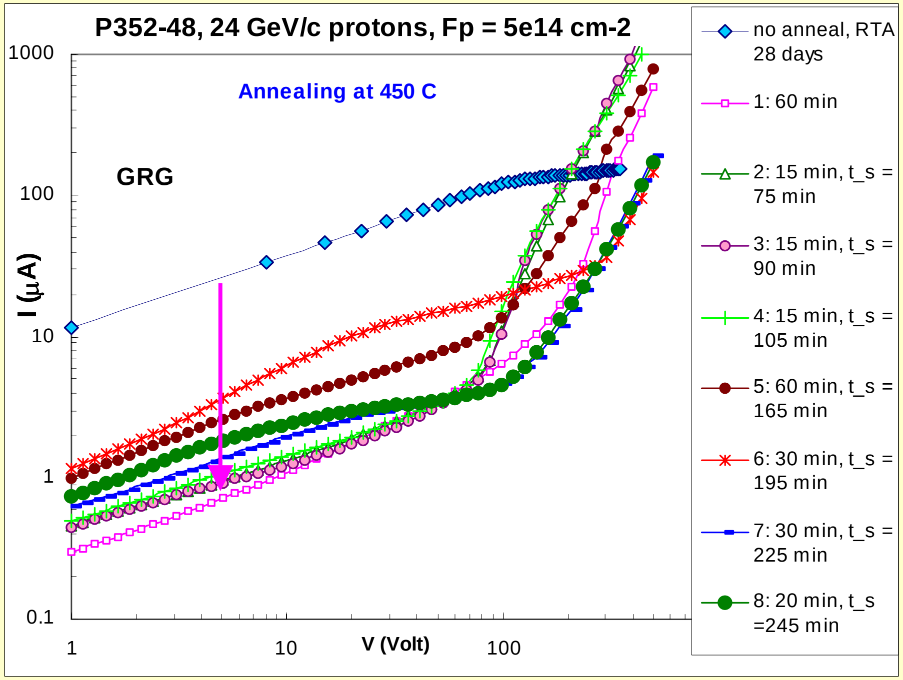
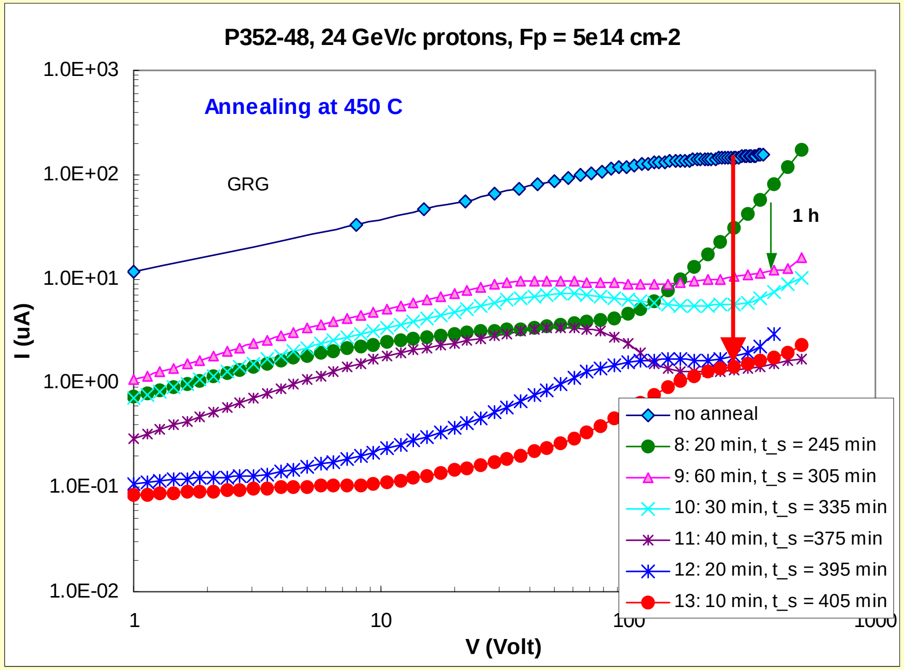
24 GeV protons, P352-48, $F_p = 5 \cdot 10^{14}$ cm^{-2}

T = 450°C





- Bulk current decreases after 1st anneal, but the leakage arises
- t_{ann} = 305 min: I_{rev} becomes saturated

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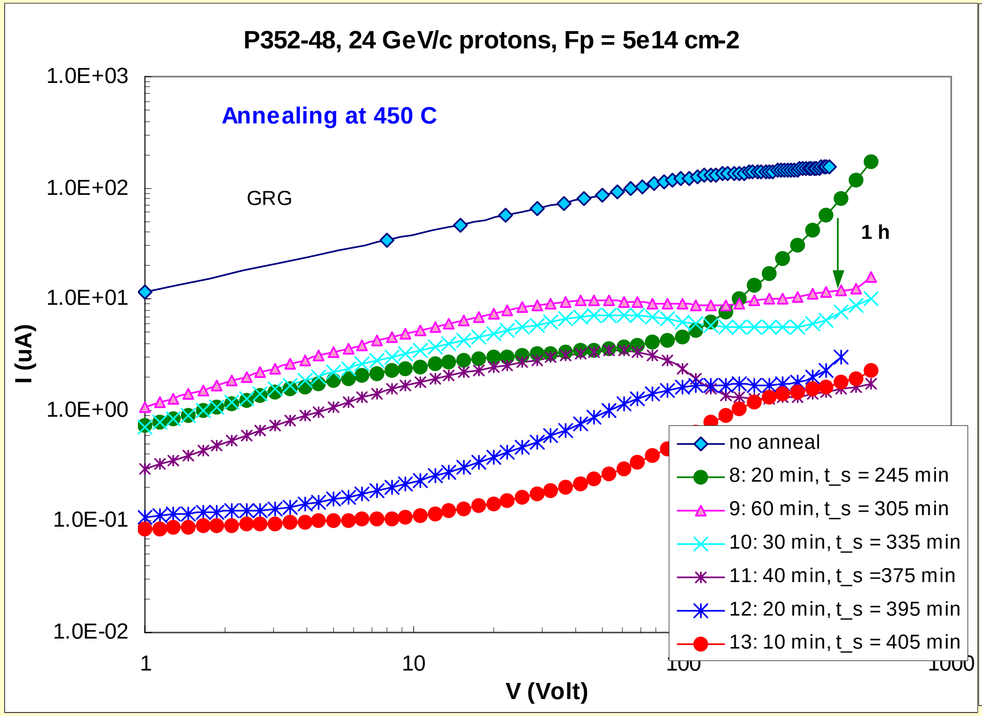
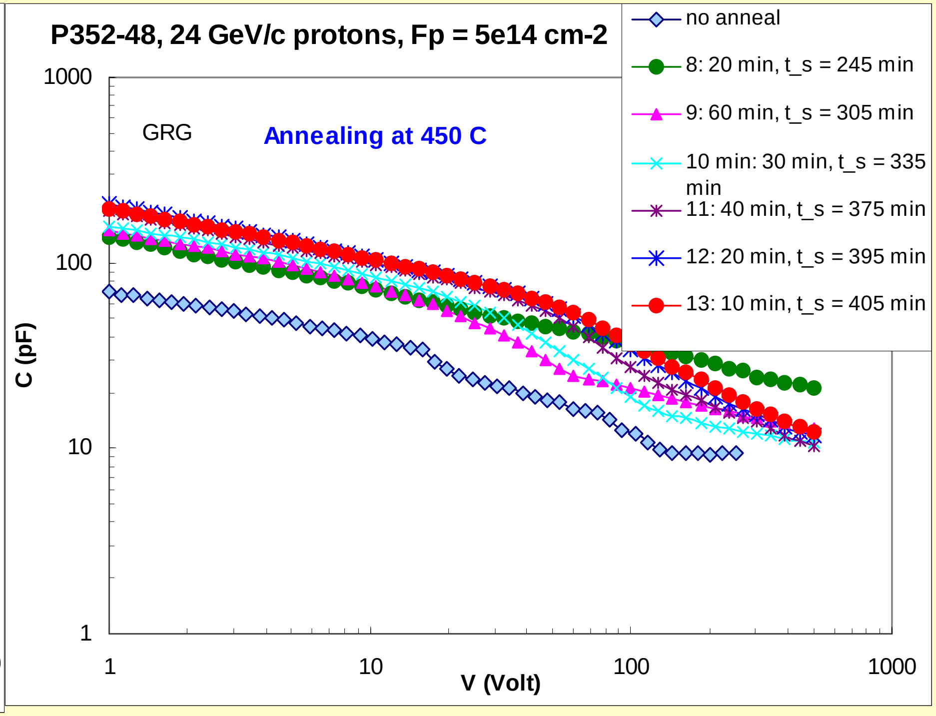
Comparison between reverse current and capacitance annealings





C increase – changes of Si-SiO_2 properties?

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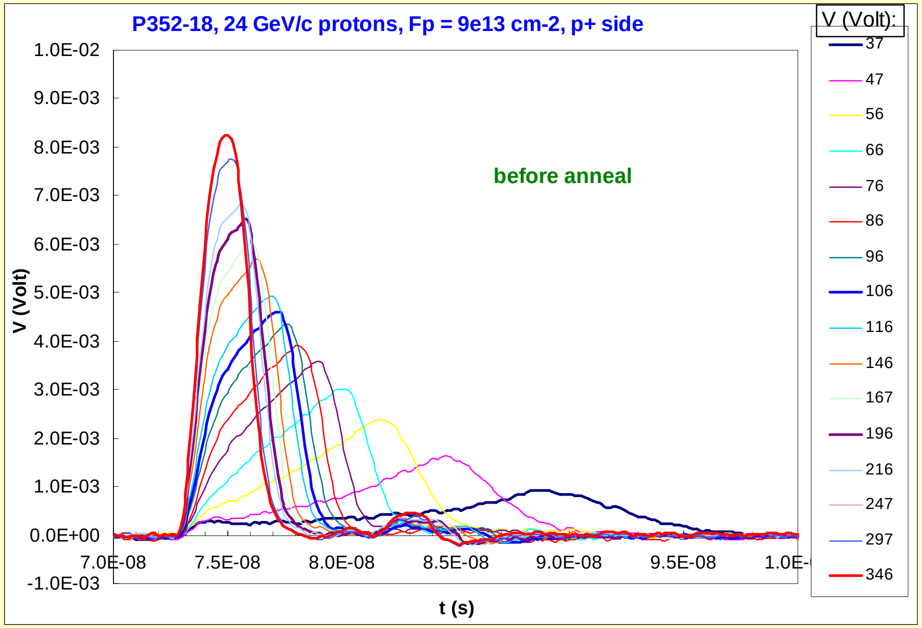
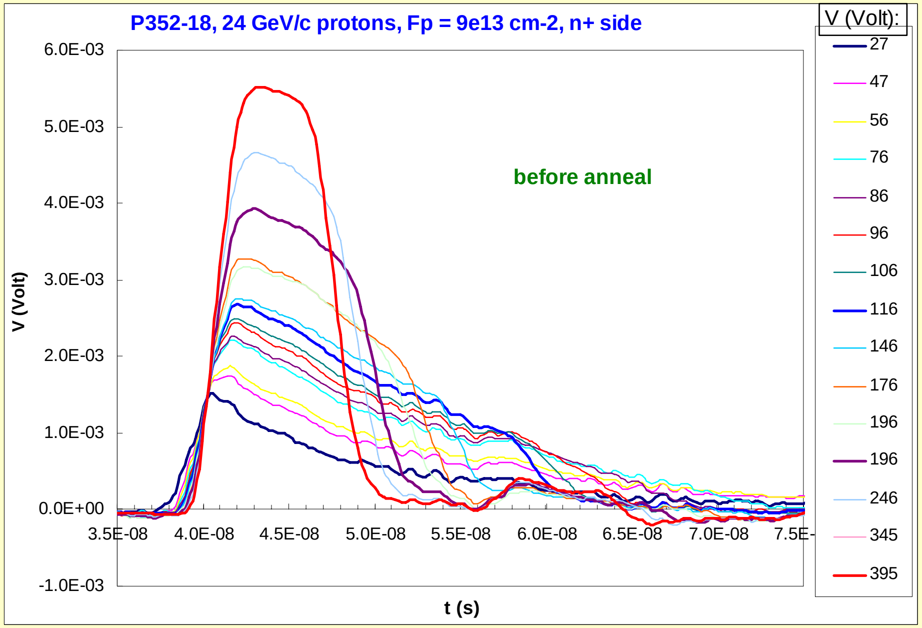
Changes of TCT signal: $F_p = 9 \cdot 10^{13}$ cm^{-2}, P352-18





SC (-)

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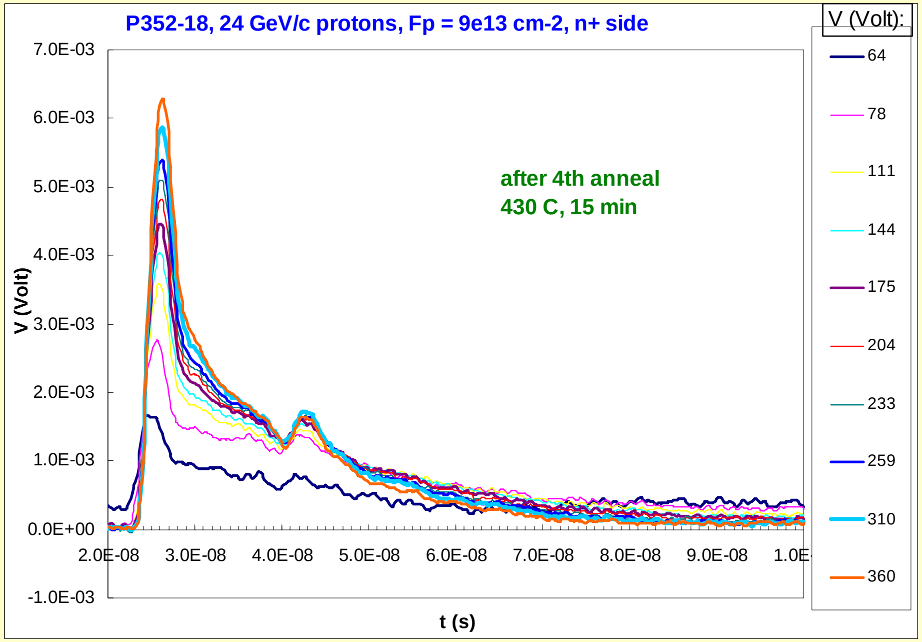
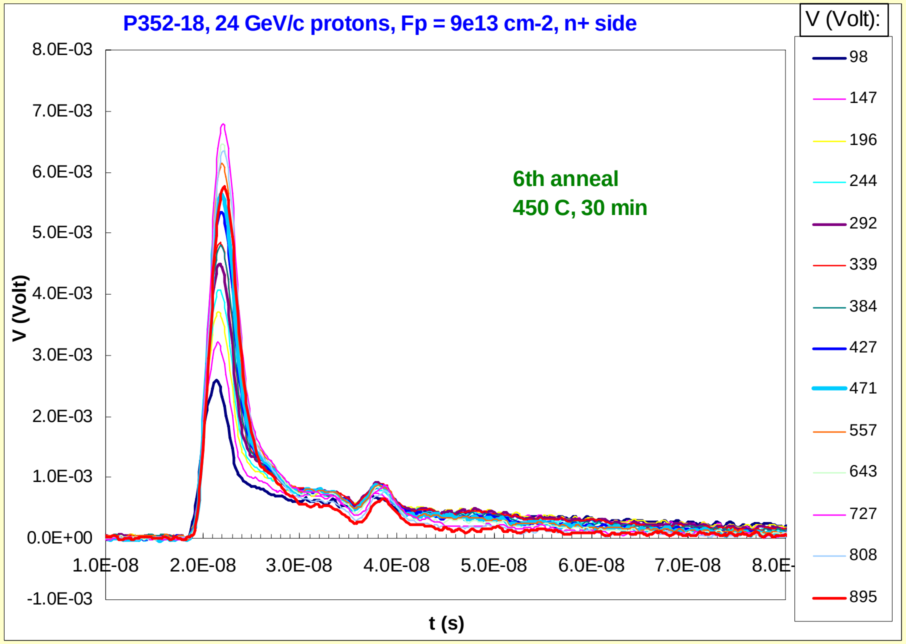
T ≥430°C: signal only from n$^+$ side





Time constant of response slow component decreases with bias voltage increase that may be only due to W reduction

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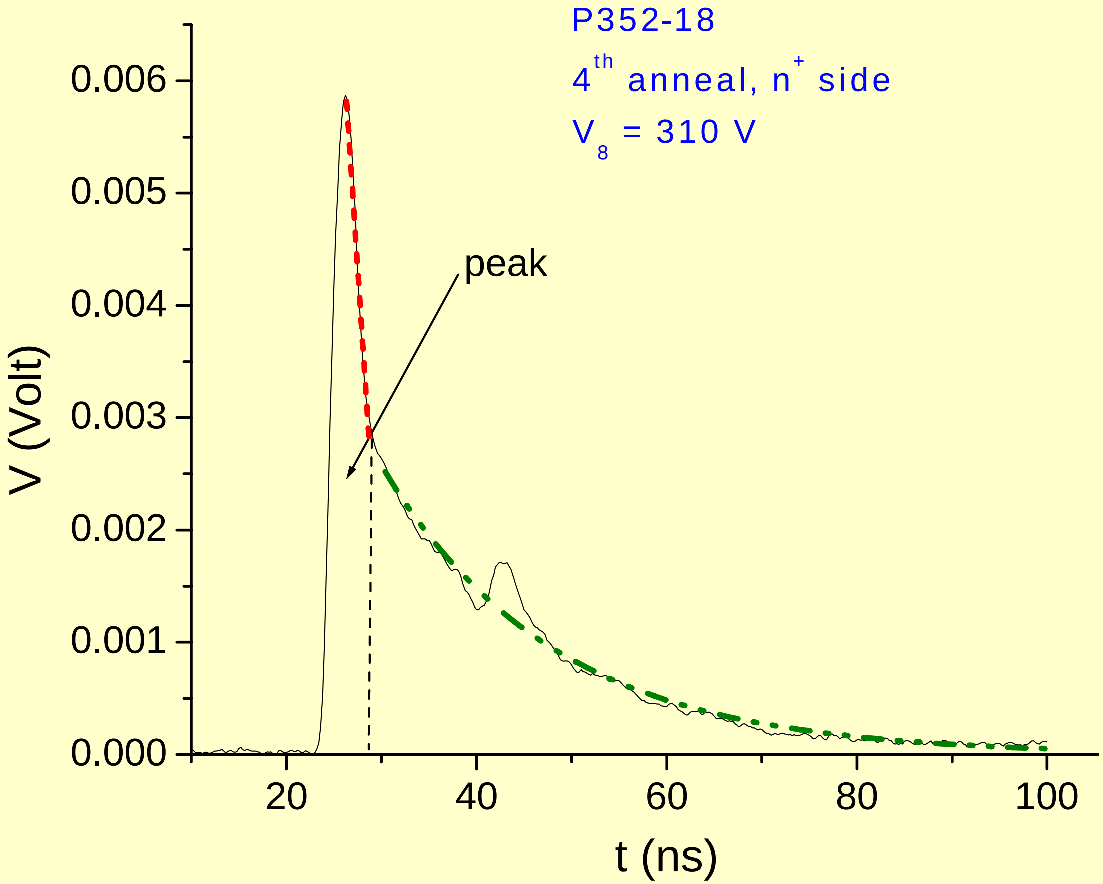
Processing TCT signal with a "tail"



$Q_{peak}/Q_{col} \sim W/d$

At n^+ contact:

$$W \sim \sqrt{V / N_{eff}}$$

By integrating TCT curves we can obtain Q_{peak}/Q_{col} and N_{eff} can be defined from $W^2(V)$ linear dependence

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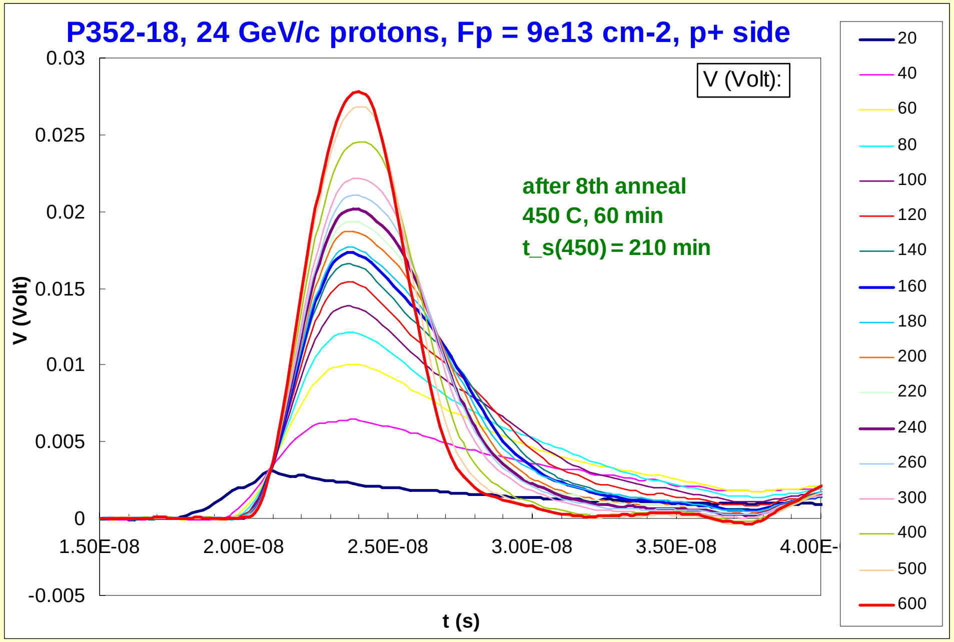
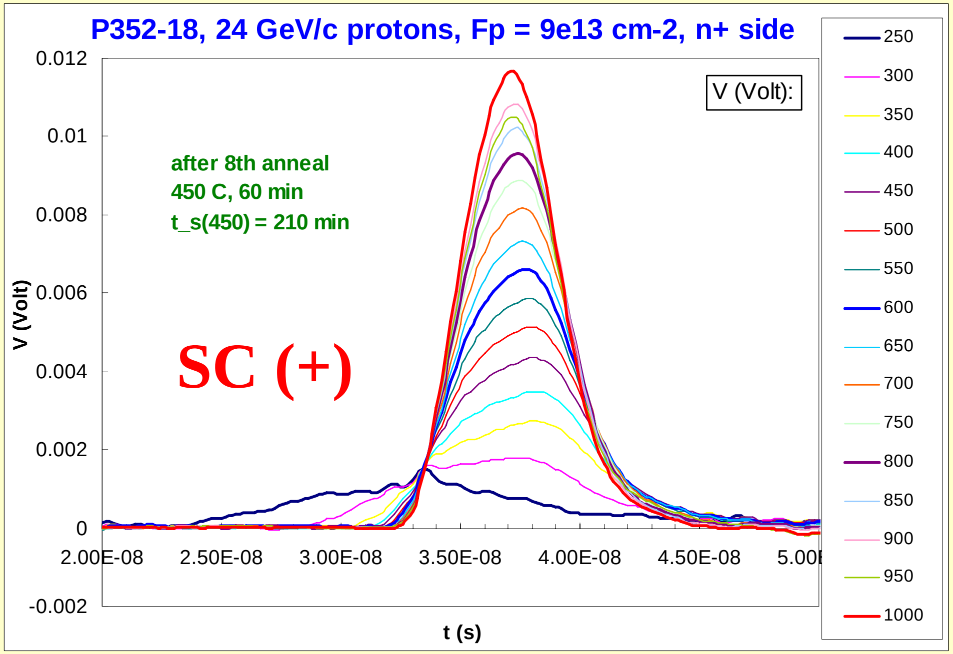
SCSI: T = 450°C, t_{ann}(450C) = 210 min





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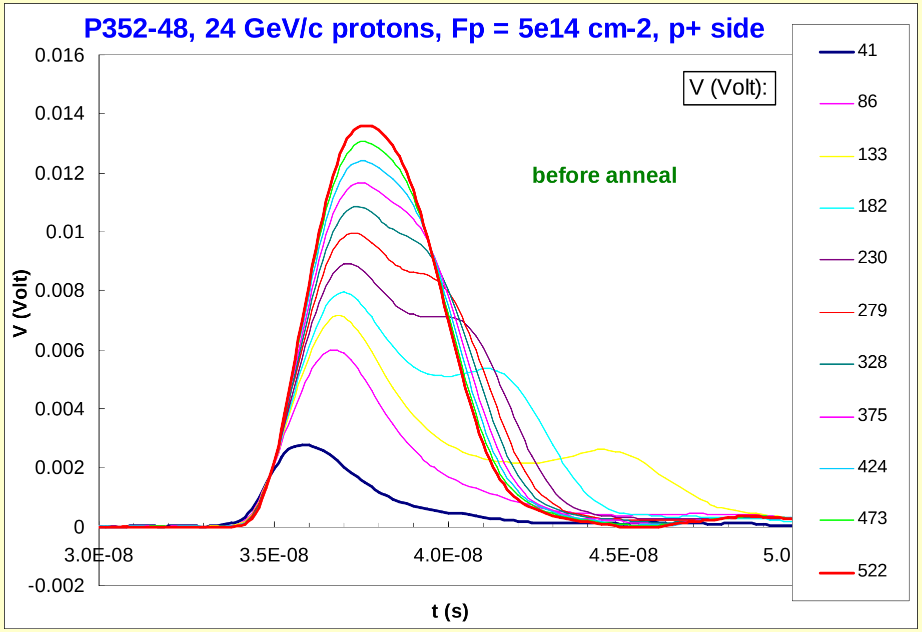
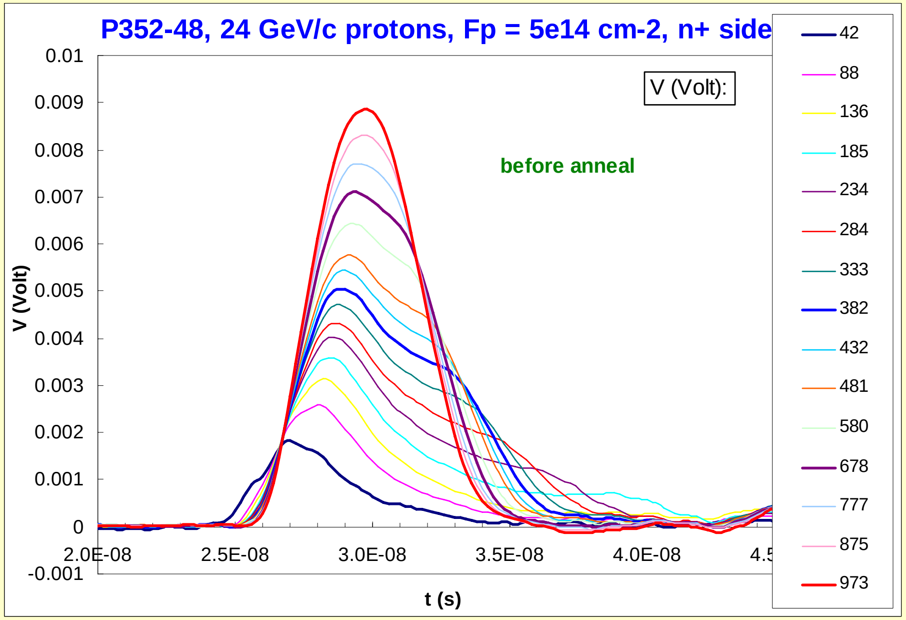
Changes of TCT signal: $F_p = 5 \cdot 10^{14}$ cm^{-2}, P352-48





Larger F_p: DP signal shape

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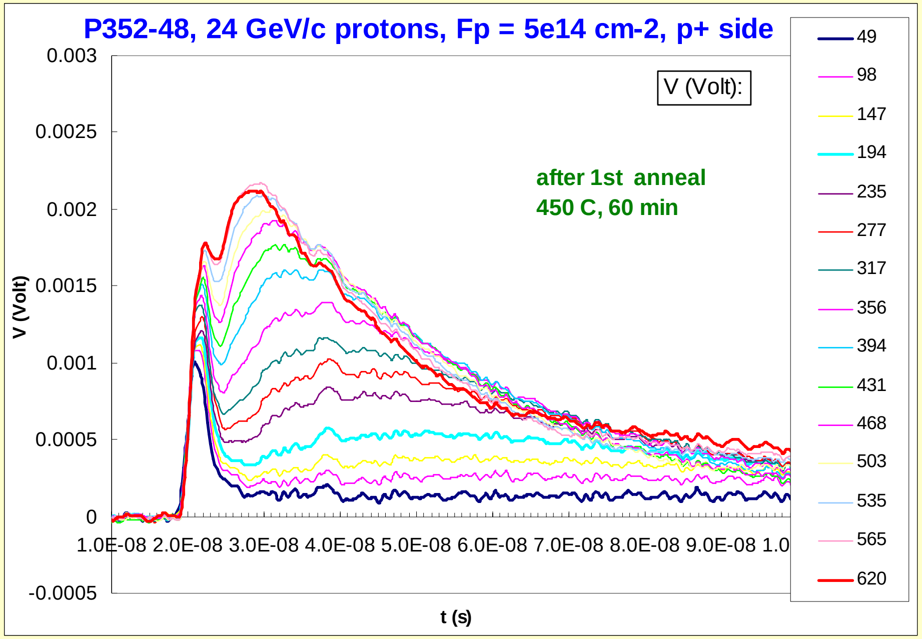
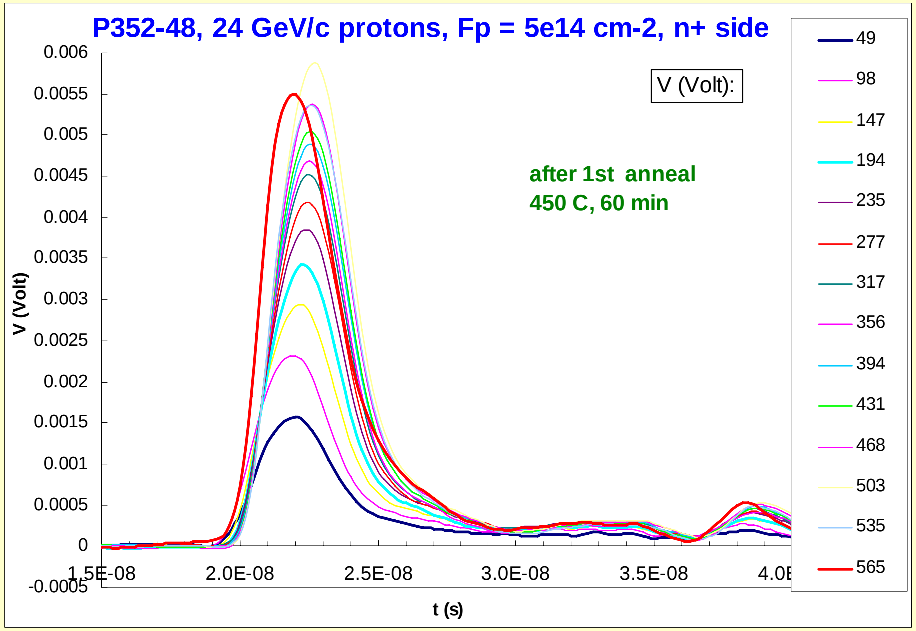
T = 450°C at all annealing steps





Signal from p$^+$ side:

- pinch-off occurs
- slow component: detrapping (time constant is independent on V

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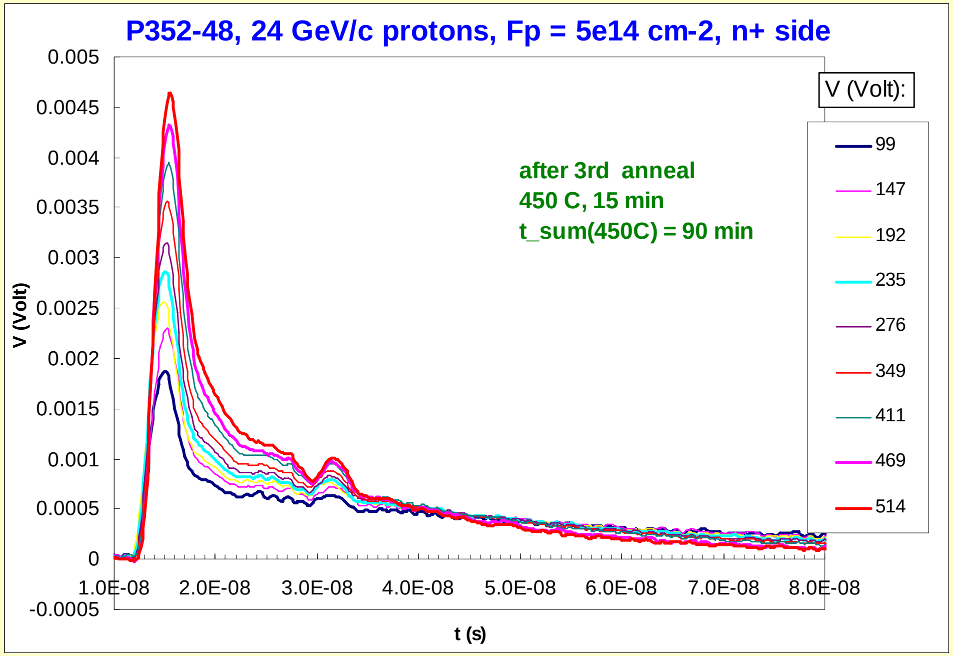
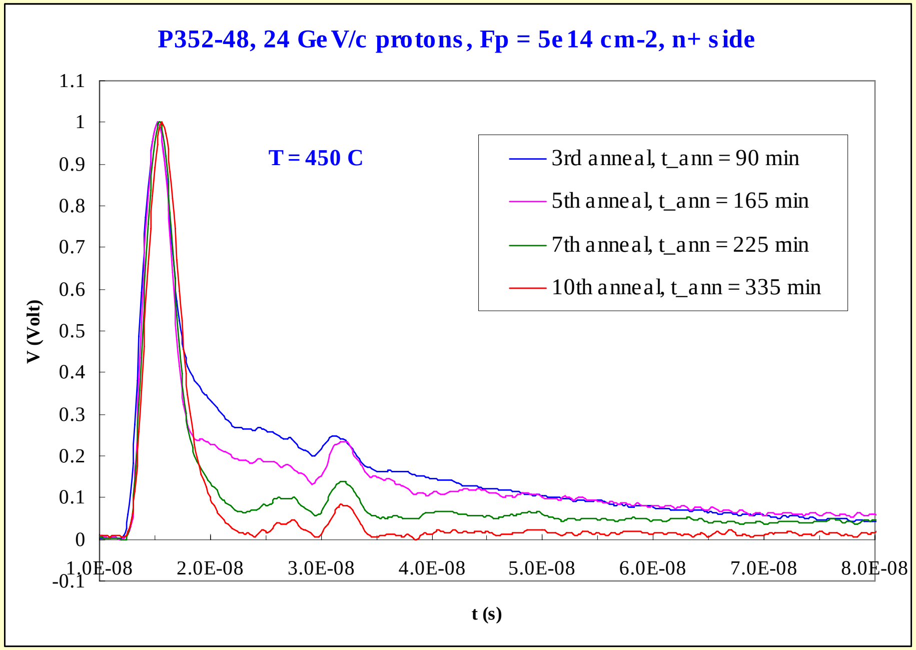
T = 450°C, t_{ann} = 90-335 min: signal only from n^+ side





Time constant changes with t_{ann}
(t_{ann} = 90-335 min)

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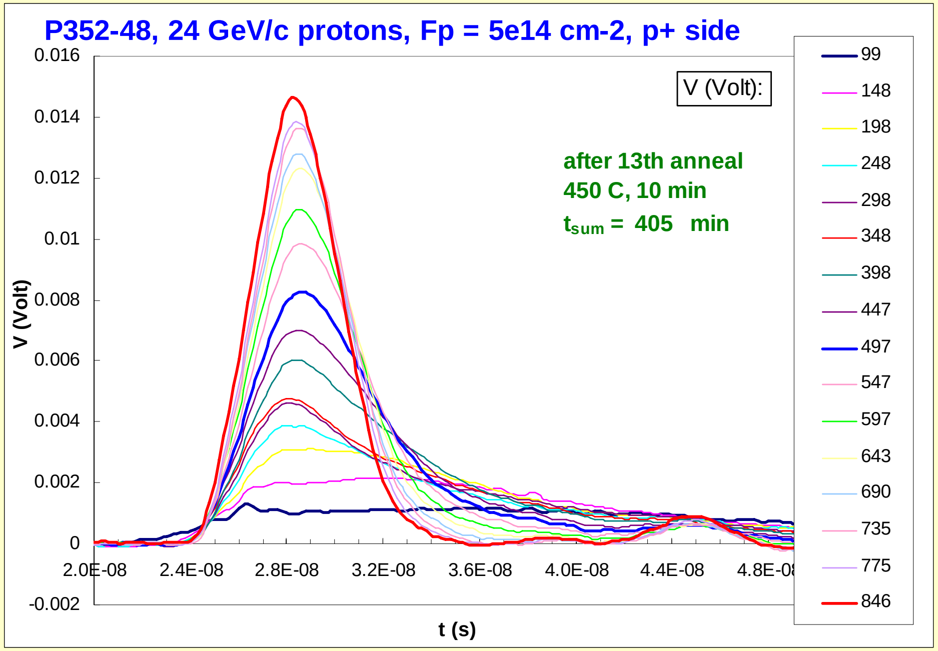
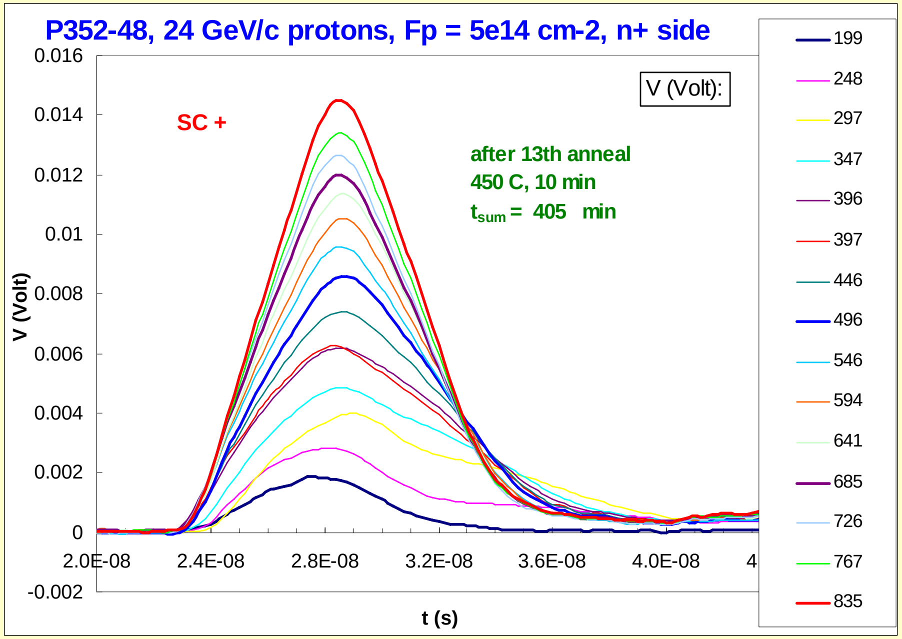
T = 450°C, t_{ann} = 335-405 min: recovery of signal from p^+ side ⇒ SCSI





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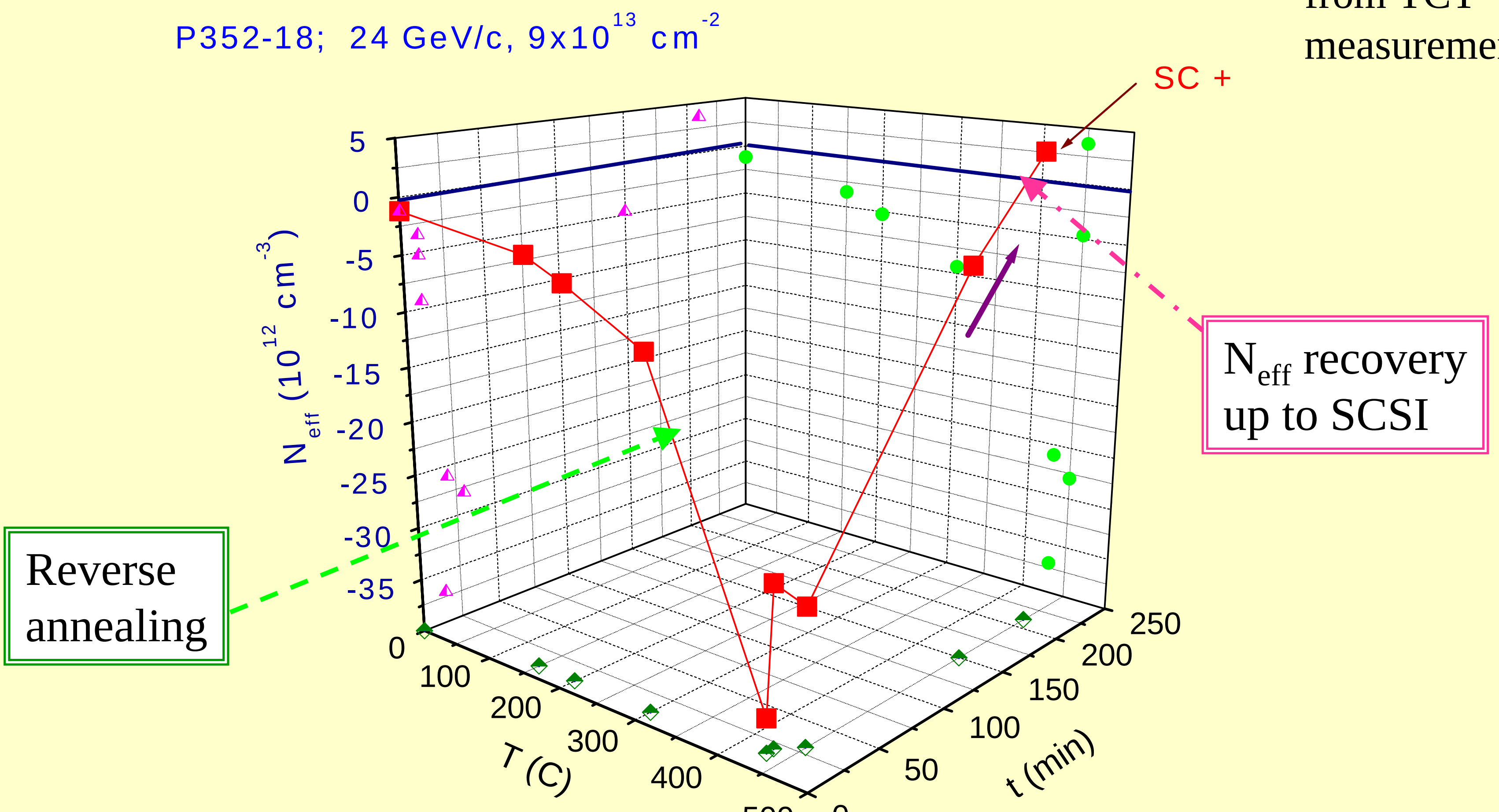
N_{eff} evolution

N_{eff} derived from TCT measurements



green dots: N_{eff} vs. T projection

magenda triangles: N_{eff} vs. t_{ann} projection

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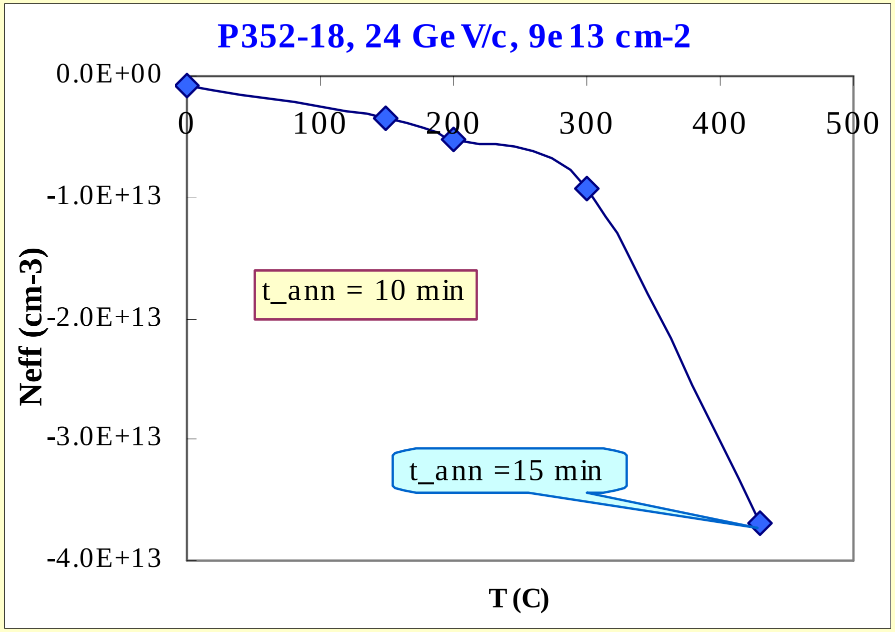
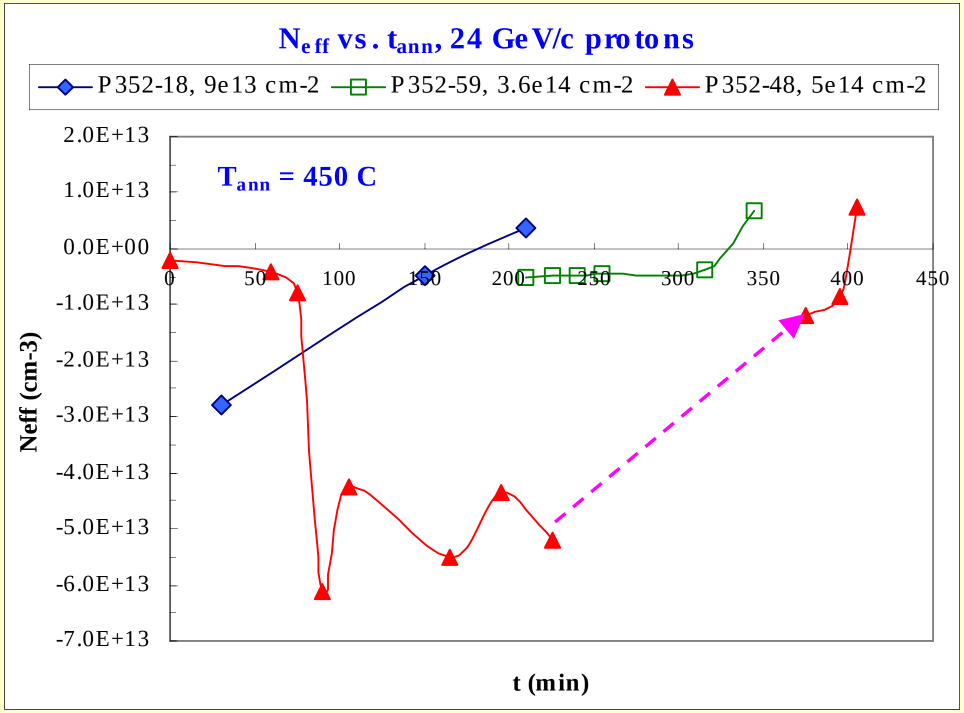
N_{eff} evolution

Range of reverse annealing



Range of TD introduction



Finally

Fp (cm-2)	Vfd (Volt)	Neff (cm-3)
9.00E+13	250	3.6E+12
3.60E+14	460	6.7E+12
5.00E+14	500	7.3E+12

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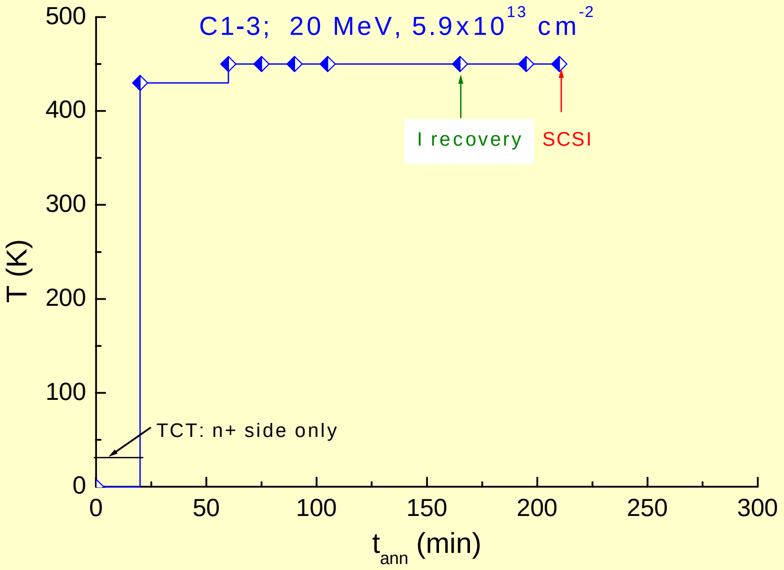
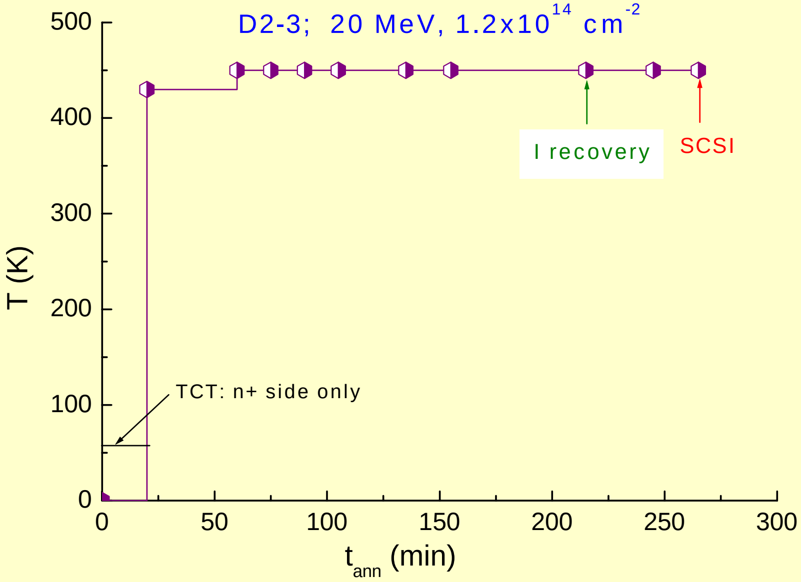
Annealing of detectors irradiated by 20 MeV protons





Compensation of acceptor-type radiation induced defects: Thermal Donors are introduced at 430-450°C

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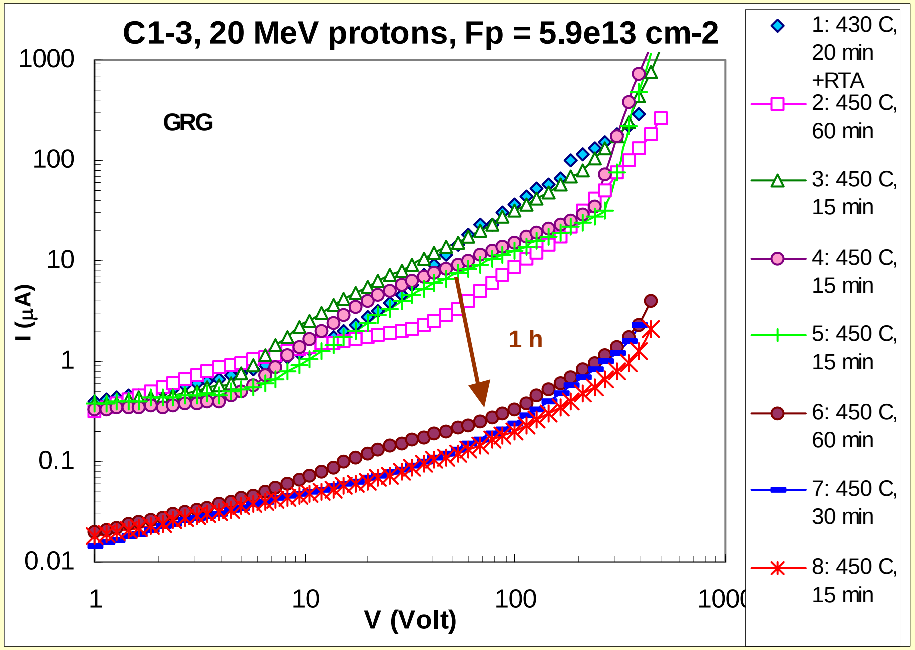
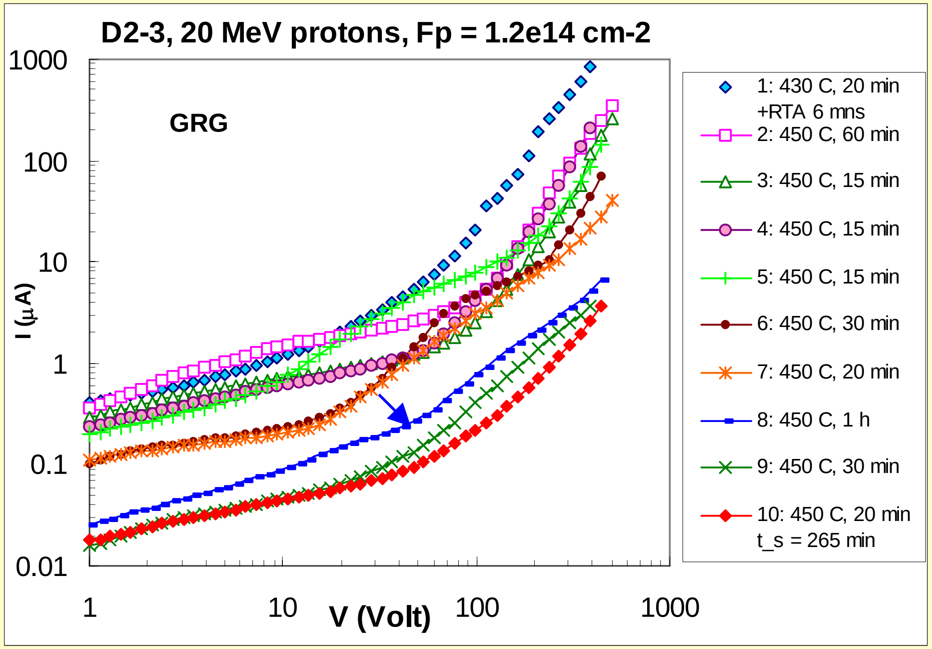
Recovery of reverse current





Leakage is observed in I-V curves

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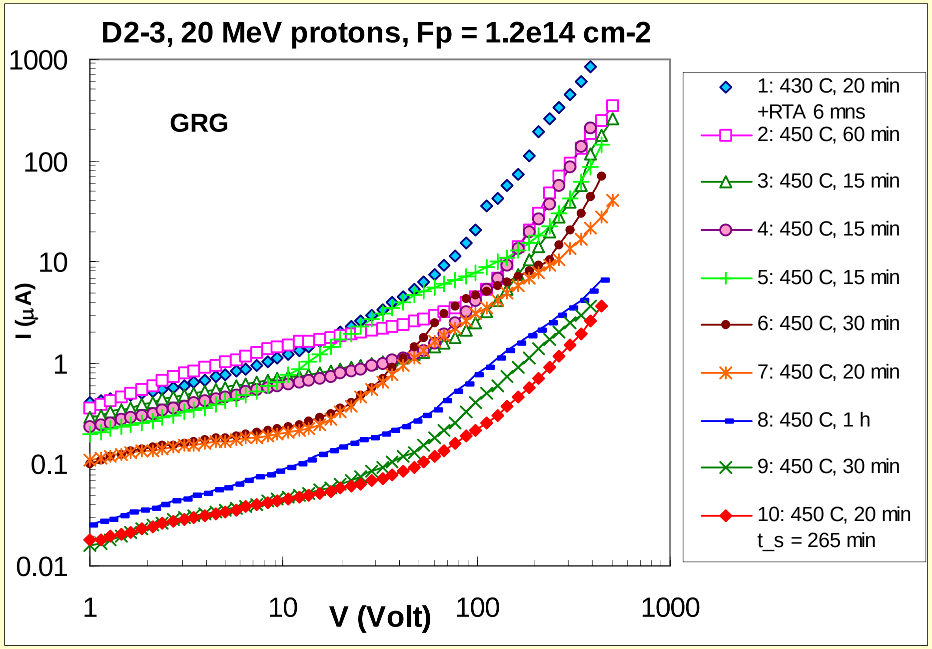
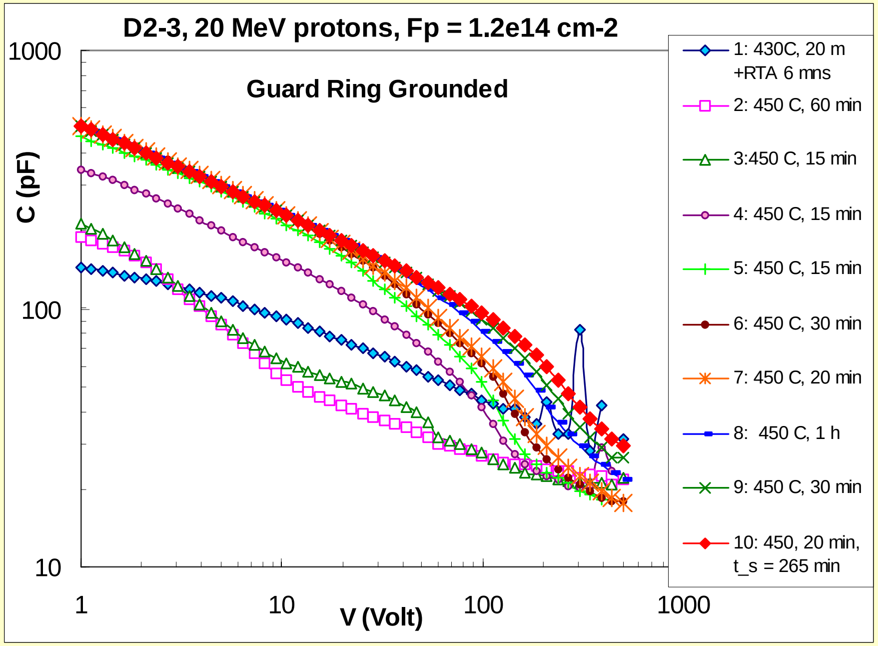
Comparison between reverse current and capacitance annealings





"Bump" in C-V curves disappears with annealing

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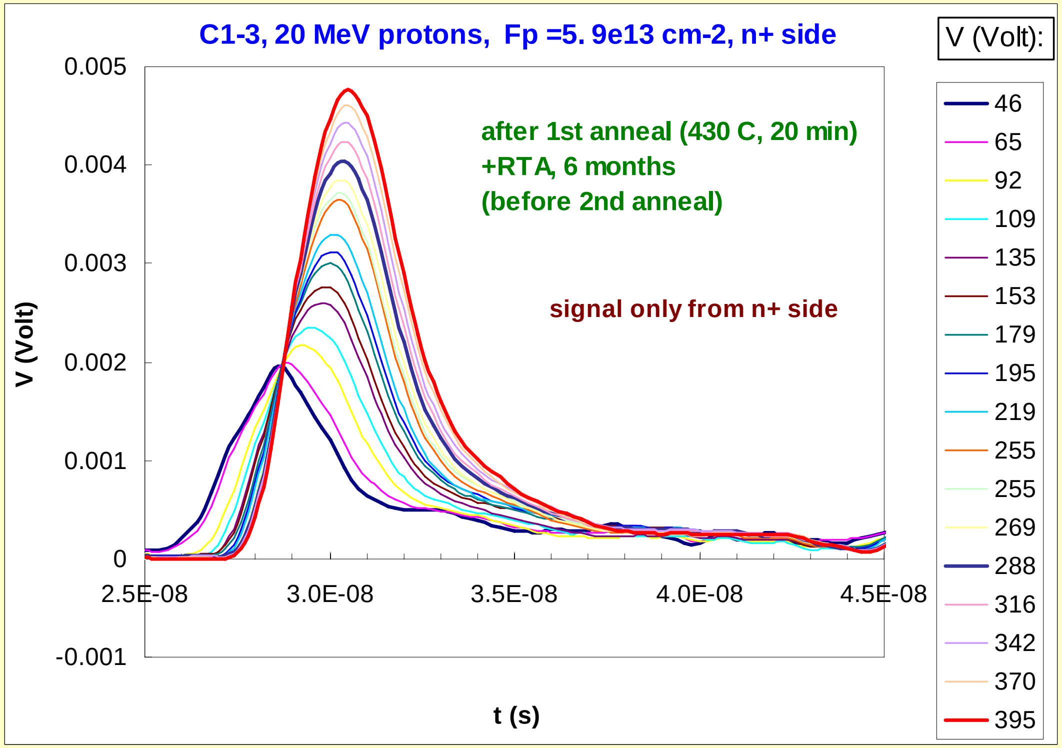
Changes of TCT signal: C1-3, 20 MeV, $F_p = 5.9 \cdot 10^{13}$ cm^{-2}



Initial stage of annealing:
430°C, 20 min
+ RTA, 6 months

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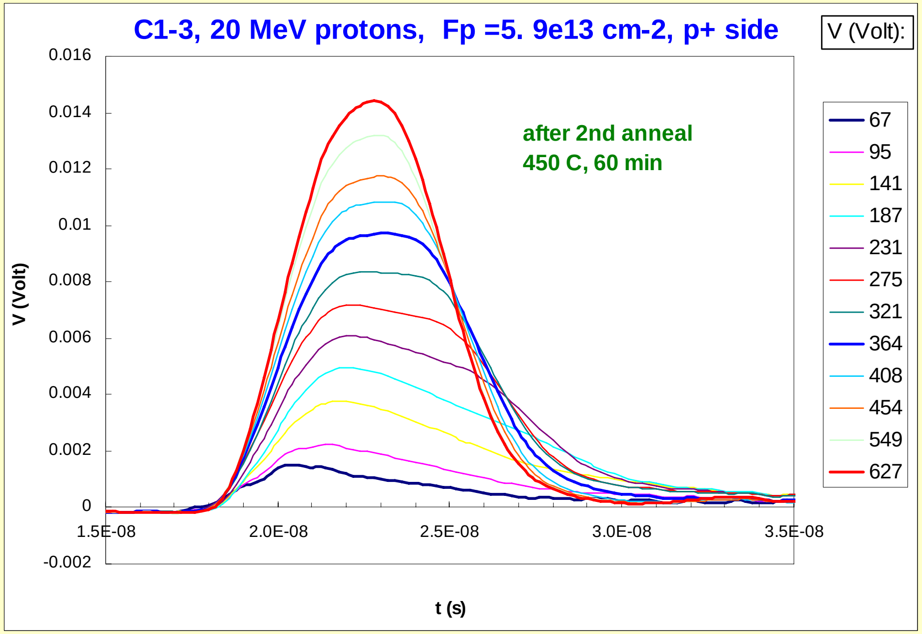
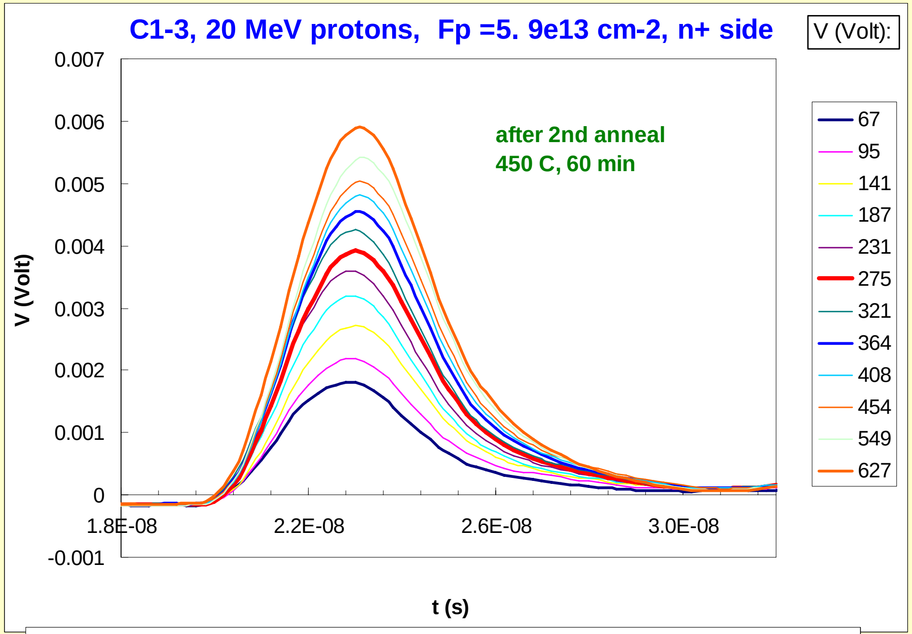
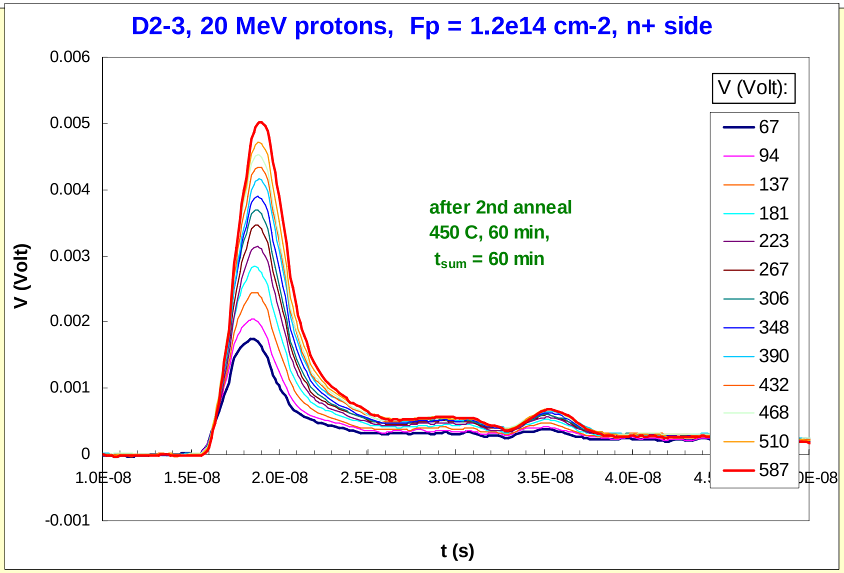
All annealings at T = 450°C: TD introduction





2nd anneal, 450°C, 60 min:

- **recovery of TCT signal from p^+ side for both F_p**
- **D2-3, $F_p = 1.2 \cdot 10^{14}$ cm^{-2}: "tail" in signal from n^+ side**



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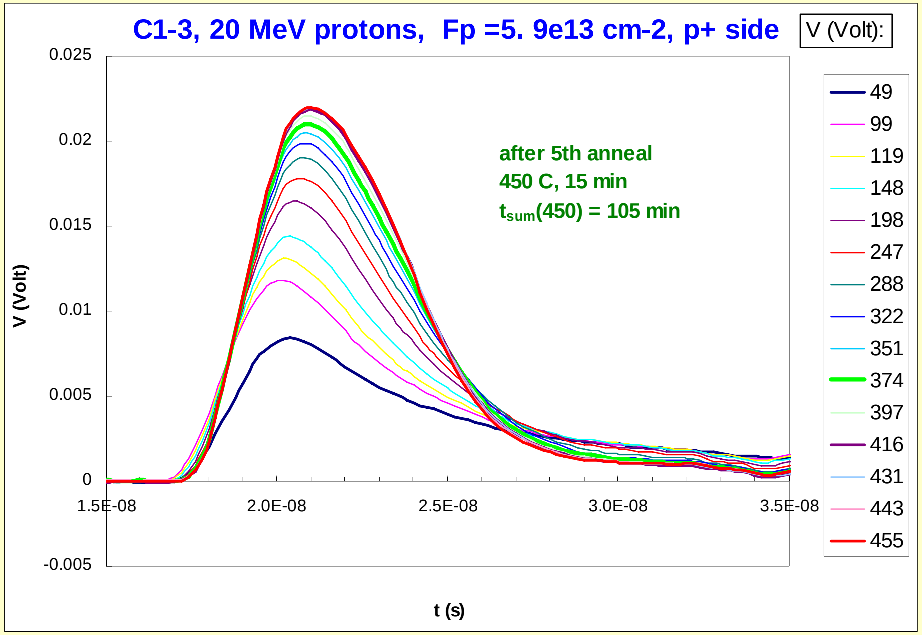
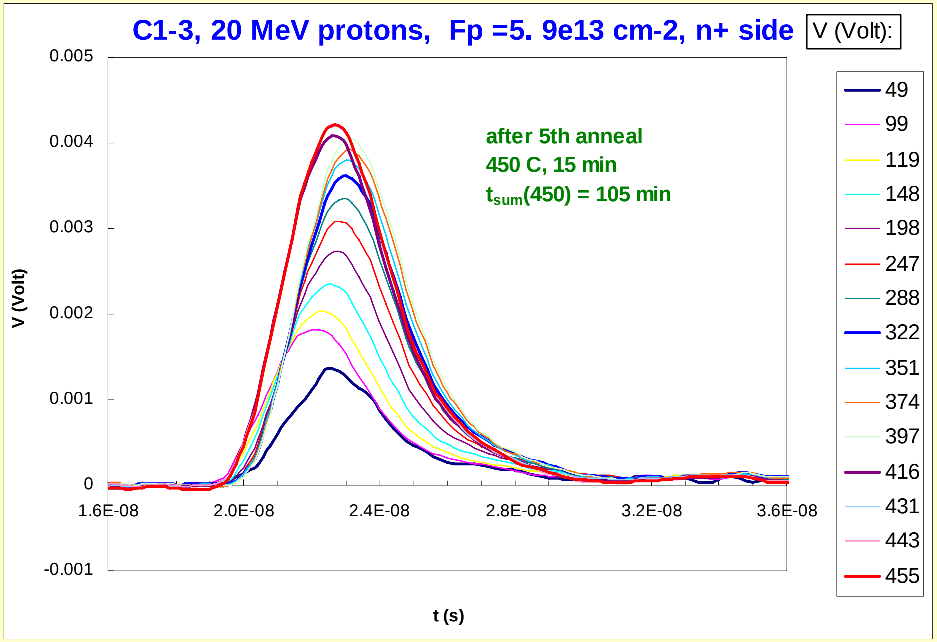
All annealings at T = 450°C: TD introduction





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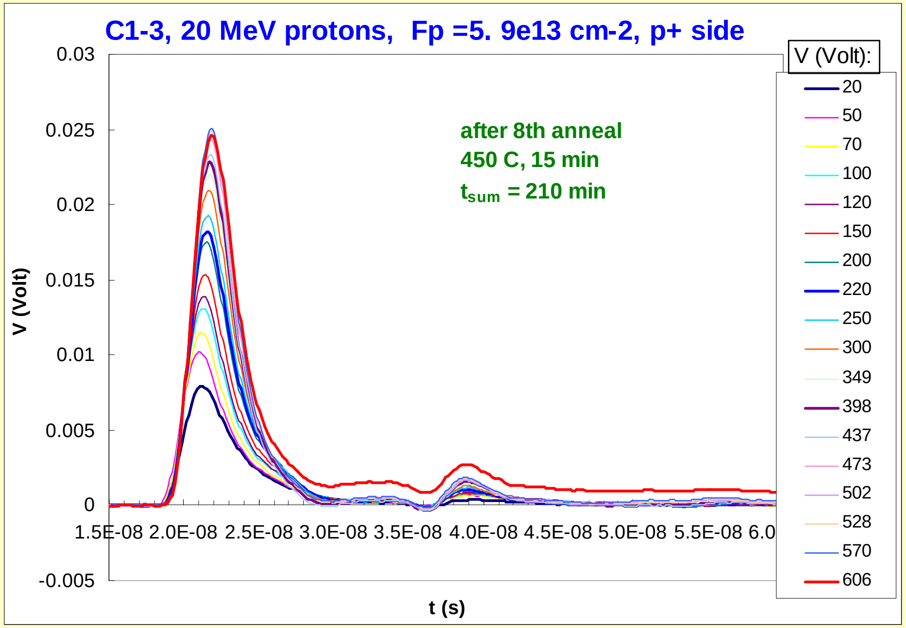
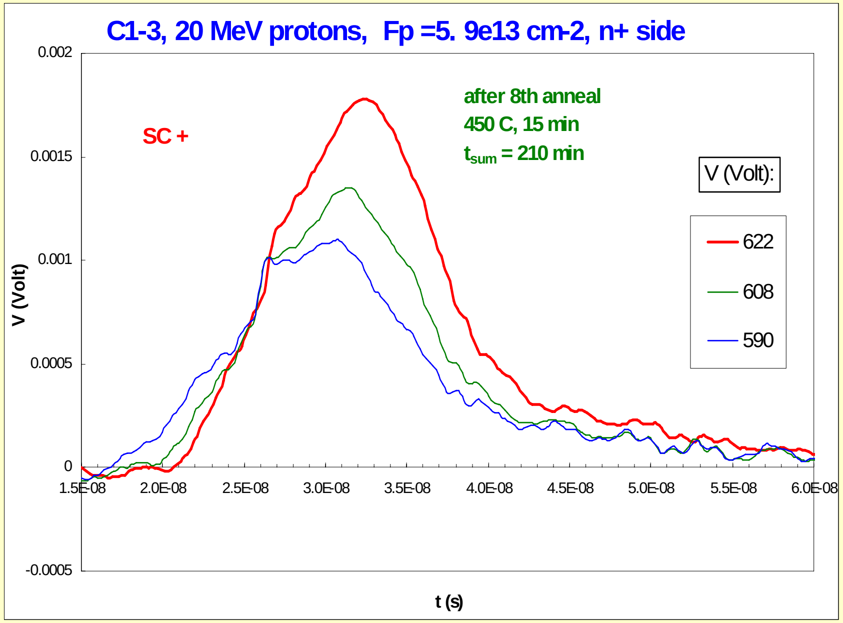
C1-3, $F_p = 5.9 \cdot 10^{13}$ cm^{-2}; T = 450°C, t_{ann} = 210 min: SCSI





- **After final anneal for both detectors irradiated by 20 MeV protons:**

  signal from p+ side: starts at 20 V

  signal from n+ side: starts at 590 V

- **t_{ann} for SCSI is different:**

  C1-3, $F_p = 5.9 \cdot 10^{13}$ cm^{-2}: 210 min

  D2-3, $F_p = 1.2 \cdot 10^{14}$ cm^{-2}: 265 min

Future task:
N_{eff} calculations

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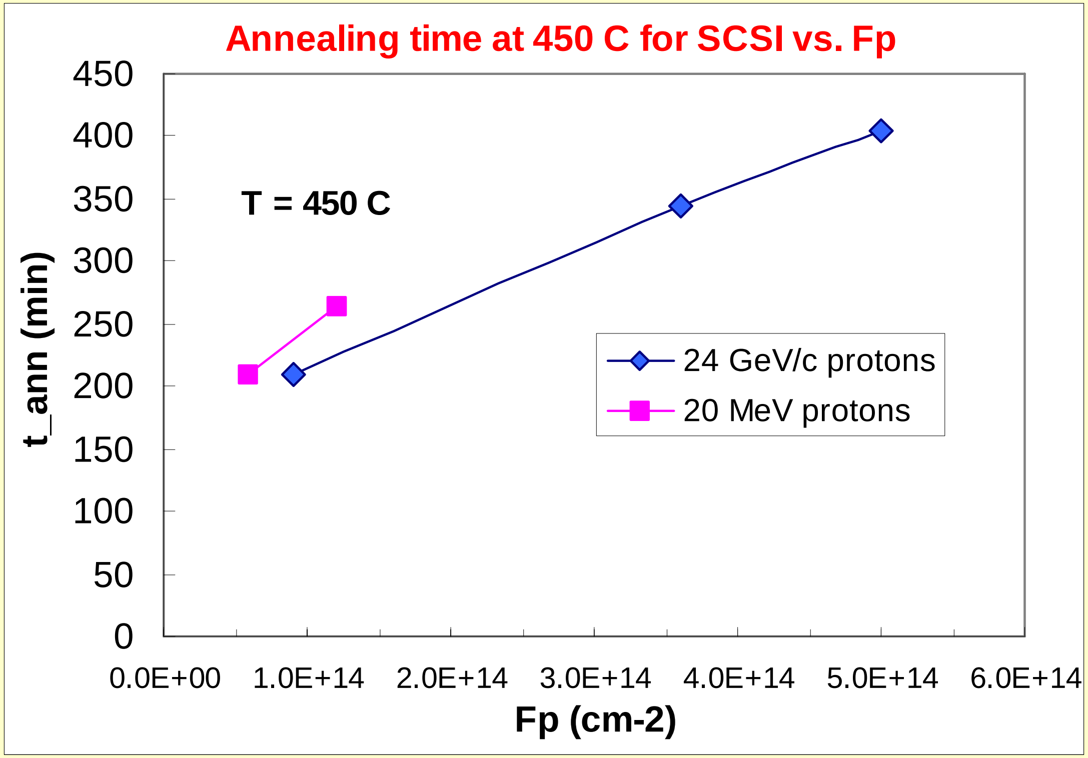
Annealing time at 450 ℃ required for SCSI



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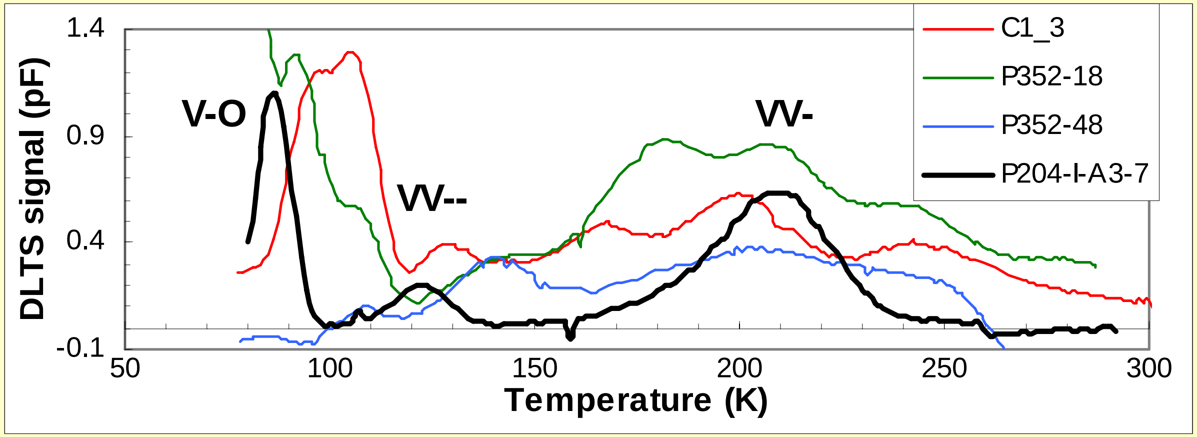
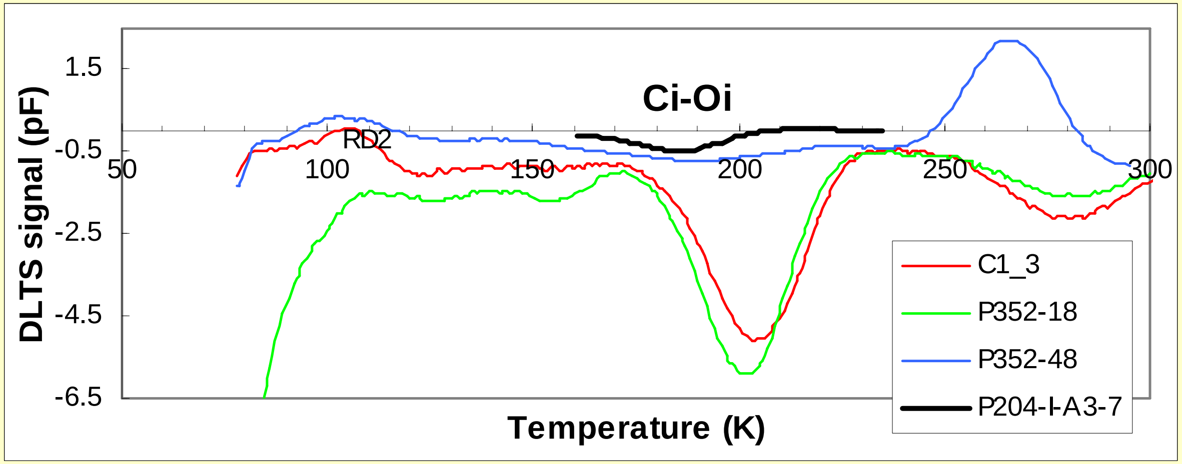
Defect spectra after SCSI



C-DLTS spectra

Reference spectra:
P204-I-A3-7:
24 GeV/c
$F_p = 1.5 \cdot 10^{11}$ cm^{-2}

with injection



- **Continuous defect spectra**
- **Increase of t_{ann} is favorable**

(for P352-48 t_{ann} is maximal)

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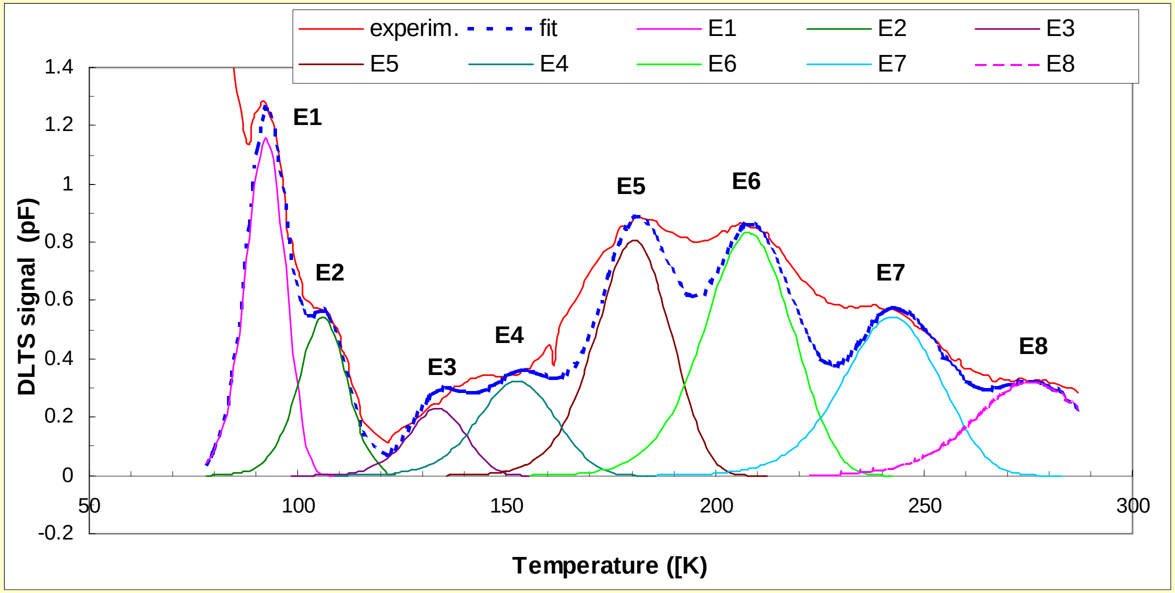
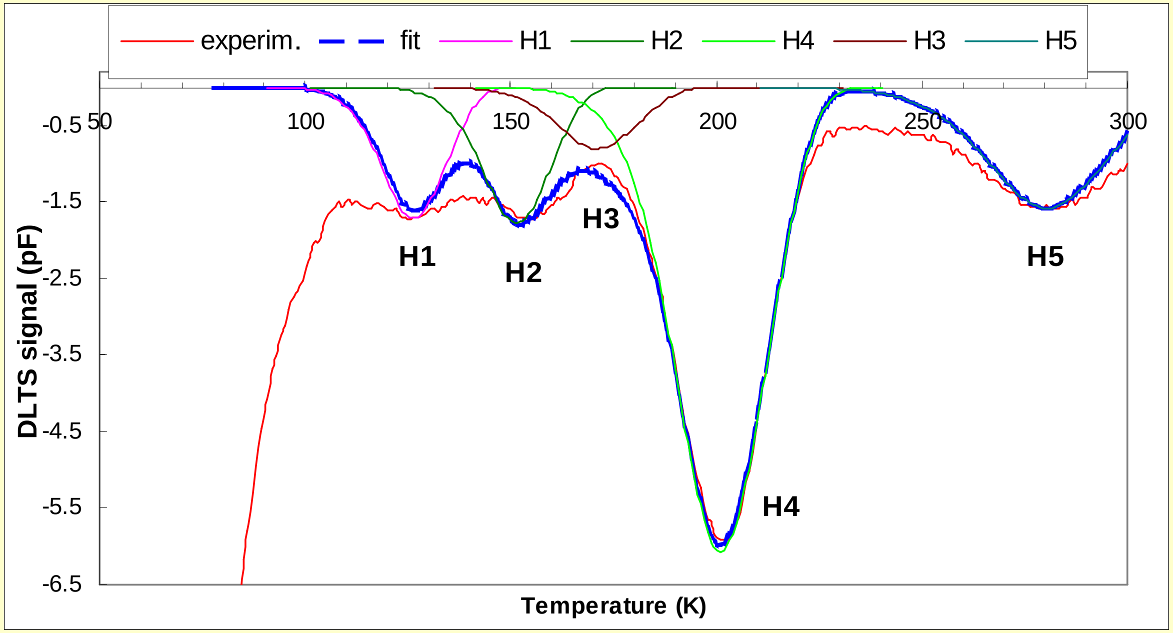
P352-18
24 GeV/c, $9\cdot10^{13}$ cm^{-2}



Electron traps



Hole traps

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Defect parameters

P352-18
24 GeV/c, $9\cdot10^{13}$ cm^{-2}

Electron traps

DL	E1	E2	E3	E4	E5	E6	E7	E8
E (eV)	$E_c - 0.18$	$E_c - 0.196$	$E_c - 0.26$	$E_c - 0.25$	$E_c - 0.37$	$E_c - 0.41$	$E_c - 0.515$	$E_c - 0.6$
σ (cm2)	3.0E-15	7.0E-16	2.0E-15	3.0E-17	3.0E-15	1.0E-15	5.0E-15	2.0E-15
N (cm-3)	1.0E+12	4.5E+11	2.0E+11	2.8E+11	6.9E+11	7.2E+11	4.5E+11	2.6E+11

Hole traps

DL	H1	H2	H3	H4	H5
E (eV)	$E_v + 0.203$	$E_v + 0.28$	$E_v + 0.3$	$E_v + 0.37$	$E_v + 0.545$
σ (cm2)	1.0E-16	1.0E-15	3.0E-16	4.0E-16	1.0E-15
N (cm-3)	1.5E+12	1.6E+12	7.0E+11	5.4E+12	1.3E+12

- **Defects detected after annealing are presumably products of RDs decay**
- **Concentrations of defects after annealing are ≤10% of as-induced RD concentrations**
- **Minimal concentrations correspond to the maximal annealing time (P352-48)**
- **Resulting spectra are different from those in RD50 2004 report – difference in radiation (report – electron irradiation)**

Ways of ETA

May be different:

1) localized laser anneal;
2) localized anneal using a lamp;
3) annealing using pre-built-in external heating resistors;
4) annealing using leakage current of the detector itself.

4) is the easiest and most practical method

Fine tuning of the annealing time is required for precise manipulation of thermal donor introduction and resulting N_{eff} – further studies are needed

Conclusions

- Over-compensation of the negative space charge in proton irradiated oxygen-rich silicon detectors and **recovery of the initial positive space charge and detector reverse current** is realized by ETA at 450°C

- The dependence of the annealing time at 450°C required for SCSI through thermal donor introduction on the fluence of 24 GeV/c protons is linear irrespective to the thermal pre-history before thermal donor introduction

Future studies: statistics, FZ Si